Overview (theory)

Astroparticle Physics

Paolo Lipari (INFN, Roma)

WIN 2019.
27th Workshop on Weak Interactions and Neutrinos

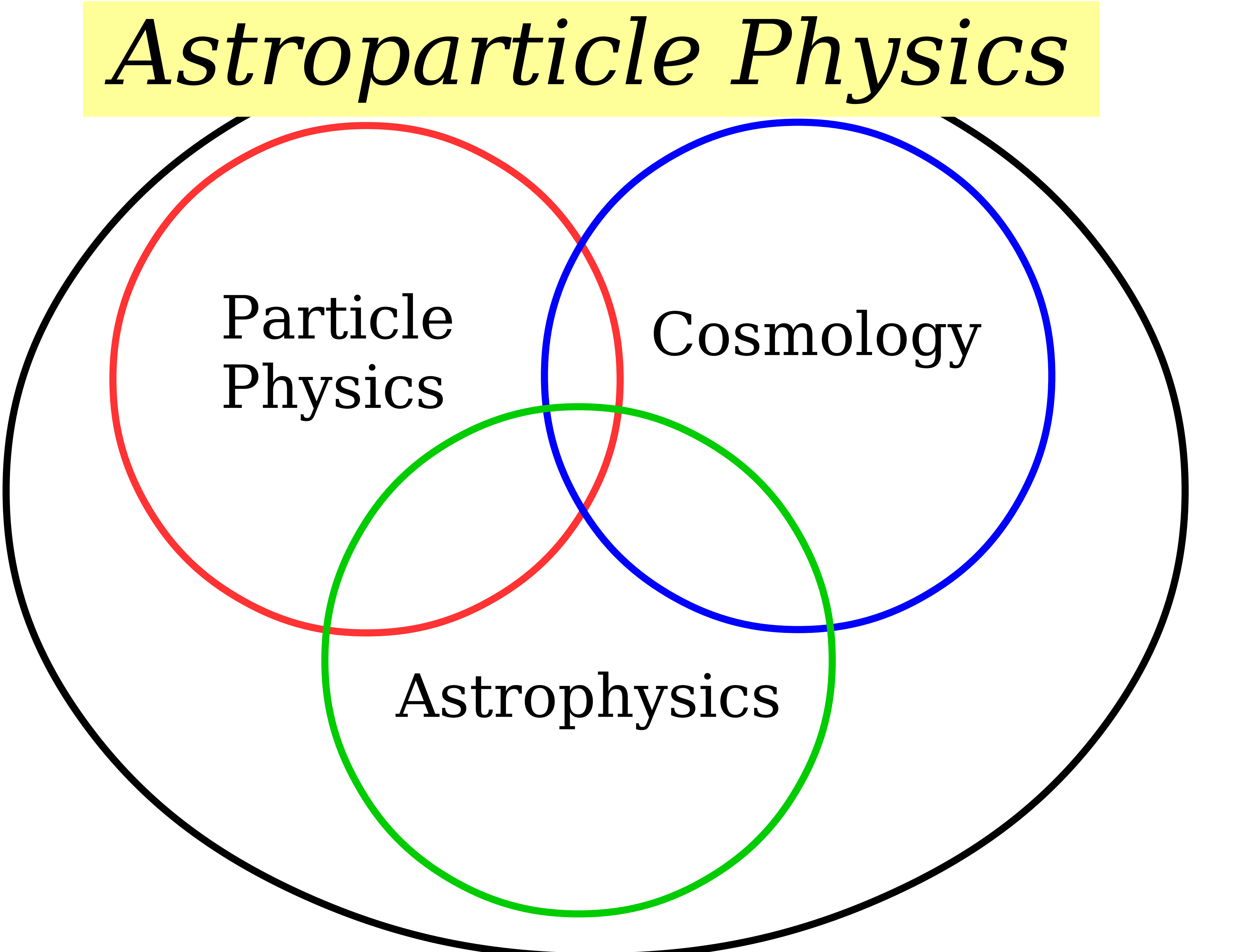
Bari, 3rd june 2019

Structure of this workshop:

four main topics:

- Neutrino Physics
- Electroweak interactions and Higgs Physics
- Flavor and Precision Physics
- Astroparticle Physics and Cosmology

Very broad field in rapid development
both experimentally and theoretically


Astroparticle Physics
Particle Physics
Cosmology
Astrophysics

At this workshop a rich program:
several plenary talks, 7 parallel sessions (~30 talks)

- Cosmology
- Dark Matter
- Gravitational Waves
- Multi-messenger Astrophysics

At this workshop a rich program:
several plenary talks, 7 parallel sessions (~30 talks)

Plenary talks:

- Cosmology [Paolo de Bernardis]
- Dark Matter
- Gravitational Waves [Fulvio Ricci]
- Multi-messenger Astrophysics

[Markus Ahlers (cosmic rays, neutrinos)]

Many contributions in the parallel sessions

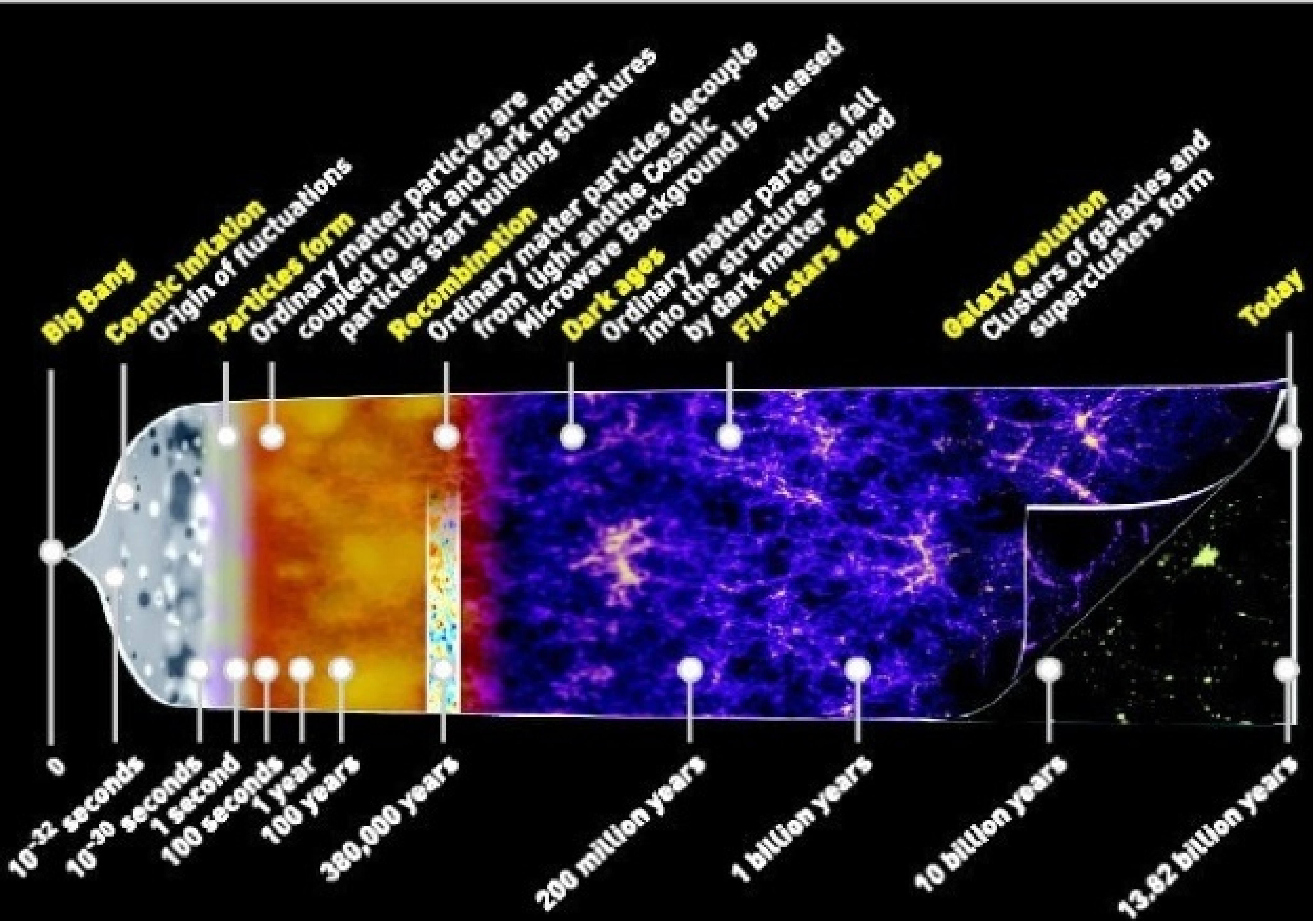
1. Cosmology

2. Dark Matter

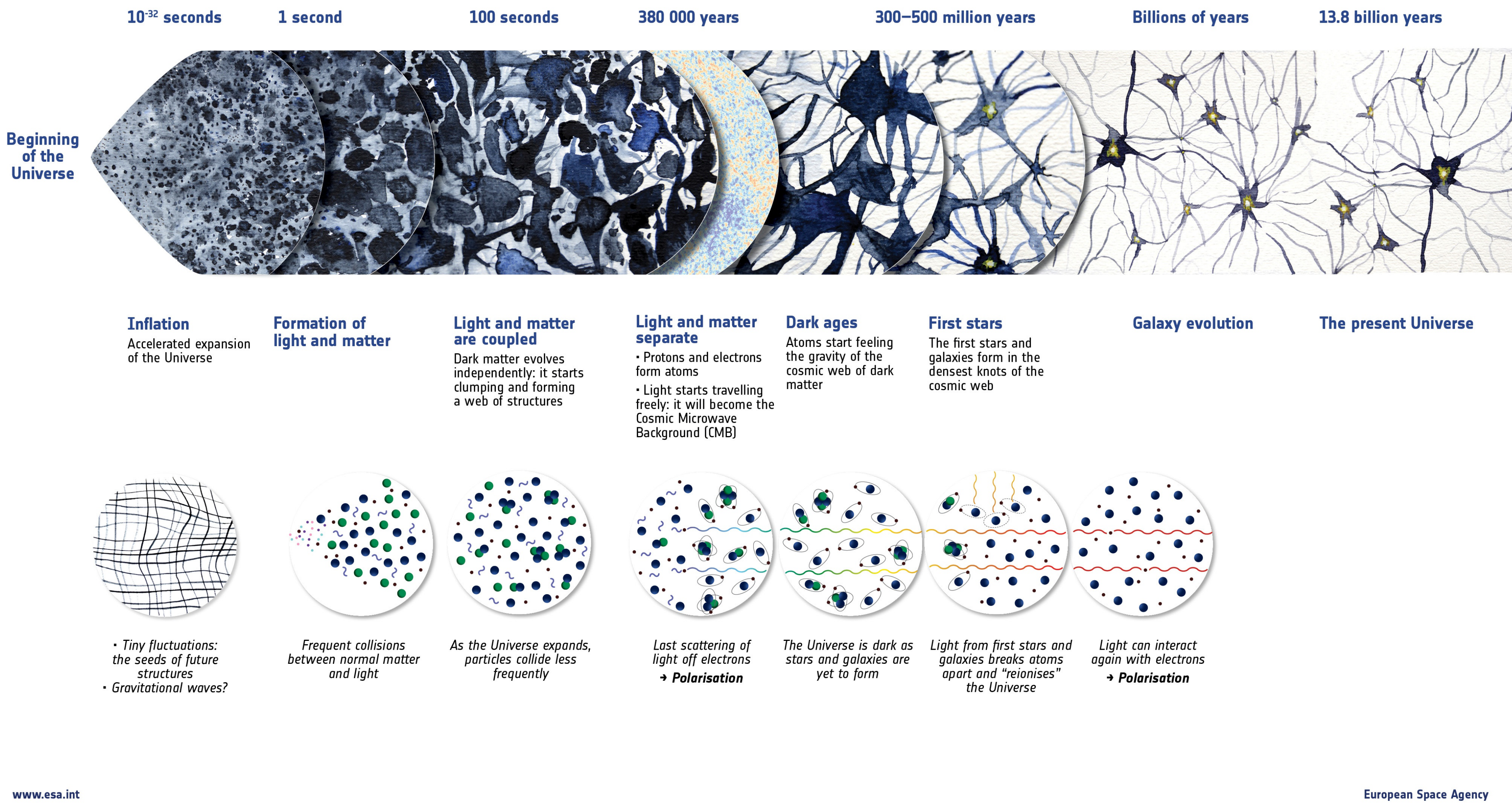
3. Gravitational Waves

4. Multi-messenger Astrophysics

Cosmology

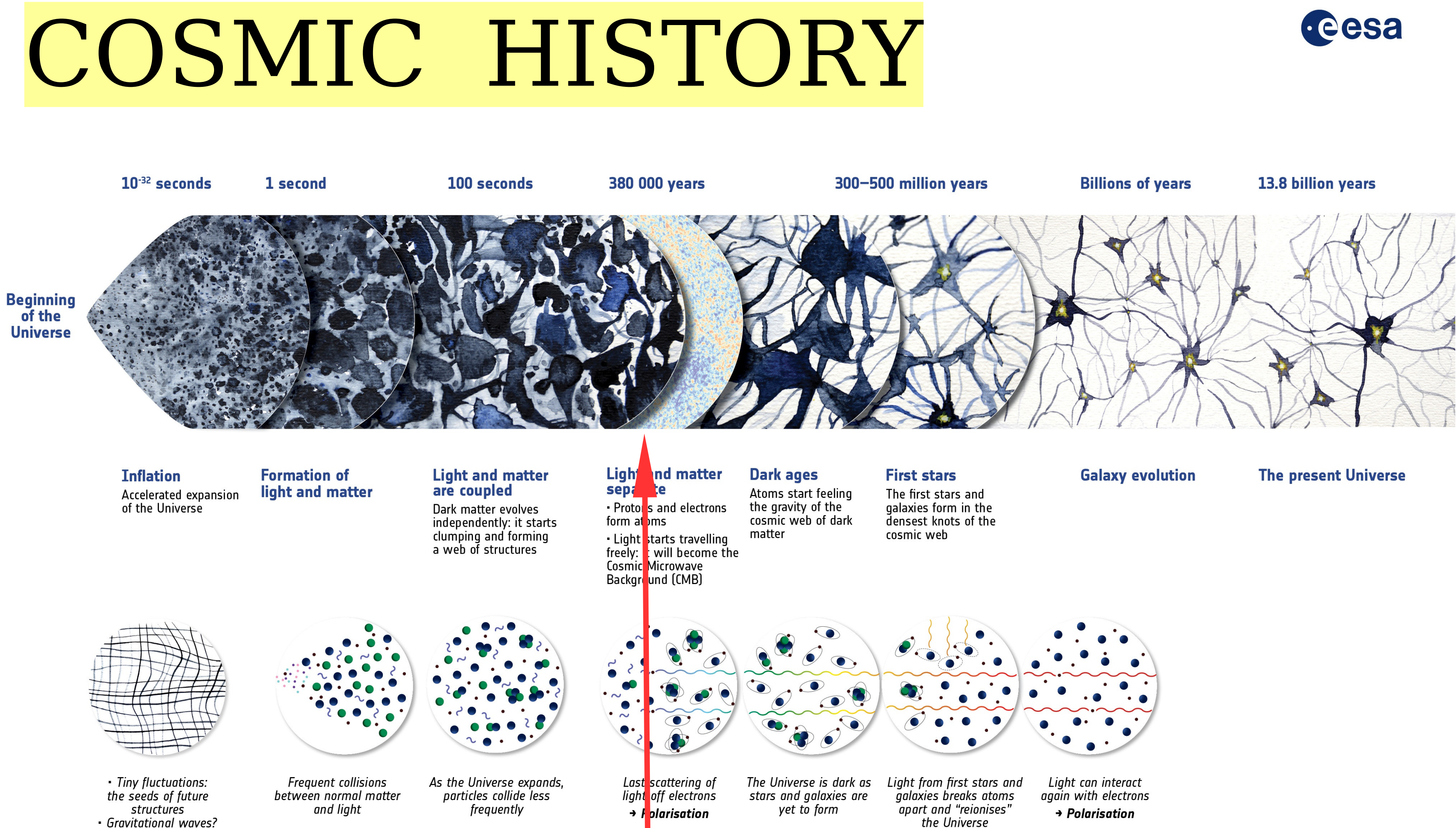

Big Bang
Cosmic Inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light andthe Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380,000 years
200 million years
1 billion years
10 billion years
13.82 billion years

COSMIC HISTORY



Credit NASA, ESA

COSMIC HISTORY



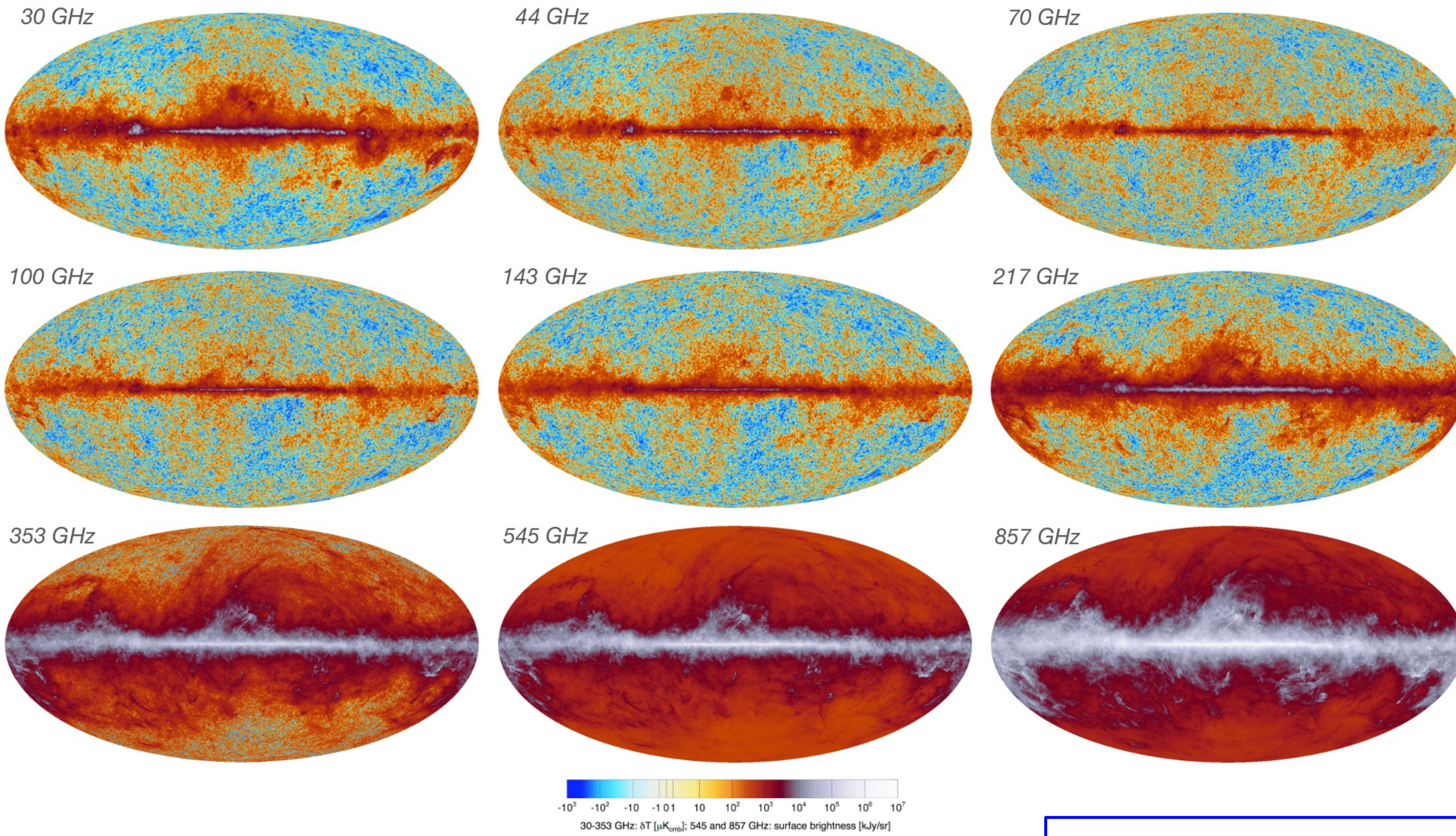
Cosmic Microwave Background (CMB)

Relic radiation emitted at recombination (2.7 Kelvin) [very uniform in the sky]

Credit NASA, ESA

Sky seen by PLANCK (2018)

9 frequency bands

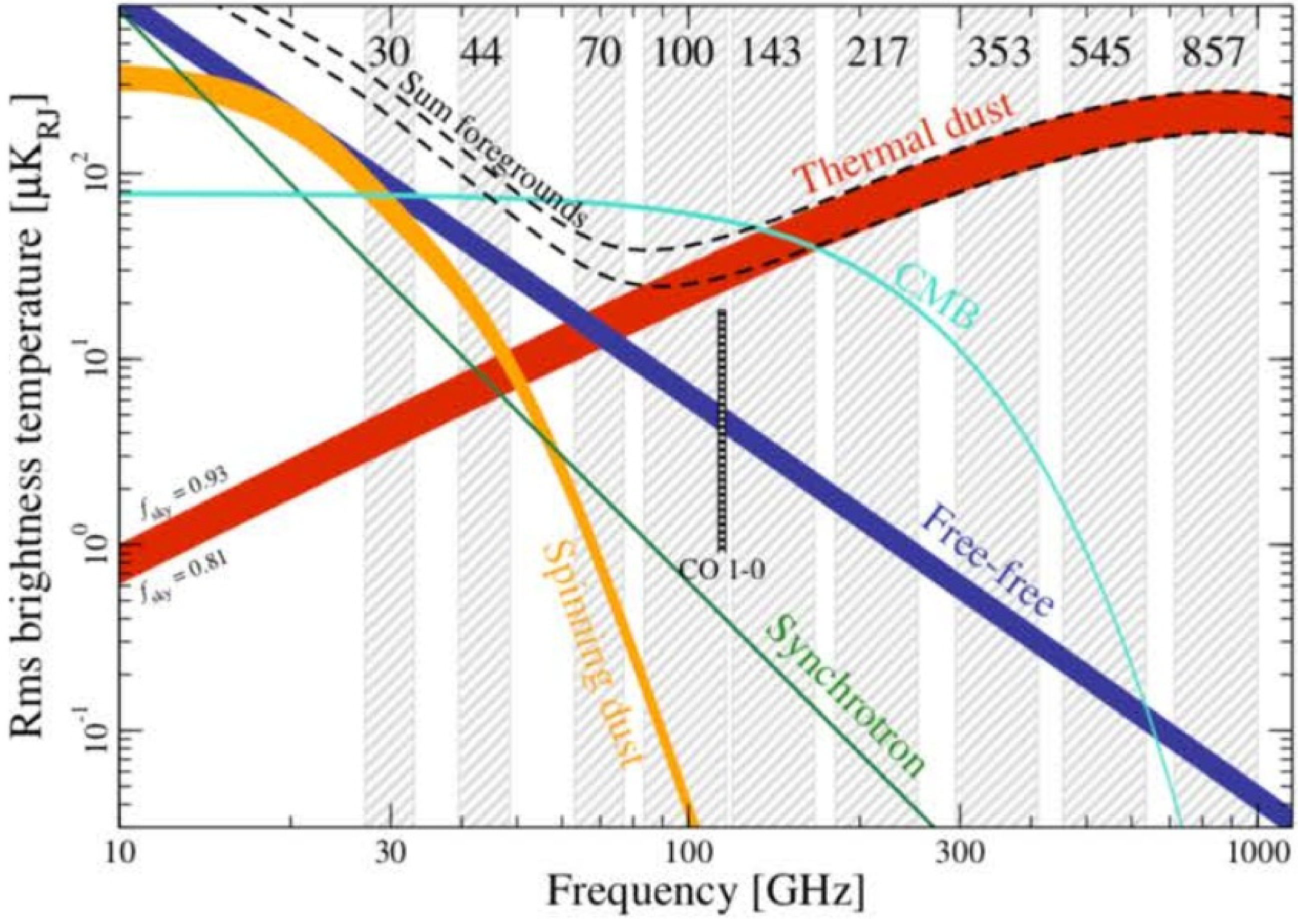


$$\delta\theta \simeq 30' \div 5'$$

$$\Delta T/T \sim 2 \times 10^{-6}$$

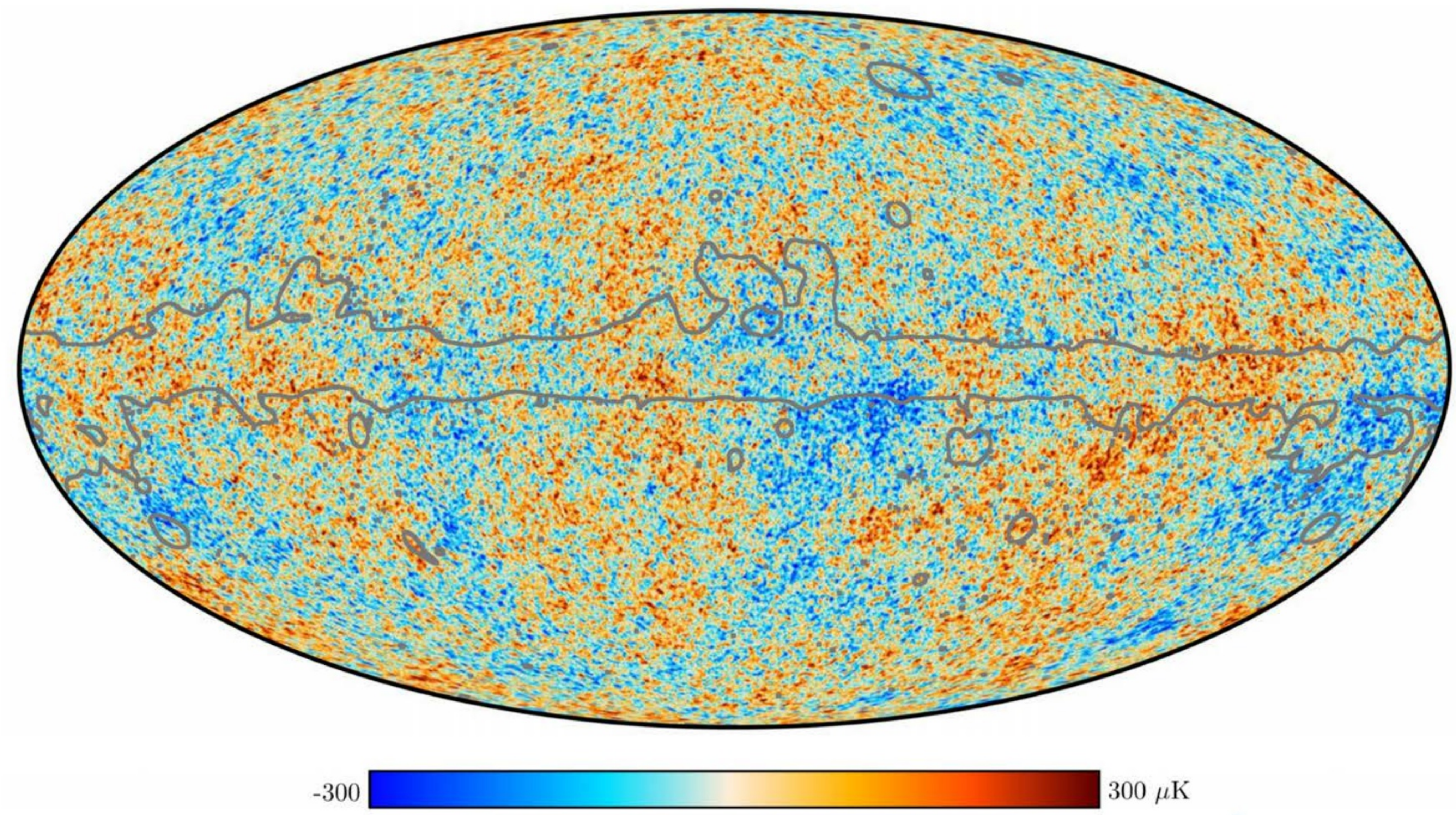
"Legacy Release" 17th july 2018

Understand foregrounds

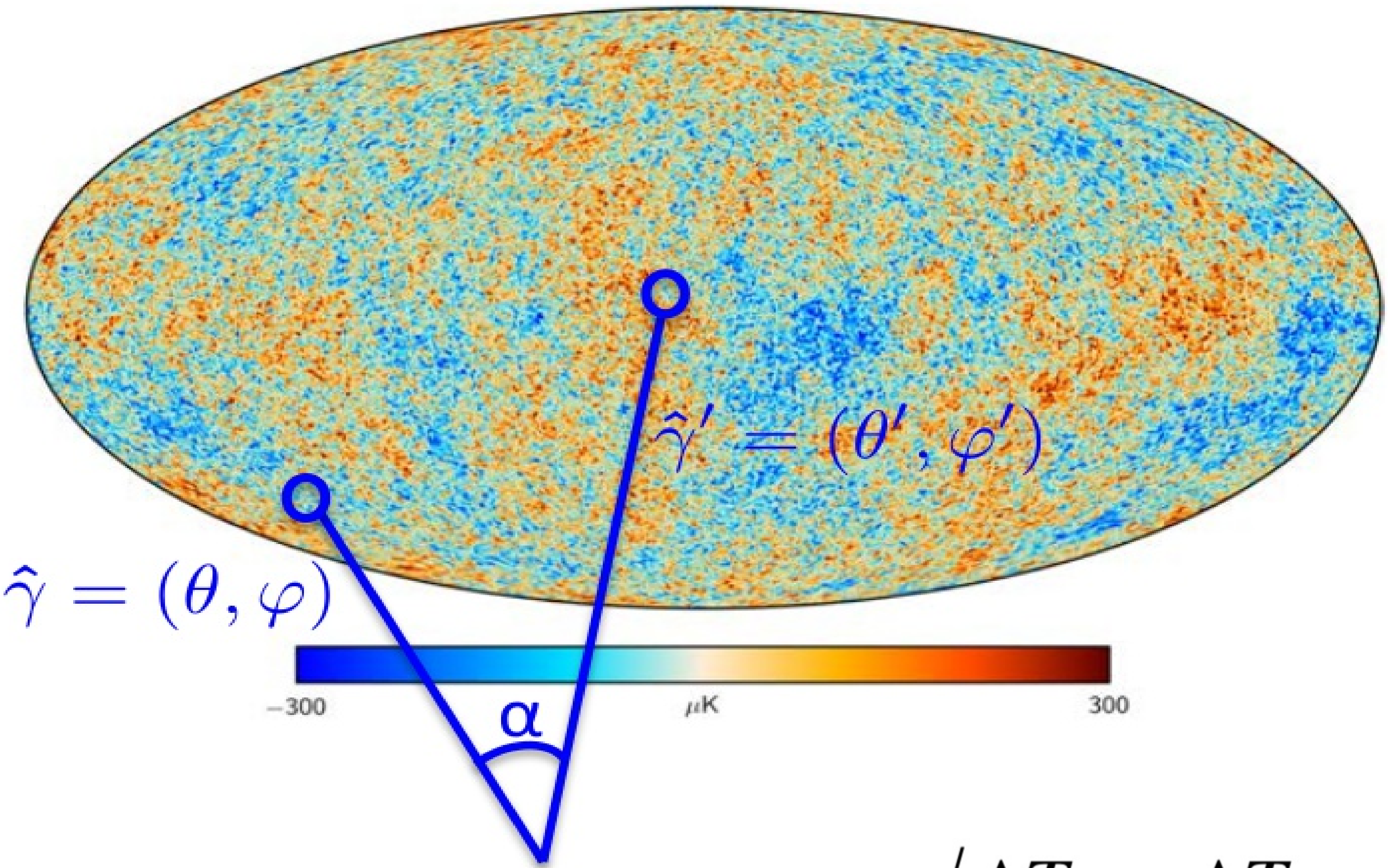


Obtain "ultimate" measurement of the CMB temperature anisotropy field

Temperature Fluctuations of the 2.7 K CMB Radiation

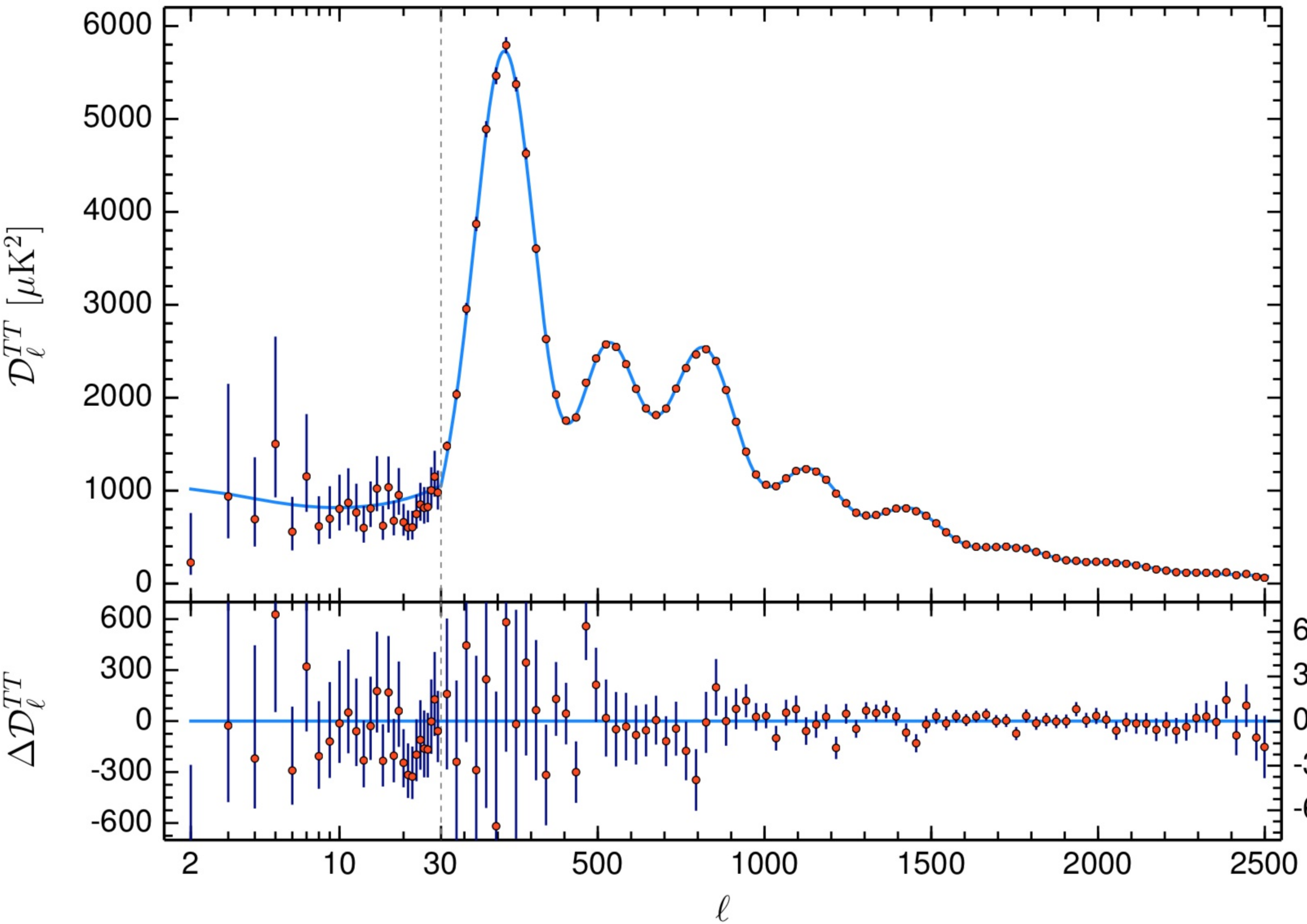


Angular distribution encodes cosmological information



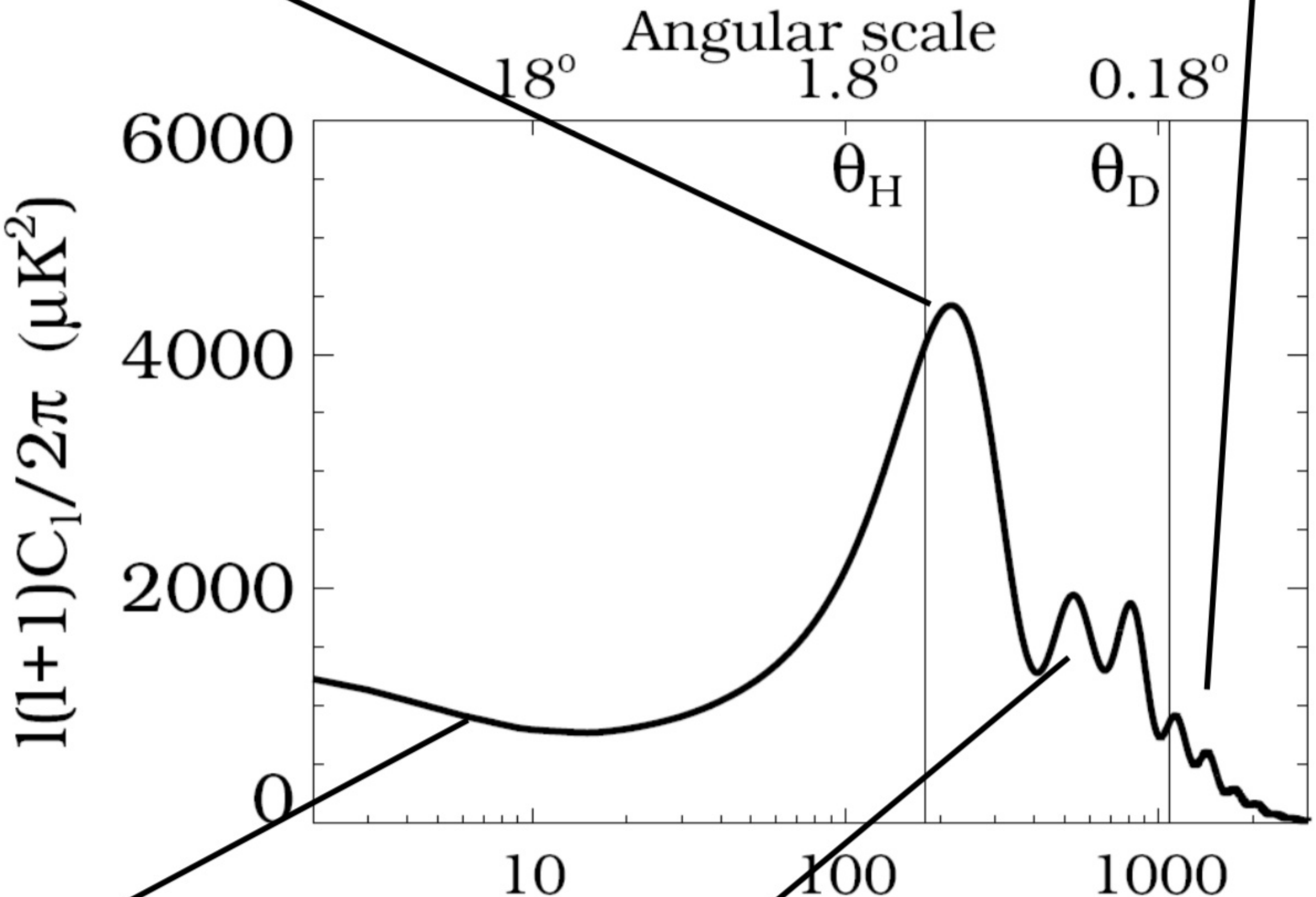
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}\,') \right\rangle$$

Power Spectrum [Acoustic Peaks]



spatial curvature
relative abundance of matter and radiation
distance to the last scattering surface
$\mathbf{H_0}$, Ω_m, Ω_k

Photon diffusion length at recombination
Slope of the primordial spectrum
$\mathbf{N_{eff}}$, Ω_b, $\mathbf{Y_p}$, $\mathbf{n_s}$

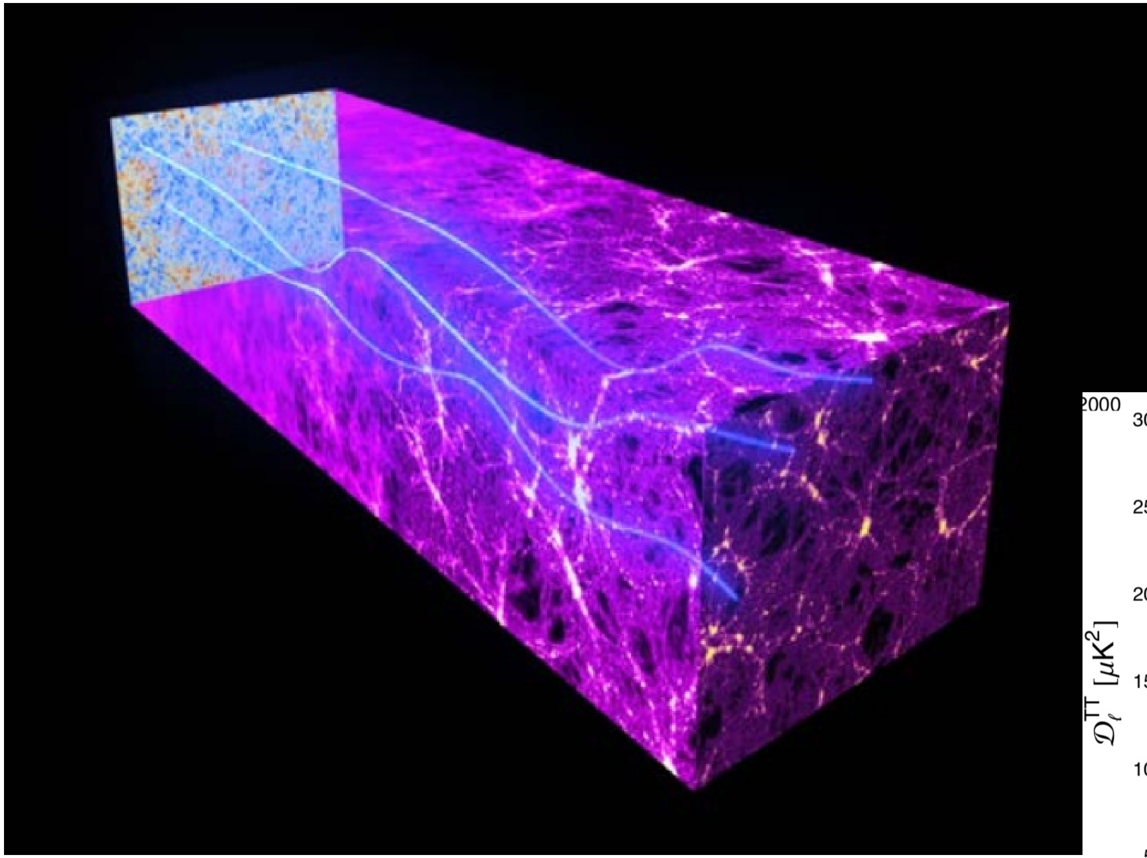


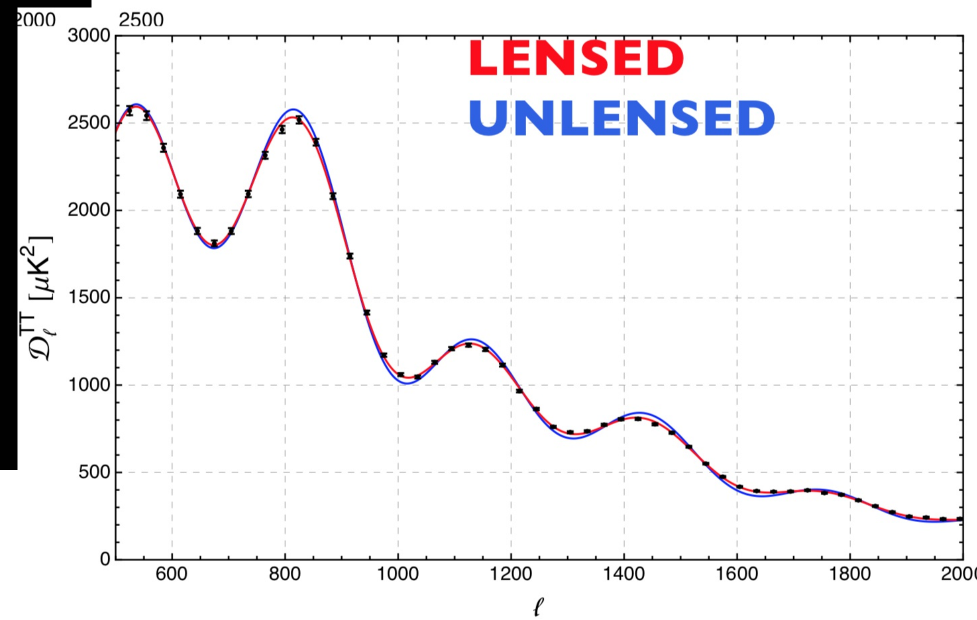
+ Overall power
$\mathbf{A_s\, e^{-2\tau}}$

+ low-ell
polarization
(not shown)
Reionization
history
τ

Primordial power spectrum
late time expansion
$\mathbf{A_s}$, Ω_Λ

Baryon abundance
Ω_b





CMB is also sensitive to the late-time density field, probing intervening structures, and giving integrated information about the matter distributions between us and the last scattering surface.

Observations consistent with the

ΛCDM Model

	Parameter	Mean	Stdev	Rel. err.
primary	$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.007
primary	$\Omega_c h^2$ Dark matter density	0.1200	0.0012	0.01
primary	100θ CMB acoustic scale	1.04092	0.00031	0.0003
primary	τ Optical depth to last scattering surface	0.0544	0.0073	0.13
primary	$\ln(A_s 10^{10})$ Primordial amolitude of perturbation	3.044	0.014	0.007
primary	n_s Primordial Scalar spectral index	0.9649	0.0042	0.004
derived	H_0 Hubble parameter today	67.36	0.54	0.008
derived	Ω_m Total matter density	0.3153	0.0073	0.023
derived	σ_8 Matter perturbation amplitude	0.8111	0.0060	0.007

$$\Omega_{\rm m}h^2 = 0.1430 \pm 0.0011$$

$$\Omega_{\rm b}h^2 = 0.02237 \pm 0.00015$$

$$\Omega_{\rm c}h^2 = 0.1200 \pm 0.0012$$

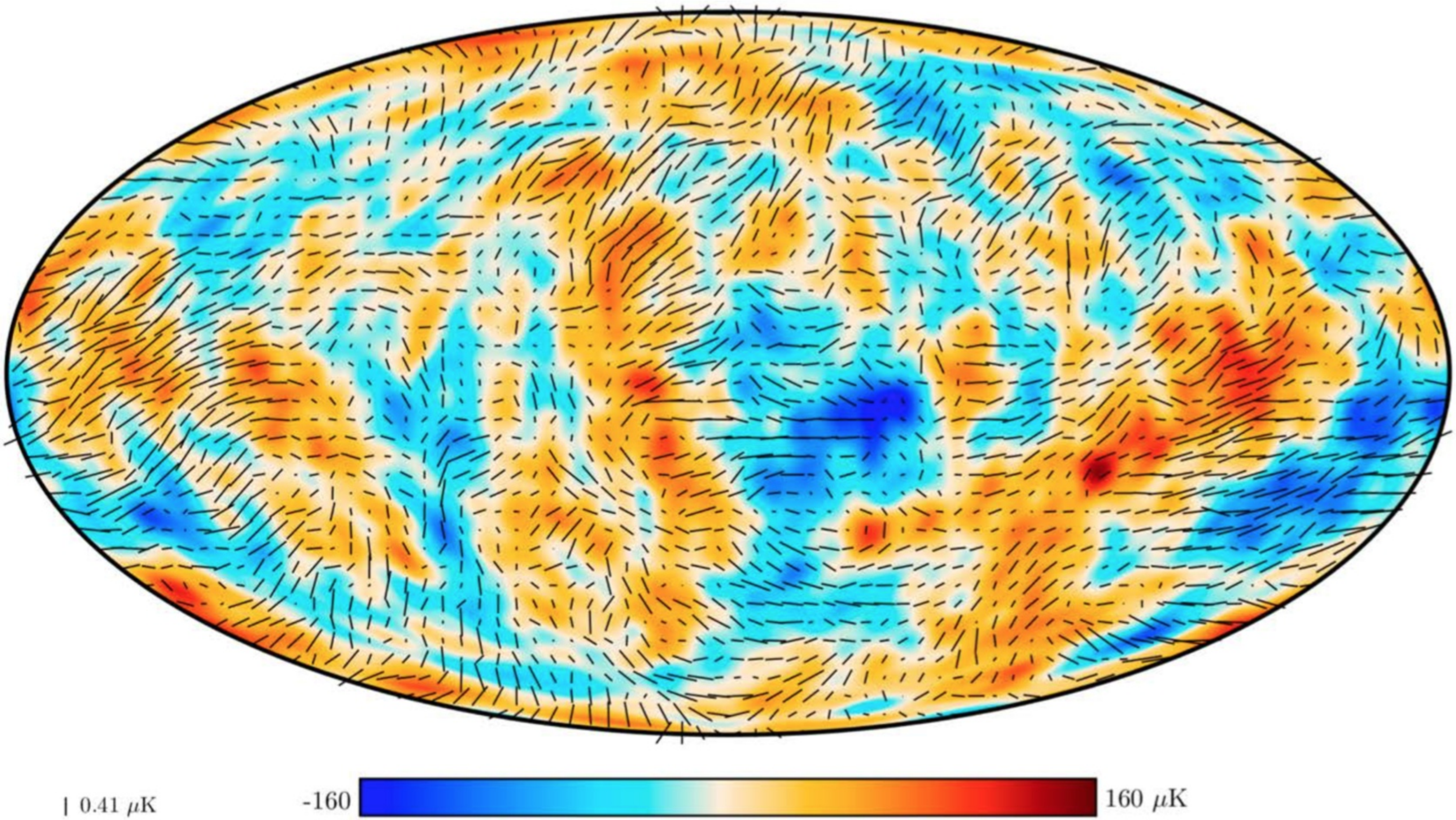
$$H_0 = (67.27 \pm 0.60)\ \text{km s}^{-1}\,\text{Mpc}^{-1}$$

$$\Omega_{\rm m} = 0.3166 \pm 0.0084$$

$$\Omega_{\Lambda} = 0.6847 \pm 0.0073$$

“Opening the door" *to*

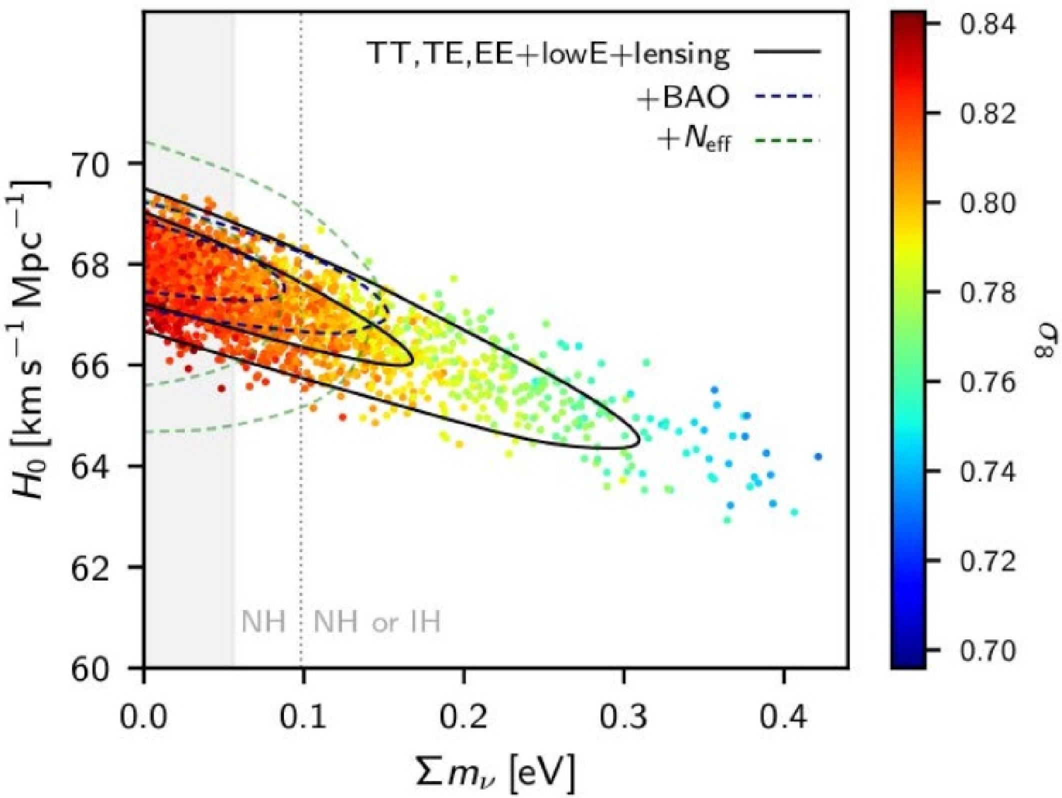
Polarization anisotropies

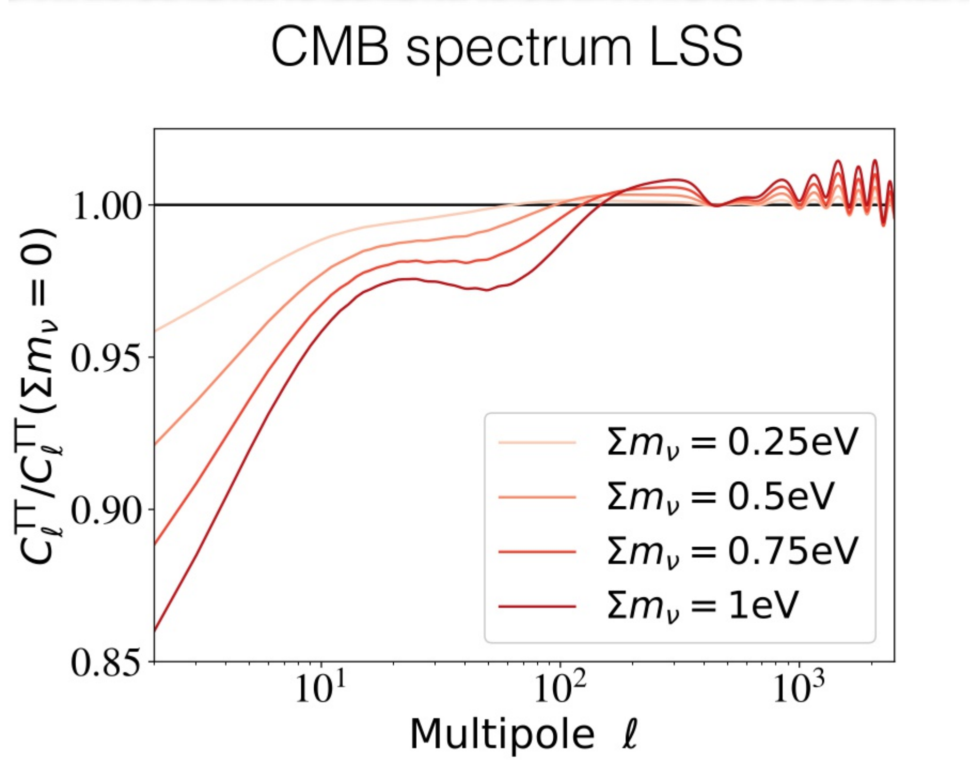


Temperature smoothed to 5 degrees

Primordial gravitational waves remain unseen

Information about Neutrinos

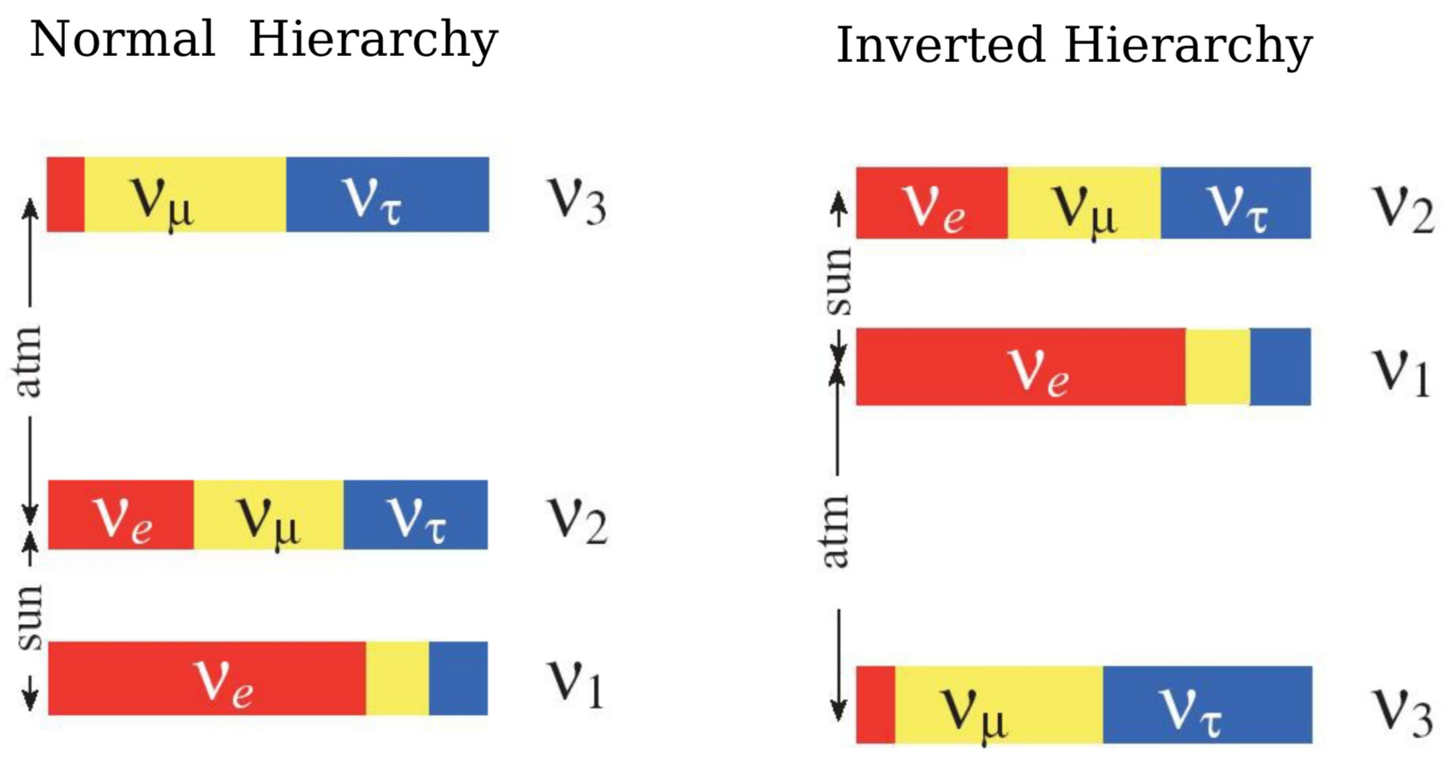




Limit on the sum of the neutrino masses:

$m_\nu < 0.44$ eV (95%CL, TT + lowE + lensing)

$m_\nu < 0.13$ eV (95% CL, TT+lowE+lensing+BAO)



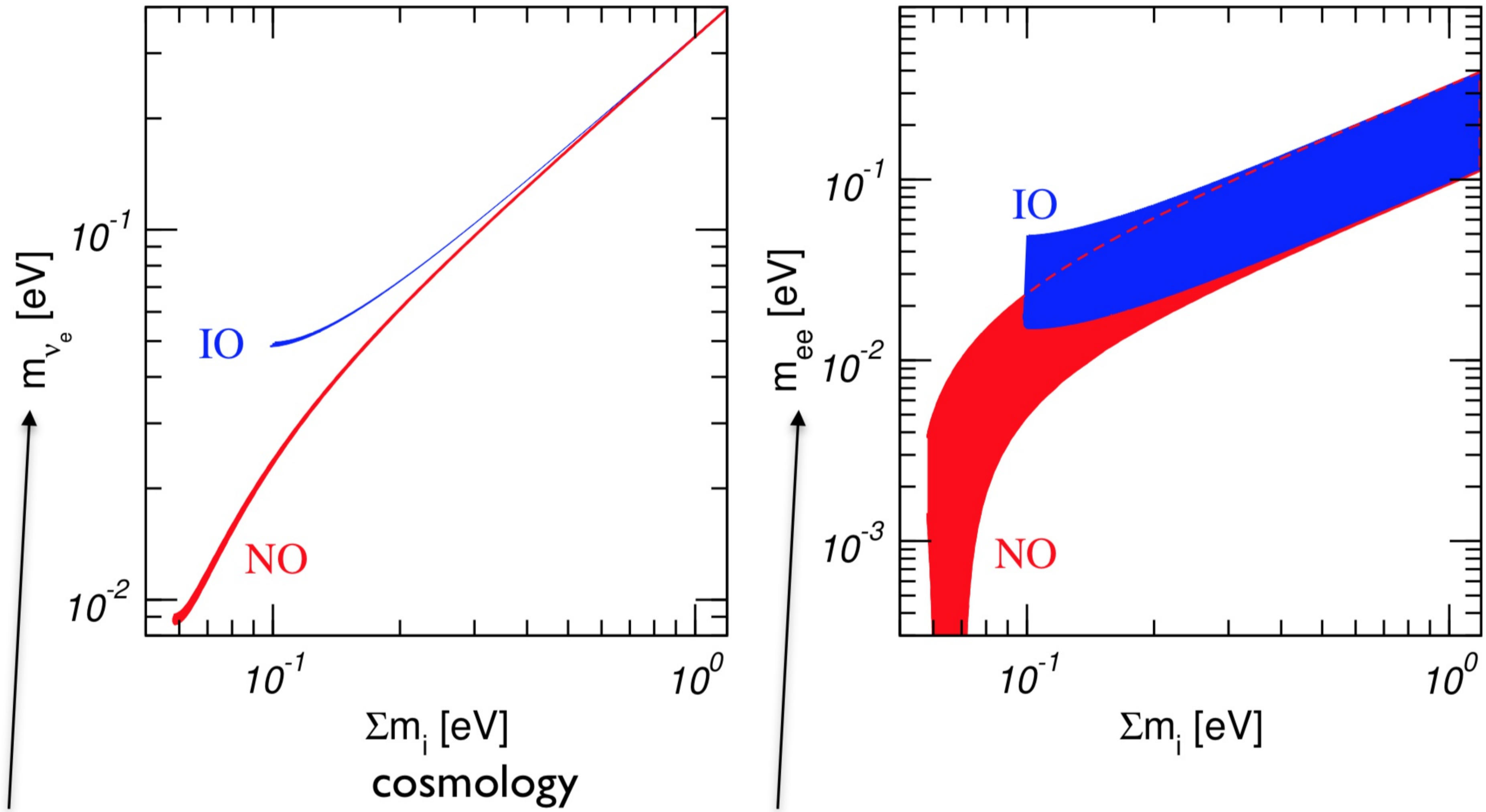
Normal mass Ordering

$$\sum_\nu m_\nu \geq \sqrt{\Delta m^2_{12}} + \sqrt{\Delta m^2_{13}} \simeq 0.059 \text{ eV}$$

Inverted mass Ordering

$$\sum_\nu m_\nu \geq \sqrt{|\Delta m^2_{13}|} + \sqrt{|\Delta m^2_{23}|} \simeq 0.101 \text{ eV}$$

Thomas Schwetz (Venezia-2019 Neutrino Telecopes)



cosmology

beta-decay endpoint

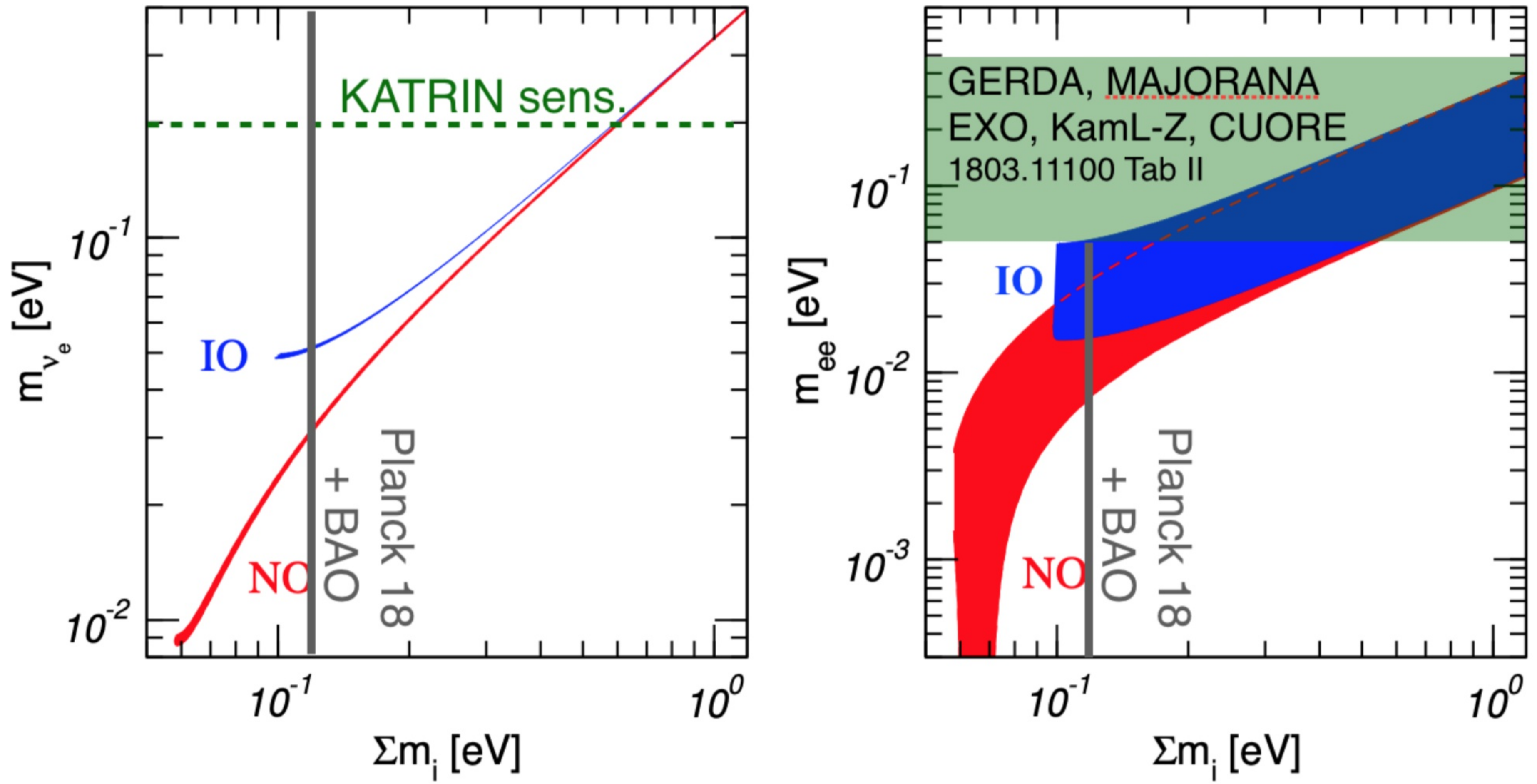
$m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$

neutrinoless double-beta decay

$m_{ee} = |\sum_i U_{ei}^2 m_i|$

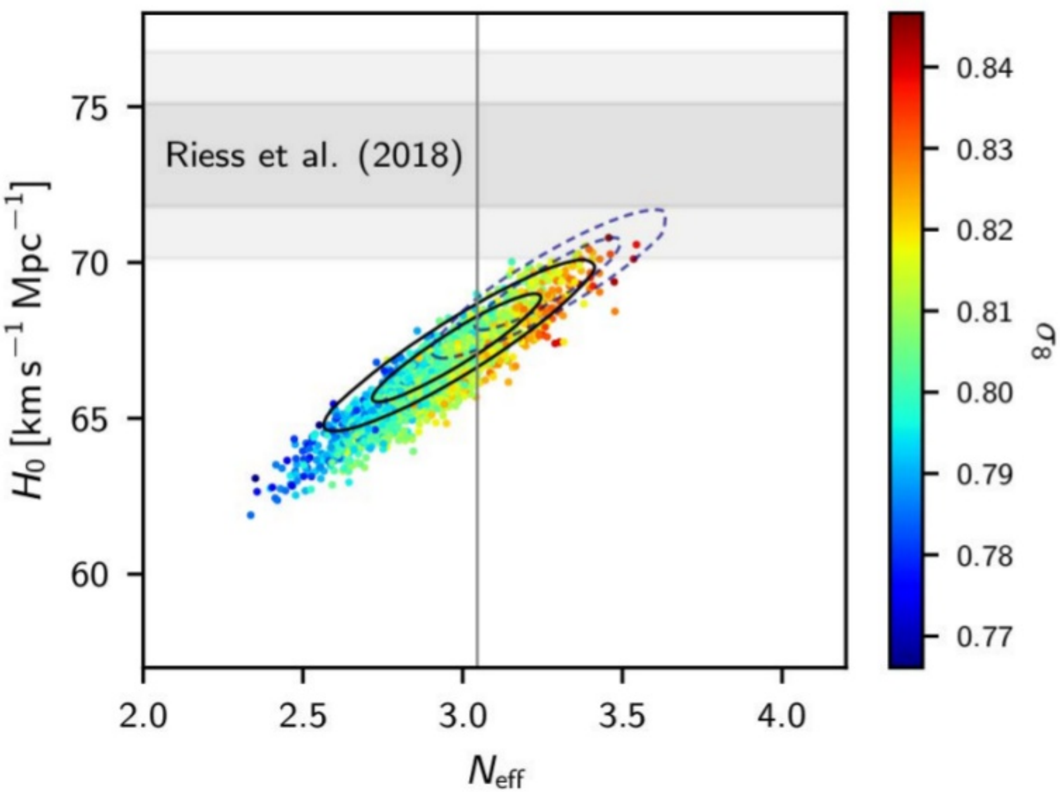
Combined cosmological limits start to "corner"
the neutrino inverted mass ordering

Thomas Schwetz (Venezia-2019 Neutrino Telecopes)



Combined cosmological limits start to "corner"
the neutrino inverted mass ordering

Effective number of Relativistic species N_{eff}



- Effective number of relativistic species is consistent with the standard expectation N_{eff} = 3.046
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species (N_{eff}=4) is excluded at 3.5 to 6 σ, depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

$$N_{eff} = 3.00^{+0.57}_{-0.53}$$ (95% CL, TT+lowE)

[P. Natoli Venezia 2019]

$$N_{eff} = 3.11^{+0.44}_{-0.43}$$ (95% CL, TT+lowE+lensing+BAO)

Conclusions

- Planck has delivered its final (legacy) release
- It has provided the ultimate (cosmic variance limited) measurement of CMB anisotropy
- … But just opened the door of CMB polarization (which was never designed to measure, by the way)
- It has fulfilled its promise of measuring the fundamental cosmological parameters to percent accuracy
- And brought remarkable constraints on particle physics parameters as well, excluding a fourth fully thermalized neutrino and constraining the total neutrino masses in the 100 meV range.
- Has measured well one relevant inflationary parameter, the primordial spectral index, allowing constraints on the inflationary paridigm
- Yet has uncovered several tensions with astrophysical measurements, which may or may not hint at new physics.
- Intrinsic anomalies do exist in the large-angle CMB field, which may also be a tracer of something new.
- If these tension/anomalies are really hinting at new physics, its signature in the CMB is scant. Accurate measurements are needed to pin down the issue.
- Primordial gravitational waves remain unseen.
- To exploit the wealth of information that still is in the CMB, we need to cope with the extraordinary complexity of the sky. This can be credibly done only with a future space mission.

Measurements of the Hubble constant

Tension (4 sigma level)
between measurements performed
with “standard candle” (SN) measurements

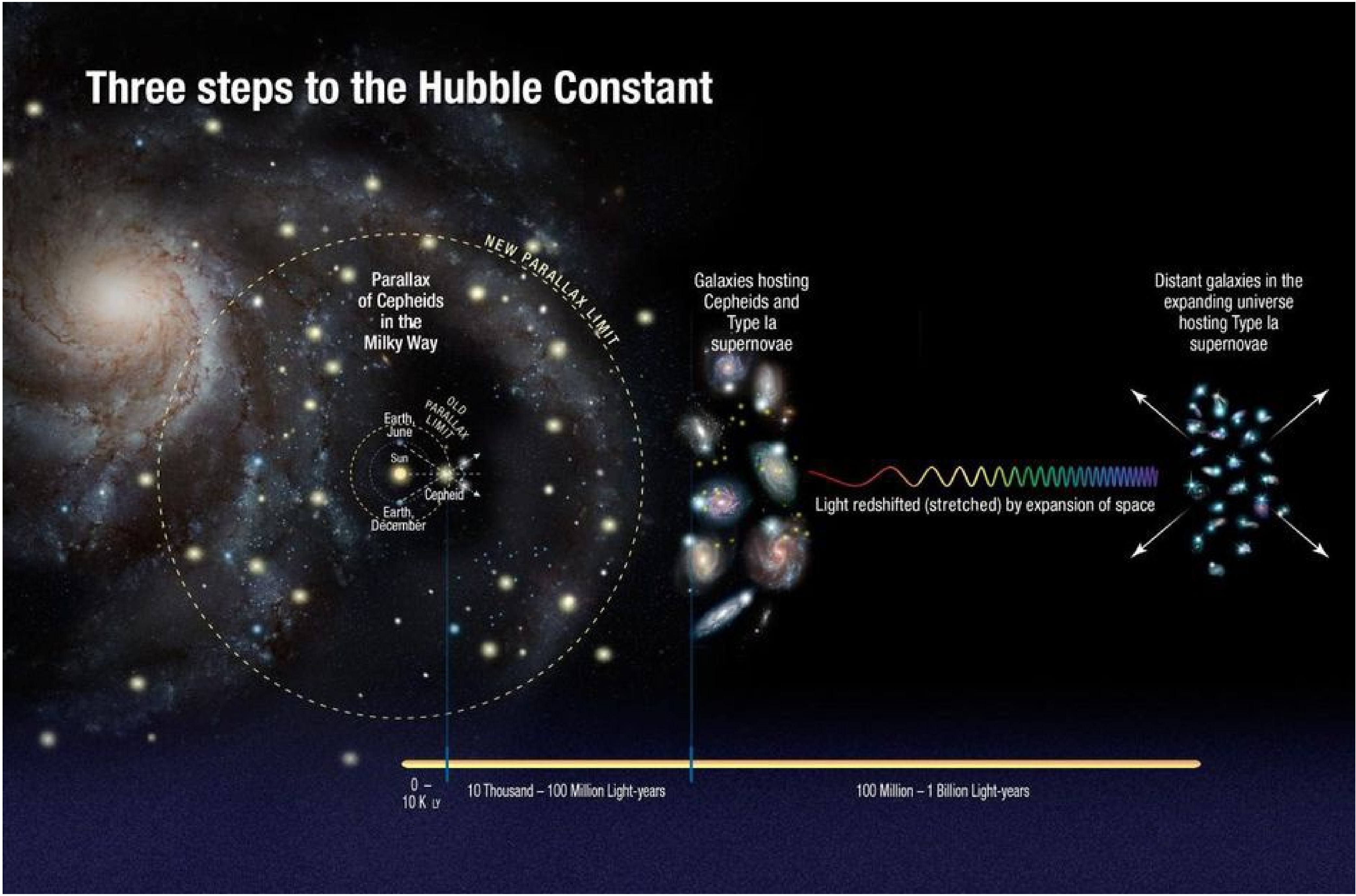
and measurements that use CMB

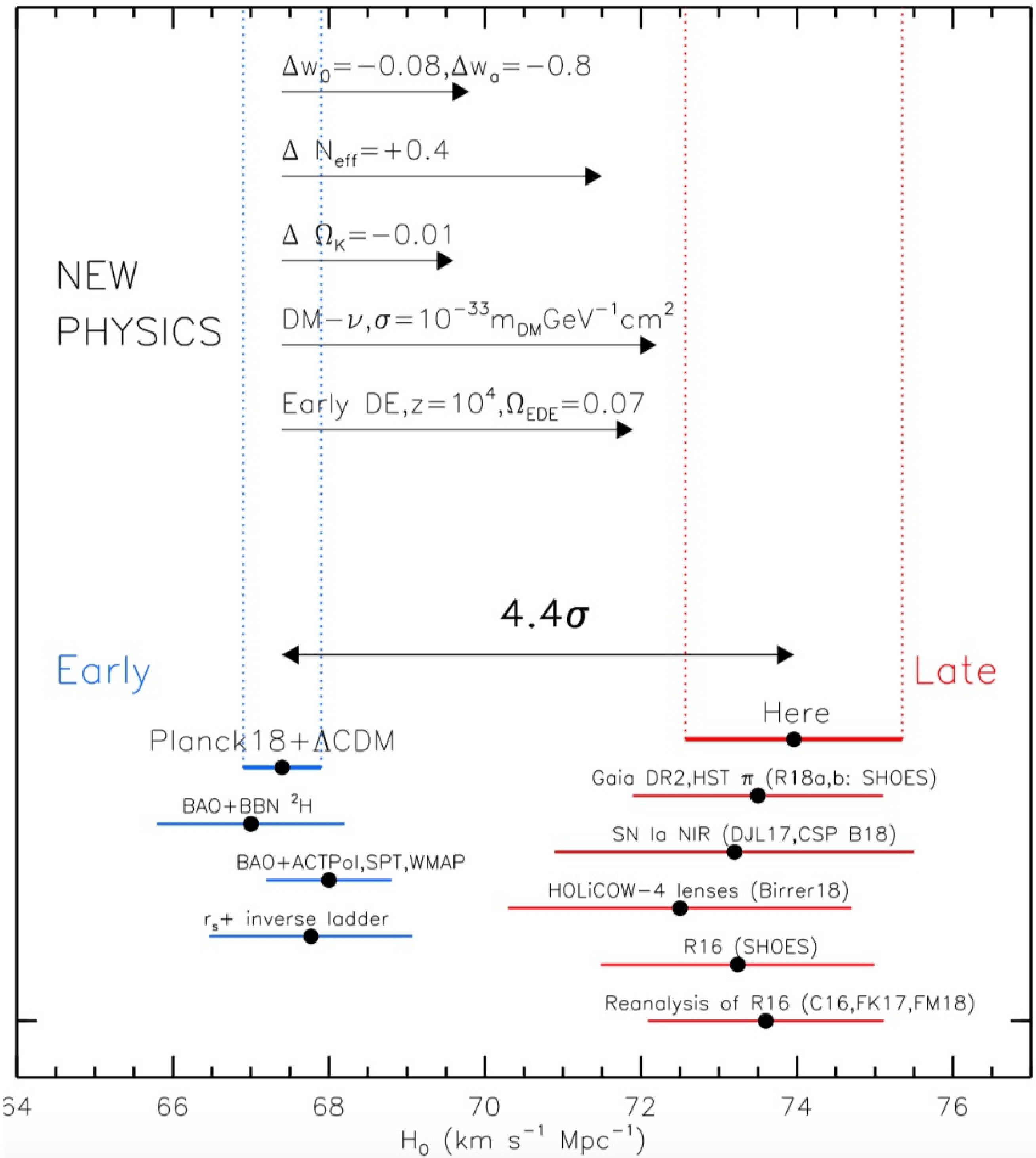
“Standard Candle”

versus

“Standard Ruler"

“Standard Candle” Measurement of the Hubble Constant

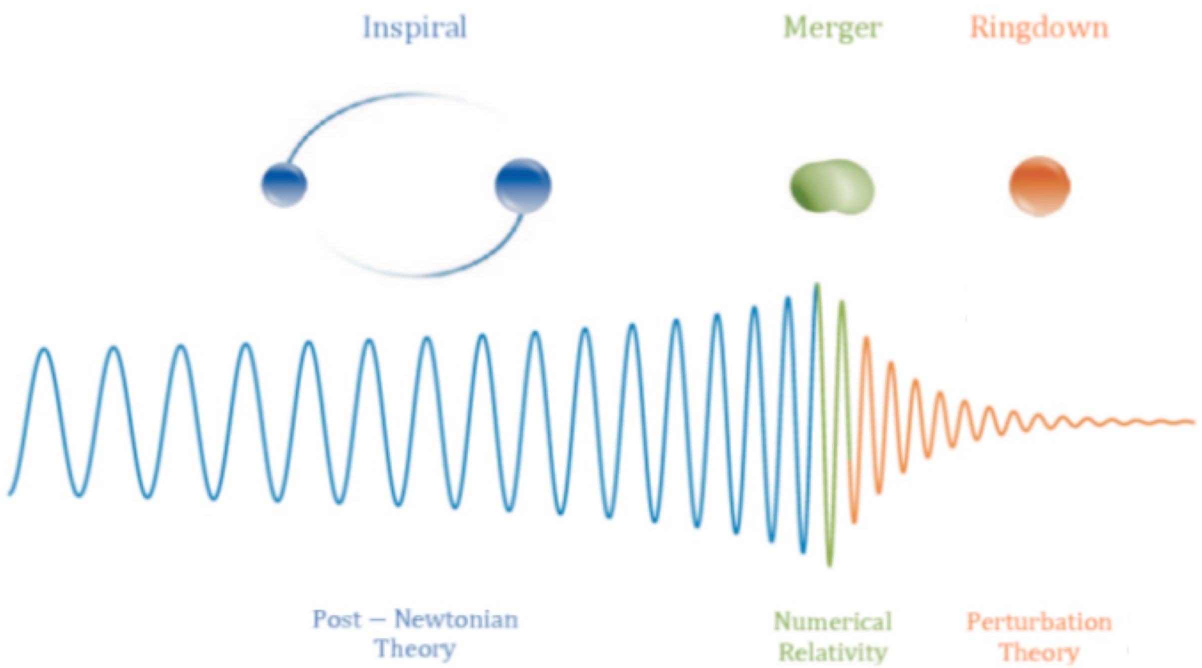


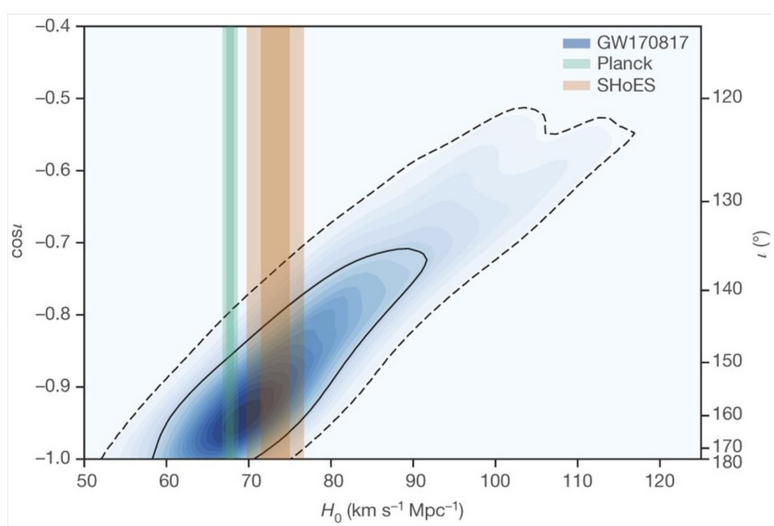


Δw$_0$=−0.08,Δw$_a$=−0.8
Δ N$_{eff}$=+0.4
Δ Ω$_K$=−0.01
NEW PHYSICS
DM−ν,σ=10^{-33}m$_{DM}$GeV^{-1}cm^2
Early DE,z=10^4,Ω$_{EDE}$=0.07
4.4σ
Early
Late
Here
Planck18+ΛCDM
Gaia DR2,HST π (R18a,b: SH0ES)
BAO+BBN ^{2}H
SN Ia NIR (DJL17,CSP B18)
BAO+ACTPol,SPT,WMAP
HOLiCOW−4 lenses (Birrer18)
r$_s$+ inverse ladder
R16 (SH0ES)
Reanalysis of R16 (C16,FK17,FM18)
64
66
68
70
72
74
76
H$_0$ (km s^{-1} Mpc^{-1})

Riess+,2019

Gravitational Waves as “Standard Sirens” to measure the Hubble Constant (10% accuracy)





Solving the tension at high z

What if the model is incorrect?

Relieving the tension acting on the neutrino sector:

1) massive neutrinos

2) additional relativistic species at recombination (e.g. light sterile)

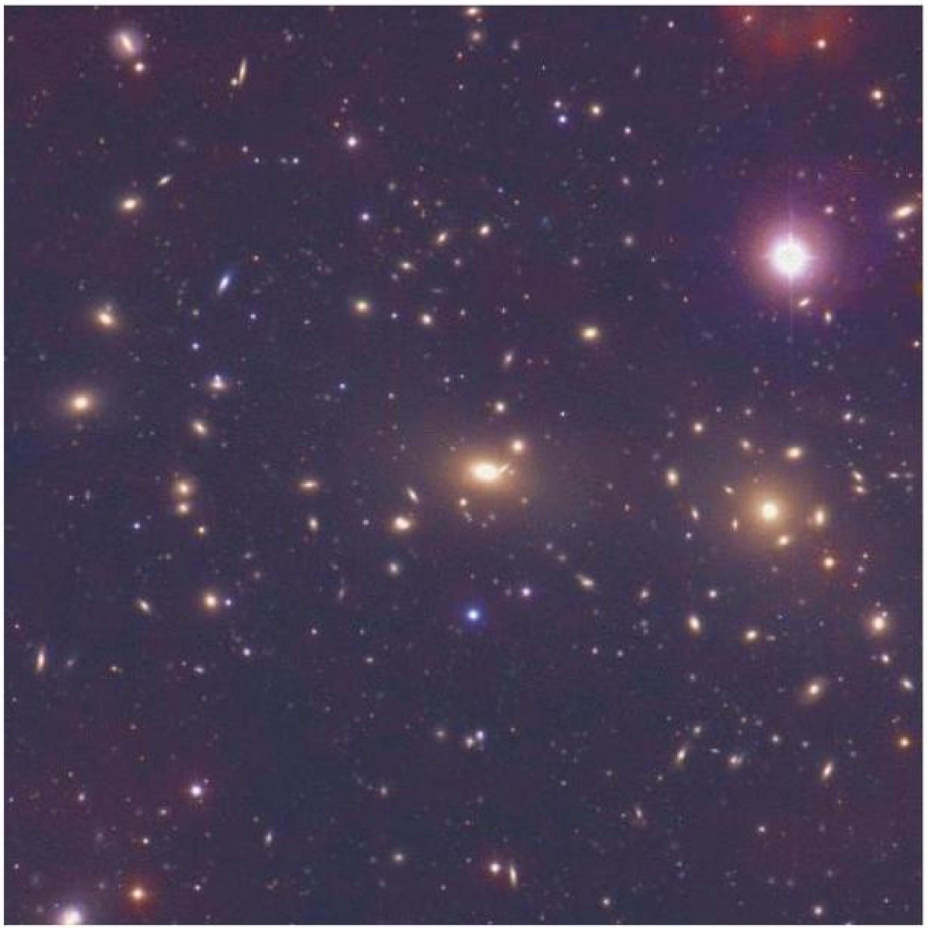
3) neutrino non-standard interactions

Dark Matter

Dynamical Evidence for Dark Matter

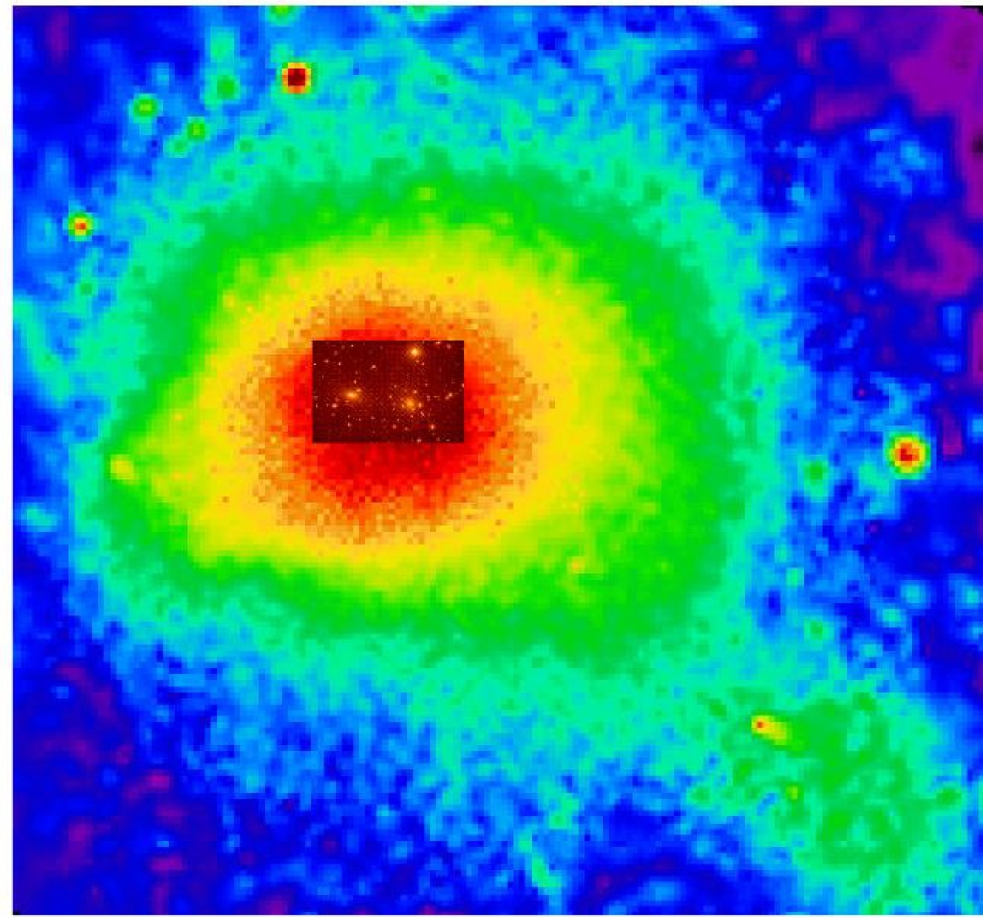
- Galaxies
- Clusters of Galaxies
- The entire Universe

COMA Galaxy Cluster



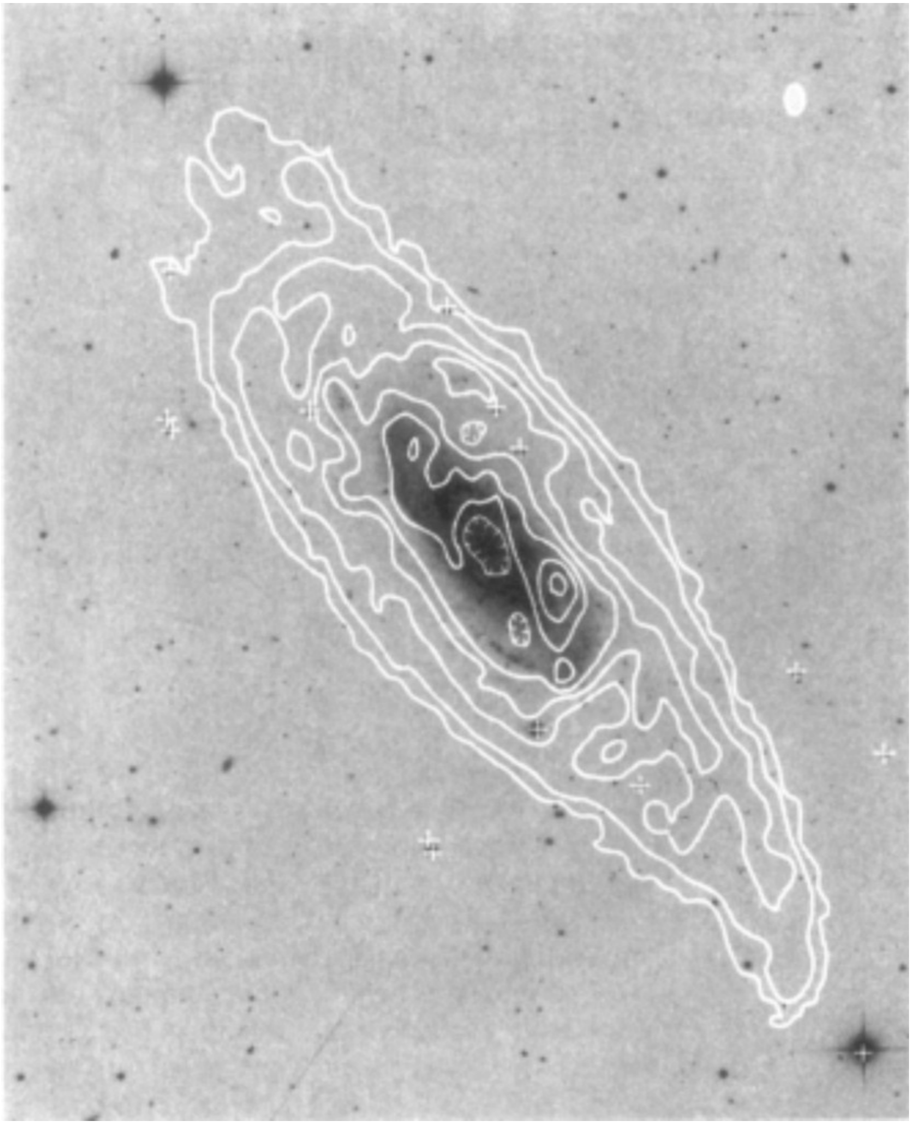
Optical

Fritz Zwicky 1933
First argument for Dark Matter
Virial theorem

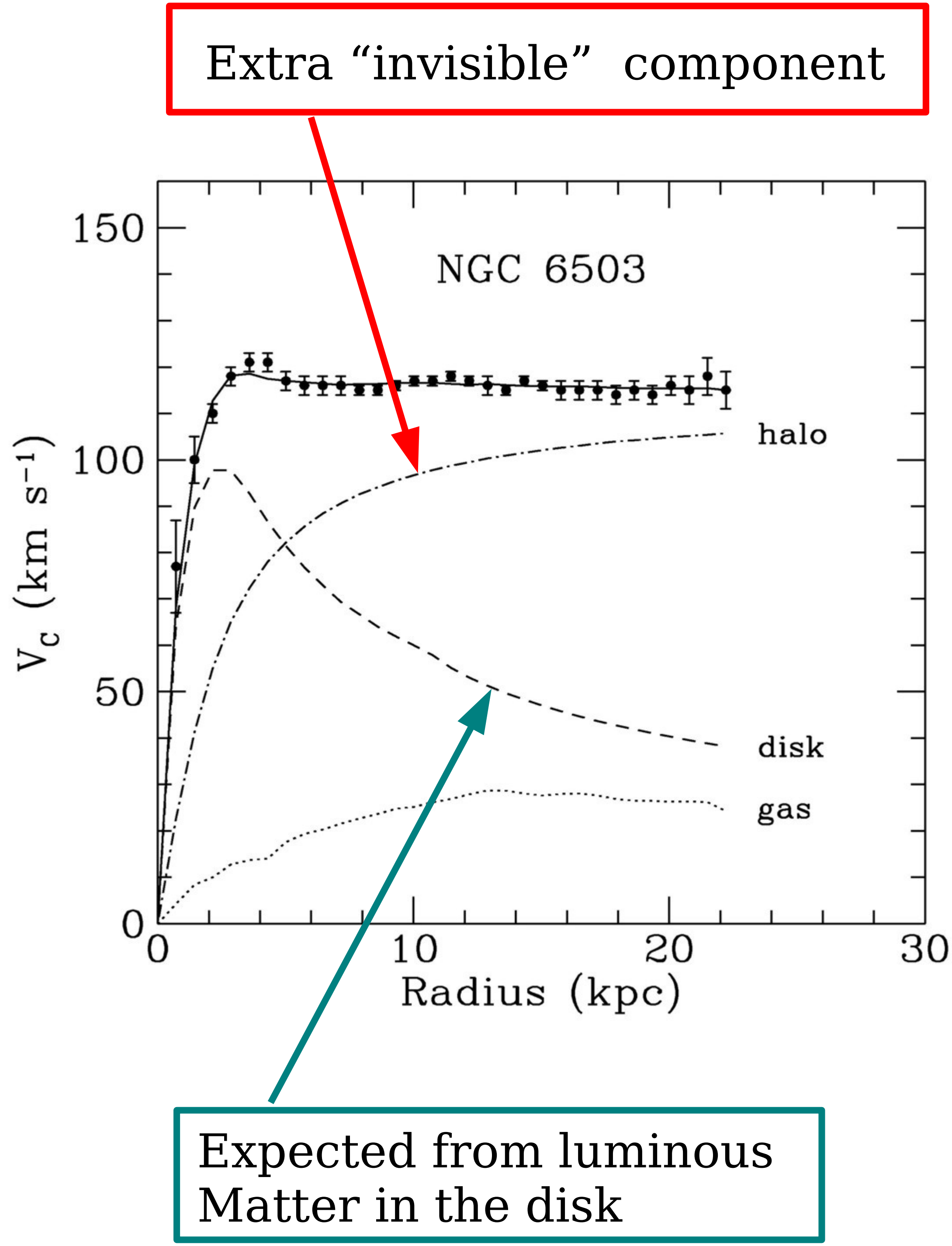


X-ray

[hot gas confined by
deep gravitational well]



Spiral galaxy NGC 3198 overlaid with hydrogen column density [21 cm] [ApJ 295 (1905) 305



2 statements that are very broadly accepted

Dark Matter Exists.

Its existence is inferred from observations of its gravitational effects on the dynamics of ordinary matter

No modifications of the the laws of gravity

(Modified Newtonian Dynamics MOND)

[as initially proposed by Milgrom in 1983]

is consistent the observations

The Dark Matter is "non baryonic"

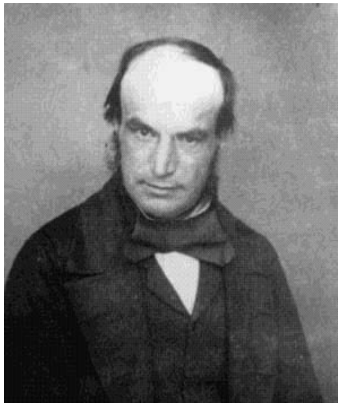
it is is an *"exotic substance"*

A field that is not contained in the Standard Model of Particle Physics

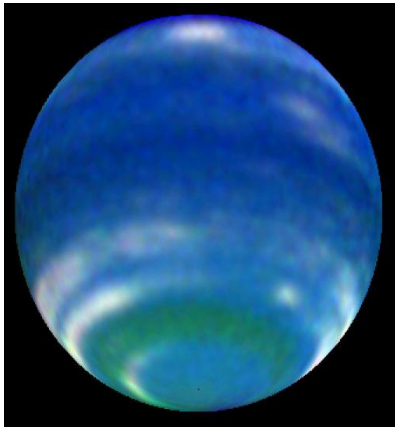
Uranus orbital anomalies

Prediction + Discovery of Neptune (23/24 september 1846)

Urbain Le Verrier

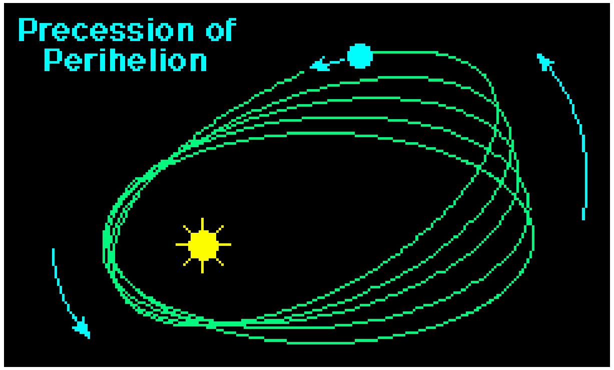


John Couch Adams

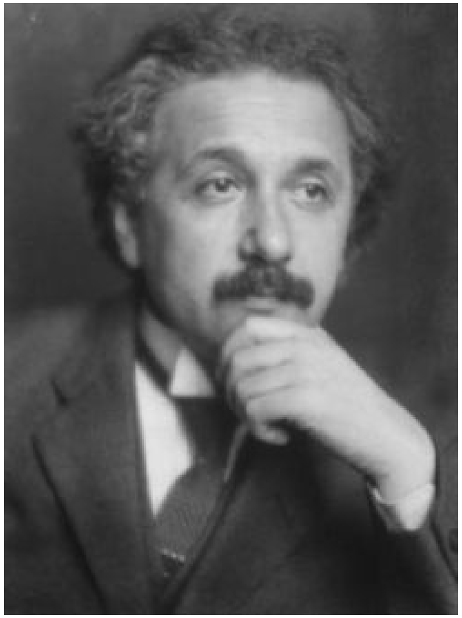


Mercury orbital anomalies

Extra 43''/century perihelion precession



New dynamics
General Relativity
(1916 Albert Einstein)



MOdified Newtonian Dynamics ["phenomenological" model]

[Milgrom 1983]

$$a_0 \simeq 10^{-8}\ \mathrm{cm/s^2}$$

$$F_{\rm grav} = \begin{cases} m a & \text{for } a >> a_0 \\ m \dfrac{a^2}{a_0} & \text{for } a << a_0 \end{cases}$$

Fundamental acceleration

$$a_0 \simeq c\, H_0/5$$

Coincidence?

$$\frac{G\,M}{r^2} = \frac{v^2}{r}$$

"Newtonian"

$$v_{\rm rot}^2 \to GM/r$$

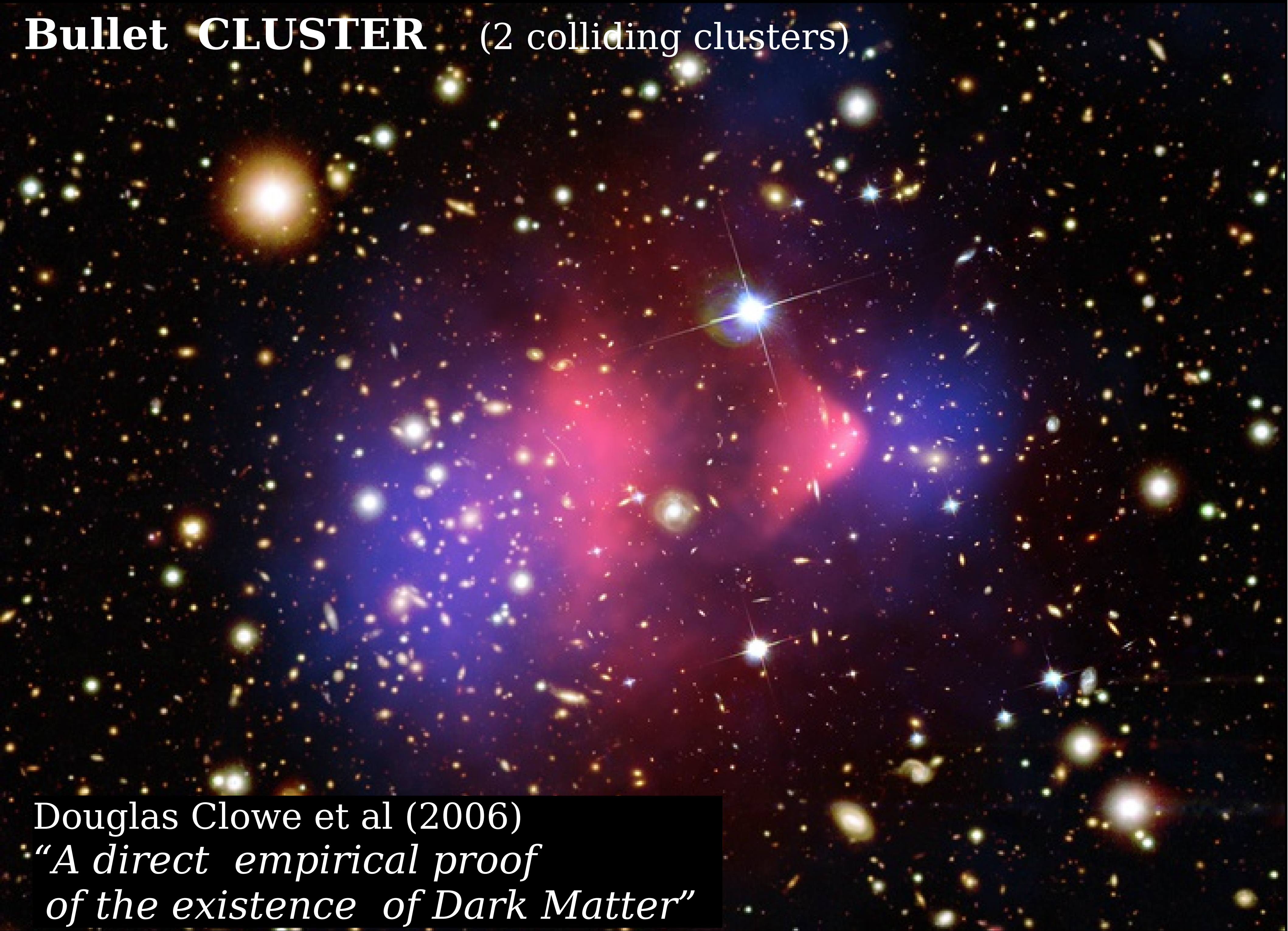
$$\frac{G\,M}{r^2} = \left(\frac{v^2}{r}\right)^2 \frac{1}{a_0}$$

Modified Newtonian (small acceleration)

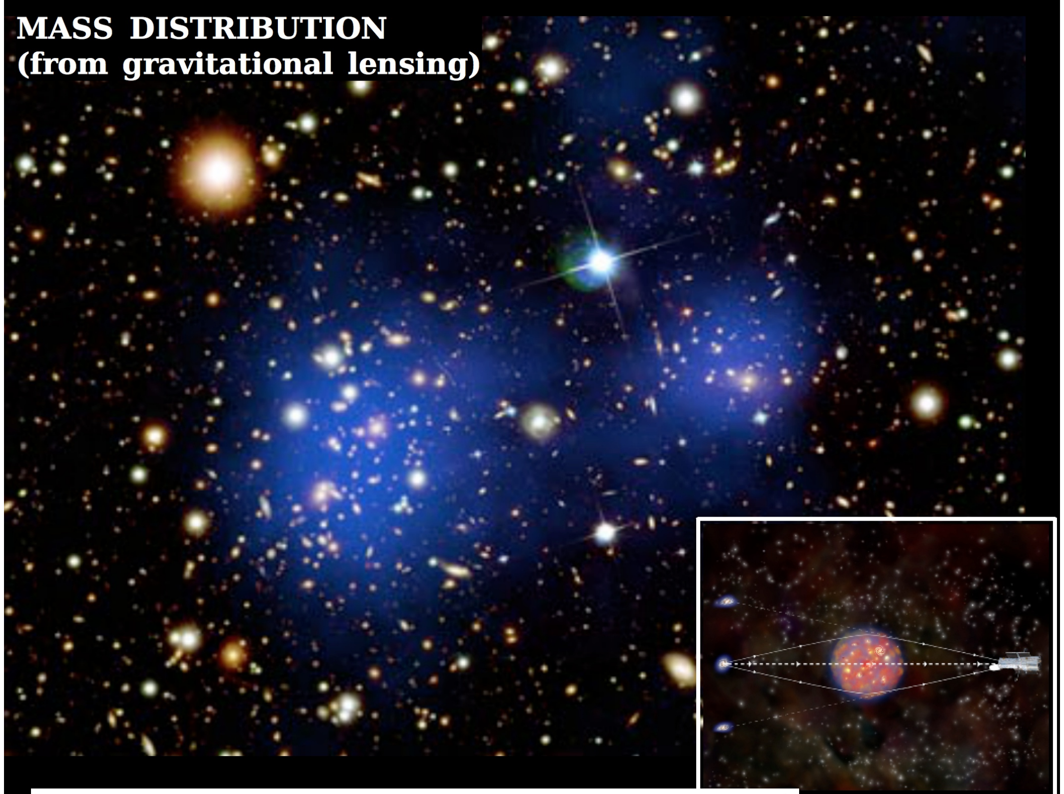
$$v_{\rm rot}^4 \to G M\, a_0$$

$$v_{\rm rot} \propto M^{1/4} \propto L^{1/4}$$

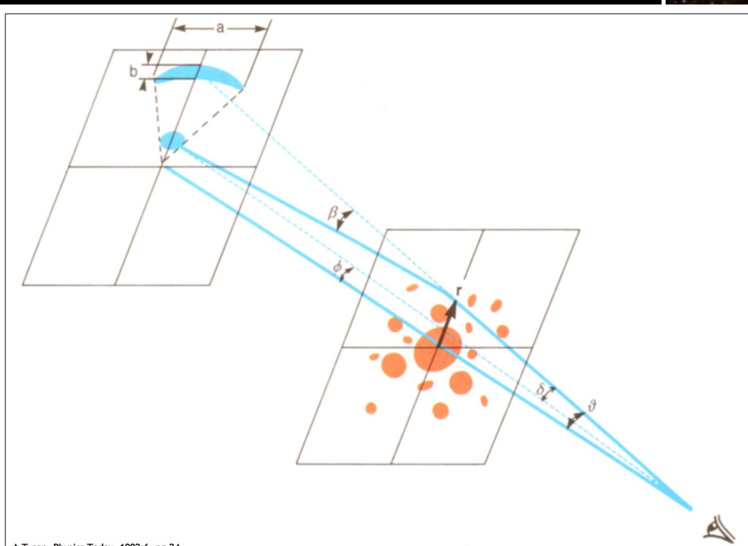
Bullet CLUSTER (2 colliding clusters)

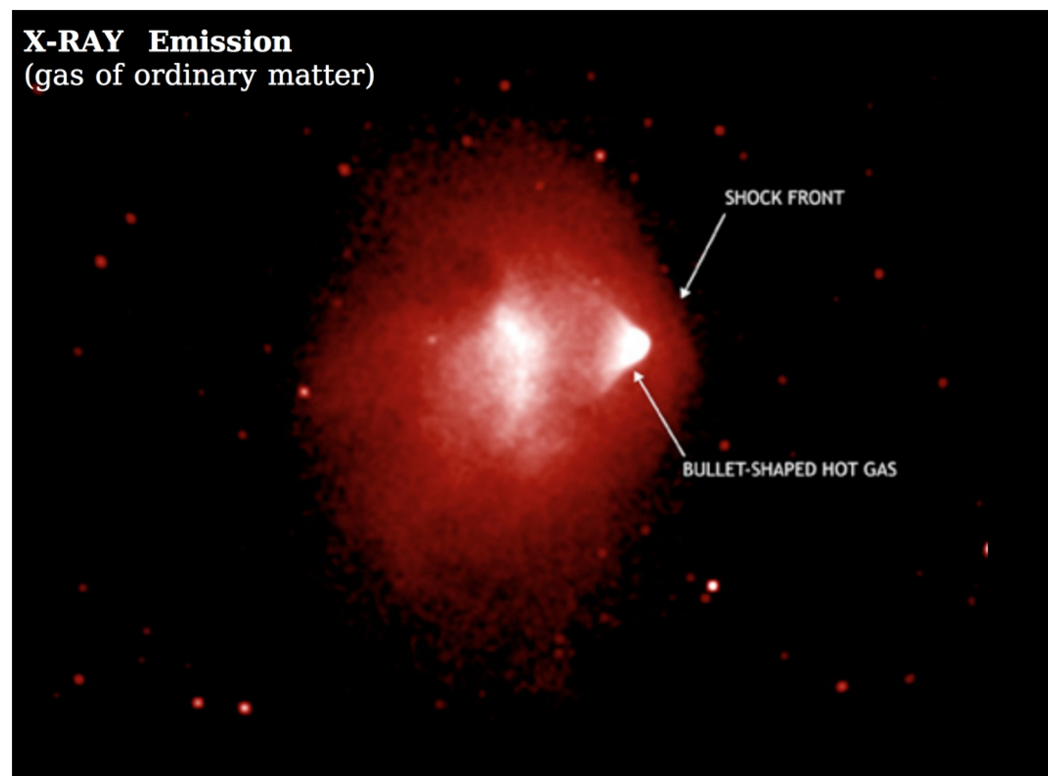


Douglas Clowe et al (2006)
"A direct empirical proof of the existence of Dark Matter"



"BULLET CLUSTER"
(Cluster 1E0657-558:
2 colliding clusters at z=0.296)
Clear separation between
Baryons and Mass.





D. Clowe, M. Bradac, A. H. Gonzalez *et al.*,
"A direct empirical proof of the existence of dark matter,"
Astrophys. J. **648**, L109-L113 (2006). [astro-ph/0608407].

It has been possible [Bekenstein 1984] to construct a consistent (Lagrangian) theory that embed MOND.

Success in describing the observed dynamics of many galaxies.

Difficulties in describing Galaxy Clusters and structure formation in Cosmology.

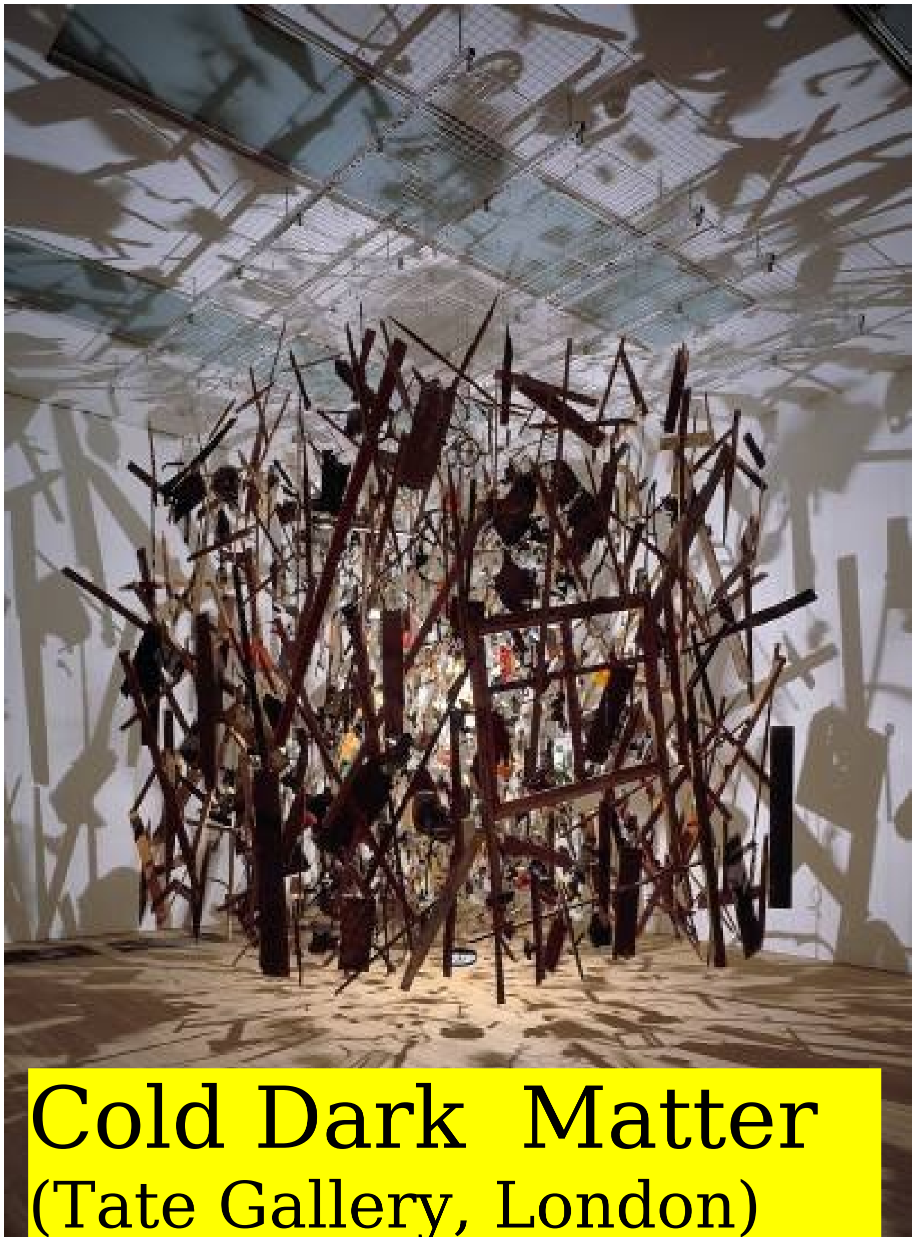
Constrains from Gravitational Wave Observations.

J. D. Bekenstein,
"Alternatives to dark matter: Modified gravity as an alternative to dark matter,"
arXiv:1001.3876 [astro-ph.CO].

1. Introduction

A look at the other papers in this volume will show the present one to be singular. Dark matter is a prevalent paradigm. So why do we need to discuss alternatives ? While observations seem to suggest that disk galaxies are embedded in giant halos of dark matter (DM), this is just an *inference* from accepted Newtonian gravitational theory. Thus if we are missing understanding about gravity on galactic scales, the mentioned inference may be deeply flawed. And then we must remember that, aside for some reports which always seem to contradict established bounds, DM is not seen directly. Finally, were we to put all our hope on the DM paradigm, we would be ignoring a great lesson from the history of science: accepted understanding of a phenomenon has usually come through confrontation of rather contrasting paradigms.

What form the Dark Matter ?



Cold Dark Matter
(Tate Gallery, London)

Cornelia Parker

What is the Dark Matter ?

Possible theoretical ideas

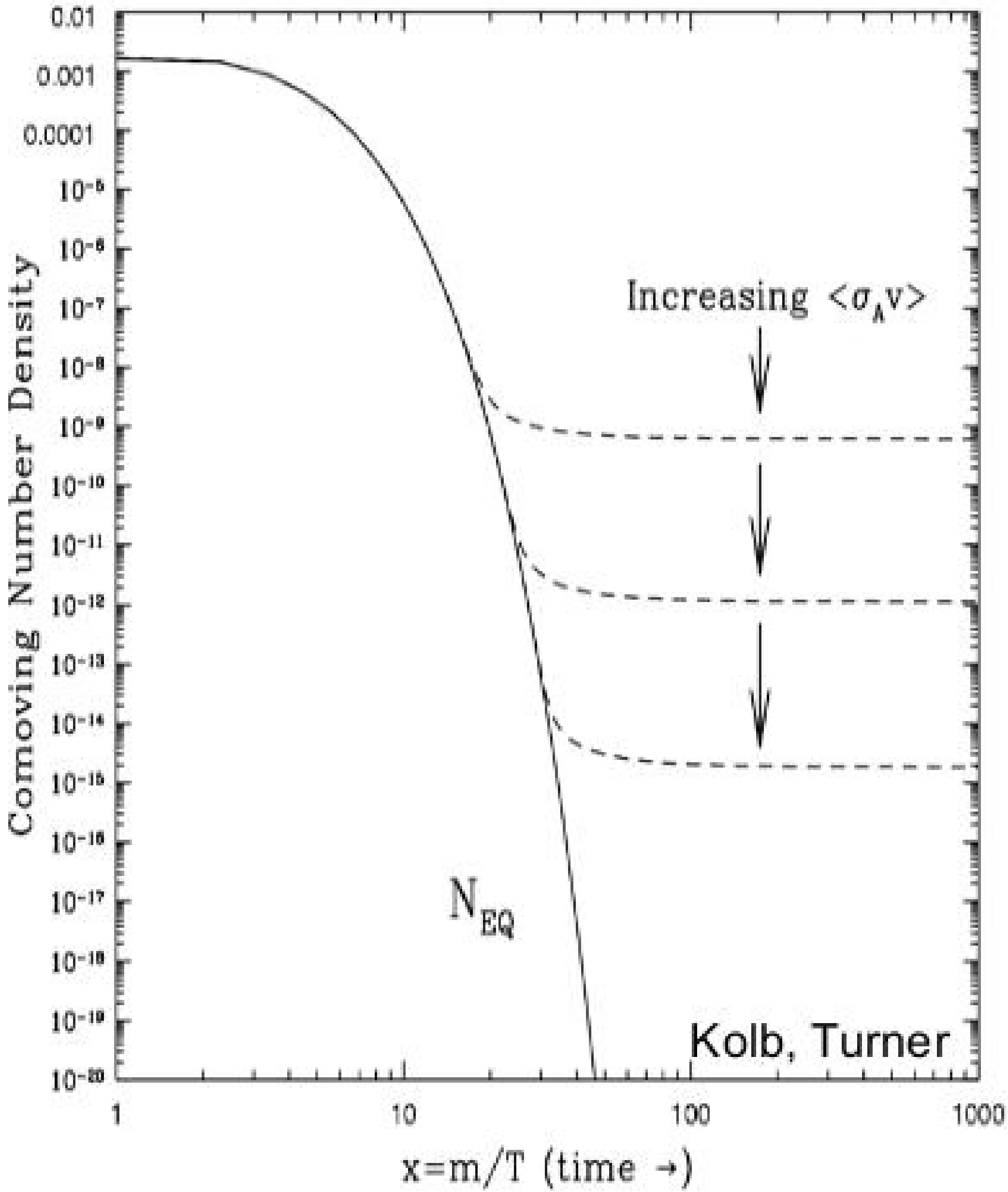
Thermal Relic [Weakly Interacting Massive Particle (WIMP)]

Sterile Neutrinos

Axion

......

Relic abundance



$$\chi + \chi \leftarrow f + \overline{f}$$

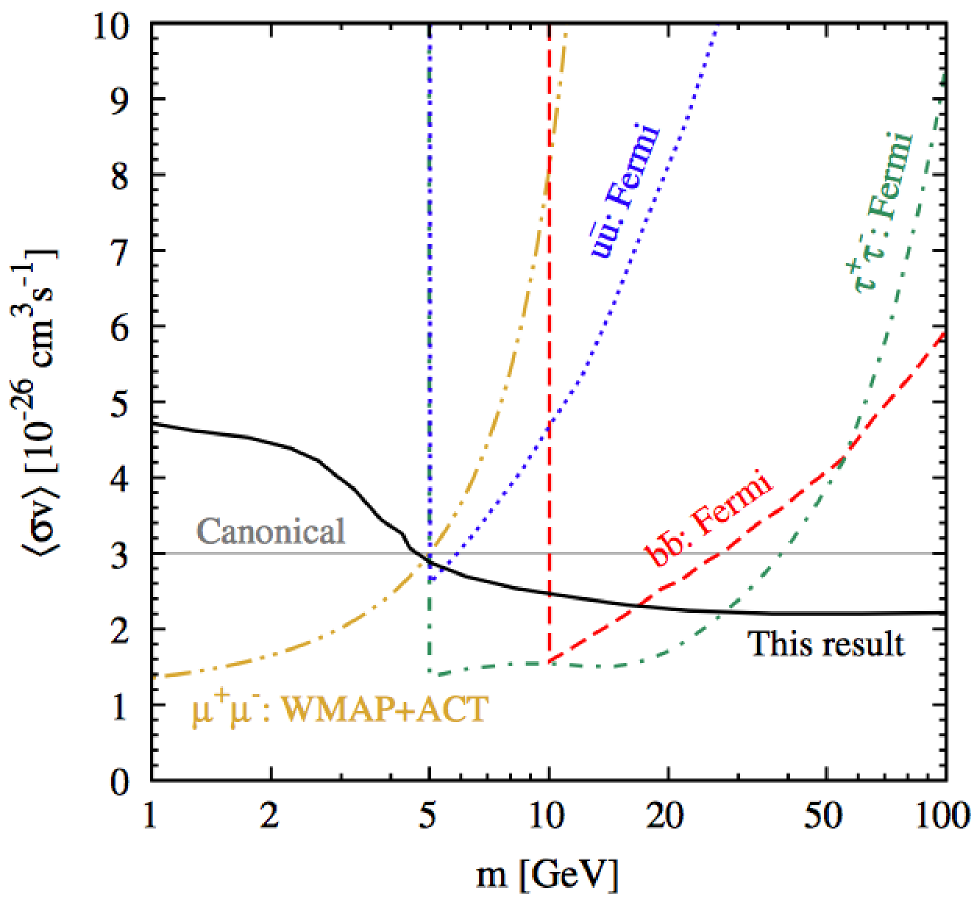
$$\chi + \chi \rightarrow f + \overline{f}$$

Annihilation cross section determines the "relic abundance"

$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle}\right]$$

$$\Omega_\chi \simeq \left(\frac{16\,\pi^{5/2}}{9\,\sqrt{\pi}}\right)\,\frac{G^{3/2}\,T_0^3}{H_0^2\,(\hbar c)^{3/2}\,c^3}\,\frac{\sqrt{g_{\rm eff}}}{\langle \sigma\, v\rangle}$$

$$\Omega_\chi^{\rm analytic} = 0.173\,\left(\frac{3\times 10^{-26}\ {\rm cm}^3\,{\rm s}^{-1}}{\langle\sigma\,v\rangle_{\rm f}}\right)\sqrt{\frac{g_{\rm eff}}{106.75}}$$



G. Steigman, B. Dasgupta and J. F. Beacom,

"Precise Relic WIMP Abundance and its Impact on Searches for Dark Matter Annihilation,"

Phys. Rev. D **86**, 023506 (2012)

arXiv:1204.3622 [hep-ph].

The "strength" of the interactions of the (hypothetical) Dark Matter particle is similar to the strength of the

WEAK INTERACTION

$W^{\pm}$ Z bosons

$$\sigma(\chi\chi \to \text{anything}) \simeq 10^{-36}\ \text{cm}^2$$

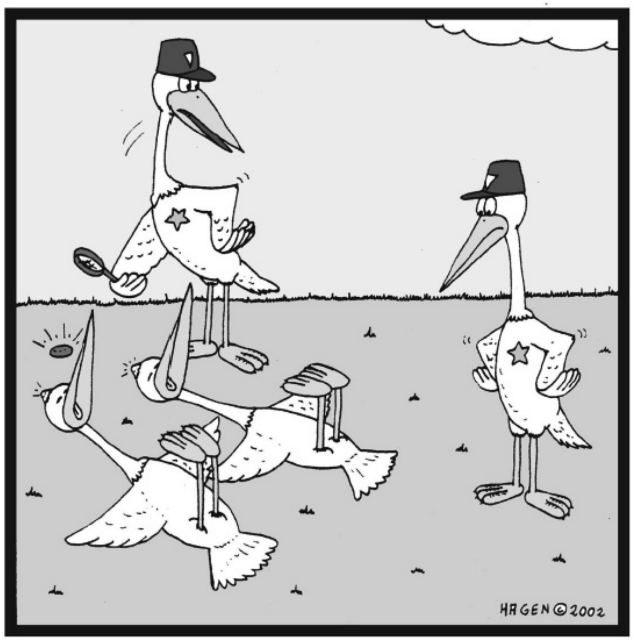
(1 picobarn)

$$\sigma \simeq \frac{\alpha^2}{M^2}\,(\hbar c)^2$$

Weak interaction mass scale

$$M \simeq 200\ \text{GeV}$$

Weakly Interacting Massive Particles (WIMP's)



Unbelievable! It looks like they've
both been killed by the same stone...

the WIMP's "miracle"

"Killing two birds with a single stone"

Dark Matter Puzzle

Direct observational problem

Theories Beyond the Standard Model
(in particular Supersymmetry)
predict new particles that have
the right properties to form the DM

"Theoretical" motivation

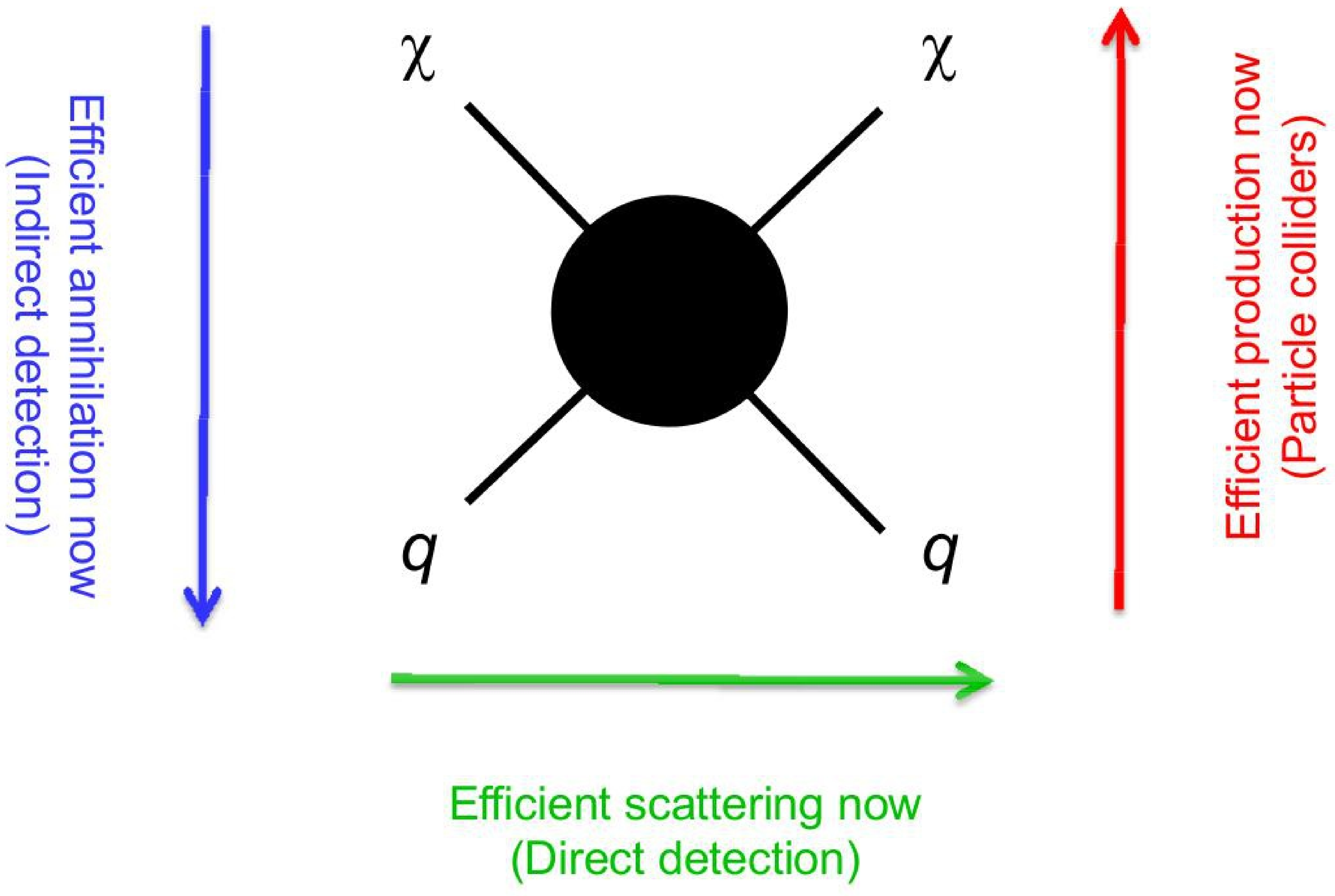
	Standard Model fields	Super-symmetric extension	
fermions	quarks	Squarks	New bosons (scalar) spin 0 S....
	leptons	Sleptons	
	neutrinos	Sneutrinos	
bosons	photon	photino	New fermions spin 1/2 ...ino
	W	Wino	
	Z	Zino	
	gluons	gluinos	
	Higgs	Higgsino	
2 Higgs →	H h	$\tilde{H}$ $\tilde{h}$	

Weak (~100 GeV) Mass scale ?

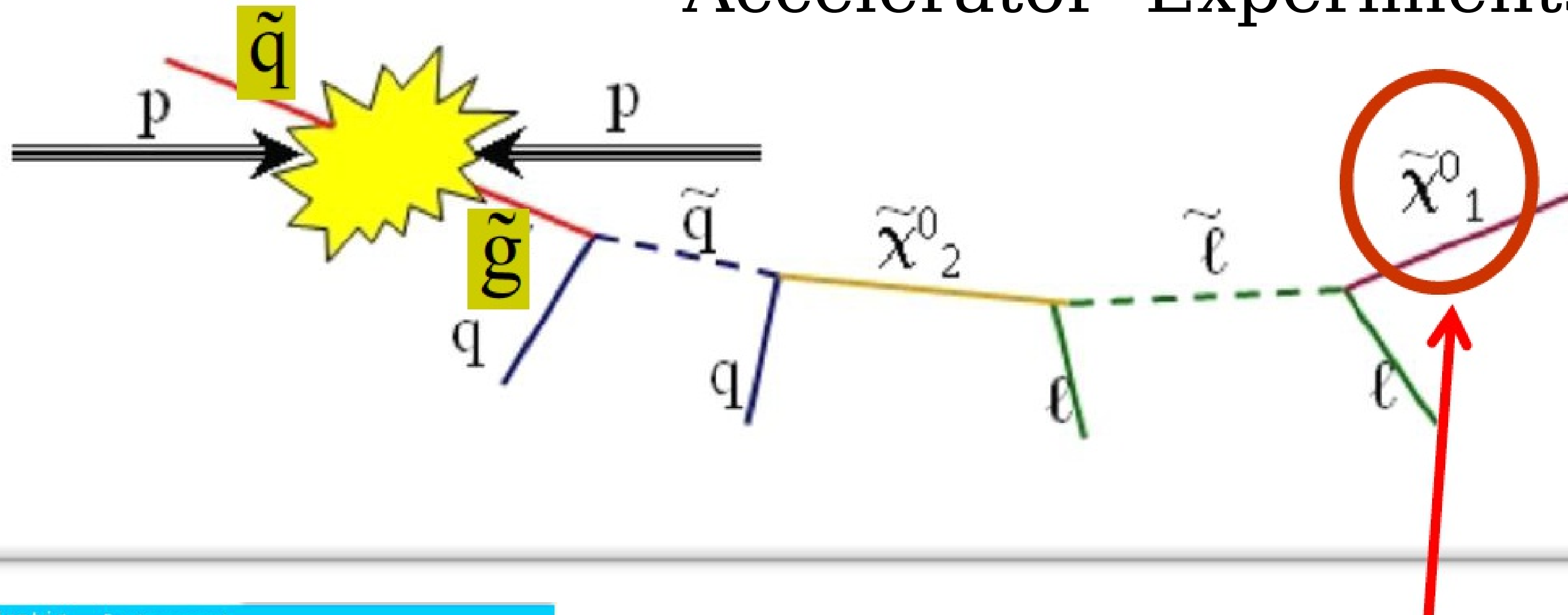
one stable new particle (R-parity conserved)

$$|\chi\rangle = c_1\,|\tilde{\gamma}\rangle + c_2\,|\tilde{z}\rangle + c_3\,|\tilde{H}\rangle + c_4\,|\tilde{h}\rangle$$

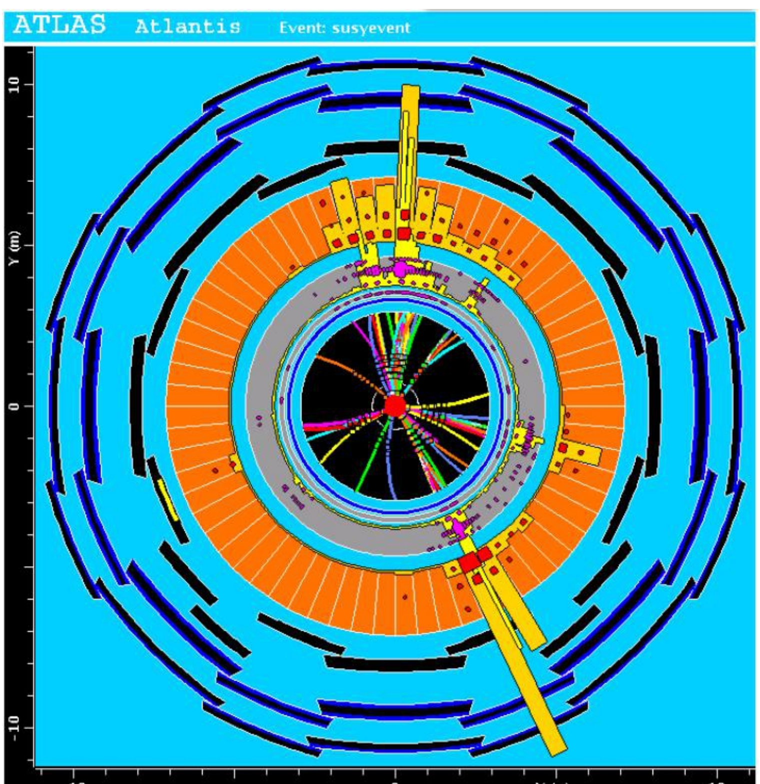
Three roads to the DM (WIMP) discovery



Accelerator Experiments



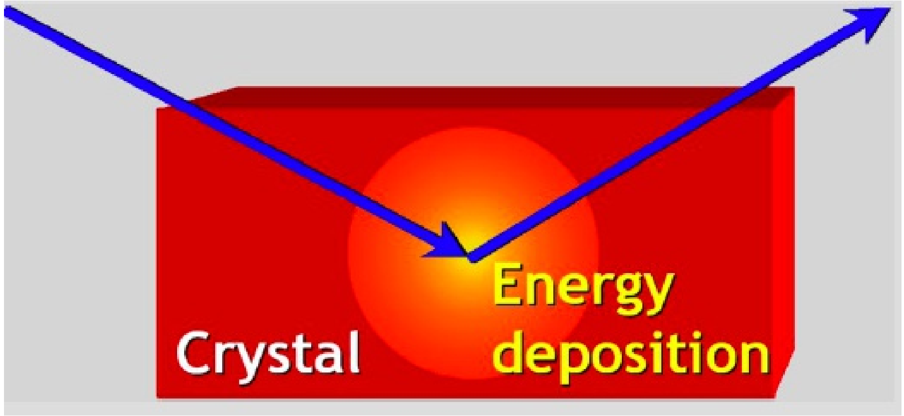
Lowest mass,
stable,
(super-symmetric)
Particle [LSP]



This particle interacts WEAKLY therefore (effectively always) traverse the detector invisibly.

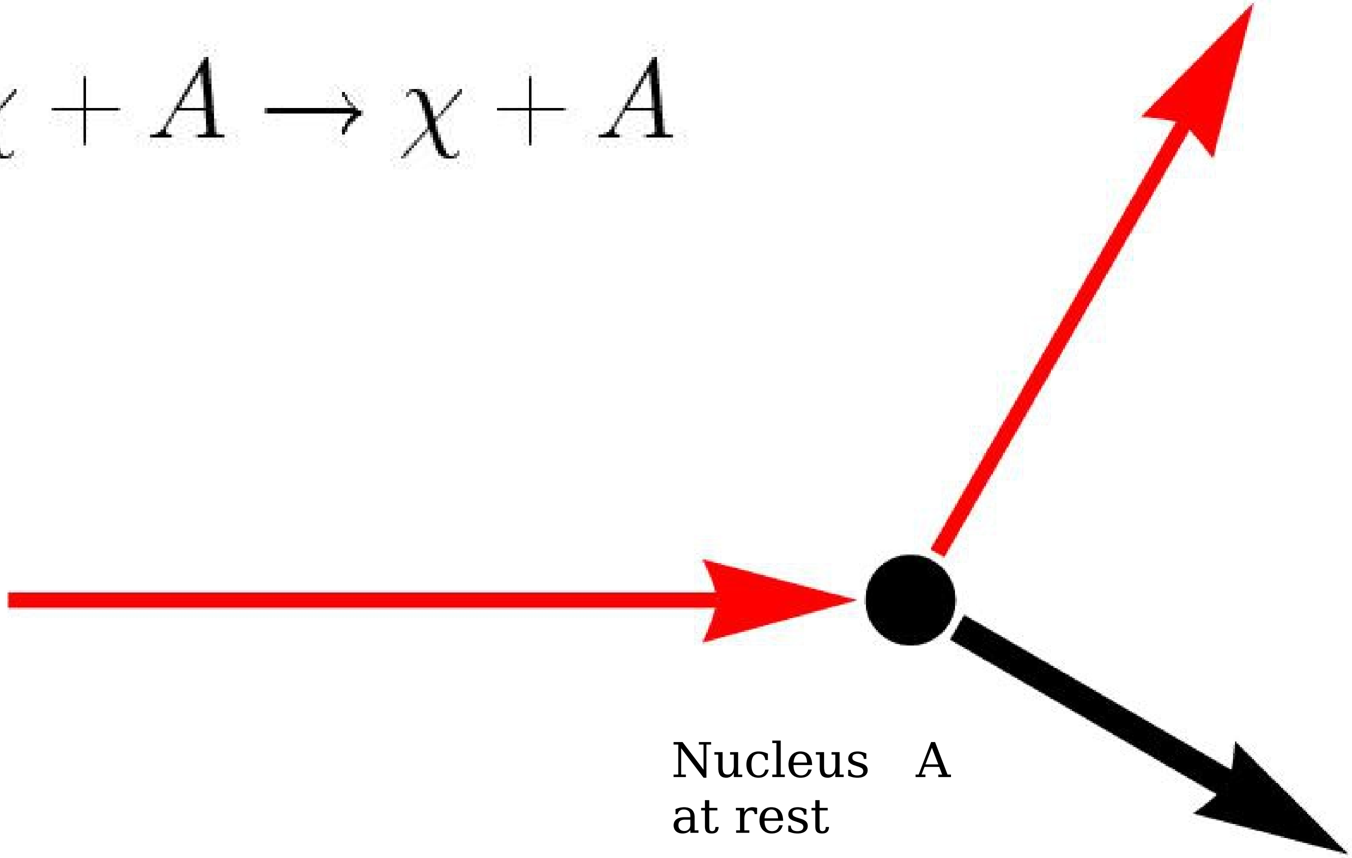
Detection via 4-momentum conservation
["Missing energy and
(transverse) momentum"]

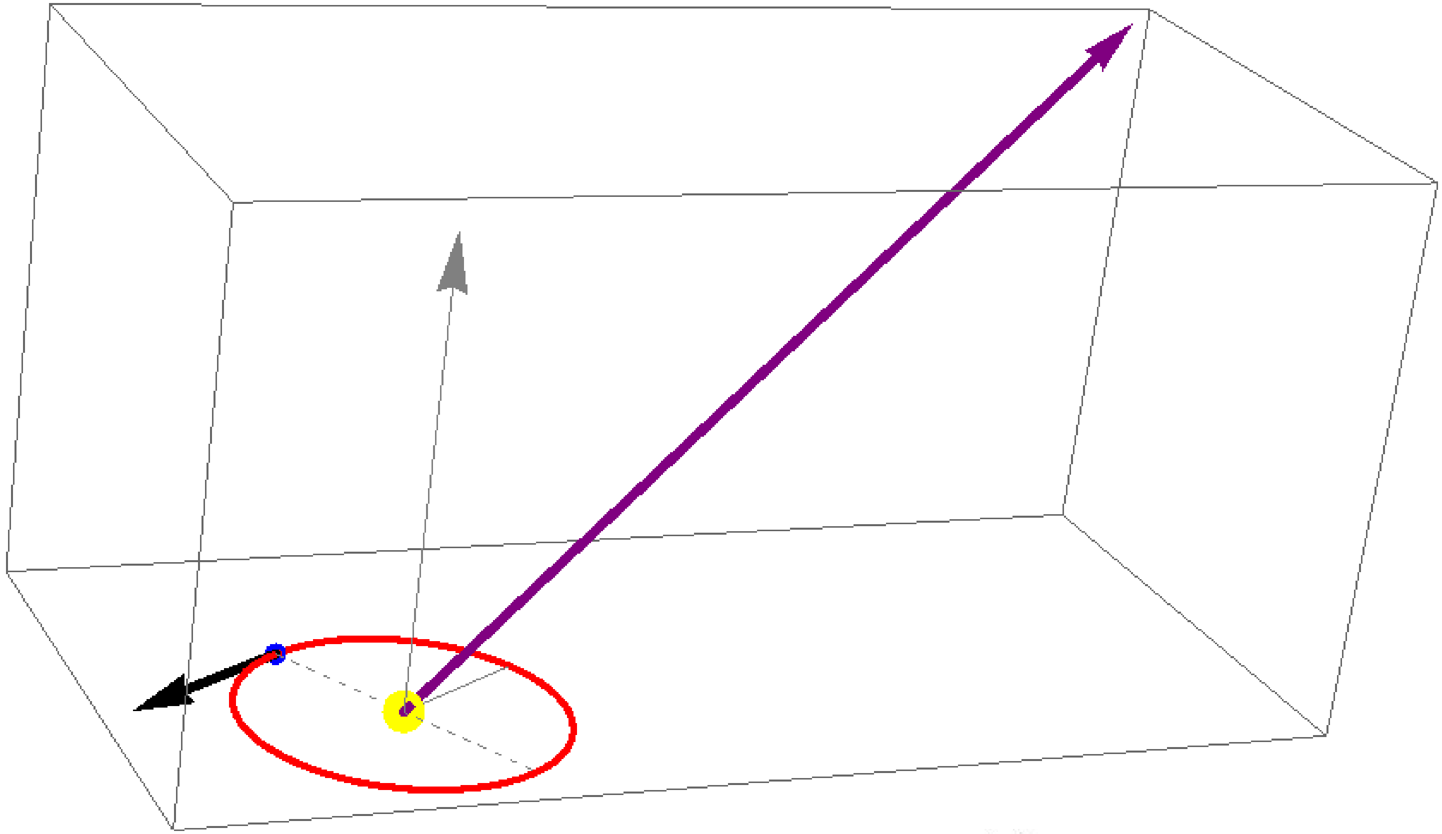
“Direct” Search
for Dark Matter



Elastic scattering

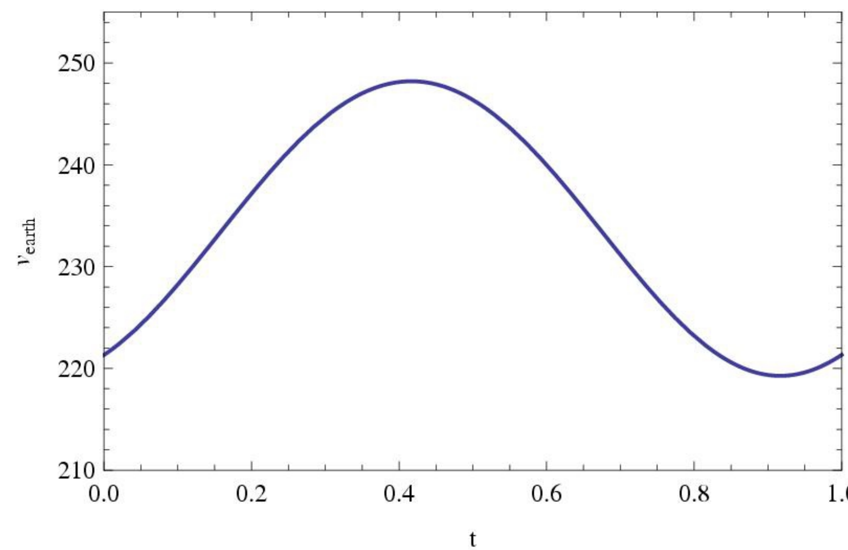
$$\chi + A \rightarrow \chi + A$$





$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma \; v_{\rm orbit} \;\; \cos[\omega(t-t_0)]$$

$$\vec{w}_{\oplus}(t) = \vec{w}_{\odot} + \vec{v}_{\rm orbit}(t)$$



“Halo rest frame”

Velocity of Earth in the Halo rest frame

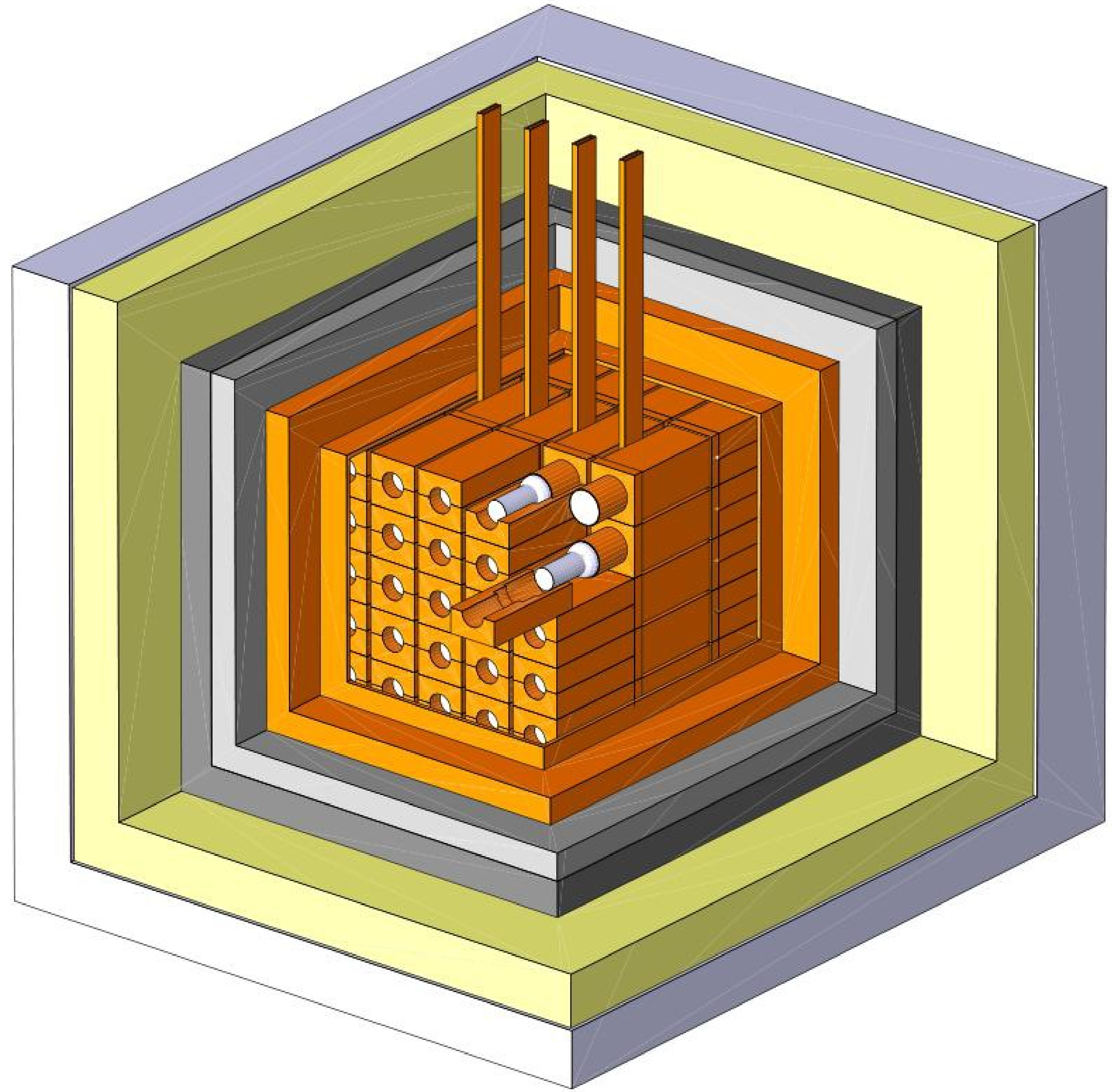
[Co-rotation ?]

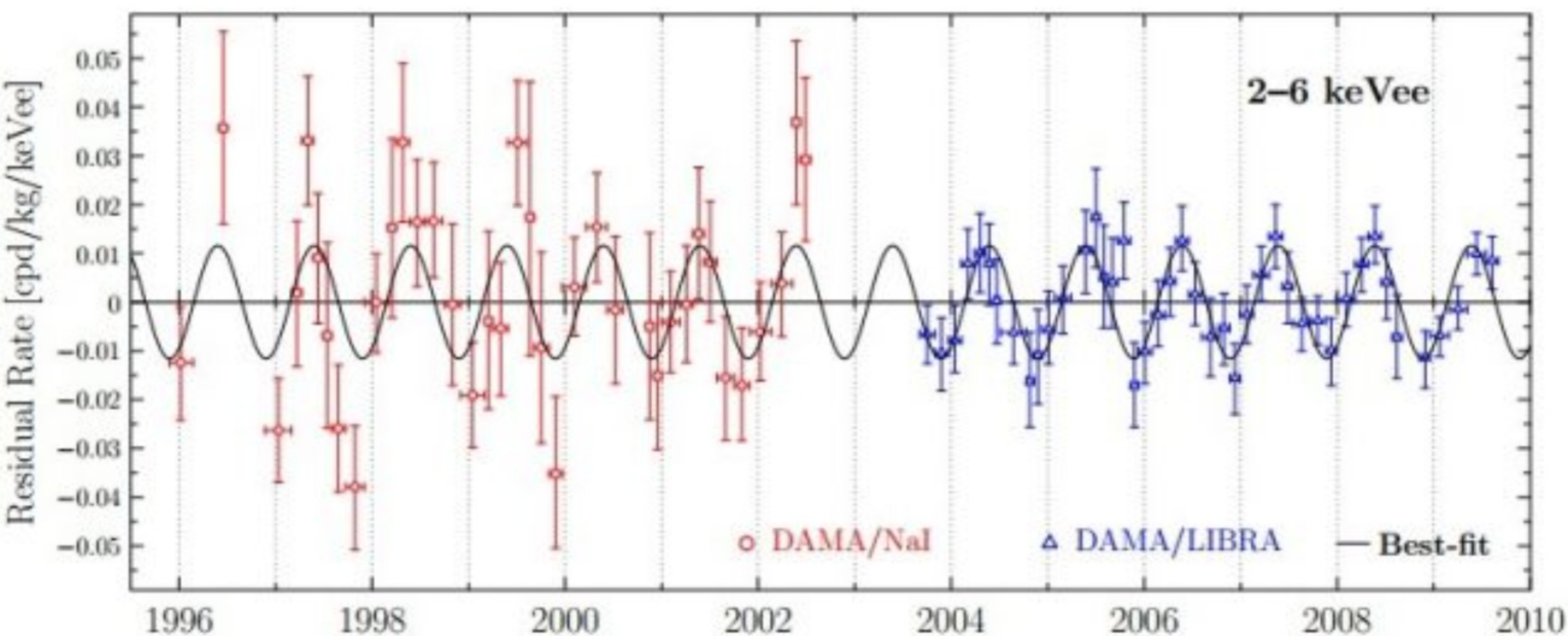
DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

Observation
of sinusoidal
time-modulation of the
Energy Deposition Rate

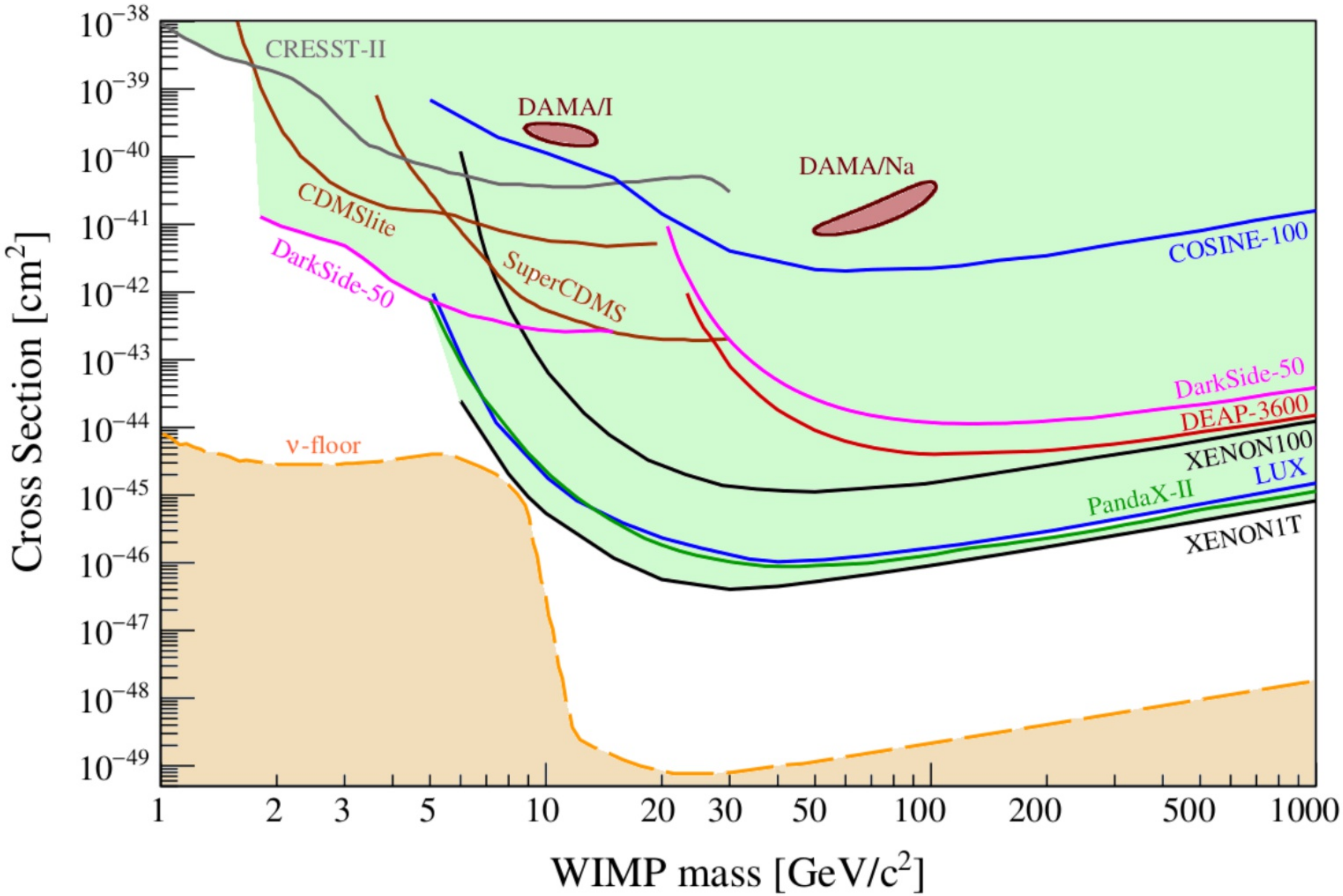
(controversial)
claim of evidence
of detection of
Galactic Dark Matter





2–6 keVee
Residual Rate [cpd/kg/keVee]
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
1996
1998
2000
2002
2004
2006
2008
2010
DAMA/NaI
DAMA/LIBRA
Best-fit

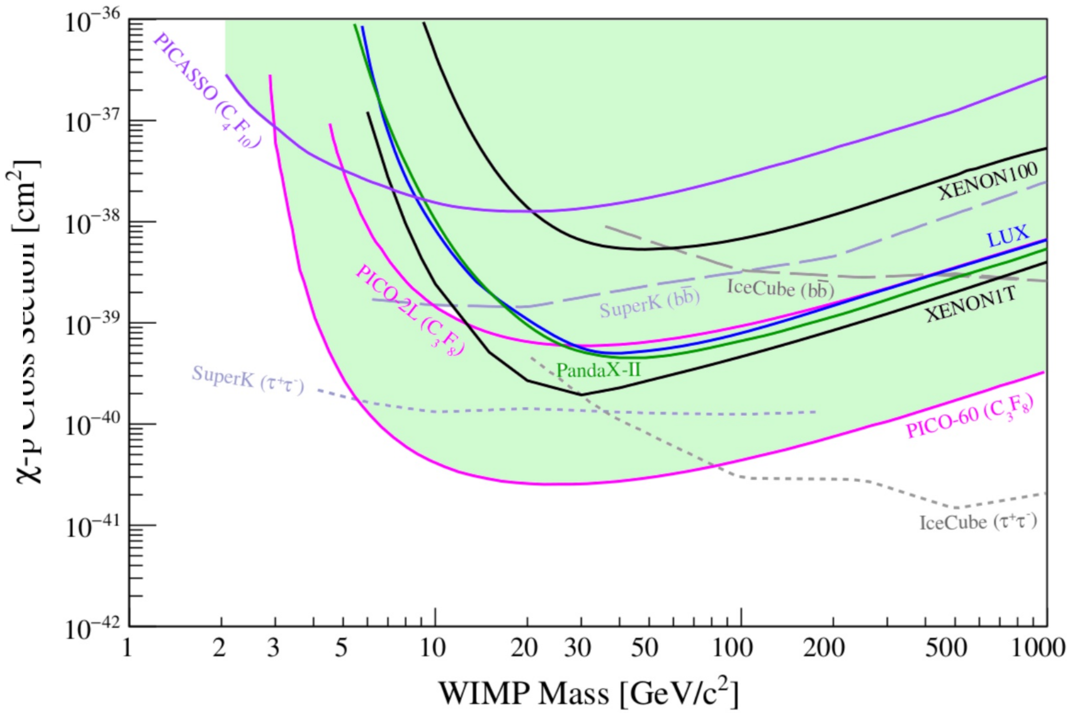
Excluded region in the plane $\{m_\chi, \sigma_{N\chi}\}$ [spin independent]



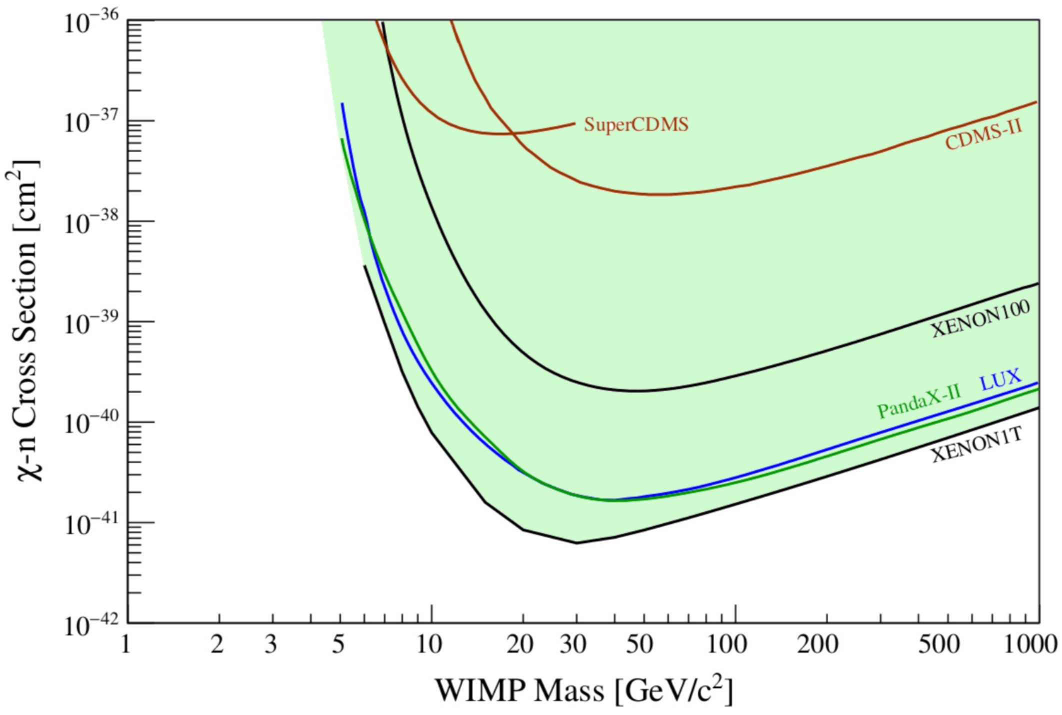
M. Schumann,
"Direct Detection of WIMP Dark Matter: Concepts and Status"
arXiv:1903.03026 [astro-ph.CO].

Excluded regions [spin dependent]

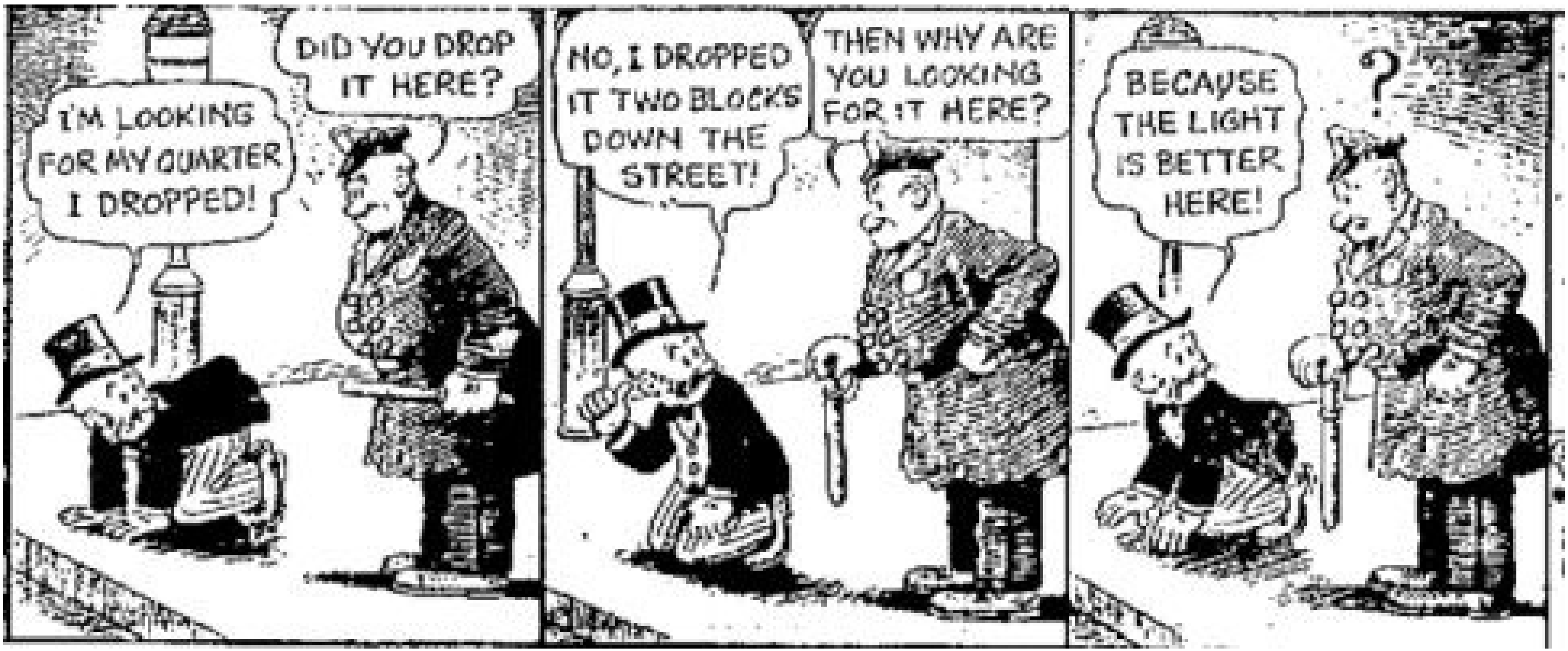
$$\sigma_{\chi p}$$



$$\sigma_{\chi n}$$



The "Lamp post joke"



Seljuk Sufi mystic Nasrudin Hodja (12th century)

Someone saw Nasrudin searching for something on the ground.
“What have you lost, Mulla?” he asked.
“My key,” said the Mulla.
So they both went down on their knees and looked for it.
After a time the other man asked:
“Where exactly did you drop it?”
“In my own house.”
“Then why are you looking here?”
“There is more light here than inside my own house.”‘

G. Bertone and T. Tait,
"A new era in the search for dark matter"
Nature **562**, no. 7725, 51 (2018)
[arXiv:1810.01668 [astro-ph.CO]].

There is a growing sense of `crisis' in the dark matter community, due to the absence of evidence for the most popular candidates such as

weakly interacting massive particles, axions, and sterile neutrinos,

despite the enormous effort that has gone into searching for these particles.

We argue that diversifying the experimental effort, incorporating astronomical surveys and gravitational wave observations, is our best hope to make progress on the dark matter problem.

In light of this situation, the new guiding principle should be *"no stone left unturned":*

We should look for dark matter not only where theoretical prejudice dictates that we ``must", but wherever we can.

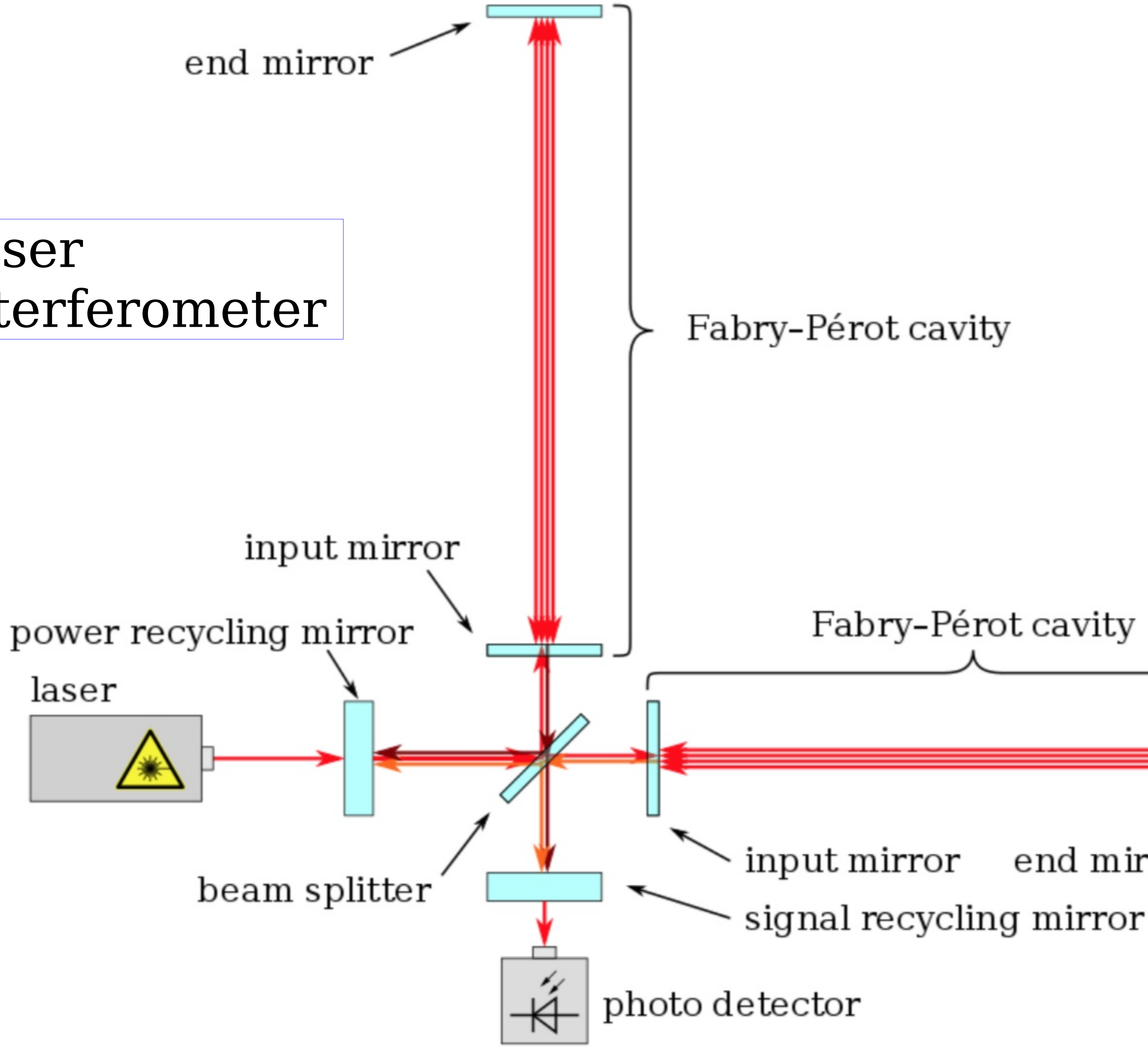
Casting a wider theoretical net offers the possibility to discover new classes of dark matter candidates and new experimental opportunities to search for them, and also helps assemble a ``composite image" of everything we currently know about the space of possibilities consistent with measurements to date.

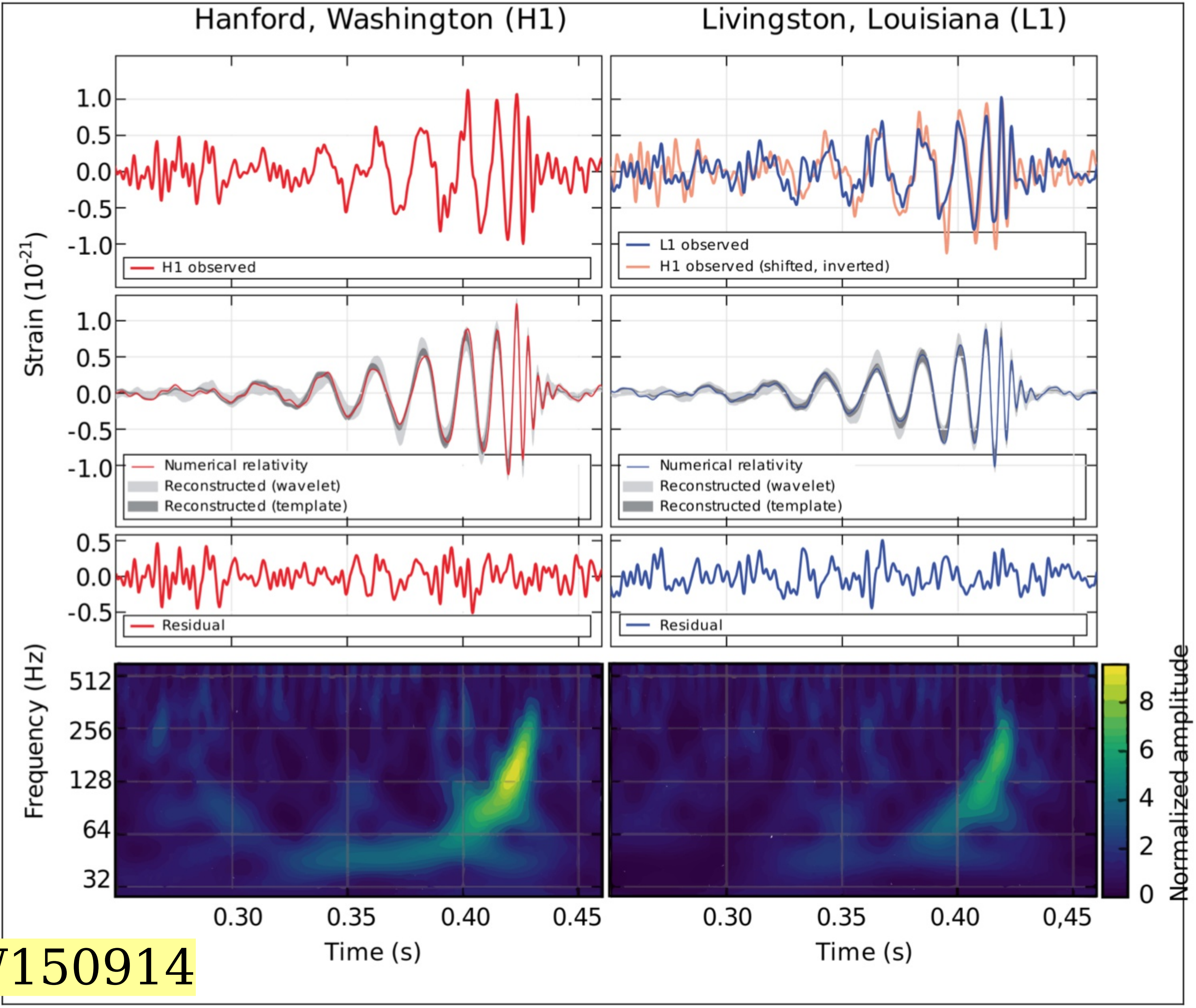
Possible Solutions to the Dark Matter Problem

Gravitational Waves

Nobel prize 2017

Laser Interferometer

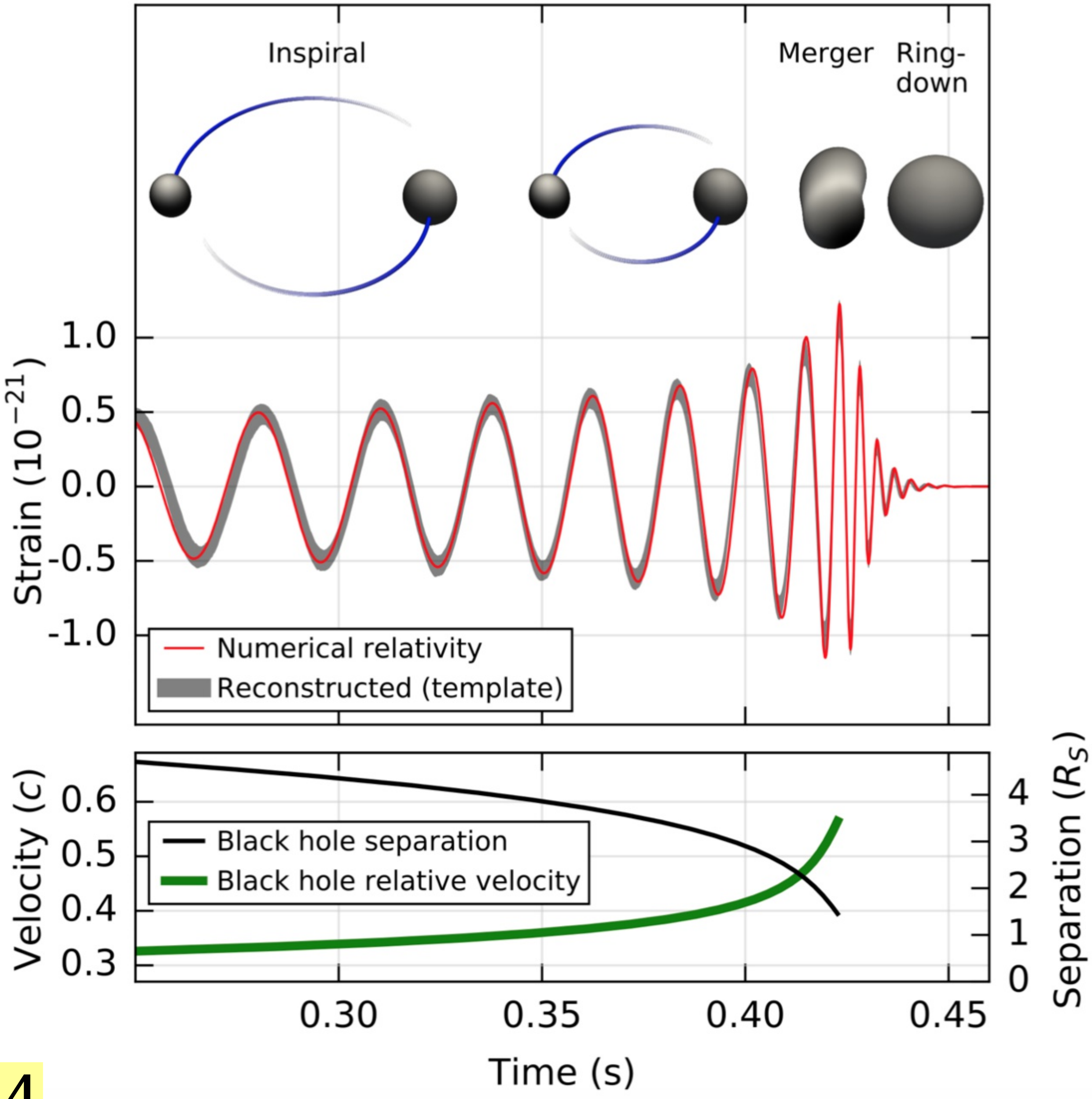




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
8
6
4
2
0
0.30
0.35
0.40
0.45
Time (s)

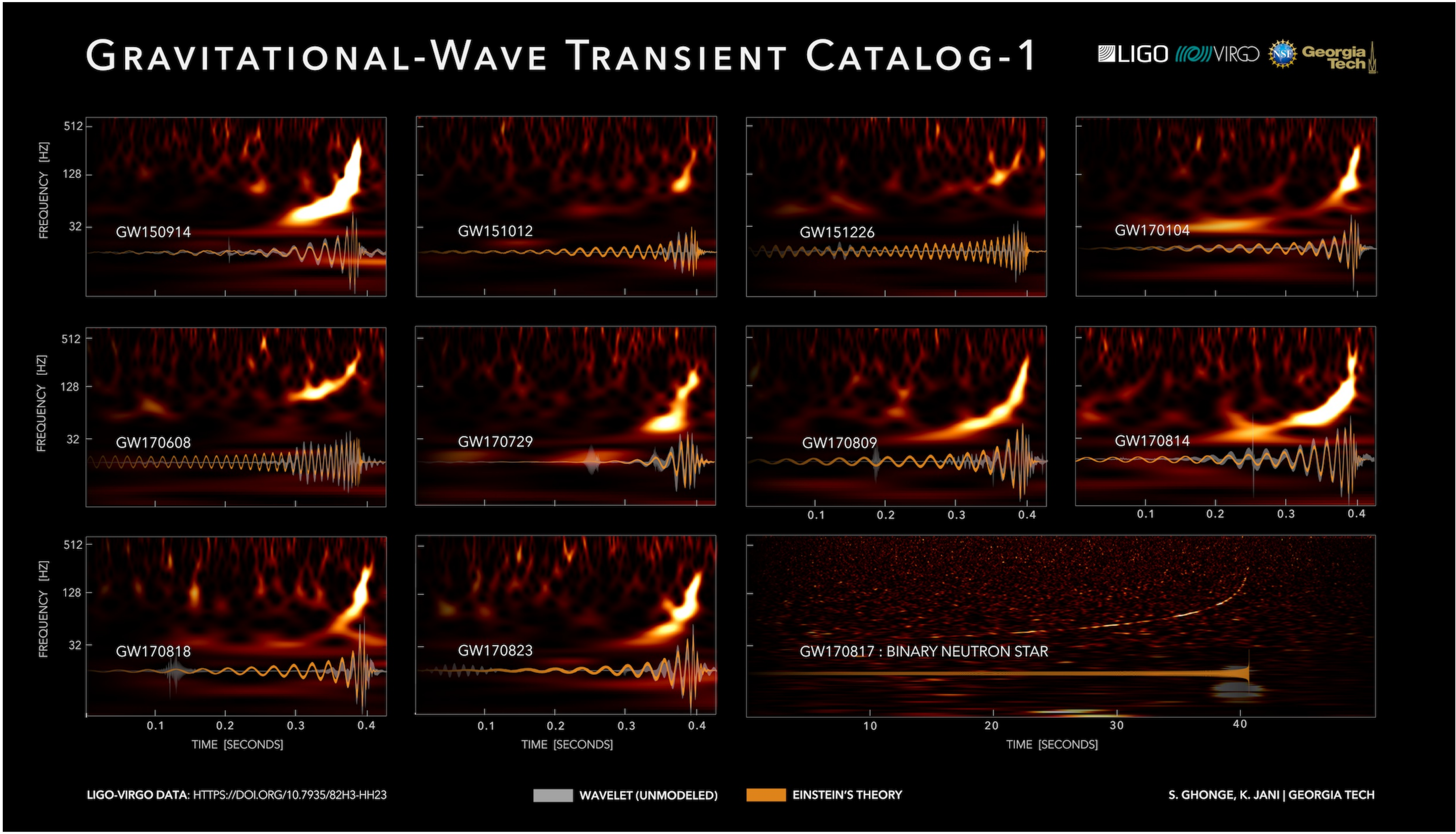
GW150914

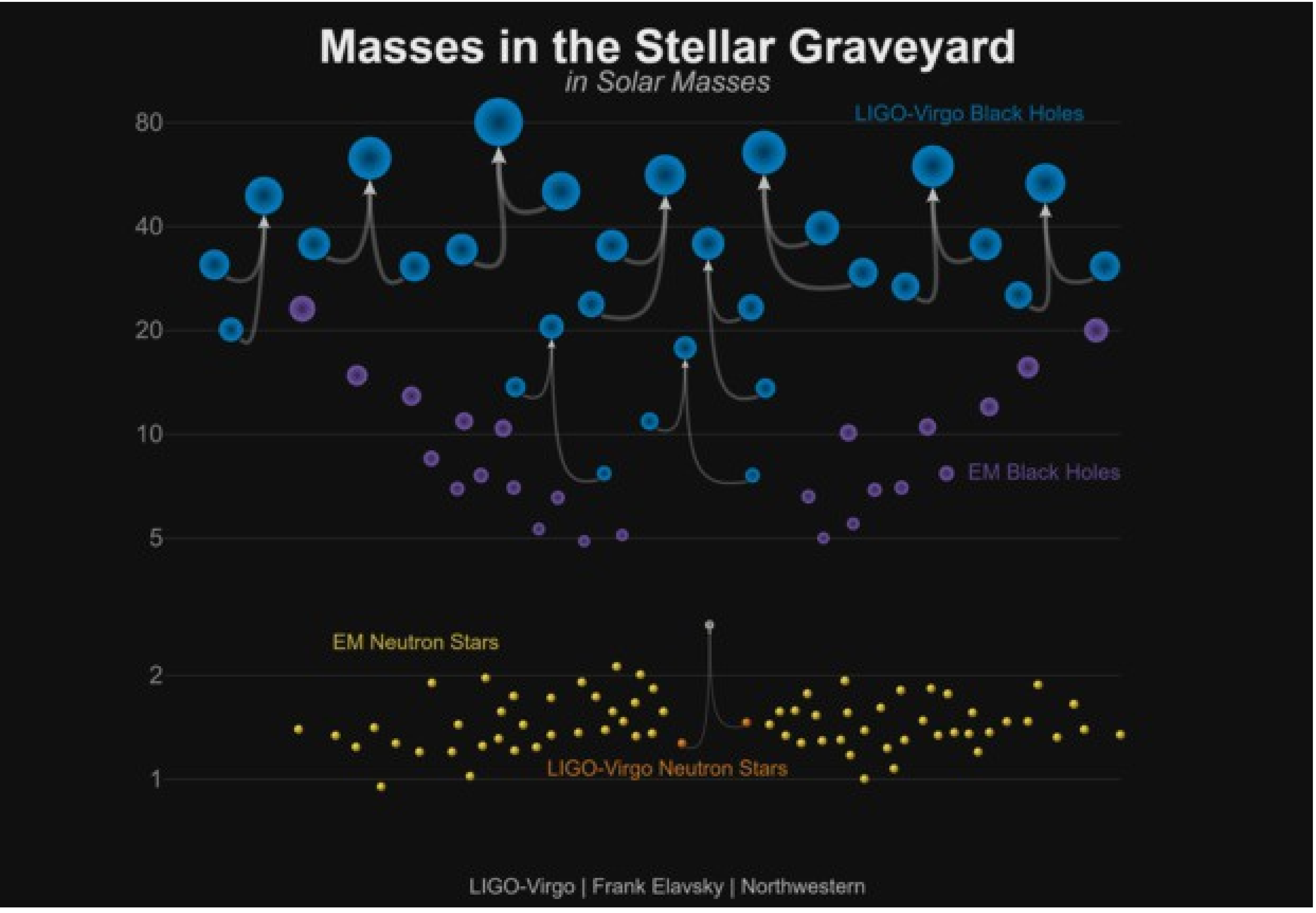
Wave form allows to reconstruct the parameters of the Binary Black Hole system *(and test General Relativity)*



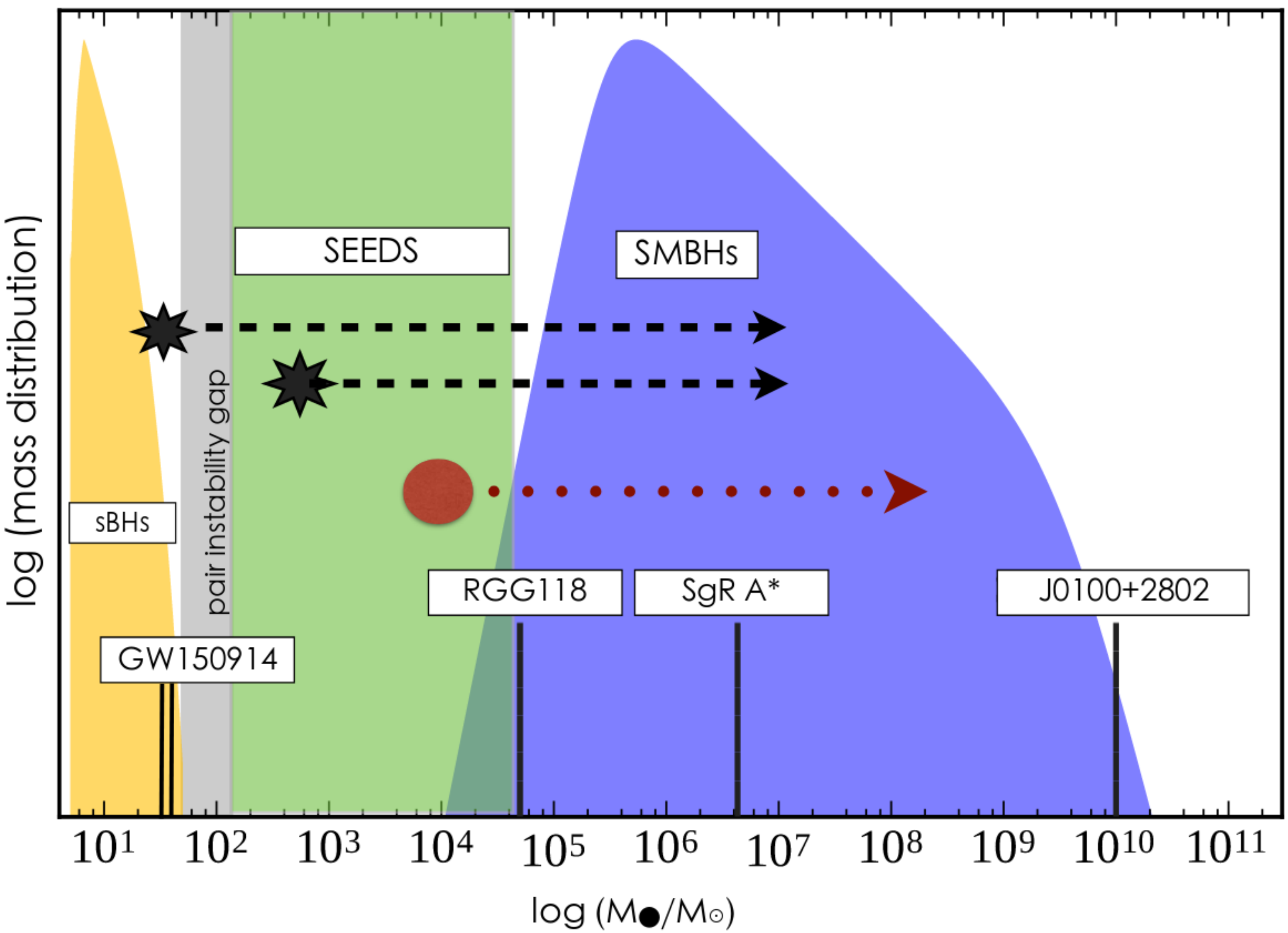
GW150914

1st Catalog of Gravitational-Wave transients



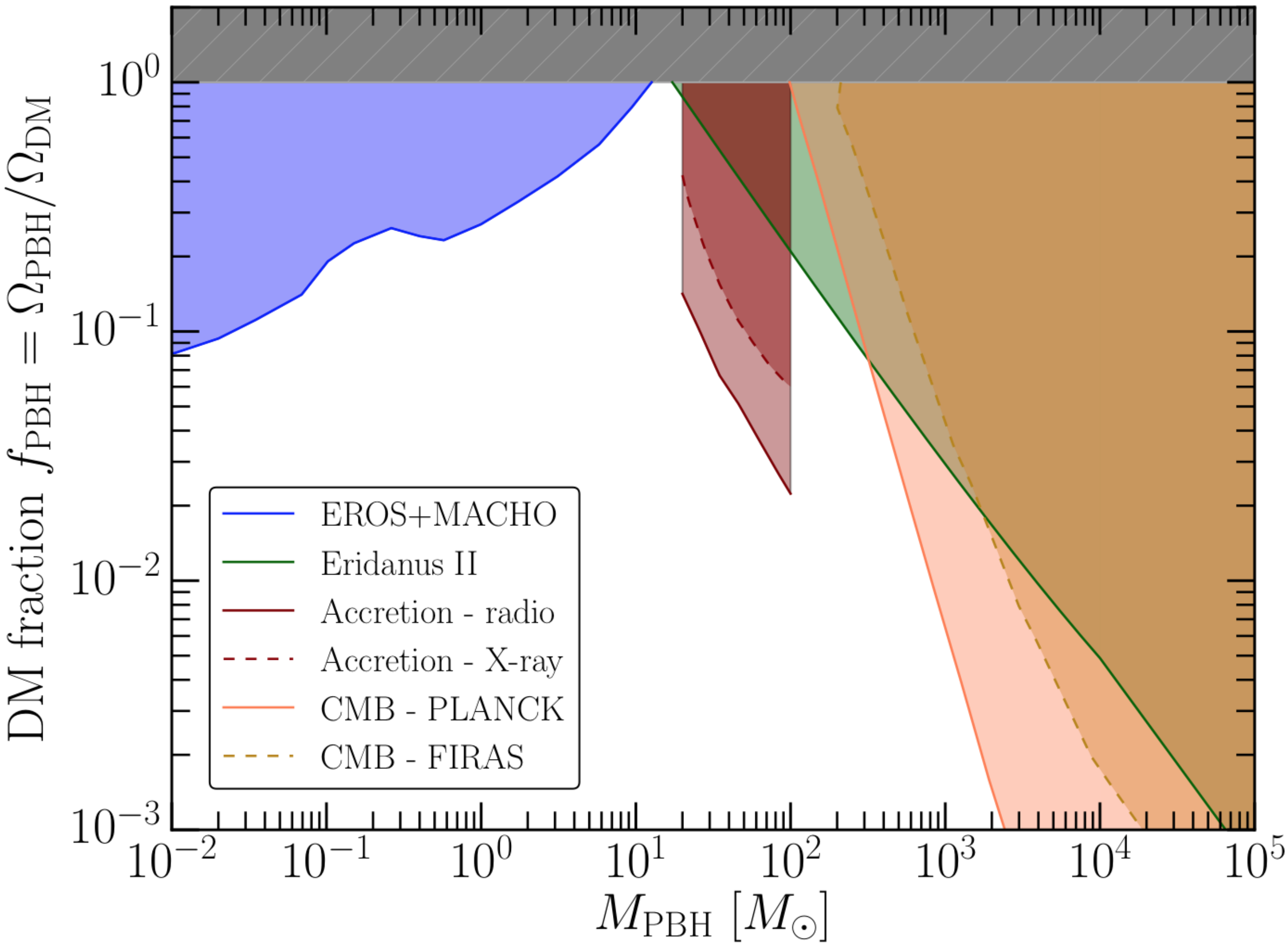

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
LIGO-Virgo | Frank Elavsky | Northwestern

Black Hole mass distribution in the Universe



L. Barack *et al.*,
"Black holes, gravitational waves and fundamental physics: a roadmap,"
arXiv:1806.05195 [gr-qc].

(Primordial) Black Holes as Dark Matter

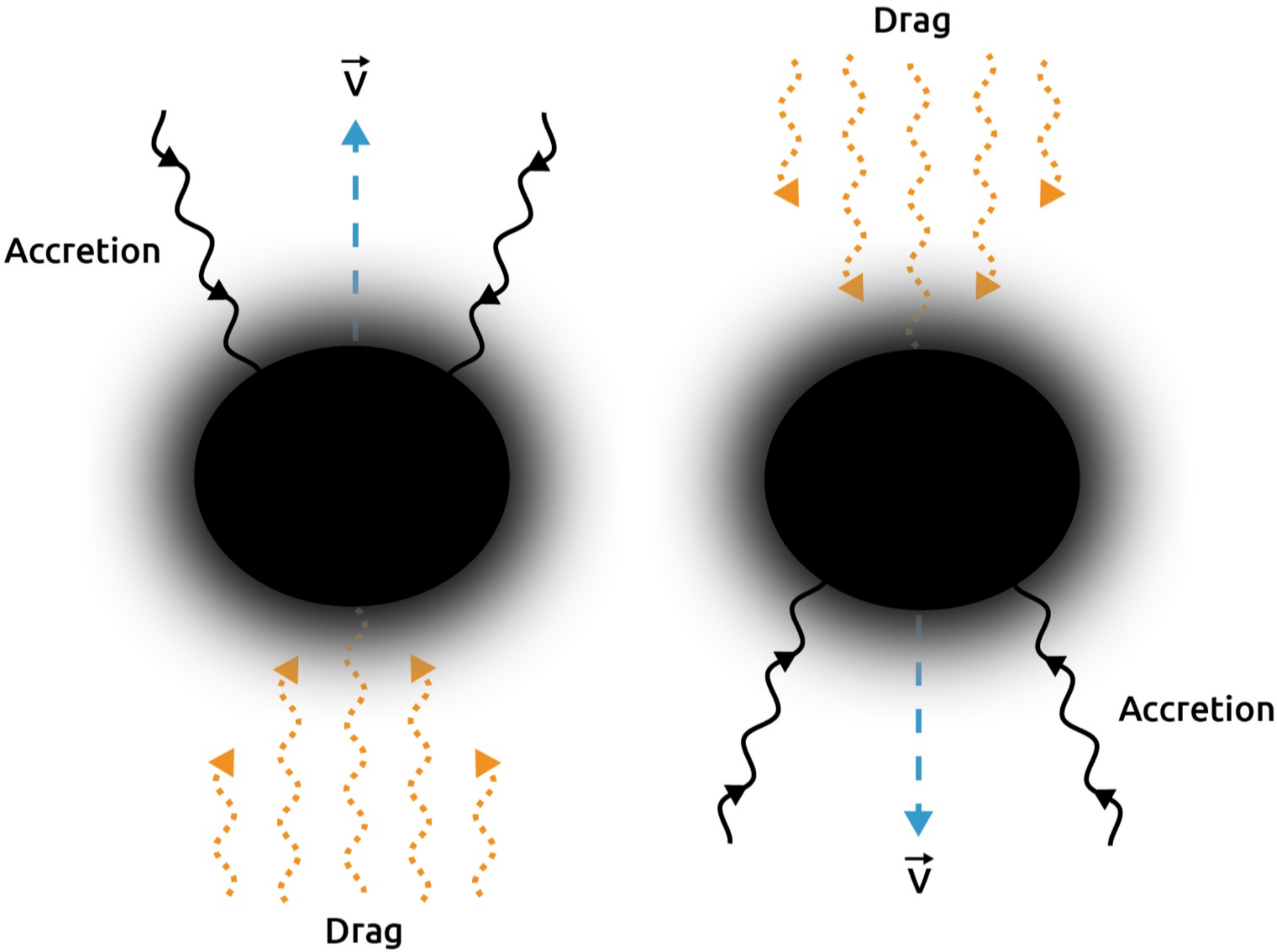


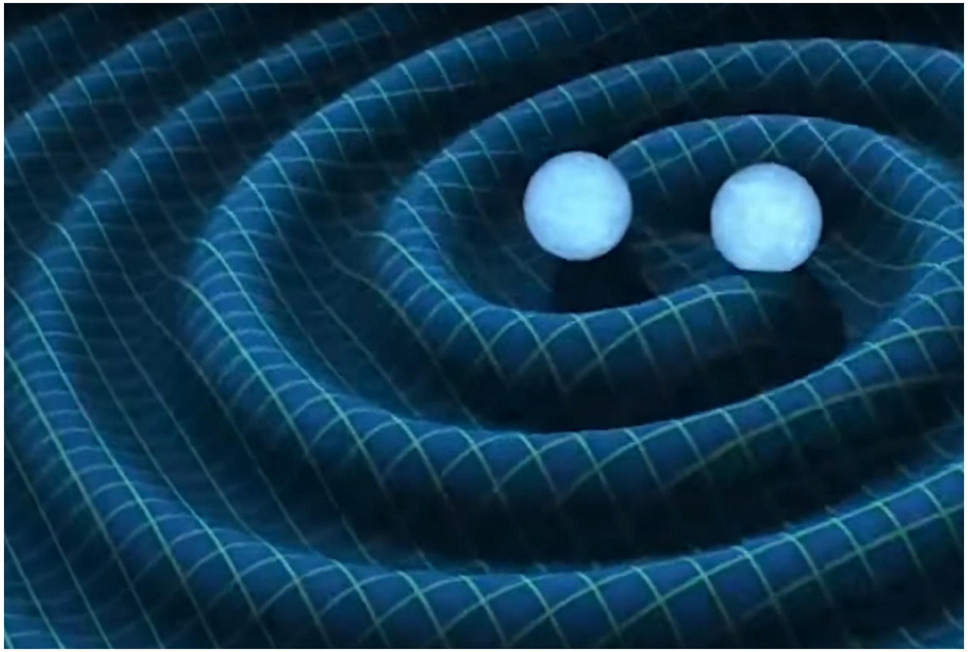
- Constraints on MOND theories
  (or deviations from General Relativity)

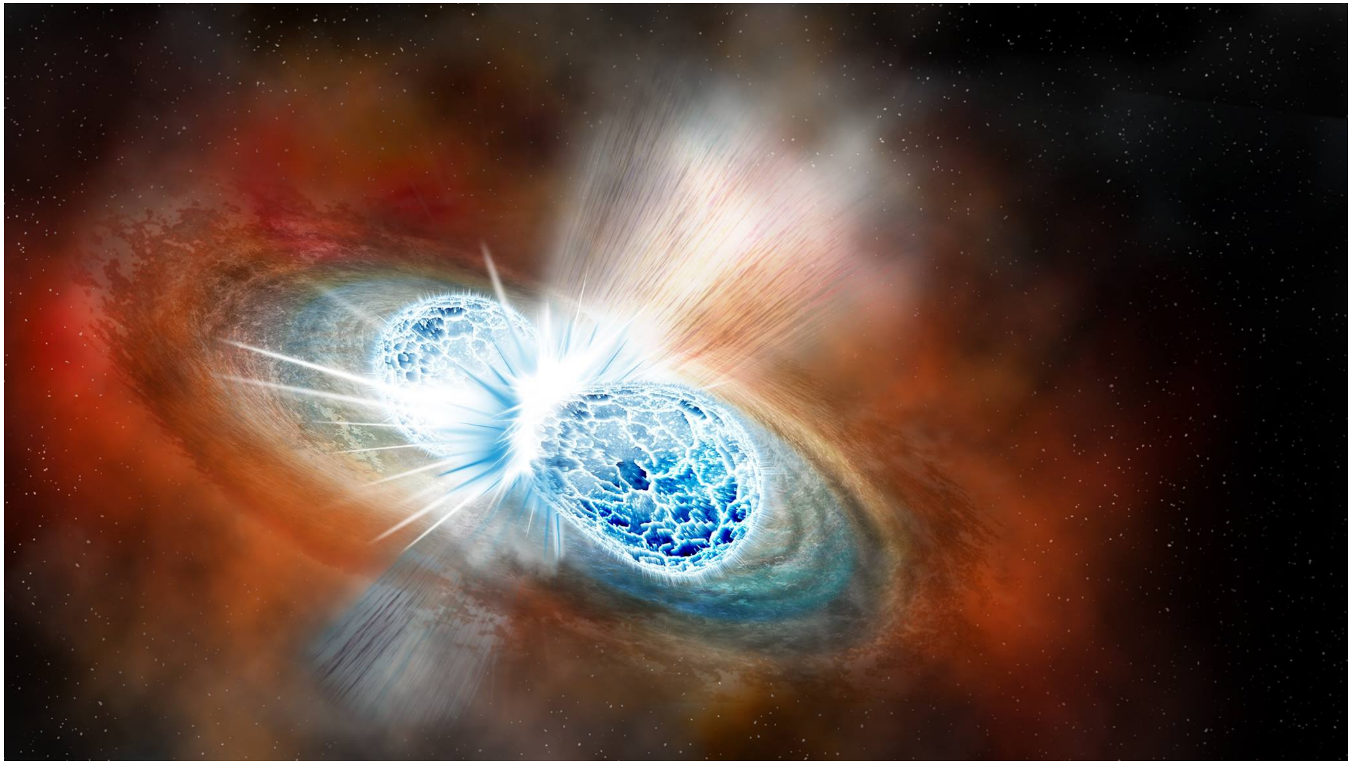
- Possible existence of Primordial Black Holes
  (formed in the Early Universe)
  that could be a component (or the entire Dark Matter)

- Probe the environment of Binary Black Holes
  (the presence of a Dark Matter overdensity
  can modify the dynamics of the merger)

Binary Black Hole system in an overdensity of DM







GW 170817

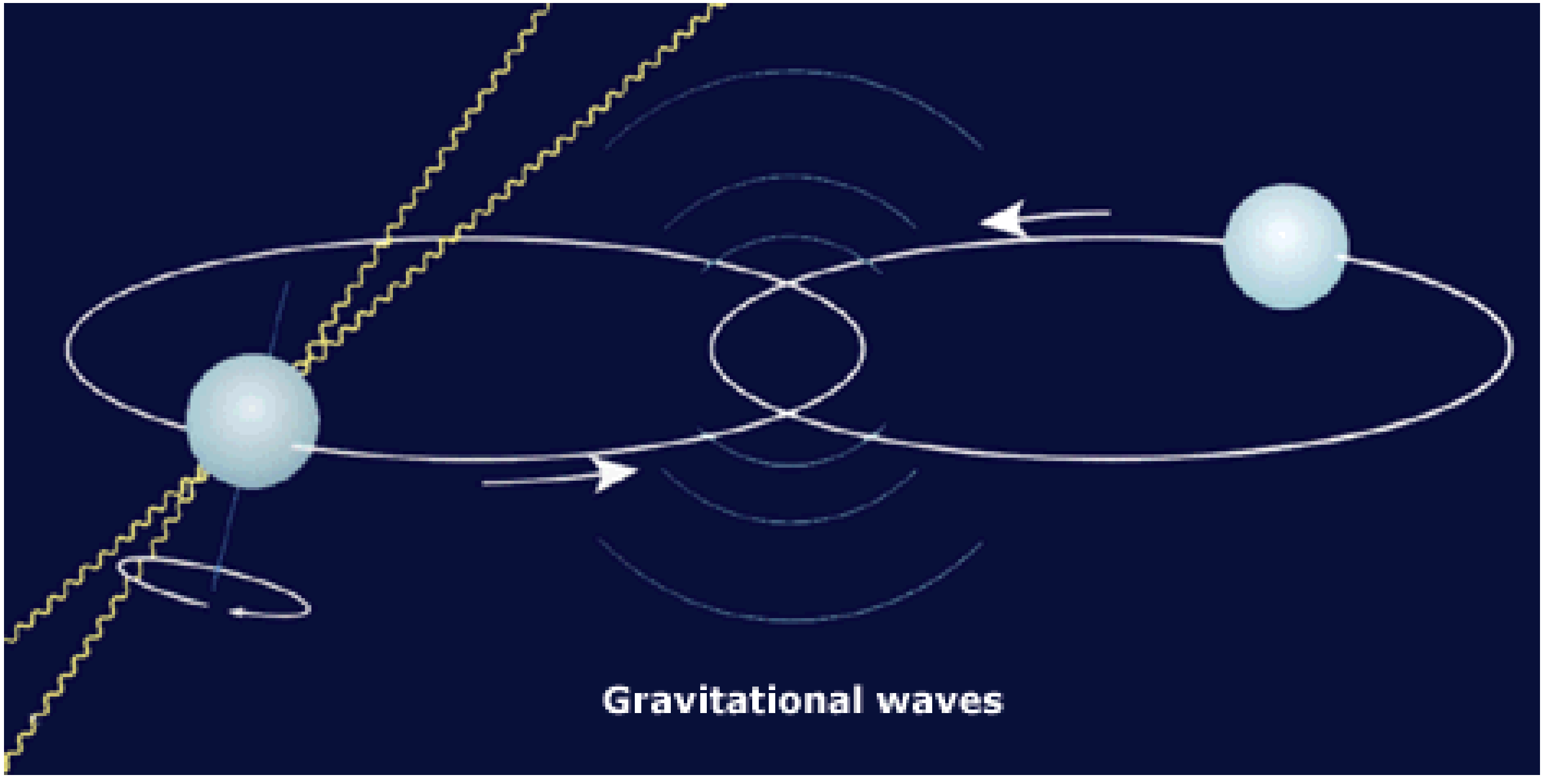
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

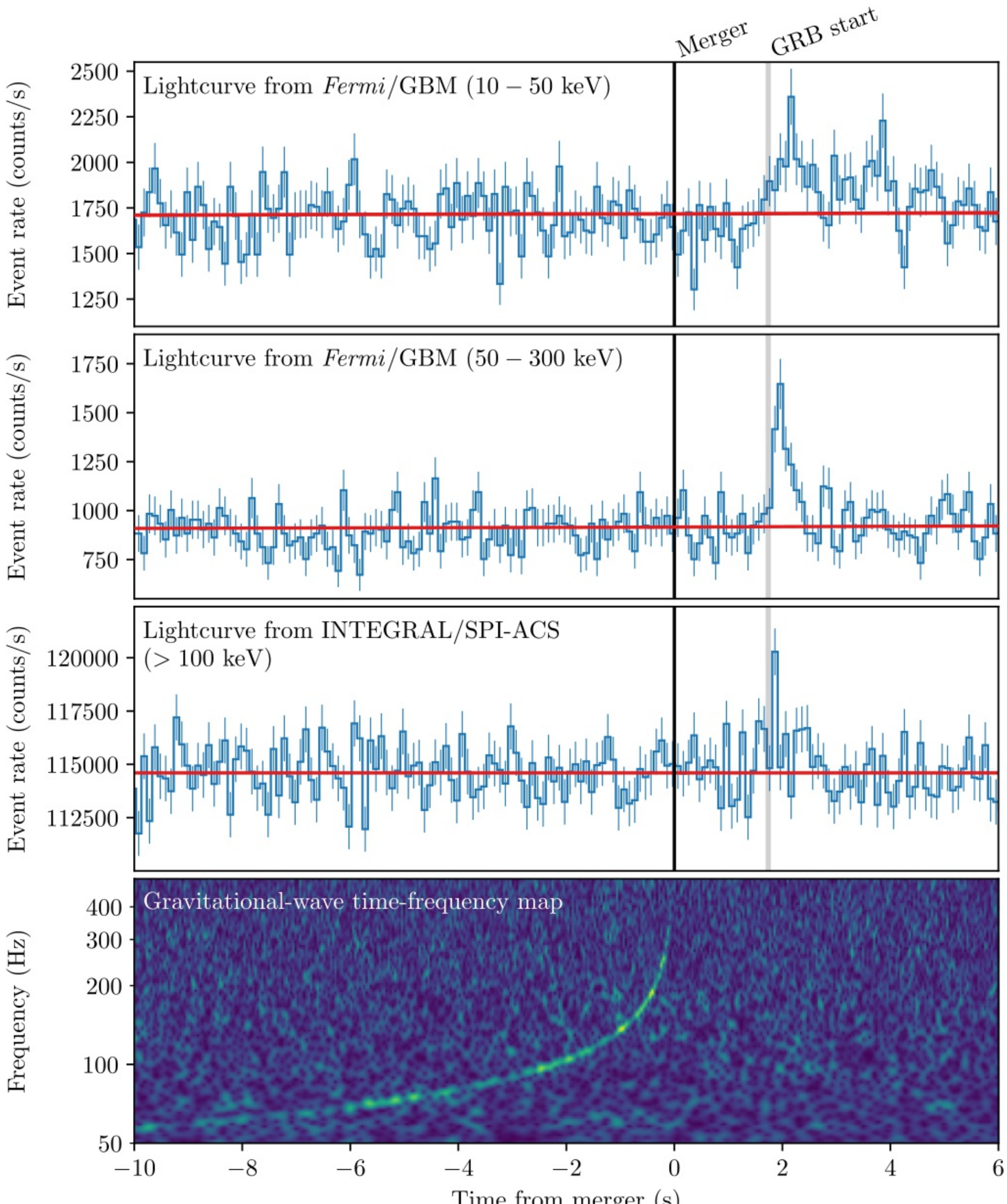
300 Myr
two neutron star coalesce

Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

Orbit smaller
3.5 m/year



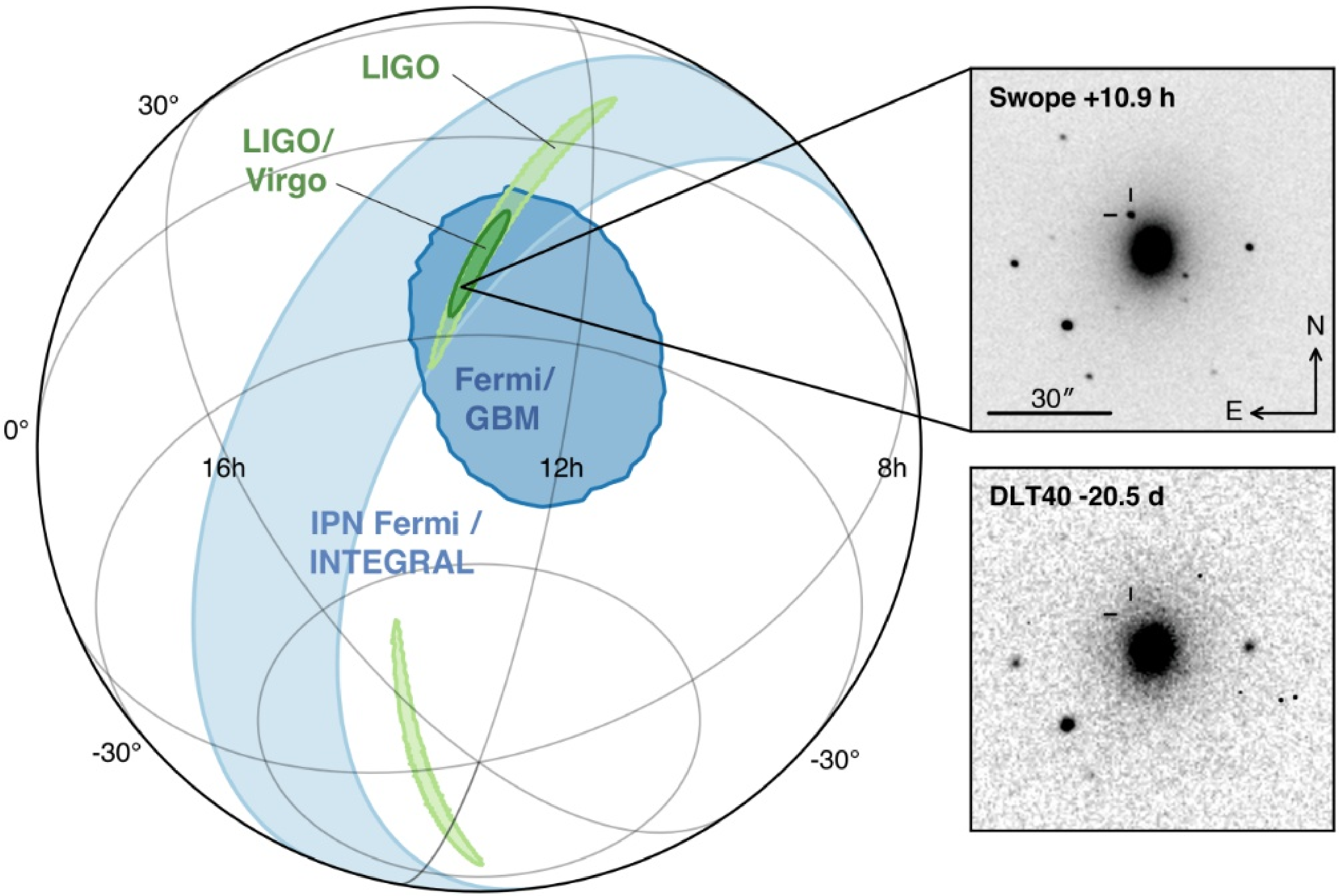


GRB 170817A

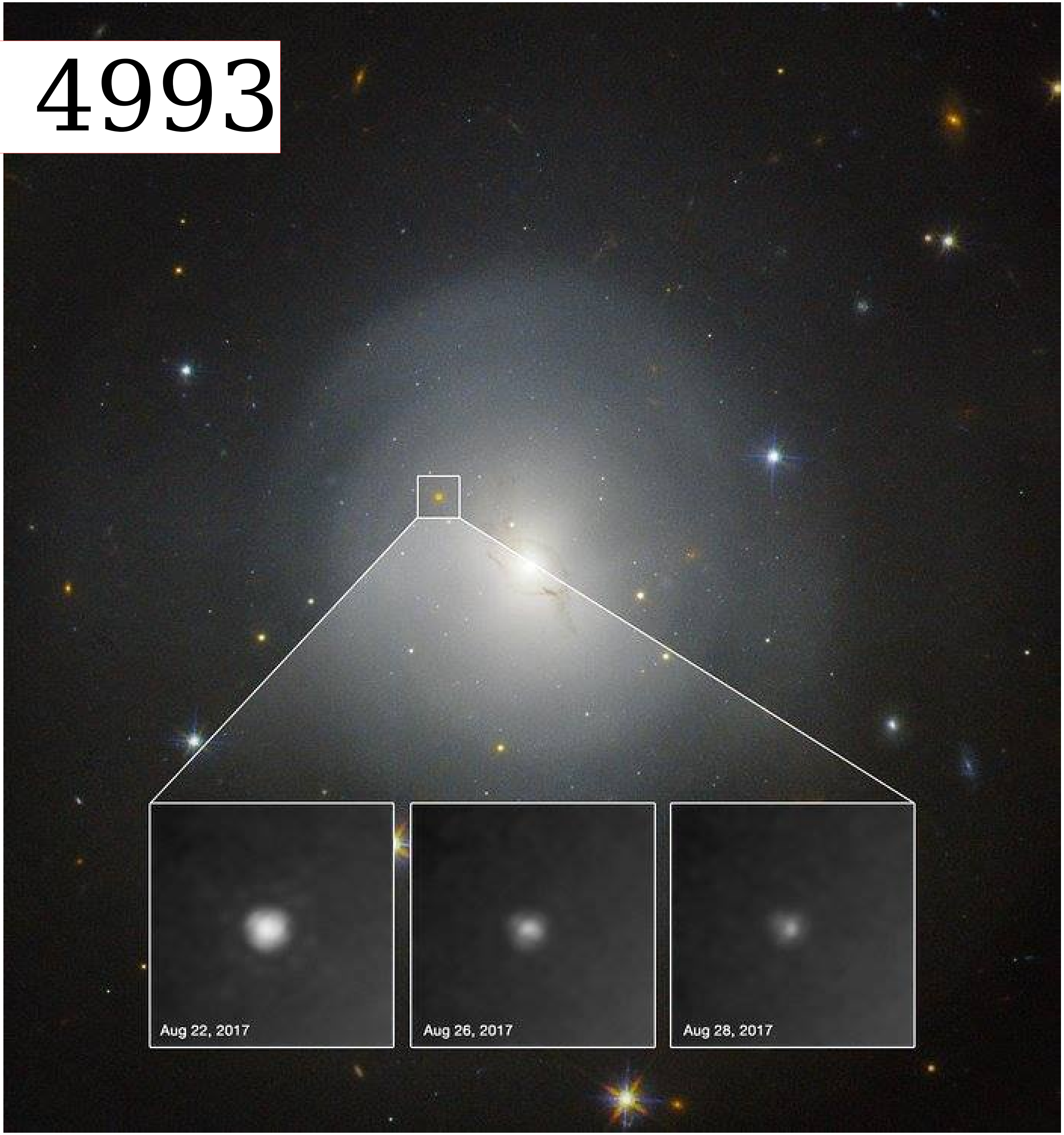
GW 170817

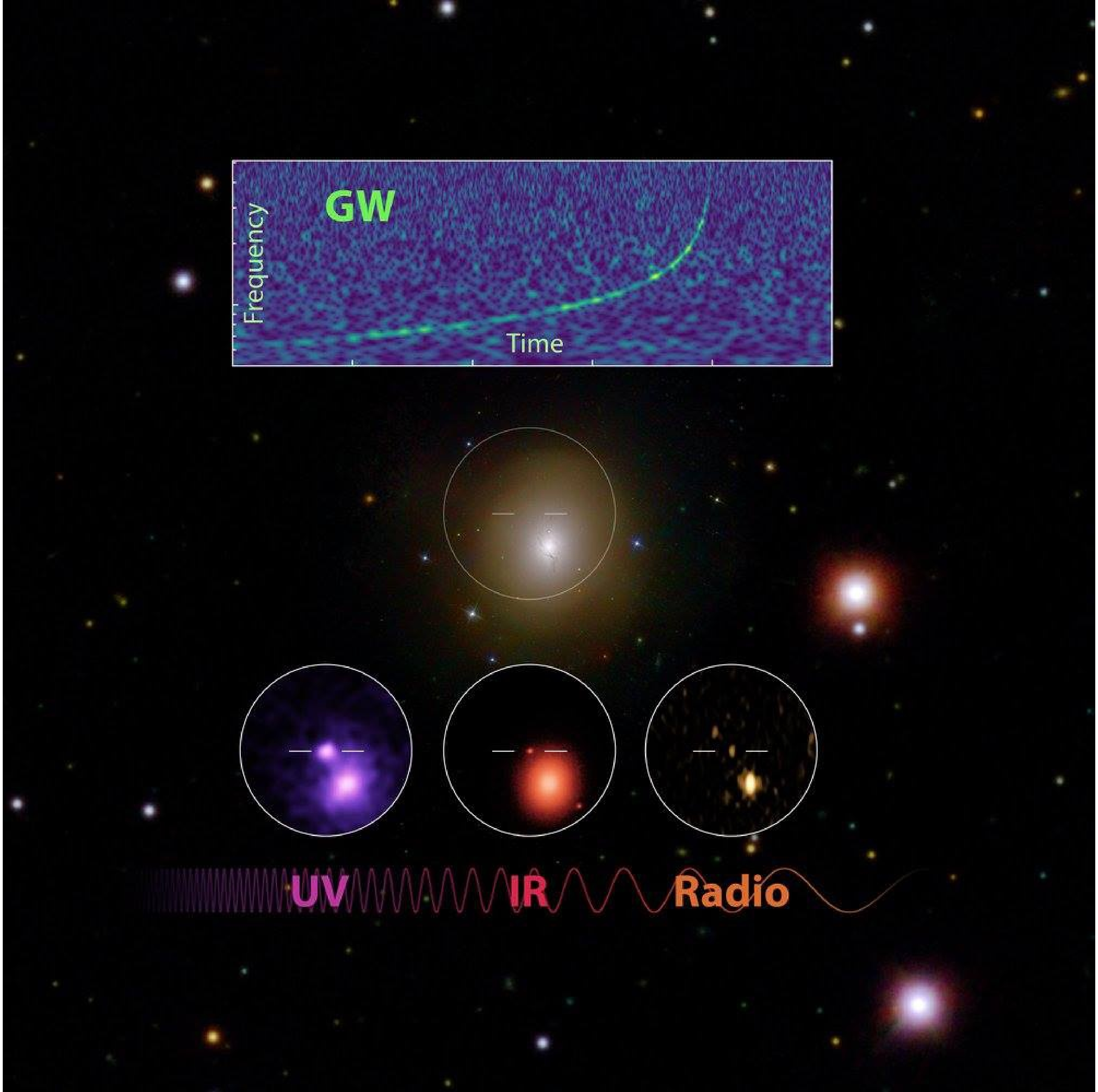
The multi-messanger sky localization of GW170817

identification of the host galaxy.



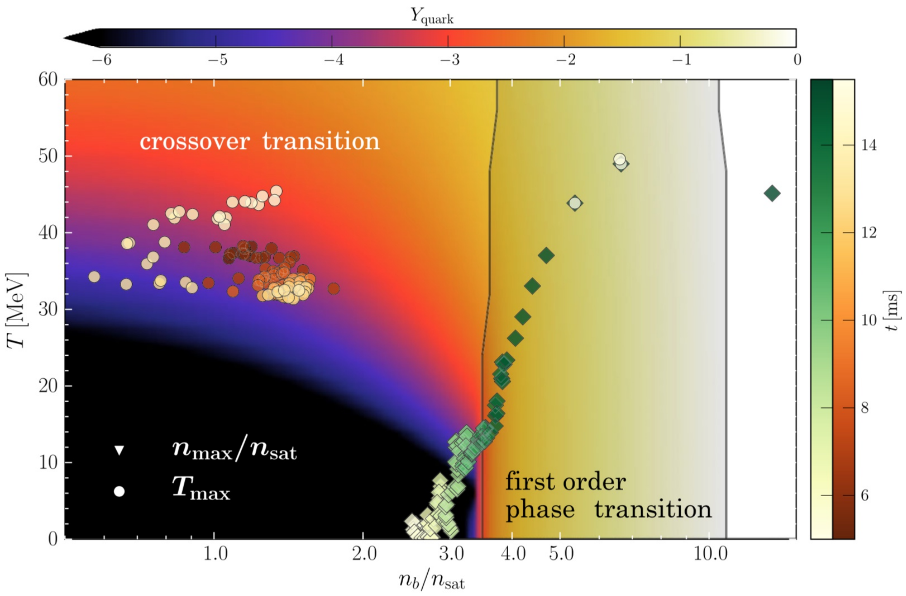
NGC 4993




GW
Frequency
Time
UV
IR
Radio

Hadronic Physics in "extreme conditions"

Quark–hadron phase transition



E. R. Most *et al.*
"Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers"
Phys. Rev. Lett. **122**, no. 6, 061101 (2019)
[arXiv:1807.03684 [astro-ph.HE]].

$$\{n_B, T\}$$

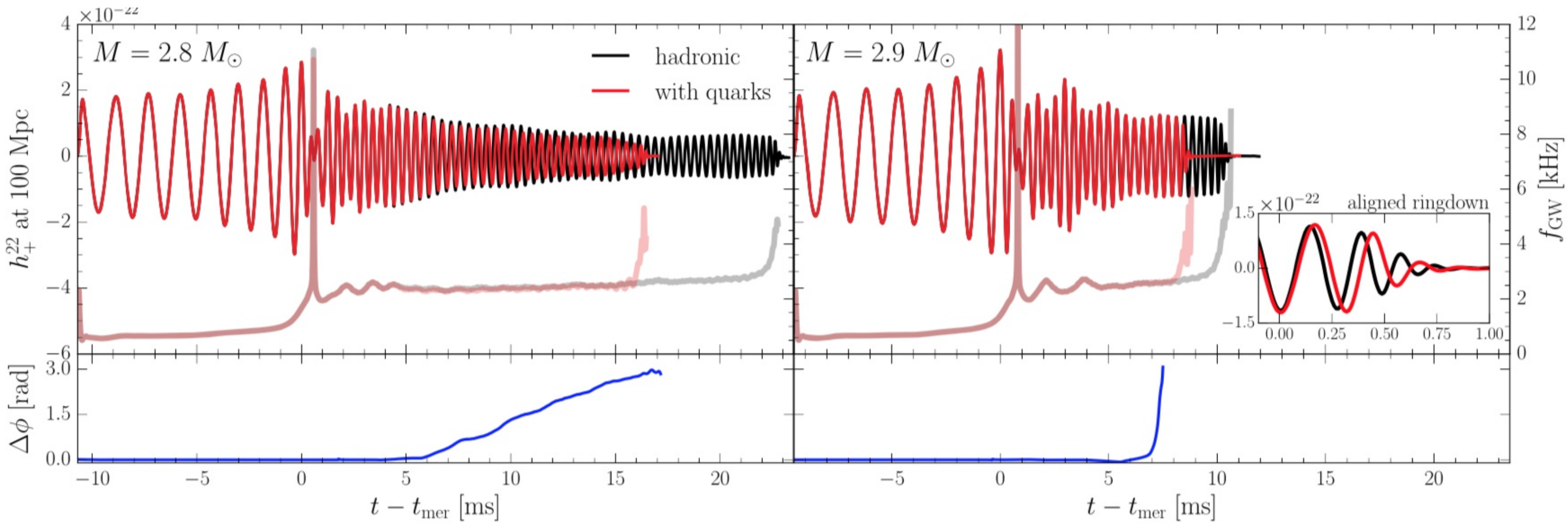


FIG. 4. Properties of the GW emission for the low- (left-hand panels) and high-mass binaries (right-hand panels). The top panels report the strain h_+^{22} for the two EOSs, together with the instantaneous GW frequency $f_{\rm GW}$ (semitransparent lines). The bottom panels show the phase difference $\Delta\Phi$ between the two signals. The inset in the top right-hand panel highlights the differences in the ringdown.

A. Bauswein, *et al.*
“Identifying a first-order phase transition
in neutron star mergers through gravitational waves”
Phys. Rev. Lett. **122**, no. 6, 061102 (2019)
[arXiv:1809.01116 [astro-ph.HE]].

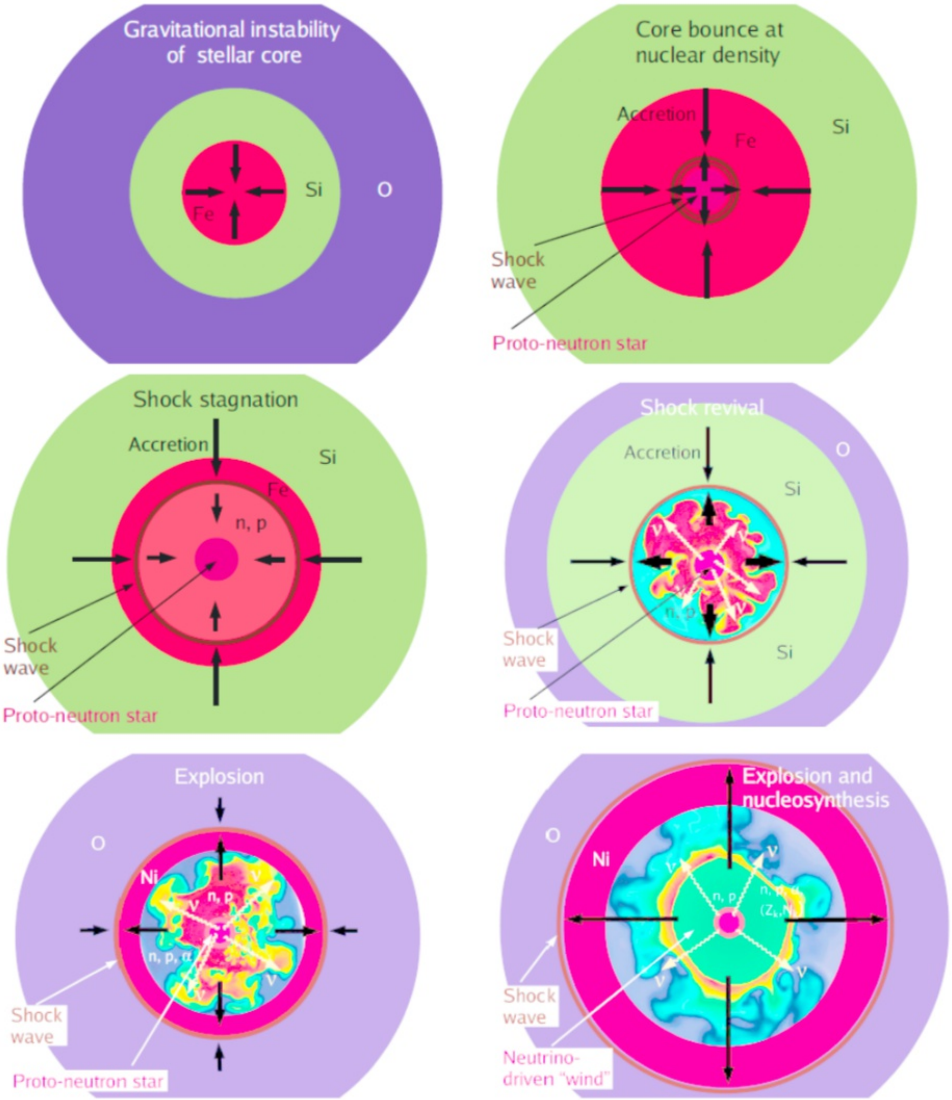
E. Burns *et al.*,
“A Summary of Multimessenger Science
with Neutron Star Mergers,”
arXiv:1903.03582 [astro-ph.HE].

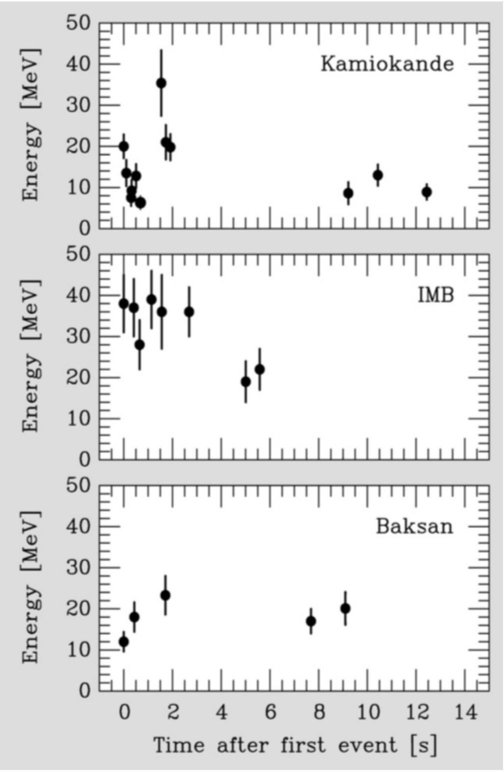
C. J. Horowitz *et al.*,
"r-Process Nucleosynthesis:
Connecting Rare-Isotope Beam Facilities with the Cosmos,"
arXiv:1805.04637 [astro-ph.SR].

Abstract. This is an exciting time for the study of *r*-process nucleosynthesis. Recently, a neutron star merger GW170817 was observed in extraordinary detail with gravitational waves and electromagnetic radiation from radio to γ rays. The very red color of the associated kilonova suggests that neutron star mergers are an important *r*-process site. Astrophysical simulations of neutron star mergers and core collapse supernovae are making rapid progress. Detection of both, electron neutrinos and antineutrinos from the next galactic supernova will constrain the composition of neutrino-driven winds and provide unique nucleosynthesis information. Finally FRIB and other rare-isotope beam facilities will soon have dramatic new capabilities to synthesize many neutron-rich nuclei that are involved in the *r*-process. The new capabilities can significantly improve our understanding of the *r*-process and likely resolve one of the main outstanding problems in classical nuclear astrophysics.

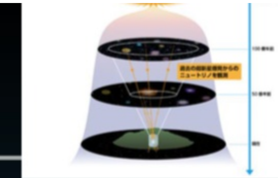
$$\bar{\nu}_e + p \to n + e^+ \qquad\qquad \nu_e + n \to p + e$$

SuperNova Neutrinos

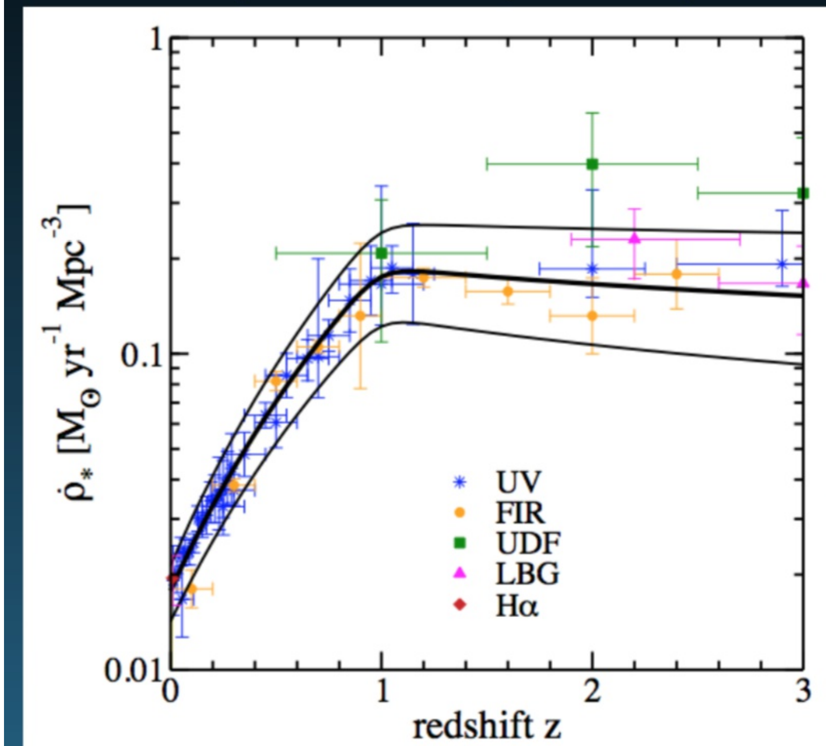




SUPERNOVA RELIC NEUTRINO



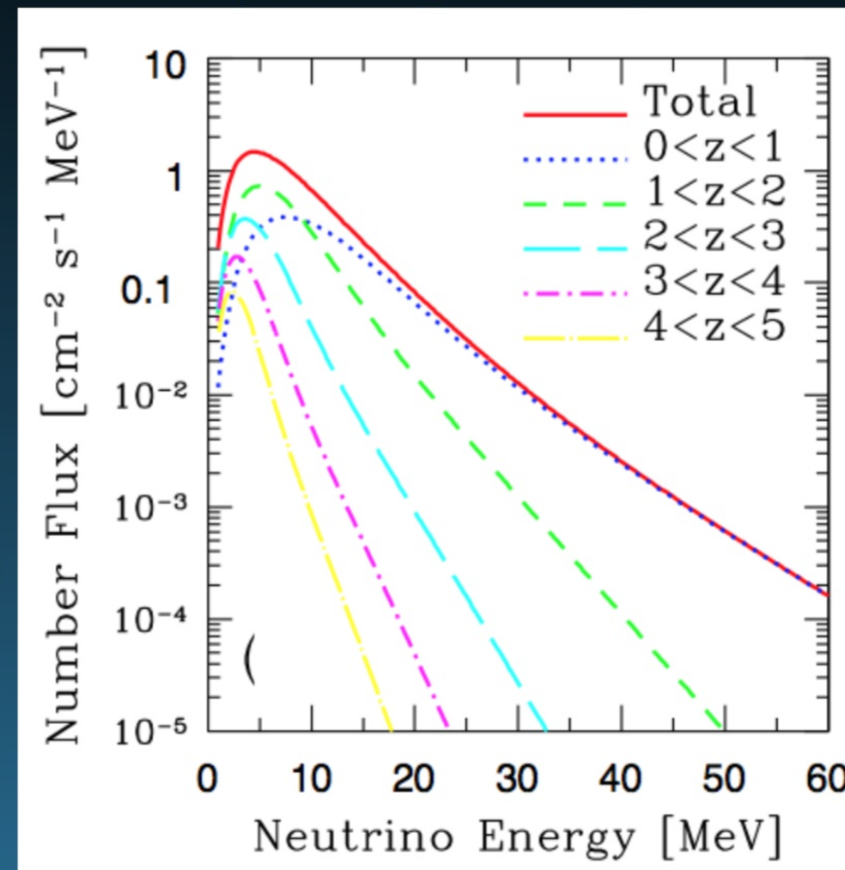
star formation rate
(= core-collapse rate)



supernova model

integrate over past supernova neutrinos

SRN energy spectrum
(including red shift)



S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}},$$

Neutrinos from supernova explosions in the early universe to the present day

Integrated flux ~10 cm^{-2}sec^{-1}

Francesca Di Lodovico (Venezia 2019)

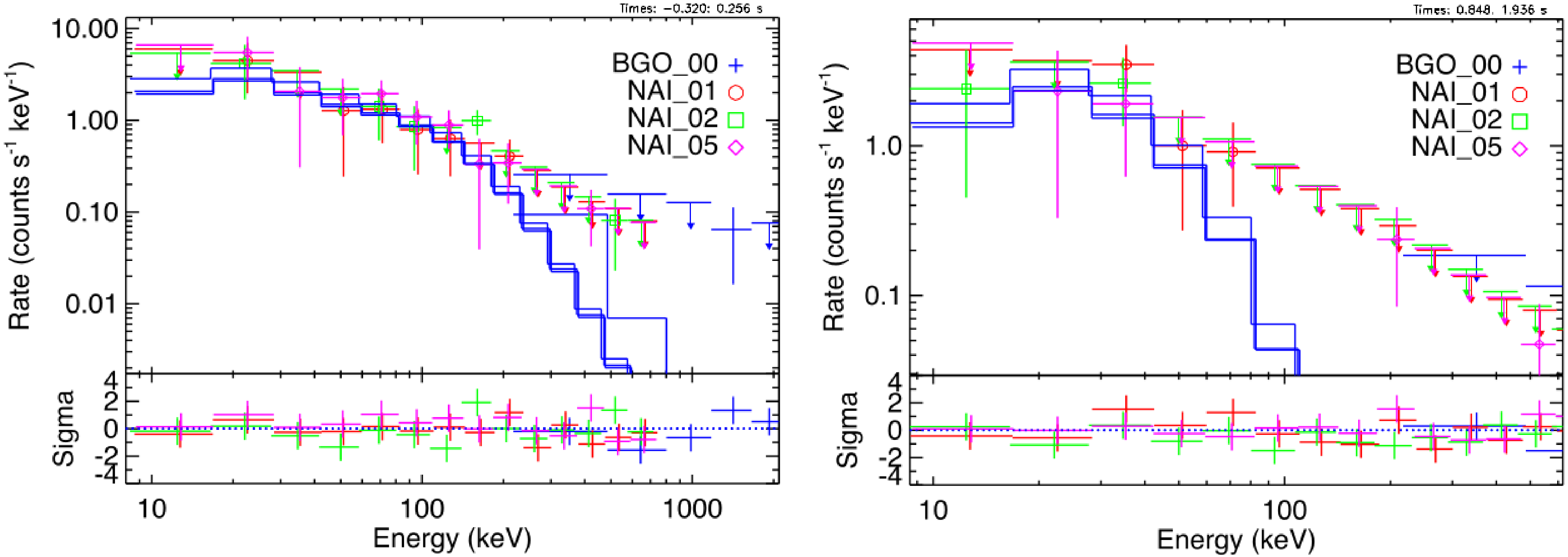
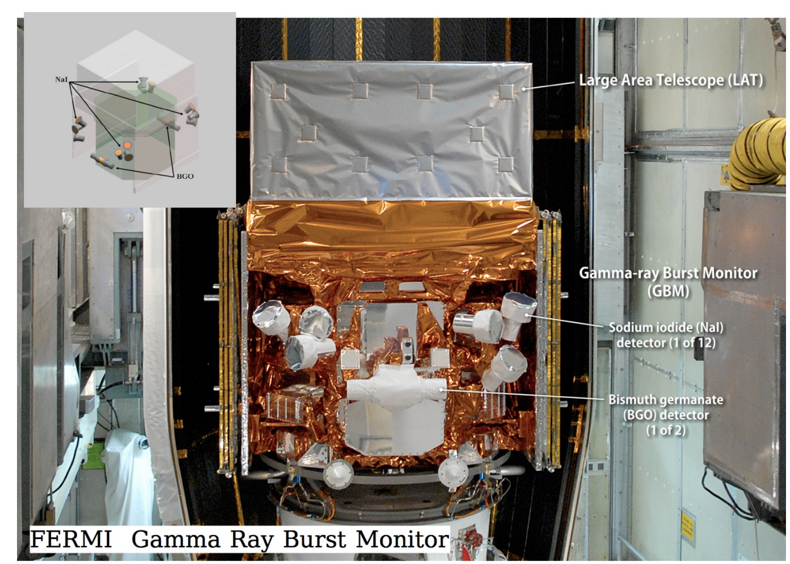


Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model variance are shown as downward-pointing arrows. The residuals are shown in the lower subpanels.

INTEGRAL
SPI-ADC



Multi-messenger Astrophysics

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

4 Messengers

for the study of the

"High Energy Universe"

"High Energy Universe"

The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy particles in the Milky Way and in the entire universe.

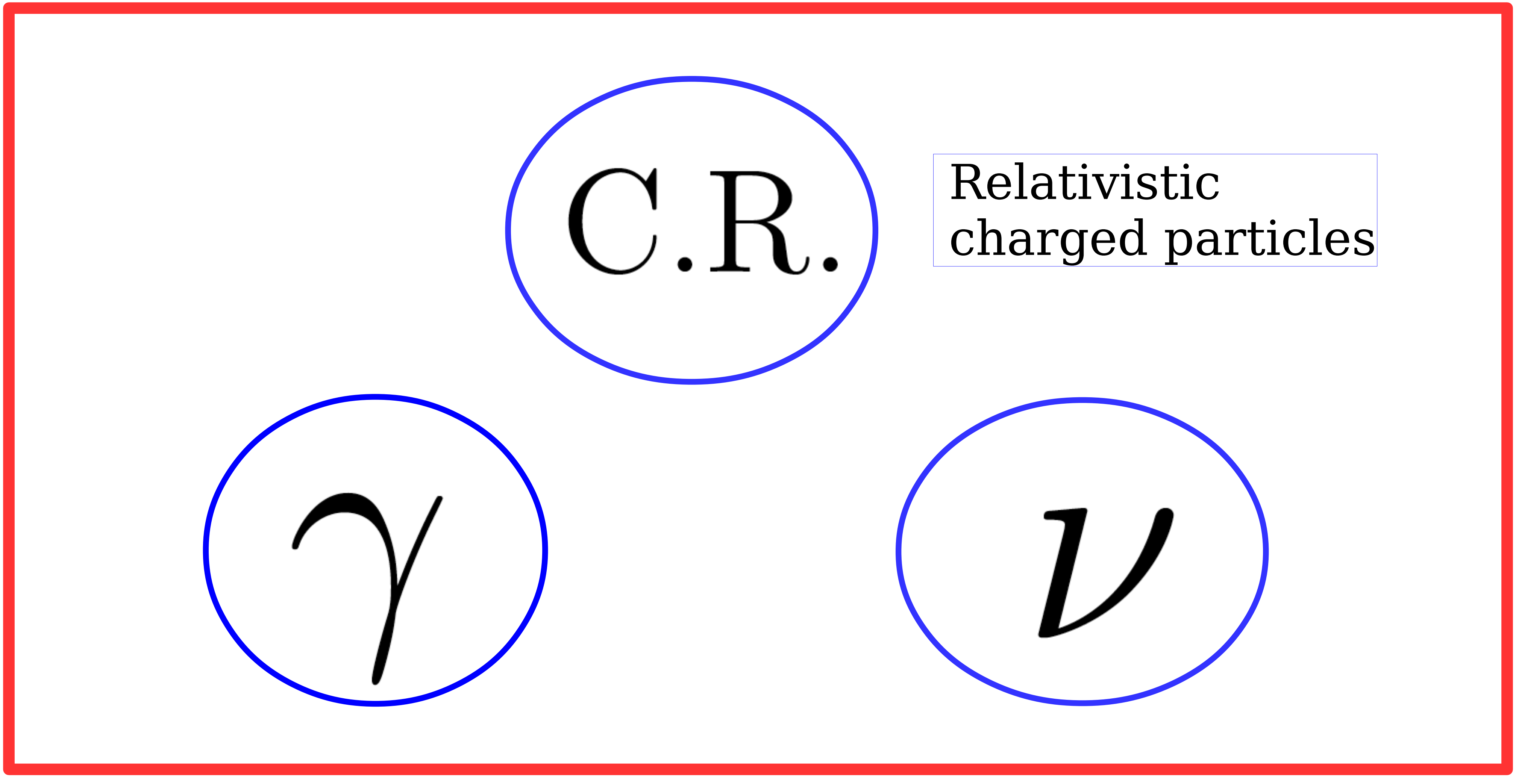
This field is one of the most significant and fascinating "Frontiers" in Science today.

1. Understanding the "*COSMOS*" where we live

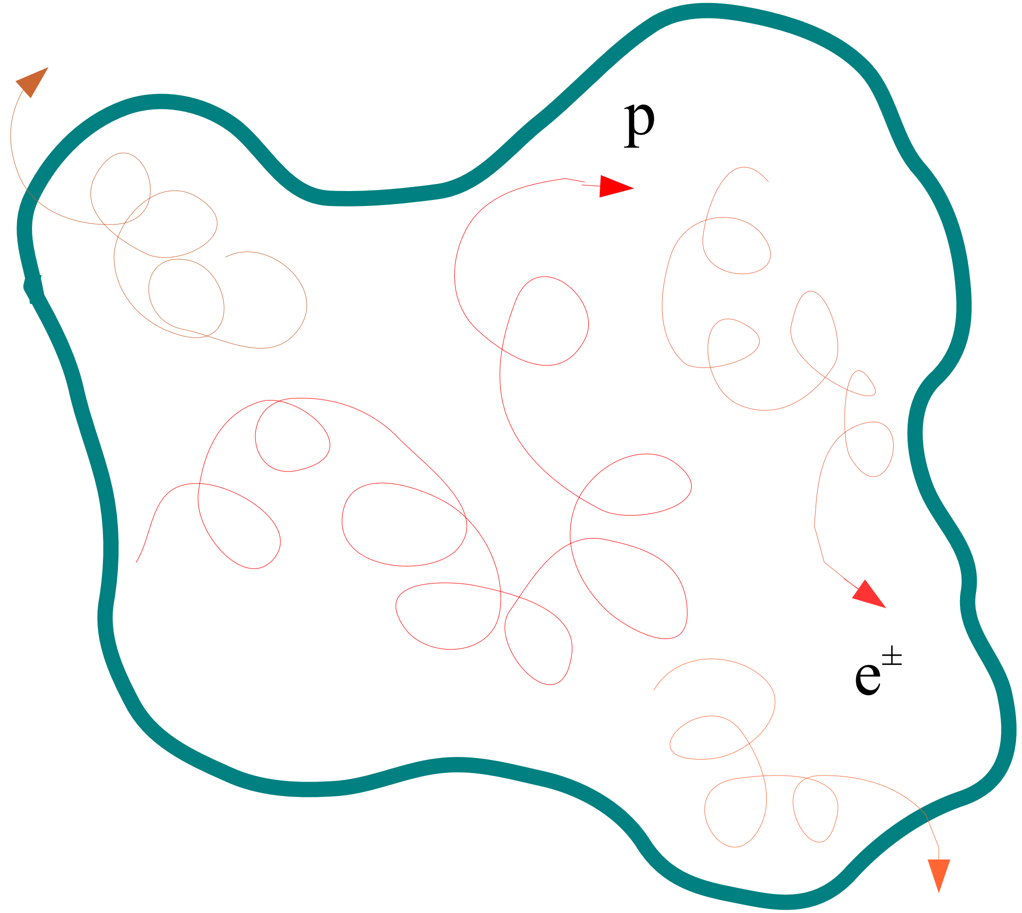
2. The sources of the High Energy radiation can be the "laboratories" where we test *(in conditions that are not achievable in "Earth based laboratories")* our Fundamental Laws of Physics.

Three messengers are "inextricably" tied together

[Cosmic Rays, Gamma Rays, High Energy Neutrinos can really be considered as three probes that study the same underlying physical phenomena]



Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

Fundamental Mechanism:

Acceleration of Charged Particles
to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic"

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

$$\pi^+ \to \mu^+ \; \nu_\mu$$

$$\hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$

"Leptonic"

$$e^\pm \; \gamma_{\mathrm{soft}} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\mathrm{syn}}$$

Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

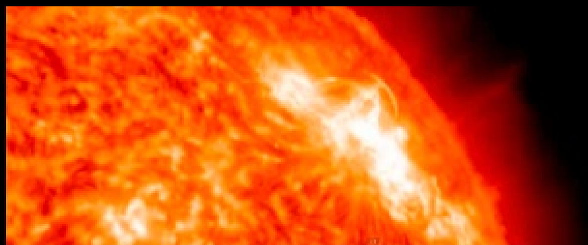
Associated to Compact Objects

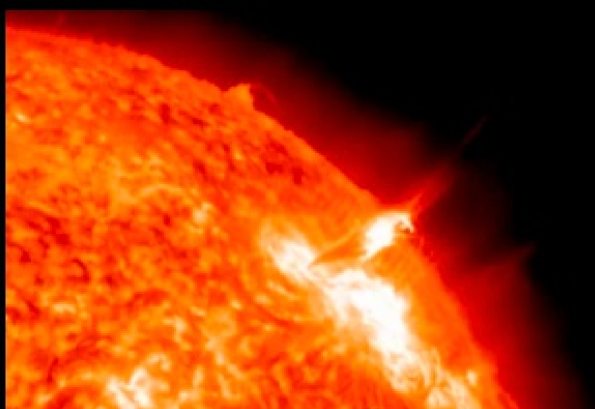
Neutron stars,
Black Holes (stellar and Supermassive)

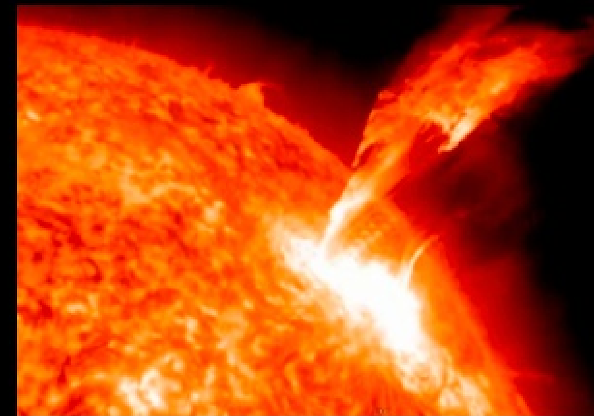
FORMATION of Compact Objects
(very large acceleration of very large masses)

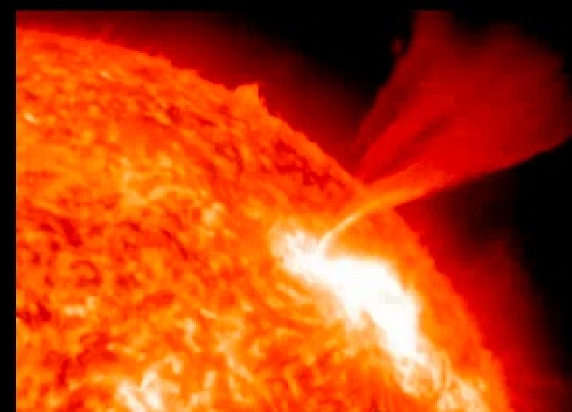
Natural connection to **Gravitational Waves**

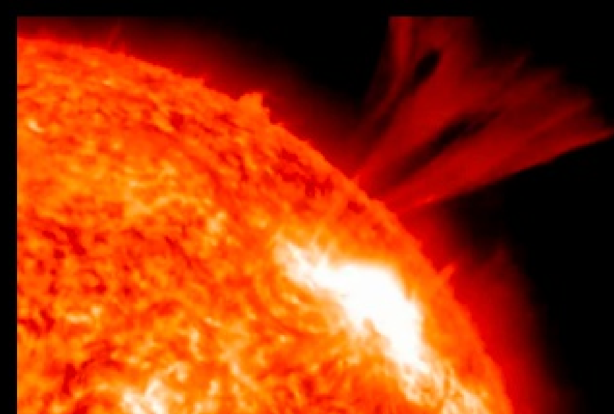
The SUN:
small scale laboratory:
Solar Flare





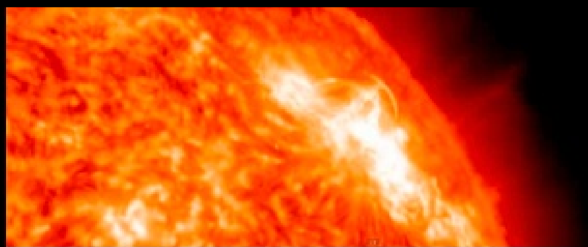


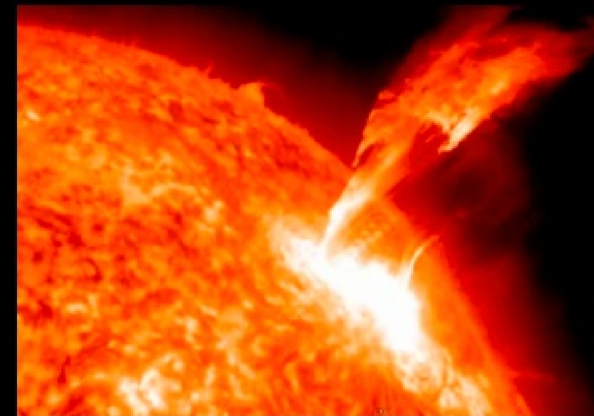


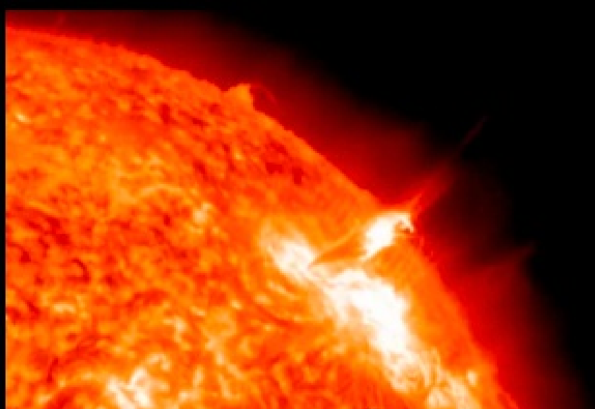


7th march 2011. 20:02 UT

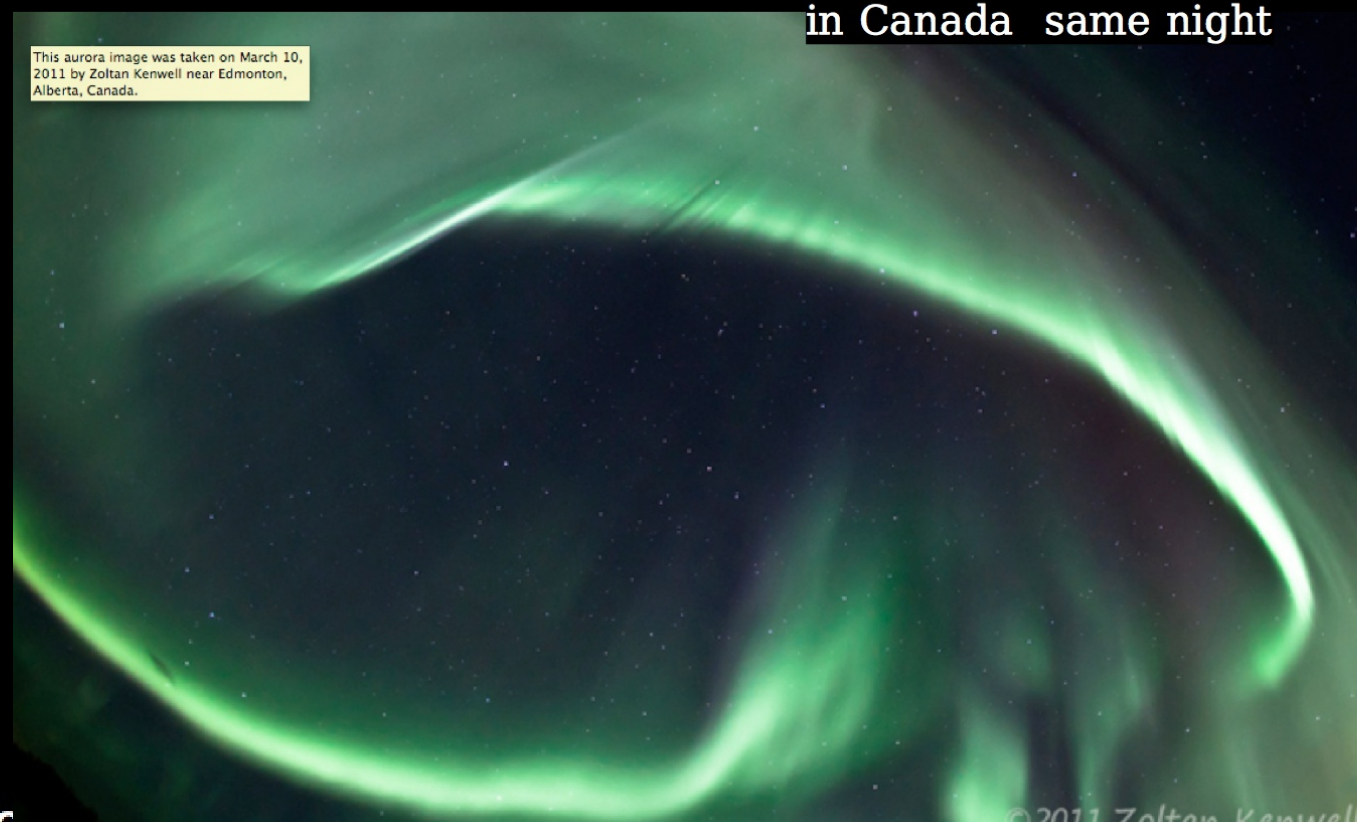
The SUN:
small scale laboratory:
Solar Flare







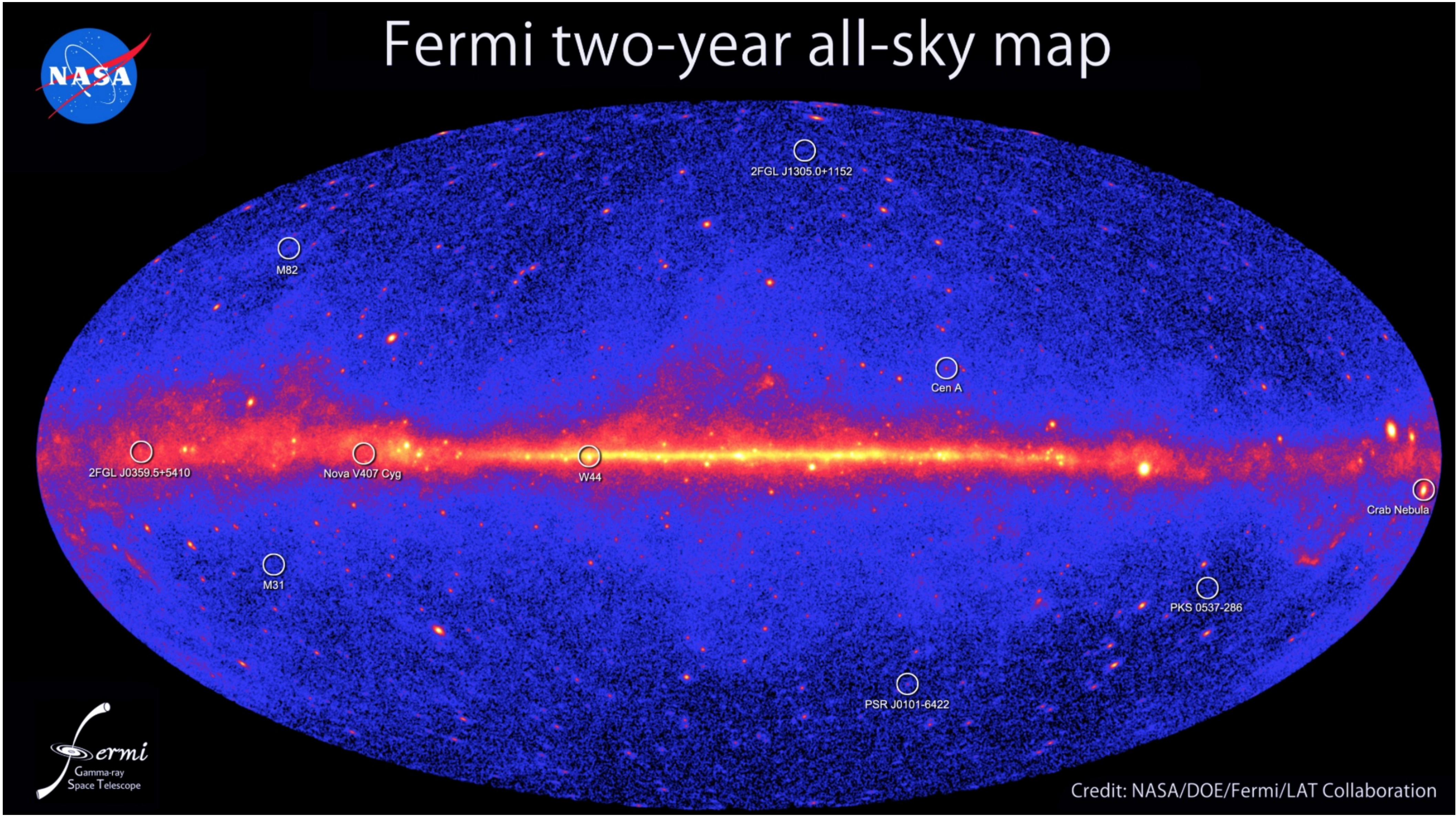
Aurora detected
in Canada same night



7^{th} march 2011. 20:

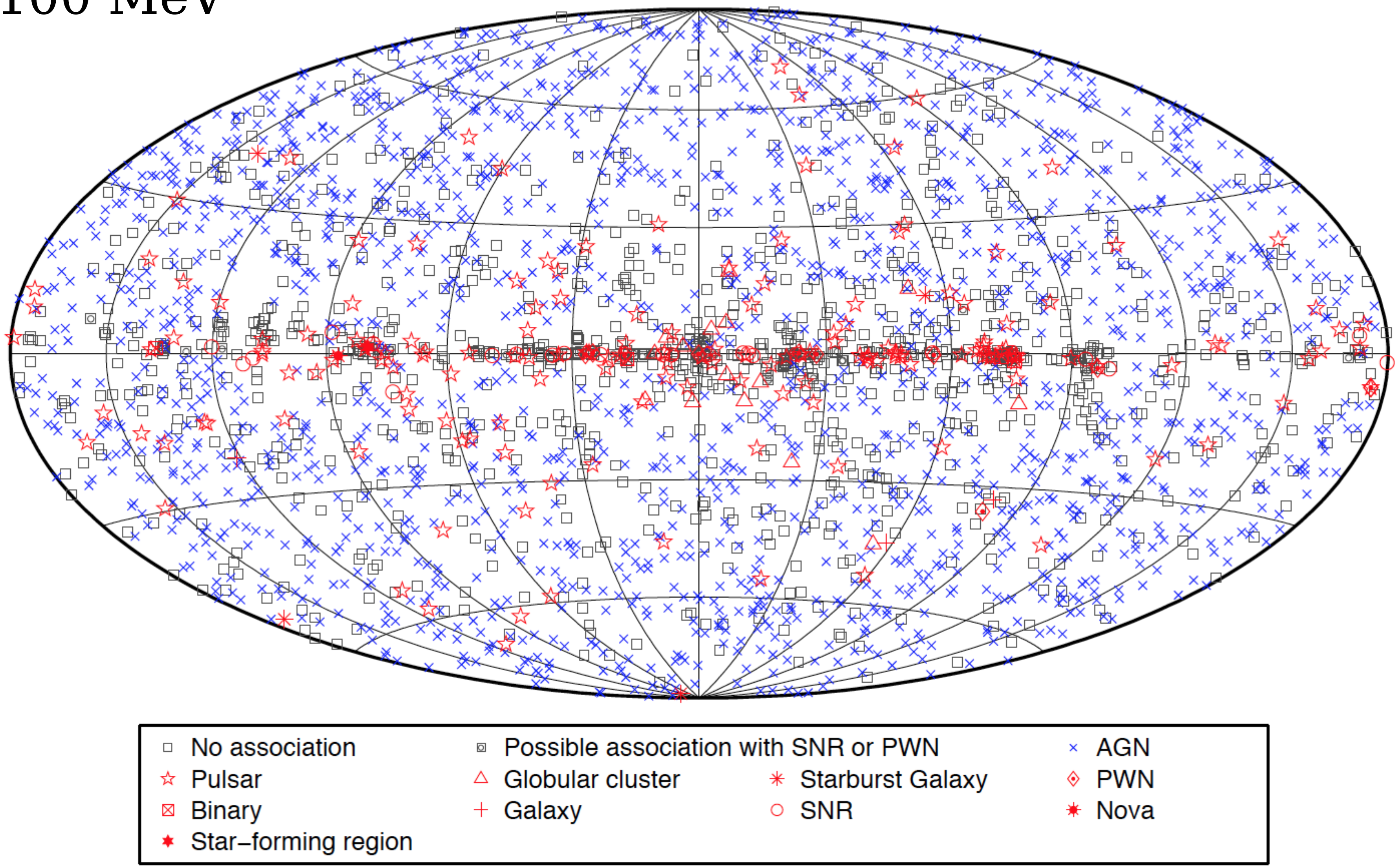
$E_\gamma \geq 100\ \mathrm{MeV}$

Gamma Ray Sky

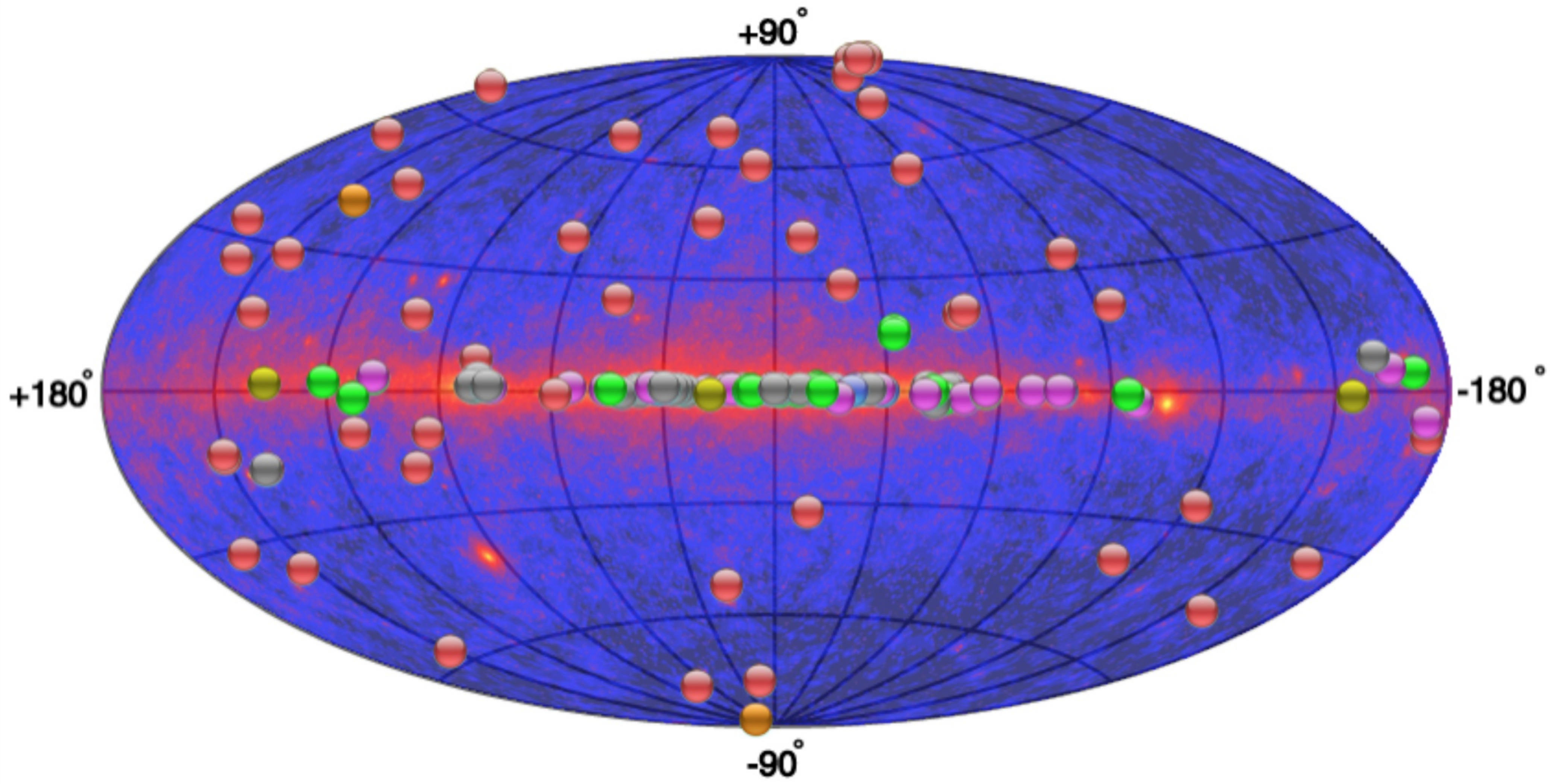


3rd FERMI Catalog 3034 sources

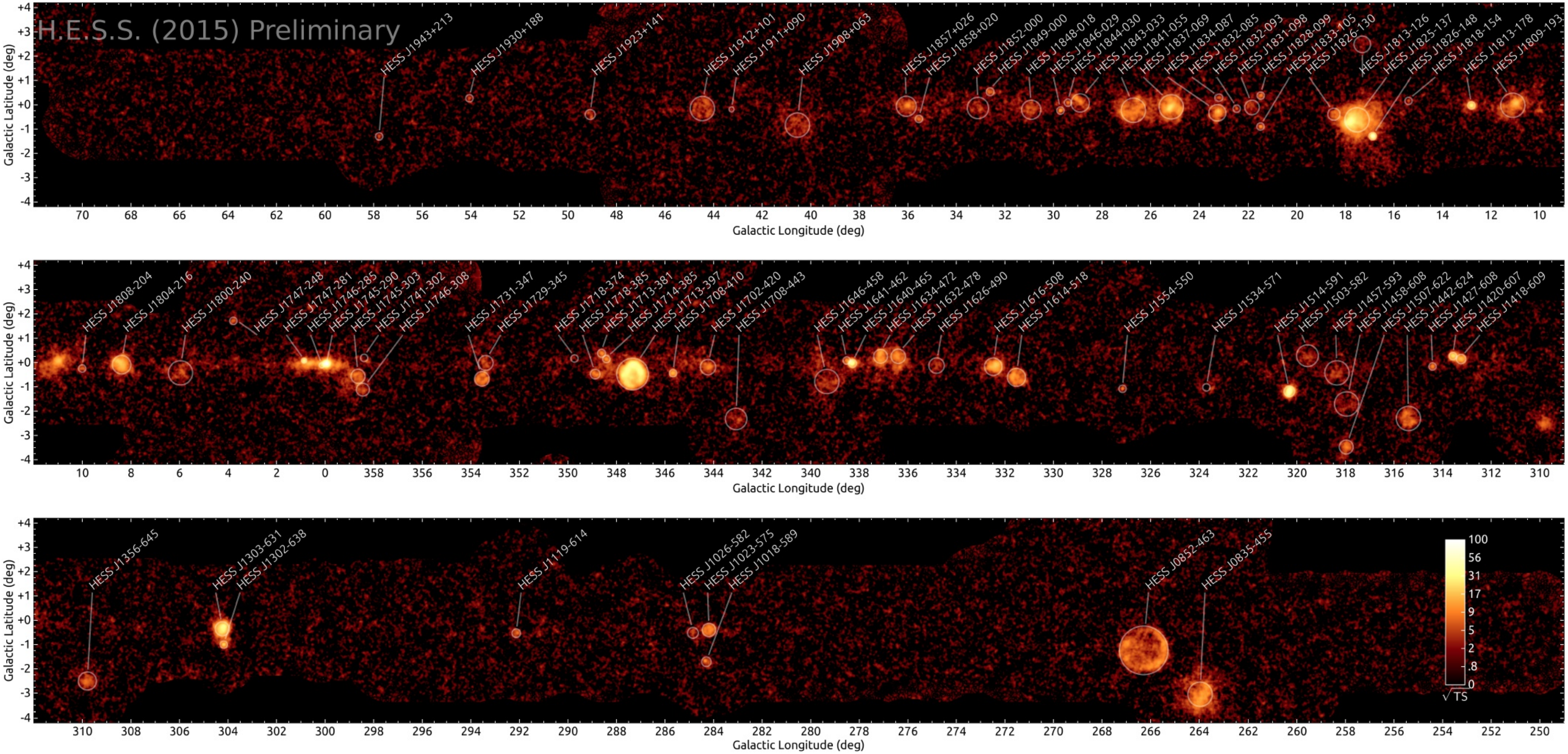
E > 100 MeV



TeV Sky 170 → 200 Sources

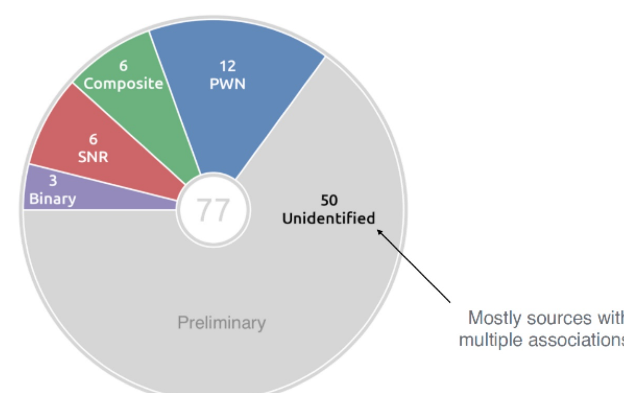


blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky



Firm identifications

HESS survey of
Galactic Plane
[ICRC 2015] 77 “firm identifications”

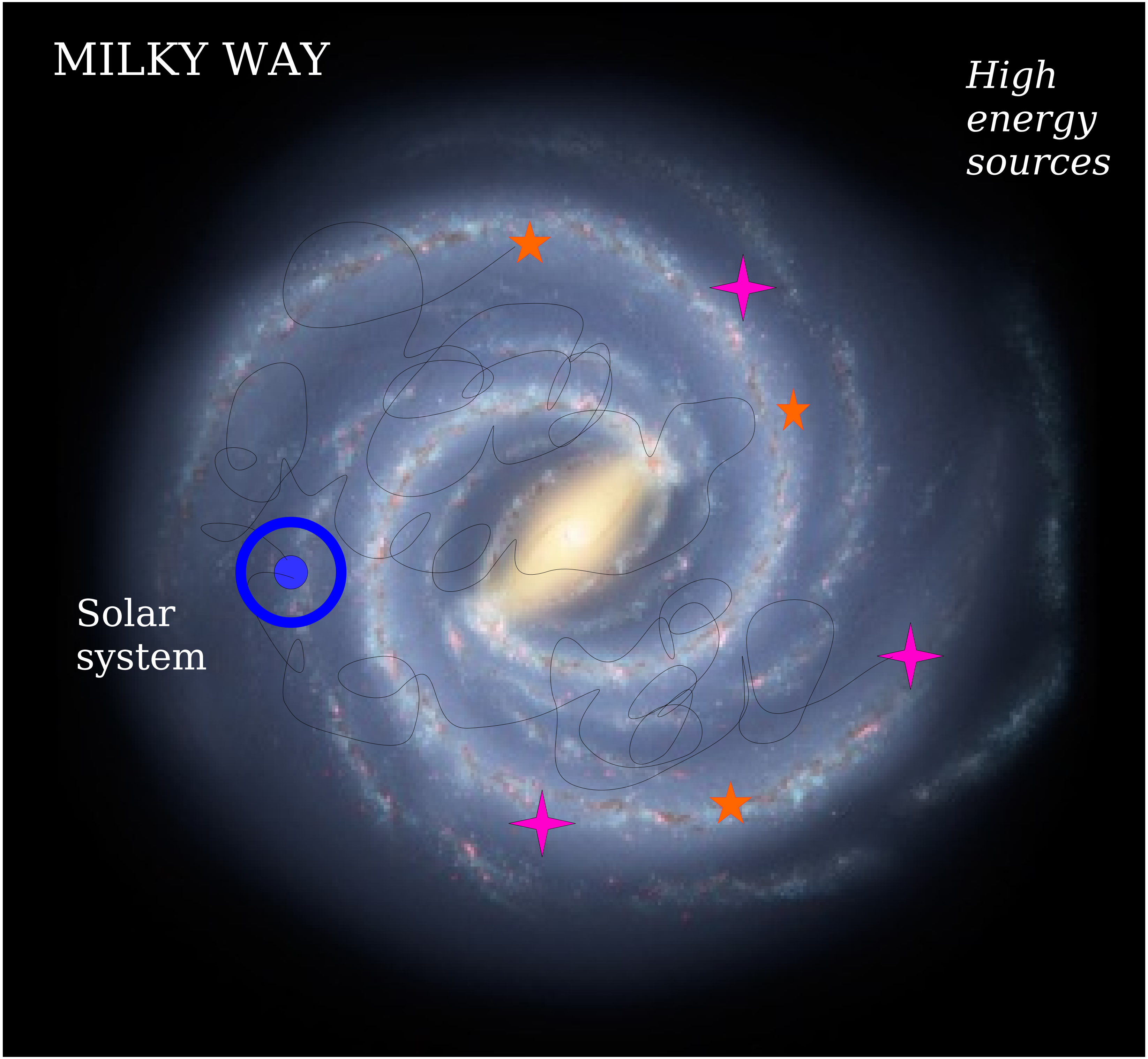


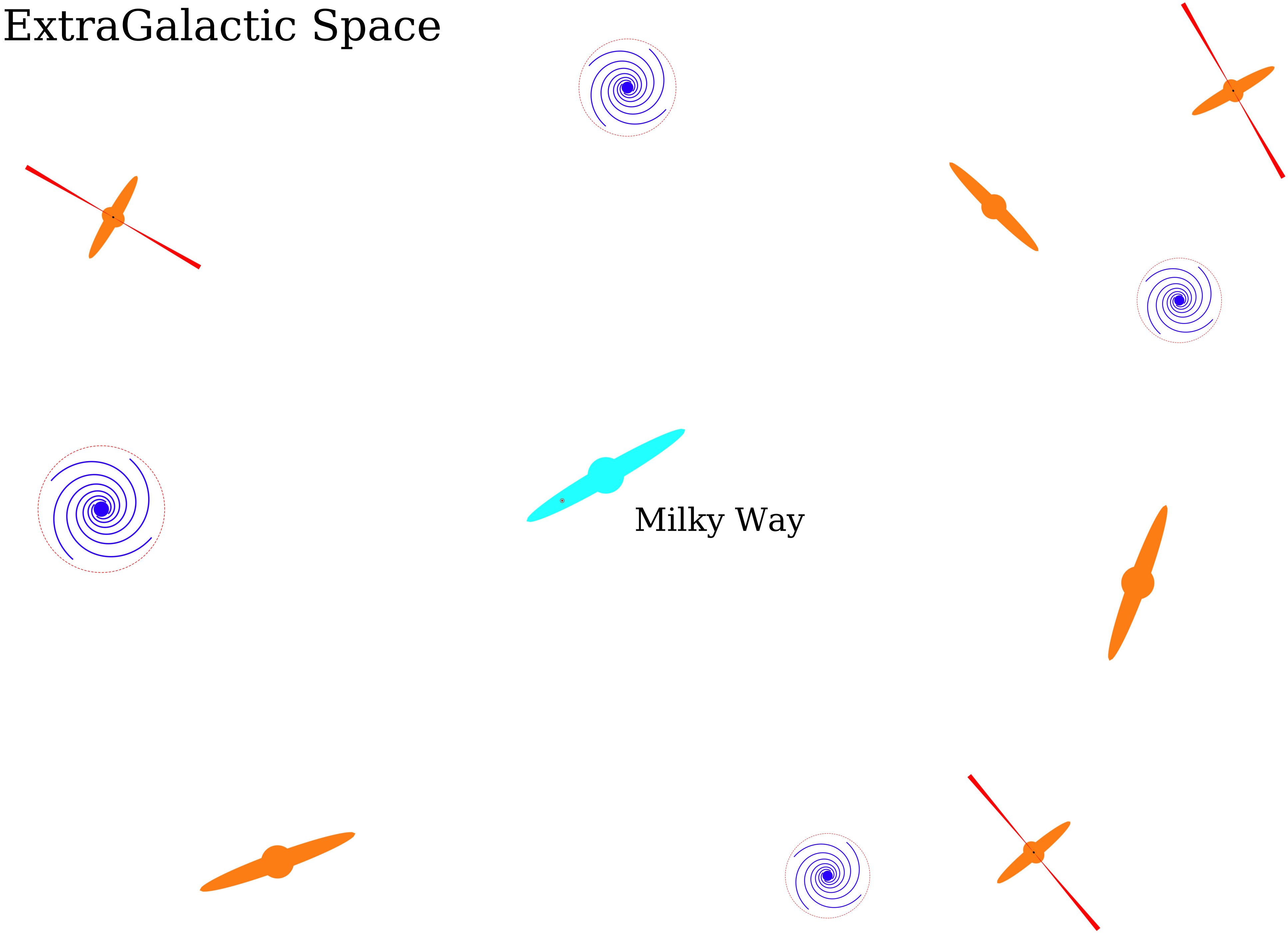
COSMIC RAYS

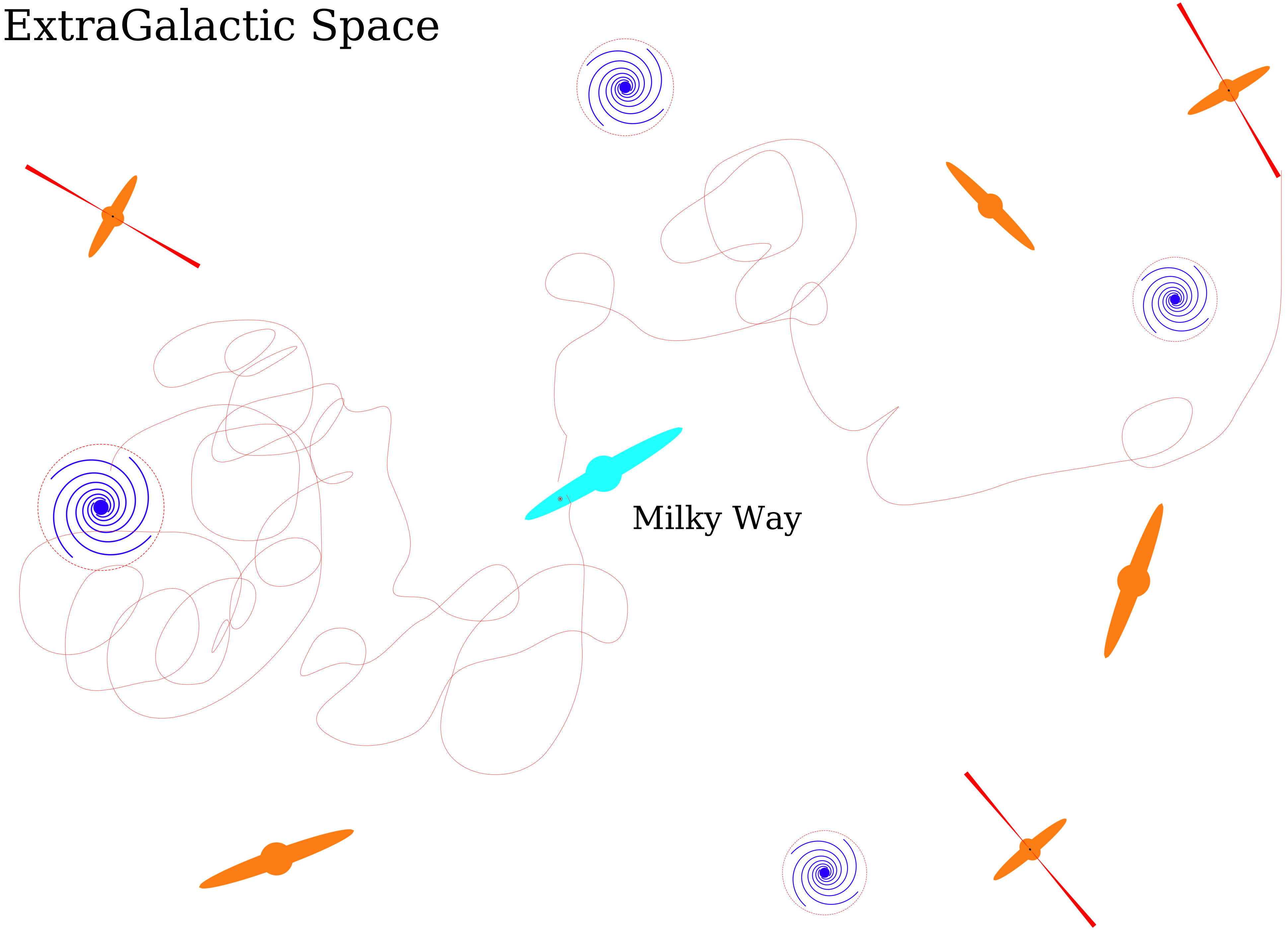
Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, *also shaped by propagation effects*.

Measurement at single point, and (effectively) single time.

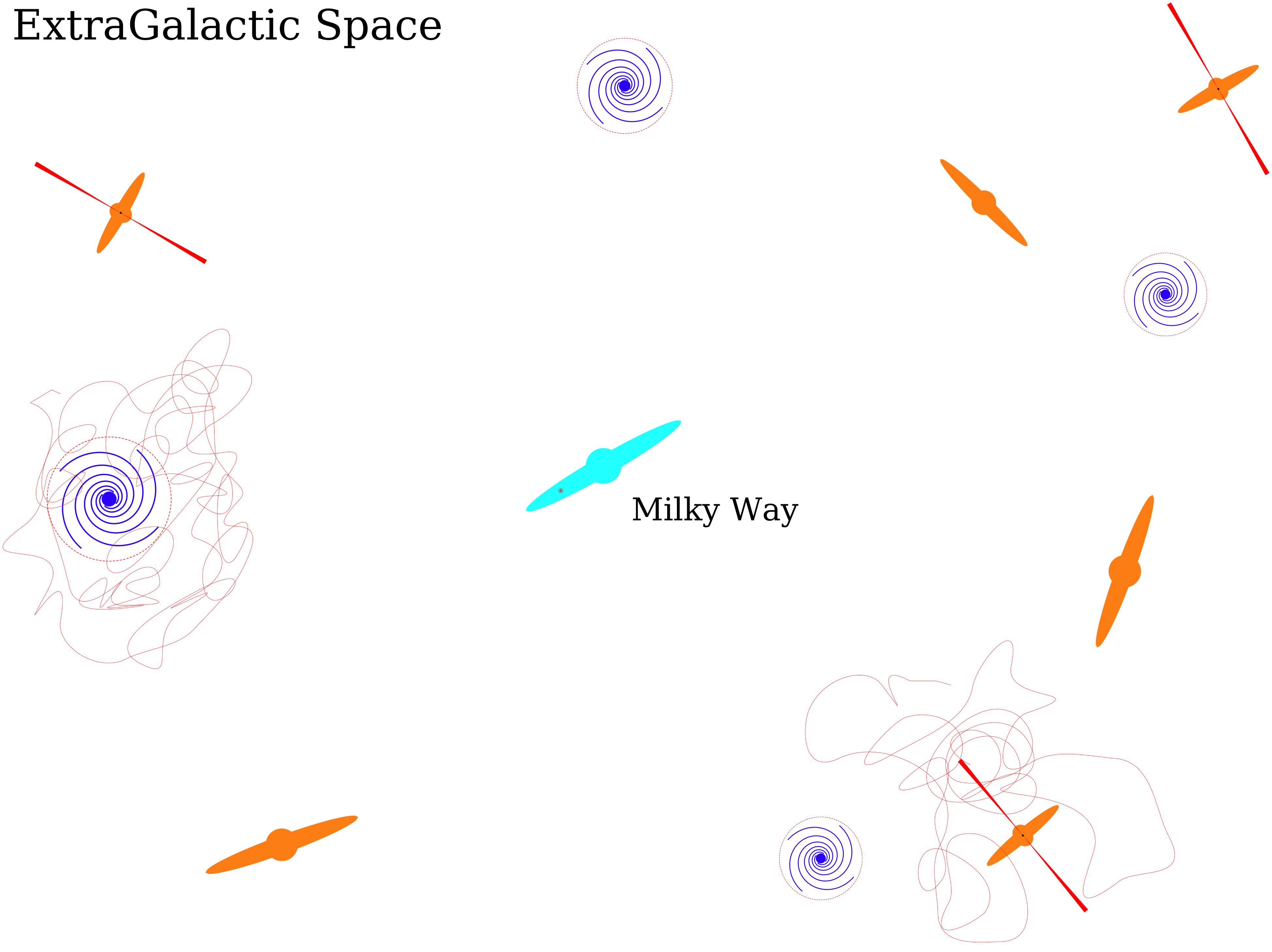
[slow time variations, geological record carries some information]

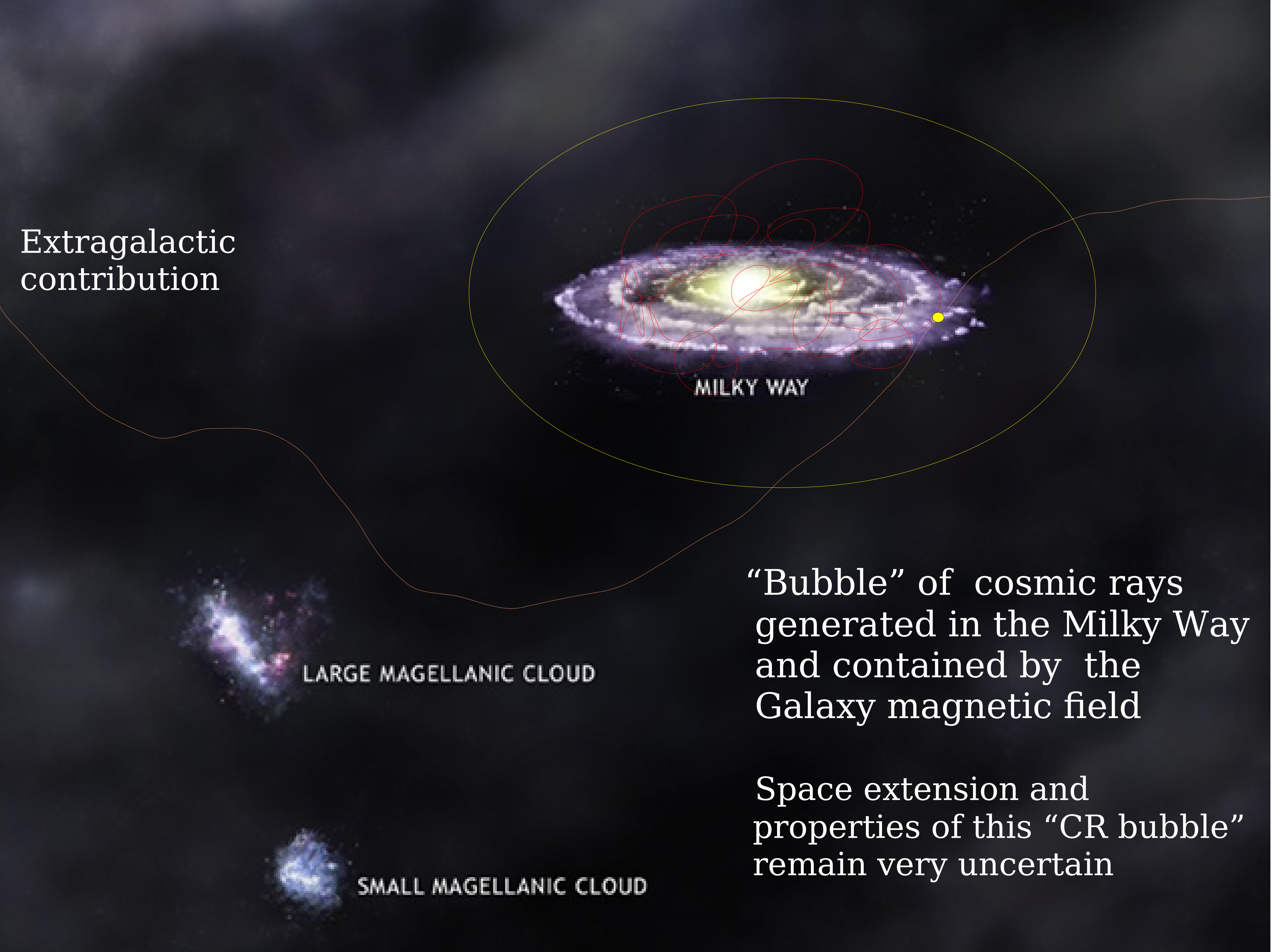

MILKY WAY
High
energy
sources
Solar
system


ExtraGalactic Space
Milky Way

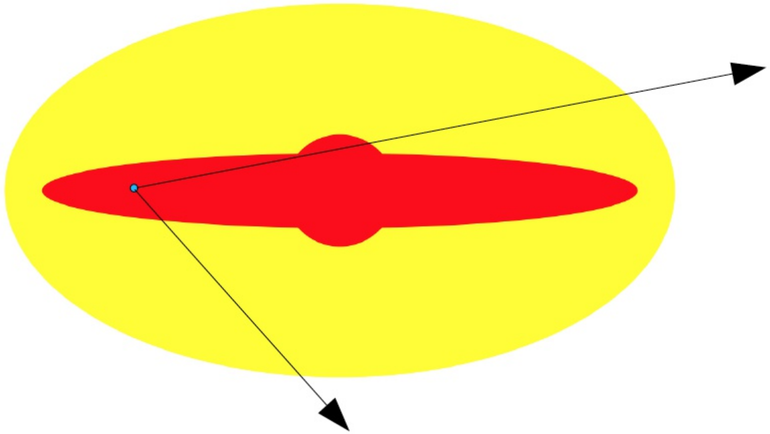

ExtraGalactic Space
Milky Way

ExtraGalactic Space



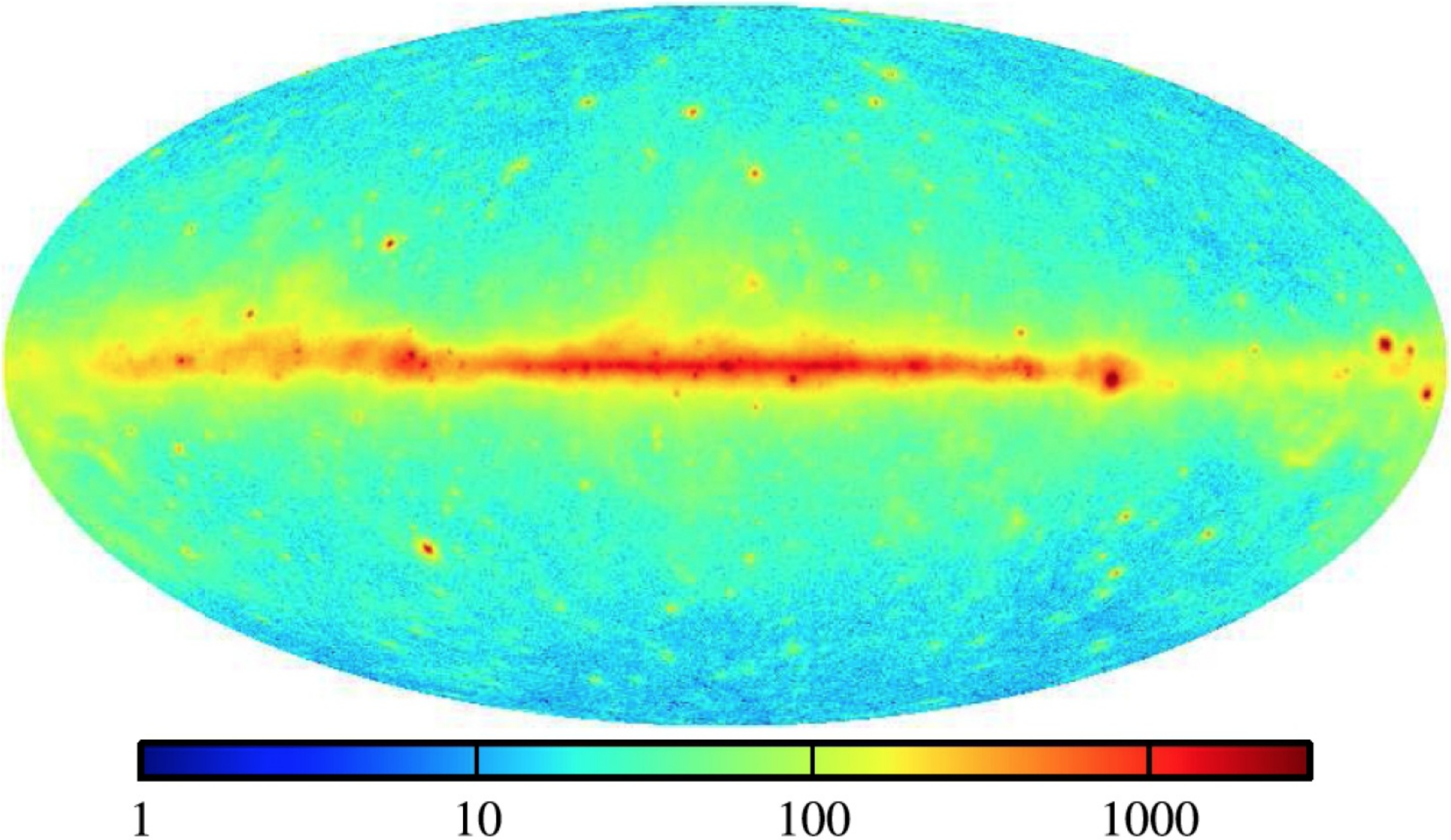

Extragalactic contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field
Space extension and properties of this "CR bubble" remain very uncertain

Diffuse Emission



Fermi–LAT counts

Galactic coordinates



energy range 200 MeV to 100 GeV

Cosmic Ray interactions in the Interstellar Medium

50% of flux
+- 5 degrees
around equator
[Galactic gas]

Non accelerator sources of High Energy Particles

Dark Matter

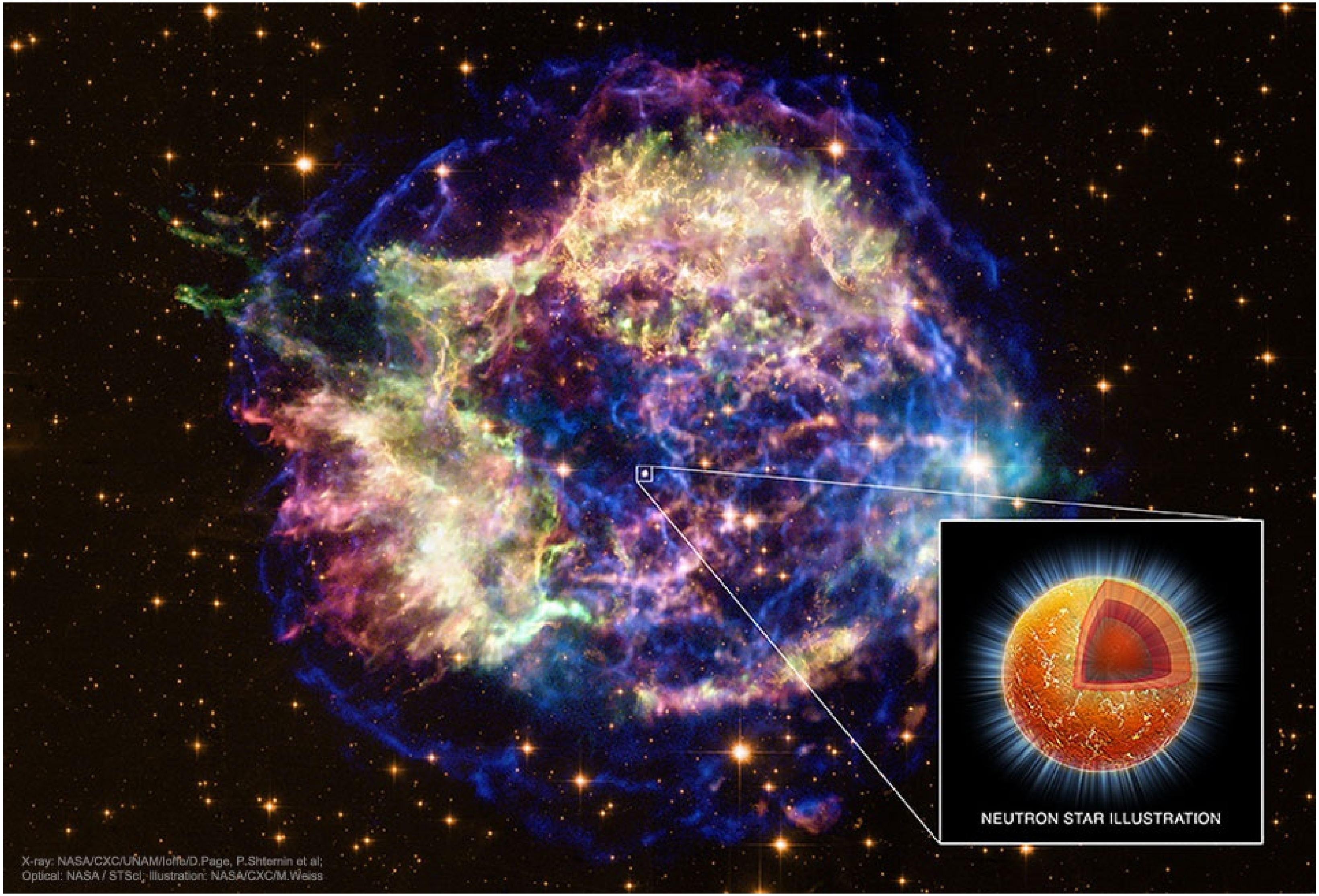
(in form of WIMP's self annihilation or decay)

Super Massive Particles

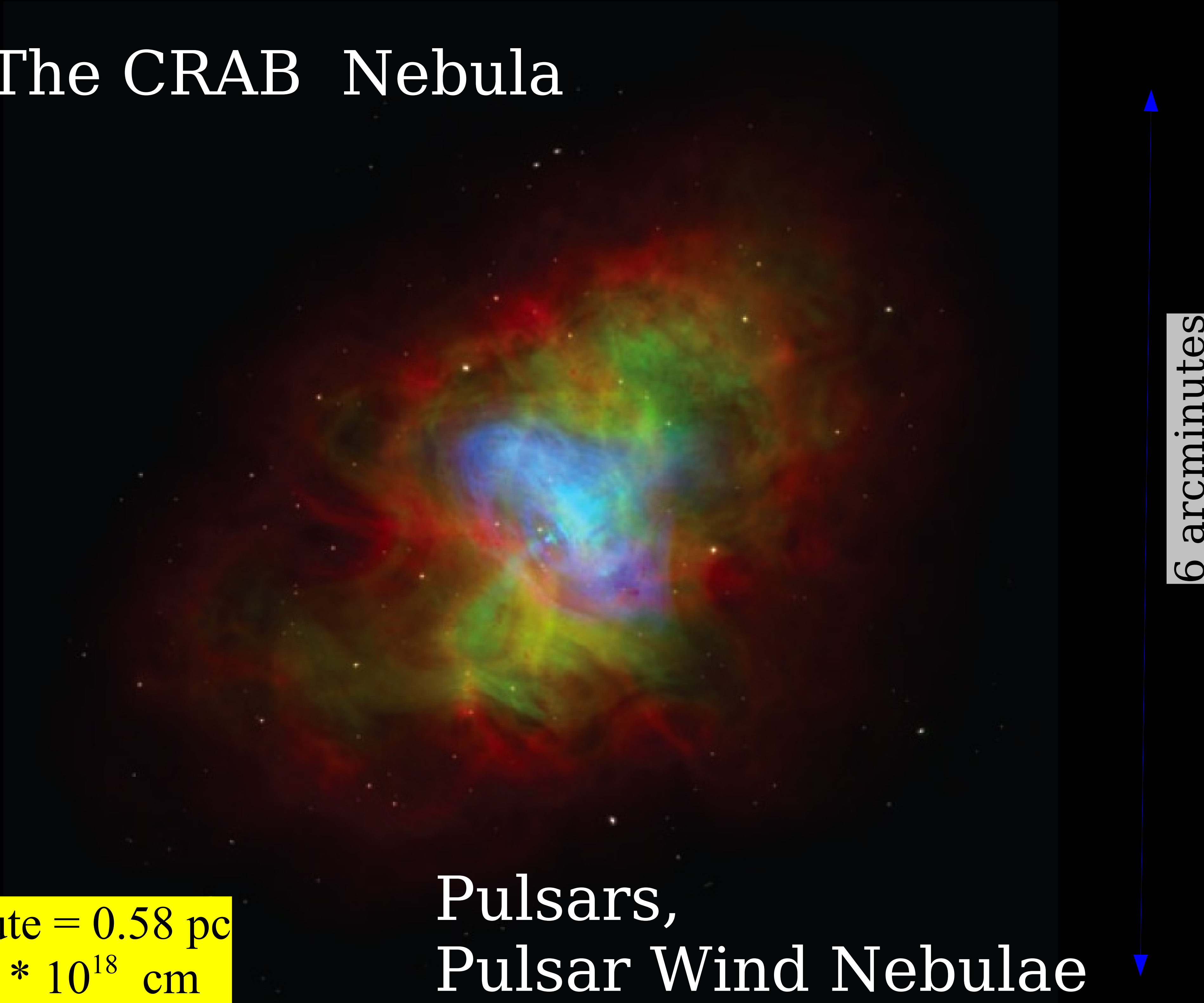
[Very High mass scales ($M_{GUT,}$ ...)]

Production of high energy particles of all types $\gamma\ ,\ \nu\ ,\ e^+\ ,\ e^-\ ,\ p\ ,\ \ldots$

SuperNova explosions



The CRAB Nebula



1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

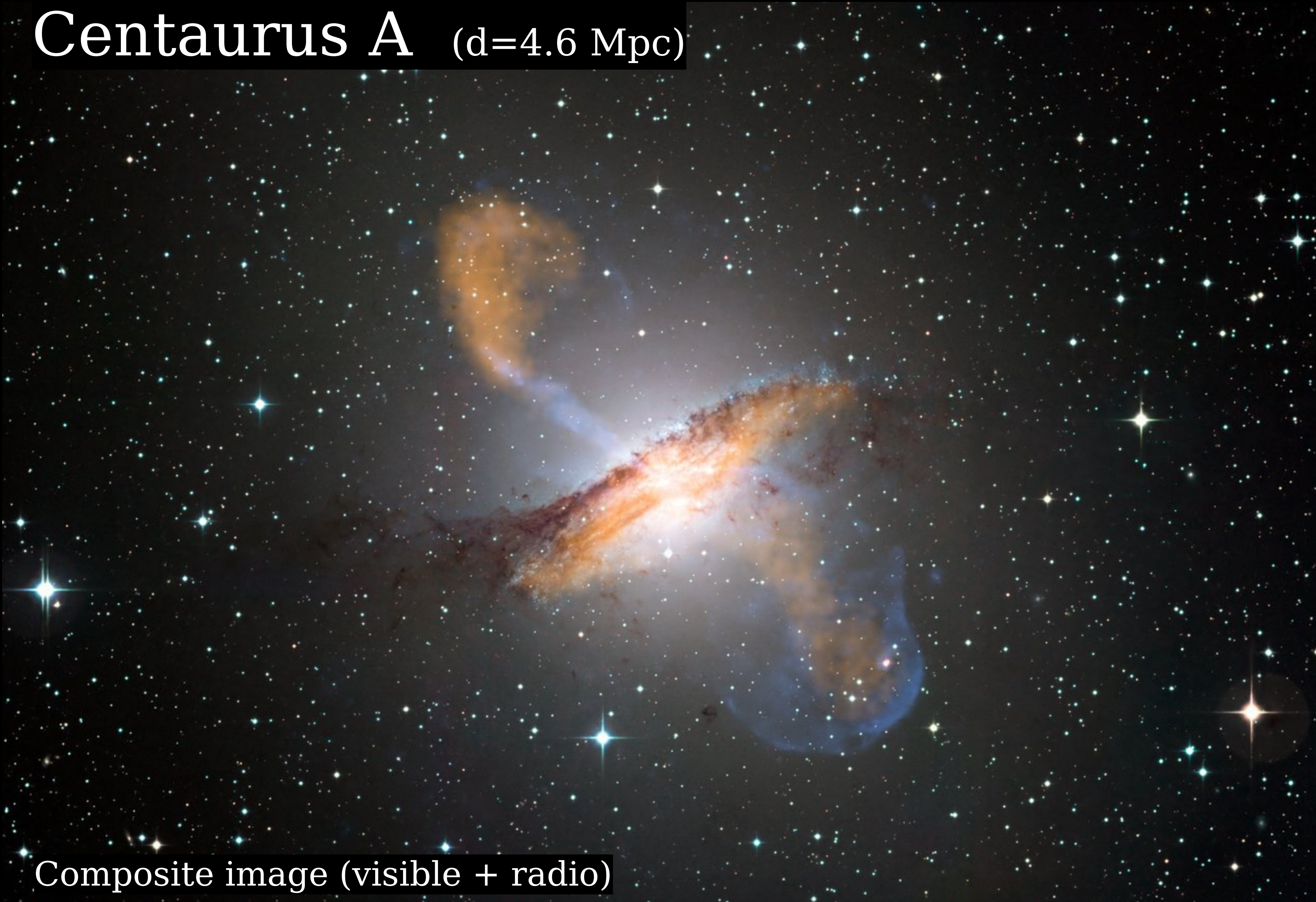
Pulsars,
Pulsar Wind Nebulae

Super Massive Black Holes
(at the center of Galaxies)

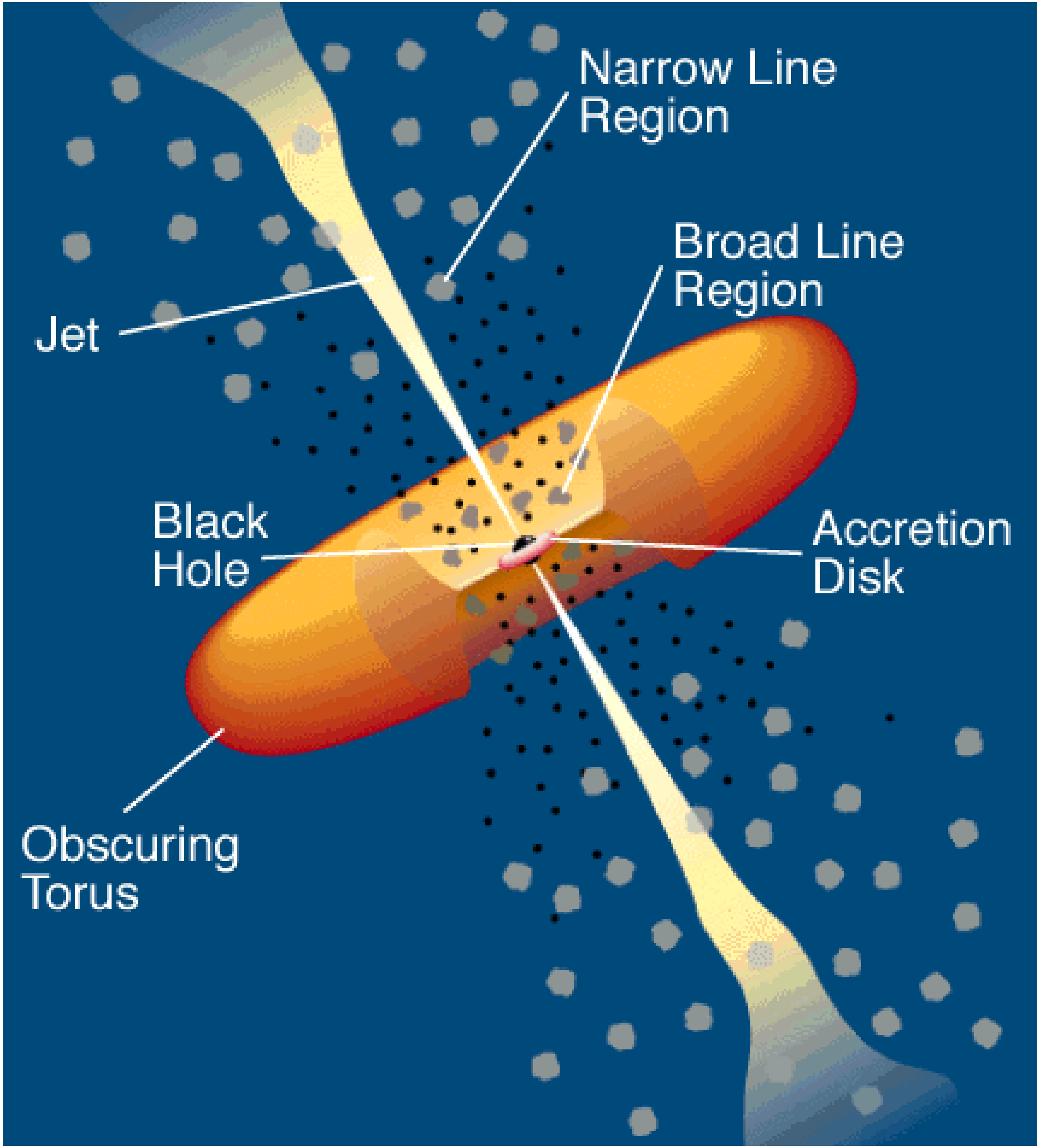
Active Galactic Nuclei

(powered by mass accretion)

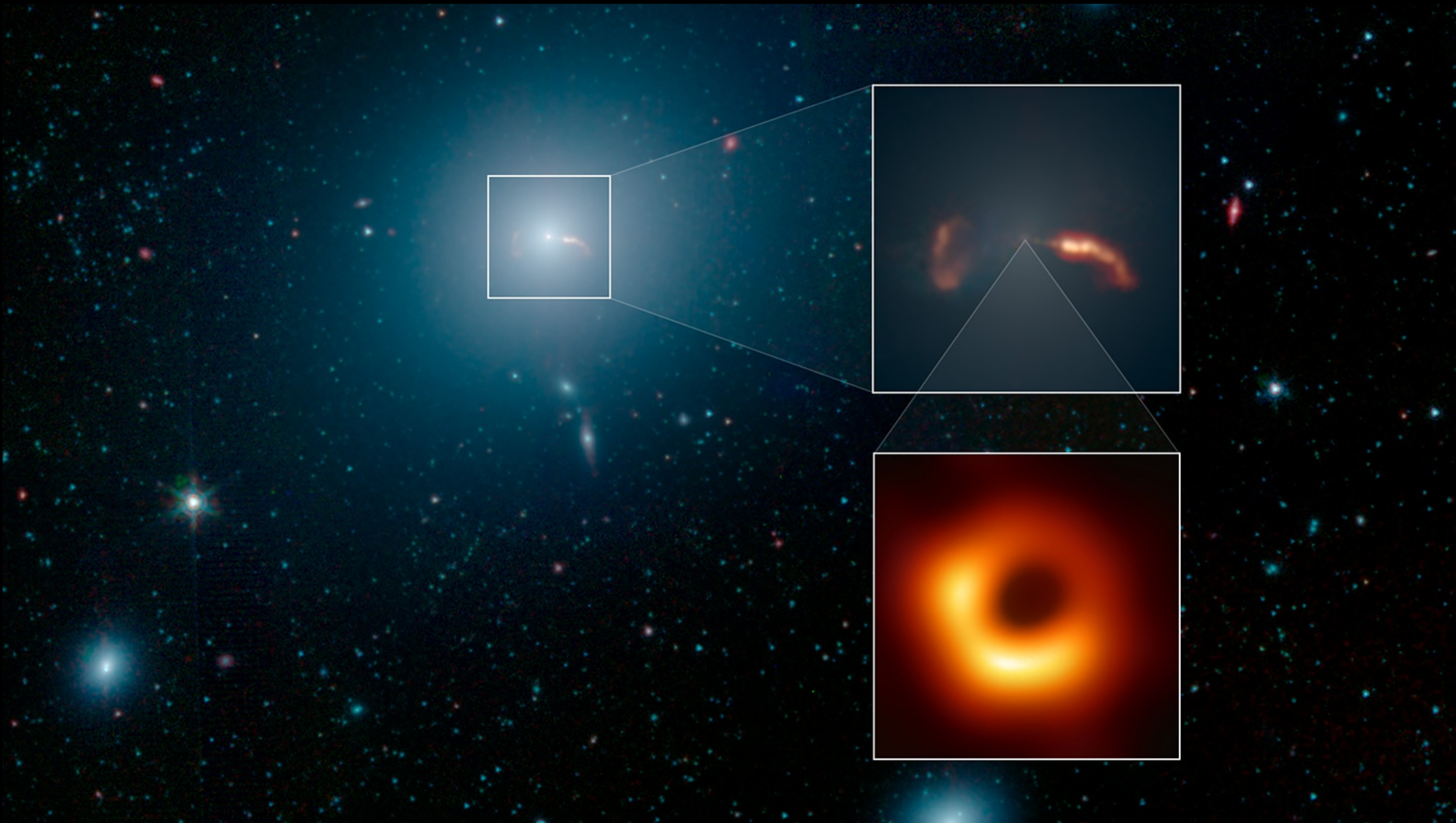
Centaurus A (d=4.6 Mpc)



Composite image (visible + radio)


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

M87 (d=17 Mpc)

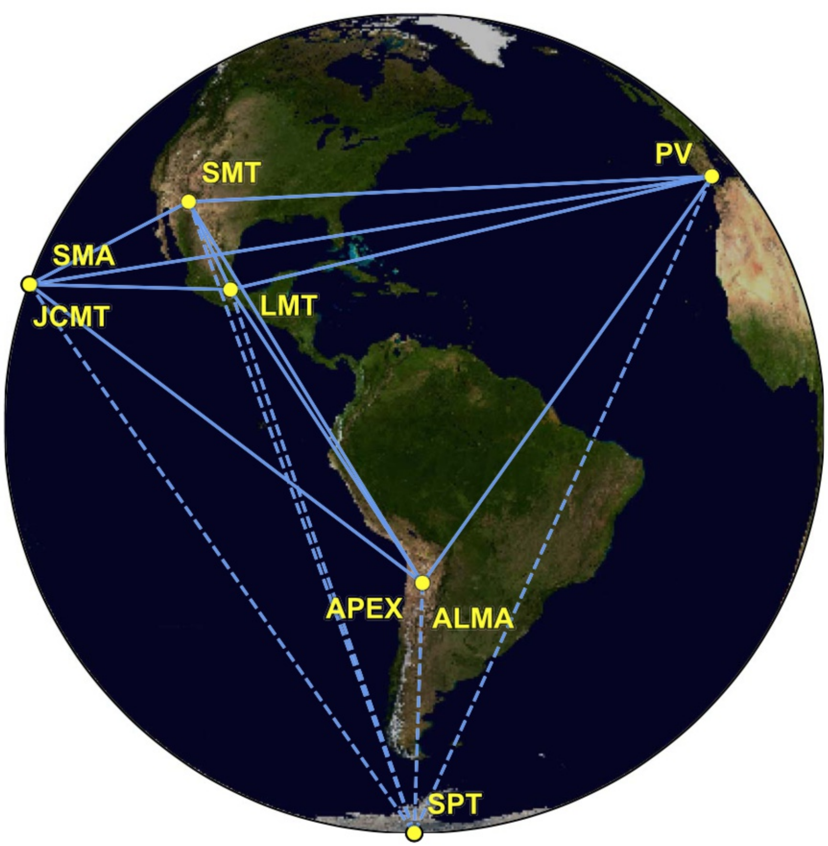


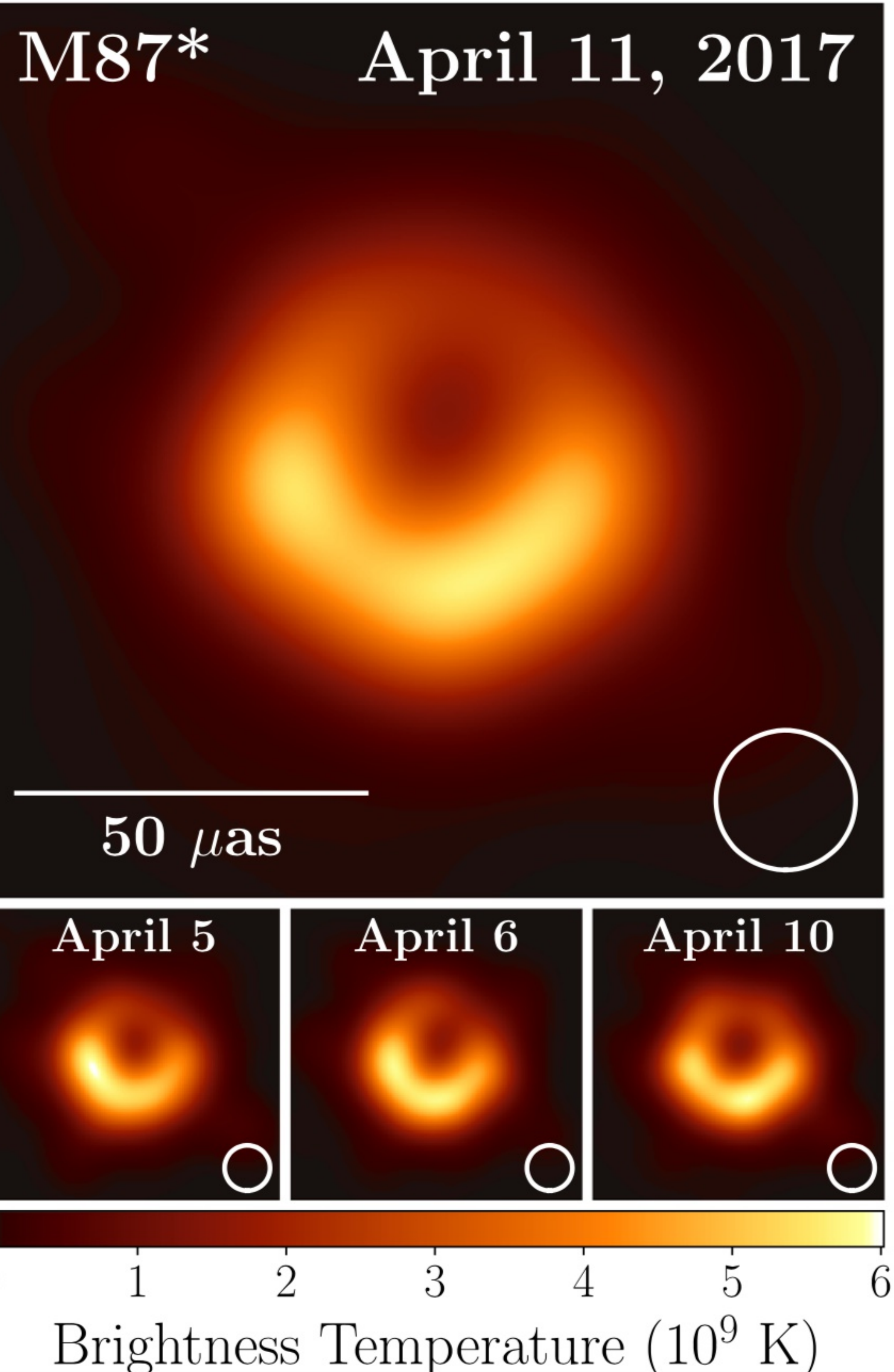
The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10





$$\text{diameter} = 42 \pm 3 \ \mu\text{as}$$

Schwarzschild radius

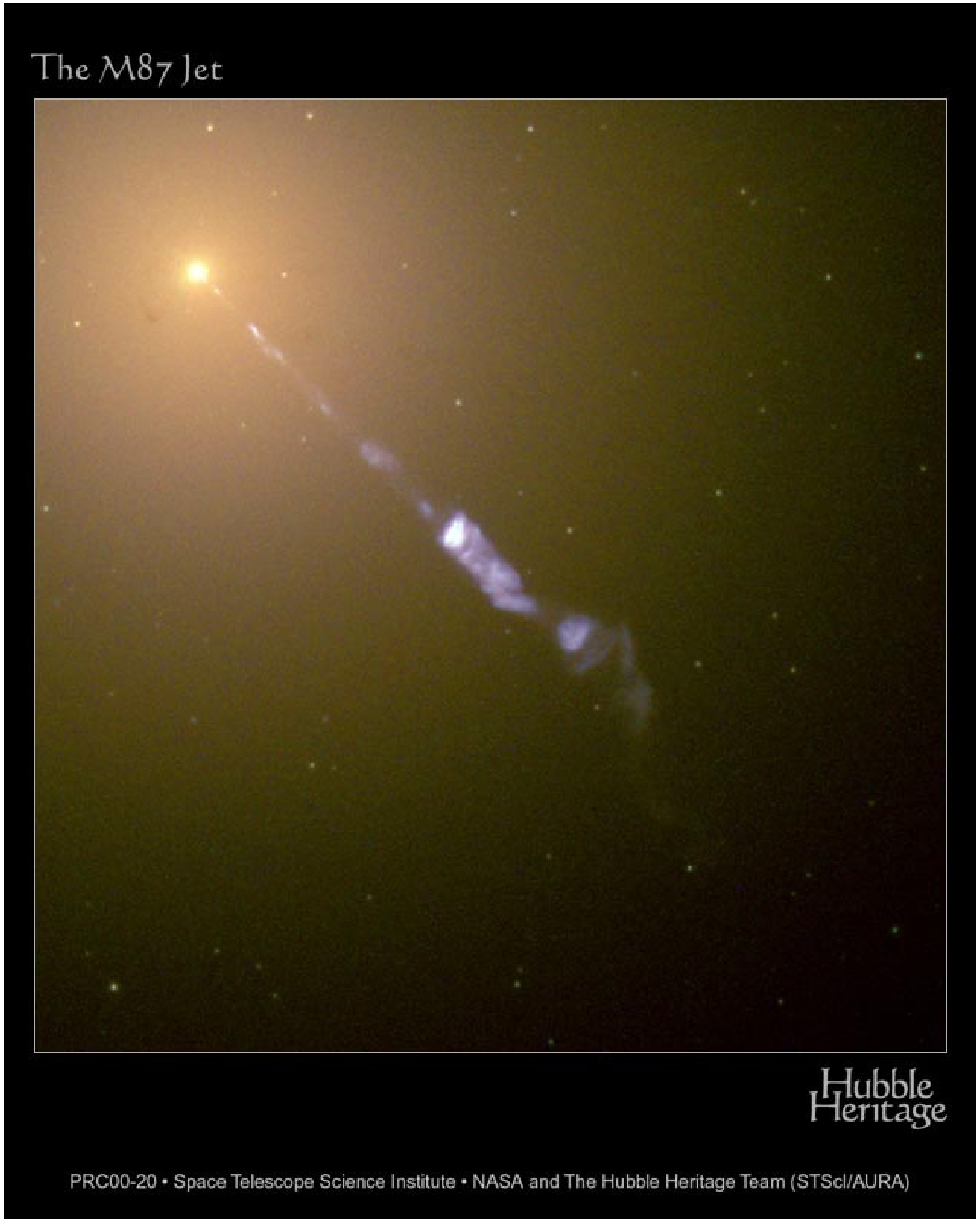
$$R_S = \frac{2\,G}{c^2}\ M$$

Photon capture radius

$$R_c = \sqrt{27}\ \frac{G}{c^2}\ M$$

$$d = 16.8 \pm 0.8 \ \text{Mpc}$$

$$M = (6.5 \pm 0.7) \times 10^9 \ M_\odot$$



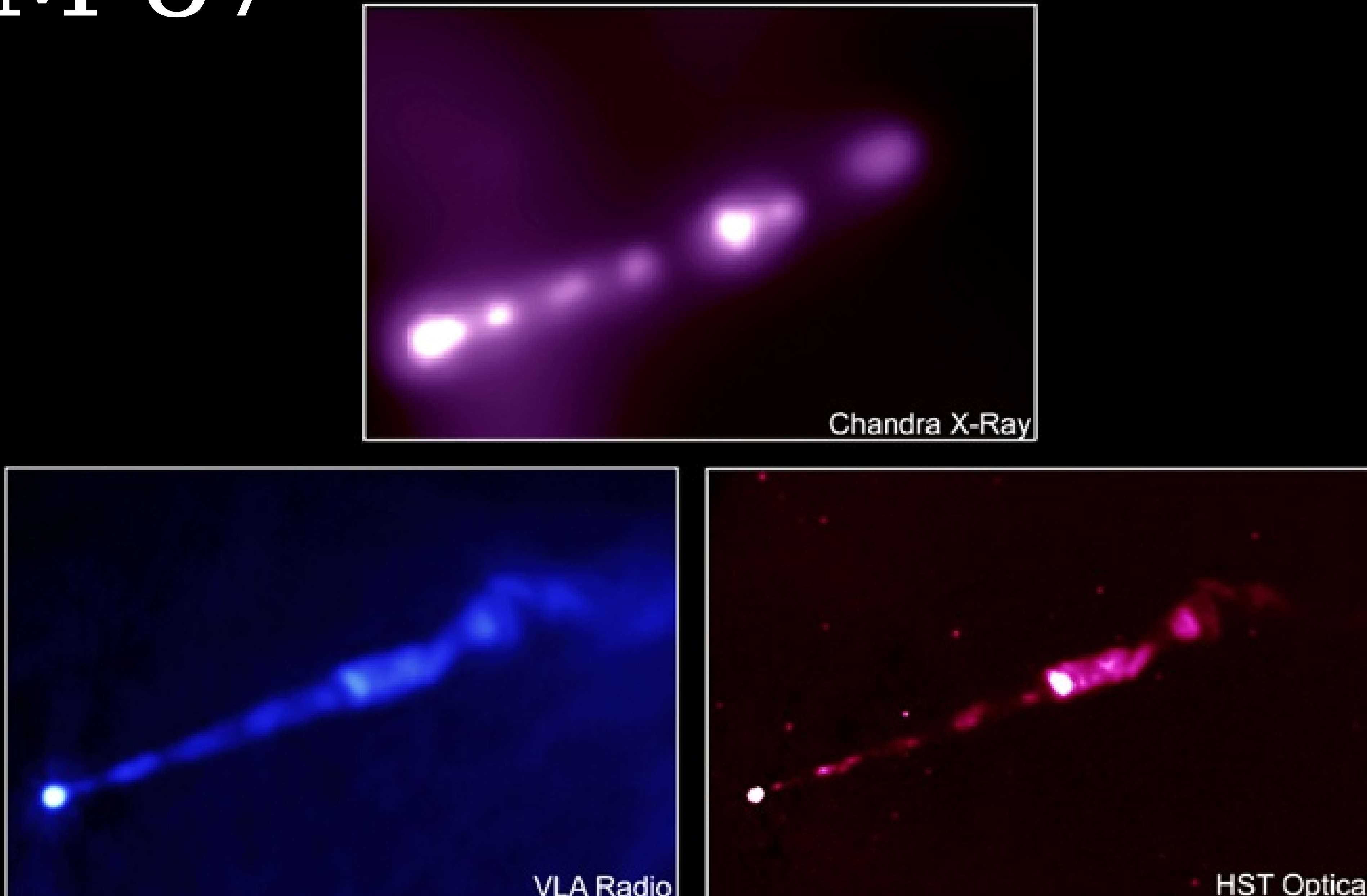
M87 JET

Heber Curtis (1918)
[Lick Observatory]

"Descriptions of 762 Nebulae and Clusters ...."

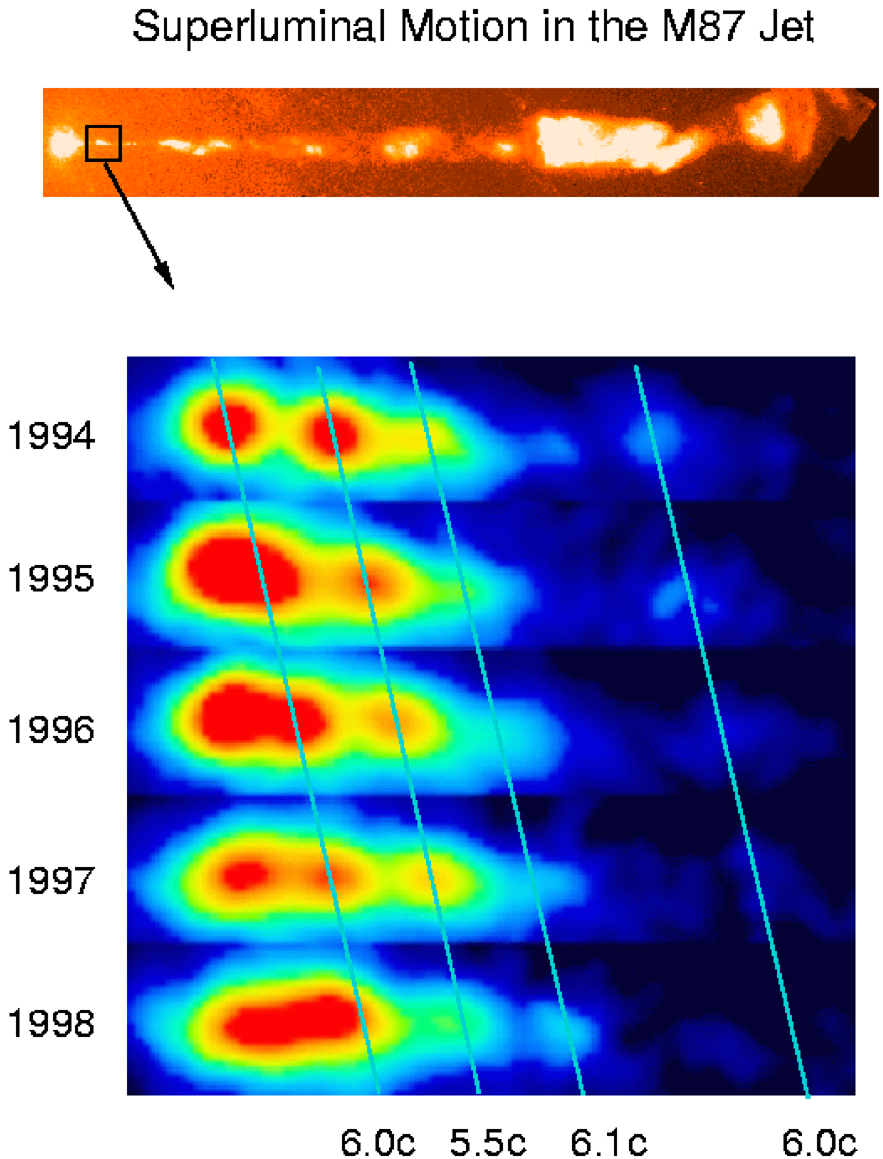
"...curious straight ray ... apparently connected with the nucleus by a thin line of matter."

M 87



First astrophysical “jet”   [1913 Heber Curtis]

Superluminal Motion



Source moving
on the celestial sphere

$$c\,\beta_{\rm app} = L\,\dot{\omega}$$

M87 :

$$\beta_{\rm app} \simeq 6$$

Observations of M87

2005
2008
2010

HESS
MAGIC
VERITAS

$E \geq 350$ GeV

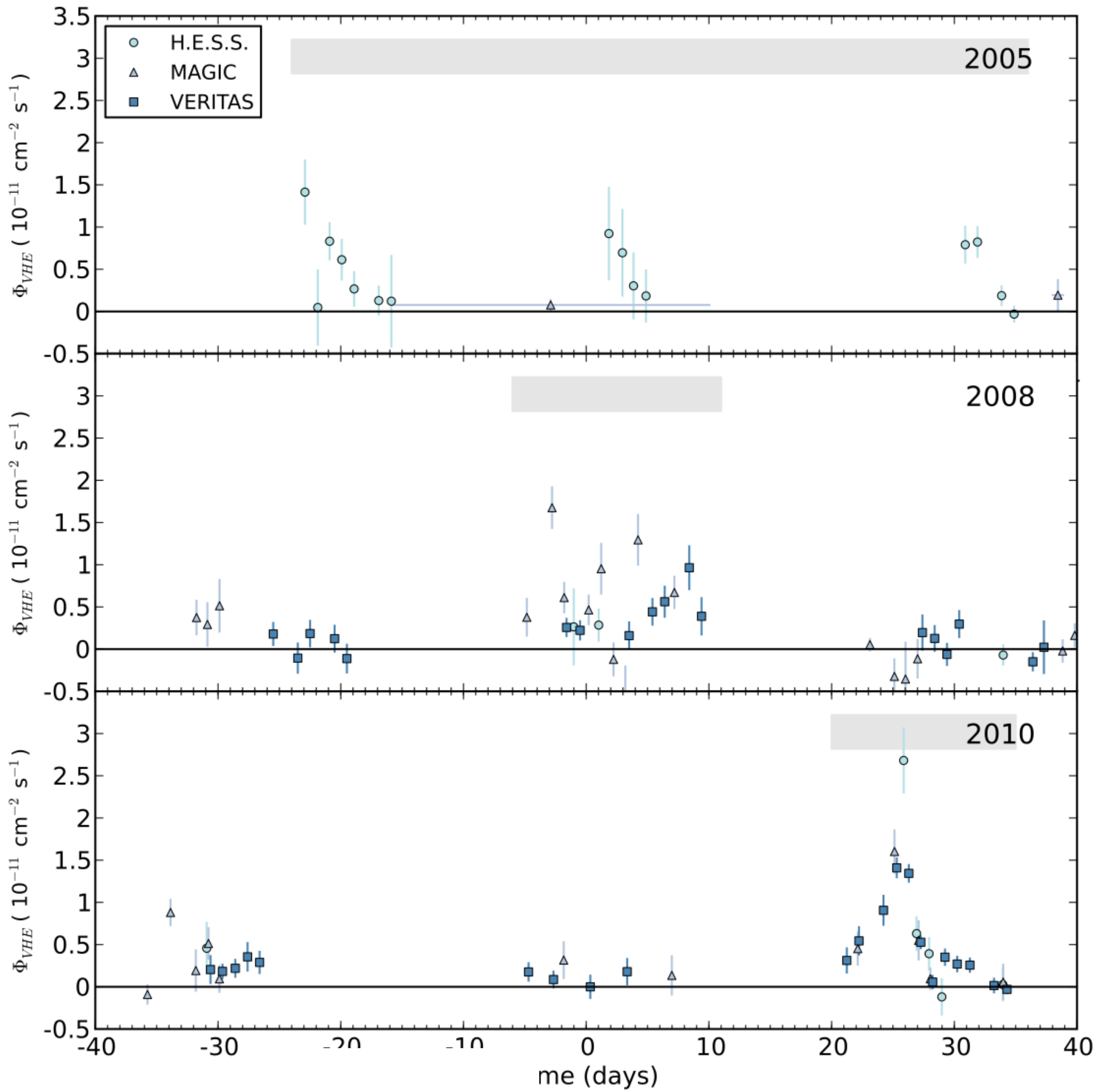
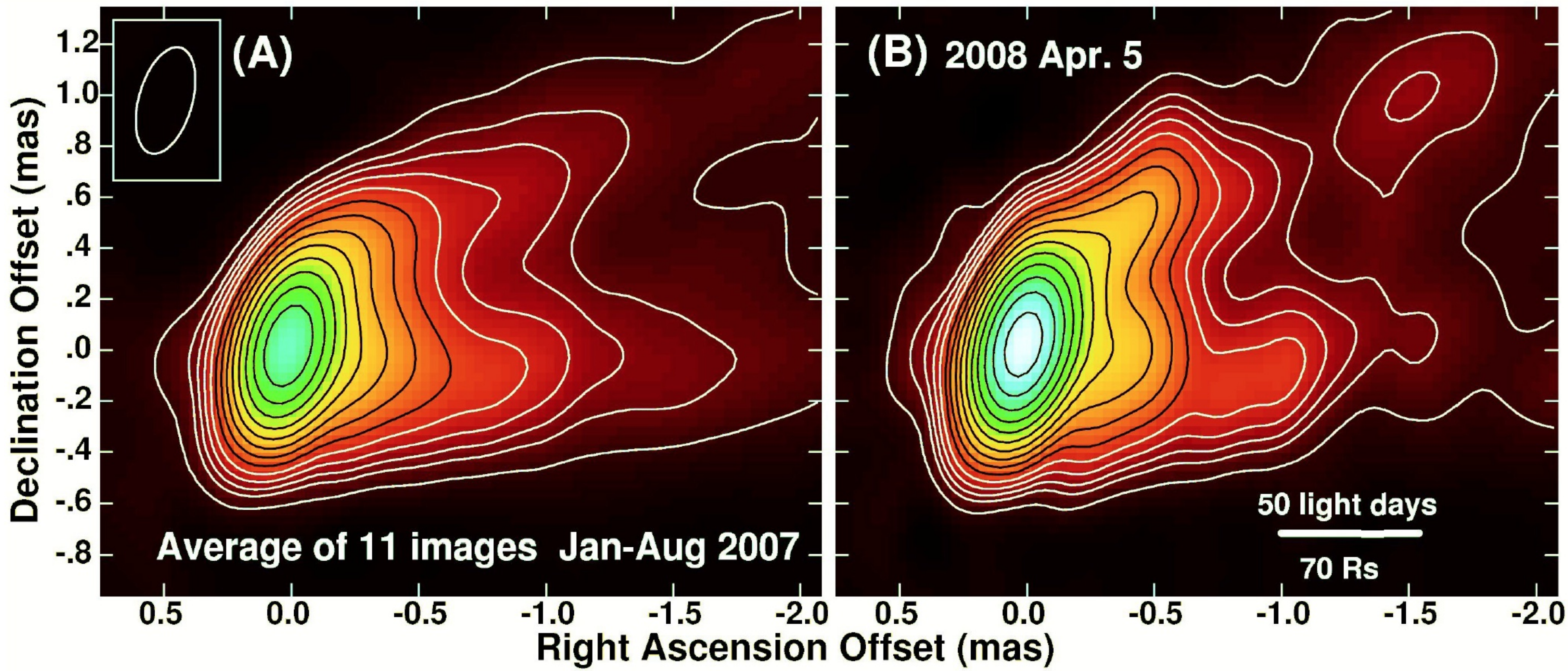


Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500, and MJD 55270 for 2005, 2008, and 2010, respectively. Flux error bars denote the 1 s.d. statistical error. Horizontal error bars denote the time span the flux has been averaged over. Note that in the case of time spans longer than one night the coverage is not continuous.

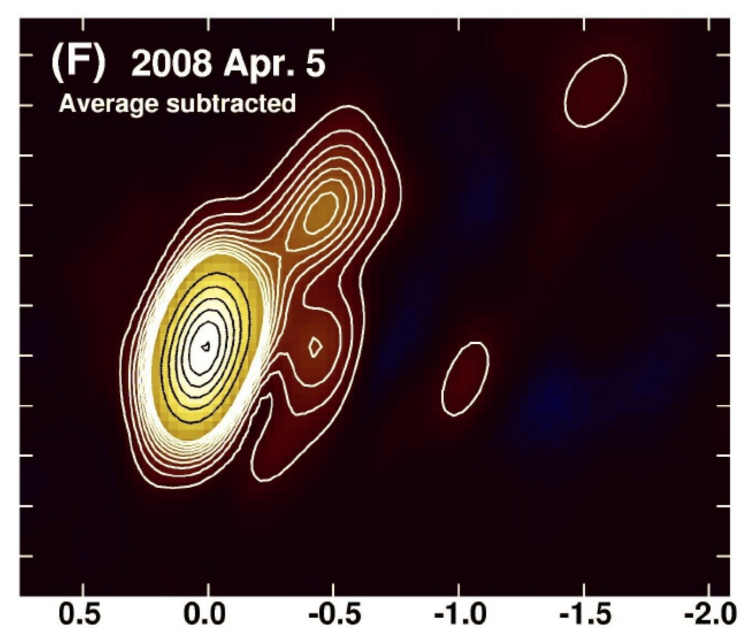


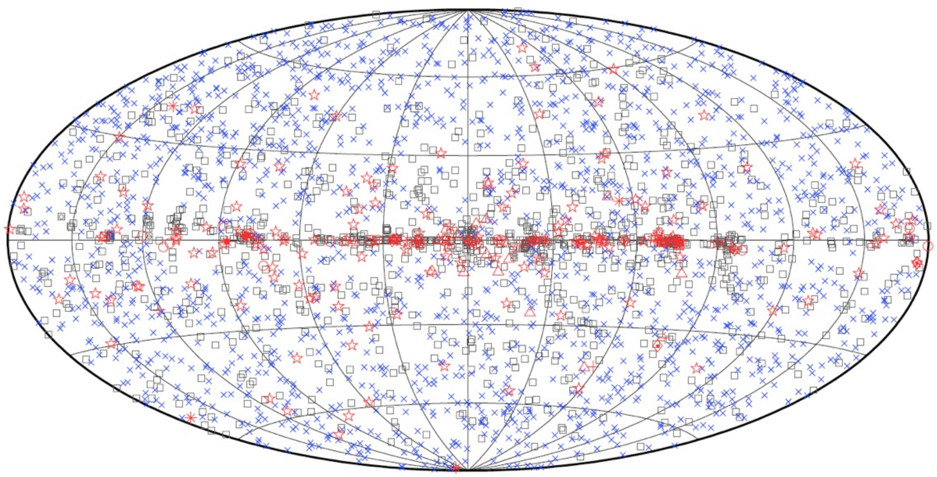
VLBA radio images of M87 at 43 GHz

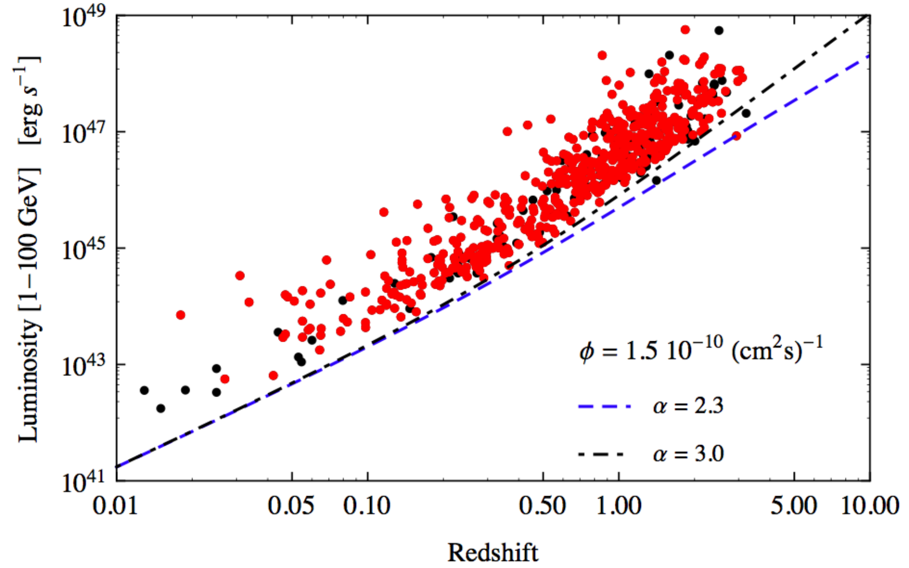
Science 24 Jul 2009:
Vol. 325, Issue 5939, pp. 444-448
DOI: 10.1126/science.1175406

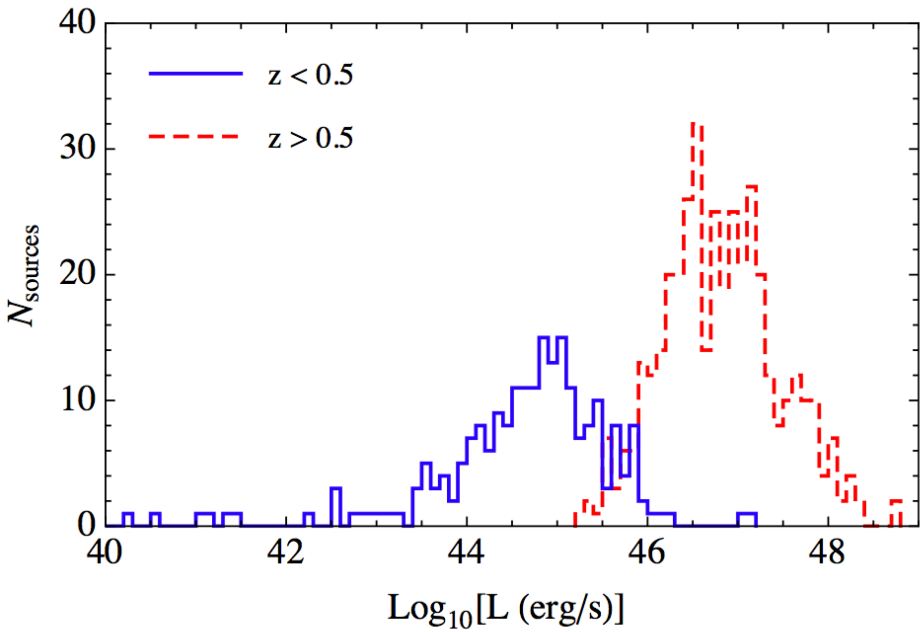
Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration





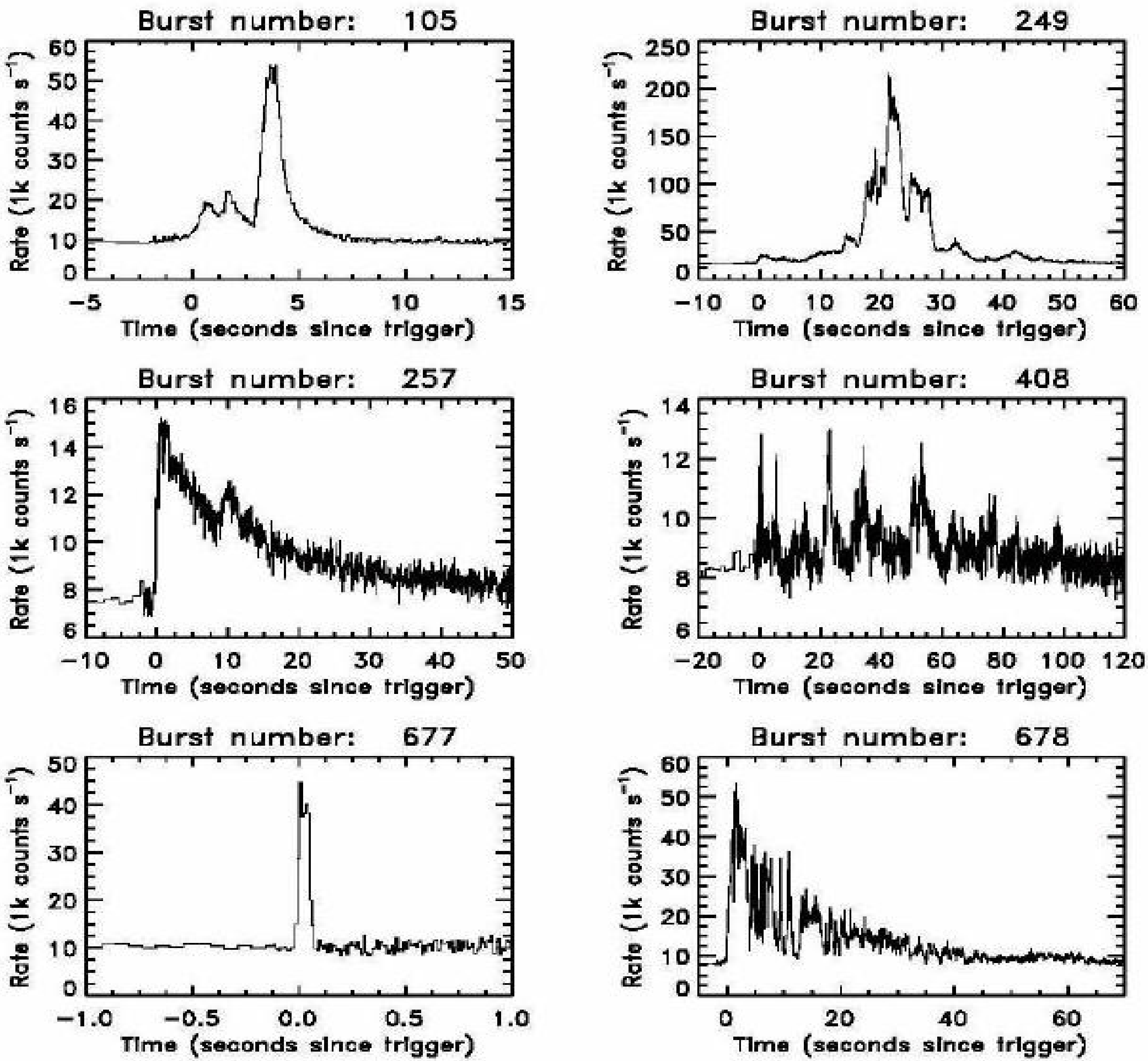


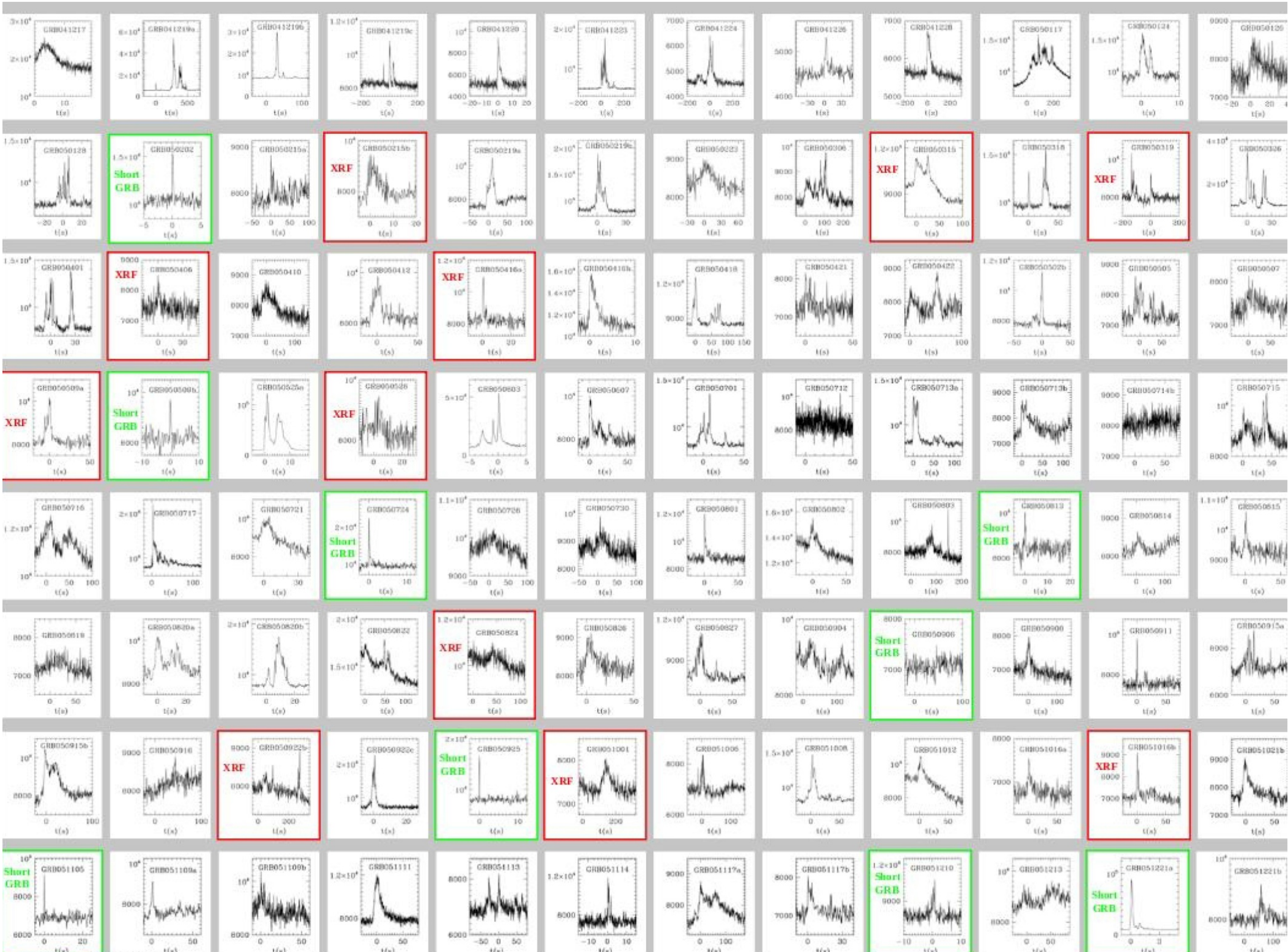


Extragalactic sources
observed by FERMI
nearly all Blazars
2LAC FERMI catalog
(1121 objects) 618 with redshift

Luminosity [1-100 GeV]

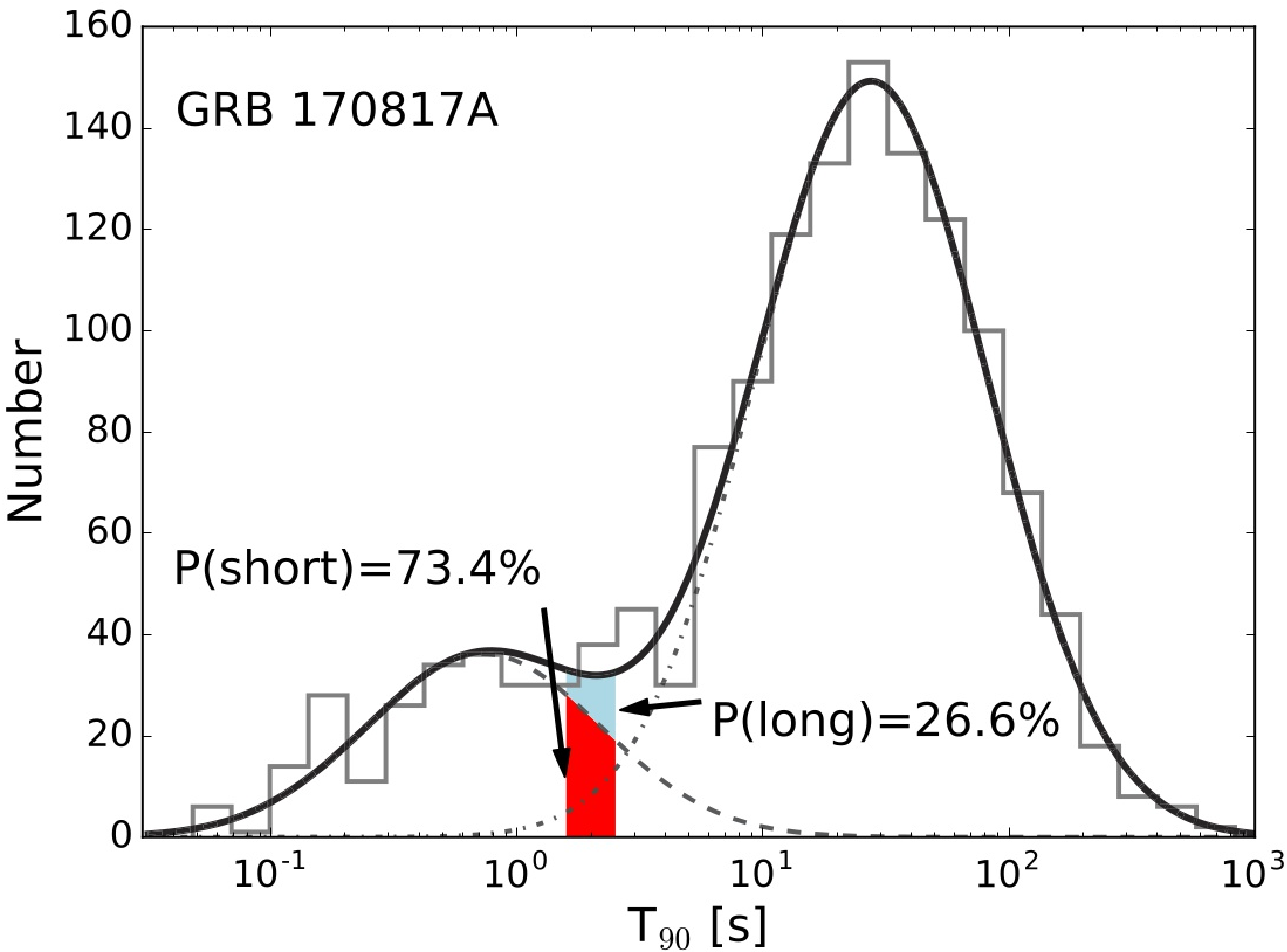
GAMMA RAY BURSTS (GRB's)

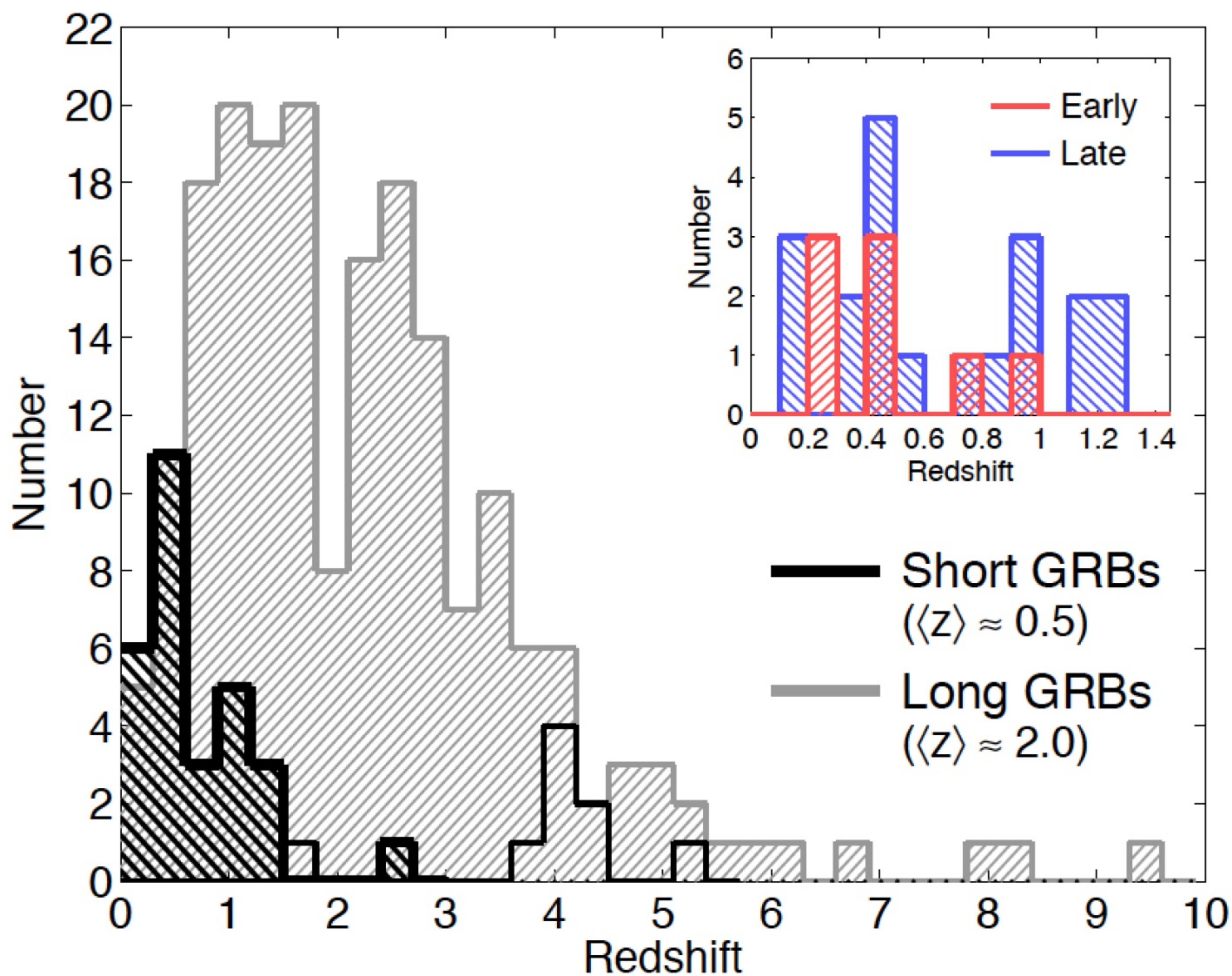




[From N. Gehrels]

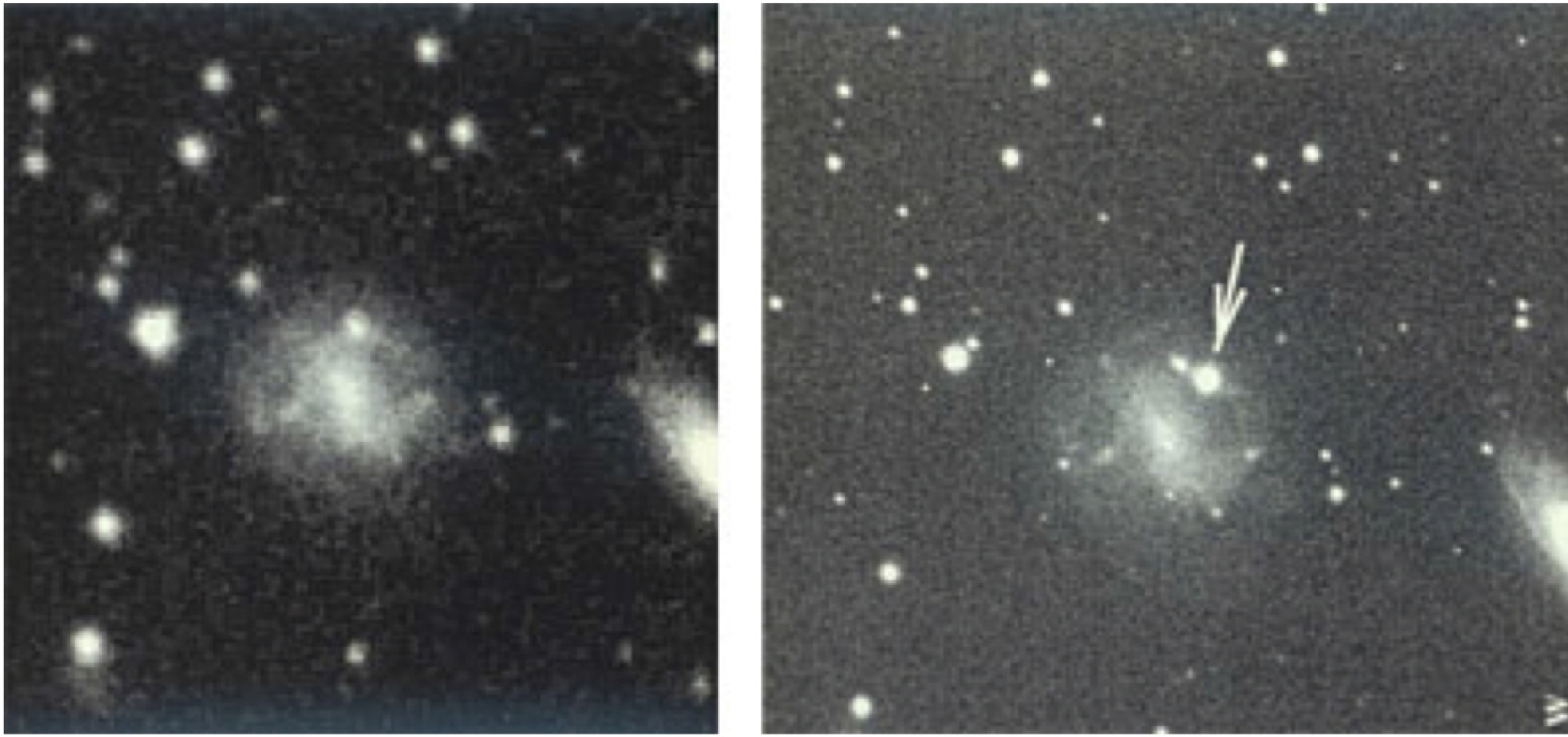
Two Classes of Gamma Ray Bursts: “Short” and “Long”





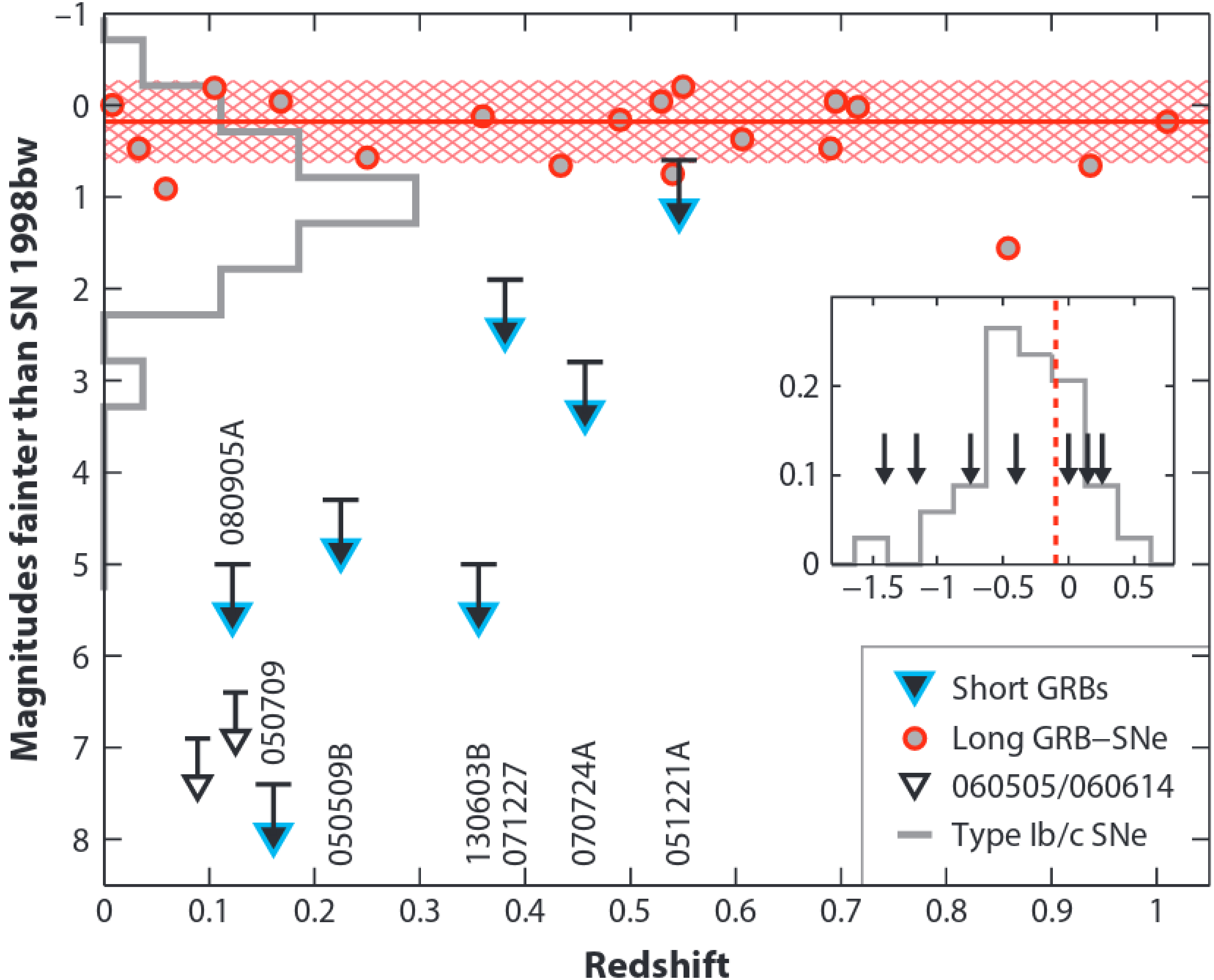
Number
Redshift
Short GRBs
(⟨z⟩ ≈ 0.5)
Long GRBs
(⟨z⟩ ≈ 2.0)
Early
Late

Association Long GRB's with SN explosions

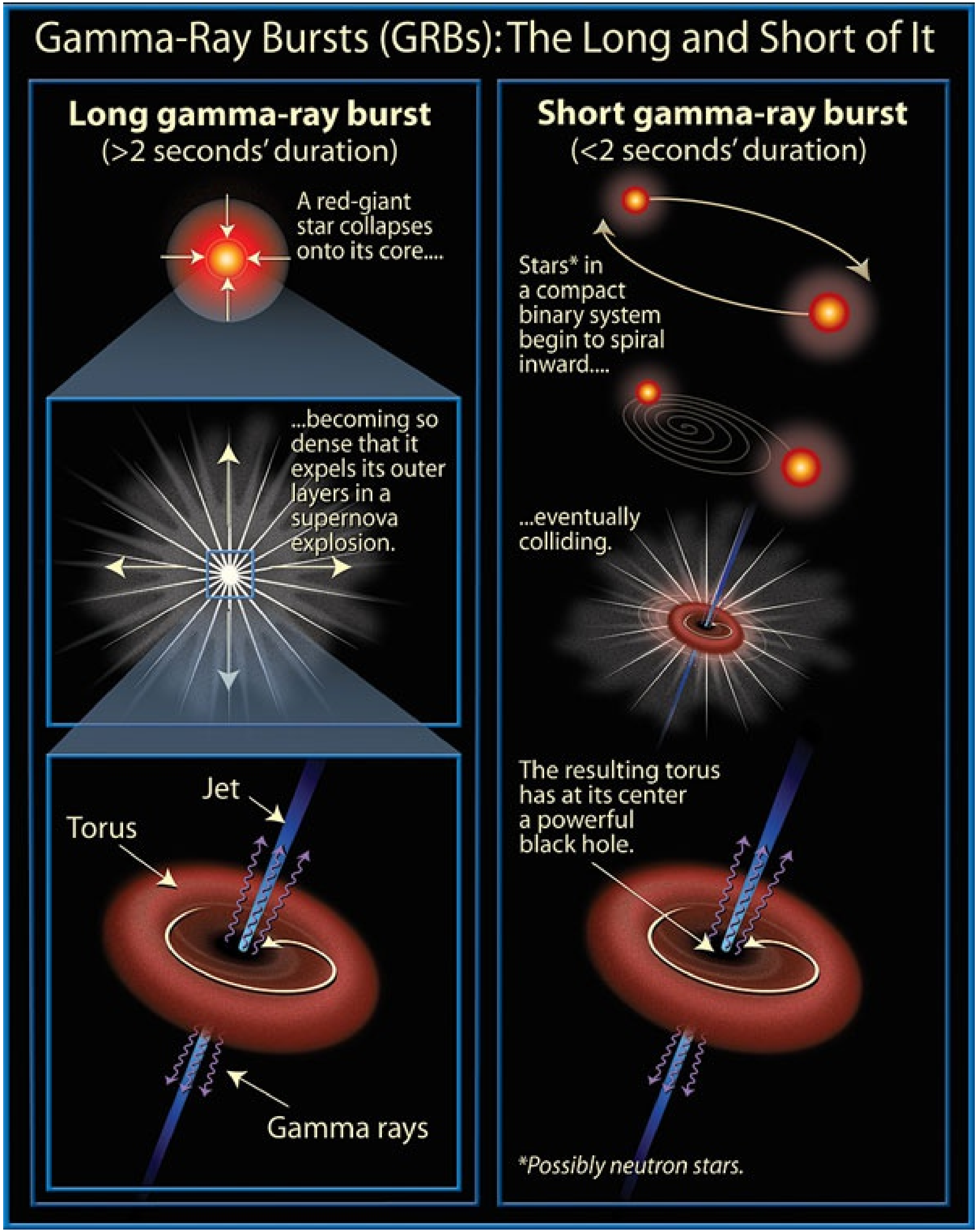


Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.

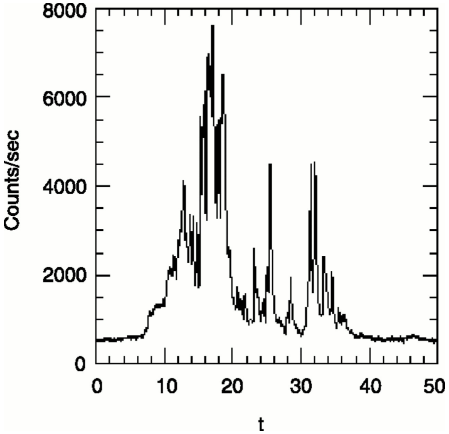
SN 1998bw GRB 980425

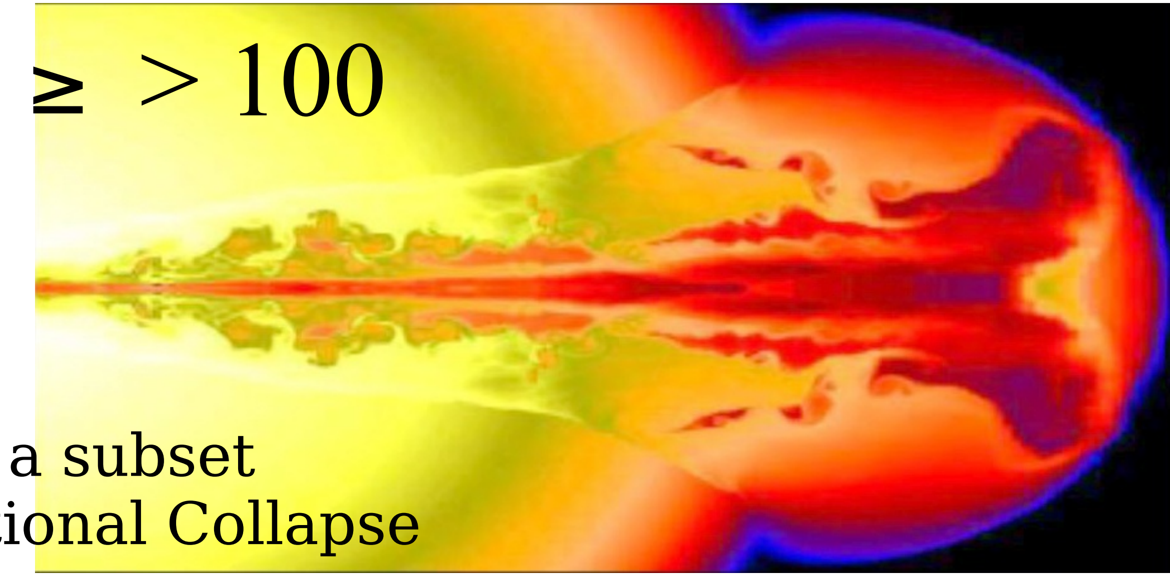


Magnitudes fainter than SN 1998bw
Redshift
080905A
050709
050509B
130603B
071227
070724A
051221A
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe



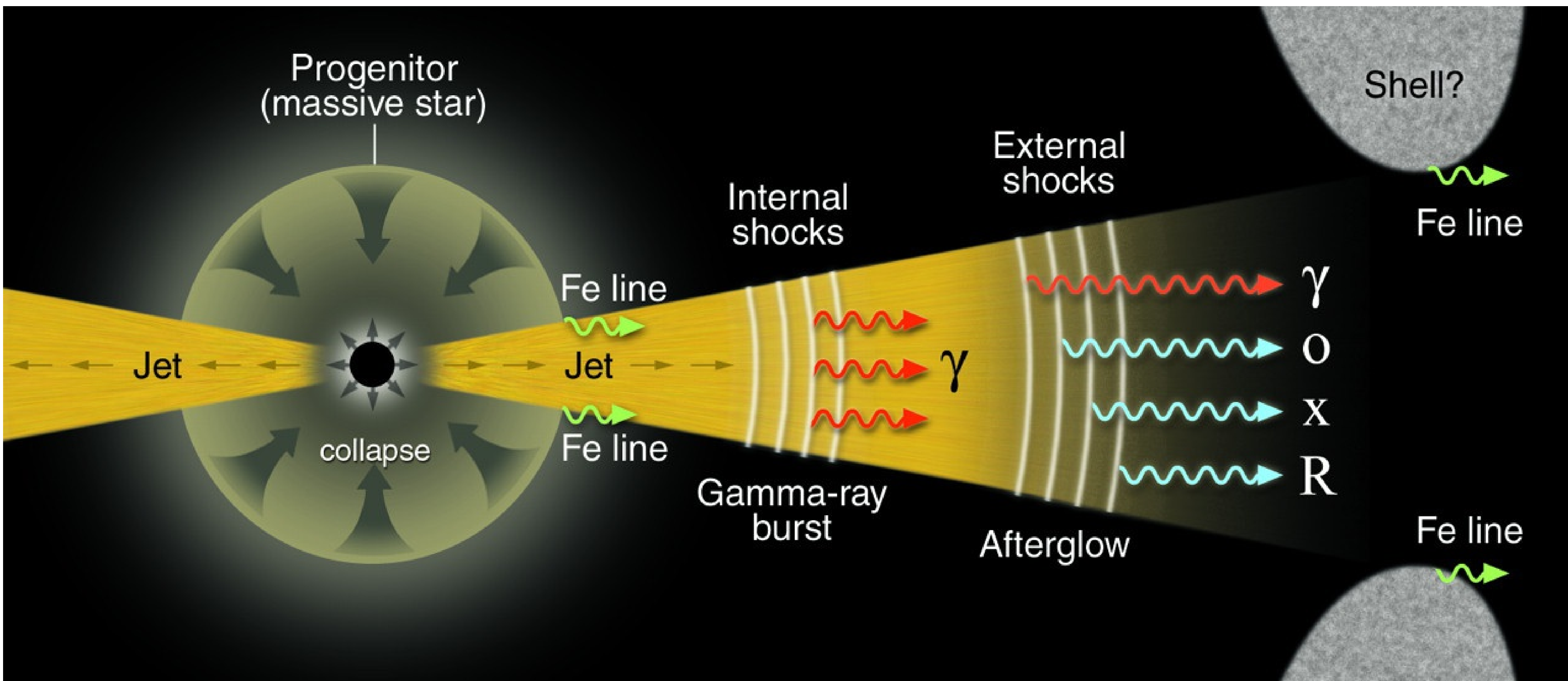
Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.





≥ > 100

GRB : associated with a subset
of SN Stellar Gravitational Collapse



GRB 130427A

$$\Gamma \gtrsim 1200 \quad !!$$

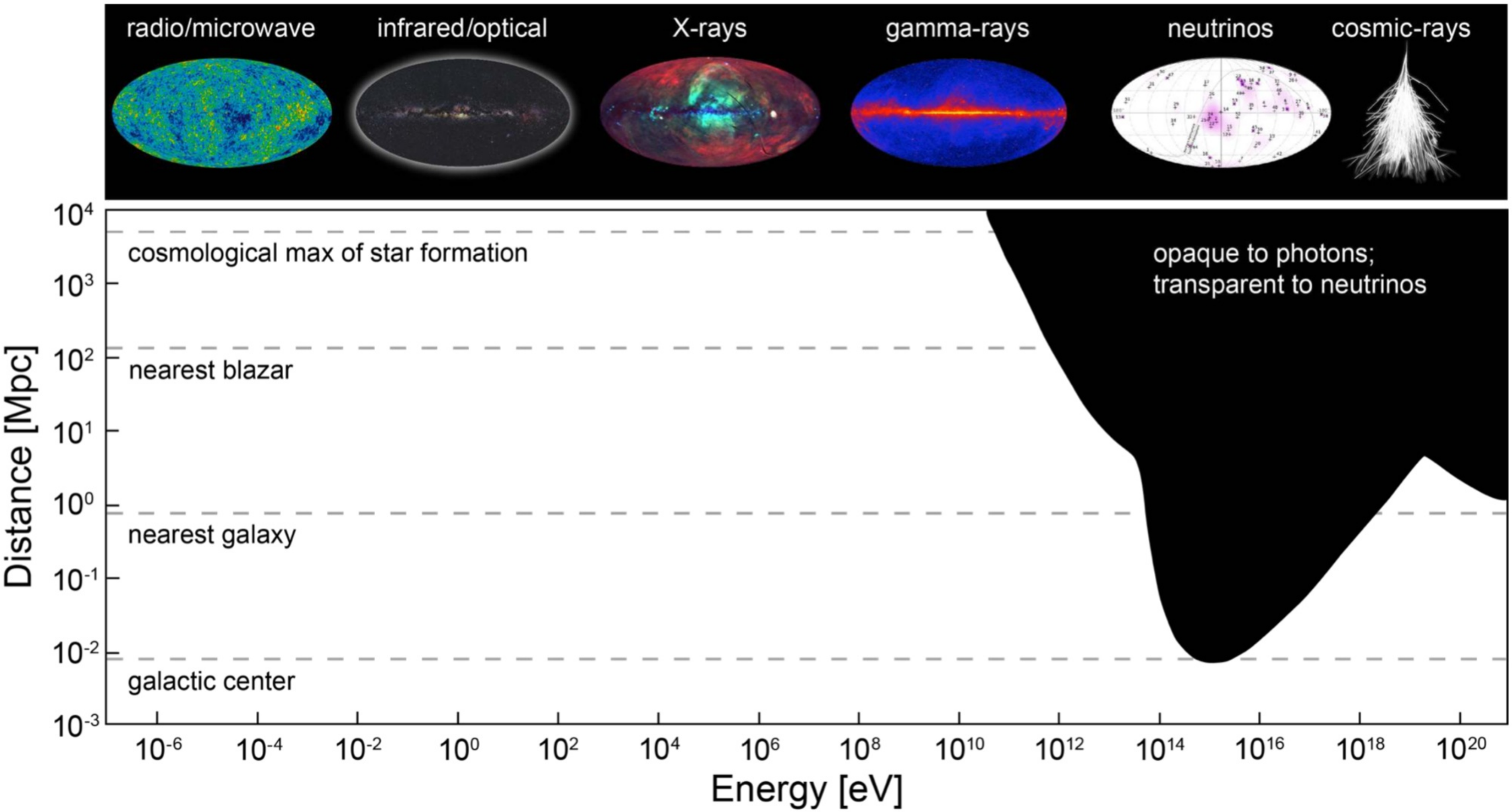
Lorentz factor of the jet

Neutrinos

Extragalactic Gamma rays absorbed for $E > 1\,\mathrm{TeV}$

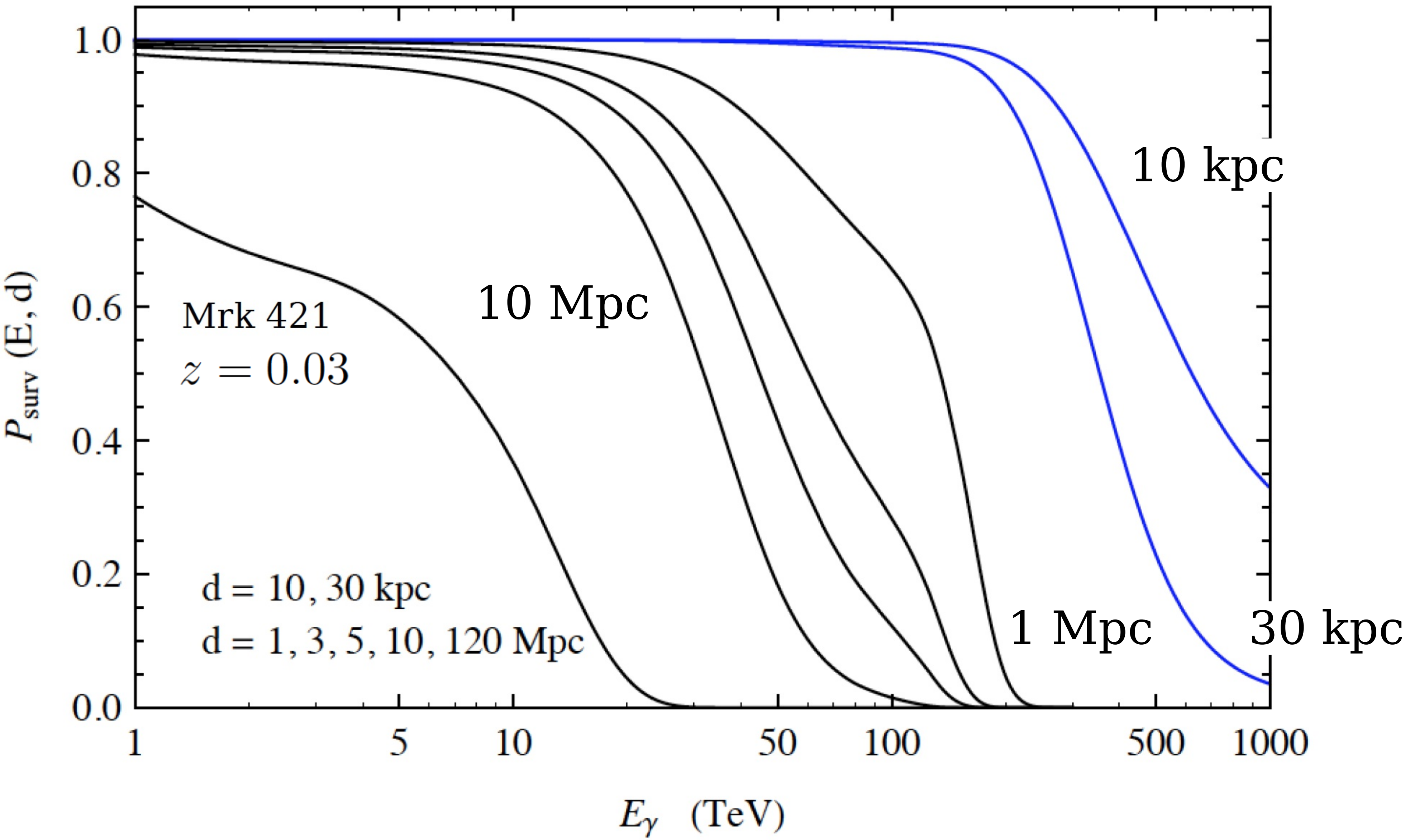
The High energy region
of highest interest because
of photon absorption

$$E \gtrsim 10\ \mathrm{TeV}$$

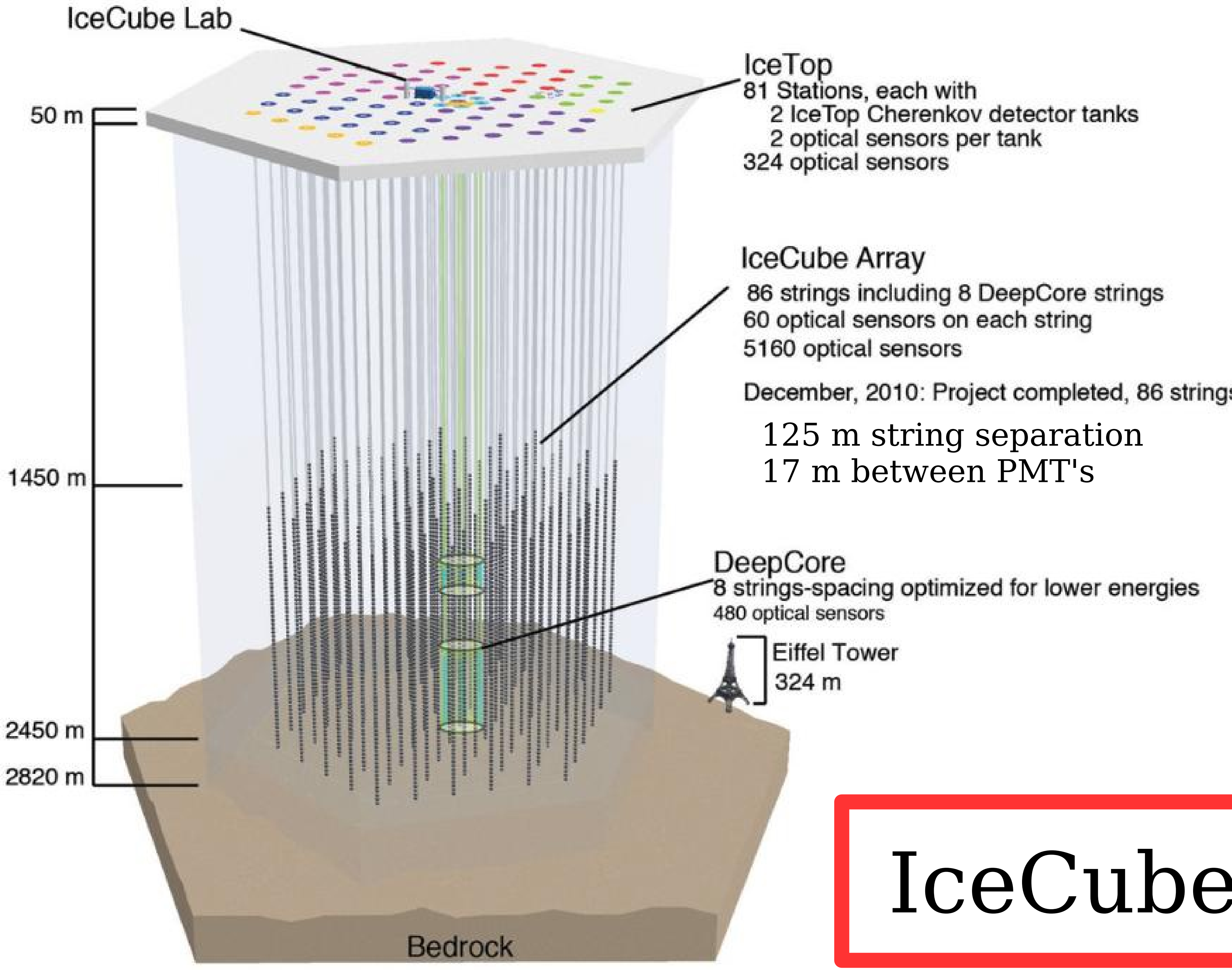


Gamma Ray absorption
(intergalactic space)

Astronomy E>100 TeV :
Galactic Astronomy



IceCube

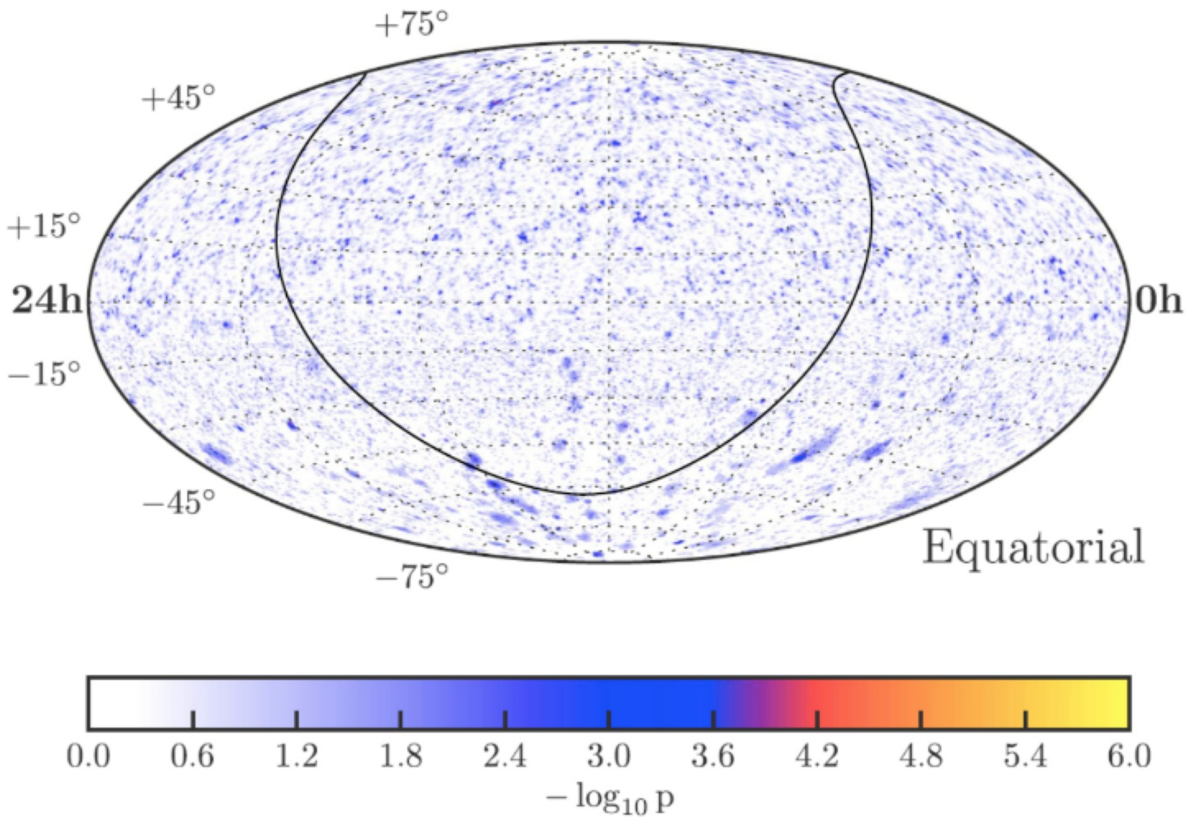


125 m string separation
17 m between PMT's

Search for Galactic Point Sources

At present only limits
but this is not unexpected given the sensitivity
of the existing instruments

IceCube - Point Sources – 7 years



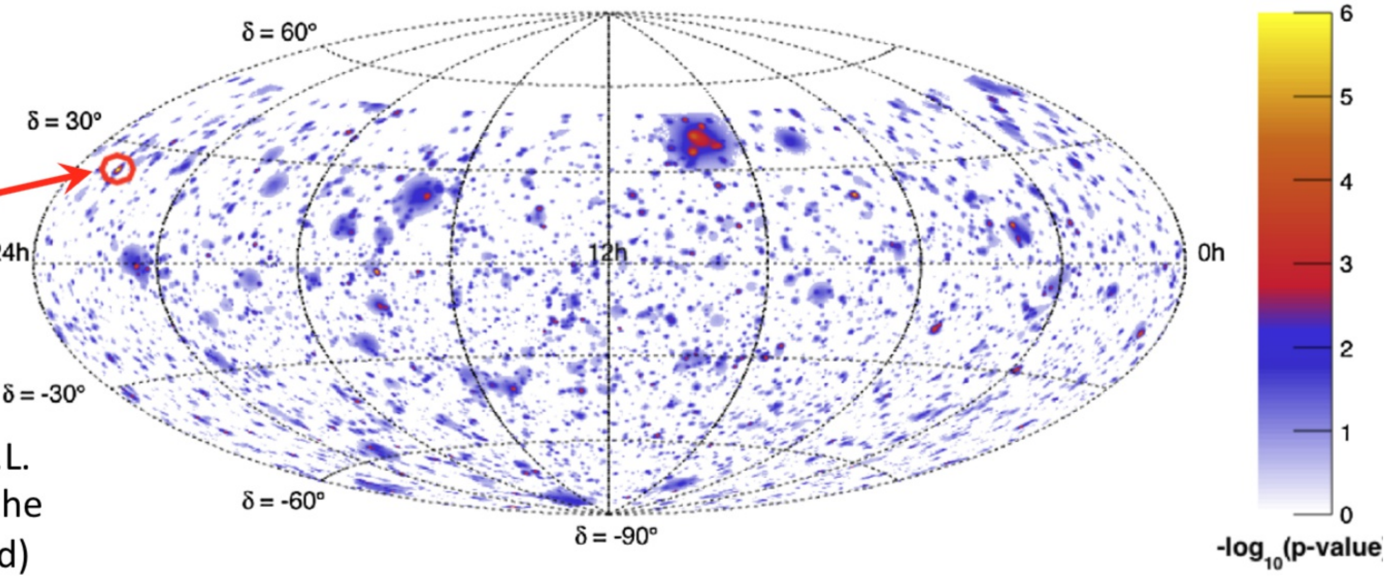
No significant PS reported

No correlation with list of 74 sources in both hemispheres. Galactic & Extragalactic

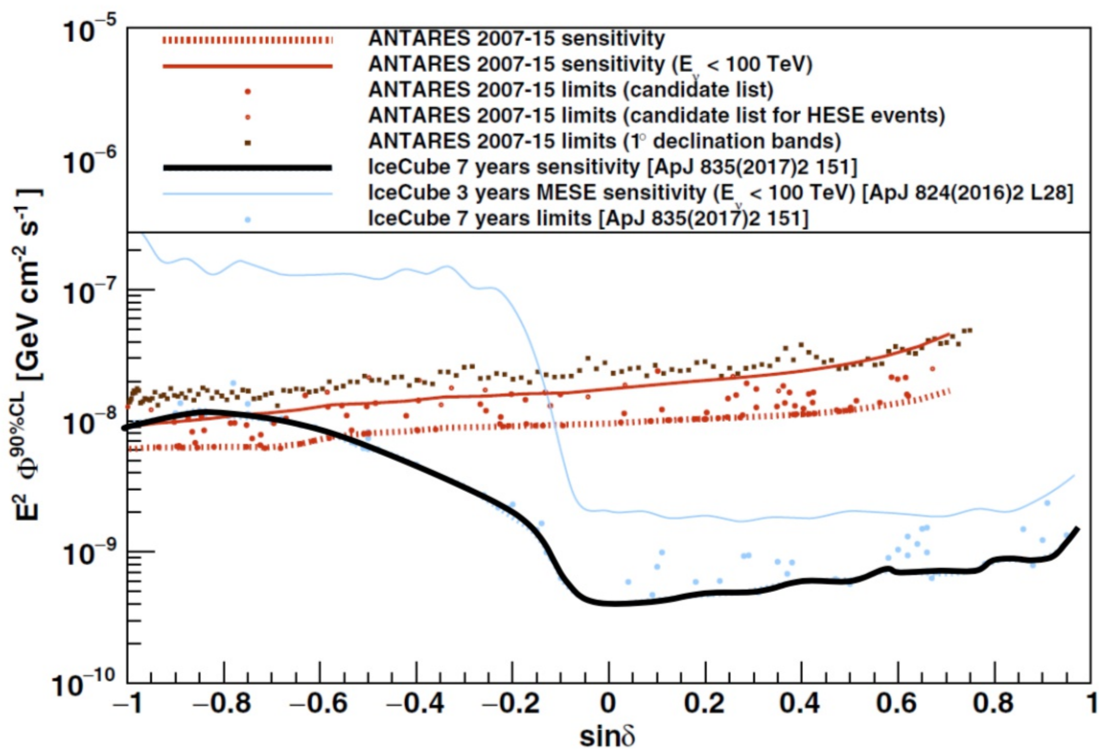
ANTARES – Point Sources

Most significant cluster c
the full-sky search (1.9σ
post-trial significance)
α = 343.8° δ = 23.5°

Sky map in equatorial coordinates of pre-trial p-values



Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)



Phys. Rev. D96 (2017), 082001

ANTARES is the most sensitive instrument for a large fraction of the southern sky below 100 TeV

IceCube is the most sensitive instrument in the northern sky and a fraction of the southern sky

Search for Galactic Point Sources

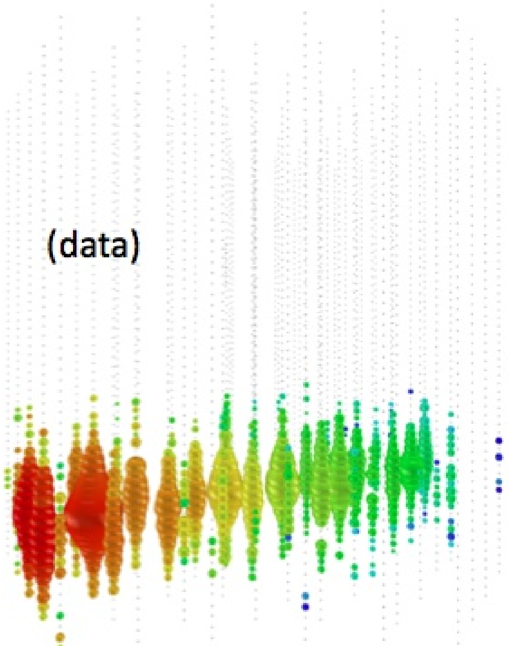
At present only limits
but this is not unexpected given the sensitivity
of the existing instruments

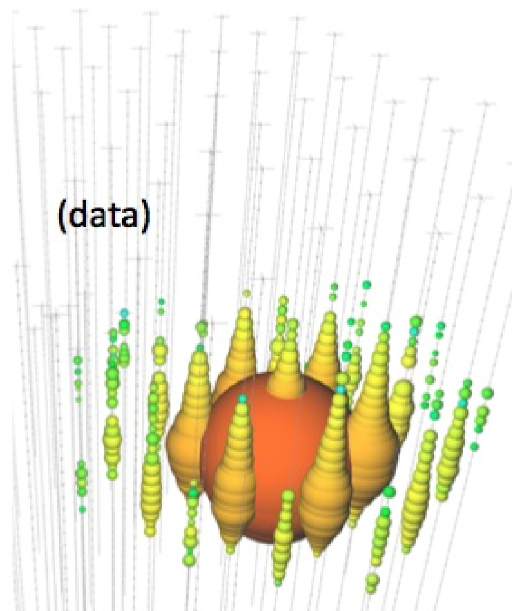
Km3Net (with view of the Southern sky, and the
Central region of the Milky Way)
Has the potential to detect (at the level of
few events/year) the brightest sources

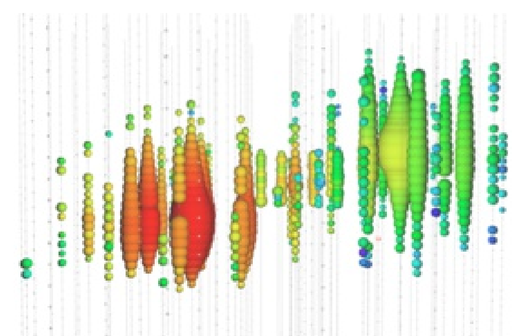
Separate the Hadronic and Leptonic components
of the Cosmic Rays in the source

Types of events and interactions

Charged-current ν_μ	**Neutral-current / ν_e**	**Charged-current ν_τ**
(data)	(data)	(simulation)







Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10-15° angular resolution (above 100 TeV)
Working on improving that.

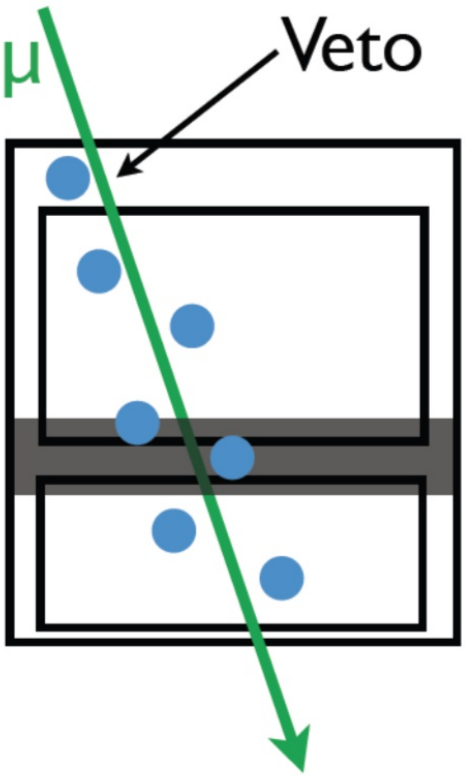
"Double-bang"

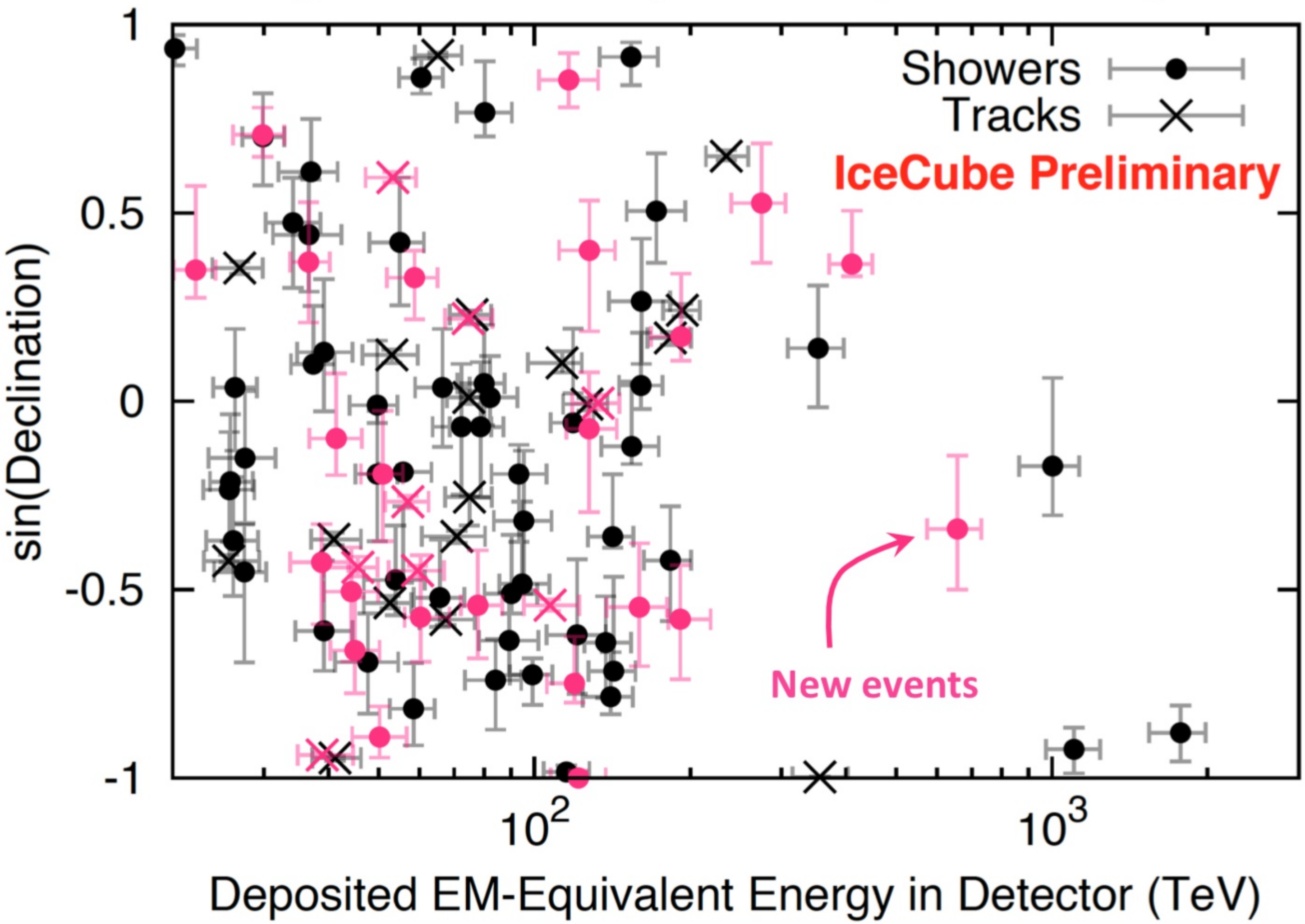
(none observed yet: τ decay length is 50 m/ PeV)

ID: above~ 100 TeV (two methods)

Early  Late

High-Energy Starting Events (HESE) – 7.5 yr





Prior result 6 years ICRC 2017 arXiv:1710.01191

Updates to calibration and ice optical properties

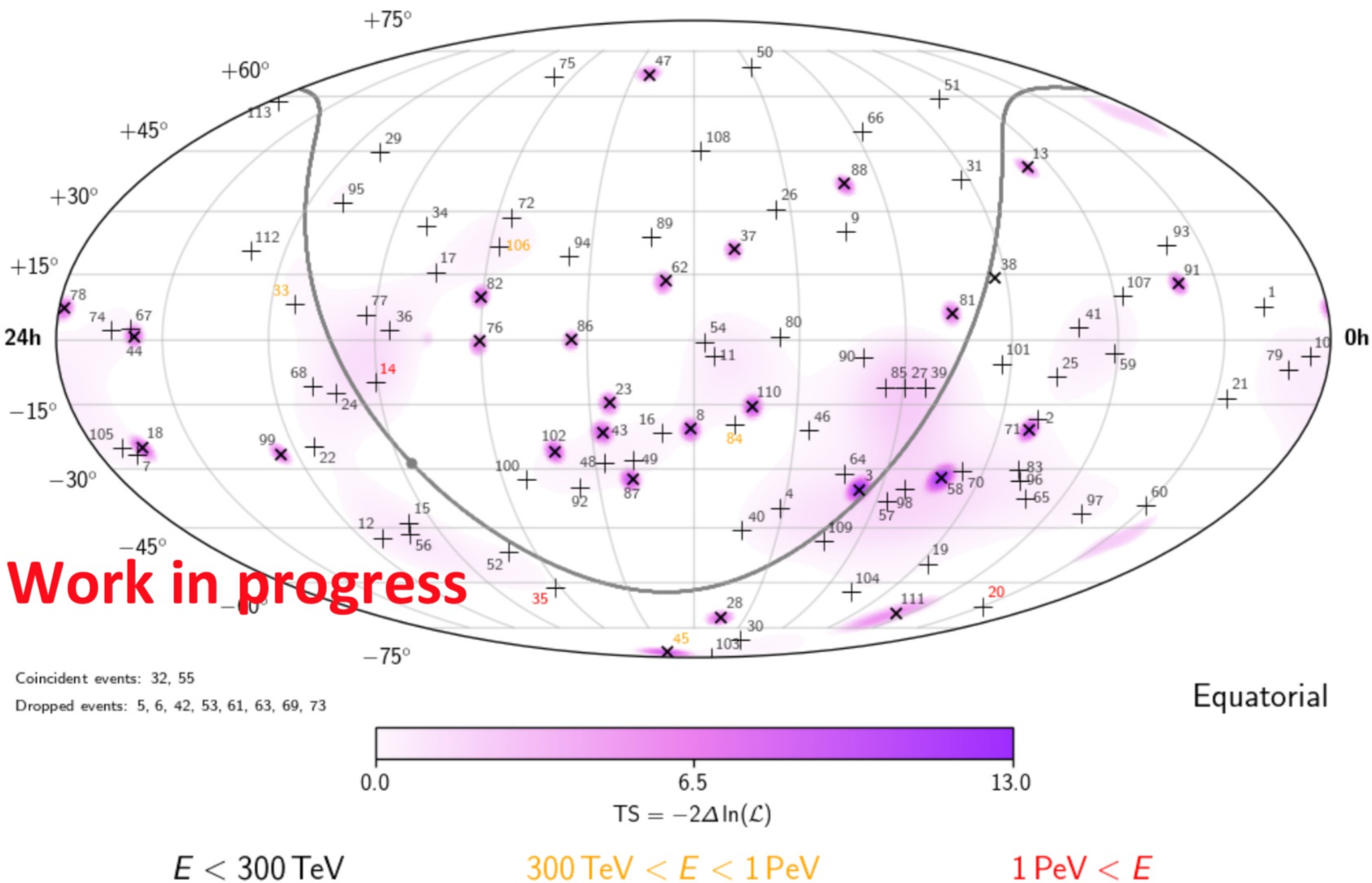
103 events, with 60 events >60 TeV

→ Changes to RA, Dec, energy

IceCube. Nature volume 551 (2017) 596

Poster #175. Wandkowsky et al. (IceCube)

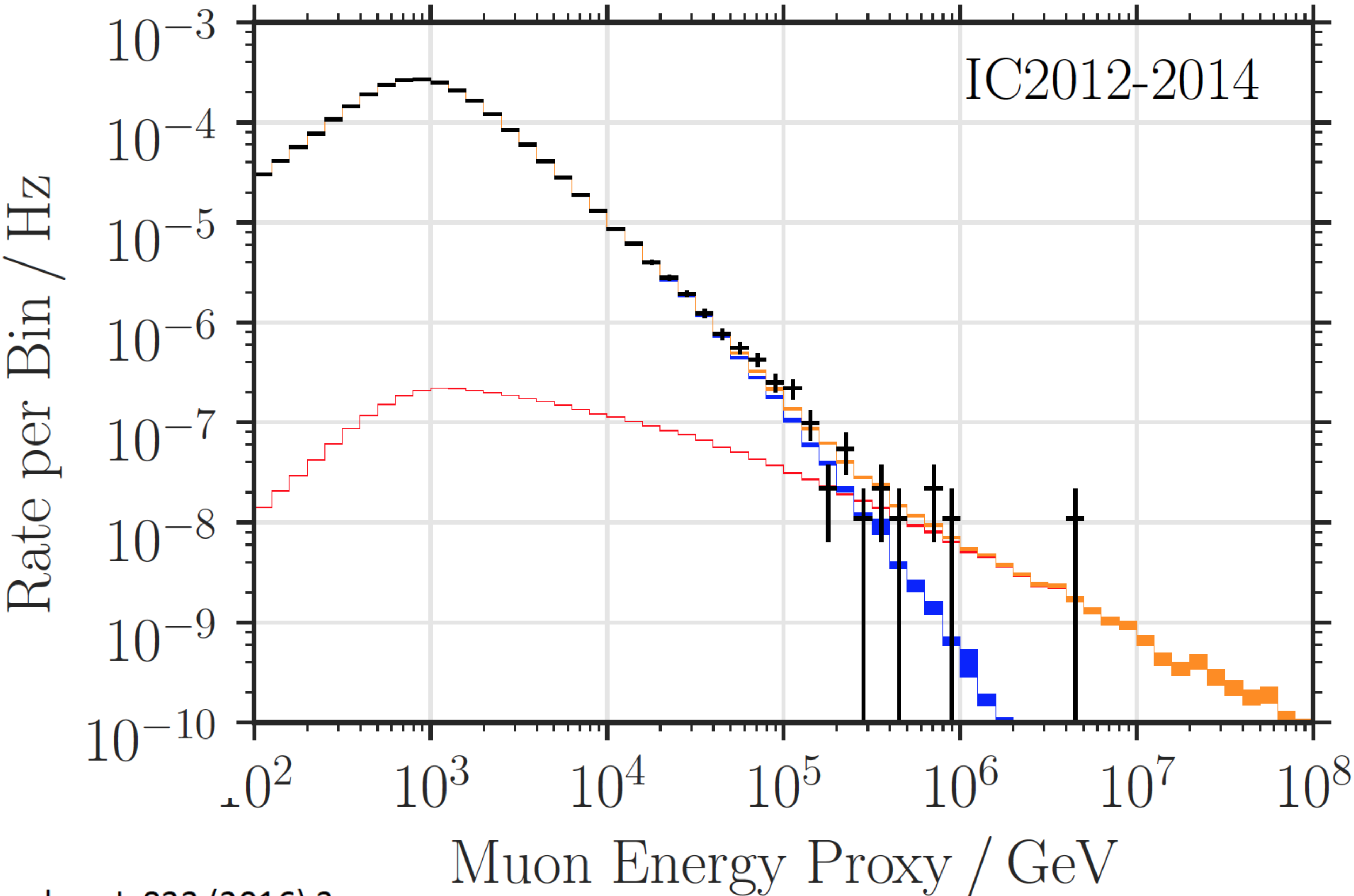
High-Energy Starting Events (HESE) – 7.5 yr



No evidence for point sources, nor a correlation with the galactic plane

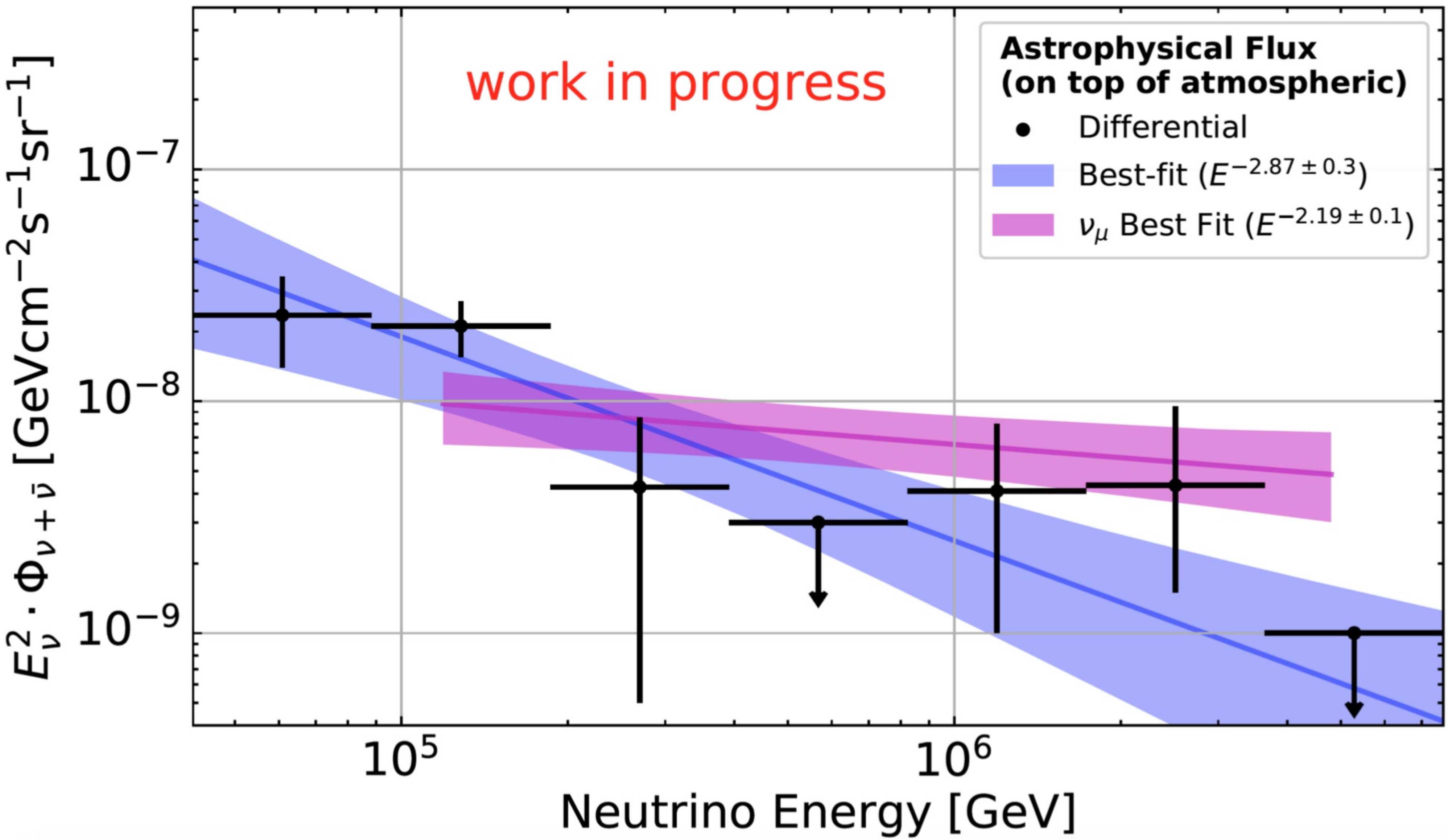
Poster #175. Wandkowsky et al. (IceCube)

Upgoing (neutrino induced) Muons

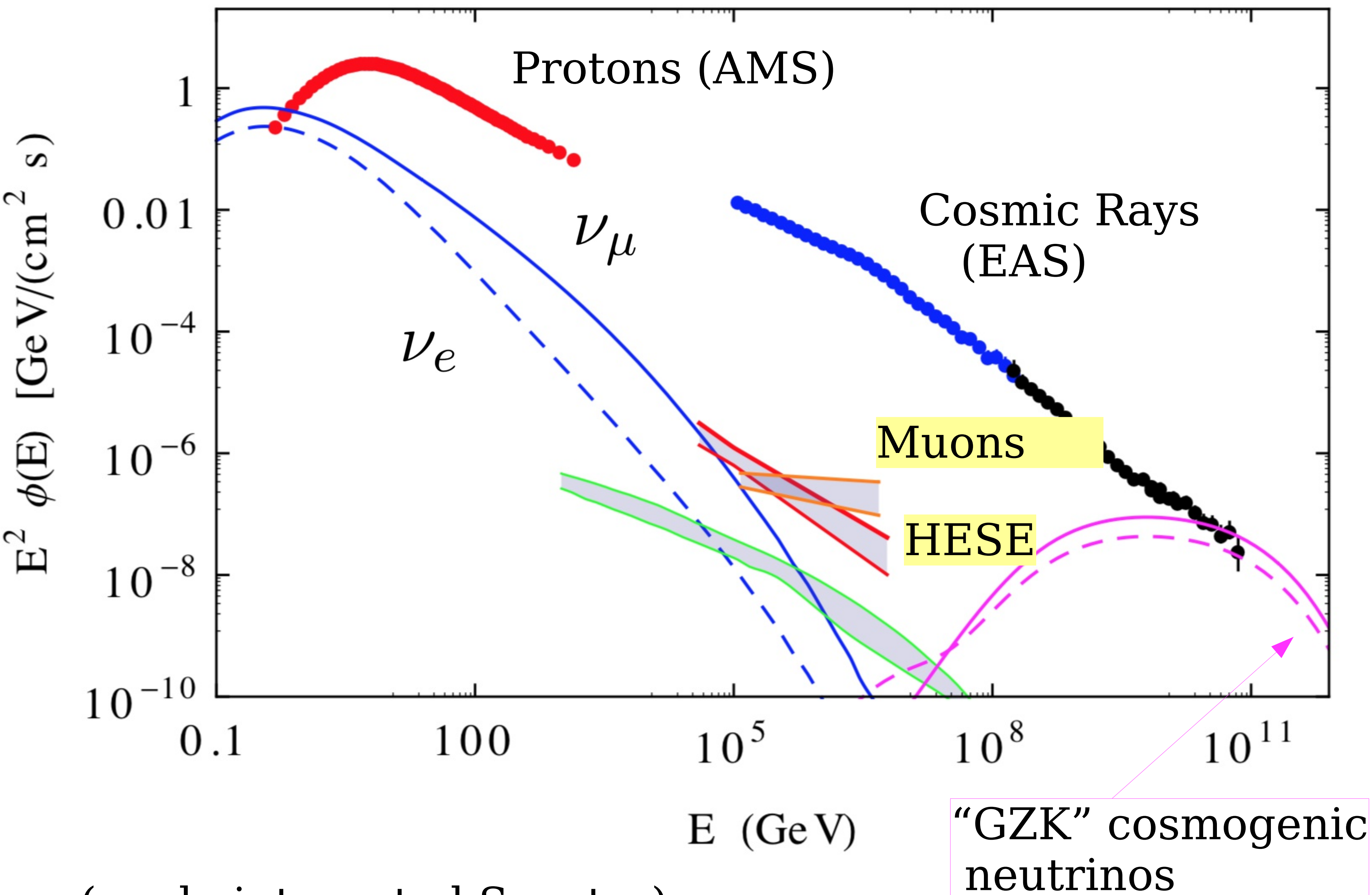


Astrophys. J. 833 (2016) 3

High-Energy Starting Events (HESE) – 7.5 yr

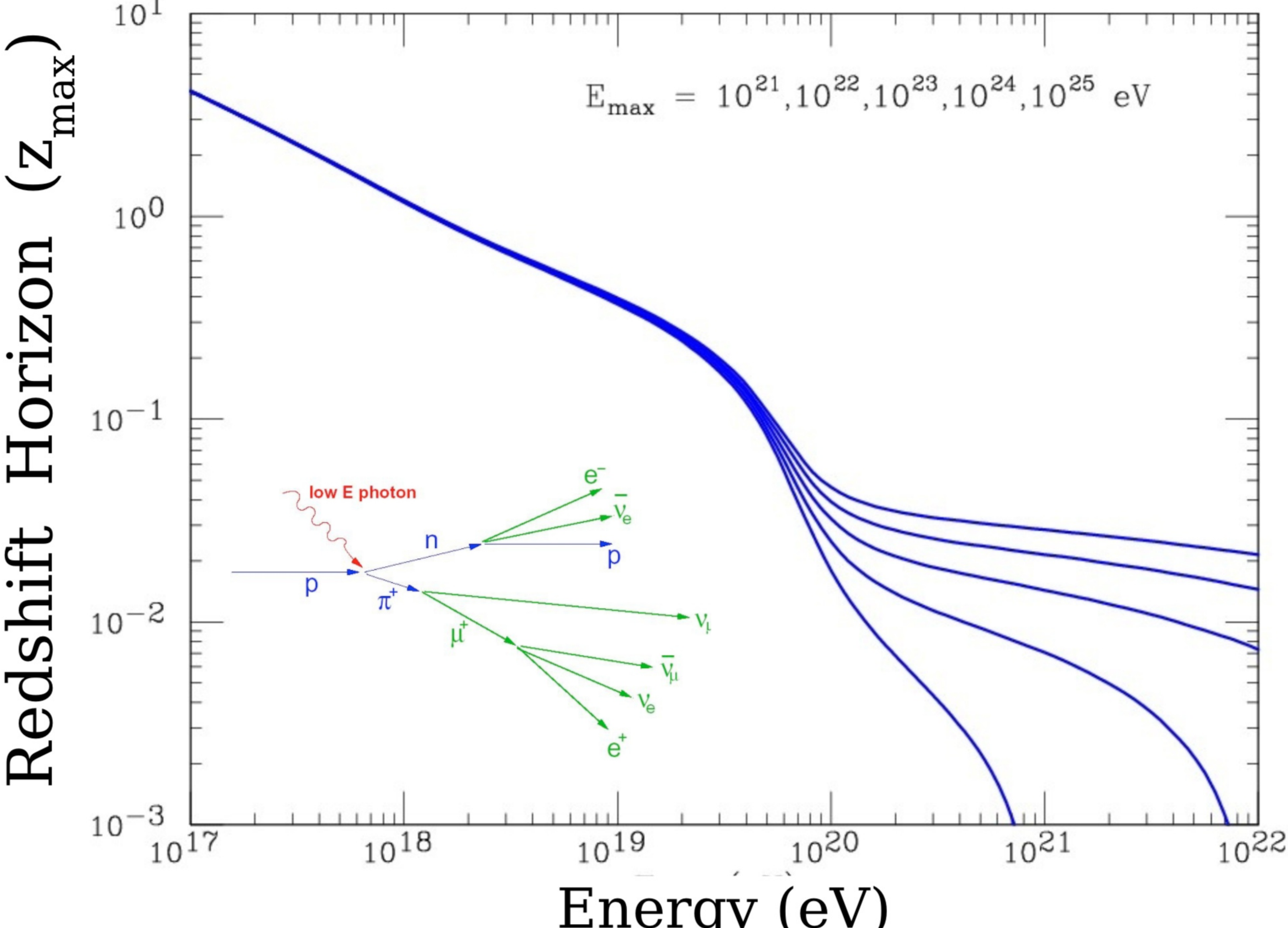


Ignacio Taboada: Neutrino 2018



(angle integrated Spectra)

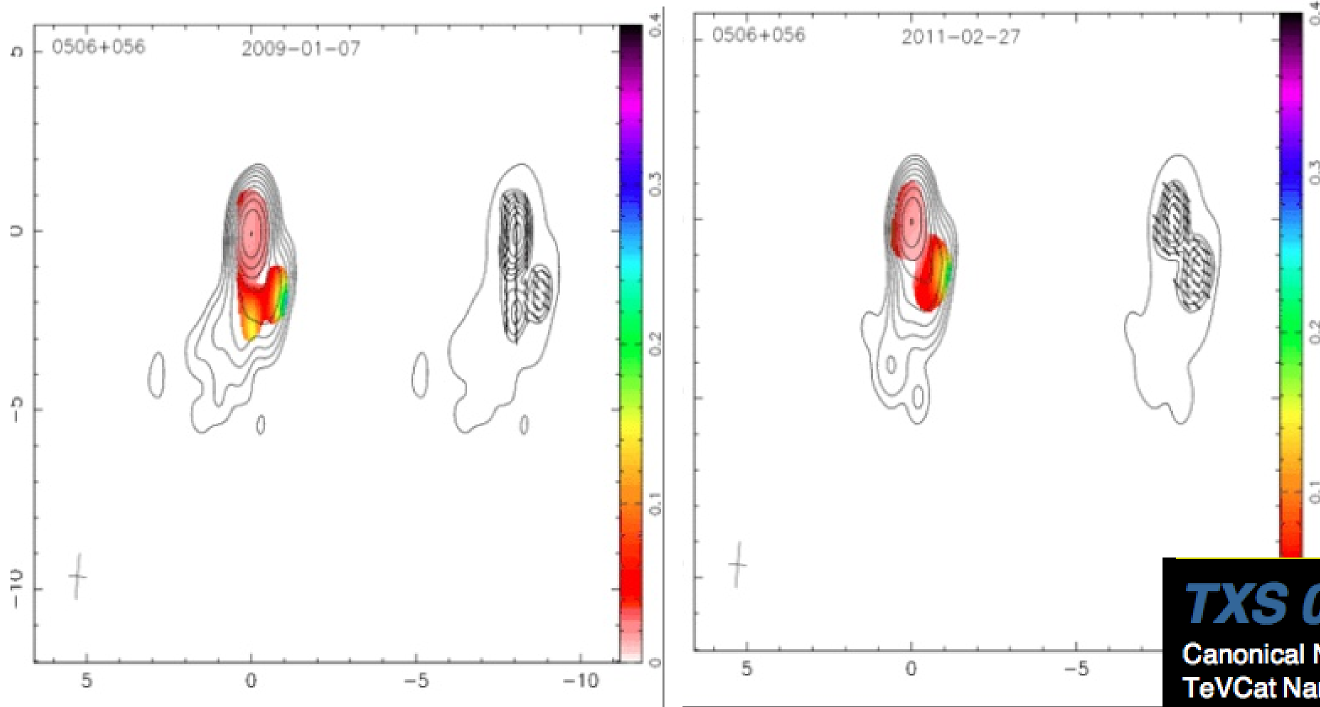
“Horizon” (in time) for protons



The *(to a high degree of confidence)* first High Energy Neutrino Source

Blazar

TXS 0506 + 056



TXS 0506+056

$$z = 0.3365 \pm 0.0010$$

$$d = 706 \text{ Mpc}$$

$$\dot{\Omega} = 332 \pm 82 \ \mu\text{as/year}$$

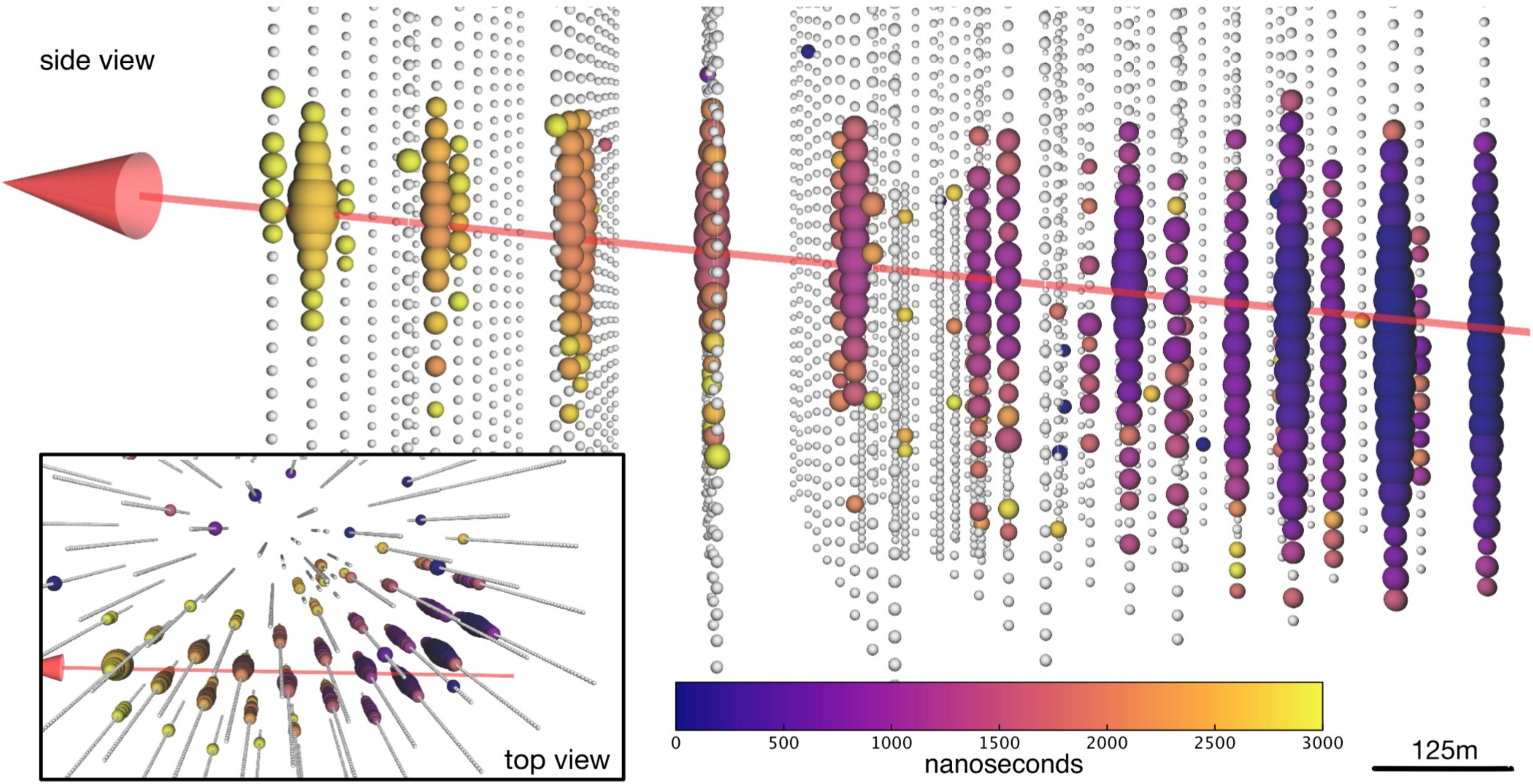
$$\beta_{\text{app}} = \frac{\dot{\Omega}\, d}{c} = 3.7 \pm 0.9$$

TXS 0506+056

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
	EHE 170922A
Other Names:	3FGL J0509.4+0541
	3FHL J0509.4+0542
Source Type:	Blazar
R.A.:	05 09 25.96370 (hh mm ss)
Dec.:	+05 41 35.3279 (dd mm ss)
Gal Long:	195.41 (deg)
Gal Lat:	-19.64 (deg)
Distance:	z=0.3365
Flux:	(Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced
Source Notes:	

The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916. Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for gamma-ray emission from positions consistent with the IceCube neutrino error circle which they thus associate with the blazar TXS 0506+056. Upper limits on the gamma-ray emission from the region were reported by H.E.S.S, HAWC and VERITAS.

22 /sept/ 2017



Icecube event E_{vis} = 23.7 +- 2.8 TeV

(Muon entering the detector:

IceCube GCN 21916 17/09/23

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical
origin. The event was identified by the  Extremely High Energy (EHE) track event selection. The IceCube detector was in a
normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the
candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica.
The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu
```

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; ***Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration***
on ***28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430

.... Great source of excitement ......

Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS .....]

The ~~A~~ neutrino event in IceCube

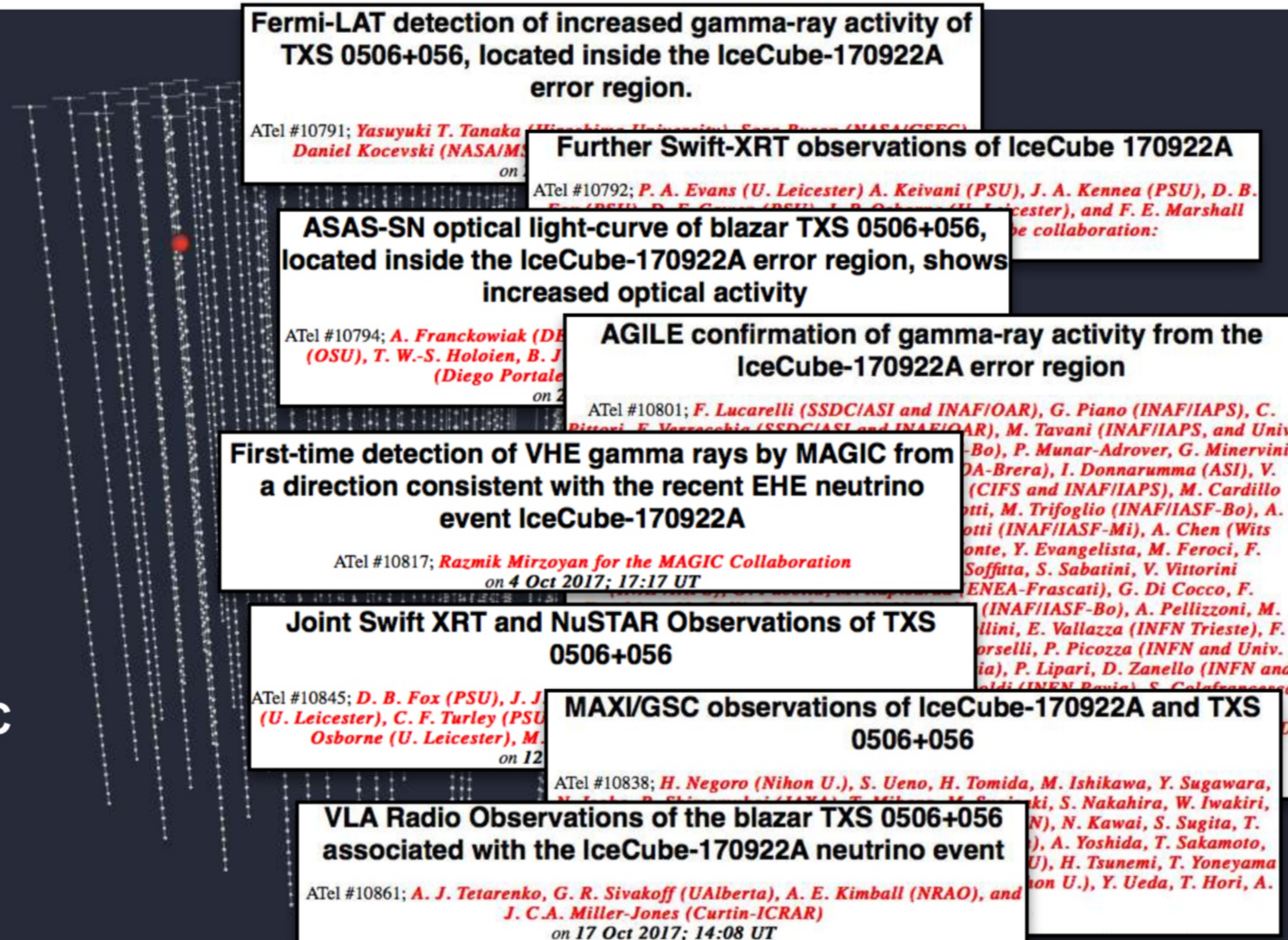
TXS 0506+56

High-energy, through going track

Event 130033/50579430-0
Time 2017-09-22 20:54:30 UTC
Duration 22468.0 ns

IC170922A
Alert sent
Sep 22, 2017
via *Realtime* stream

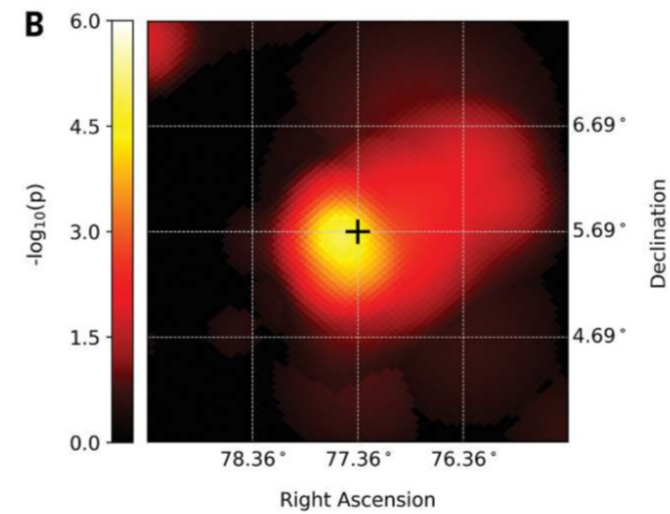
Coincident observations by Fermi-LAT and MAGIC



Science 361 (2018) no.6398, eaat1378

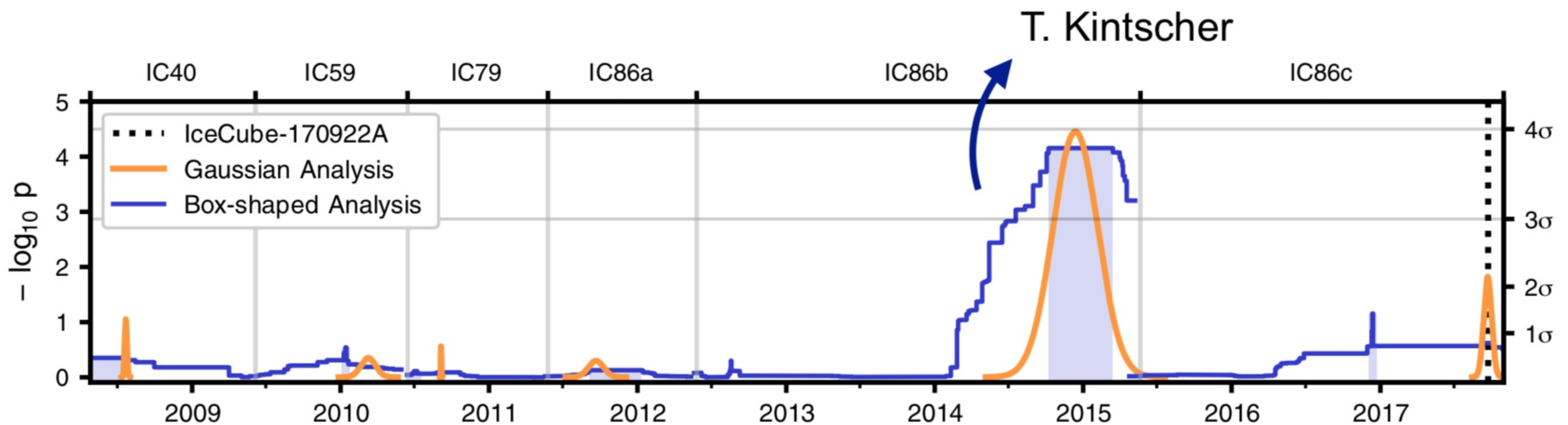
IC170922A / TXS 0506+56

First evidence for a neutrino point source



Archival search

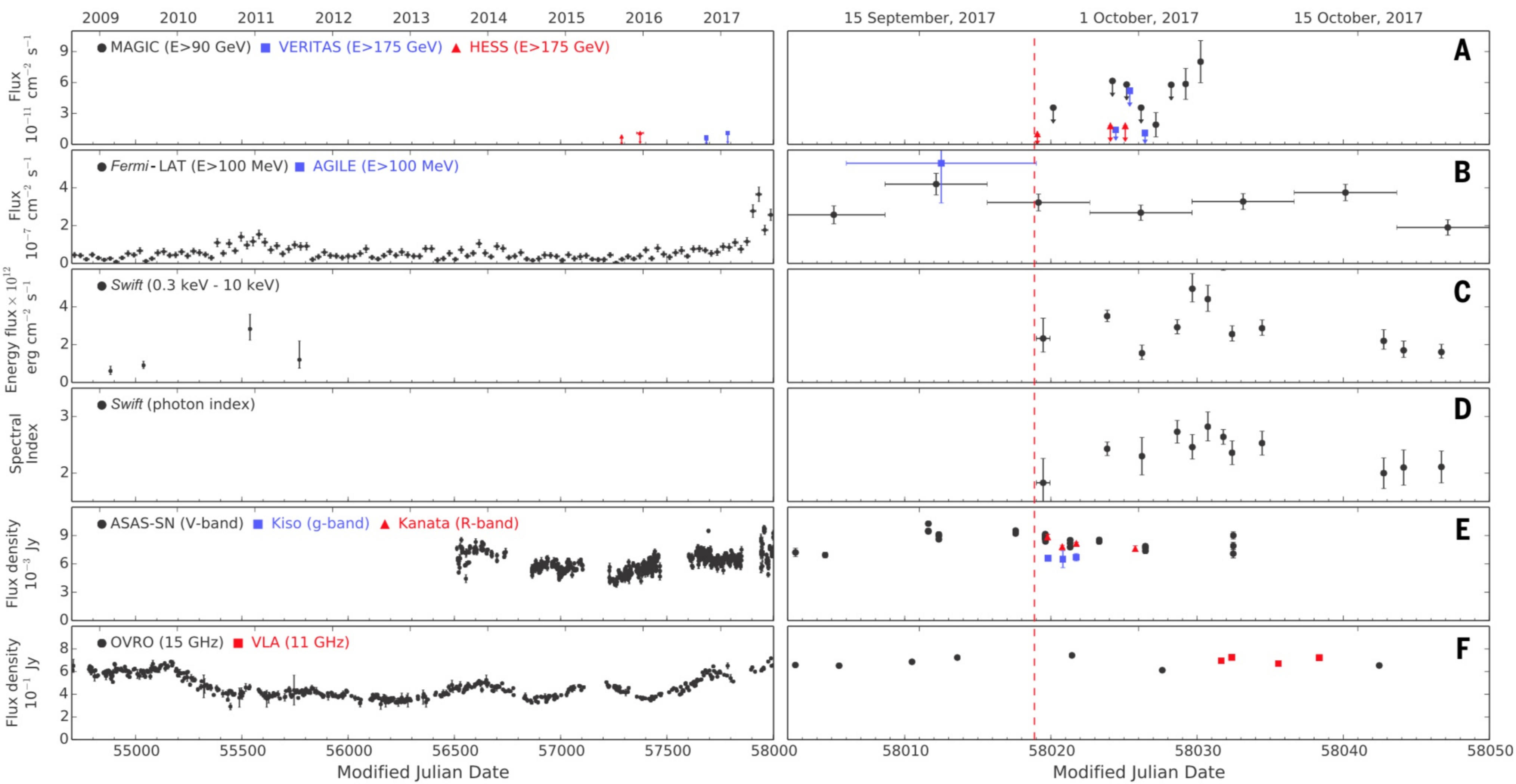
- Check historical IceCube data for pileup of neutrinos from direction of TXS 0506+56
- Look for clustering in time



Science 361 (2018) no.6398, 147-151

Inconsistent with background-only hypothesis at the 3.5σ level

Independent of the 2017 alert when looking in this specific direction!



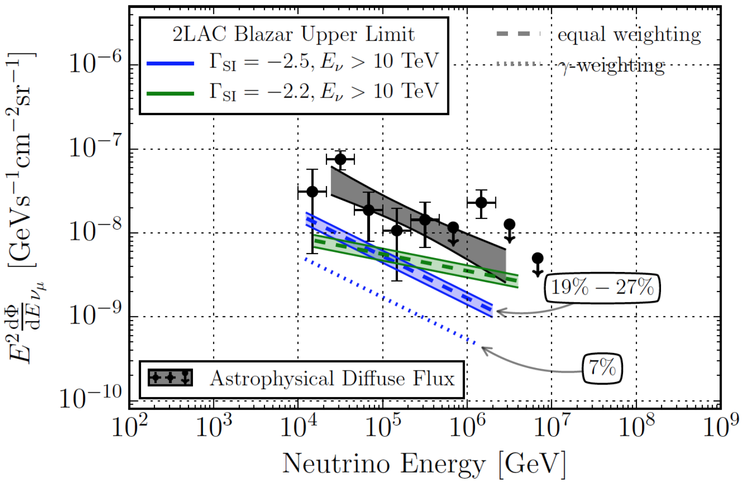
2009 2010 2011 2012 2013 2014 2015 2016 2017
15 September, 2017
1 October, 2017
15 October, 2017
MAGIC (E>90 GeV) VERITAS (E>175 GeV) HESS (E>175 GeV)
Flux 10^{-11} cm^{-2} s^{-1}
A
Fermi-LAT (E>100 MeV) AGILE (E>100 MeV)
Flux 10^{-7} cm^{-2} s^{-1}
B
Swift (0.3 keV - 10 keV)
Energy flux × 10^{12} erg cm^{-2} s^{-1}
C
Swift (photon index)
Spectral Index
D
ASAS-SN (V-band) Kiso (g-band) Kanata (R-band)
Flux density 10^{-3} Jy
E
OVRO (15 GHz) VLA (11 GHz)
Flux density 10^{-1} Jy
F
Modified Julian Date
Modified Julian Date

What is the emission mechanism ?

Why only one source identified ?

Are all astrophysical Neutrinos from Blazars ?

[An Ice Cube paper claims (at most 19-27 % are from Blazars)]



If not what other sources ?

Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

Very High Energy $\sim$ PeV

10^6 GeV

Very Long Path-length (extragalactic) $\sim$ Gpc

10^{27} cm

Very large (astrophysical) uncertainties about source spectra

New Physics effects

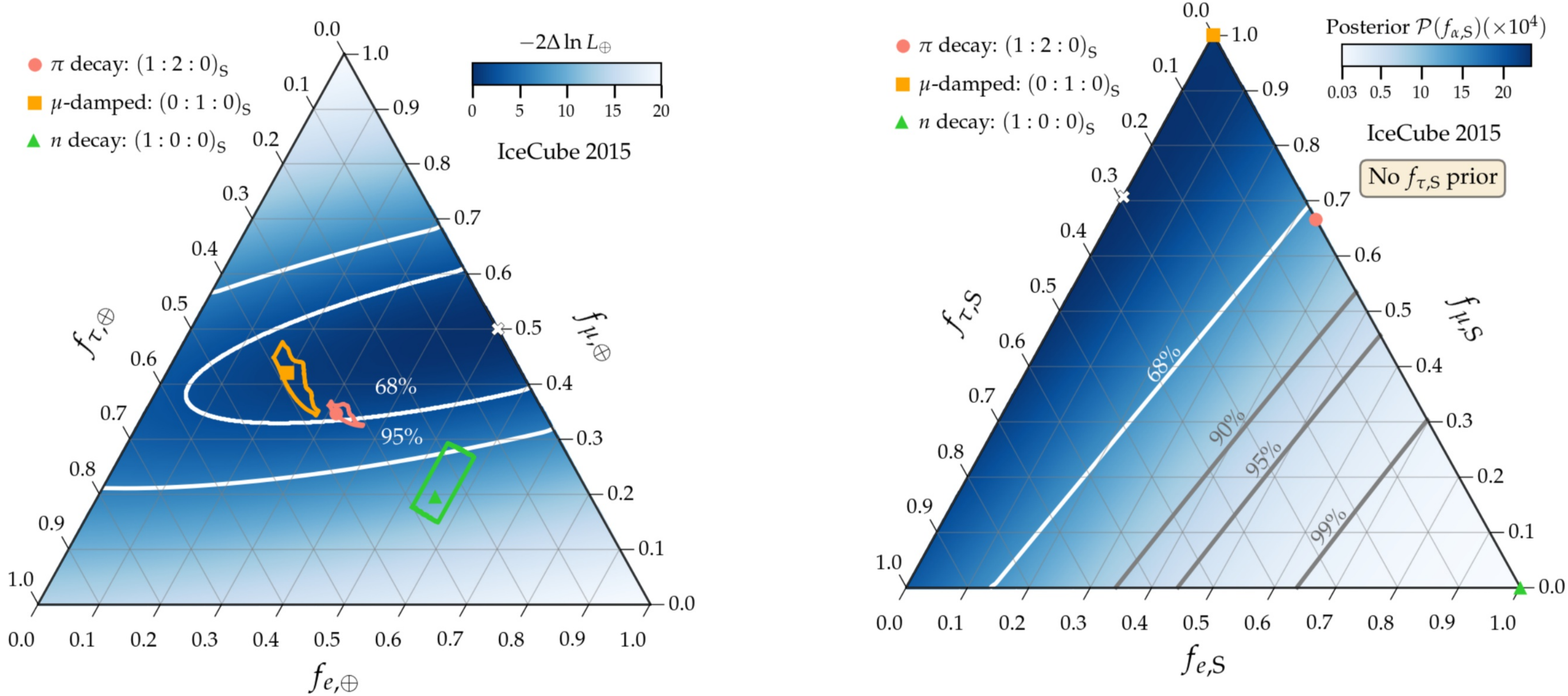
$$\propto k \; E^{n} \; L$$

$n = 0$

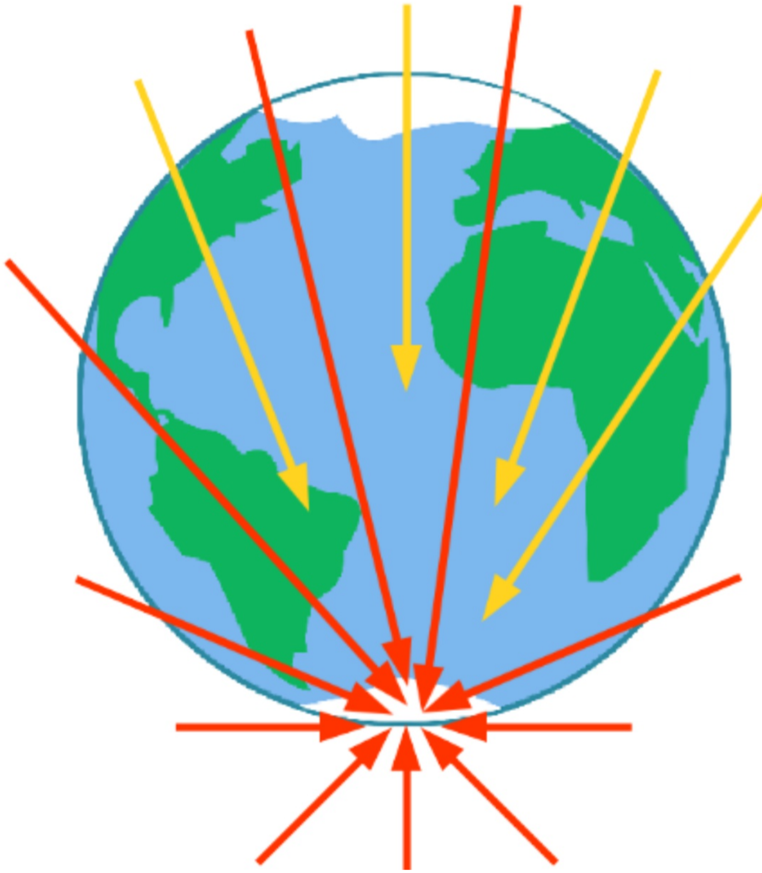
$n = 1$ Lorentz invariance violations

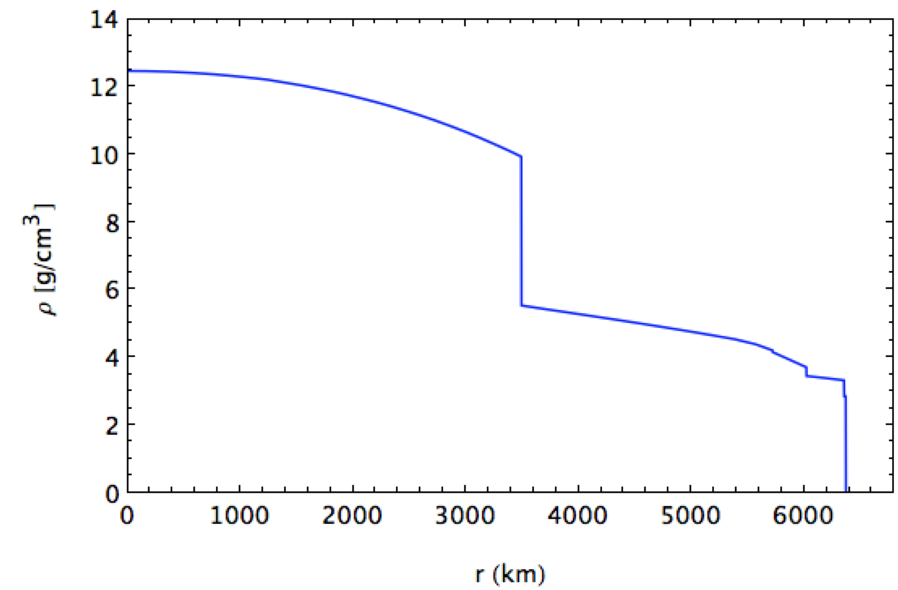
Study very favorable with Astrophysical Neutrinos

Flavor content inferred from track/shower ratio

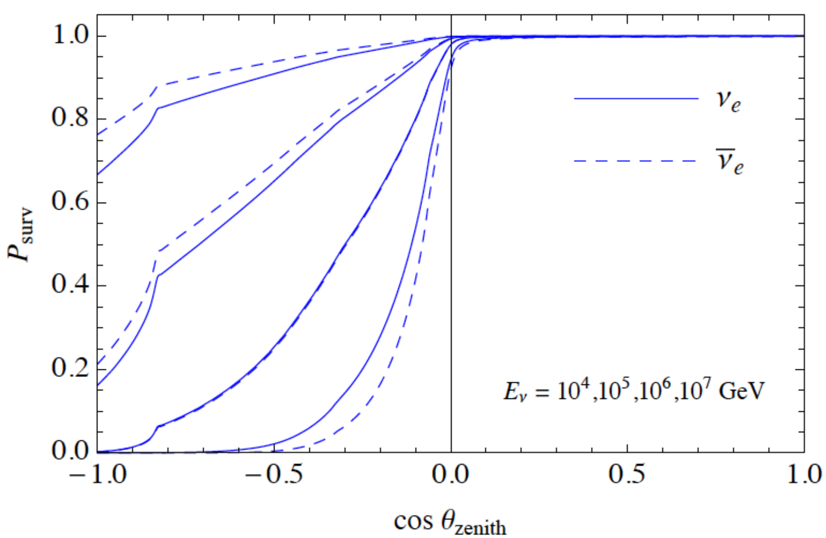


M. Bustamante and M. Ahlers,
"Inferring the flavor of high-energy astrophysical neutrinos at their sources,"
arXiv:1901.10087 [astro-ph.HE].





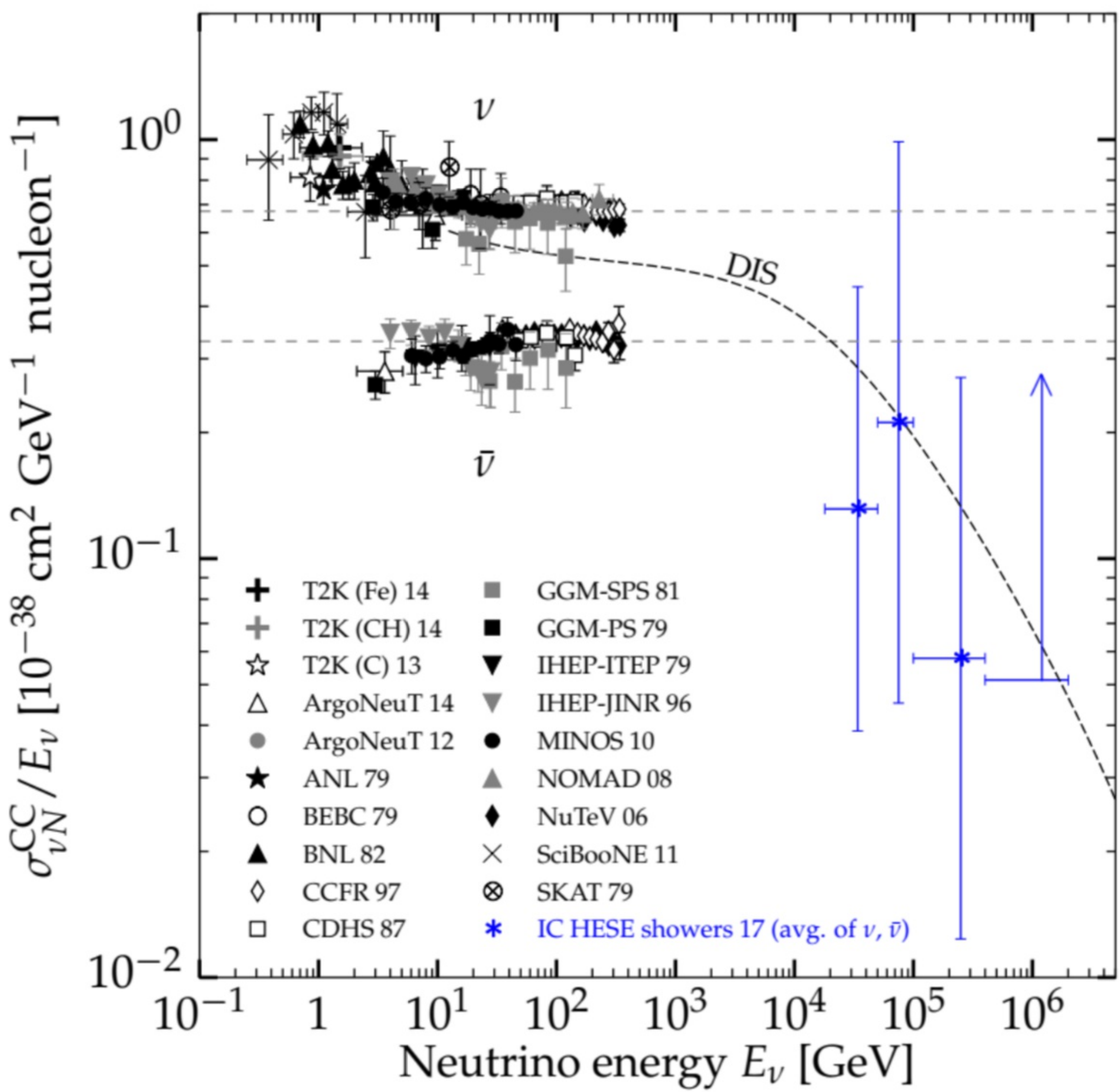
$$P_{\rm surv} = e^{-\tau(E,\Omega)}$$



$$\tau = \frac{X}{m_p}\,\sigma_\nu$$

$$\frac{X_\oplus}{m_p} \simeq 6.5\ \mathrm{nb}^{-1}$$

$$\tau = 1 \Longleftrightarrow E \simeq 40\ \mathrm{TeV}$$



$\sigma_{\nu N}^{CC}/E_\nu$ [10^{-38} cm^2 GeV^{-1} nucleon^{-1}]
Neutrino energy E_ν [GeV]
ν
$\bar{\nu}$
DIS
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
IC HESE showers 17 (avg. of ν, $\bar{\nu}$)

Concluding remarks

Astroparticle Physics is a field
of *extraordinary* richness and potential

- Cosmology remains the *"ultimate laboratory" to test the fundamental laws of nature.*
  Planck has left his "legacy" but more is needed.

- When will we understand the nature of Dark Matter ?
  (and Dark Energy) *["No stone should be left unturned"]*

- Gravitational Waves are seeing the "first sunrise"
  of what promise to be a golden epoch

- The multi messenger study of the "High Energy Universe"
  is of great interest and significance