Gravitational-wave sources and multi-messenger astronomy

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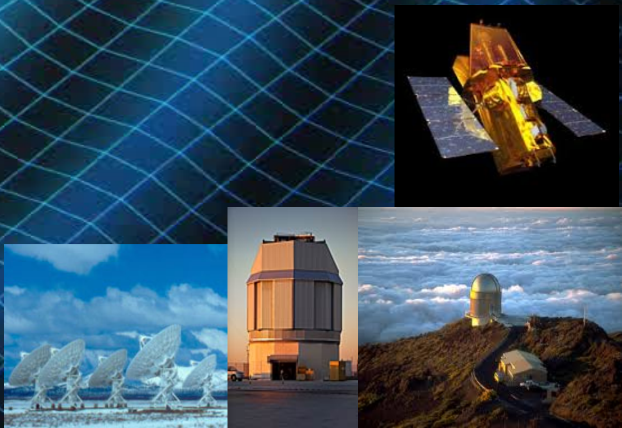
Gran Sasso Science Institute



The era of gravitational wave astrophysics

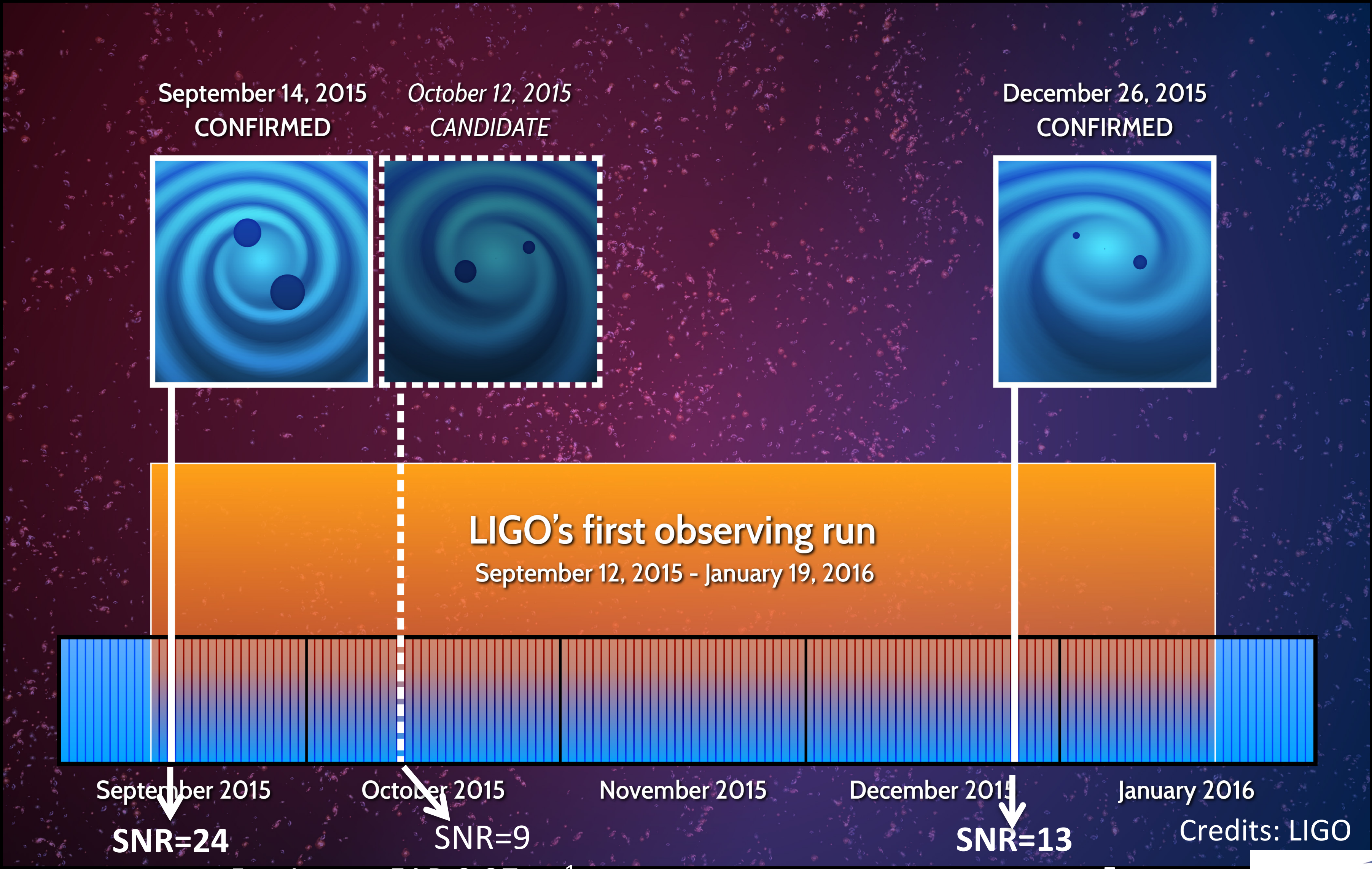
The first observing run O1 of Advanced LIGO lasted for months from September 12, 2015 to January 19, 2016

Total coincident time about 50 days

LSC

VIRGO

The era of GW astronomy started!



September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED

LIGO's first observing run
September 12, 2015 - January 19, 2016

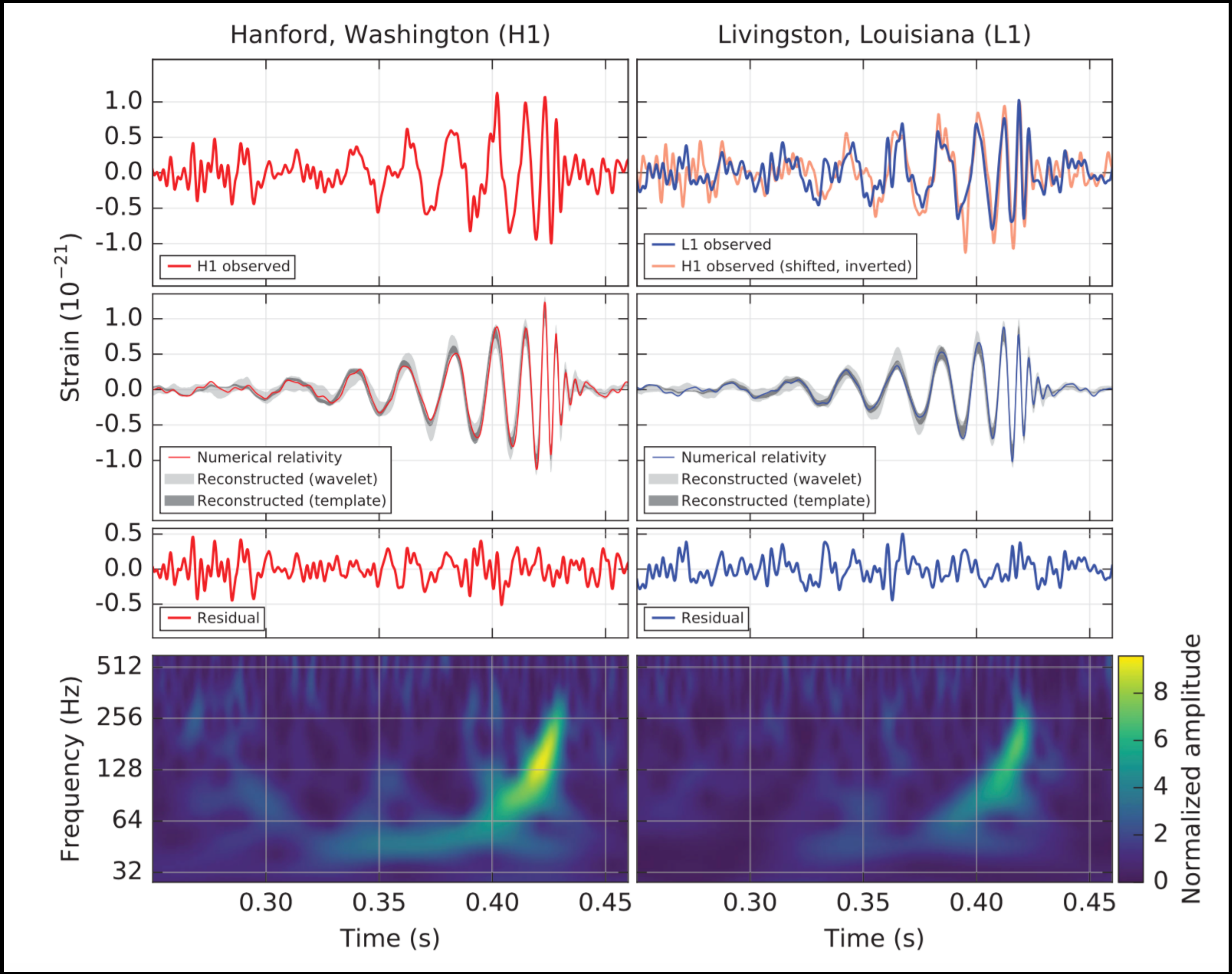
Credits: LIGO

SNR=24
FAR < 6 x 10^{-7} yr^{-1}
Significance > 5.3 σ

SNR=9
FAR 0.37 yr^{-1}
Significance = 1.7 σ

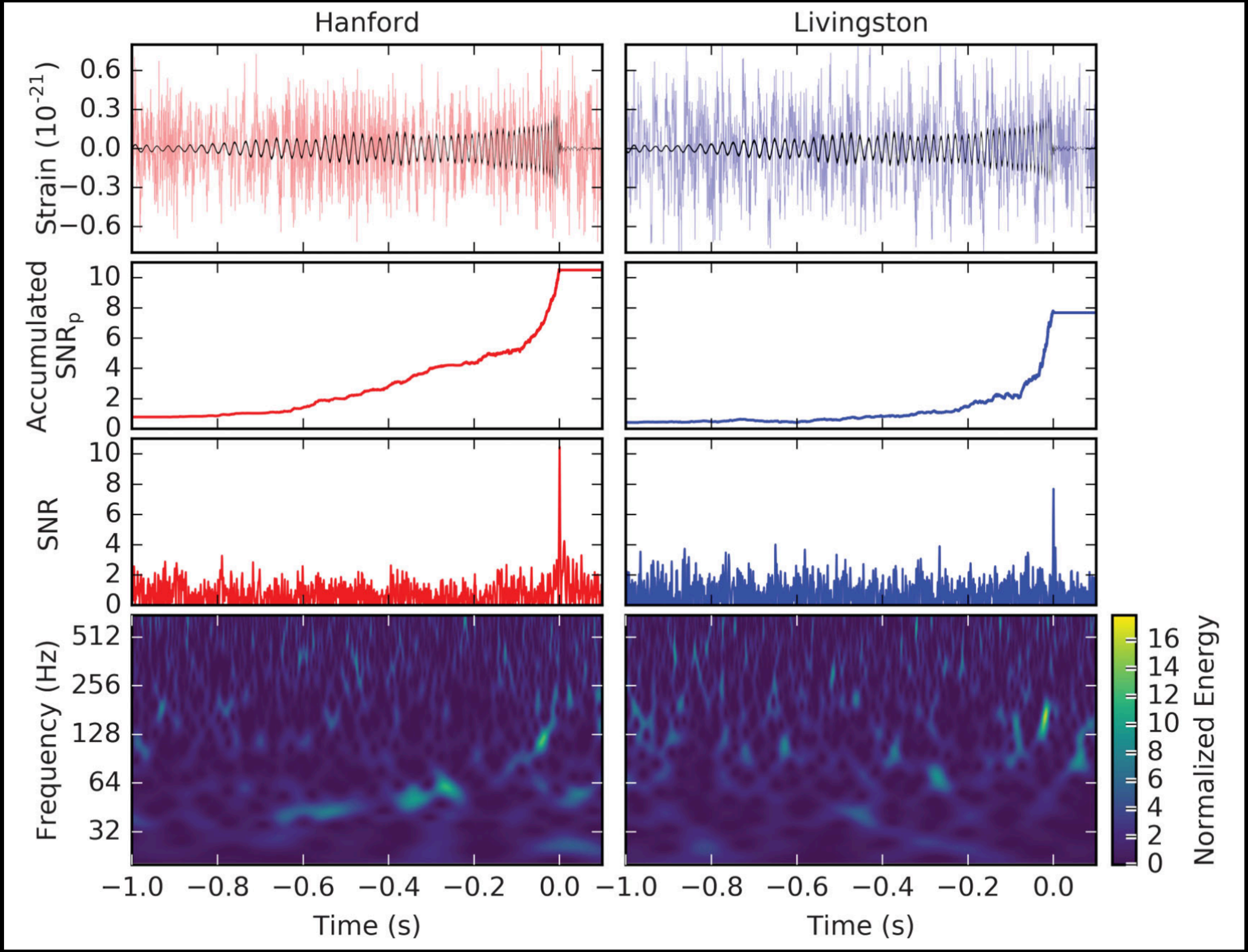
SNR=13
FAR < 6 x 10^{-7}
Significance > 5.3 σ

GW150914



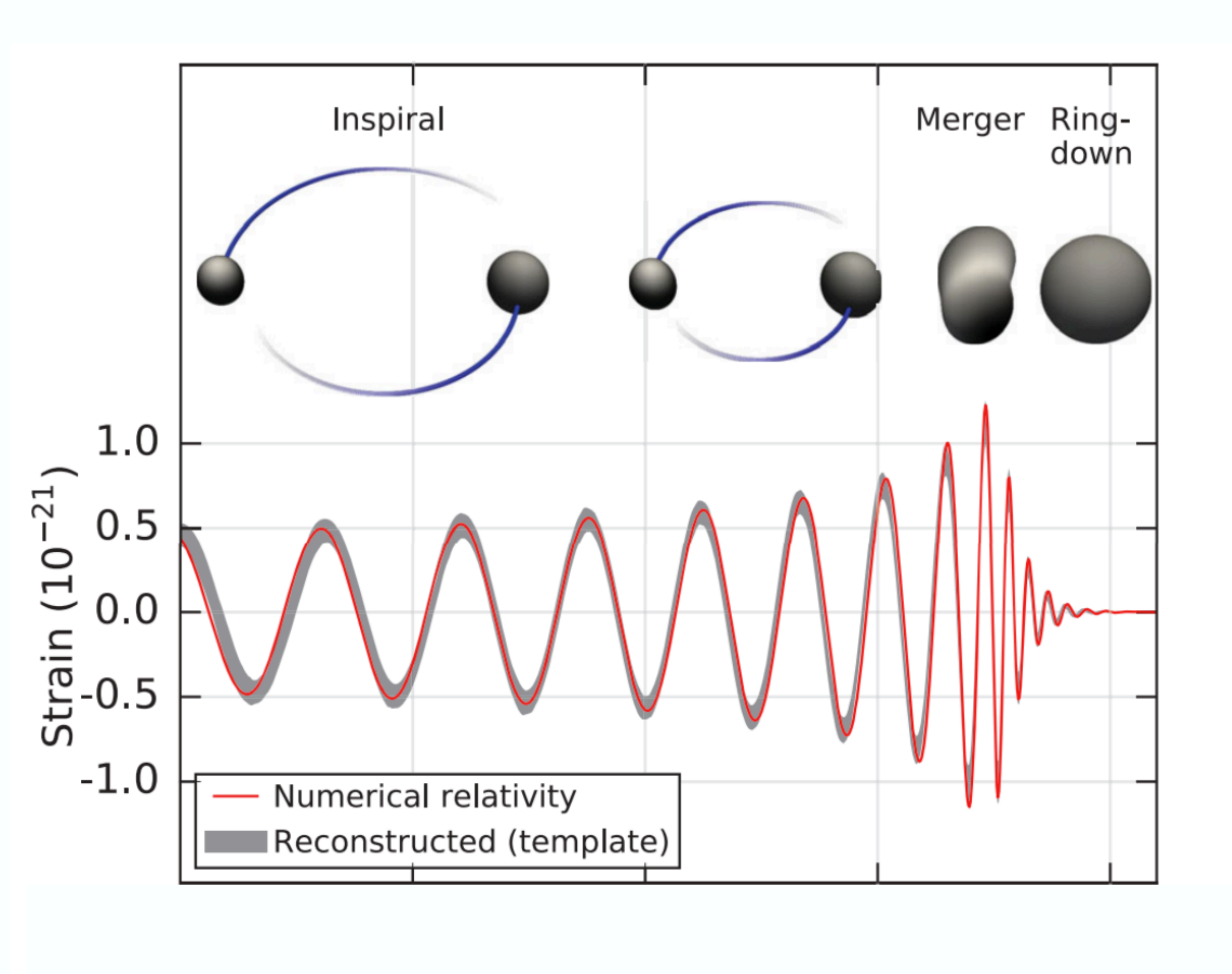
Abbott et al. 2016, Physical Review Letters, 116, 061102

GW151226



Abbott et al. 2016, Physical Review Letters, 116, 241103

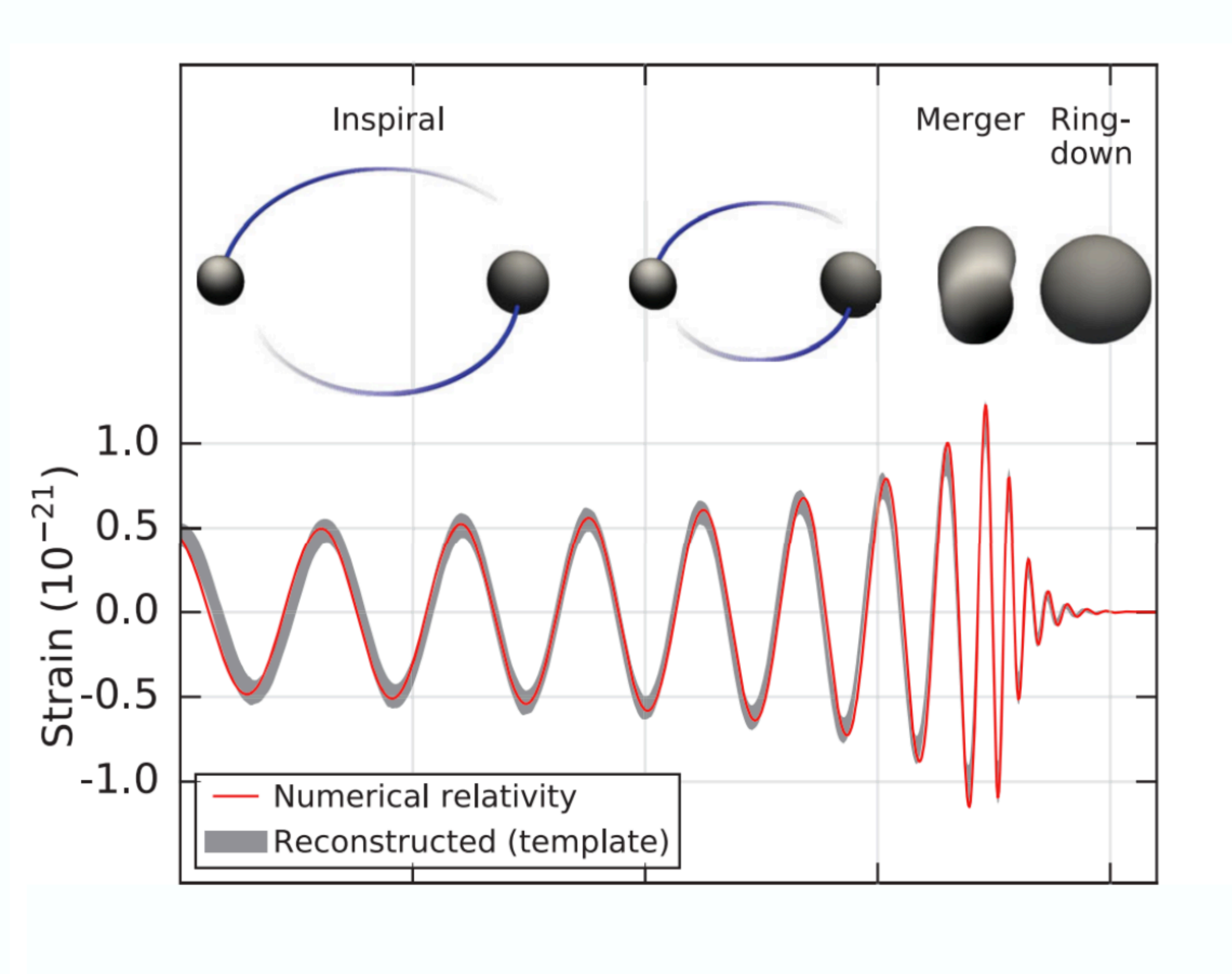
Source modelling



Post Netwonian

Numerical relativity

Quasi normal mode

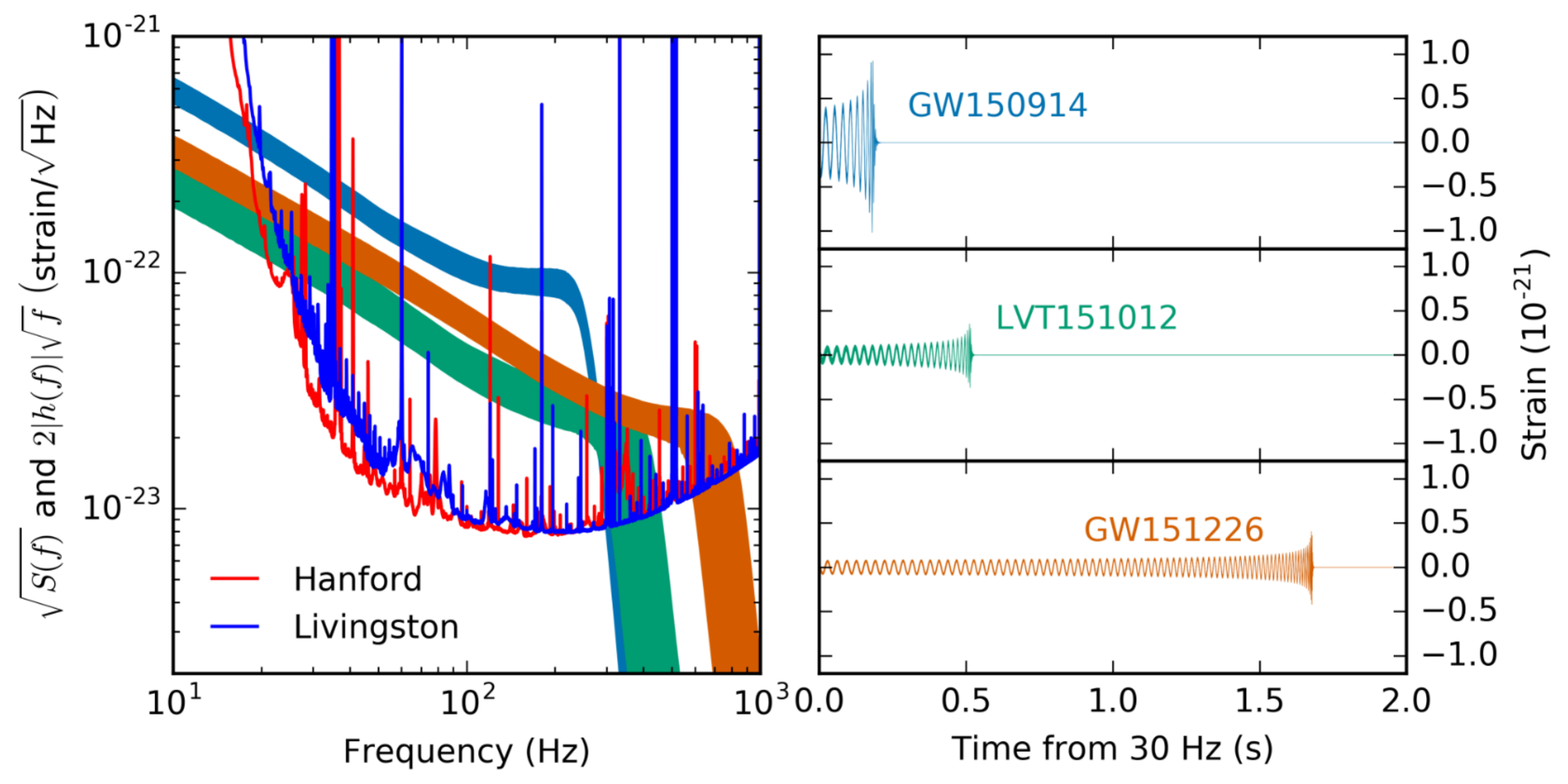


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

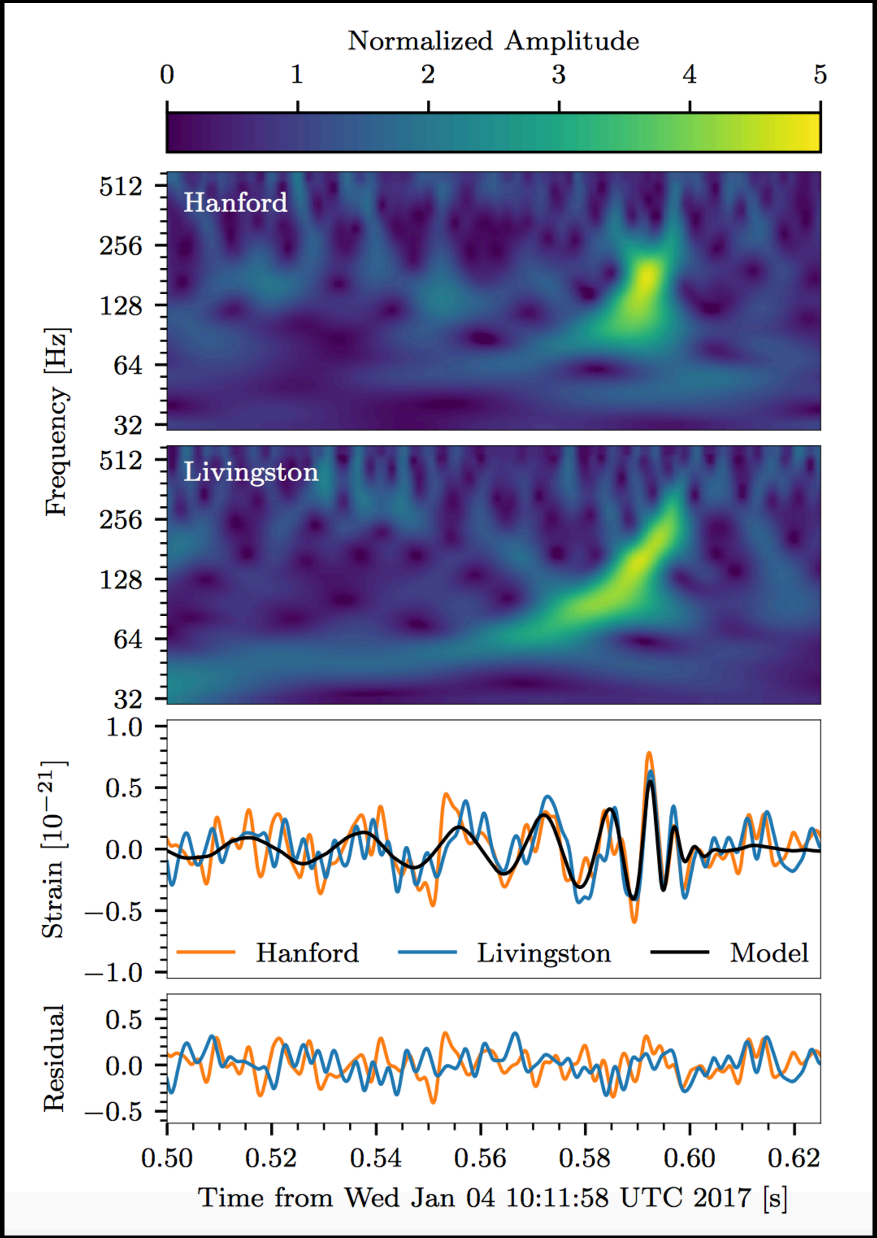
Chirp mass drive the early inspiral

Late inspiral and merger
→ individual masses

Typical O1 instrument noise
+ waveforms of GW150914, GW151226 and LVT151012



Time series of the three waveforms

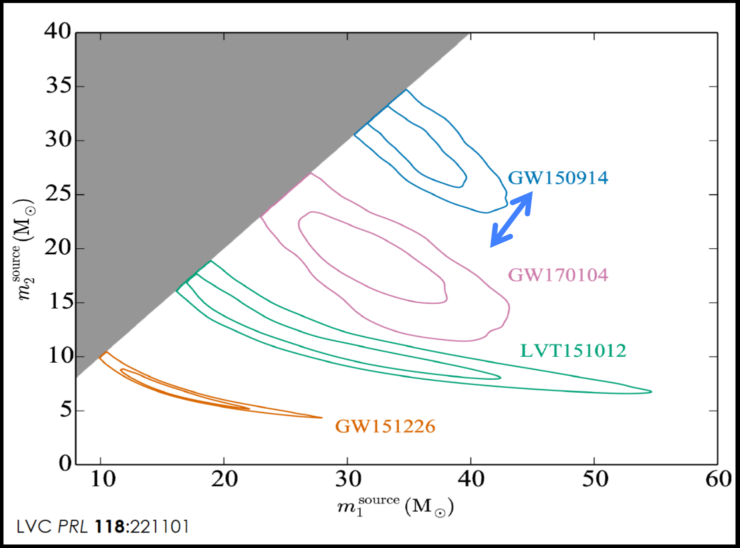


O2 published result:
another BBH GW170104

SNR=13 FAR= 1 in 70,000 years

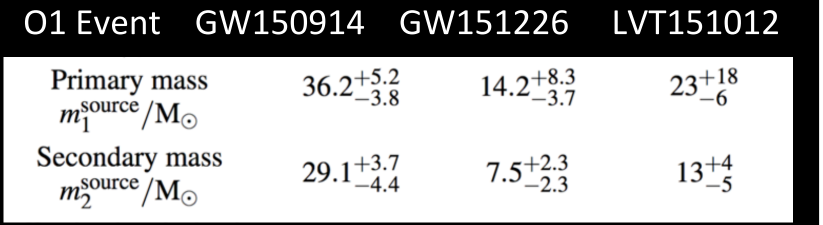
LVC 2017 Phys. Rev. Lett. 118

Parameters of the BBH systems



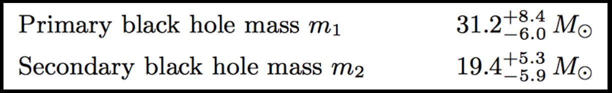
LVC *PRL* **118**:221101

Component masses

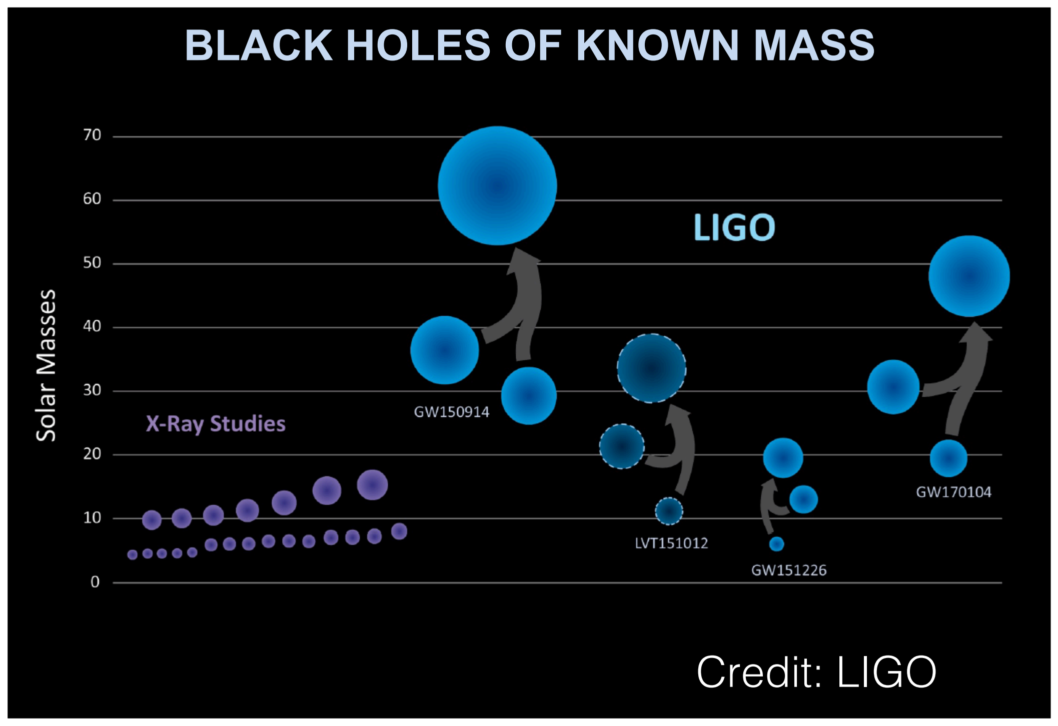


O1 Event	GW150914	GW151226	LVT151012
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}

O2 Event GW170104 .....



Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\ M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\ M_\odot$



Credit: LIGO

LVC 2016 Phys. Rev. Lett. 116, 061102
LVC 2016 ApJL, 818, 22
LVC 2016 Phys. Rev. Lett. 116, 241103

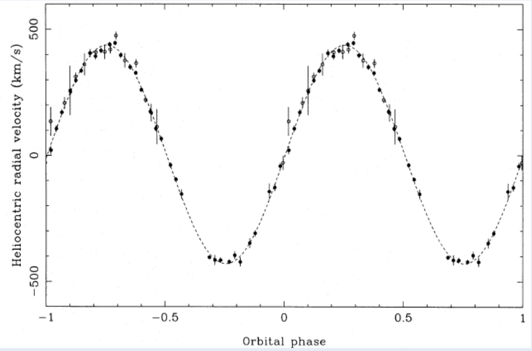
LVC 2016 Phys. Rev. X, 6
LVC 2017 Phys. Rev. Lett. 118

Stellar-mass BHs through photons….

1970s the mass of X-ray binary Cygnus X-1 was measured to exceed maximum mass of NS (3 Mo)

→ BHs from theory to observational reality

Dynamical estimates of BH mass in X-ray binaries



$$\frac{PK^3}{2\pi G} = \frac{\boxed{M}\sin^3 i}{(1+q)^2}$$

Direct observable:

- system’s orbital period P,
- radial velocity amplitude of the companion K

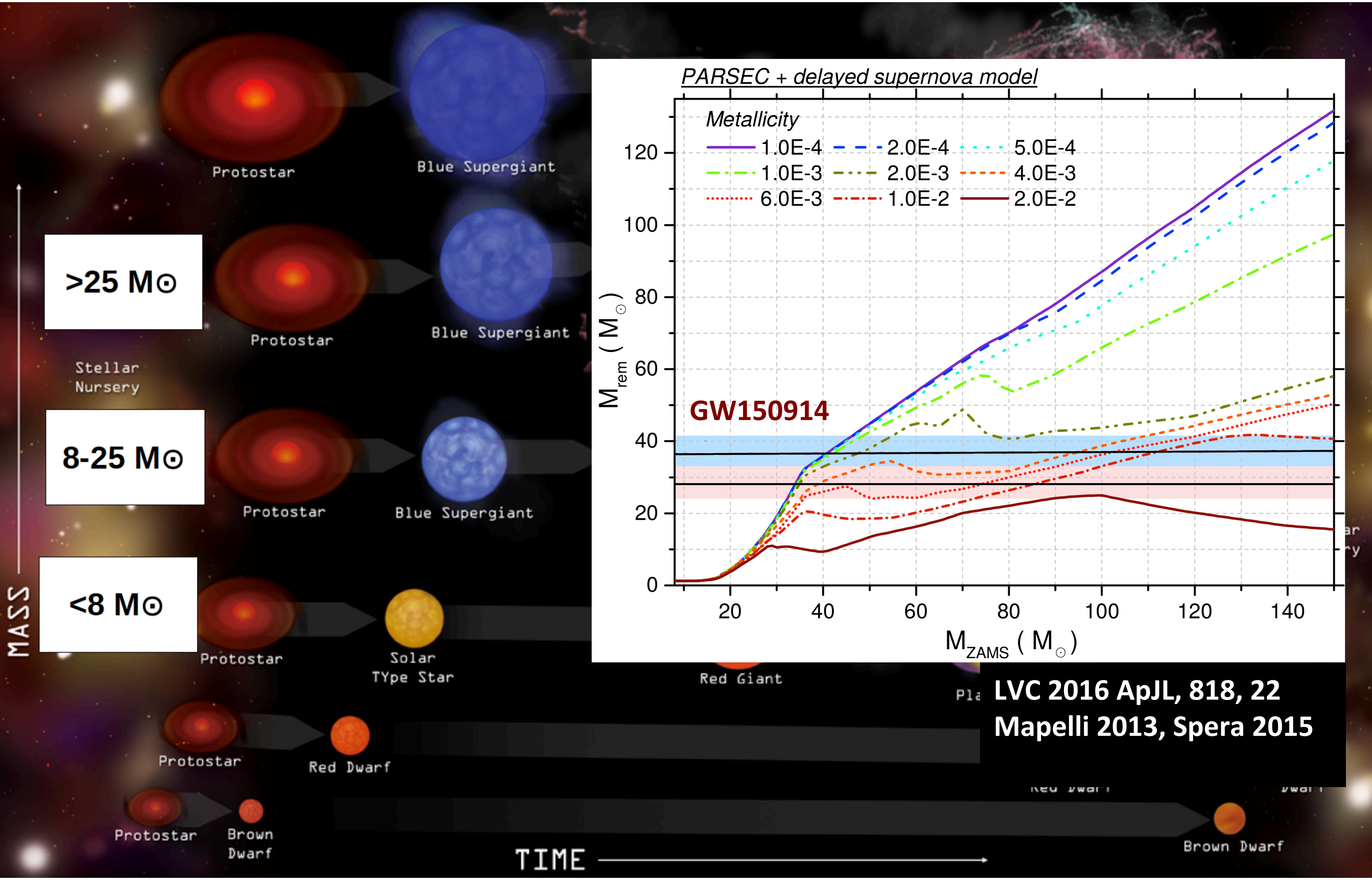
Constraints on:

- binary inclination i
- mass ratio q

MASS ESTIMATES 5-20 Mo

How do black holes form?

Credit: Chandra



>25 M⊙

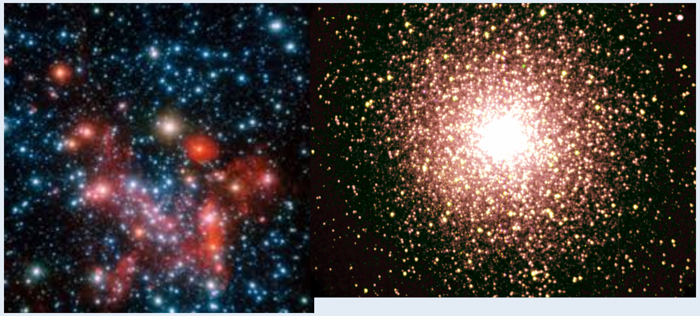
8-25 M⊙

<8 M⊙

LVC 2016 ApJL, 818, 22
Mapelli 2013, Spera 2015

Formation pathways to form massive black holes (>25 Mo)

BHs can form in dense environment or in the galaxy field:



- Globular Cluster/Young Star Cluster

R ~ 1-10 pc, N ~ 10^{3-7} stars

- Galaxy field

R~10 kpc, N ~10^{10} stars

Massive BHs form:

1) from direct collapse in metal-poor environment
   (BOTH CLUSTER AND FIELD)
2) dynamically triggered mergers of lower mass BHs or BH-star favored by three-body encounters(CLUSTER ONLY)

→ in GC unlikely since BBH ejected from host cluster before merger

→ in YSC low rate

Where do binary black holes form?

Galaxy field

R~10 kpc,

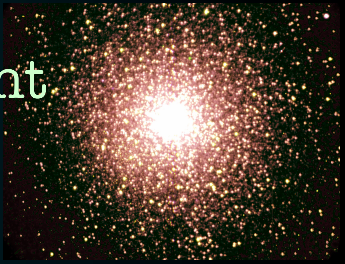
N ~ 10^{10} stars

Dense environment

star clusters

R~1-10 pc,

N ~ 10^{3-7} stars



How do they form binary systems?

Isolated binary

Dynamical interactions

Both formation paths are consistent with GW150914, GW151226 and GW170104

For GW150914 and GW170104 → low metallicities

Where do black holes form?

Galaxy field

R~10 kpc,

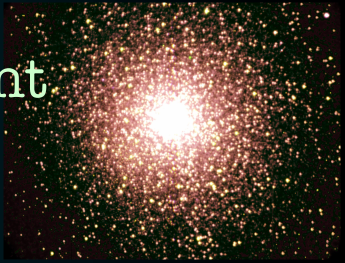
N ~ 10^{10} stars

Dense environment

star clusters

R~1-10 pc,

N ~ 10^{3-7} stars



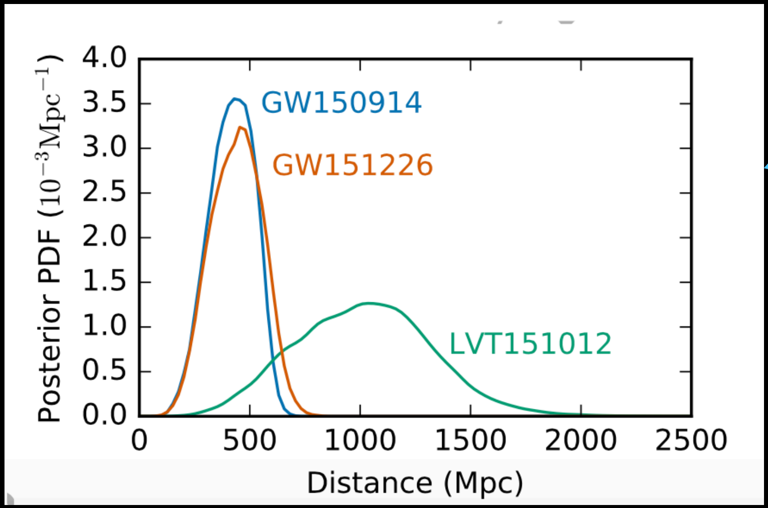
How do they form binary systems?

Isolated binary

Dynamical interactions

Crucial: identify the host galaxy and study the GW source environment

Challenges to identify the host galaxy



Distances

O1 Event	GW150914	GW151226	LVT151012	GW170104
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}	880^{+450}_{-390}

LVC 2016 Phys. Rev. X, 6

Sky localizations

90% credible areas of about

2000 deg^2 GW170104

600 deg^2 GW150914

1600 deg^2 LVT15012

1000 deg^2 GW151226

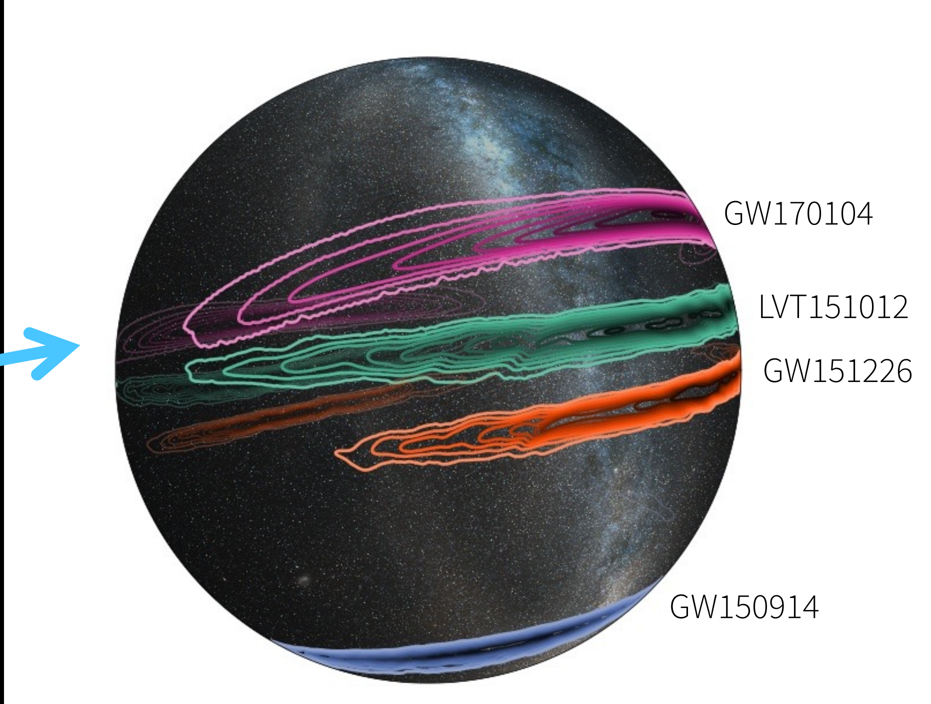


Image credit: LIGO/L. Singer/A. Mellinger

In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 there are 10^5-10^6 galaxies

The multi-messenger astronomy is required...

Main challenges of multi-messenger EM/GW astronomy:

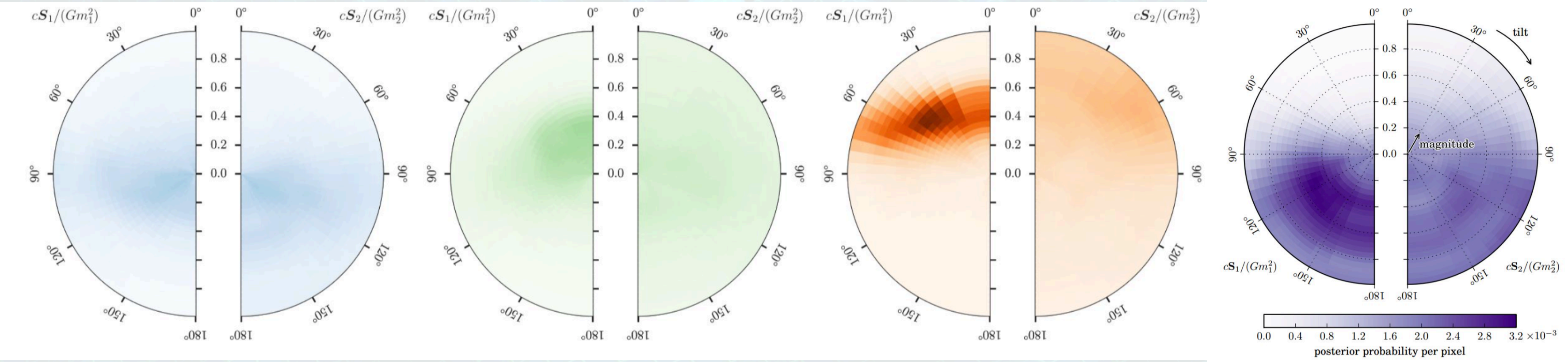
- ***Rapid transient EM/GW emission (emission models?)***
- ***Rare events (rates?)***
- ***Poor sky localization (observational strategies?)***

…how can we constrain formation models of BBH?

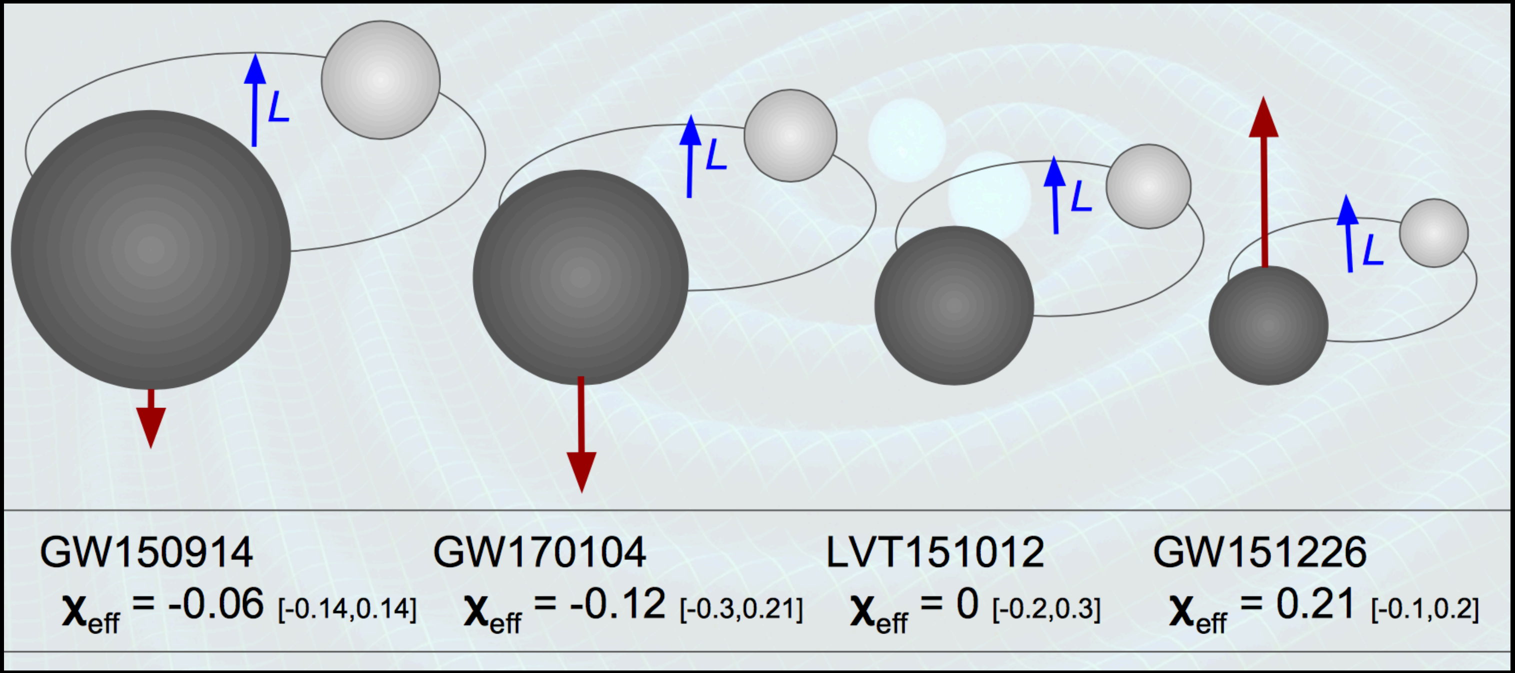
- **Masses** and **merger rate densities** as a **function of z**
- **Initial eccentricities** → small for isolated binaries and possible large for dynamical formation, but current predictions indicate circularized orbit by the time the system enters the frequencies of LIGO and Virgo
- **Spin misalignment** indication for dynamical formation, but GW spin measurements not well constrained

Orbit-aligned spin component:

$$\chi_{\mathrm{eff}} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \hat{\boldsymbol{L}}$$



GW150914 LVT151012 GW151226 G170104



Credit: Hanna GWPAW

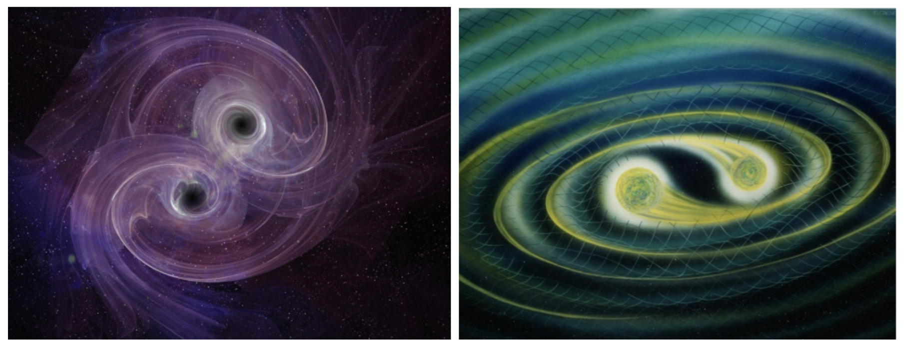
Orbit-aligned components: χeff= 0.21[−0.10+0.21] for GW151226, but consistent with zero for the other events

In-planecomponents (which would cause precession during inspiral):little information from the events detected so far

The conclusion so far → these binary systems did not have large black-hole spins positively aligned with the orbital axis

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

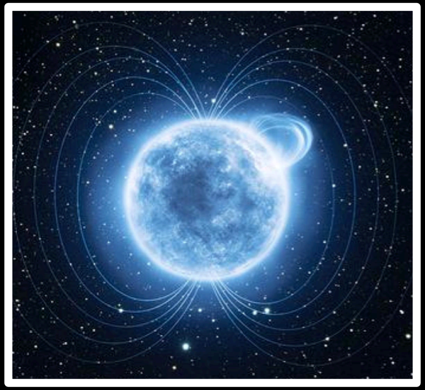
Coalescence of binary system of neutron stars (BNS) and NS-BH



- Orbital evolution and GW signals accurately modeled by post-Newtonian approximation and numerical simulations → precise waveforms
- **Energy emitted in GWs (BNS): ~$10^{-2}M_oc^2$**

Core-collapse of massive stars

Isolated NSs instabilties



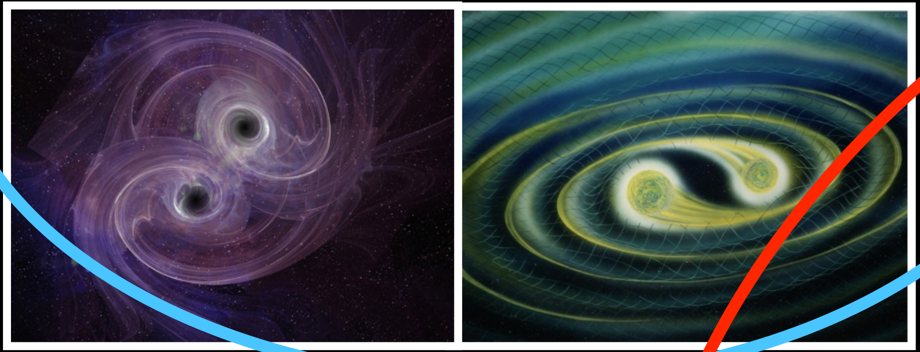
- Modeling of the GW shape and strength is complicated → **uncertain waveforms**
- **Energy emitted in GWs:**

~10^{-8} – 10^{-5} M_oc^2 for the core-collapse

~10^{-16} – 10^{-6} M_oc^2 for isolated NSs

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

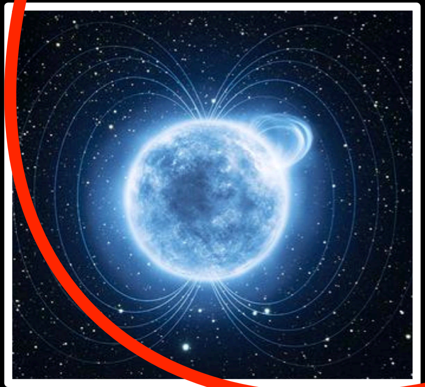
Coalescence of binary system of neutron stars and/or stellar-mass black-hole



→ MATCHED-FILTER MODEL SEARCHES

Core-collapse of massive stars

Isolated neutron-star



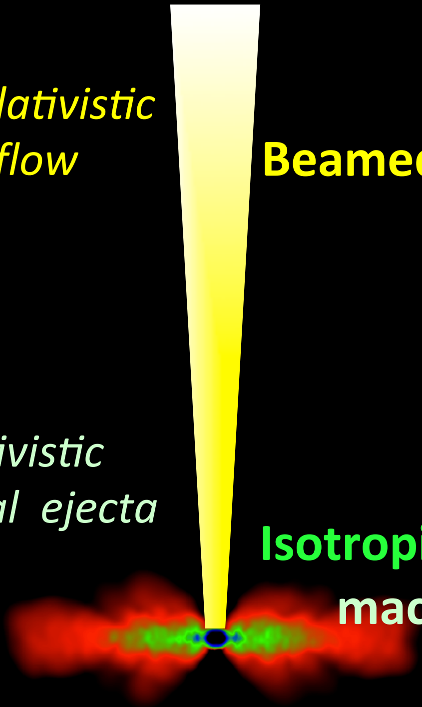
UNMODELED SEARCHES

Electromagnetic emissions from gravitational wave sources detectable by ground-based detectors (10-1000 Hz)

EM emissions

NS-NS and NS-BH mergers

Short Gamma Ray Burst (sGRB)



Ultra-relativistic outflow

Beamed emission

Sub-relativistic dynamical ejecta

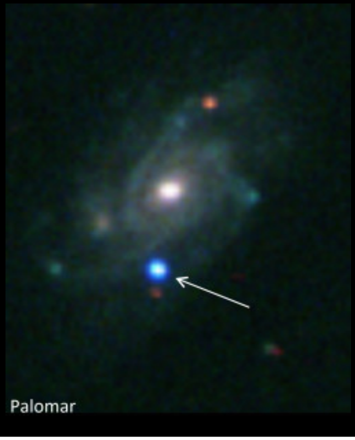
Isotropic emission

macronova

disk wind outflow

spin-down luminosity

Core-collapse of massive stars


Palomar

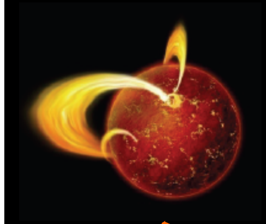
SBO X-ray/UV

Optical

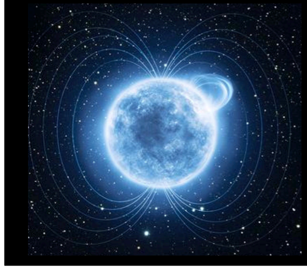
Radio

+ Long GRB

Isolated NS instabilities

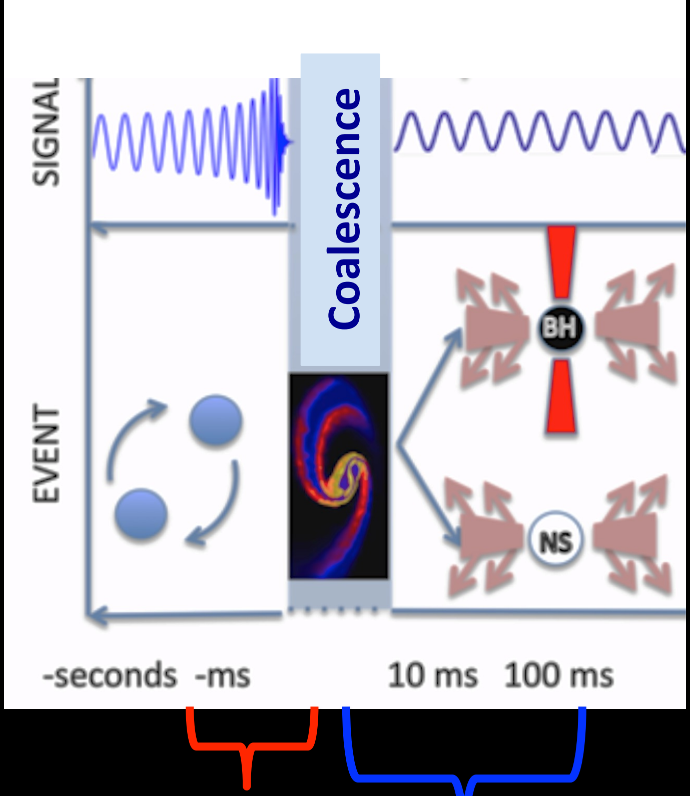


Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

NS-NS and NS-BH inspiral and merger



Dynamical Phase

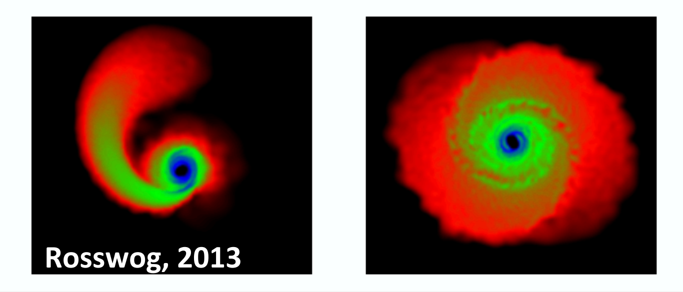
Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

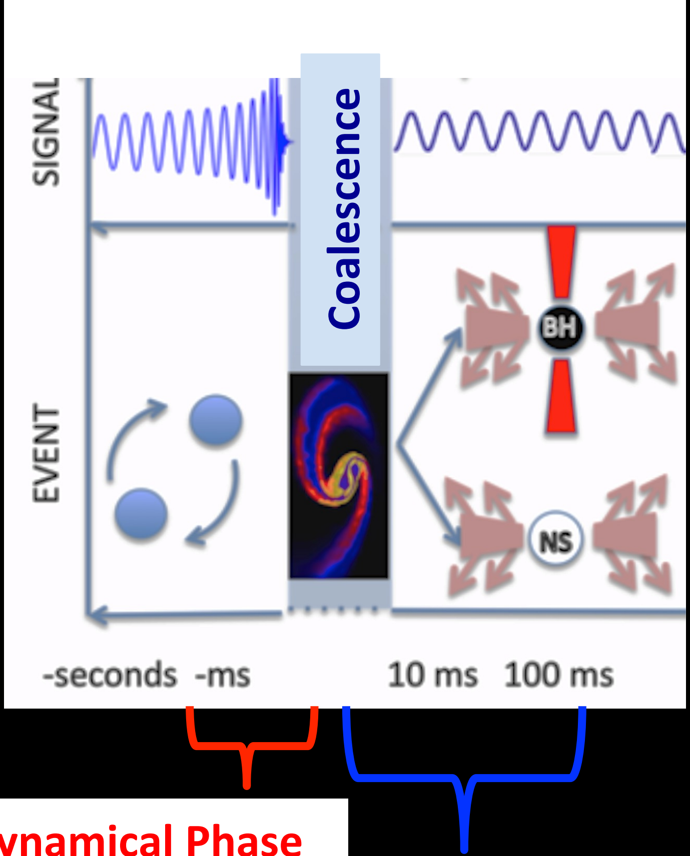
- dynamically ejected unbound mass
- ejected mass gravitationally bound to the central remnant either falls back or circularizes into an accretion disk

NS-NS binary → unbound mass of 10^{-4} -10^{-2} Mo ejected at 0.1-0.3c, which depends on **total mass, mass ratio, EOS NS and binary eccentricity**



Rosswog, 2013

NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound to the central remnant either falls back or circularizes into an accretion disk

NS-BH binary → unbound mass up to 0.1 Mo depends on **ratio of the tidal disruption radius to the innermost stable circular orbit**

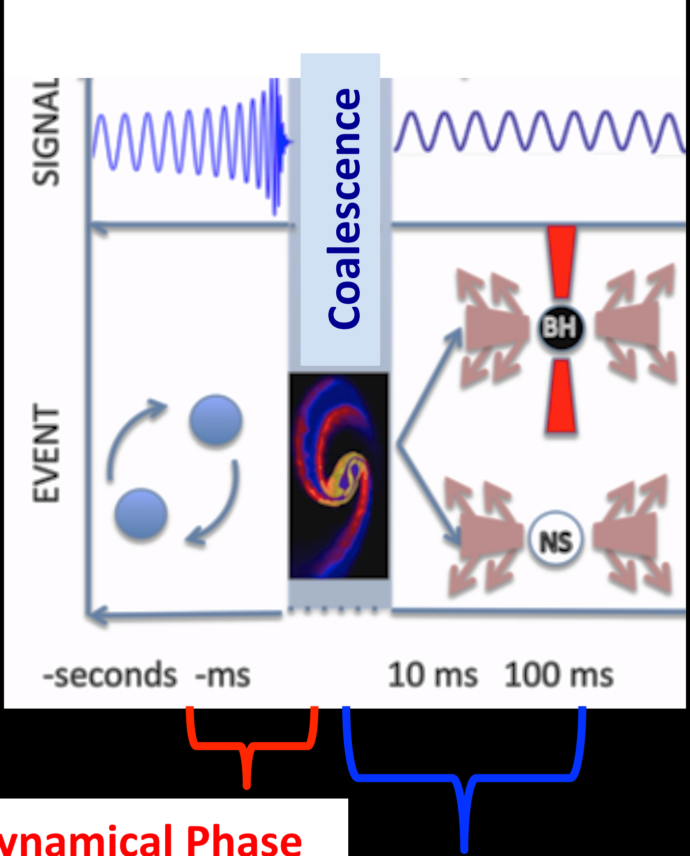
If < 1 → NS swallowed by the BH no mass ejection

If > 1 NS → tidally disrupted, long spiral arms

which depends on **the mass ratio, the BH spin and the NS compactness**

See Kawaguchi et al. 2016,ApJ, 825, 52

NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

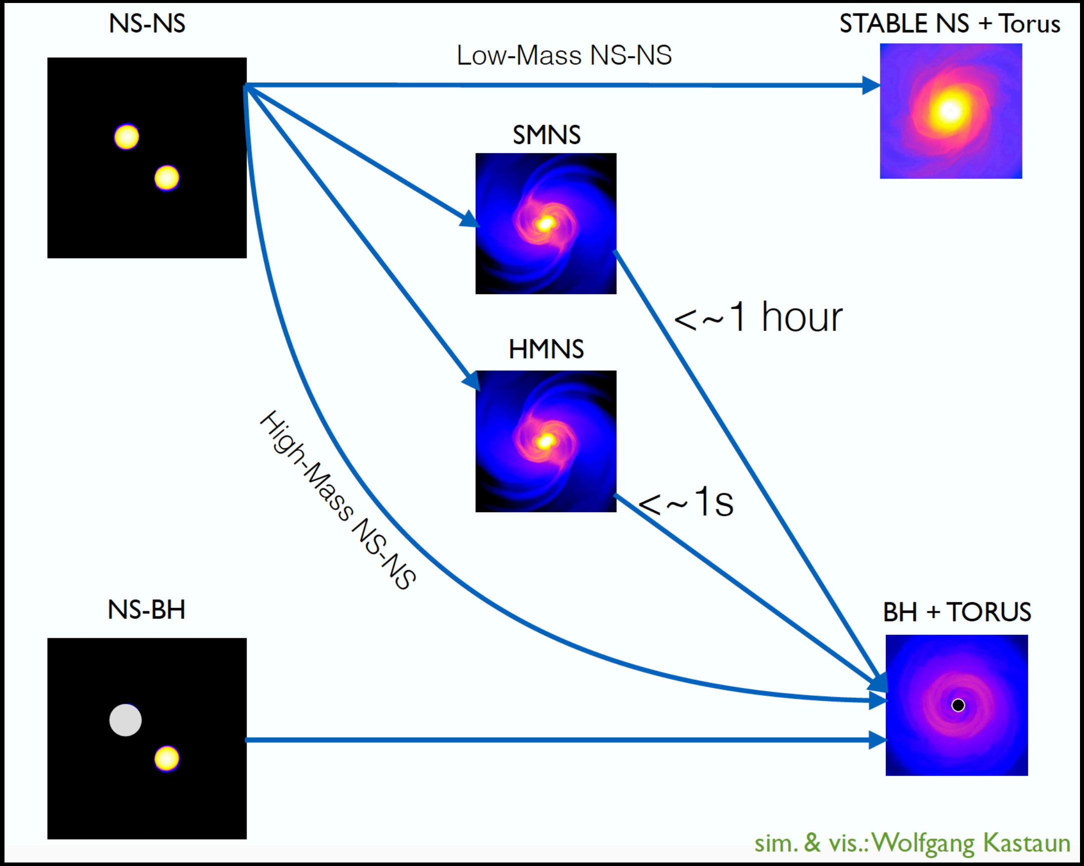
- Ejected material gravitationally bound from the central remnant can fall back or circularizes into an accretion disk

Disk mass up to ~ **0.3Mo**
Disk mass depends on the **mass ratio of the binary, the spins of the binary components, the EOS, and the total mass of the binary**

For NS-BH see e.g. Foucart 2012, PhRvD, 86;
Maselli & Ferrari, PhRvD, 89;
Pannarale & Ohme, ApJL, 791

Outflow mass and geometry influence the EM emission

Central remnant of NS-NS or NS-BH merger



sim. & vis.: Wolfgang Kastaun

The central remnant influences GW and EM emission

What is central remnant?

- It depends on the total mass of the binary
- The mass threshold above which a BH forms directly depends on EOS

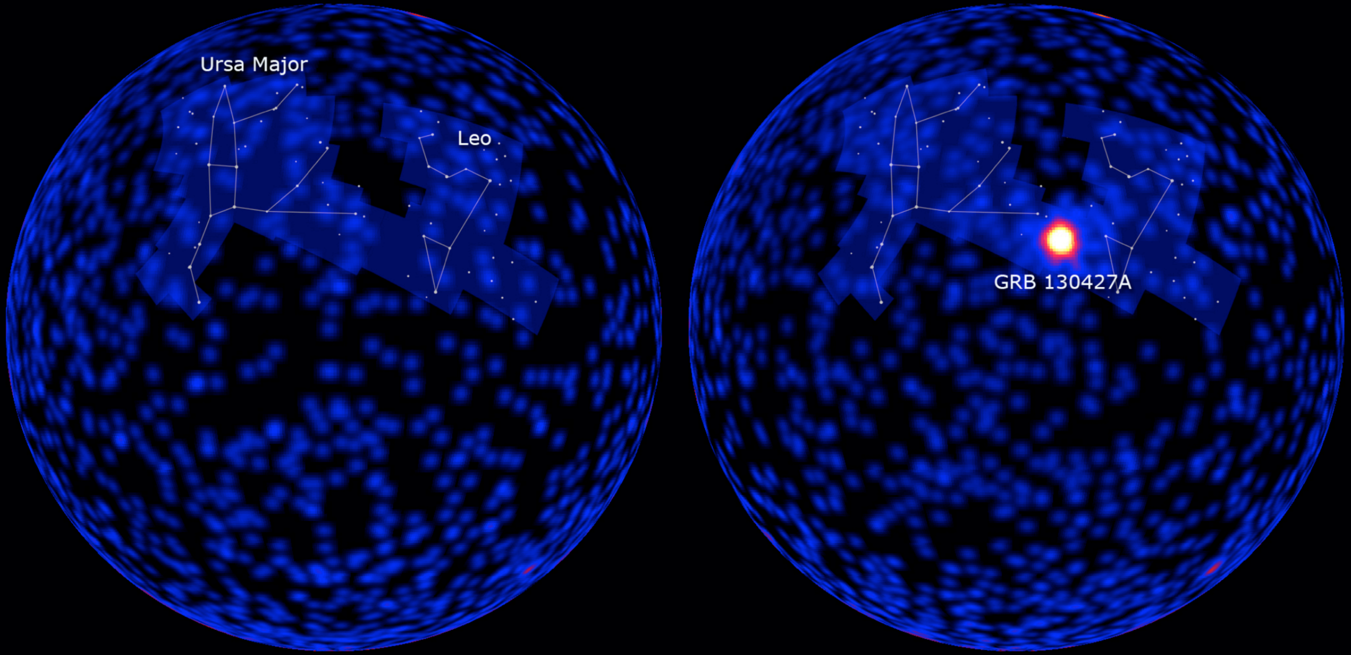
GWs

- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance

EM emission

- Beamed and isotropic EM emissions
- Energetics
- Nuclear astrophysics

Gamma-Ray Bursts

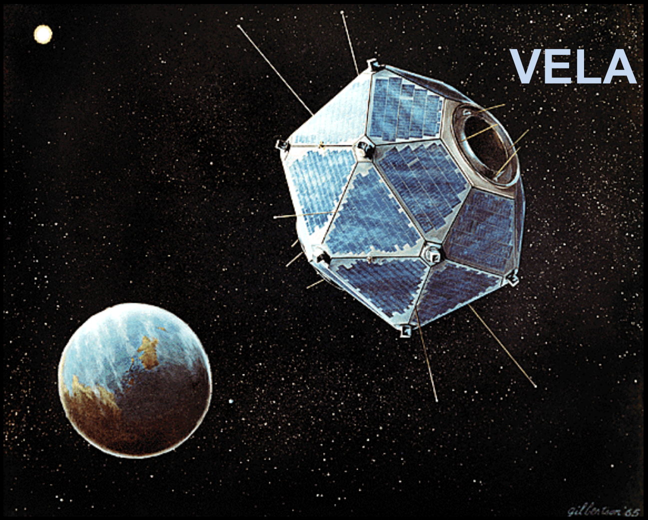


Before and after Fermi LAT observation of GRB 130427A

Brief, sudden, intense flashes of gamma ray radiation which release energy up to **~ 10^{53} erg** (isotropic-equivalent)

Duration: **from few ms to hundreds of s**
Observational band: **10 keV – 1 MeV**
Flux: **10^{-8} - 10^{-4} erg cm^{-2} s^{-1}**

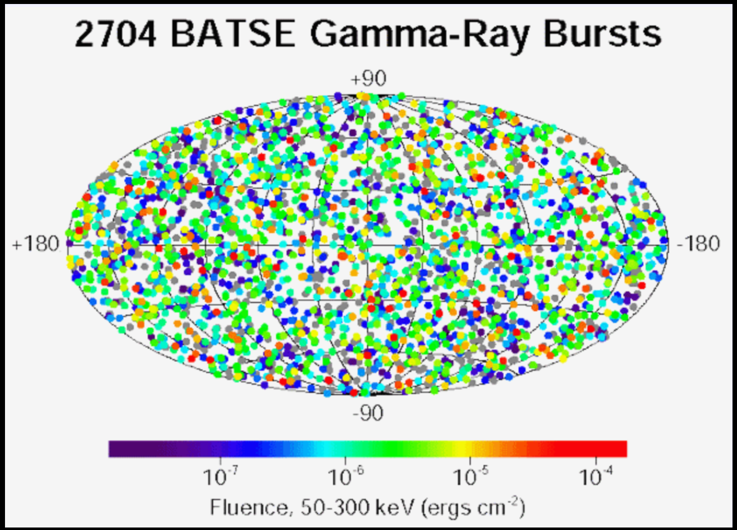
GRBs were discovered serendipitously in the late 1960s by U.S. military satellites looking out for Soviet nuclear testing

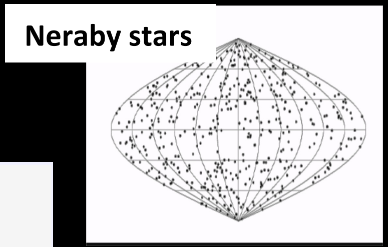


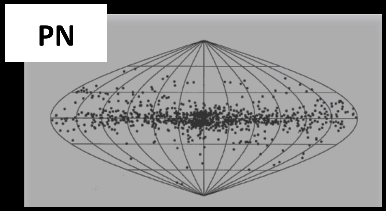
Galactic or cosmological?

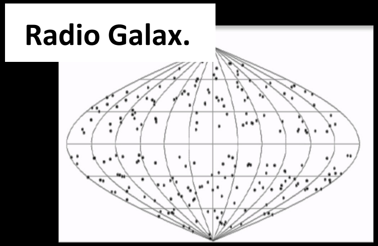
BATSE
20 keV-MeV
(1991-2000)

Isotropic angular distribution







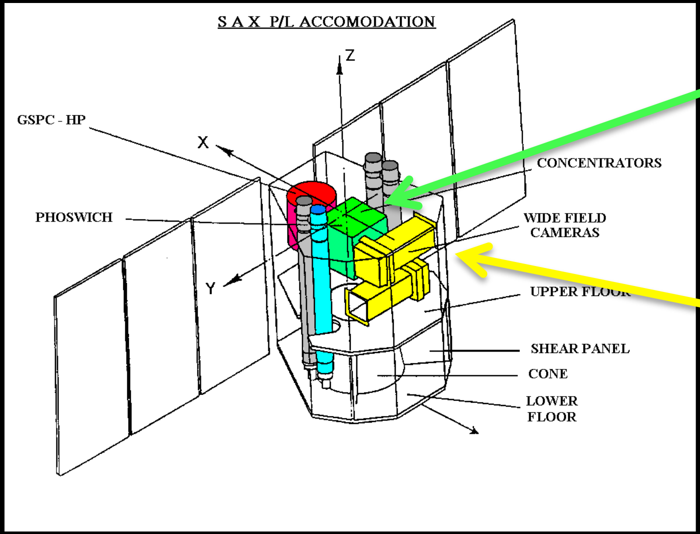


Paczynsky, PASP, 107, 1167

BeppoSAX

(1996-2002)

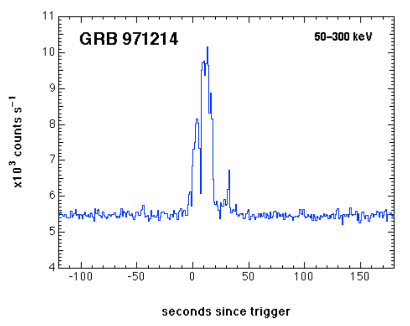
Italian–Dutch satellite for X-ray astronomy
resolved the origin of gamma-ray bursts

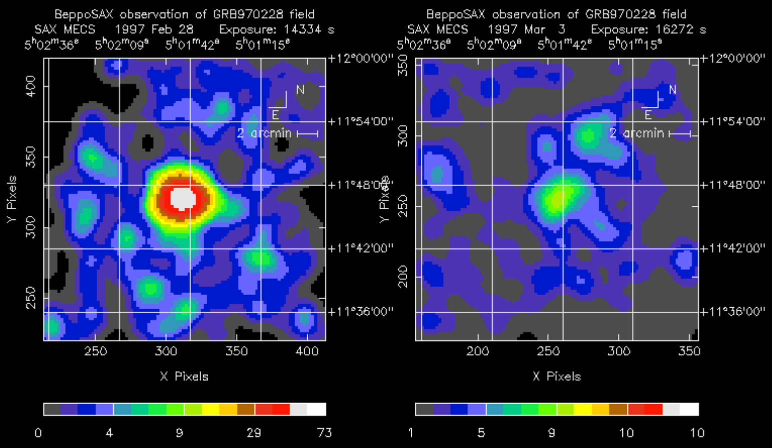


Scintillator for gamma-rays
60-600 keV, poor angular resolution

Wide Field Camera (WFC)
2-30 keV; 20x20 degree FoV
5 arcmin angular resolution

GRB 970228 in the FOV of the WFC

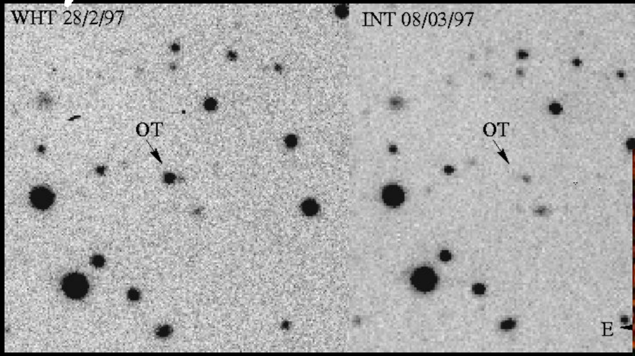




Well localized fading X-ray afterglow !

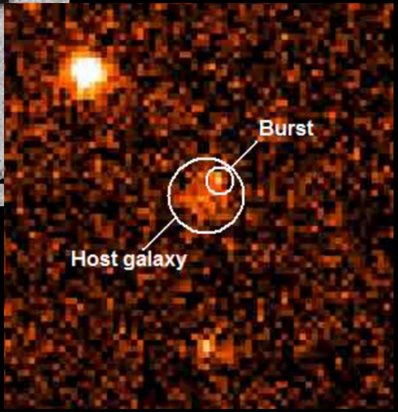
Costa et al., 1997

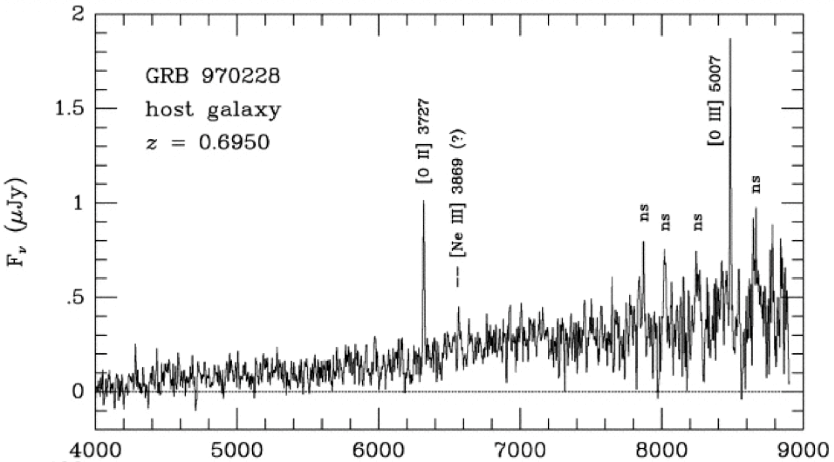
Optical afterglow/host galaxy



z=0.695, D_L=3.6 Gpc

Cosmological redshift



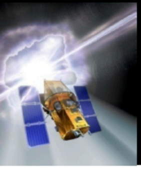


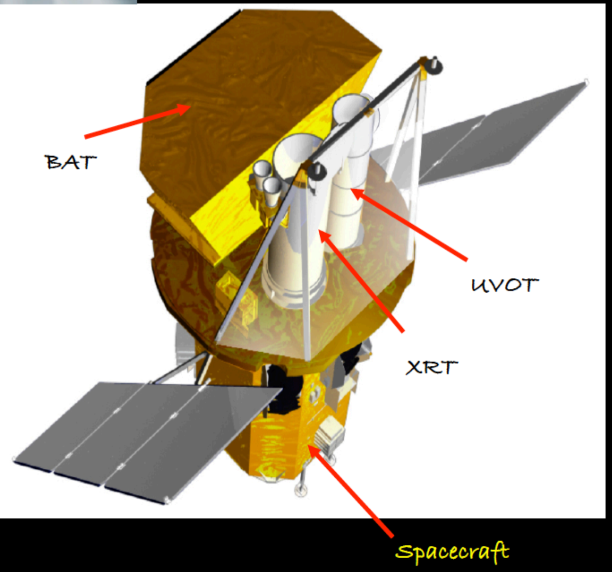
Groot, Galama, van Paradijs, et al IAUC 6584, March 12, 1997

van Paradijs et al., 1997

Swift: "everything in space"

Since Nov. 2004



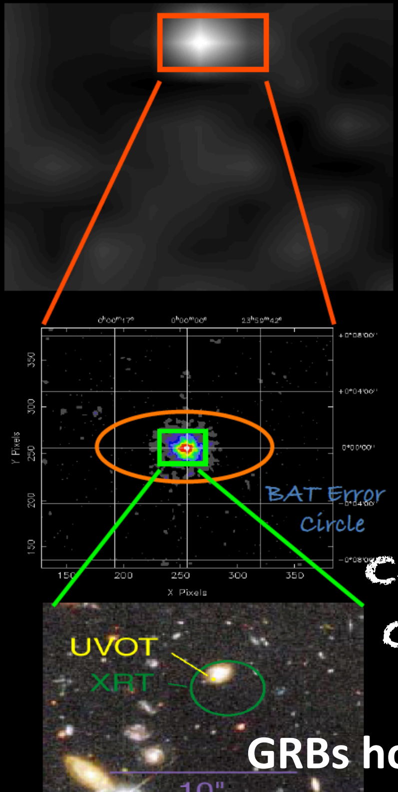


Satellite slews (1 min) and repoints its X ray (XRT) and UV telescopes to observe the error region of the GRB.

$T < 10$ sec
$\theta < 4'$
$E > 15$ keV

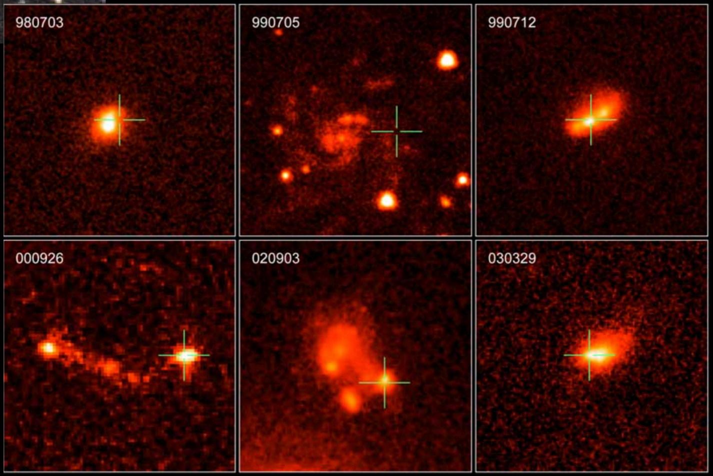
$T < 100$ sec
$\theta < 5''$
$E < 10$ keV

$T < 300$ sec
Optical/NIR



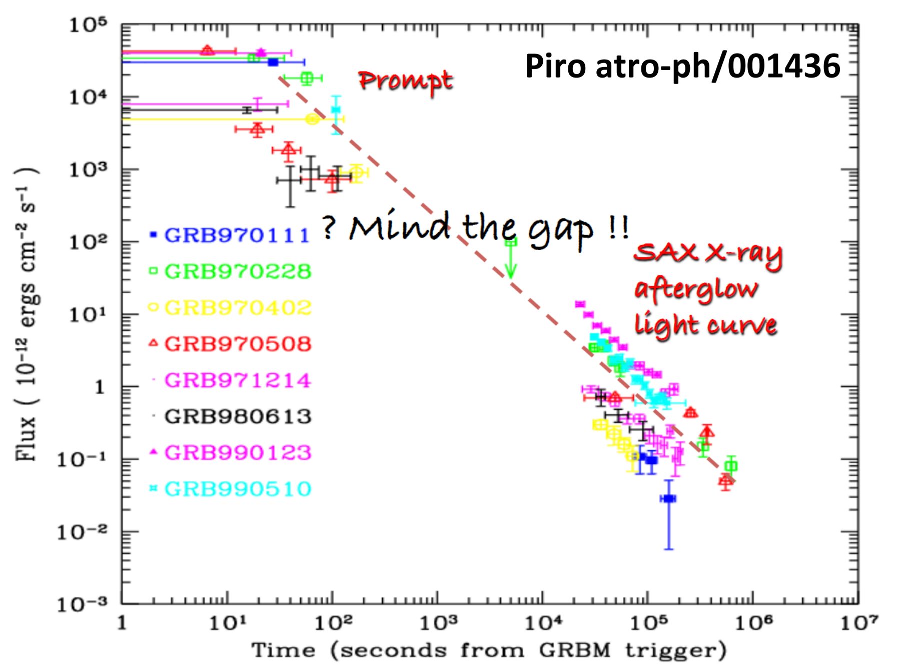
GRBs are extragalctic, cosmological, and occur in galaxies

GRBs host galaxies observed by HST



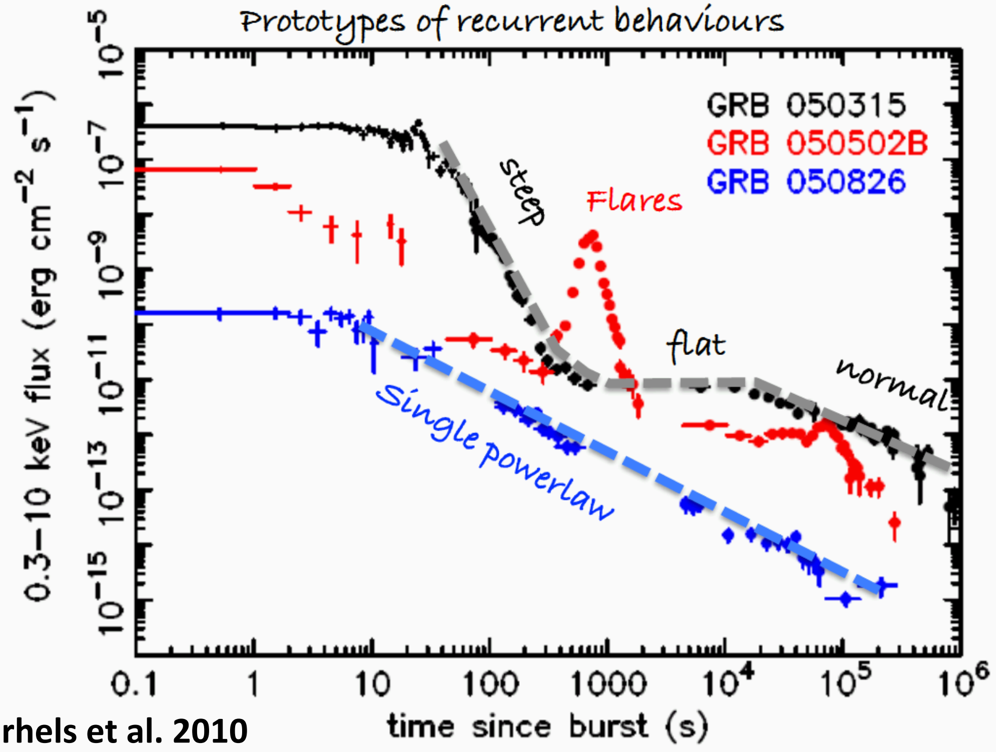
Afterglow

- 99% X-ray
- 60-70 % Optical
- 30% radio

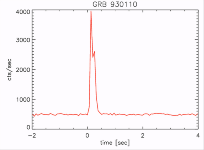

Piro atro-ph/001436

X-ray afterglow before Swift

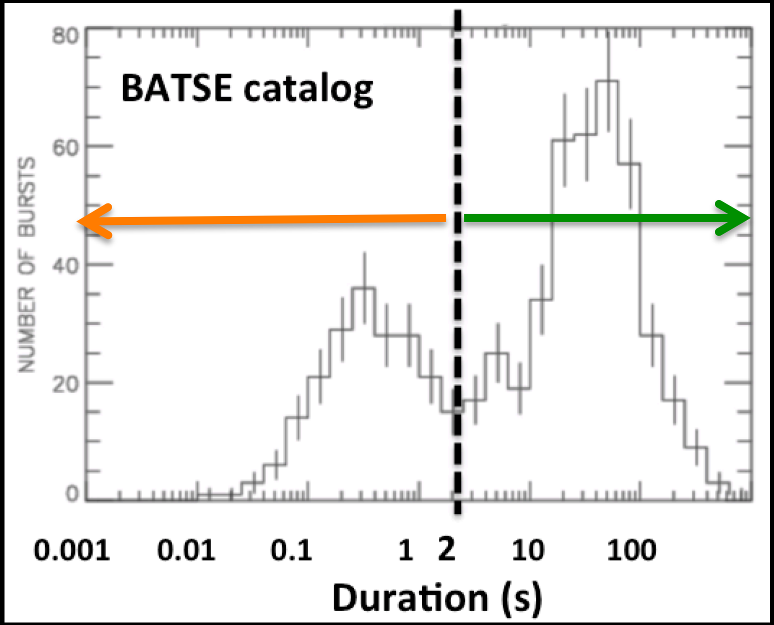
X-ray afterglow NOW



Gerhels et al. 2010

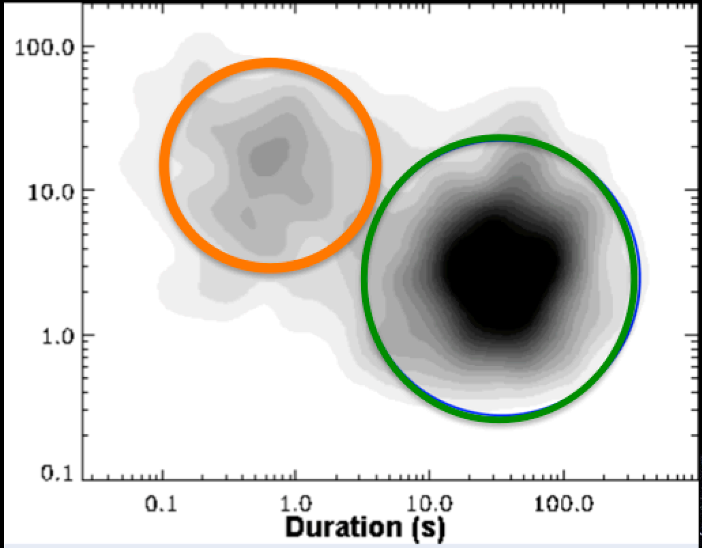


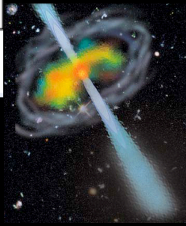
Bimodal duration distribution



Kouveliotou et al. 1993

Hardness ratio





Different Progenitor

Short Hard GRB

- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)
- accretion timescale of disk in binary merger model is short (t ~ 1s)

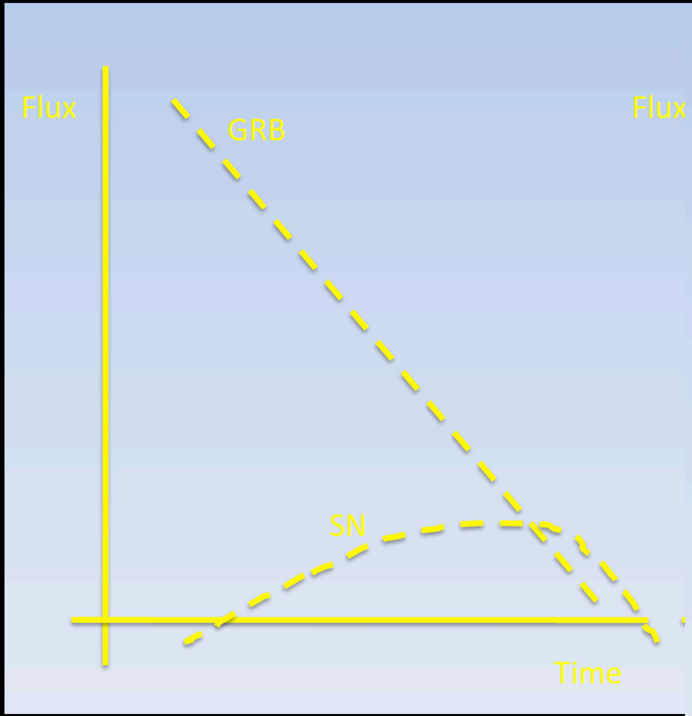
→ **NS-NS NS-BH mergers**

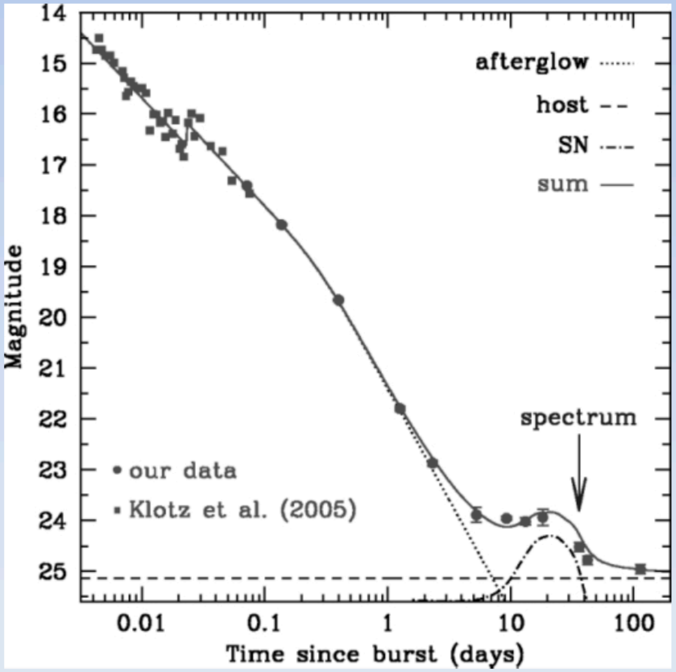
Long Soft GRB

- observed Type Ic SN spectrum
- accretion disk is fed by fallback of SN material onto disk, timescale t ~ 10-100s

→ **Core-collapse of massive stars**

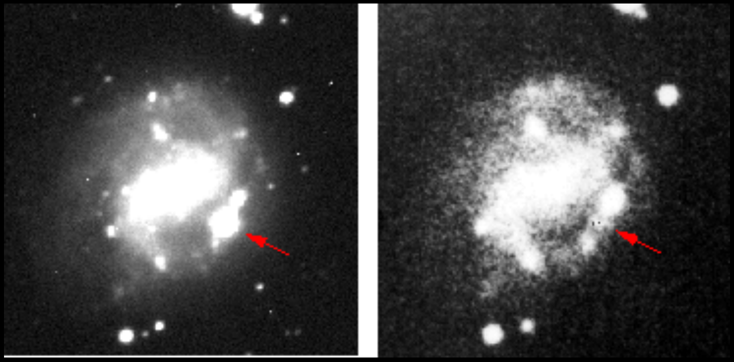
Long GRB and Supernovae





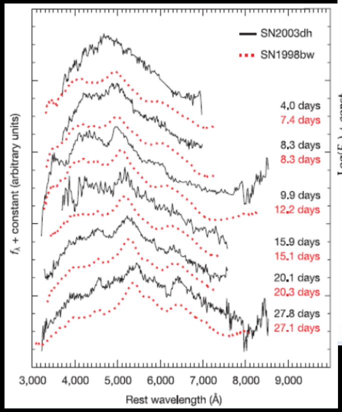
Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melnadri et al. 2014 and others…

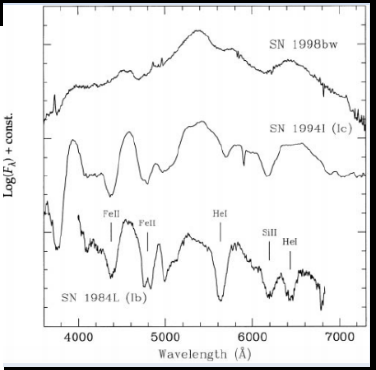
SN 1998bw/GRB 980425
Type Ic supernova



Iwamoto et al 1998; Woosley et al. 1999

Spectra

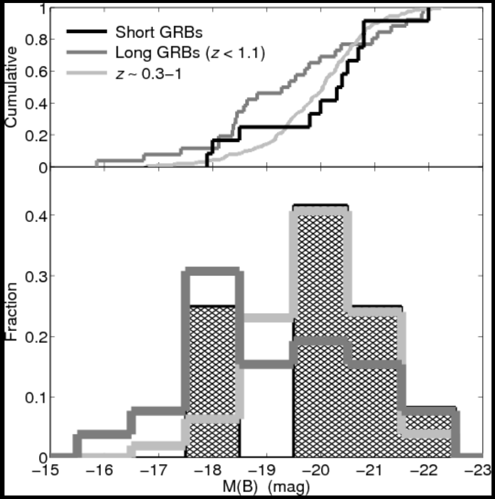




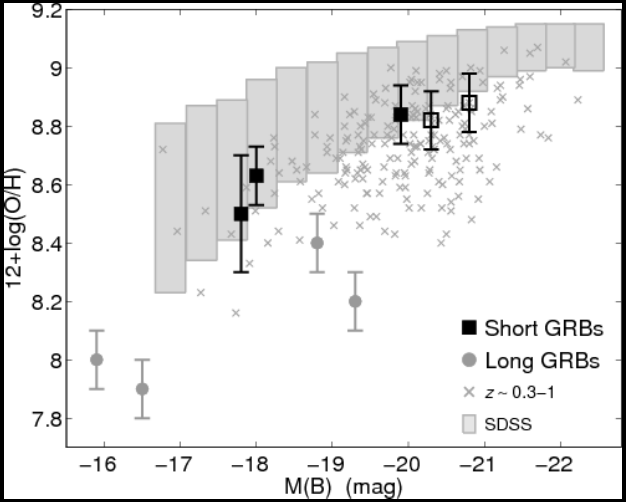
Short vs. long GRB host galaxies

Berger 2009; 2014

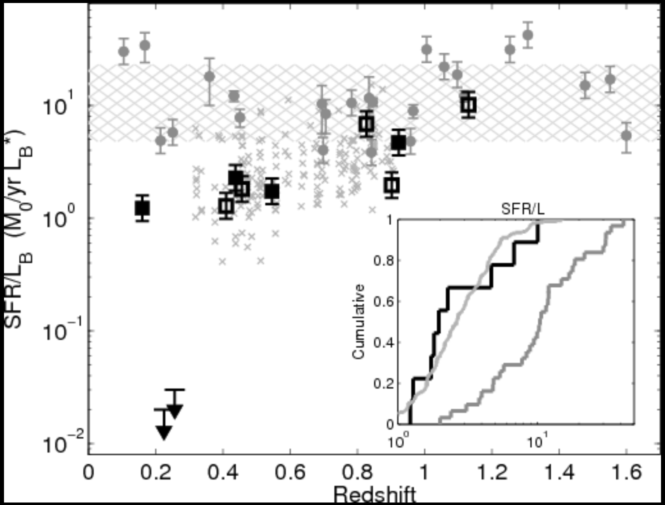
Absolute B-magnitude



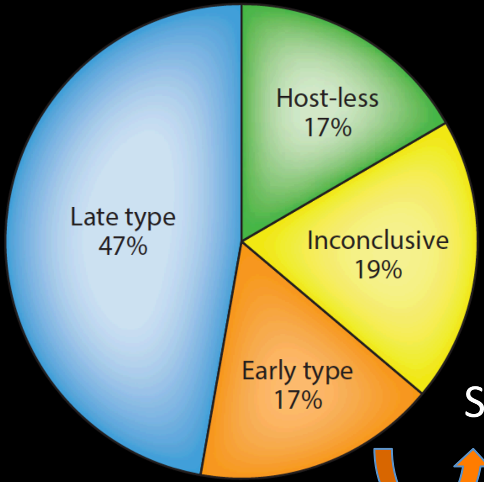
Metallicity



Star Formation Rate



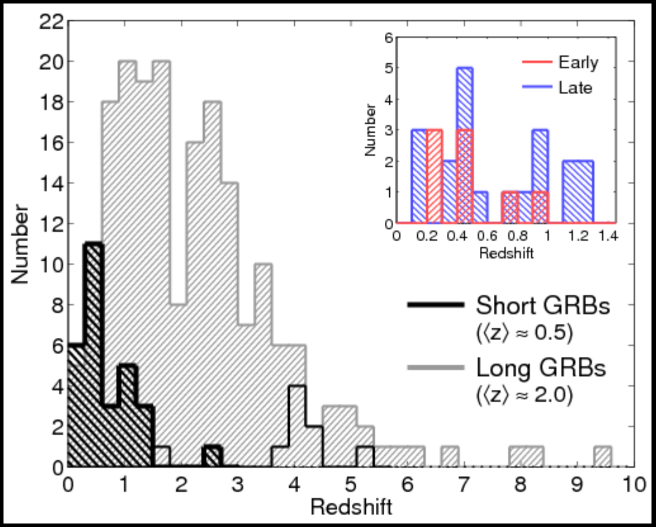
- Long GRB HGs are on average more star forming, fainter and with low metallicity
- Short GRB HGs share the same observational properties of field galaxies



Short GRB host galaxies

Short GRBs also in early type galaxies

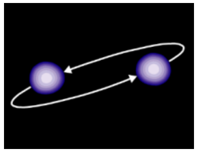
Redshift



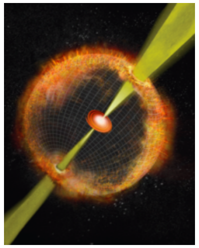
GRBs emission - Fireball Model

Cataclysmic event

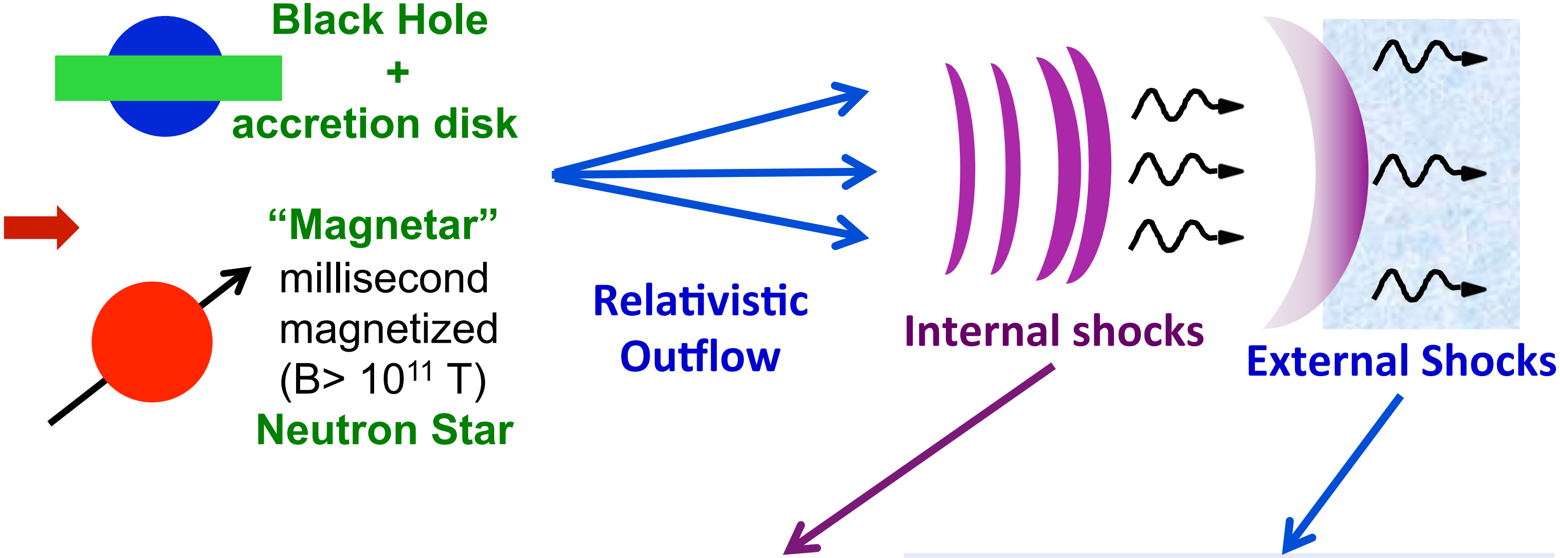
NS-NS NS-BH merger



Core Collapse



Central engine



Black Hole + accretion disk

"Magnetar" millisecond magnetized (B> 10^{11} T) **Neutron Star**

Relativistic Outflow

Internal shocks

Surrounding medium

External Shocks

Prompt emission

ϒ-ray - within seconds

Afterglow emission

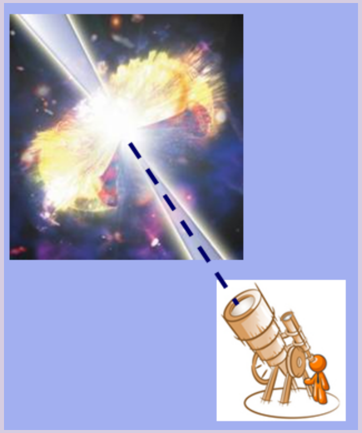
Optical, X-ray, radio - hours, days, months

Kinetic energy of the relativistic jet converted into radiation

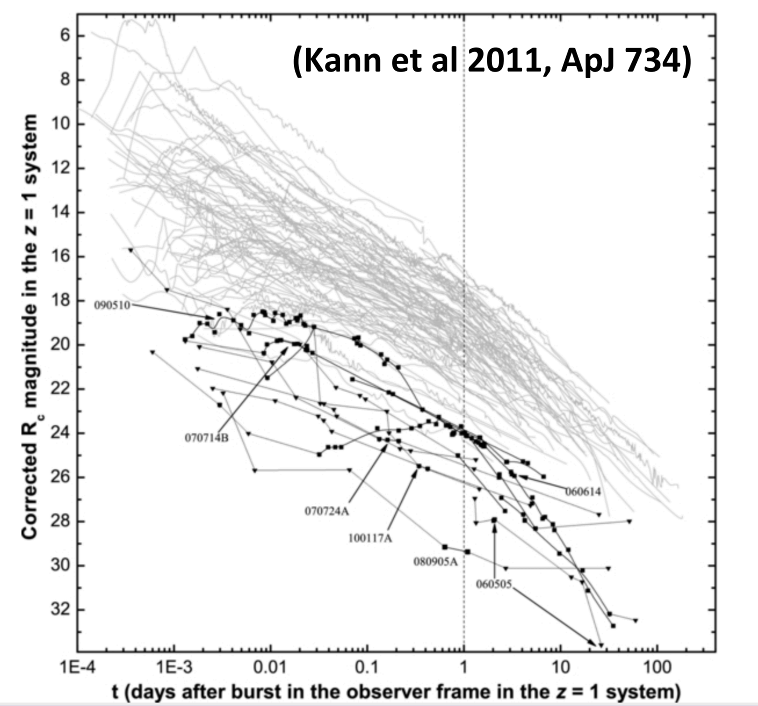
Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

Optical afterglows of on-axis GRBs

On-axis GRBs

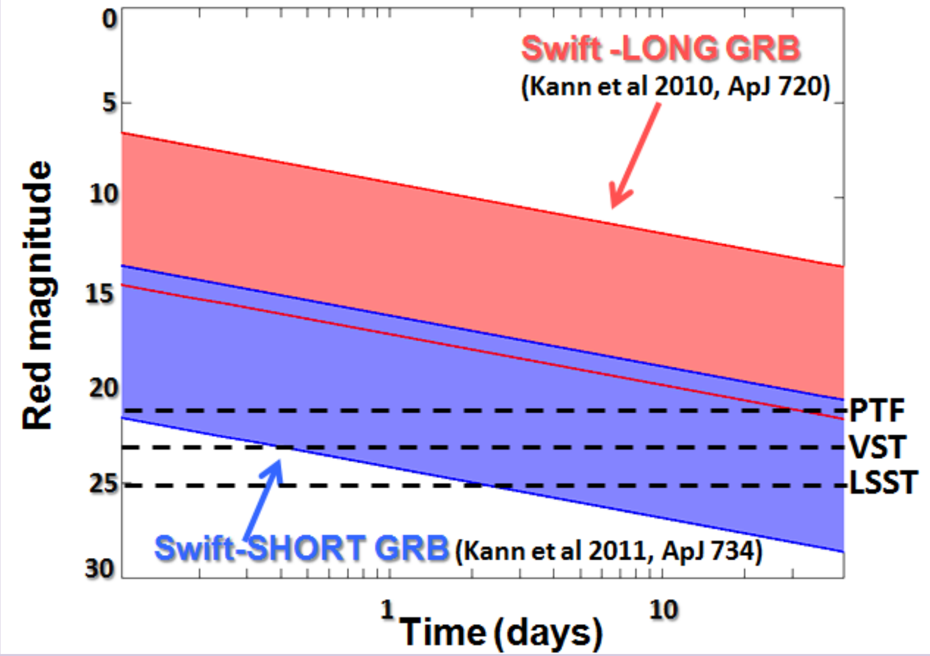


Observed GRB optical afterglows



(Kann et al 2011, ApJ 734)

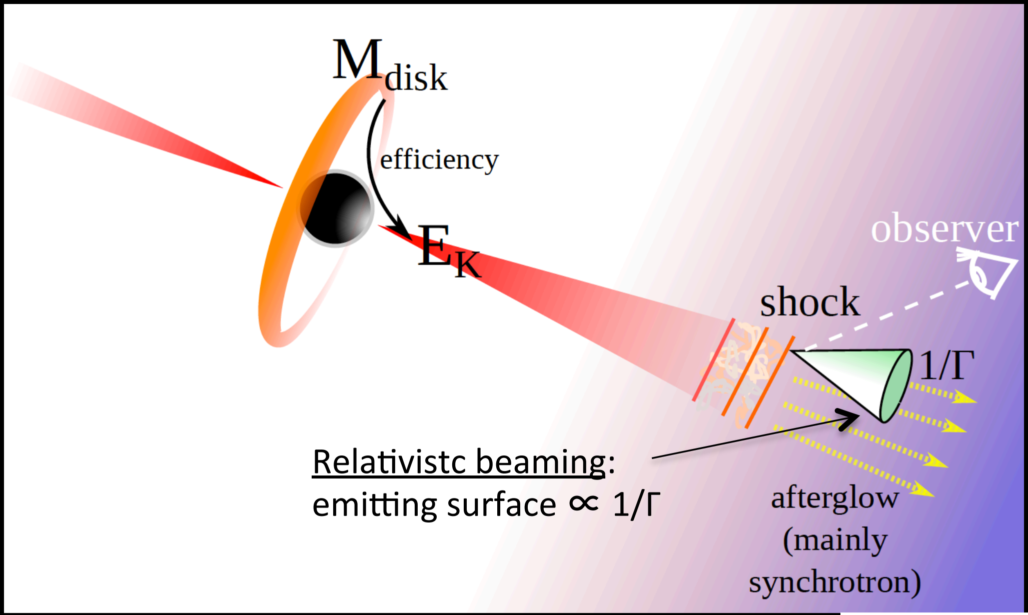
Source at 200 Mpc



(Kann et al 2010, ApJ 720)

(Kann et al 2011, ApJ 734)

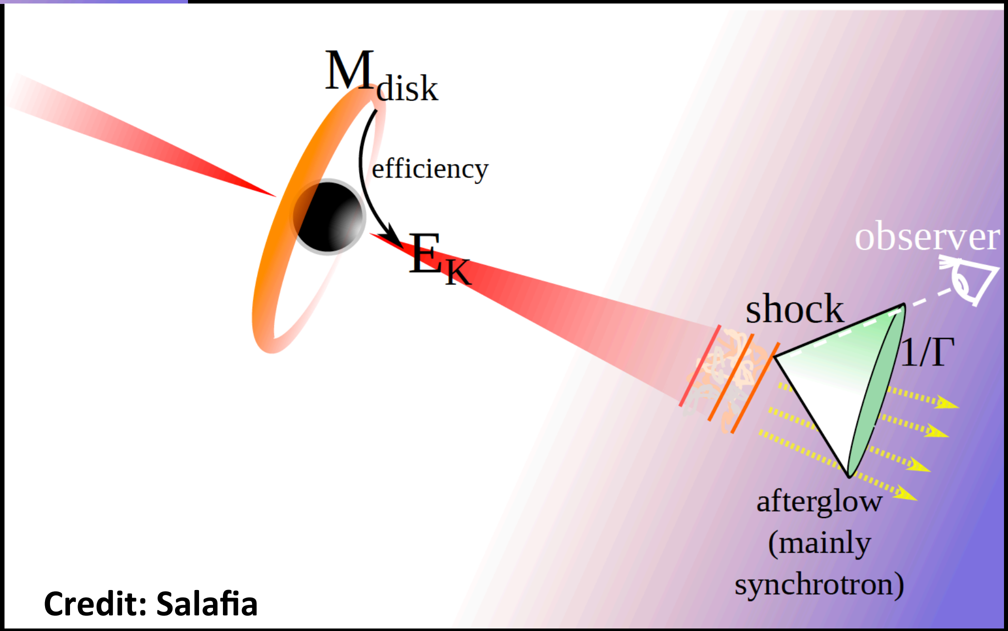
On average the optical afterglow decays as a **power law time**$^{-\alpha}$ with **α in the range 1 to 1.5**



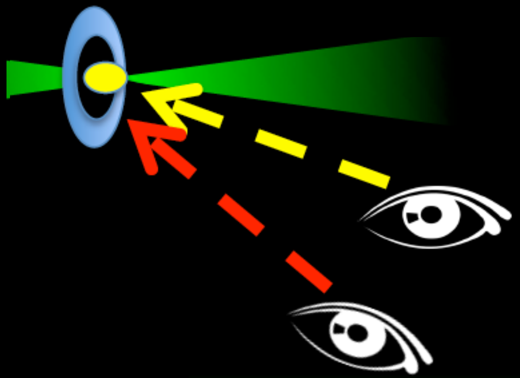
Relativistc beaming:
emitting surface ∝ 1/Γ

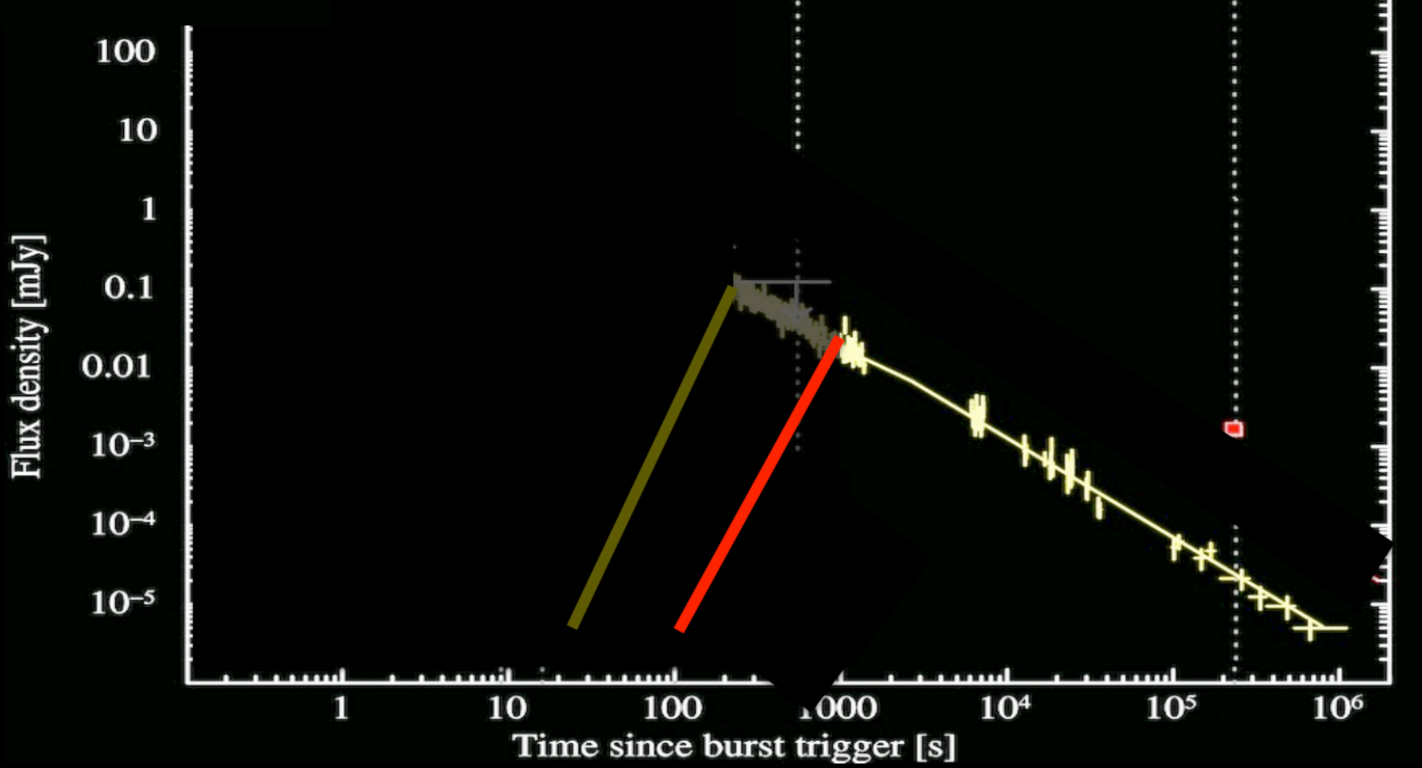
Early EM emission
detectable only by
on-axis observers

EM emission
detectable also by
off-axis observers

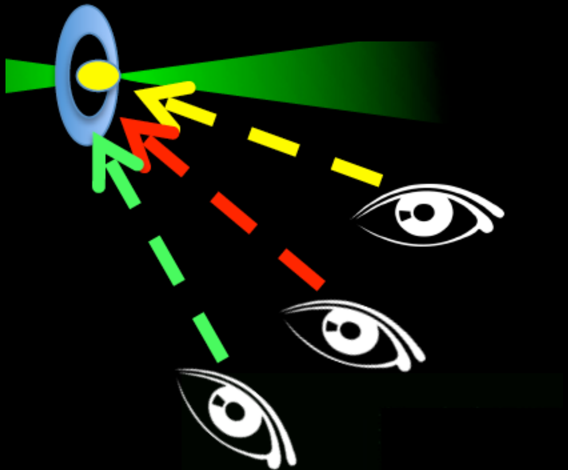


Credit: Salafia





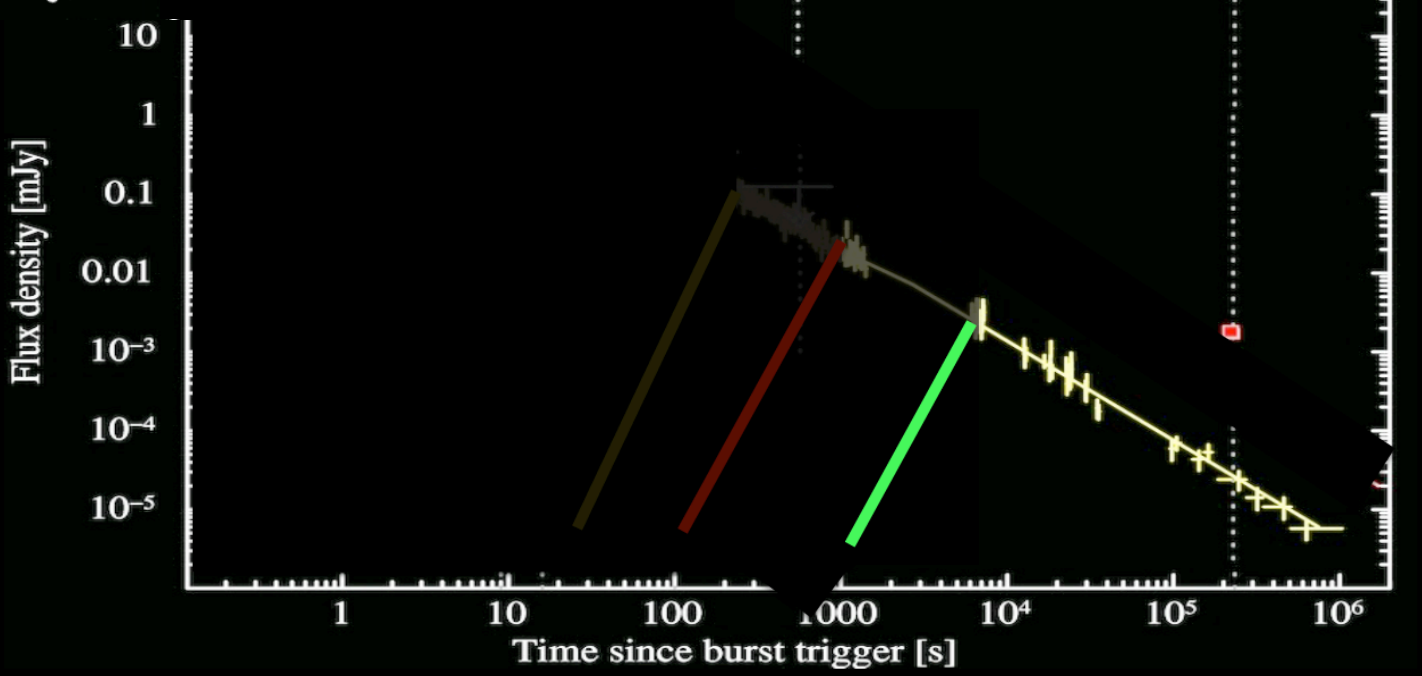
Credit: Ghirlanda



More off—axis:

(a) the emission peaks later

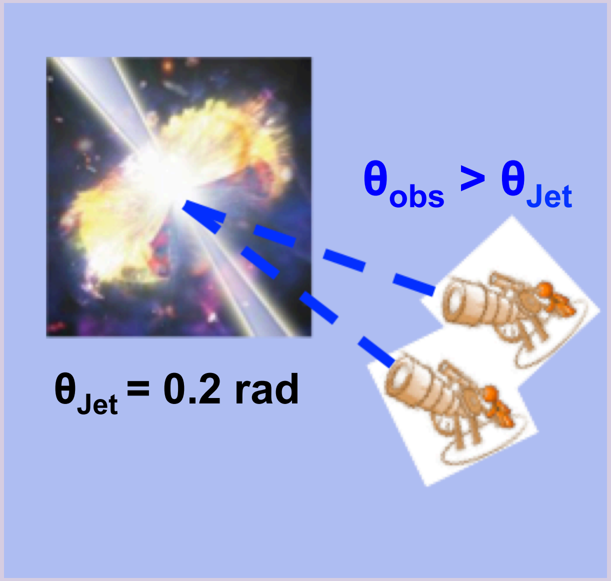
(b) the flux at peak is fainter



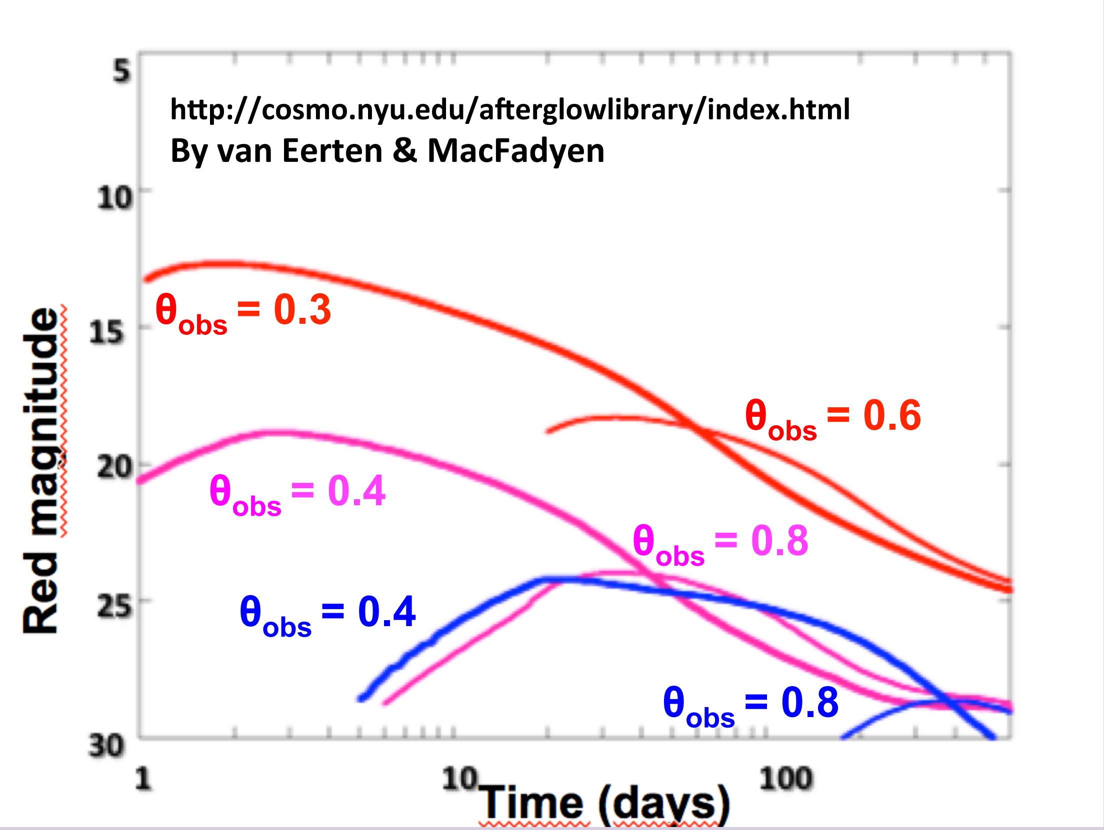
Credit: Ghirlanda

Optical afterglows of Off-axis GRBs

Off-axis GRB



Modelled afterglows - Source at 200 Mpc


http://cosmo.nyu.edu/afterglowlibrary/index.html
By van Eerten & MacFadyen

LONG bright GRB

E_jet = 2e51 erg, n = 1 cm^{-3}

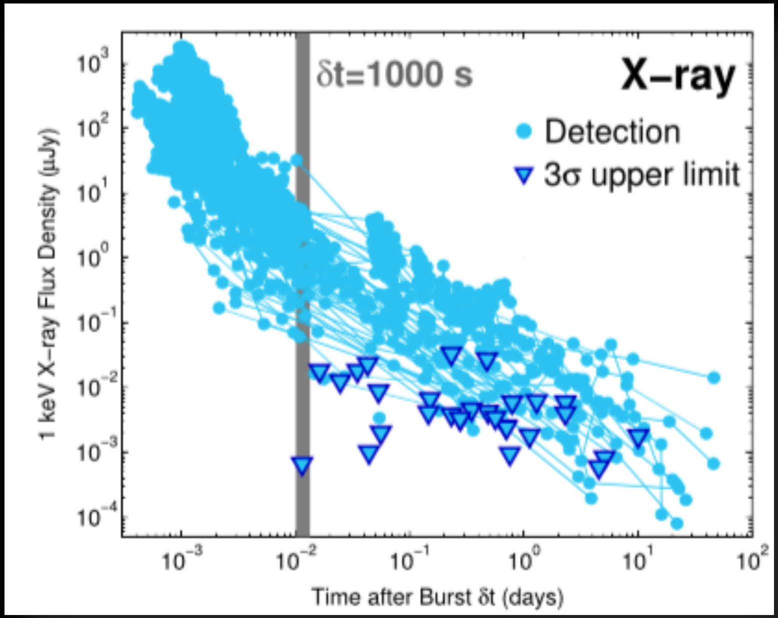
LONG faint/ SHORT bright GRB

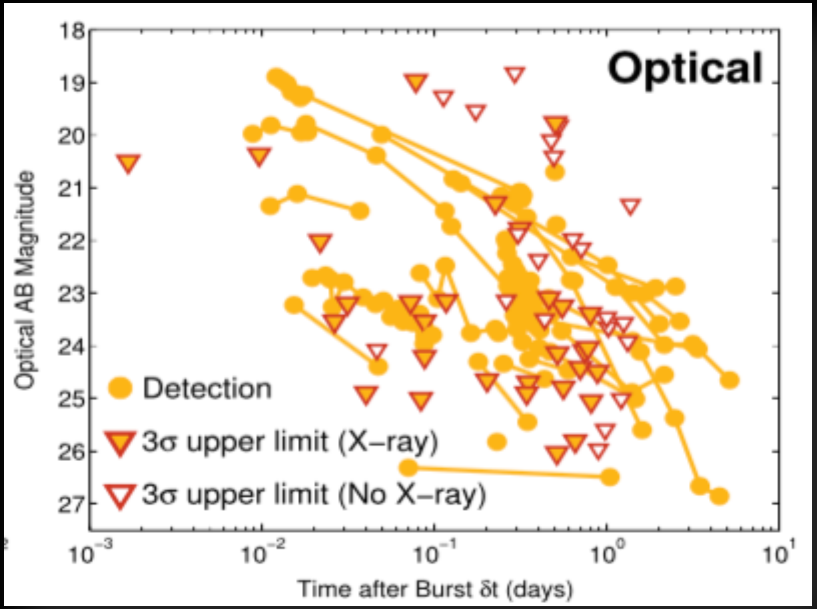
E_jet = 1e50 erg , n=1 cm-3

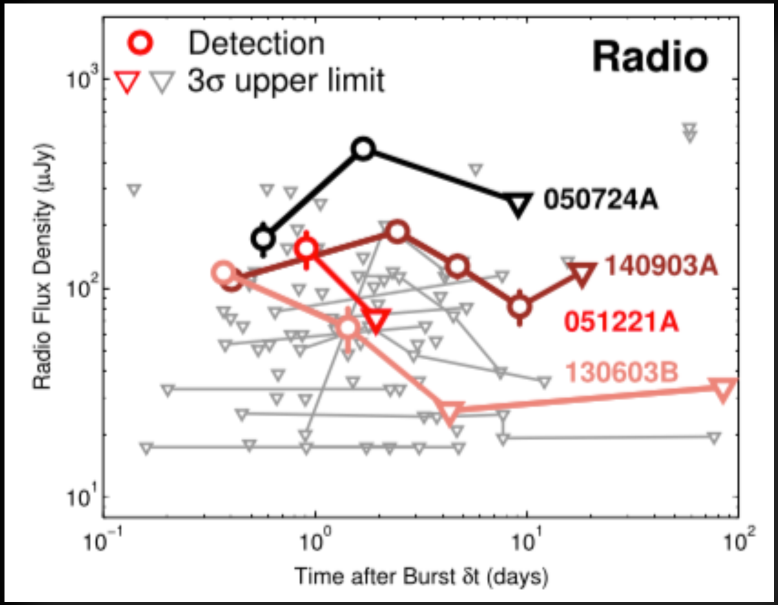
SHORT GRB

E_jet = 1e50 erg , n=10^{-3} cm^{-3}

Short GRB afterglows in numbers





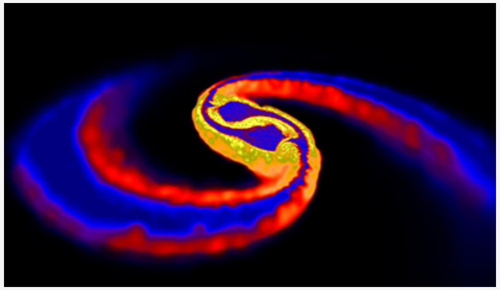


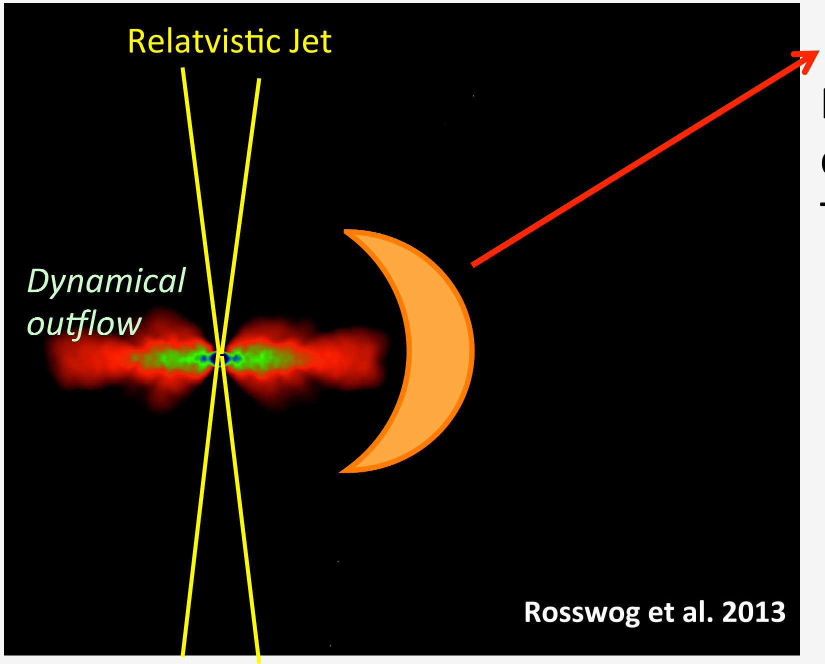
- About 140 SGRBs detected since 2005
- Afterglow detection percentage :
  - 90% in X-rays
  - 40% in opt
  - 7% in radio
- About 30 with redshift
- z_{min}=0.12 → 560 Mpc
- Energy =10^{48-52} erg

Fong et al. 2015

Macronova/Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected**
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.3 c)**





Rosswog et al. 2013

r-process

Neutron capture rate much faster than decay, special conditions:
$T > 10^9$ K, high neutron density 10^{22} cm^{-3}

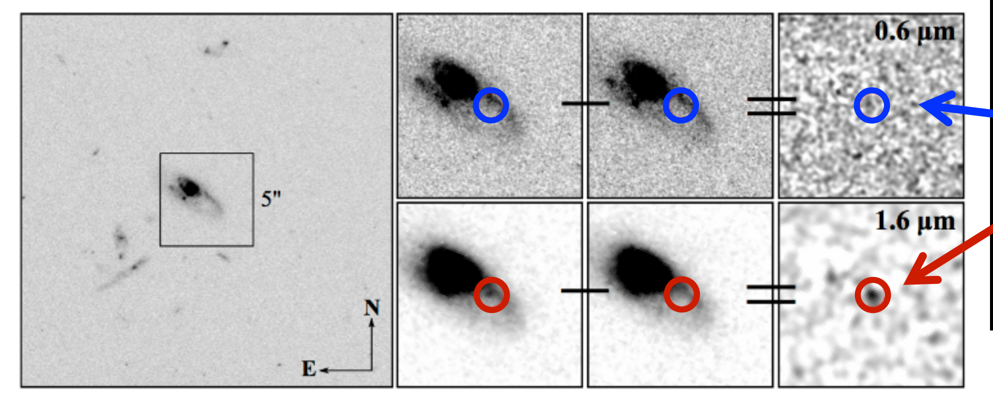
nucleosynthesis of heavy nuclei

radioactive decay of heavy elements

Power MACRONOVA
short lived IR-UV signal (days)

Are neutron stars mergers the primary source for the production of heavy elements in the Universe?
[Beniamini et al. 2016, APJL 2016]

Possible HST kilonova detection for short GRB130603B after 9.4 days (Tanvir et al. 2013, Nature ,500)



HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

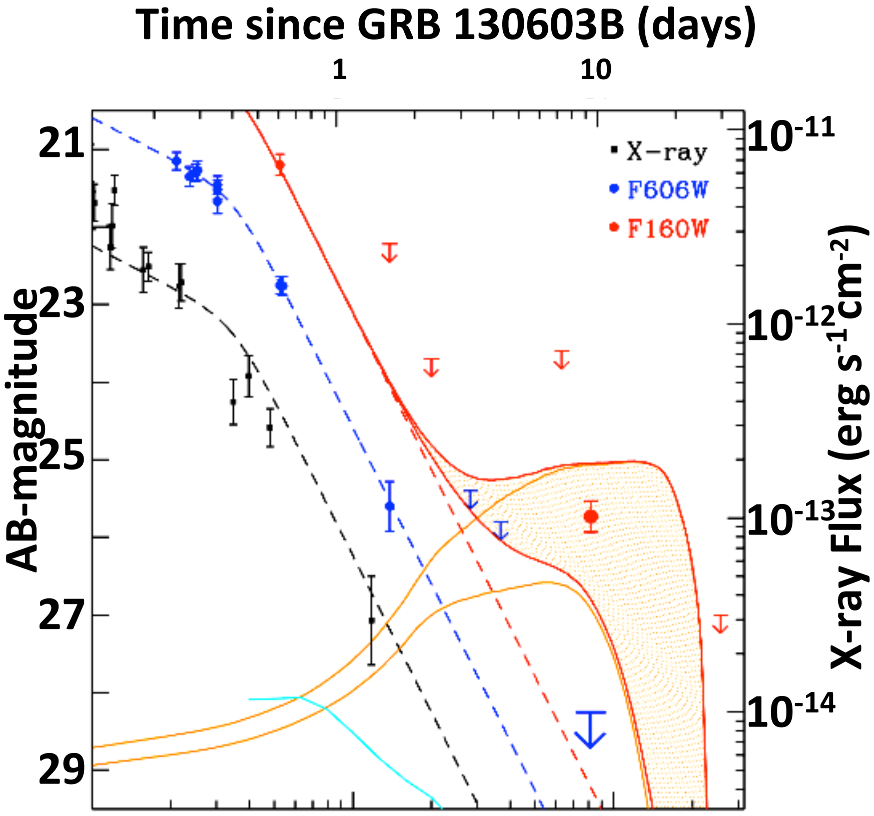
Afterglow and host galaxy z=0.356

Orange curves → kilonova NIR model

ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model



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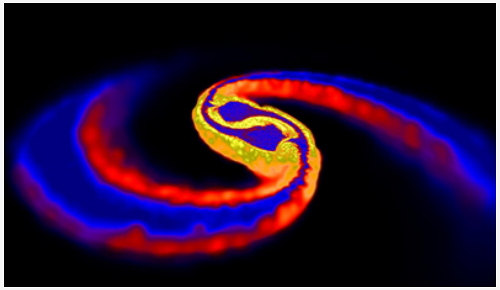

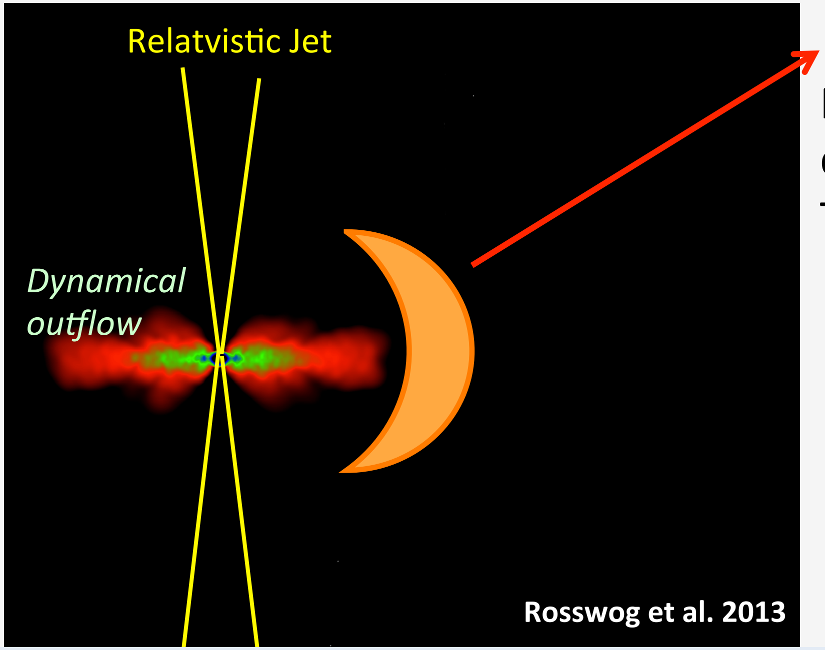

Rosswog et al. 2013

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↓

nucleosynthesis of heavy nuclei

↓

radioactive decay of heavy elements

↓

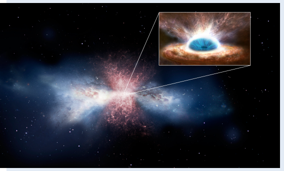
Power MACRONOVA
short lived IR-UV signal (days)

Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406; Tanaka et al. 2014 ApJ, 780;
Barnes & Kasen 2013, ApJ, 775.

Accretion disc wind outflow

→winds unbind a fraction of the disk

→neutrino irradiation raises the electron fraction → No nucleosynthesis heavier element/high-opacity
→ brief (~ 2 day)
blue optical transient



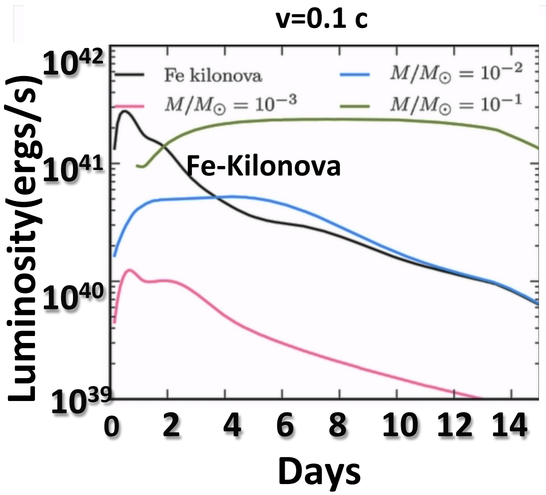
Kasen et al. 2015, MNRAS, 450
Perego et al. 2014, 443, 3134

EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

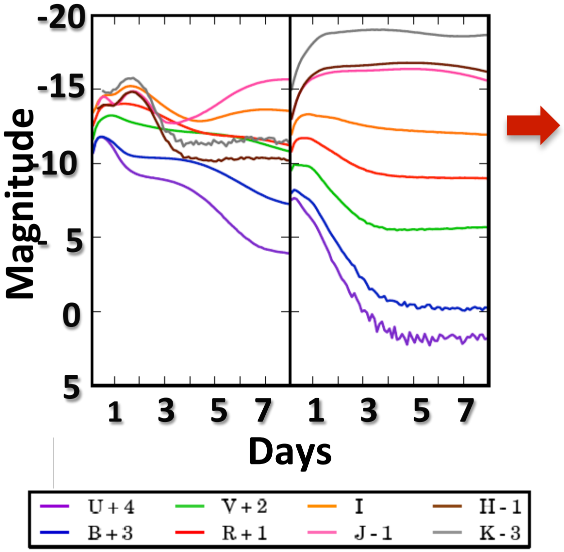
OPACITY of Fe and "heavy r-process elements"

Barnes & Kasen 2013, ApJ, 775



Opacities:

Fe r-process

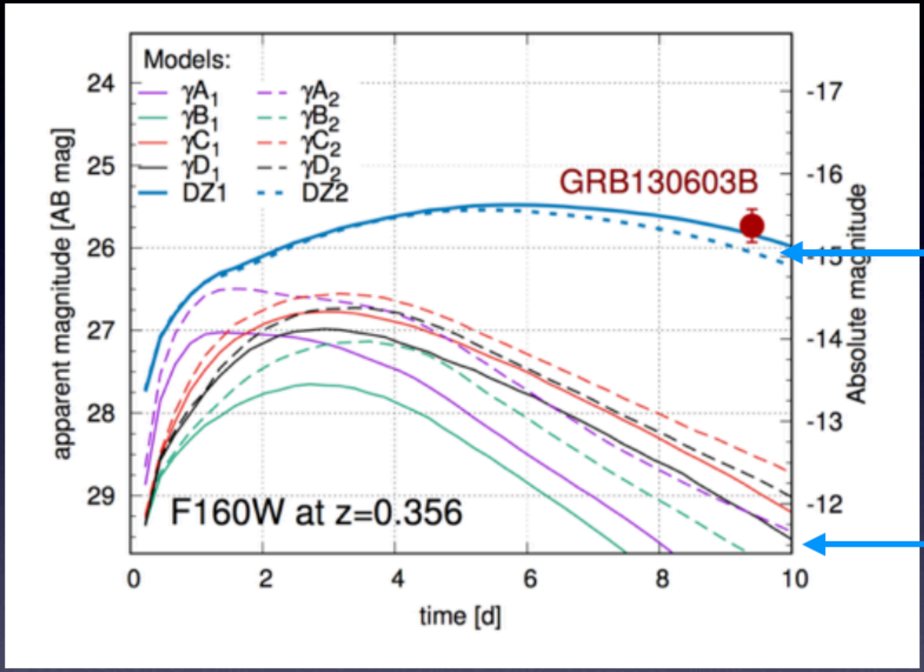


r-process opacity

- broader light curve
- suppression of UV/O emission and shift to IR

EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

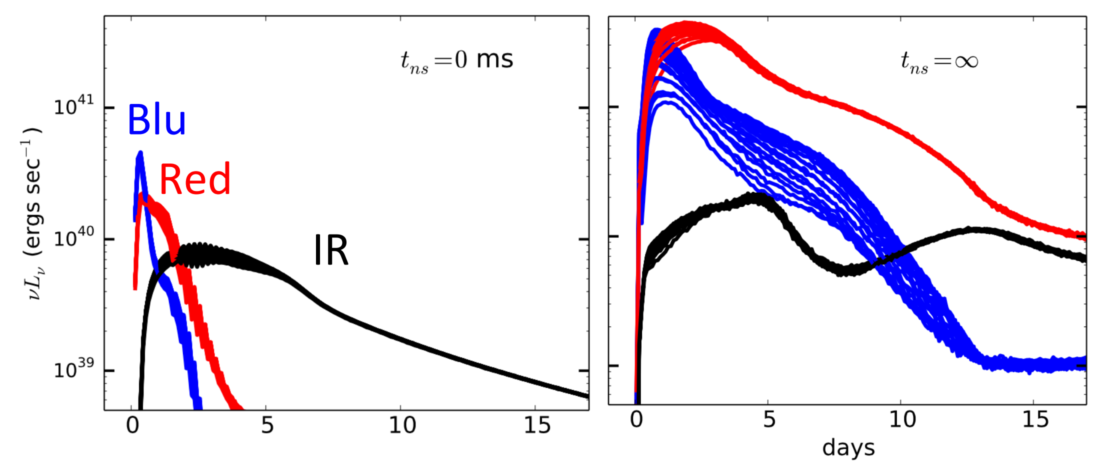


Duflo-Zuker heating
(nsns 1.4 + 1.4 M⊙, on-axis)

FRDM heating

Credit:
Rosswog@GWPAW2017

longer-lived NS → stronger neutrino irradiation

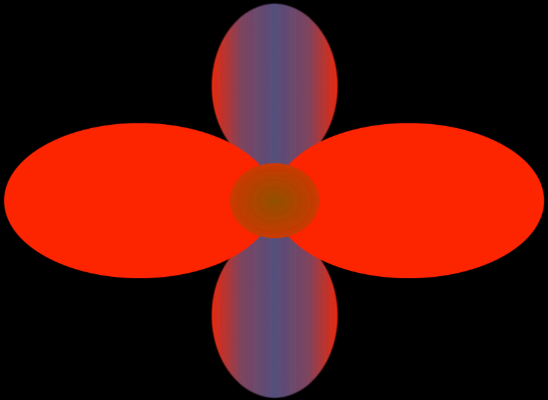


Kasen et al. 2015, MNRAS, 450

Cartoon picture

- “winds”, Ye ~ 0.3
- “weak r-process” (A <130)
- lanthanide/actinide-free
- moderately opaque ⇒ blue
- τpeak ~ 1 day

⇩



⇨

- **Dynamic ejecta**, Ye ~ 0.1
- “strong r-process”
- lanthanide/actinide
- very opaque ⇒ Red/IR
- τpeak ~ 1 week/10 days

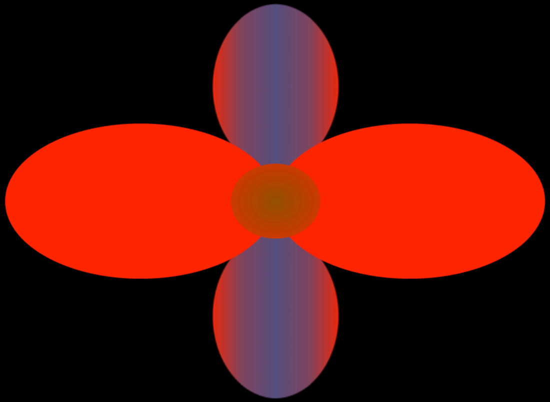
Credit:
Rosswog@GWPAW2017

Cartoon picture

- “winds”, Ye ~ 0.3
- “weak r-process” (A <130)
- lanthanide/actinide-free
- moderately opaque ⇒ blue
- τpeak ~ 1 day

- **Neutron-rich dynamical ejecta** acts as a “lanthanide-curtain”, **obscuring the optical wind emission** from certain viewing angles
- NSBH → equatorial plane dynamical ejecta → “wind” emission along polar axis

⇩



⇨

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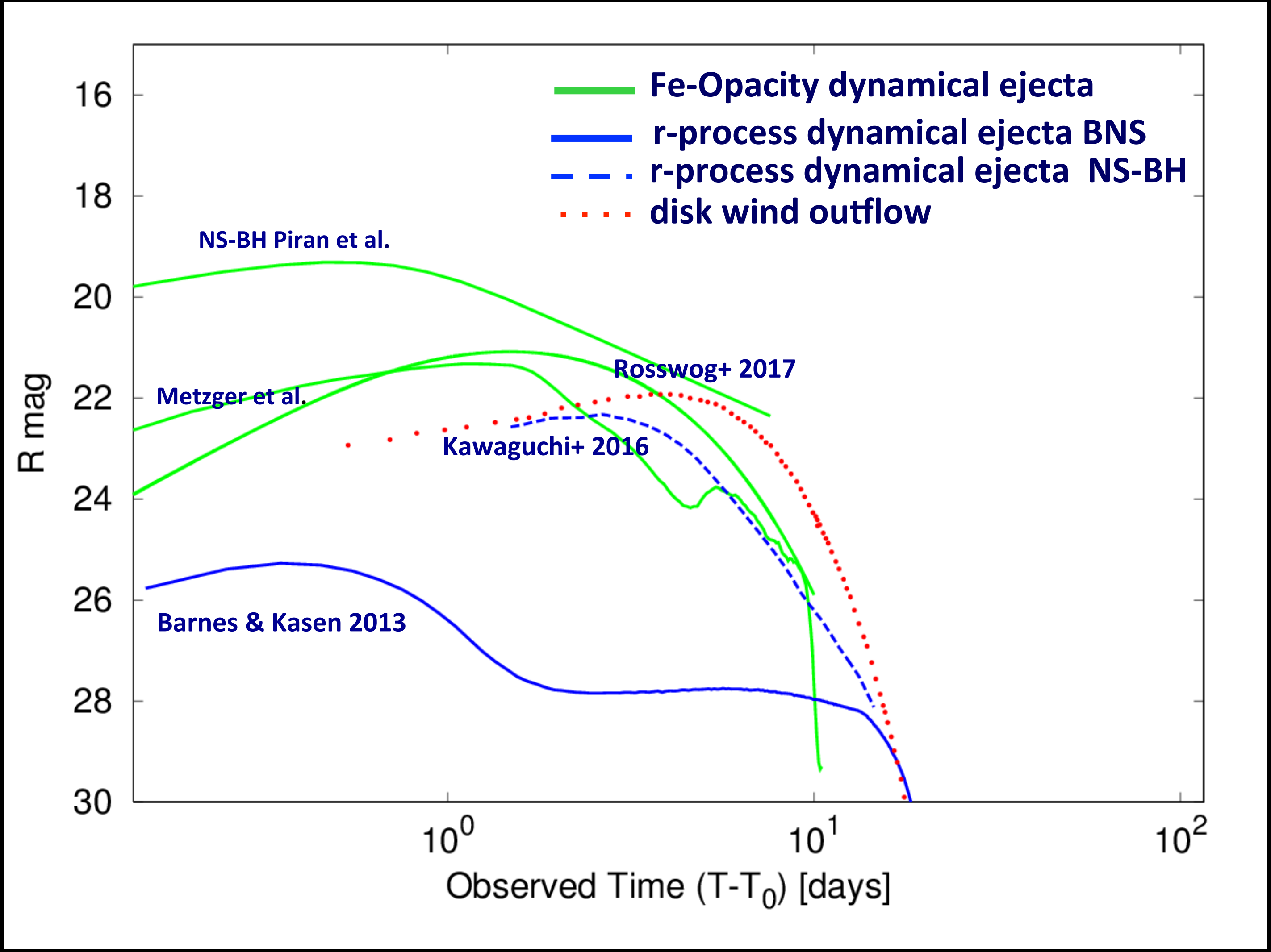
Credit:
Rosswog@GWPAW2017

Examples of Optical marconova ligth curves



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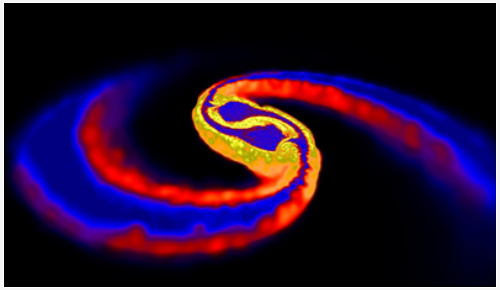
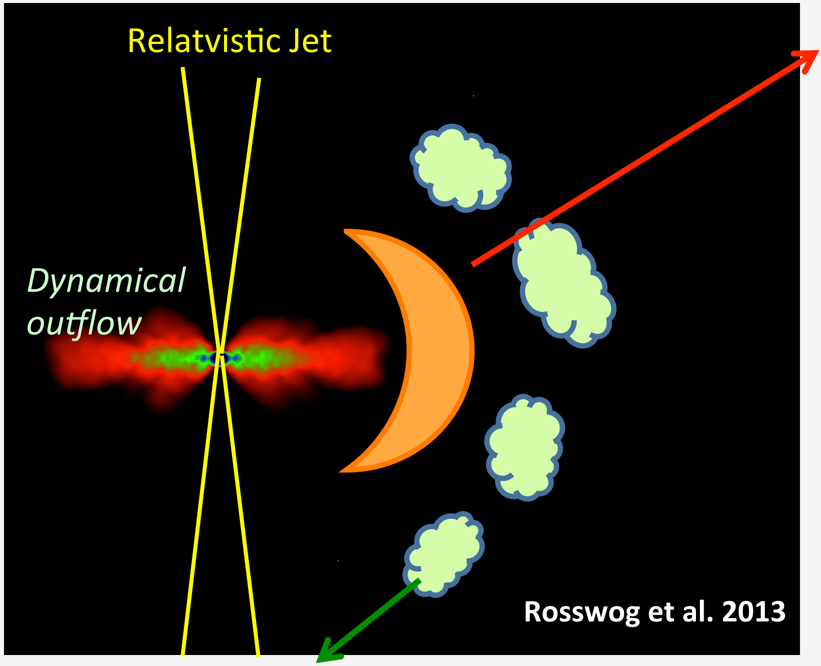


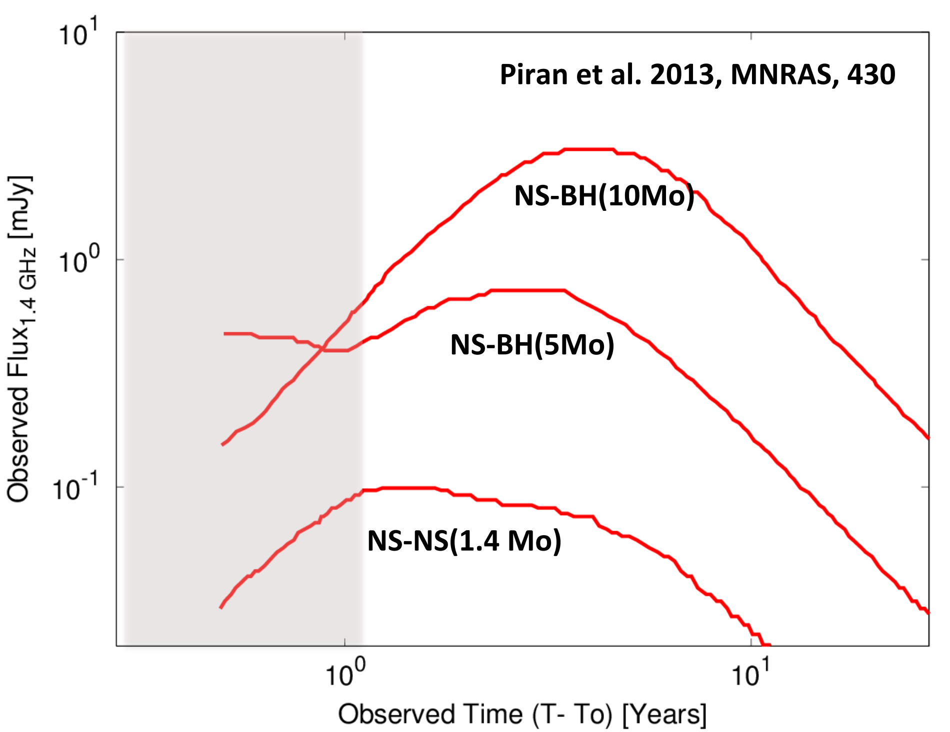


Rosswog et al. 2013

Power MACRONOVA
short lived IR-UV signal (days)

RADIO REMNANT

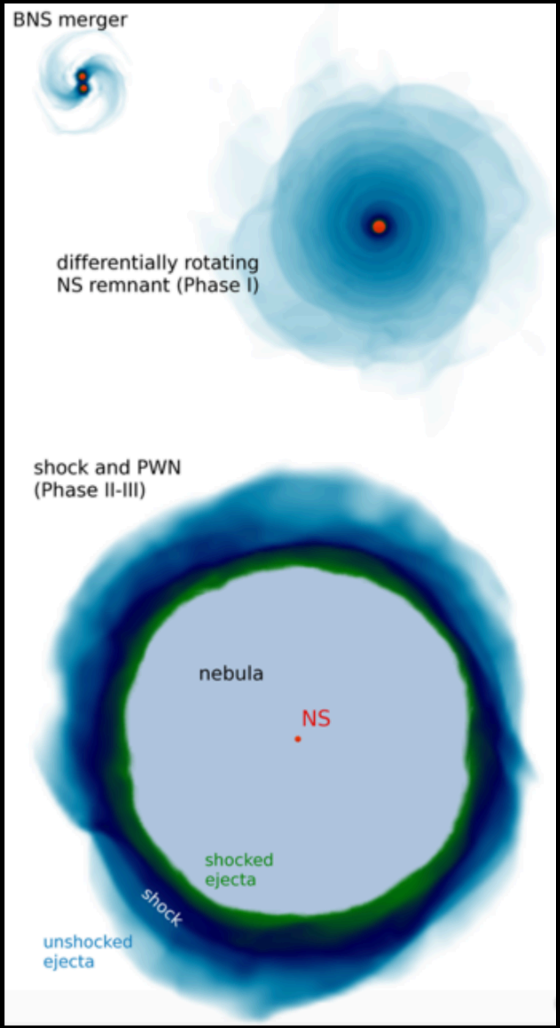
long lasting radio signals (months-years)
produced by interaction of sub-relativistic outflow with surrounding matter



Piran et al. 2013, MNRAS, 430

Piran et al. 2013, MNRAS, 430
Hotokezaka 2016, ApJ, 831, 190

X-ray emission from the long-lived NS remnant

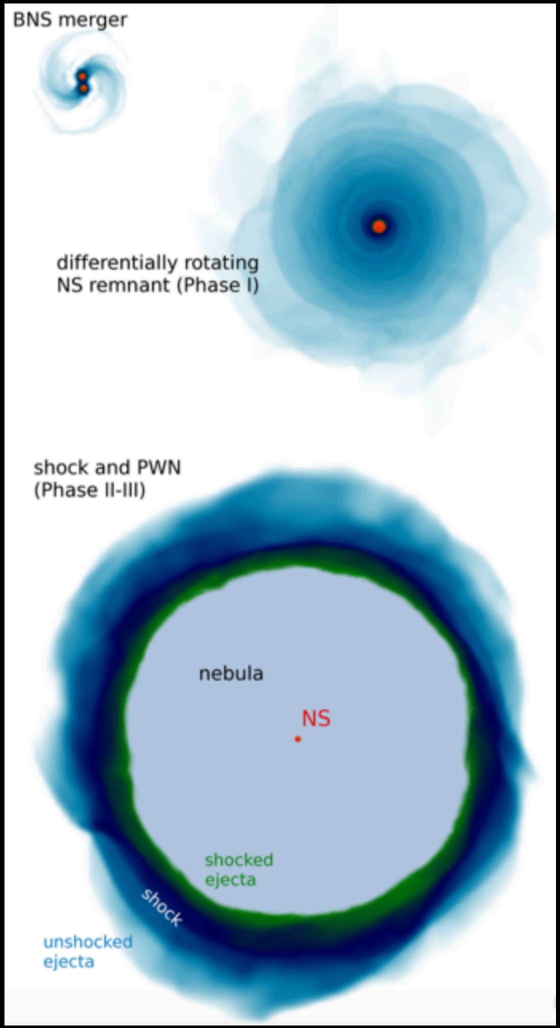


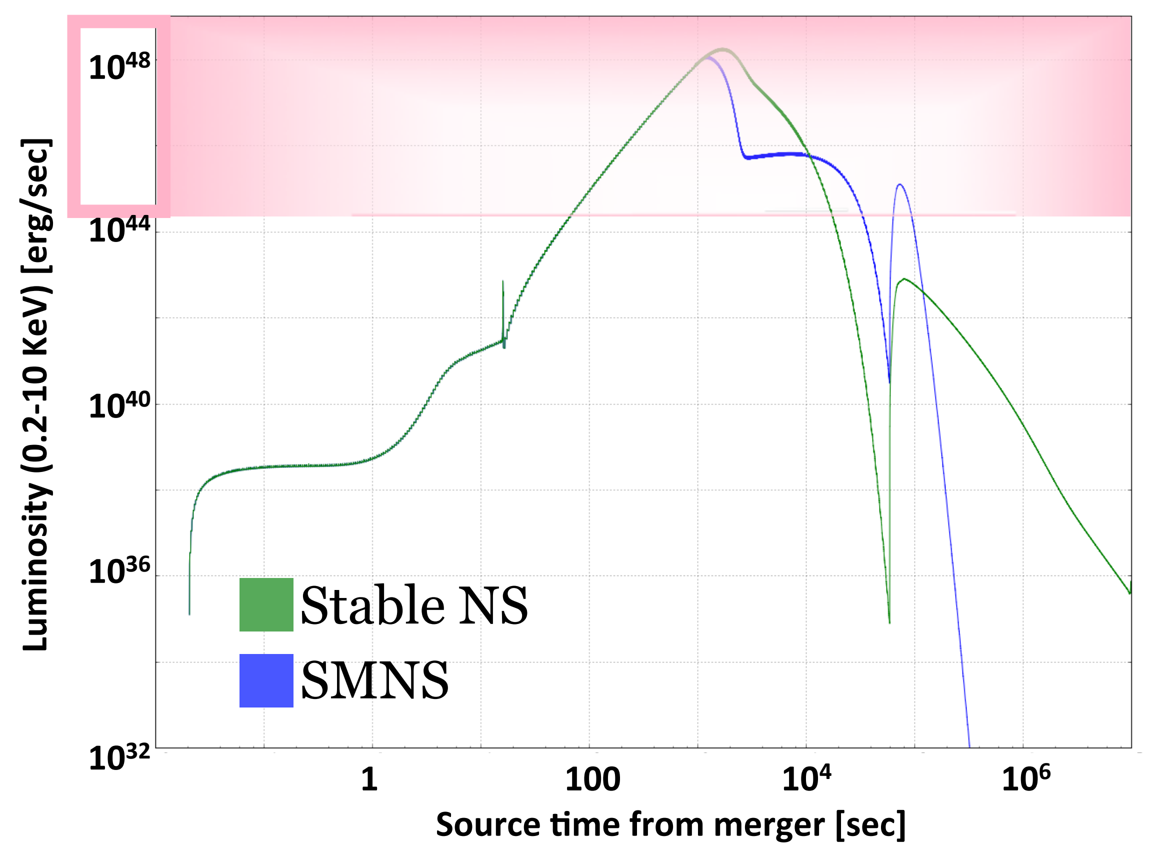
- X-ray afterglow radiation produced by spin-down energy extracted from the NS prior to collapse, slowly diffusing through optically thick environment composed of a pulsar wind nebula (PWN) and outer shell of ejected material
- signal peaks at 10^2-10^4 s after the merger
- luminosities 10^{46}-10^{49} erg/s
- mostly in the soft X-rays (0.2-10 keV)

Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

X-ray emission from the long-lived NS remnant

- ISOTROPIC
- BRIGHT
- LONG LASTING



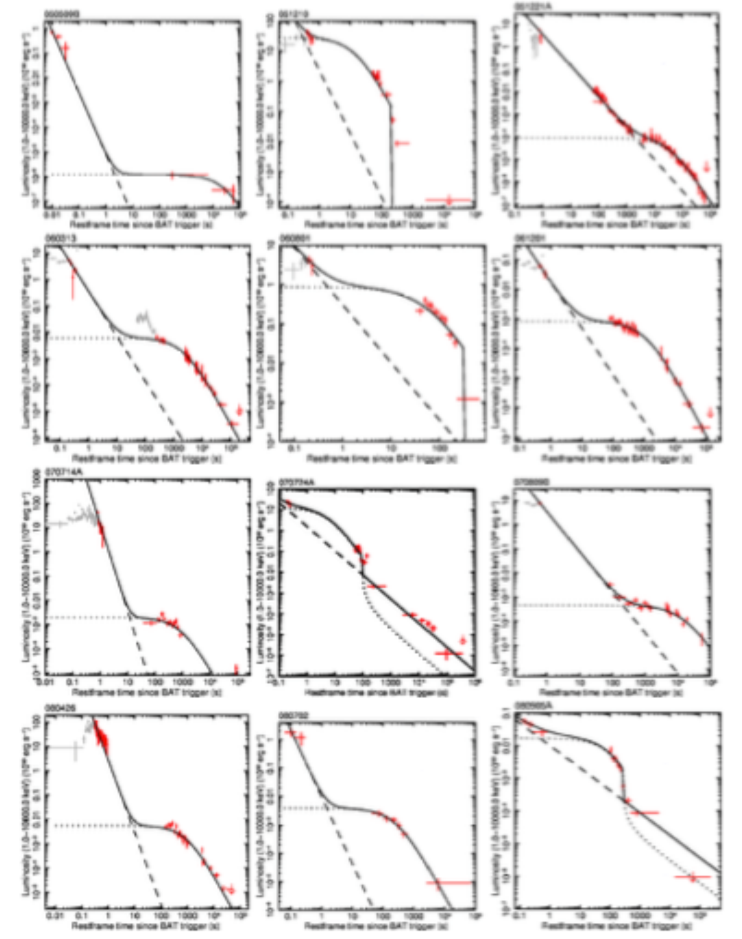


Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

"X-ray plateaus"

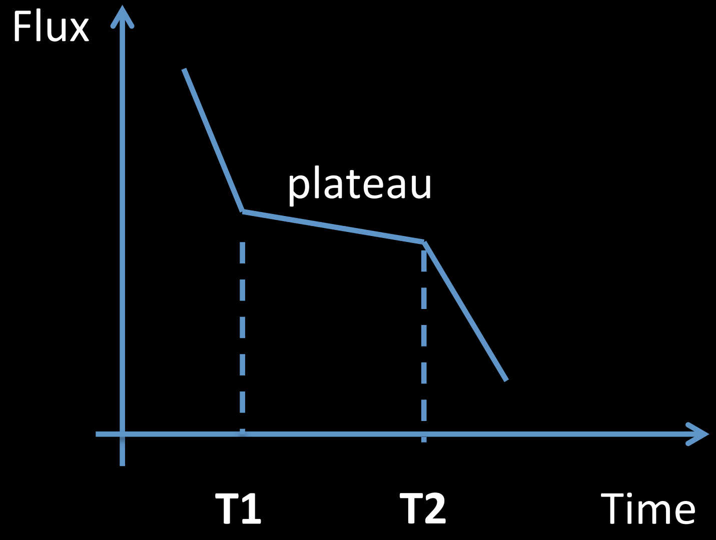
- Plateaus are found in a large fraction of long GRB X-ray light curves
- Possible evidence of ongoing central engine activity

Rowlinson+2013 found that ~50% Short GRB X-ray afterglows show a plateau phase in their light curves

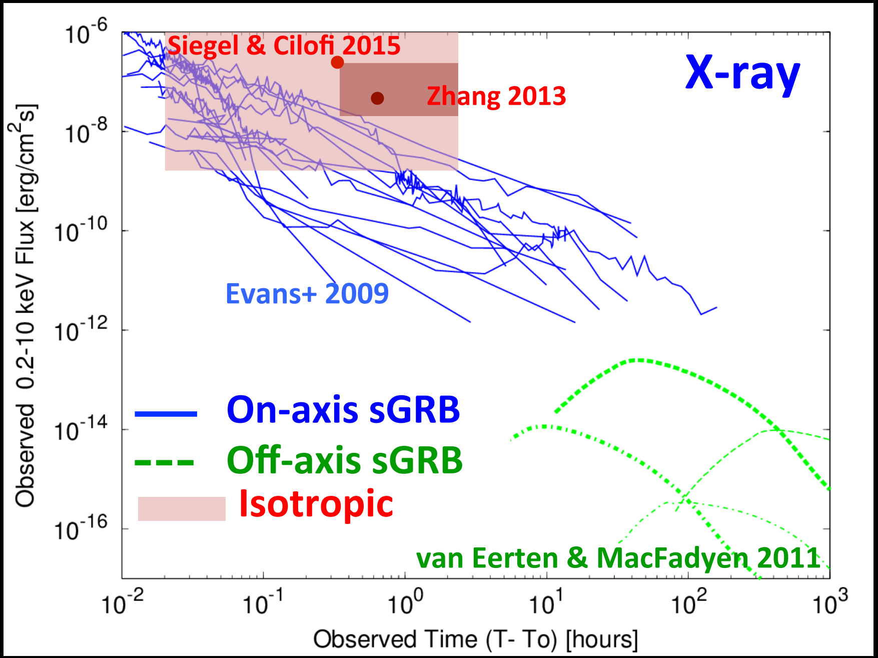


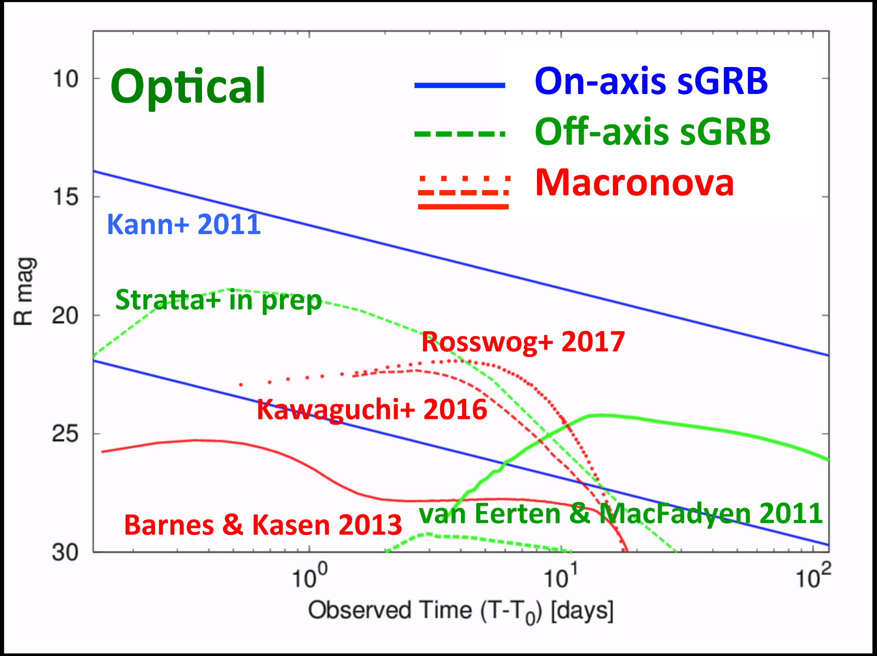
Rowlinson et al. 2013

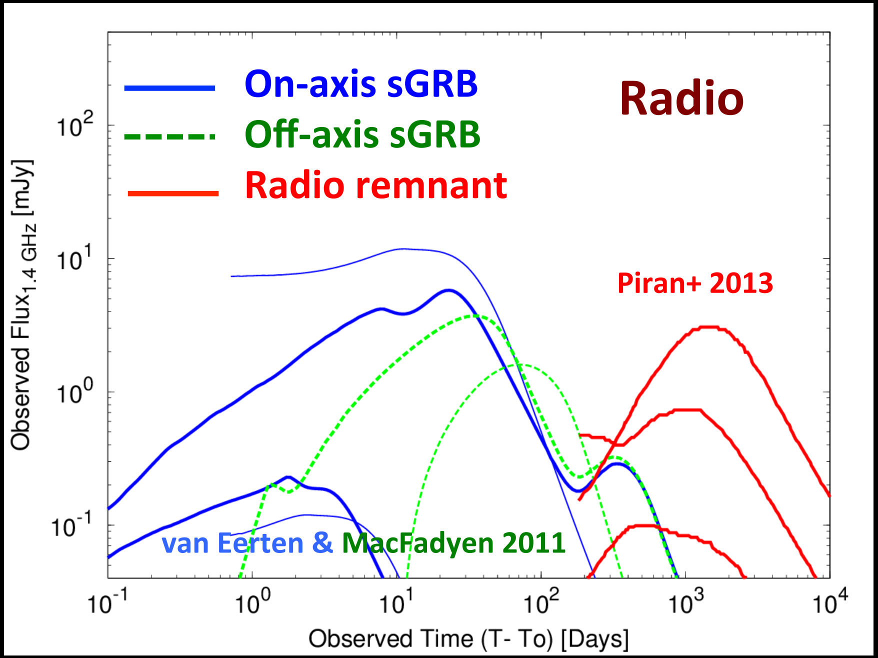
The plateaus can be explained with the spin-down of magnetar or SMNS

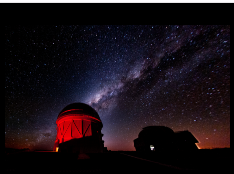


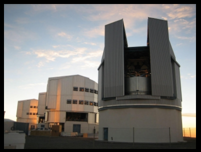
NS-NS merger EM-emissions











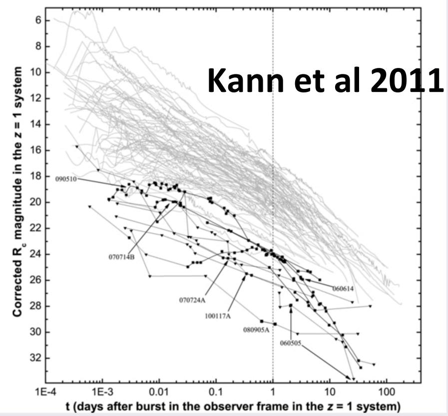
Source at 200 Mpc

Other EM-signatures

Core collapse of massive star

Long GRBs

Prompt & **afterglow** emissions **brighter** than short GRBs

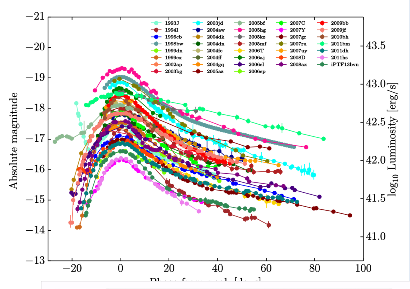


Kann et al 2011

Optical afterglow

Core-Collapse Supernovae

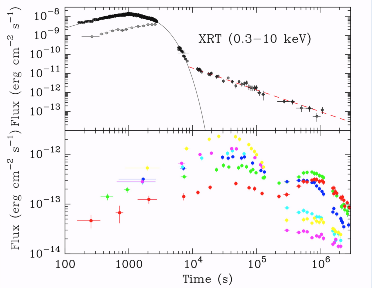
Optical light curve



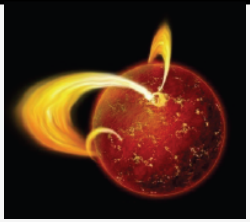
Shock breakout

short (thousands seconds) and long (several days)

X-ray/UV flashes

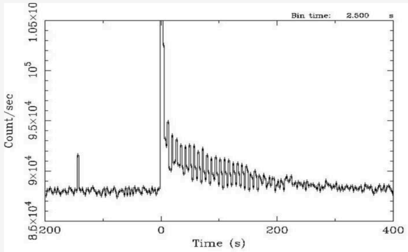


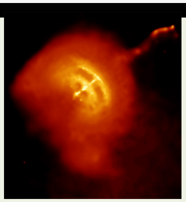
Isolated NS Instabilities



Soft Gamma Ray Repeaters & Anomalous X-ray Pulsars

Magnetars which emit **hard X-ray/gamma repetitive 0.1 sec flares** (10^{42} erg/s) and **giant flares** (10^{47} erg/s)

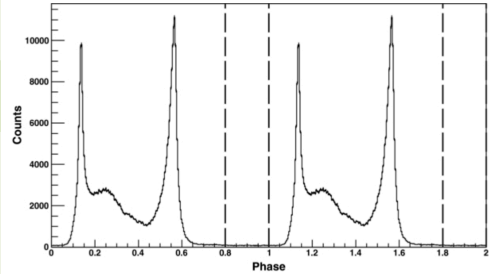




Pulsar glitches:

sudden increase in the NS rotational phase, frequency or frequency derivatives observable in **radio and gamma-ray pulsars**

Vela – Fermi-LAT



Different timescale

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio

(minutes, hours, days, months)

Off-axis

afterglo

Macr

mission

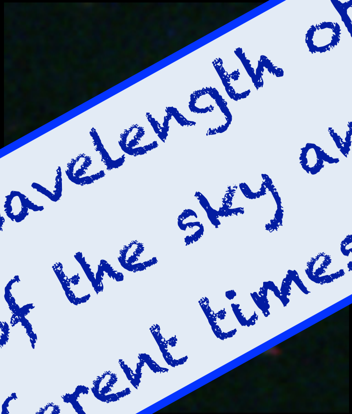
X-r

s)

Radio remnants

(months, years)

Core-coll



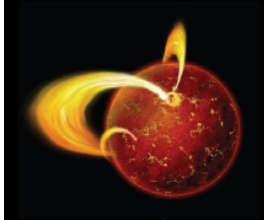
s)

io

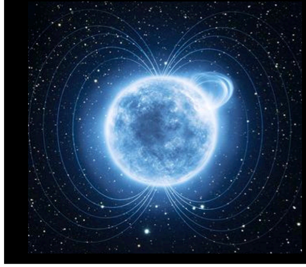
(years)

+ Long GRB

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

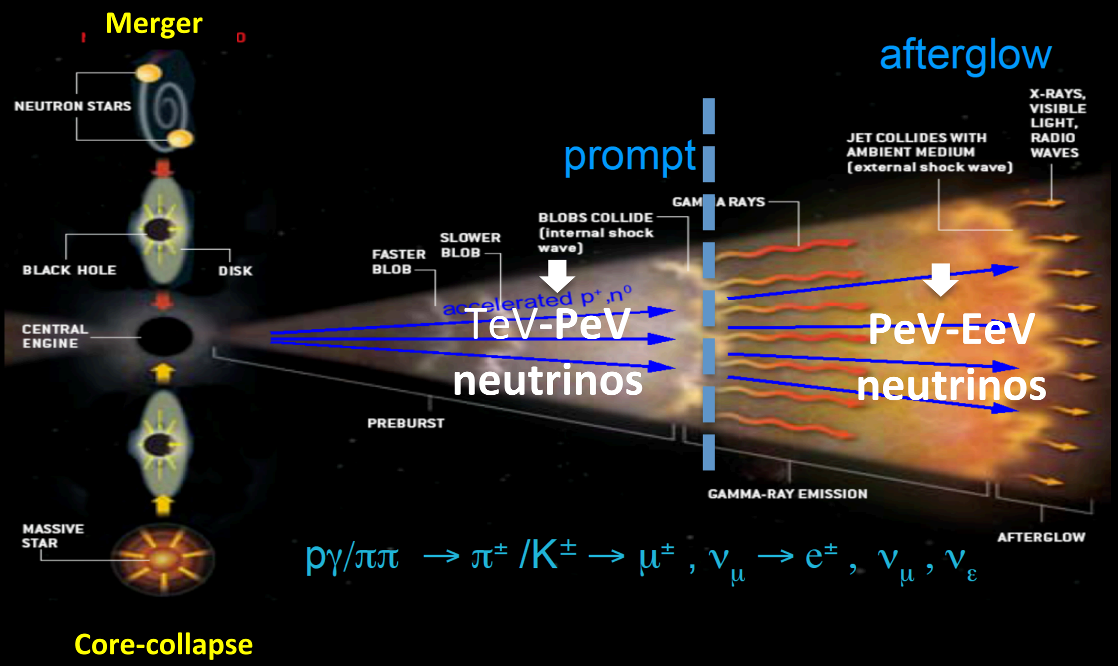


Radio/gamma-ray Pulsar glitches

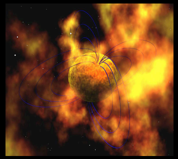
Request for network of multi-wavelength observatories which cover huge region of the sky and repeat observations over different timescales...

Neutrino emission

High energy neutrinos (HEN) from TeV to PeV are expecetd to be produced by GRBs and SGRs



$p\gamma/\pi\pi \rightarrow \pi^{\pm}/K^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_{\mu}, \nu_{\varepsilon}$



Low-energy (few tens MeV) neutrinos are emitted by core-collapse supernova

BH-BH mergers → EM emission ?

Stellar-mass BH mergers *are* ***not expected to produce detectable counterparts****, due to the absence of baryonic matter*
(no NS tidal disruption → no accreting material)

Some unlikely scenarios that might produce unusual presence of matter around BBH:

- from the remnants of the stellar progenitors
  (Loeb,2016; Perna et al., 2016; Janiuk et al., 2017)
- the tidal disruption of a star in triple system with two black holes
  (Seto & Muto, 2011; Murase et al., 2016)
- enviroment of binaries residing in active galactic nuclei
  (Bartos et al., 2017; Stone et al., 2017)

Multi-Messenger Searches with GWs

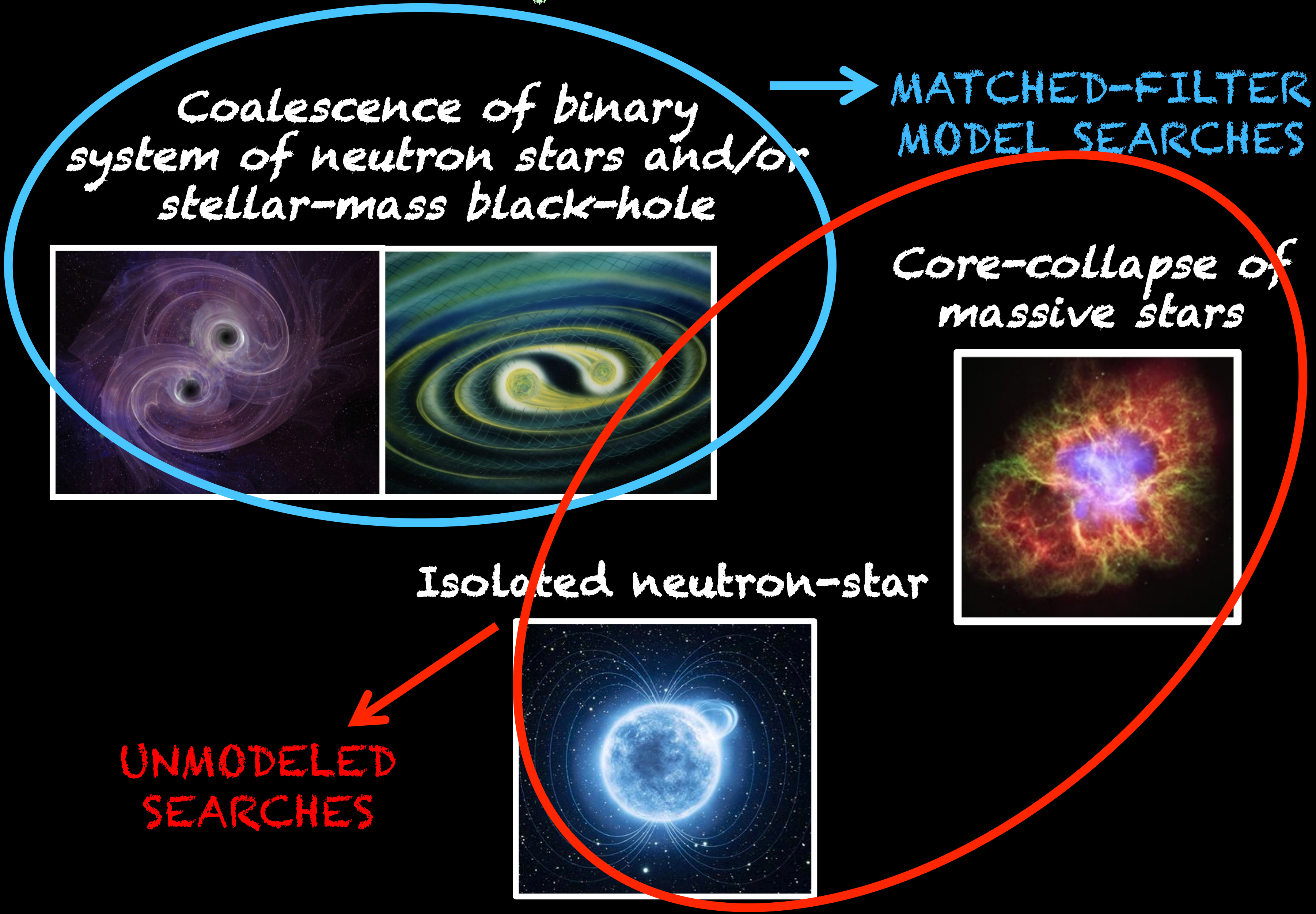
LIGO & Virgo have signed MOUs with 93 groups for rapid EM/neutrino follow-up of GW candidate events found in low-latency

INVOLVED:

- **About 200 EM instruments** - satellites and ground based telescopes covering the full spectrum from radio ti very high-energy gamma-rays
- ***Worldwide astronomical institutions, agencies and large/small teams of astronomers***

Multi-messenger searches

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)



Coalescence of binary system of neutron stars and/or stellar-mass black-hole

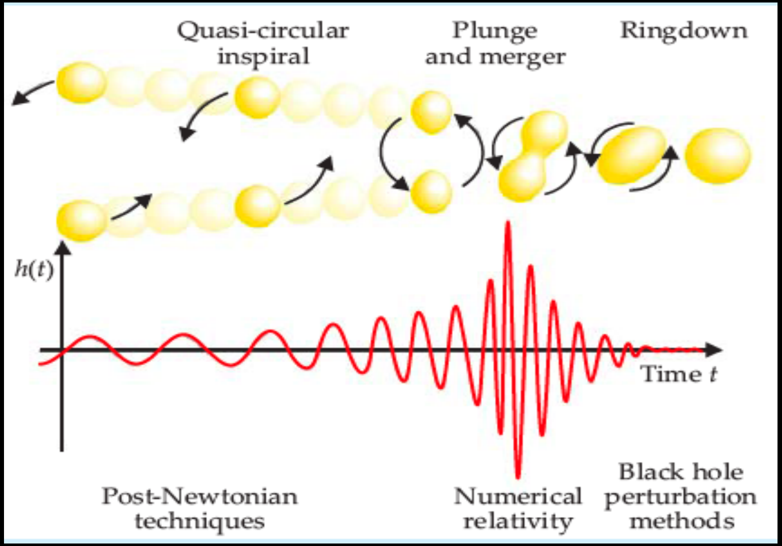
→ MATCHED-FILTER MODEL SEARCHES

Core-collapse of massive stars

Isolated neutron-star

UNMODELED SEARCHES

Modelled compact binary coalescence searches



Waveforms depend on

- ***intrinsic parameters**: **masses** and **spins** of the binary system (plus eccentricity, NS compactness, tidal deformability)*
- ***extrinsic parameters** that describe location, distance, merger time and system orientation with respect to an observer*

Detection phase: known waveforms → **MATCHED FILTERING**

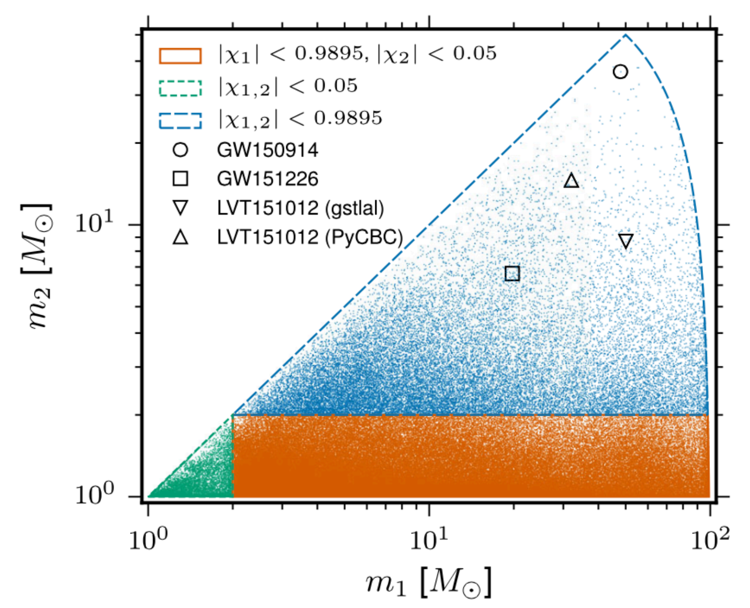
- Using waveform templates for a range of intrinsic parameters (masses and spin)
- "Extrinsic" parameters absorbed in overall amplitude

After detection → ***Source PARAMETER RECONSTRUCTION:***

- Algorithms to explore the full-parameter space and find most likely values for sky location, masses, distance, orientation, spin…

Matched filtering searches

O1 template bank



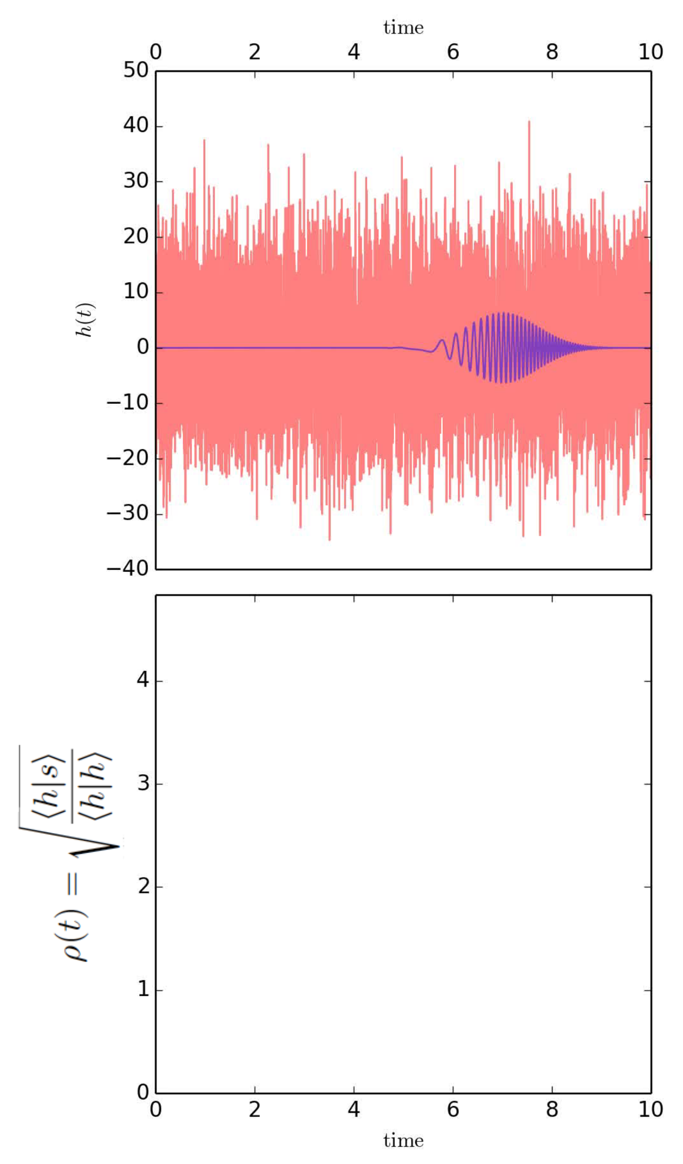
LVC Phys. Rev. X 6 (2016)

TEMPLATE

OBSERVATIONS

$$\langle h|s\rangle(t) = 4\Re \int_0^\infty \frac{\tilde{h}^*(f)\tilde{s}(f)e^{2\pi i f t}}{S_\mathrm{n}(f)} df$$

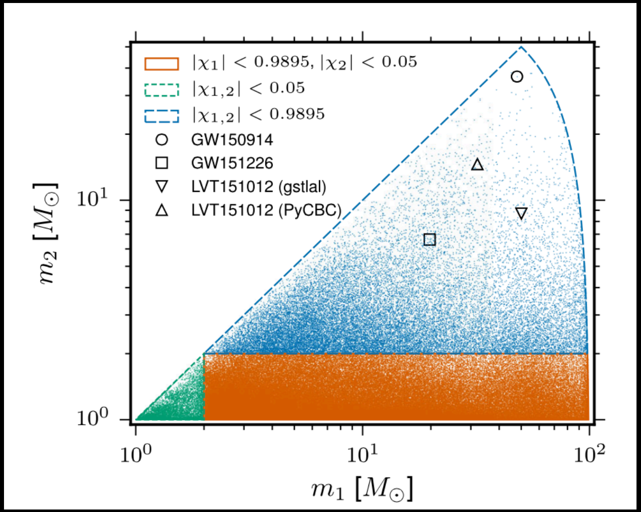
NOISE MODEL



→ *Improve analysis to detect more signasl:*

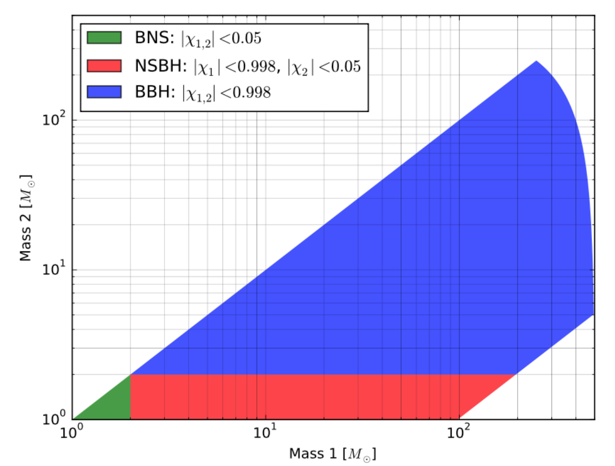
- Cover parameter space densely enough with templates
- Increase size of template bank
- Improve waveform models to fit real signals

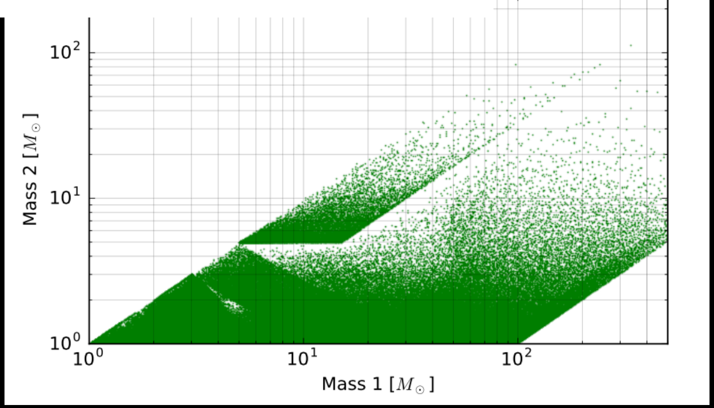
O1 template bank



LVC Phys. Rev. X 6 (2016)

O2 parameter space



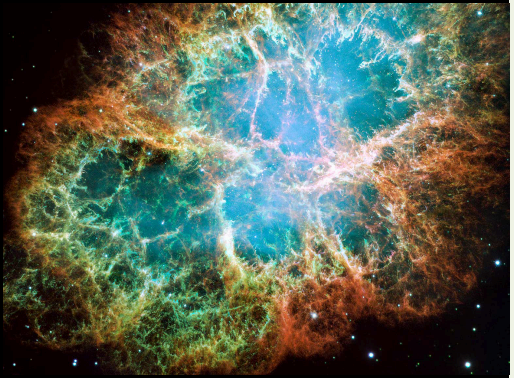


Template distribution

Dal Canton & Harry, arXiv:1705.01845

Models and searches are still missing:
- precession
- higher-order modes
- eccentricity
- neutron-star physics

Unmodeled GW transient searches



Transient sources:

- Core-collapse of massive stars
- Cosmic strings
- Neutron star instabilities
- ...
- ... the unknown

Poorly modelled

→ Can't use matched filtering

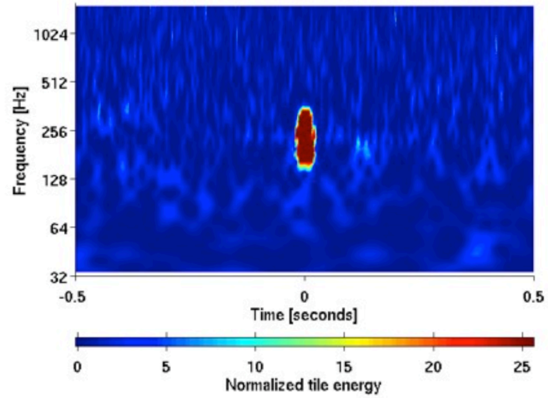
Detection without unknown waveform

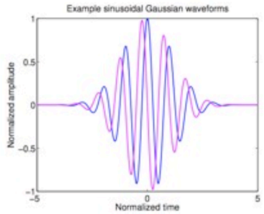
→ **LOOK FOR "EXCESS POWER"**

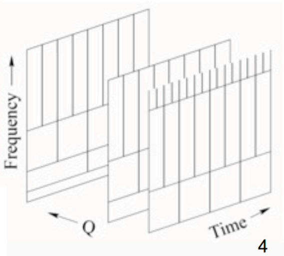
All-sky, all-time search for transient as increase in power (hot pixels) in time-frequency map, minimal assumptions:

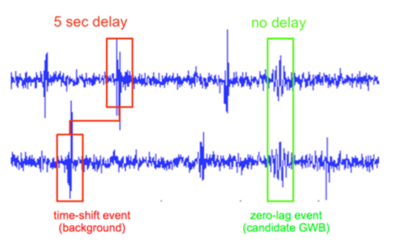
1. Duration: 1 ms to 1 s (characteristic time scale for stellar mass objects) → now also to a few hundreds of sec
2. Frequency: 10 to 5000 Hz (determined by detector's sensitivity)
3. **Signal appears coherently** in multiple detectors, consistent with antenna pattern → coincidence, coherent statistics, sky location

Noise fluctuations can be eliminated based on their non-correlation between detectors







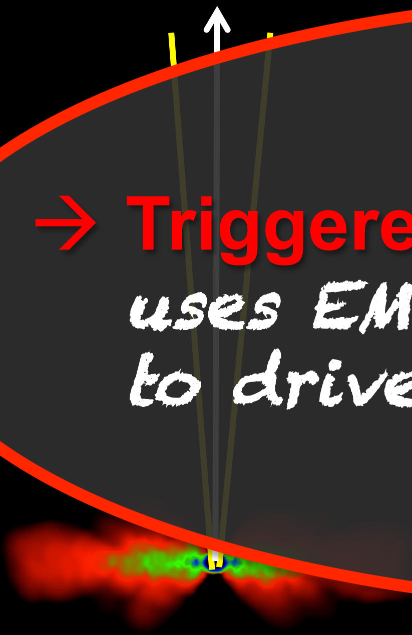


Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma

HEN Neutrinos



Core-collapse of massive stars

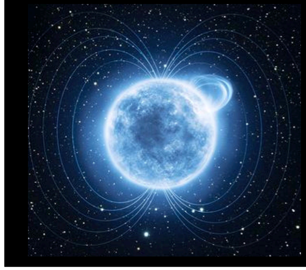
SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Low-energy Neutrinos

Isolated NS instabilities

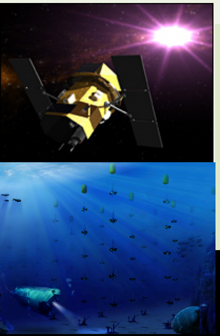
Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

→ **Triggered Analysis:** search that uses EM or neutrino observations to drive the detection of GWs

GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino → GW TRIGGERED ANALYSIS



Known **event time** and **sky position:**

→ reduction in search parameter space

→ gain in search sensitivity

Abadie et al. 2012, ApJ, 760

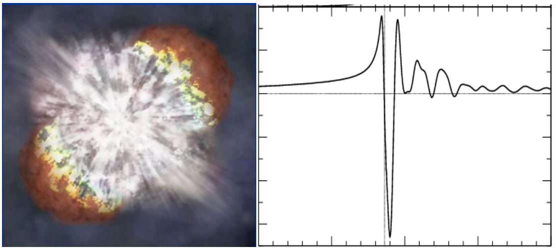
Aasi et al. 2014,PhRvL, 113

Abadie et al. 2012, ApJ, 755

Adrián-Martínez et al. 2013, JCAP

Aartsen et al, PhysRevD, 90, 102002

GW transient searches

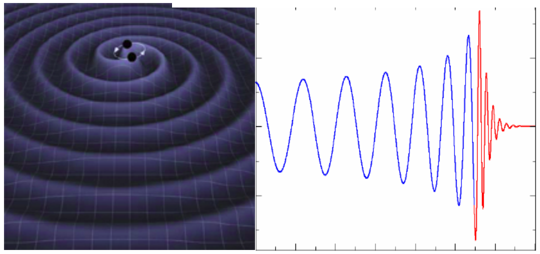


Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

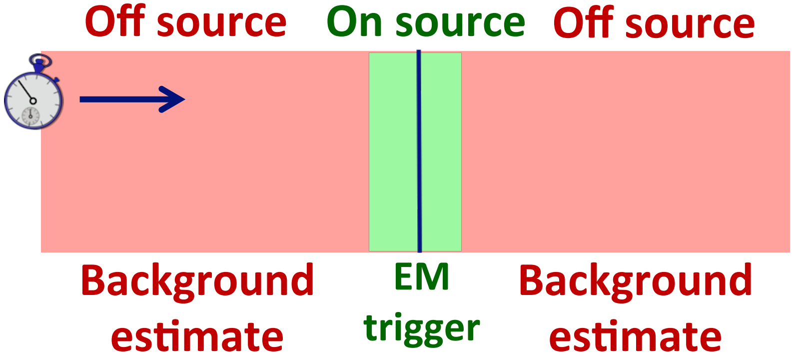
→ **Excess power**



Compact Binary Coalescence

Known waveform

→ **Matched filter**



Off source

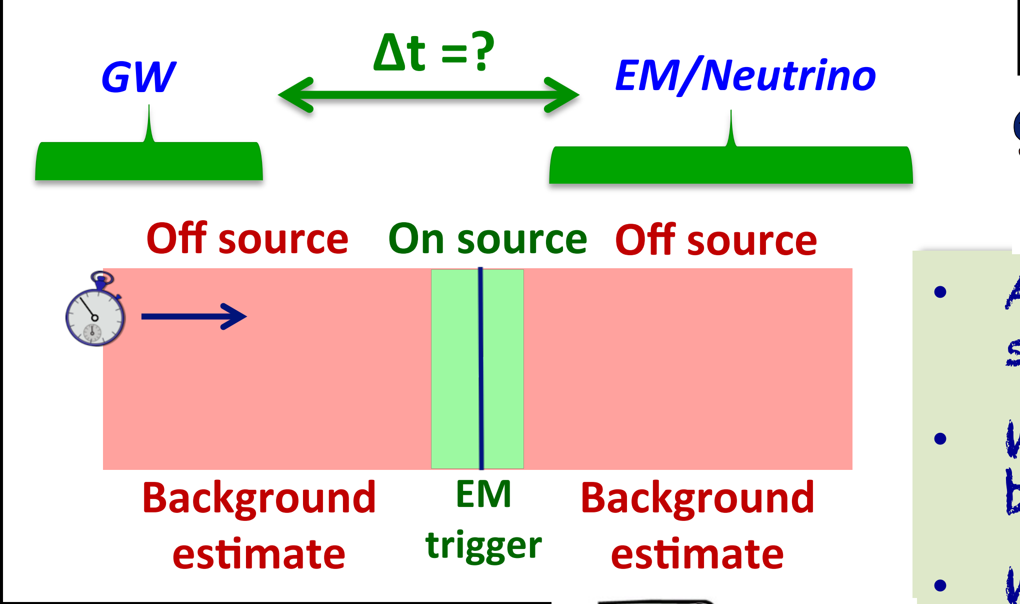
On source

Off source

Background estimate

EM trigger

Background estimate



GW

Δt =?

EM/Neutrino

Off source

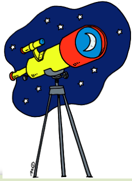
On source

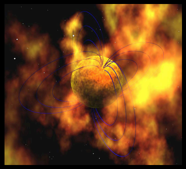
Off source

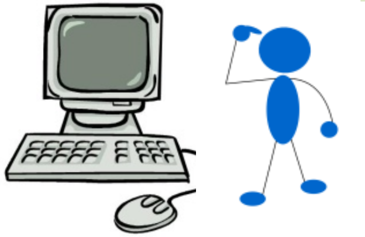
Background estimate

EM trigger

Background estimate

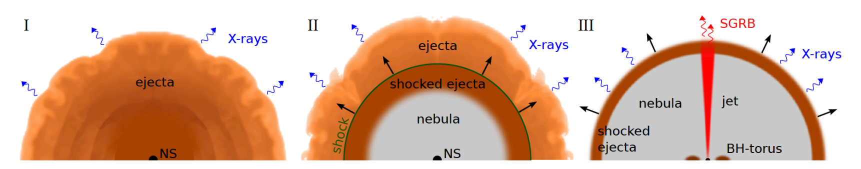




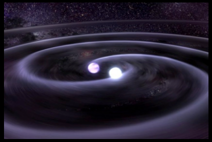


- Are the GW and EM emissions simultaneous?
- What is the possible time delay between GW and EM?
- What are the uncertainities in the observed EM event time?
- What is the temporal on-source window to use?

→ ***"Time-reversal" scenario for NS-NS merger*** (Ciolfi & Siegel 2014)***:***

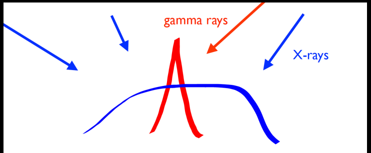


Merger



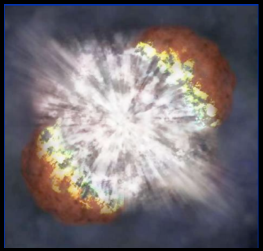
Supramassive NS lifetime 10^3 s

Collapse to BH

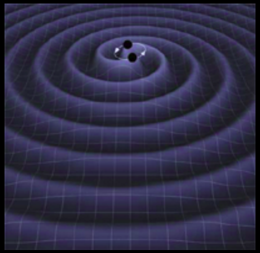


GWs → X-ray → Gamma-ray

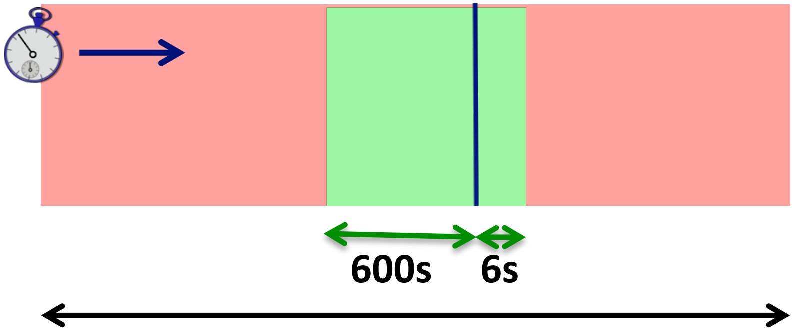
O1 GRB prompt emission Triggered Search



Unmodeled GW burst



Compact Binary Coalescence



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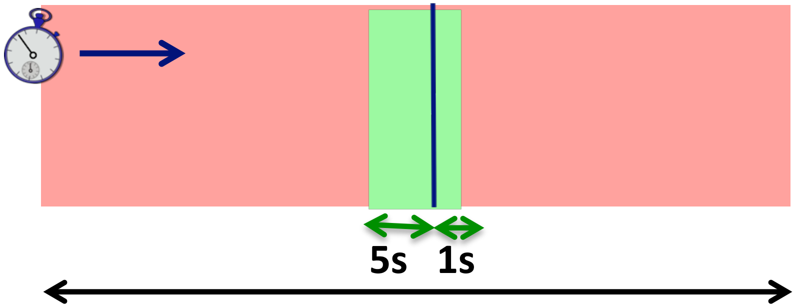
31 Long and short GRBs

600s 6s

3 hrs

Minimal assumption about signal morphology:

- CSG=circular sine-gaussian
- ADI=accreation disk instabilities



Off source On source Off source

19 Short GRBs

5s 1s

30 min

CBC signals :

- BNS
- NSBH

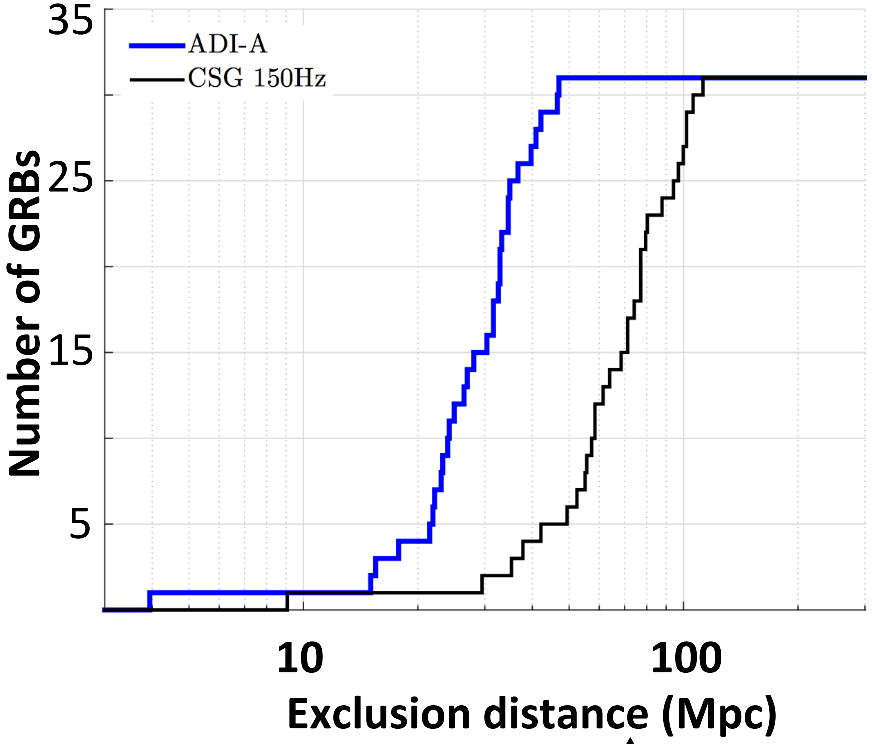
O1 GRB prompt emission Triggered Search

Non GW-detection result: **lower bounds on the progenitor distance**

Abbott et al. 2016, ApJ, 841

Unmodeled GW burst (31 GRBs)

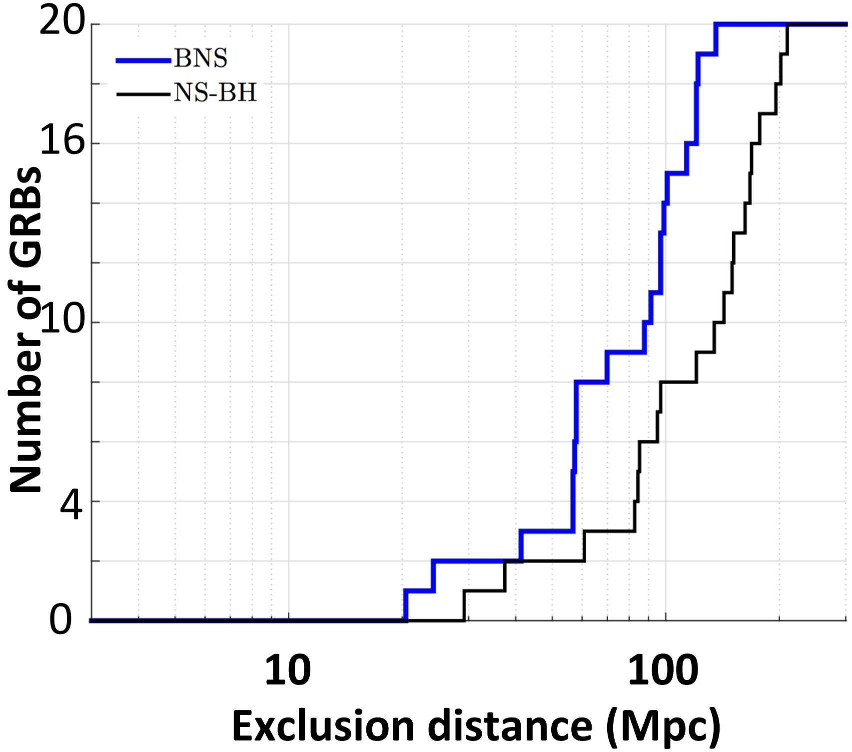
with **10^{-2} Moc^2 energy in GW** (optimistic)



Median distances: 31 71 Mpc

Binary system coalescence

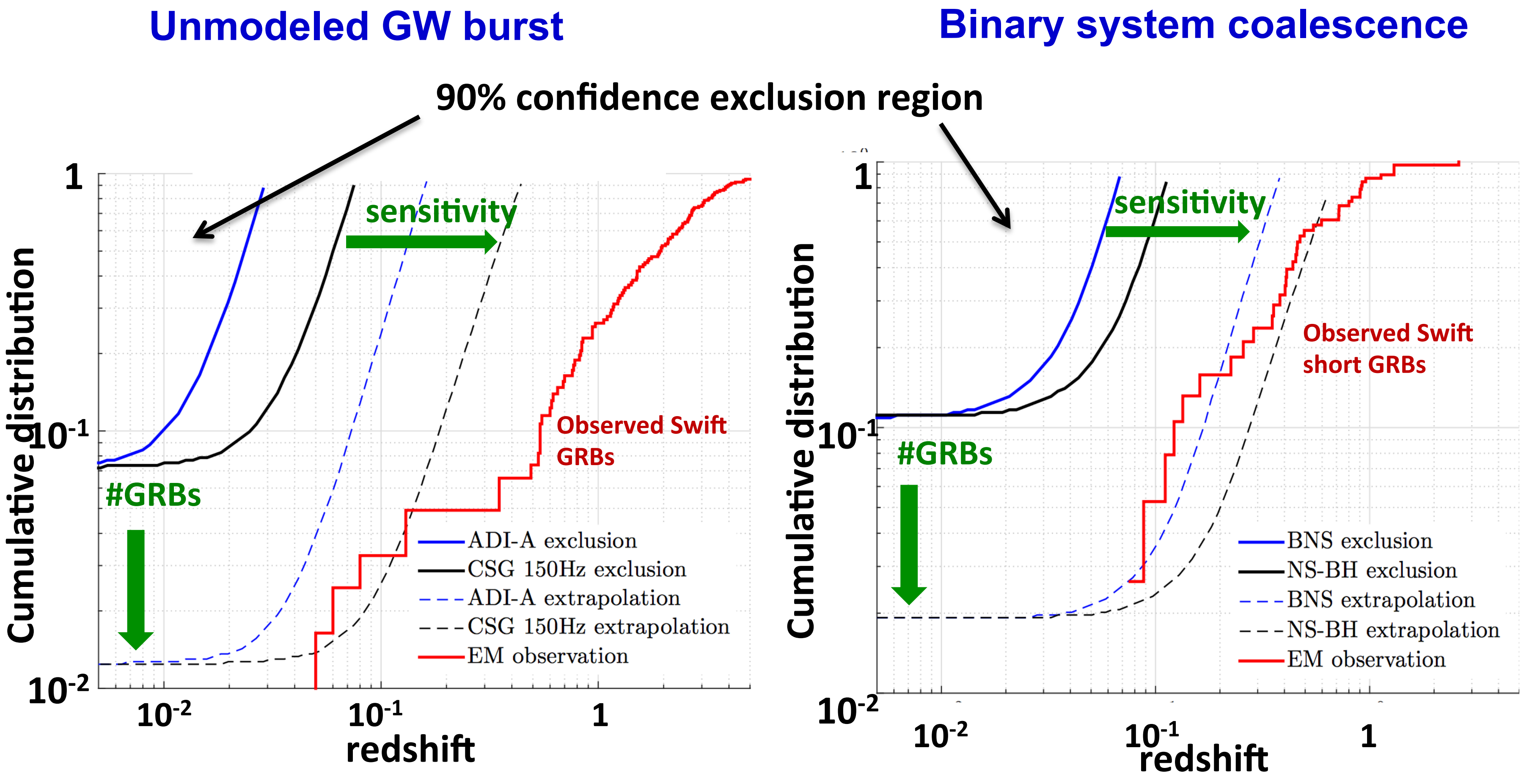
(19 short GRBs)



Median distances: 90 150 Mpc

Population exclusion on cumulative redshift distribution

O1 results & prospects for 2 yrs of Advanced LIGO/Virgo design sensivity



Unmodeled GW burst

Binary system coalescence

90% confidence exclusion region

2yrs Advanced LIGO and Virgo

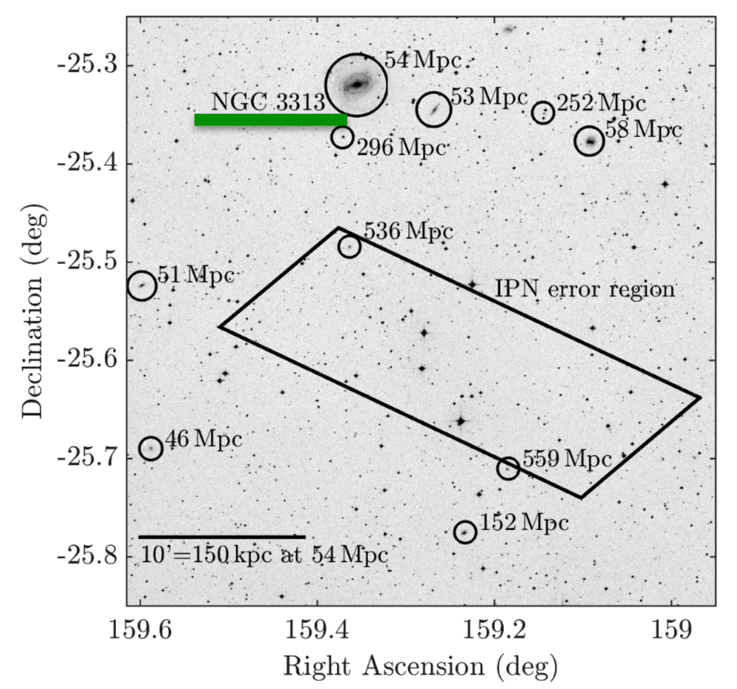
Long GRBs→ lack of detection constrain most extreme scenario

Short GRBs→ likely detection or no detection in tension with BNS merger progenitor

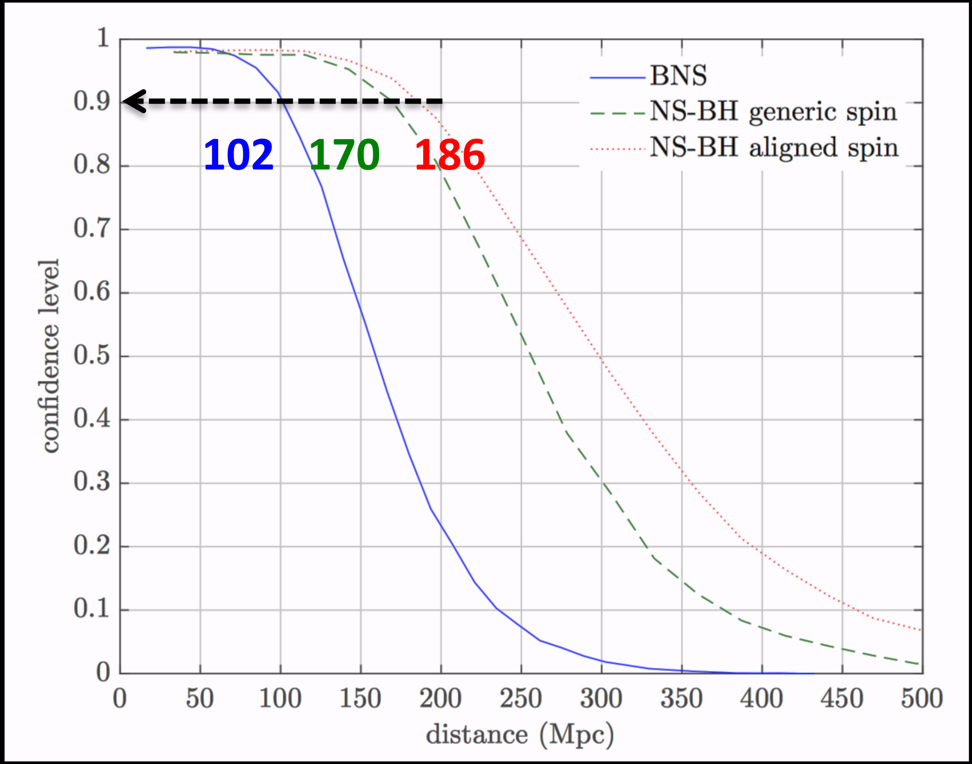
Abbott et al. 2017, ApJ, 841C

GRB150906B BNS or NS-BH merger in NGC3313?

Triggered Search



- ❖ GRB 150906B – Sep 06, 2015 at 08:42:20 UTC, detected by IPN
- ❖ Short-duration/hard-spectrum GRB close to the local galaxy NGC3313 (D=54Mpc)
- ❖ Only LIGO Hanford on at the time



- ❖ Assuming a jet half-opening angle ≤ 30˚ → BNS and NS-BH progenitors in NGC 3313 excluded at >99%
- ❖ No evidence for NS-NS/BH GW signals up to 102/170 Mpc

Abbott et al. 2017, ApJ, 841

Multi-messenger searches

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio

(minutes, hours, days, months)

off-axis afterglow

Isotropic emission

Macronovae (days)

Radio remnants

(months, years)

Siegel & Ciolfi
2016, ApJ → X-ray (min, hrs)

Core-collapse of massive stars

SBO X-ray/UV

(minutes,days)

Optical

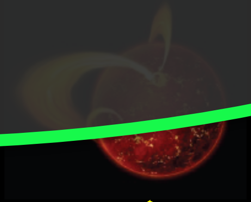
(weeks, months)

Radio

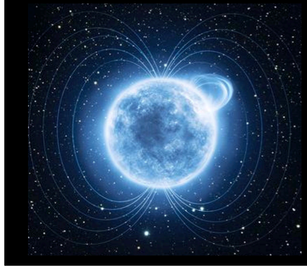
(years)

BH-BH mergers ?

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

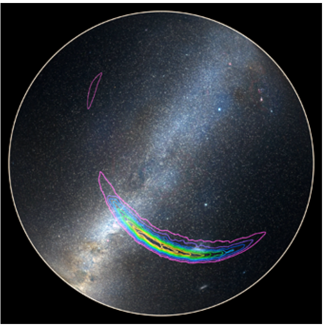
→ **EM follow-up:** low-latency GW candidate events to trigger prompt EM observations and → archival searches

Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alert to obtain EM observations

GW candidates **Sky Localization** **EM facilities**

LIGO-H **LIGO-L**

Virgo

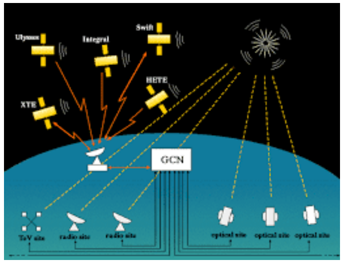


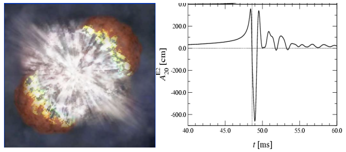
Event validation

Low-latency Search
to identify the GW-candidates

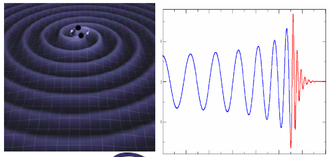
Software to

- select statistically significant triggers wrt background
- check detector sanity and data quality
- determine source localization





Unmodeled GW burst search

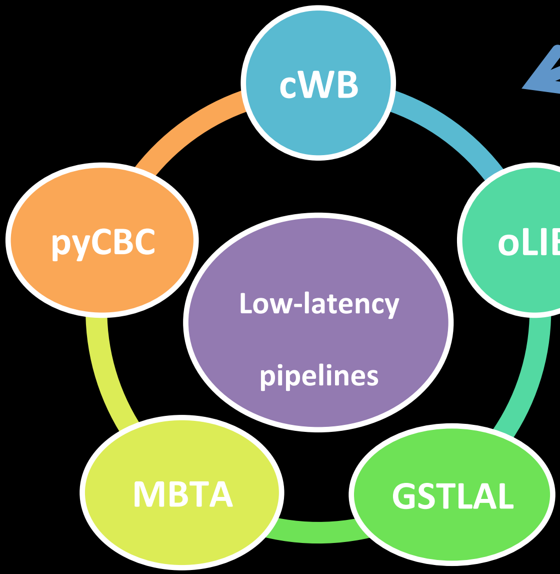


Matched filter with waveforms of compact binary coalescence

→ **a few min** → **30 min**

Parameter estimation codes → **Hours,days** → **GW candidate updates**

Online and offline GW data analysis pipelines



cWB

oLIB

GSTLAL

MBTA

pyCBC

Low-latency pipelines

Low-latency online pipelines:

- *All five low-latency pipelines detect candidates within < 1min of data acquisition*
- *Quick estimate of significance, candidate may not be real GW events*

Offline pipelines:

- *optmized results within 1-2 weeks*
- *~5 days of coincident data for background estimation*
- *final significance to distinguish real GW events*

Nitz et al., arXiv:1705.01513; Usman et al. 2016, CQG 33, 215004 [pyCBC]

Adams et al. 2015 CQG 33, 175012 [MBTA]

Messick et al. 2017 Phys. Rev. D 95, 042001 [gstlal]

Lynch et al, arXiv:1511.05955 [oLIB]

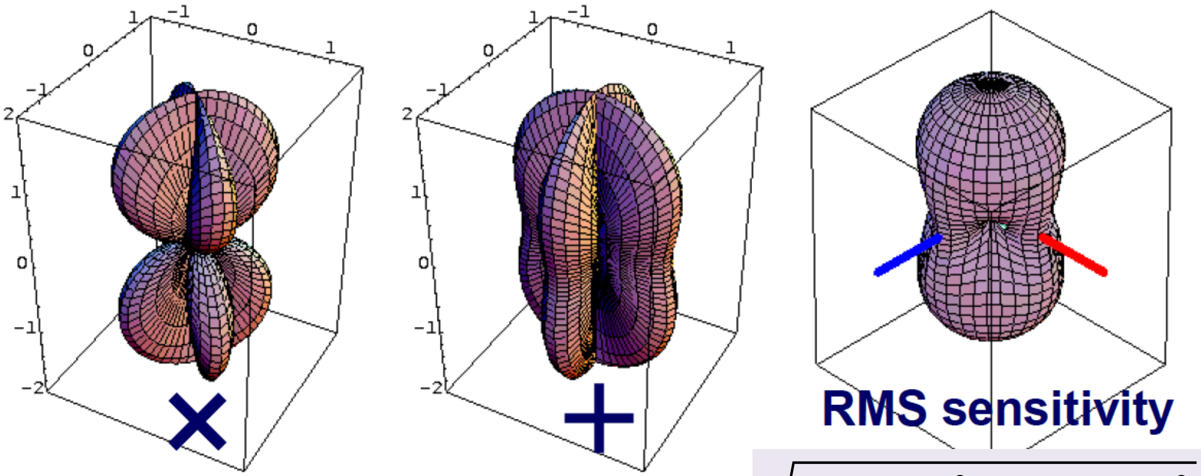
Klimenko et al. 2016 Physical Review D, 93; Drago 2015, arXiv:1511.05999 [cWB]

Veitch et al. 2015, PRD 91, 042003 [LALInference]

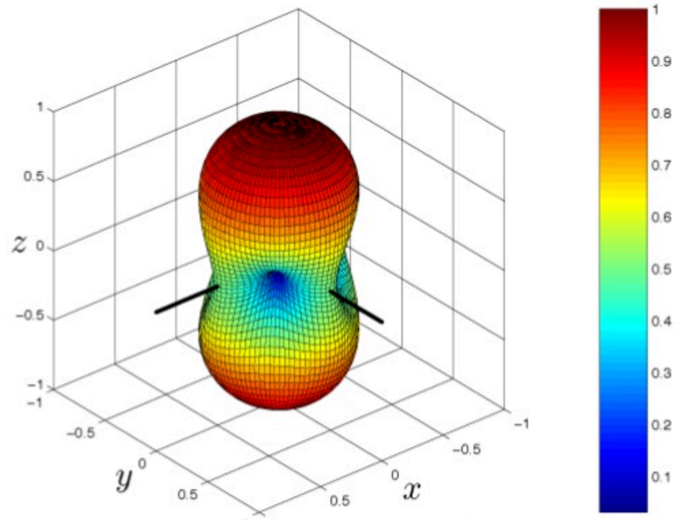
Sky location - single GW detector directional sensitivity

$$\frac{\Delta L}{L} = h_{\text{det}}(t) = F_+ h_+(t) + F_x h_x(t)$$

The **antenna pattern** depends on the polarization in a certain (x,+) basis



$$\sqrt{F_+(\theta,\phi)^2 + F_x(\theta,\phi)^2}$$

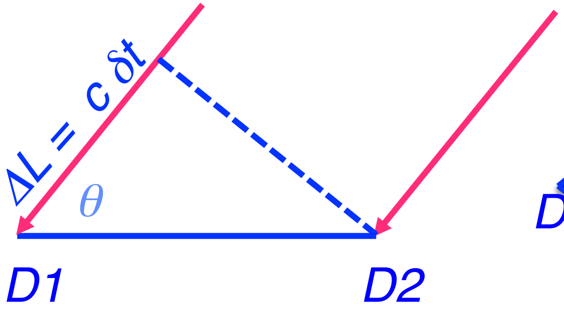


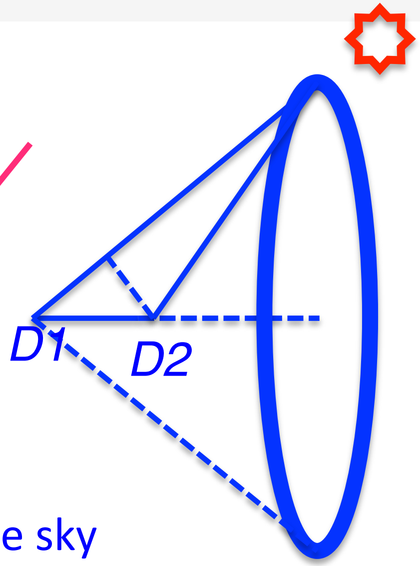
$\sqrt{F_+^2(\theta,\phi,\psi=0)+F_\times^2(\theta,\phi,\psi=0)}$

- ➢ Single GW detector is a **good all-sky monitor**, nearly omni-directional (the transparency of Earth to GWs)
- ➢ But does not have good directional sensitivity, **not a pointing instrument!** It has a very poor angular resolution (about 100 deg)

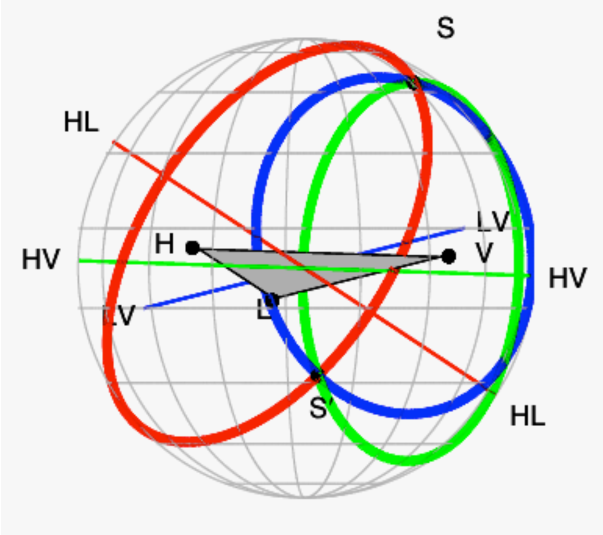
The source localization requires a network of GW detectors

*The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites*





2-detectors → annulus in the sky



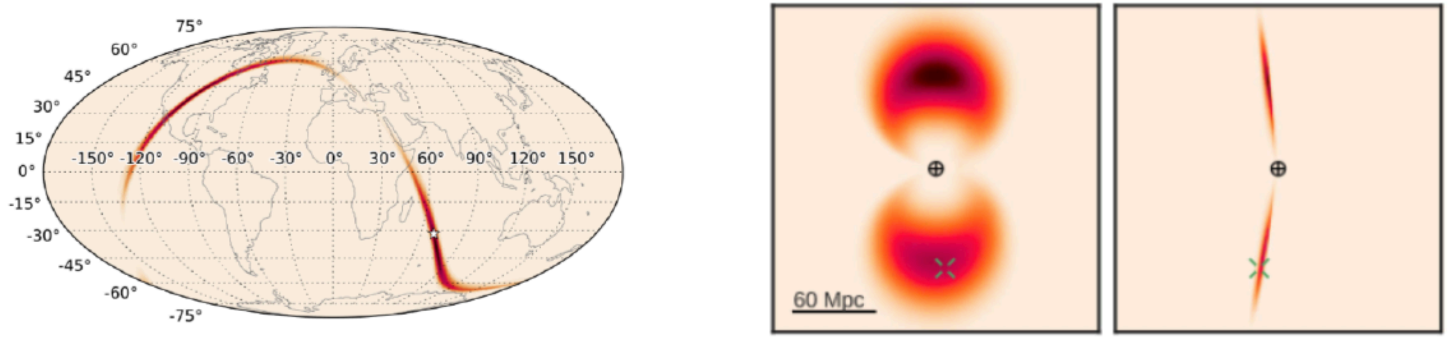
3-detectors → localize

CBC Sky localization map

Arrival time
Amplitudes
Phase

→ sky location
→ distance to the source
→ binary orientation

➡ **Sky location also in 3 D**



Sky direction

Projections of 3d location

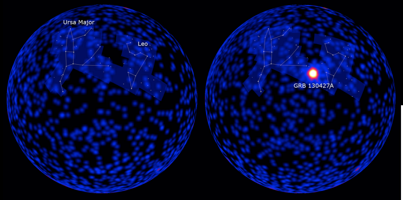
Online pipelines estimate → arrival time, phase, signal amplitude at each detector

These estimates + template masses : constrain direction of GW arrival and distance to the source

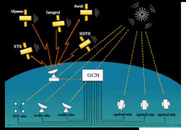
→ **BAYESTAR (Singer et al 2014, ApJ, 795, 2016 ApJL, 829)**: estimate 3D location in <1 minute

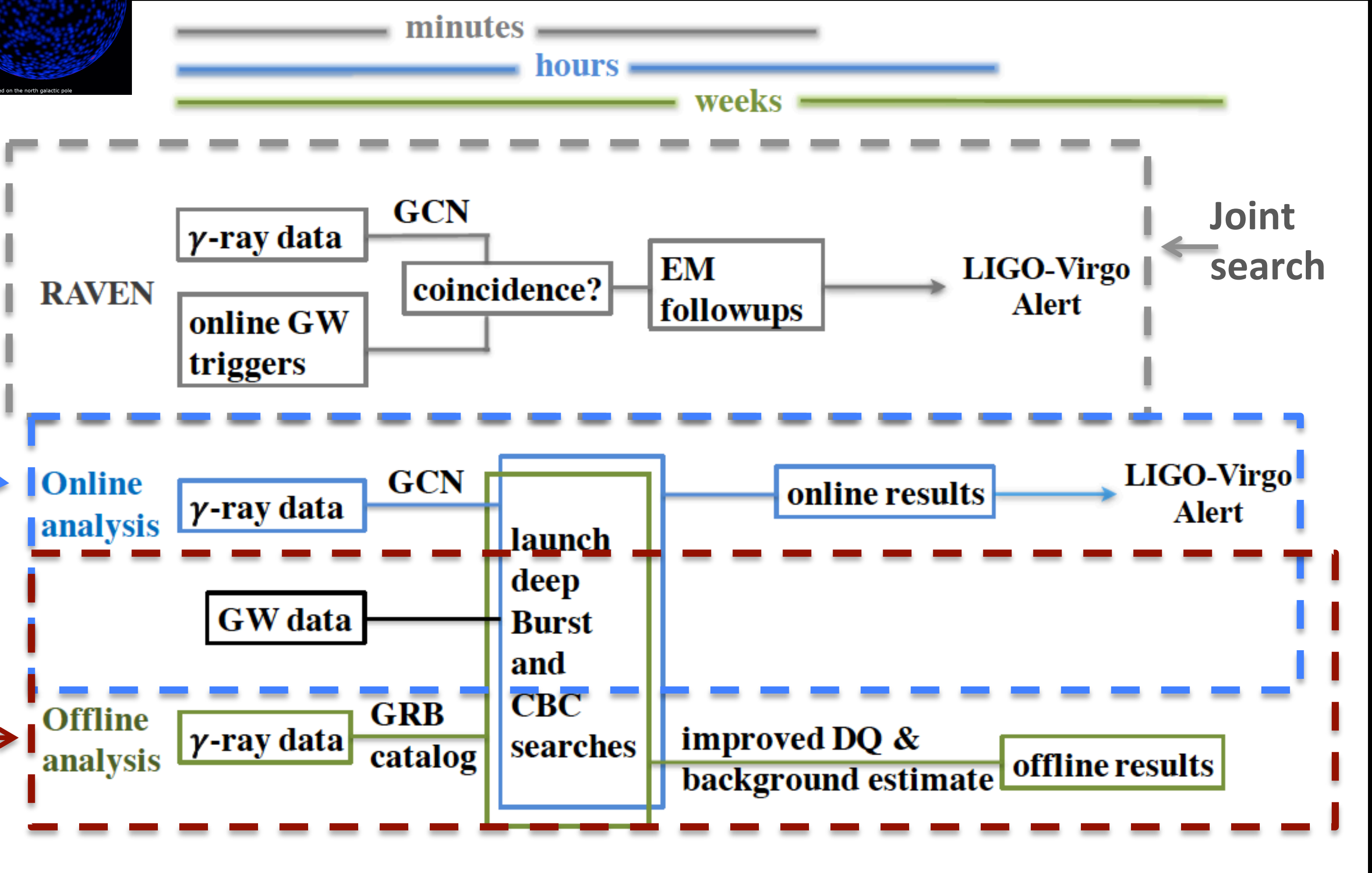
→ **LALInference**, **full PE Bayesian MCMC** **(Veitch 2015; Berry et al. 2015)**, modeling the inspiral-merger-ring down phase and taking into account the calibration uncertainty

Low-latency joint/external triggered search



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole





minutes

hours

weeks

RAVEN

γ-ray data

GCN

online GW triggers

coincidence?

EM followups

LIGO-Virgo Alert

Joint search

External triggered search online

Online analysis

γ-ray data

GCN

launch deep Burst and CBC searches

online results

LIGO-Virgo Alert

GW data

External triggered search offline

Offline analysis

γ-ray data

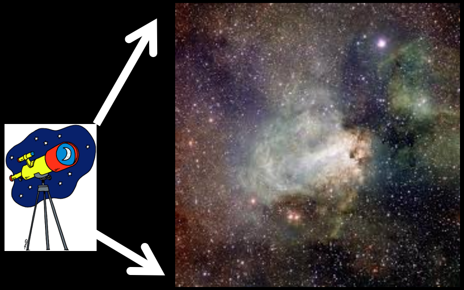
GRB catalog

improved DQ & background estimate

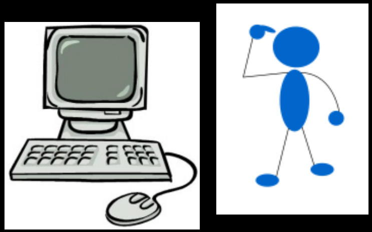
offline results

Credit: Pannarale

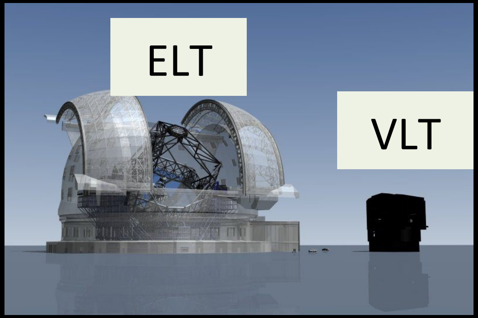
Hunt the elusive EM-counterpart!



Wide-field telescope
FOV >1 sq.degree



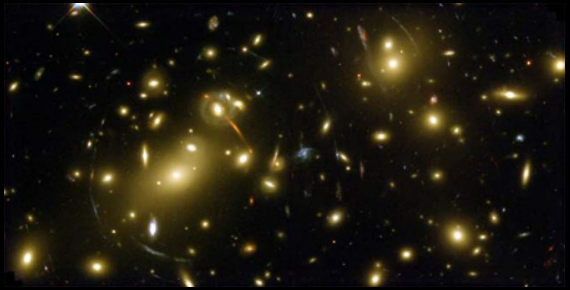
“Fast” and “smart” software to select a sample of candidate counterparts



Larger telescope to **characterize** the candidate nature

The EM Counterpart!

Not easy to cover hundreds of square degrees with FOV 1-10 sq. degrees!

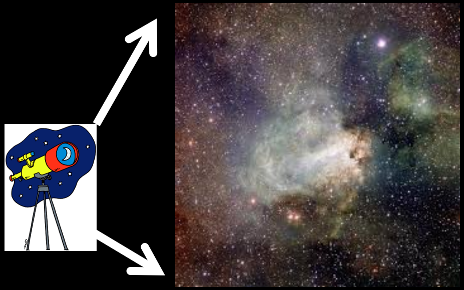


Galaxy-targeting observational strategy

Nissanke et al. 2013, ApJ, 767
Aasi et al. 2014, ApJS, 211
Gehrels et al. 2016, ApJ, 820

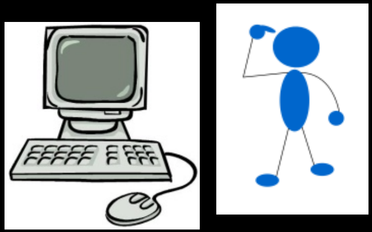
Hunt the elusive EM-counterpart!

Optical/NIR band



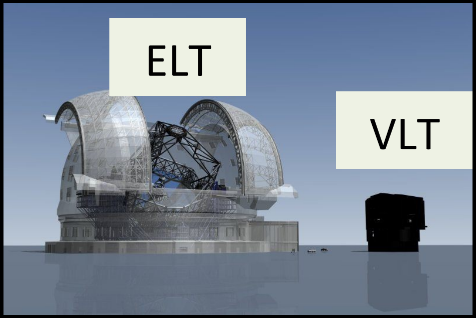
Wide-field telescope
FOV >1 sq.degree

↓



“Fast” and “smart” software to select a sample of candidate counterparts

↓



Larger telescope to **characterize** the candidate nature

↓

The EM Counterpart!

10^4-10^5 variable objects over 100 sq. degrees

↓

Artifacts and many astrophysical contaminants

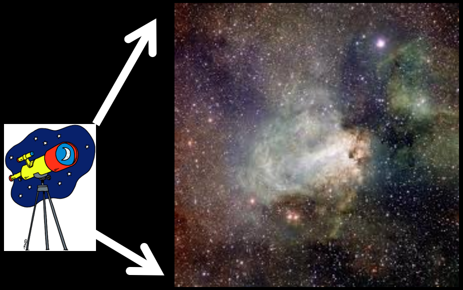
M-dwarf flares (min to hrs)
3 (0.3) deg^{-2} up to red mag 24
at 20 (80) deg latitude
(Ridgway et al., 2014)

Supernovae (days to month)
7 deg^{-2} up to red mag 24
(Graur et al., 2014; Dahlen et al., 2012; Cappellaro, 2014)

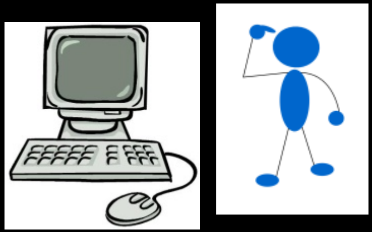
↓

A few tens of candidate counterparts

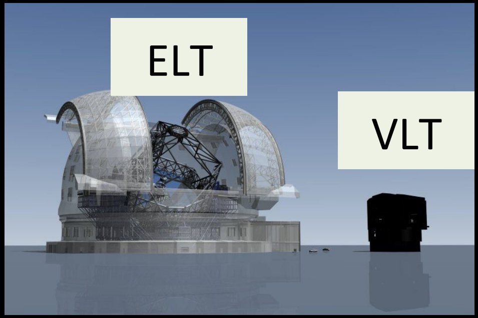
Hunt the elusive EM-counterpart!



Wide-field telescope
FOV >1 sq.degree



“Fast” and “smart” software to select a sample of candidate counterparts



Larger telescope to **characterize** the candidate nature

The EM Counterpart!

X-rays

✓ less contaminants

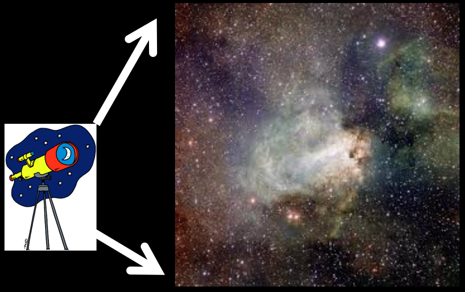
Transient rate **2.5×10^{-3} deg^{-2}**
flux$_{0.2\text{-}2KeV}$ > 3×10^{-12}ergs^{-1}cm^{-2}
(Kanner et al. 2013)

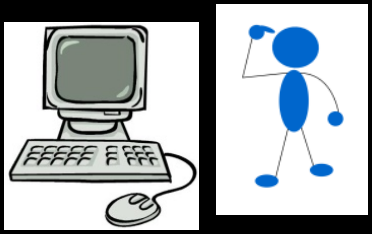
x no wide-field telescope

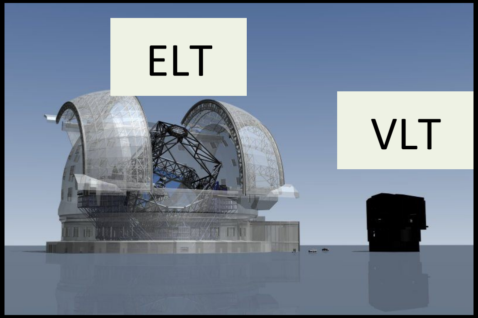
Gamma-rays

✓ less contaminants
✓ all-sky monitors
x beamed emission

Hunt the elusive EM-counterpart!







Wide-field telescope
FOV >1 sq.degree

"Fast" and "smart" software to select a sample of candidate counterparts

Larger telescope to **characterize** the candidate nature

The EM Counterpart!

Radio

✓ less contaminants

Transient rate < 0.37 deg^{-2}
peak-flux_1.4 GHz > 0.21 mJy
timescales 1 d – 3 m
(Mooley et al., 2013)

✓ wide-field array at low frequencies (MHz)

x faint sources

x long delay GW → radio emission

GCN Alerts contents to support observing startegy

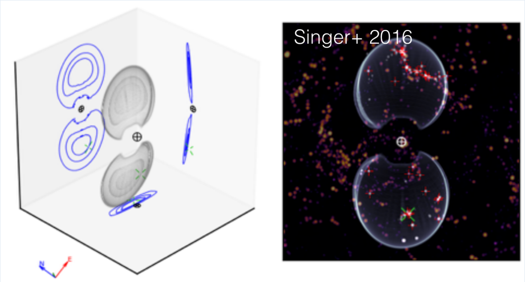
- Event **time** and **probability sky localizatiom map** (HEALPix FITS file)
- Estimate of **False Alarm Rate** of event candidate (FAR < 1/1month)
- **Basic source classification**: found by CBC, Burst, or both pipelines;

For CBC candidates LVC GCN will have:

- ***"EM bright" indicators:***
  - **Source classifier** → Probability of **presence of a NS** in the binary (object m<2.8 solar mass)
  - **Remnant mass classifier** → Probability of **presence of any NS tidally disrupted mass left outside the BH**

(*Foucart 2012, PhRvD, Pannarale* & Ohme, 2014, ApJ*)*

- ***Luminosity distance*** marginalized over whole sky (mean+/-standard deviation)
- ***3D sky maps with direction-dependent distance*** (e.g. Singer et al. 2016, ApJL 829, L15)



highly significant FAR = 1/100 yr

significant

low significance FAR = 1/yr

FAR = 1/month

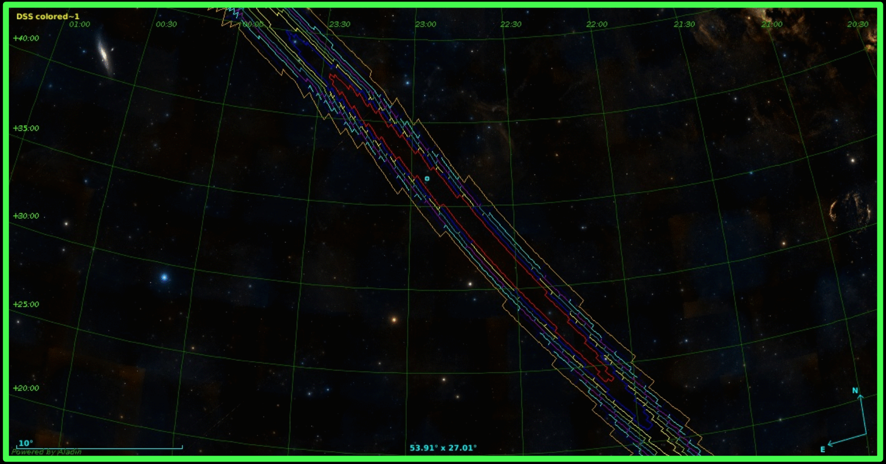
FAR = Rate of noise events louder than the candidate event

Candidates to be observed selected based on the observer's choice of FAR threshold

Sky map + basic source classification

Credit: G. Greco, GWsky https://github.com/ggreco77/GWsky

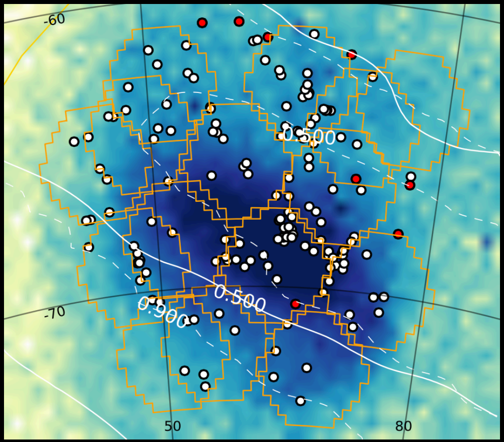
To decide the search type



Tiling the sky map to maximize the enclosed localization probability

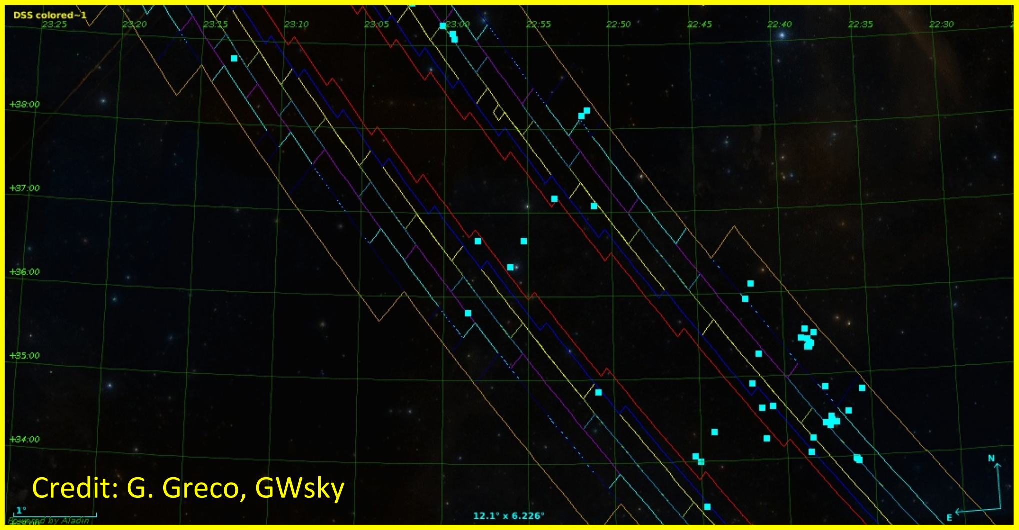
DES, Annis et al. 2016, ApJL

Burst → failed-SNe



Search for missing Supergiants in the LMC

➡ Sky map + source classification + (distance + system type)

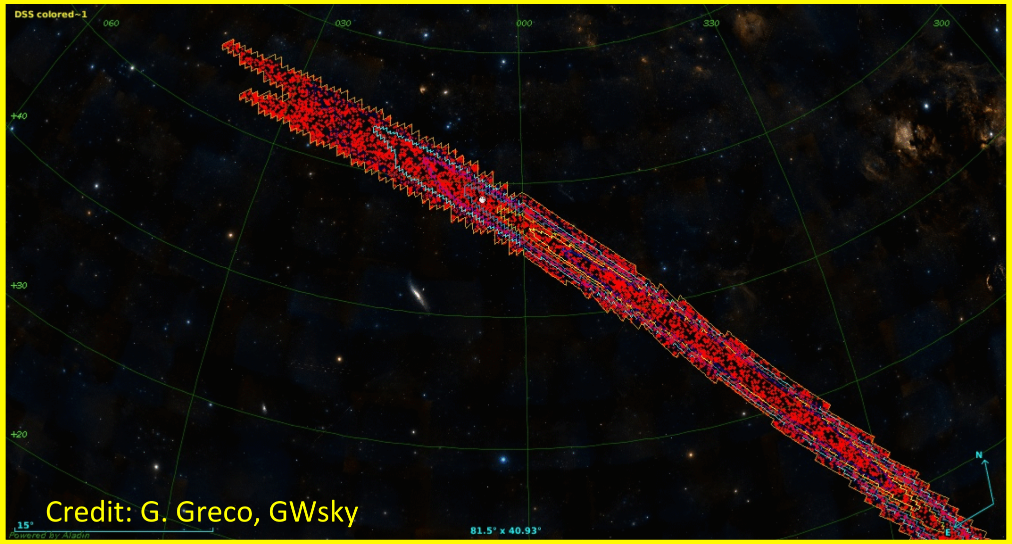


Credit: G. Greco, GWsky

➡

Targeting ranked galaxies

(Small FoV instruments)



Credit: G. Greco, GWsky

⬅

Targeting ranked FoV pointings

(Instruments FoV > 1 deg^2)

Sky map weighted by galaxy luminosity

For each FoV →

$$P = \sum \frac{L_i}{L_{tot}} P_{GW}$$

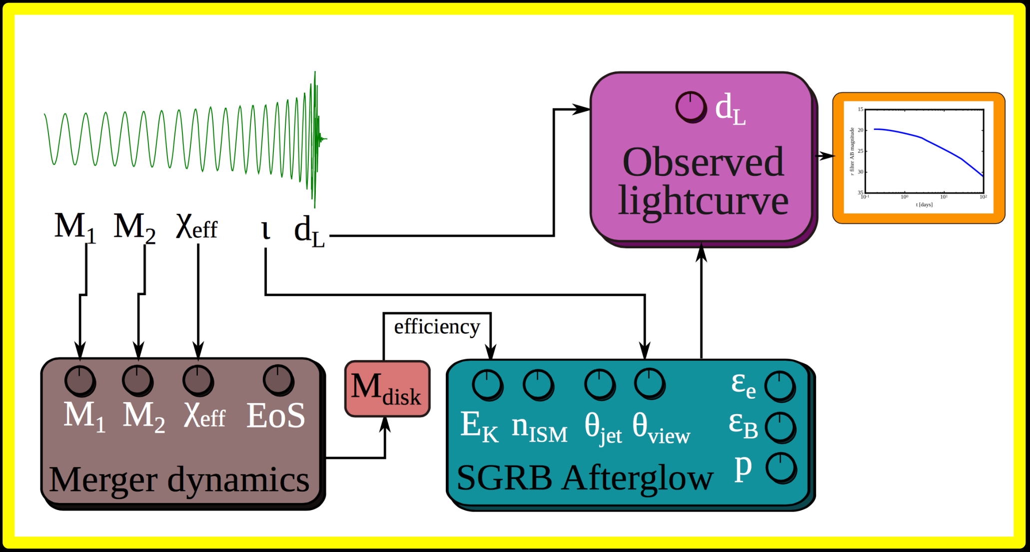
P_{GW} = probability that GW candidate lies within the FoV **See e.g Evans et al. 2016, MNRAS**

Optimizing the observational strategy: when and where?

GWs

- Mass
- Spins
- EOS

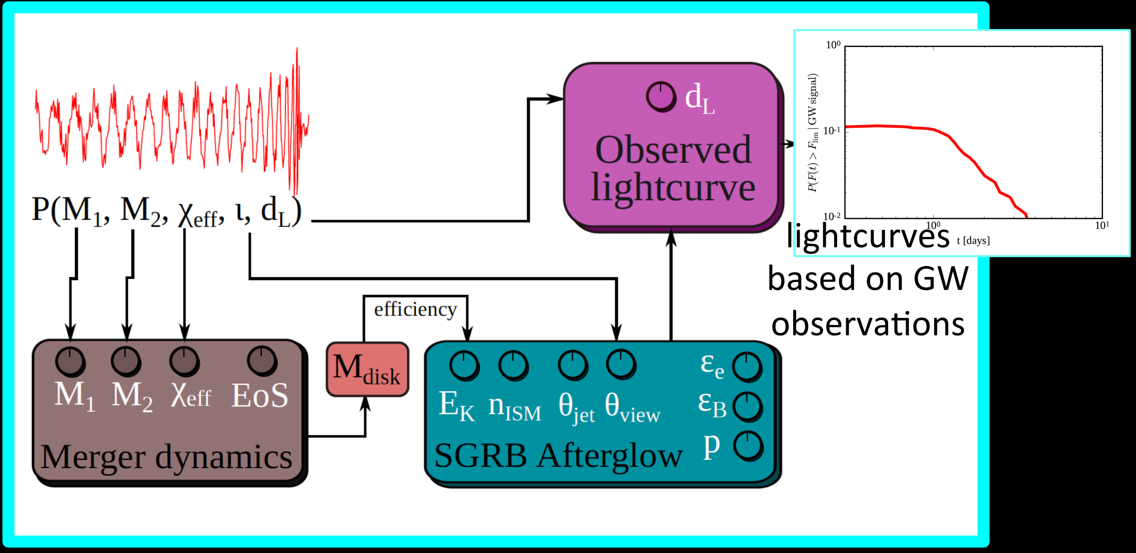
EM emission



Optimizing the observational strategy: when and where?

Posterior distributions of GW parameters

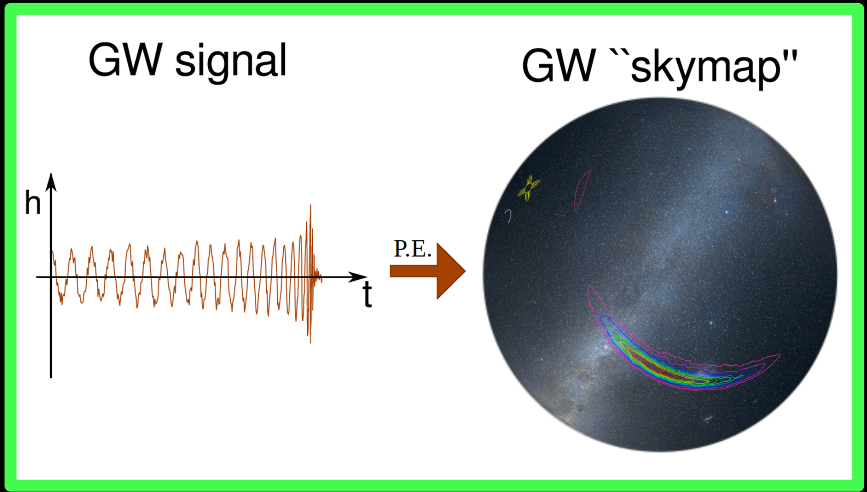
The same signal can be produced by different combinations of the parameter values



lightcurves based on GW observations

A posteriori detectability
P (F(t) > F_{lim} |GWsignal)

Salafia et al. arXiv:1704.05851



3D sky map

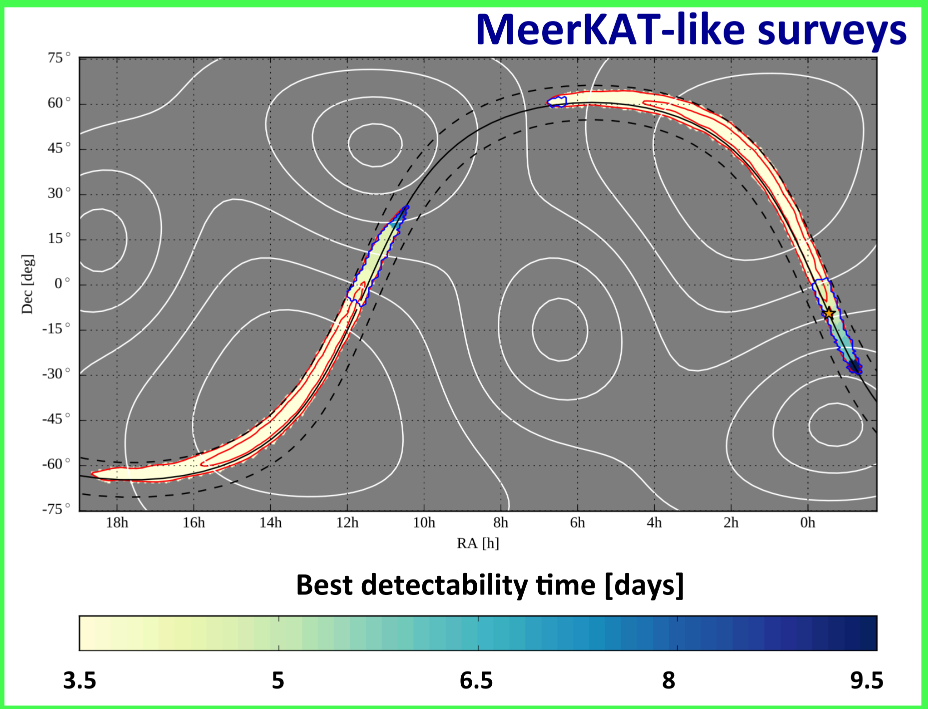
Sky localization probability with direction-dependent distance and its distribution

Singer et al. 2016 ApJL, ApJS

Detectability map
P (F(t) > Flim |RA,DEC, D_L)

Sky-position-conditional posterior distribution

→ Detectability map P (F(t) > Flim |RA,DEC, GW signal)



Salafia et al. arXiv:1704.05851

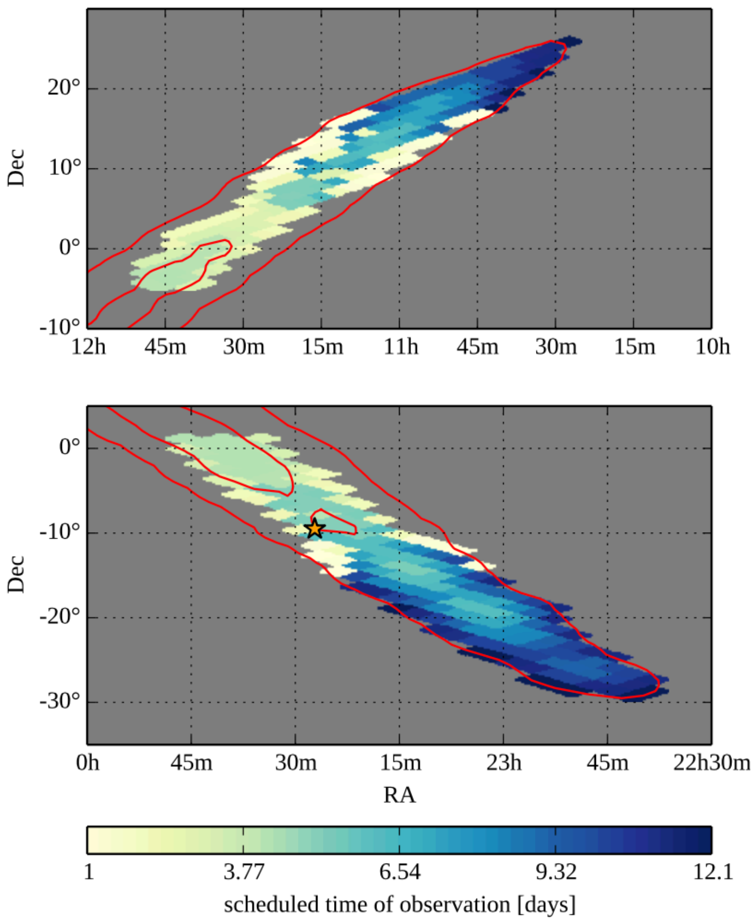
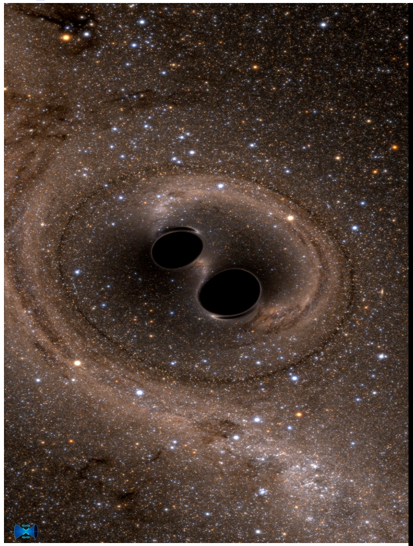


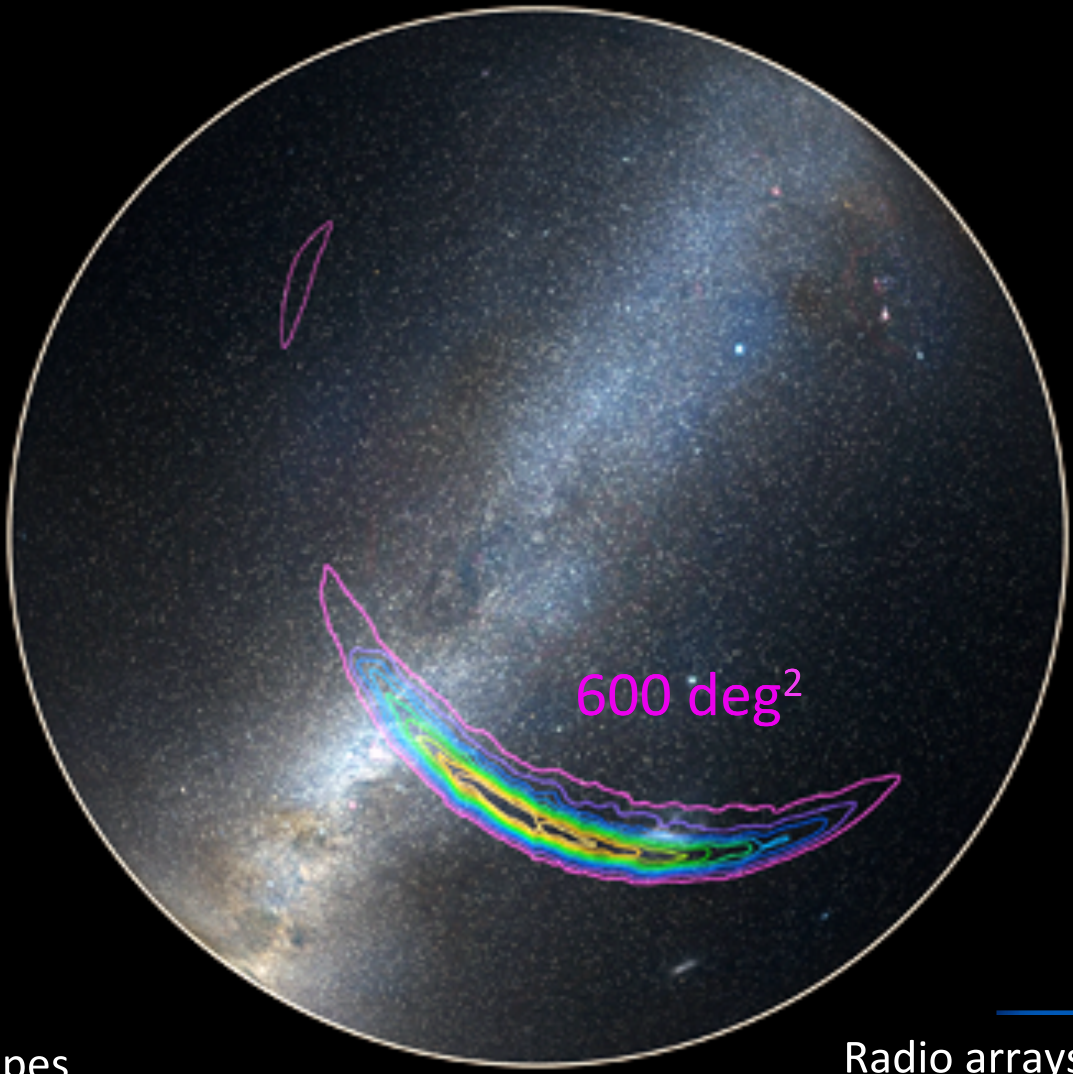
Figure 8. Time and position of the Radio follow-up observations of our test example (§4). The star marks the injection position.

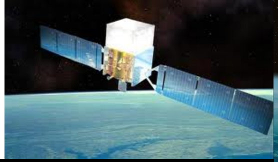
→ Optimize the sequence of tiles and observational epochs

→ Reduce area to be observed and telescope time

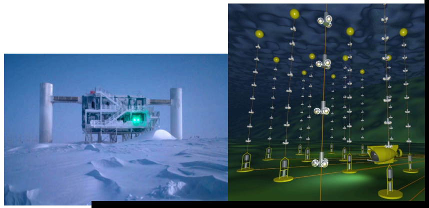
The first multi-messenger campaign including GW/photons and neutrinos…..







Gamma and
X-ray
satellites



Neutrino
observatories

Optical telescopes

Radio arrays

EM follow-up program - O1 run

- **Three alerts** sent to 65 groups of astronomers with observational capabilities
- **About 40 groups followed-up at least one alert** giving a broadband coverage of the sky maps and the rapid characterization of the candidate counterparts

GW150914

2 days

Alert!
Initial sky maps

19 days

Update
BBH
nature

4 months

Updates:
Final FAR and
sky map

G194575

6.5 hrs

Alert!
Initial sky maps

29 days

Update
Noise event

Retraction

GW151226

1.6 days

Alert!
Initial sky maps

15/17 days

Updates:
Redshift
Final FAR

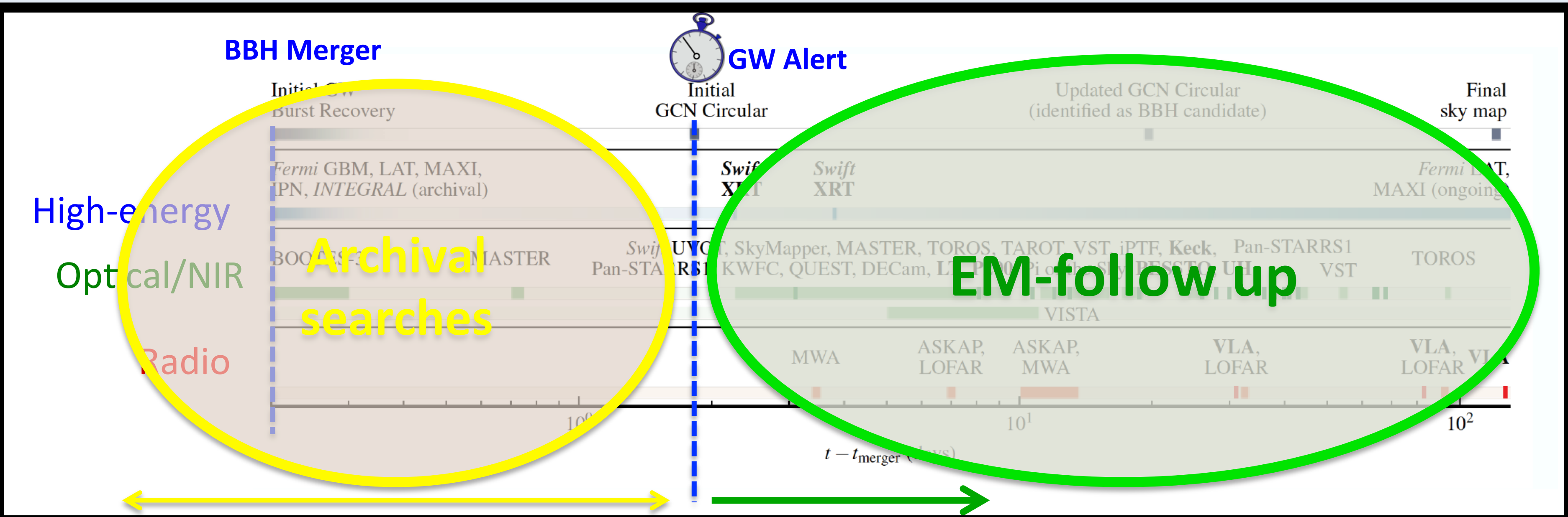
23 days

Updates:
Final sky map

GW150914

EM follow up observations and archival searches

- ***Twenty-five teams** of observers responded to the GW alert*
- *The EM observations involved **satellites and ground-based telescopes** around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*

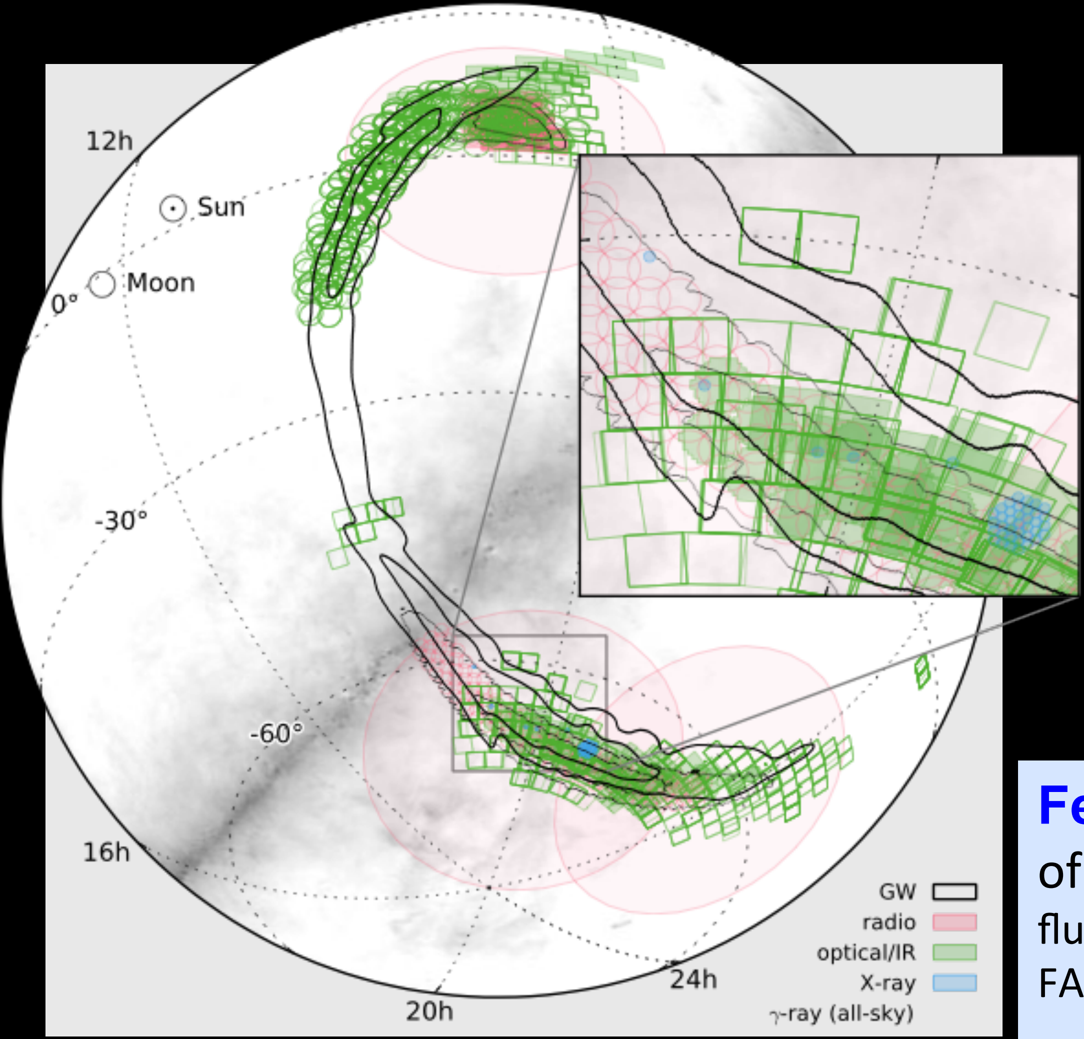


LVC+astronomers, ApJL, 826, 13
LVC+astronomers ApJS, 225,8
Connaughton et al. ApJL, 826, 6
Savchenko et al. 2016 ApJL 820, 36
Fermi-LAT collaboration ApJL, 823,2
Hurley et al. ApJL, 829, 12

Evans et al. MNRAS 460, L40
Morokuma et al. PASJL, 68, 9
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. ApJL, 823, 33
Annis et al. ApJL, 823, 34
Smartt et al. MNRAS, 462, 4094

Kasliwal et al. ApJL, 824, 24
Diaz et al. ApL 828, 16
Greiner et al. ApJL, 827, 38
Tavani et al. ApJL, 825, 4
Troja et al. ApJL, 827, 102

Sky map coverage



LVC+astronomers ApJL, 826, 13
LVC+astronomers ApJS, 225, 8

- *Covered sky map contained probabilty:*
  100% gamma-ray
  86% radio
  50% optical
- ***In the optical**, candidate counterparts rapidly characterized and identified to be normal population SNe, dwarf novae and AGN*

Fermi-GBM → **weak signal**

of 1 sec 0.4 s after GW15014

fluence(1 keV-10 MeV) = 2.4×10^{-7} erg cm^{-2}

FAR 4.79×10^{-4} Hz, FAP 0.0022

(**Connaughton et al. 2016 ApJL, 826**)

INTEGRAL → no signal but **stringent upper limit**

(**Savchenko et al. 2016 ApJL, 820**)

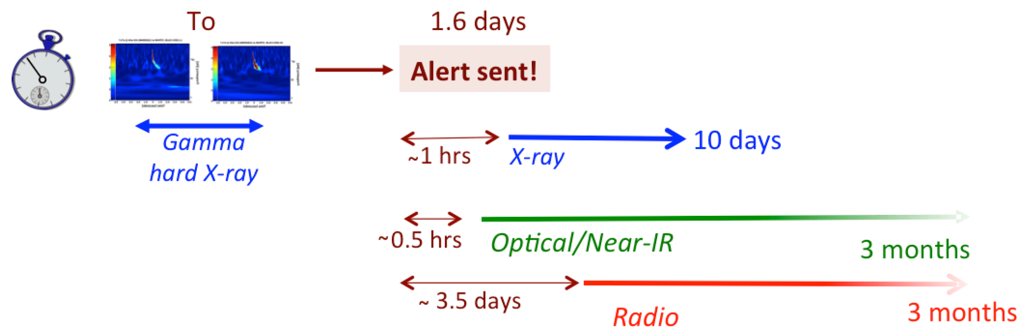
GW151226

***Thirty-one groups** responded to the GW alert:*

High-energy and Very high-energy→ Swift, XMM-Slew, MAXI, AGILE, Fermi, CALET, CZTI, IPN, MAGIC, HAWC

Optical-NIR → MASTER, GRAWITA, GOTO, Pan-STARRS1, J-GEM, DES, La Silla–QUEST, iPTF, Mini-GWAC SVOM, LBT-Garnavich, Liverpool Telescope, PESSTO, VISTA-Leicester, Pi of the Sky observations, LCOGT/UCSB, CSS/CRTS, GTC

Radio → VLA-Corsi, LOFAR, MWA



To

1.6 days

Alert sent!

Gamma
hard X-ray

~1 hrs

X-ray

10 days

~0.5 hrs

Optical/Near-IR

3 months

~ 3.5 days

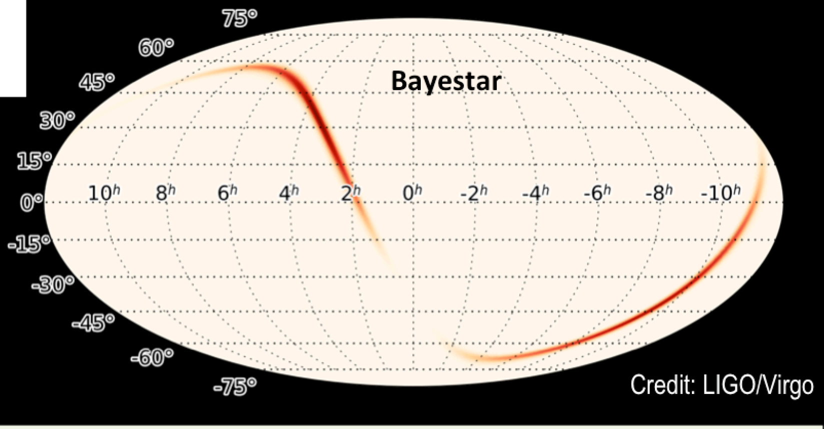
Radio

3 months

All the info from public GCNs: http://gcn.gsfc.nasa.gov/gcn3_archive.html

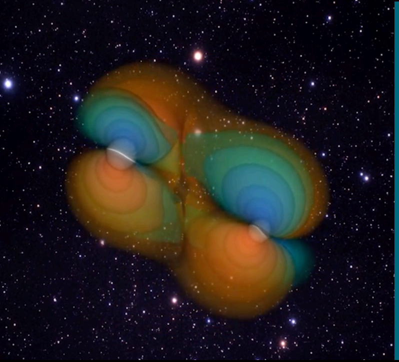
Racusin et al. 2017, ApJ, 835
Smartt et al. 2016, ApJL, 827
Copperwheat et al. MNRAS, 462, 3528

Cowperthwaite et al., ApJL, 826, 29
Evans et al. MNRAS, 462, 1591
Adriani et al.ApJL, 829, 20
Palliyaguru et al. ApJL, 829, 28



Credit: LIGO/Virgo

- *Large portions of the GW sky map observed*
- *Candidate counterparts rapidly characterized*
- *In the optical, candidate counterparts identified to be normal population SNe, dwarf novae and AGN*
- ***No EM counterpart reported***



The O1 EM follow-up demonstrates the capability to cover large area, to identify candidates, and to rapidly chracterize them.

No stellar-BBH EM emission expected due to the absence of the accreting material

...but some mechanisms that could produce unusual presence of matter around BHs recently discussed

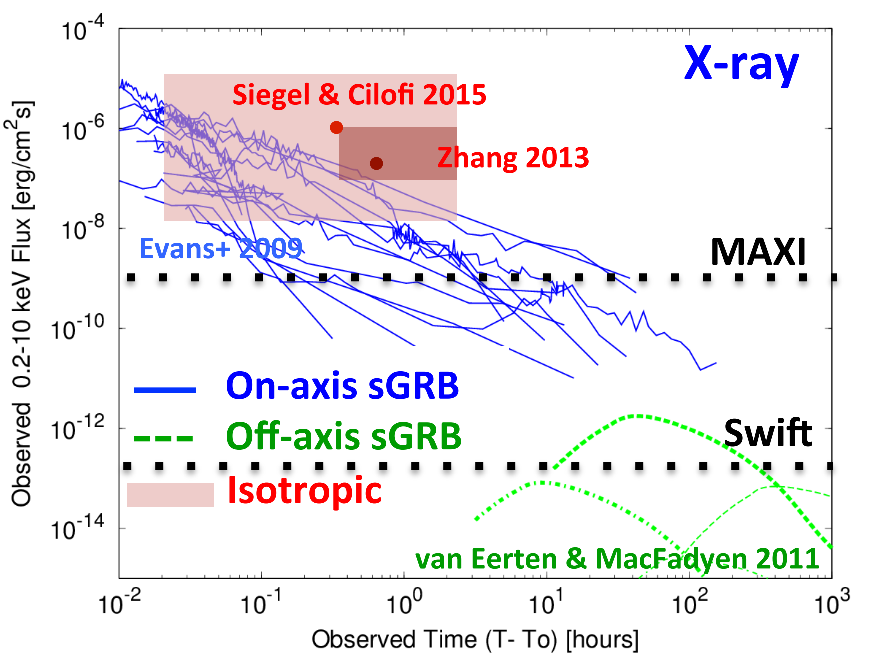
(e.g. Loeb 2016 ; Perna et al. 2016 ; Murase et al. 2016, Bartos et al. 2016)

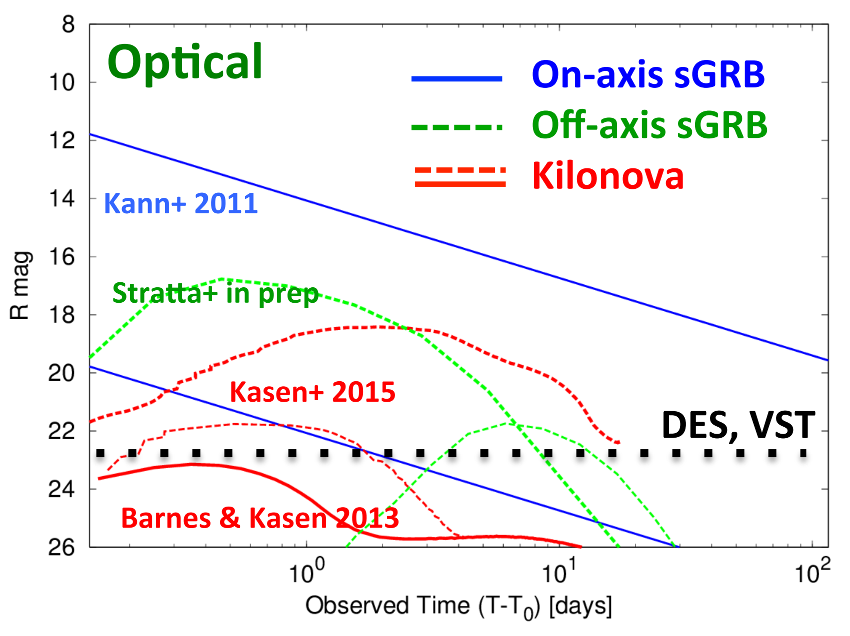
Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

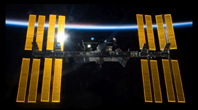
The follow-up campaign was sensitive to emission expected from BNS mergers at 70 Mpc range

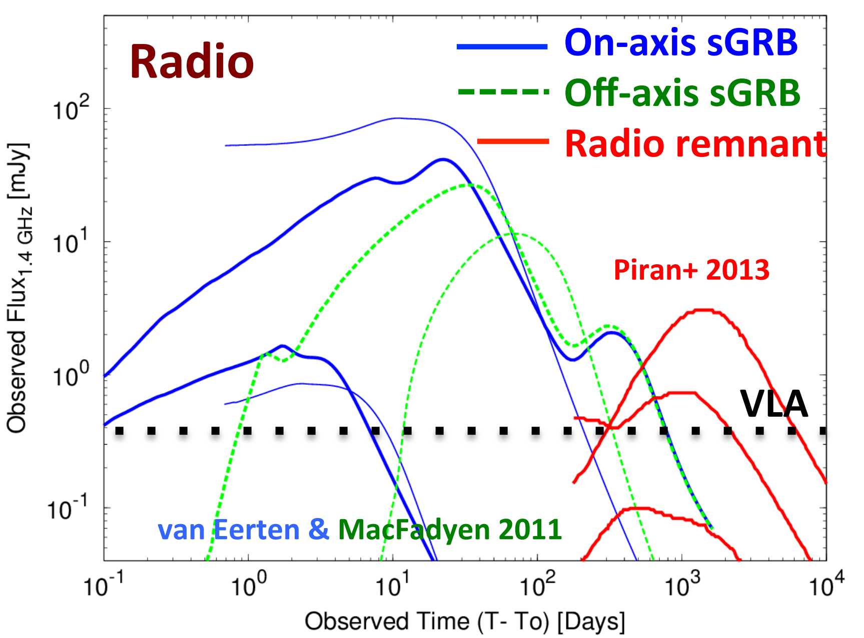
The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

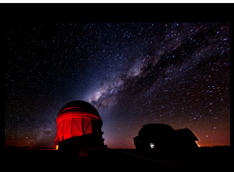
NS-NS merger EM-emissions

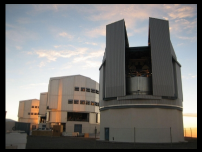








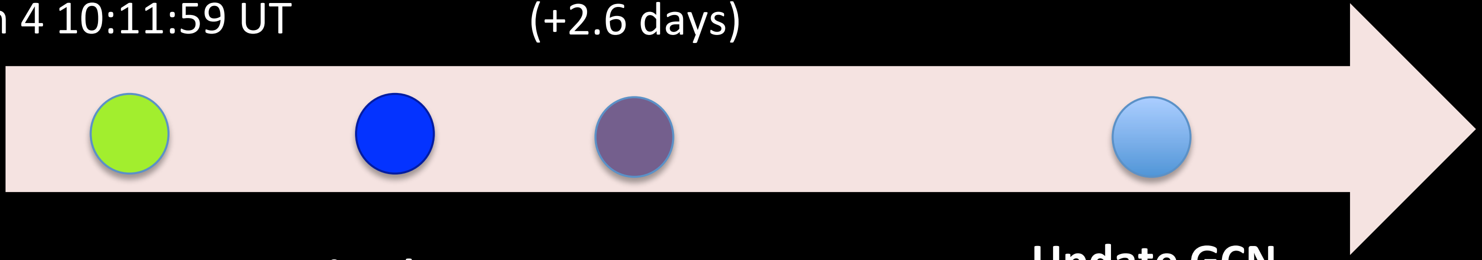




Source at 70 Mpc
(O1-O2 BNS range)

GW170104 EM/neutrino follow-up

LVC 2016 Phys. Rev. Lett. 118, 221101



GW Event!

Jan 4 10:11:59 UT

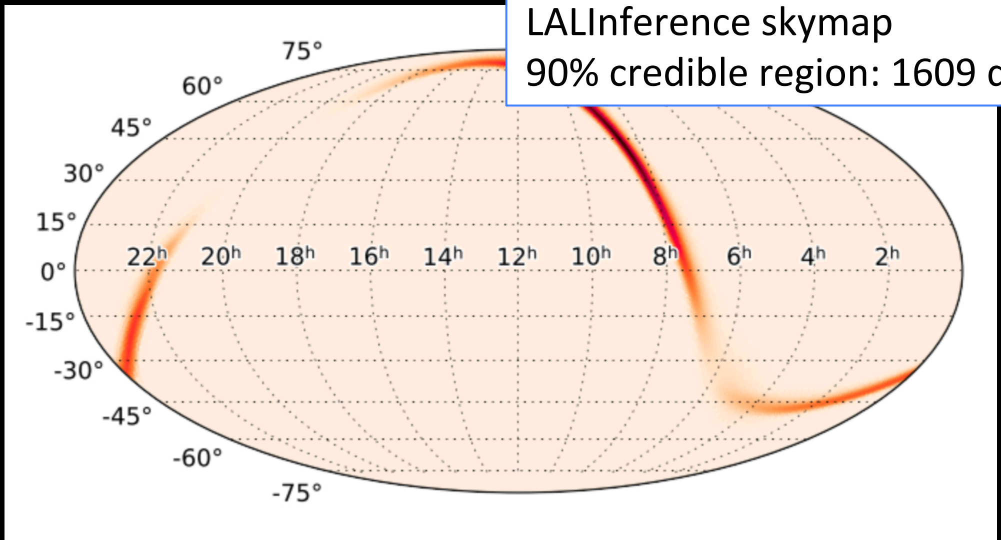
Update GCN 20385
LALinference sky map
(+2.6 days)

Additional info:
FAR < 1/100 yrs
90% sky map cr 2065 deg^2

GCN Circular 20364
BAYESTAR skymap
(+6.3h)

Additional info:
FAR = one per 6 months
EM-bright flag 0%
90% sky map cr 1632 deg^2

Update GCN
LALinference sky map
(+4 months)



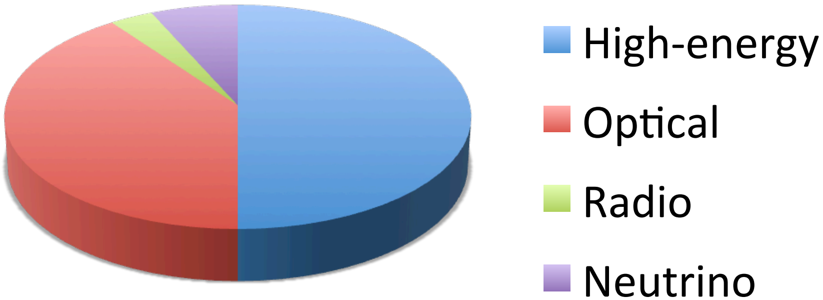
LALInference skymap
90% credible region: 1609 deg^2

LSC

VIRGO

→ About **30 groups** and **50 instruments** involved in the EM/Neutrino follow-up

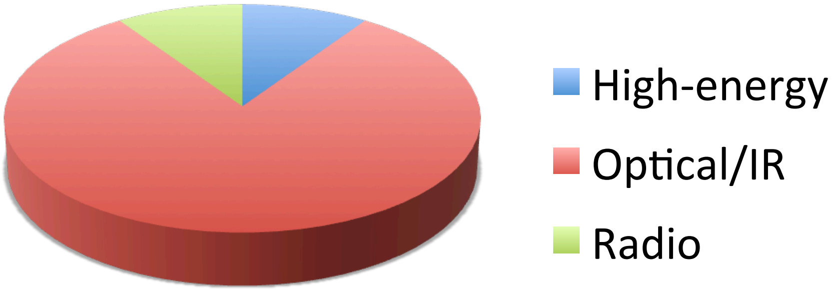
→ About **70 GCNs** sent https://gcn.gsfc.nasa.gov/other/G268556.gcn3



30 instruments to tile the sky-map

22 instruments to characterize the candidate counterparts

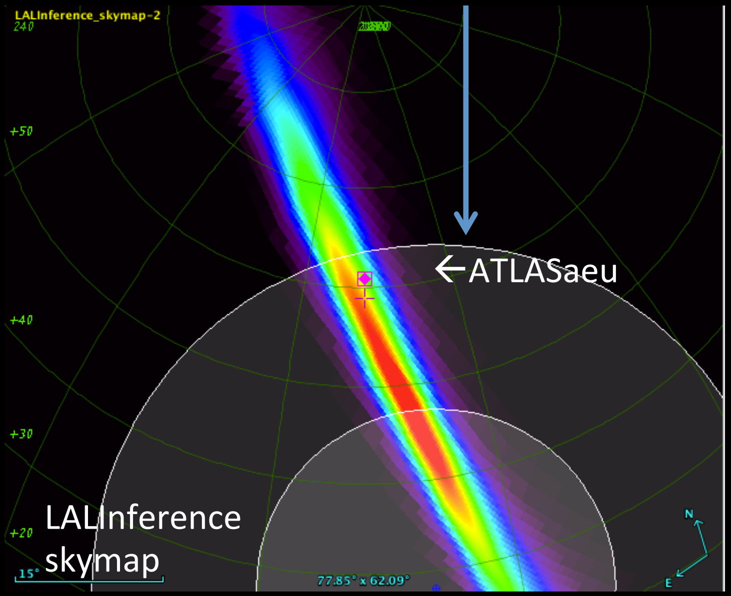
Hundred of candidate counterparts, part of them characterized and classified as contaminants



Astrophysical interesting transient ATLAS17aeu (15 GCNs)

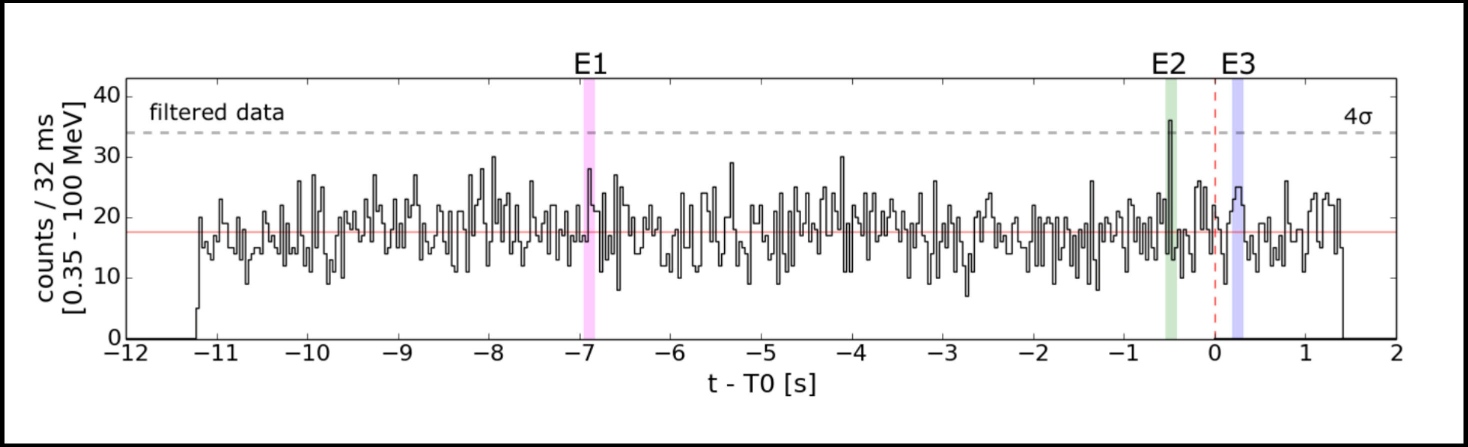
- Discovered 1 day after GW170104 within the 16% probability contour Fast fading optical, X-ray and radio flux (GCN#20382, 20390,20400,20415,20396)
- Time zero consistent with GRB070105A by POLAR (GCN#20387) and ASTROSAT (GCN#20389)→ GRB afterglow (GCN#203993)
- IPN, Konus-Wind, AstroSat CZTI position coincidence GRB070105A/ATLAS17aeu and classified GRB170105A as long GRB (GCN#20412, 20406, 20413)
- Possible TNG host galaxy detection close to the position of ATALS17aeu (GCN#20735)

GRB 170105 localization with IPN (annulus)



Evidences of long GRB/ ATLASaeu connection

AGILE Observations of the Gravitational Wave Source GW170104



Varrecchia et al. arXiv:1706.00029

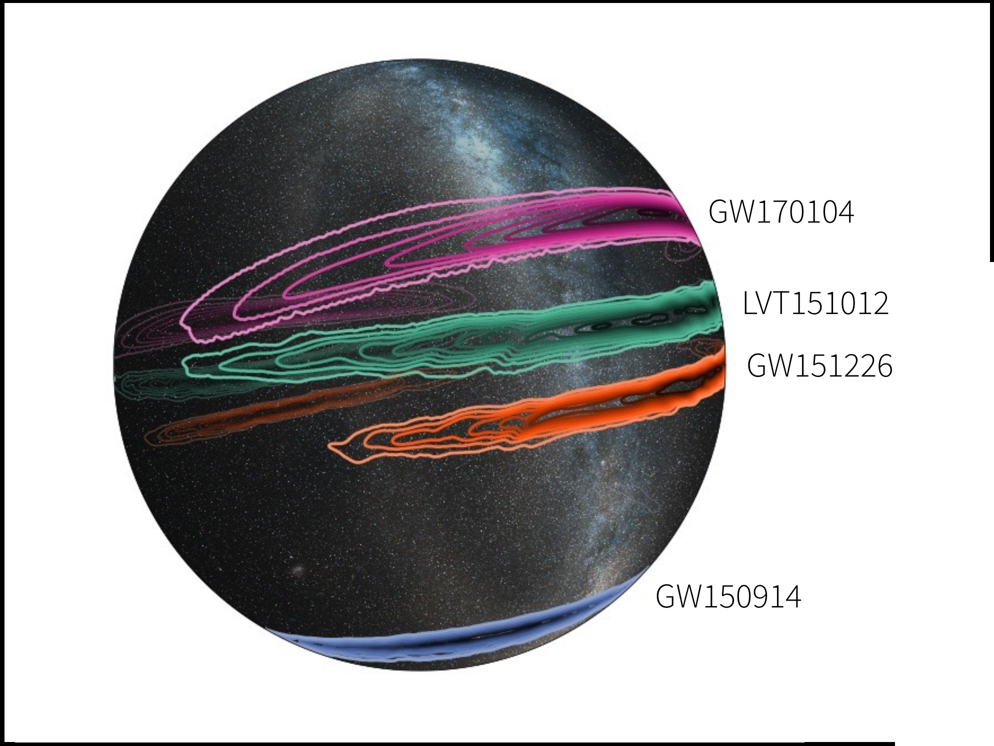
Weak precursor (E2) signal 0.46s before GW170104 detected by MCAL (0.4-100 MeV)
→ post trials significance of 3.4 sigma for temporal coincidence with GW170104

Not confirmed by other high-energy satellites!

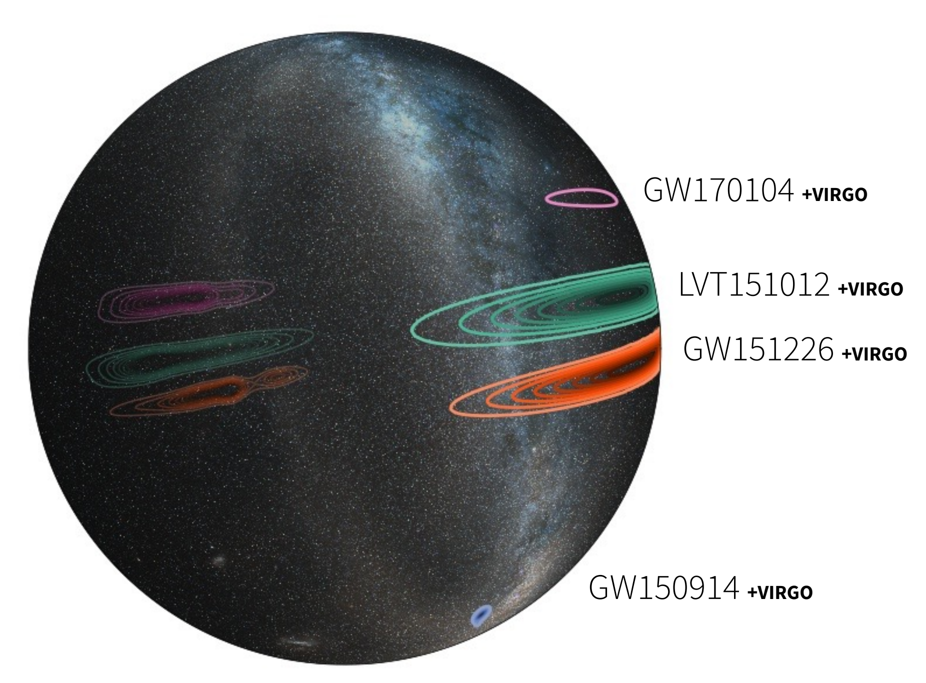
Prospects of observing and localizing GWs in O2 and the next LIGO and VIRGO scientific runs

Sky localization with Virgo

Current LIGO H+L



LIGO H+L+V

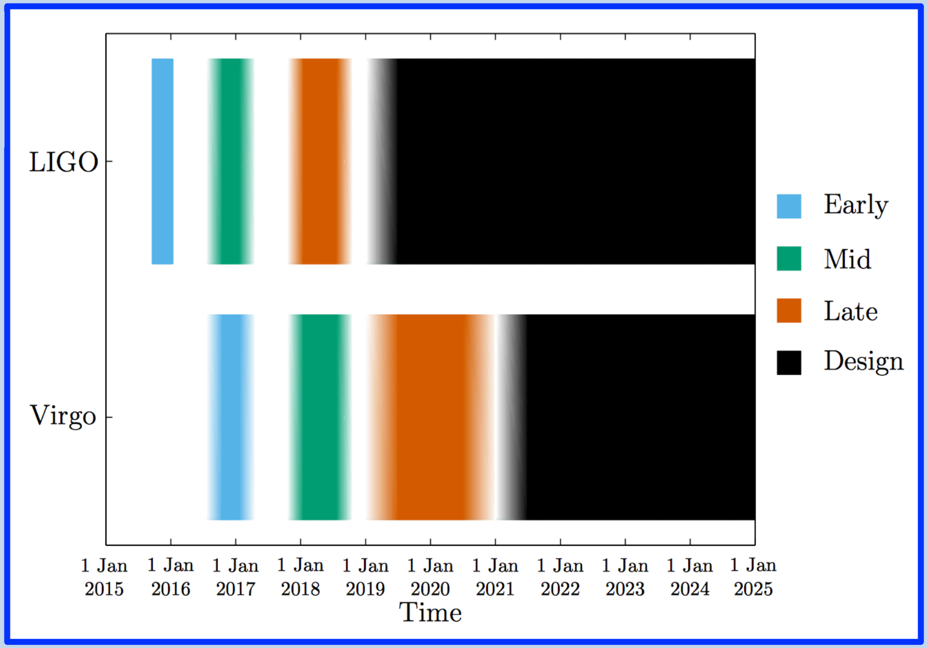


Virgo is expected to join O2 run in July/August!

Image credit: LIGO/L. Singer/A. Mellinger

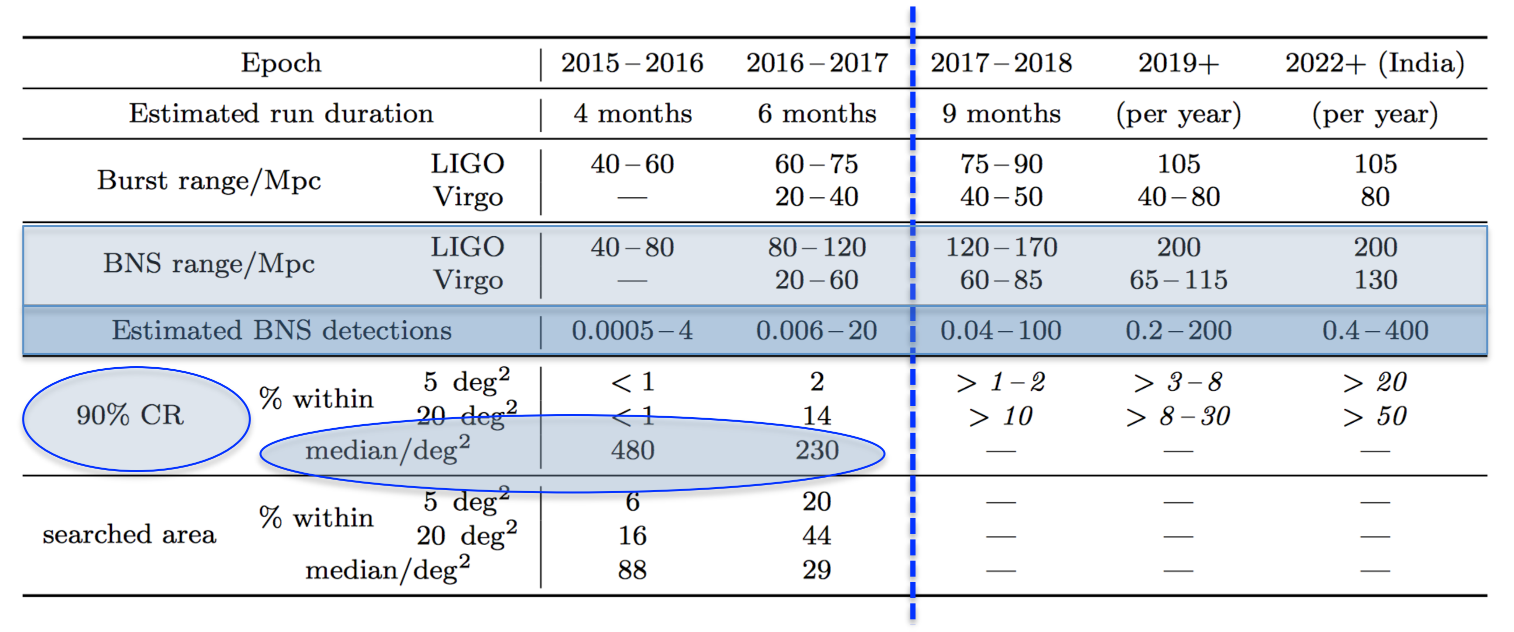
Prospects for Observing and Localizing GWs

Sensitivity evolution
and observing runs



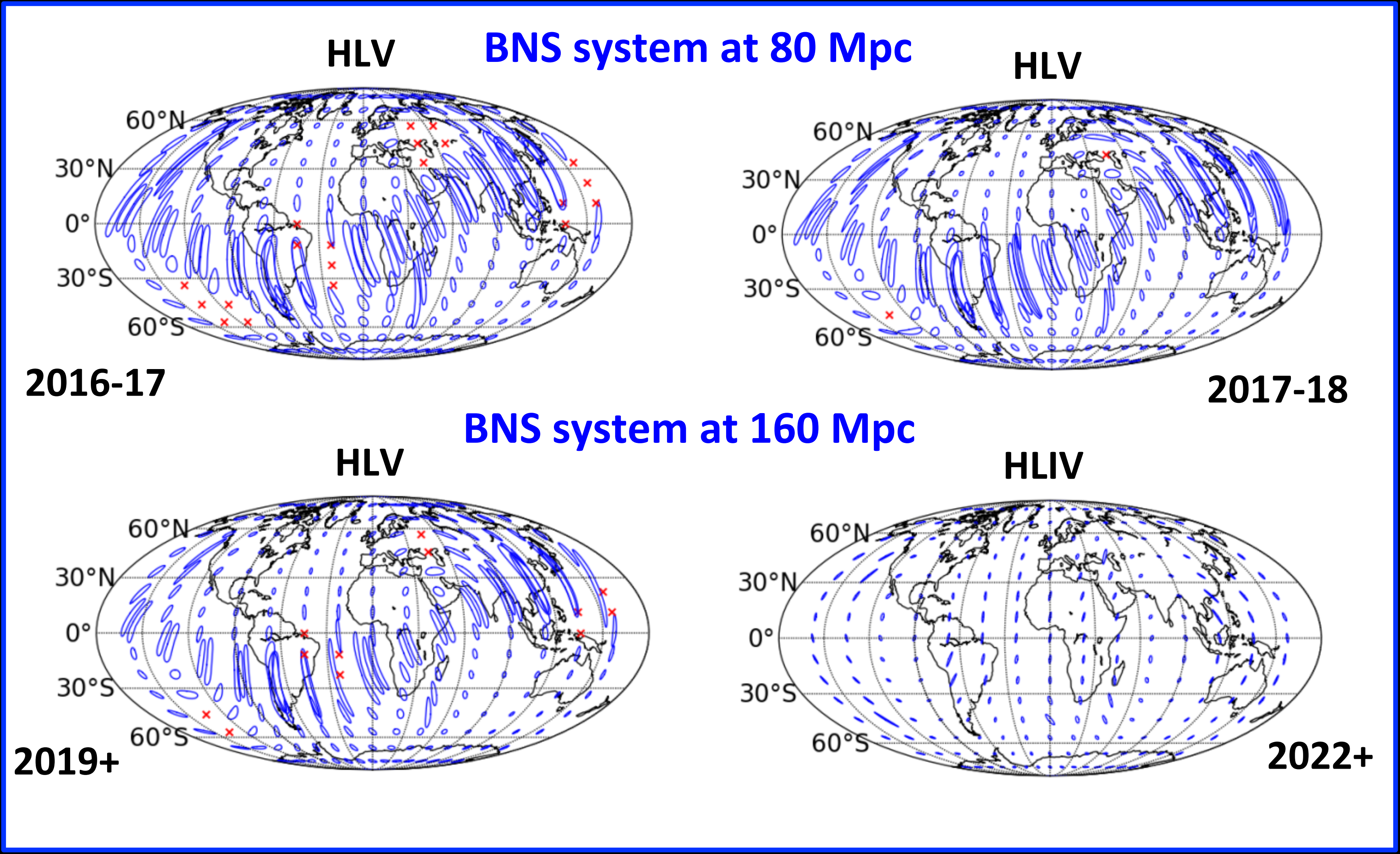
LVC 2016, LRR, 19, 1

Observing schedule, sensitivities, and source localization for BNS



Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

Sky Localization of Gravitational-Wave Transients



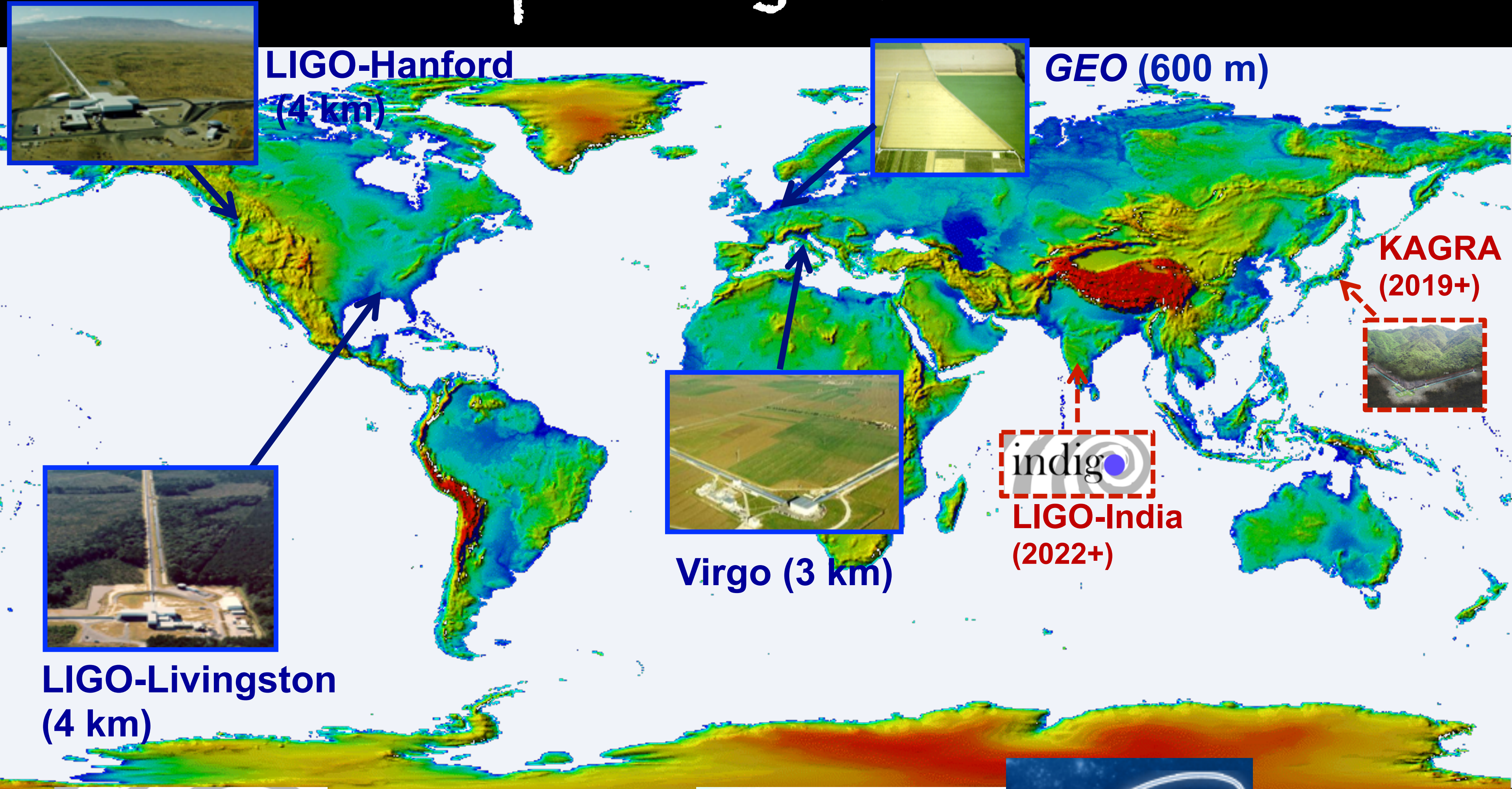
Position uncertainties
with areas of **tens to hundreds of sq. degrees**

⬭ → 90% confidence localization areas

X → signal not confidently detected

LVC 2016, Living Reviews in Relativity, 19

Upcoming network



LIGO-Hanford (4 km)

GEO (600 m)

KAGRA (2019+)

LIGO-India (2022+)

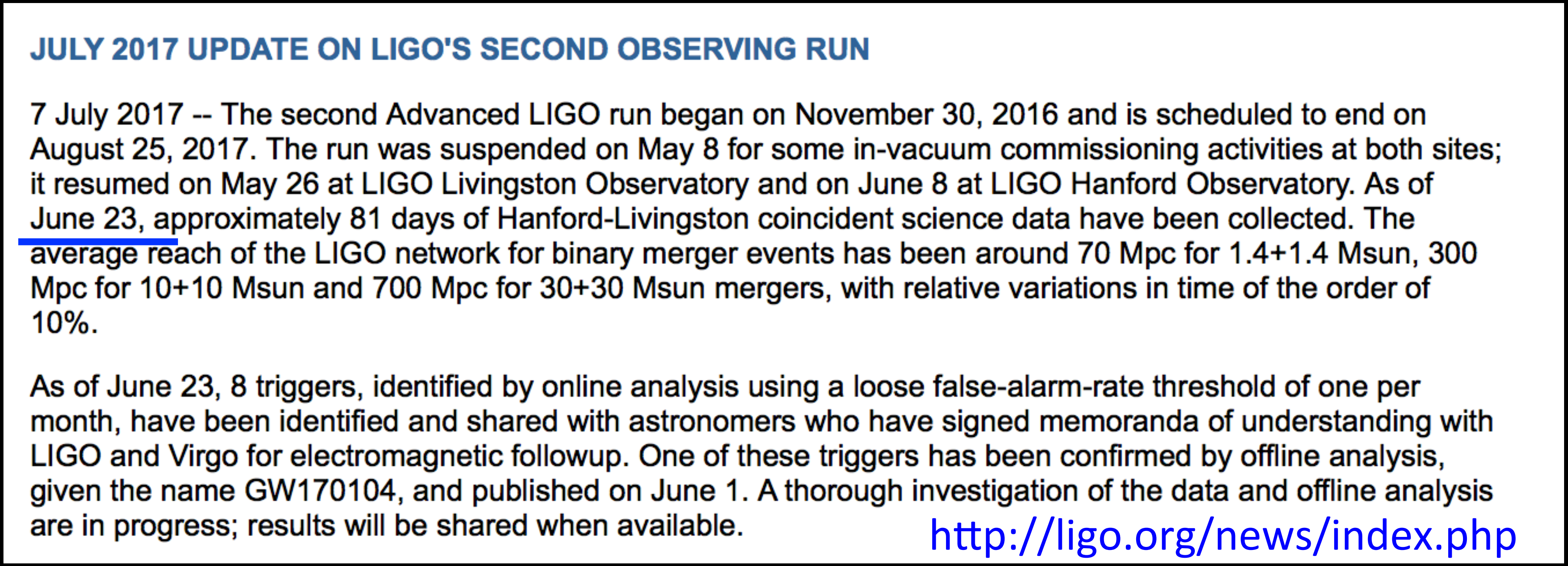
Virgo (3 km)

LIGO-Livingston (4 km)

LIGO detector in India
(4 km)

Underground detector in
Kamioka mine (3km)

O2 run – triggers shared



JULY 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

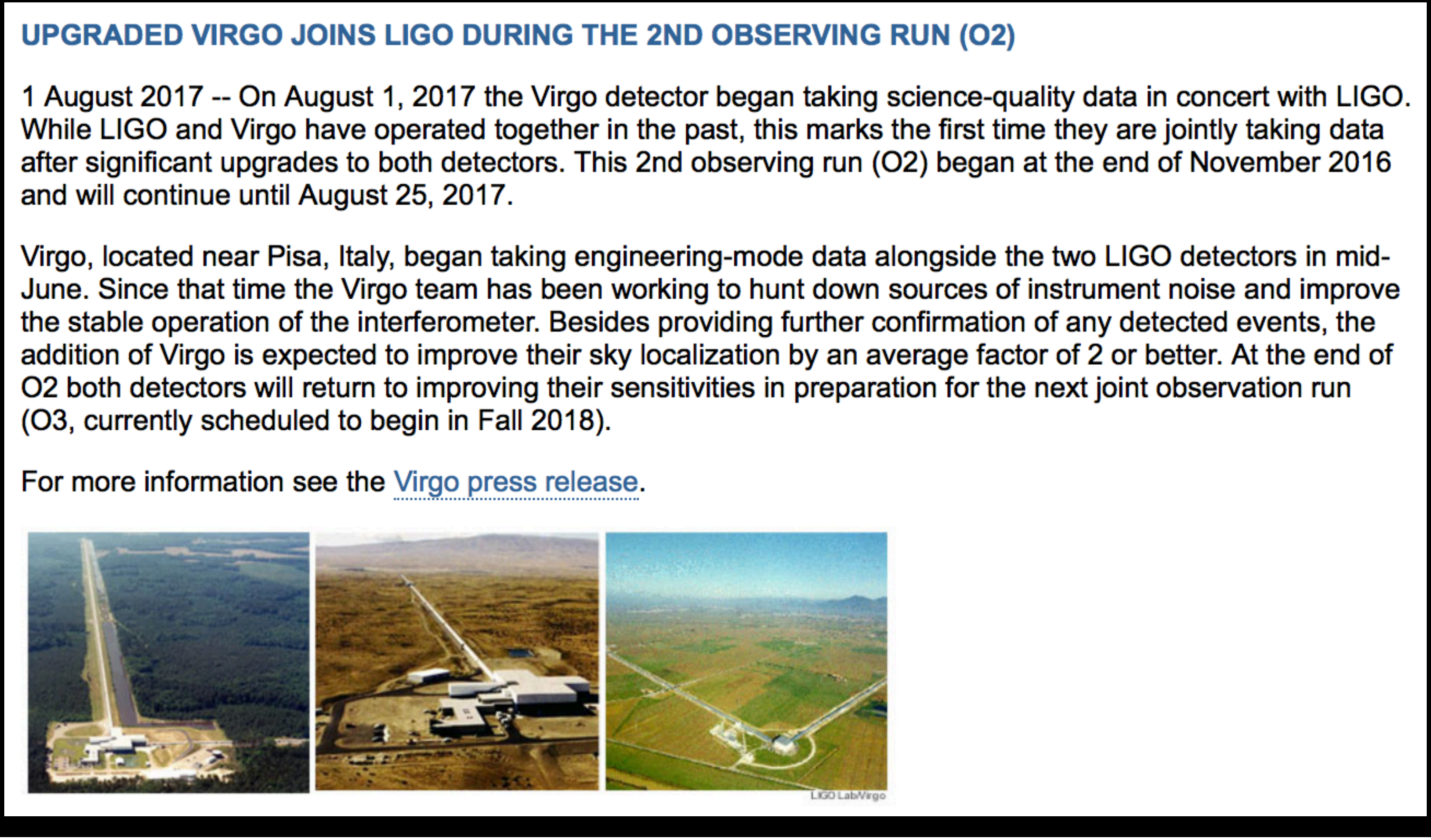
7 July 2017 -- The second Advanced LIGO run began on November 30, 2016 and is scheduled to end on August 25, 2017. The run was suspended on May 8 for some in-vacuum commissioning activities at both sites; it resumed on May 26 at LIGO Livingston Observatory and on June 8 at LIGO Hanford Observatory. As of June 23, approximately 81 days of Hanford-Livingston coincident science data have been collected. The average reach of the LIGO network for binary merger events has been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

As of June 23, 8 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. One of these triggers has been confirmed by offline analysis, given the name GW170104, and published on June 1. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

http://ligo.org/news/index.php

- About 81 days of coincident Handford and Livingston science data
- Range: BNS 70 Mpc,
  BBH (M=10+10 Mo) 300 Mpc,
  BBH (M=30+30 Mo) 700 Mpc
- 8 triggers (FAR < 1/month) sent to astronomers

Loose FAR threshold → these are not all real events!



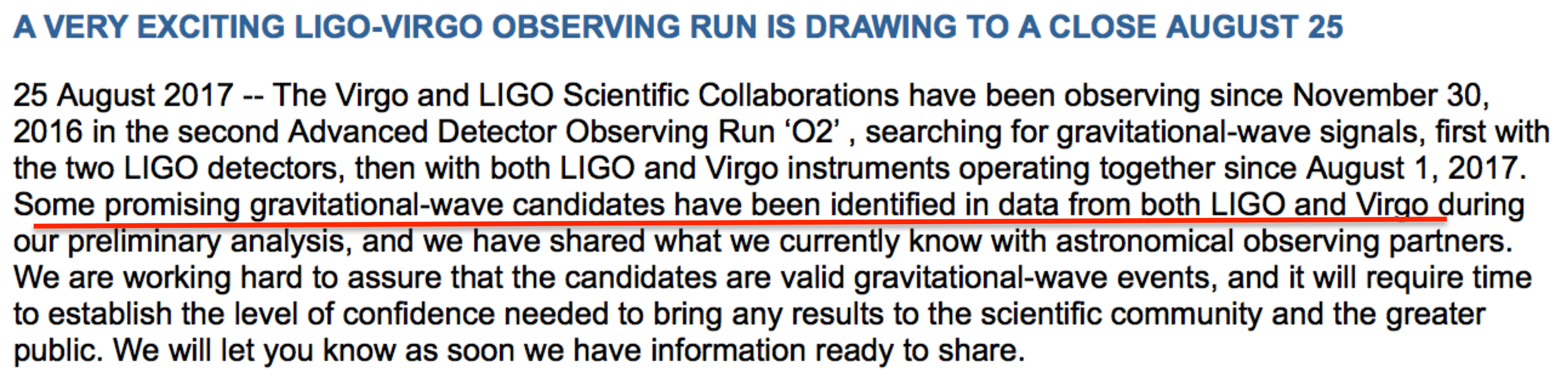
UPGRADED VIRGO JOINS LIGO DURING THE 2ND OBSERVING RUN (O2)

1 August 2017 -- On August 1, 2017 the Virgo detector began taking science-quality data in concert with LIGO. While LIGO and Virgo have operated together in the past, this marks the first time they are jointly taking data after significant upgrades to both detectors. This 2nd observing run (O2) began at the end of November 2016 and will continue until August 25, 2017.

Virgo, located near Pisa, Italy, began taking engineering-mode data alongside the two LIGO detectors in mid-June. Since that time the Virgo team has been working to hunt down sources of instrument noise and improve the stable operation of the interferometer. Besides providing further confirmation of any detected events, the addition of Virgo is expected to improve their sky localization by an average factor of 2 or better. At the end of O2 both detectors will return to improving their sensitivities in preparation for the next joint observation run (O3, currently scheduled to begin in Fall 2018).

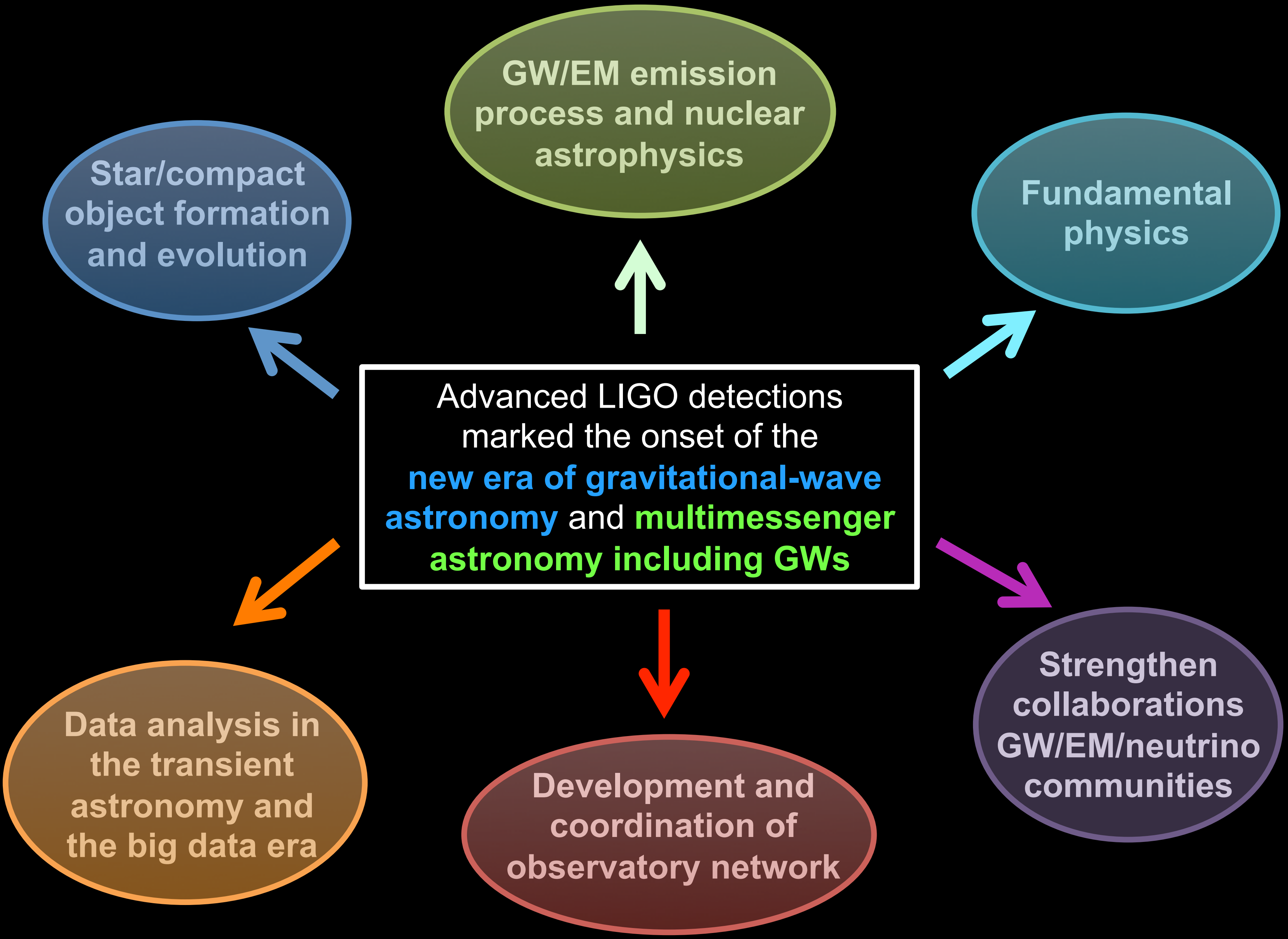
For more information see the Virgo press release.

LIGO Lab/Virgo



A VERY EXCITING LIGO-VIRGO OBSERVING RUN IS DRAWING TO A CLOSE AUGUST 25

25 August 2017 -- The Virgo and LIGO Scientific Collaborations have been observing since November 30, 2016 in the second Advanced Detector Observing Run ‘O2’ , searching for gravitational-wave signals, first with the two LIGO detectors, then with both LIGO and Virgo instruments operating together since August 1, 2017. Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis, and we have shared what we currently know with astronomical observing partners. We are working hard to assure that the candidates are valid gravitational-wave events, and it will require time to establish the level of confidence needed to bring any results to the scientific community and the greater public. We will let you know as soon we have information ready to share.



Advanced LIGO detections marked the onset of the **new era of gravitational-wave astronomy** and **multimessenger astronomy including GWs**

GW/EM emission process and nuclear astrophysics

Fundamental physics

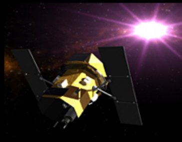
Strengthen collaborations GW/EM/neutrino communities

Development and coordination of observatory network

Data analysis in the transient astronomy and the big data era

Star/compact object formation and evolution

Multi-messenger astronomy with the advanced GW detectors



GWs

- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance
- Compact object binary rate

EM emission

- Energetics
- Magnetic field strength
- Precise (arcsec) sky localization
- Host galaxy, environment
- Redshift
- Nuclear astrophyisics

→ To confirm the short GRB progenitor

→ To probe geometry of the systems and emission models

→ To probe birth and evolution of compact objects

→ To investigate the origin of the heavy elements in the Universe

→ To probe the NS equation of state