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ISAPP School Institut Pascal - 25/03/2020

Multi-messenger astroparticle physics Introductory course

Outline of this lecture

1. A multi-messenger picture is the natural way

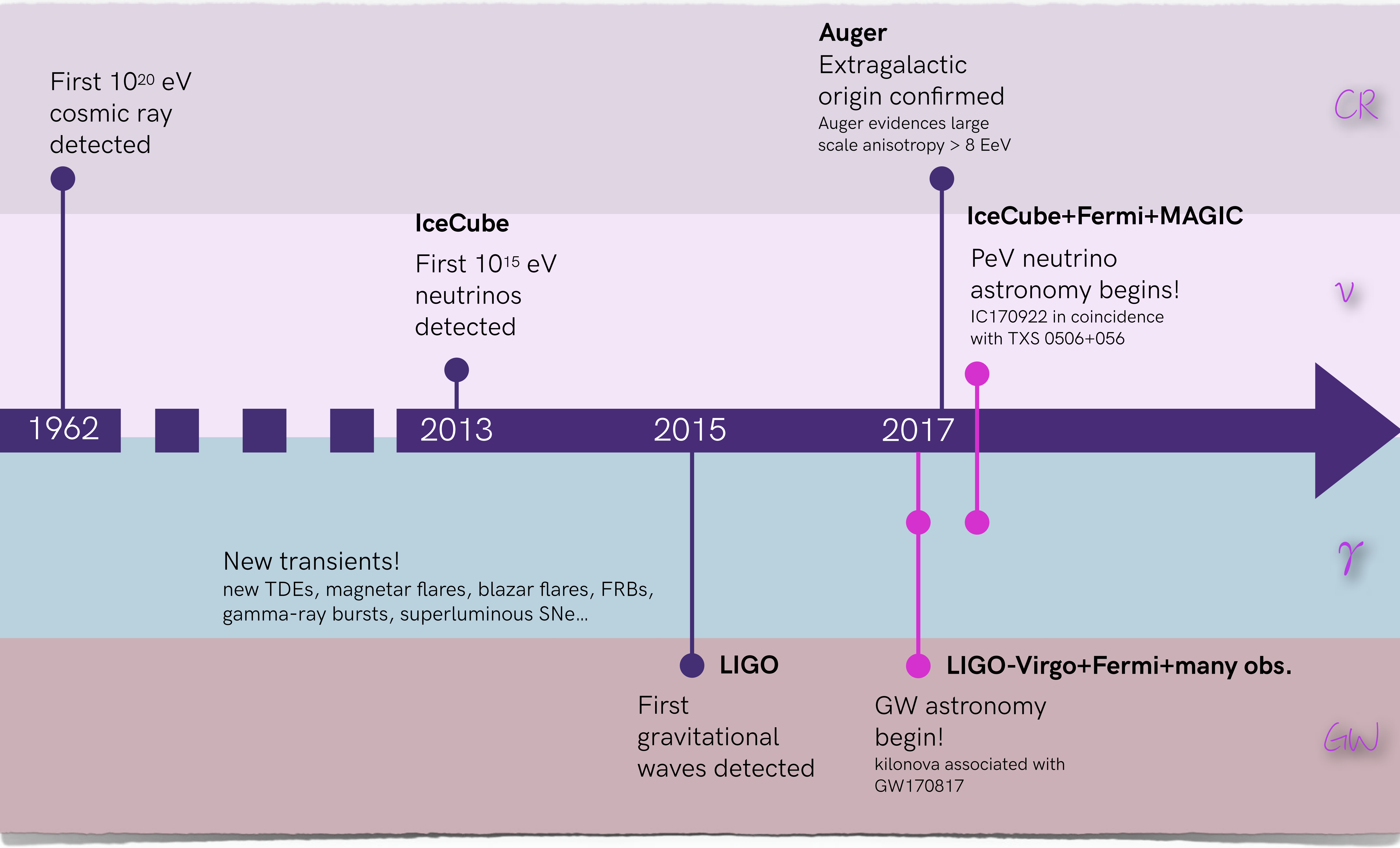
2. Tools for multi-messenger astrophysics
   - Secondary production channels
   - Maximum energies & simple flux estimates
   - Cosmogenic neutrinos
   - Specificities of gamma rays
   - Panorama of simulation tools

3. Can we really do multi-messenger astrophysics?
   - GW-neutrino sources
   - Focus on neutrinos from transient sources
   - Opening the UHE neutrino window

1. A multi-messenger picture is the natural way

Introduction

Exciting times!



First 10^{20} eV cosmic ray detected

Auger
Extragalactic origin confirmed
Auger evidences large scale anisotropy > 8 EeV

IceCube
First 10^{15} eV neutrinos detected

IceCube+Fermi+MAGIC
PeV neutrino astronomy begins!
IC170922 in coincidence with TXS 0506+056

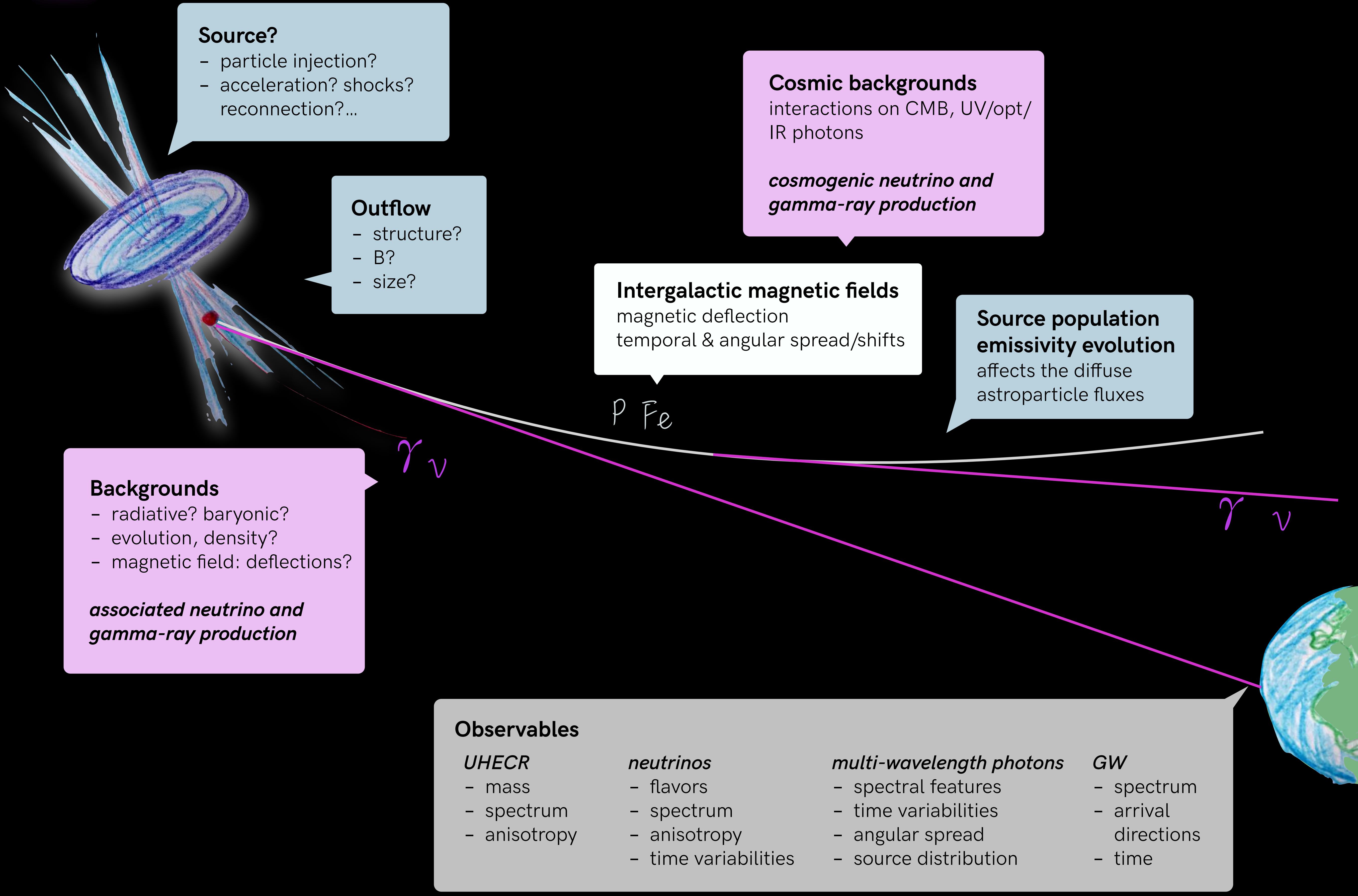
New transients!
new TDEs, magnetar flares, blazar flares, FRBs, gamma-ray bursts, superluminous SNe...

LIGO
First gravitational waves detected

LIGO-Virgo+Fermi+many obs.
GW astronomy begin!
kilonova associated with GW170817

And we still don't know the origin of UHECRs

The complicated cosmic-ray journey



Source?
- particle injection?
- acceleration? shocks? reconnection?...

Outflow
- structure?
- B?
- size?

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

Intergalactic magnetic fields
magnetic deflection
temporal & angular spread/shifts

Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

Source population emissivity evolution
affects the diffuse astroparticle fluxes

Observables

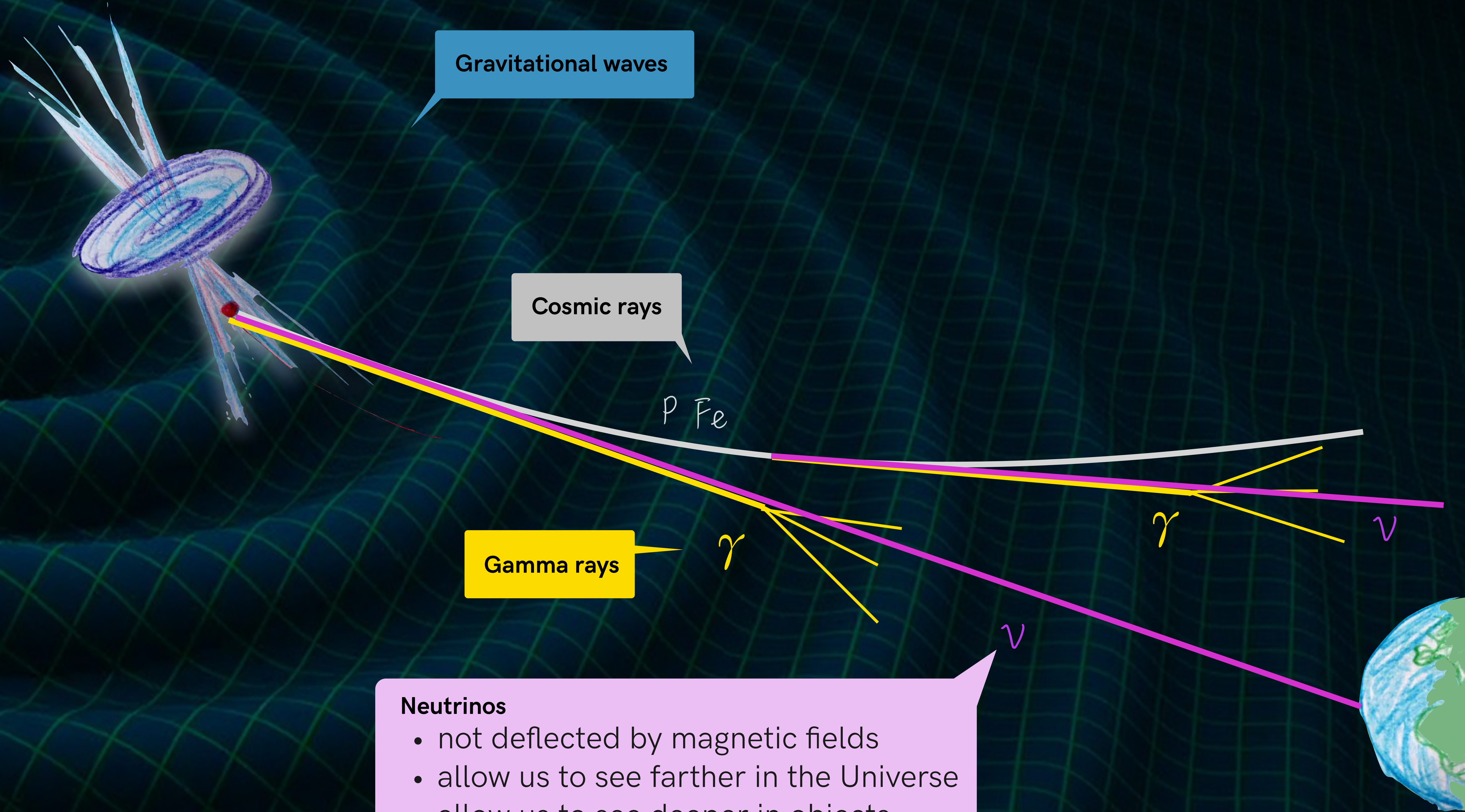
UHECR
- mass
- spectrum
- anisotropy

neutrinos
- flavors
- spectrum
- anisotropy
- time variabilities

multi-wavelength photons
- spectral features
- time variabilities
- angular spread
- source distribution

GW
- spectrum
- arrival directions
- time

Cosmic rays and friends



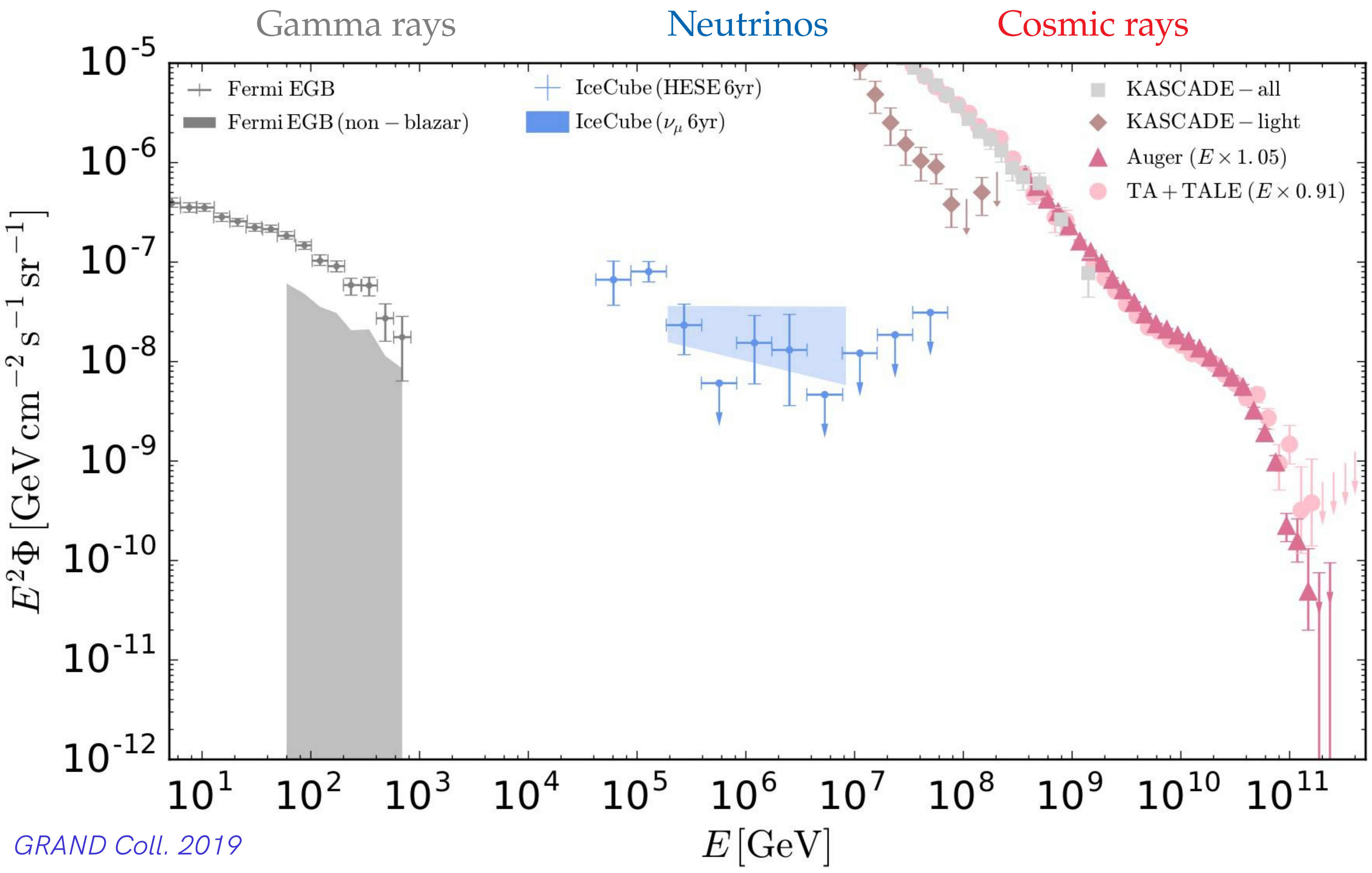
Gravitational waves

Cosmic rays

Gamma rays

Neutrinos
- not deflected by magnetic fields
- allow us to see farther in the Universe
- allow us to see deeper in objects
- clear hadronic acceleration signature
- but: difficult to detect

A multi-messenger picture also *looks* like a natural way



GRAND Coll. 2019

A common multi-messenger source? *e.g., Fang & Murase 2017*

2. Tools for multi-messenger astrophysics

Secondary production channels

Photo-hadronic interactions

Dermer & Menon, Princeton University Press, 2009

Table 9.1 Multiplicities ζ and Mean Fractional Energies χ of Secondaries Formed in Photomeson Production

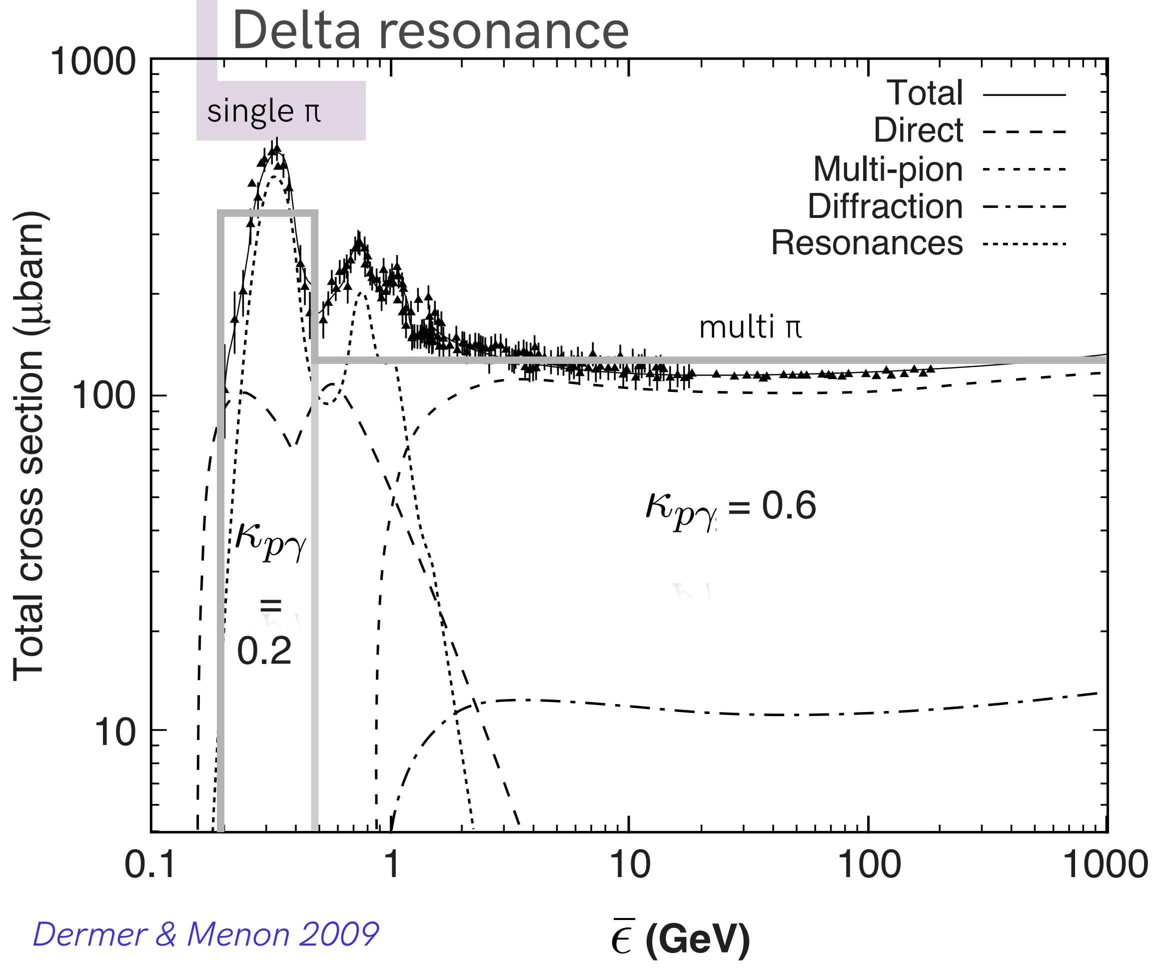
Species	Single π		Multi-π	
Neutrinos	$\zeta_\nu^s = 3/2$	$\chi_\nu^s = 0.05$	$\zeta_\nu^m = 6$	$\chi_\nu^m = 0.05$
Leptons	$\zeta_e^s = 1/2$	$\chi_e^s = 0.05$	$\zeta_e^m = 2$	$\chi_e^m = 0.05$
γ-rays	$\zeta_\gamma^s = 1$	$\chi_\gamma^s = 0.1$	$\zeta_\gamma^m = 2$	$\chi_\gamma^m = 0.1$
Neutrons	$\zeta_n^s = 1/2$	$\chi_n^s = 0.8$	$\zeta_n^m = 0.5$	$\chi_n^m = 0.4$
Protons	$\zeta_p^s = 1/2$	$\chi_p^s = 0.8$	$\zeta_p^m = 0.5$	$\chi_p^m = 0.4$
β-electrons	$\zeta_{\beta,e}^s = 1/2$	$\chi_{\beta,e}^s = 10^{-3}$	$\zeta_{\beta,e}^m = 1/2$	$\chi_{\beta,e}^m = 10^{-3}$
β-neutrinos	$\zeta_{\beta,\nu}^s = 1/2$	$\chi_{\beta,\nu}^s = 10^{-3}$	$\zeta_{\beta,\nu}^m = 1$	$\chi_{\beta,\nu}^m = 10^{-3}$

$$p + \gamma_{\rm target} \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$p + \gamma_{\rm target} \rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$



Dermer & Menon 2009

cross-section

$$\sigma_{p\gamma}(\bar{\epsilon}) = \begin{cases} 340\,\mu\text{b}, & \bar{\epsilon}_{\rm th} < \bar{\epsilon} < 500\text{MeV}\,, \\ 120\,\mu\text{b}, & \bar{\epsilon} > 500\text{MeV}\,, \end{cases}$$

inelasticity

$$\kappa_{p\gamma}(\bar{\epsilon}) = \begin{cases} 0.2, & \bar{\epsilon}_{\rm th} < \bar{\epsilon} < 500\text{MeV}\,, \\ 0.6, & \bar{\epsilon} > 500\text{MeV}\,, \end{cases}$$

Atoyan & Dermer, 2003

interaction timescale $t_{p\gamma}$

$$t_{p\gamma}^{-1}(\varepsilon_p) = \frac{c}{2\gamma_p^2} \int_{\bar{\varepsilon}_{\rm th}}^{\infty} d\bar{\varepsilon}\, \sigma_{p\gamma}(\bar{\varepsilon}) \kappa_p(\bar{\varepsilon}) \bar{\varepsilon} \int_{\bar{\varepsilon}/2\gamma_p}^{\infty} d\varepsilon\, \varepsilon^{-2} n_\varepsilon$$

Photo-hadronic interaction timescale

barred quantities in proton rest frame

invariant energy of interaction =
photon energy in proton rest frame

$$\sqrt{s_{\rm int}} = \bar\epsilon = \gamma_p \epsilon (1 + \beta_p \bar\mu)$$

photon energy $\epsilon = h\nu / m_e c^2$
proton Lorentz factor $\gamma_p = E_p / m_p c^2 = (1 - \beta_p^2)^{-1/2}$
angle between proton and photon: θ $\mu = \cos\theta$

$$t_{p\gamma}^{-1} = \frac{1}{\gamma_p}\left|\frac{{\rm d}\gamma_p}{{\rm d}t}\right| = \frac{1}{\gamma_p}\left|\frac{{\rm d}\gamma_p}{{\rm d}\bar t}\right|\frac{{\rm d}\bar t}{{\rm d}t}$$

$$= \frac{1}{\gamma_p}\int_{\bar\Omega}\int_0^\infty n_{\rm ph}(\bar\epsilon, \bar\Omega)\, c\, \sigma_{p\gamma}(\bar\epsilon)\, \kappa_{p\gamma}(\bar\epsilon)\, {\rm d}\bar\epsilon\, {\rm d}\bar\Omega$$

$$= \frac{c}{\gamma_p}\int_0^\infty {\rm d}\bar\epsilon \int_0^{2\pi} {\rm d}\phi \int_{-1}^{+1} {\rm d}\bar\mu\, n_{\rm ph}(\bar\epsilon, \bar\Omega)\, \sigma_{p\gamma}(\bar\epsilon)\, \kappa_{p\gamma}(\bar\epsilon)$$

$${\rm d}\bar t = \frac{1}{\gamma_p}{\rm d}t$$

$$n_{\rm ph}(\epsilon, \Omega) \equiv \frac{{\rm d}N_{\rm ph}}{{\rm d}\epsilon {\rm d}\Omega {\rm d}V}$$

$$\sqrt{s_{\rm int}} = \bar\epsilon = \gamma_p \epsilon (1 + \beta_p \bar\mu) \longrightarrow \begin{cases} \bar\mu = \dfrac{1}{\beta_p}\left[\dfrac{\epsilon}{\gamma_p \bar\epsilon} - 1\right] \quad \text{and} \quad {\rm d}\bar\mu = \dfrac{1}{\beta_p \gamma_p}\dfrac{{\rm d}\epsilon}{{\rm d}\bar\epsilon} \\ n_{\rm ph}(\bar\epsilon, \bar\Omega) = n_{\rm ph}(\epsilon)/4\pi \quad \text{isotropic photon flux} \end{cases}$$

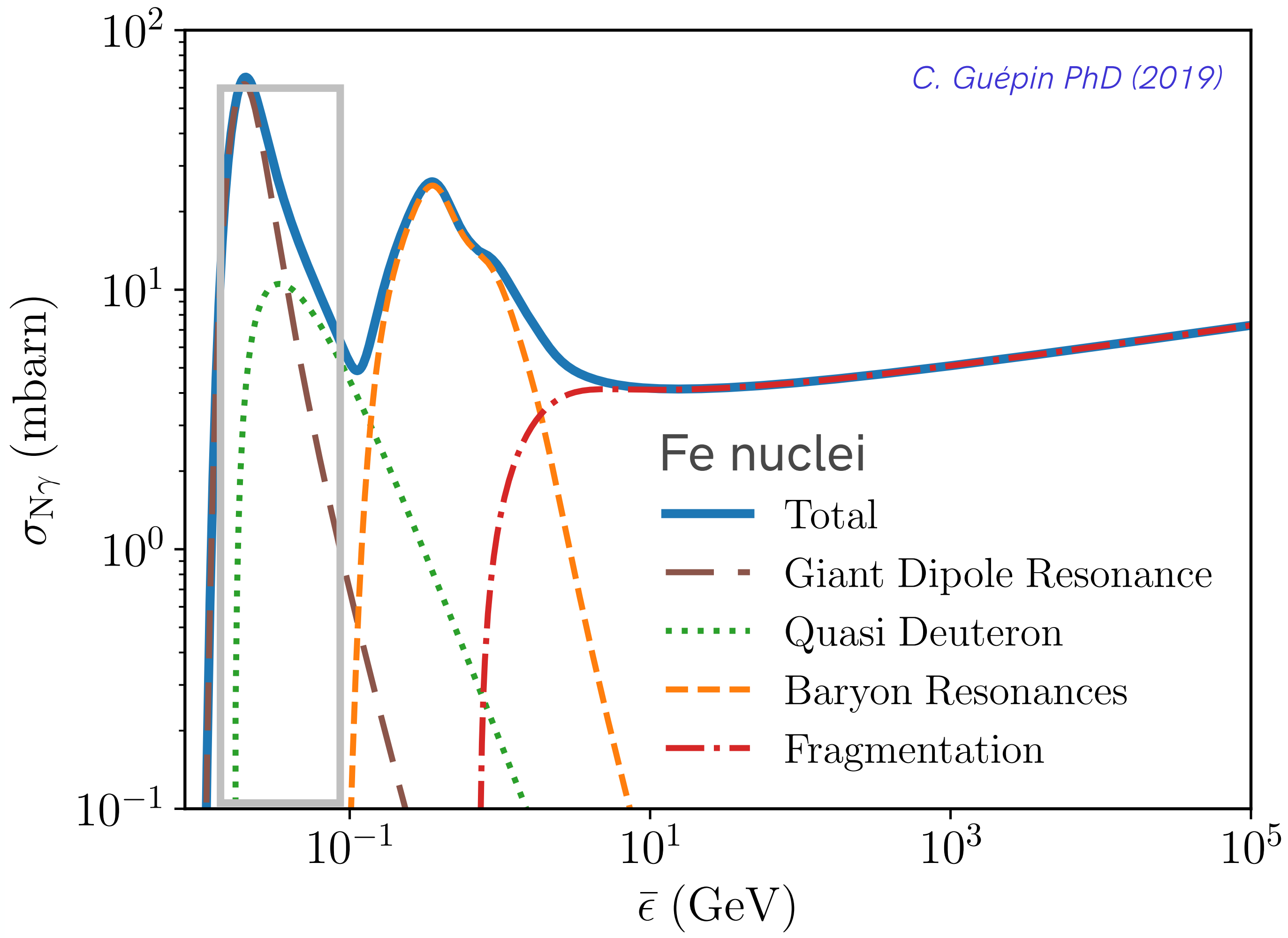
$$t_{p\gamma}^{-1} = \frac{c}{2\gamma_p^2 \beta_p}\int_0^\infty \frac{n_{\rm ph}(\epsilon)}{\epsilon^2}\int_{\bar\epsilon_{\rm min}}^{\bar\epsilon_{\rm max}} \sigma_{p\gamma}(\bar\epsilon)\, \kappa_{p\gamma}(\bar\epsilon) {\rm d}\bar\epsilon$$

$$\bar\epsilon_{\rm min} = \frac{\epsilon}{\gamma_p (1 + \beta_p)} \sim \frac{\epsilon}{2\gamma_p} \rightarrow 0$$

$$\bar\epsilon_{\rm max} = \frac{\epsilon}{\gamma_p (1 - \beta_p)} \sim 2\gamma_p \epsilon$$

Photo-disintegration $A + \gamma_{\mathrm{target}}$

nucleus energy $E_A = \gamma_A A m_p c^2$



C. Guépin PhD (2019)

For all these processes:
E_A/A: energy per nucleon does not change

They don't all allow the direct production of pions, but they produce α particles
—> pions (i.e. secondaries)

} direct
π production

} production of nucleons
—> π production

"Delta" approximation:

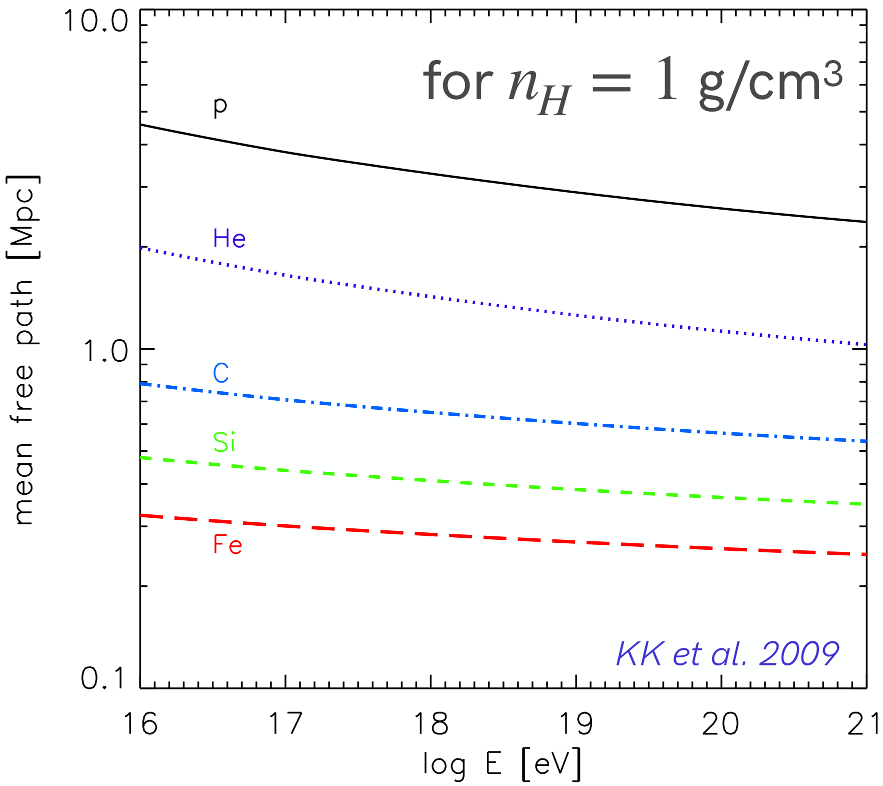
$$\sigma_{\mathrm{GDR}} \sim 1.45 \times 10^{-27}\,\mathrm{cm}^2\,A$$
$$\bar{\varepsilon}_{\mathrm{GDR}} \sim 42.65 A^{-0.21}\ \mathrm{MeV}$$
$$\Delta\bar{\varepsilon} \ \sim \ 8\ \ \mathrm{MeV}$$

Murase et al. PRD (2008)

For interaction channel i:

$$t^{-1}_{A\gamma,i} = \frac{c}{2\gamma_A^2}\int_0^\infty \frac{n_{\mathrm{ph}}(\epsilon)}{\epsilon^2}\int_0^{2\gamma_A\bar{\epsilon}} \sigma_{A\gamma,i}(\bar{\epsilon})\mathrm{d}\bar{\epsilon}$$

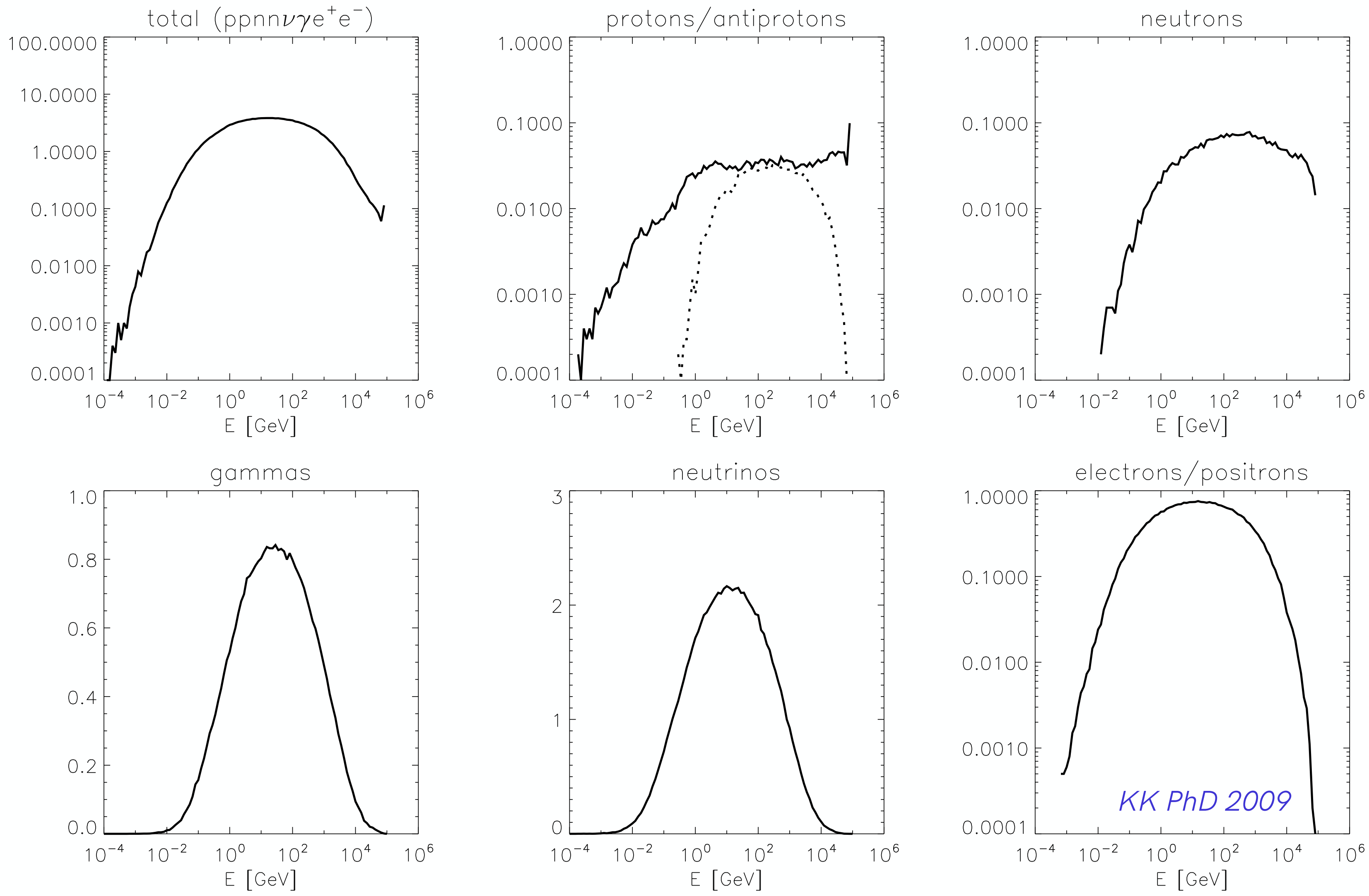
Hadronic interactions $A + A_{\rm target} \rightarrow N(\pi^0 + \pi^+ + \pi^-) + X$



spallation cross-section $A + p_{\rm target}$:

$$\sigma_{\rm sp}(E') \simeq \left[50.44 - 7.93\log(E') + 0.61\log^2(E')\right] \; A^{\beta_{\rm sp}}\,{\rm mb}$$

$$t_{\rm sp}^{-1} = n_A \sigma_{\rm sp}\, c$$



Energy distribution of secondary particles produced by a pp interaction
Calculated with EPOS

2. Tools for multi-messenger astrophysics

Maximum energies
& simple flux estimates

Maximum cosmic ray energy at the source

e.g., Guépin & KK (2017), Guépin et al. (2018) and many refs. therein

For cosmic rays: $t'_{\rm acc} \lesssim t'_{\rm dyn}, t'_{\rm esc}, t'_{\rm loss}, t'_{\rm age} \dots$

tip: *write all these timescales in the comoving frame (primed quantities)*

$$t'_{\rm acc} = \mathcal{A}\, t'_{\rm L}$$

depends on acc. mechanism and environment

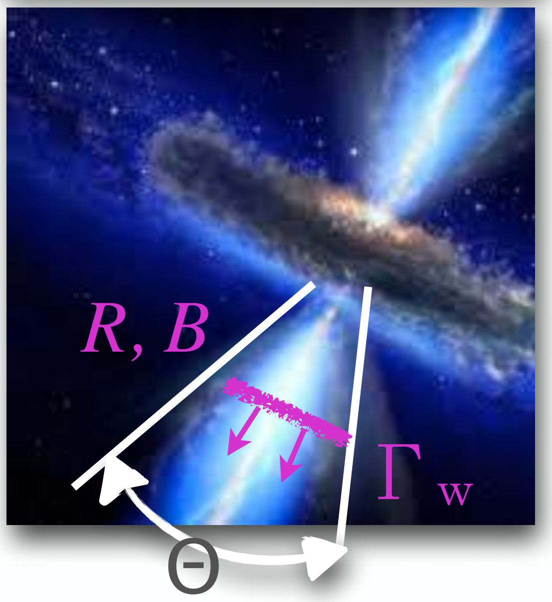
Larmor time

$\mathcal{A} \gg 1$

$\mathcal{A} \sim 1$ at best

e.g., Norman et al. 1995,
Waxman 1995,
Lyutikov & Ouyed 2005,
Waxman 2005
Lemoine & Waxman 2009

$$t_{\rm dyn} \sim R/\beta_{\rm W}\Gamma_{\rm W}c$$



depends on
B strength
and structure

photo-hadronic/hadronic interactions

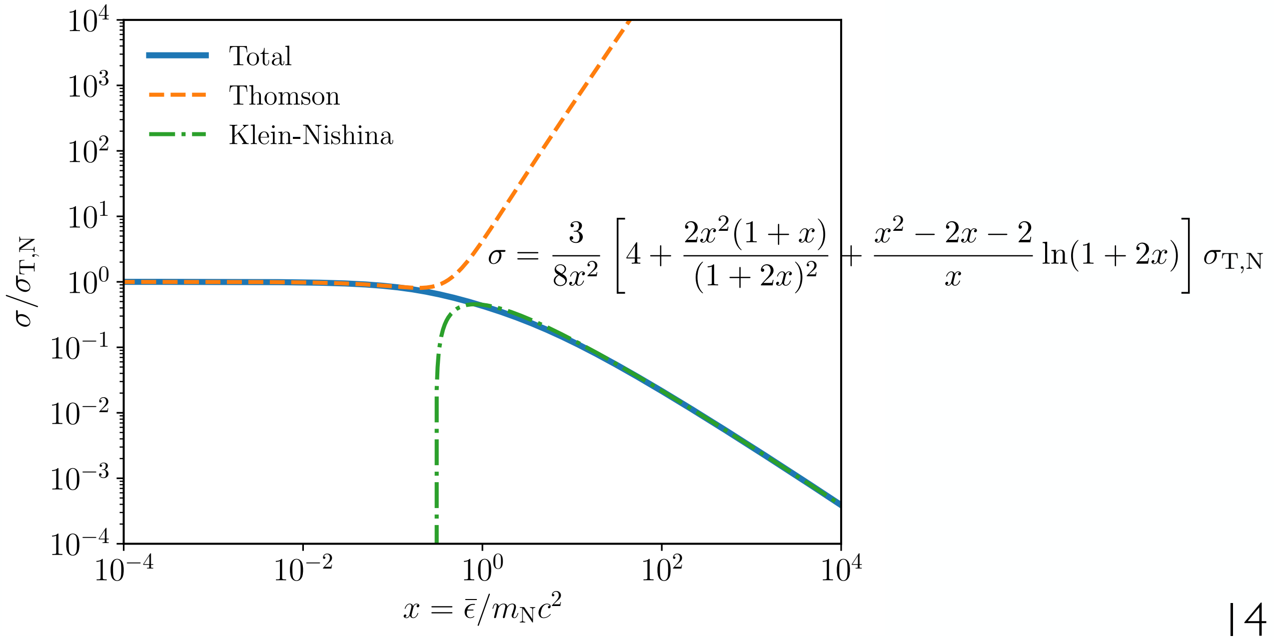
$$t'^{-1}_{N\gamma} = \frac{c}{2\gamma'^2}\int_0^\infty \frac{{\rm d}\epsilon'}{\epsilon'^2}\frac{{\rm d}n'_\gamma}{{\rm d}\epsilon'}(\epsilon')\int_0^{2\gamma'\epsilon'} {\rm d}\bar\epsilon\,\bar\epsilon\,\sigma_{N\gamma}(\bar\epsilon)$$

synchrotron radiation in B

$$t'_{\rm syn} = \frac{3m_{\rm p}c}{4\sigma_{\rm T,p}U'_B}\frac{A^3}{Z^4}\frac{1}{\gamma'}$$

$U'_B = B'^2/8\pi$
magnetic energy density

inverse Compton



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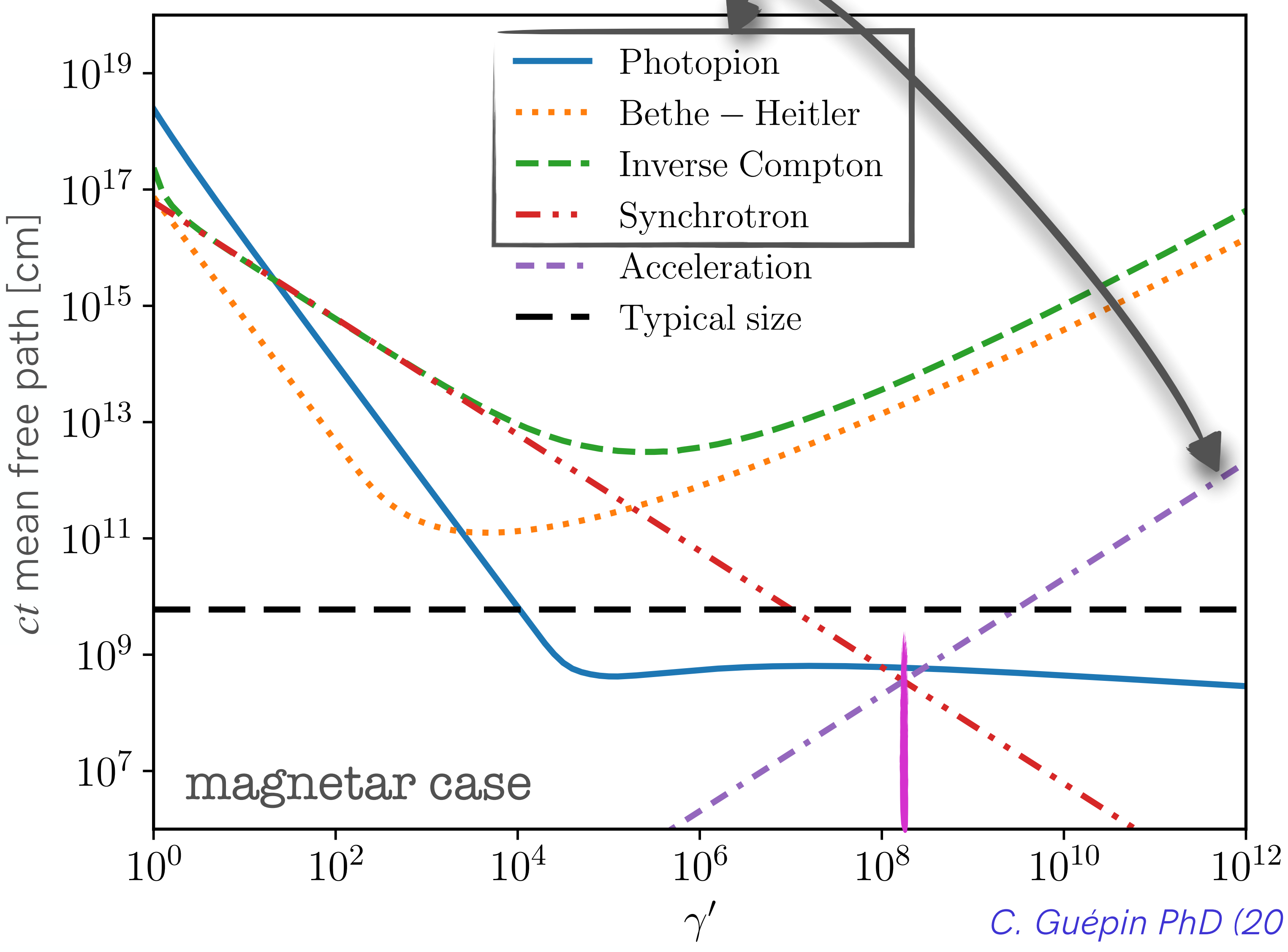


C. Guépin PhD (2019)

Secondary neutrino & gamma-ray energies

photo-hadronic interactions

$$A + \gamma_{\text{target}} \to N(\pi^0 + \pi^+ + \pi^-) + X$$

hadronic interactions

$$A + A_{\text{target}} \to N(\pi^0 + \pi^+ + \pi^-) + X$$

$$\left.\right\}$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \to \gamma + \gamma$$

$$E_\pi \sim \frac{1}{5} E_A / A$$

$$E_{\nu_\mu} \sim \frac{1}{4} E_\pi$$

$$E_\nu \sim \frac{1}{5}\frac{1}{4} E_p \sim 0.05 \frac{E_A}{A}$$

$$E_\gamma \sim \frac{1}{2} E_\pi$$

$$E_\gamma \sim \frac{1}{5}\frac{1}{2} E_p \sim 0.1 \frac{E_A}{A}$$

Neutrino energies at the source

pion & muon cooling in dense environments

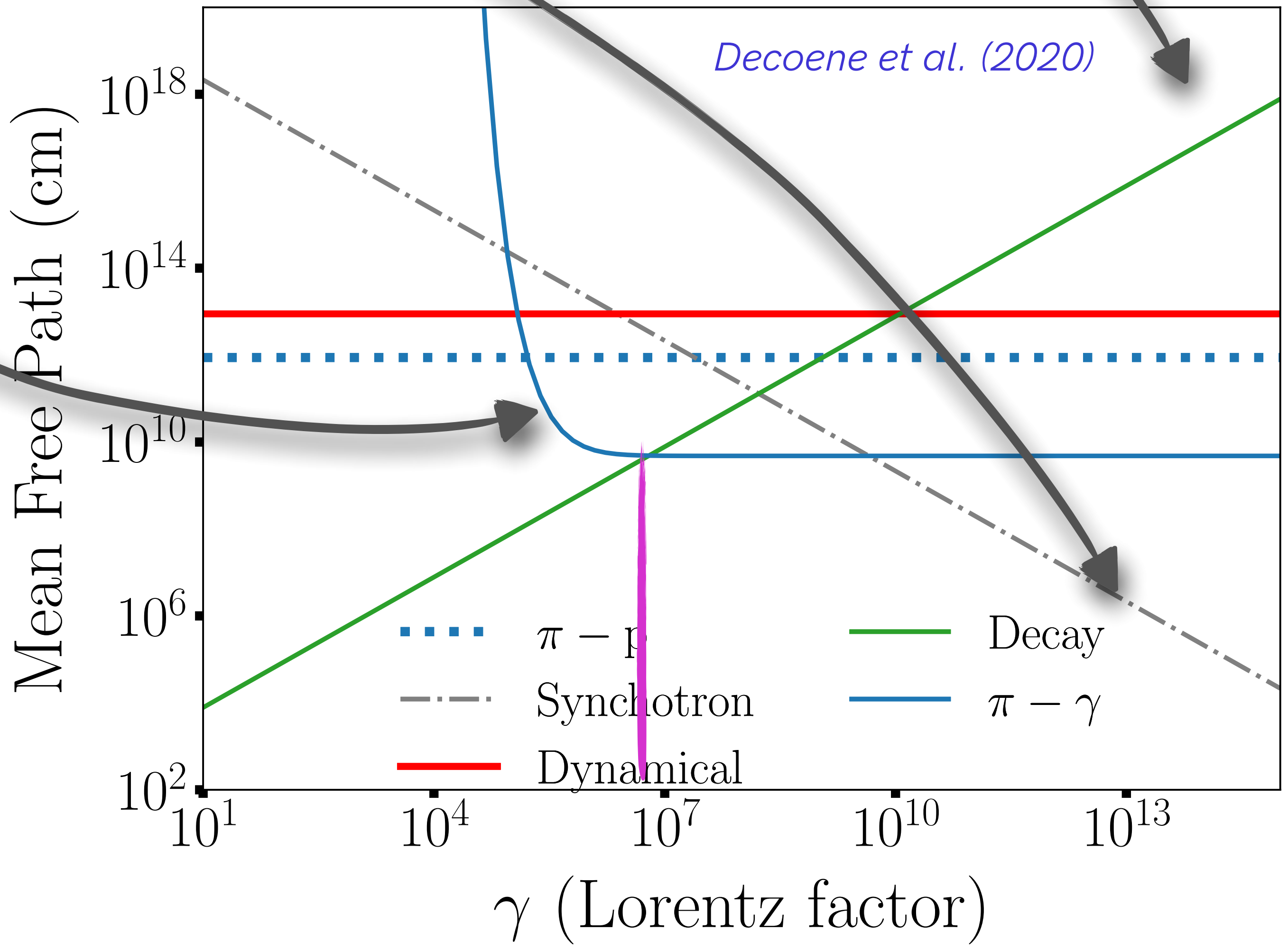
$$p + \gamma_{\mathrm{target}} \to n + \pi^+$$

$$\pi^+ \cancel{\to} \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

cascades
no HE ν

synchrotron cooling
no HE ν

$\pi^+ + \gamma \to \ldots$



Decoene et al. (2020)

Example: pions in a kilonova ejecta

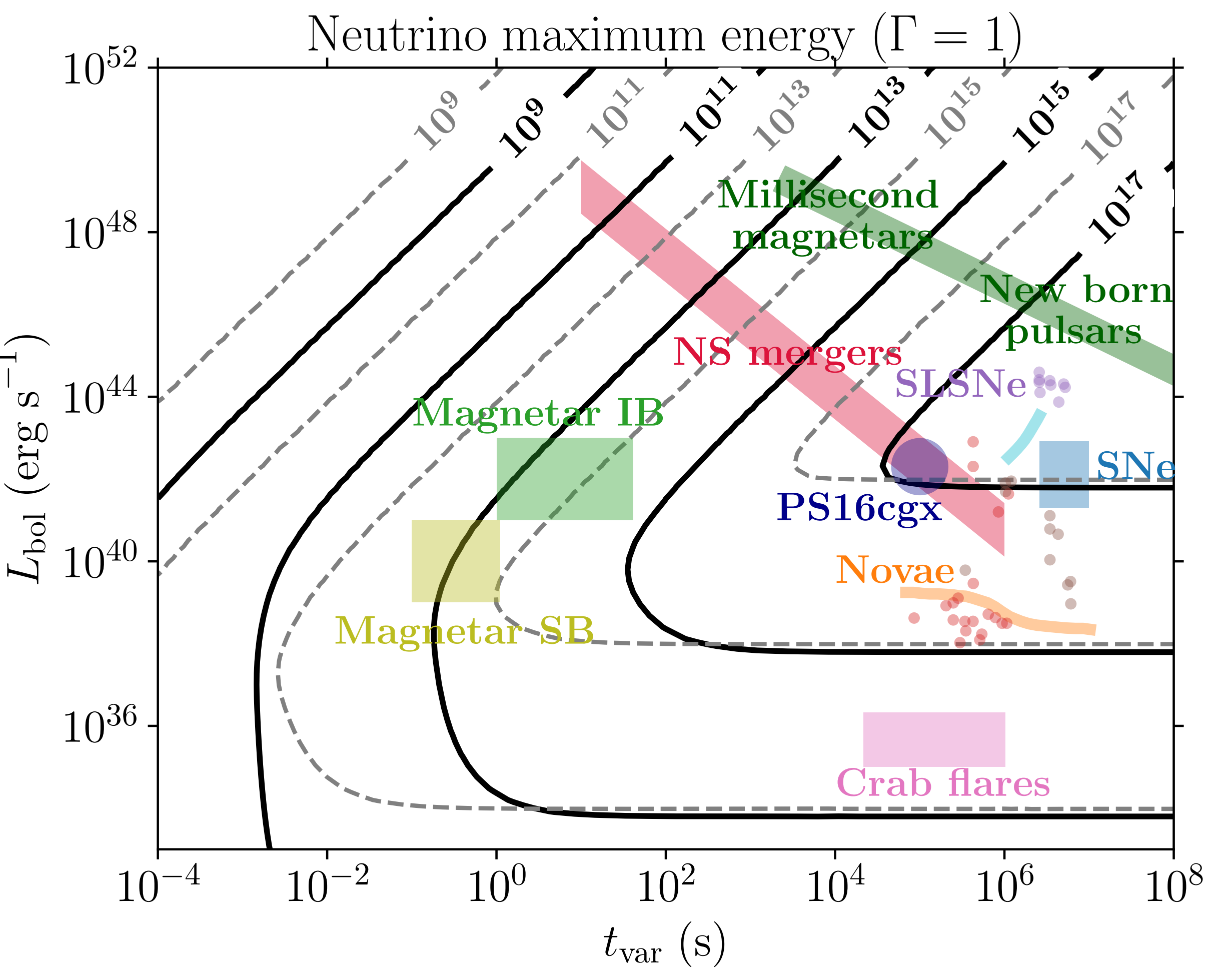
Maximum neutrino energy for transient sources

Guépin & KK (2017)
Guépin, KK, Oikonomou, Nat. subm.

$E_\nu \sim 0.05 E_p$ + taking into account possible pion and muon cooling

Bolometric luminosity $L_{\rm bol}$ related to magnetic field strength B (hence to $t_{\rm syn}$, $t_{\rm acc}$, $t_{\rm dyn}$)

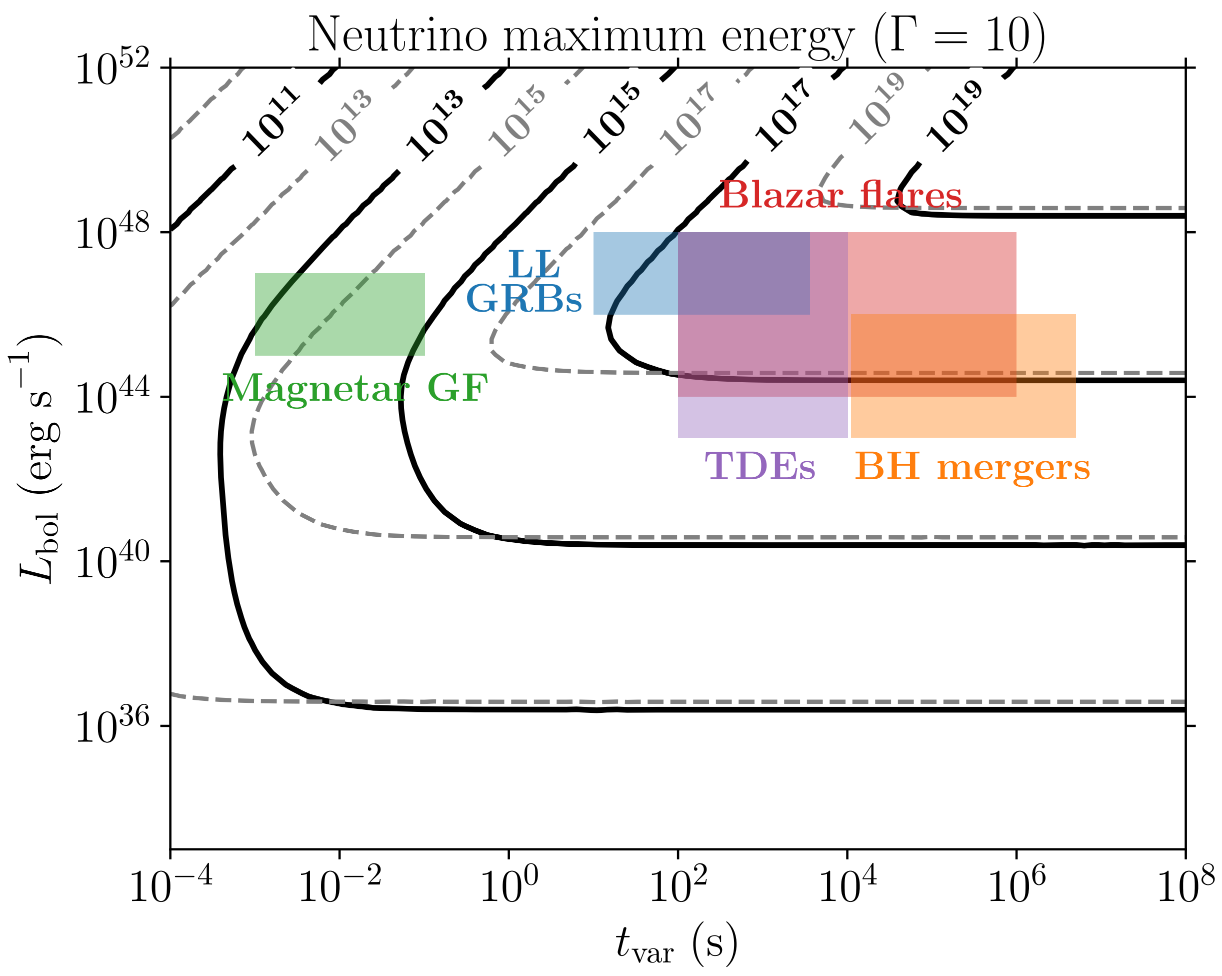
non-relativistic outflows



transient bolometric luminosity

transient variability timescale

mildly relativistic outflows



transient variability timescale

Simple estimates of secondary particle fluxes

photo-hadronic interactions

$$p + \gamma_{\text{target}} \to n + \pi^+$$

$$p + \gamma_{\text{target}} \to p + \pi^0$$

$$K_\pi = \frac{N_{\pi\pm}}{N_{\pi 0}} \sim 1$$

hadronic interactions

$$p + p_{\text{target}} \to N(\pi^0 + \pi^+ + \pi^-) + X$$

$$K_\pi = \frac{N_{\pi\pm}}{N_{\pi 0}} \sim 2$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \to \gamma + \gamma$$

$$E_\pi \sim \frac{1}{5} E_p$$

$$E_{\nu_\mu} \sim \frac{1}{4} E_\pi$$

$$E_\gamma \sim \frac{1}{2} E_\pi$$

$$f_{\text{mes}}\ ?$$

$p\gamma$

$$\begin{cases} E_\nu^2 \Phi_\nu \sim 3 \dfrac{K_\pi}{1 + K_\pi} \dfrac{1}{4} E_\pi^2 \Phi_\pi \sim \dfrac{3}{8} f_{\text{mes}}\, E_p^2 \Phi_p \\ E_\gamma^2 \Phi_\gamma \sim 2 \dfrac{1}{1 + K_\pi} \dfrac{1}{2} E_\pi^2 \Phi_\pi \sim \dfrac{1}{2} f_{\text{mes}}\, E_p^2 \Phi_p \end{cases}$$

(3 flavors)

$$E_\nu^2 \Phi_\nu \sim \frac{3}{4} E_\gamma^2 \Phi_\gamma$$

pp

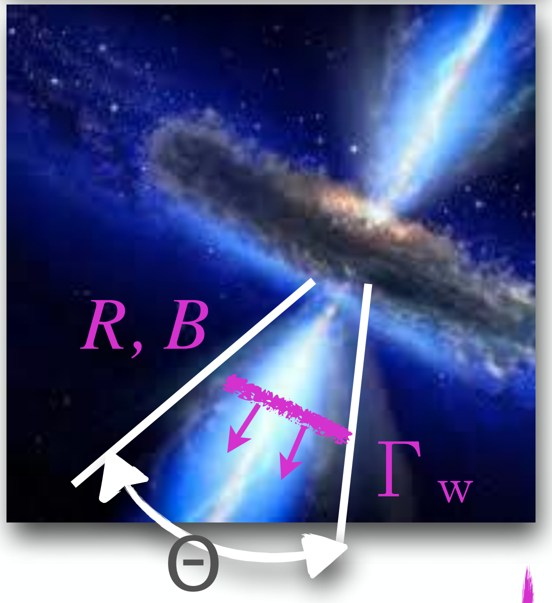
$$\begin{cases} E_\nu \Phi_\nu \sim 3 \dfrac{2}{3} \dfrac{1}{4} E_\pi^2 \Phi_\pi \sim \dfrac{1}{2} f_{\text{mes}}\, E_p^2 \Phi_p \\ E_\gamma^2 \Phi_\gamma \sim 2 \dfrac{1}{3} \dfrac{1}{2} E_\pi^2 \Phi_\pi \sim \dfrac{1}{3} f_{\text{mes}}\, E_p^2 \Phi_p \end{cases}$$

$$E_\nu^2 \Phi_\nu \sim \frac{3}{2} E_\gamma^2 \Phi_\gamma$$

Meson production rates

tip: *write all these timescales in the comoving frame (primed quantities)*

$$t_{\rm dyn} \sim R/\beta_{\rm W}\Gamma_{\rm W} c$$



examples:

synchrotron radiation in B

$$t'_{\rm syn} = \frac{3 m_{\rm p} c}{4 \sigma_{\rm T,p} U'_B} \frac{A^3}{Z^4} \frac{1}{\gamma'}$$

$U'_B = B'^2/8\pi$
magnetic energy density

inverse Compton

$$t'_{\rm min} = \min\left(t'_{\rm dyn}, t'_{\rm acc}, t'_{\rm loss}, t'_{\rm diff}, \ldots\right)$$

$$f_{\rm mes} = \frac{t'_{\rm min}}{t'_{p\gamma,pp}}$$

$$\begin{cases} t'^{-1}_{N\gamma} = \dfrac{c}{2\gamma'^2} \displaystyle\int_0^\infty \frac{d\epsilon'}{\epsilon'^2} \frac{dn'_\gamma}{d\epsilon'}(\epsilon') \int_0^{2\gamma'\epsilon'} d\bar{\epsilon}\, \bar{\epsilon}\, \sigma_{N\gamma}(\bar{\epsilon}) \\ t'^{-1}_{\rm pp} = n_p \sigma_{\rm pp}\, c \end{cases}$$

modeling according to theory+observations

Secondary spectra at the source

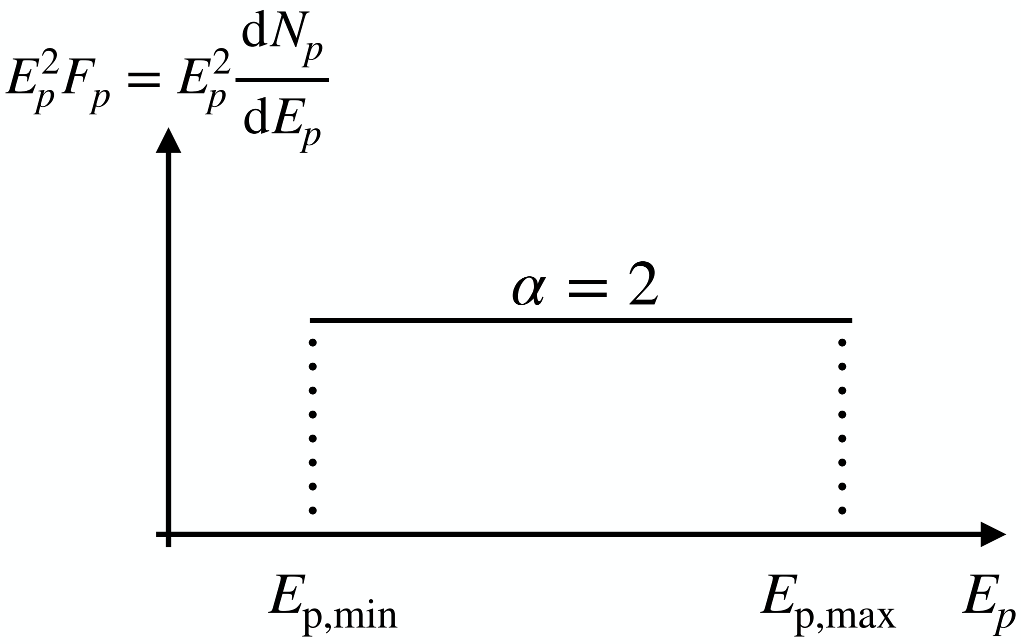
Cosmic-ray spectrum:

Assuming some acceleration mechanism

$$E_p^2 F_p = \frac{1}{4\pi D_{\rm L}^2}\,\frac{(2-\alpha)\eta_p L_{\rm bol}}{E_{p,\max}^{2-\alpha} - E_{p,\min}^{2-\alpha}}\,E_p^{2-\alpha} \qquad 1 \lesssim \alpha \lesssim 3$$

source distance

fraction of source bolometric luminosity



Photon spectrum: Broken power-law

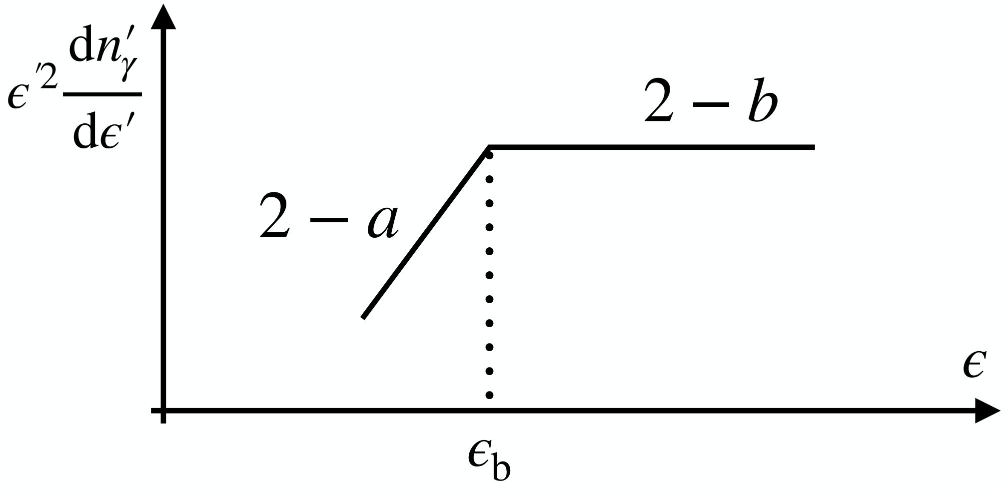
observed break energy

$$L_\gamma(\epsilon) = \epsilon^2 \frac{d\dot{N}_\gamma}{d\epsilon} = \begin{cases} L_{\rm b}\ (\epsilon/\epsilon_{\rm b})^{2-a} & \epsilon_{\min} \le \epsilon \le \epsilon_{\rm b}, \\ L_{\rm b}\ (\epsilon/\epsilon_{\rm b})^{2-b} & \epsilon_{\rm b} < \epsilon < \epsilon_{\max}\,. \end{cases}$$

ex: Prompt GRB gamma-ray spectrum (Band function)

In the comoving frame (primed quantities):

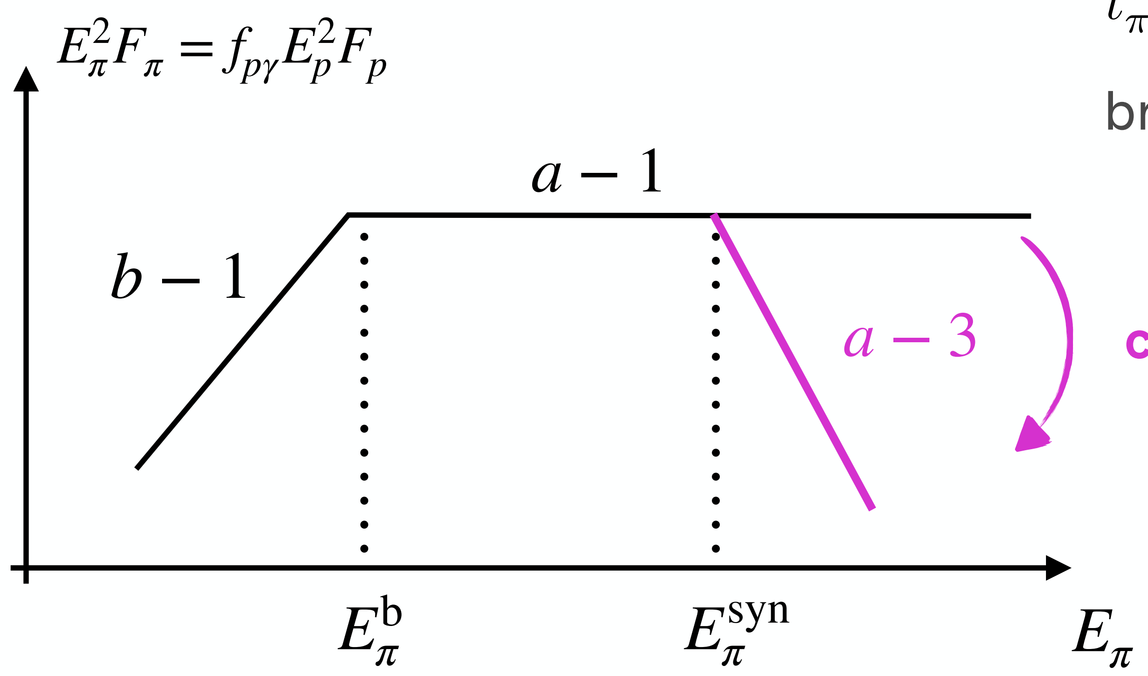
$$\frac{dn'_\gamma}{d\epsilon'}(\epsilon') = \frac{L'_{\rm b}}{4\pi R'^2 c\epsilon'^2_{\rm b}} \times \begin{cases} (\epsilon'/\epsilon'_{\rm b})^{-a} & \epsilon' < \epsilon'_{\rm b}\,, \\ (\epsilon'/\epsilon'_{\rm b})^{-b} & \epsilon' > \epsilon'_{\rm b}\,. \end{cases}$$



Secondary spectra at the source

Waxman & Bahcall, 1997

Meson spectrum



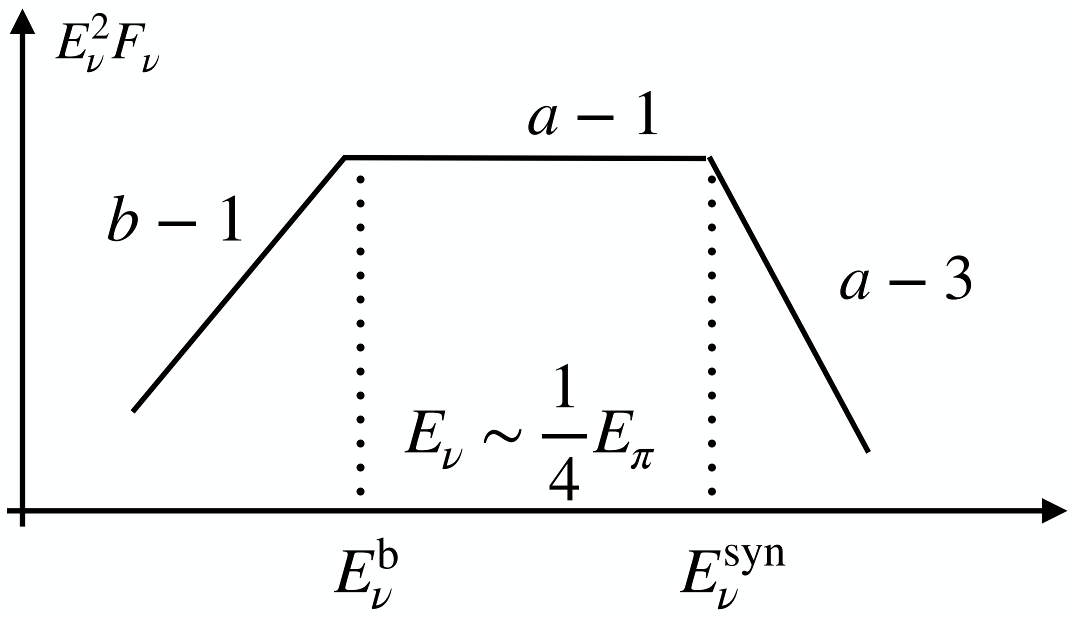
cooling of charged mesons

pion decay time:

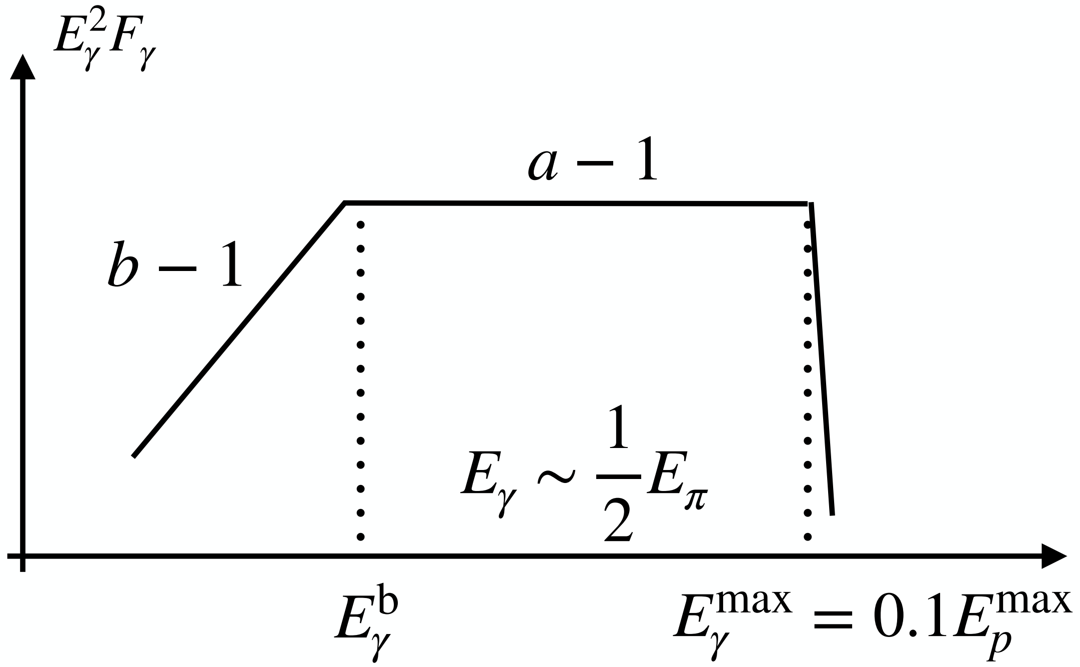
$$t'_\pi(E_\pi) = \tau_\pi E_\pi (1+z)((1+\beta)\Gamma m_\pi c^2)^{-1} \sim 0.9\,\mathrm{s}\,E_{\pi,18}\,\Gamma_2^{-1}$$

break energy: $E_\pi^{\mathrm{b}} \sim 0.07\,\mathrm{GeV}^2\Gamma^2/\epsilon_{\mathrm{b}}$

Neutrino spectrum



Gamma-ray spectrum



Computing secondary fluxes at the source: key points

mechanisms:
shock acceleration
magnetic reconnection…

at various locations:
inner/external/side jet
wind
accretion disk…

—> max. acceleration energy spectrum

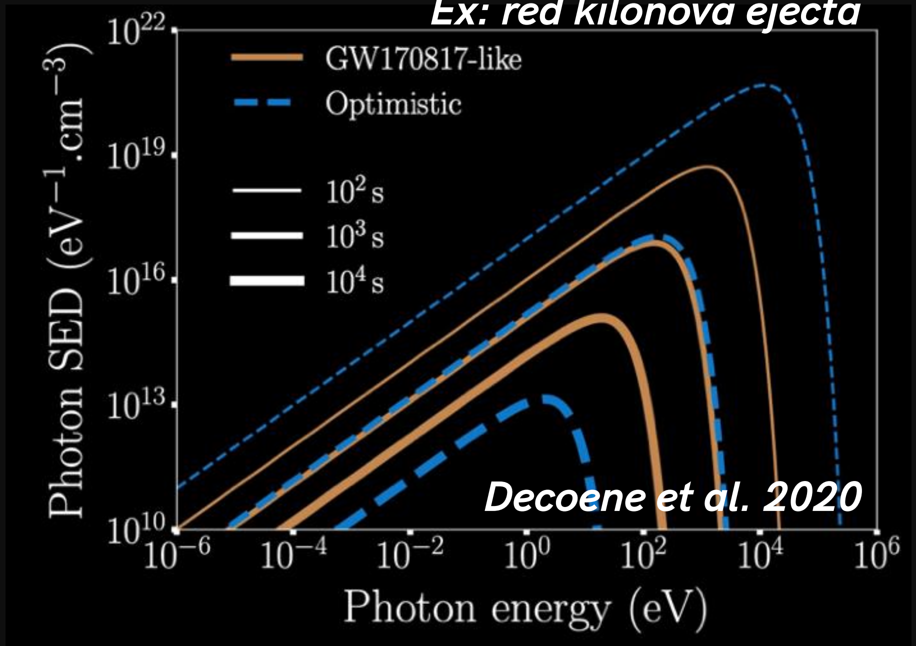
Cosmic-ray acceleration

Cosmic-ray interactions + cooling
Secondary particle cooling

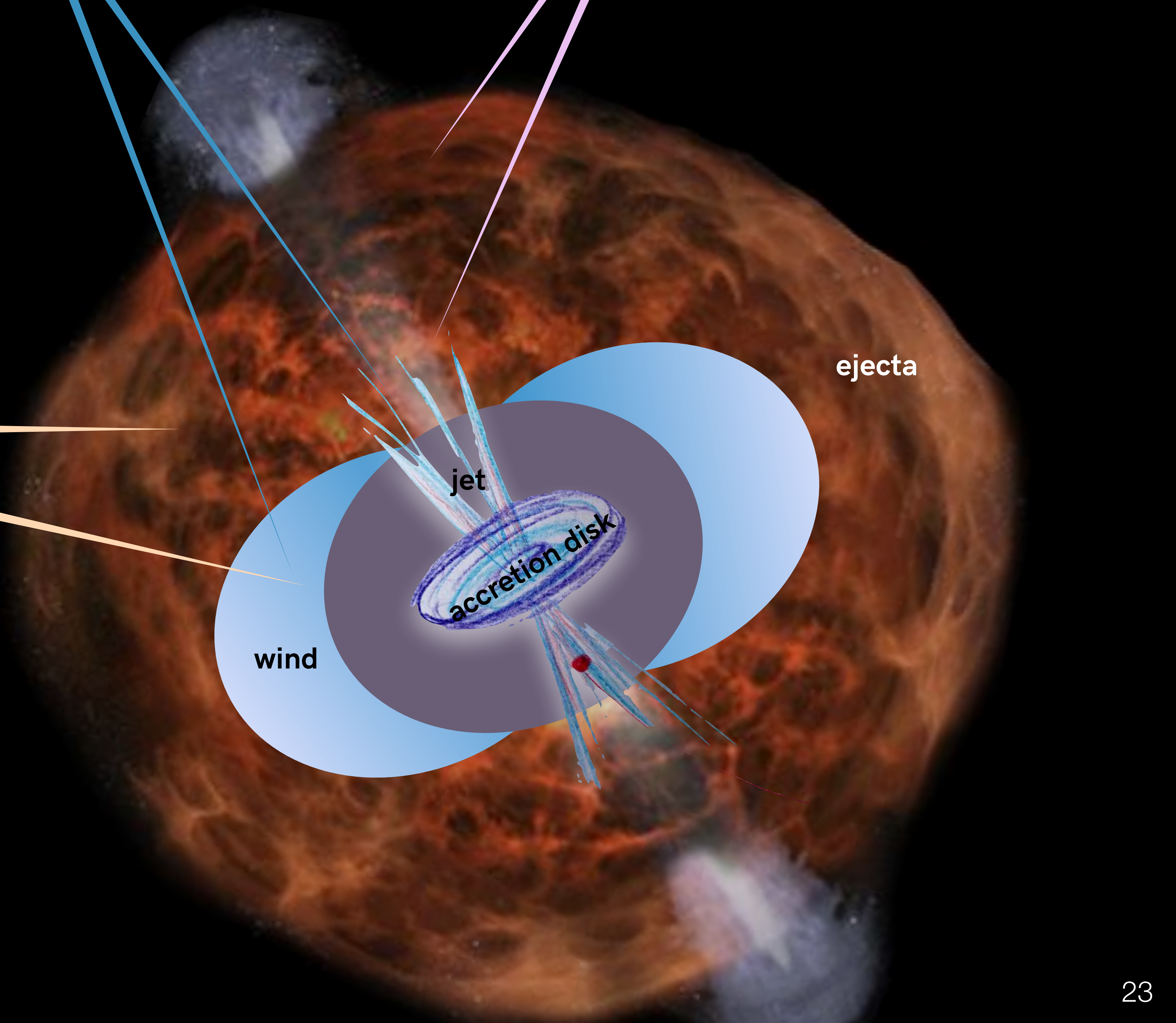
Radiative + hadronic backgrounds

density, spectra, time evolution
in acceleration region and beyond

Ex: red kilonova ejecta



Decoene et al. 2020



Integrating over source population

primed quantities in comoving frame

$$\Phi_\nu(E_\nu) = \frac{f_{\rm s}}{4\pi} \int_0^{z_{\rm max}} \int_0^{t_\nu} \frac{{\rm d}N_\nu[E_\nu(1+z)]}{{\rm d}t'\,{\rm d}E_\nu\, 4\pi D'^2} {\rm d}t'\, \Re(z)\, 4\pi D'^2 \frac{{\rm d}D'}{{\rm d}z}\,{\rm d}z$$

normalization
factor to fit UHECR
spectrum if related

comoving
distance

$N_\nu[E_\nu(1+z)]$
total number
of neutrinos
produced by
1 source

$$\dot{\Re}(z) = g(z)\dot{\Re}(0)$$

comoving source emissivity in Mpc^{-3} yr^{-1}

$g(z)$ = redshift evolution rate

for uniform evolution $g(z) = 1$

for star formation rate (SFR) evolution

$$g(z) = \begin{cases} (1+z)^{3.4}, & z < 1 \\ N_1(1+z)^{-0.3}, & 1 < z < 4 \\ N_1N_4(1+z)^{-3.5}, & z > 4 \end{cases}$$

$$\Phi_\nu(E_\nu) = f_{\rm s}\, \frac{c}{4\pi} \int_0^{z_{\rm max}} \dot{\Re}(z) \frac{{\rm d}N_\nu[E_\nu(1+z)]}{dE'}(1+z)\frac{dt}{dz}dz$$

$E' = E_\nu(1+z)$
comoving energy

$$dt/dz = 1/\left(H_0(1+z)\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}\right)$$

Waxman-Bahcall "limit"

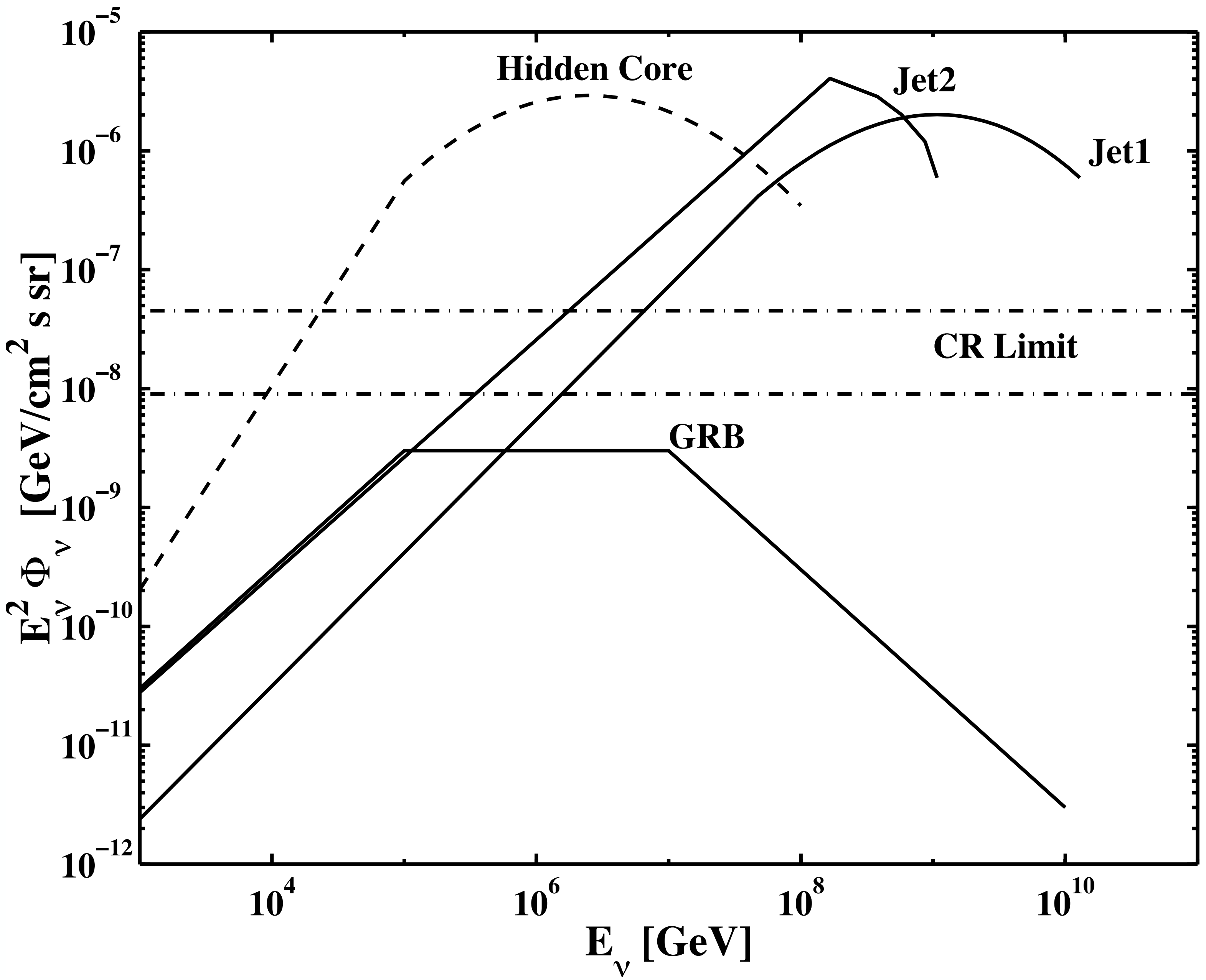
Waxman & Bahcall, 1997

redshift energy loss
of neutrinos ~1

$$E_\nu^2\Phi_\nu \sim \xi_z t_H \frac{c}{4\pi}\frac{3}{8} f_{\mathrm{mes}} E_{\mathrm{CR}}^2\Phi_{\mathrm{CR}}$$

$$E_\nu^2\Phi_\nu \sim 1.5\times10^{-8}\xi_z f_{\mathrm{mes}}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

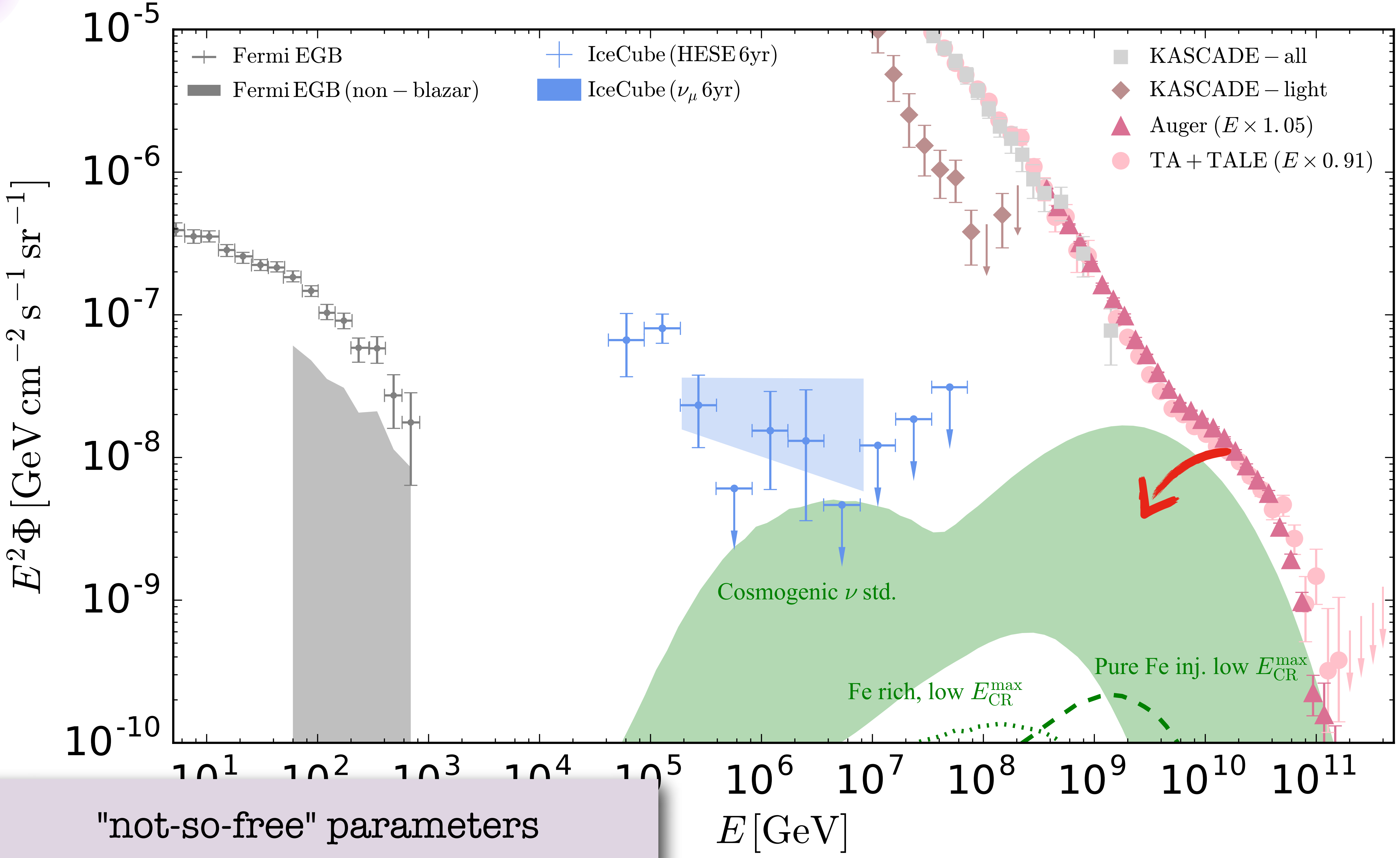
$$\Phi_{\nu_e} \approx \Phi_{\bar{\nu}_\mu} \approx \Phi_{\nu_\mu}$$



2. Tools for multi-messenger astrophysics

Cosmogenic neutrinos

The guaranteed cosmogenic neutrinos



K. Fang

"not-so-free" parameters

- A flux normalisation
- γ injection spectral index
- R_{max} (max. rigidity ~ max. p energy)
- composition
- source evolution history

cosmogenic neutrinos guaranteed
if sources of UHECRs
@cosmological distances

Cosmogenic neutrinos: production channels

$$p + \gamma_{\mathrm{target}} \rightarrow n + \pi^{+}$$

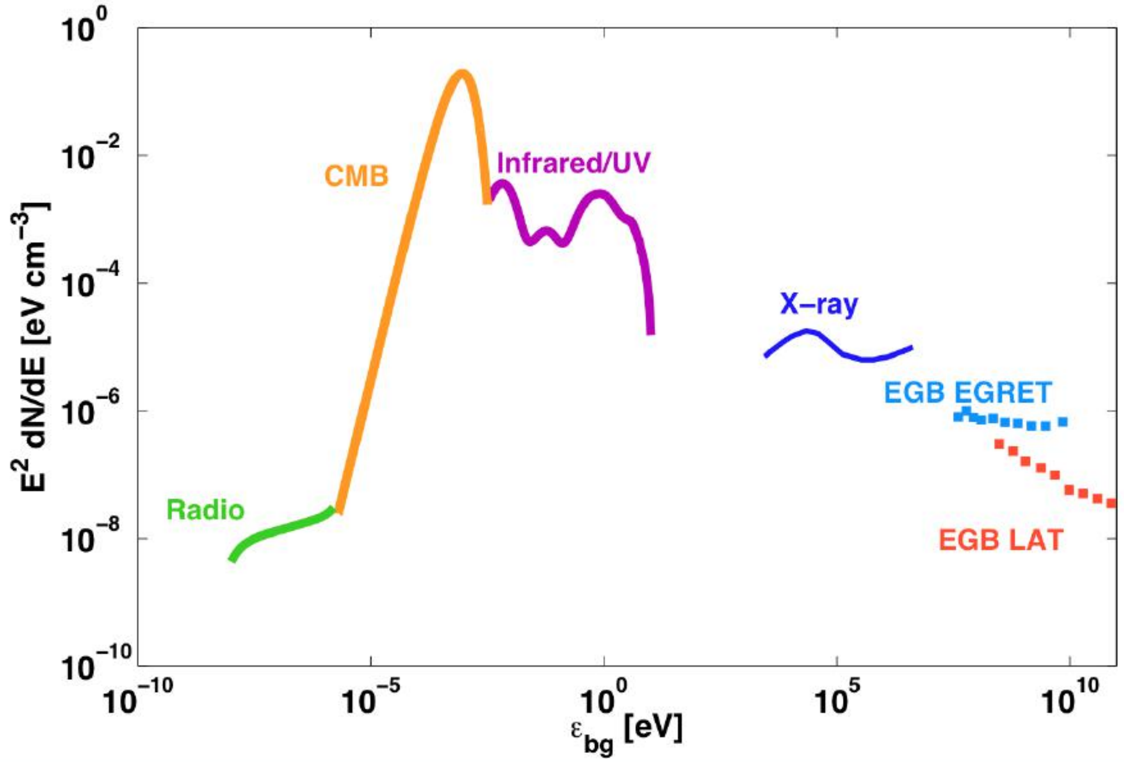
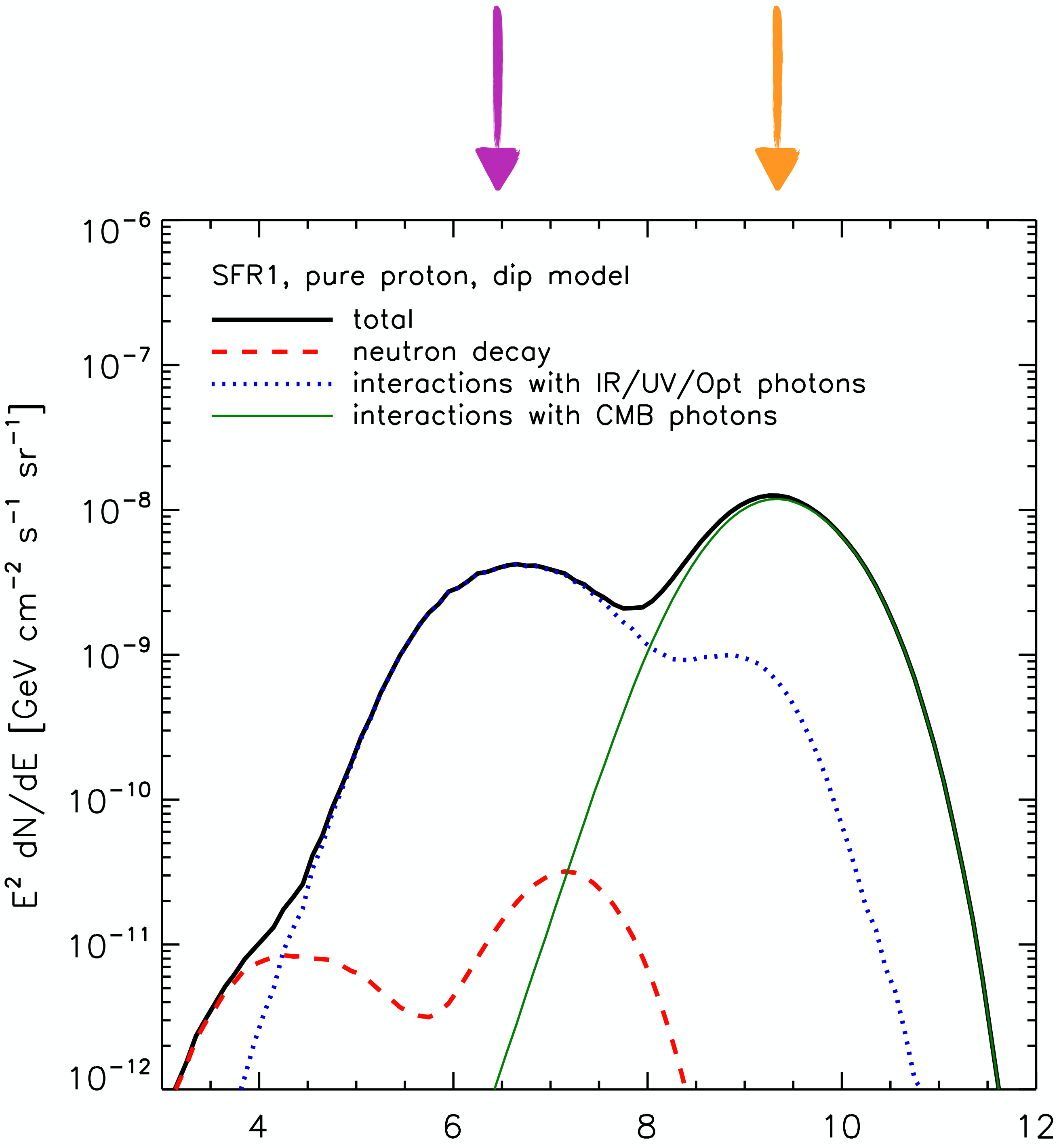


Figure 2.1. The spectrum of cosmic background radiations. The CMB is modelled as a blackbody spectrum at 2.725 K. The IR and UV backgrounds are from the work of Kneiske & Dole (2008). The extragalactic gamma-ray background datapoints (EGB) are from EGRET measurements (Sreekumar et al. 1998) and *Fermi*-LAT measurements (Abdo et al. 2010). For the X-ray and radio backgrounds the models presented in the works of Fabian & Barcons (1992), Clark et al. (1970) are shown respectively.

F. Oikonomou, PhD, 2014



KK, Allard, Olinto 2010

Cosmogenic neutrinos: principal ingredients

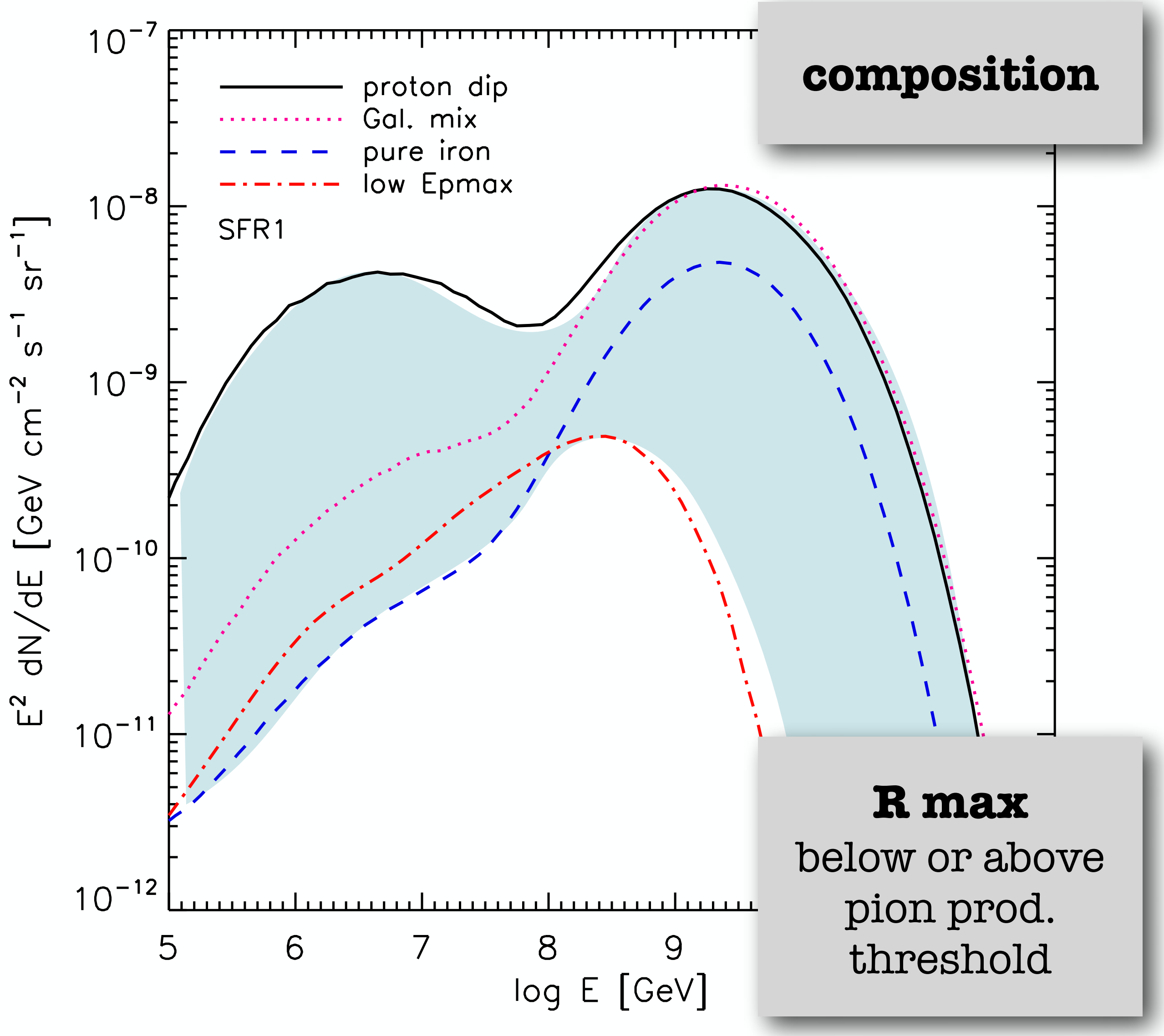
KK, Allard, Olinto 2010

"not-so-free" parameters

- *A* flux normalisation
- χ injection spectral index
- $R_{\max}$ (max. rigidity ~ max. p energy)
- composition
- source evolution history

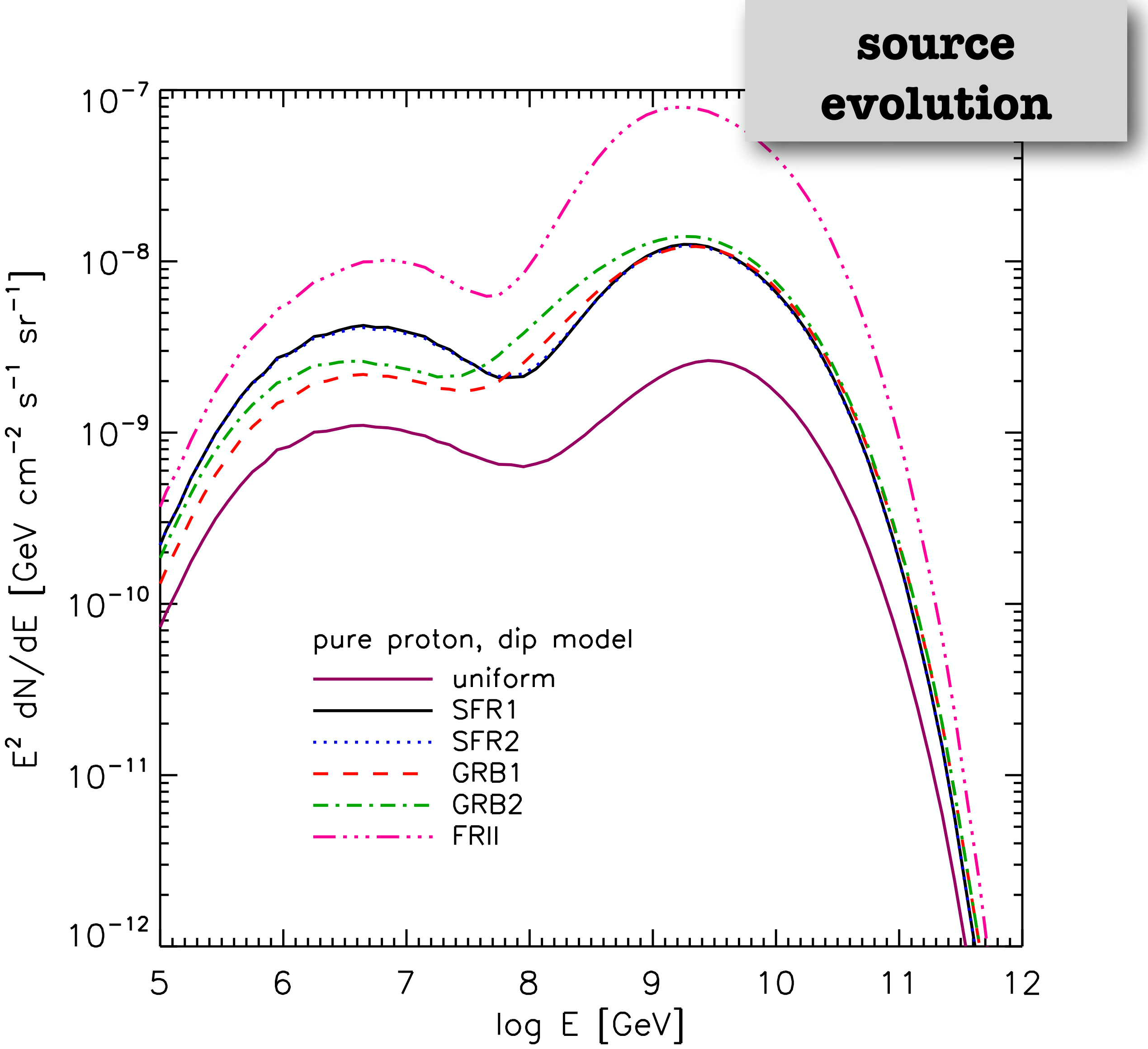
▶ depend strongly on observations of UHECRs

▶ less dependent but affects injection spectrum



composition

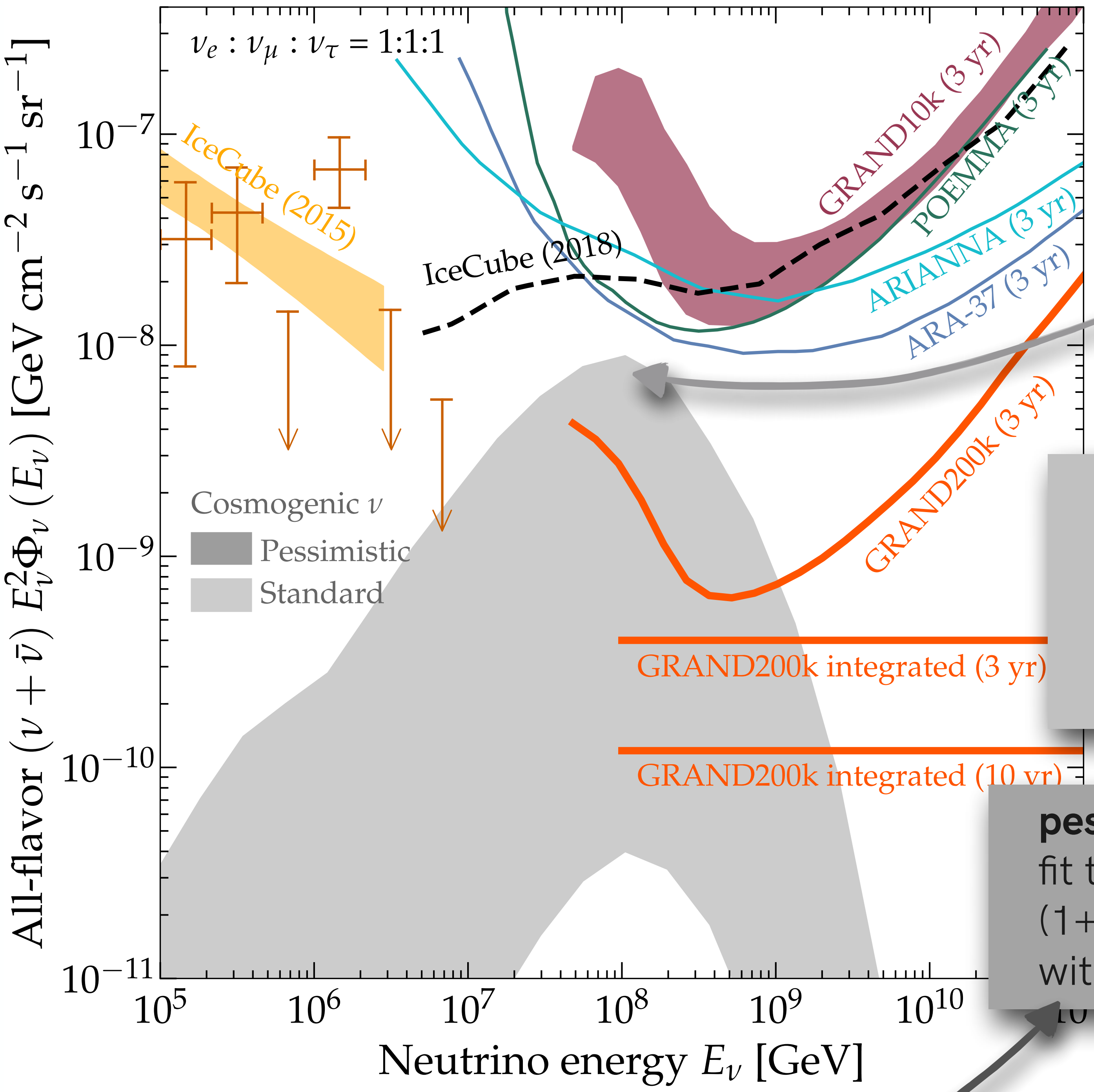
R max
below or above pion prod. threshold



source evolution

Learning from secondary neutrinos?

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010
Van Vliet et al. arXiv:1707.04511



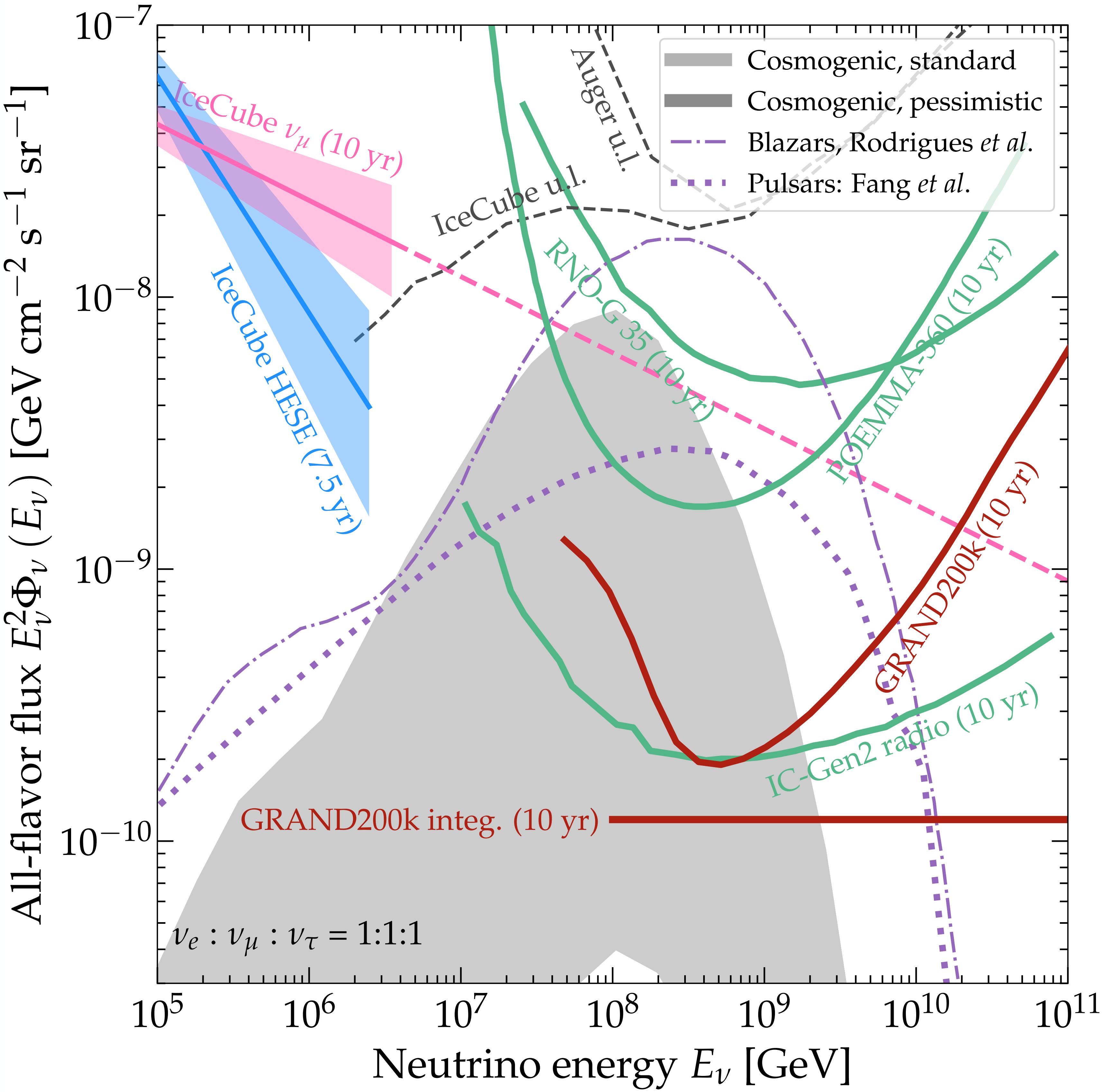
second minimum of
Auger combined fit

standard
fit to Auger
among generic SFR,
AGN, GRB source
evolutions, z_{max}=6

pessimistic
fit to Auger data with
$(1+z)^m$ source evolution
with m < 0

most pessimistic!
adding IGMF —> harder α —> increases neutrino flux
alleviating simplifying assumption —> increases neutrino flux

Diffuse astrophysical & cosmogenic fluxes



courtesy M. Bustamante

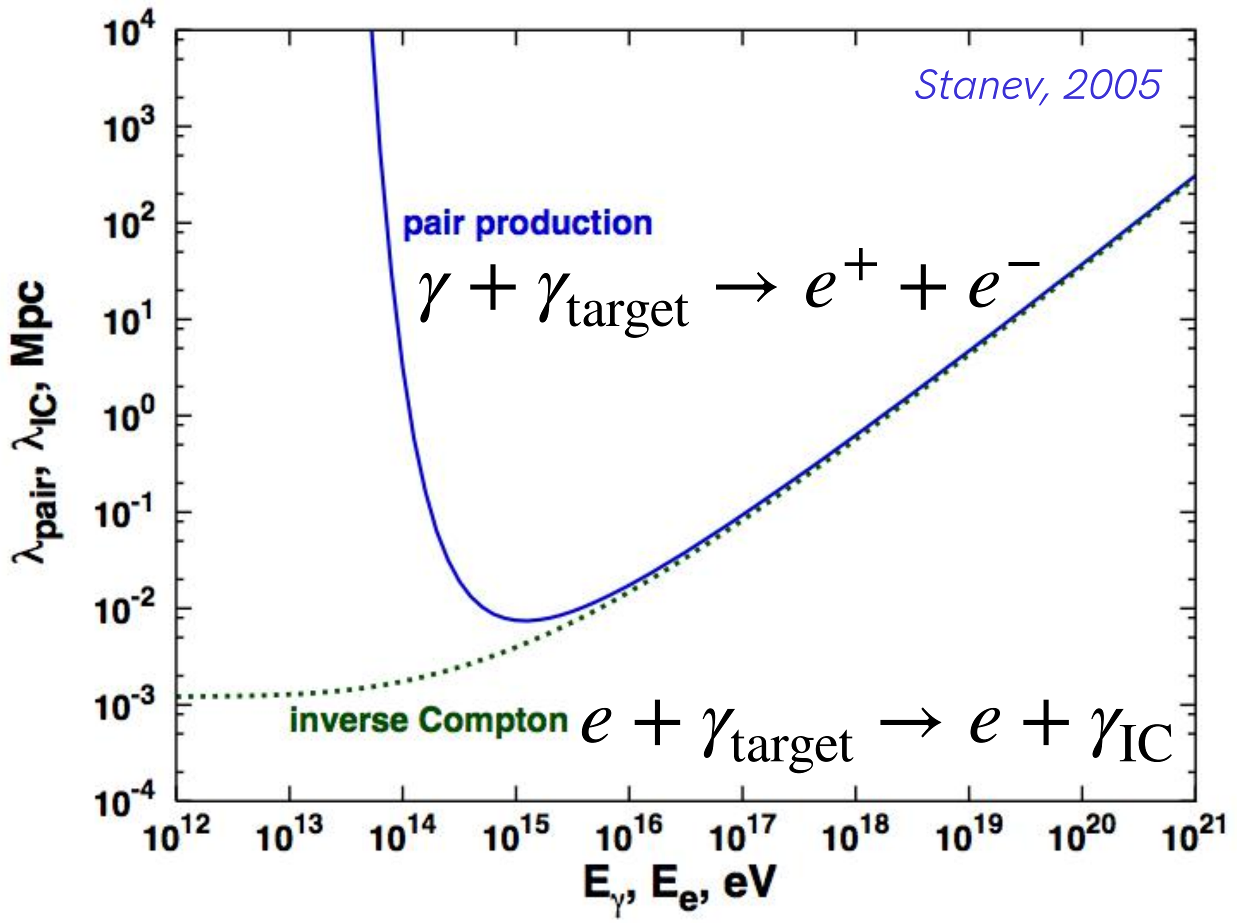
2. Tools for multi-messenger astrophysics

Specificities of gamma rays

Gamma-ray cascades

$p + \gamma_{\mathrm{target}} \to \gamma, e^{\pm}, \ldots$

$\gamma \to e \to \gamma \to e\ldots$



Stanev, 2005

pair production cross-section

$$\sigma_{\gamma\gamma}(s) = \frac{\pi r_e^2}{2}\left(1-\beta_{\mathrm{cm}}^2\right)\left[\left(3-\beta_{\mathrm{cm}}^4\right)\ln\left(\frac{1+\beta_{\mathrm{cm}}}{1-\beta_{\mathrm{cm}}}\right) - 2\beta_{\mathrm{cm}}\left(2-\beta_{\mathrm{cm}}^2\right)\right]$$

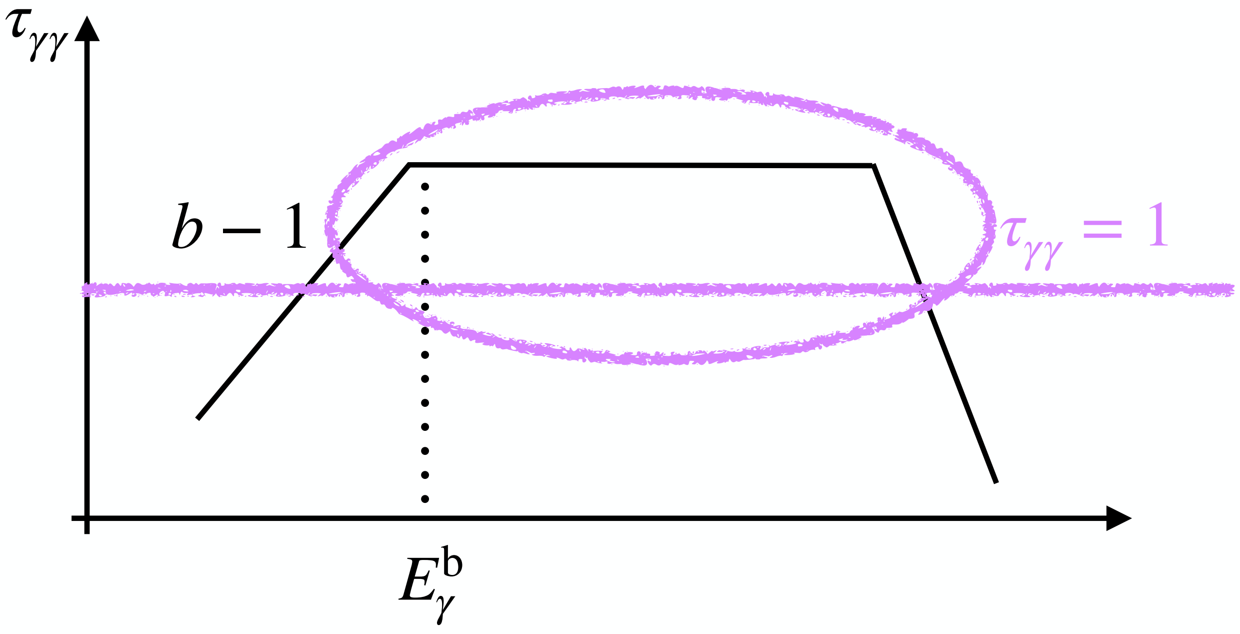
gamma-ray absorption probability per unit length

$$\frac{\mathrm{d}\tau_{\gamma\gamma}}{\mathrm{d}x}(\epsilon_\gamma) = \frac{2}{\epsilon_\gamma^2}\int_{1/\epsilon_\gamma}^{\infty}\frac{\mathrm{d}\epsilon}{\epsilon^2}\frac{\mathrm{d}n_\gamma}{\mathrm{d}\epsilon}(\epsilon)\int_1^{\epsilon\epsilon_\gamma}\mathrm{d}s\, s\,\sigma_{\gamma\gamma}(s)$$

attenuation of intrinsic gamma-ray spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}E}_{\mathrm{observed}} = \frac{\mathrm{d}N}{\mathrm{d}E}_{\mathrm{intrinsic}} \cdot e^{-\tau(E,z)}$$

Gamma-ray attenuation at the source



these gamma rays cannot escape the source

Gamma-ray opacity $\tau_{\gamma\gamma}$ related to f_{mes}

$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_{\mathrm{mes}}$$

$\uparrow$

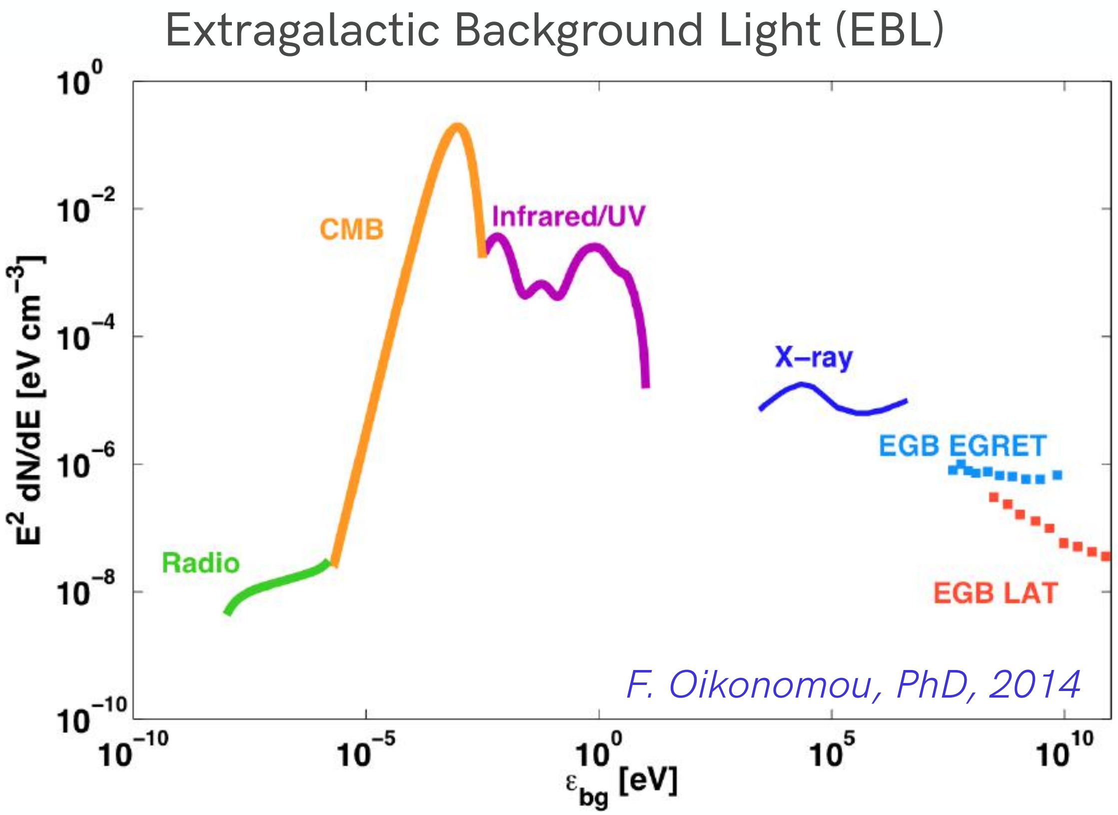
$\sigma_{p\gamma}\kappa_{p\gamma}$

η factor depending on photon spectral slope

Murase et al., 2016

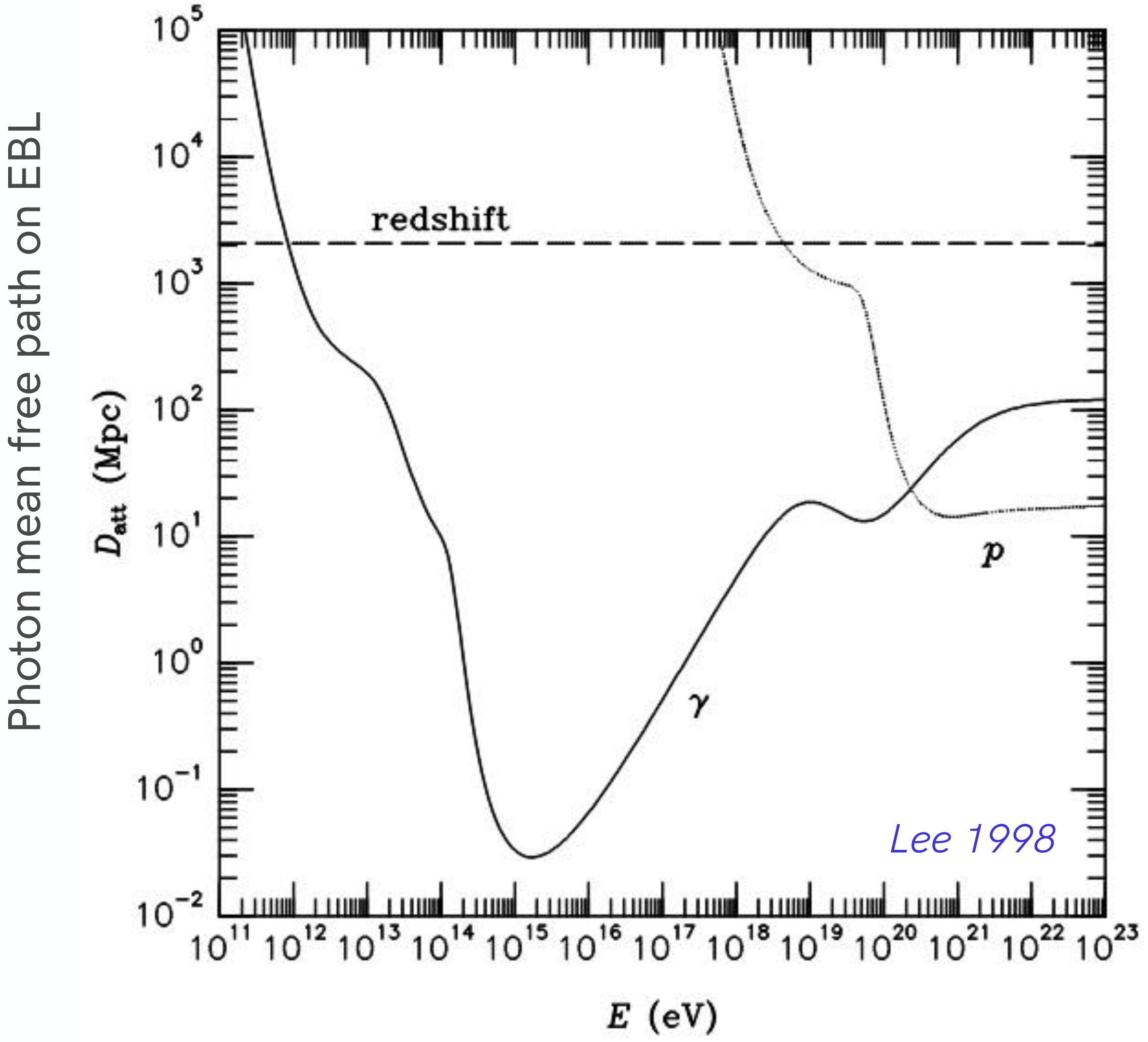
Gamma-ray cascades in the EBL

$$\frac{\mathrm{d}N}{\mathrm{d}E}_{\mathrm{observed}} = \frac{\mathrm{d}N}{\mathrm{d}E}_{\mathrm{intrinsic}} \cdot e^{-\tau(E,z)}$$

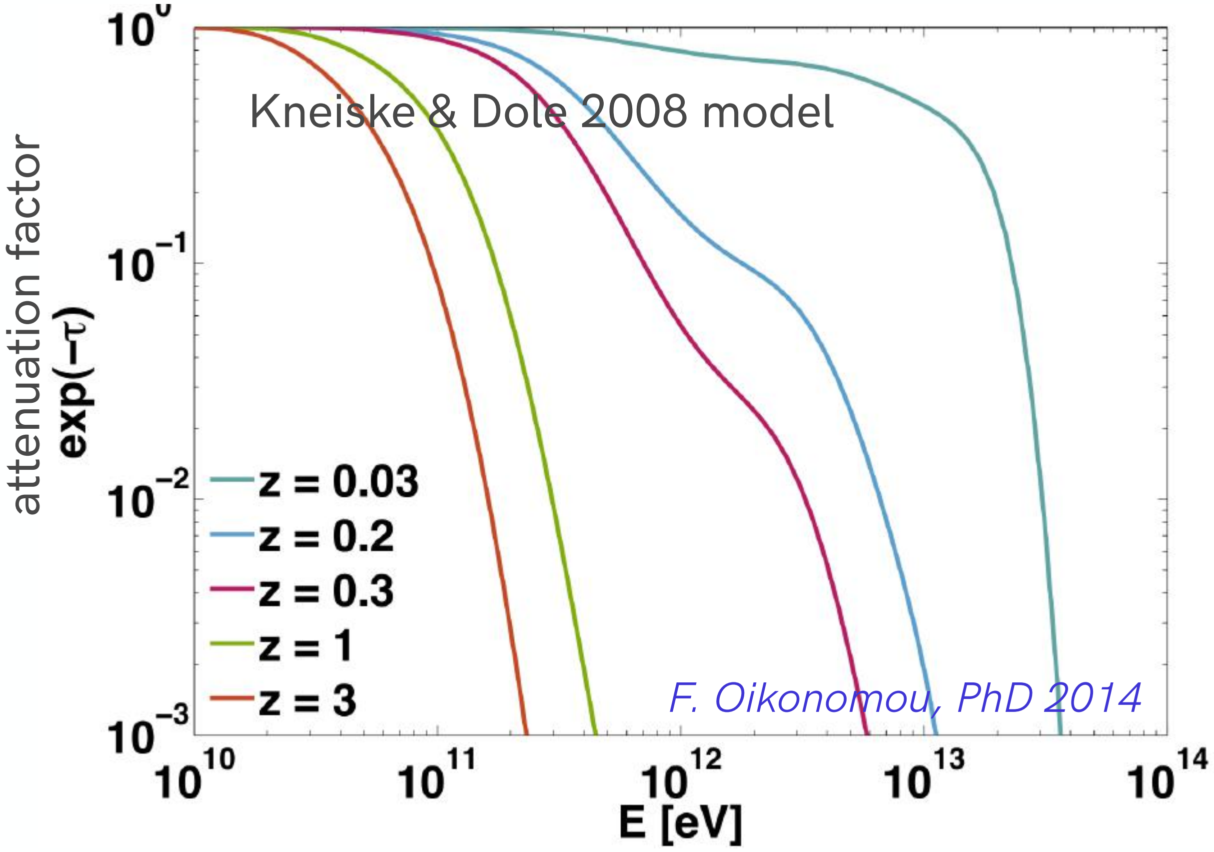


Extragalactic Background Light (EBL)

F. Oikonomou, PhD, 2014

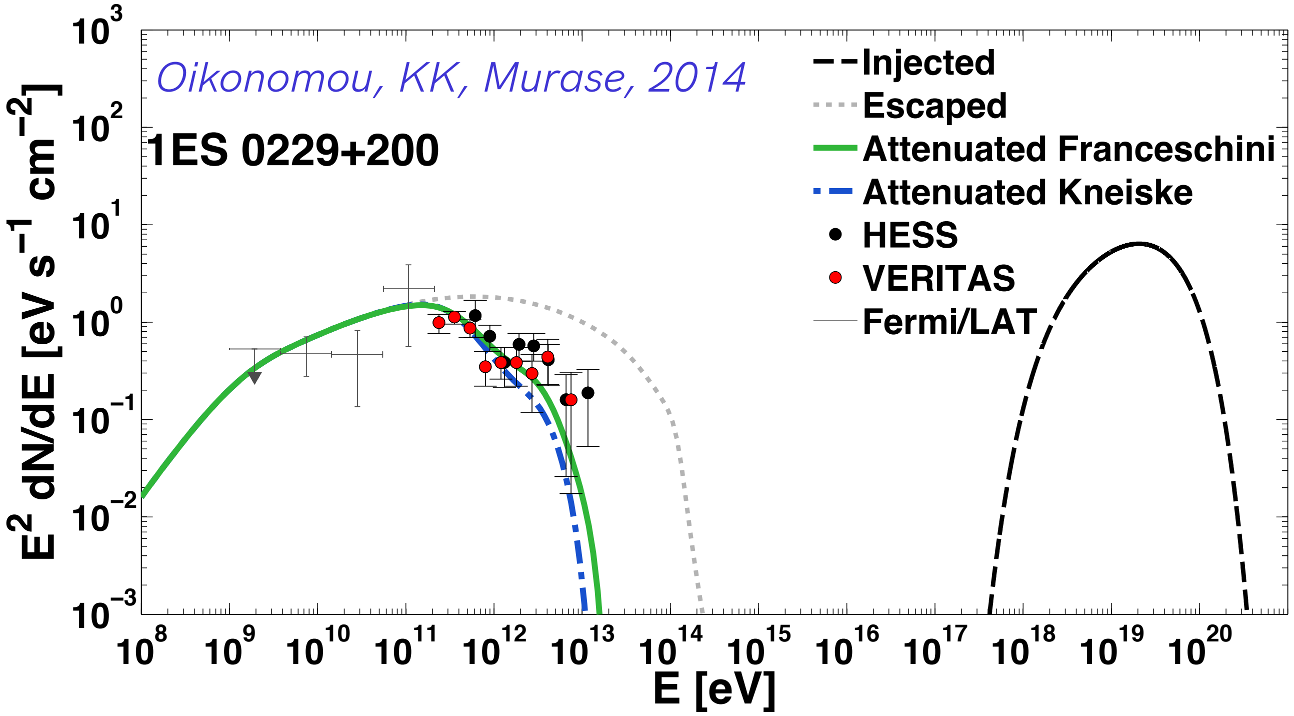


Lee 1998



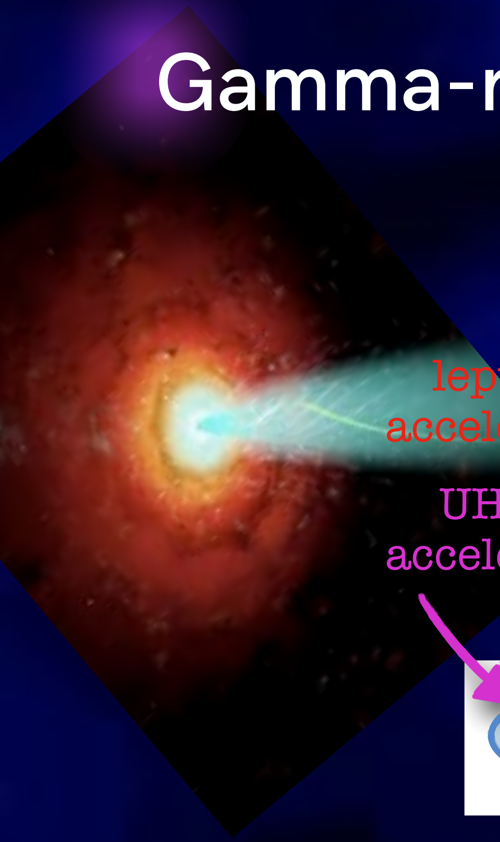
Kneiske & Dole 2008 model

F. Oikonomou, PhD 2014



Oikonomou, KK, Murase, 2014

Gamma-ray propagation in the intergalactic medium



leptonic acceleration

UHECR acceleration

Cascade in IGM

e.g., Aharonian et al. 94,, 06,
Coppi & Aharonian 97, Tavecchio et al. 11...

$\gamma\gamma_{\rm bg} \to \boxed{e^+e^-} \longrightarrow e\,\gamma_{\rm bg} \to e\,\gamma \longrightarrow \;\ldots\; \gamma_{\rm TeV\text{-}GeV}$

pair production

Inverse Compton

no more interactions

interactions with Extragalactic Background Light (EBL)

$\boxed{\rm UHECR} + \gamma_{\rm bg} \longrightarrow \boxed{e^{\pm},\ \gamma_{\rm UHE}}$

interactions with CMB/IR photons

Essey & Kusenko 10, 13,
Essey et al. 10, 11,
Murase et al. 12, Takami et al. 13

deflections
dilution of signal

Cosmic Magnetic fields

homogeneous B: flux completely diluted if $B_{\rm IGM} > 3\times10^{-11}$G

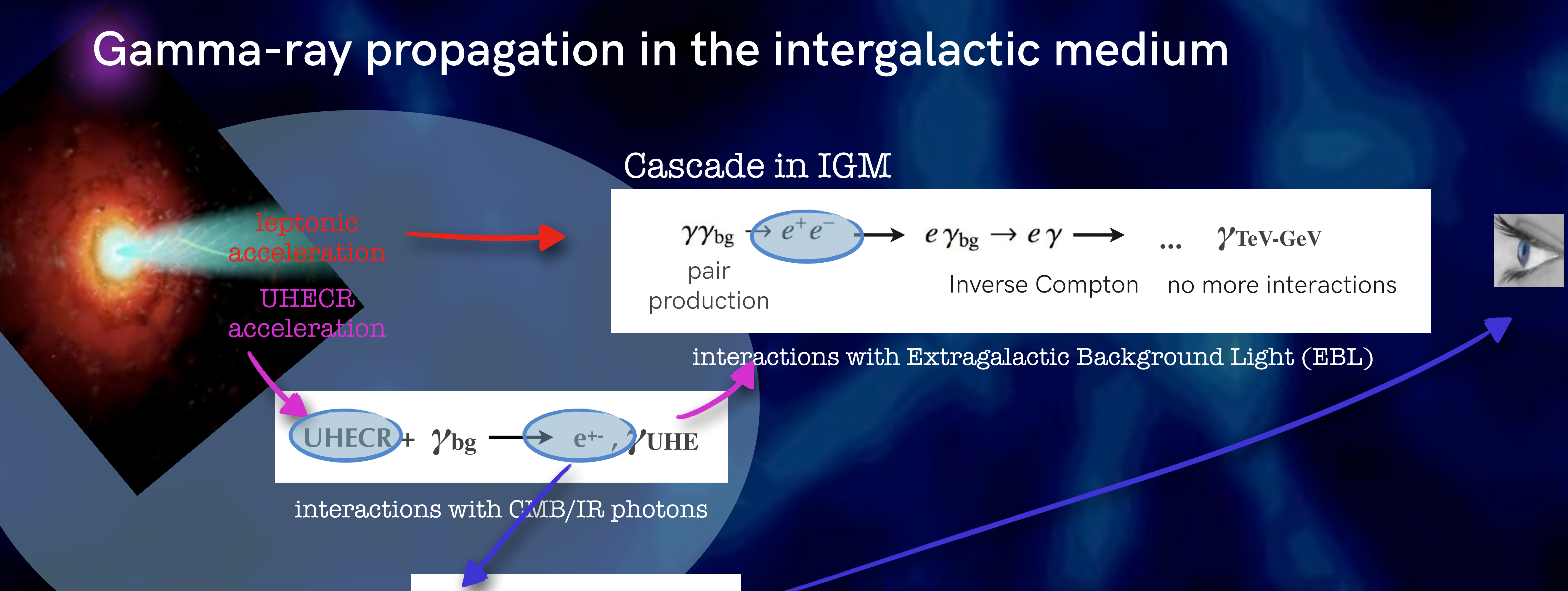
Protheroe 86, Protheroe & Stanev 93, Aharonian et al. 94

inhomogeneous B: flux dilution according to fraction of Universe where $B_{\rm IGM} > 3\times10^{-11}$G

$$E_\gamma^2 \frac{{\rm d}N_\gamma}{{\rm d}E_\gamma} \approx \boxed{f_{\rm 1d}(< B_\theta)}\,\chi_e \frac{L_{\rm cr}}{8\pi d^2}\left(\frac{E_\gamma}{E_{\gamma,\max}}\right)^{1/2}$$

K.K., Allard & Lemoine 2010

Gamma-ray propagation in the intergalactic medium



leptonic acceleration

UHECR acceleration

Cascade in IGM

$\gamma\gamma_{bg} \to e^+e^- \to e\,\gamma_{bg} \to e\,\gamma \to \;\dots\; \gamma_{\text{TeV-GeV}}$

pair production

Inverse Compton

no more interactions

interactions with Extragalactic Background Light (EBL)

$\text{UHECR} + \gamma_{bg} \to e^{+-},\ \gamma_{\text{UHE}}$

interactions with CMB/IR photons

$e^{+-} \to \gamma_{\text{GeV}}$

no more interactions

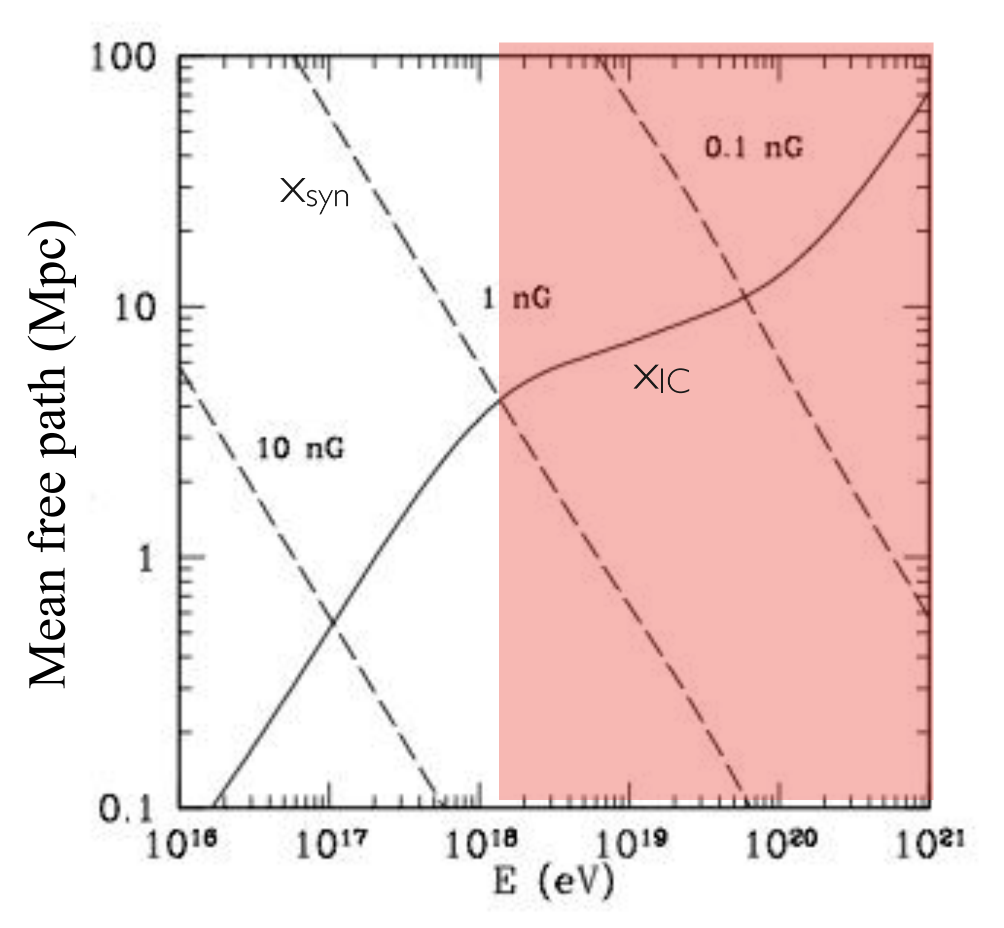
magnetized filament

Synchrotron on B

NB: Confined UHECRs should produce UHE neutrals (e.g, photons) at source *(Murase 2009, Murase 2012, Dermer et al. 2012)*

guaranteed if $x_{syn} > x_{IC}$

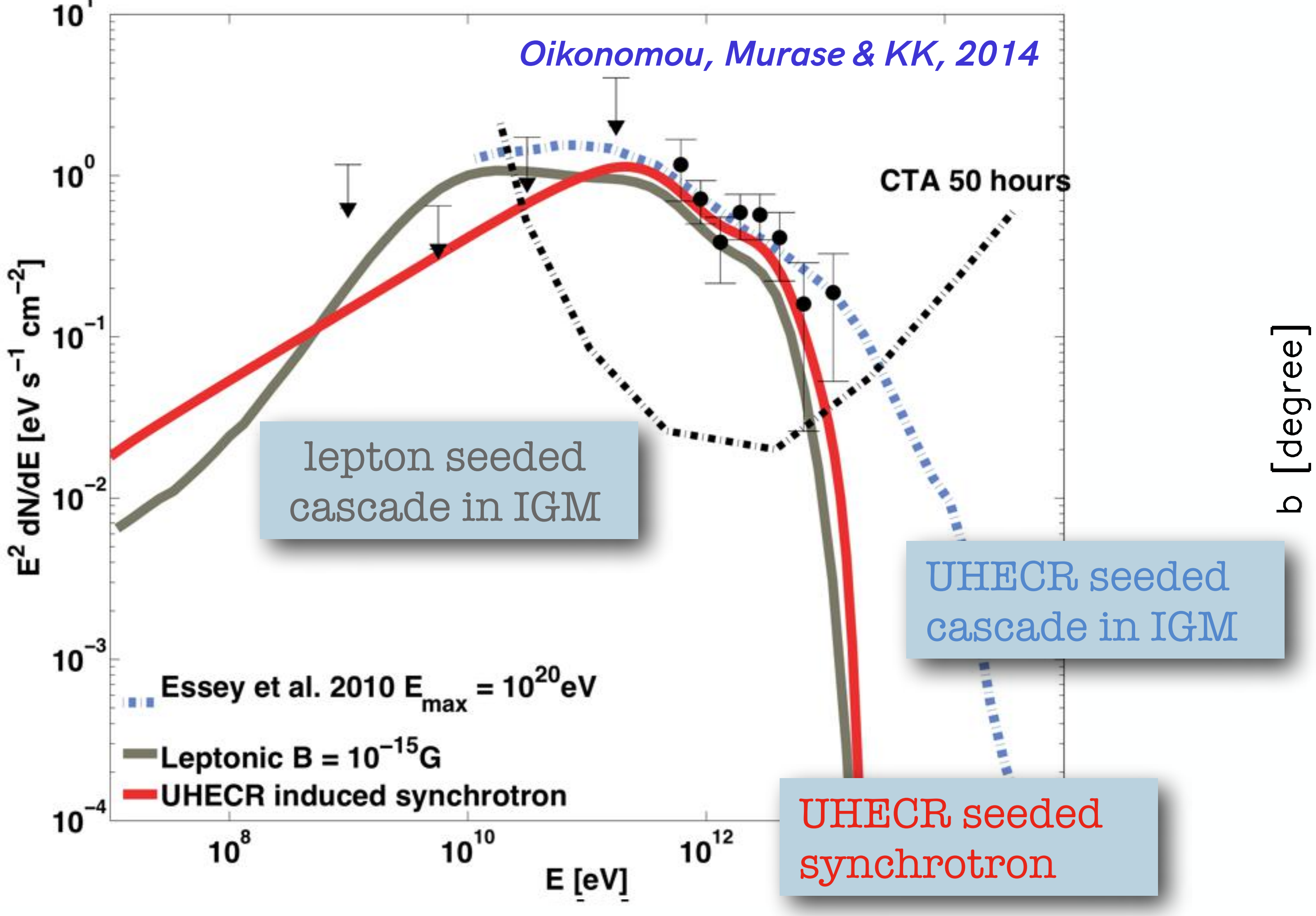
Gabici & Aharonian 06



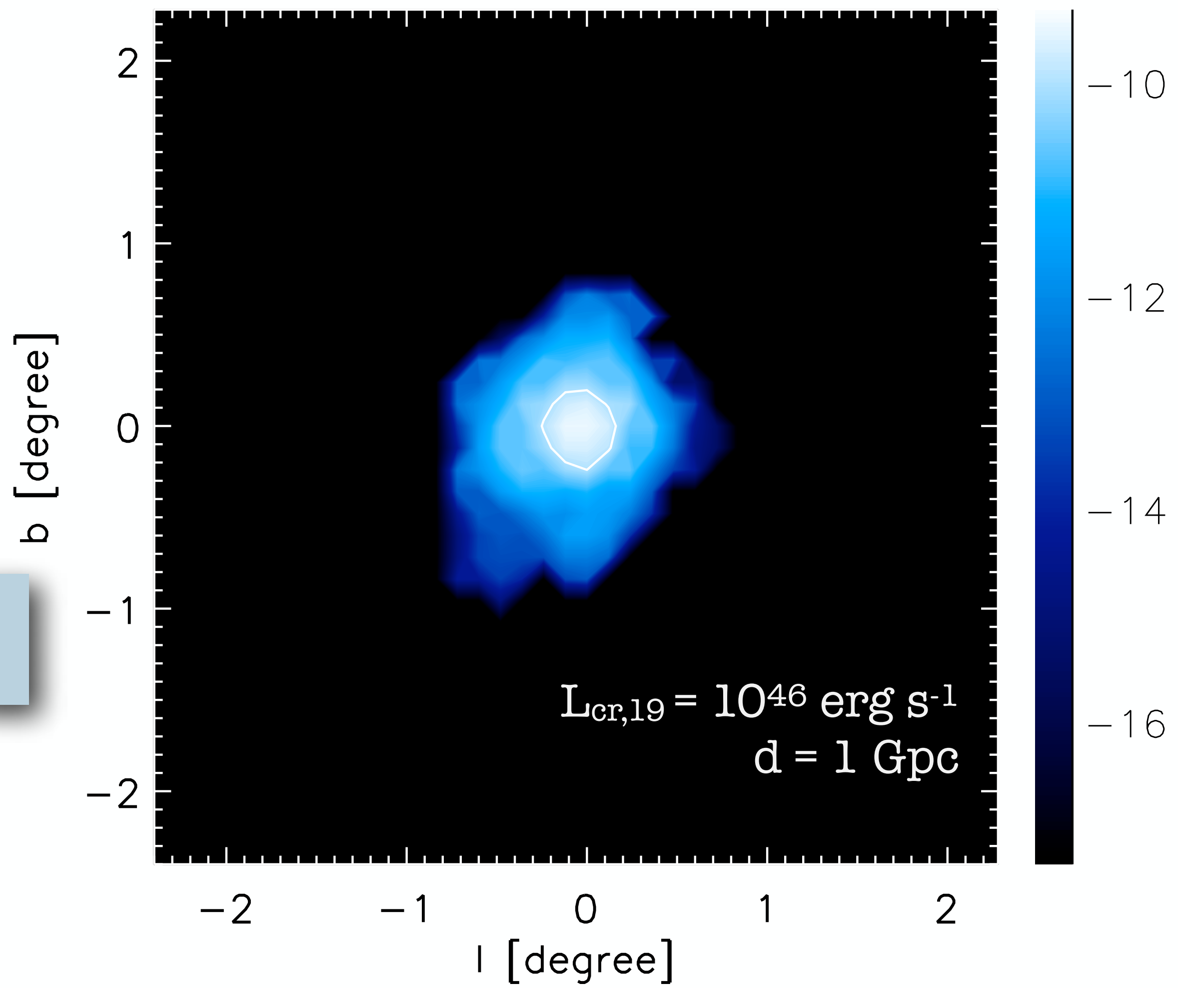
Learning from gamma rays: UHECR pair echoes/haloes

disentangling gamma-rays from leptons and cosmic rays

1ES 0229+200 *(HESS Coll. 2007, VERITAS Coll. 2010, 2013)*



K.K., Allard & Lemoine 2010



Proton UHECRs
$B_{3\ Mpc}$ = 316 nG
Injection spectral index = 2 $E_{MAX} = 10^{21}$ eV
$L_{CR,j} = 10^{44.5}$ erg s^{-1}

Fermi/CTA at 10 GeV:
~ 10^{-10} GeV cm^{-2} s^{-1} (θ_{source}/1°)

***also** Takami et al. 2013*

spectra observation with CTA:
disantangle UHECR cascade/leptonic
but not UHECR synchrotron/leptonic

Synchrotron haloes around sources
with strongly magnetized environ.
for cosmic-ray scenarios

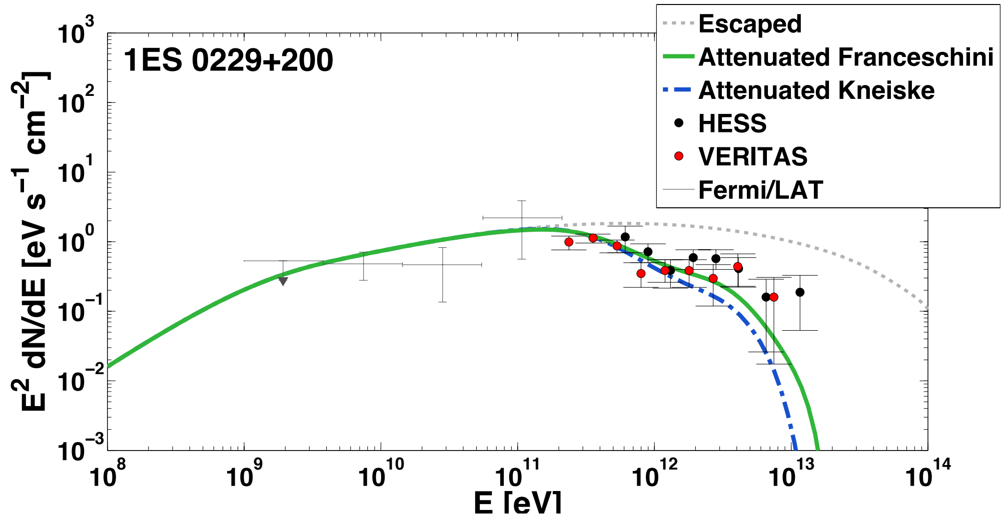
Pair echoes: time variabilities

Oikonomou, Murase & KK, 2014

$$\delta t \sim 2\theta_e^2 d/2c \sim 0.3\ \mathrm{yr}\ (E_{\mathrm{syn}}/10^{2.5}\ \mathrm{GeV})(\min[d, \lambda_{\gamma\gamma}]/\mathrm{Mpc})$$

deflection in B

d = magnetised region ~ few Mpc, $\lambda_{\gamma\gamma}$ ~ 2 Mpc



UHE photons

Injection spectral index = 1.5

$B_{3\ \mathrm{Mpc}}$ = 316 nG

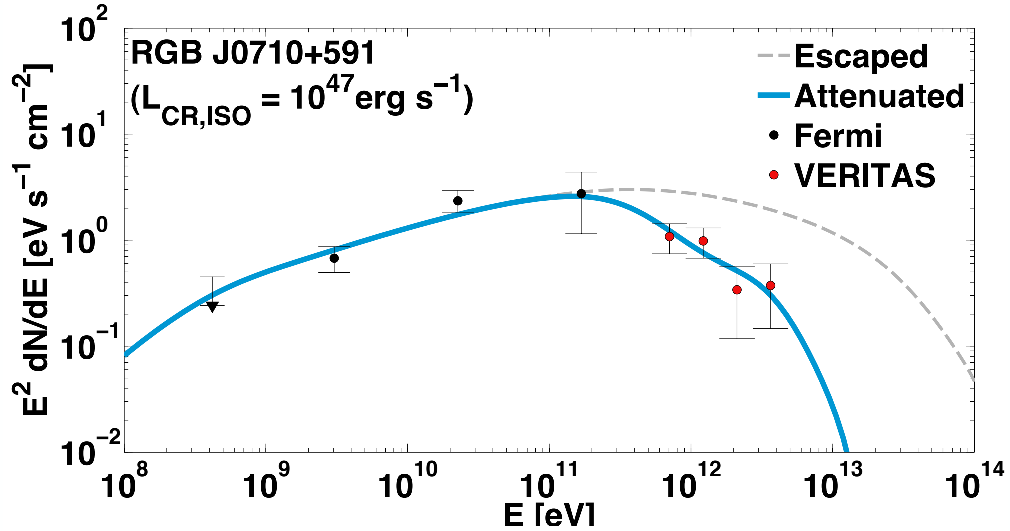
$E_{\gamma,\mathrm{MAX}} = 10^{19.5}$ eV

$L_\gamma = 10^{45}$ erg s^{-1}

~ year? *Aliu et al 2014*

If confirmed:

- disfavours UHECR synchrotron cascade
- rules out UHECR IC cascade



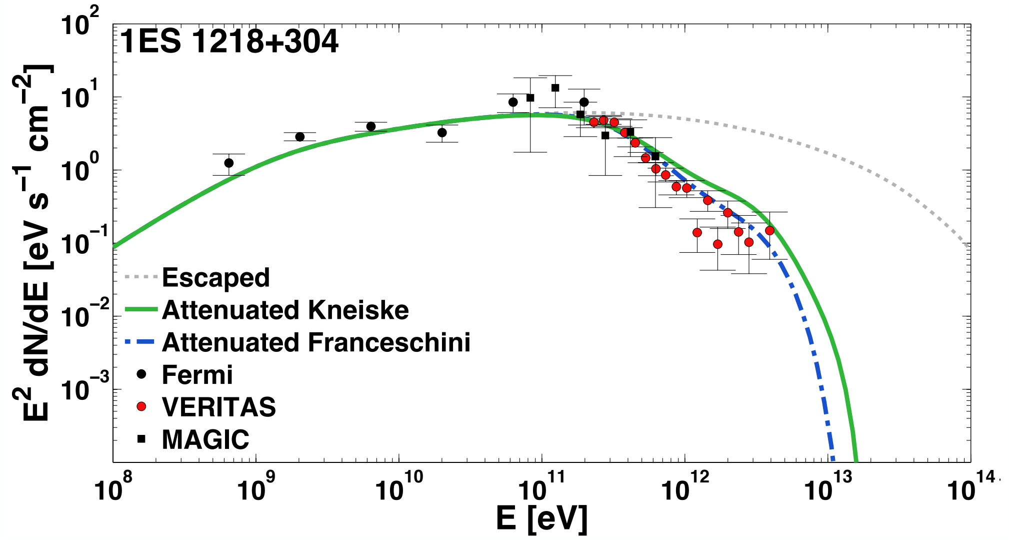
UHE protons

$B_{3\ \mathrm{Mpc}}$ = 100 nG

Injection spectral index = 2

$E_{\mathrm{MAX}} = 10^{20.5}$ eV

None



UHE photons

Injection spectral index = 1.5

$B_{3\ \mathrm{Mpc}}$ = 100 nG

$E_{\gamma,\mathrm{MAX}} = 10^{19.5}$ eV

$L_\gamma = 8\times10^{45}$ erg s^{-1}

~ day *Acciari et al 2010*

UHE neutrals could account for ~ day variability if emission region < pc size

detailed modeling needed

2. Tools for multi-messenger astrophysics

Very quick
panorama of simulation tools

Some public propagation and interaction codes

Cosmic-ray interstellar & intergalactic propagation tools

GALPROP DRAGON PICARD …	propagation of cosmic ray densities at high energies treated by solving transport equations
CRPropa SimProp …	at UHE: numerical integration of the equation of motion of single particles CRPropa: unify HE+UHE

Interaction codes/tables

SOPHIA	$p\gamma$
TALYS	$N\gamma$
EPOS/SIBYLL	hadronic
…	

Challenges

- treatment of different scales (including microscopic & MHD processes)
- time-dependencies
- self-consistency (radiation production & impact)

Gamma-ray cascades

CRPropa
ELMAG
…

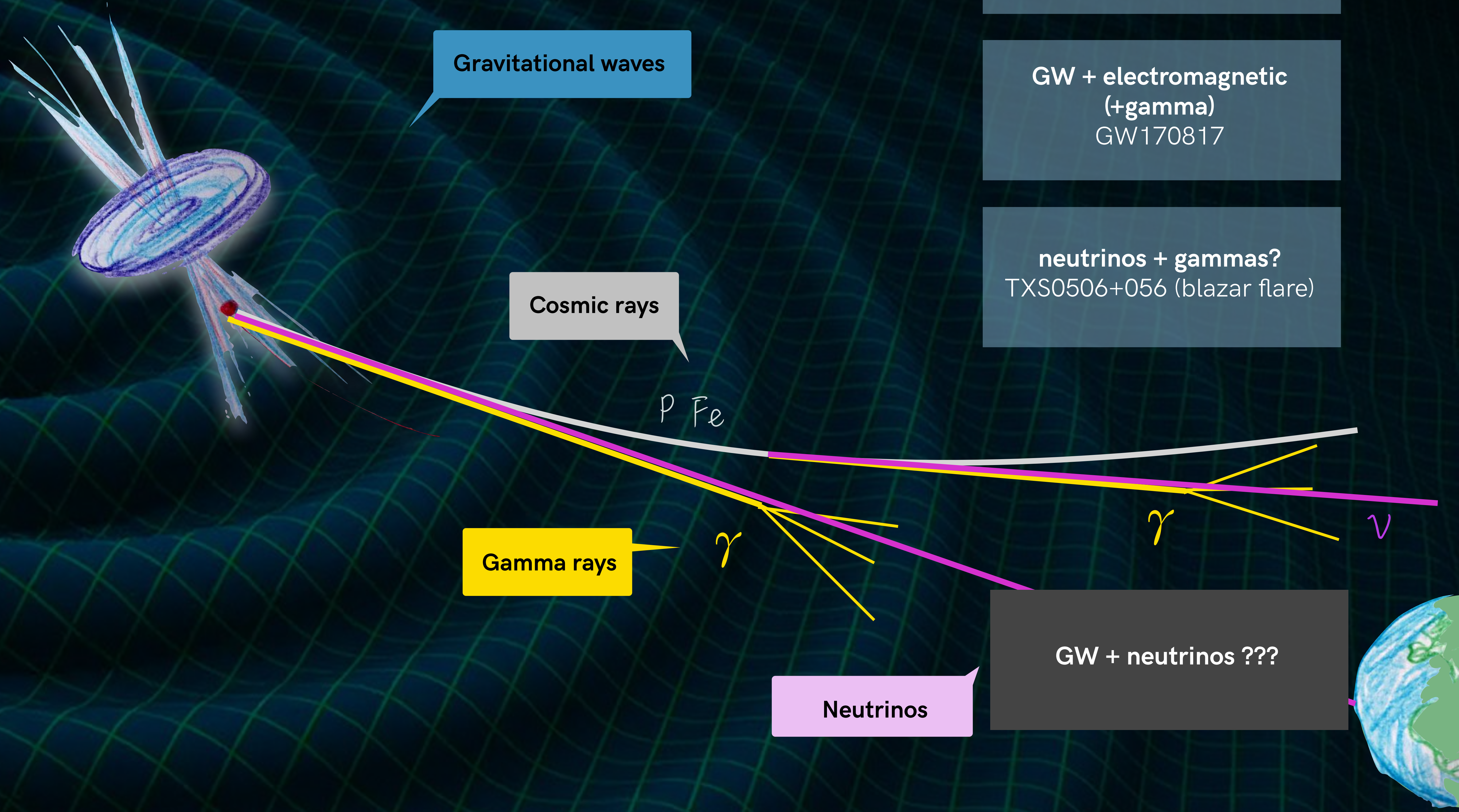
Radiation from accelerated leptons & hadrons

AM3, ATHEvA, B13, LeHaParis…

3. Can we really do multi-messenger astrophysics?

GW-neutrino sources

Multi-messengers?



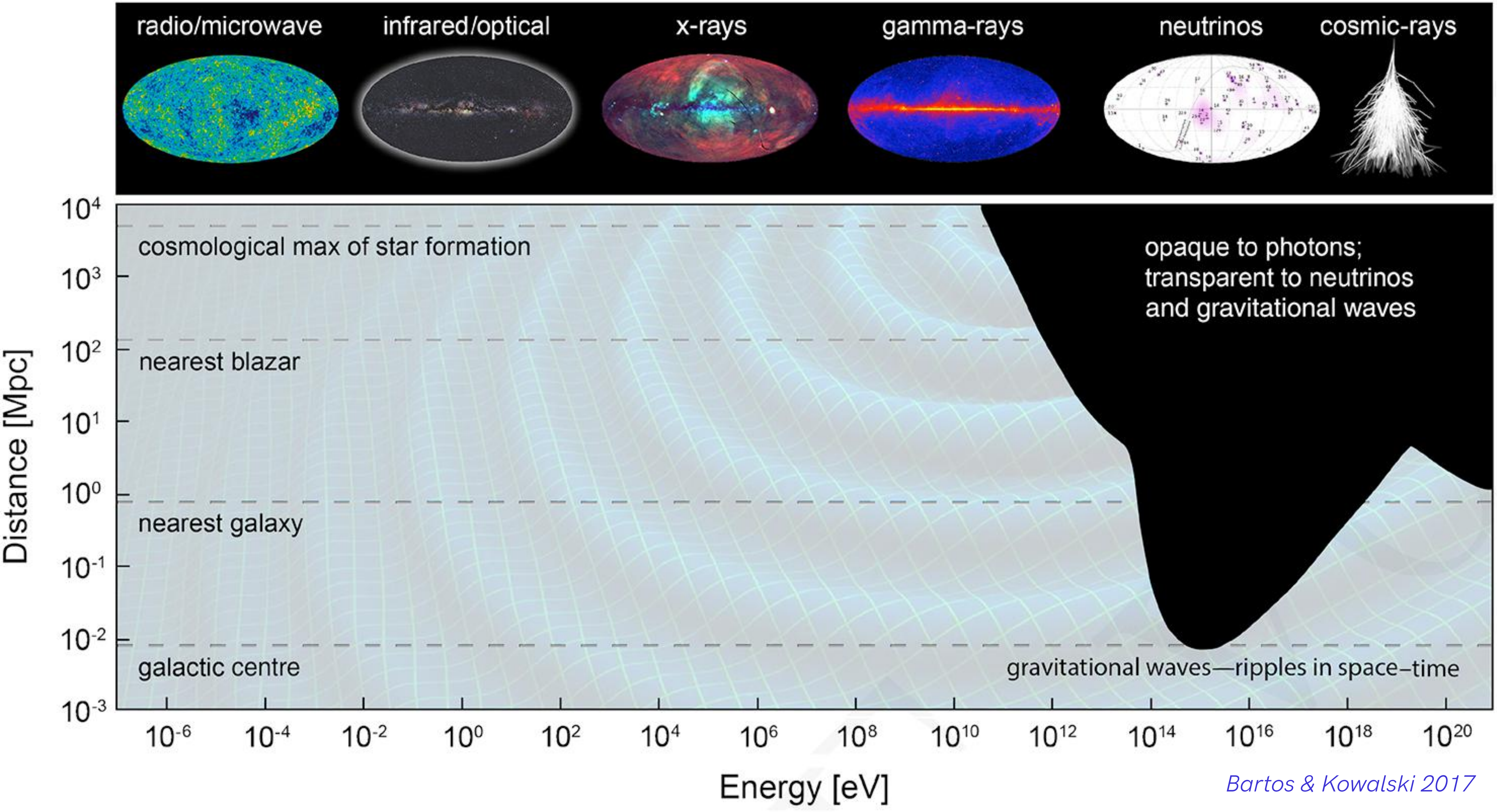
cosmic rays + others
—> temporal coincidence
impossible (deflections)
but studies of diffuse fluxes

GW + electromagnetic (+gamma)
GW170817

neutrinos + gammas?
TXS0506+056 (blazar flare)

GW + neutrinos ???

Multi-messengers?

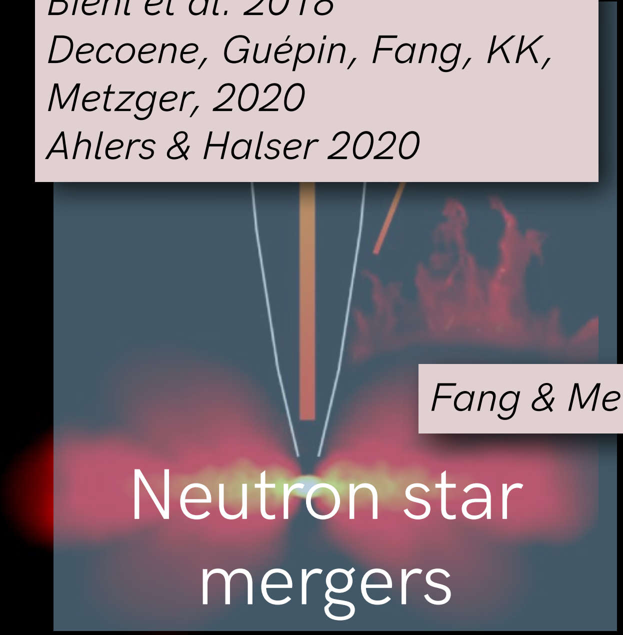


Bartos & Kowalski 2017

Possible gravitational wave sources

Murase & Bartos 2019
Guépin & KK 2017

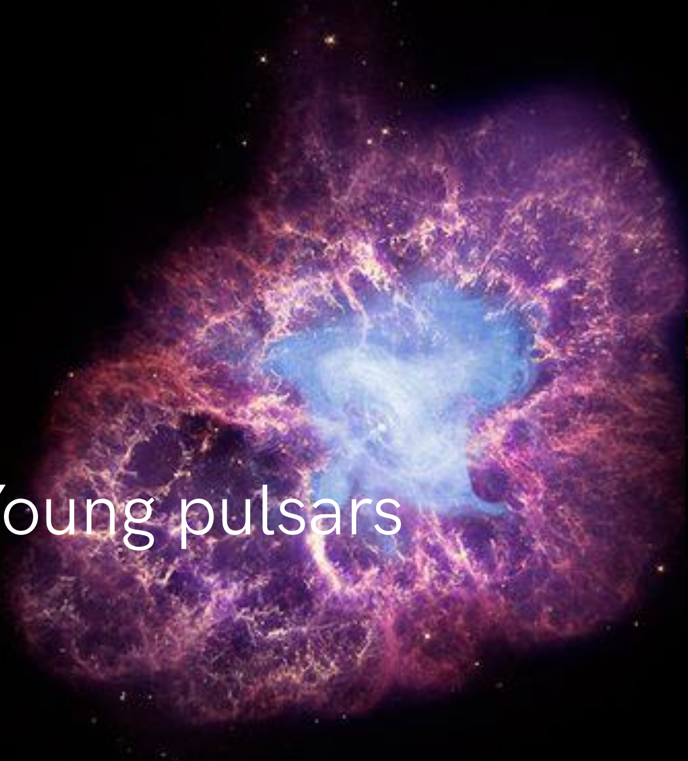
e.g., Kimura et al. 2017, 2018
Biehl et al. 2018
Decoene, Guépin, Fang, KK, Metzger, 2020
Ahlers & Halser 2020



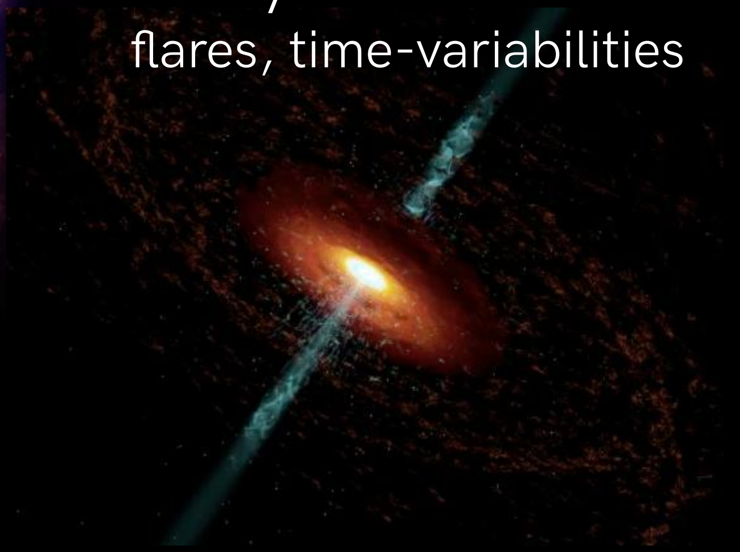
Neutron star mergers

Fang & Metzger 2018

Magnetars
(AXP/SGR)

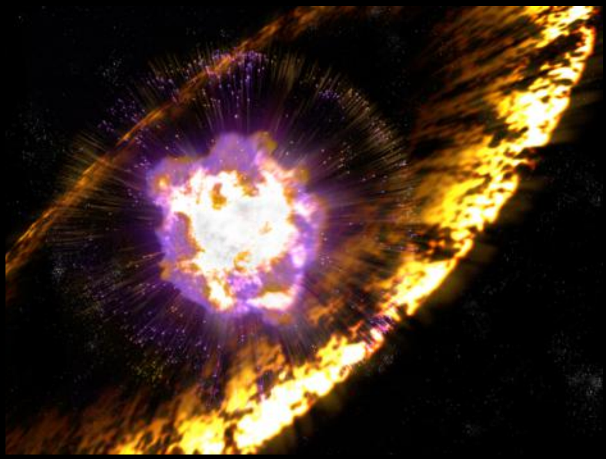


Young pulsars



AGN/Blazars
flares, time-variabilities

Long Gamma Ray Bursts



Superluminous Supernovae

KK & Silk 2016
De Wasseige et al. 2019
Shi & Yuan 2020

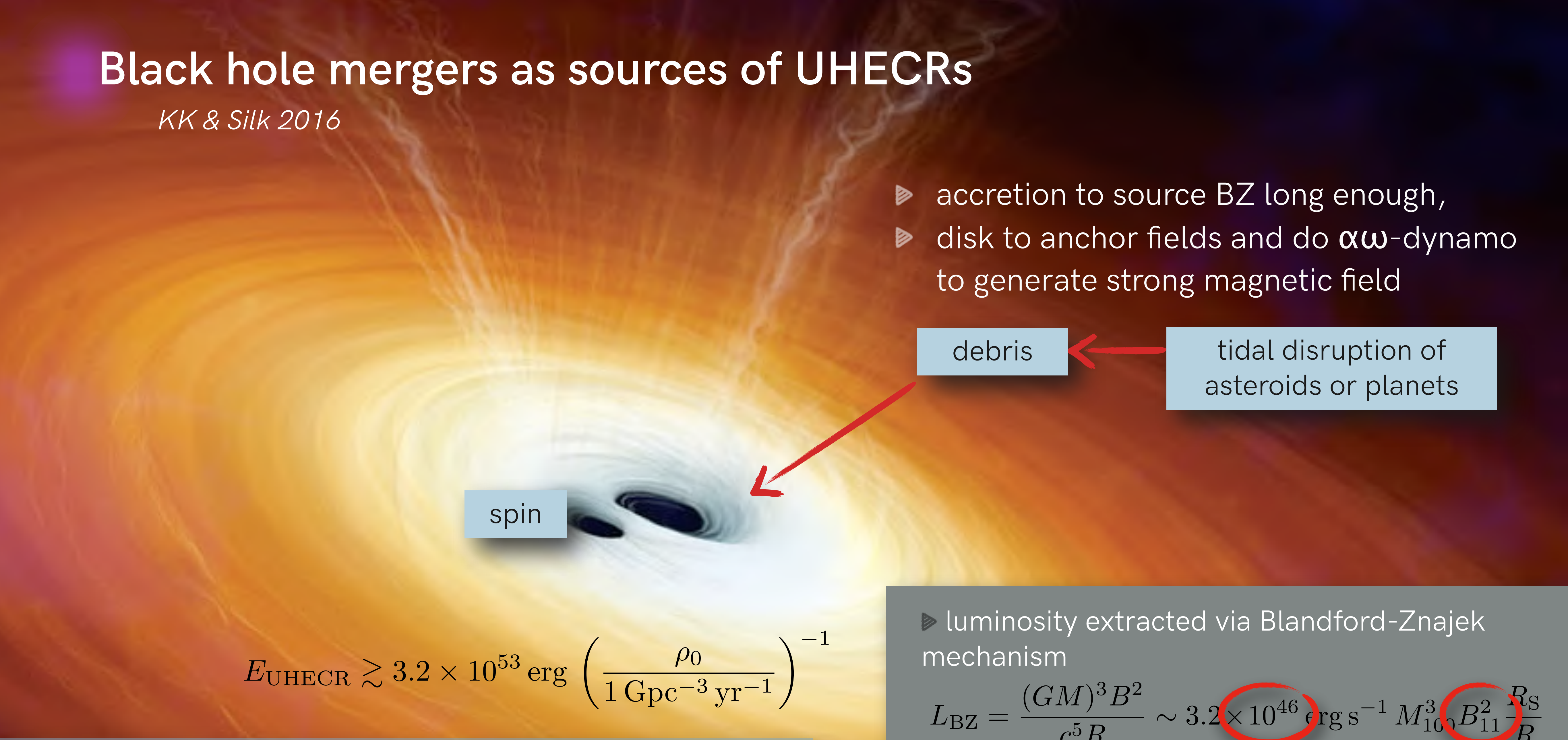
BH-BH and BH-NS mergers

Tidal disruption events

Black hole mergers as sources of UHECRs

KK & Silk 2016

- accretion to source BZ long enough,
- disk to anchor fields and do **αω**-dynamo to generate strong magnetic field



debris ← tidal disruption of asteroids or planets

spin

$$E_{\rm UHECR} \gtrsim 3.2 \times 10^{53}\,{\rm erg} \left(\frac{\rho_0}{1\,{\rm Gpc^{-3}\,yr^{-1}}} \right)^{-1}$$

learnt from GW150914

- comfortable energetics:
  - $E_{GW} = 3.0+0.5\ M_{sun}\,c^2 \sim$ **5.4 ×10⁵⁴ erg** per source
  - population rate $\rho_{BH} \sim 2 - 400\ {\rm Gpc^{-3}\ yr^{-1}}$
  - **efficiency < 3%** required in UHECRs per event per unit of GW energy release
- heavy composition possible:
  - iron-enriched residual debris around merging BHs

- luminosity extracted via Blandford-Znajek mechanism

$$L_{\rm BZ} = \frac{(GM)^3 B^2}{c^5 R} \sim 3.2 \times 10^{46}\,{\rm erg\,s^{-1}}\,M_{100}^3 B_{11}^2 \frac{R_{\rm S}}{R}$$

$$R_{\rm S} = 2GM/c^2 \sim 3.0 \times 10^7\,M_{100}\,{\rm cm}$$

- magnetic field strength via **αω**-dynamo

$$B \sim 10^{12}\,{\rm G}\,(P/300\,{\rm ms})^{-1}$$

- luminosity has to last for 7 hours to 2 months to reach $E_{\rm UHECR}$

- BZ timescale (as long as BH accretes after merger - sourced by debris)

$$t_{\rm BZ} = Mc^2/L_{\rm BZ} \sim 22\,M_{100} B_{11}^{-2} (R_{\rm S}/R)^2\,{\rm yr}$$

High-energy neutrinos from binary neutron-star mergers

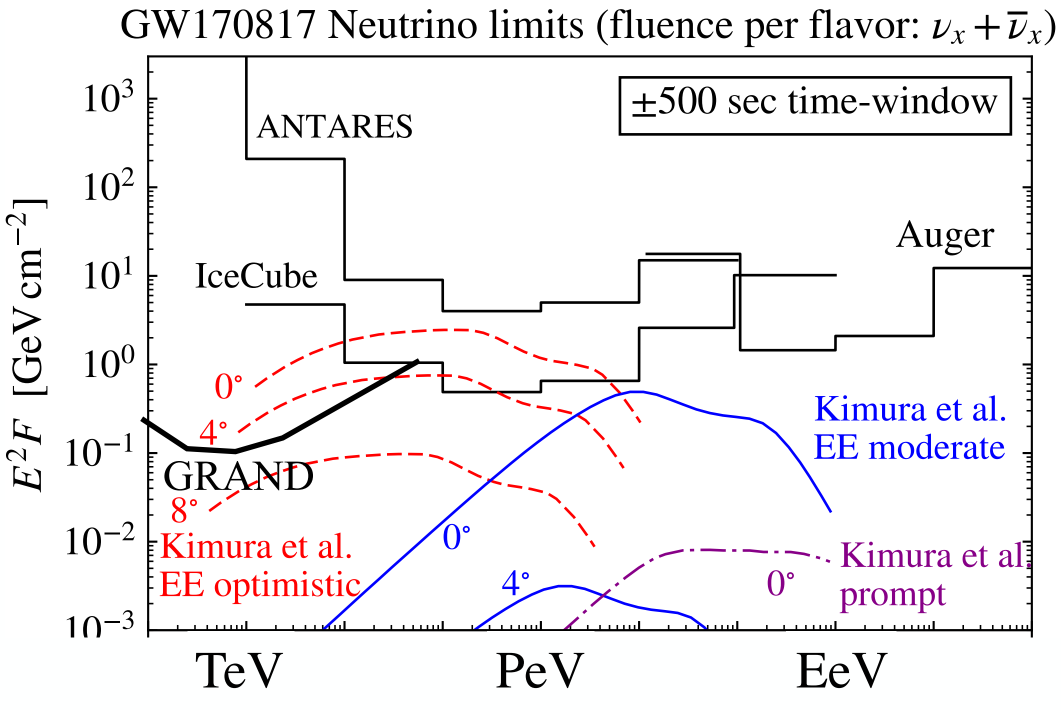
Successful jet

Kimura et al. 2017
Biehl et al. 2018
Ahlers & Halser 2020

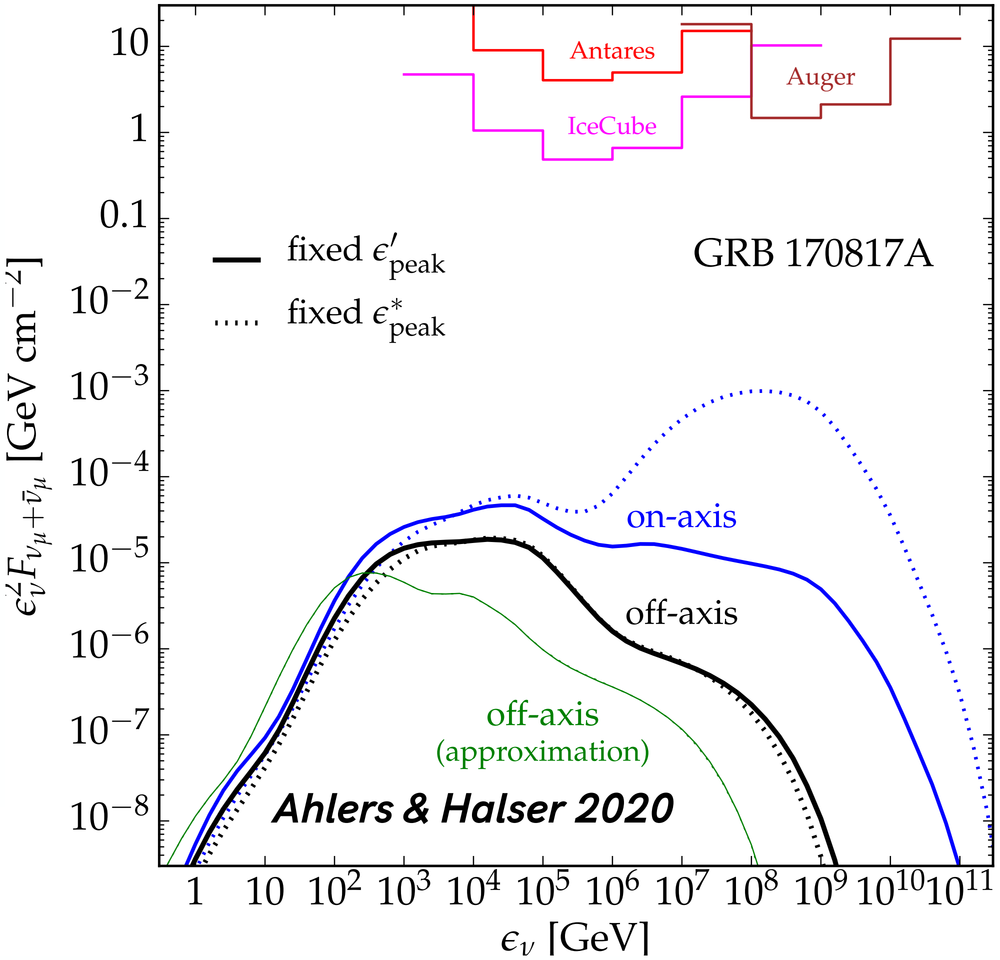
Choked jet

Kimura et al. 2018

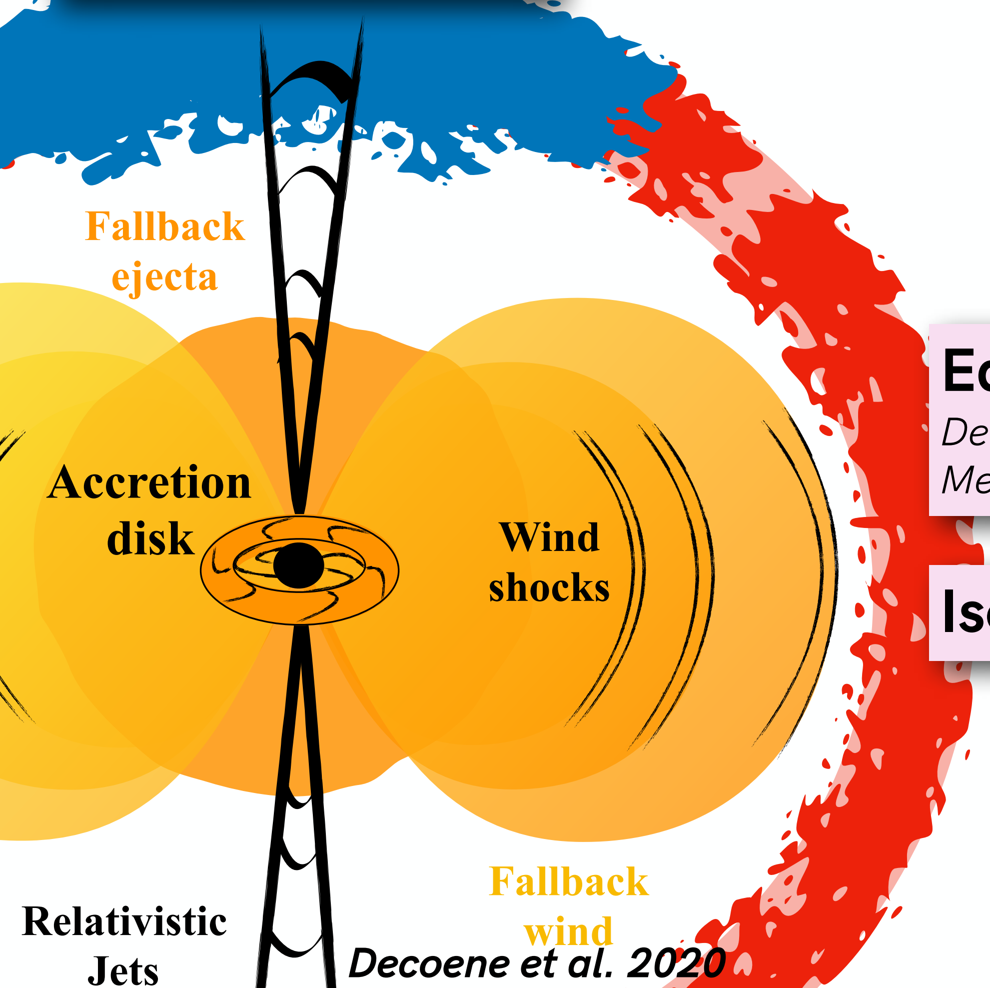
Beamed and intense emission



LIGO, VIRGO, IceCube, Auger, ANTARES 2017
Kimura et al. 2017



Ahlers & Halser 2020

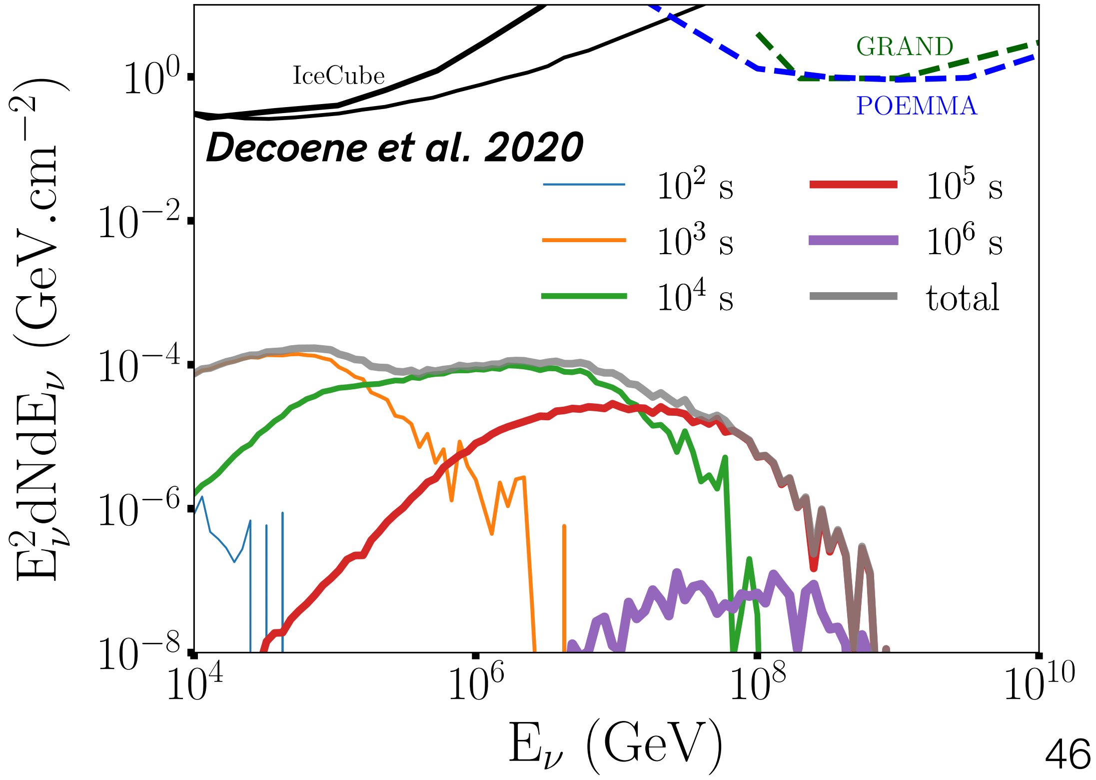


Decoene et al. 2020

Equatorial emission

Decoene, Guépin, Fang, KK, Metzger, 2020

Isotropic emission



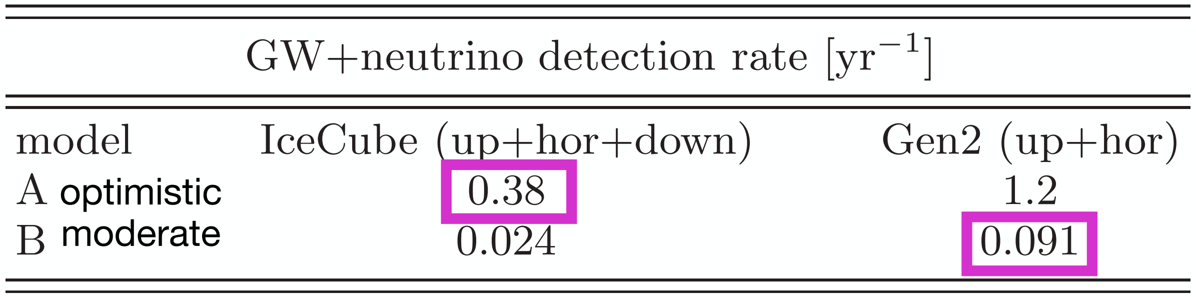
Decoene et al. 2020

BNS: coincident detection with gravitational waves

Choked jet

Kimura et al. 2018

Optimistic model:
Coincident detection possible already with IceCube

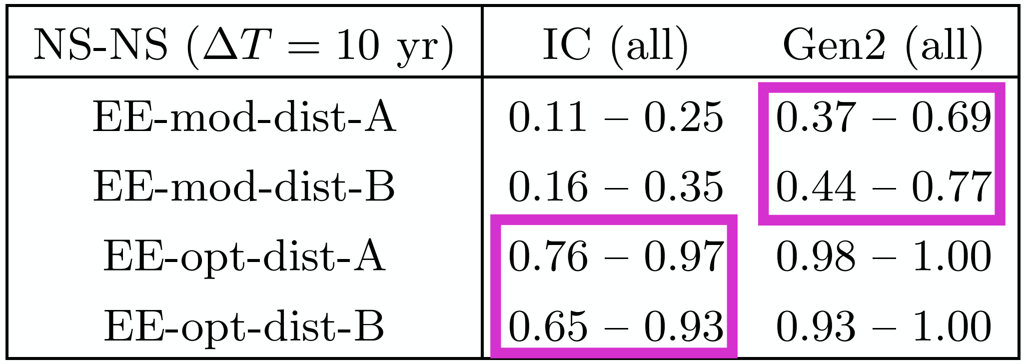


GW+neutrino detection rate [yr^{-1}]		
model	IceCube (up+hor+down)	Gen2 (up+hor)
A optimistic	0.38	1.2
B moderate	0.024	0.091

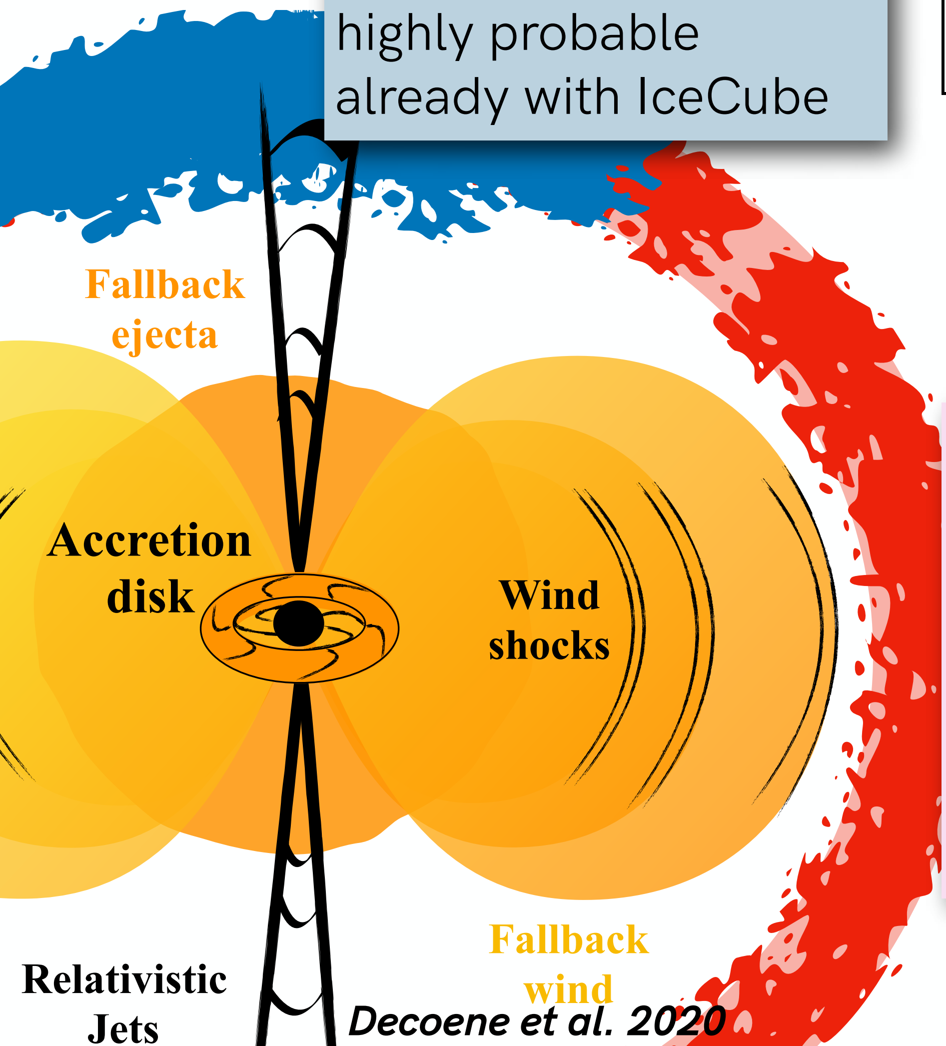
Successful jet

Kimura et al. 2017

Optimistic model:
Coincident detection highly probable already with IceCube



NS-NS ($\Delta T = 10$ yr)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.11 – 0.25	0.37 – 0.69
EE-mod-dist-B	0.16 – 0.35	0.44 – 0.77
EE-opt-dist-A	0.76 – 0.97	0.98 – 1.00
EE-opt-dist-B	0.65 – 0.93	0.93 – 1.00

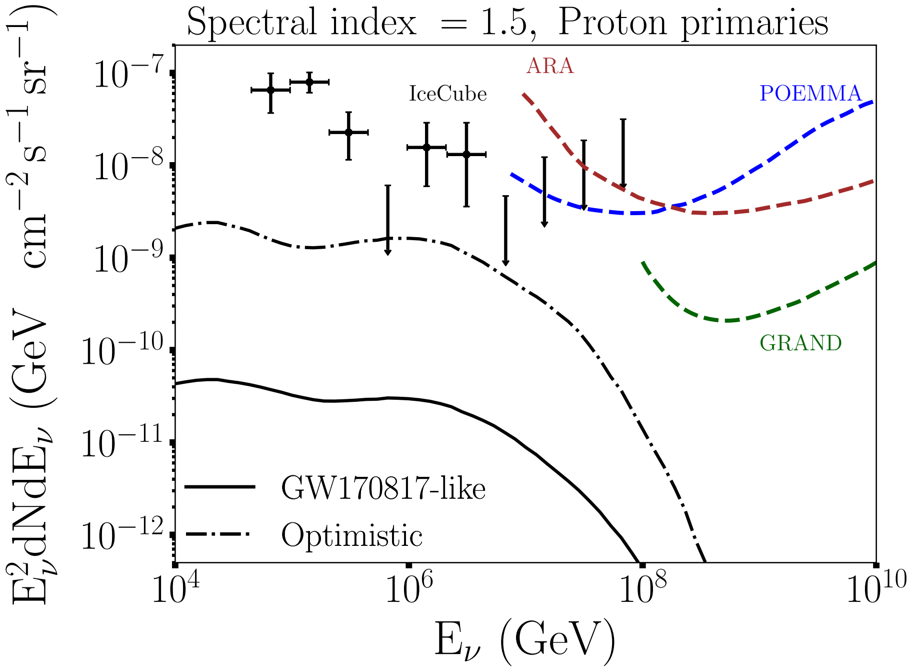


Decoene et al. 2020

Equatorial emission

Decoene, Guépin, Fang, KK, Metzger, 2020

Optimistic model:
10% of IceCube diffuse flux
Interesting for stacking and cross-correlation searches

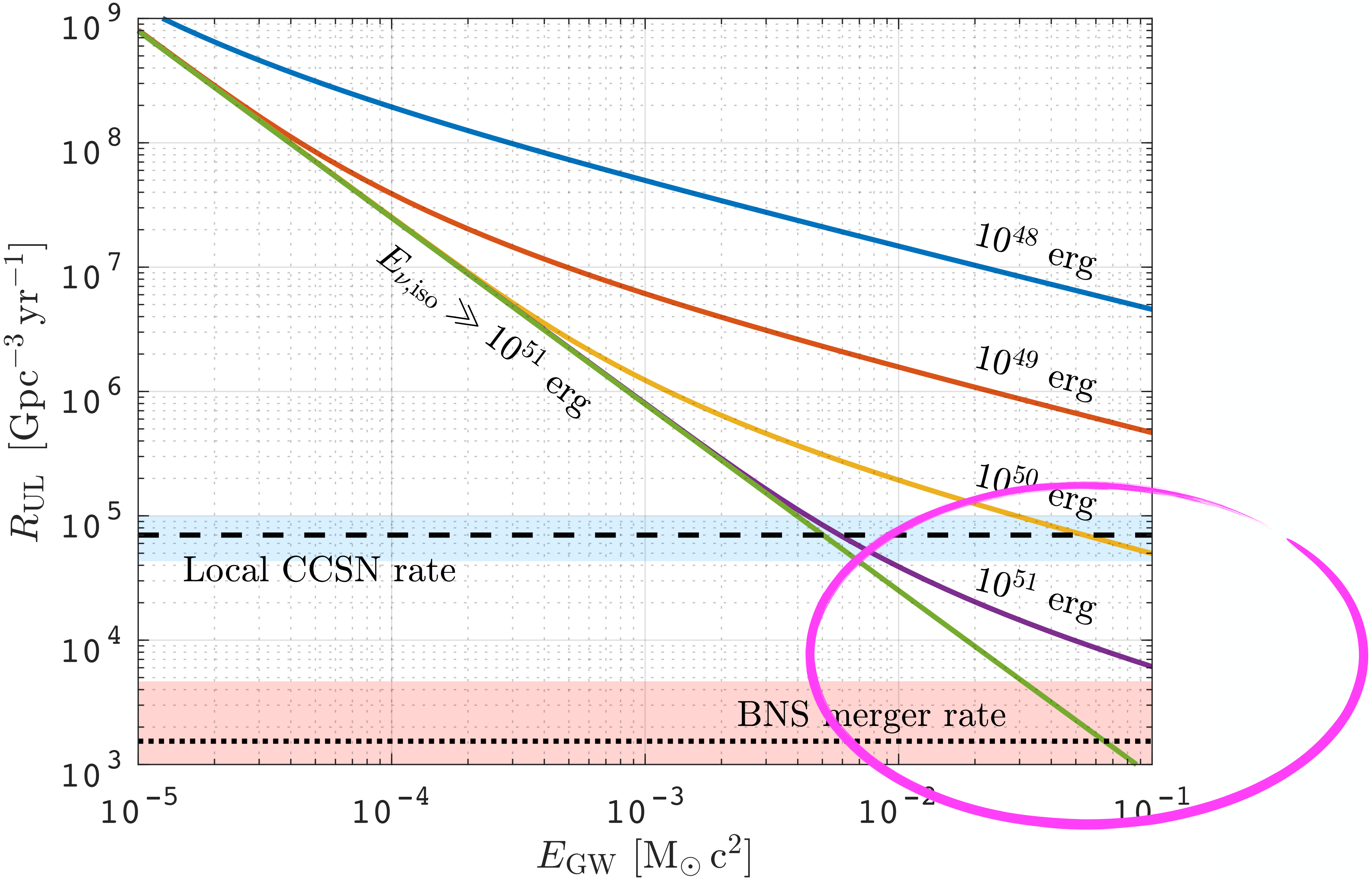


Population constraints from GW+neutrino non-detection

Advanced LIGO

IceCube+ANTARES

Upper limits on rate density of GW+neutrino sources

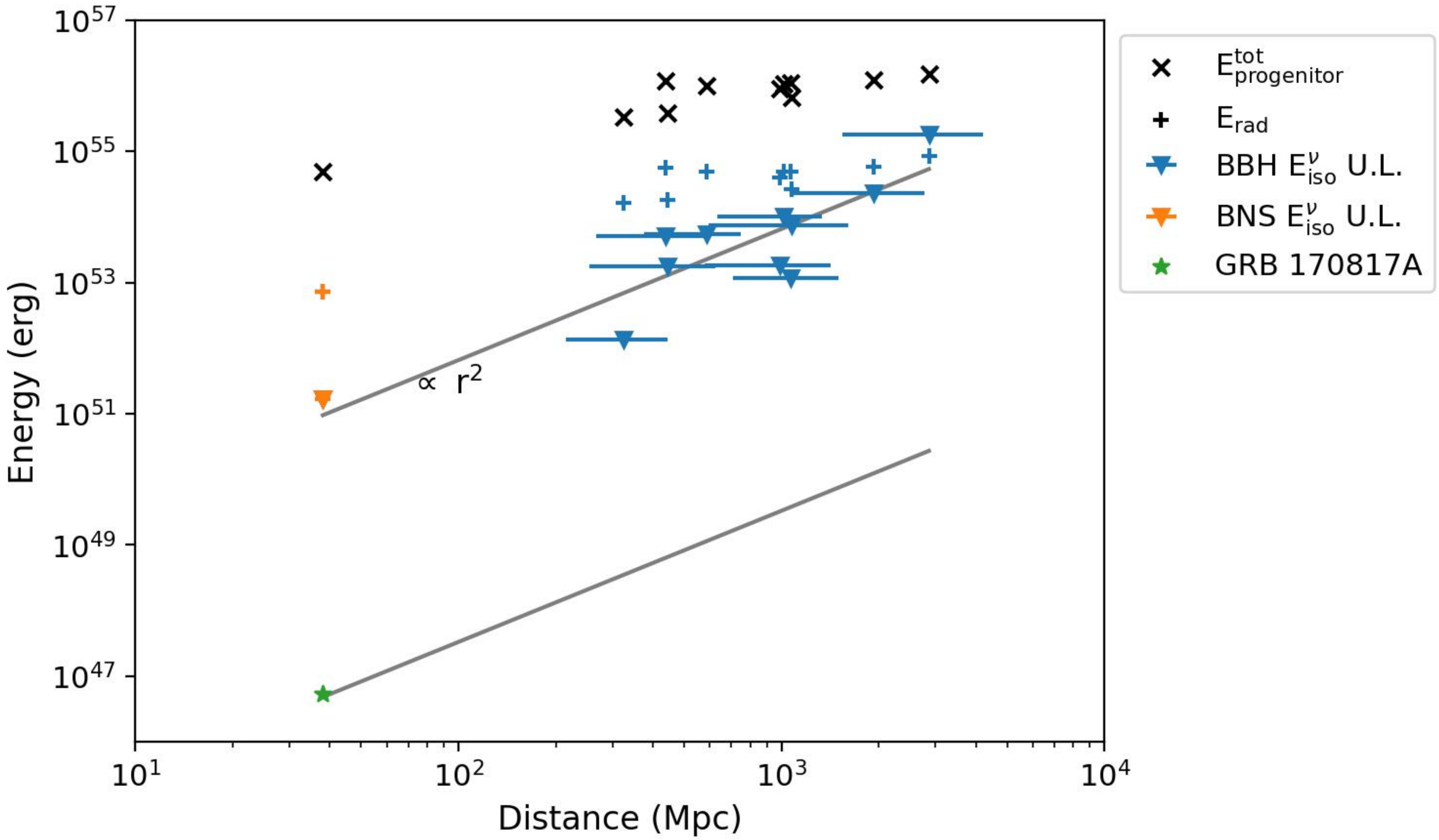


Albert et al. 2019 ApJ 870 134

Population constraints from GW+neutrino non-detection

Advanced LIGO

IceCube



No significant neutrino coincidence is seen by either search during the first two observing runs of the LIGO-Virgo detectors. Upper limits on the time-integrated neutrino emission within the 1000 second window for each of the 11 GW events.

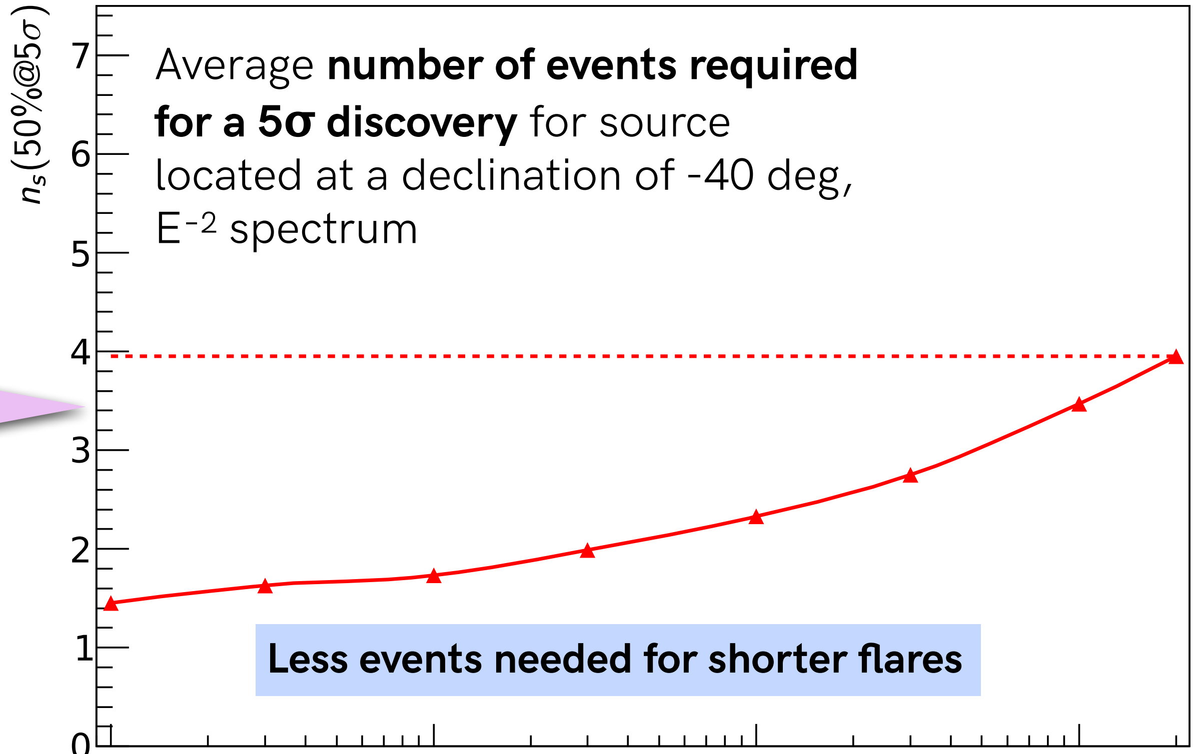
Aartsen et al. 2020 arXiv:2004.02910v2

3. Can we really do multi-messenger astrophysics?

Focus on neutrinos from transients sources

Why focus on transient sources?

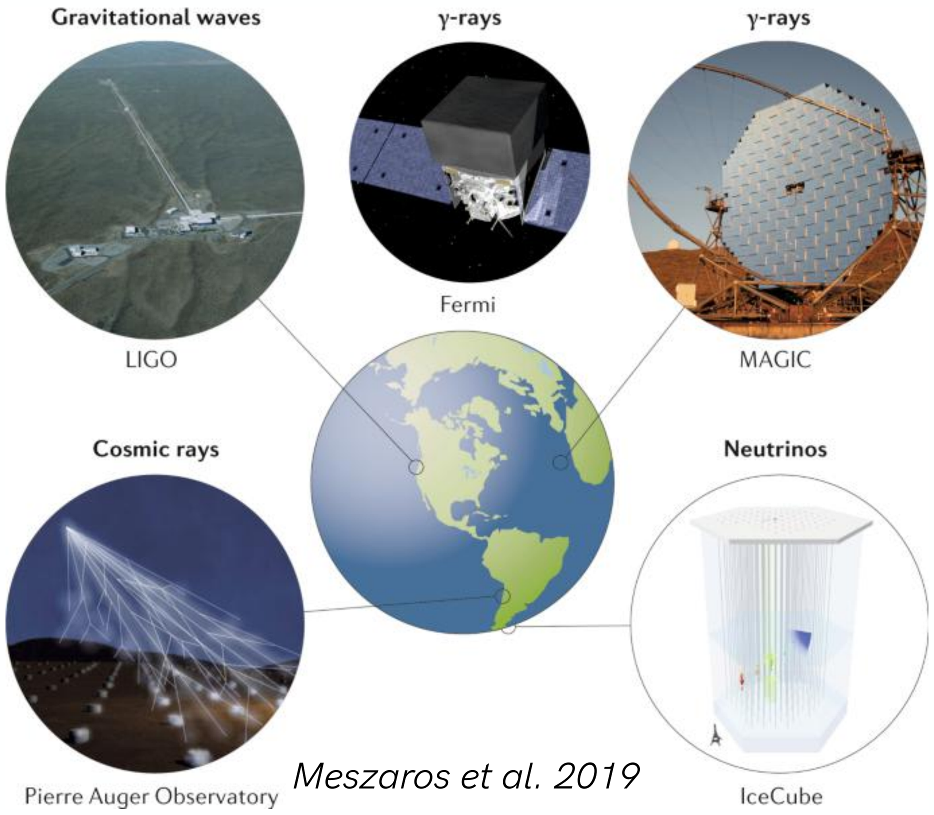
time-dependent neutrino searches **reduce the background** for sub-PeV energies (atmospheric neutrinos+muons)



Average **number of events required for a 5σ discovery** for source located at a declination of -40 deg, E^{-2} spectrum

Less events needed for shorter flares

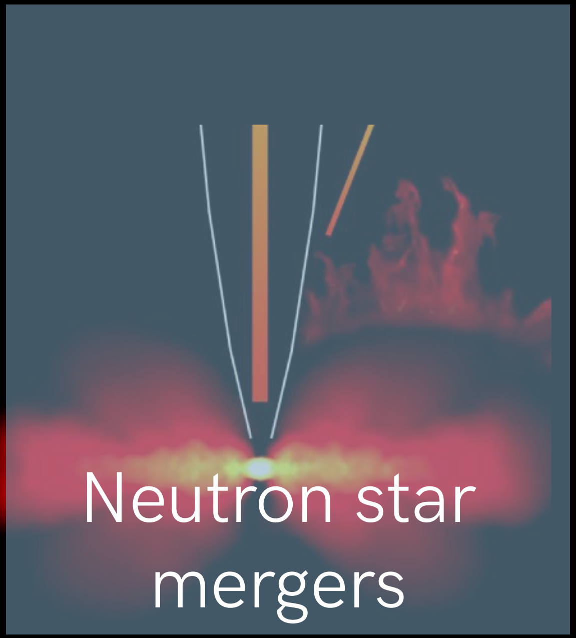
ANTARES Coll. JCAP12(2015)014



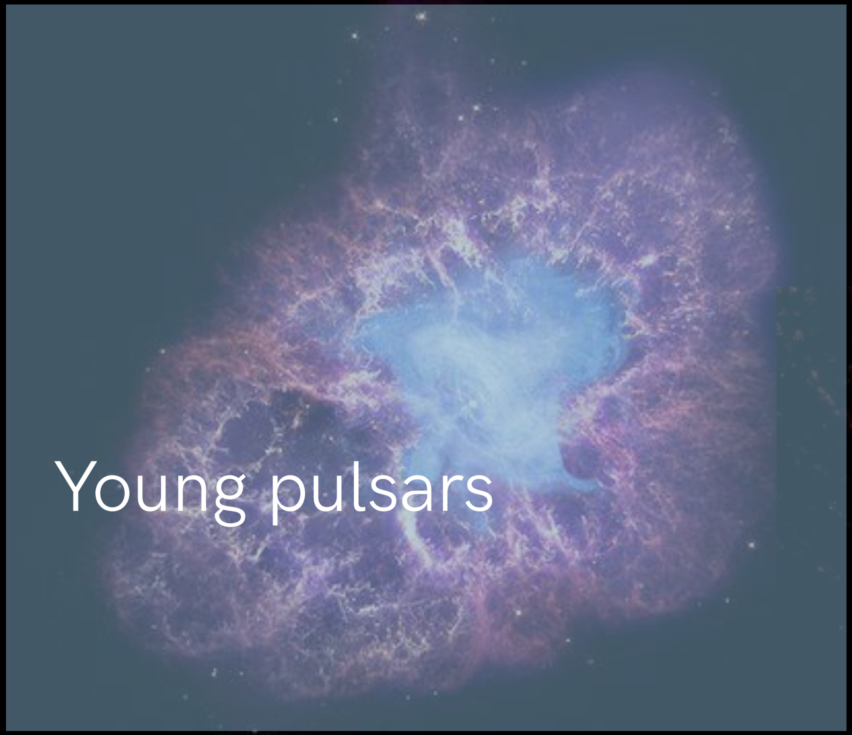
Meszaros et al. 2019

Real-time analysis + multi-messenger follow-up on alerts increase statistical significance of signals

The new high-energy transient zoo

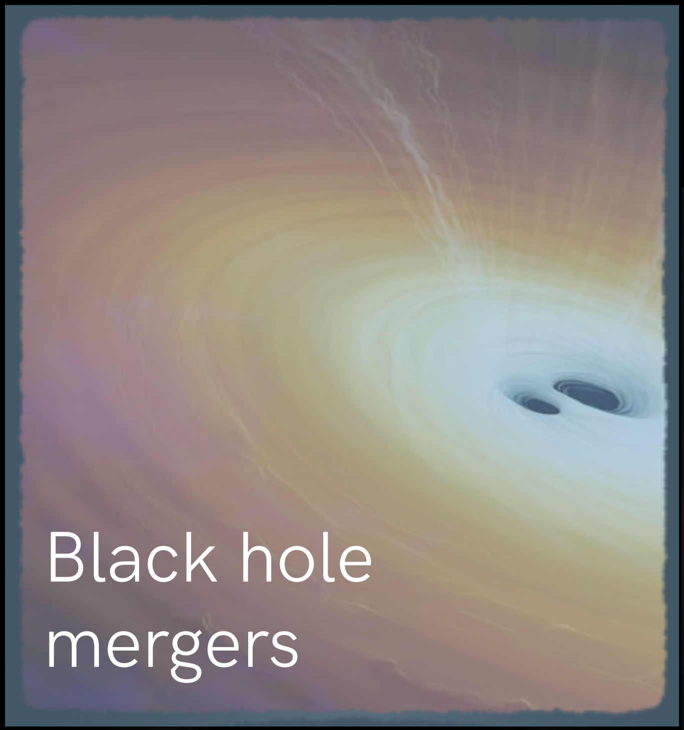

Neutron star mergers


Magnetars (AXP/SGR)

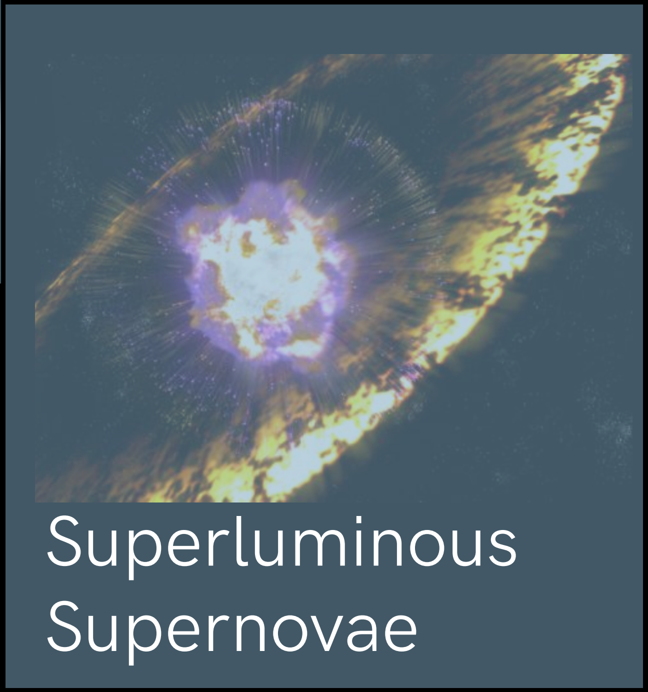

Young pulsars


AGN/Blazars
flares, time-variabilities


Long Gamma Ray Bursts


Black hole mergers


Tidal disruption events


Superluminous Supernovae

The new high-energy transient zoo

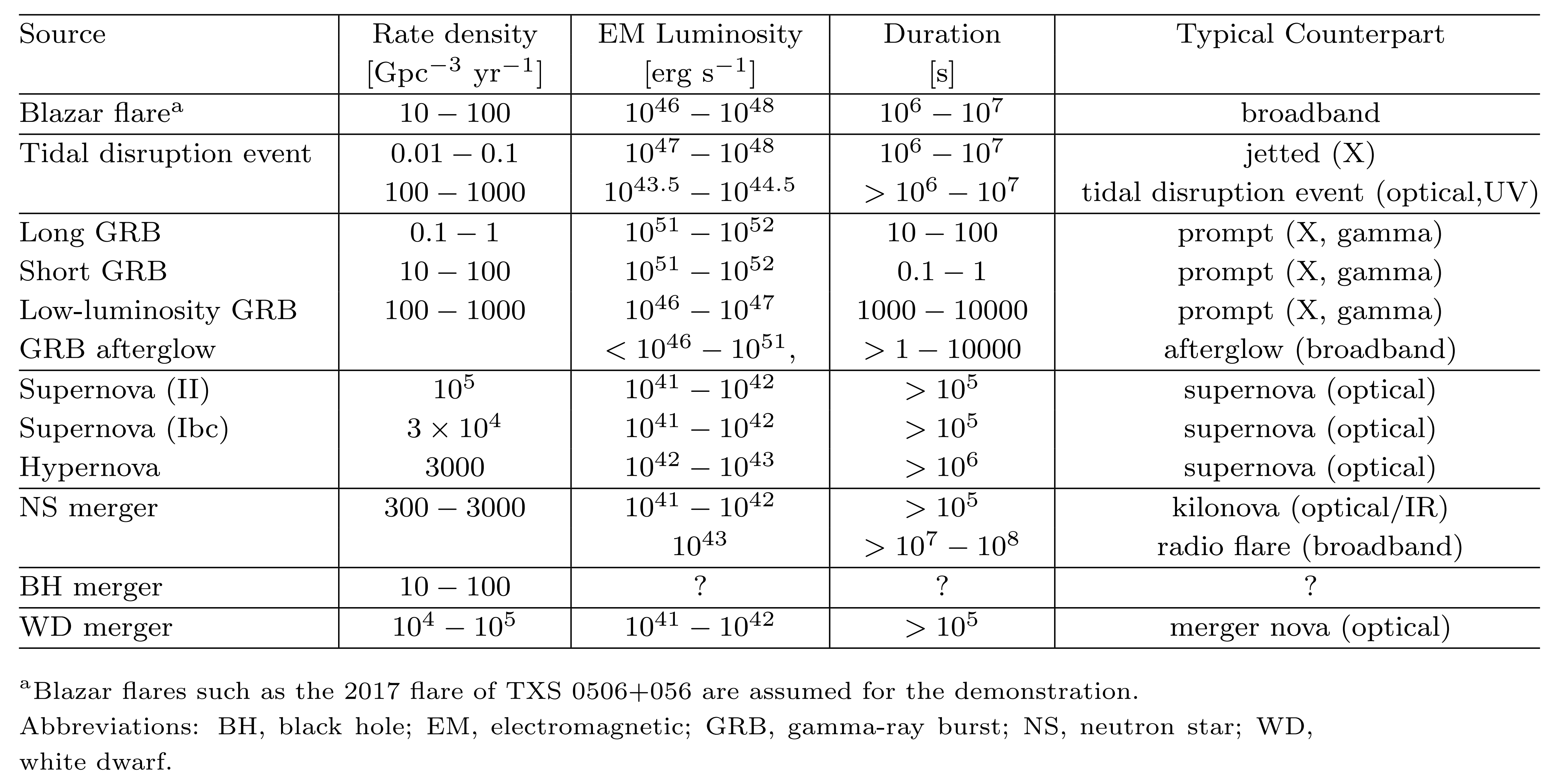
Murase & Bartos 2019

AGN/Blazars

es

Ne

r



Source	Rate density $[\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}]$	EM Luminosity $[\mathrm{erg\ s}^{-1}]$	Duration [s]	Typical Counterpart
Blazar flare[a]	$10 - 100$	$10^{46} - 10^{48}$	$10^{6} - 10^{7}$	broadband
Tidal disruption event	$0.01 - 0.1$	$10^{47} - 10^{48}$	$10^{6} - 10^{7}$	jetted (X)
	$100 - 1000$	$10^{43.5} - 10^{44.5}$	$> 10^{6} - 10^{7}$	tidal disruption event (optical,UV)
Long GRB	$0.1 - 1$	$10^{51} - 10^{52}$	$10 - 100$	prompt (X, gamma)
Short GRB	$10 - 100$	$10^{51} - 10^{52}$	$0.1 - 1$	prompt (X, gamma)
Low-luminosity GRB	$100 - 1000$	$10^{46} - 10^{47}$	$1000 - 10000$	prompt (X, gamma)
GRB afterglow		$< 10^{46} - 10^{51},$	$> 1 - 10000$	afterglow (broadband)
Supernova (II)	10^{5}	$10^{41} - 10^{42}$	$> 10^{5}$	supernova (optical)
Supernova (Ibc)	3×10^{4}	$10^{41} - 10^{42}$	$> 10^{5}$	supernova (optical)
Hypernova	3000	$10^{42} - 10^{43}$	$> 10^{6}$	supernova (optical)
NS merger	$300 - 3000$	$10^{41} - 10^{42}$	$> 10^{5}$	kilonova (optical/IR)
		10^{43}	$> 10^{7} - 10^{8}$	radio flare (broadband)
BH merger	$10 - 100$	?	?	?
WD merger	$10^{4} - 10^{5}$	$10^{41} - 10^{42}$	$> 10^{5}$	merger nova (optical)

[a] Blazar flares such as the 2017 flare of TXS 0506+056 are assumed for the demonstration.

Abbreviations: BH, black hole; EM, electromagnetic; GRB, gamma-ray burst; NS, neutron star; WD, white dwarf.

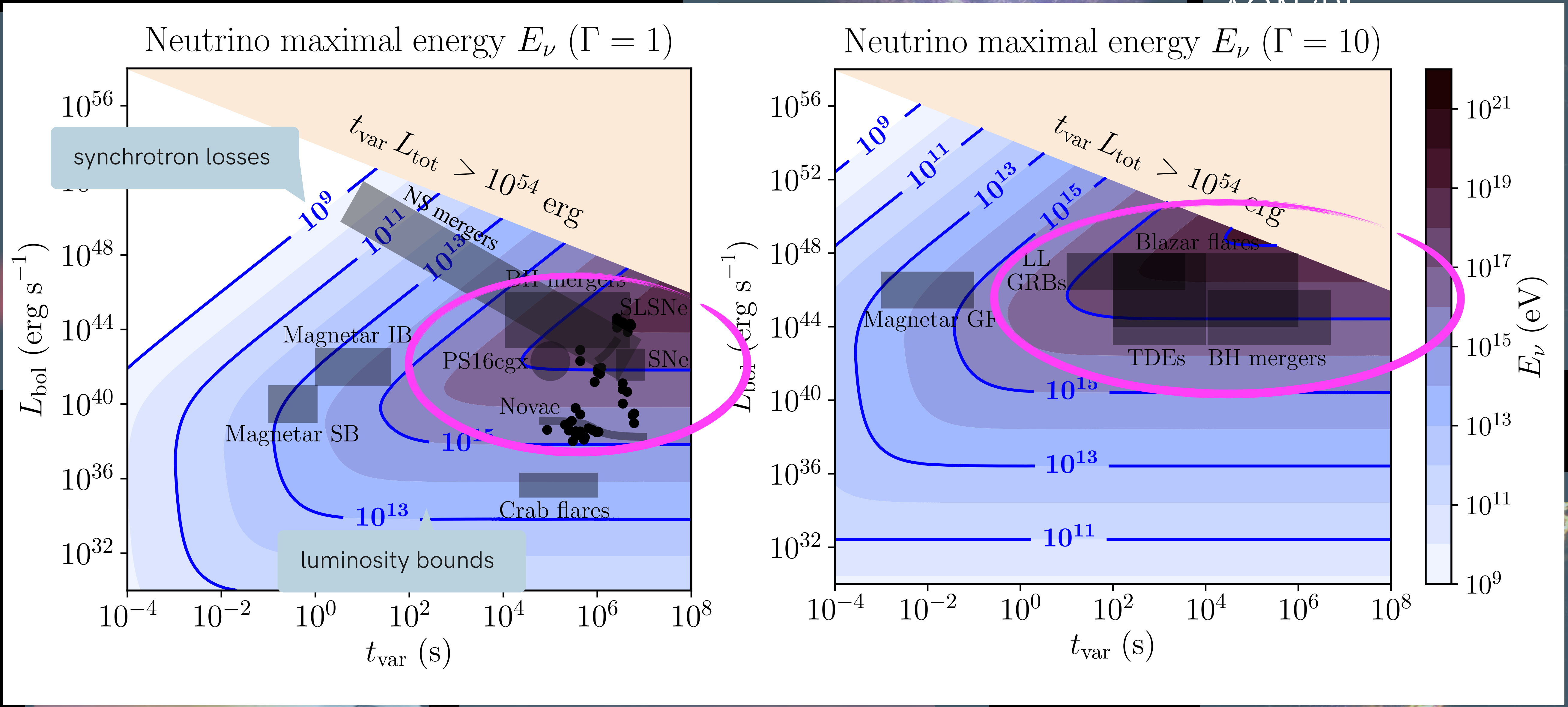
Black hole mergers

Tidal disruption events

Superluminous Supernovae

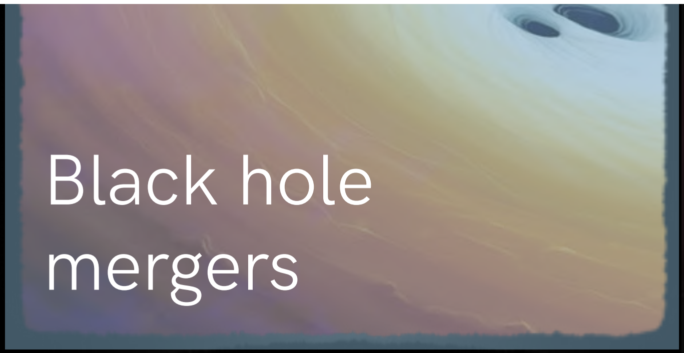
A "Hillas diagram" for high-energy neutrino transients

Guépin & KK 2017



synchrotron losses

luminosity bounds



Black hole mergers

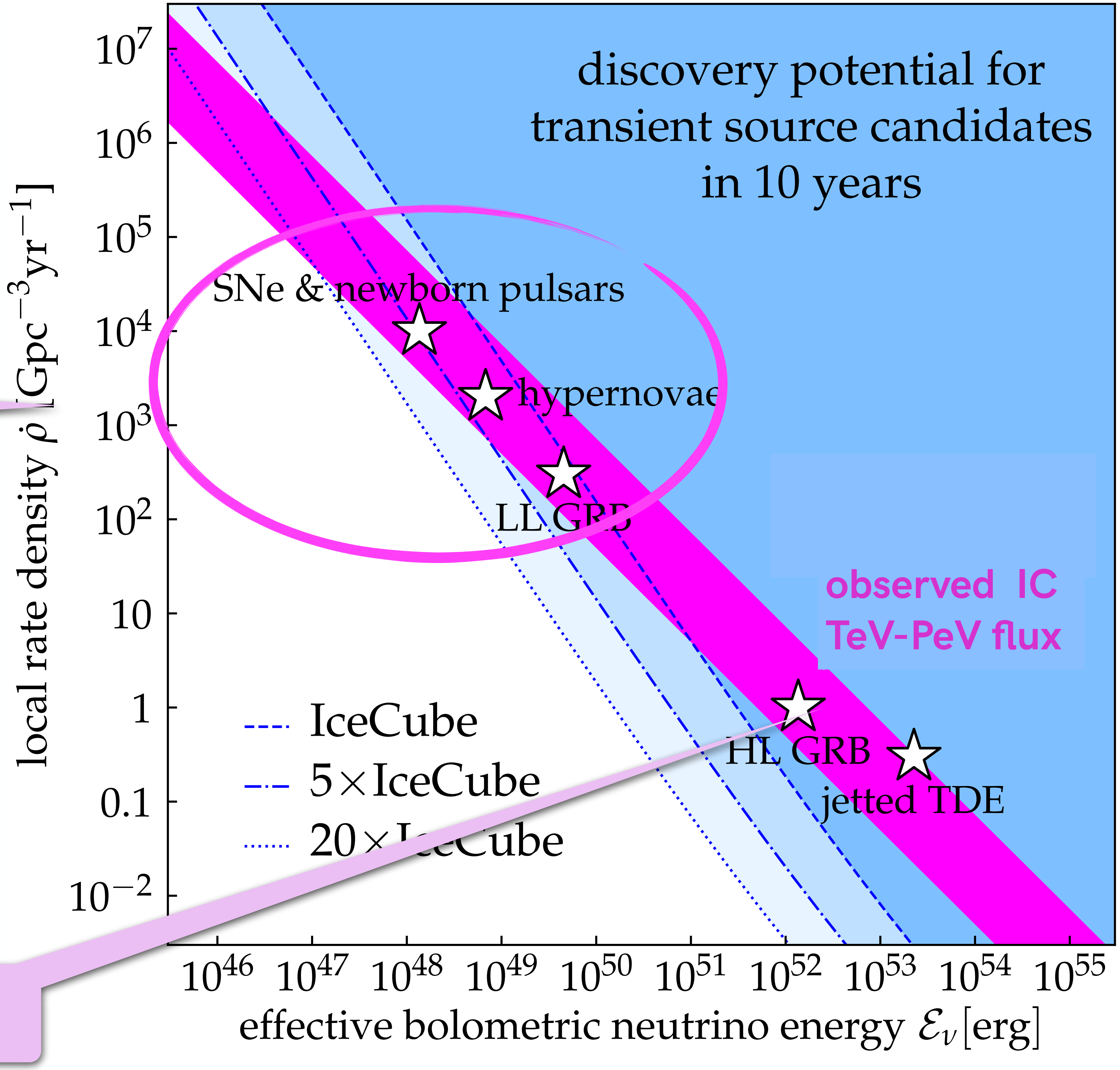
Tidal disruption events

Superluminous Supernovae

IceCube neutrinos: soon to be probed transients

Detection of **multiplets** depends on number density of sources

Could be probed in the next decade



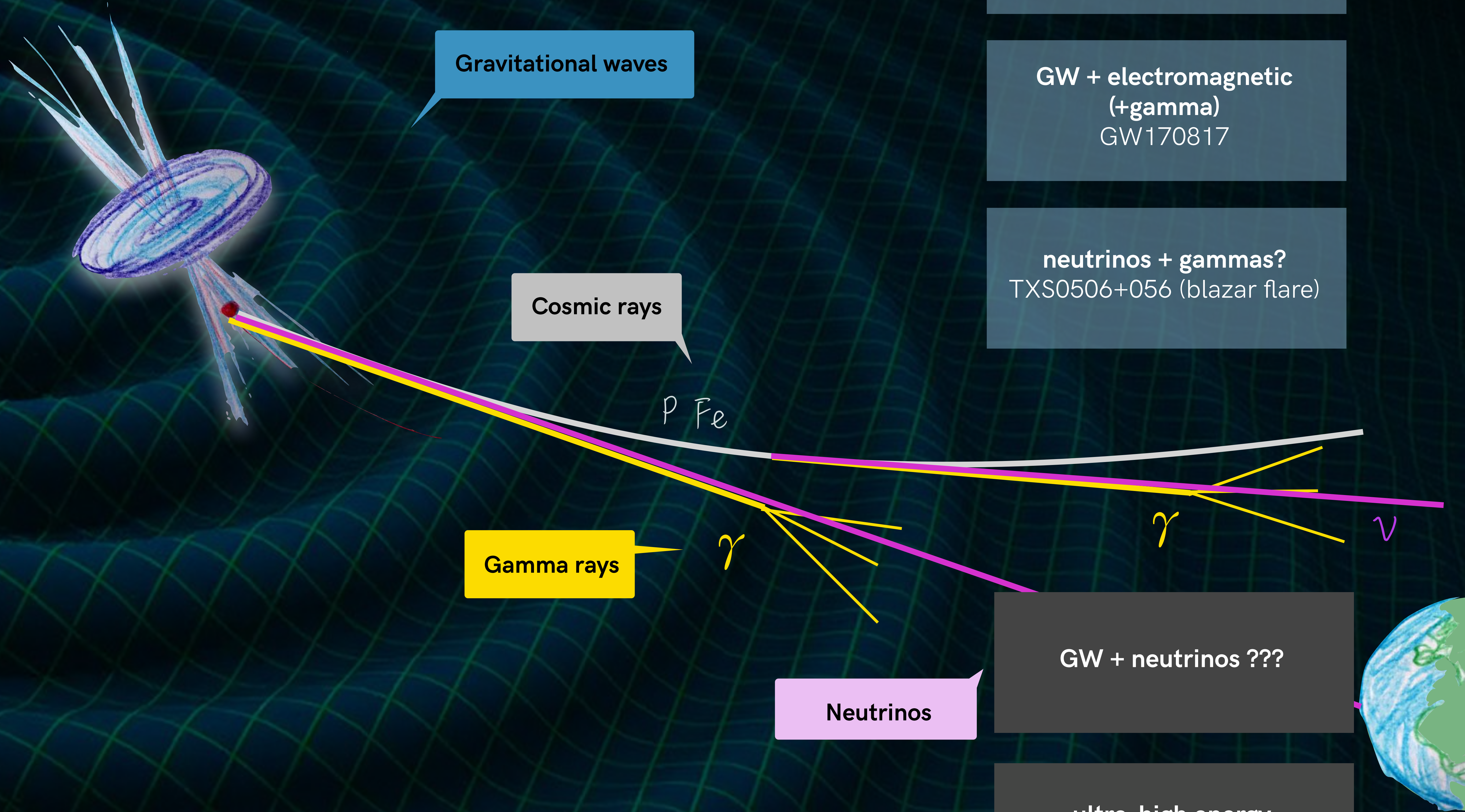
Rare powerful sources are excluded

Murase & Waxman 2016, Ackermann et al. 2019

3. Can we really do multi-messenger astrophysics?

Opening the UHE neutrino window

Multi-messengers!



Gravitational waves

Cosmic rays

Gamma rays

Neutrinos

cosmic rays + others
—> temporal coincidence
impossible (deflections)
but studies of diffuse fluxes

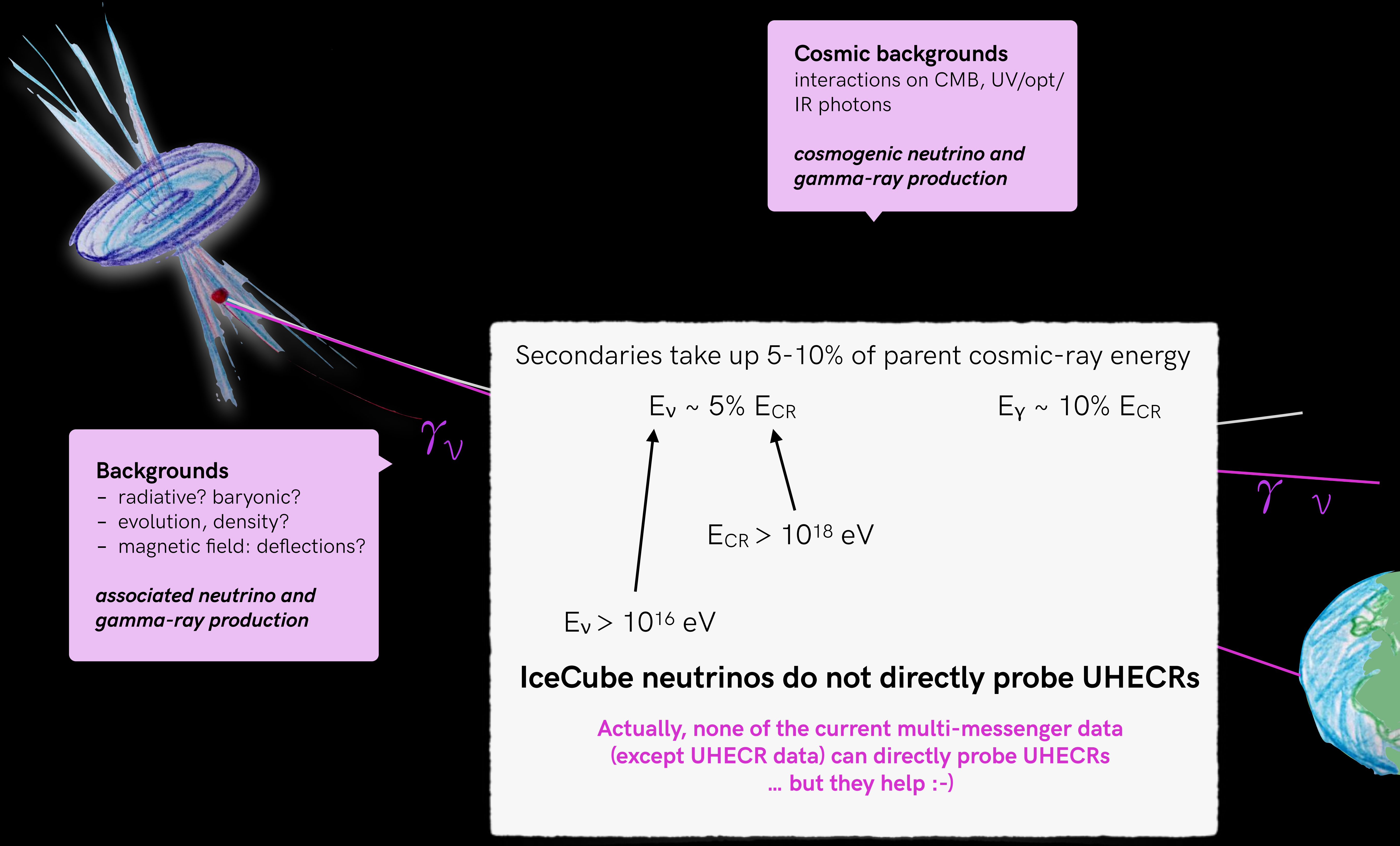
GW + electromagnetic (+gamma)
GW170817

neutrinos + gammas?
TXS0506+056 (blazar flare)

GW + neutrinos ???

ultra-high energy neutrinos ???

Current multi-messenger data: useful to understand UHECRs?



Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

Secondaries take up 5-10% of parent cosmic-ray energy

$E_\nu \sim 5\% \, E_{CR}$

$E_\gamma \sim 10\% \, E_{CR}$

$E_{CR} > 10^{18}$ eV

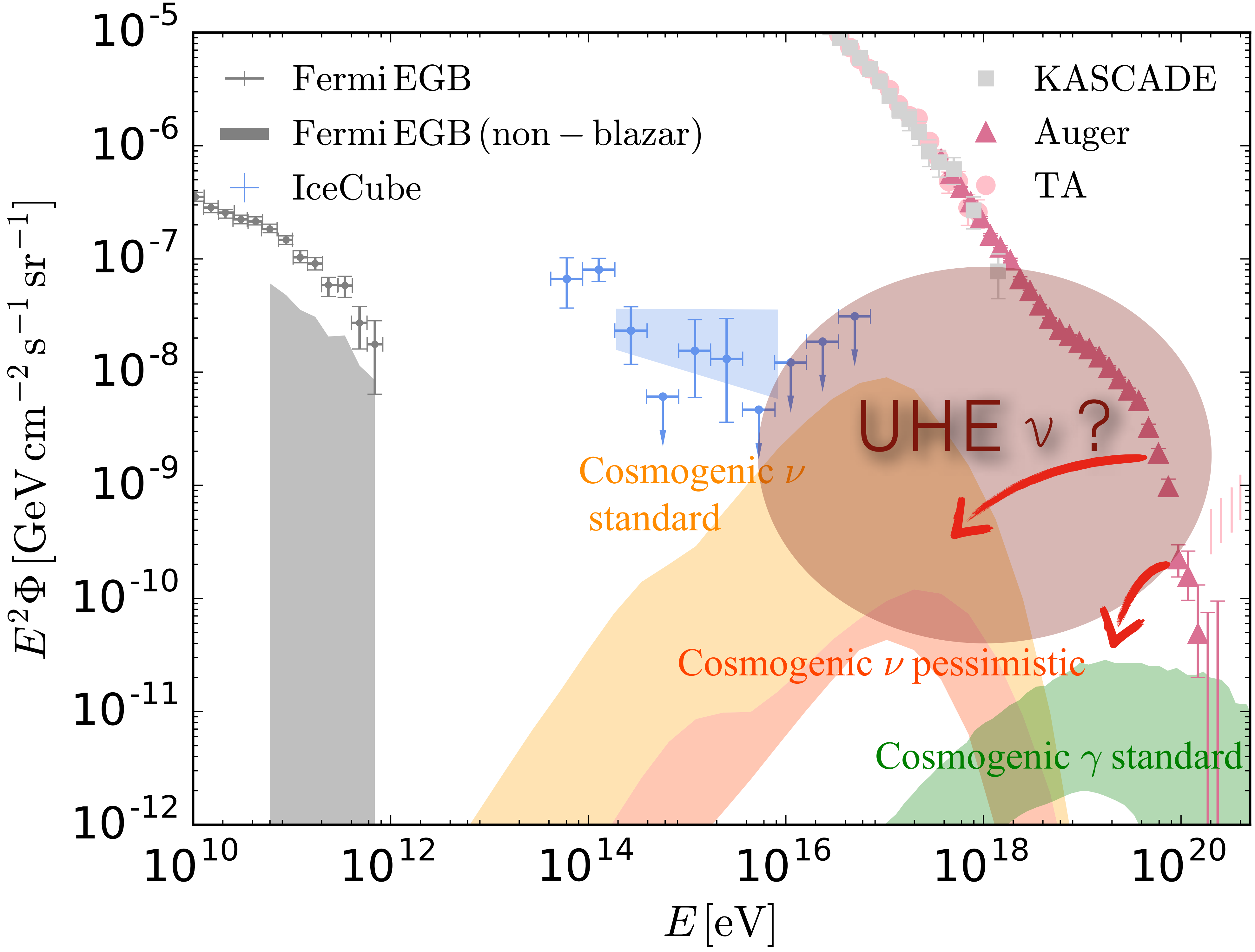
$E_\nu > 10^{16}$ eV

IceCube neutrinos do not directly probe UHECRs

Actually, none of the current multi-messenger data (except UHECR data) can directly probe UHECRs … but they help :-)

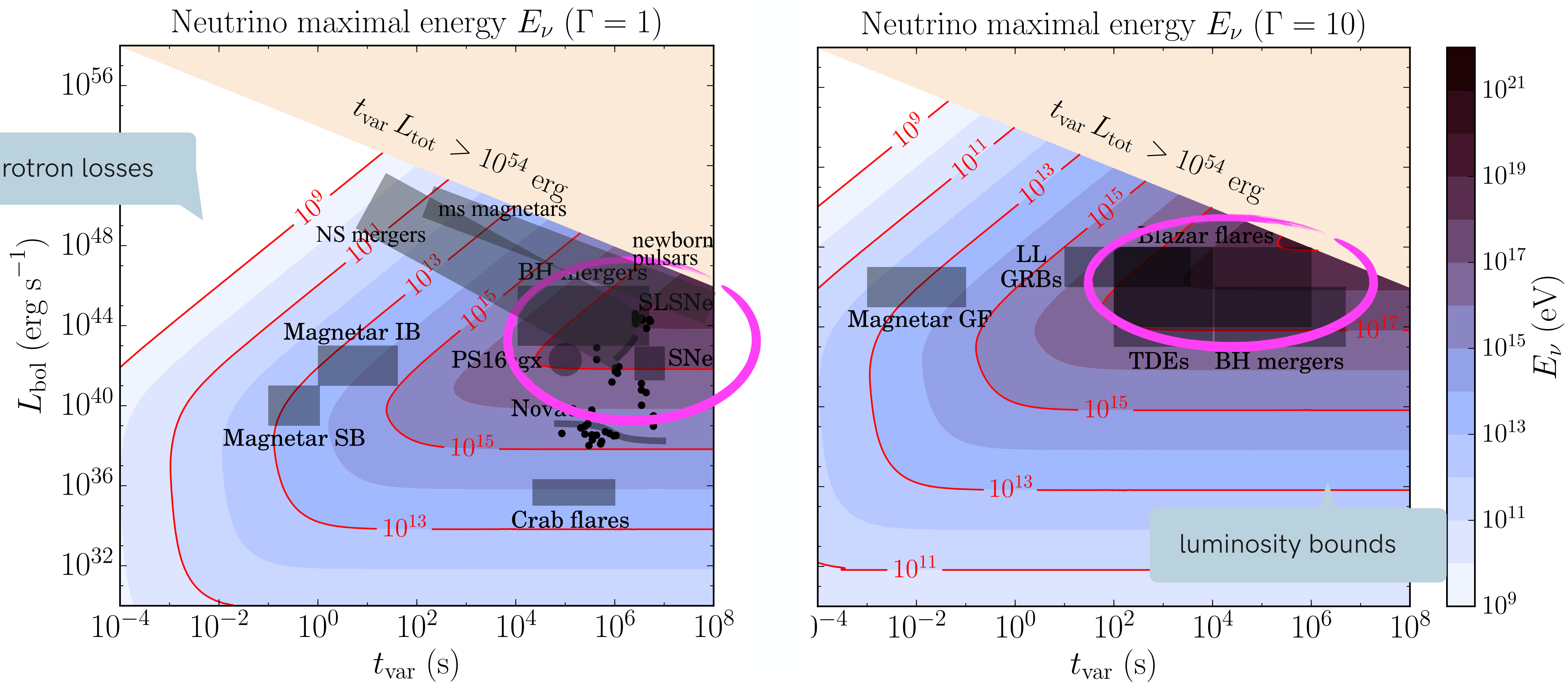
UHE neutrinos: a challenging no-man's land

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010



UHE neutrino production for transients

many transient sources could make it *Guépin & KK 2016*



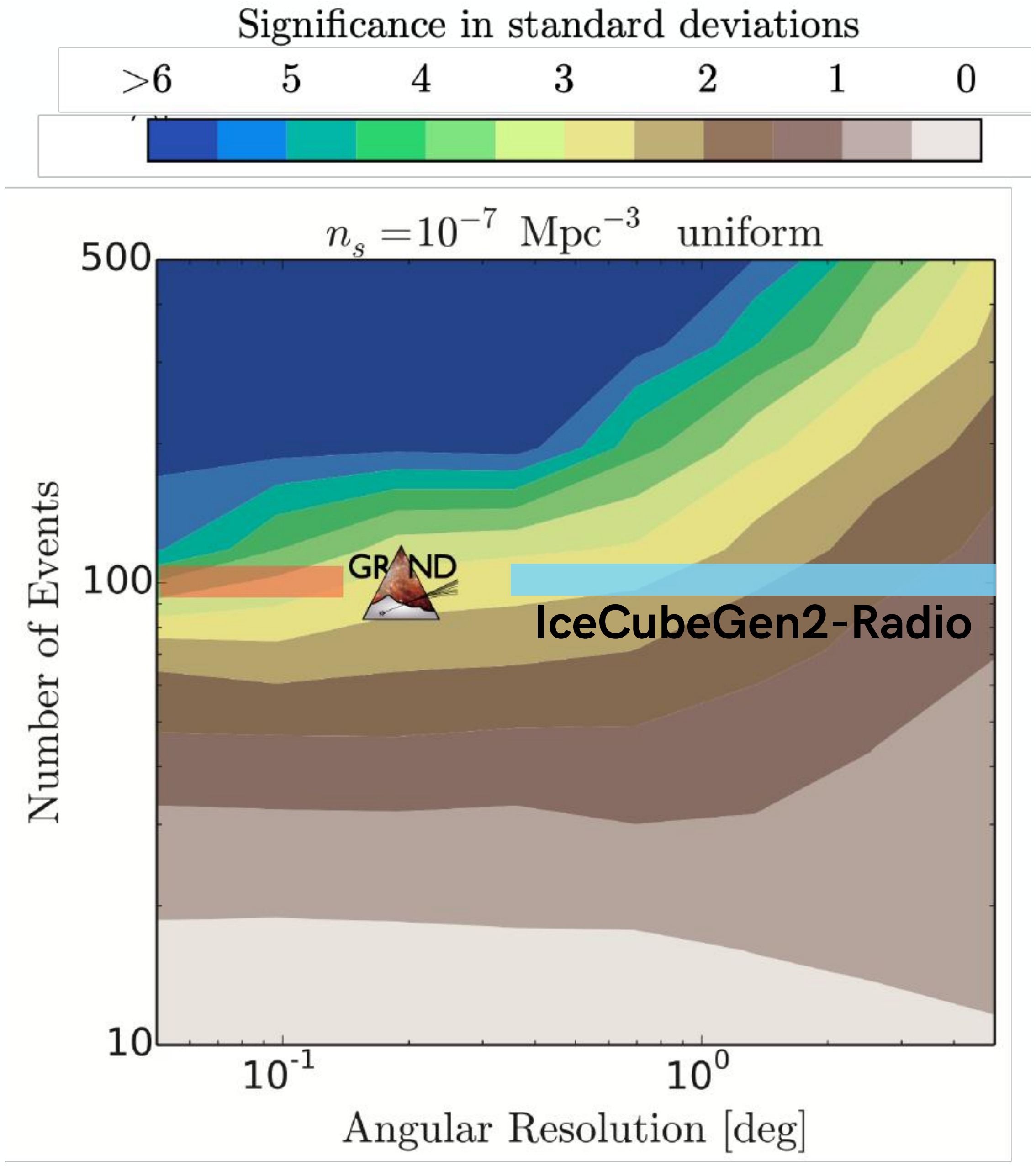
synchrotron losses

luminosity bounds

Can we hope to detect very high-energy neutrino sources?

Neutrinos don't have a horizon: won't we be polluted by background neutrinos?

Fang, KK, Miller, Murase, Oikonomou JCAP 2016



boxes for experiments assuming neutrino flux: 10^{-8} GeV cm^{-2} s^{-1}

YES if

- good angular resolution (< fraction of degree)
- number of detected events > 100s

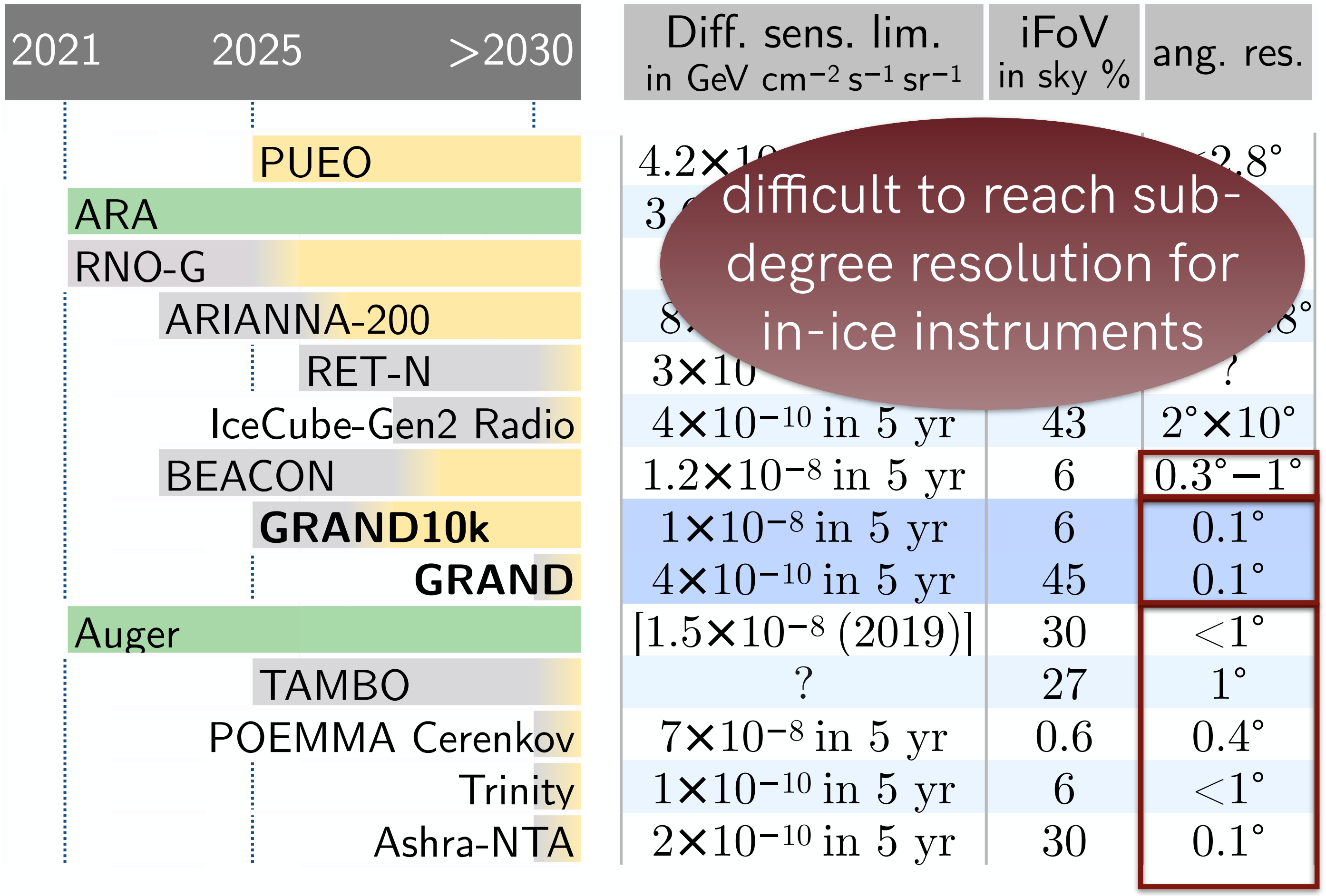
Towards UHE multi-messenger astronomy

What will we need?

✓ Excellent sensitivity
✓ Sub-degree angular resolution
✓ Wide instantaneous field of view

The angular resolution is key for multi-messenger networks

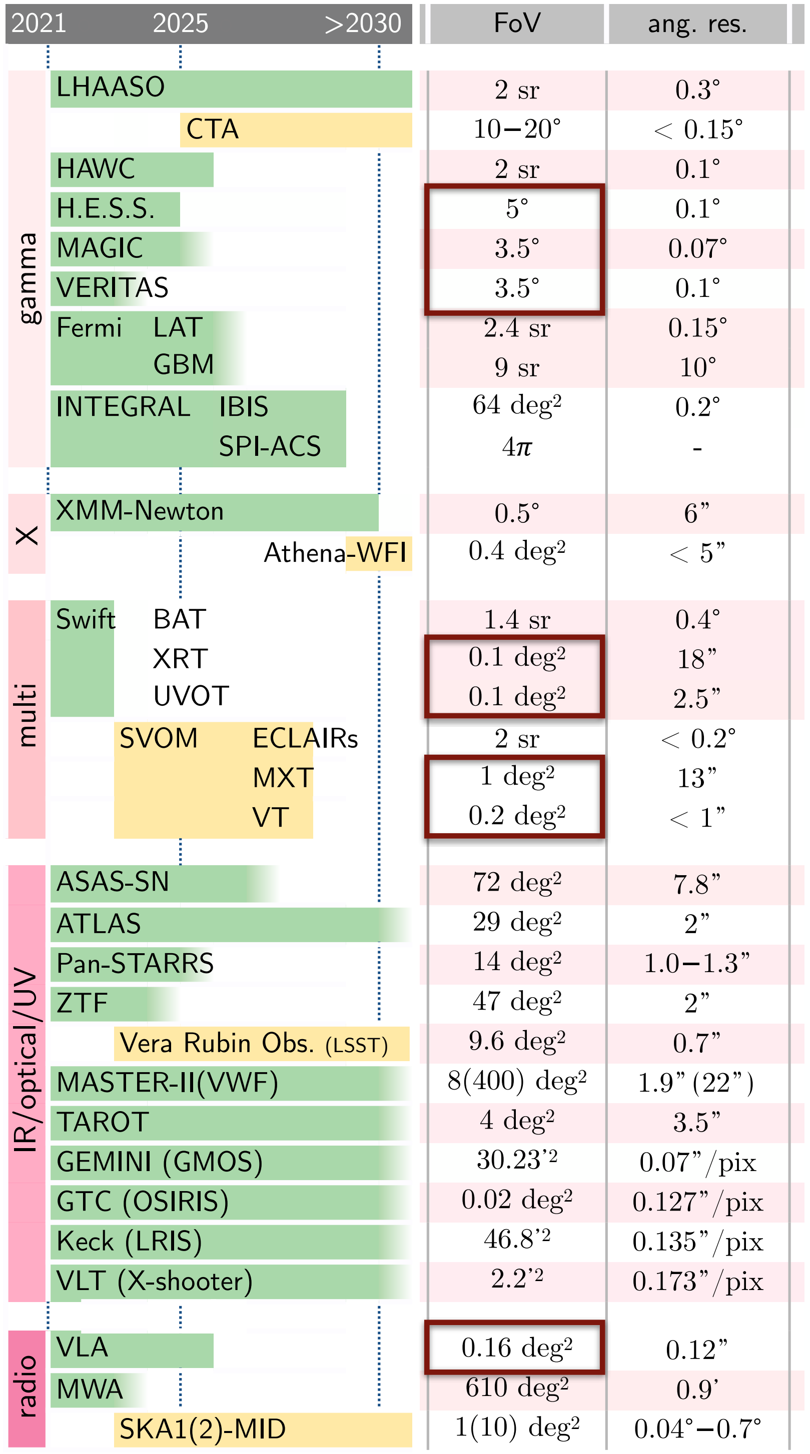
- development of MM-networks, of EM instruments
  —> false associations will be extremely common
- skim interesting events + narrow down search area
  —> requires angular resolution



2021 2025 >2030	Diff. sens. lim. in GeV cm^{-2} s^{-1} sr^{-1}	iFoV in sky %	ang. res.
PUEO	4.2×10		<2.8°
ARA	3		
RNO-G			
ARIANNA-200	8		.8°
RET-N	3×10		?
IceCube-Gen2 Radio	4×10^{-10} in 5 yr	43	2°×10°
BEACON	1.2×10^{-8} in 5 yr	6	0.3°−1°
GRAND10k	1×10^{-8} in 5 yr	6	0.1°
GRAND	4×10^{-10} in 5 yr	45	0.1°
Auger	[1.5×10^{-8} (2019)]	30	<1°
TAMBO	?	27	1°
POEMMA Cerenkov	7×10^{-8} in 5 yr	0.6	0.4°
Trinity	1×10^{-10} in 5 yr	6	<1°
Ashra-NTA	2×10^{-10} in 5 yr	30	0.1°

difficult to reach sub-degree resolution for in-ice instruments

adapted from ***Guépin, KK, Oikonomou, Nature Phys. Rev. subm.***



	2021 2025 >2030	FoV	ang. res.
gamma	LHAASO	2 sr	0.3°
	CTA	10−20°	< 0.15°
	HAWC	2 sr	0.1°
	H.E.S.S.	5°	0.1°
	MAGIC	3.5°	0.07°
	VERITAS	3.5°	0.1°
	Fermi LAT	2.4 sr	0.15°
	Fermi GBM	9 sr	10°
	INTEGRAL IBIS	64 deg^2	0.2°
	INTEGRAL SPI-ACS	4π	-
X	XMM-Newton	0.5°	6”
	Athena-WFI	0.4 deg^2	< 5”
multi	Swift BAT	1.4 sr	0.4°
	Swift XRT	0.1 deg^2	18”
	Swift UVOT	0.1 deg^2	2.5”
	SVOM ECLAIRs	2 sr	< 0.2°
	SVOM MXT	1 deg^2	13”
	SVOM VT	0.2 deg^2	< 1”
IR/optical/UV	ASAS-SN	72 deg^2	7.8”
	ATLAS	29 deg^2	2”
	Pan-STARRS	14 deg^2	1.0−1.3”
	ZTF	47 deg^2	2”
	Vera Rubin Obs. (LSST)	9.6 deg^2	0.7”
	MASTER-II(VWF)	8(400) deg^2	1.9” (22”)
	TAROT	4 deg^2	3.5”
	GEMINI (GMOS)	30.23’^{2}	0.07”/pix
	GTC (OSIRIS)	0.02 deg^2	0.127”/pix
	Keck (LRIS)	46.8’^{2}	0.135”/pix
	VLT (X-shooter)	2.2’^{2}	0.173”/pix
radio	VLA	0.16 deg^2	0.12”
	MWA	610 deg^2	0.9’
	SKA1(2)-MID	1(10) deg^2	0.04°−0.7°

Some references (a personal selection)

General perspectives and ideas

Alves Batista et al., Front. Astron. Space Sci. (2019)
Halzen & Kheirandish, Front. Astron. Space Sci. (2019)
Bartos & Murase, ARAA (2020)
Guépin, KK, Oikonomou, Nature Phys. Rev. (subm.)

Specific calculations

Dermer & Menon, Princeton University Press (2009)
KK, Allard, Olinto, JCAP (2010)
Guépin & KK, Phys. Rev. D (2017)

absolutely NOT exhaustive!