Cosmology: from fundamental questions to computing challenges

Réza Ansari

CDS kick-off meeting

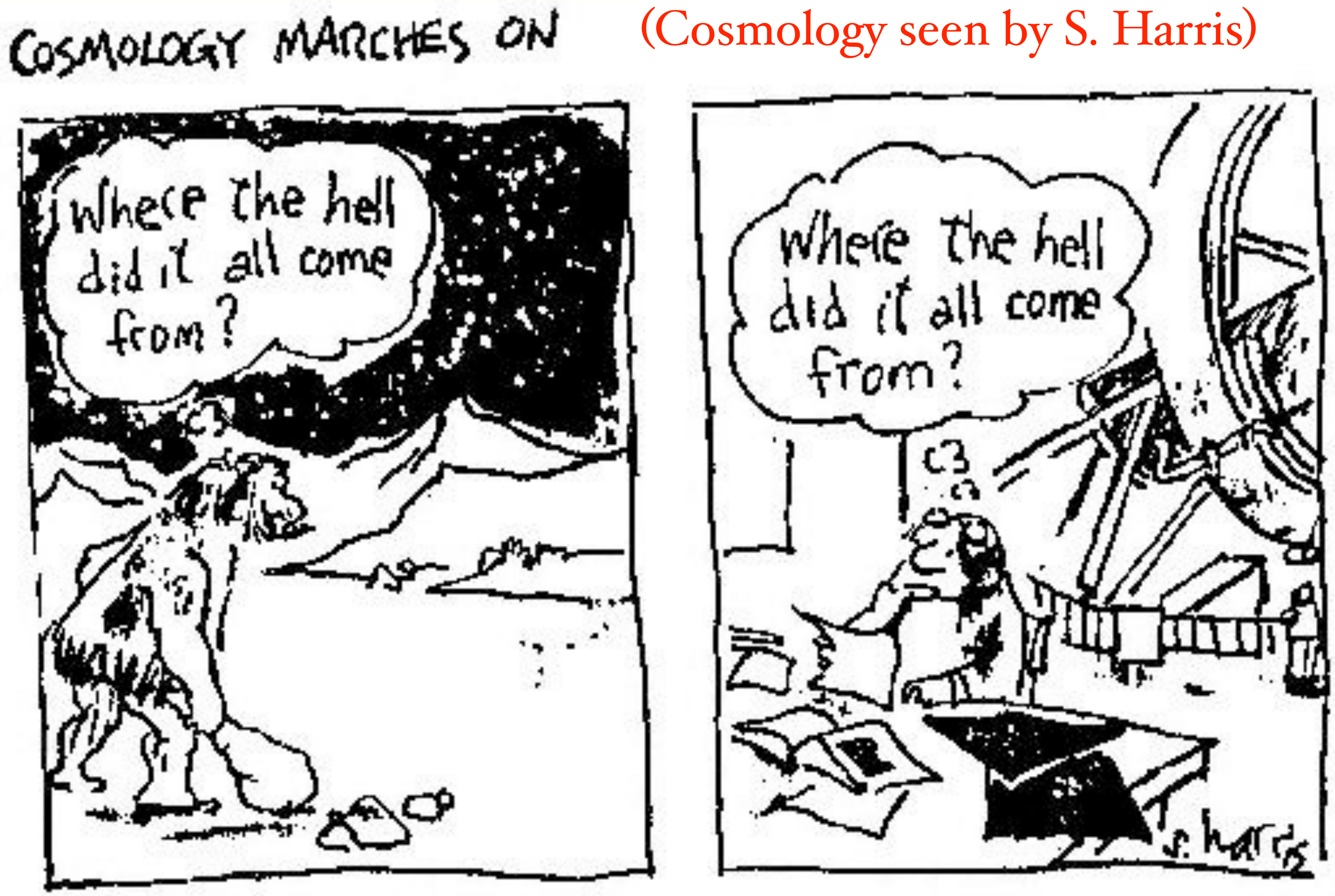
- Cosmology : fundamental questions and puzzles
  - Dark matter and dark energy
- Observing the universe
  - The electromagnetic spectrum and instruments
  - SKA, Planck, EUCLID
- Computing and data management challenges
  - The LSST case

Cosmology

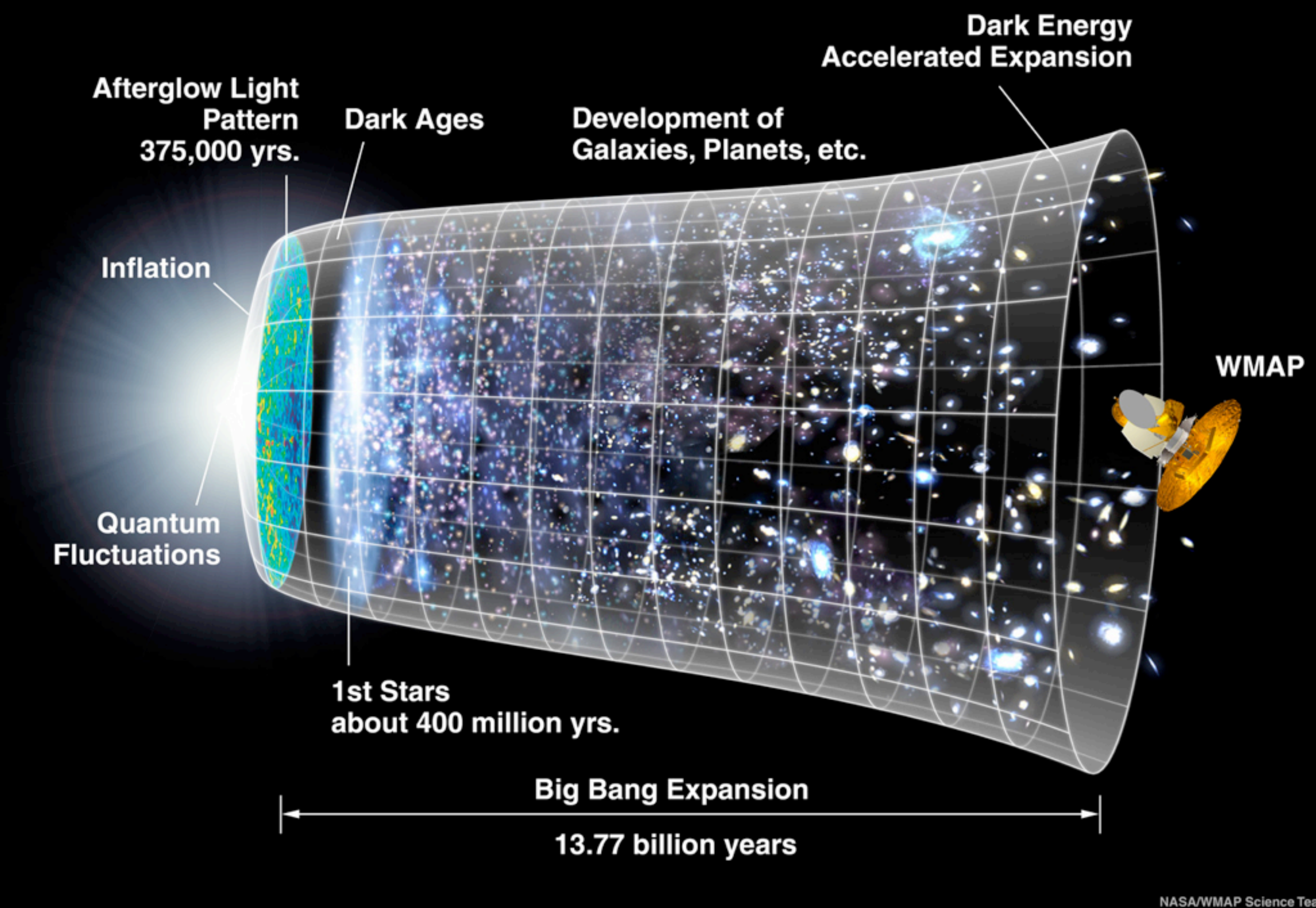
Oxford dictionary of english

cosmology |kɒzˈmɒlədʒi|
noun (pl. **cosmologies**) [mass noun]
the science of the origin and development of the universe. Modern cosmology is dominated by the Big Bang theory, which brings together observational astronomy and particle physics.
• [count noun] an account or theory of the origin of the universe.
DERIVATIVES
cosmological |-məˈlɒdʒɪk(ə)l|adjective,
cosmologist noun
ORIGIN mid 17th cent.: from French ***cosmologie*** or modern Latin ***cosmologia***, from Greek ***kosmos* 'order or world'** + ***-logia* 'discourse'**.

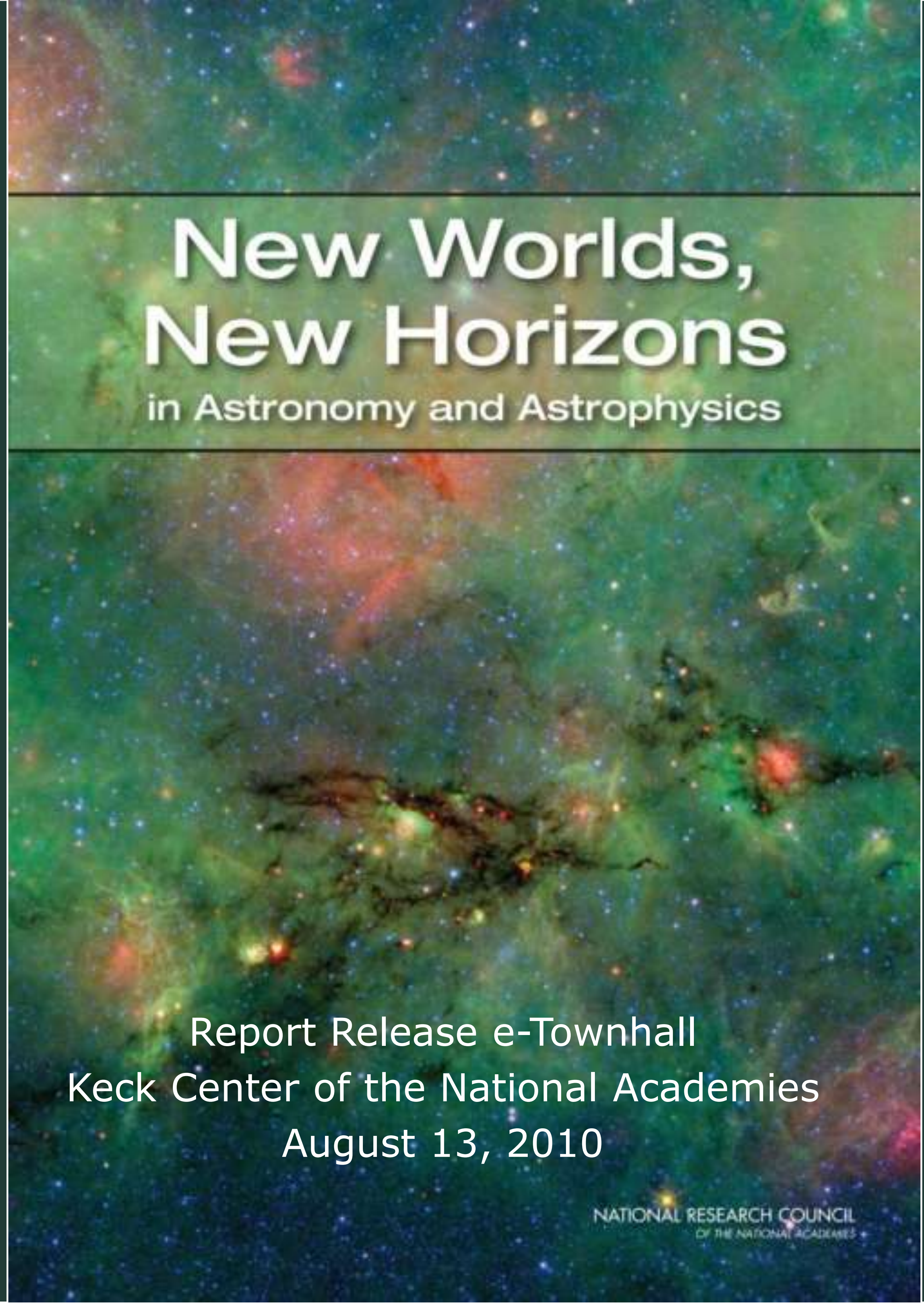
(Cosmology seen by S. Harris)



From ancient cosmography to modern **Physical Cosmology**
(General relativity & Standard model of particles and interactions)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Tea

Quoting from 2010 decadal survey

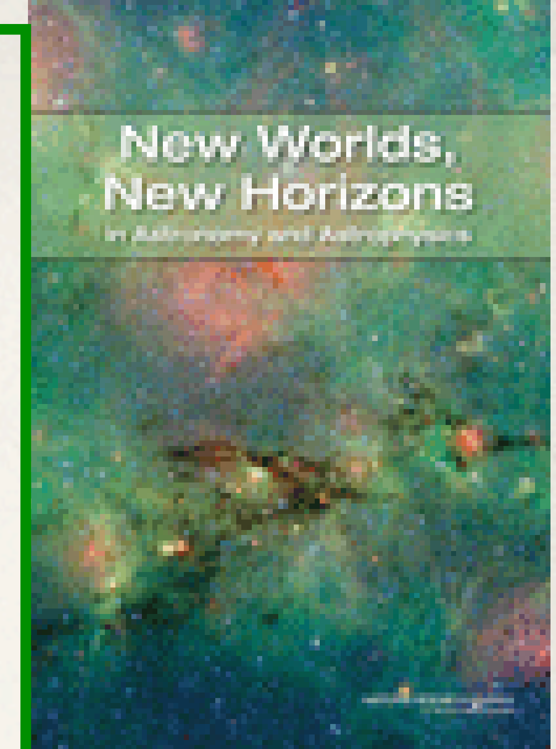


DISCOVERY

New technologies, observing strategies, theories, and computations open vistas on the universe and provide opportunities for transformational comprehension, i.e. discovery.

Science frontier discovery areas are:

- ***Identification and characterization of nearby habitable exoplanets***
- ***Gravitational wave astronomy***
- ***Time-domain astronomy***
- ***Astrometry***
- ***The epoch of reionization***



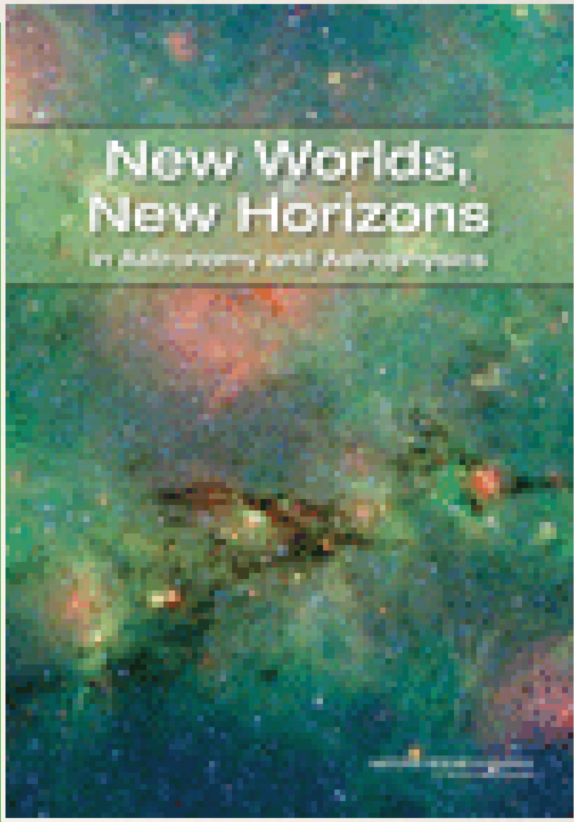
New Worls, New Horizons
Astro 2010 decadal survey

ORIGINS

Study of the origin and evolution of astronomical objects including planets, stars, galaxies, and the universe itself can elucidate our origins.

Science frontier questions in this category are:

- ***How did the universe begin?***
- ***What were the first objects to light up the universe and when did they do it?***
- ***How do cosmic structures form and evolve?***
- ***What are the connections between dark and luminous matter?***
- ***What is the fossil record of galaxy assembly and evolution from the first stars to the present?***
- ***How do stars and black holes form?***
- ***How do circumstellar disks evolve and form planetary systems?***



UNDERSTANDING THE COSMIC ORDER

When known physical laws interact, often in complex ways, outcomes of great astrophysical interest and impact result and their study improves our understanding of the cosmic order.

Science frontier questions in this category are:

- ***How do baryons cycle in and out of galaxies and what do they do while they are there?***
- ***What are the flows of matter and energy in the circumgalactic medium?***
- ***What controls the mass-energy-chemical cycles within galaxies?***
- ***How do black holes work and influence their surroundings?***
- ***How do rotation and magnetic fields affect stars?***
- ***How do massive stars end their lives?***
- ***What are the progenitors of Type Ia supernovas and how do they explode?***
- ***How diverse are planetary systems and can we identify the telltale signs of life on an exoplanet?***

New Worls, New Horizons
Astro 2010 decadal survey

FRONTIERS OF KNOWLEDGE

New fundamental physics, chemistry, and biology can be revealed by astronomical measurements, experiments, or theory and hence push the frontiers of human knowledge.

Science frontier questions in this category are:

- ***Why is the universe accelerating?***
- ***What is dark matter?***
- ***What are the properties of the neutrinos?***
- ***What controls the masses, spins and radii of compact stellar remnants?***

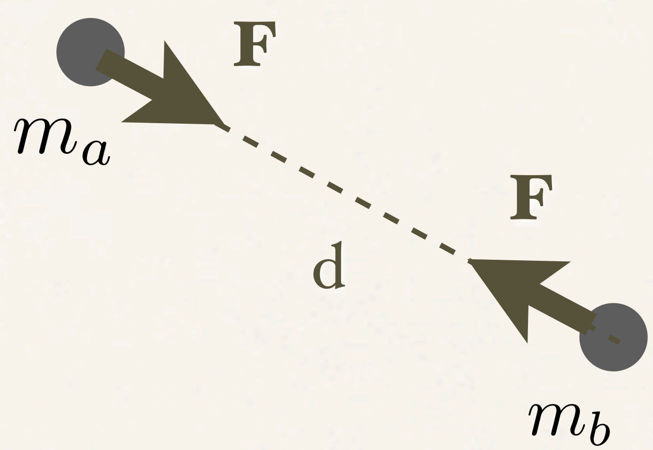
Cosmology: main questions and tools

- Energy and matter content of the universe (Dark matter, dark energy)
- Structure formation and evolution
- Primordial cosmology: inflation …
- Primordial nucleosynthesis
- Formation and evolution of galaxies and stars
- Cosmic microwave background: temperature and polarisation C(l) spectrum
- Statistical properties of large scale structures
- Geometrical probes: $d_A(z)$, $d_L(z)$ … : SNIa , Clusters, BAO …

Dark Matter : invisible matter revealed by its gravitational effects

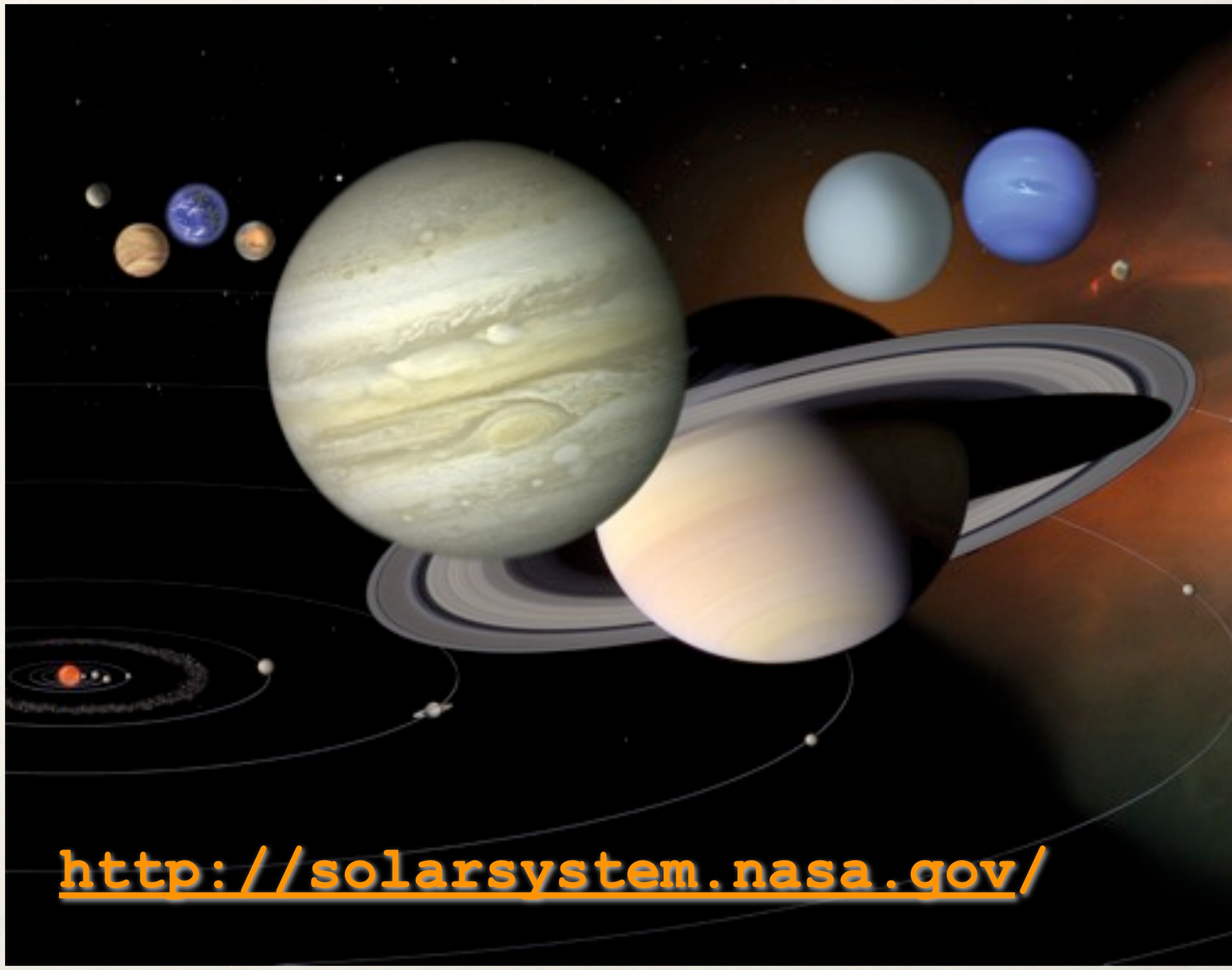
$$\mathbf{F} = G\,\frac{m_a\,m_b}{d^2}\,\vec{u_{ab}}$$

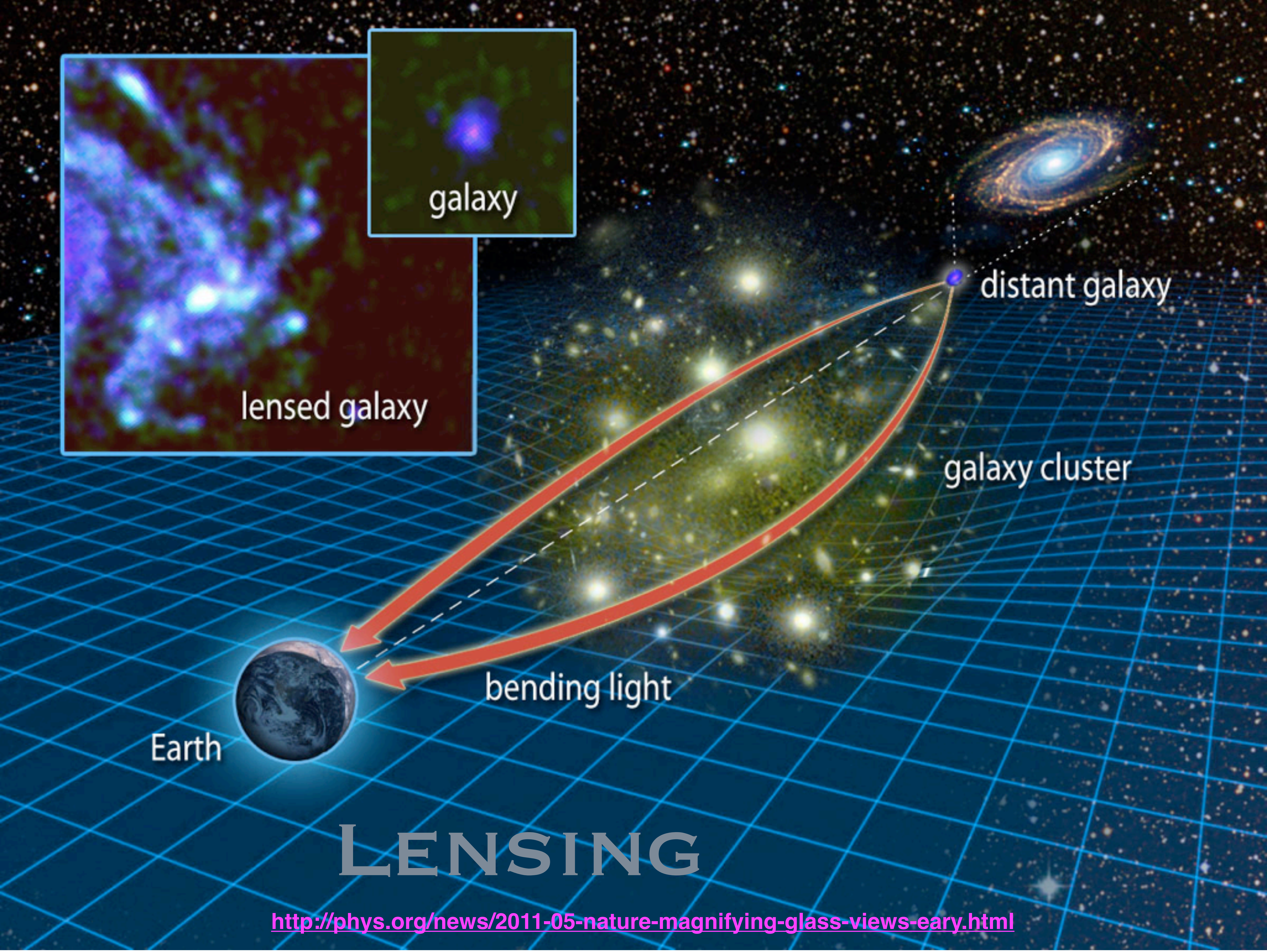
$$\Phi(r) = -G\,\frac{m}{r}$$



Urbain Le Verrier (1811-1877)

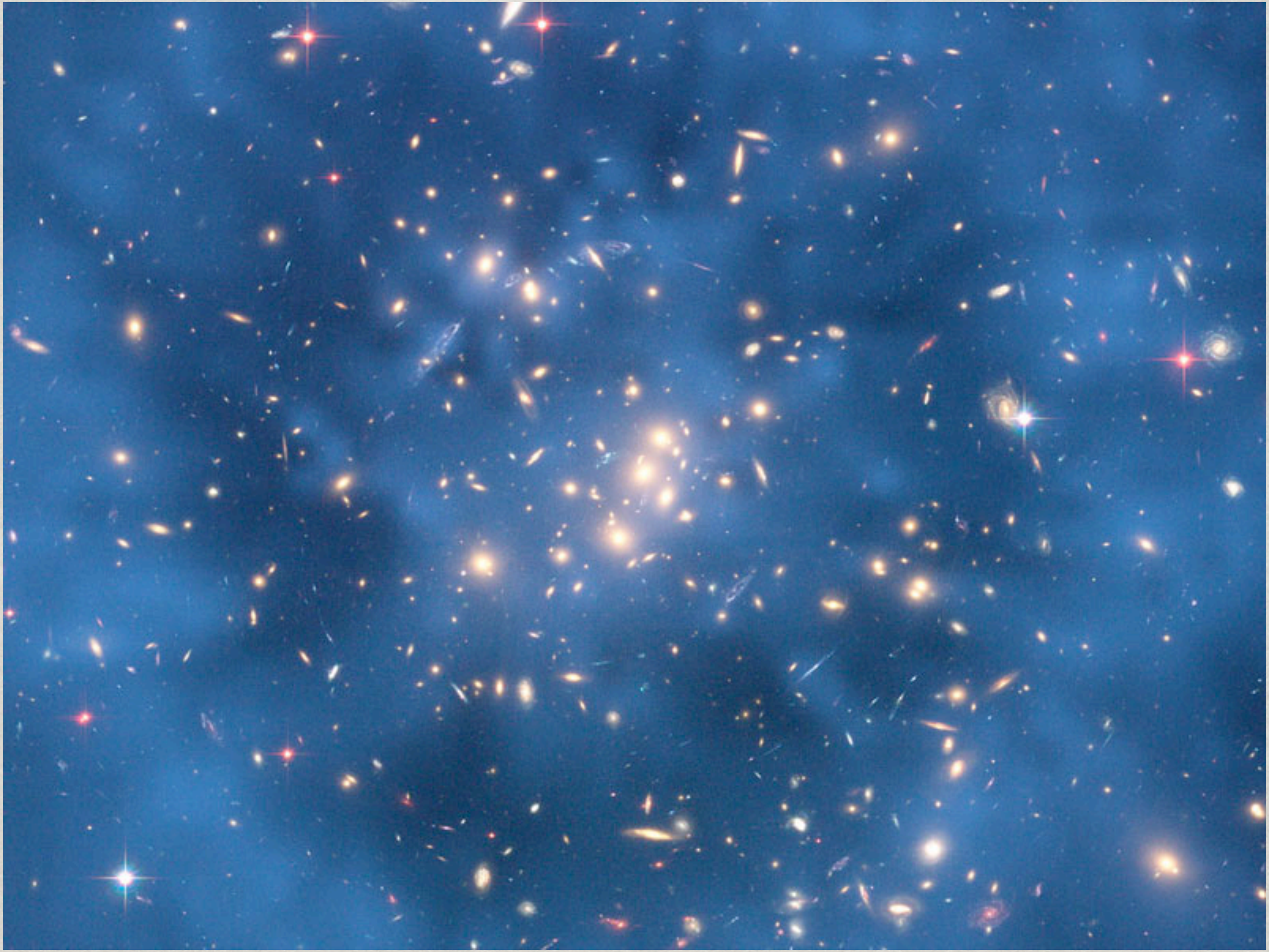
Le Verrier computed Neptune's characteristics from the Uranus movement anomalies





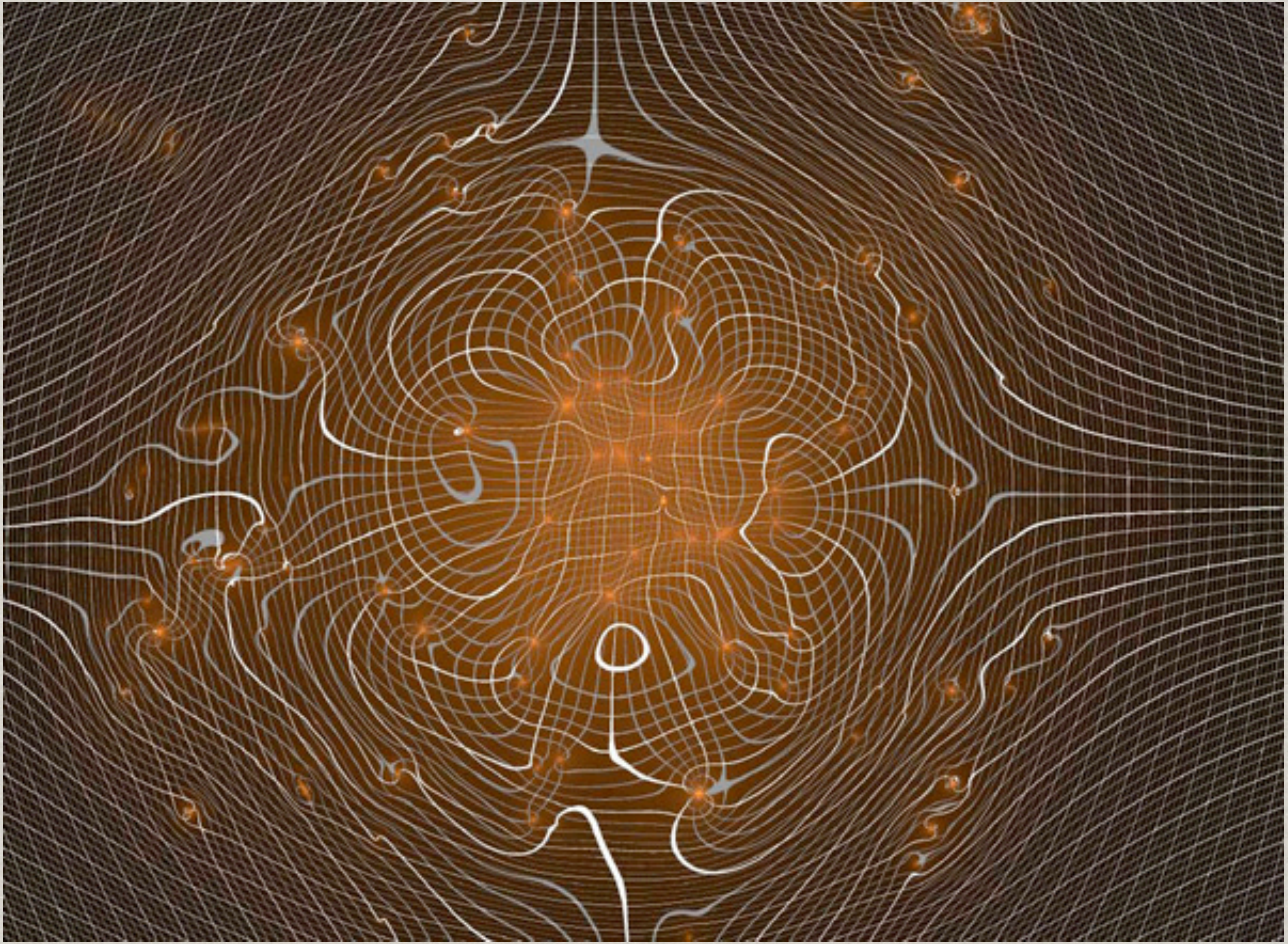
Lensing

http://phys.org/news/2011-05-nature-magnifying-glass-views-eary.html



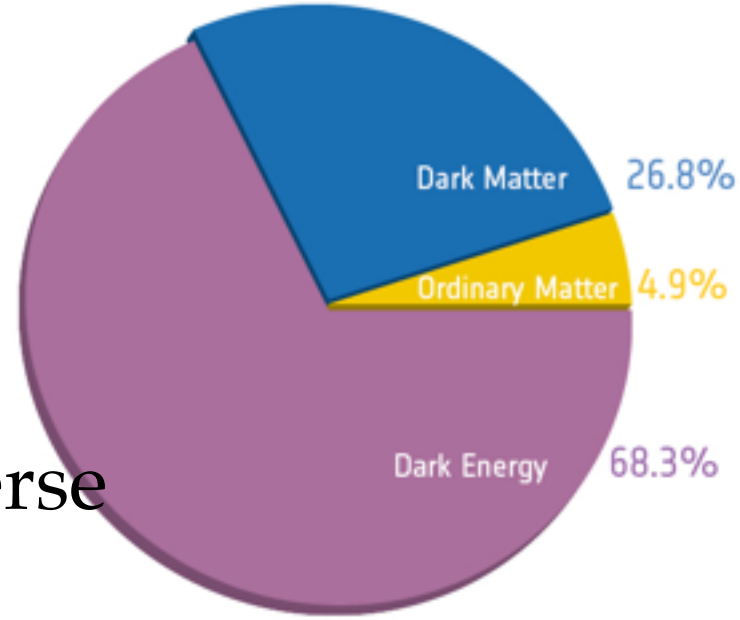
Galaxy cluster CL0024+17 (z ~ 0.39 , ~ 5. 10^9 AL) seen by HST

Gravitational reconstruction of the gravitational potential for CL0024+17



http://www.lsst.org/lsst/science

Dark Energy (or Λ)



Planck-2013

- ✤Recent cosmological observations imply a flat universe
- ✤Matter (including dark matter) is about a quarter of the critical density. Most of the energy density in the universe seems to be made of a mysterious component behaving like Λ
- ✤Λ : Repulsive gravity !
- ✤Vaccum energy (quantum fluctuations) ➠ Dark Energy ?
- ✤Determination of state equation of this cosmic fluid:

$$p = w(z)\,\varrho$$

- ✤$w(z) = -1$ for the cosmological constant (Λ)

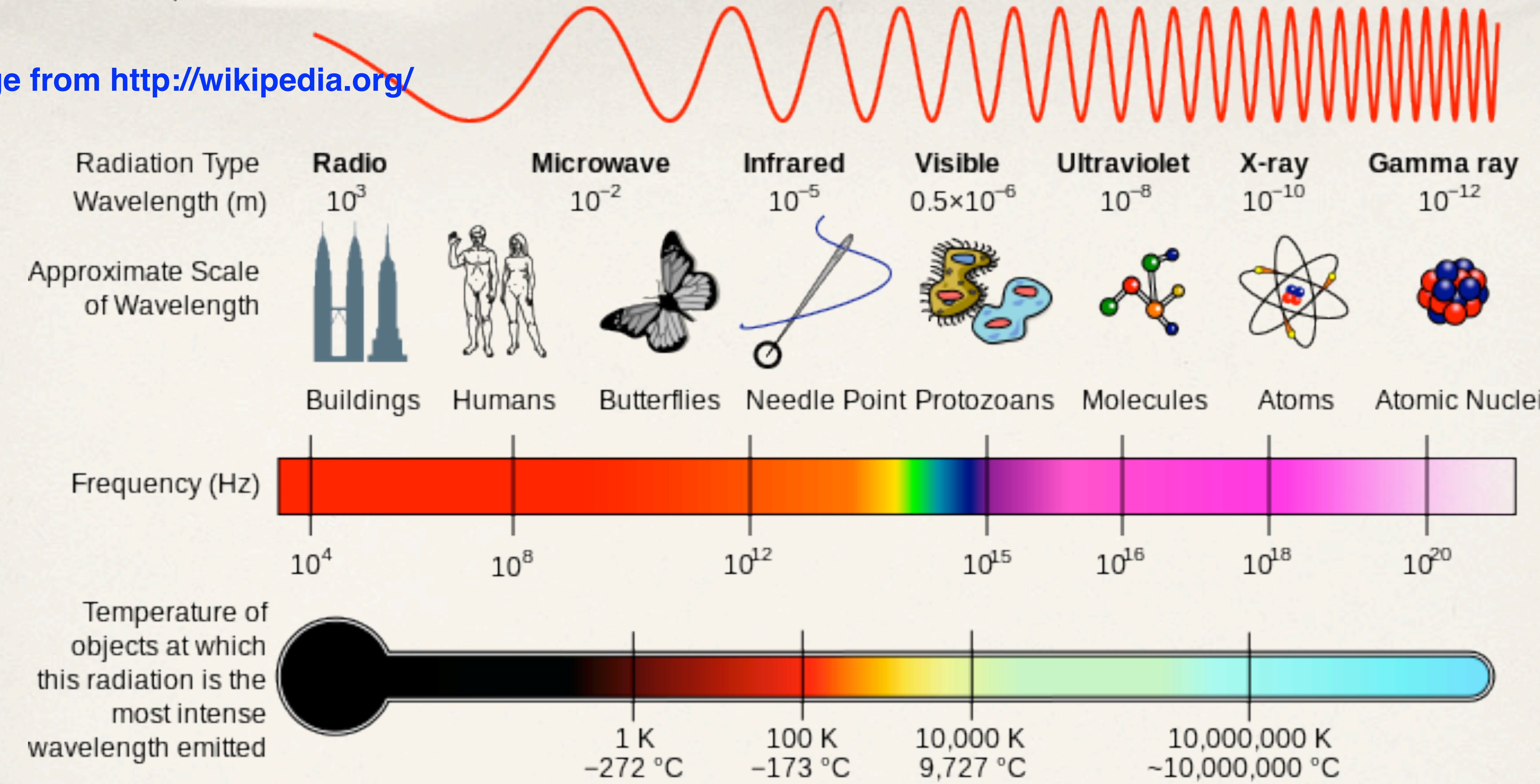
http://www.nsf.gov/mps/ast/detf.jsp

R. Ansari - March 2014

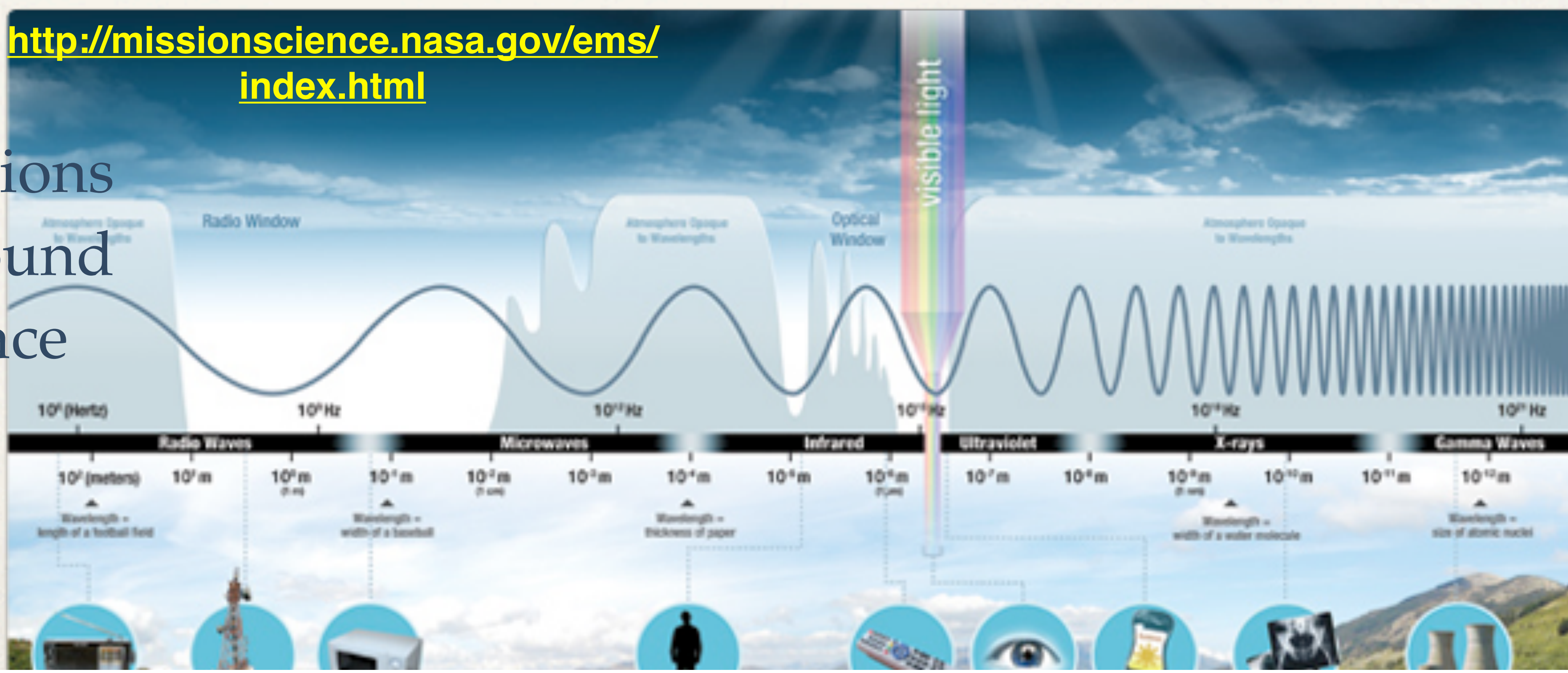
Observing the universe …

- Through the electromagnetic spectrum, but also energetic particles (cosmic rays) and maybe GW (gravitational waves) in the future
- SKA (future very large radio telescope ; ground based ; 2020-2030)
- Planck (ESA CMB mission, 2009-2013 - space mission)
- EUCLID (future ESA optical/IR dark energy mission - 2024)
- …

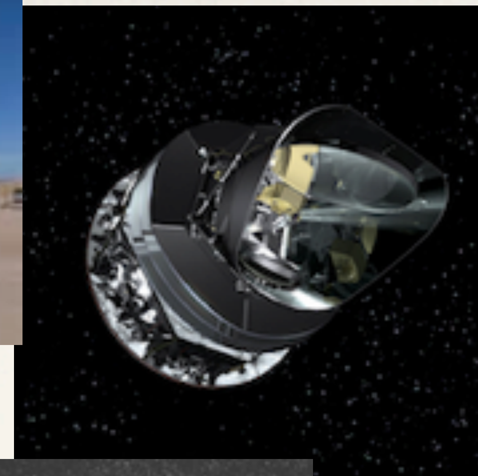
Image from http://wikipedia.org/

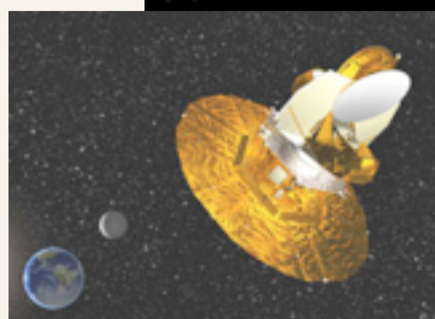


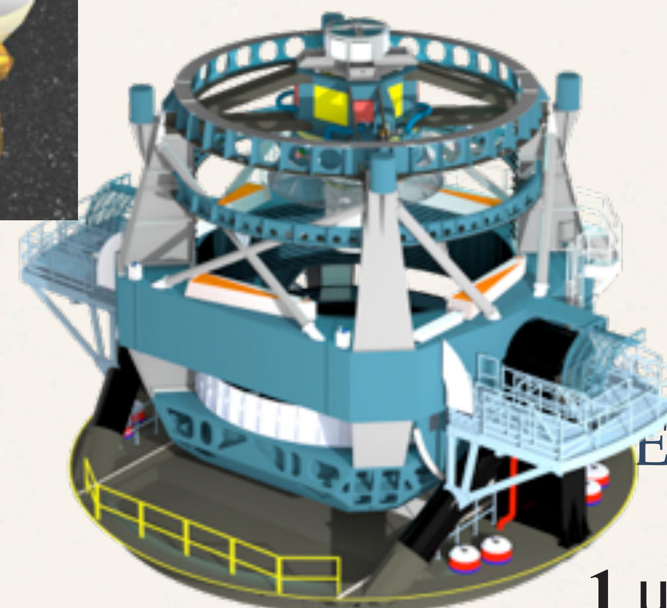
http://missionscience.nasa.gov/ems/index.html



Observations from Ground and space







SKA
VLA
...

ALMA

Planck
WMAP
...

ELT
LSST
VLT
SDSS
CFHT
EUCLID
...

XMM
Chandra
Fermi
...

1 m — 1 mm — 1 µm

10^2 — 10 — 1 — 10^{-1} — 10^{-2} — 10^{-3} — 10^{-4} — 10^{-5} cm

Longueur d'onde

10^8 — 10^9 — 10^{10} — 10^{11} — 10^{12} — 10^{13} — 10^{14} — 10^{15} Fréquence (Hz)

adio - Télévision

Téléphones mobiles

Micro-ondes

IR — UV

Lumière visible (0.4 - 0.8 µm)

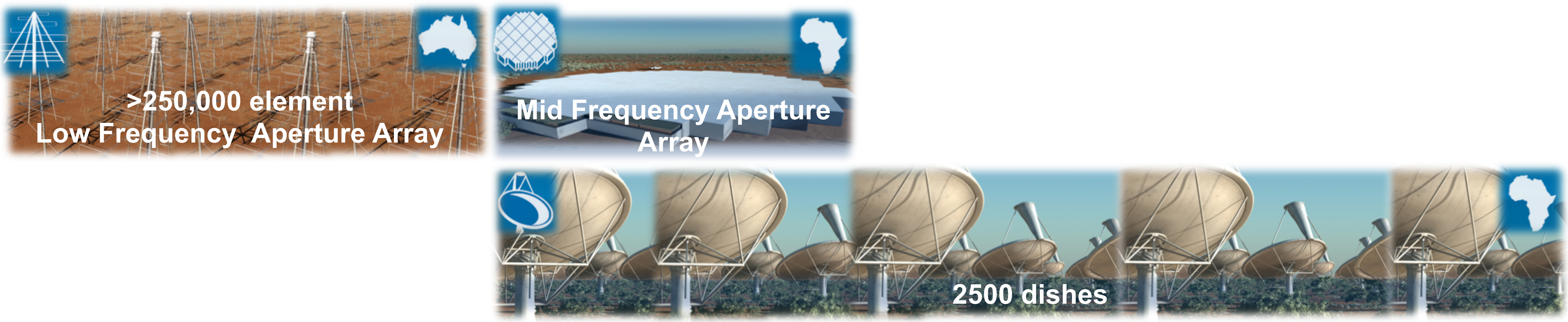
Exploring the Universe with the world's largest radio telescope

SKA SQUARE KILOMETRE ARRAY

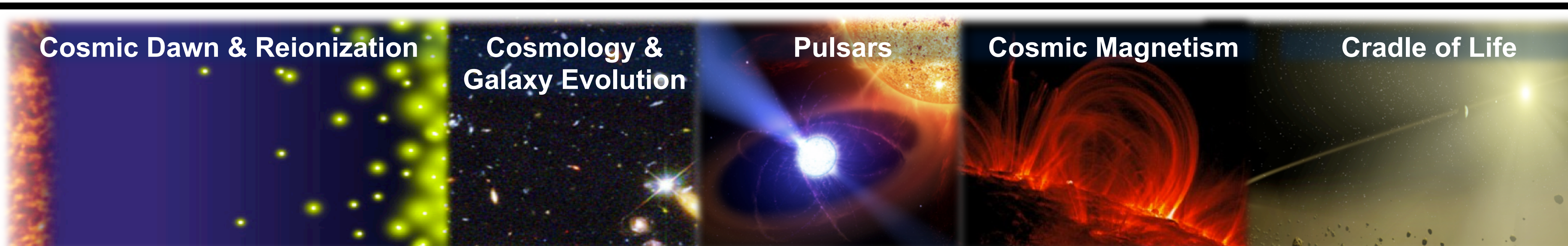
Phase I : 2020

Slide by R. Braun
SKA Science director

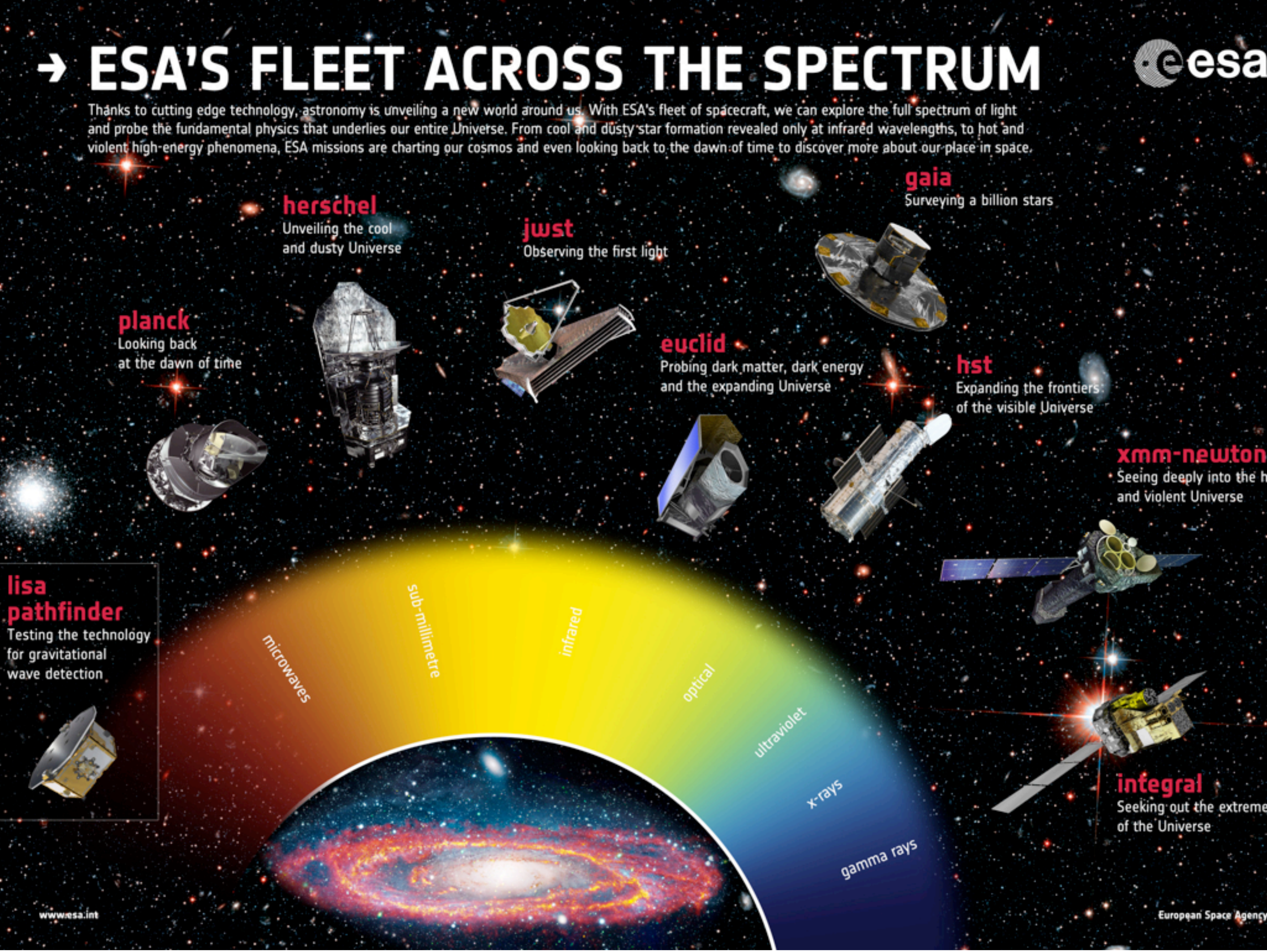
Phase II : 2024



Science

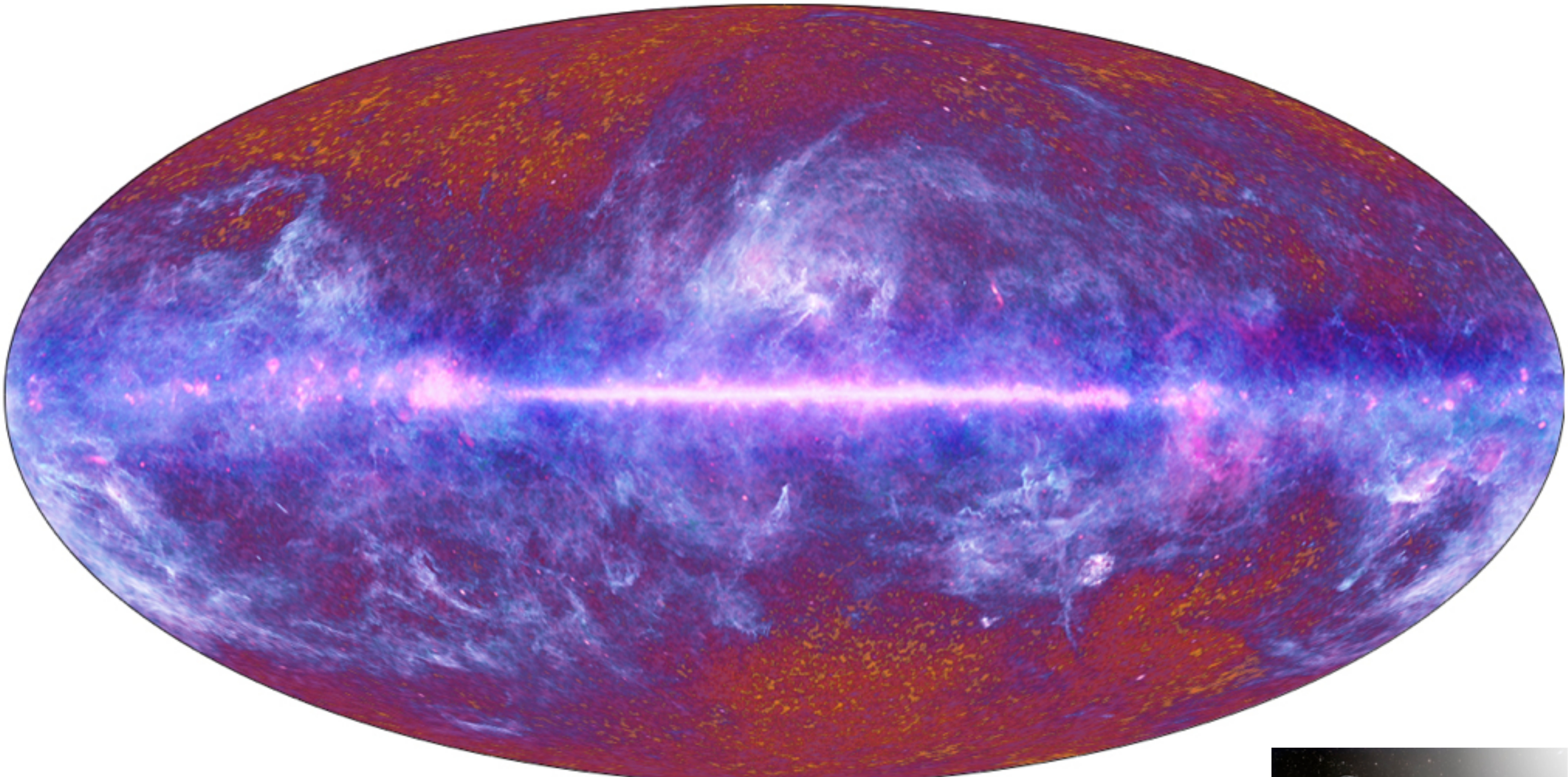


50 MHz **100 MHz** **1 GHz** **10 GHz**



→ ESA'S FLEET ACROSS THE SPECTRUM
esa
Thanks to cutting edge technology, astronomy is unveiling a new world around us. With ESA's fleet of spacecraft, we can explore the full spectrum of light and probe the fundamental physics that underlies our entire Universe. From cool and dusty star formation revealed only at infrared wavelengths, to hot and violent high-energy phenomena, ESA missions are charting our cosmos and even looking back to the dawn of time to discover more about our place in space.
herschel
Unveiling the cool and dusty Universe
jwst
Observing the first light
gaia
Surveying a billion stars
planck
Looking back at the dawn of time
euclid
Probing dark matter, dark energy and the expanding Universe
hst
Expanding the frontiers of the visible Universe
xmm-newton
Seeing deeply into the
and violent Universe
lisa pathfinder
Testing the technology for gravitational wave detection
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
integral
Seeking out the extreme
of the Universe
www.esa.int
European Space Agency

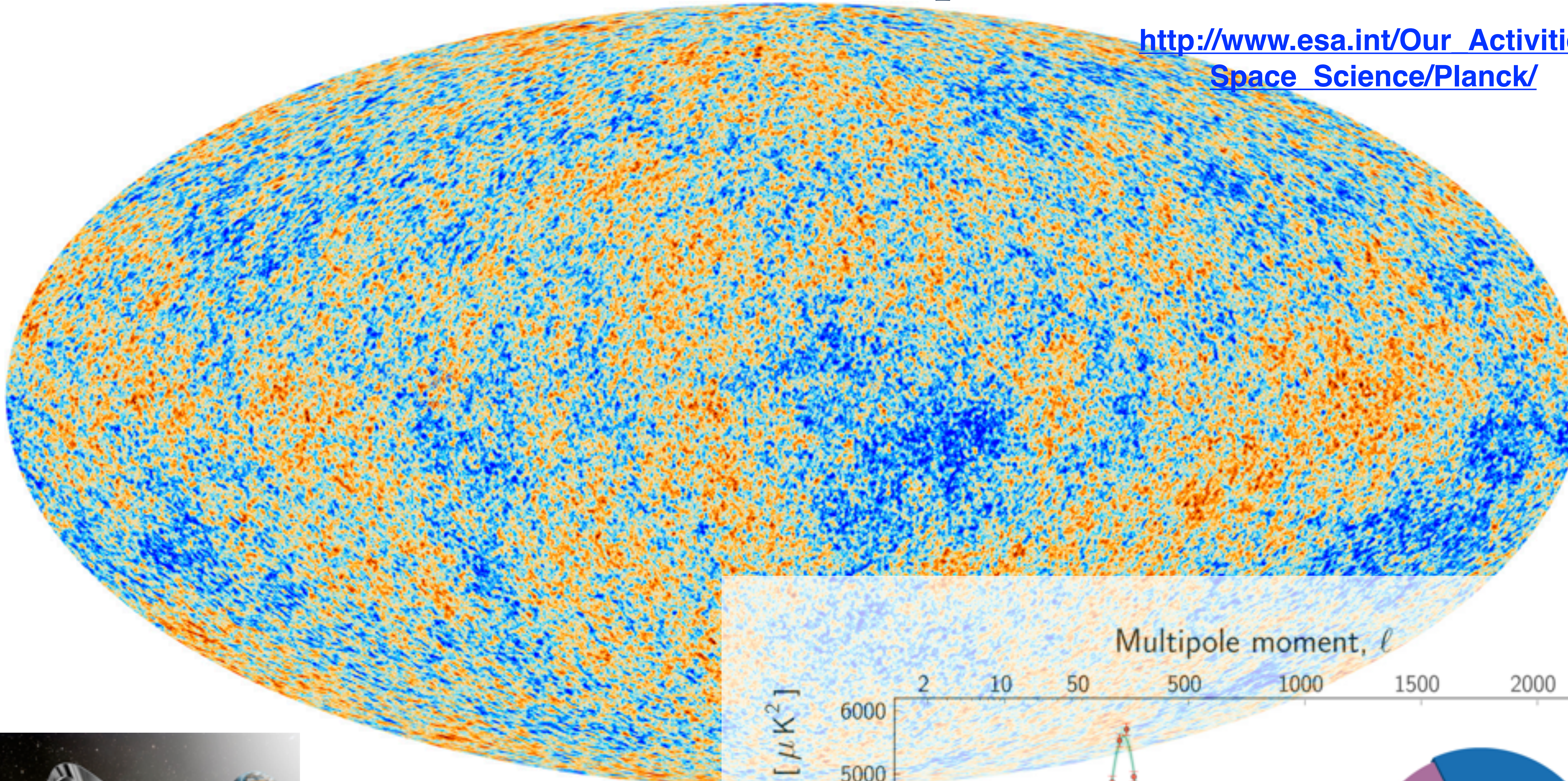
Microwave sky as seen by **Planck**
(composite image 30 GHz … 850 GHz)



http://www.esa.int/Our_Activities/Space_Science/Planck/

Planck

Planck CMB map (2013)



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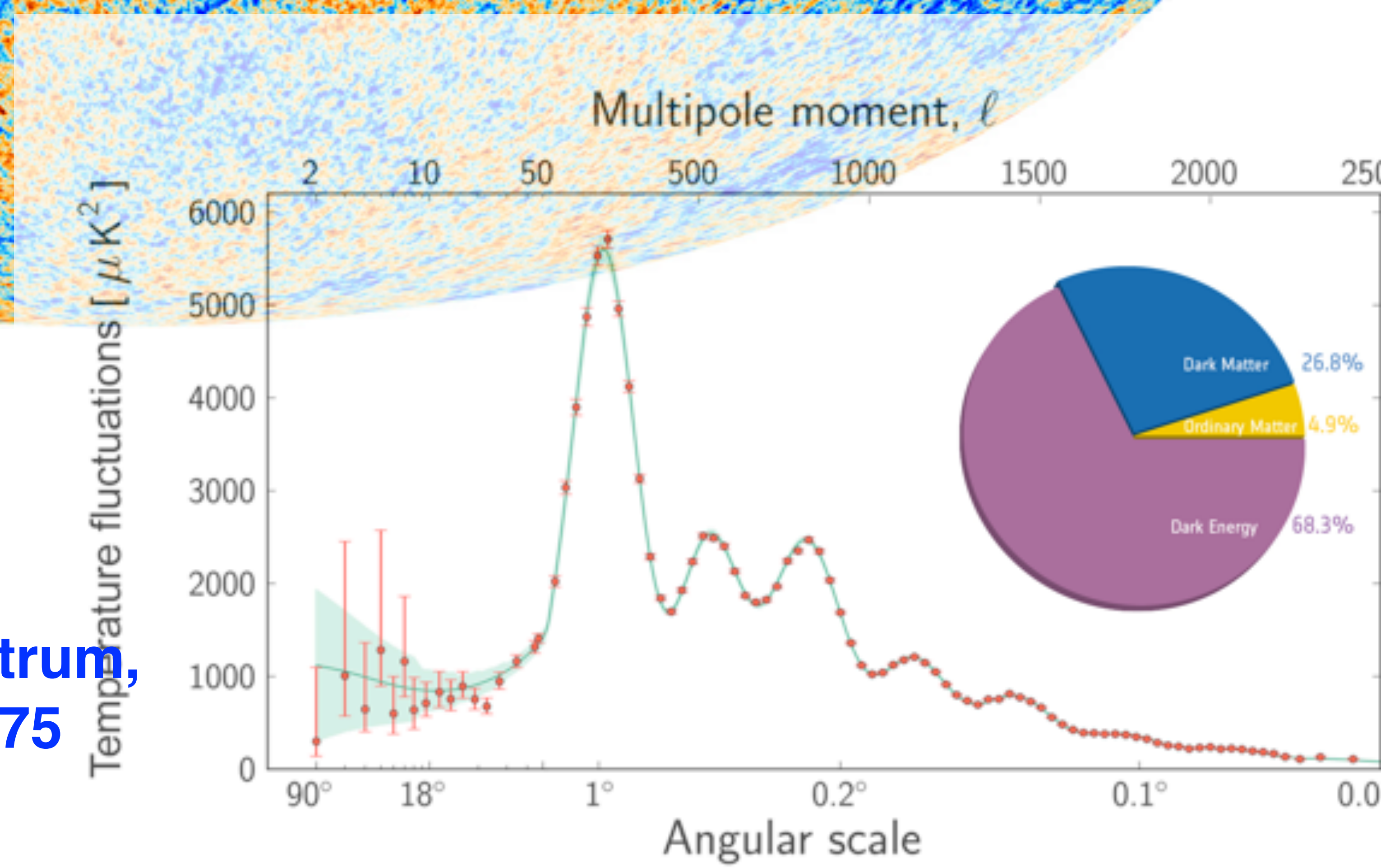
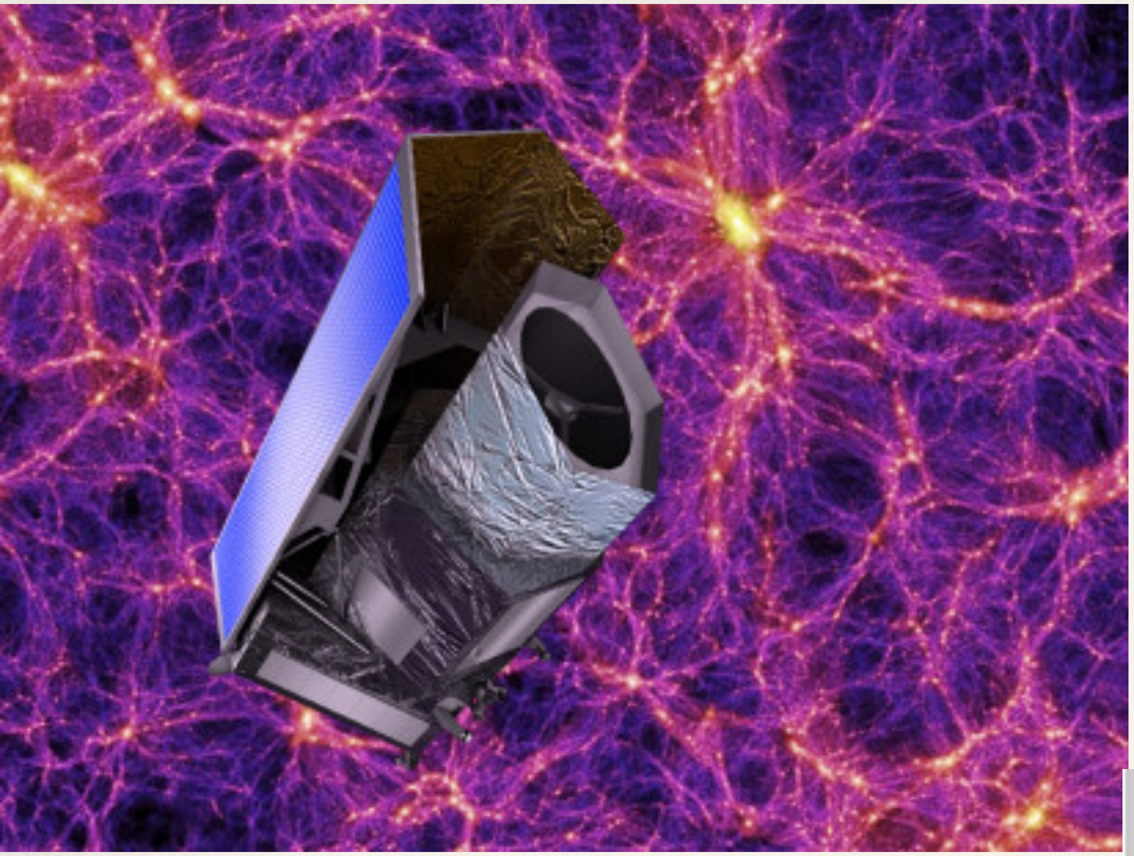


Planck CMB map, and TT power spectrum, Planck collaboration arXiv 1303.5075

EUCLID



Instrument characteristics Visual imager (VIS)	
Field-of-view	0.787 deg × 0.709 deg
Capability	Visual imaging
Wavelength range	550 - 900 nm
Sensitivity	2.5 mag 10σ extended source
Detector Technology	36 arrays 4k × 4k CCD
Pixel Size **Spectral resolution**	0.1 arcsec

Instrument characteristics Near-infrared spectrometer and photometer (NISP)				
Field-of-view	0.763 deg × 0.722 deg			
Capability	Near-infrared imaging photometry			Near-infrared spectroscopy
Wavelength range	Y (920 -1146 nm)	J (1146 - 1372 nm)	H (1372 - 2000 nm)	1100 - 2000 nm
Sensitivity	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3×10^{-16} erg cm^{-2} s^{-} 3.5σ unresolved line flux
Detector Technology	16 arrays 2k × 2k near-infrared sensitive HgCdTe detectors			
Pixel Size **Spectral resolution**	0.3 arcsec			0.3 arcsec R=250

- M-class mission selected by ESA in october 2011
- Launch in 2020
- 2100 kg spacecraft, D=1.2 m mirror
- Visible camera (VIS) and IR camera and spectrometer (NISP

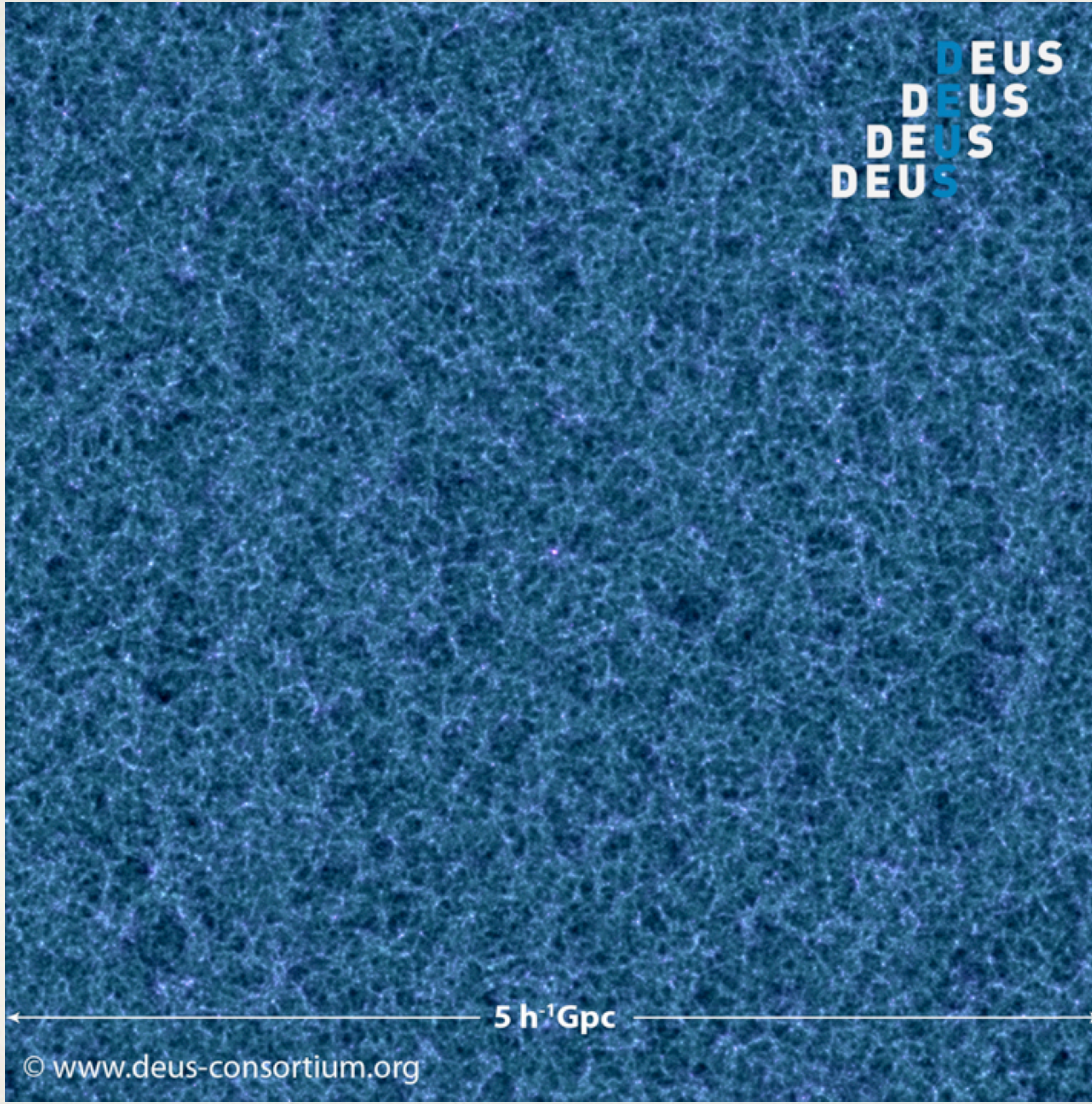
http://sci.esa.int/euclid/46676-spacecraft/

Computing challenges

- Data acquisition (volume, on-line processing …)
- Data processing and reduction : image and signal processing methods
- Large volume data storage and management
- Statistical inference
- Large scale modeling and simulation
- Making data usable and available to the scientific community

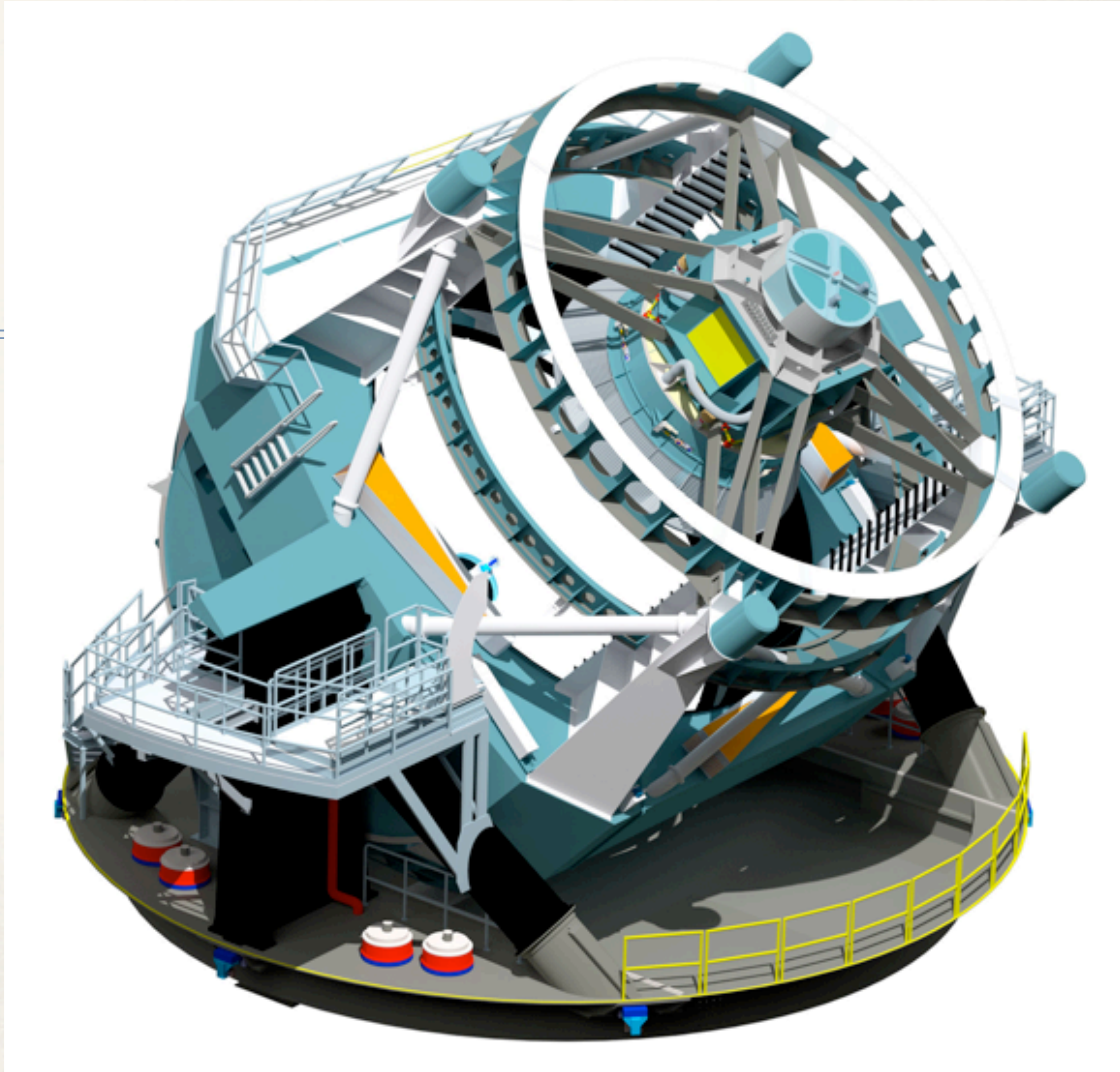
Large scale cosmological
simulations :
High performance computing,
millions hours of CPU …

http://www.deus-consortium.org



LSST

- Instrument
- LSST data management

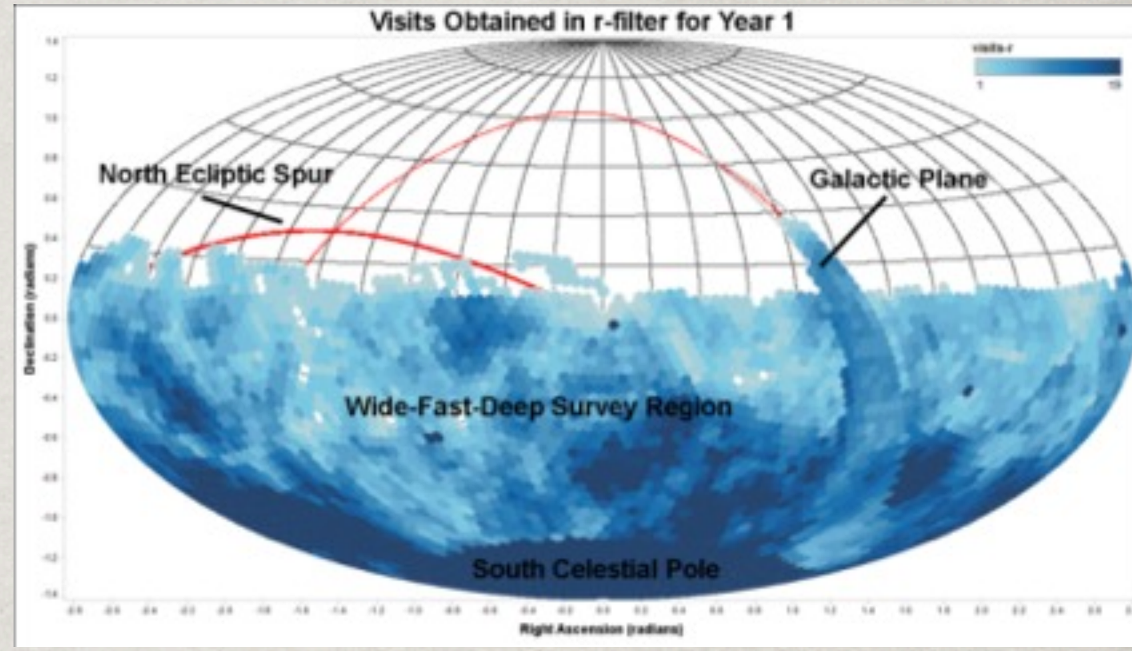



LSST (Large Synoptic Survey Telescope)
Wide … Fast … Deep

LSST "MISSION"

Large Synoptic Survey Telescope

- Photometric survey of half of the sky (~ 20 000 sq. deg.) during 10 years
- Complete coverage every 4 nights
- One 10 sq. deg. field every 40 seconds
- Fast alert system (60s) for detection of violent phenomenon

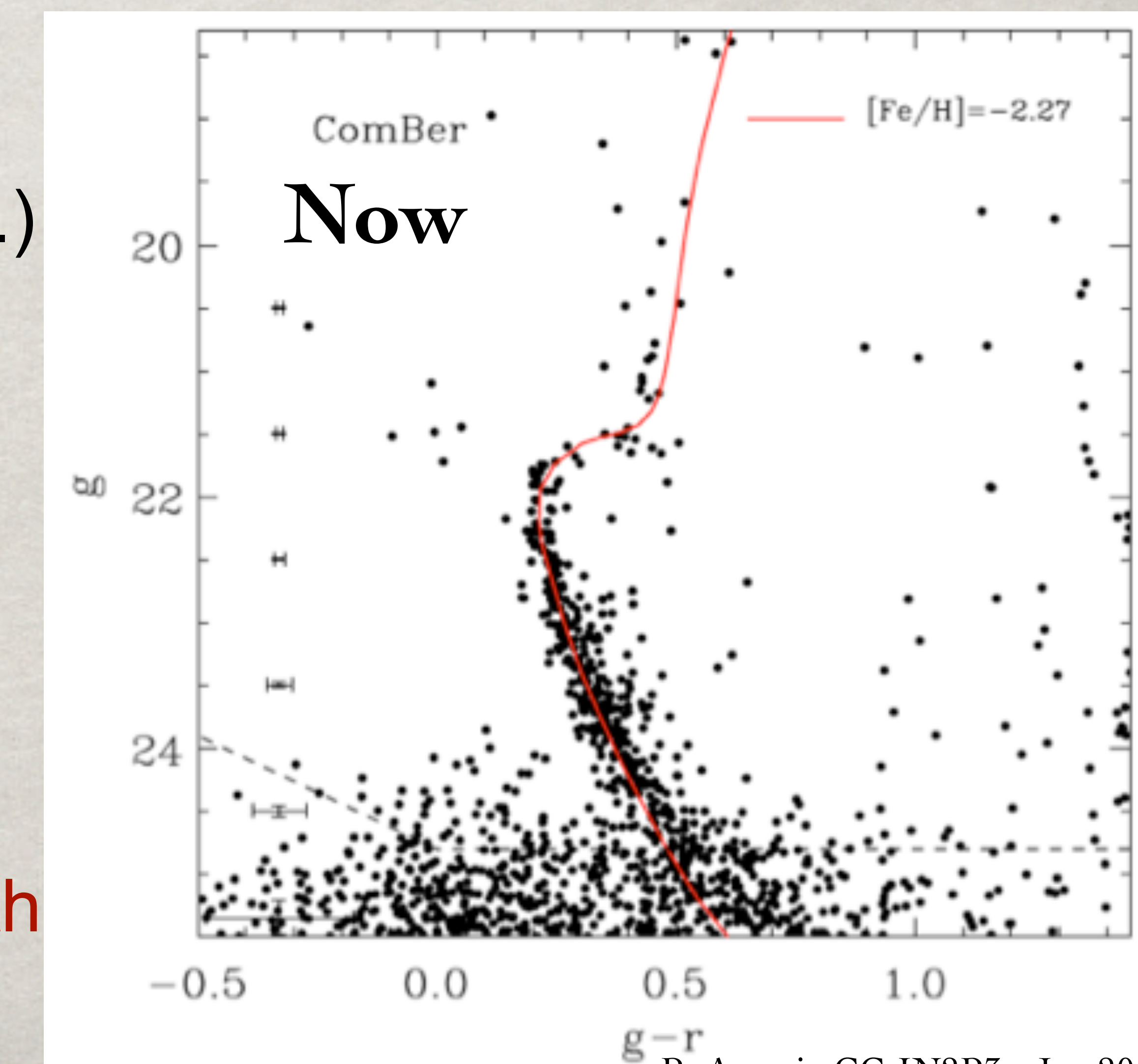


Deliverables

- « 4D » object mapping (stars, galaxies...)
  (α,δ) positions on the sky
  Redshifts z
  Time variations (SN, lensing, AGN…)

Cosmology

- Archive more than 3×10^9 galaxies with photometric redshifts up to z=3
- Detection of 250 000 SN Ia per year (with photo-z < 0.8).



R. Ansari , CC-IN2P3, Jan 2014

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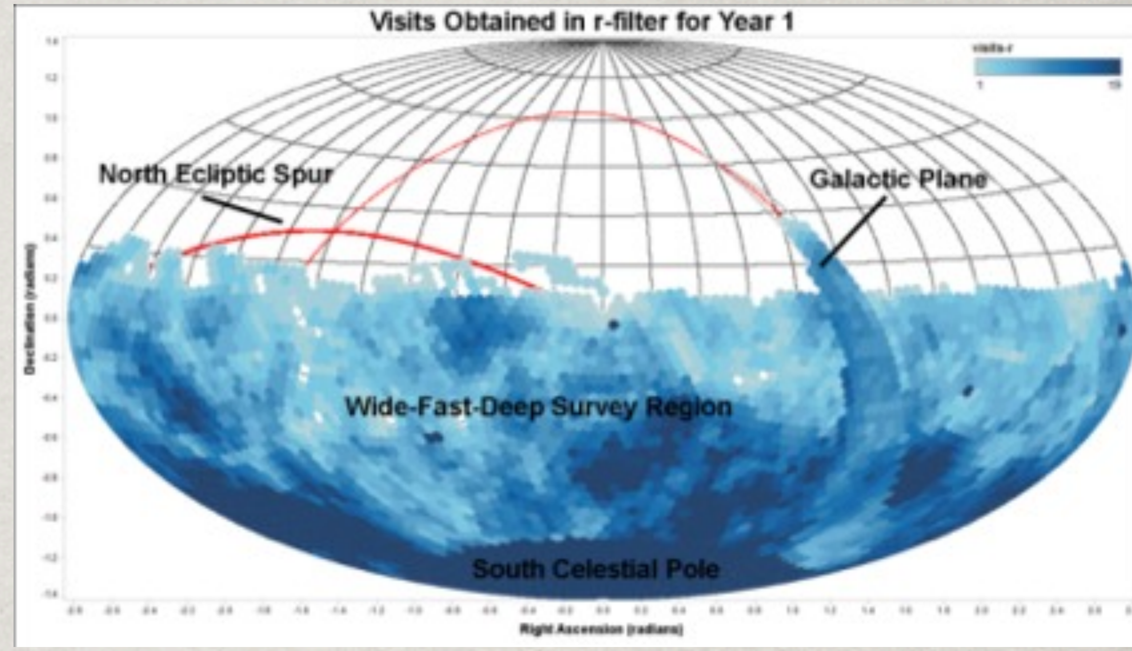
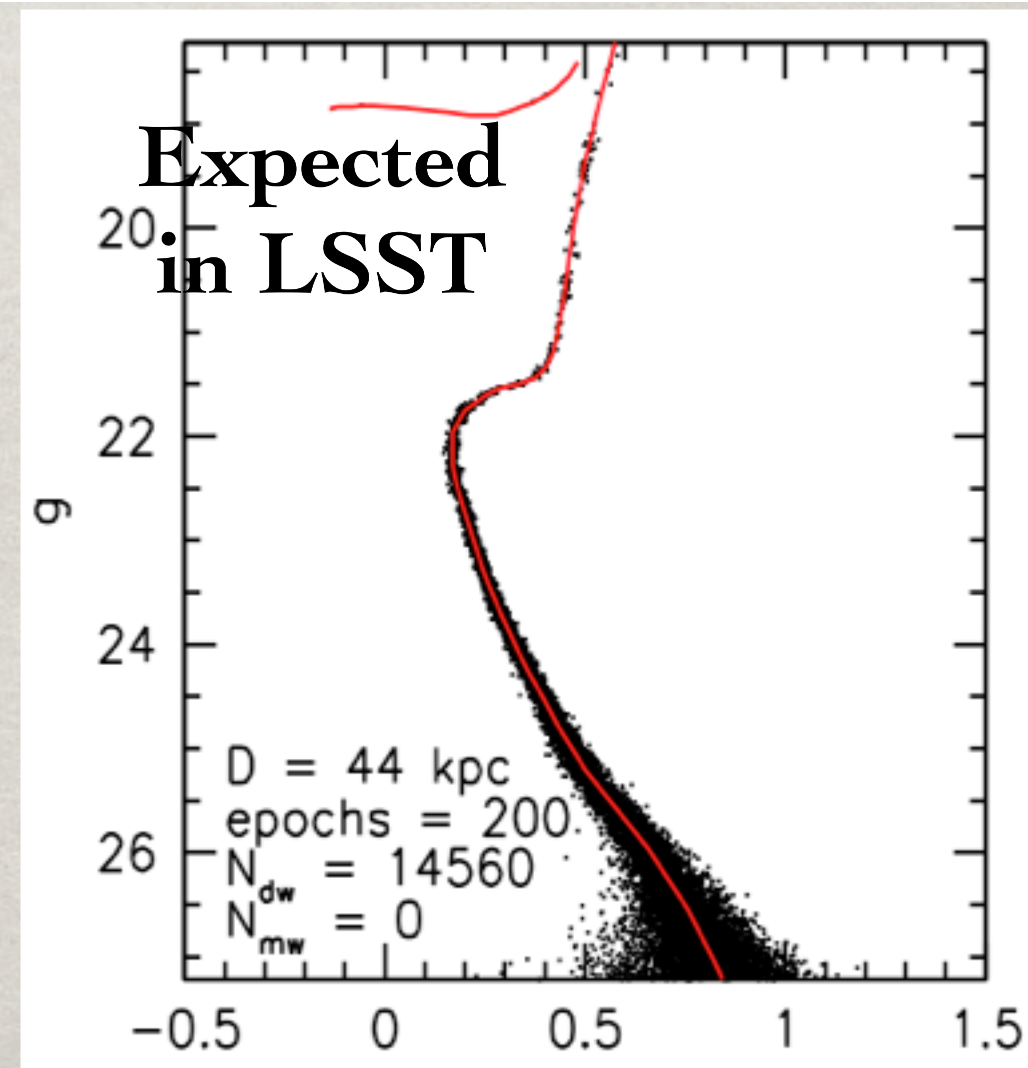
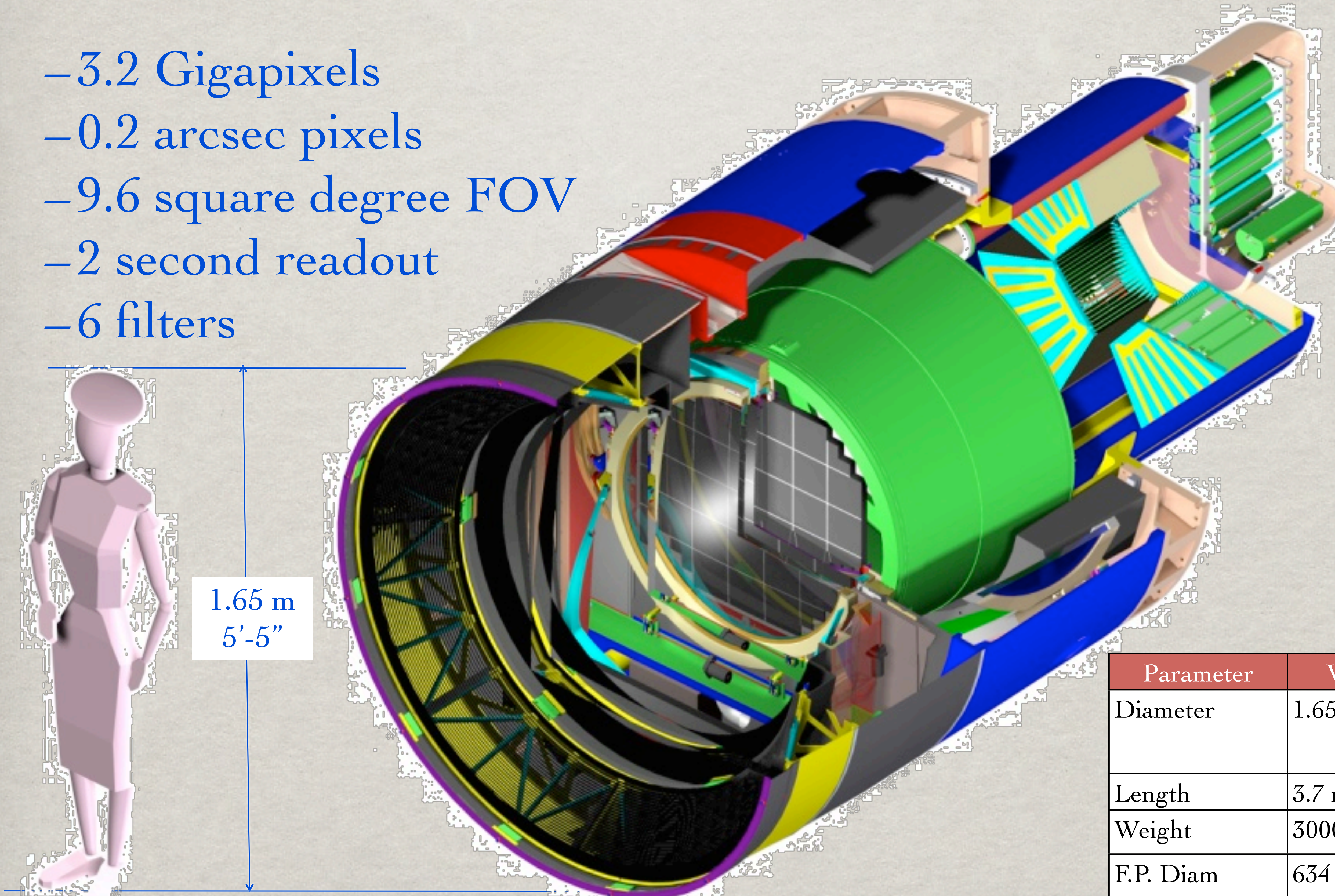




R. Ansari , CC-IN2P3, Jan 2014

LSST Camera Overview

- –3.2 Gigapixels
- –0.2 arcsec pixels
- –9.6 square degree FOV
- –2 second readout
- –6 filters



Parameter	Value
Diameter	1.65 m
Length	3.7 m
Weight	3000 kg
F.P. Diam	634 mm

R. Ansari, Jan 2014

LSST DATA

Images: 3. 10^6 x 2 x 189 CCD : ~ 100 PB

6 GB/17 sec, 15 TB / night

~ 40 10^9 objects (~100 TB), 5000 10^9 observations (5 PB)

Catalogues

Table	Size [TB]	rows	columns	description
Object	109	~38 billion	~500	Most heavily used, for all common queries on stars/galaxies, including spatial correlations and time series analysis using summarized information
CalibSource	24	~100 billion	~25	Sources used for calibration
DiaSource	71	~200 billion	~50	Alert-related follow up analysis
Source	3,600	~5 trillion	~100	Time series analysis of bright objects and detections
ForcedSource	1,089	~23 trillion	~7	Specialized analysis of faint objects and detections

Data Base table volume : 5 PB !

R. Ansari , CC-IN2P3, Jan 2014

Conclusions

- Very large data volumes produced by the current and future instruments in Astrophysics, Cosmology and Particle-Astrophysics
- Complex image and signal processing
- HPC : high performance computing
- opportunities to apply machine learning technics to these large data sets
- Strong community present in the Paris-Saclay perimeter