High Energy Sources
and
Multi-Messenger High Energy Astrophysics

Paolo Lipari (INFN, Roma)

LNF, September 17, 2020

"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.

Victor Hess
[1912]

Walter Kolhörster
[1913]

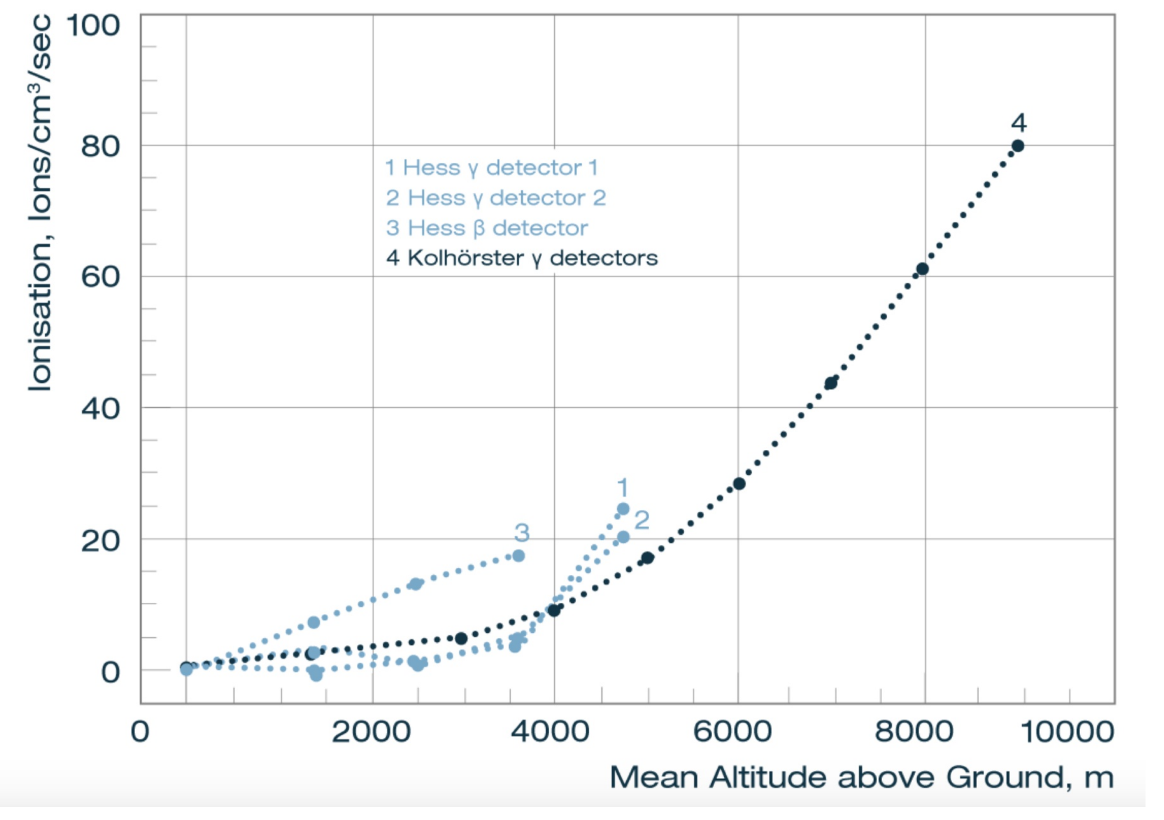
The first step

Discovery of COSMIC RAYS
and the *“High Energy Universe”*

Study of the rate of ionization in air
with discharge electroscopes:
existence of Extraterrestrial source of Radiation

Victor Hess
[1912]

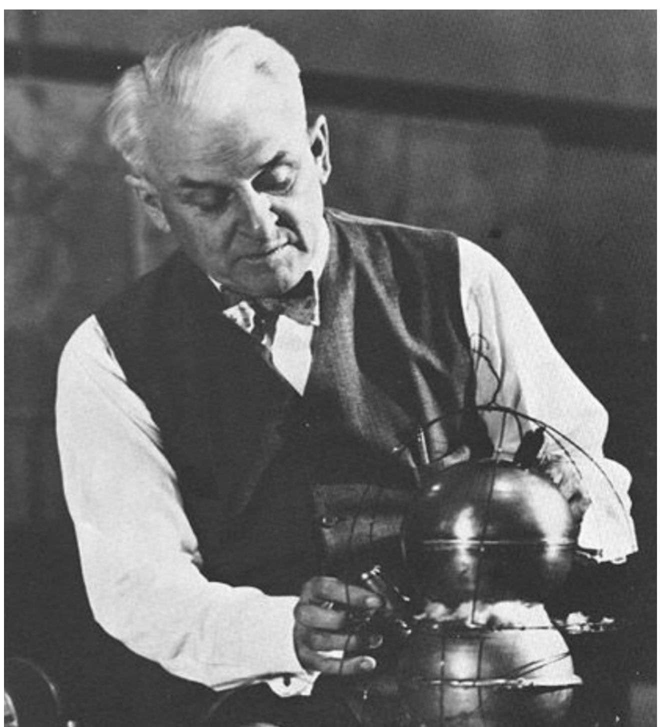
Walter Kolhörster
[1913]

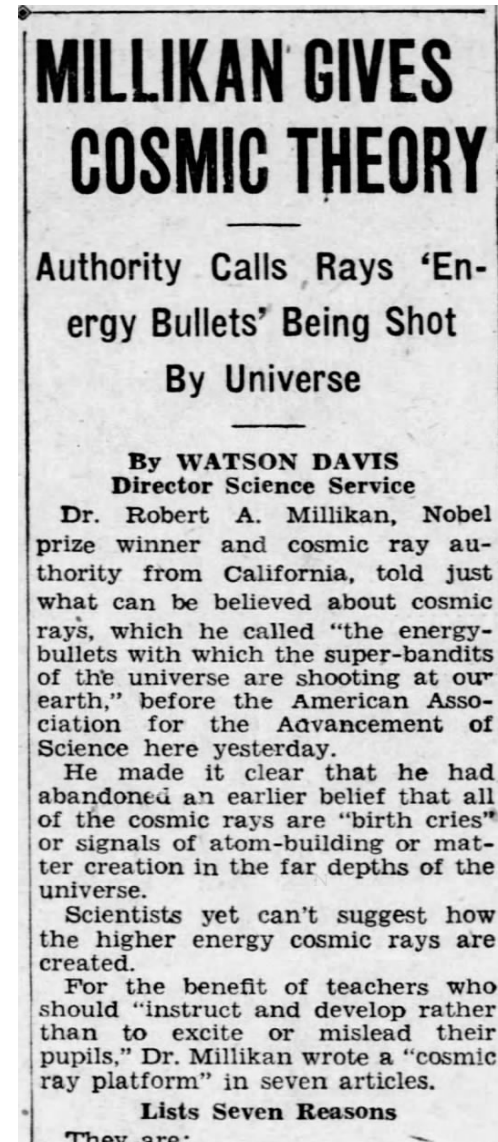


Understanding the nature of Cosmic Rays:

[Relativistic charged particles (mostly protons and ionized nuclei)]

For nearly 20 years the commonly accepted theory was that cosmic rays where gamma rays: Robert Millikan *“The birth cries of infant atoms”*





MILLIKAN GIVES COSMIC THEORY

Authority Calls Rays ‘Energy Bullets’ Being Shot By Universe

By WATSON DAVIS
Director Science Service

Dr. Robert A. Millikan, Nobel prize winner and cosmic ray authority from California, told just what can be believed about cosmic rays, which he called “the energy-bullets with which the super-bandits of the universe are shooting at our earth,” before the American Association for the Advancement of Science here yesterday.

He made it clear that he had abandoned an earlier belief that all of the cosmic rays are “birth cries” or signals of atom-building or matter creation in the far depths of the universe.

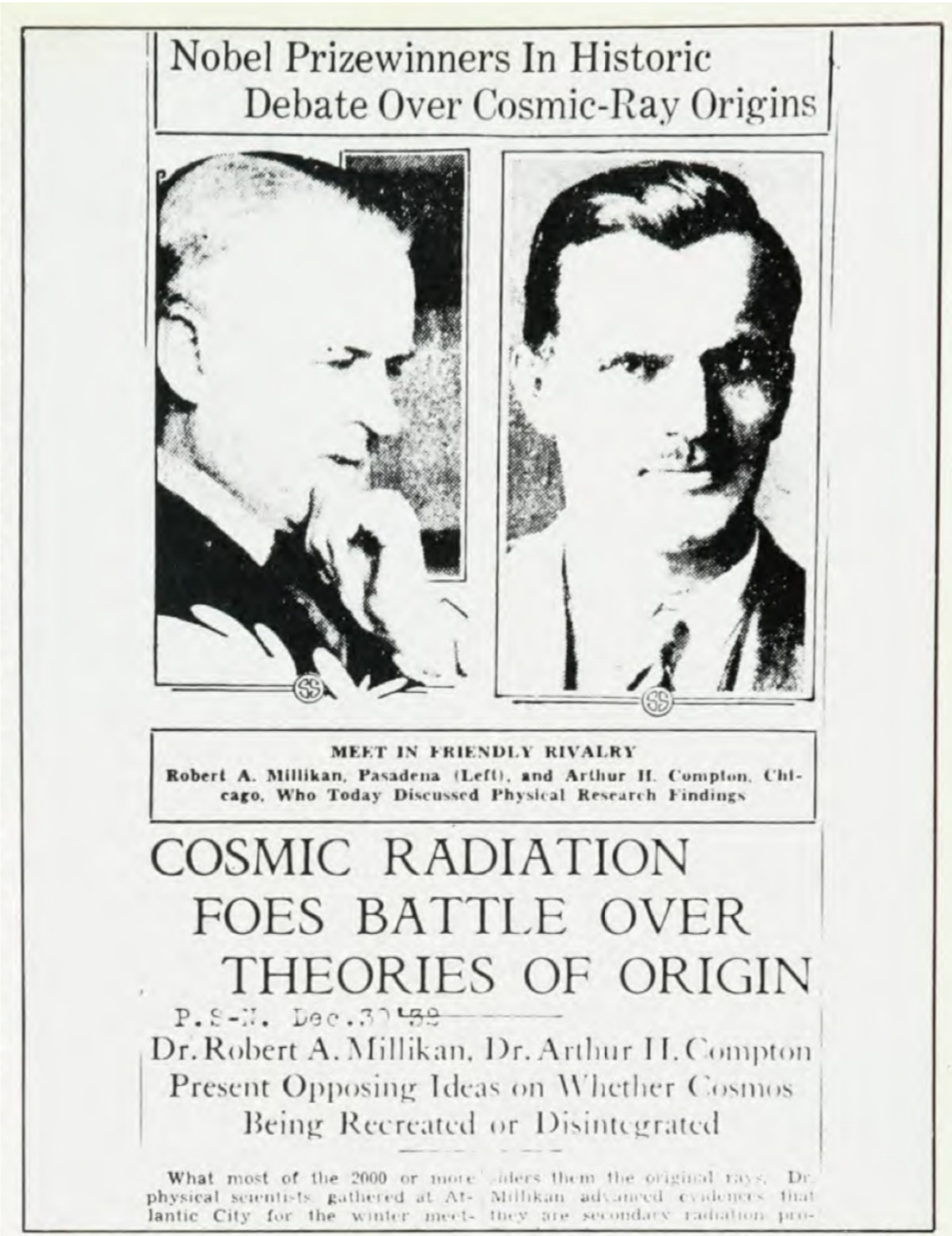
Scientists yet can’t suggest how the higher energy cosmic rays are created.

For the benefit of teachers who should “instruct and develop rather than to excite or mislead their pupils,” Dr. Millikan wrote a “cosmic ray platform” in seven articles.

Lists Seven Reasons

They are:

Compton- Millikan "Controversy"



Nobel Prizewinners In Historic Debate Over Cosmic-Ray Origins

MEET IN FRIENDLY RIVALRY

Robert A. Millikan, Pasadena (Left), and Arthur H. Compton, Chicago, Who Today Discussed Physical Research Findings

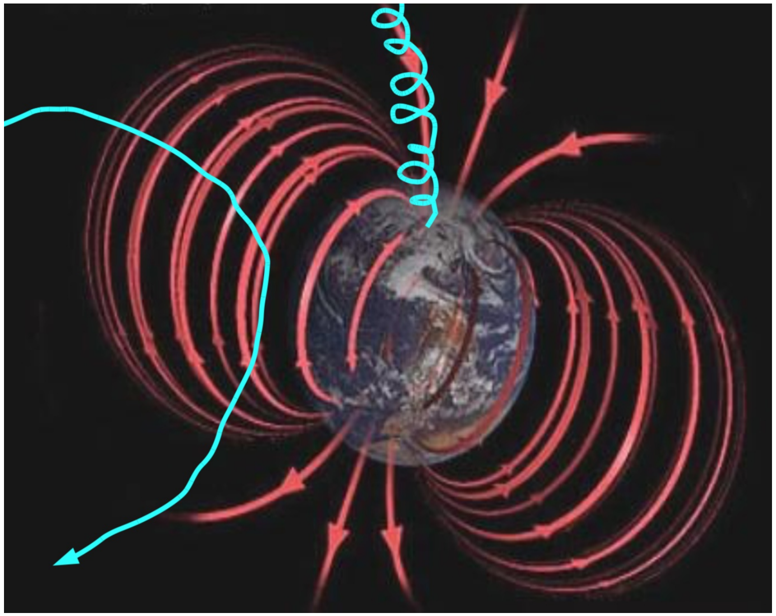
COSMIC RADIATION FOES BATTLE OVER THEORIES OF ORIGIN

P.S-N. Dec.30'32

Dr. Robert A. Millikan, Dr. Arthur H. Compton Present Opposing Ideas on Whether Cosmos Being Recreated or Disintegrated

What most of the 2000 or more physical scientists gathered at Atlantic City for the winter meet- ... siders them the original rays. Dr. Millikan advanced evidences that they are secondary radiation pro-

The *Latitude Effect*



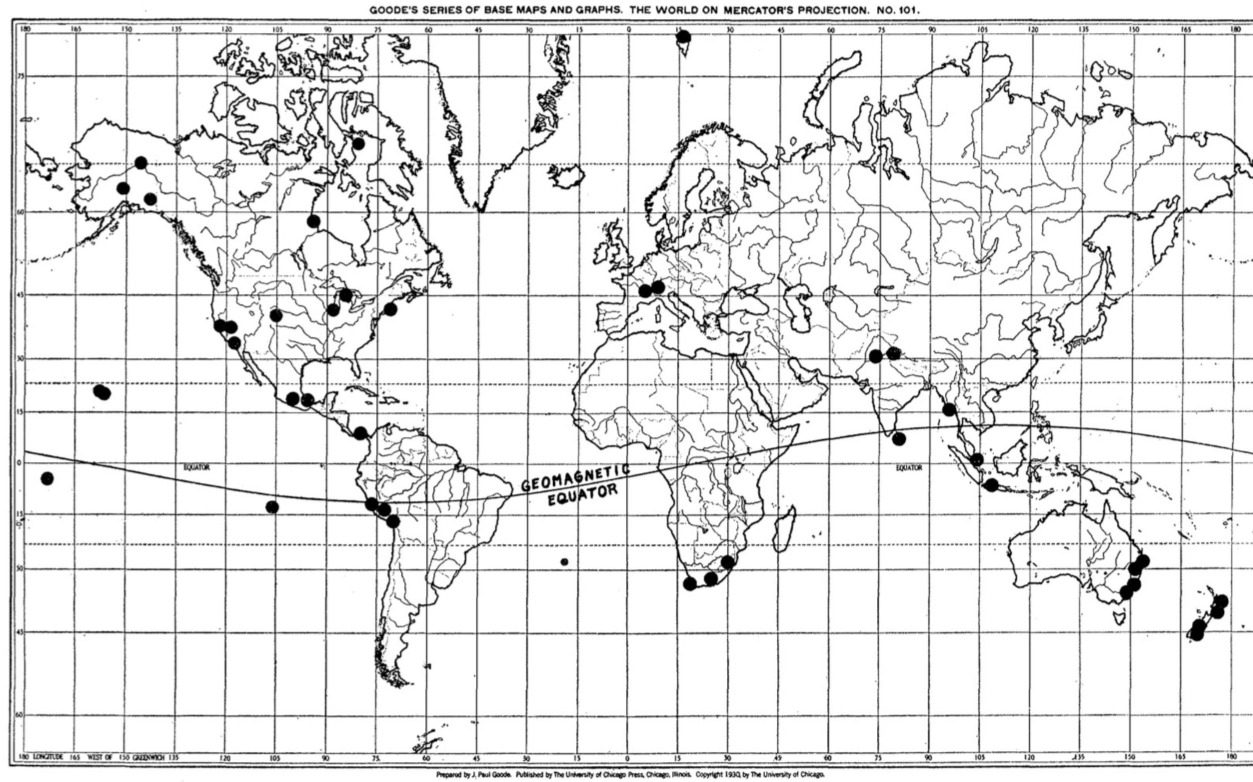


FIG. 1. Map showing location of our major stations for observing cosmic rays.

Arthur Compton
Phys. Rev. 15th march 1933

Cosmic Rays are electrically charged particles.

Alvarez, Compton (april 1933)
East-West Effect
(most) Cosmic rays have positive charge

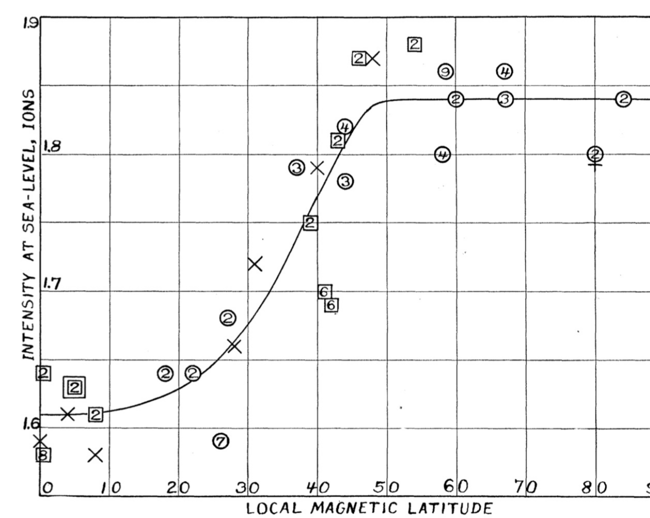
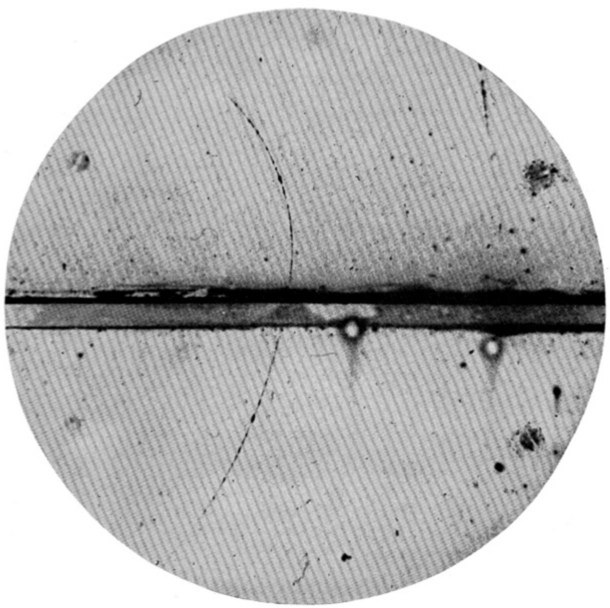


FIG. 9. Intensity *vs.* local magnetic latitude.

Understanding the propagation of Cosmic Rays in the atmosphere [Birth of *Particle Physics*]

Same issue of Physical Review [15th march 1933]
of Compton "Geographic Study of Cosmic Rays"

article of Carl Anderson
"The positive electron"



"Wilson chamber" in
a magnetic field.

Chapter 1:

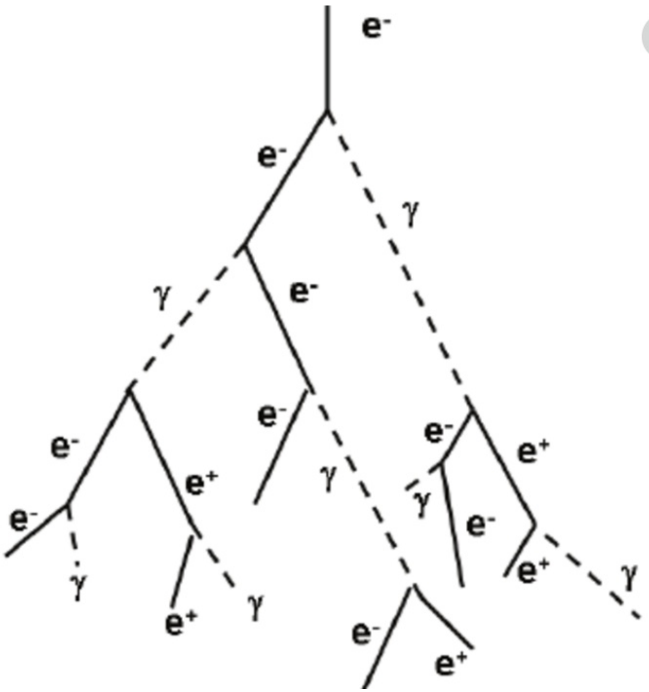
Theory of Electromagnetic Shower

$$\gamma\, Z \to e^{+}\, e^{-}\, Z$$

Bethe – Heitler
(pair production)

$$e^{\pm}\, Z \to e^{\pm}\, \gamma\, Z$$

Bremsstrahlung



Chapter 2:

The Penetrating Component

[Muons and charged pions]

$$\pi^+ \rightarrow \mu^+ \, \nu_\mu$$

$$\mu^+ \rightarrow e^+ \, \nu_e \, \overline{\nu}_\mu$$

+ charged conjugate modes

nuclear emulsions

$e^\pm$

$\mu^\pm$

$\pi^\pm$ stopping

Chapter 3:

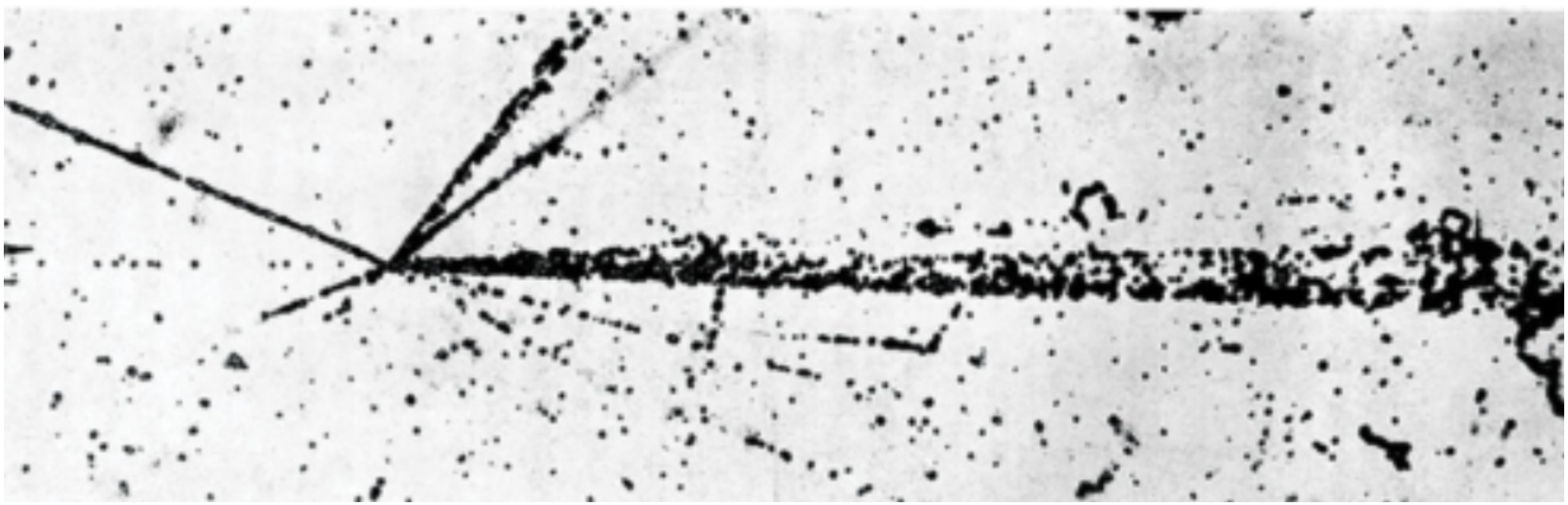
Nuclear interactions

[*Prediction* for neutral pion]

[Discovery of strange particles ....]

$$\pi^{\pm} \quad \pi^{0}$$

$$\pi^{0} \to \gamma\,\gamma$$



$$p + \text{Air nucleus} \to \text{many particles}$$

[Problem that remains open
(or not calculable from first principles)]

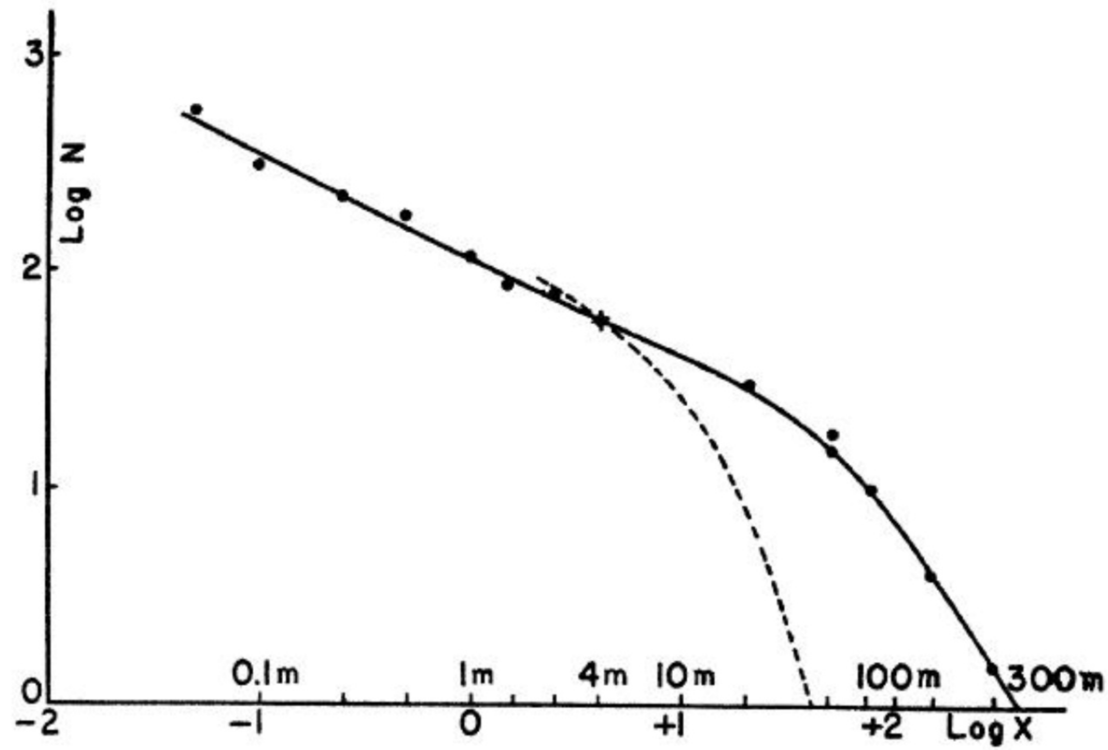
Measuring the energy spectrum
[and mass composition of the cosmic rays]

- *Power Law* spectrum
- that extends to *very high energy*

Study of “Extensive Air Showers”
[coincidences of detectors at increasing large distances]

Pierre Auger (et al.)

Physical Review (1939)



Shower at the ground extending for < 300 meters

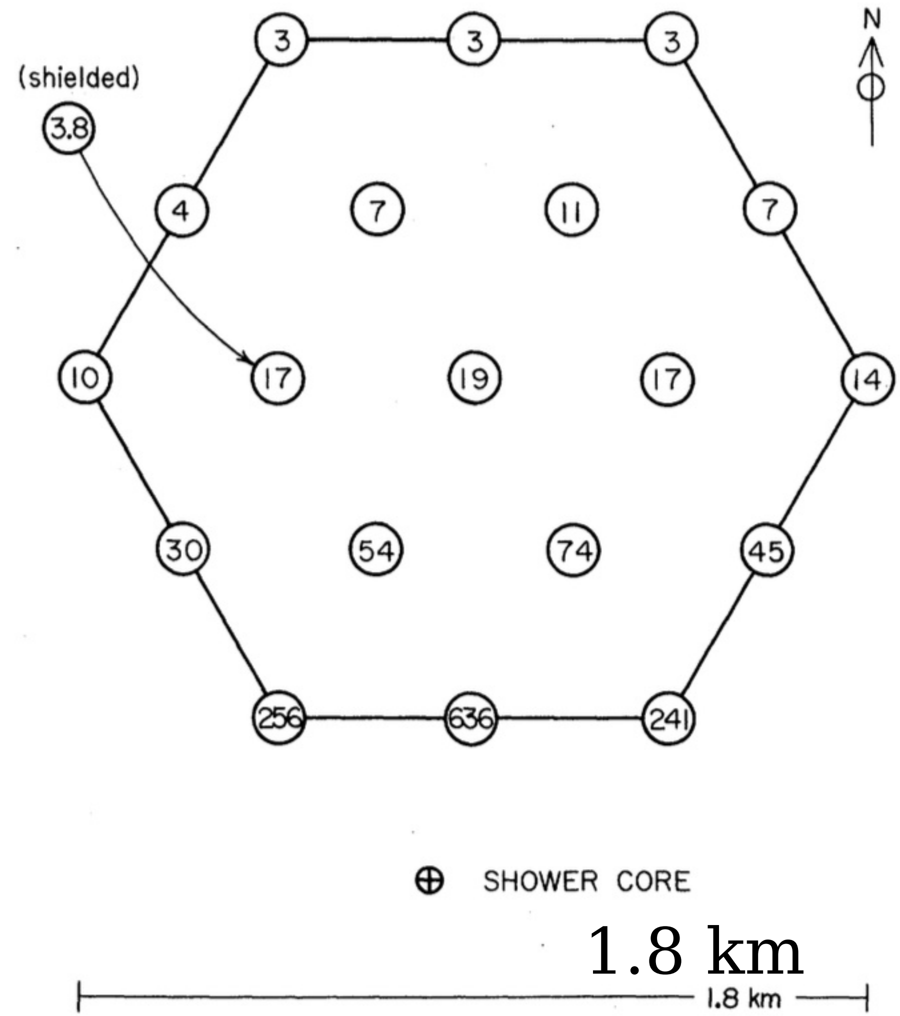
Estimated energies $E \sim 10^{15}$ eV $\sim 10^{16}$ eV

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,† and Bruno Rossi

Phys. Rev. Lett. 6 485, (1961).

$$E \sim 10^{20}\ \mathrm{eV}$$



1.8 km

MIT Volcano Ranch detector (New Mexico)

- Where are these very high energy particles coming from ?

- How do they obtain their energy ?

[No imaging of the sources because of Galactic and extragalactic magnetic fields]

Only now we are starting to get answers to these questions.

A “prophetic” [?] speculation (1934)

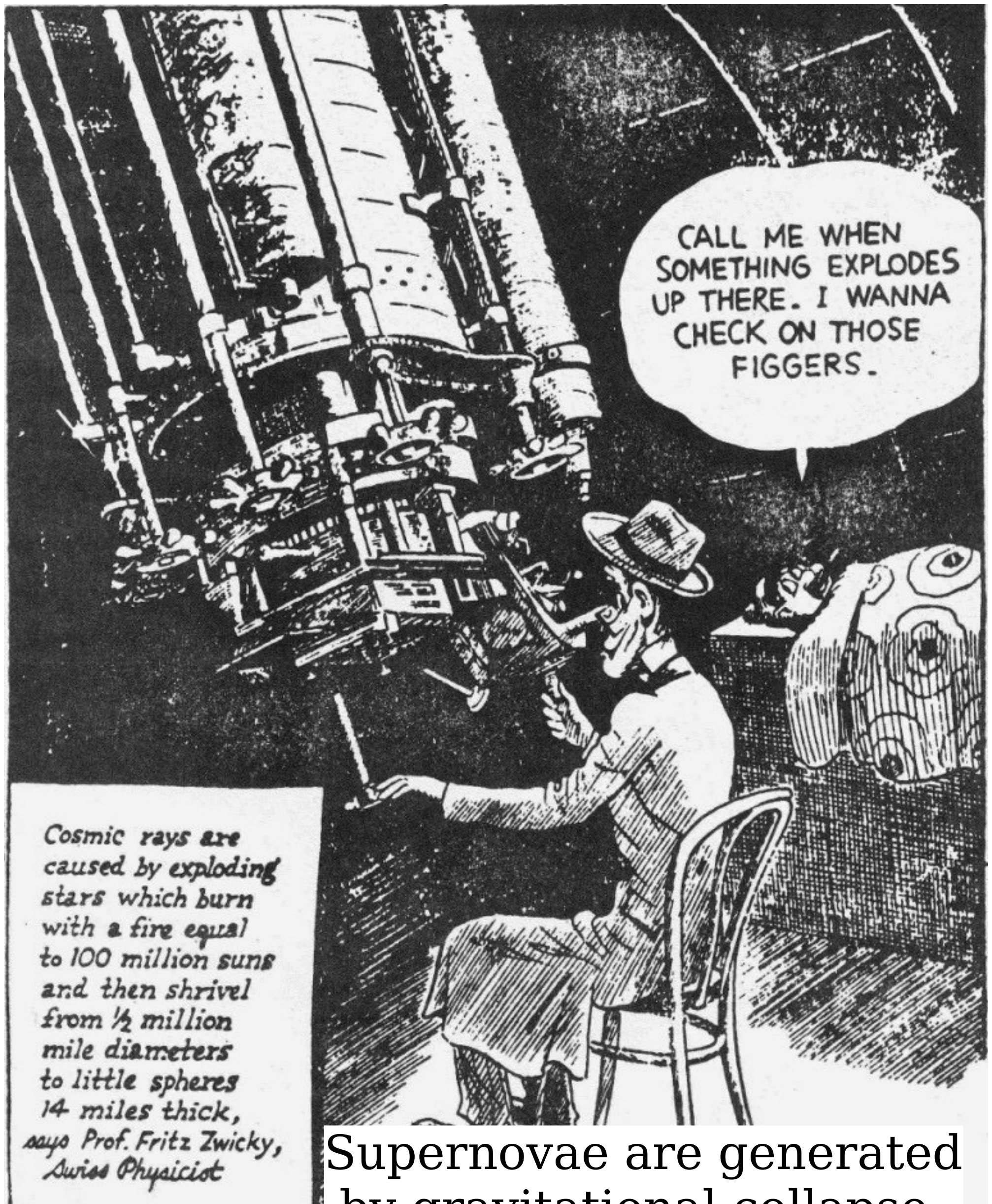
COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

Comic Strip
Los Angeles Times [jan. 1934]



Supernovae are generated by gravitational collapse to a neutron star

Baade-Zwicky ideas:

Cosmic Rays are *extragalactic* fill the universe uniformly

Are a mixture of electrons and positrons.

Super-Novae are created by core-collapse of stars to neutron stars

All binding energy of a neutron star is emitted as cosmic rays.

[Mechanism of production is not discussed.]

Enrico Fermi (1949) theory on the acceleration of Cosmic Rays:

PHYSICAL REVIEW
VOLUME 75, NUMBER 8
APRIL 15, 1949

Cosmic Ray are Galactic
(fill a “bubble" around the Galaxy)

On the Origin of the Cosmic Radiation

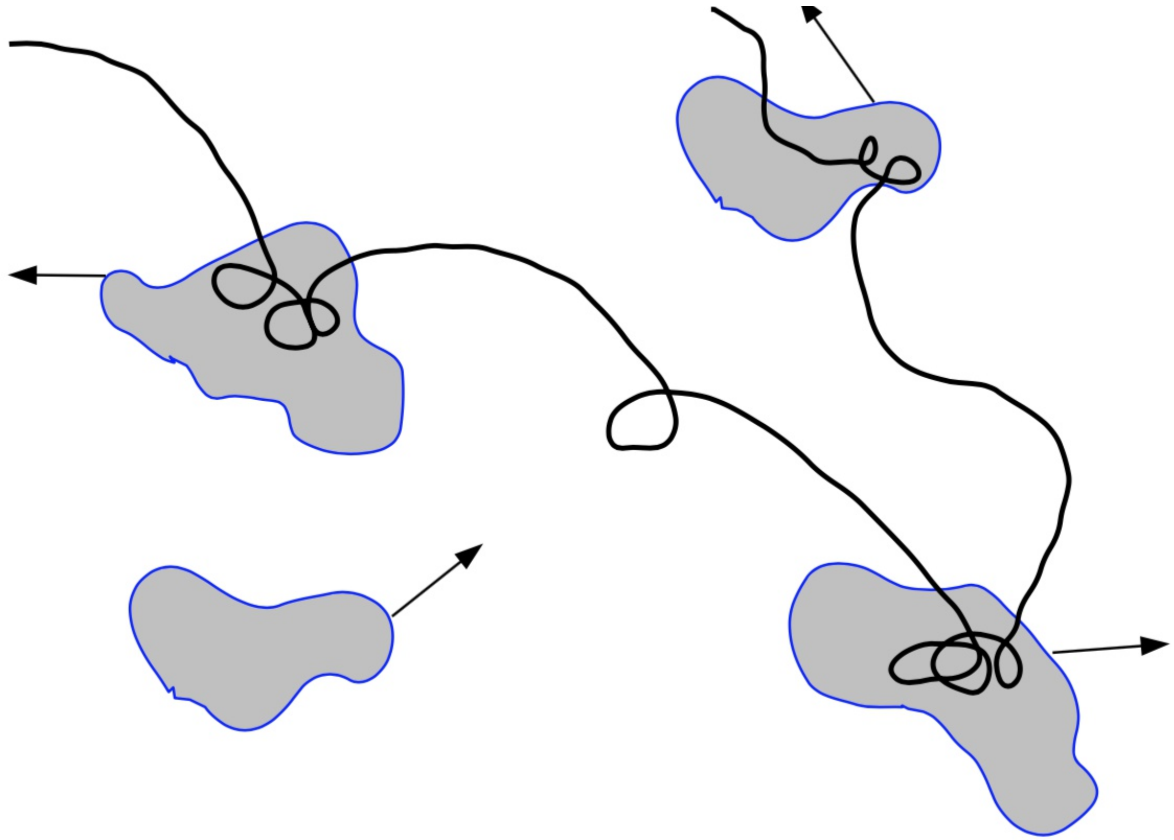
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

“Collisions against moving magnetic fields...
...yield naturally an inverse power law”

Enrico Fermi
original idea:

“Collisions against moving magnetic fields...
...yield naturally an inverse power law”



Encounter with a cloud
of velocity β

$$E_{\rm out} = E_{\rm in} \;\; (1 + \xi)$$

$$\langle \xi \rangle = \frac{4}{3}\,\beta^2$$

GLAST renamed

FERMI gamma-ray Space Telescope

Launch
June 11th 2008

crucial instrument
to study the
"High energy Universe"
name in honor of
Enrico Fermi and his seminal idea

Very important modification / development
of Fermi original idea:

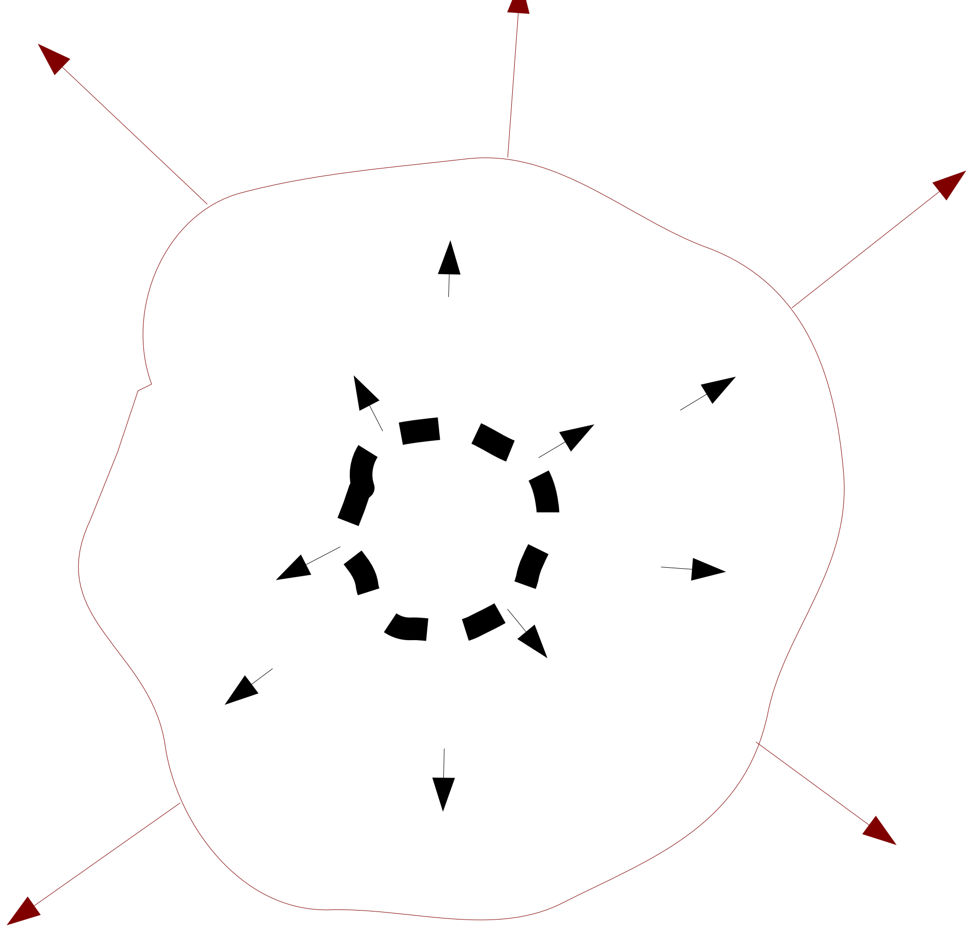
Acceleration due to interaction with a moving
magnetized plasma.

But the moving plasma is inside a source freshly accelerated, and forming shocks.

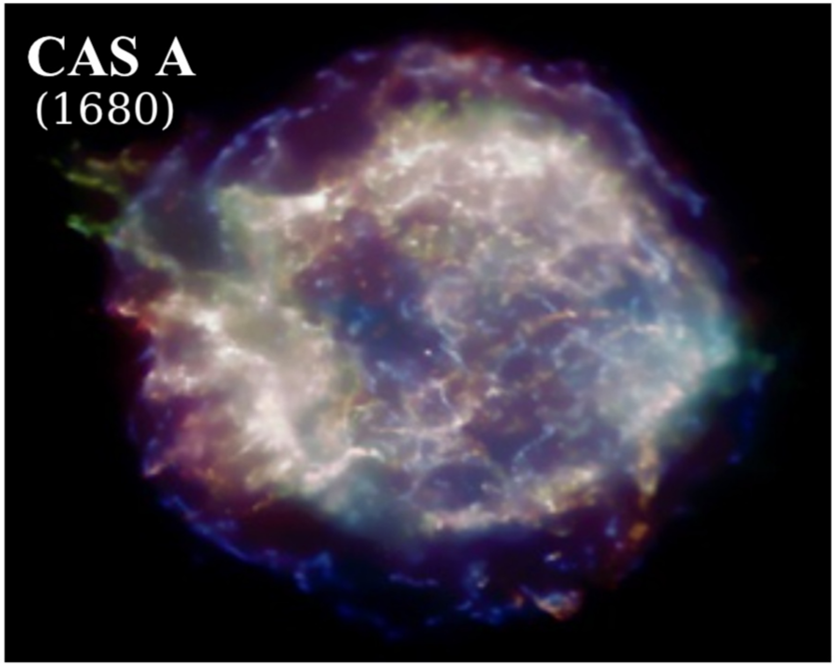
Fermi Diffusive Shock Acceleration

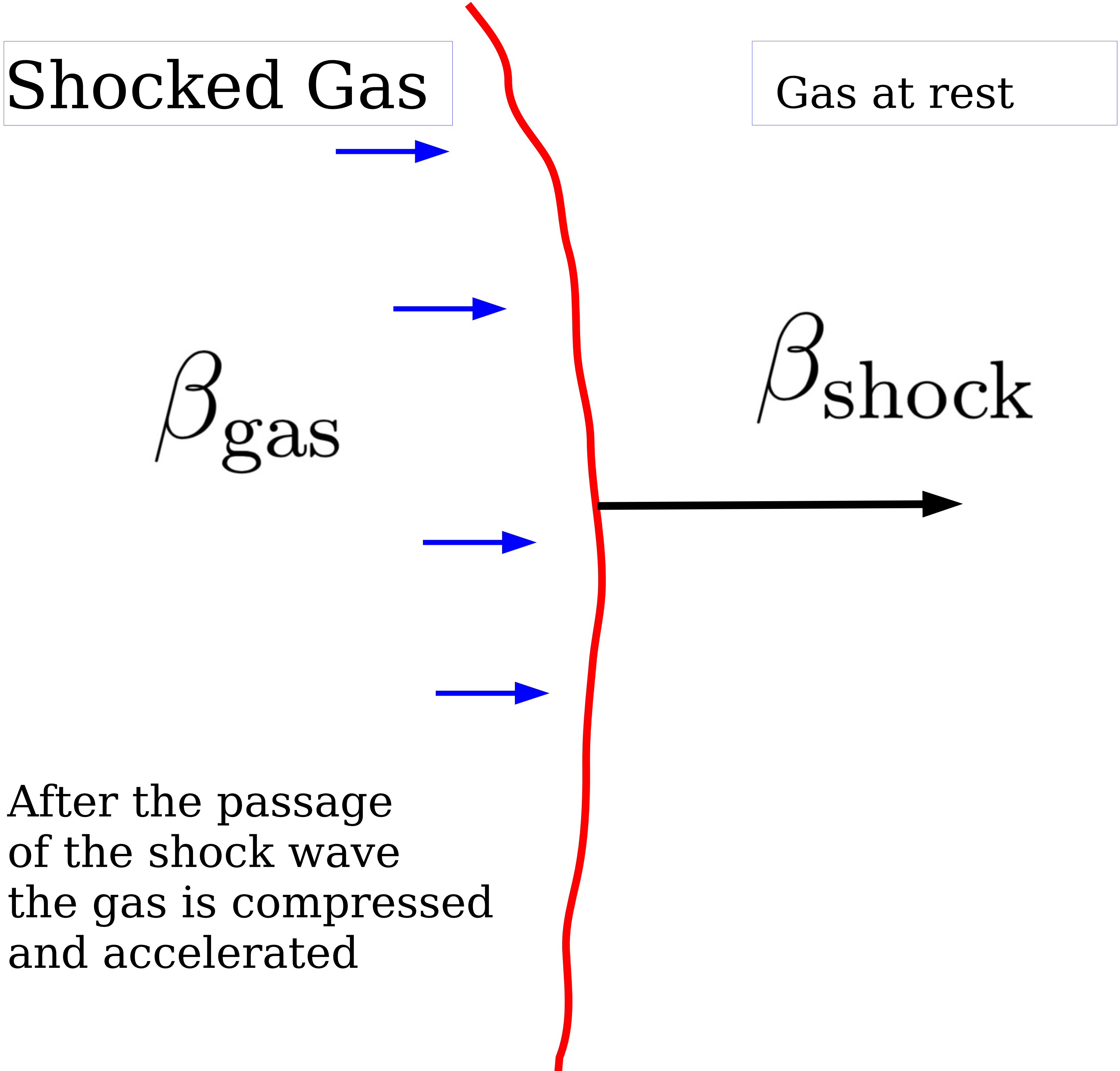
idea is present in works of
a few authors [Parker (1958), Hoyle (1960), ...]

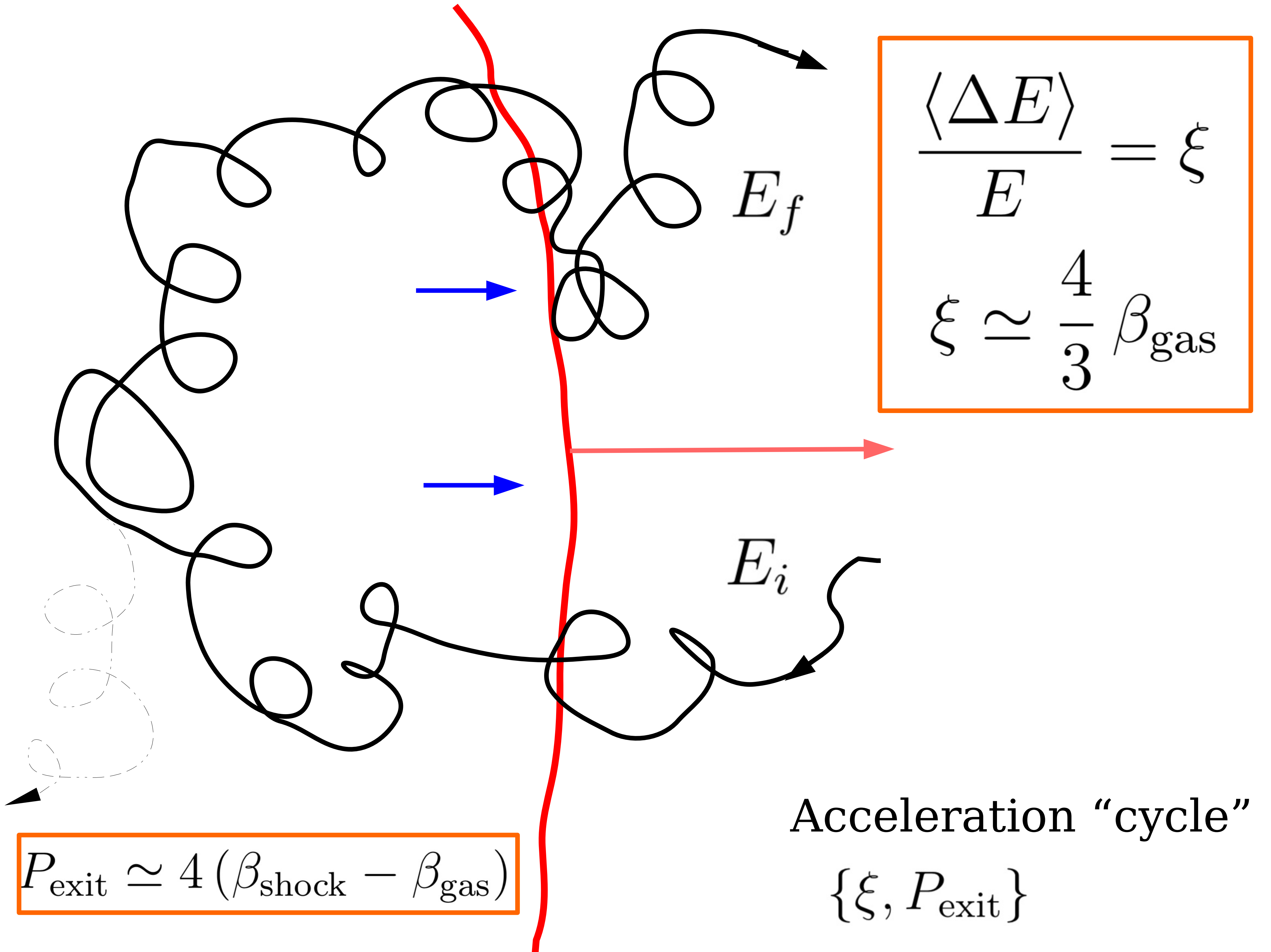
Idea (mature and "in the air")
expressed in the "modern form"
by several authors more less at the same time
Krymsky(1977), Axford(1977),
Bell (1978), Blandford+Ostriker (1978)



Blast Wave
of a SuperNova
explosion




Shocked Gas
Gas at rest
β_{gas}
β_{shock}
After the passage
of the shock wave
the gas is compressed
and accelerated



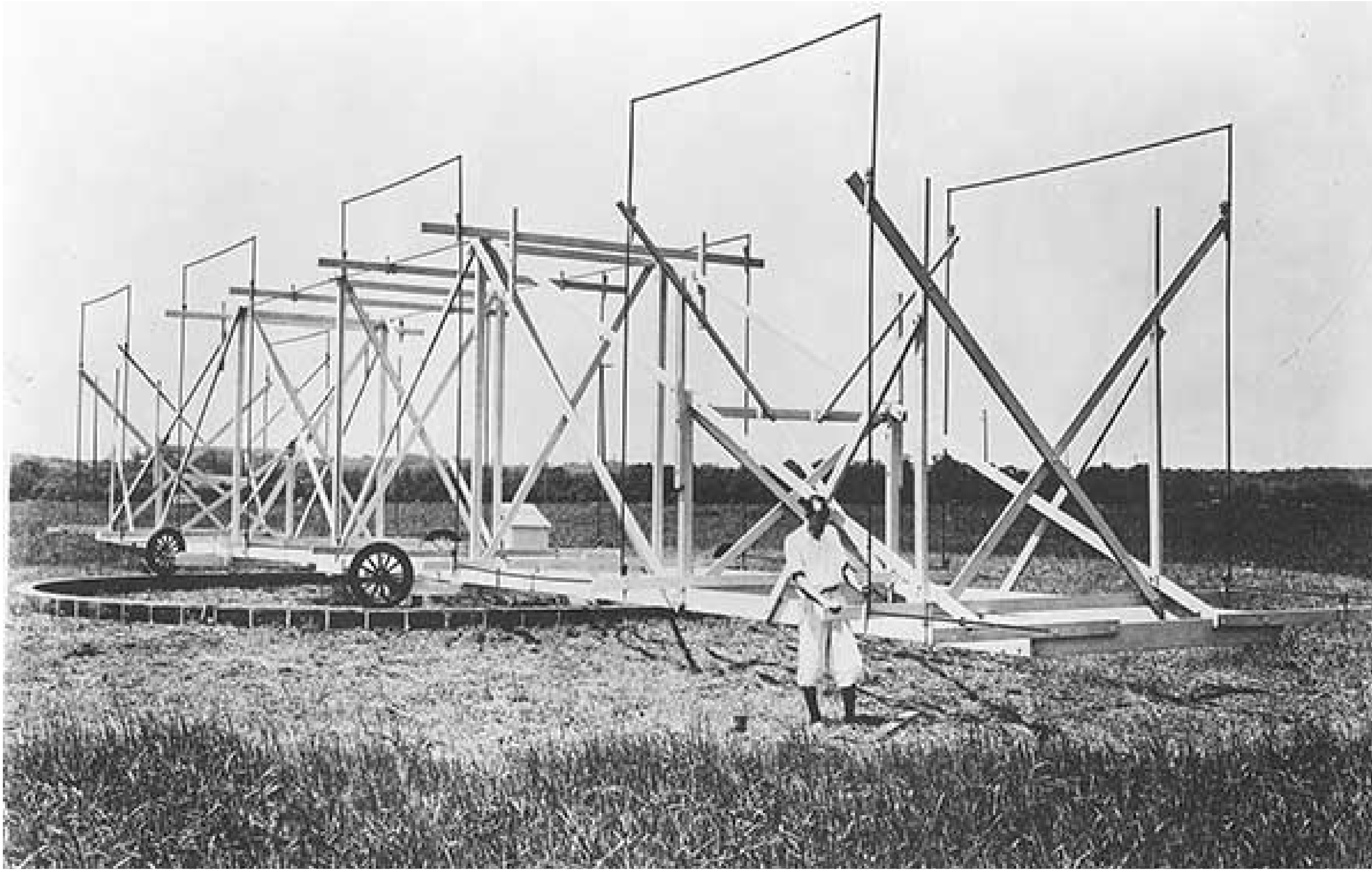
$\frac{\langle \Delta E \rangle}{E} = \xi$
$\xi \simeq \frac{4}{3} \beta_{\rm gas}$
E_f
E_i
Acceleration "cycle"
$\{\xi, P_{\rm exit}\}$
$P_{\rm exit} \simeq 4\left(\beta_{\rm shock} - \beta_{\rm gas}\right)$

Motivation for the construction of
theories for the acceleration of relativistic particle
came also from new Astronomical Observations

new wavelengths:

$\boxed{\begin{array}{c}\text{Radio}\\ \\ \text{X-ray}\end{array}}$

that revealed the existence of new classes of sources



Karl Jansky [1905-1950]

first radio telescope (1931-1932) “Jansky merry go-round”

Astrophysical Observations in new Wavelengths:

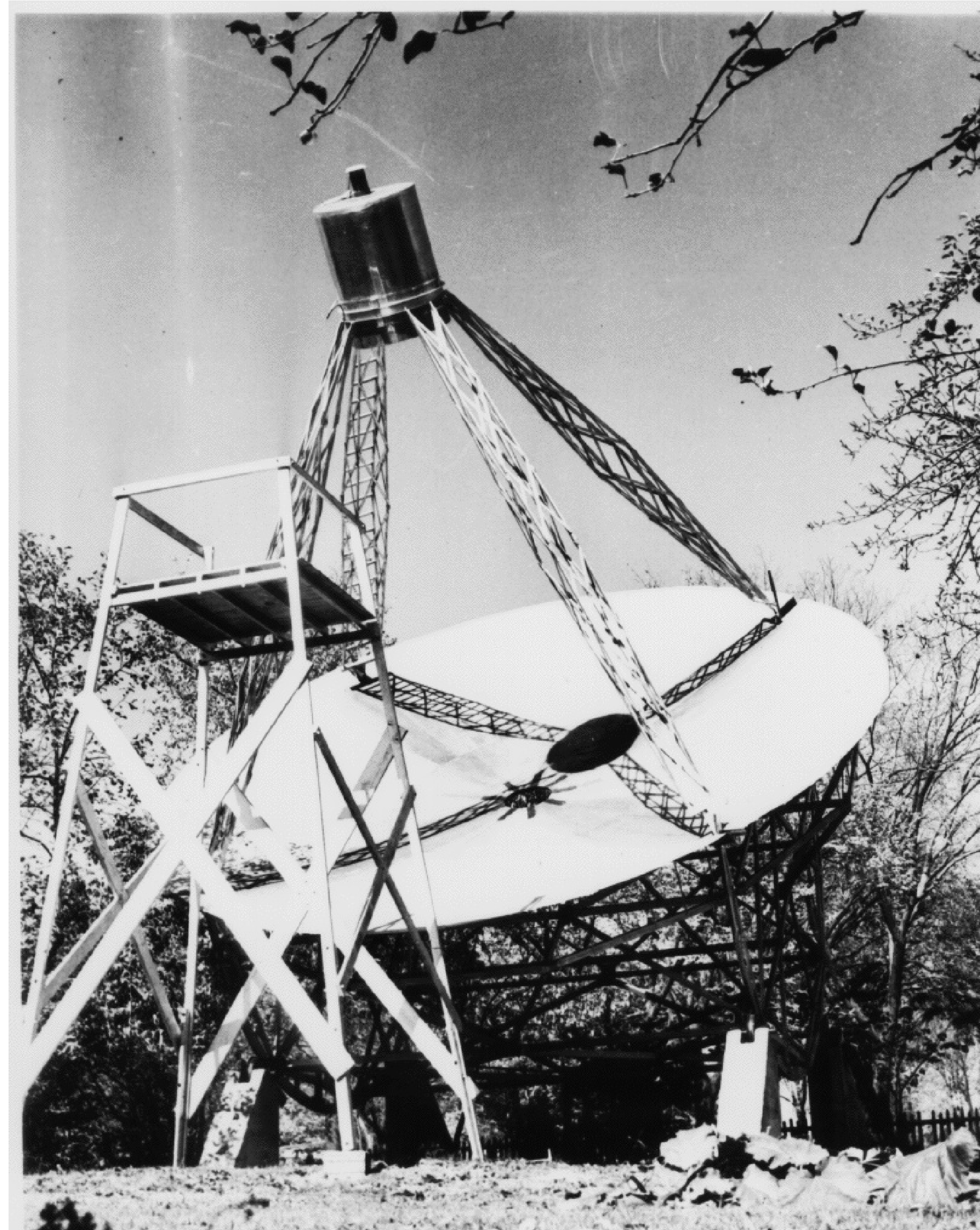
Electrical Phenomena that apparently are of Interstellar Origin

By KARL G. JANSKY*

Electromagnetic waves of an unknown origin were detected during a series of experiments on atmospherics of short wave-lengths. Directional records have been taken of these waves for a period of nearly two years. The data obtained from these records show that the azimuth of the direction of arrival changes from hour to hour and from day to day in a manner that is exactly similar to the way in which the azimuth of a star changes. This fact leads to the conclusion that the direction of arrival of these waves is fixed in space; that is to say, that the source of these waves is located in some region that is stationary with respect to the stars.

Source in Sagittarius [Galactic Center]

Radio Antenna
(1937)
Grote Reber



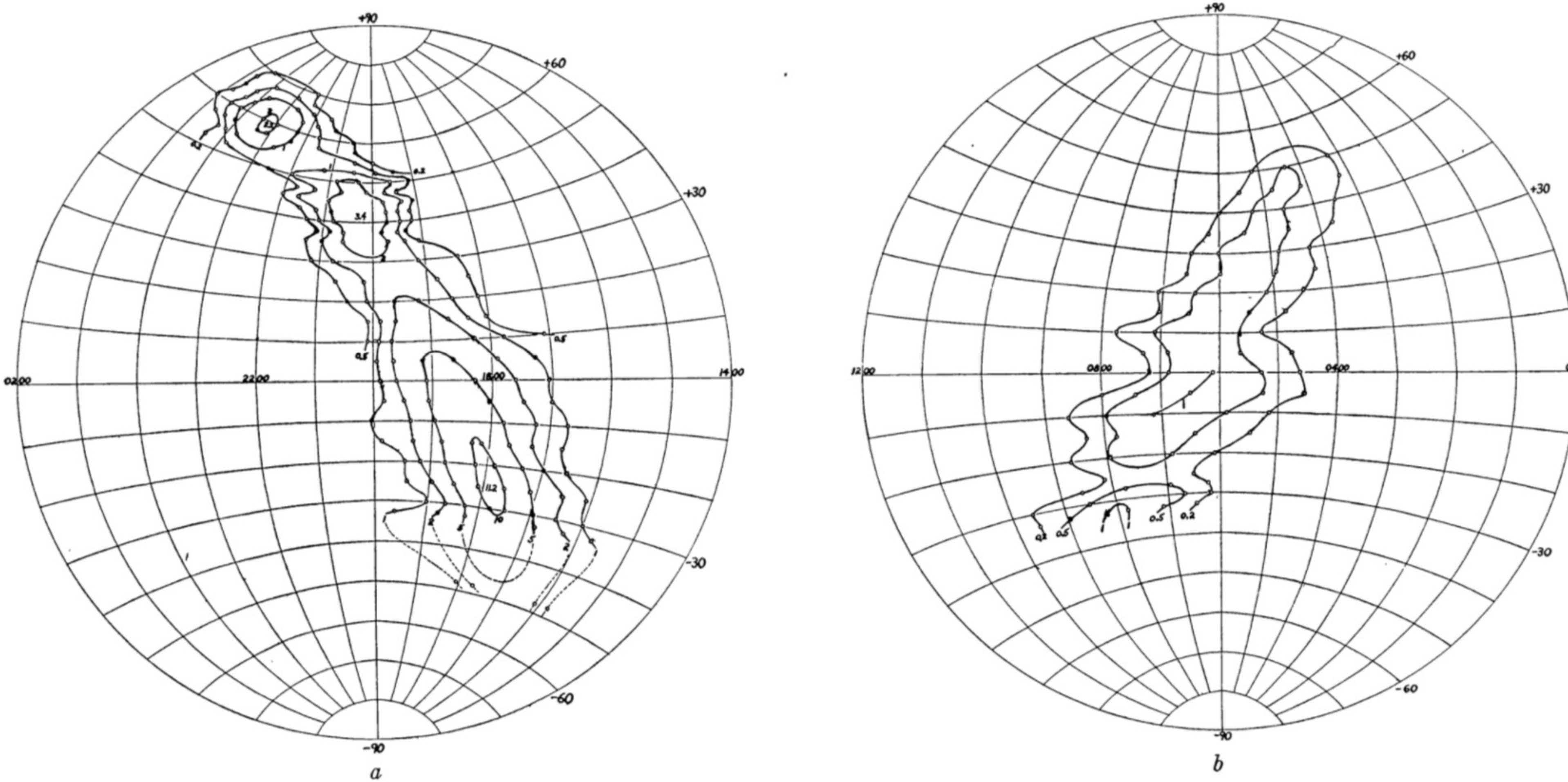


Fig. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

First radio Sky Map:
Astrophysical Journal, 100, p.279 (1944)

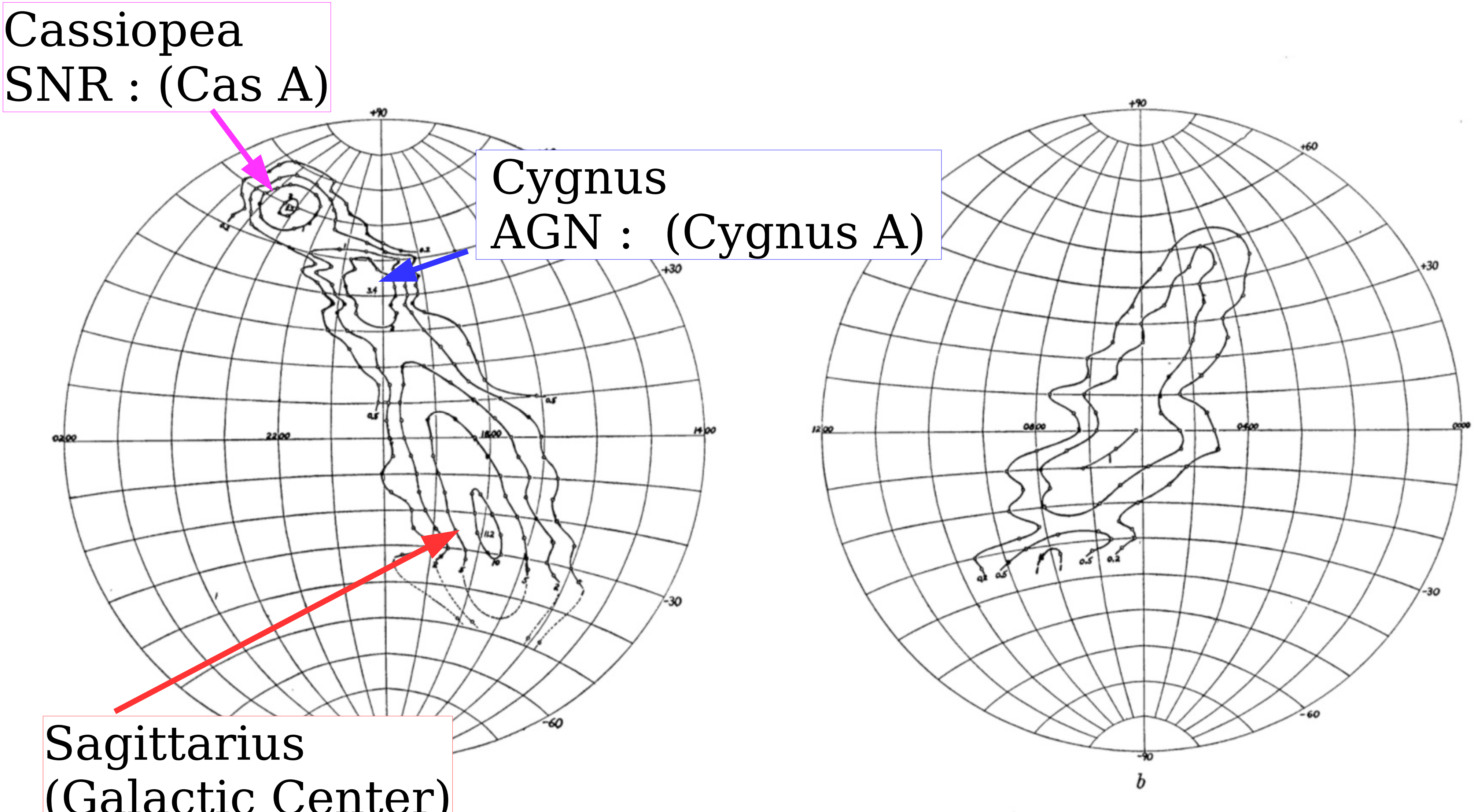
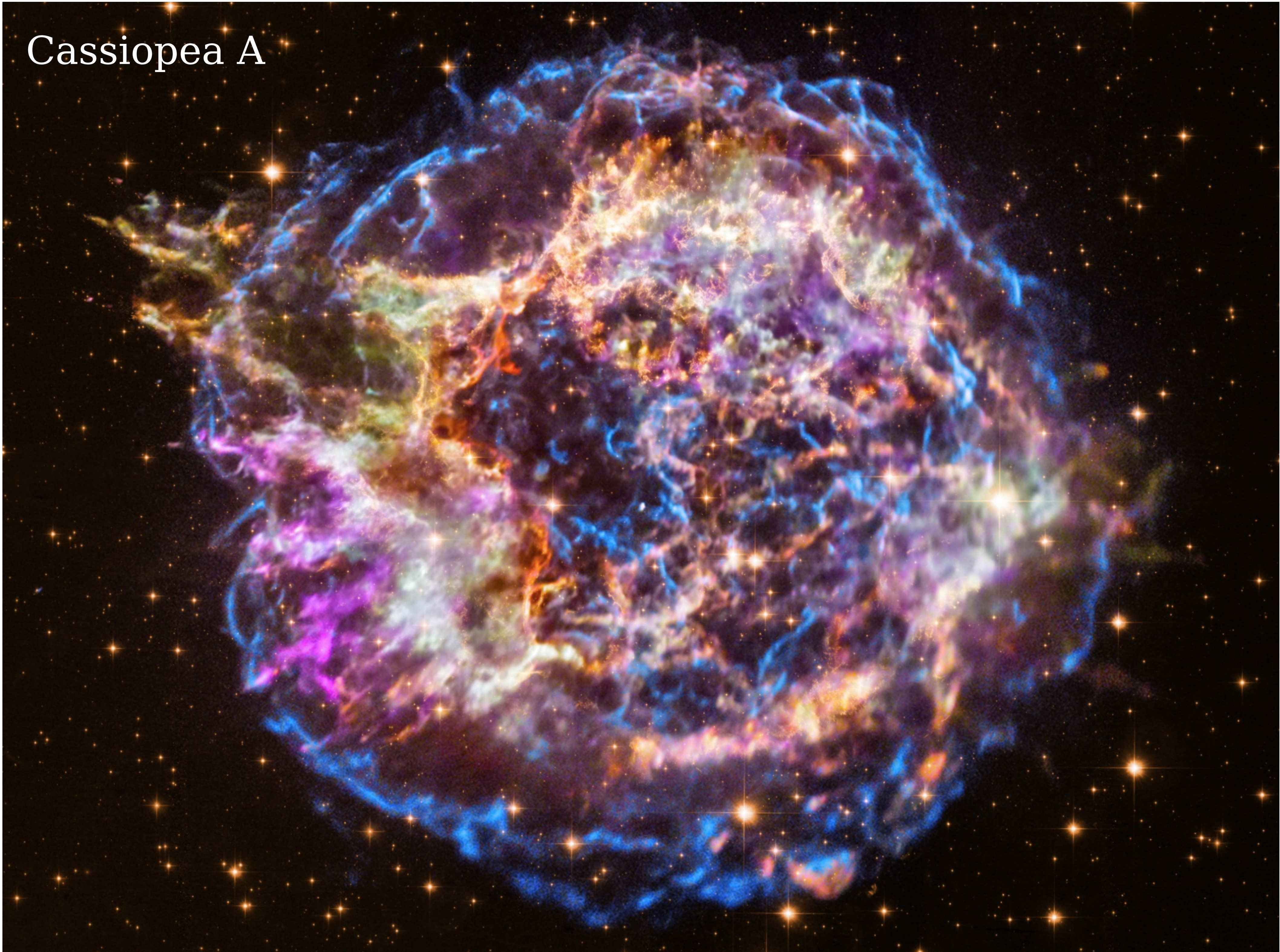
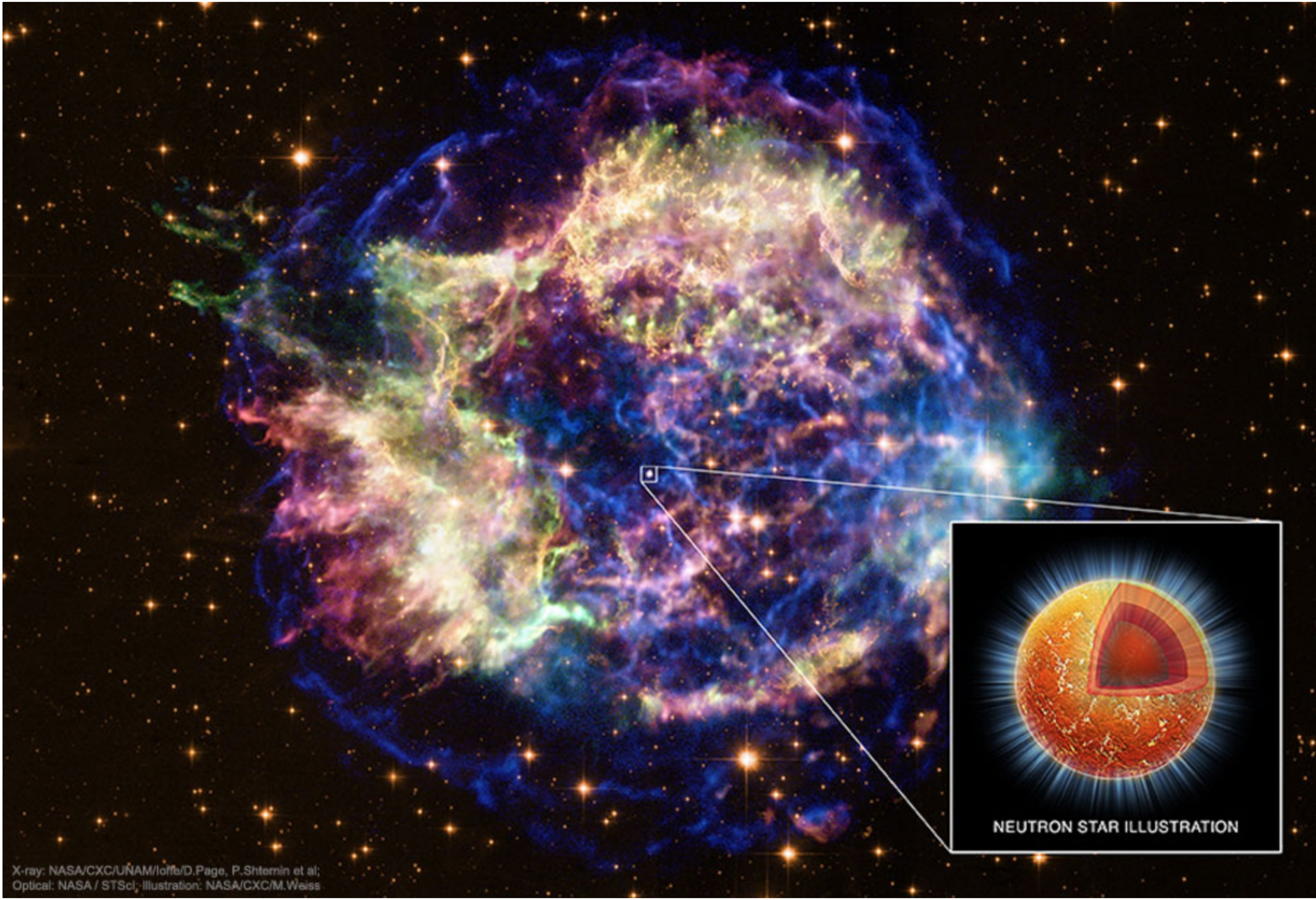


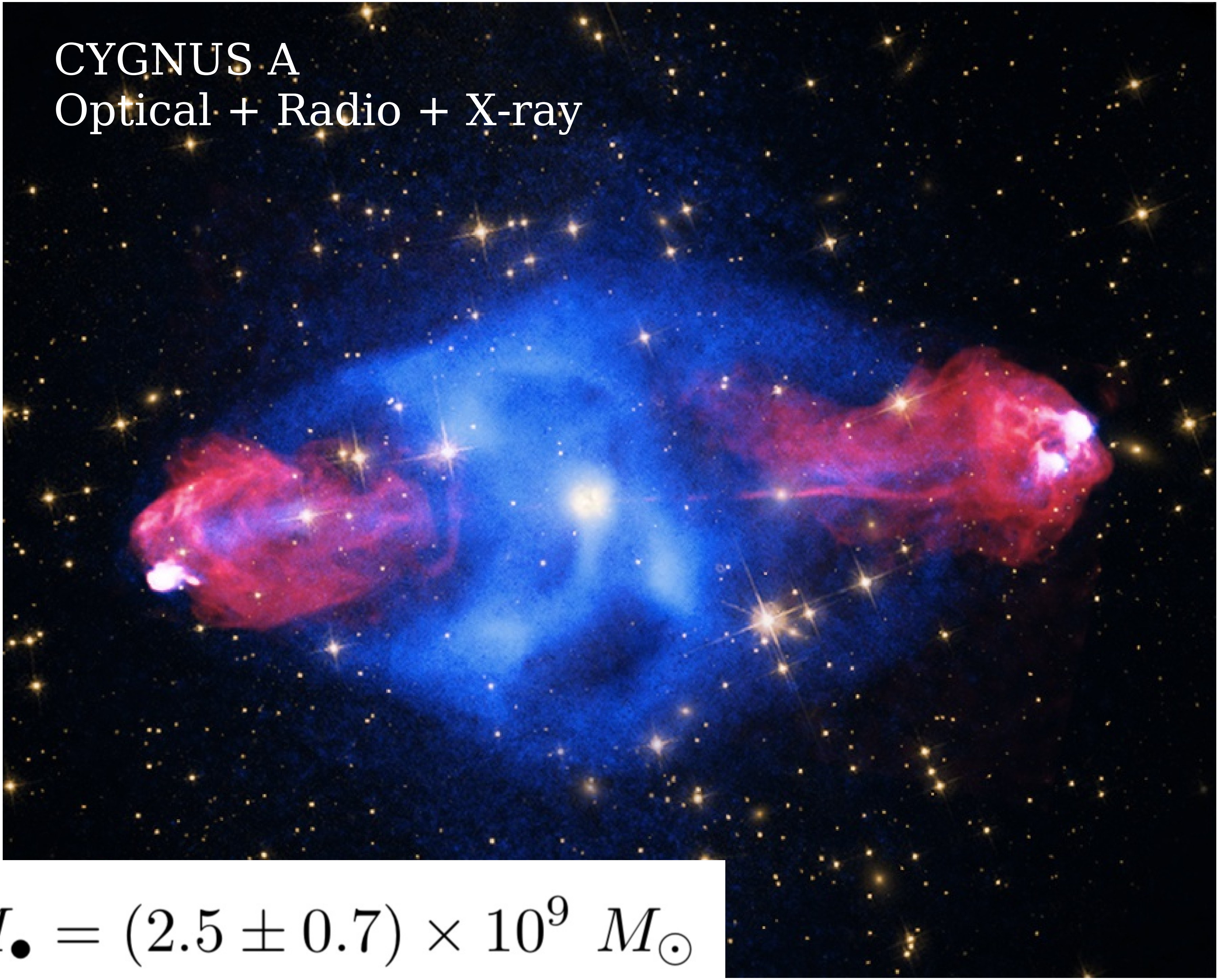
FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

Sky Map:
Astrophysical Journal,
100, p.279 (1944)

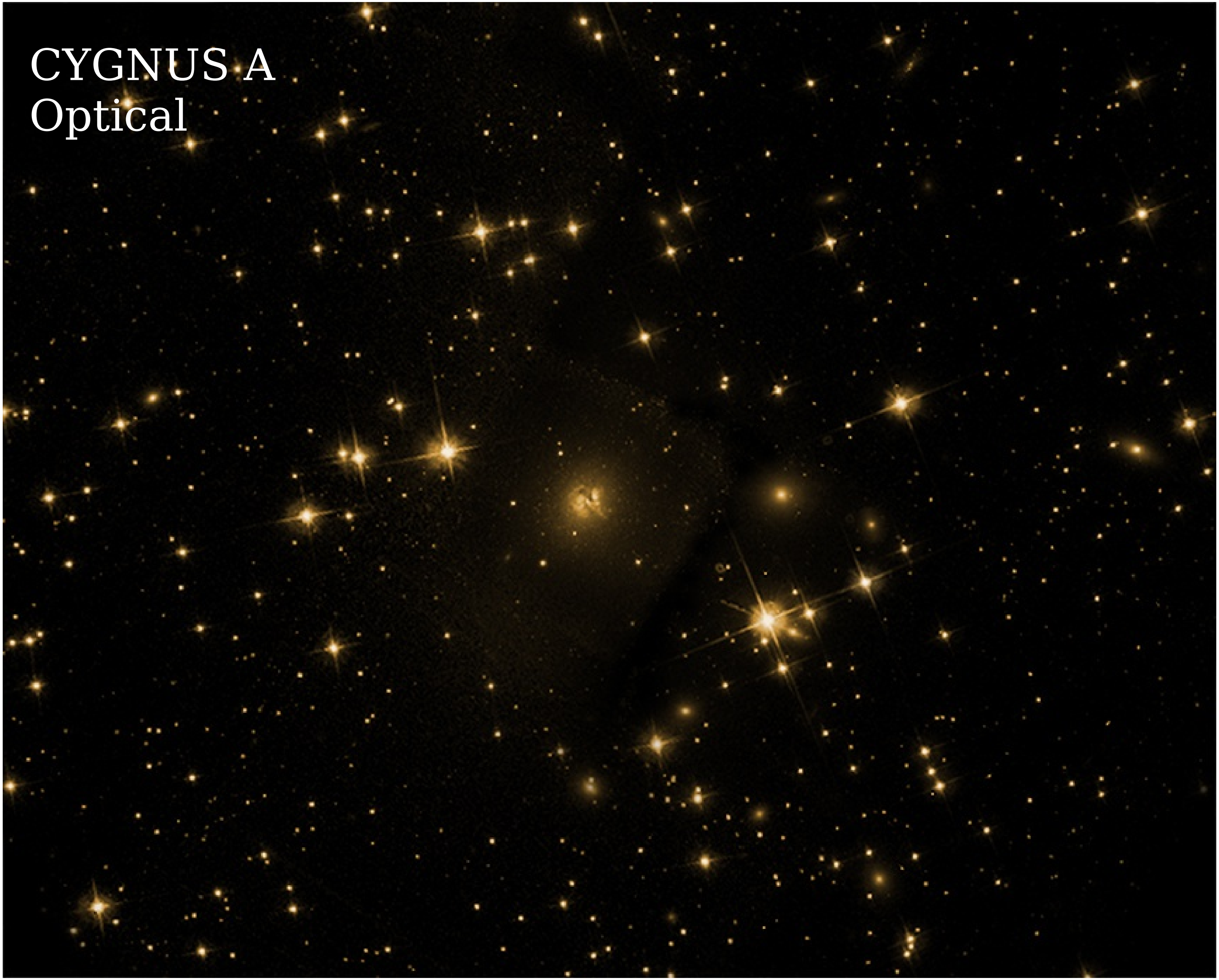
Synchrotron emission
from relativistic

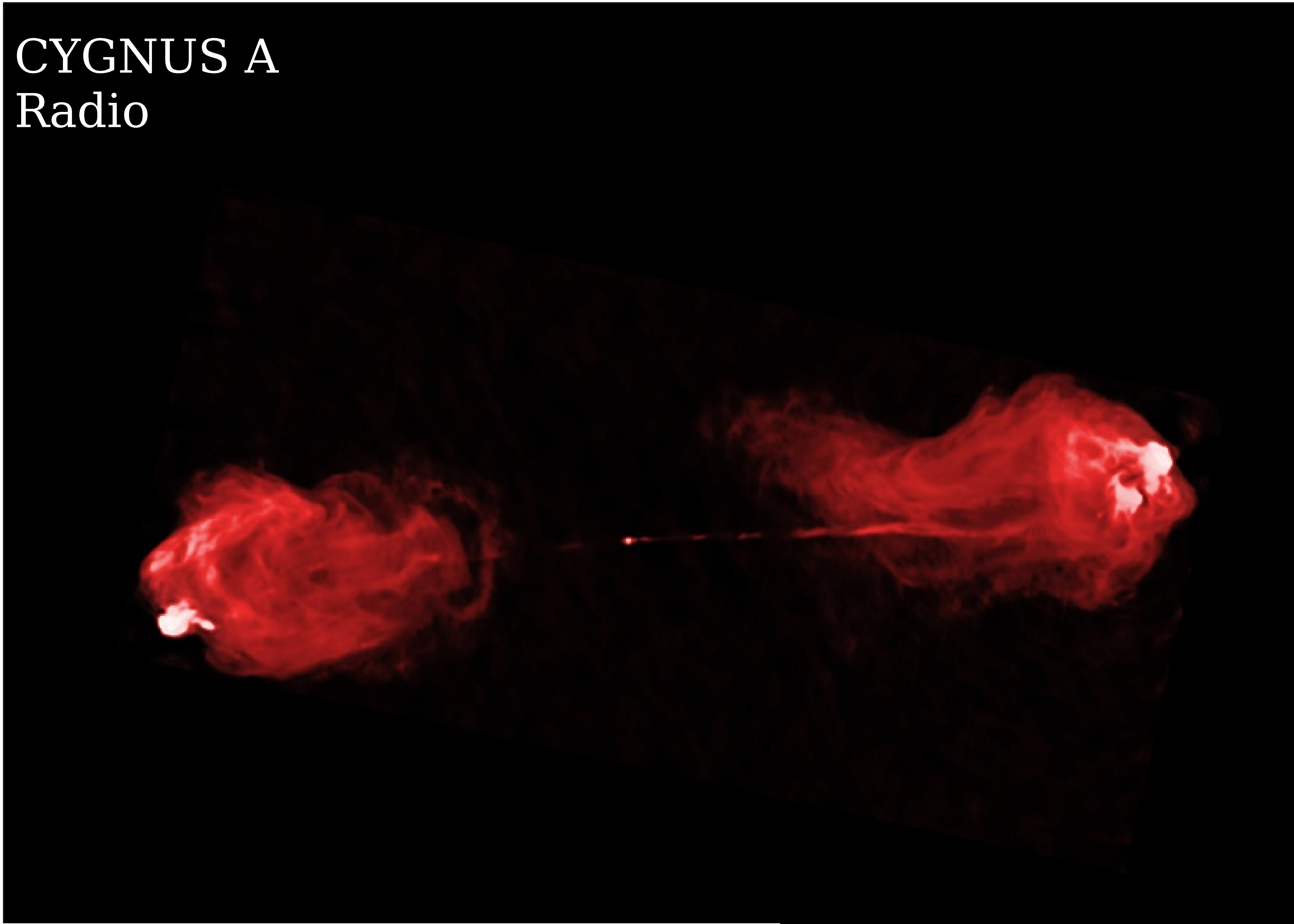

Cassiopea A


NEUTRON STAR ILLUSTRATION
X-ray: NASA/CXC/UNAM/Ioffe/D.Page, P.Shternin et al;
Optical: NASA / STScI; Illustration: NASA/CXC/M.Weiss

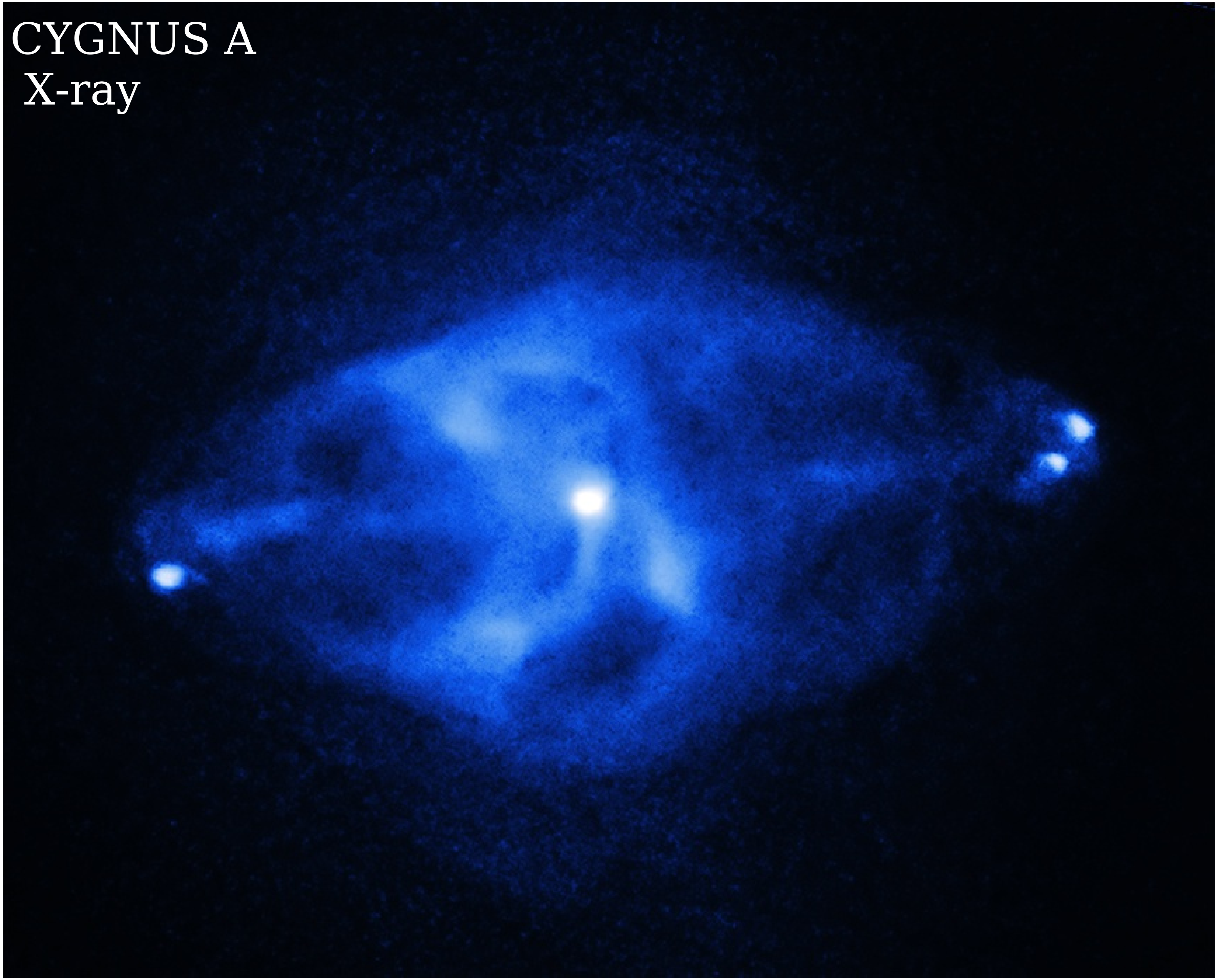


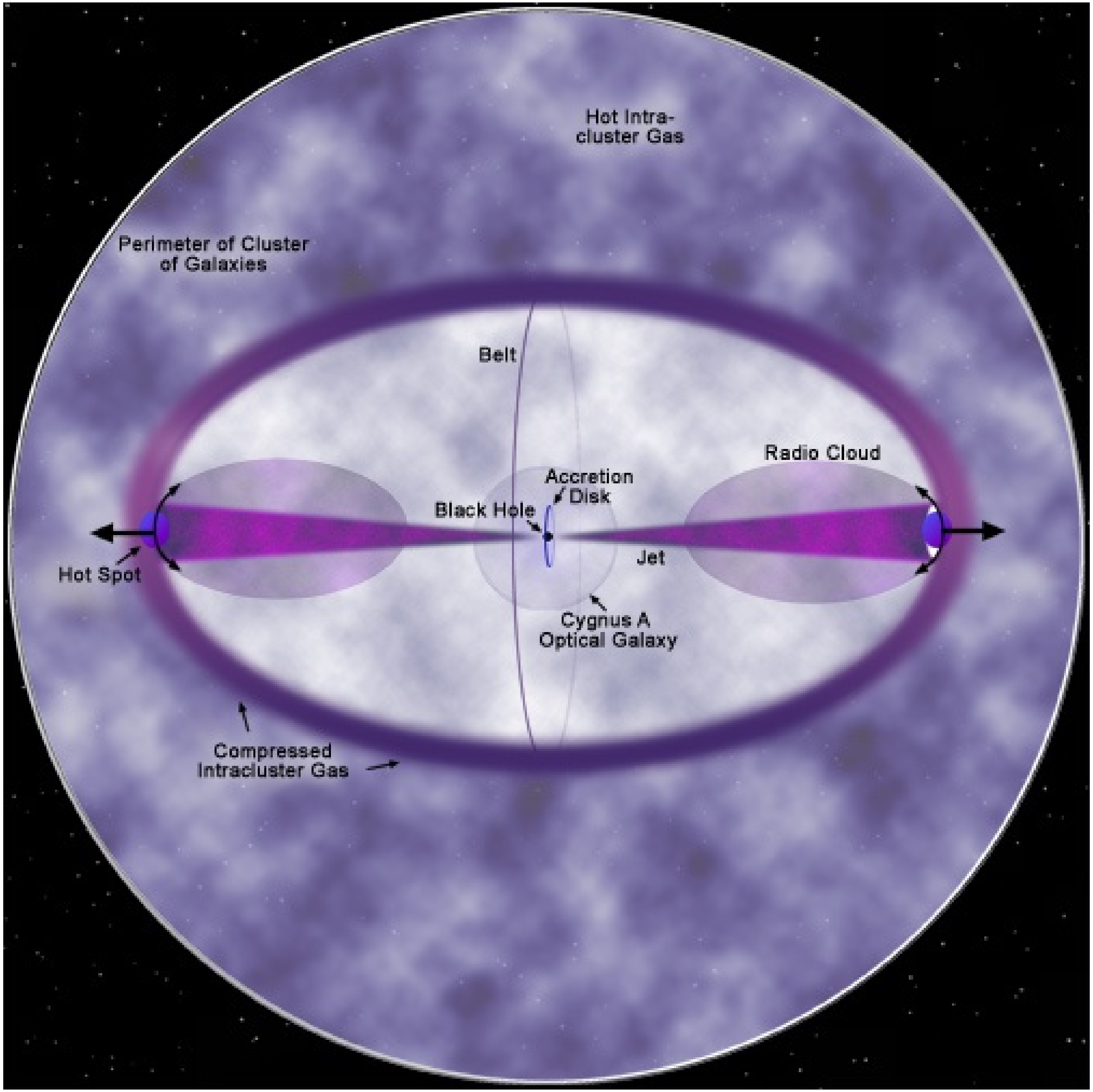
$$M_\bullet = (2.5 \pm 0.7) \times 10^9 \ M_\odot$$


CYGNUS A
Optical



$M_\bullet = (2.5 \pm 0.7) \times 10^9 \ M_\odot$ [redacted] $d \approx 232$ Mpc


CYGNUS A
X-ray



Hot Intra-
cluster Gas
Perimeter of Cluster
of Galaxies
Belt
Radio Cloud
Accretion
Disk
Black Hole
Jet
Hot Spot
Cygnus A
Optical Galaxy
Compressed
Intracluster Gas

NATURE
March 16, 1963

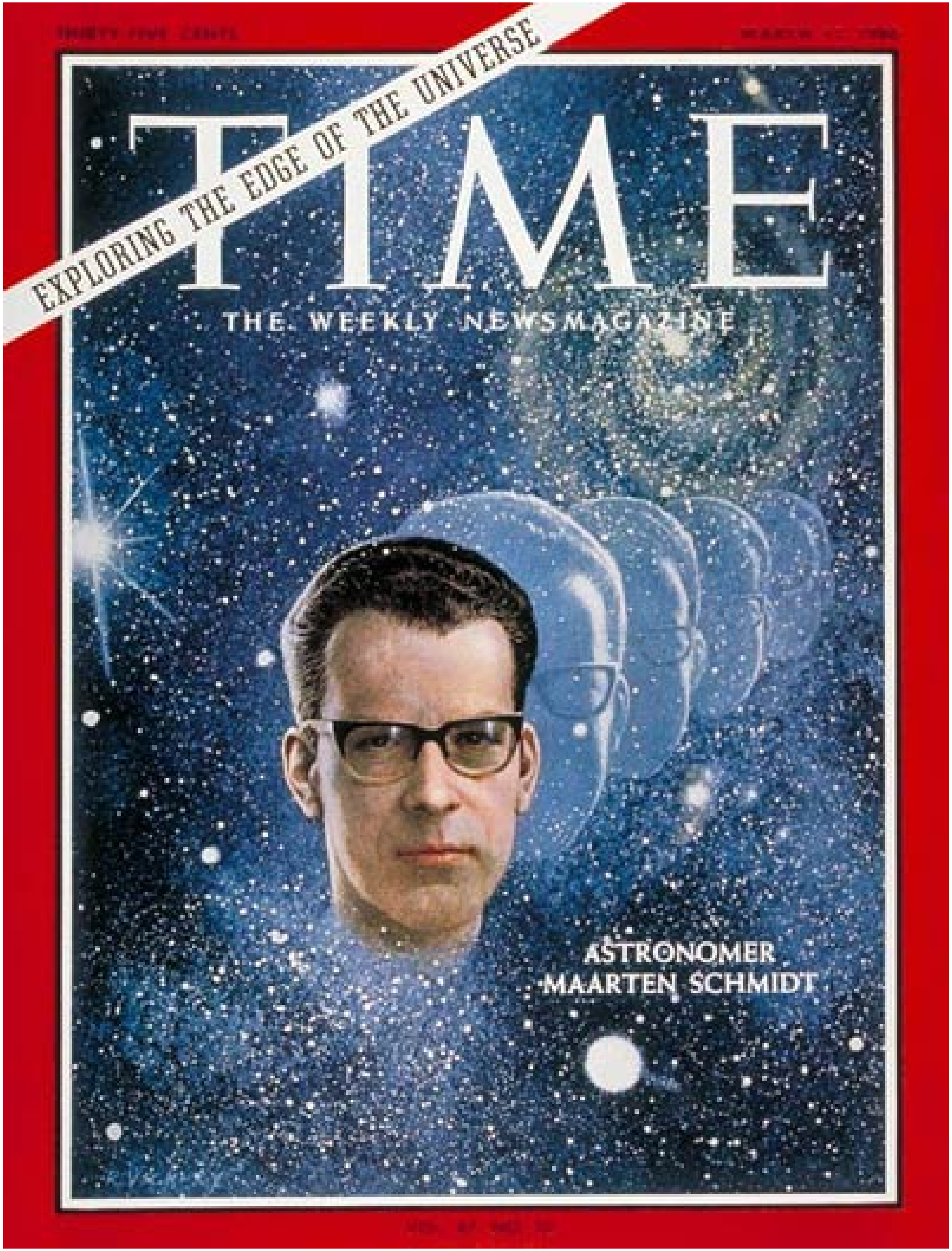
By Dr. M. SCHMIDT

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

z = 0.158

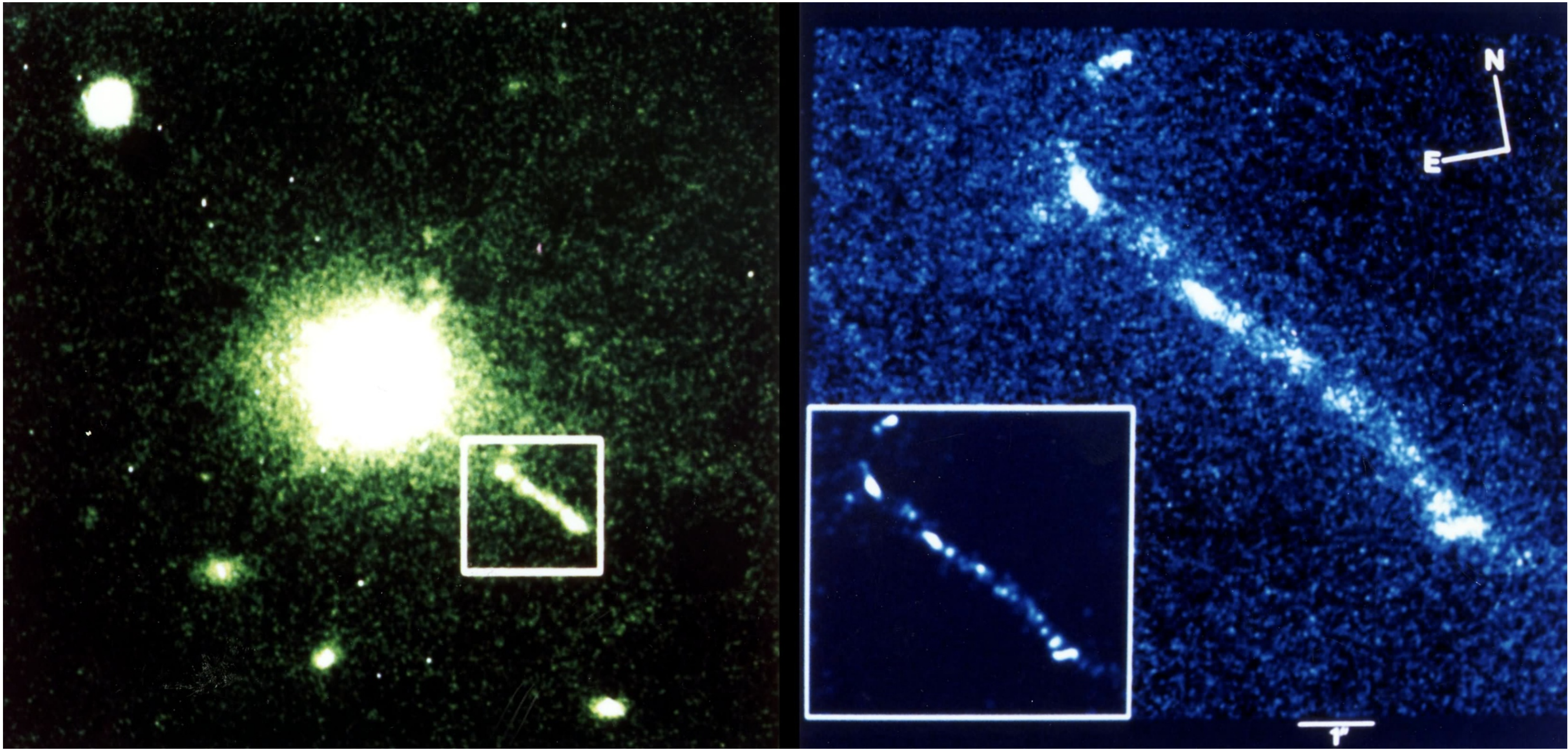
THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the

Discovery of "QUASARS"



Time magazine
March 11th 1966

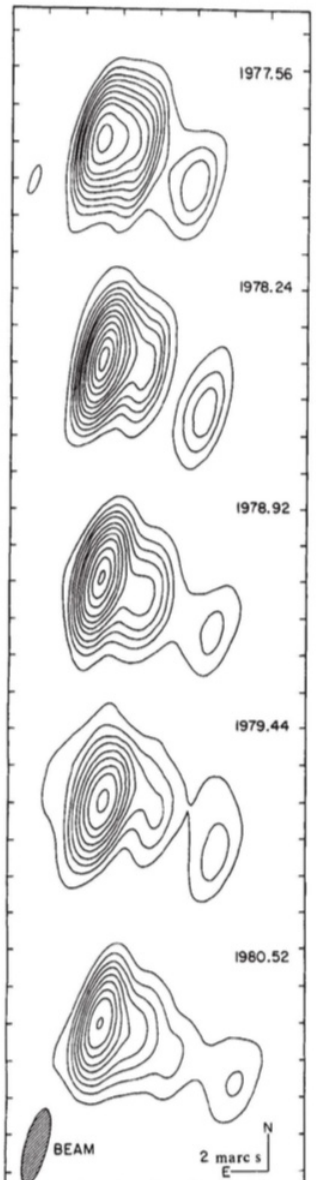
Hubble telescope image of 3C 273



Maarten Schmidt [1963]
… a thirteenth magnitude star, and a faint wisp or jet…
…

Superluminal expansion of quasar 3C273

VLBI (Very Long Baseline Interferometry) Observations



Pearson et al.
Nature 290, 365, (1981).

Maps of the radio structure of 3C273 show directly that it expanded with an apparent velocity of 10 times the speed of light from mid-1977 to at least mid-1980

$$d \approx 749 \text{ Mpc}$$

$$M_{\bullet} = (0.886 \pm 0.197) \times 10^{9}\ M_{\odot}$$

Multi-messenger Astrophysics

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

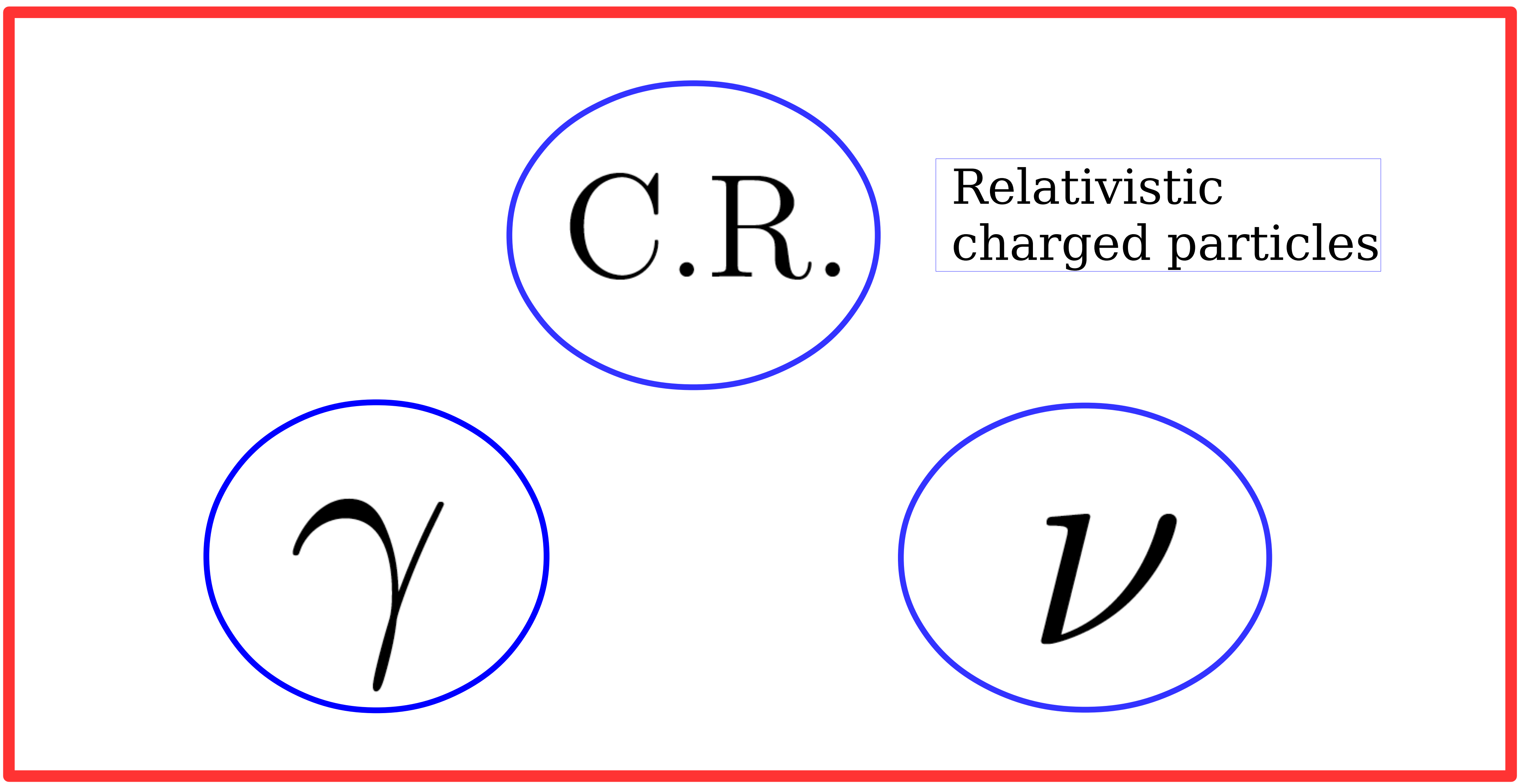
4 Messengers

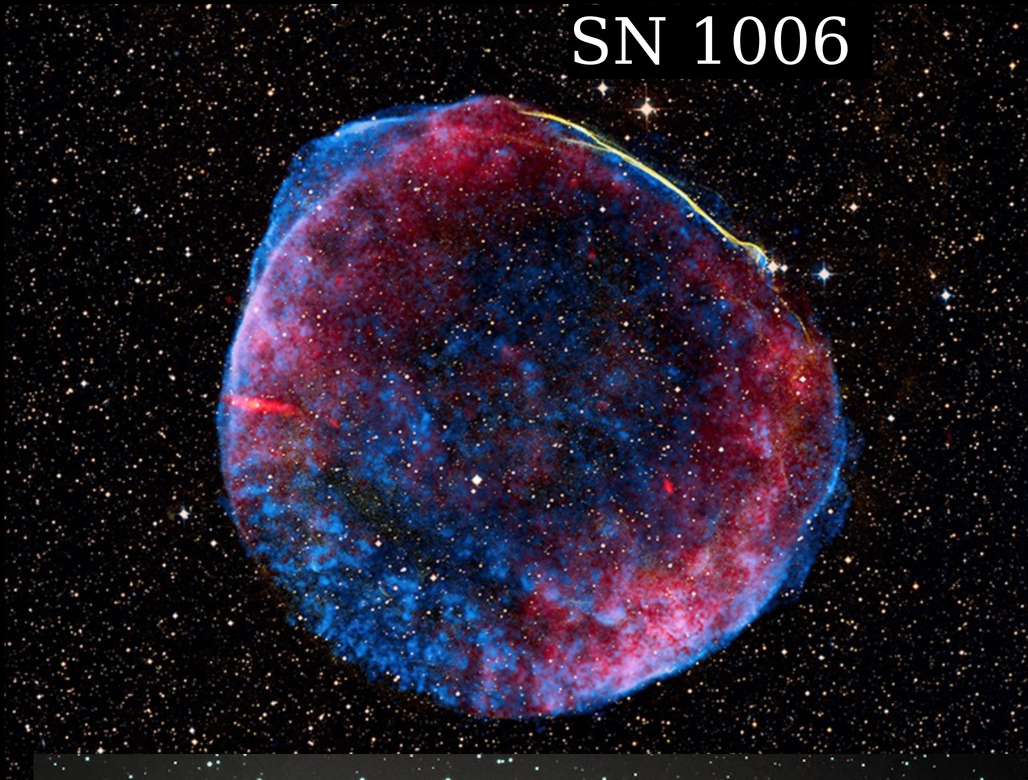
for the study of the

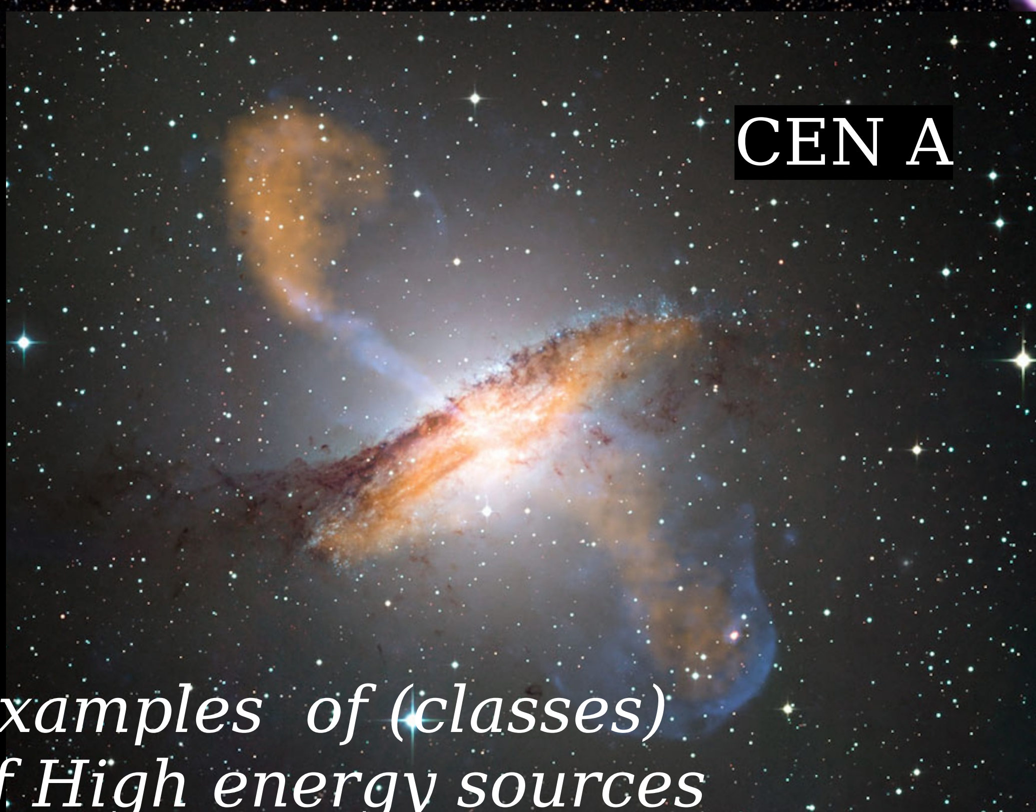
"High Energy Universe"

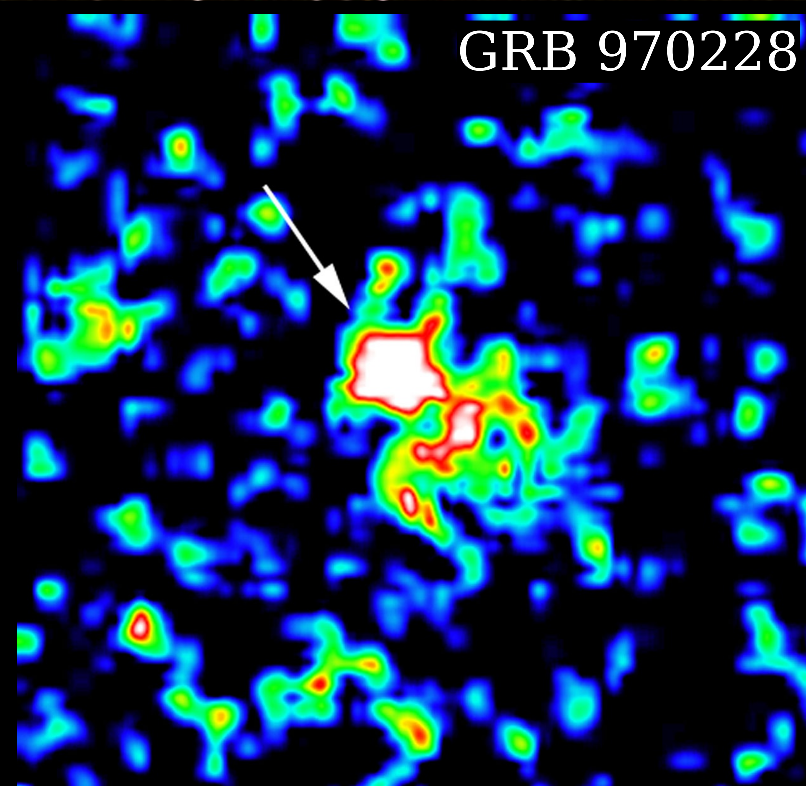
Three messengers are “inextricably” tied together

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



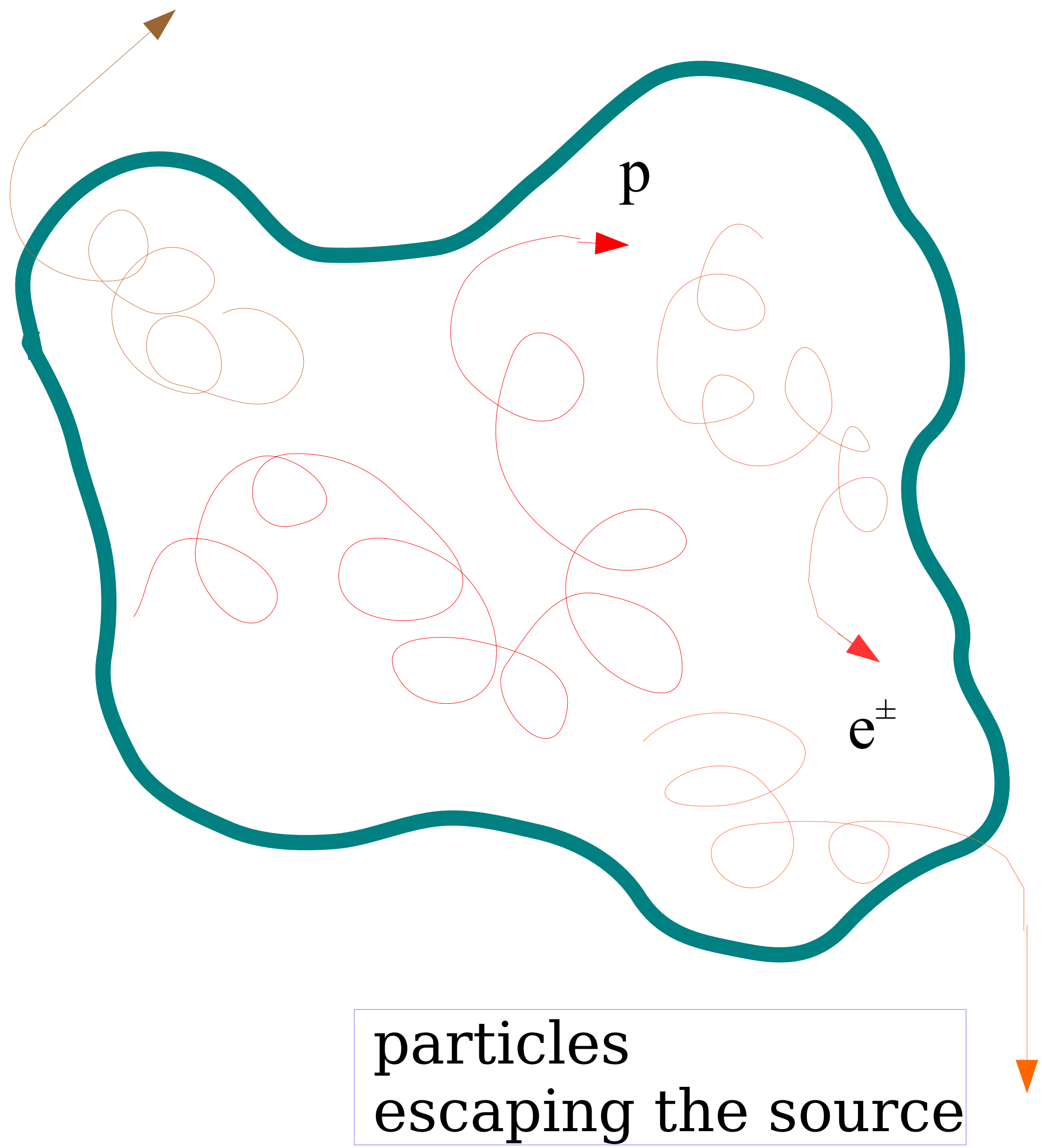






Examples of (classes) of High energy sources

Cosmic Ray Accelerator



Astrophysical object/transient 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 "

$$e^\pm \ \gamma_{\rm soft} \to e^\pm \ \gamma$$

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

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

Sources are transients

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

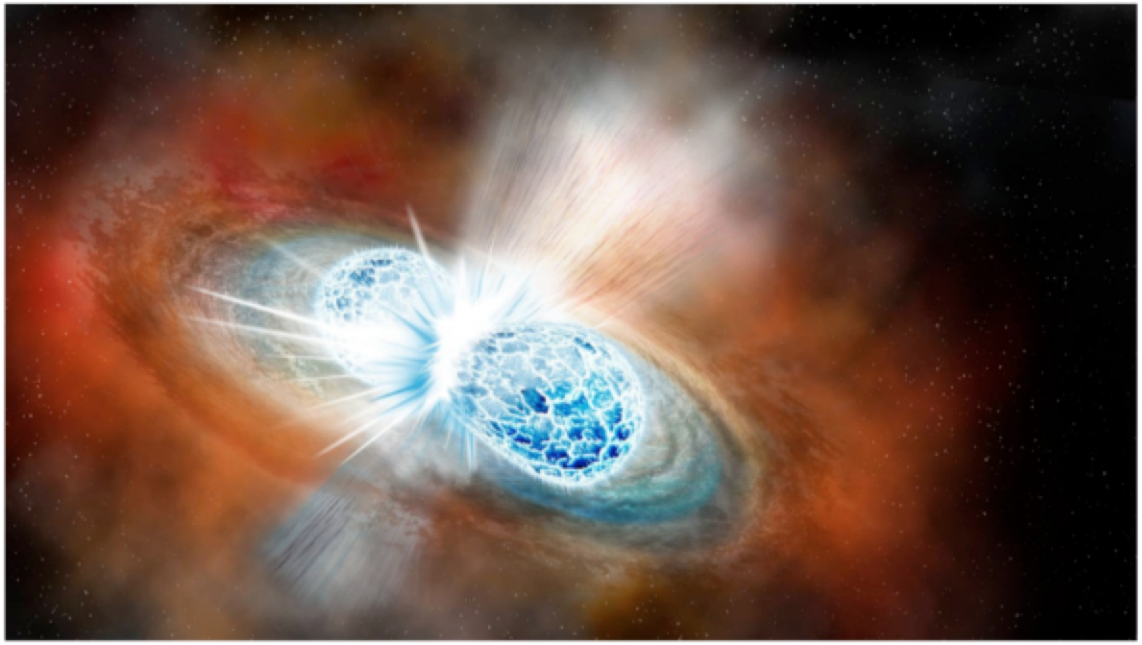
Associated to Compact Objects

Neutron stars,
Black Holes (stellar and Supermassive)

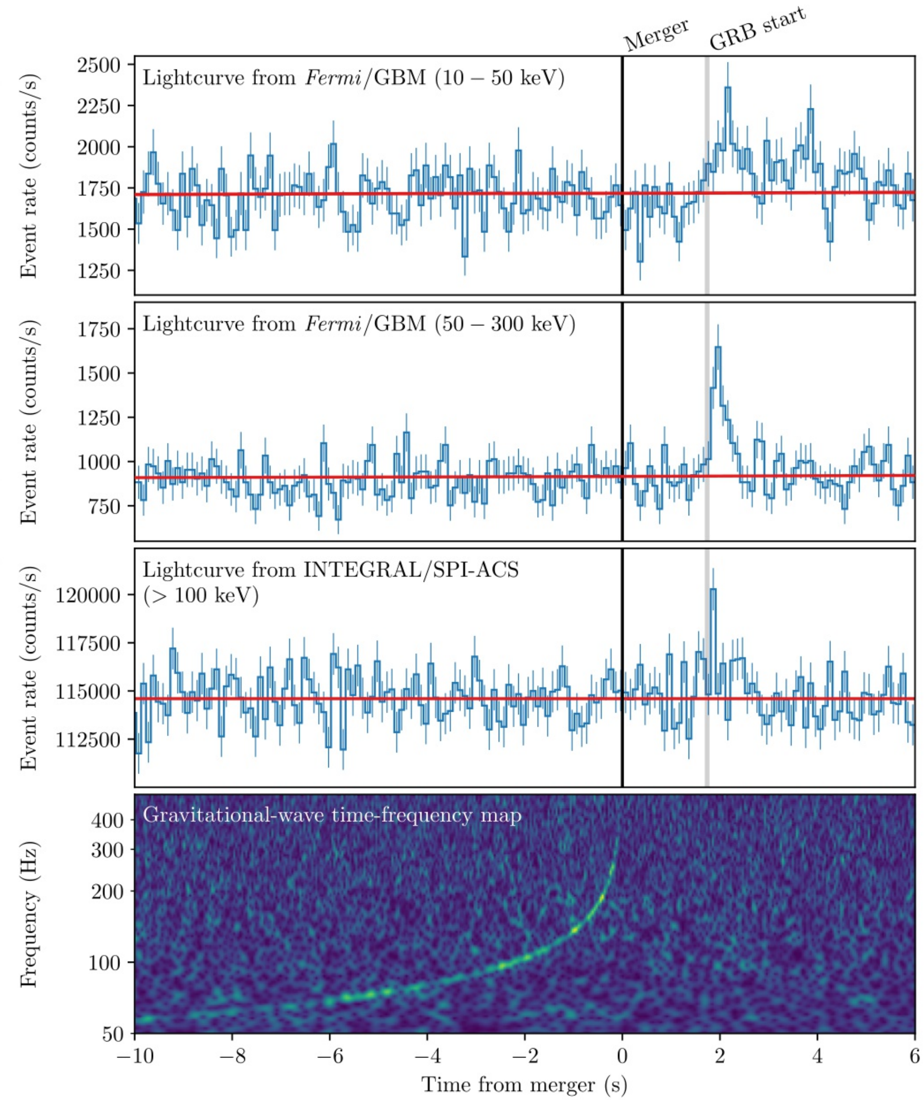
FORMATION of Compact Objects
(very large acceleration of very large masses)

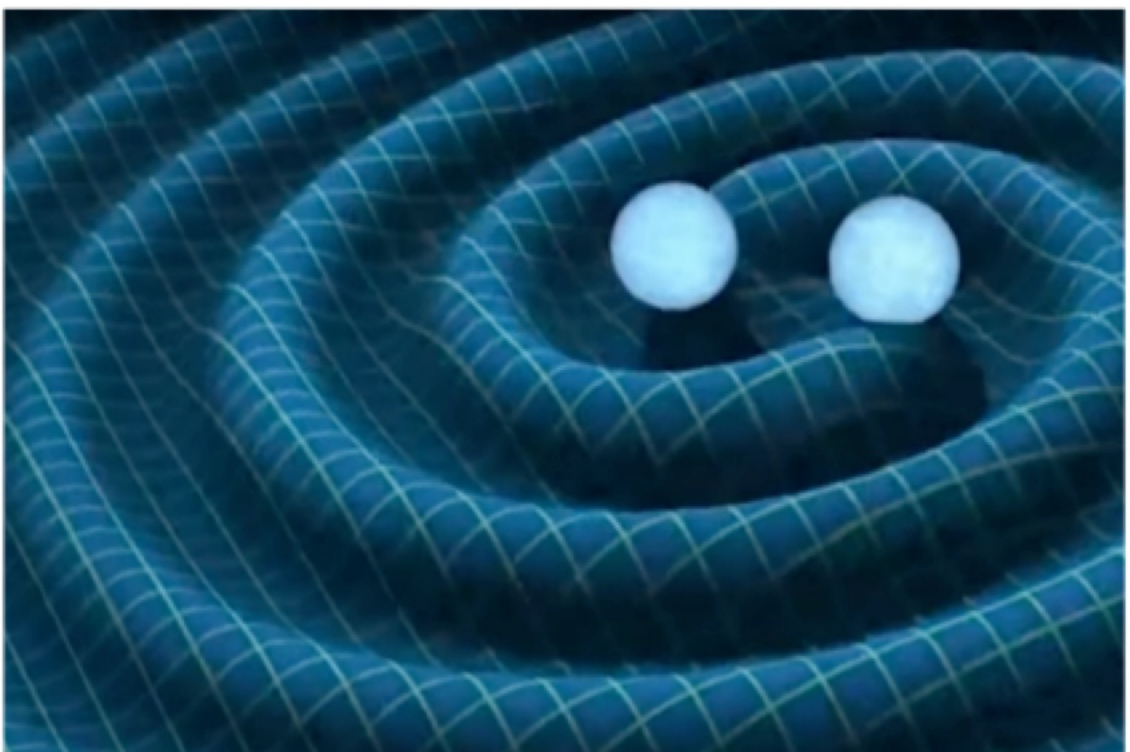
Natural connection to **Gravitational Waves**

neutron-star neutron-star merging



GRB 170817A





GW 170817

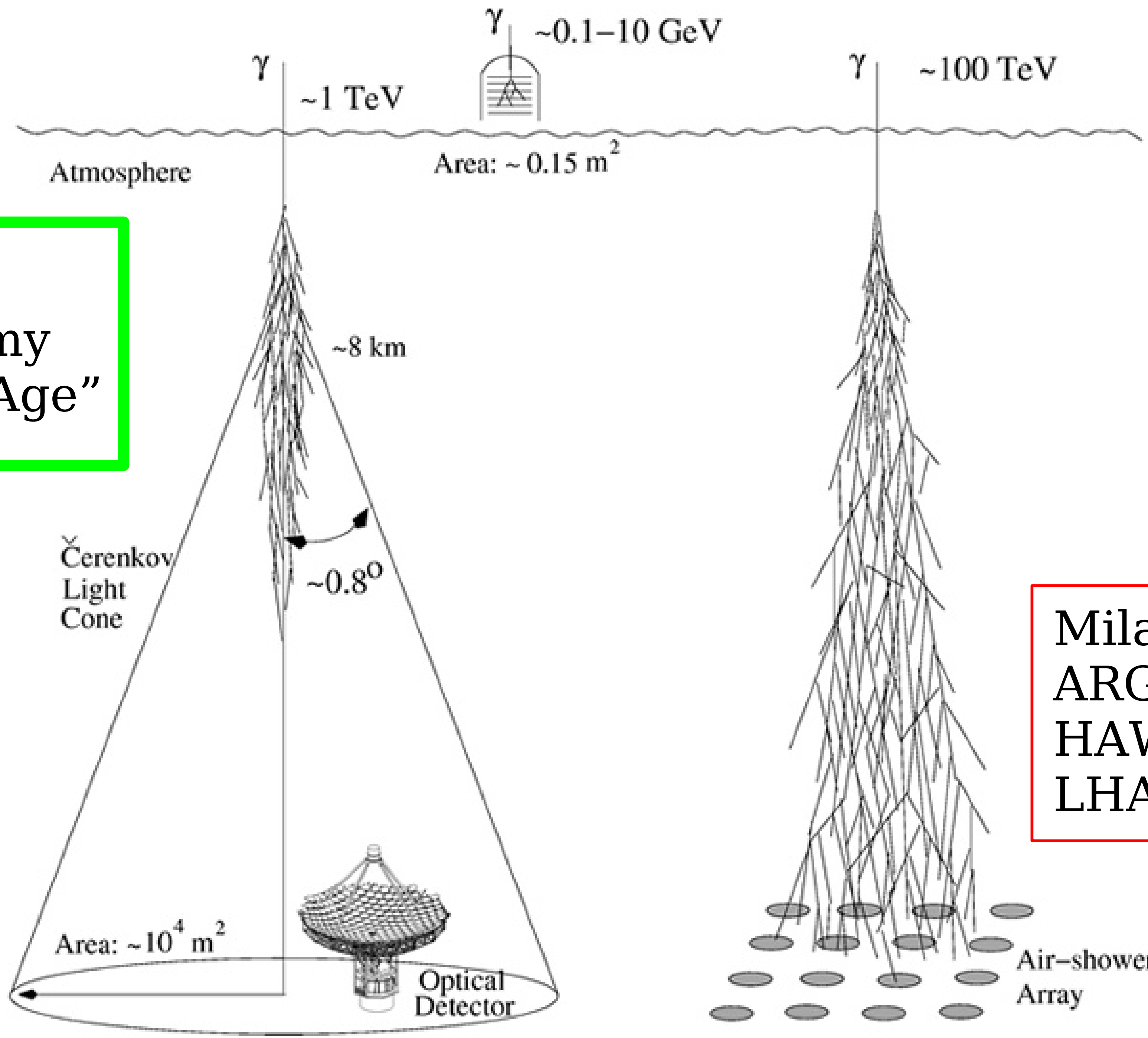
Gamma Rays

$$E > 100 \text{ MeV}$$

More in general
photons in a very broad range
of energy (wavelength)
[21 orders of magnitudes]
from Radio to 100 TeV
(and above in the future)

Egret
Agile
Fermi

Gamma
Astronomy
“Golden Age”



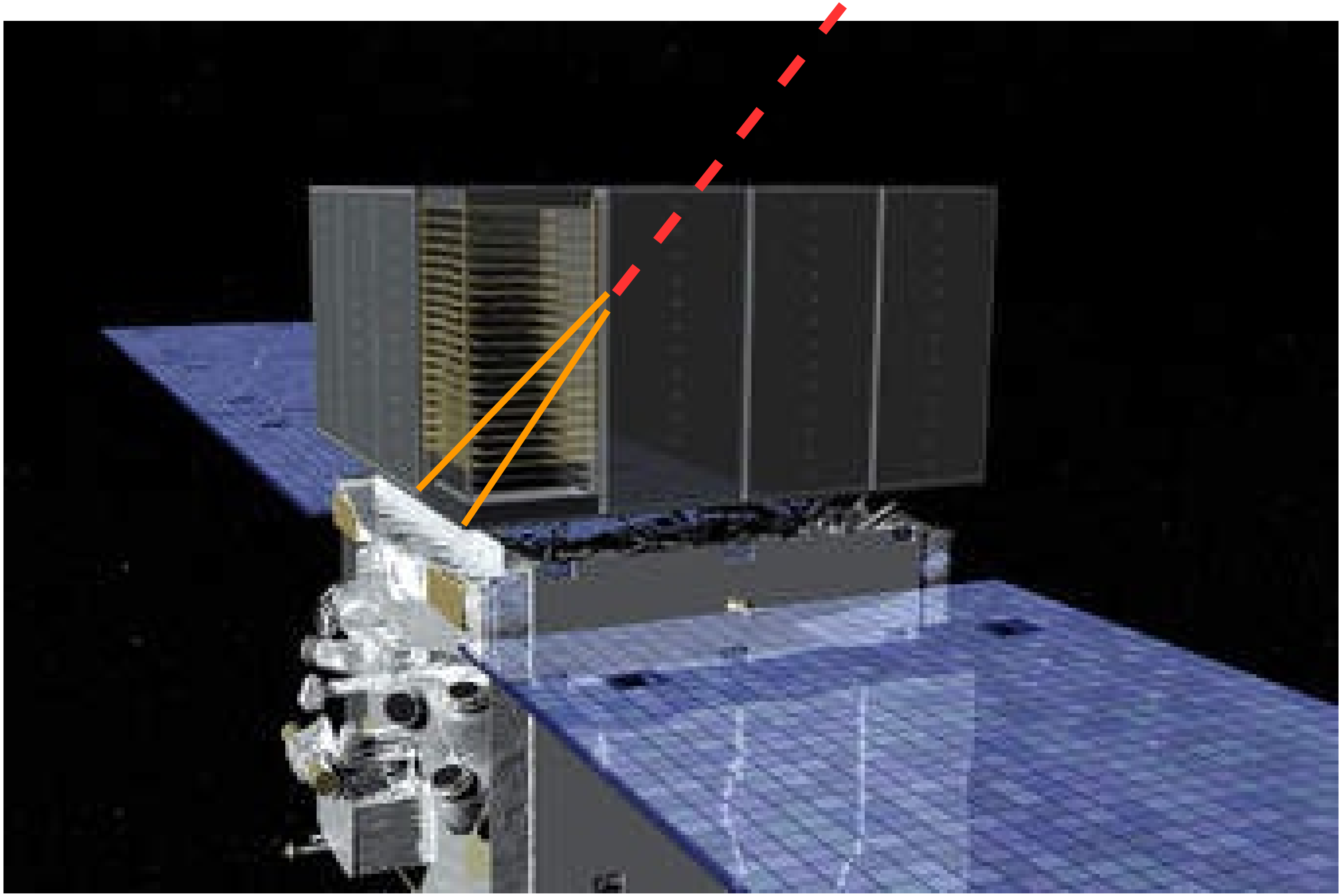
Hess
Magic
Veritas

CTA

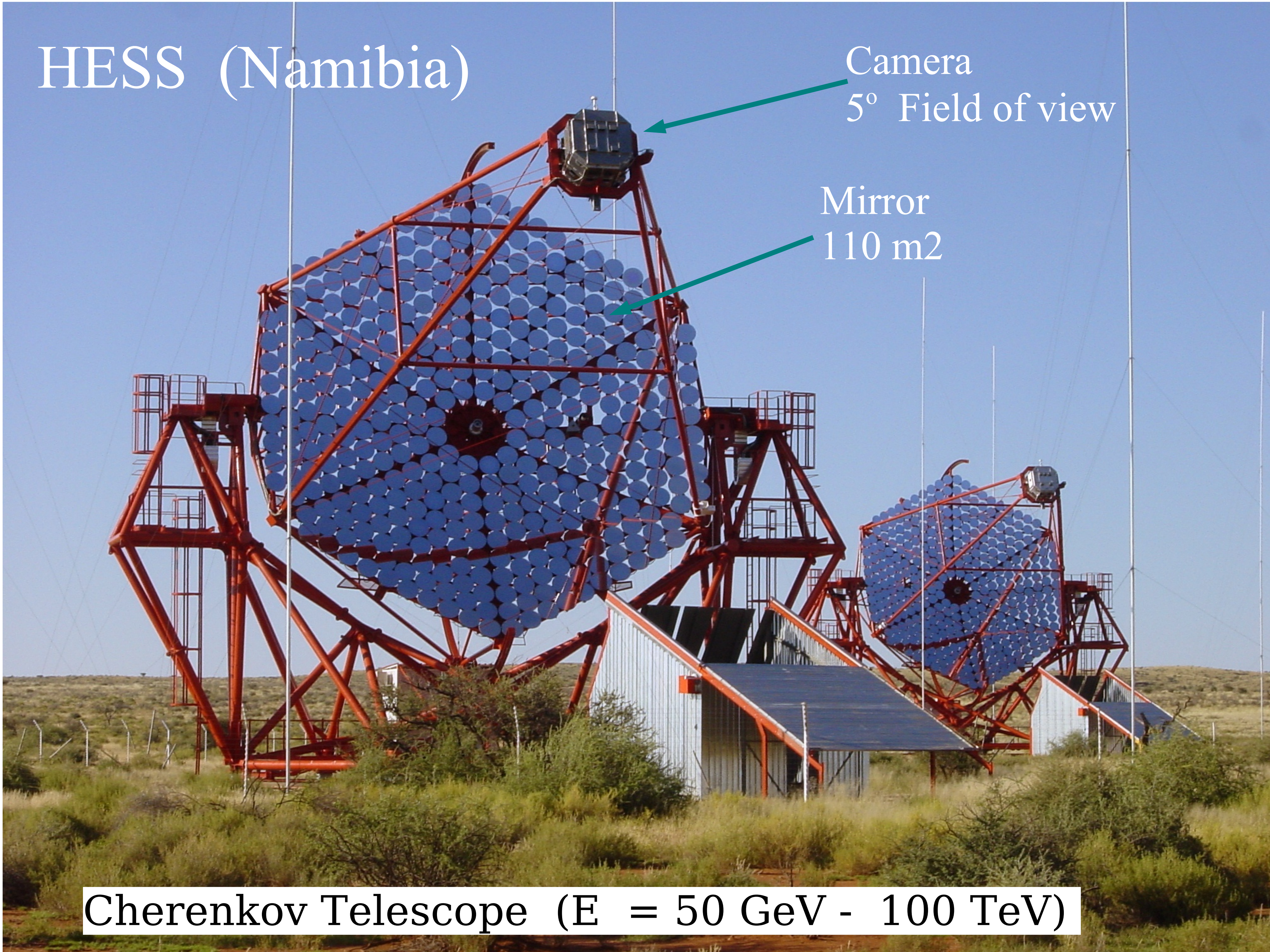
Milagro
ARGO
HAWC
LHAASO

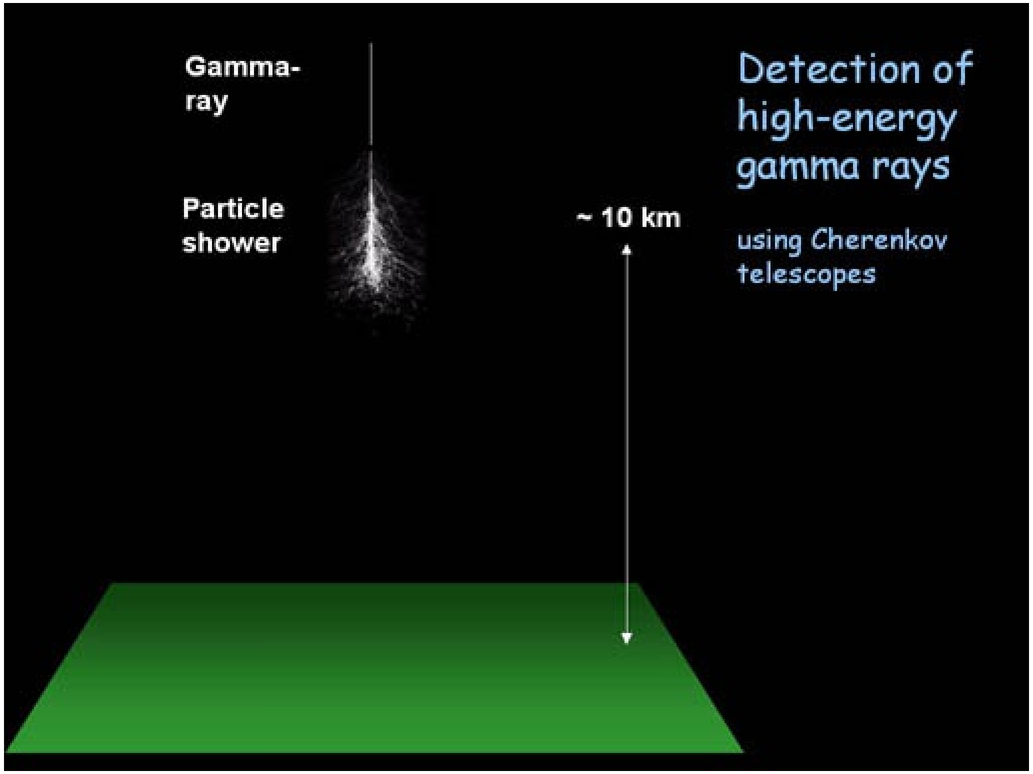
FERMI Telescope (E > 30 MeV)

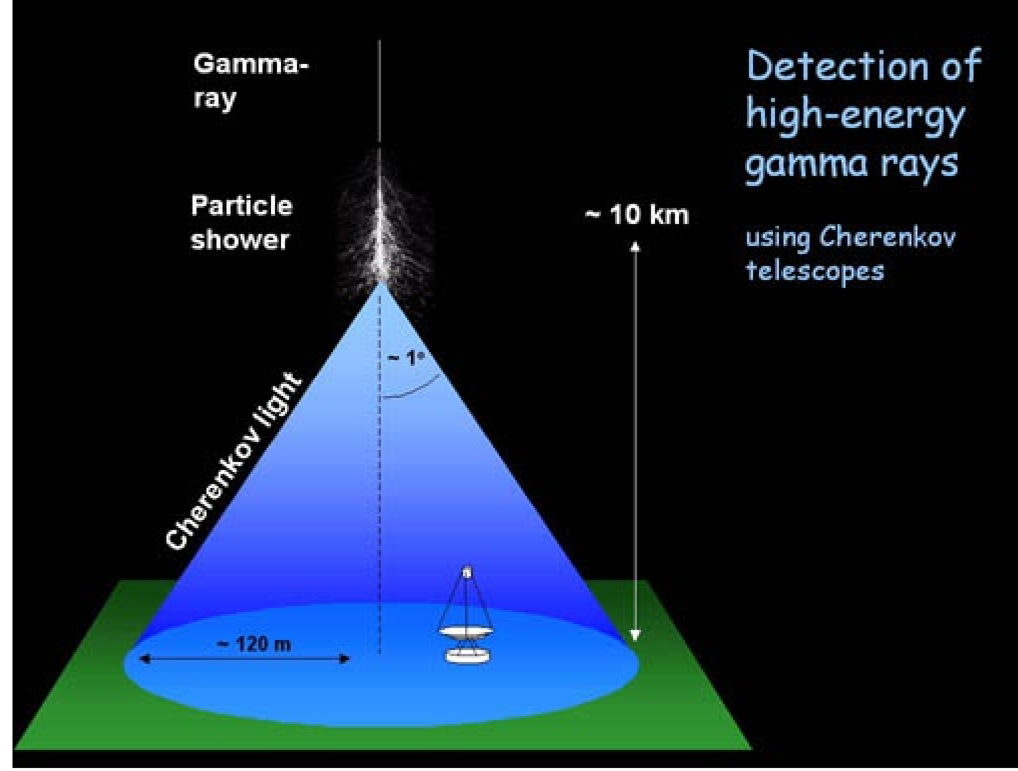
[acceptance allows observations up $E \lesssim 1\ \mathrm{TeV}$

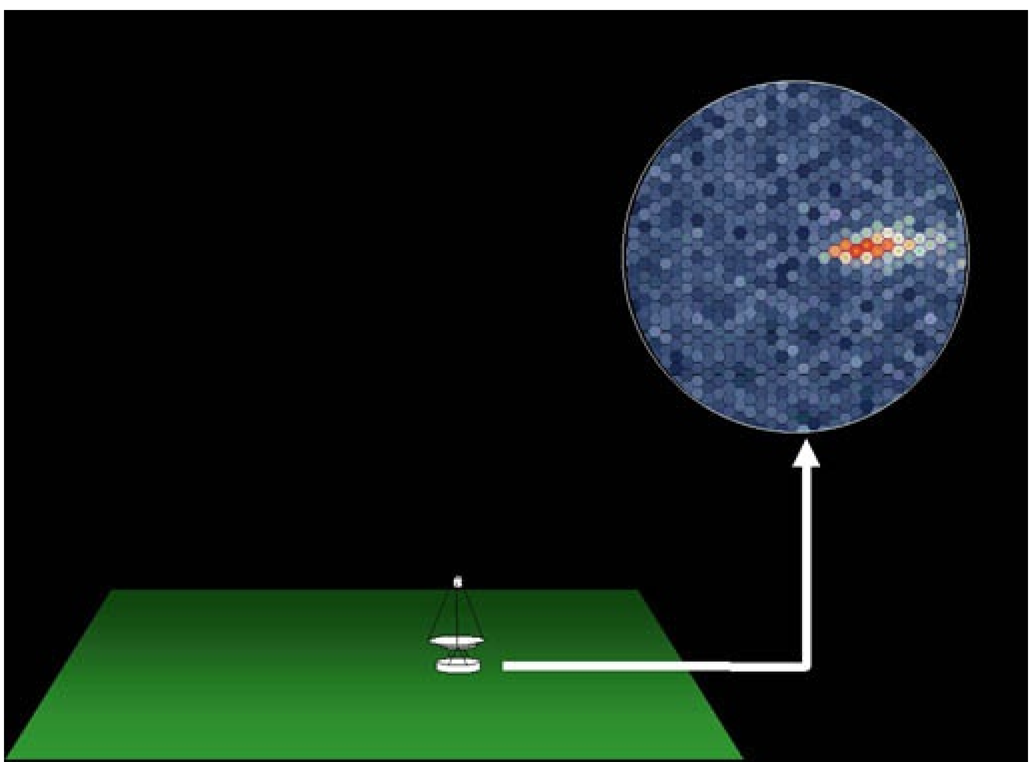


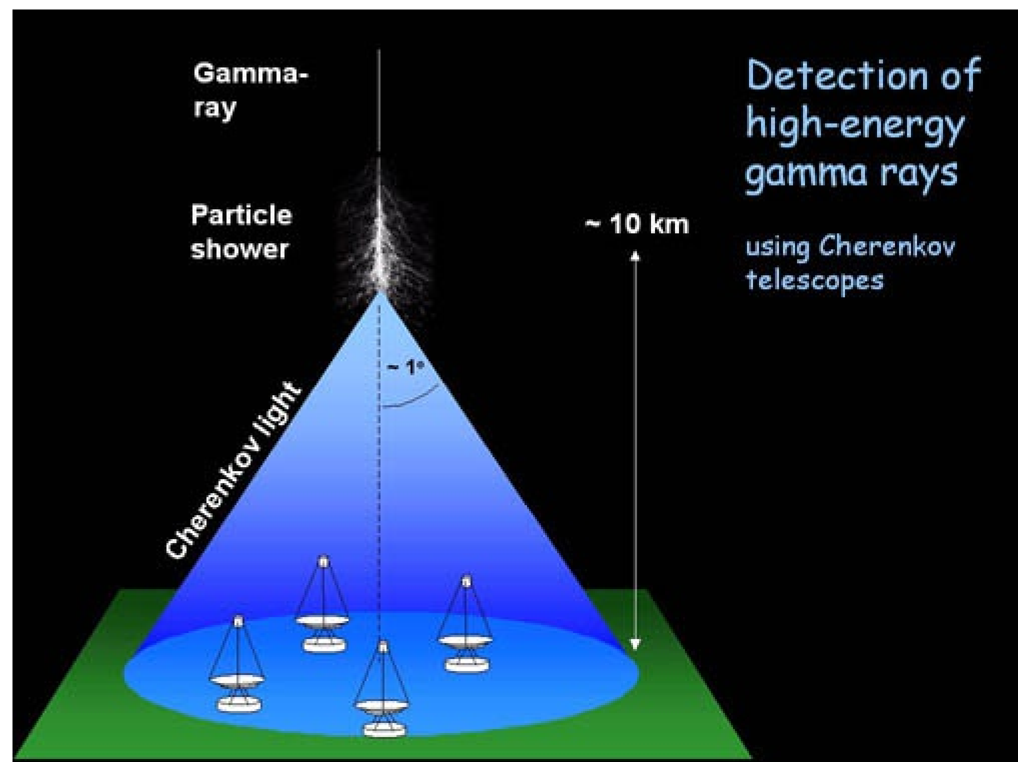
Gamma Ray Burst Monitor [GBM] (E = 10 KeV – 10 MeV)


HESS (Namibia)
Camera
5º Field of view
Mirror
110 m2
Cherenkov Telescope (E = 50 GeV - 100 TeV)

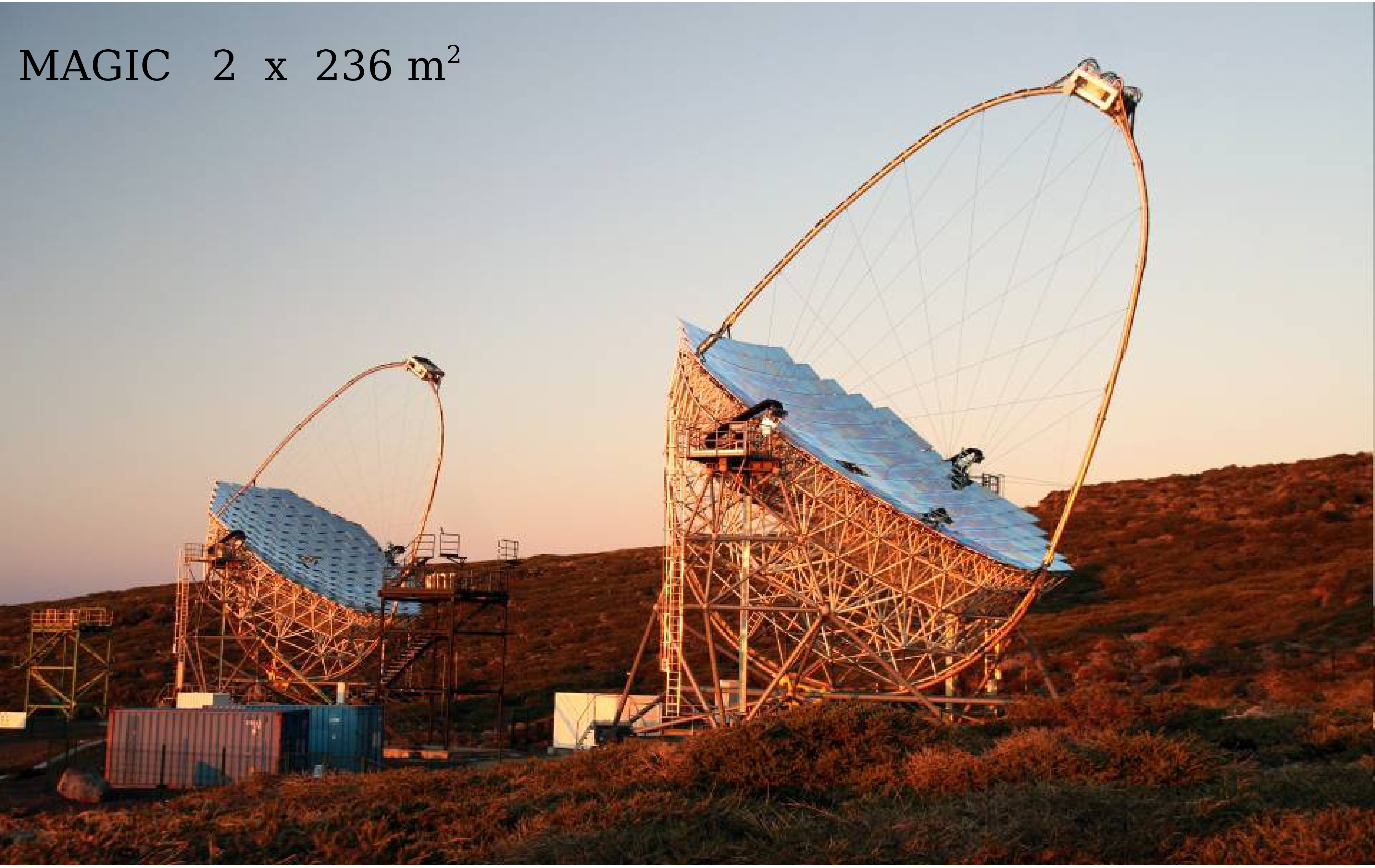

Gamma-
ray
Particle
shower
~ 10 km
Detection of
high-energy
gamma rays
using Cherenkov
telescopes


Gamma-
ray
Particle
shower
~ 10 km
Detection of
high-energy
gamma rays
using Cherenkov
telescopes
~ 1°
Cherenkov light
~ 120 m



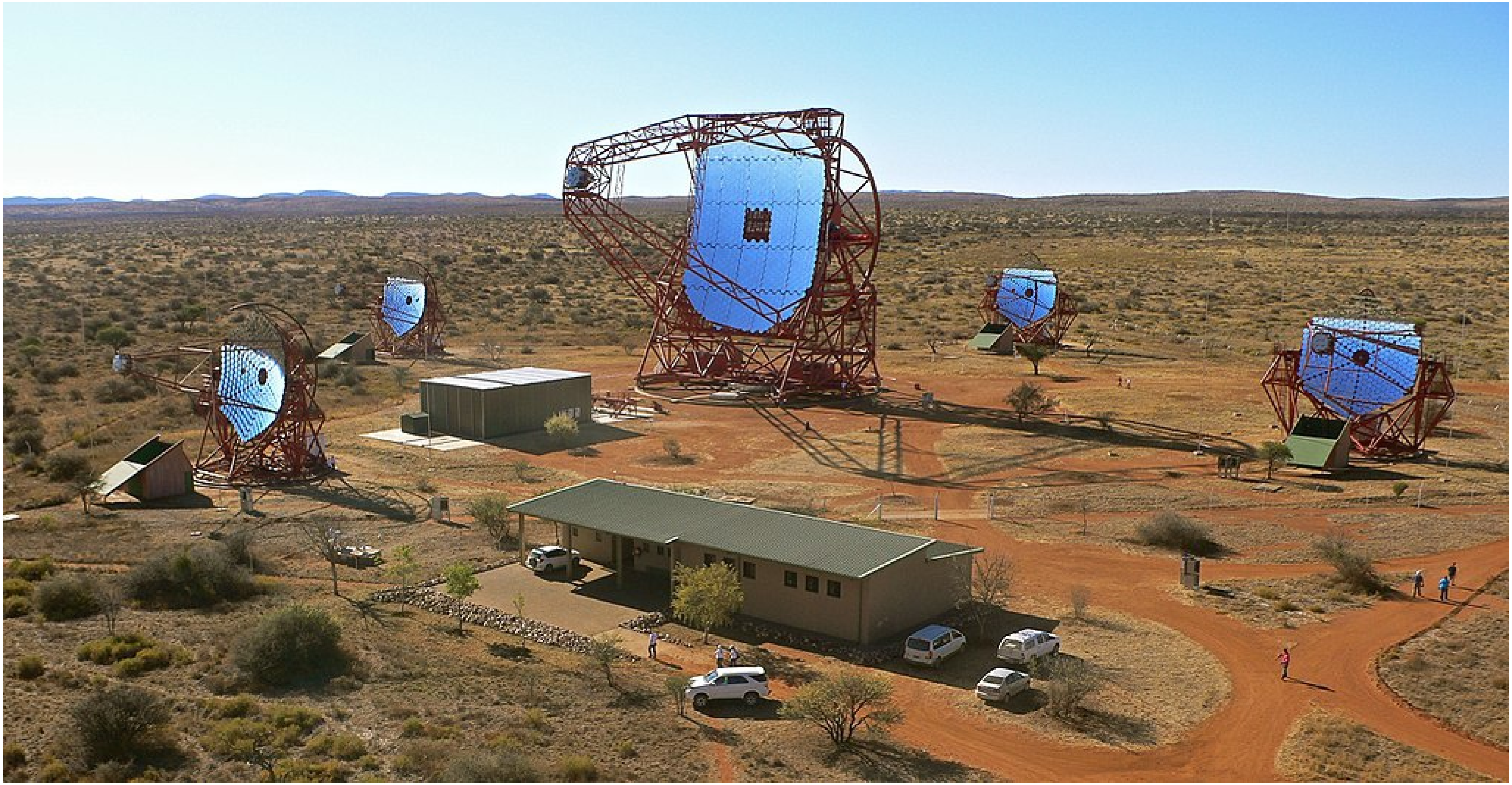

Gamma-
ray
Particle
shower
~ 10 km
Detection of
high-energy
gamma rays
using Cherenkov
telescopes
~ 1°
Cherenkov light

MAGIC 2 x 236 m^2



HESS Telescope
(Namibia)

4 12 m diameter telescopes
1   28 m   “   “



LHAASO detector in China

Western view

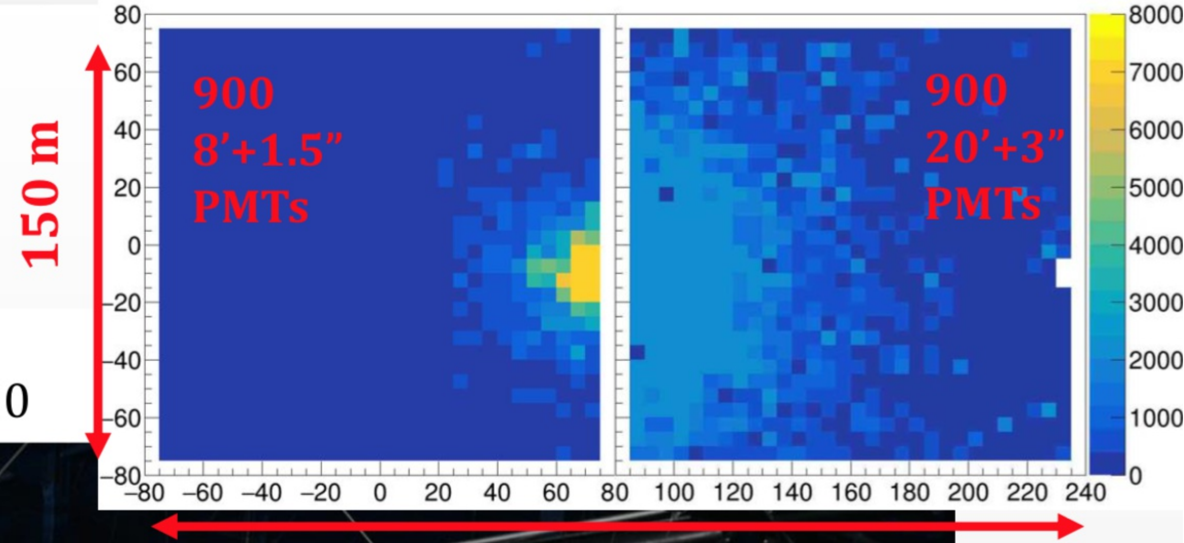
Eastern view

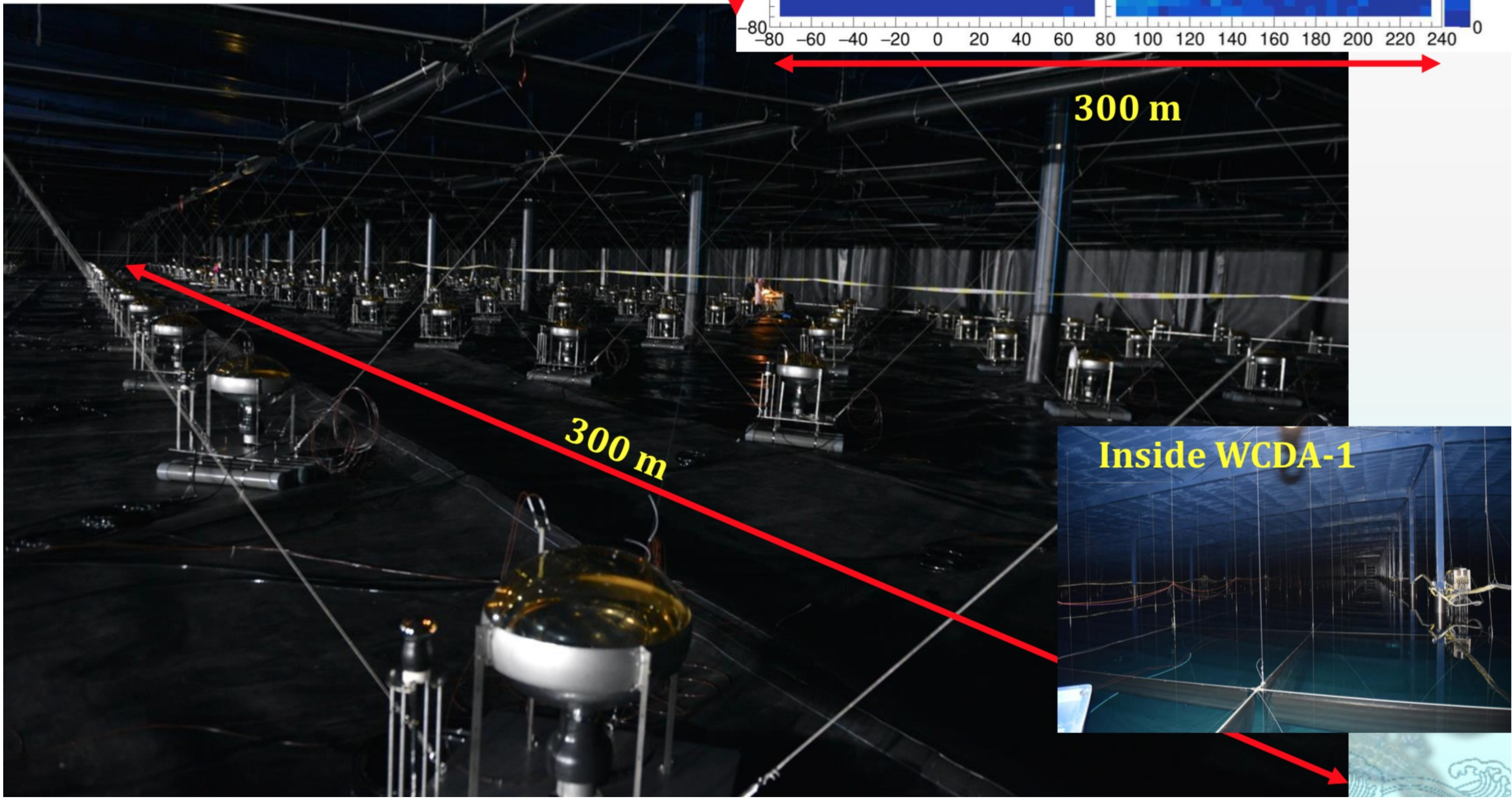
- LHAASO bird view in Oct. 2019

LHAASO
高海拔宇宙线观测站

Inside WCDA-3

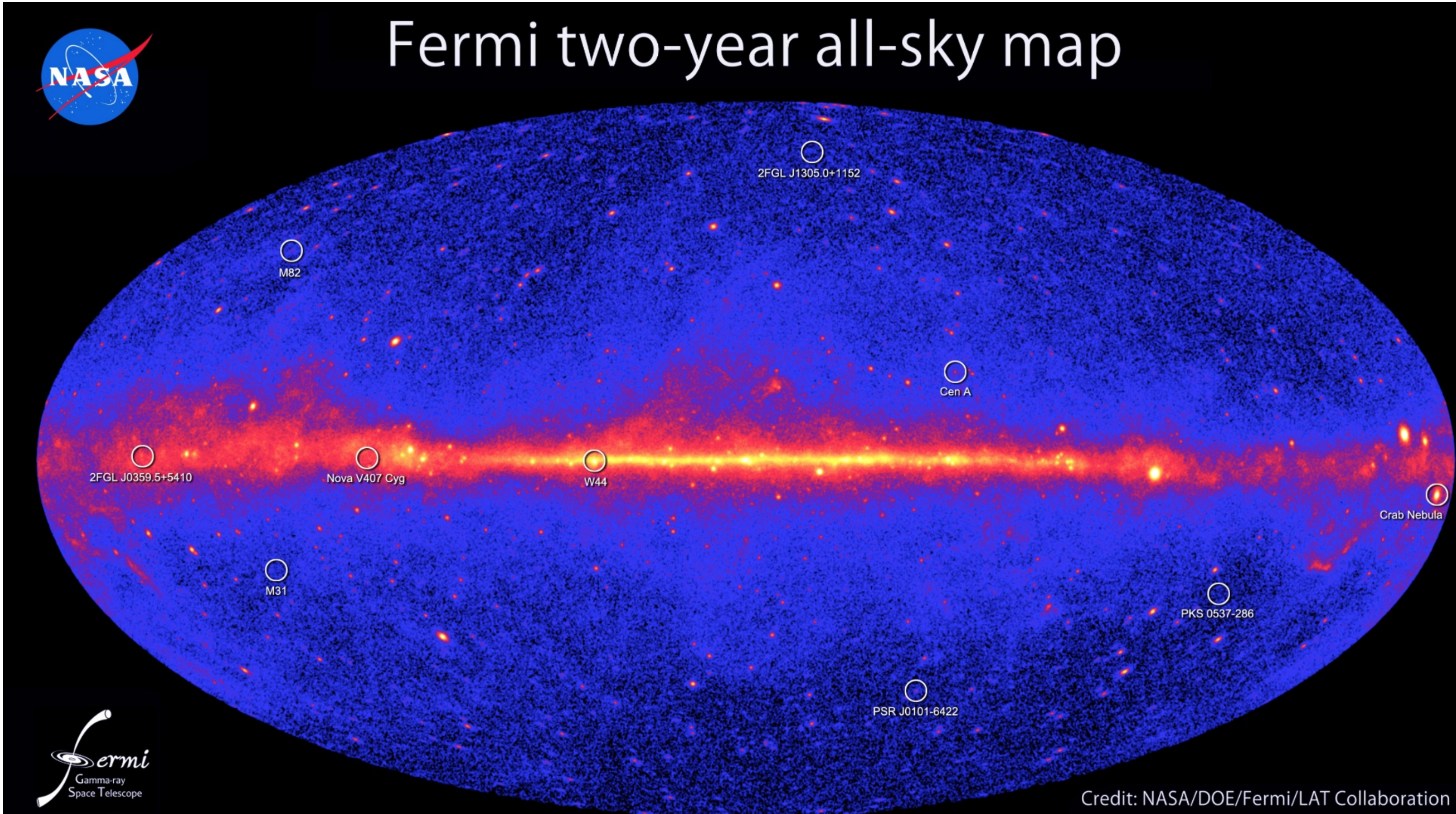
- WCDA-1 started operating April 2019
- WCDA-1 started operating January 2020





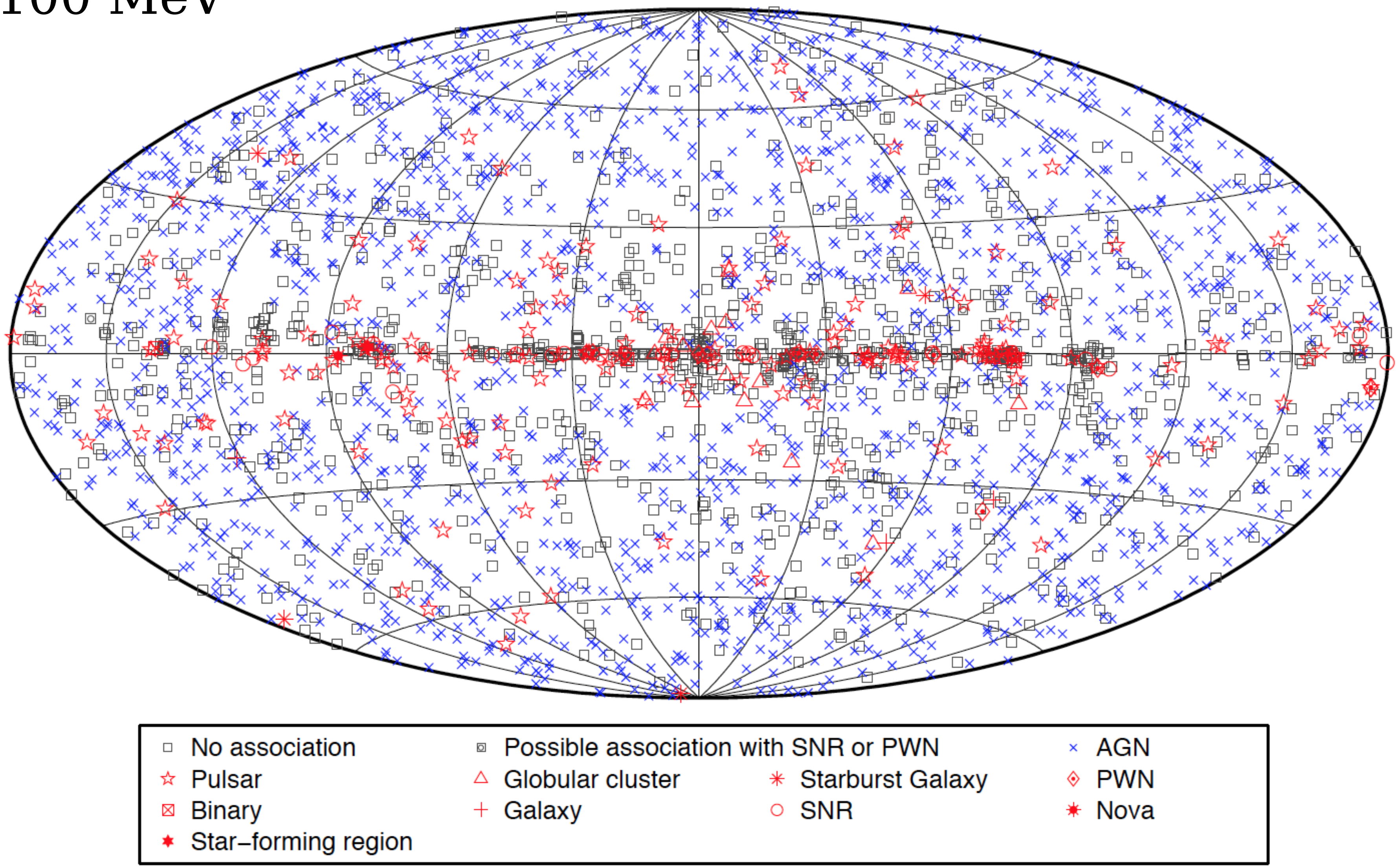
$E_\gamma \geq 100$ MeV

Gamma Ray Sky

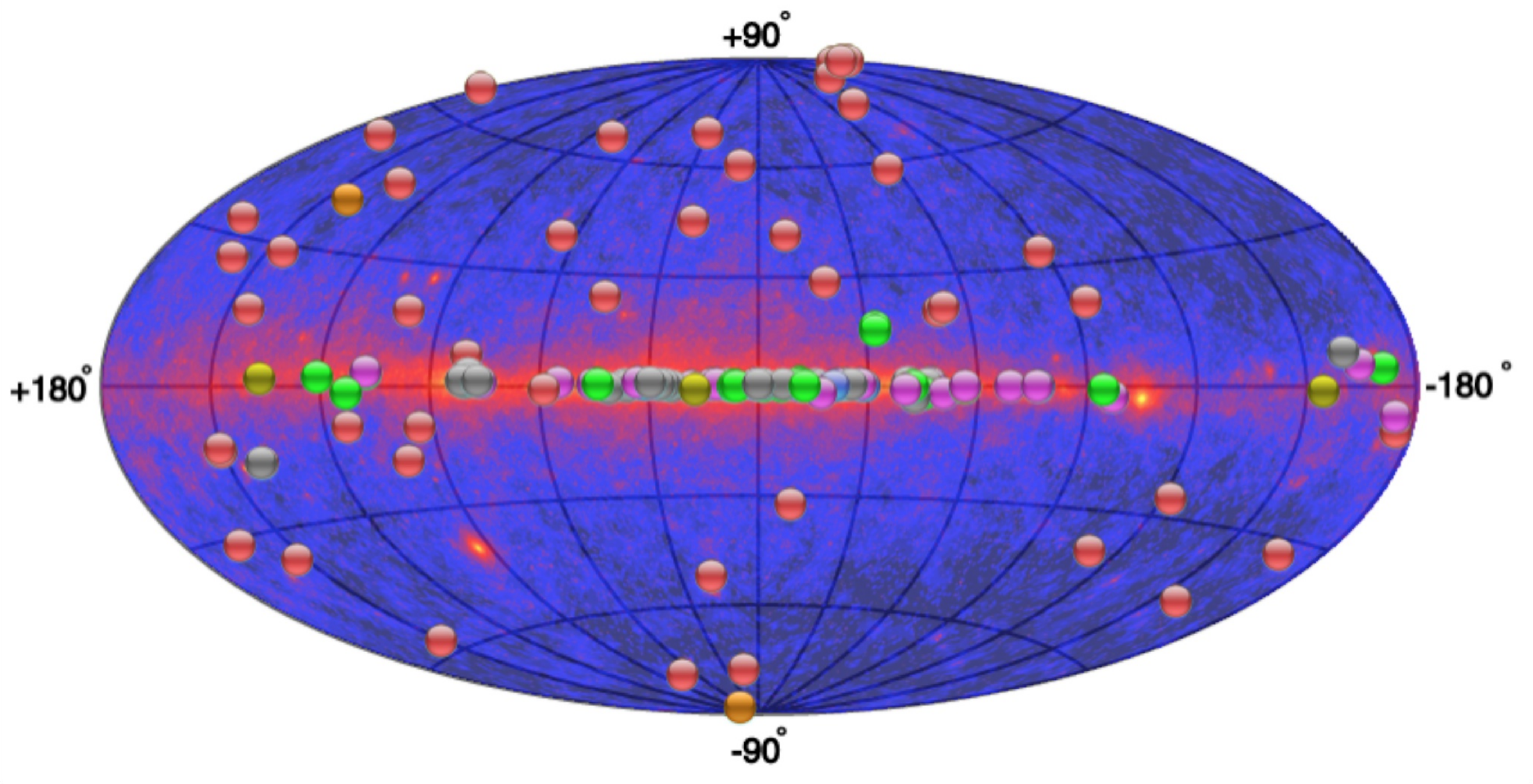


3^{rd} FERMI Catalog 3034 sources

E > 100 MeV



TeV Sky 170 → 200 Sources



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

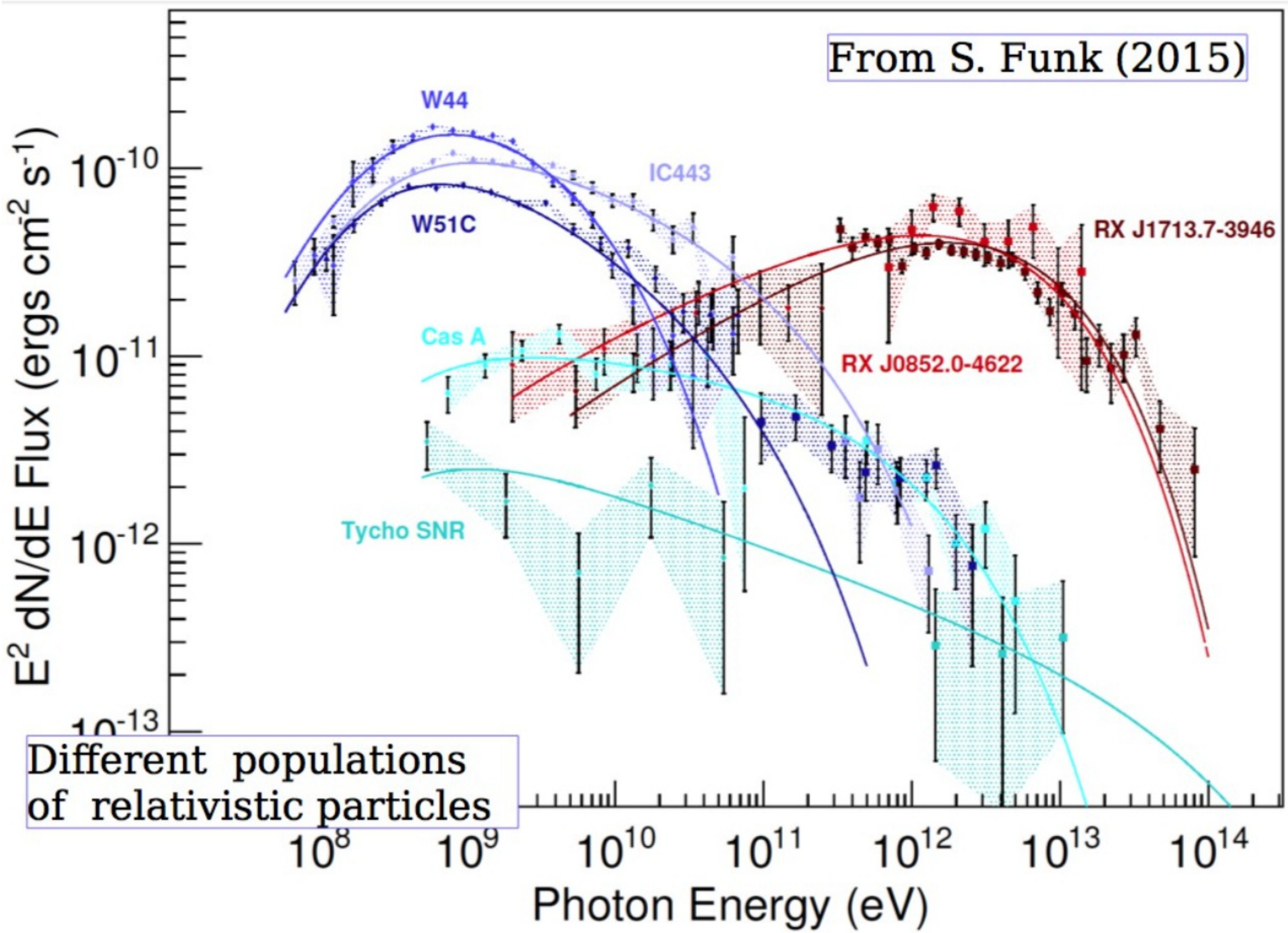
The sky in gamma rays:

1. A diffuse flux generated by the radiation of cosmic rays that fill the Galaxy interacting with gas and radiation fields.

2. An ensemble of Galactic (quasi)-point sources

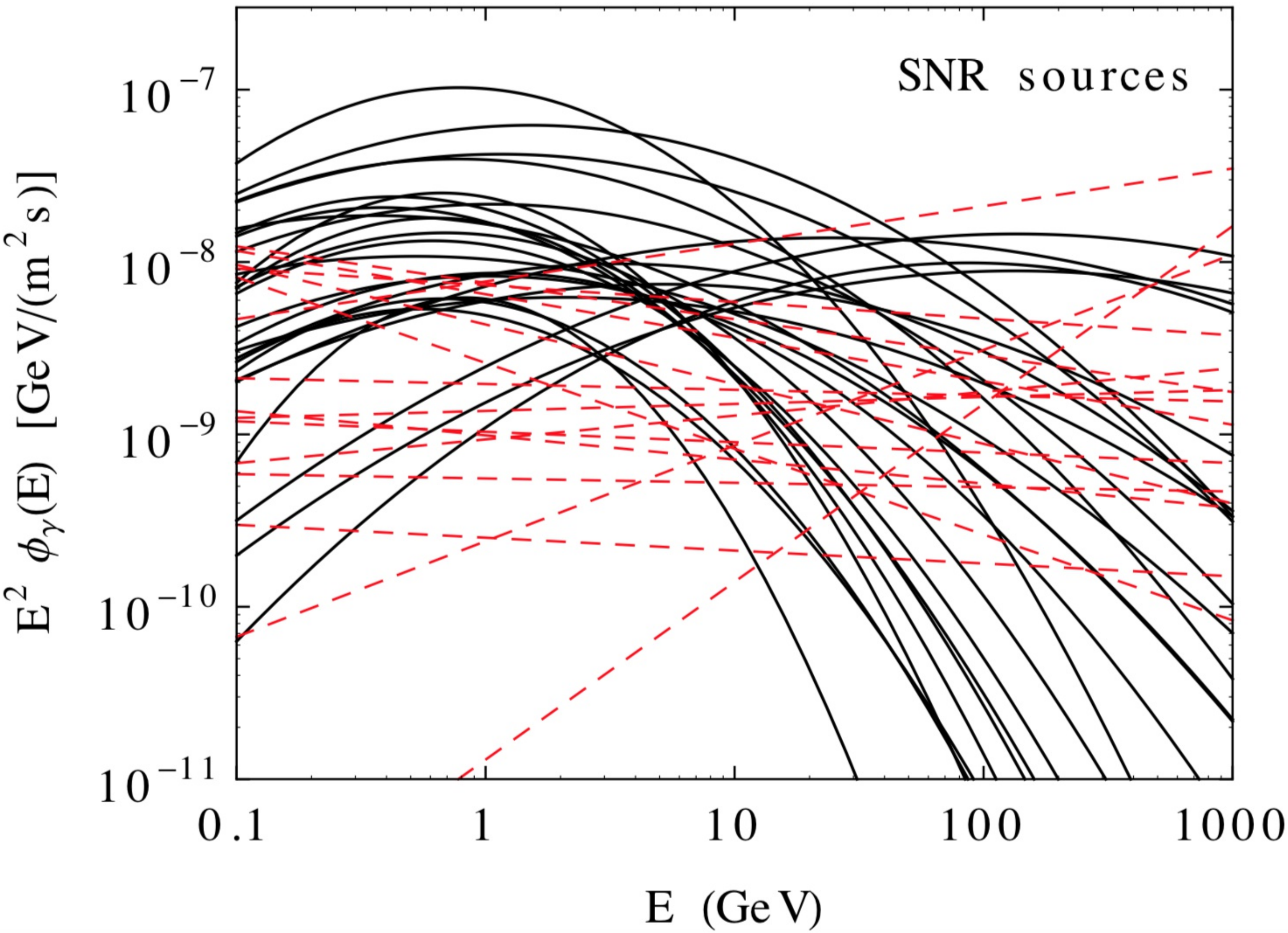
3. An ensemble of extragalactic point sources

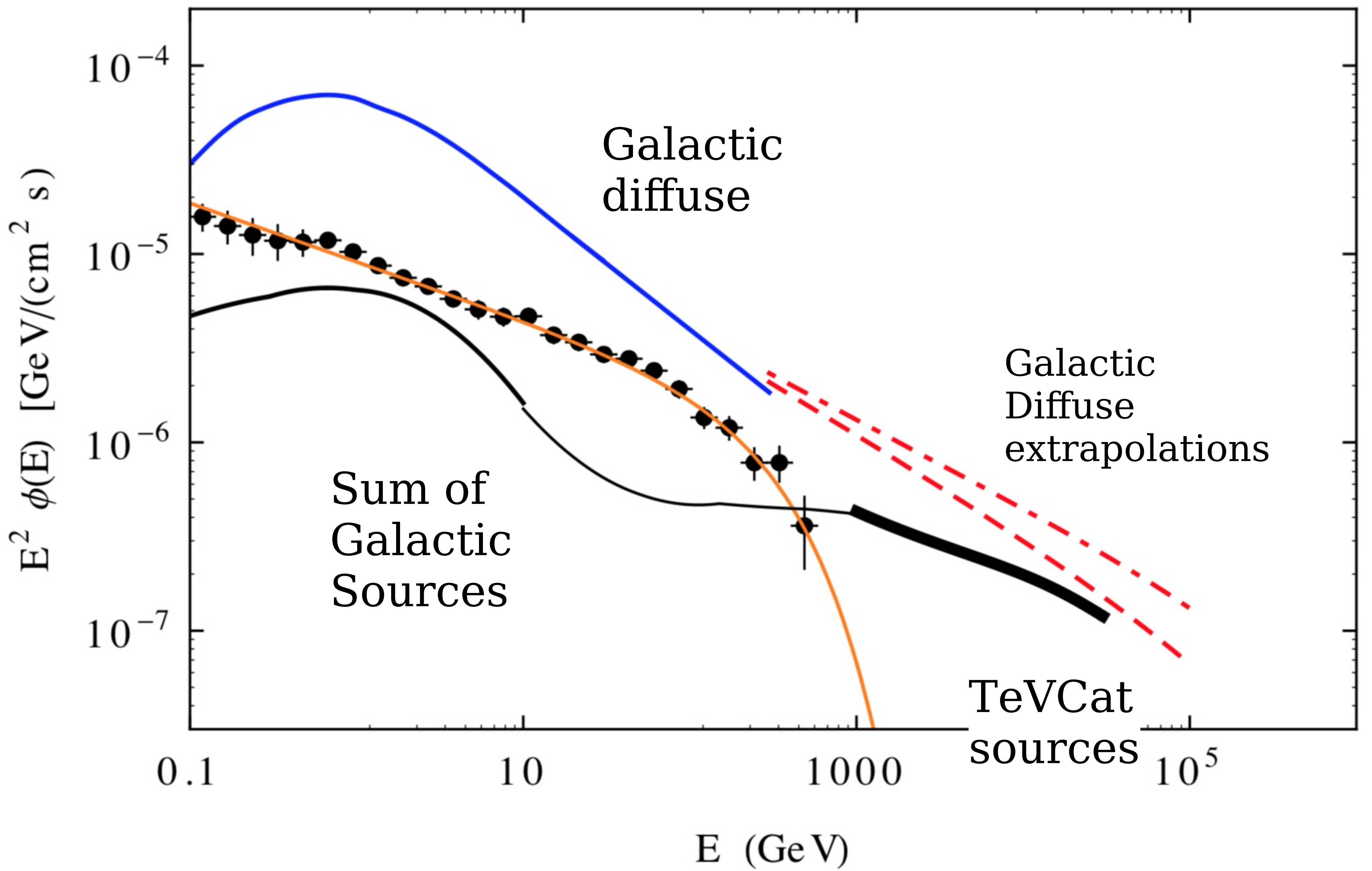
Spectra of sources associated with Supernovae



Different populations of relativistic particles

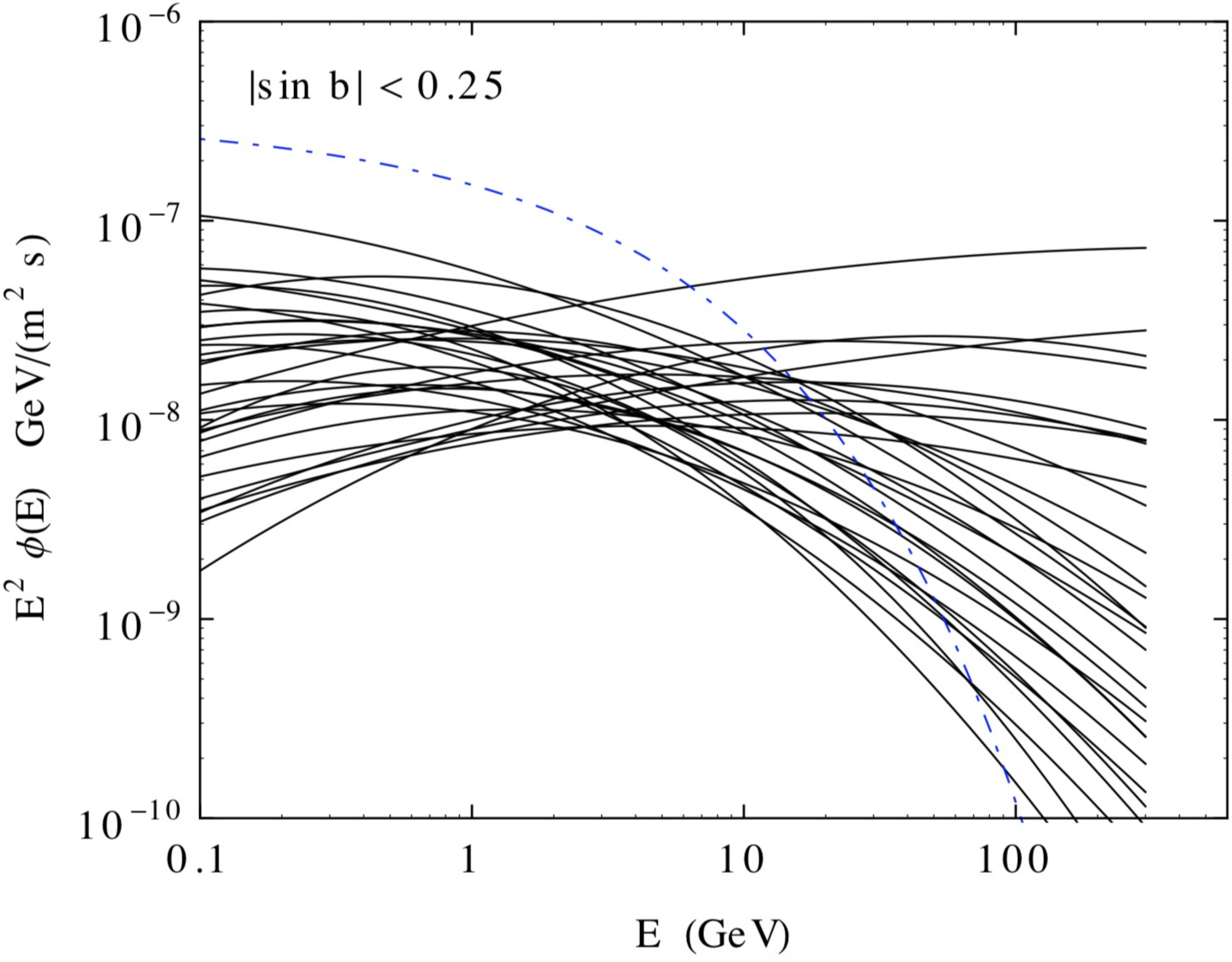
Fits to the FERMI sources associated with Supernova Remnants





Galactic
diffuse
Galactic
Diffuse
extrapolations
Sum of
Galactic
Sources
TeVCat
sources
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E^2\ \phi(E)$ [GeV/(cm^2 s)]
0.1
10
1000
10^5
E (GeV)

Fits to the 30 brightest extragalactic sources in FERMI catalog

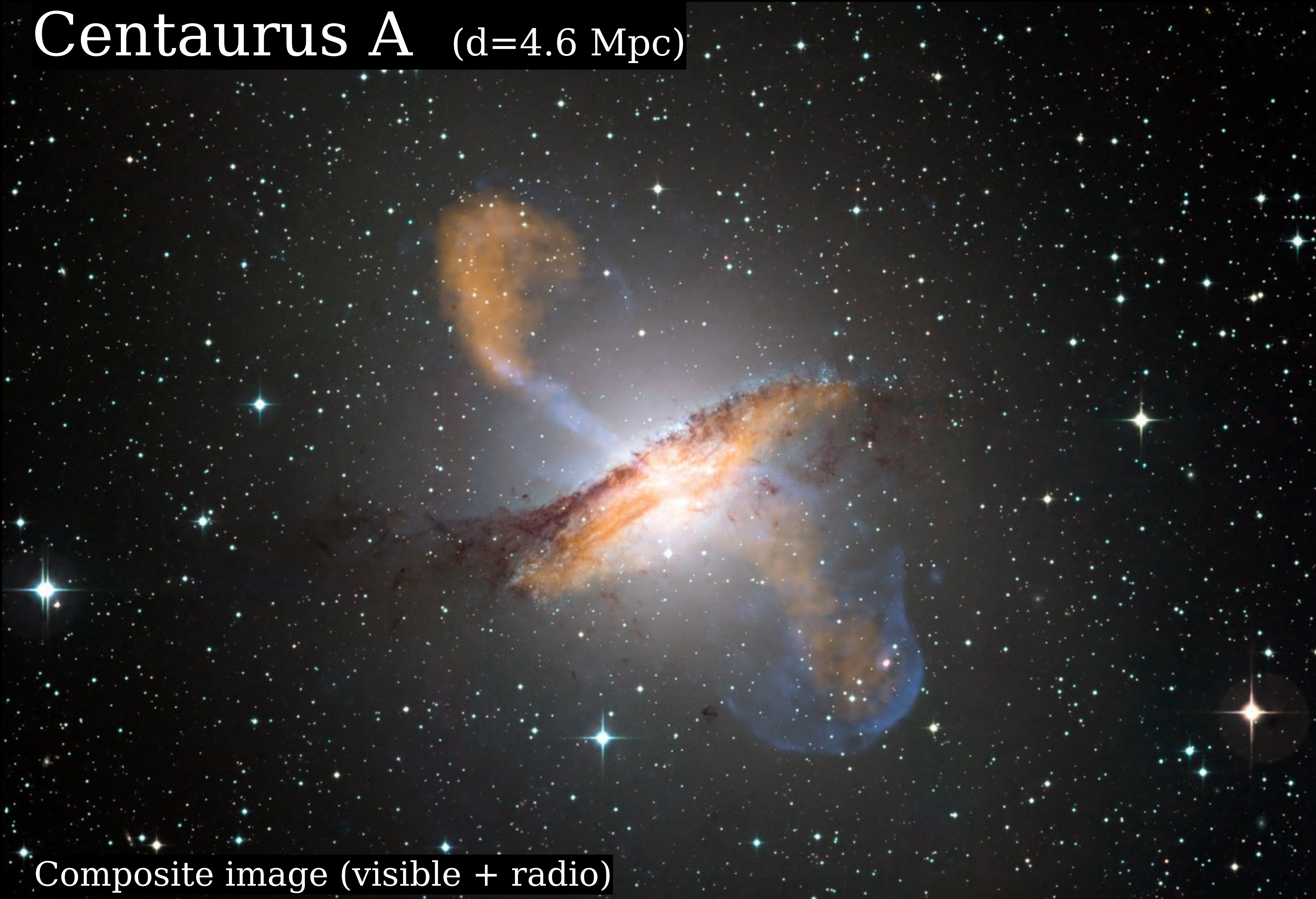


Super Massive Black Holes
(at the center of Galaxies)

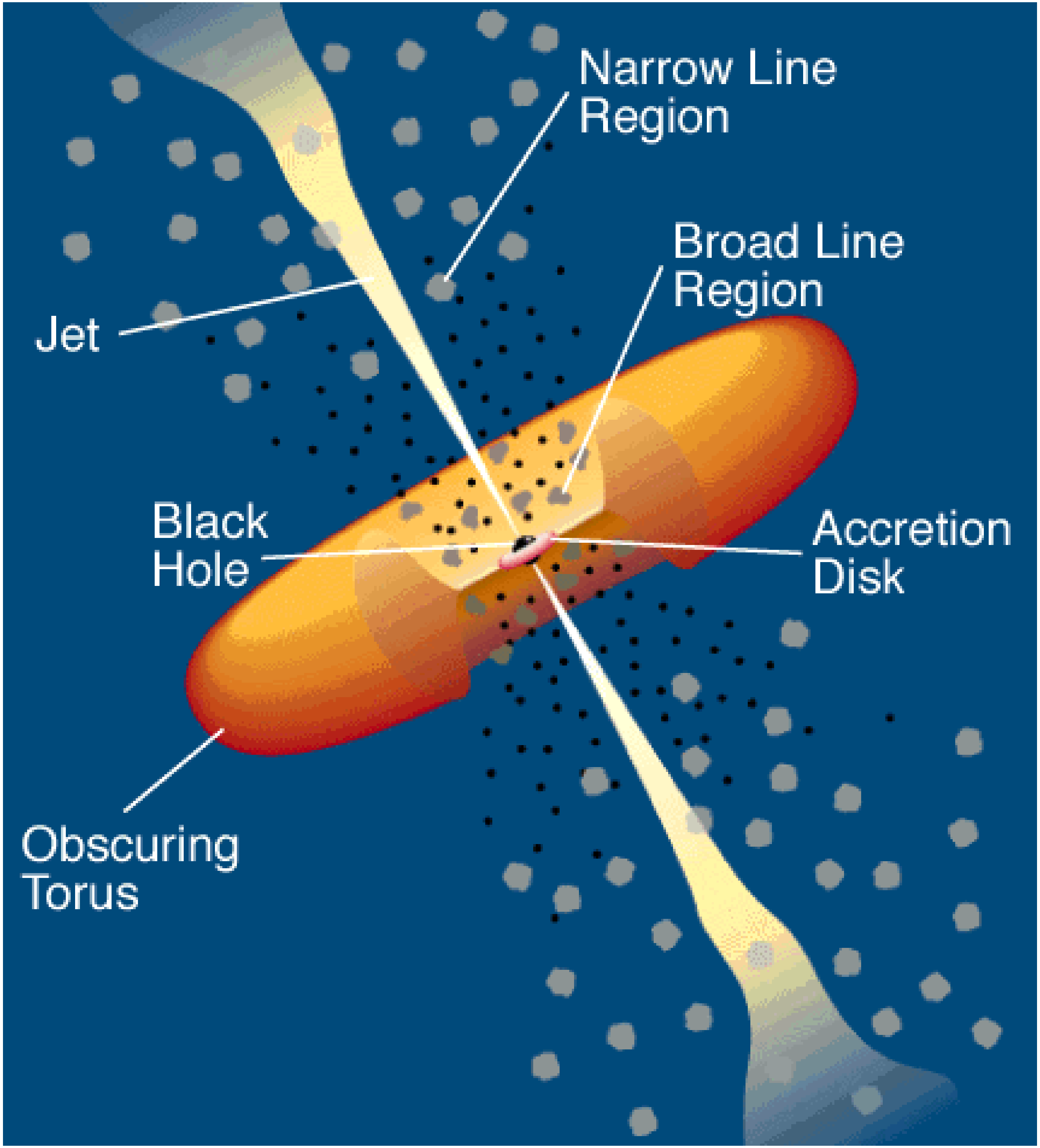
Active Galactic Nuclei

(powered by mass accretion)

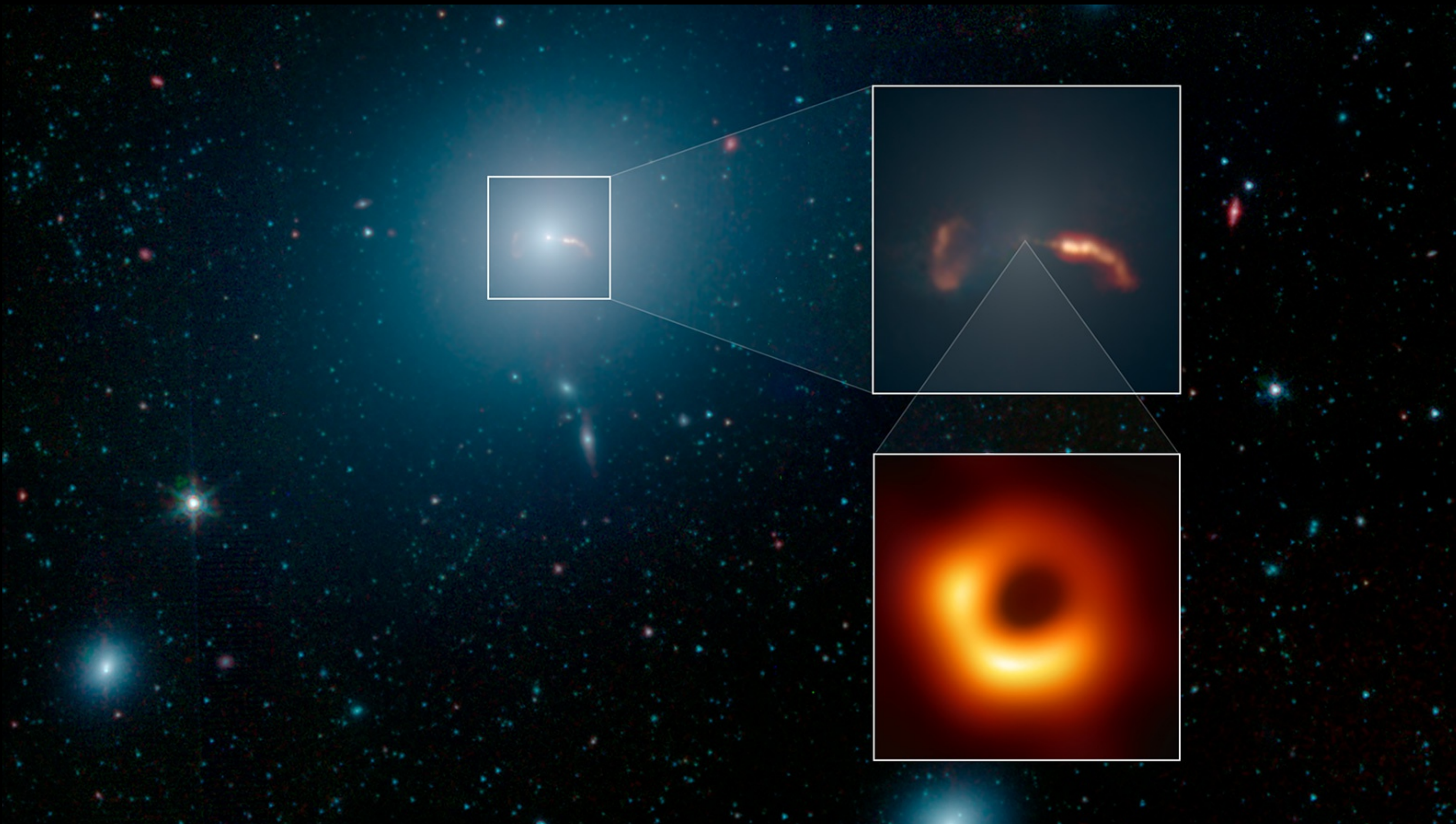
Centaurus A (d=4.6 Mpc)



Composite image (visible + radio)


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

M87 (d=17 Mpc)

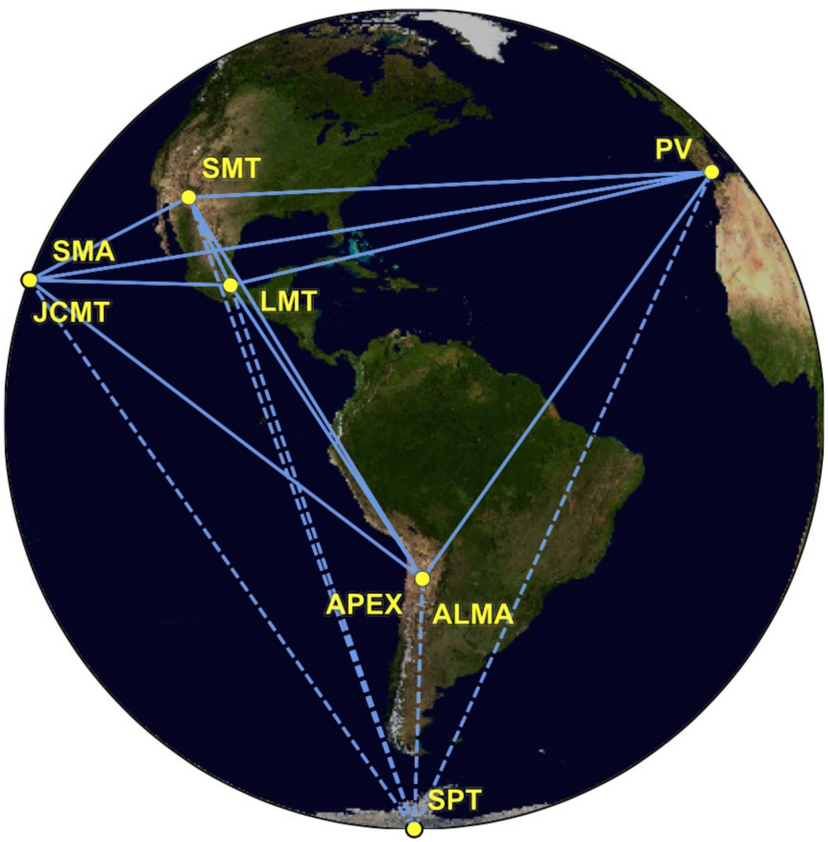


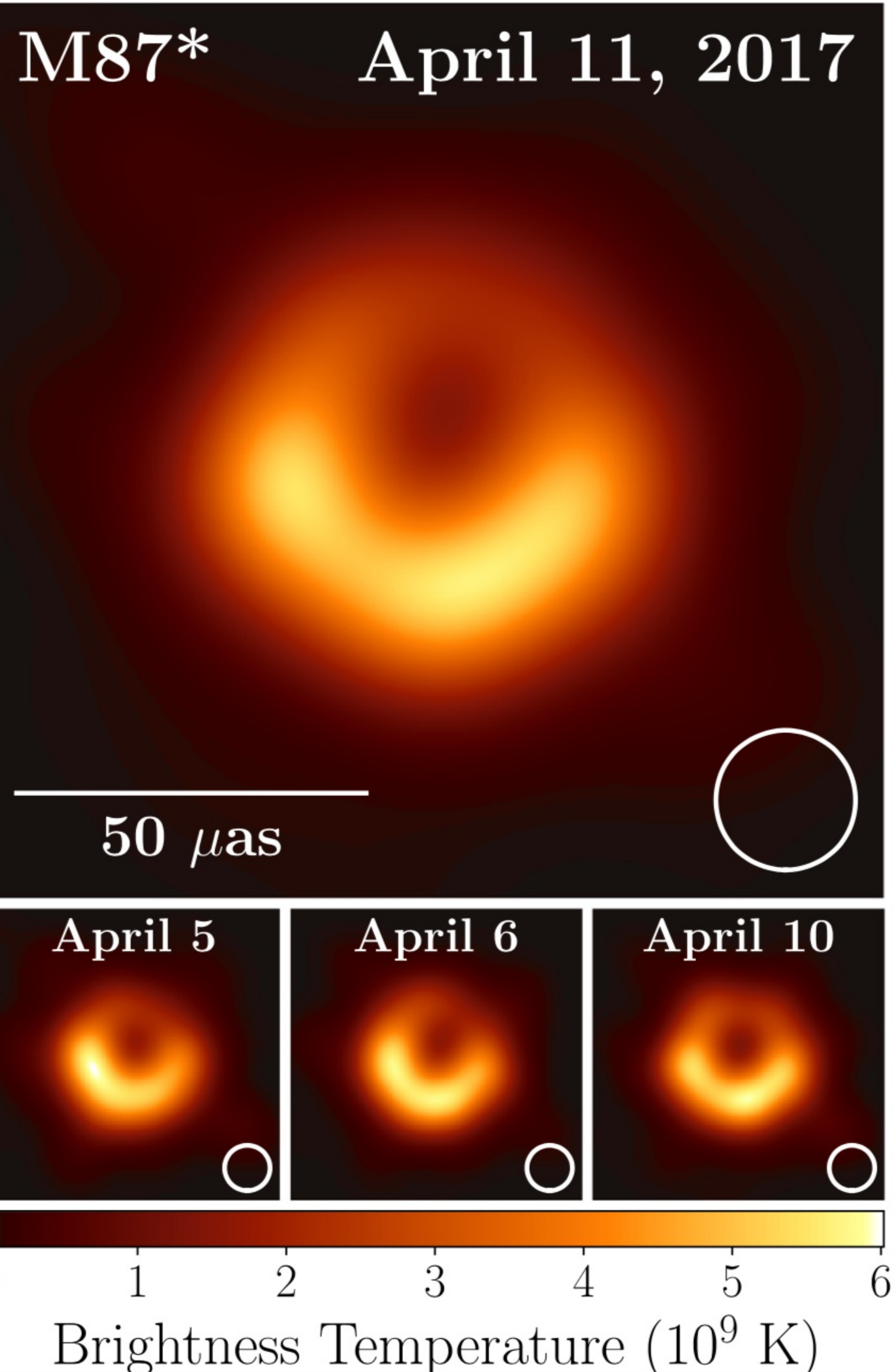
The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10

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

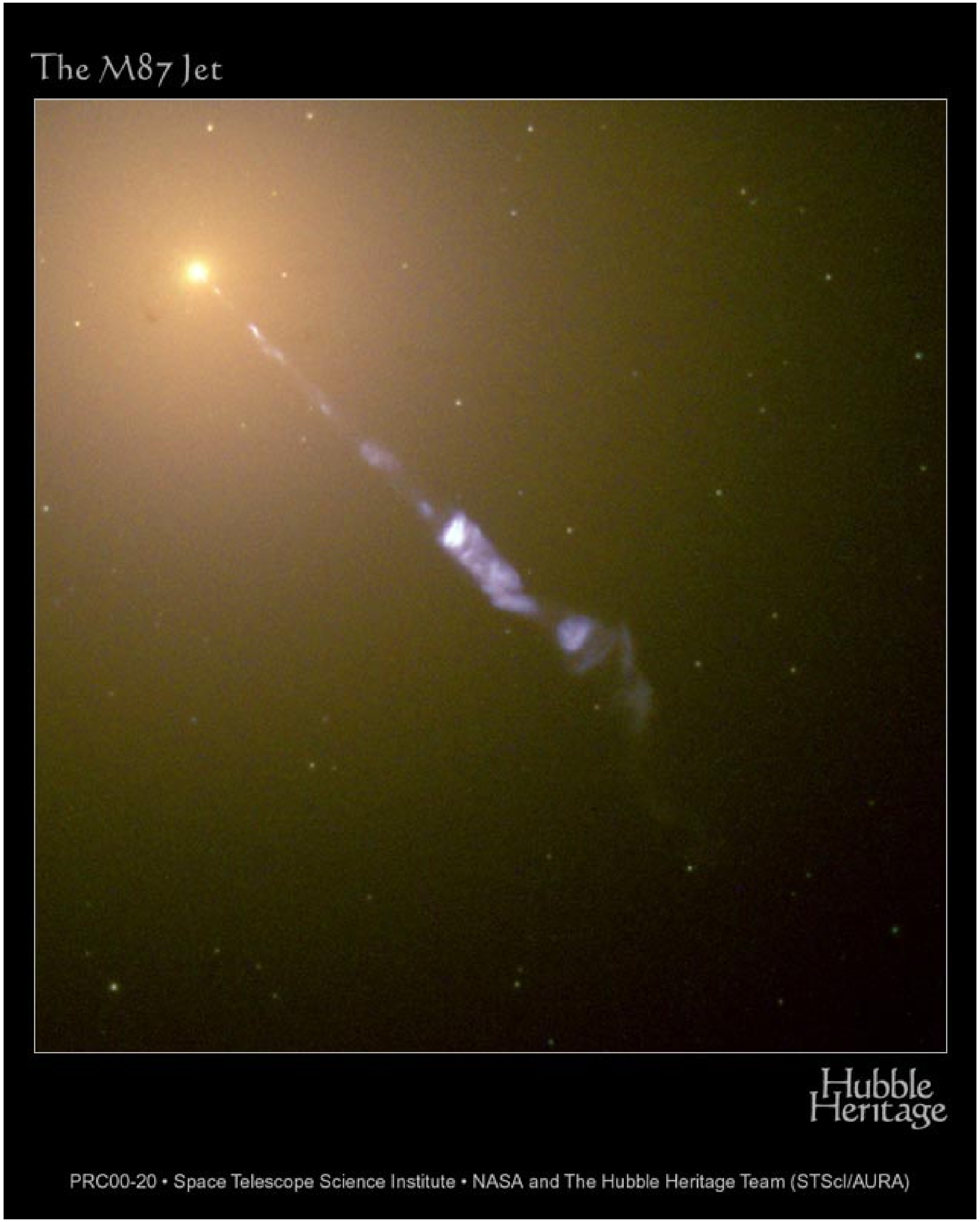
$$R_S = \frac{2\,G}{c^2}\ M$$

Photon capture radius

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

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

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



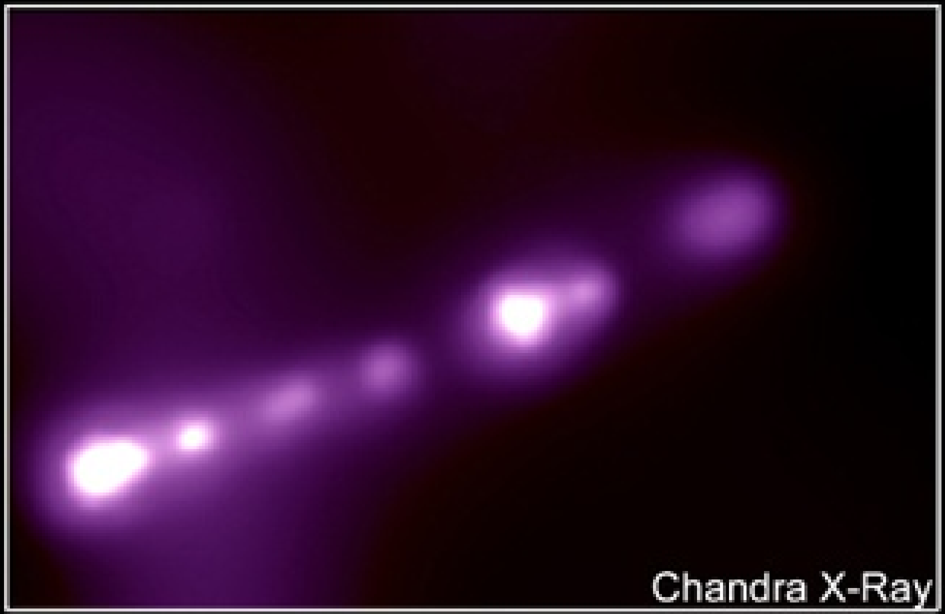
M87 JET

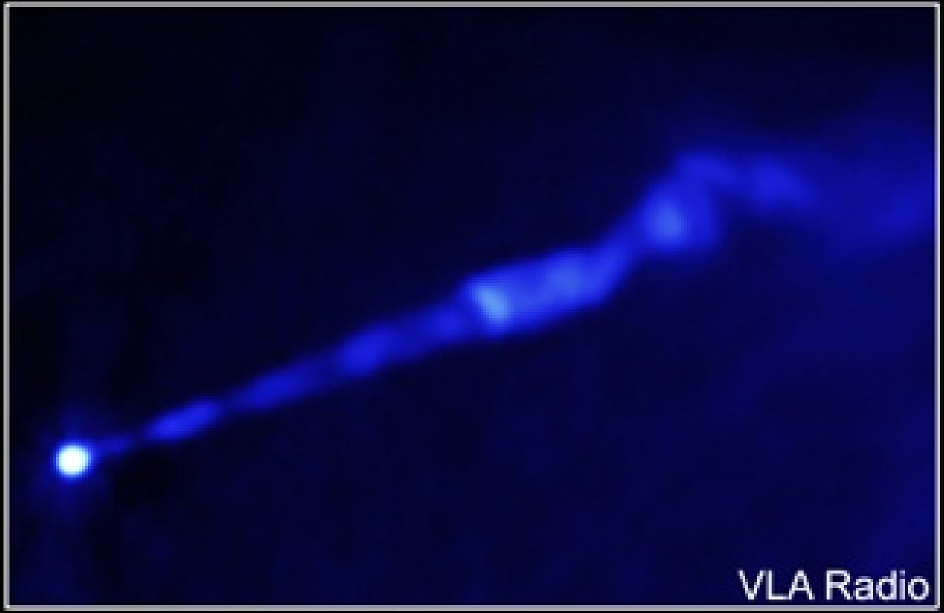
Heber Curtis (1918)
[Lick Observatory]

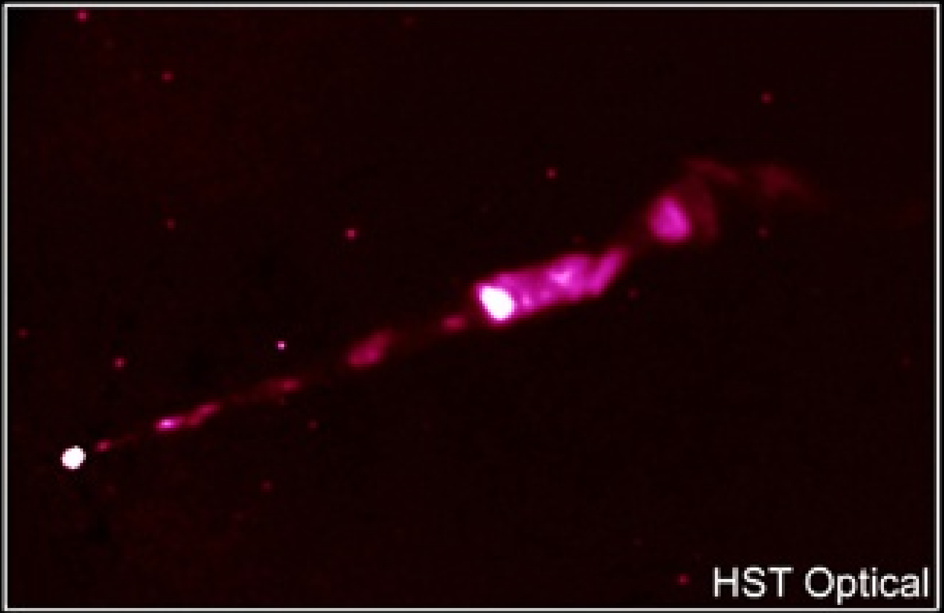
"Descriptions of 762
Nebulae and Clusters …."

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

M 87

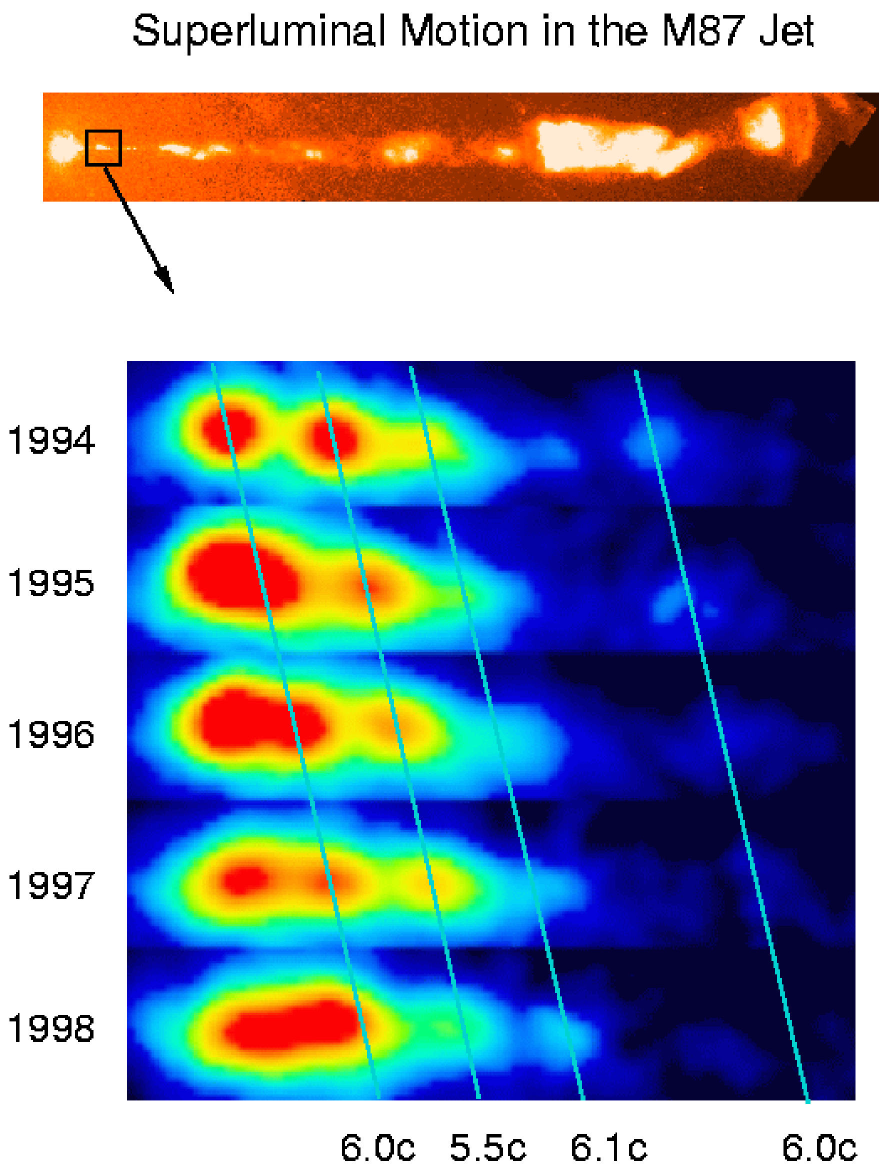






First astrophysical “jet”   [1913 Heber Curtis]

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

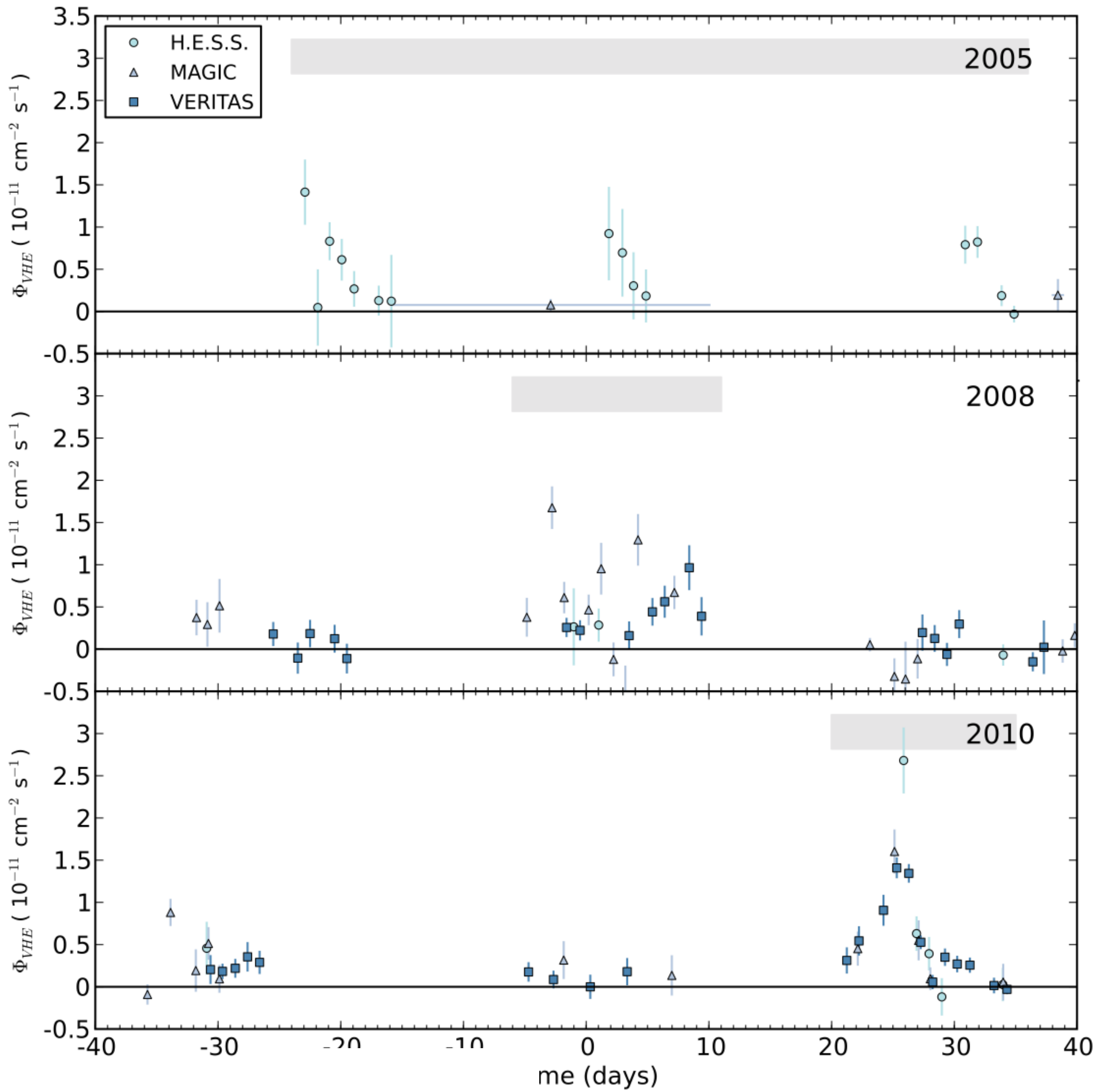
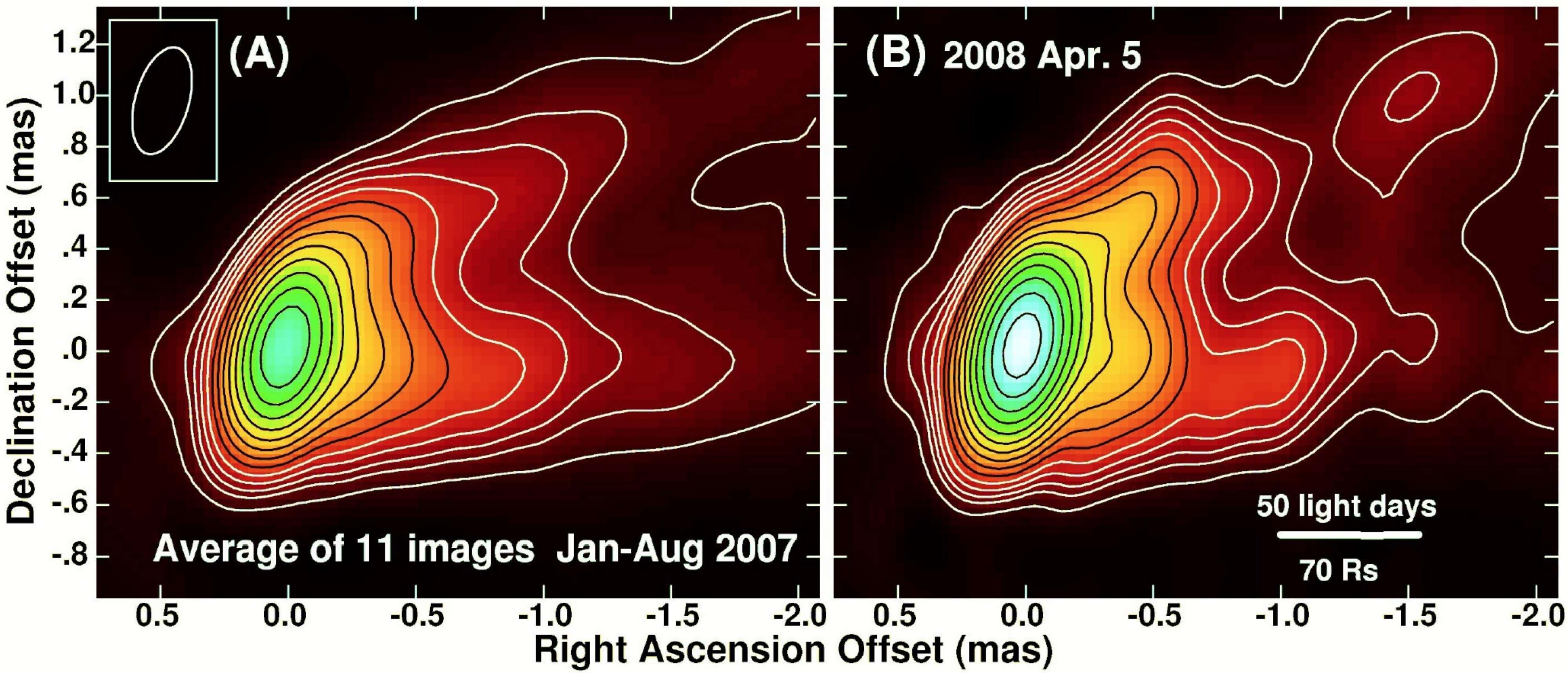


Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500, 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.

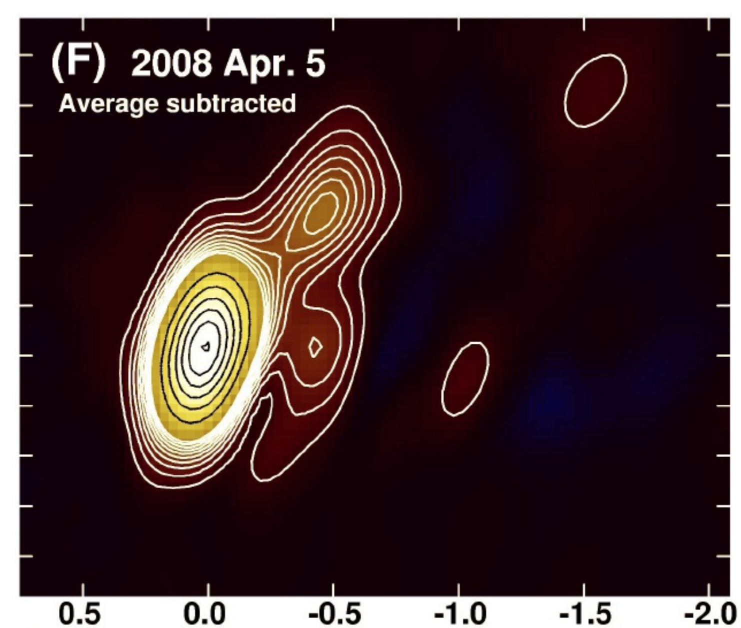


VLBA radio images of M87 at 43 GHz

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

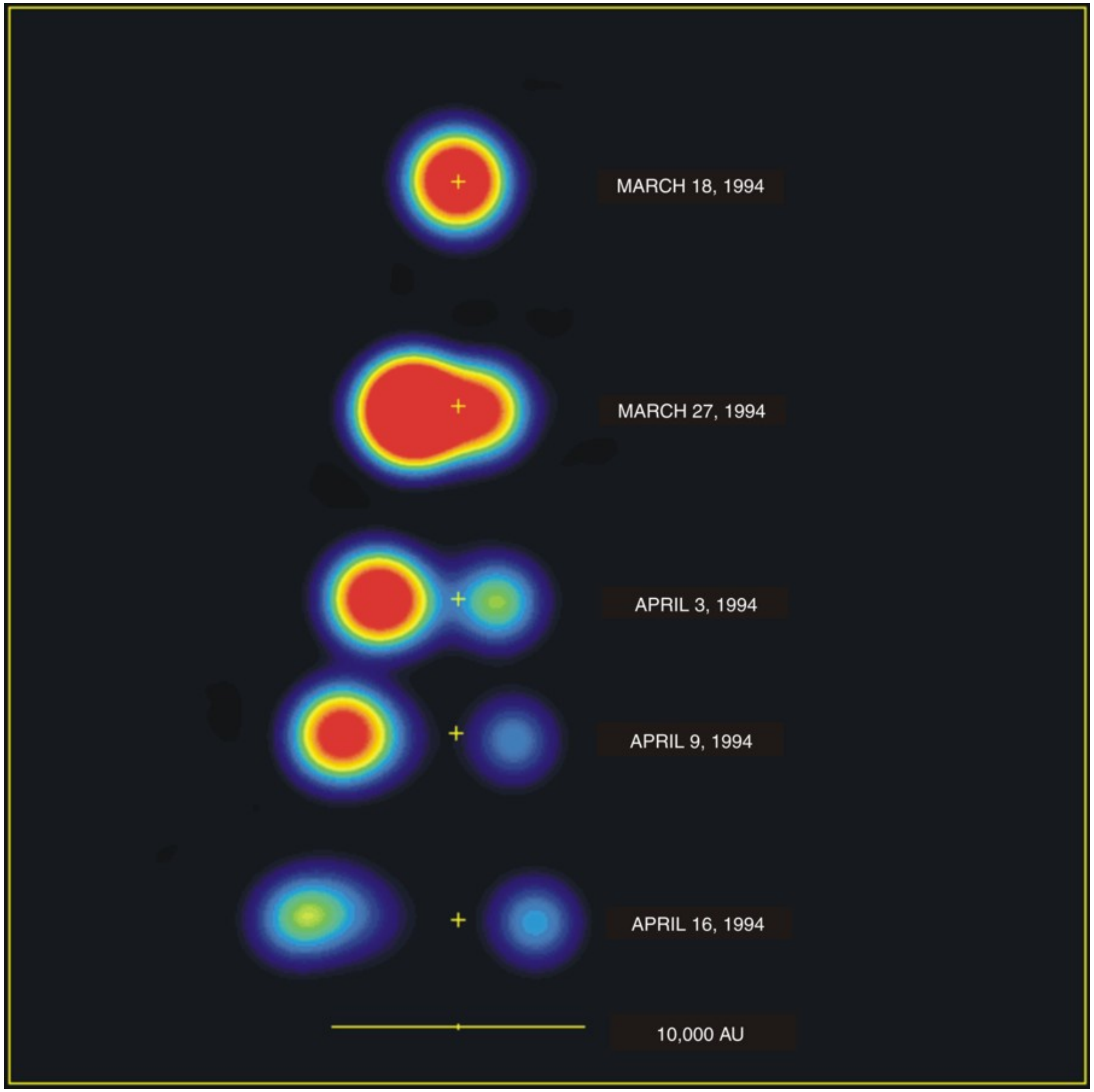
Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

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



Superluminal Motions in microQuasars in our Galaxy

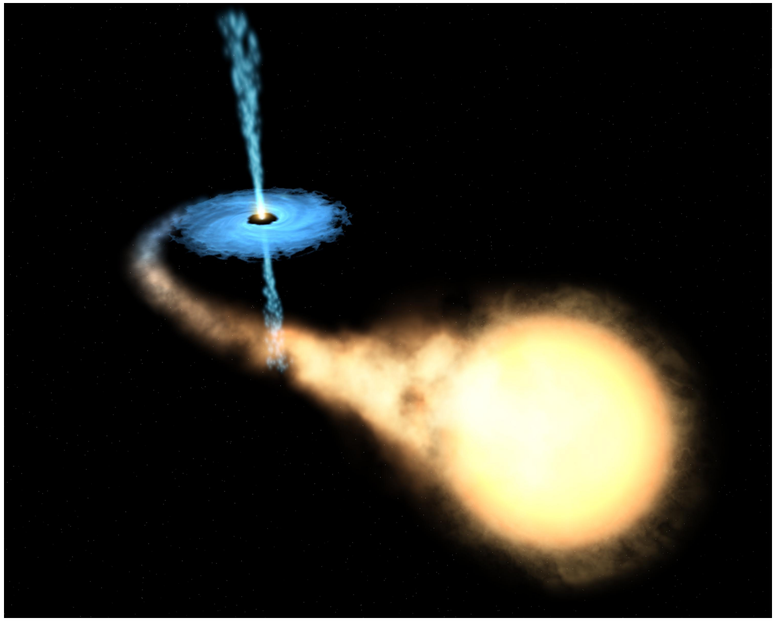
GRS1915+105

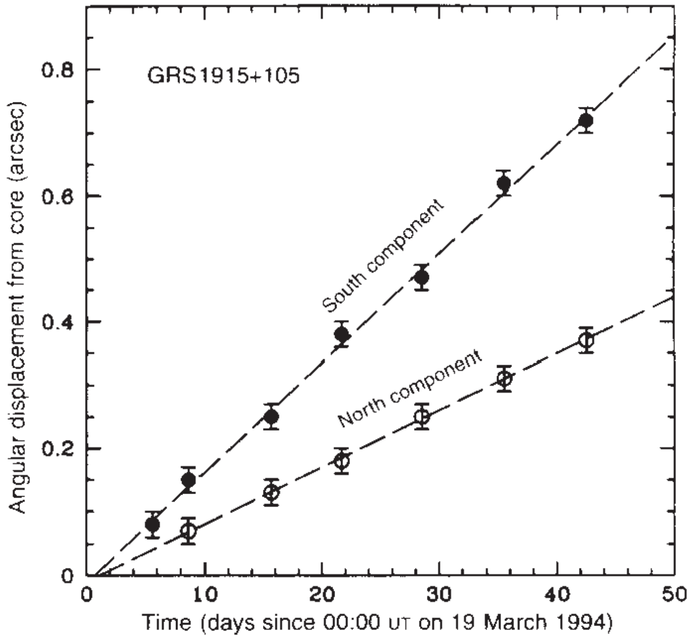


Observations in radio

$$\lambda = 3.5 \text{ cm}$$

“Two pairs of bright radio condensations”





$$\mu_a \simeq 17.6 \pm 0.4 \ \frac{\text{mas}}{\text{day}}$$

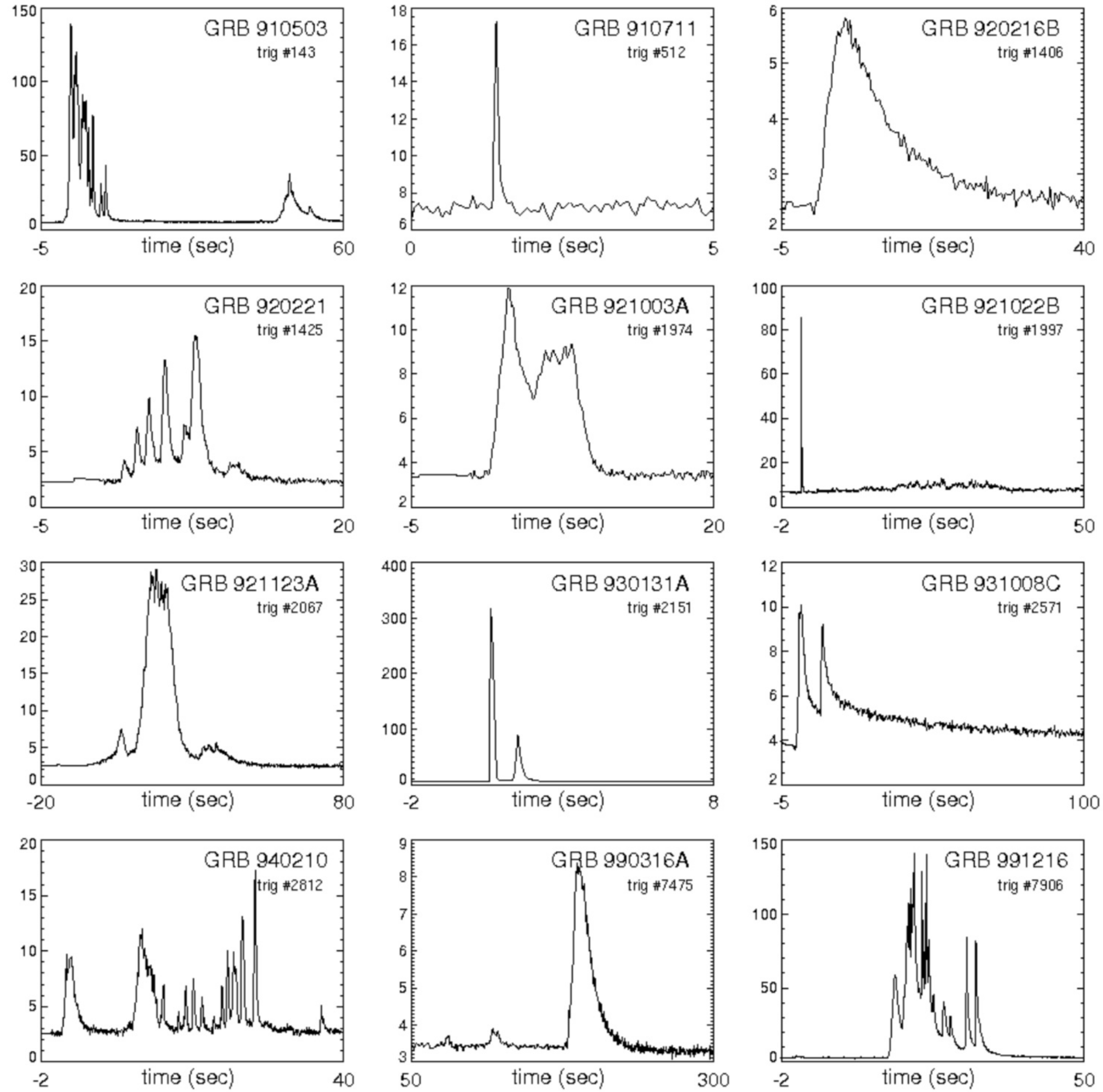
$$\mu_r \simeq 9.0 \pm 0.1 \ \frac{\text{mas}}{\text{day}}$$

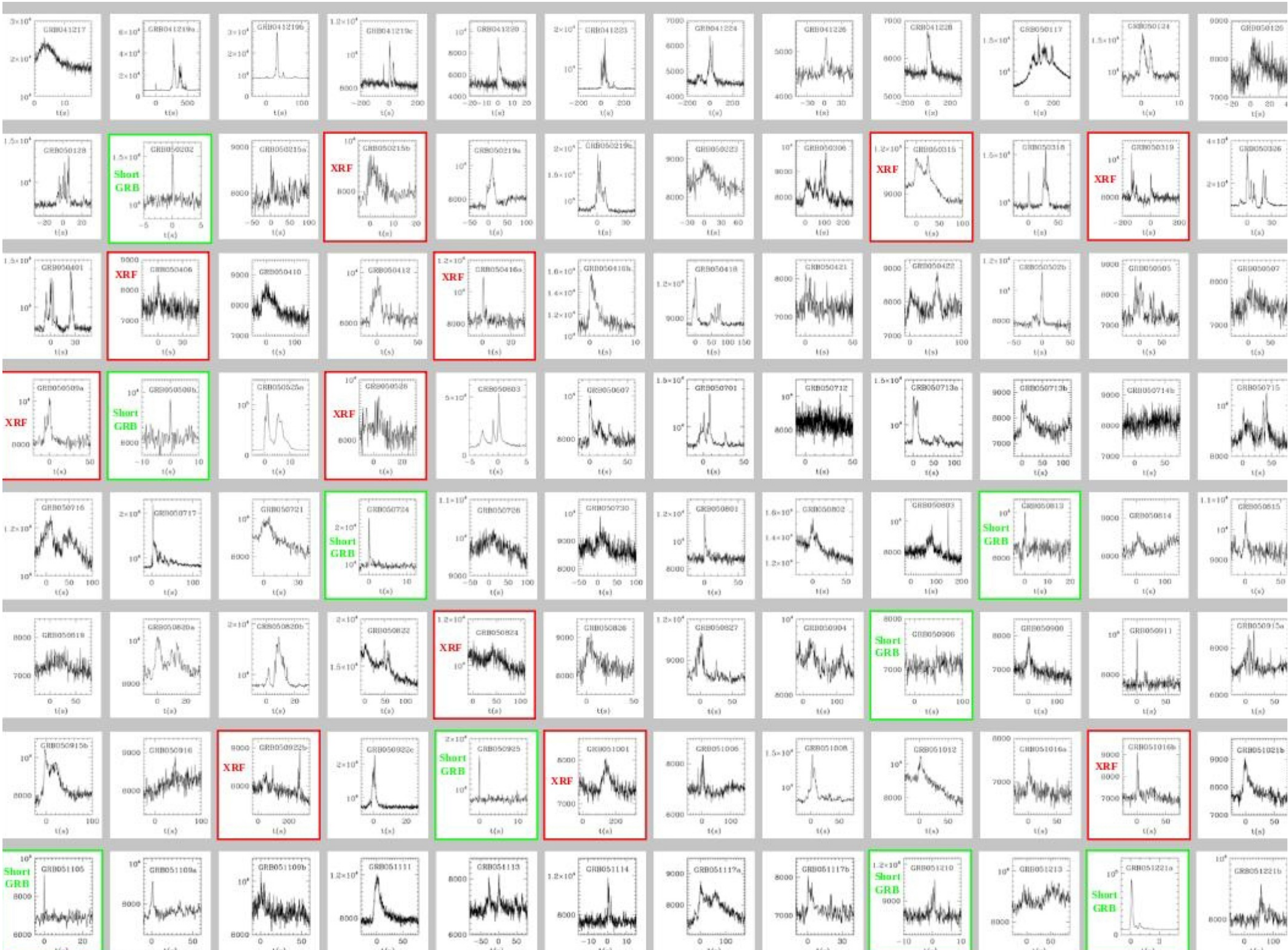
$$\boxed{\mu_{a,r} = \frac{\beta \ \sin\theta}{1 \pm \beta \ \cos\theta} \ \frac{c}{D} \qquad D = 12.5 \pm 1.5 \ \text{kpc}}$$

$$\beta = 0.92 \pm 0.08$$

$$\theta = (70 \pm 2)^\circ$$

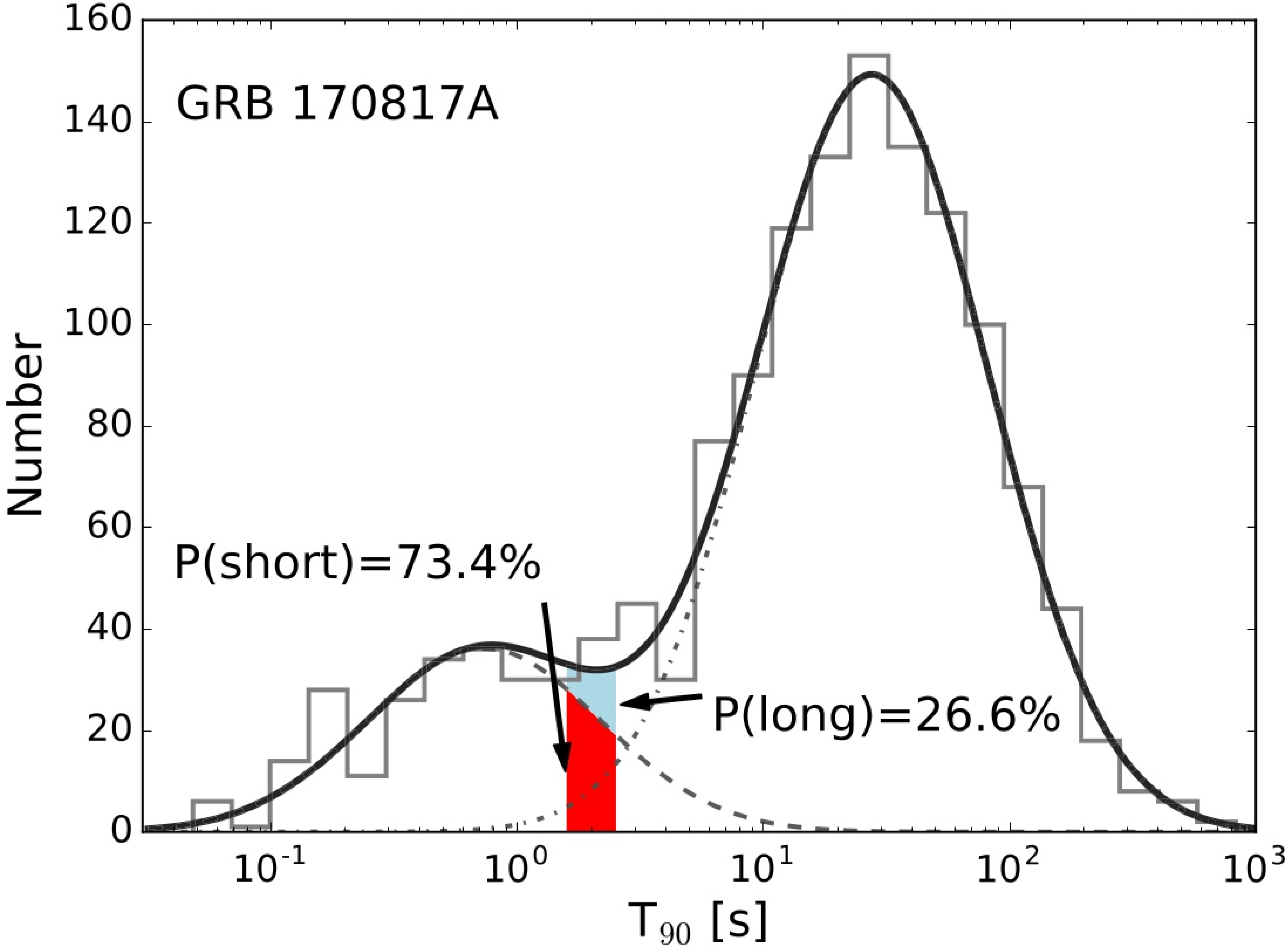
GAMMA RAY BURSTS (GRB's)

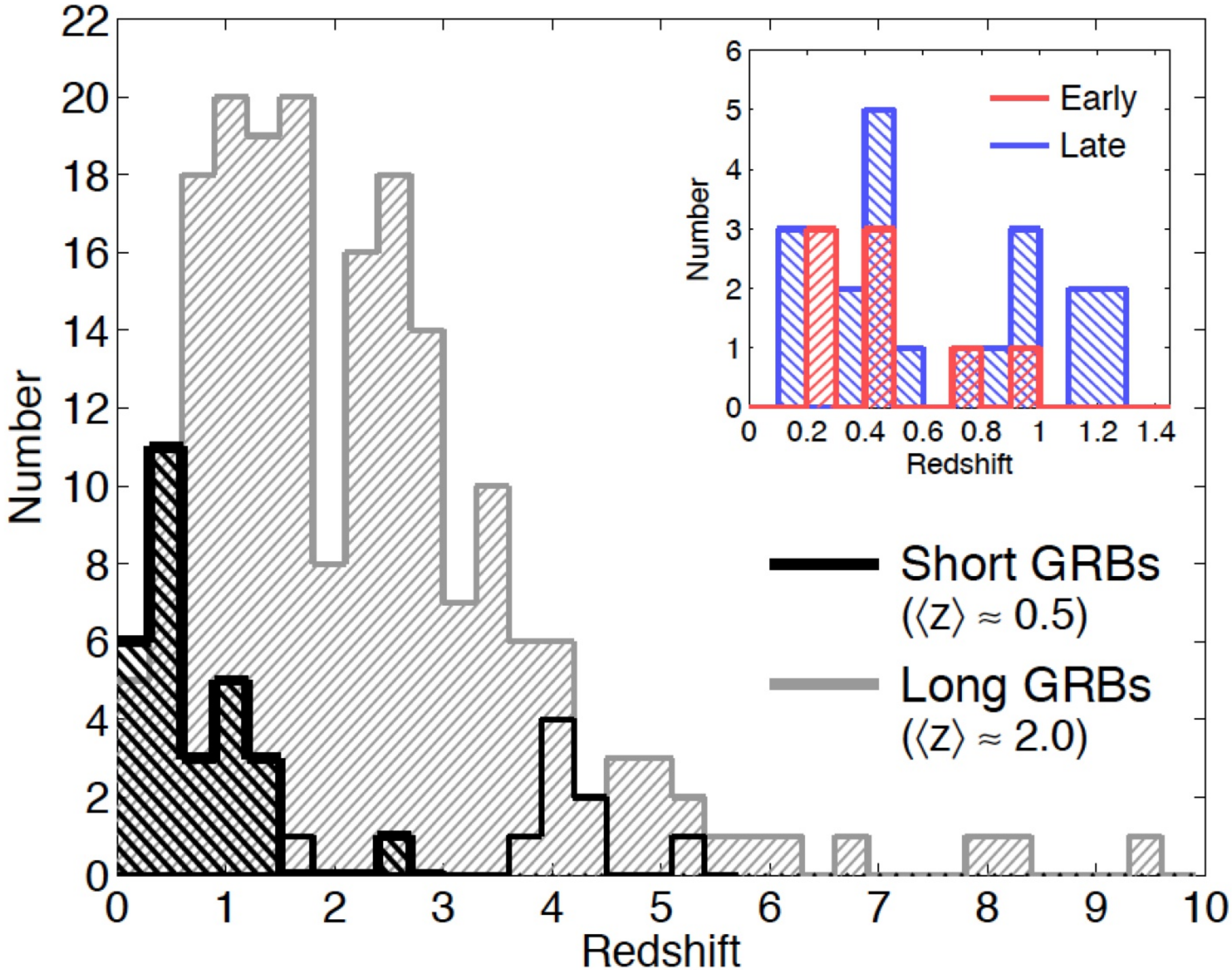




[From N. Gehrels]

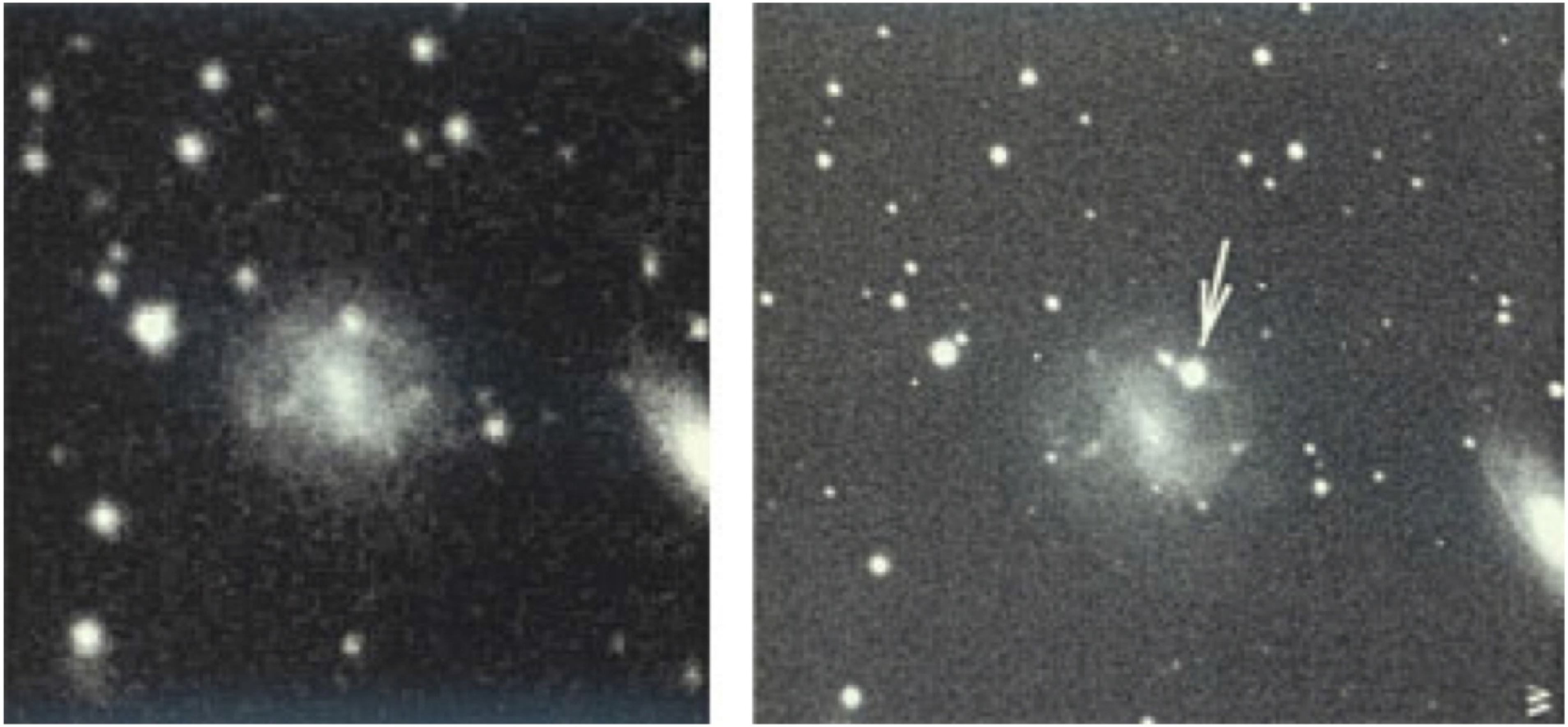
Two Classes of Gamma Ray Bursts: "Short" and "Long"





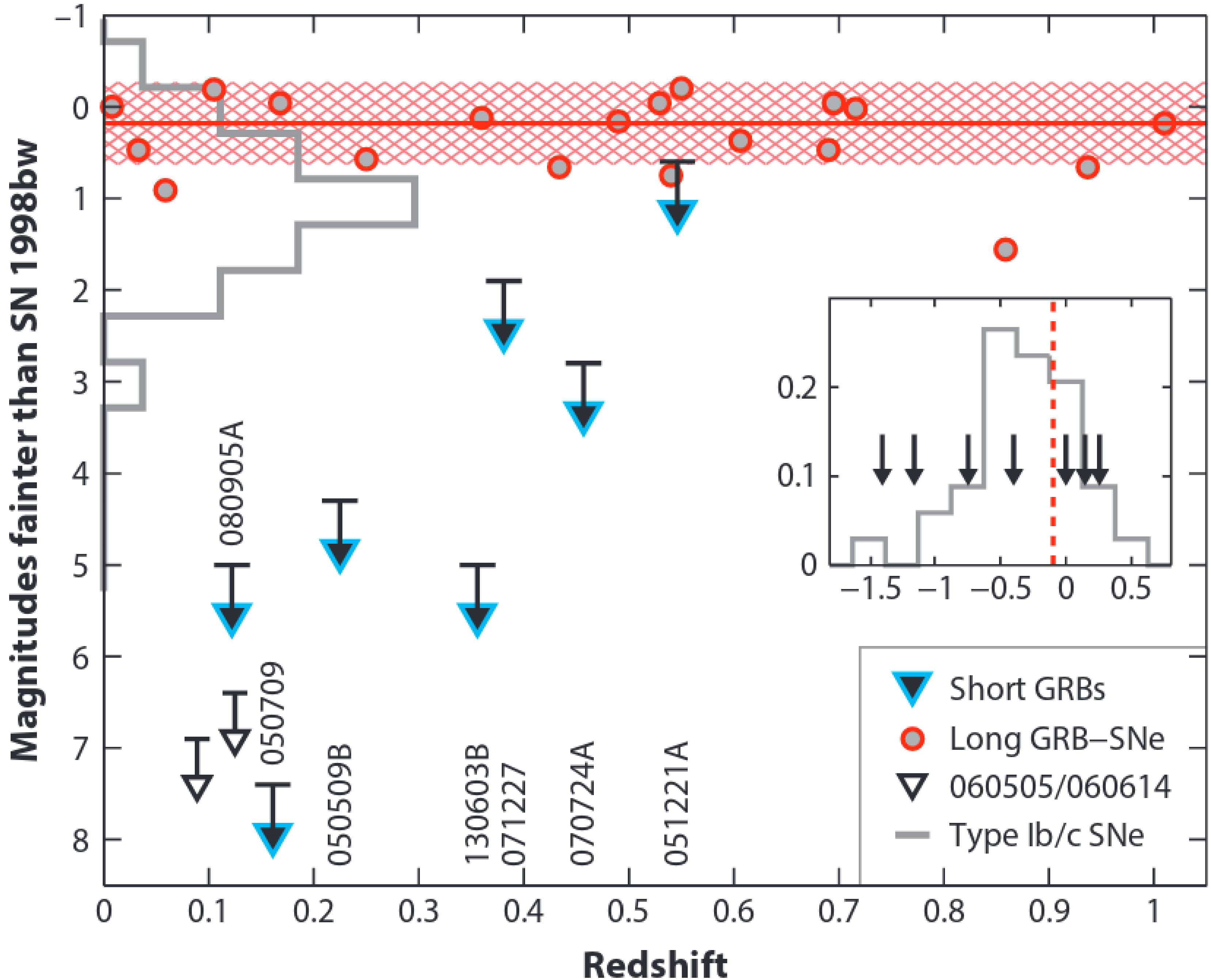
Number
Redshift
Short GRBs
(⟨z⟩ ≈ 0.5)
Long GRBs
(⟨z⟩ ≈ 2.0)
Early
Late

Association Long GRB's with SN explosions

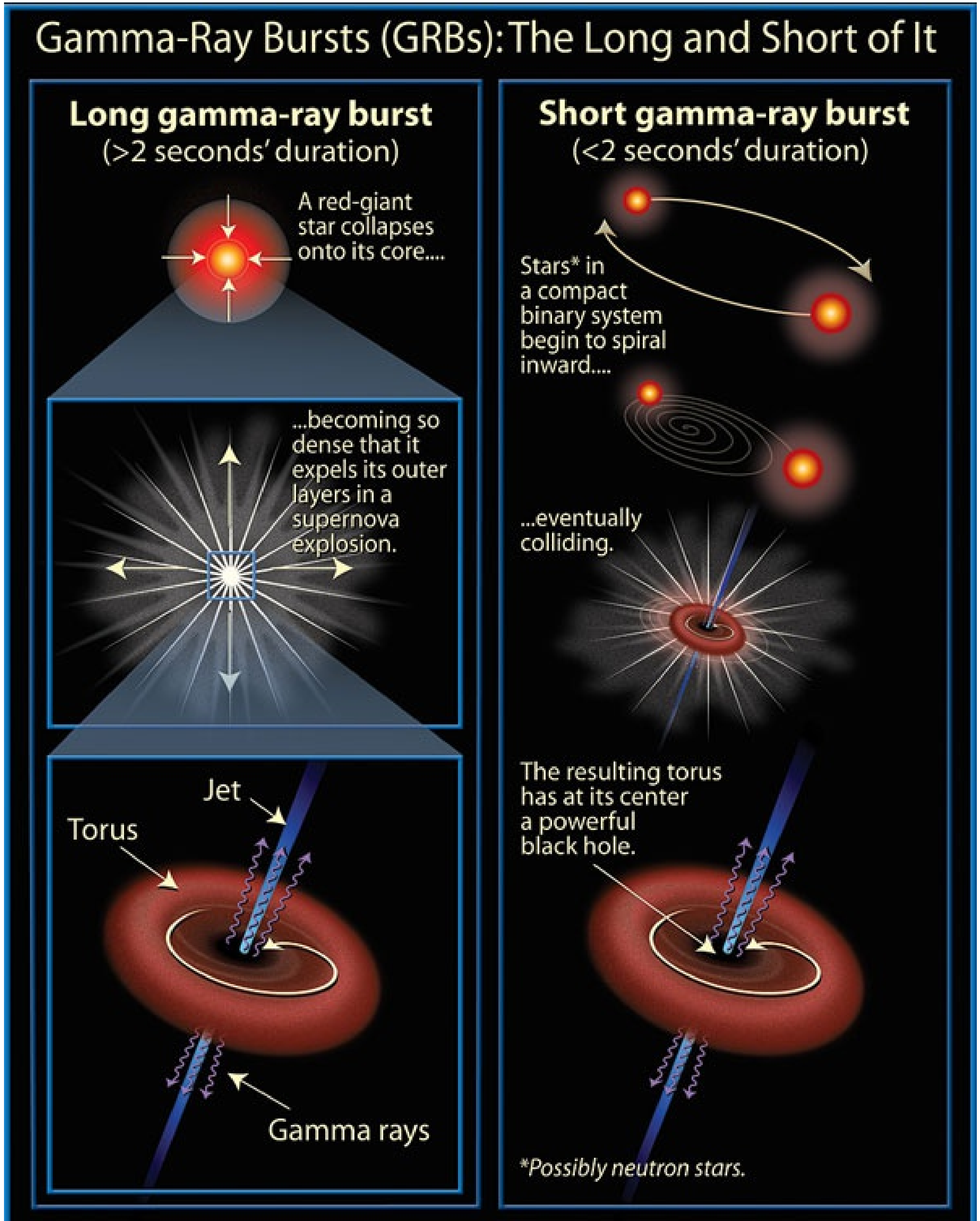


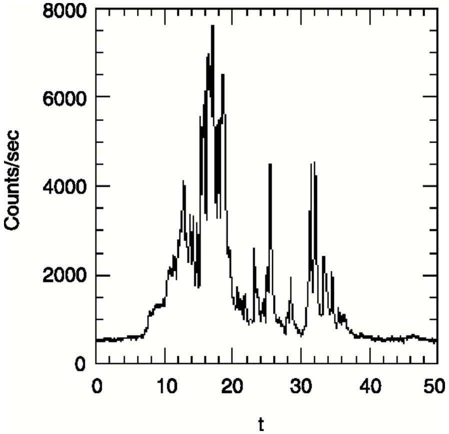
Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.

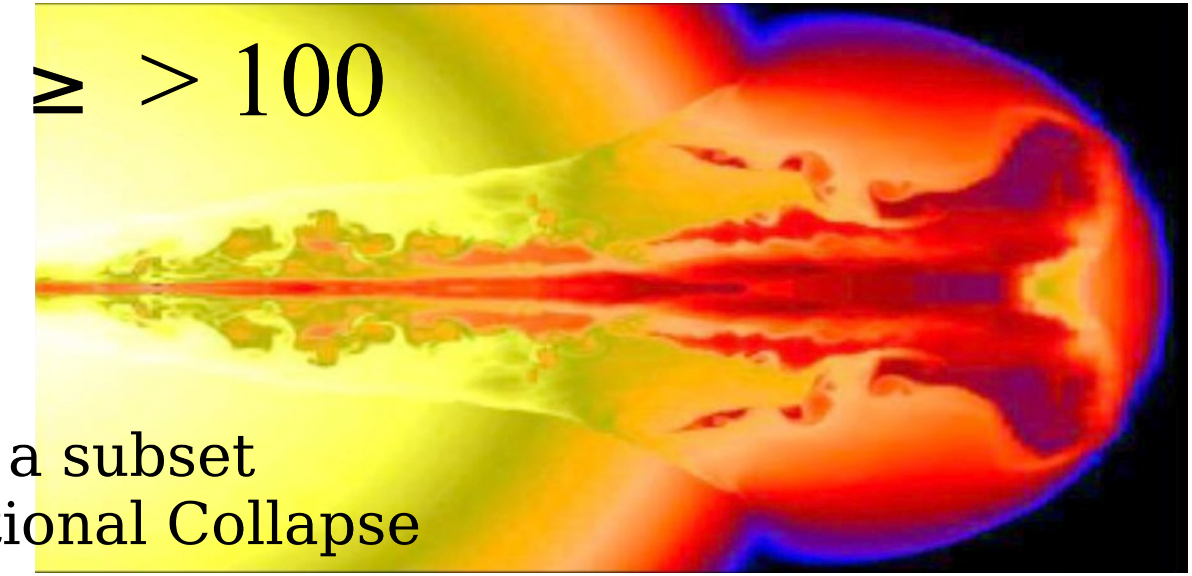
SN 1998bw GRB 980425



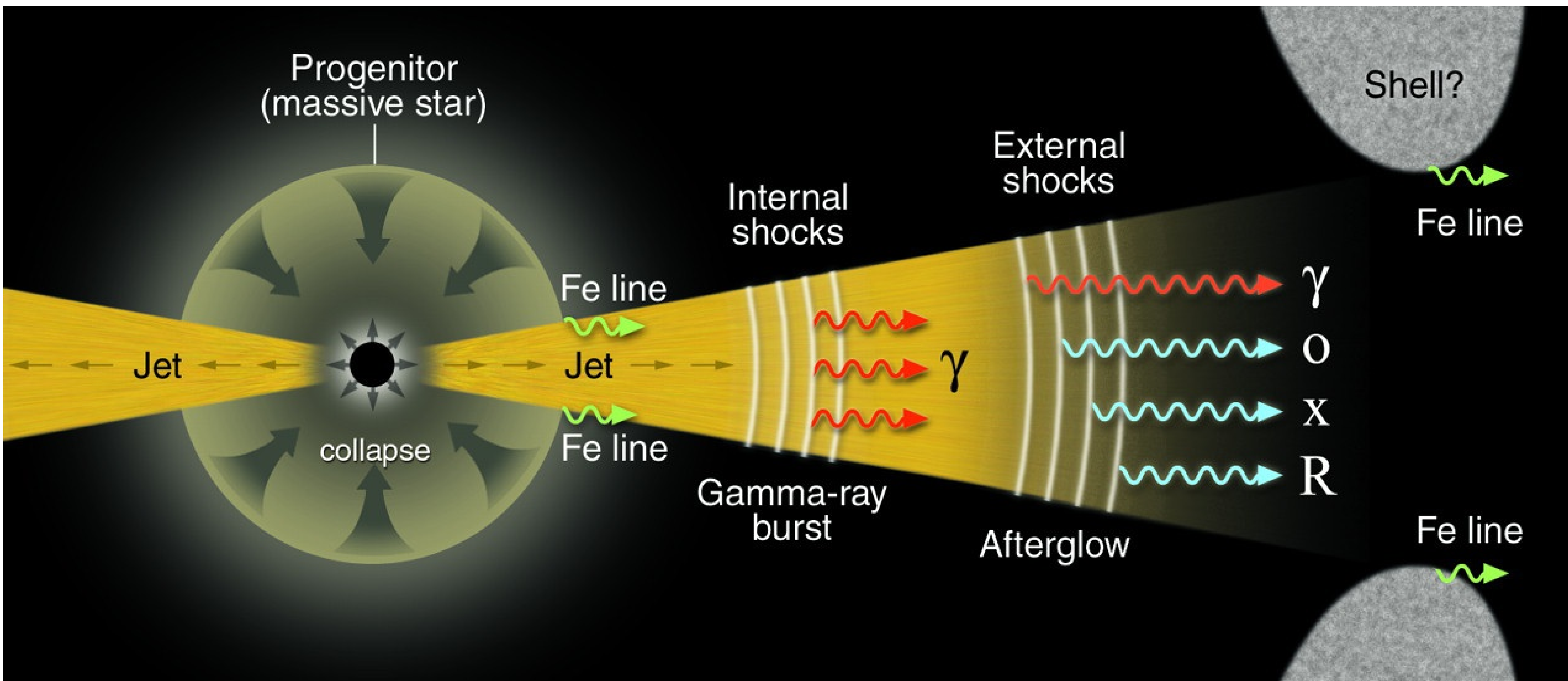
Magnitudes fainter than SN 1998bw
Redshift
−1
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
080905A
050709
050509B
130603B
071227
070724A
051221A
0.2
0.1
0
−1.5
−1
−0.5
0
0.5
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe


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.





GRB : associated with a subset of SN Stellar Gravitational Collapse



Dark Matter

Understanding the nature and properties of Dark Matter is of *central importance for fundamental physics.*

Observations of the "High Energy Universe" [gamma, neutrino, pbar ,e^+] can put limits or detect the signatures of Dark Matter.

The presence of DM can be important for the structure of astrophysical sources [for example galactic nuclei]

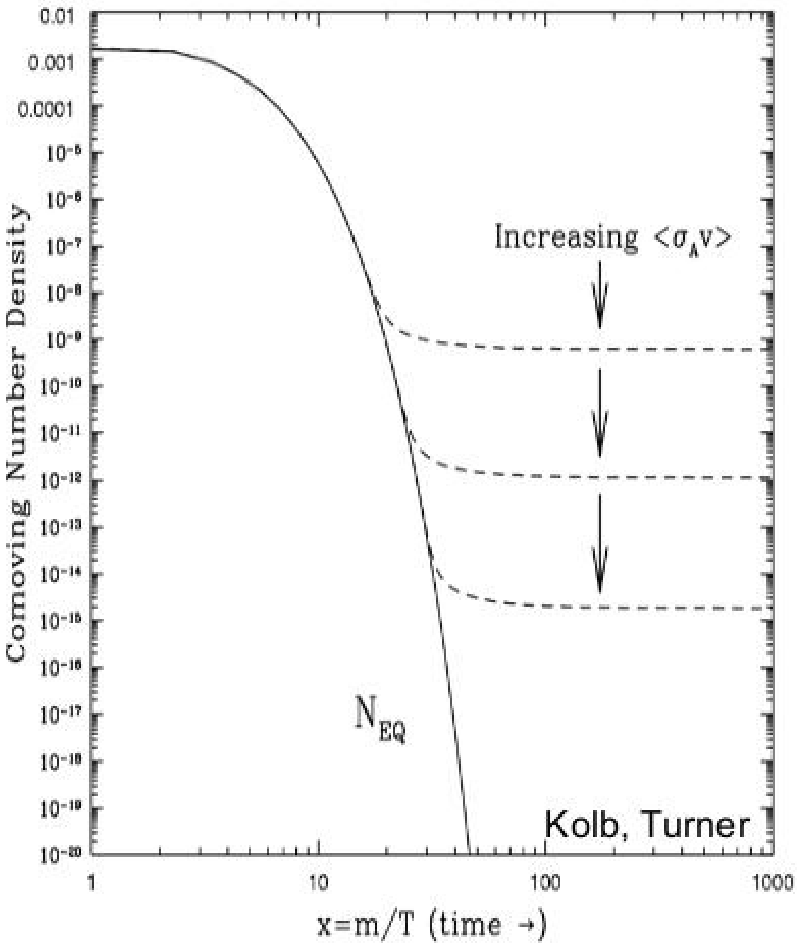
"Dark Matter"
Cornelia Parker
Tate Gallery London

Weakly Interacting Massive Particle

Thermal Relic

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

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



site that contains a DM mass density $\rho_\chi(\vec{x})$

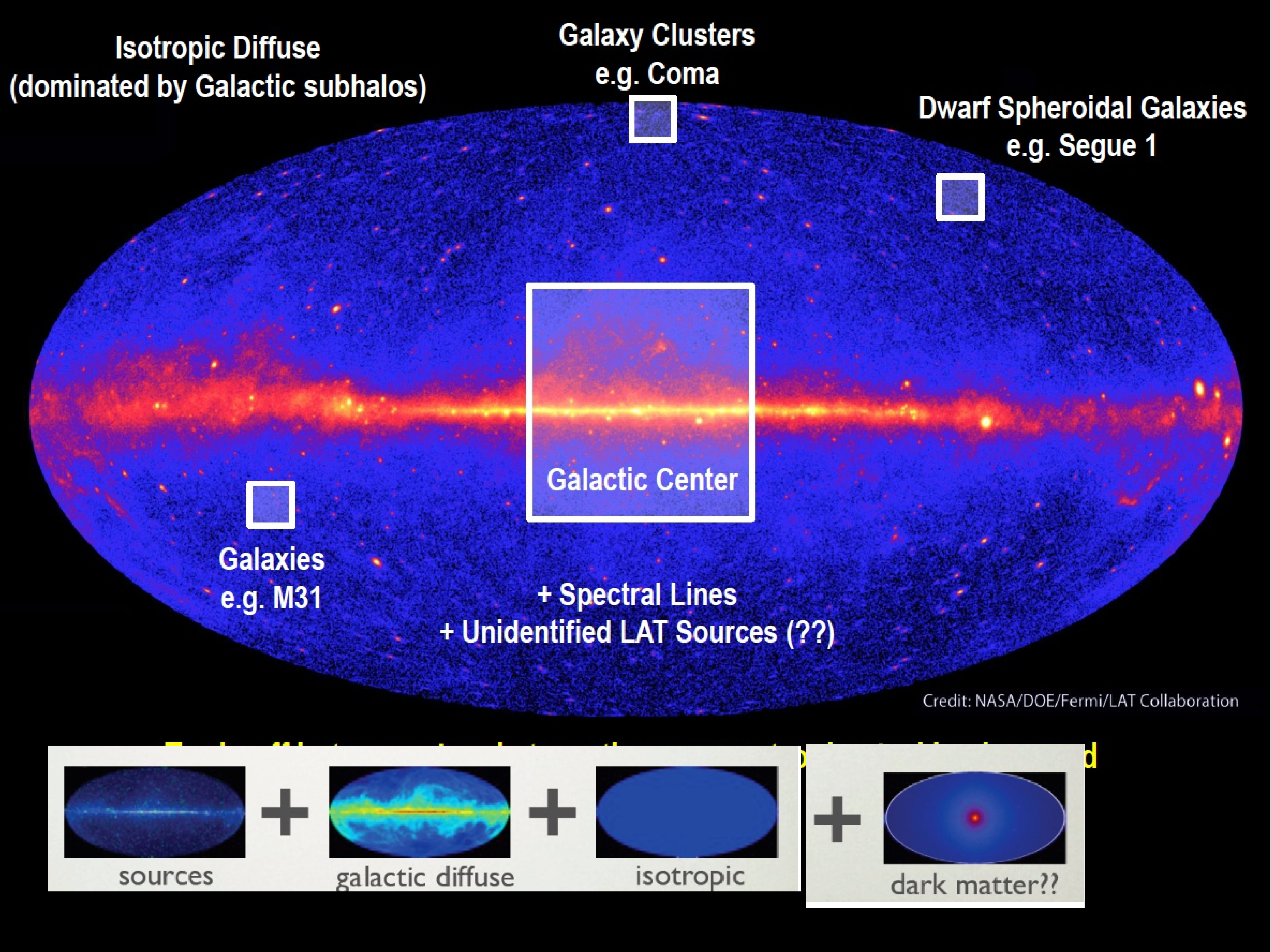
$$n_\chi(\vec{x}) = \frac{\rho_\chi(\vec{x})}{m_\chi}$$

Rate of energy release per unit volume, unit time:

$$(2\, m_\chi) \left[\frac{1}{2}\, n_\chi^2(\vec{x}) \langle\sigma\, v\rangle\right] d^3x\; dt$$

$$\nu \quad \gamma \quad \overline{p} \quad e^+ \quad \ldots$$

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


Isotropic Diffuse
(dominated by Galactic subhalos)
Galaxy Clusters
e.g. Coma
Dwarf Spheroidal Galaxies
e.g. Segue 1
Galactic Center
Galaxies
e.g. M31
+ Spectral Lines
+ Unidentified LAT Sources (??)
Credit: NASA/DOE/Fermi/LAT Collaboration
sources
galactic diffuse
isotropic
dark matter??

No evidence for Dark Matter signal

1. Galactic Center

2. Dwarf Galaxies

3. Spectral lines

M. Ackermann *et al.* [Fermi-LAT Collaboration],
"The Fermi Galactic Center GeV Excess and Implications for Dark Matter,"
Astrophys. J. **840**, no. 1, 43 (2017)
[arXiv:1704.03910 [astro-ph.HE]].

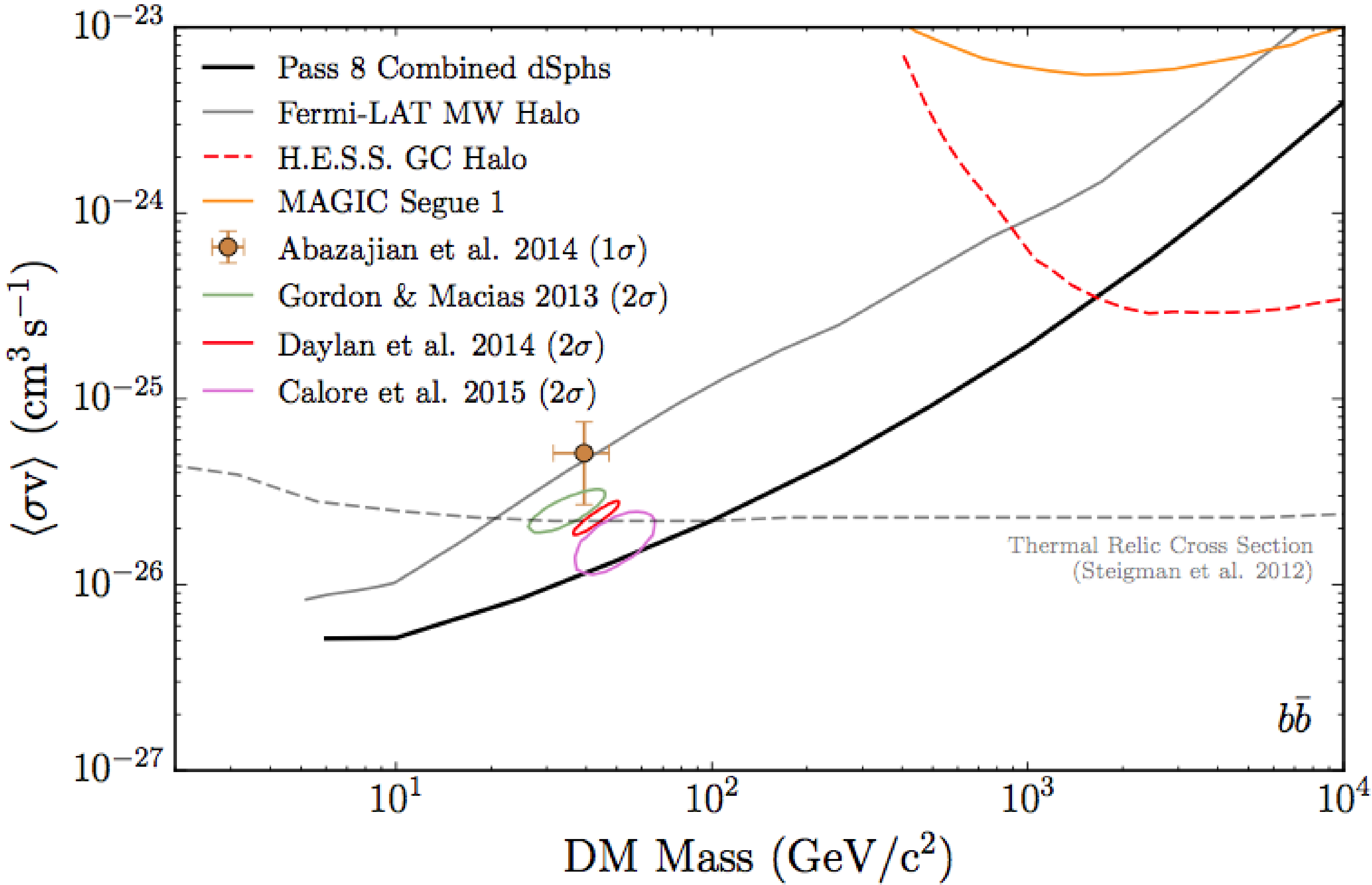
M. Ackermann *et al.* [Fermi-LAT Collaboration],
"Searching for Dark Matter Annihilation from Milky Way
Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,"
Phys. Rev. Lett. **115**, no. 23, 231301 (2015)
[arXiv:1503.02641 [astro-ph.HE]].

M. Ackermann *et al.* [Fermi-LAT Collaboration],

"Searching for Dark Matter Annihilation from Milky Way
Dwarf Spheroidal Galaxies with Six Years
of Fermi Large Area Telescope Data,"

Phys. Rev. Lett. **115**, no. 23, 231301 (2015)

[arXiv:1503.02641 [astro-ph.HE]].



Pass 8 Combined dSphs
Fermi-LAT MW Halo
H.E.S.S. GC Halo
MAGIC Segue 1
Abazajian et al. 2014 (1σ)
Gordon & Macias 2013 (2σ)
Daylan et al. 2014 (2σ)
Calore et al. 2015 (2σ)
Thermal Relic Cross Section
(Steigman et al. 2012)
$b\bar{b}$
$\langle \sigma v \rangle$ ($cm^3 s^{-1}$)
DM Mass (GeV/c^2)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

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

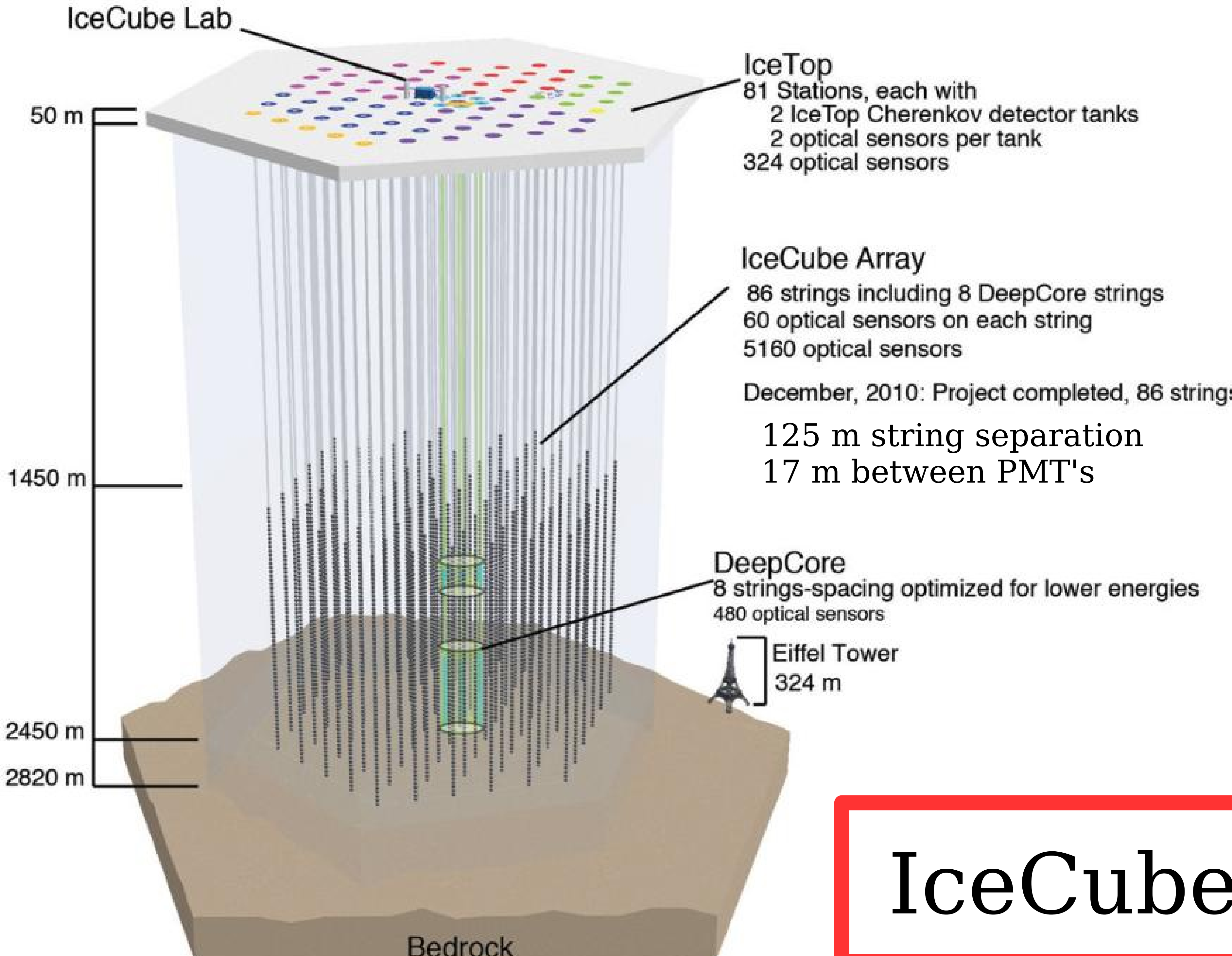
Casting a wider theoretical net offers the possibility to explore new classes of dark matter candidates and develop new experimental methods to search for them.

Possible solutions to the Dark Matter Problem
(from Bertone et al. 2019)

Neutrinos

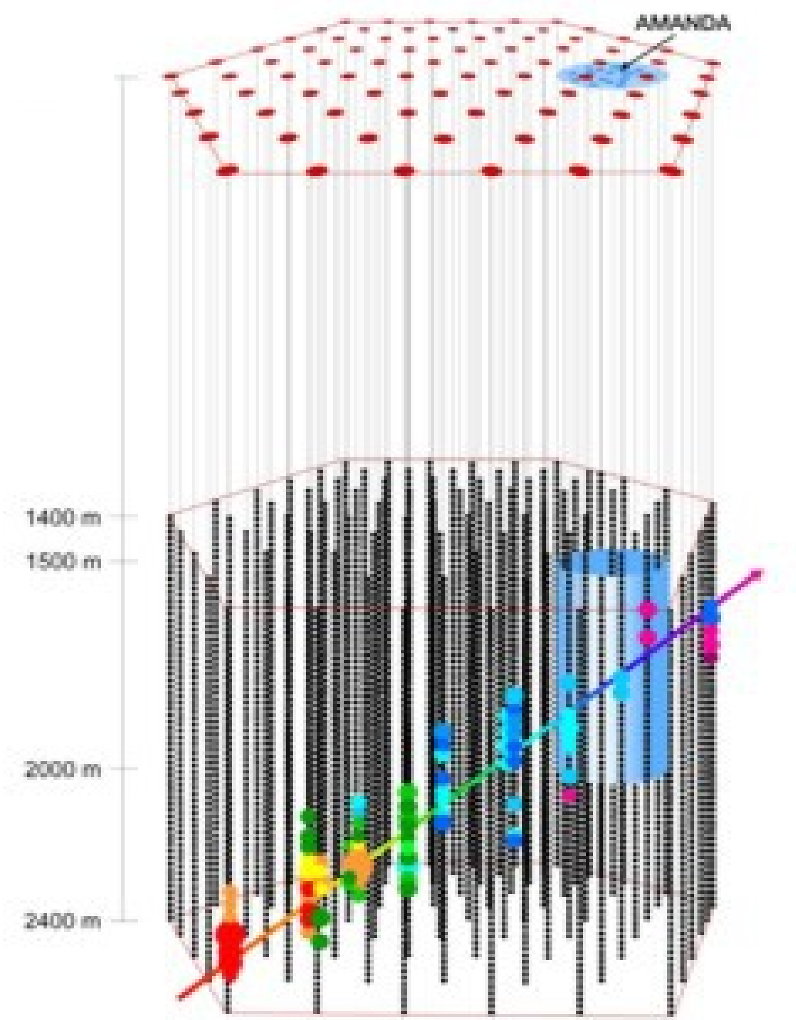
Extragalactic Gamma rays
absorbed for $E > 1$TeV

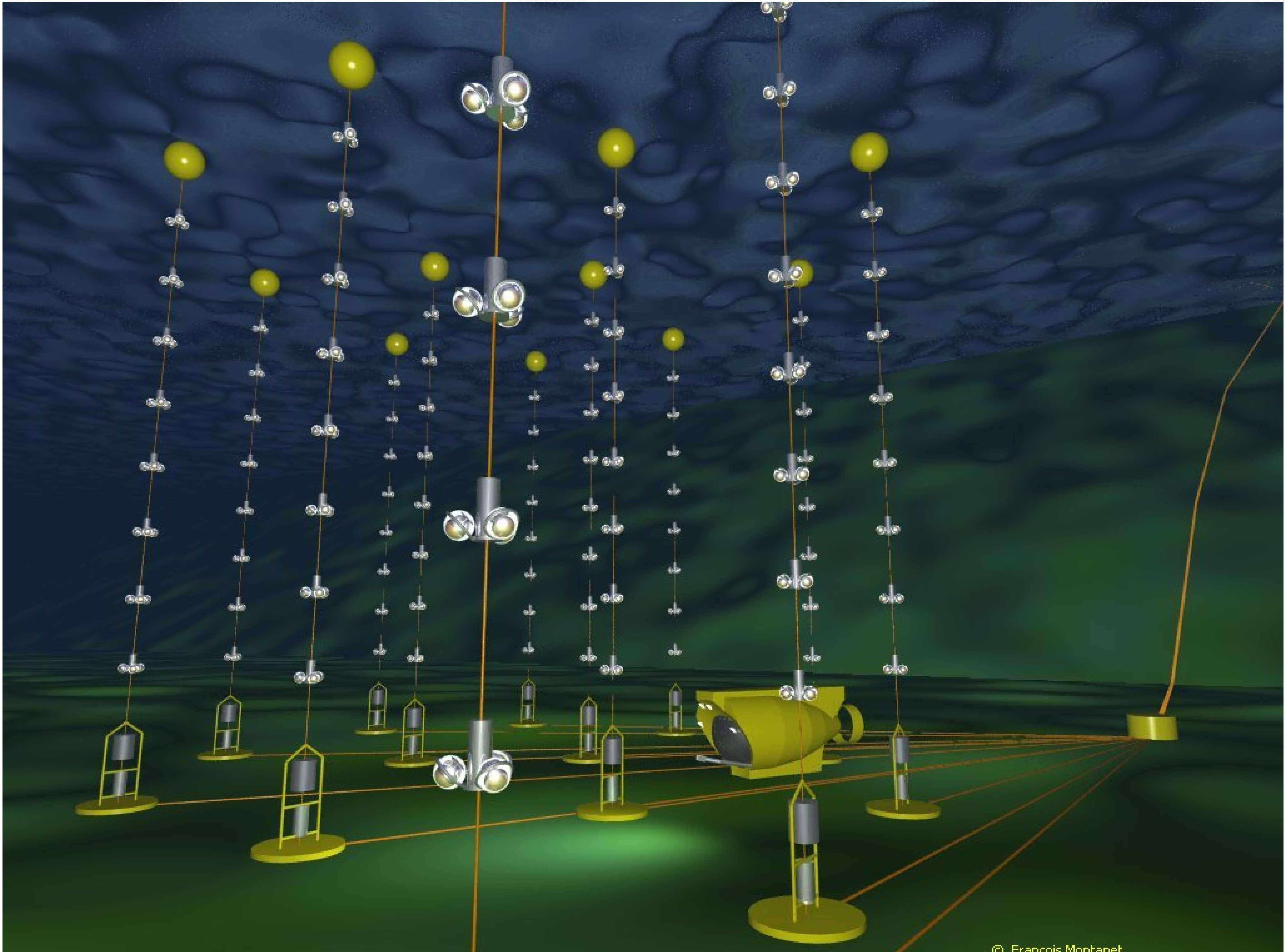
IceCube

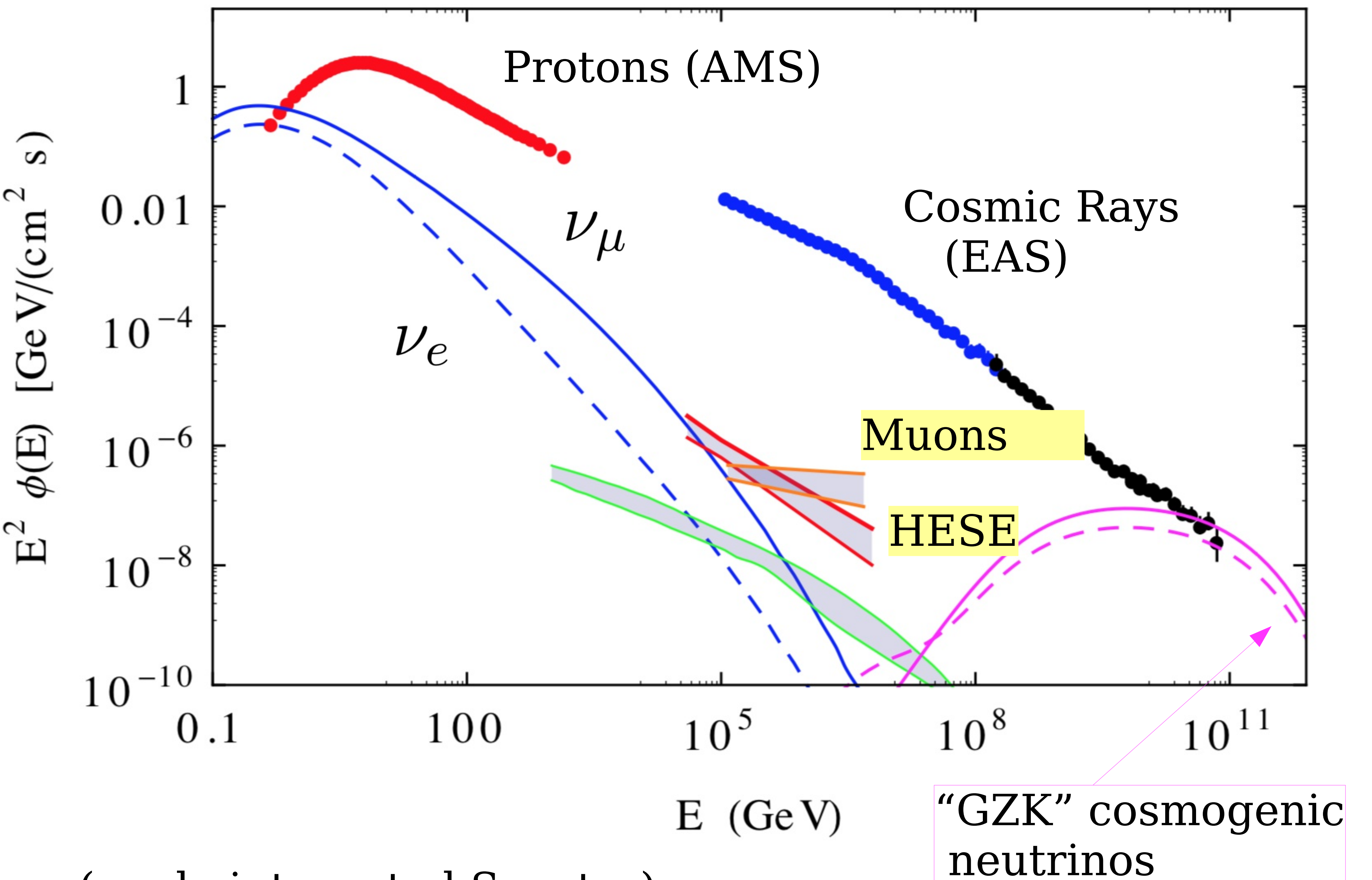


125 m string separation
17 m between PMT's

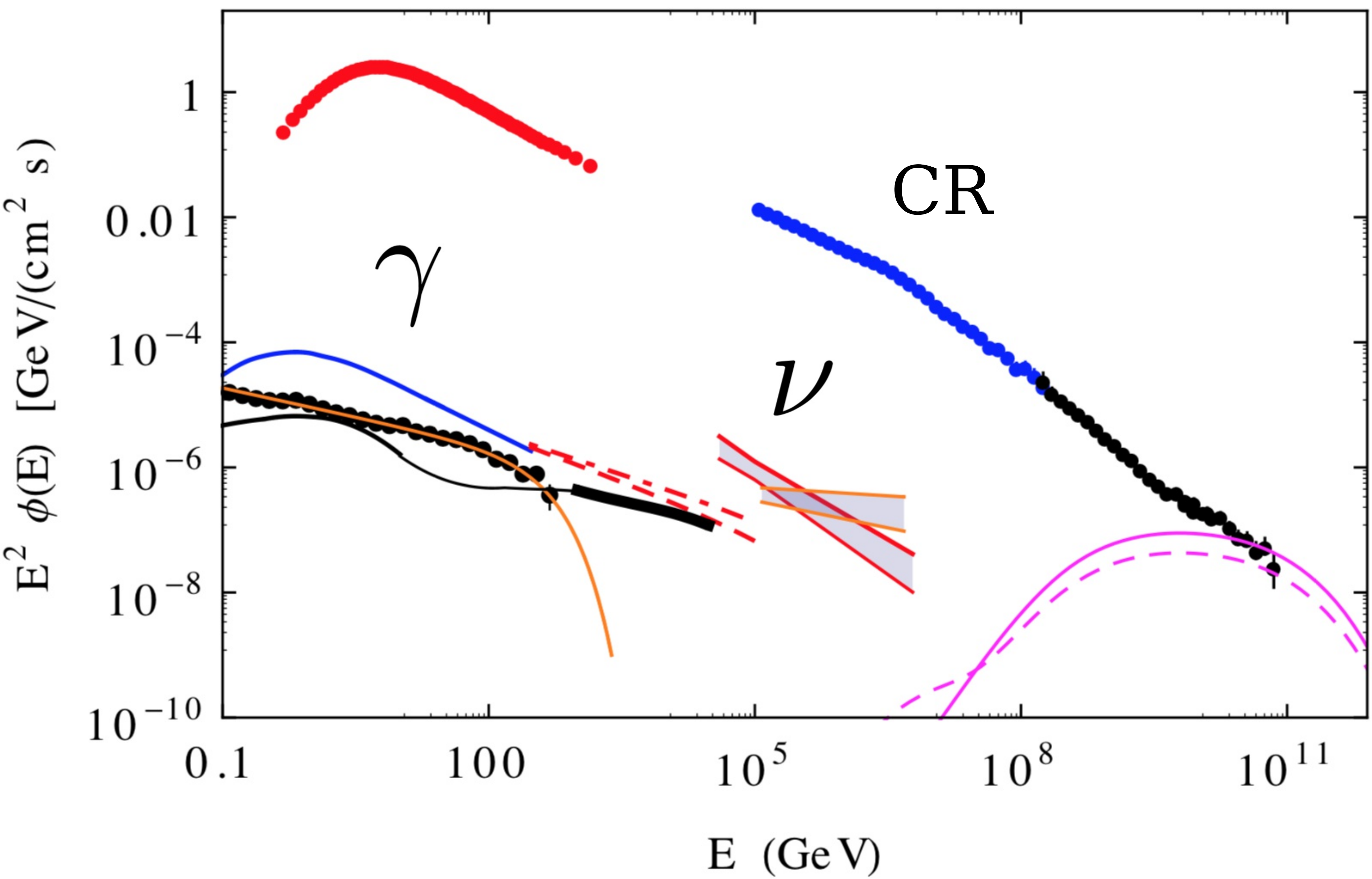
Deployment of the strings



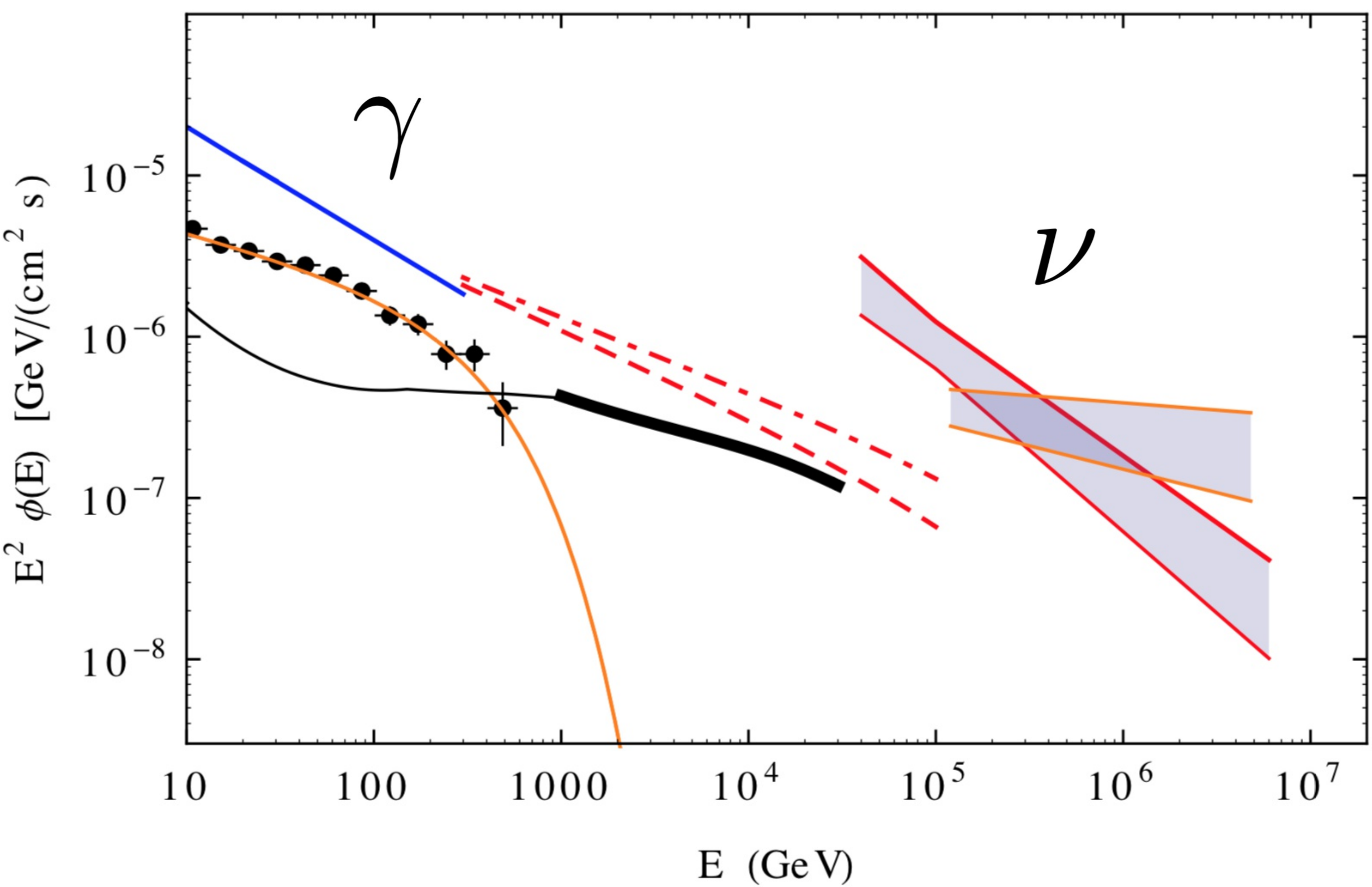

© François Montanet



(angle integrated Spectra)

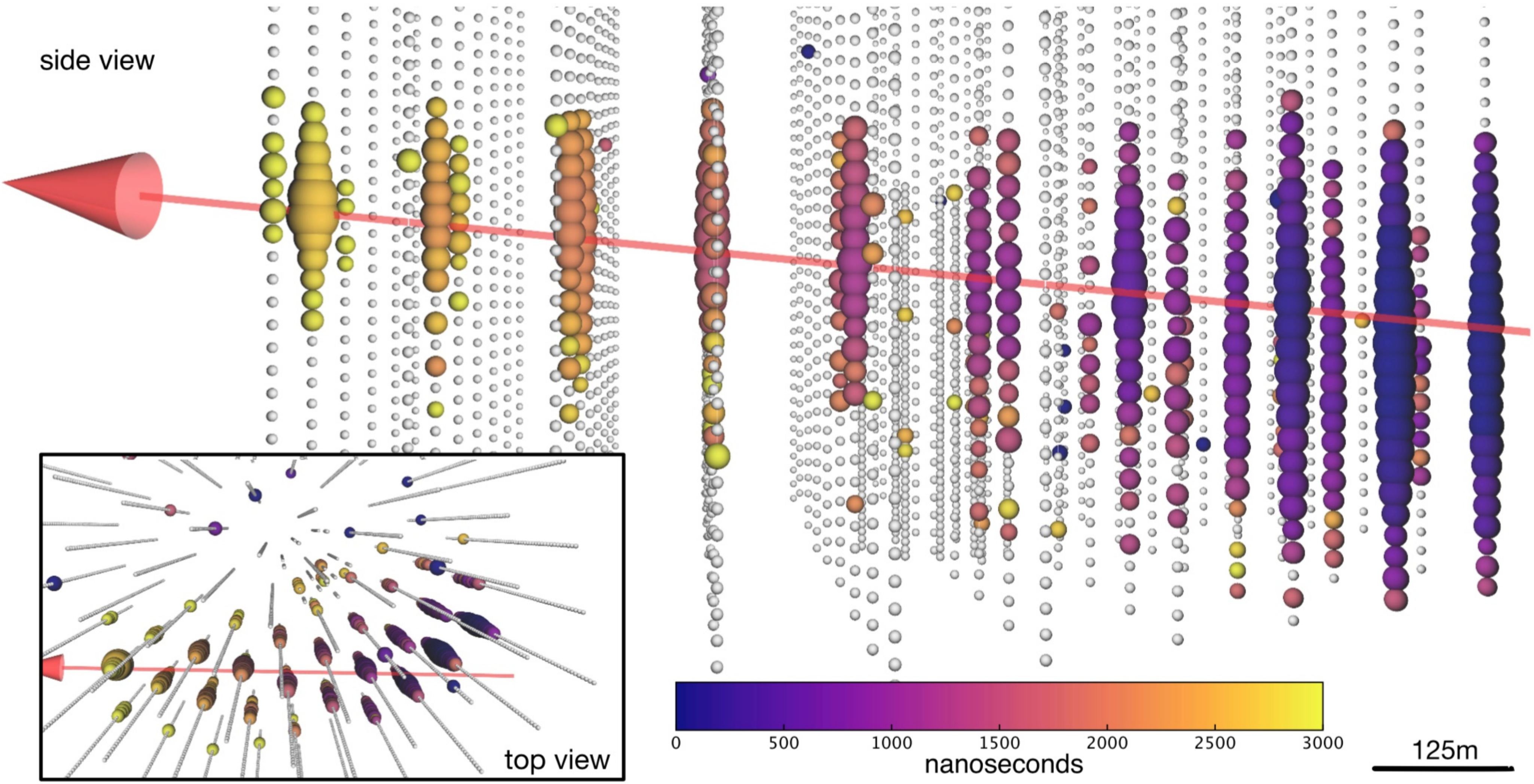


CR
γ
ν
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.1
100
10^5
10^8
10^{11}
E (GeV)
$E^2\ \phi(E)$ [GeV/(cm^2 s)]



γ
ν
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$E^2\ \phi(E)$ [GeV/(cm^2 s)]
10
100
1000
10^4
10^5
10^6
10^7
E (GeV)

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.

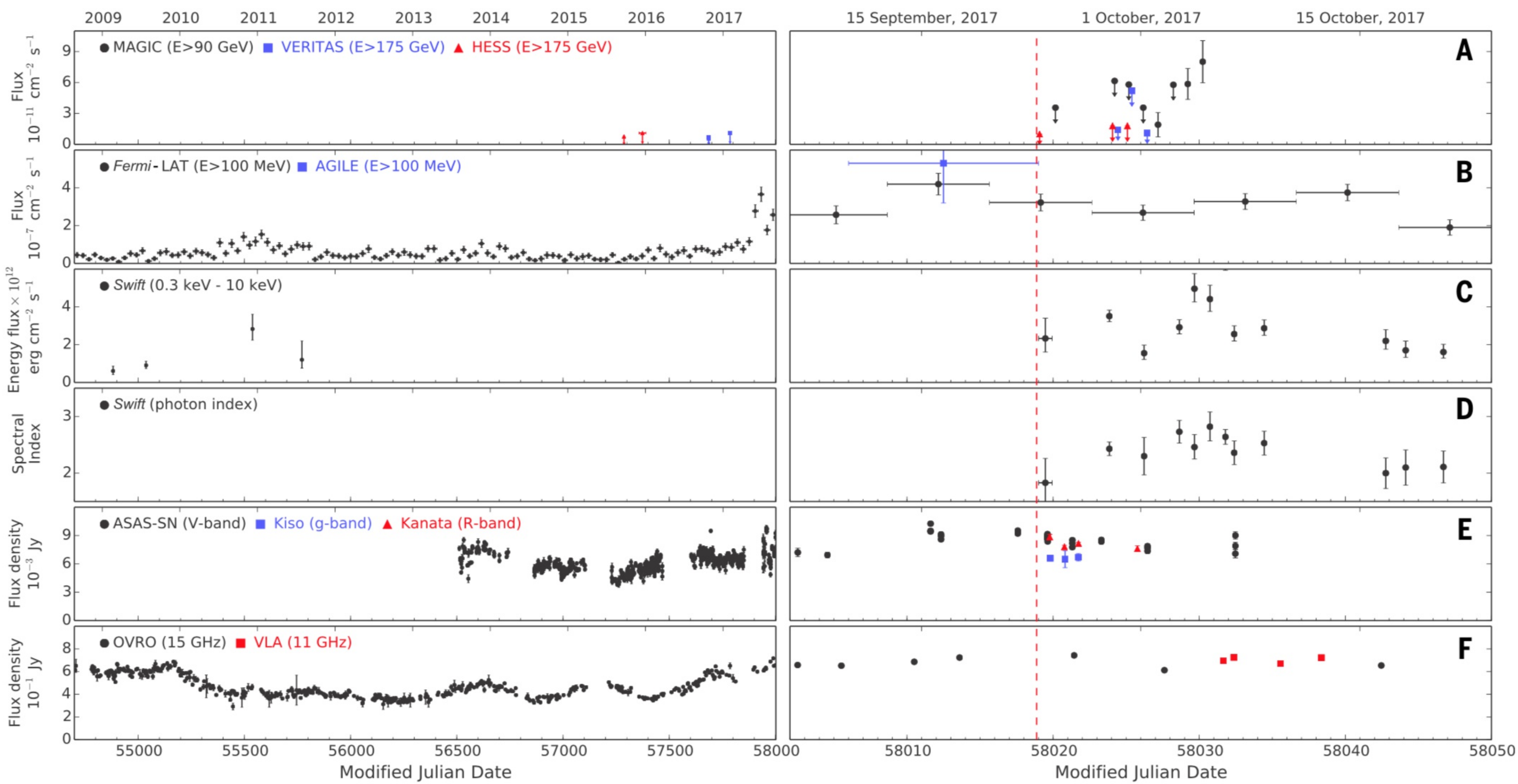
ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on ***28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

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

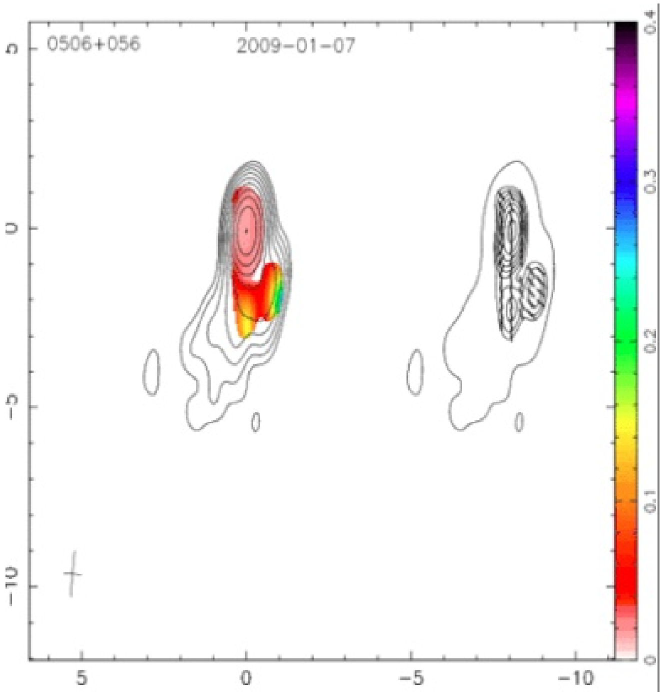
…. Great source of excitement ……

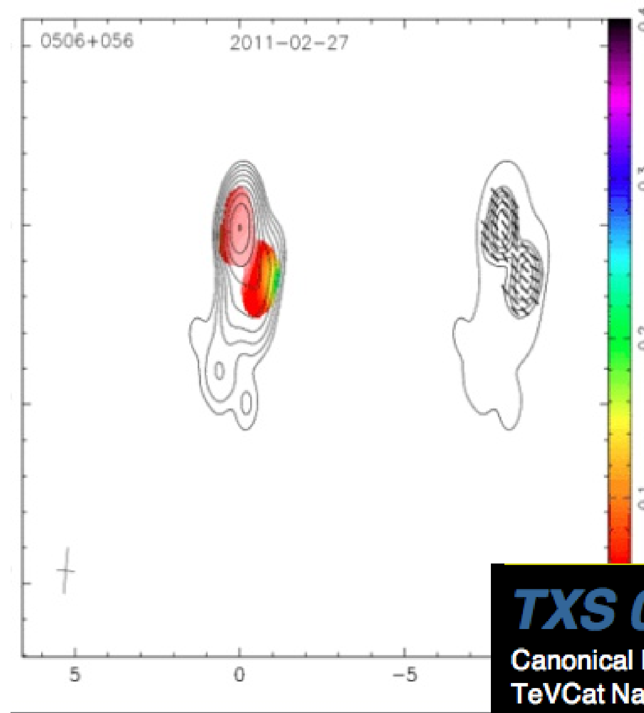
Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS …..]



MAGIC (E>90 GeV)
VERITAS (E>175 GeV)
HESS (E>175 GeV)
Fermi-LAT (E>100 MeV)
AGILE (E>100 MeV)
Swift (0.3 keV - 10 keV)
Swift (photon index)
ASAS-SN (V-band)
Kiso (g-band)
Kanata (R-band)
OVRO (15 GHz)
VLA (11 GHz)
A
B
C
D
E
F
15 September, 2017
1 October, 2017
15 October, 2017
Modified Julian Date
Spectral Index

TXS 0506+056



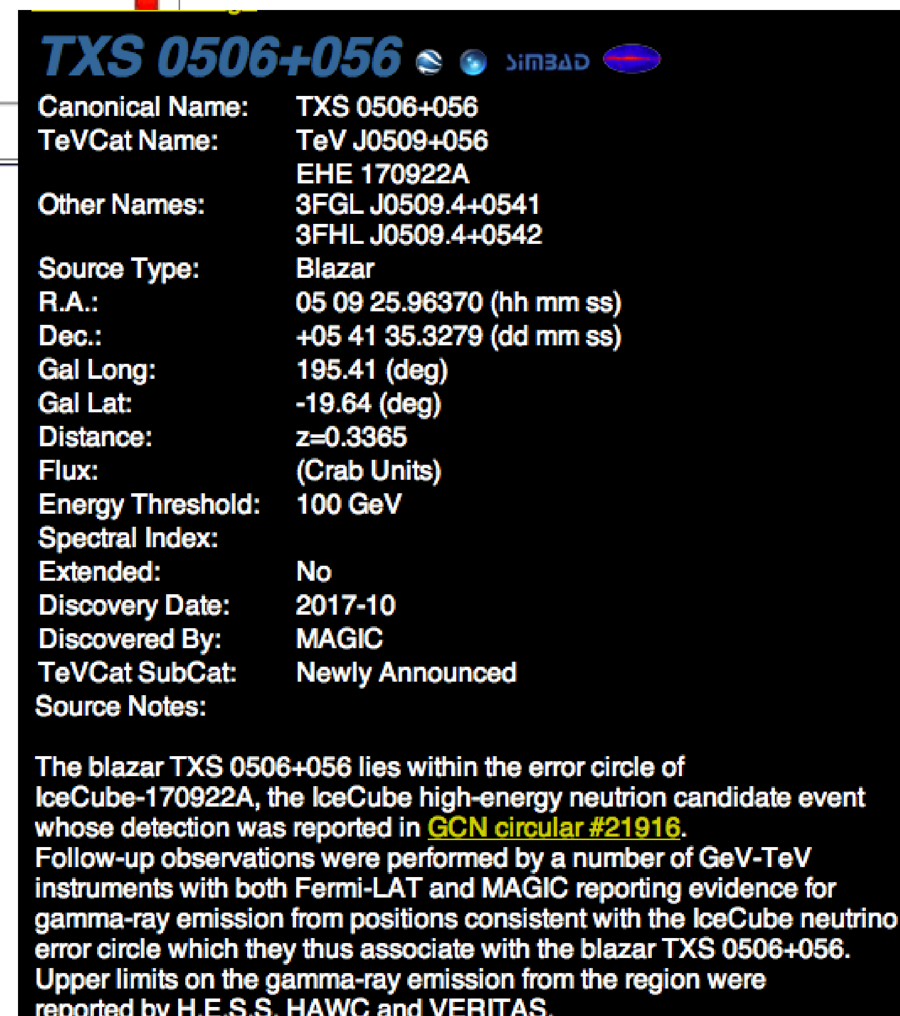


$$z = 0.3365 \pm 0.0010$$

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

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

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



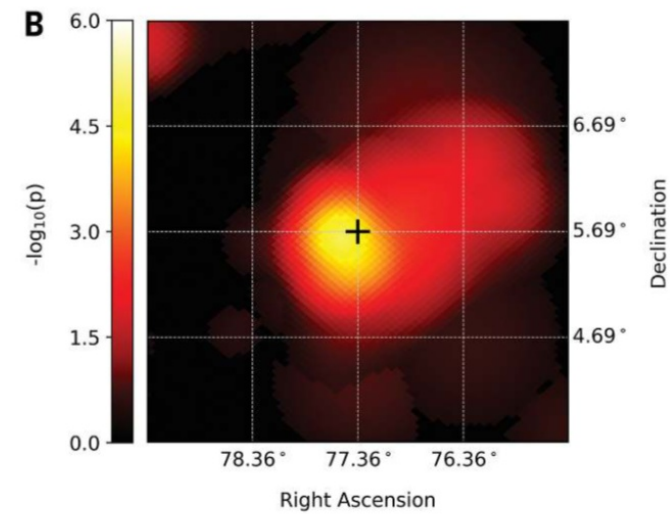
TXS 0506+056

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.

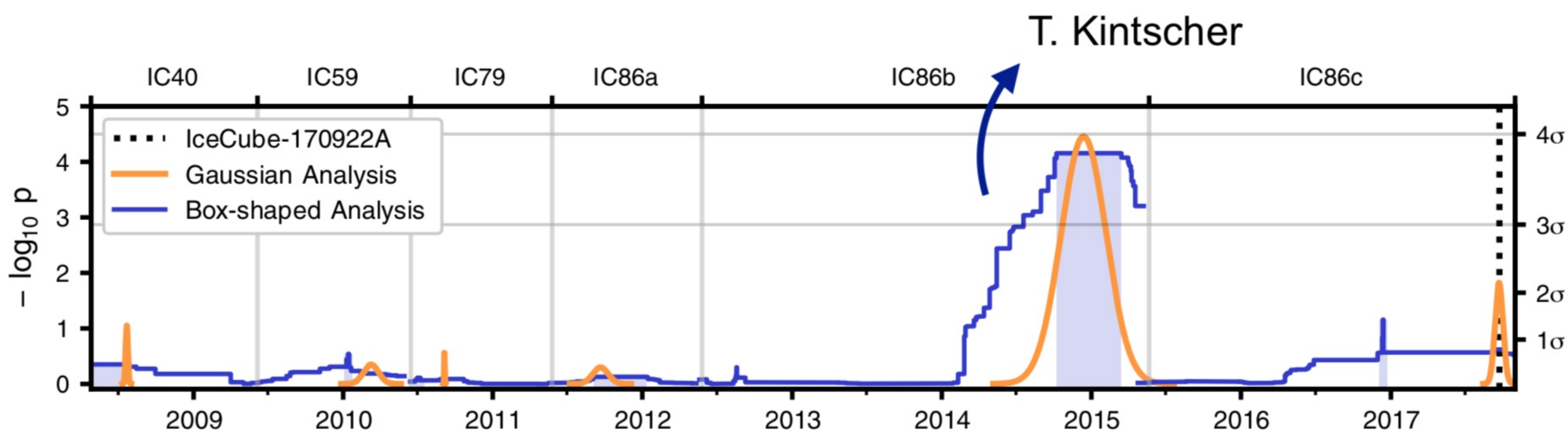
IC170922A / TXS 0506+56

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!

Study of neutrino properties with very high energy astrophysical neutrinos

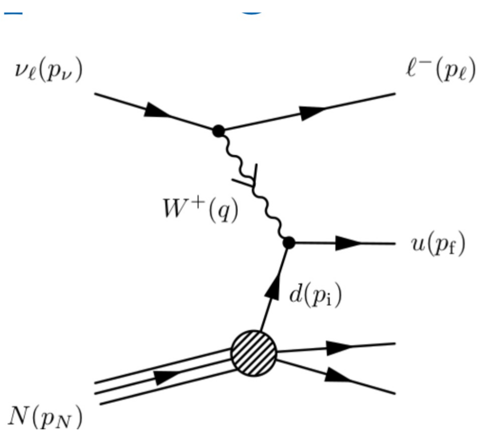
A. Neutrino Cross section

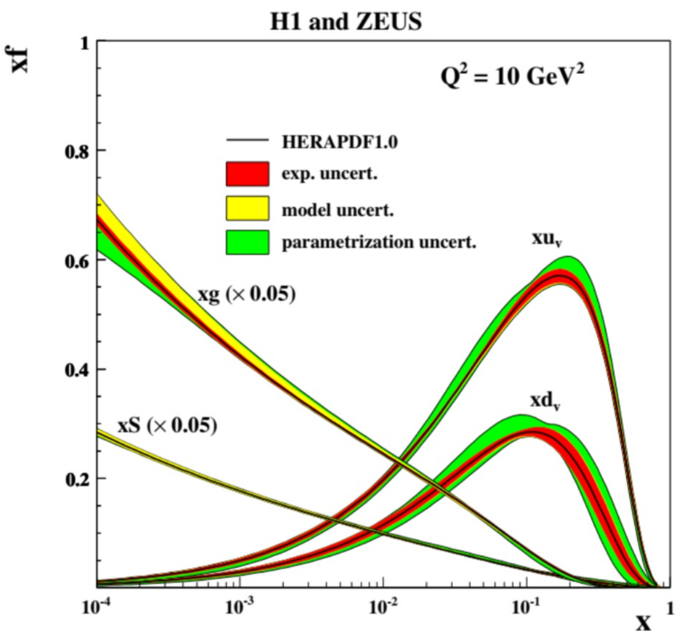
B. Neutrino Flavor evolution

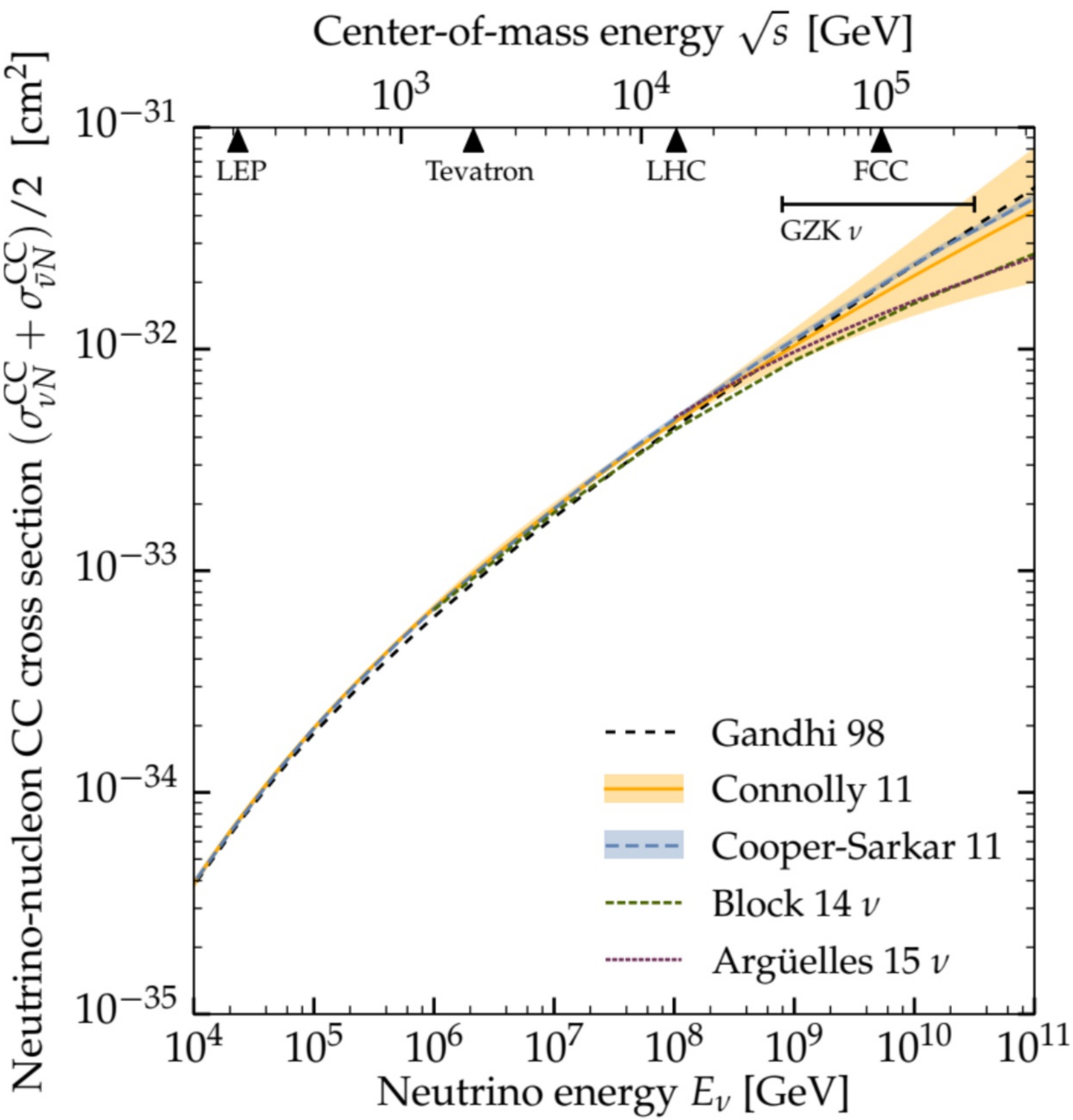
C. New Neutrino Interactions

$$\nu\text{--}\nu \qquad \nu\text{--}\mathrm{DM}$$

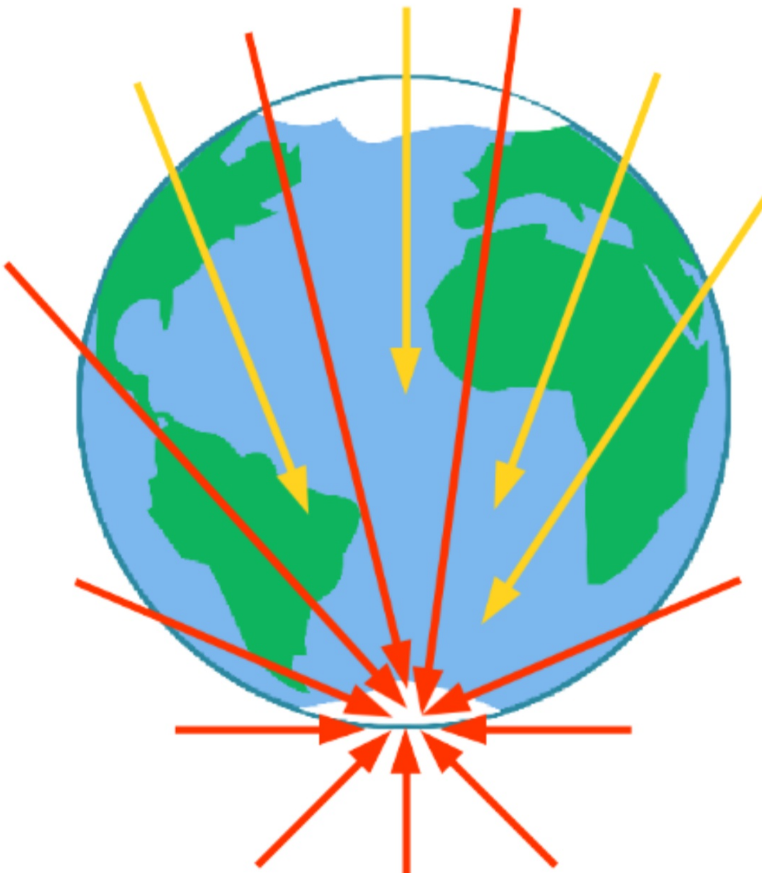
Standard Model calculation of the (DIS) neutrino cross section

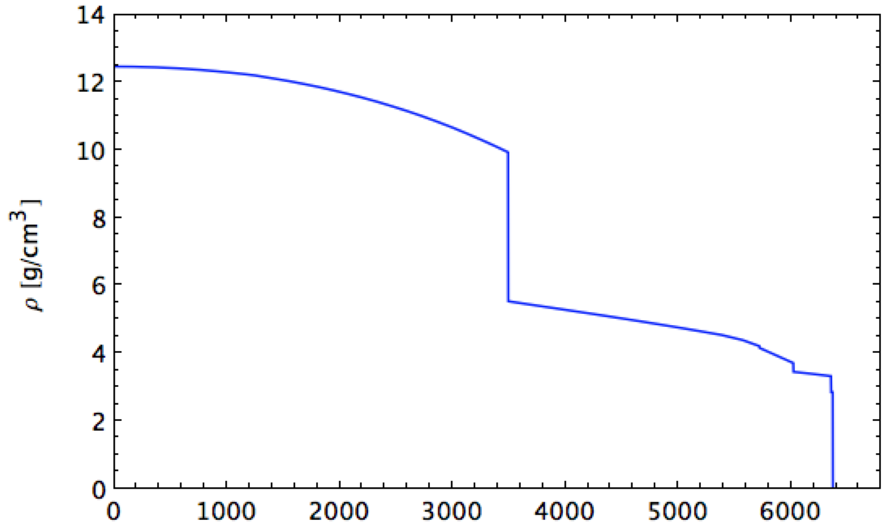




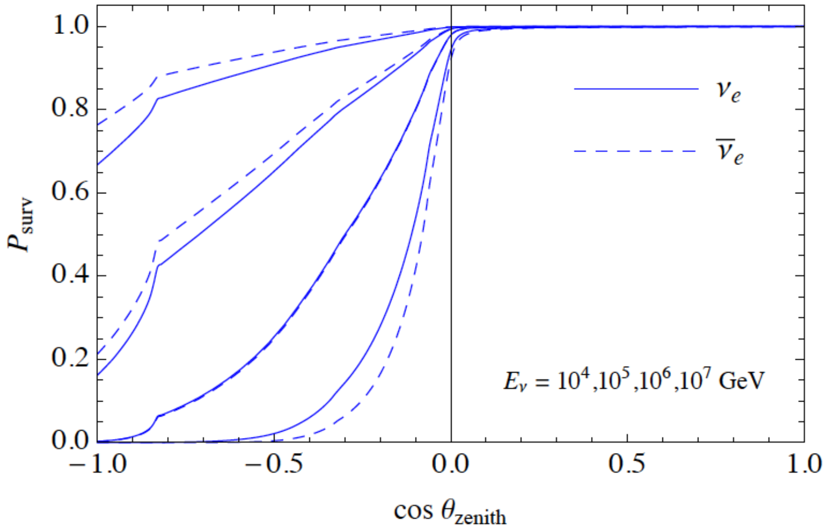


Measure Cross section





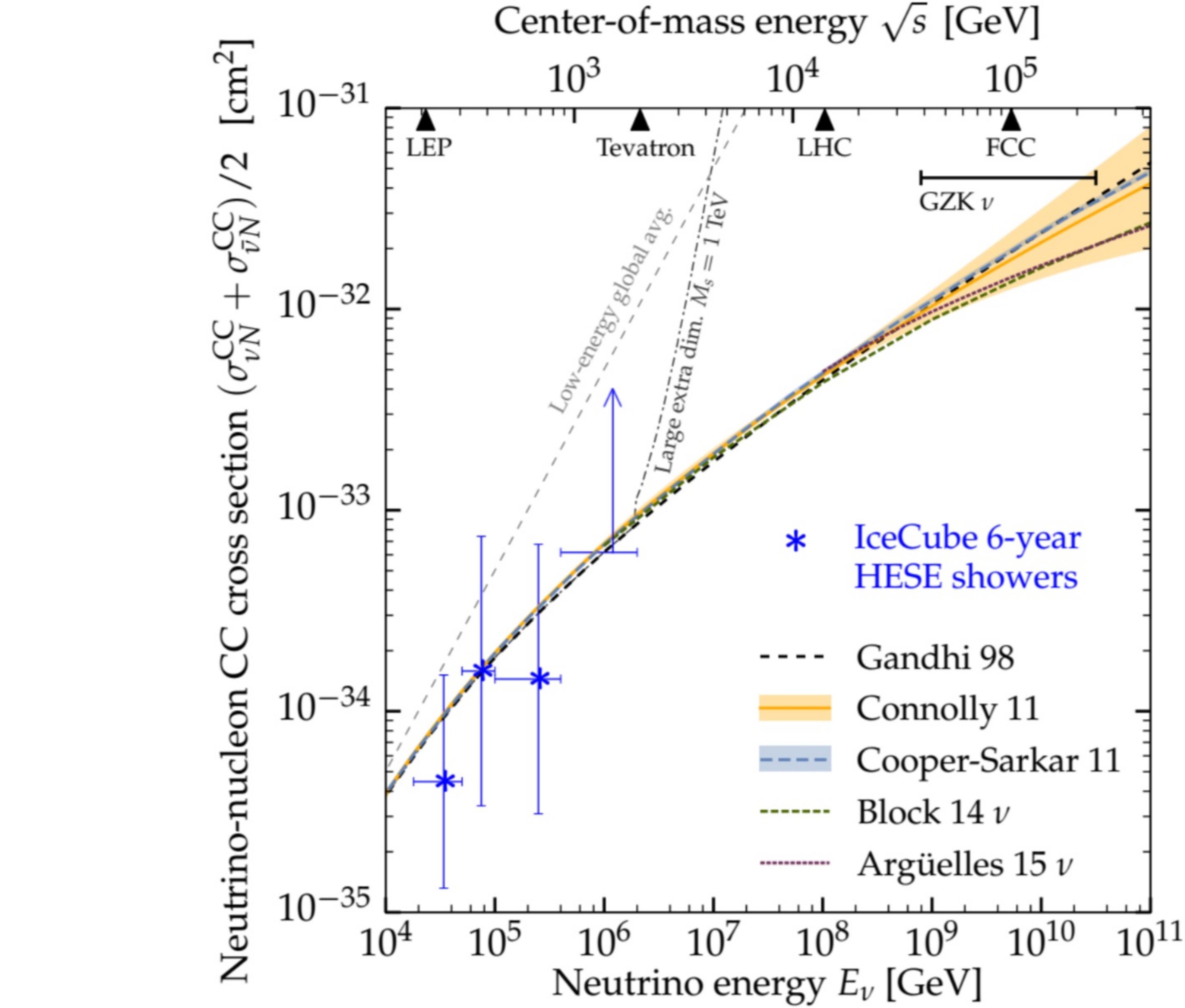
$$P_{\rm surv} = e^{-\tau(E,\Omega)}$$



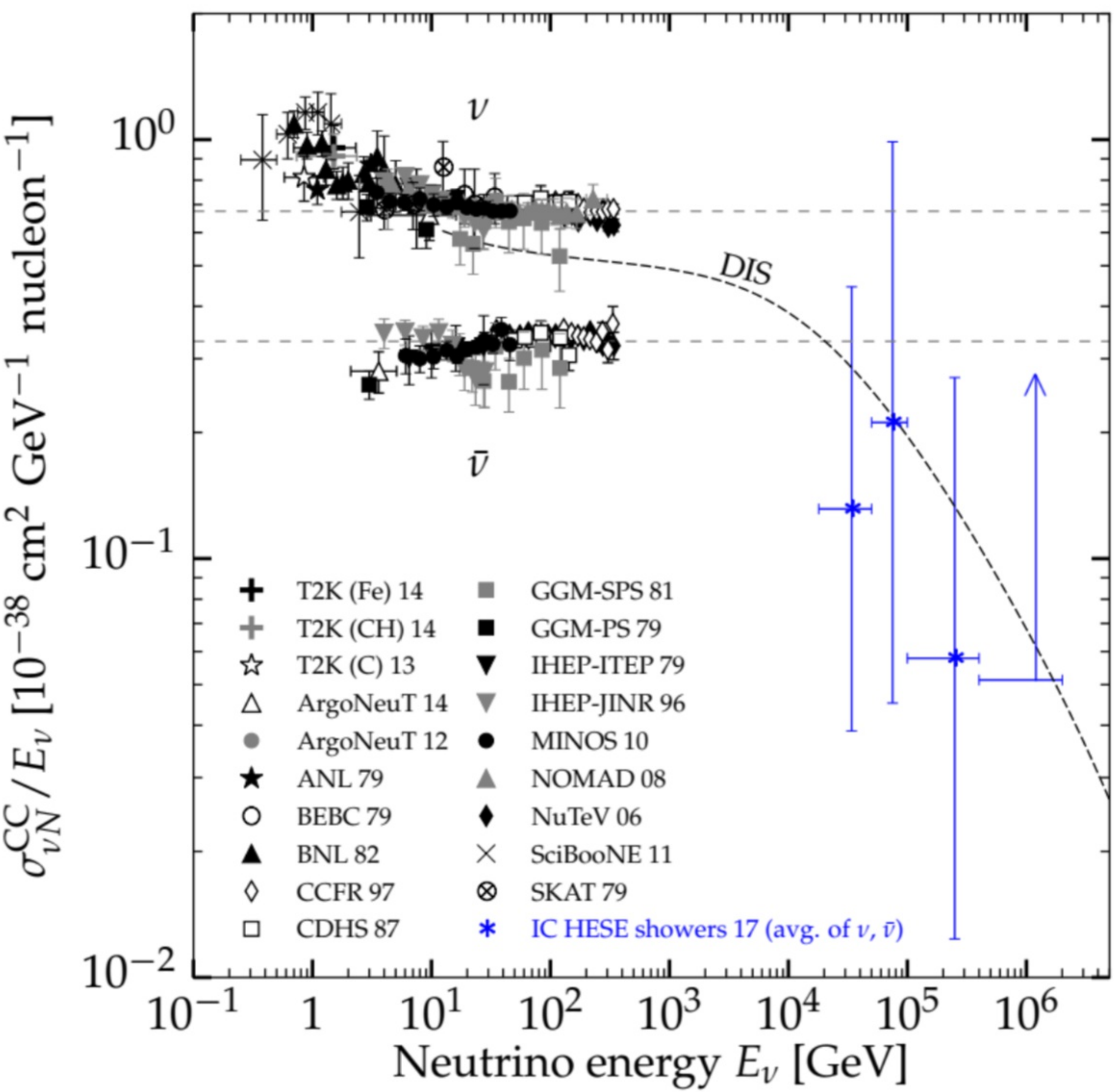
$$\tau = \frac{X}{m_p}\,\sigma_\nu$$

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

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



Center-of-mass energy $\sqrt{s}$ [GeV]
10^3
10^4
10^5
LEP
Tevatron
LHC
FCC
GZK ν
Low-energy global avg.
Large extra dim. $M_s = 1$ TeV
IceCube 6-year HESE showers
Gandhi 98
Connolly 11
Cooper-Sarkar 11
Block 14 ν
Argüelles 15 ν
Neutrino-nucleon CC cross section $(\sigma_{\nu N}^{CC} + \sigma_{\bar{\nu} N}^{CC})/2$ [cm^2]
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy E_ν [GeV]



$\sigma_{\nu N}^{CC}/E_\nu$ [10^{-38} cm^2 GeV^{-1} nucleon^{-1}]
Neutrino energy E_ν [GeV]
ν
$\bar{\nu}$
DIS
10^0
10^{-1}
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
10^6
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, $\bar{\nu}$)

Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

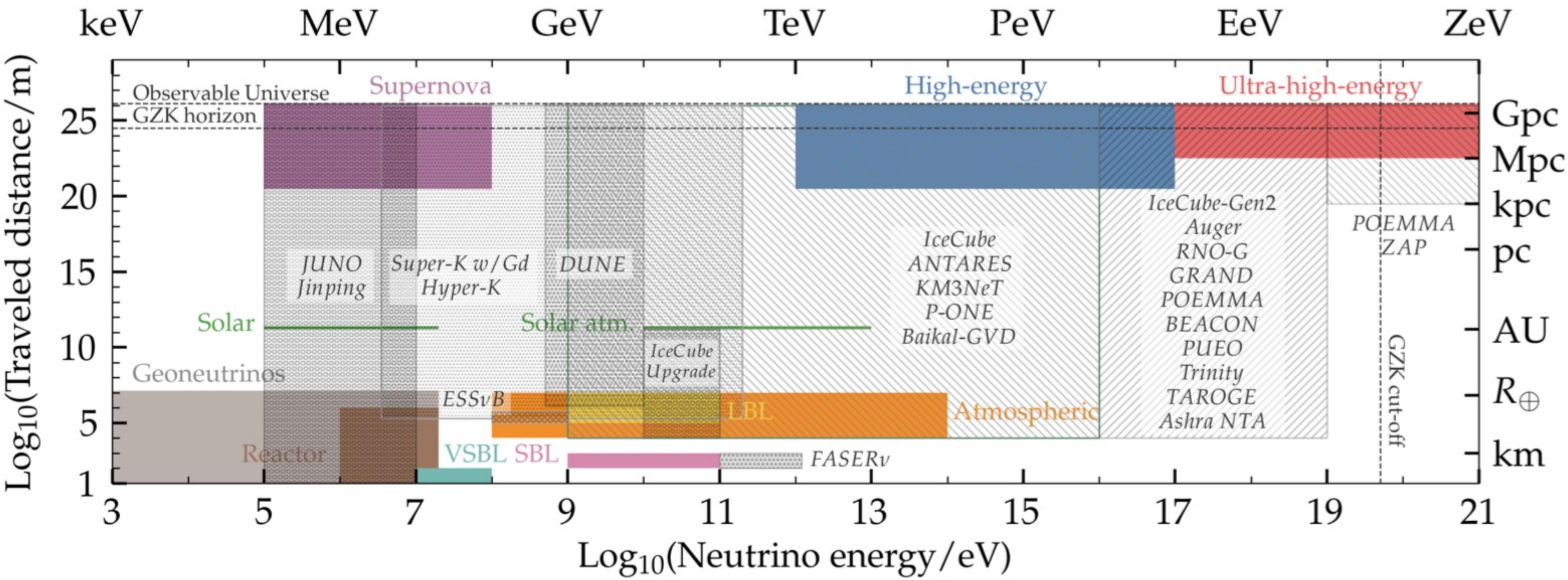
Very High Energy $\sim \mathrm{PeV}$

$10^6\ \mathrm{GeV}$

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

$10^{27}\ \mathrm{cm}$

Very large (astrophysical) uncertainties about source spectra



Cosmic Neutrino Probes of Fundamental Physics

LoI Snowmass 2021

New Physics effects

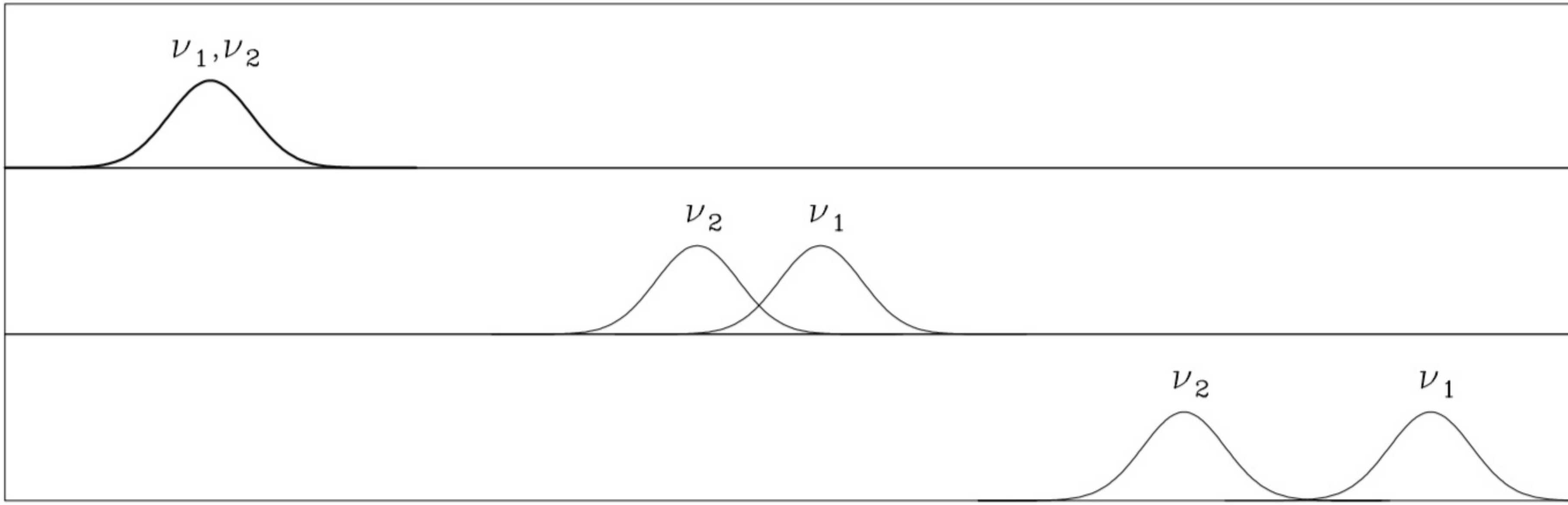
$$\propto k\ E^n\ L$$

$n = 0$

$n = 1$ Lorentz invariance violations

Study very favorable with Astrophysical Neutrinos

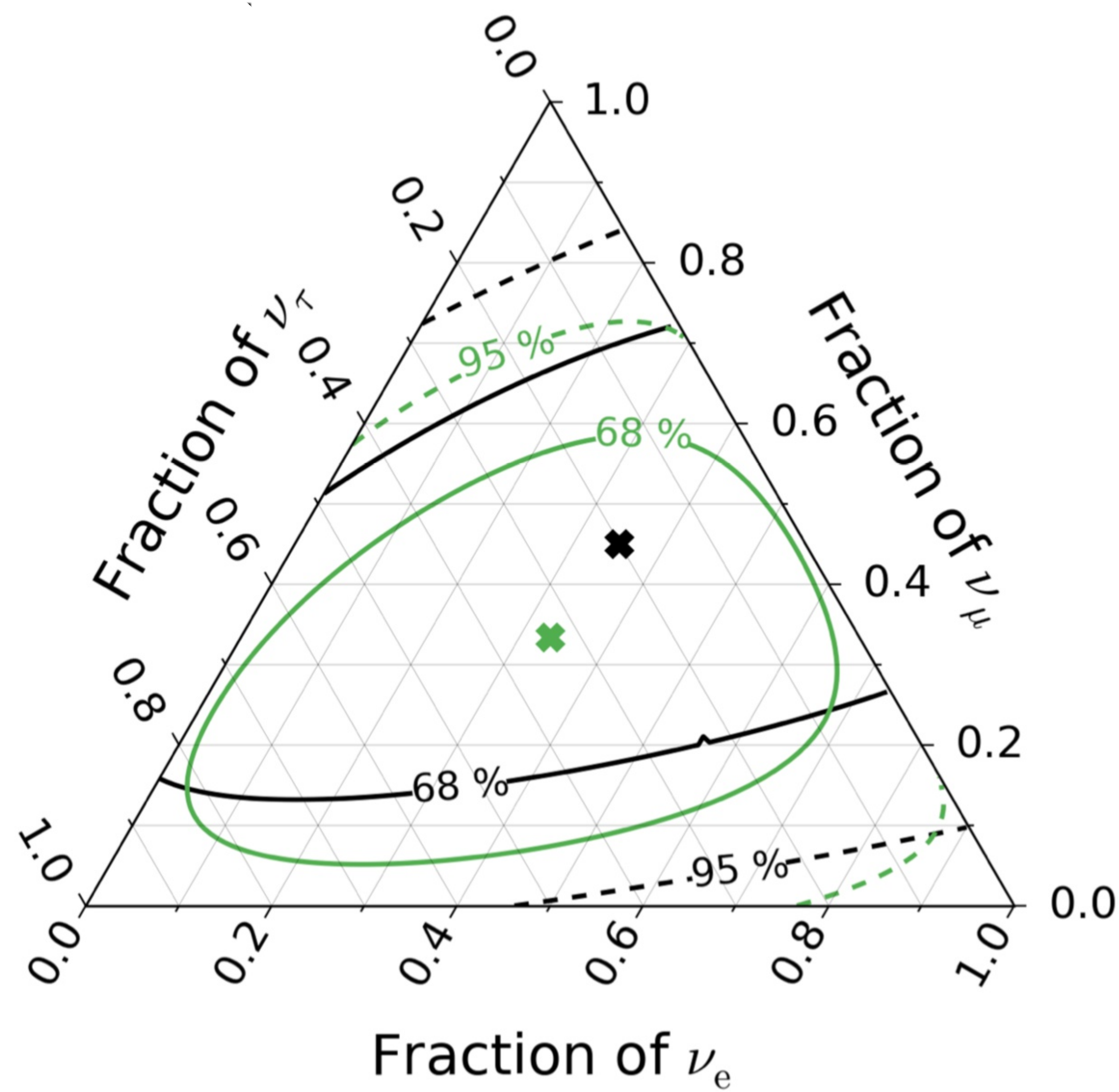
Decoherence



Astrophysical extragalactic neutrinos arrive at the detector as mass eigenstates

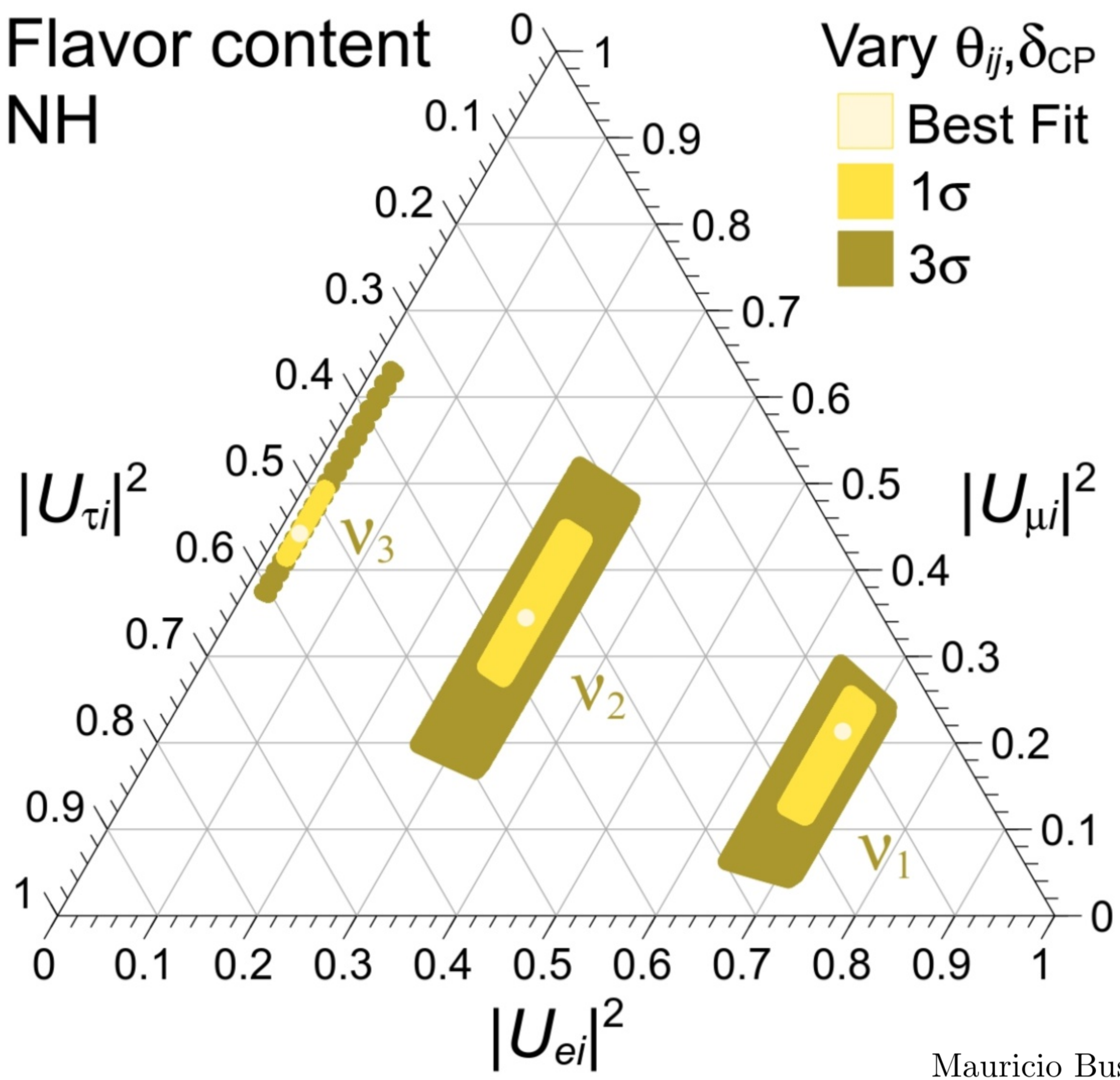
Y. Farzan and A. Y. Smirnov,
"Coherence and oscillations of cosmic neutrinos,"
Nucl. Phys. B **805**, 356 (2008)
[arXiv:0803.0495 [hep-ph]].

E. Akhmedov, D. Hernandez and A. Smirnov,
"Neutrino production coherence and oscillation experiments,"
JHEP **1204**, 052 (2012)
[arXiv:1201.4128 [hep-ph]].

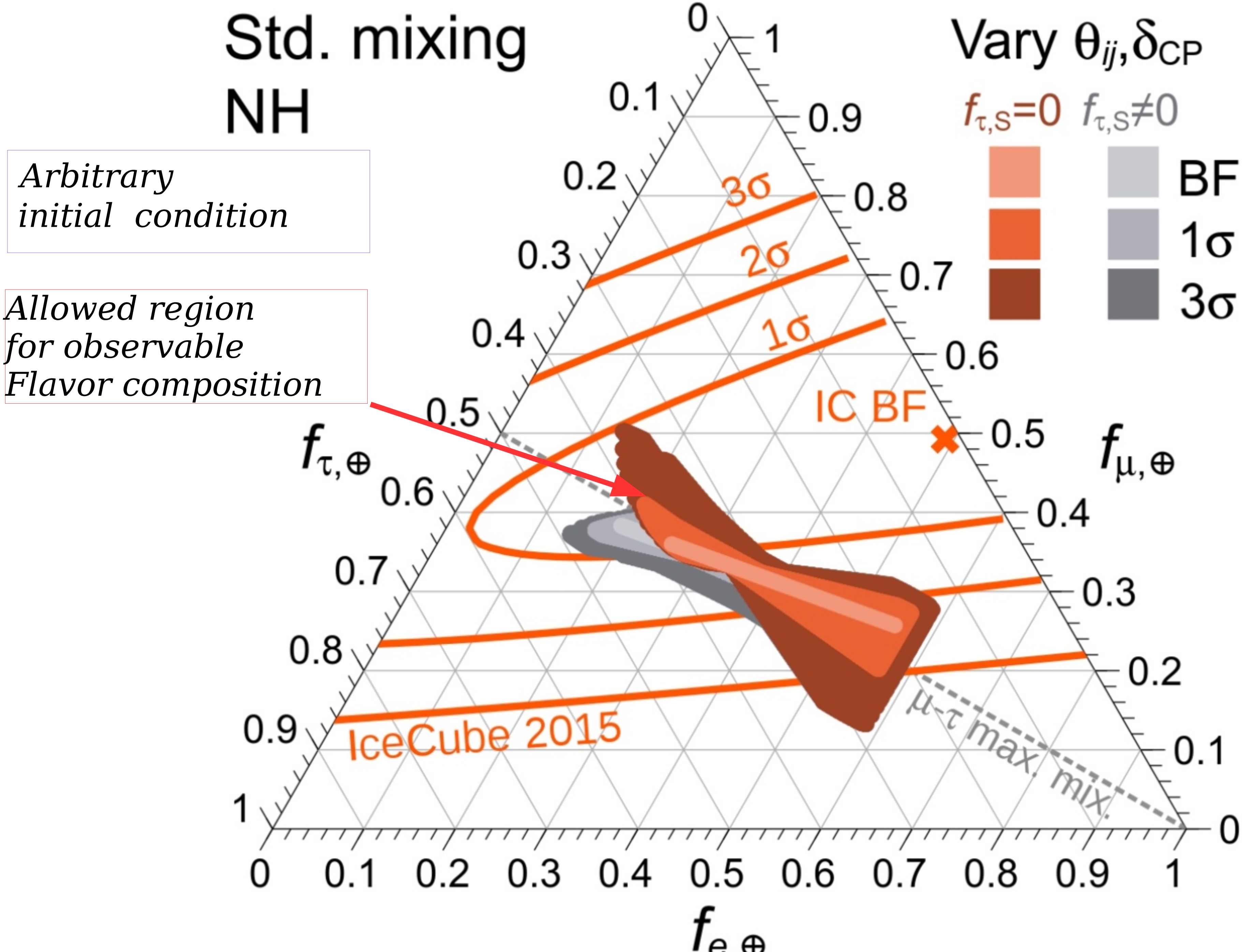


Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
0.0
0.2
0.4
0.6
0.8
1.0
95 %
68 %
68 %
95 %

Potential to study non-standard neutrino propagation properties



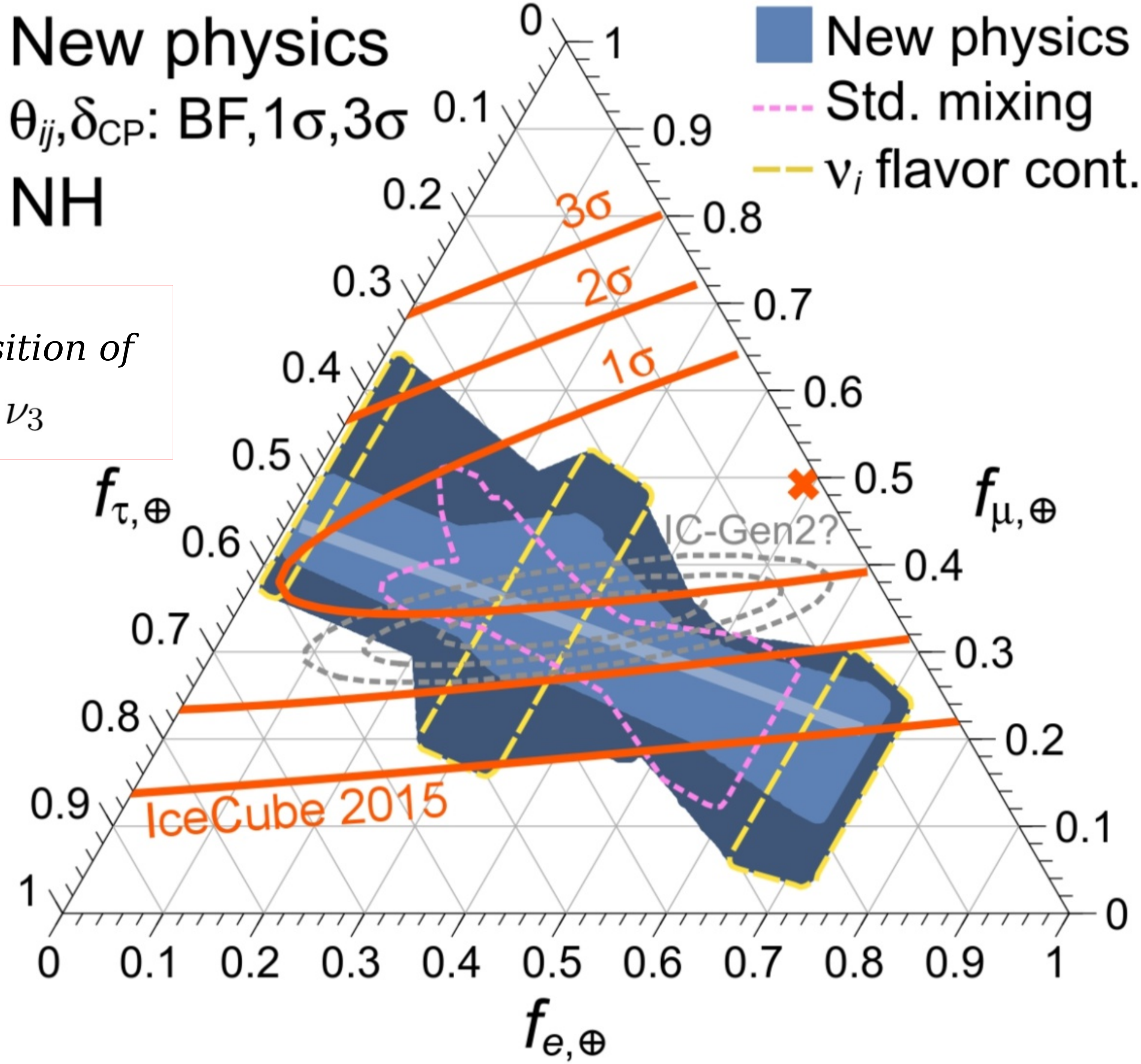
Mauricio Bustamante, John F. Beacom, and Walter Winter,
"Theoretically palatable flavor combinations of astrophysical neutrinos",
Phys. Rev. Lett. 115, 161302 (2015),
arXiv:1506.02645 [astro-ph.HE].



Std. mixing
NH
Arbitrary initial condition
Allowed region for observable Flavor composition
Vary θ_{ij}, δ_{CP}
$f_{\tau,S}=0$
$f_{\tau,S}\neq0$
BF
1σ
3σ
3σ
2σ
1σ
IC BF
IceCube 2015
μ-τ max. mix.
$f_{\tau,\oplus}$
$f_{\mu,\oplus}$
$f_{e,\oplus}$

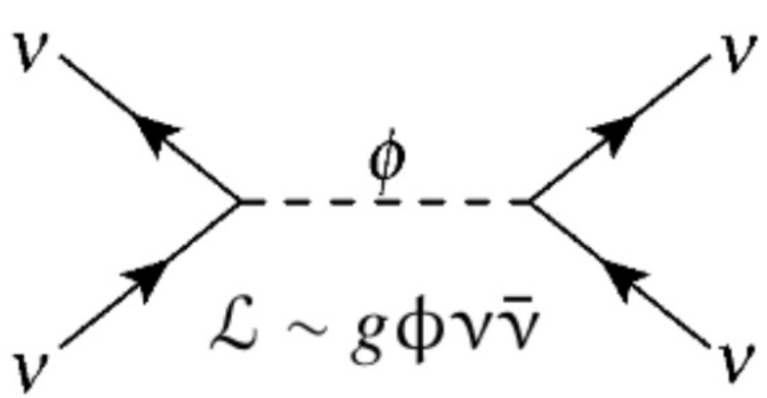
General superposition of

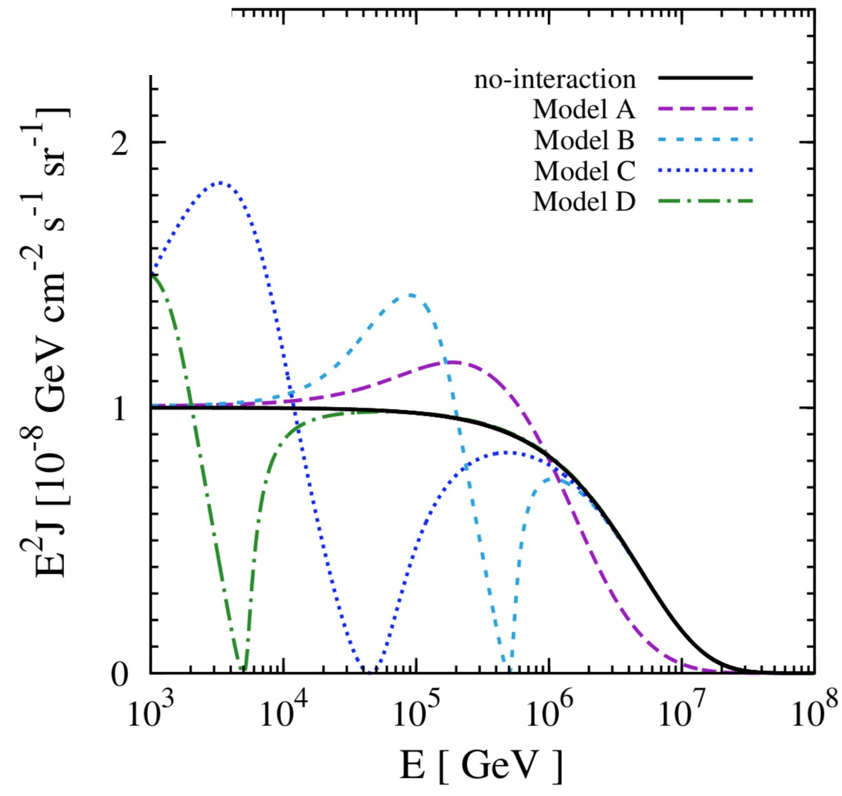
$\nu_1 \quad \nu_2 \quad \nu_3$



Interactions between astrophysical neutrinos (PeV energy) with relic neutrinos (meV energy)

K. C. Y. Ng and J. F. Beacom,
"Cosmic neutrino cascades from secret neutrino interactions,"
Phys. Rev. D **90**, no. 6, 065035 (2014)
[arXiv:1404.2288 [astro-ph.HE]].

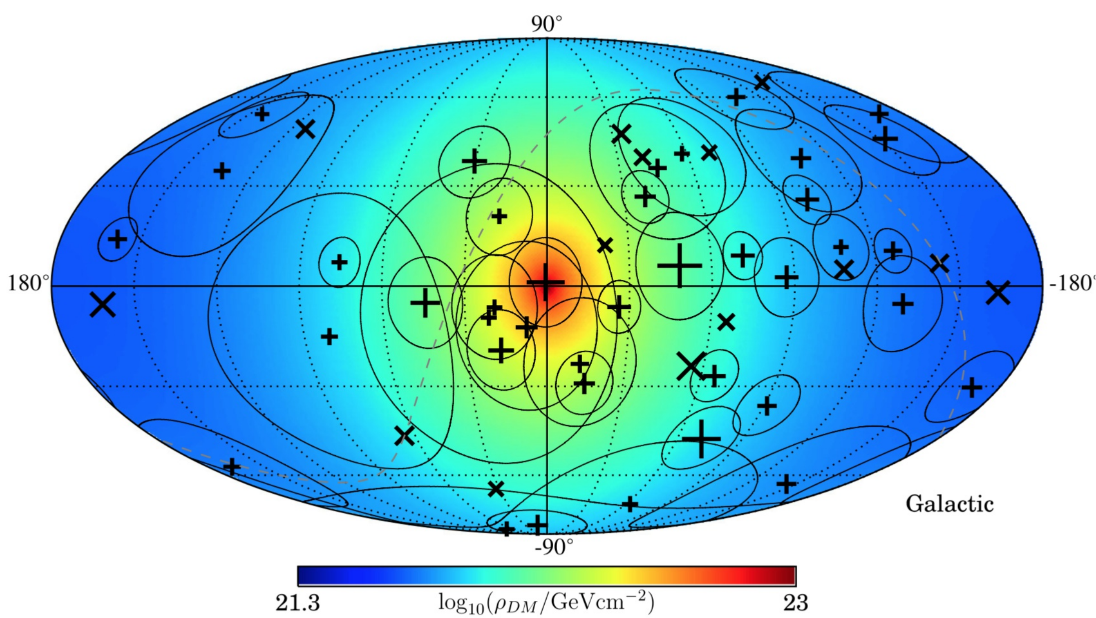


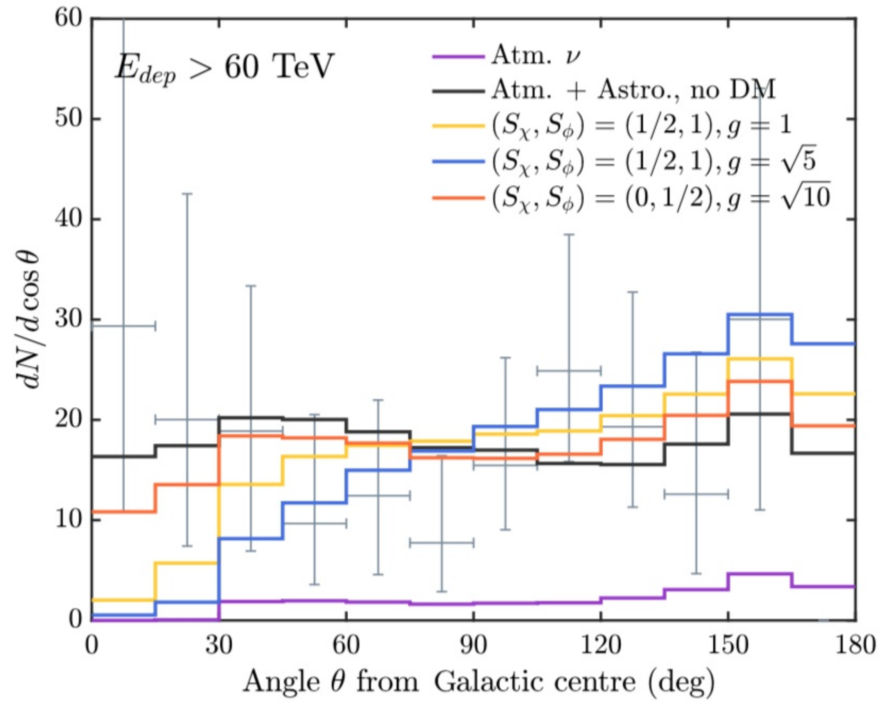


Neutrino-DM interactions

(Absorption feature in the direction of the Galactic Center)

C. A. Argüelles, A. Kheirandish and A. C. Vincent,
"Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos,"
Phys. Rev. Lett. **119**, no. 20, 201801 (2017)
[arXiv:1703.00451 [hep-ph]].



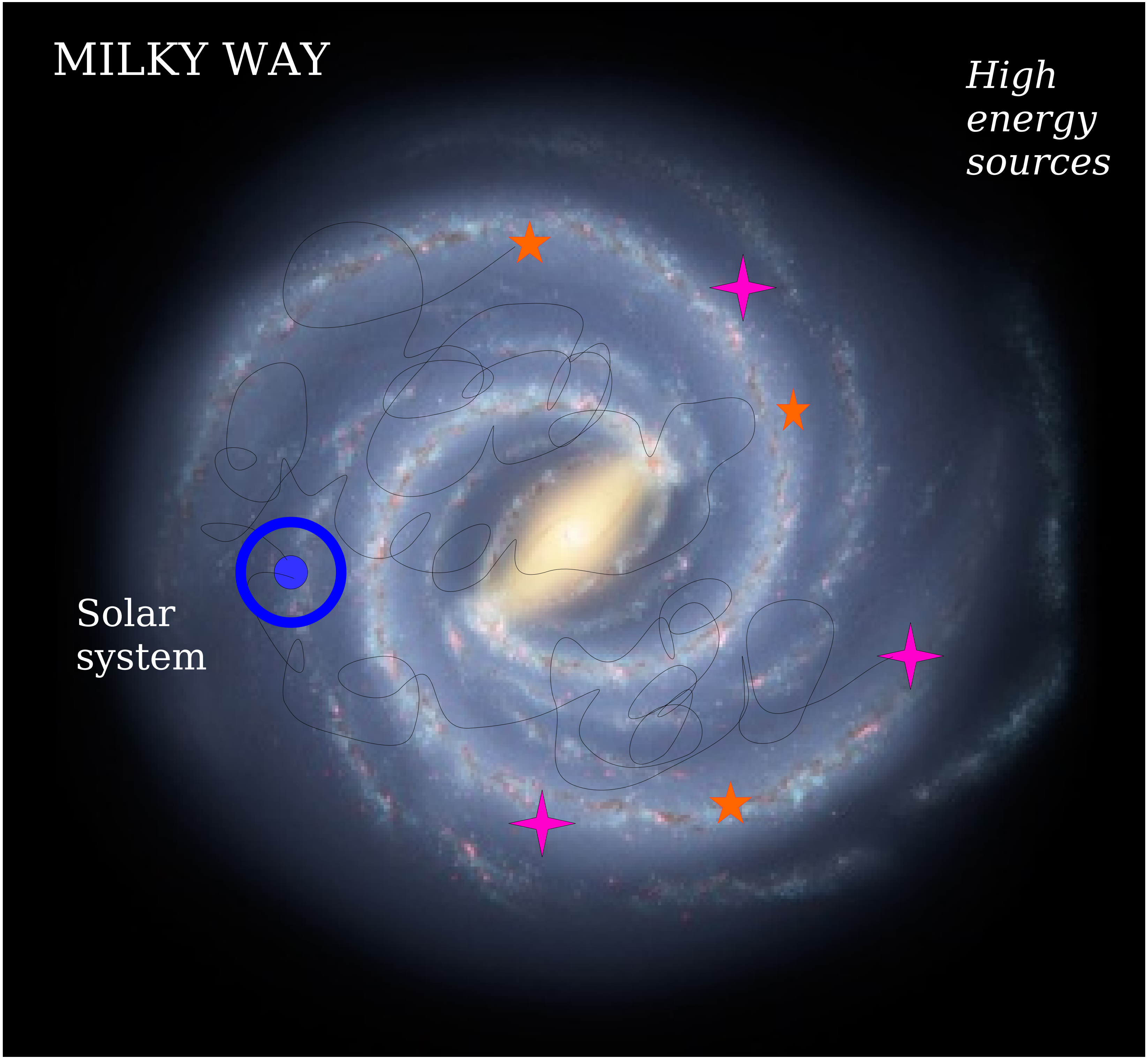


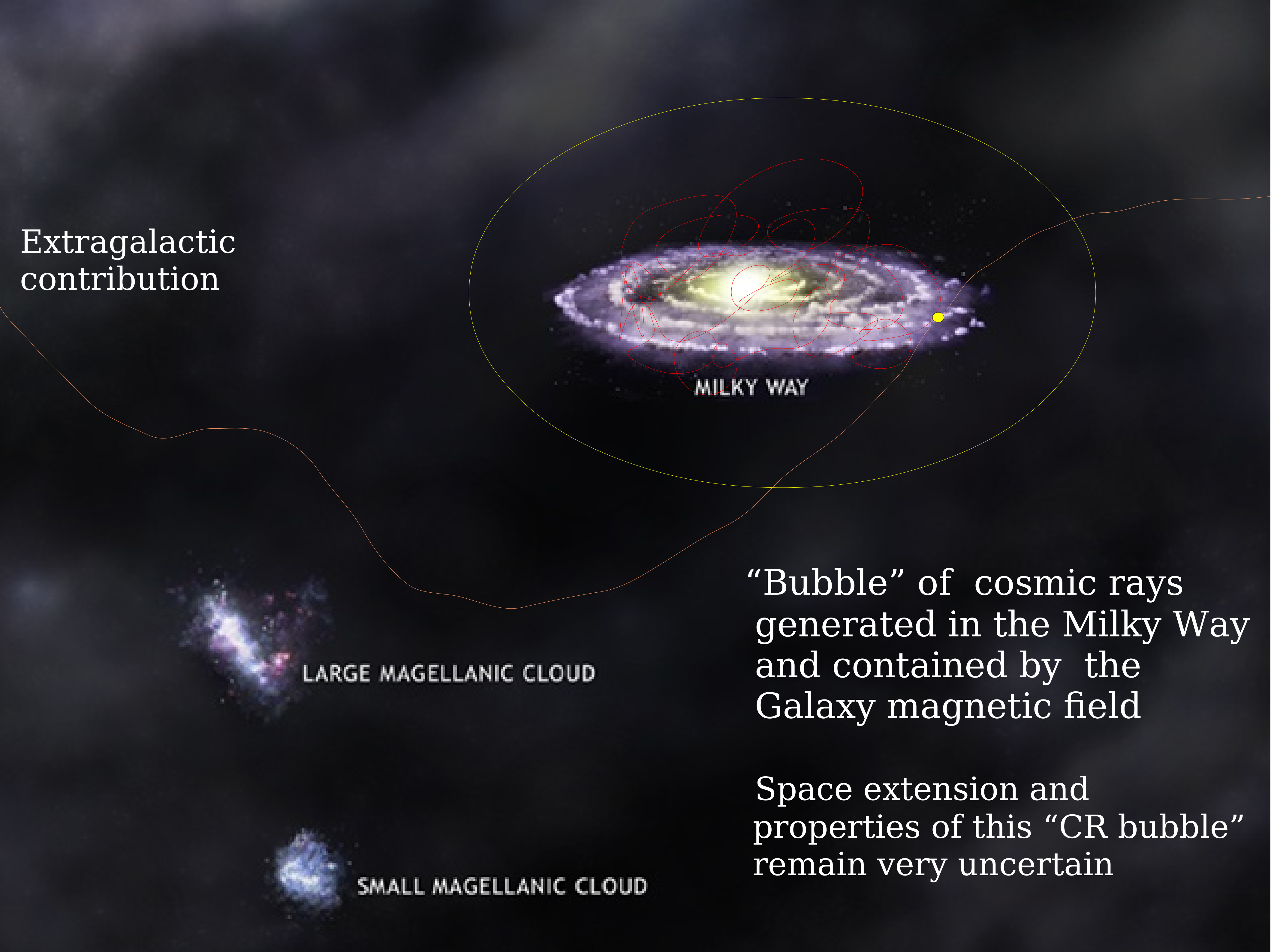
COSMIC RAYS

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]

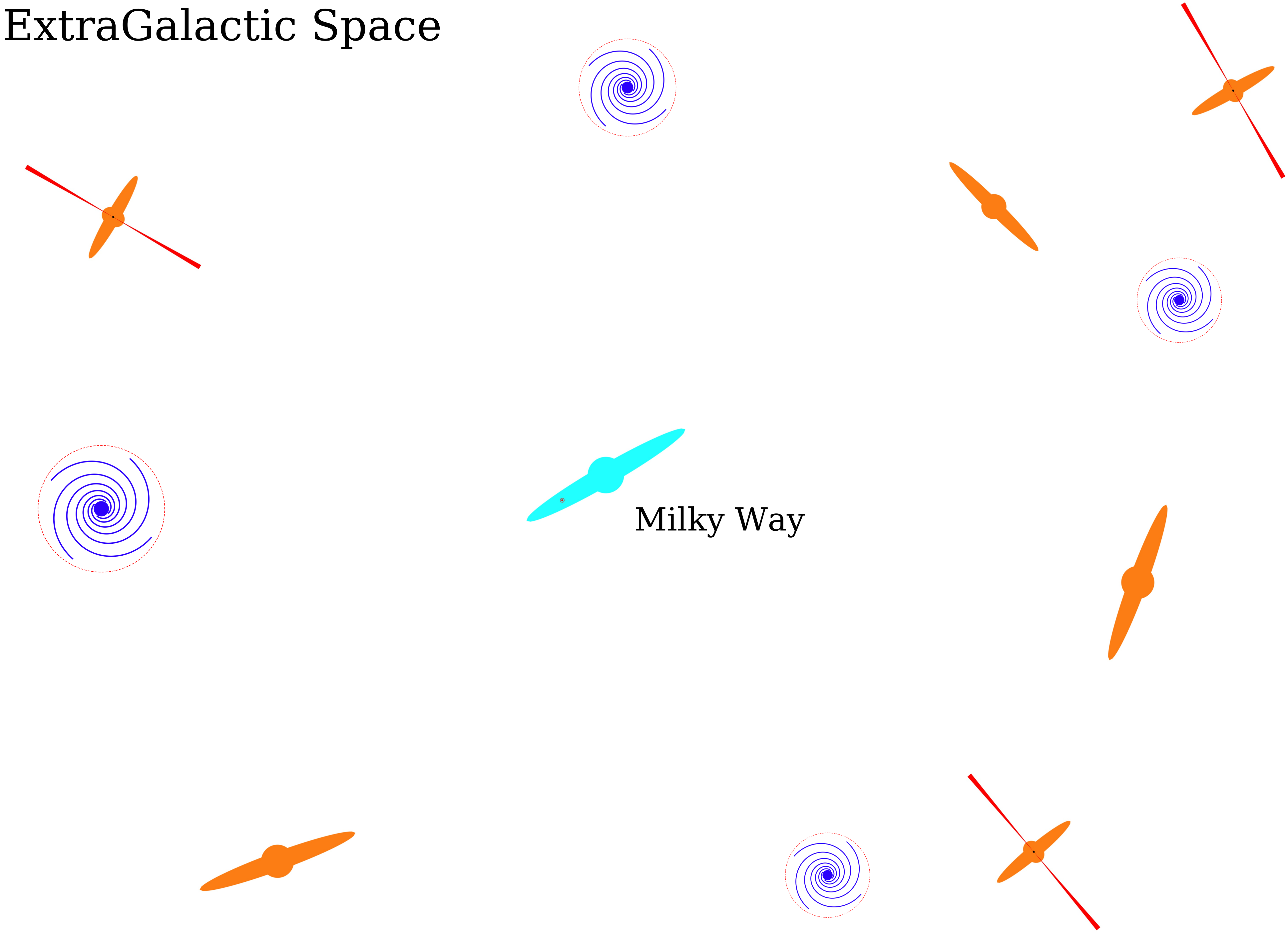

MILKY WAY
High energy sources
Solar system



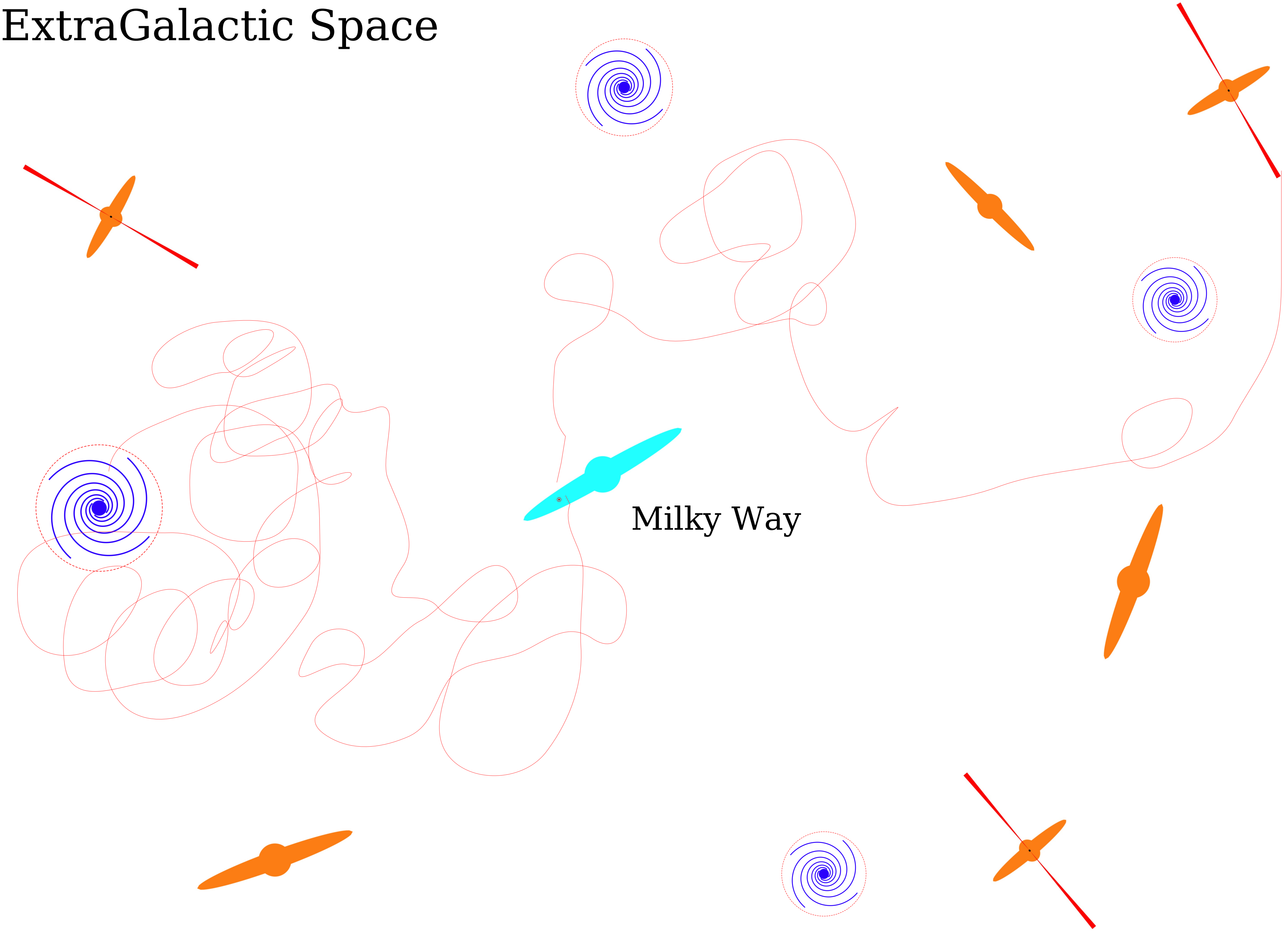
Extragalactic contribution

"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

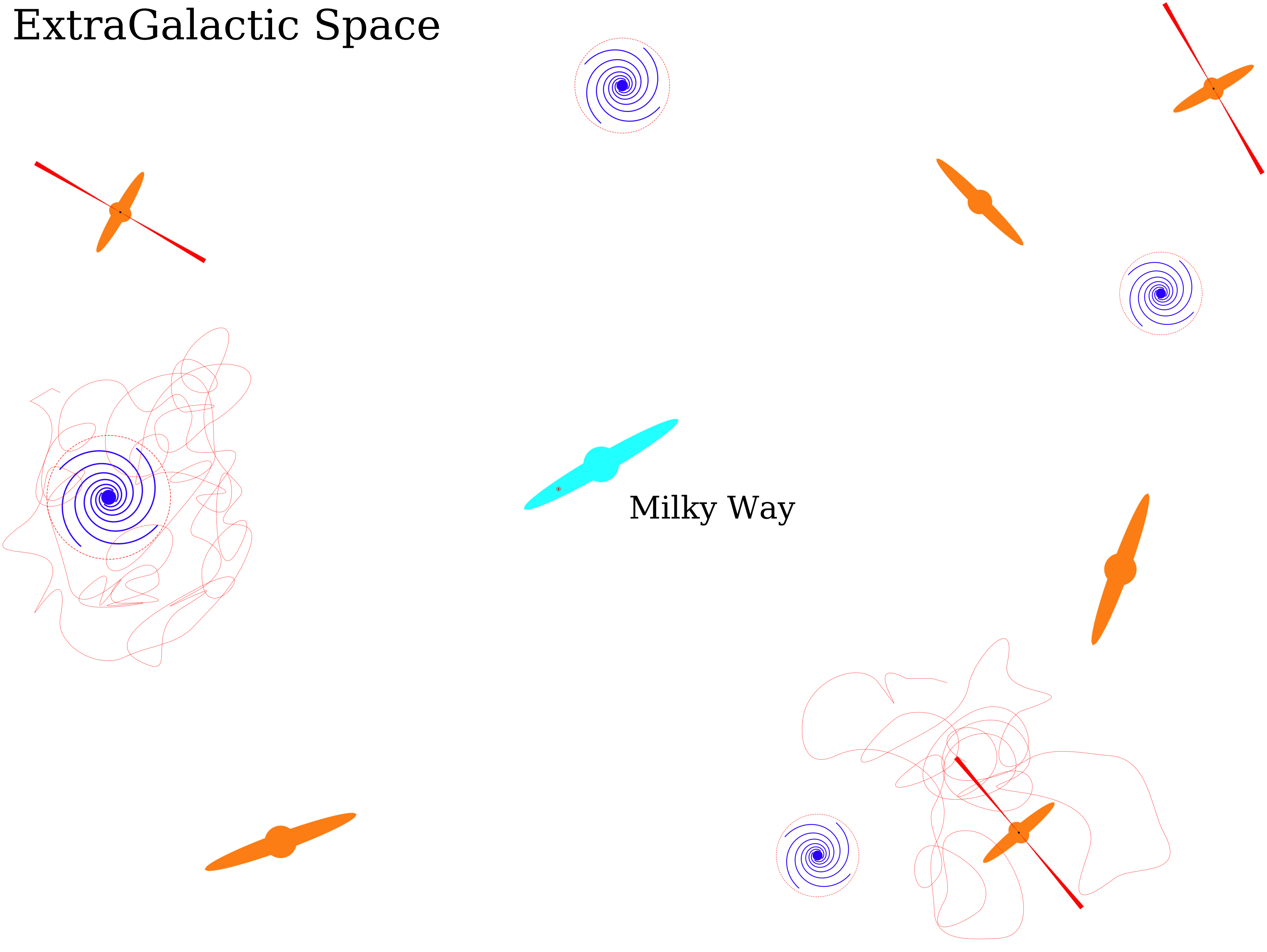
Space extension and properties of this "CR bubble" remain very uncertain


ExtraGalactic Space
Milky Way

ExtraGalactic Space



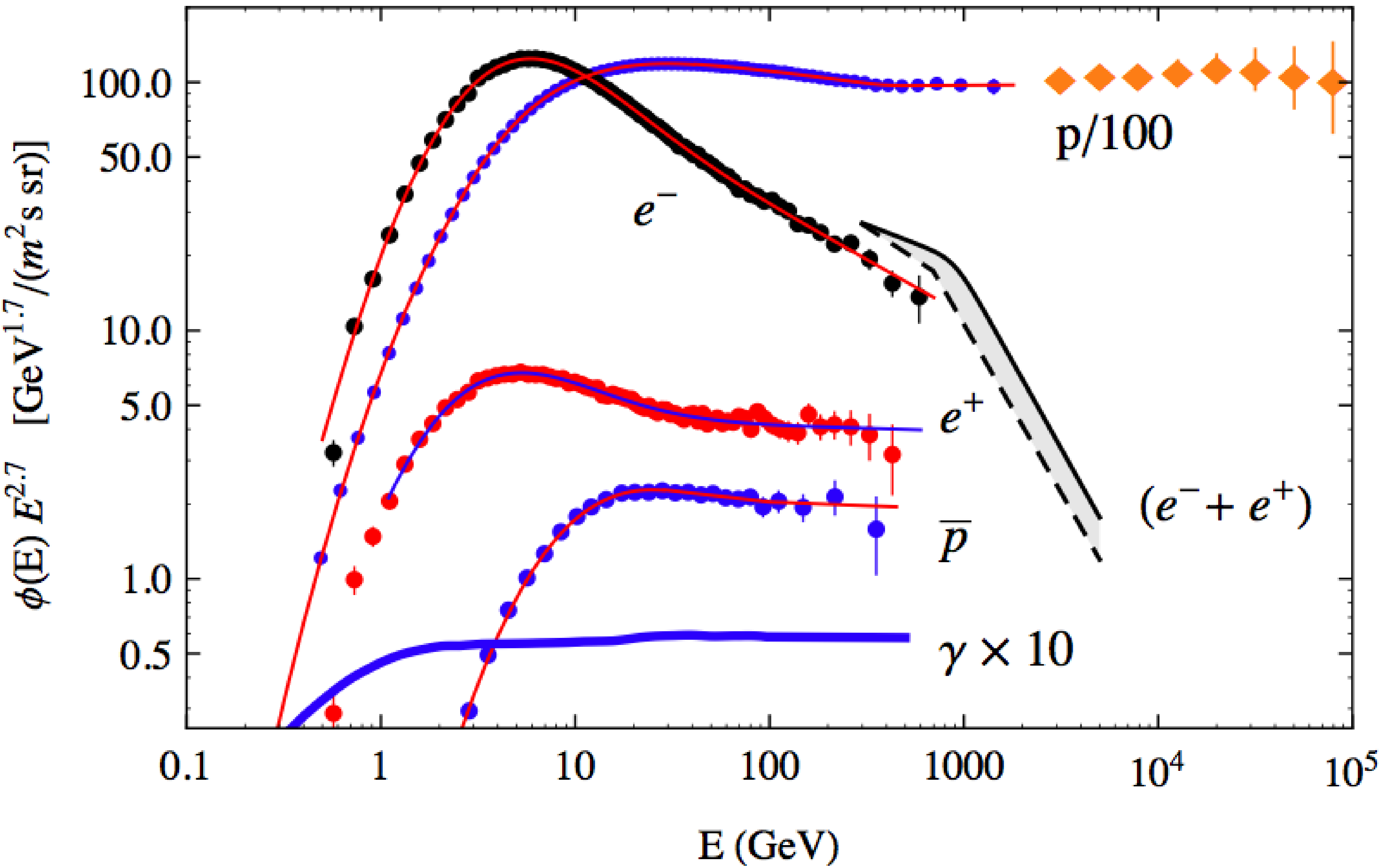
ExtraGalactic Space



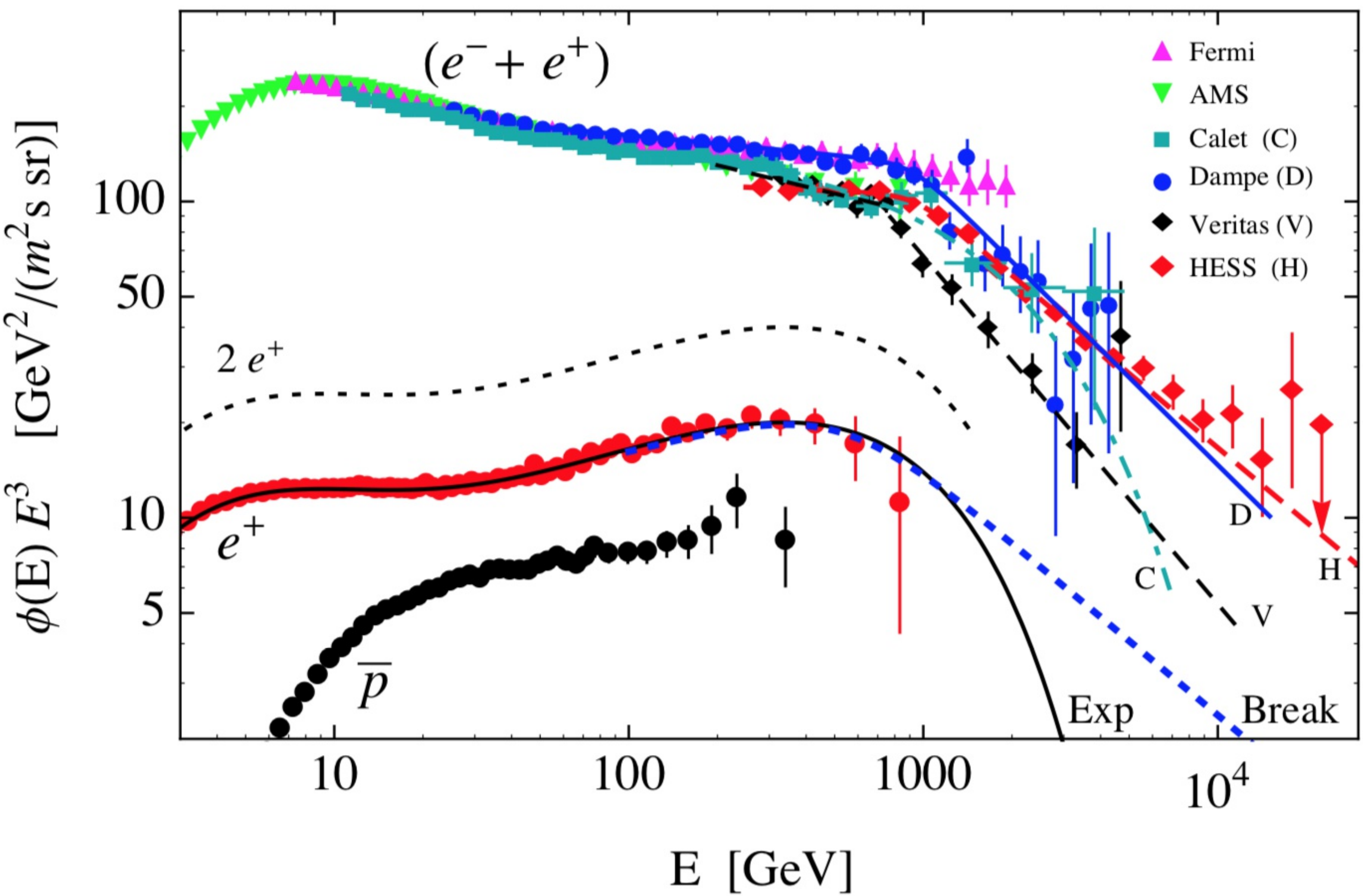
Cosmic Ray Spectra p e^- e^+ $\overline{p}$

AMS02

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)



$(e^- + e^+)$
Fermi
AMS
Calet (C)
Dampe (D)
Veritas (V)
HESS (H)
$2\,e^+$
e^+
$\overline{p}$
D
C
V
H
Exp
Break
$\phi(E)\,E^3$ [GeV^2/(m^2s sr)]
E [GeV]
100
50
10
5
10
100
1000
10^4

"Conventional mechanism"
for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

$$pp \to \pi^+ + \ldots$$
$$\quad \hookrightarrow \mu^+ + \nu_\mu$$
$$\qquad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$pp \to \pi^\circ + \ldots$$
$$\quad \hookrightarrow \gamma + \gamma$$

"Standard mechanism" for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected

Hadronic Interactions

“The Dark Side”

of the Standard Model

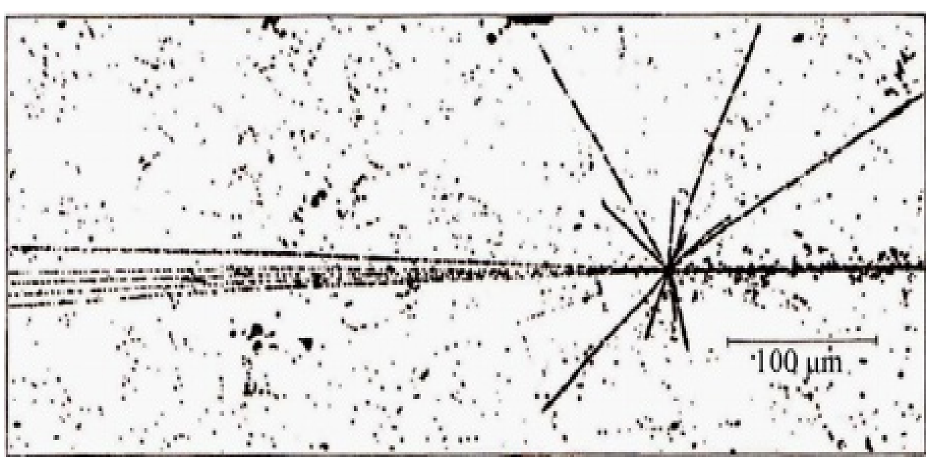
Fundamental **QCD Lagrangian density**

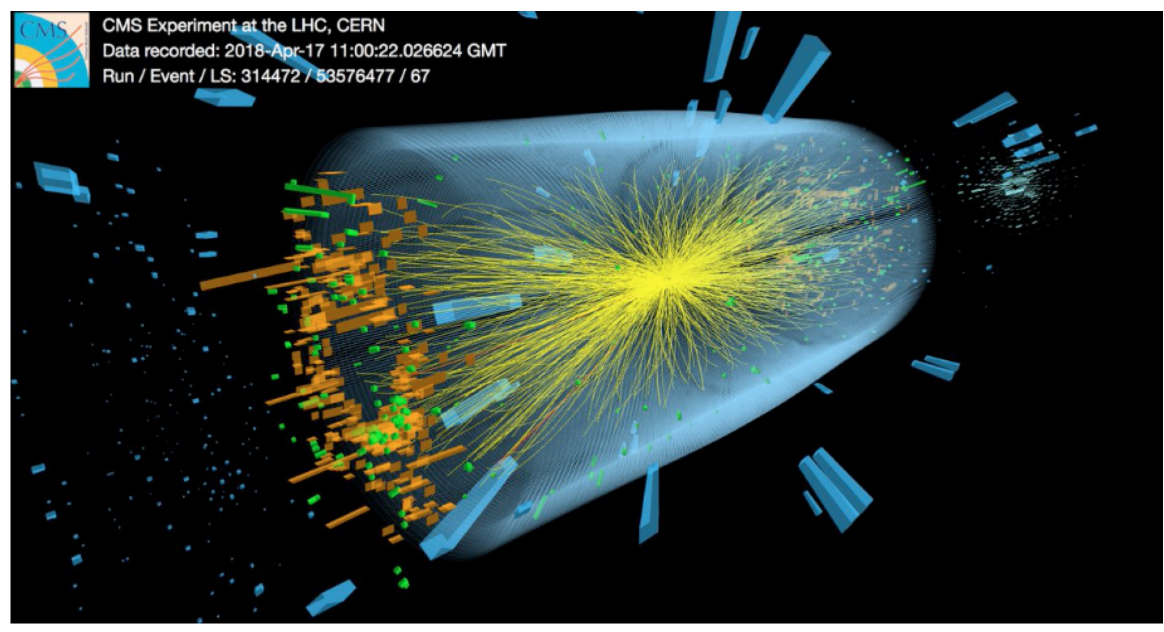
(in terms of quarks and gluon fields)

$$\mathcal{L} = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F^{A}_{\mu\nu} + \sum^{n_f} \bar{q}_j(i\not{D} - m_j)q_j$$

$$D_\mu = \partial_\mu - ie_s\sum_{A} t^A g^A_\mu$$

Multi-particle production





Study of Ultra High Energy Cosmic Rays

(interpretation of the observations
of Cosmic Ray showers in the atmosphere)

requires an *extrapolation of LHC data*

laboratory energy
(proton primary)

c.m. energy
(nucleon-nucleon collisions)

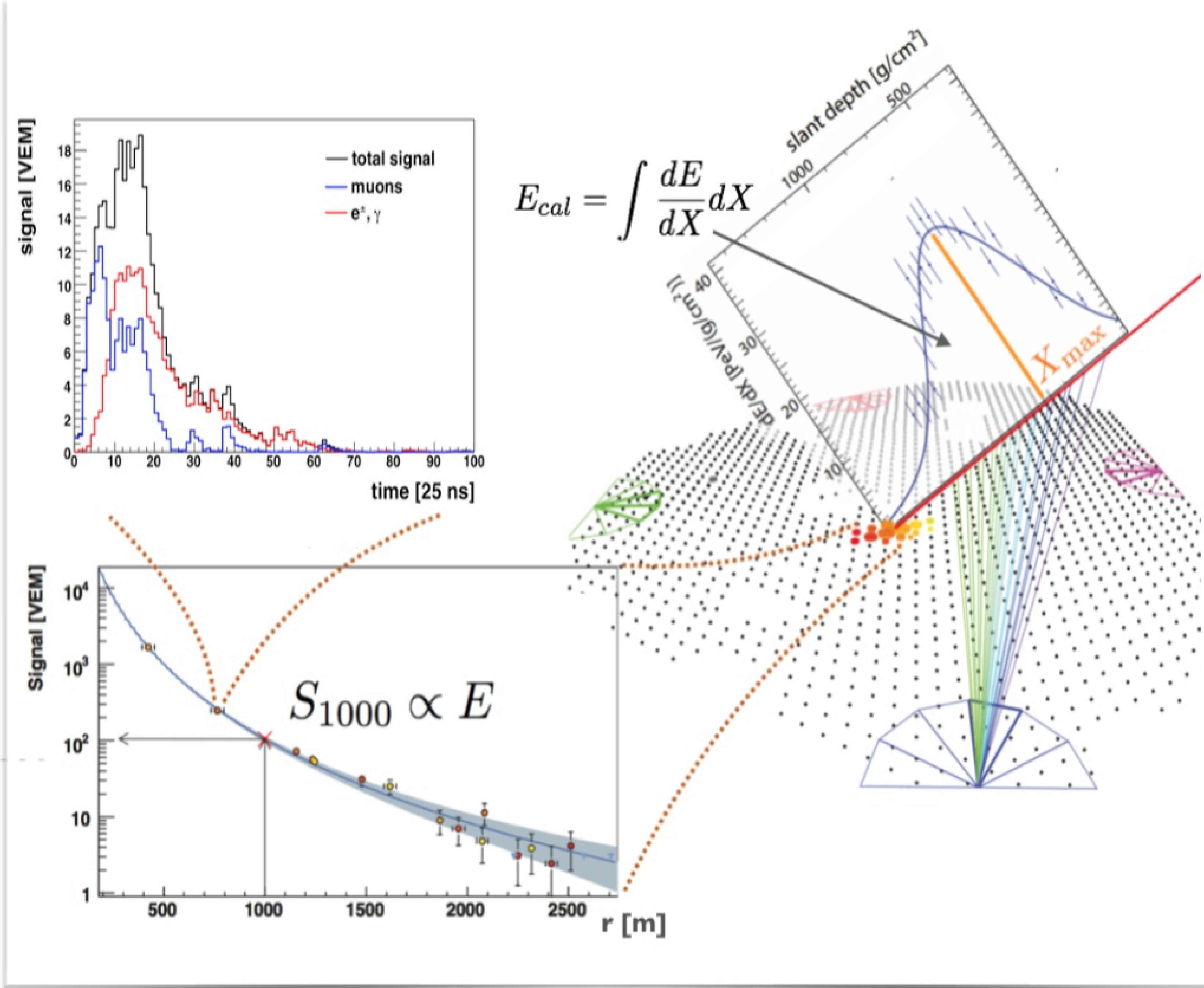
$$E \gtrsim 10^{17} \text{ eV}$$

$$\sqrt{s} \gtrsim 13.7 \text{ TeV}$$

$$E = 10^{20} \text{ eV}$$

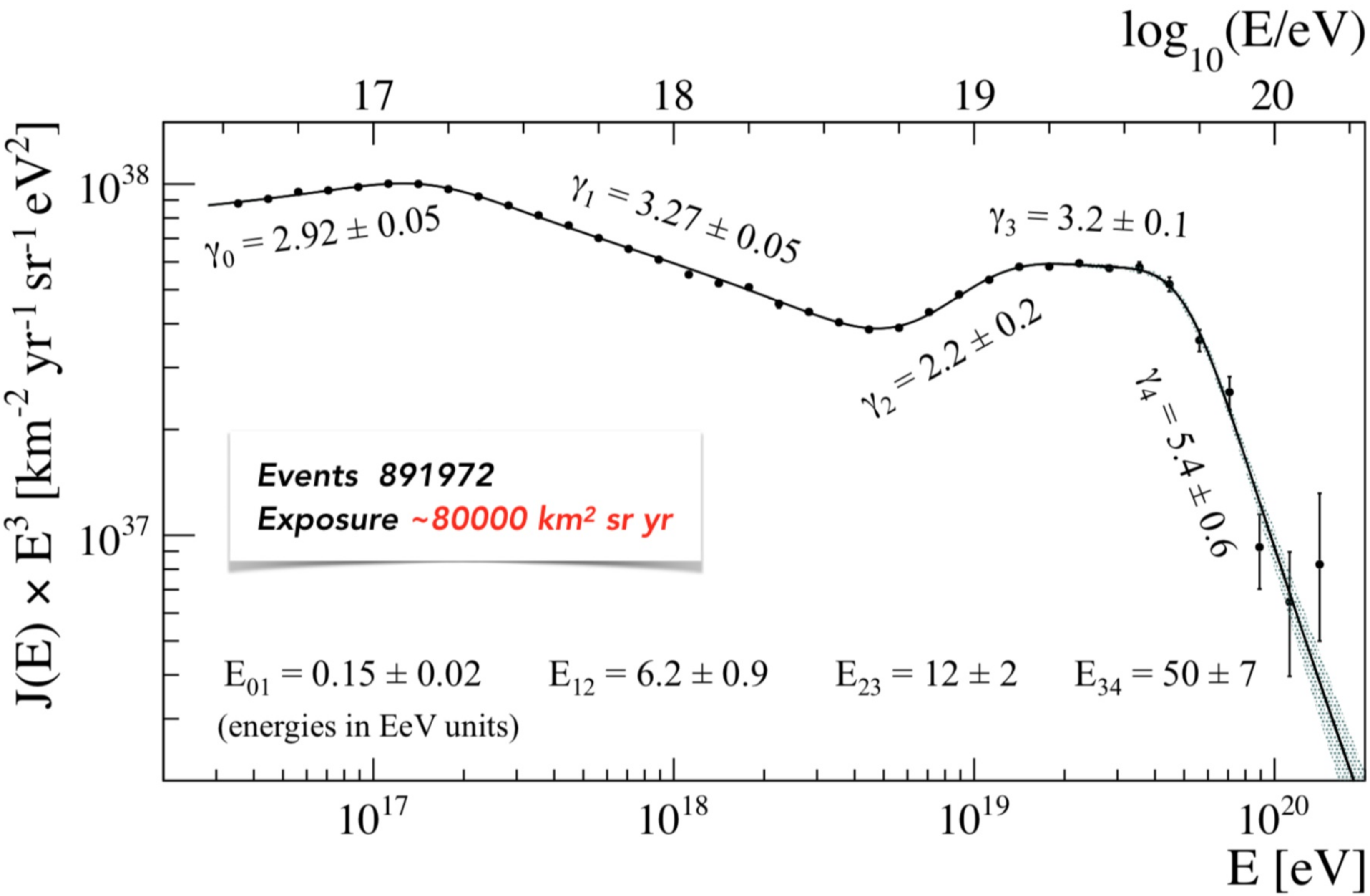
$$\sqrt{s} \simeq 433 \text{ TeV}$$

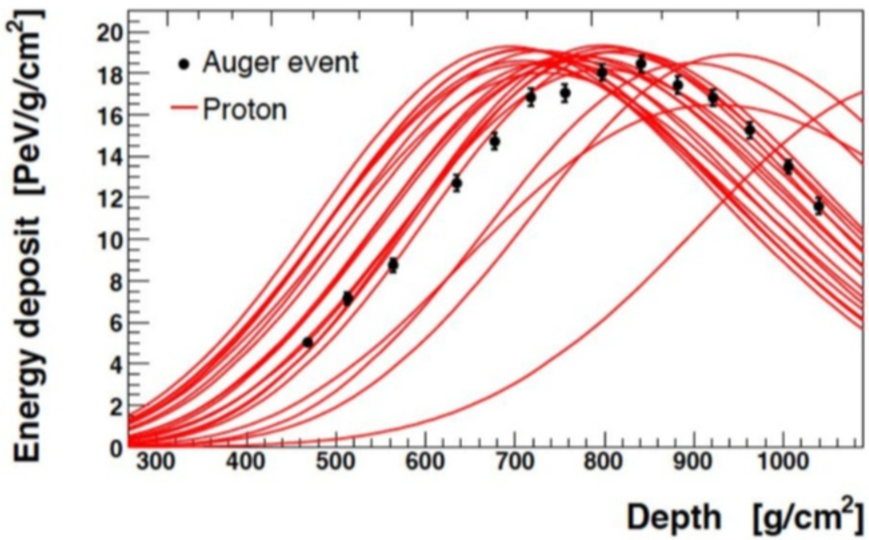
Precise description of *interactions at lower energy*
is also essential to correctly describe
very high energy showers



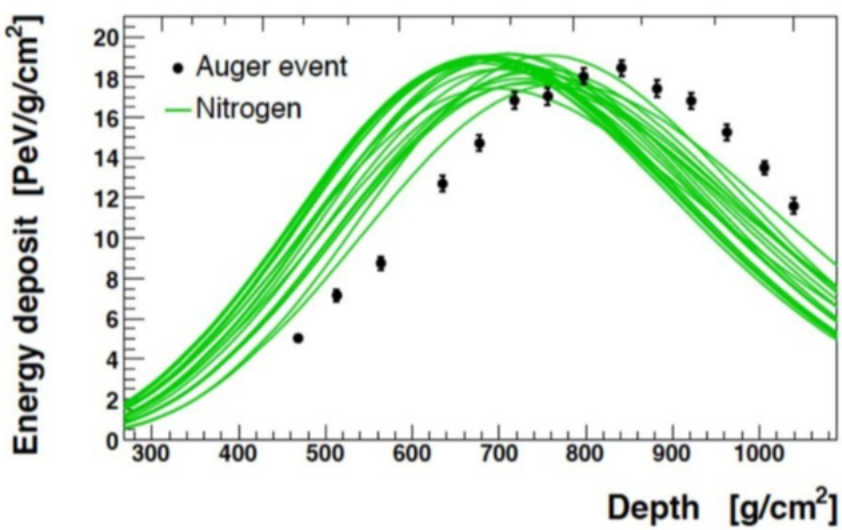
signal [VEM]
total signal
muons
e±, γ
time [25 ns]
$E_{cal} = \int \frac{dE}{dX} dX$
slant depth [g/cm²]
dE/dX [PeV/(g/cm²)]
X_{max}
Signal [VEM]
$S_{1000} \propto E$
r [m]

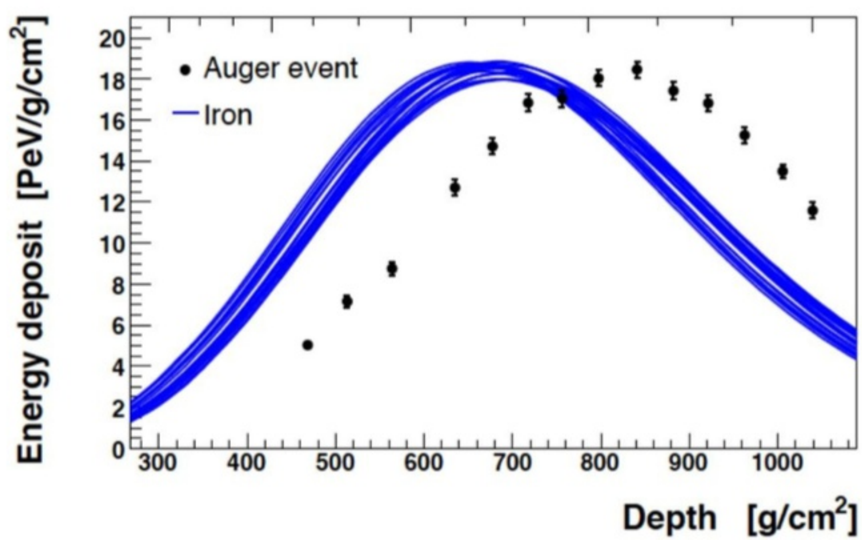
The energy spectrum



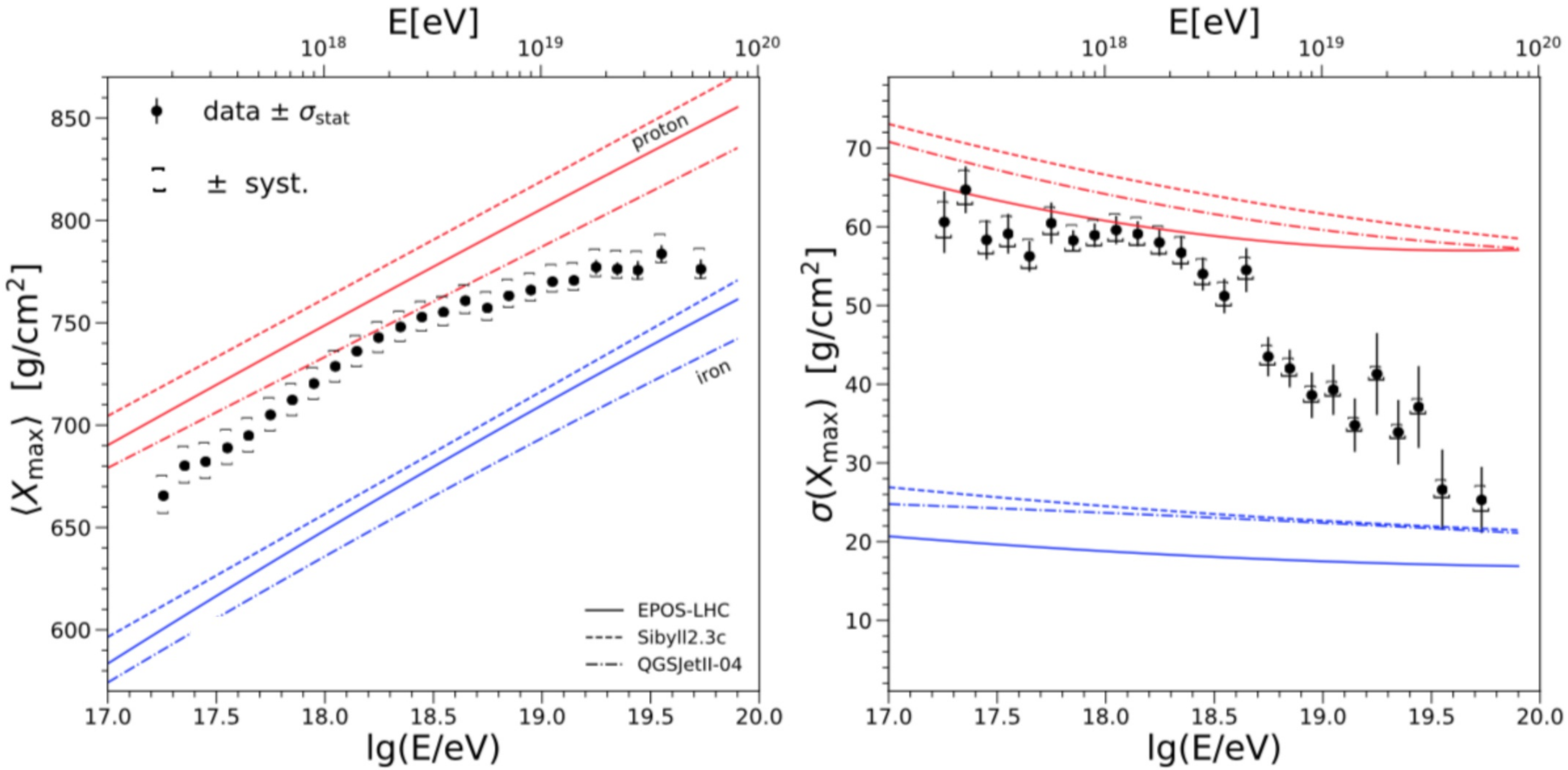


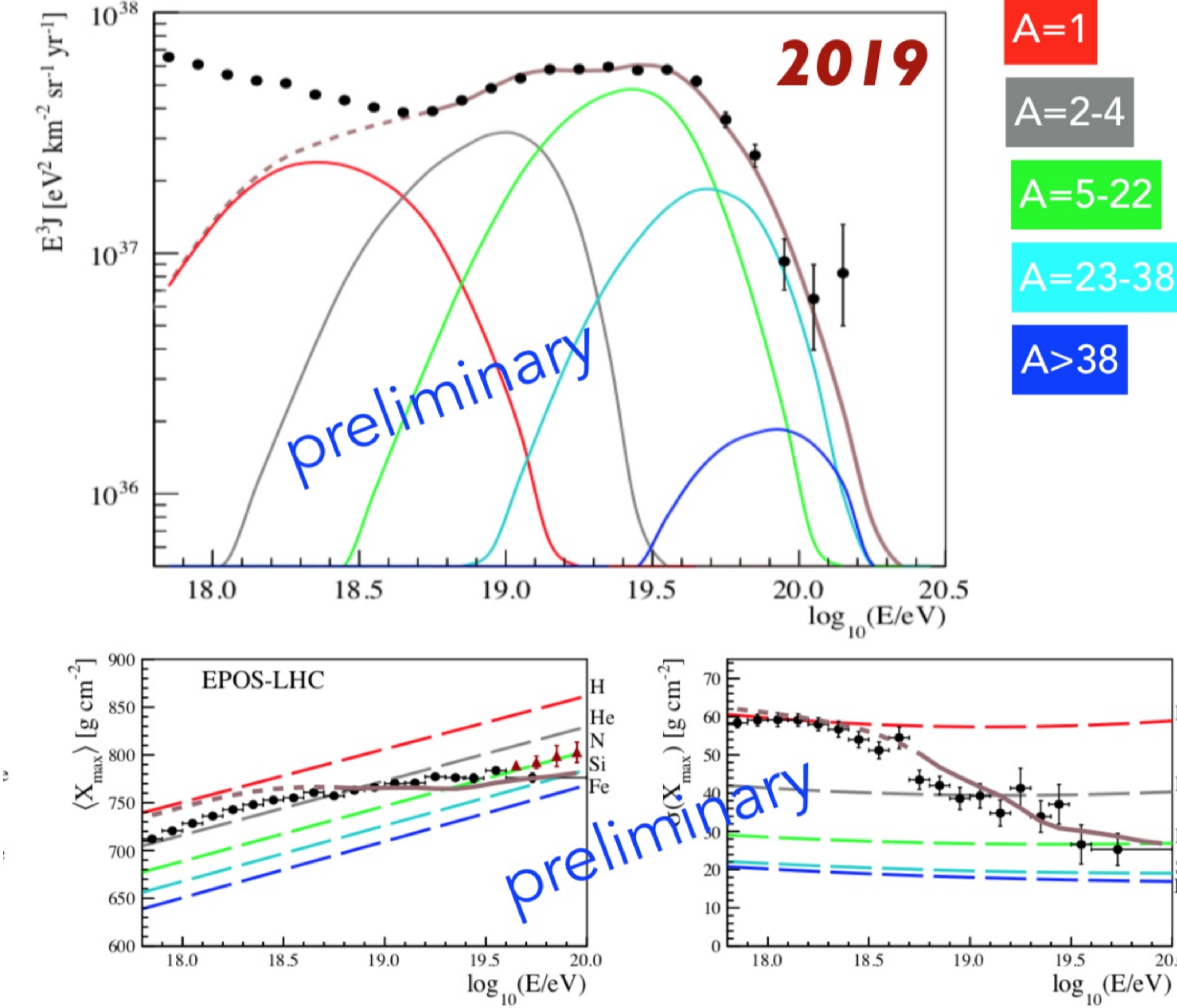
$$E \simeq 10^{20}\ \mathrm{eV}$$





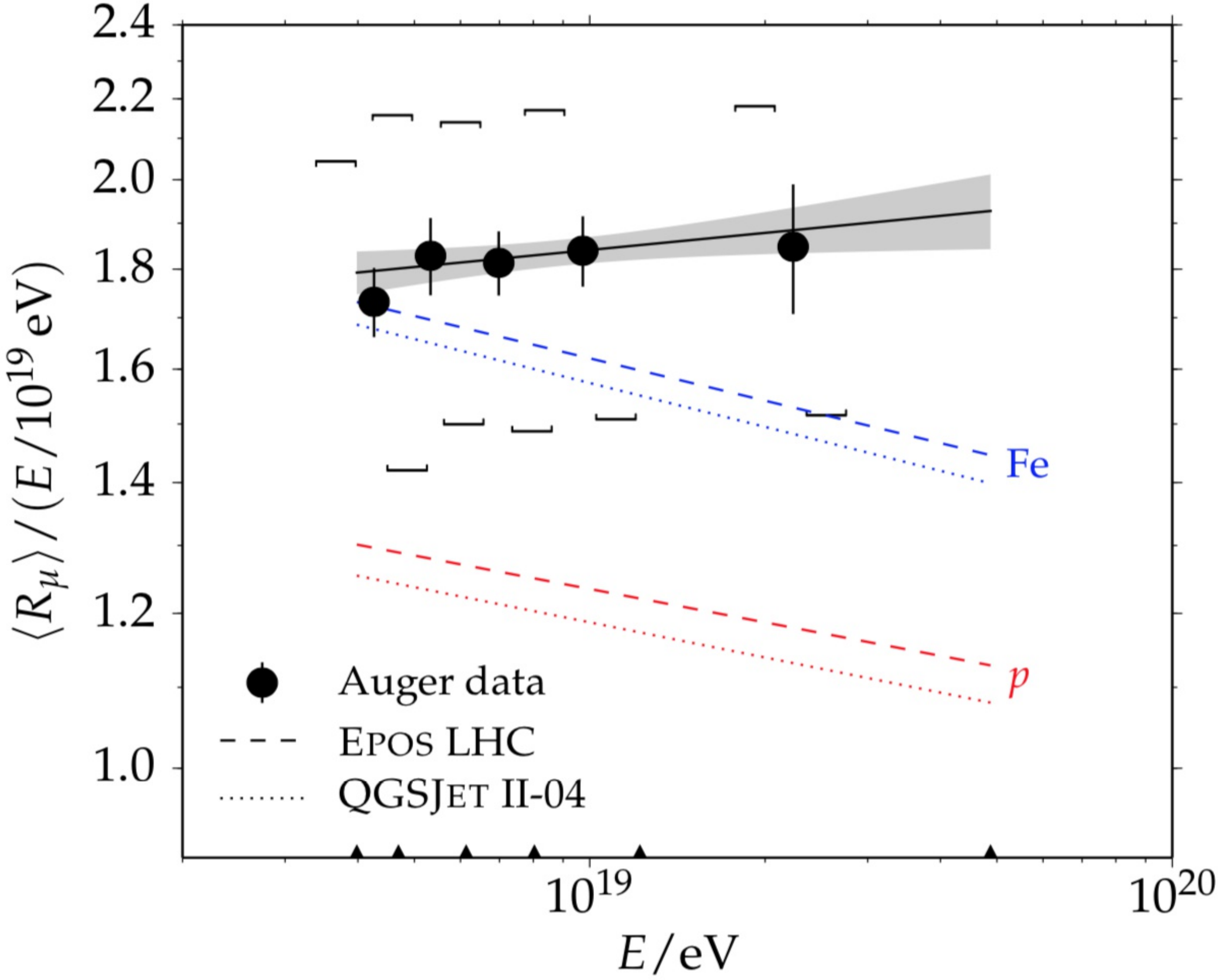
Auger Observation of the Maximum of the shower development





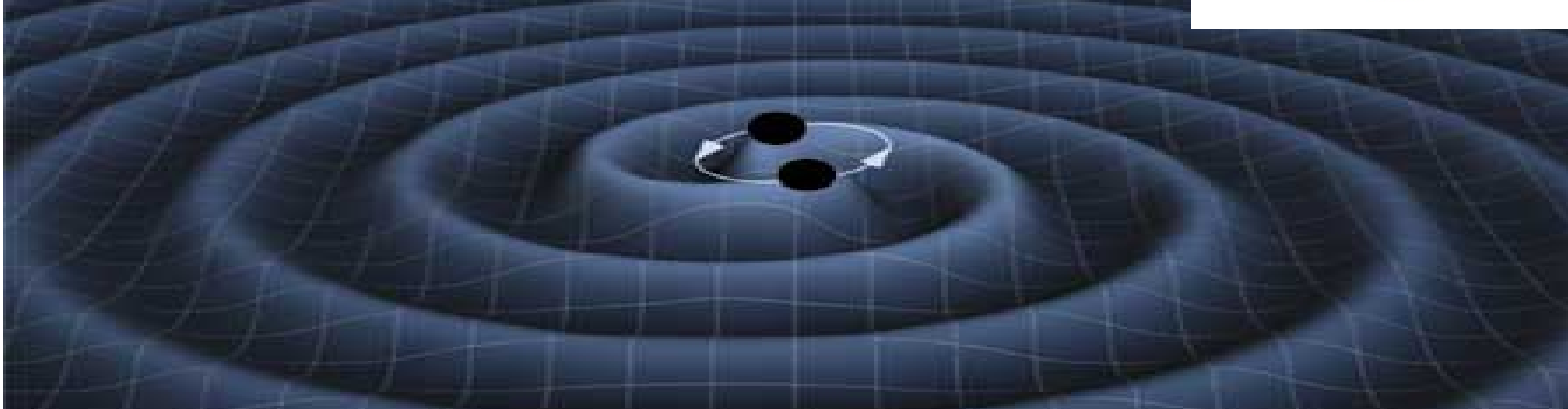
2019
A=1
A=2-4
A=5-22
A=23-38
A>38
preliminary
E^3J [eV^2 km^-2 sr^-1 yr^-1]
log10(E/eV)
EPOS-LHC
⟨Xmax⟩ [g cm^-2]
σ(Xmax) [g cm^-2]
H
He
N
Si
Fe
preliminary

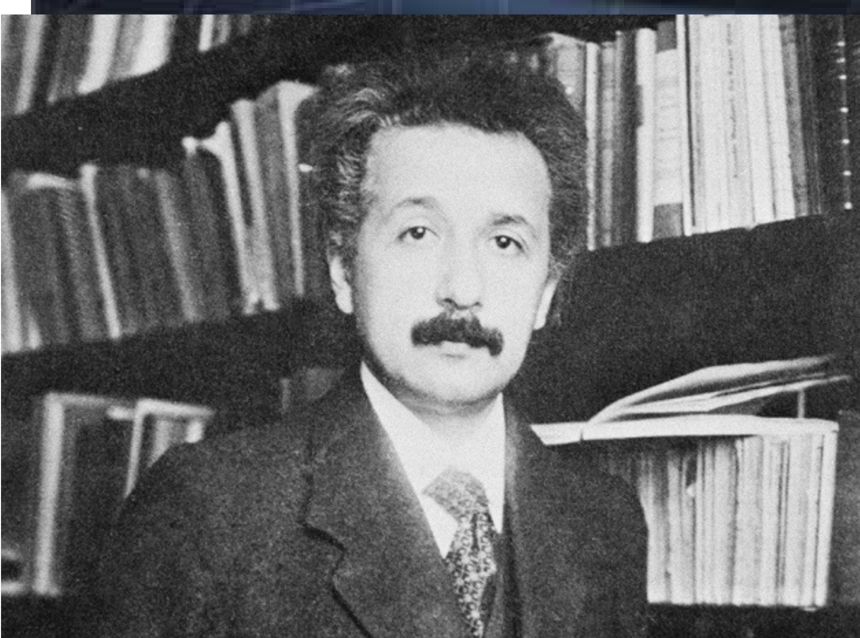
The "Muon problem" in Ultra High Energy Cosmic Rays

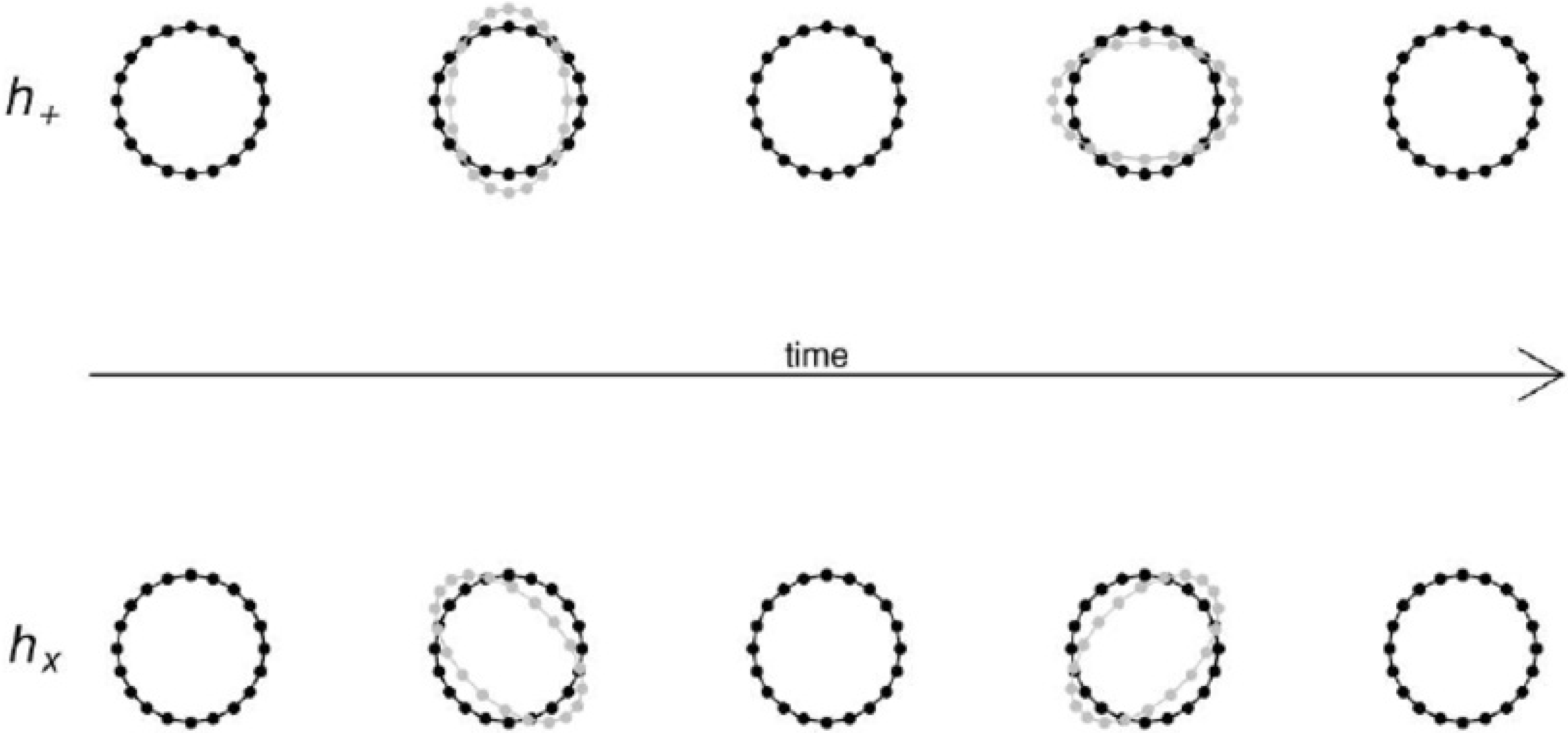


Gravitational Waves

Nobel prize 2017





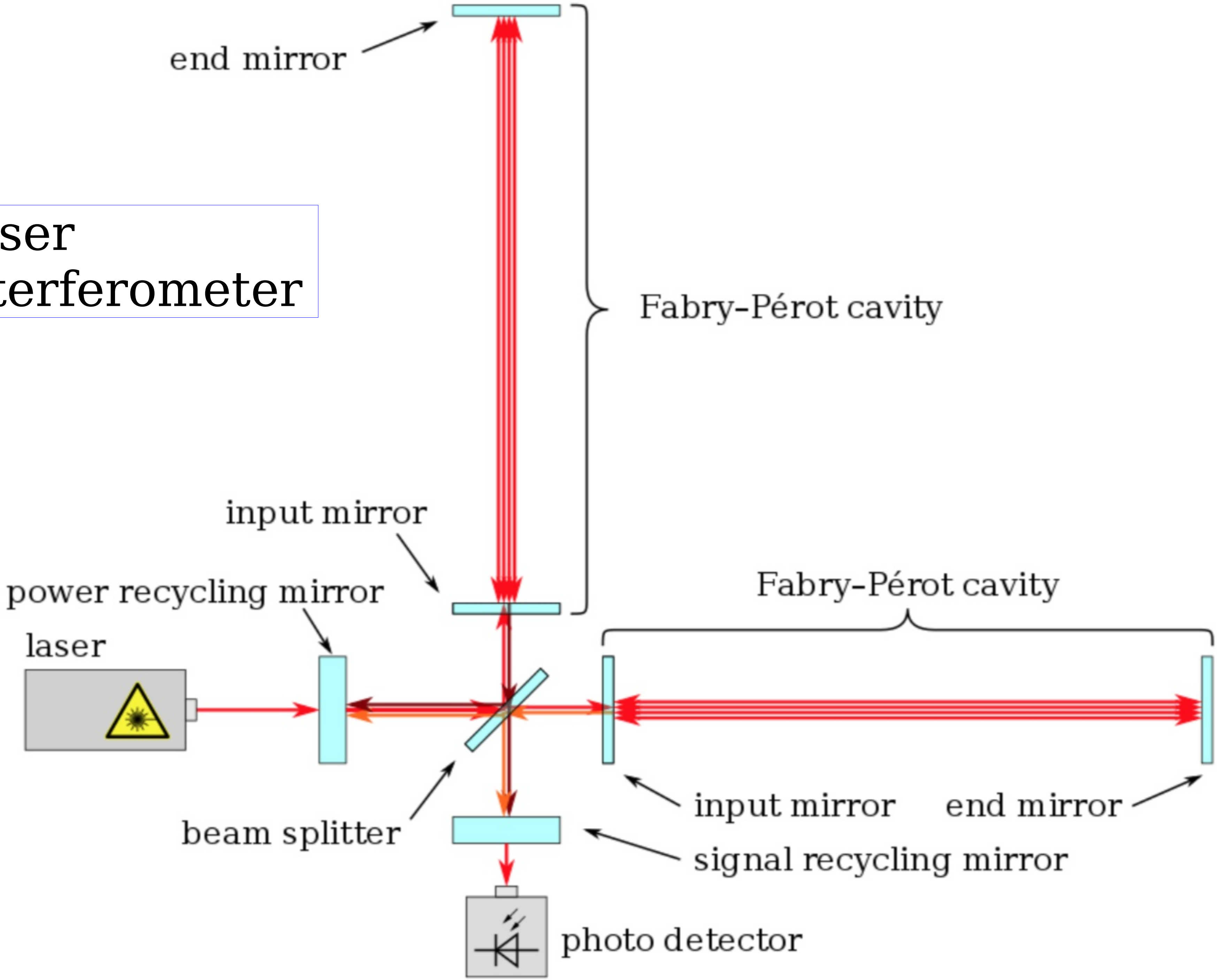


Effect of a gravitational wave
on a ring of particles

Extraordinarily small amplitude

$$h = \frac{\Delta L}{L}$$

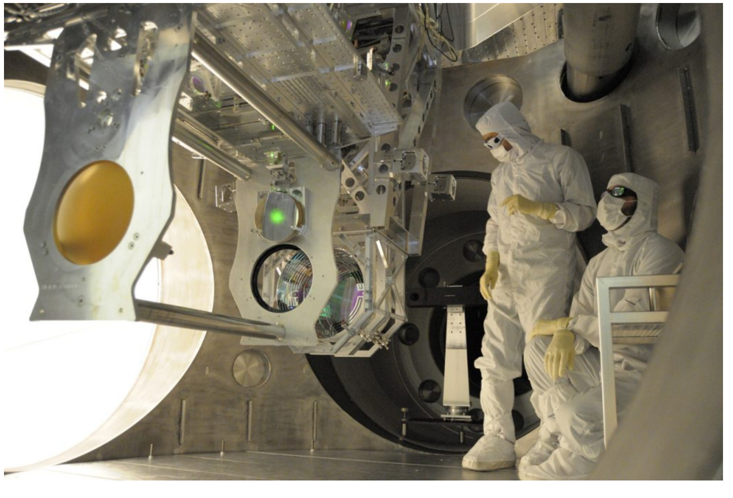
Laser Interferometer

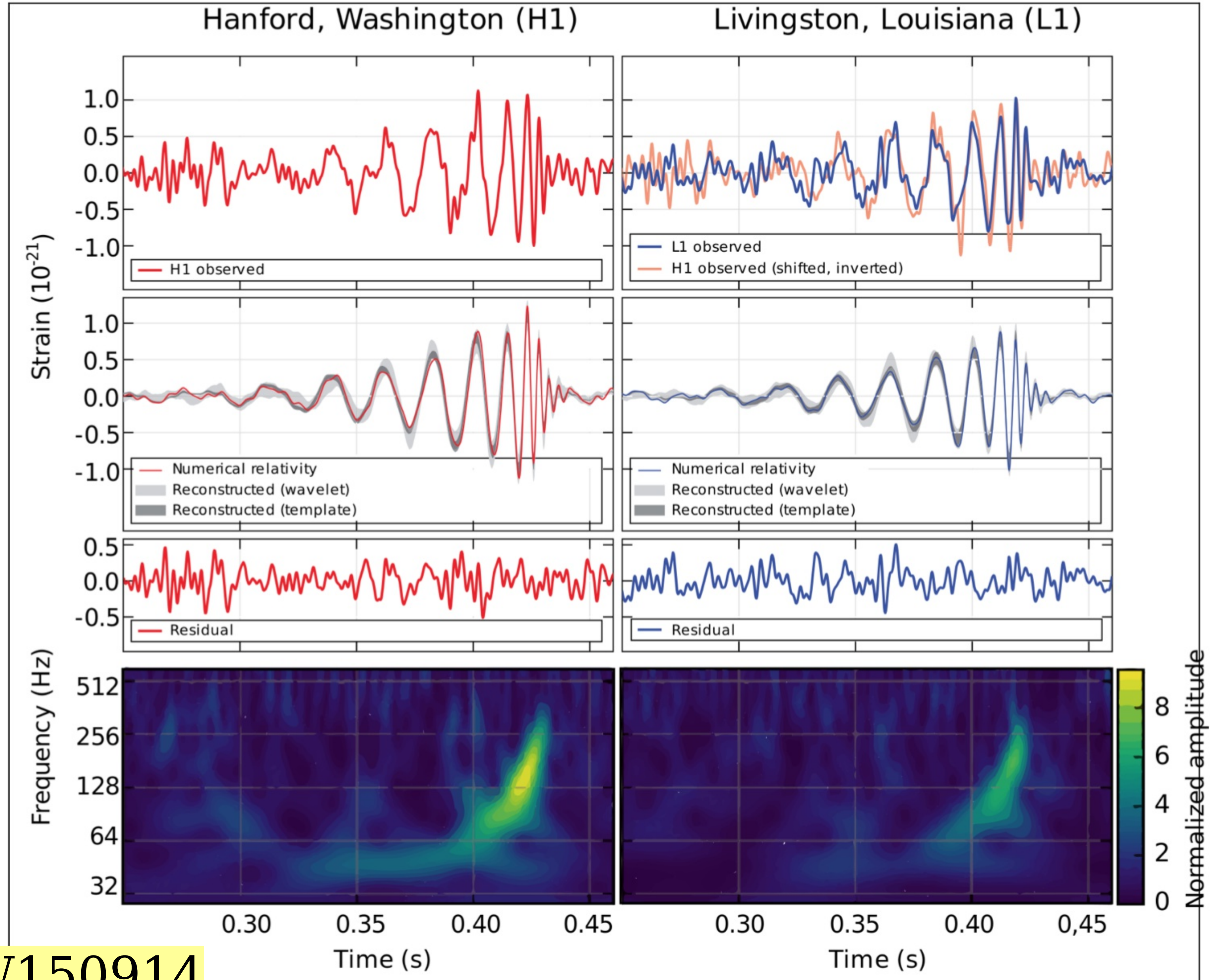


LIGO
Hanford
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston
Observatory

LIGO

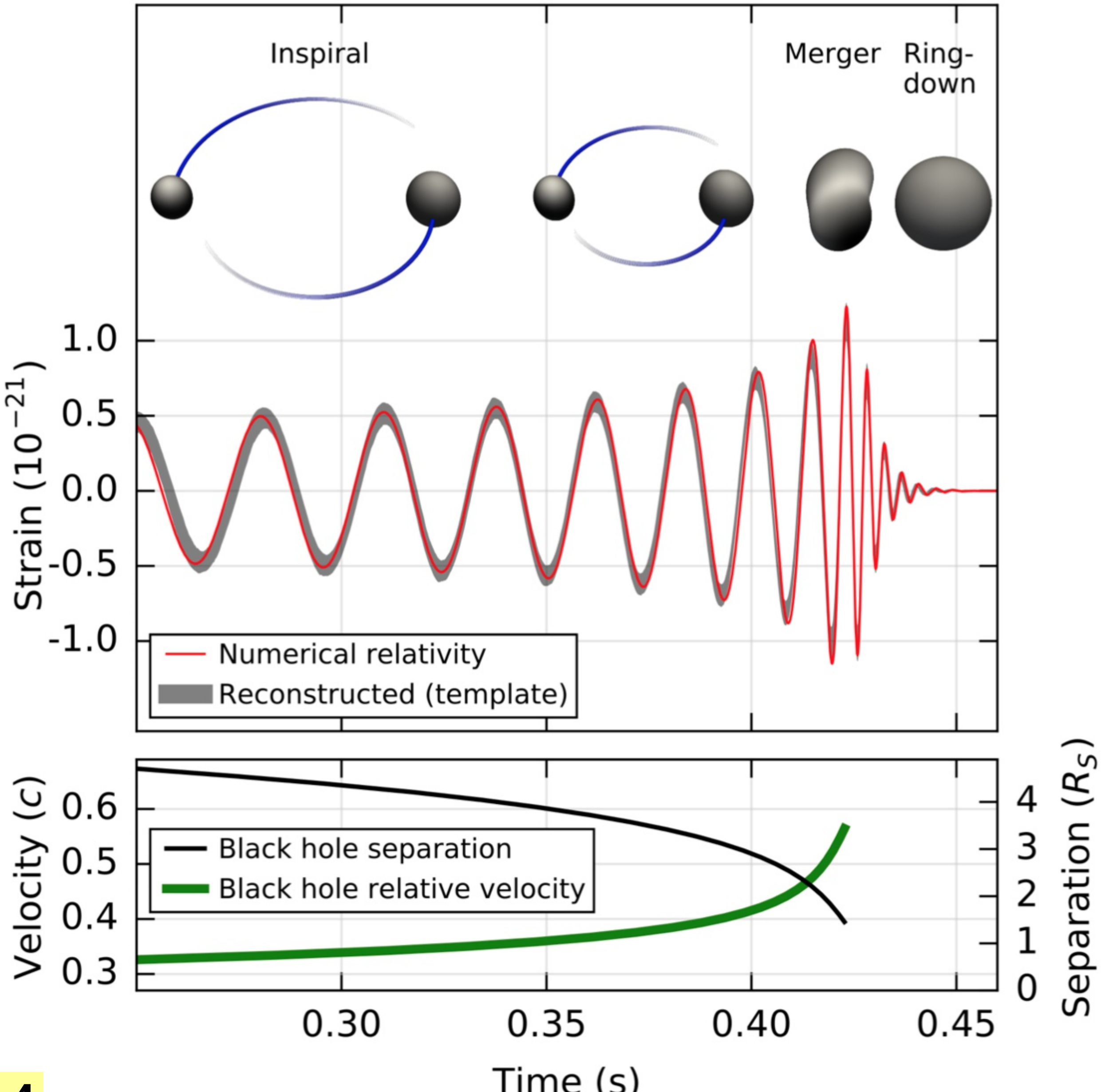
VIRGO
(Italy)




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

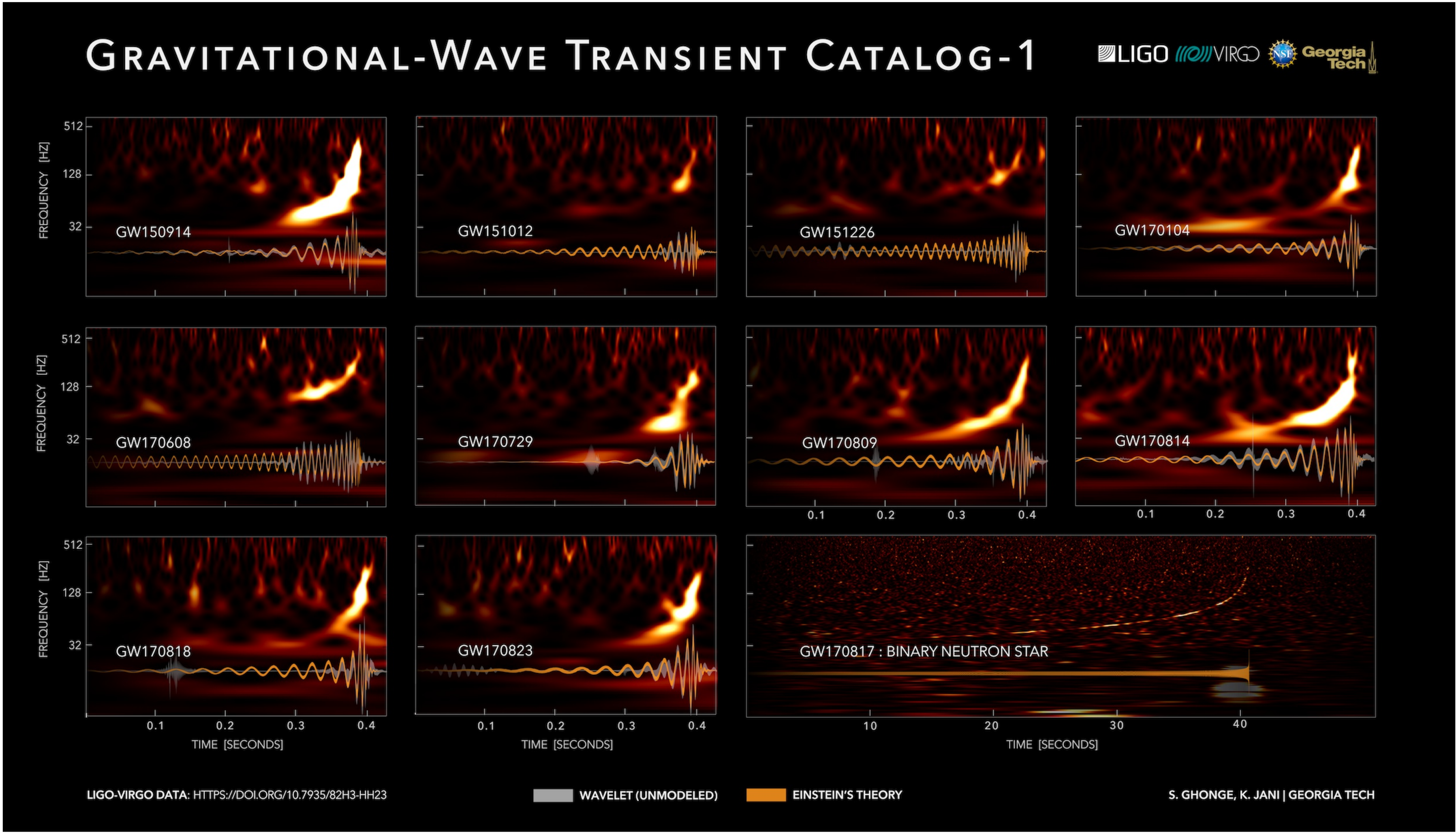
GW150914

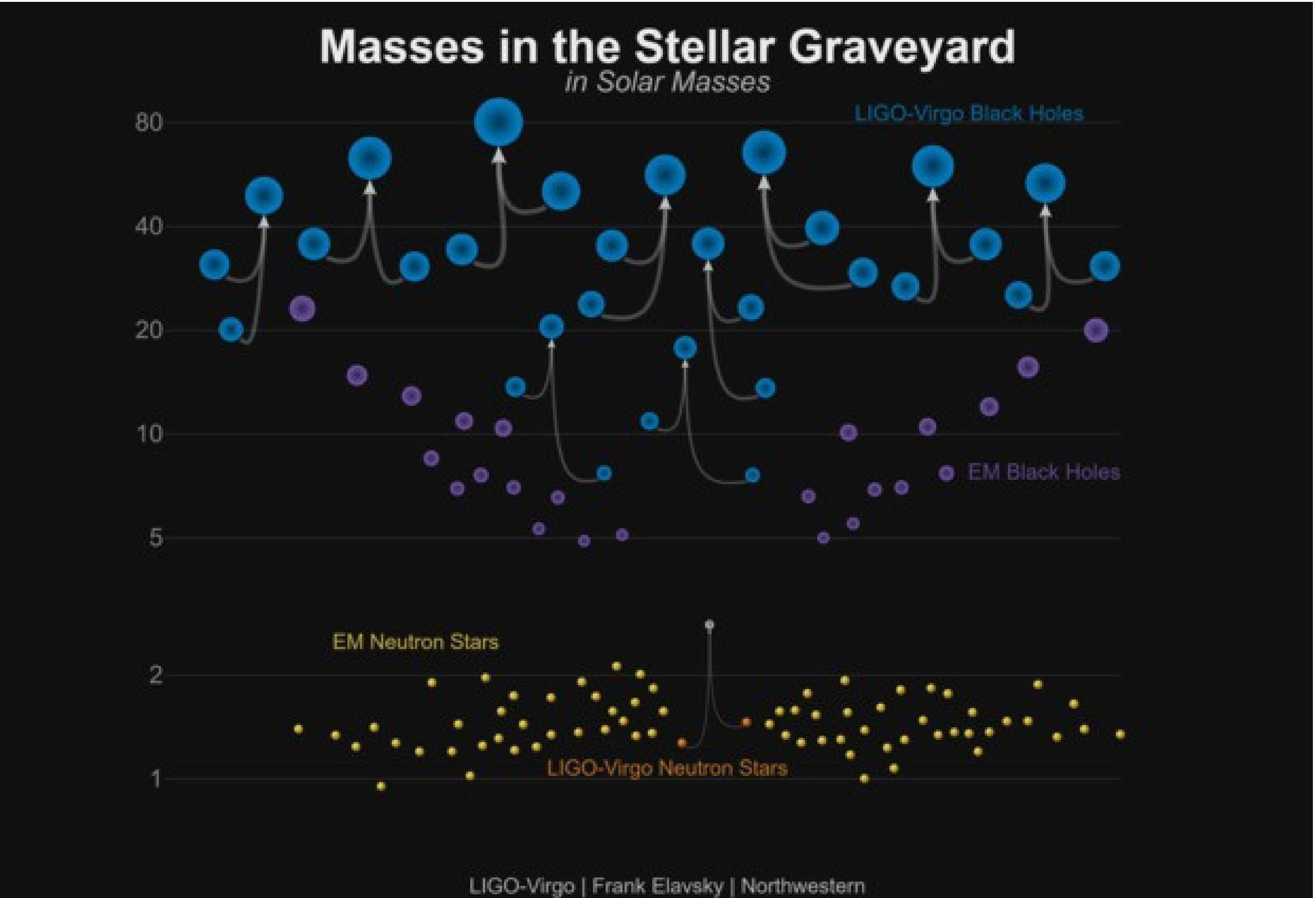
Wave form allows to reconstruct the parameters of the Binary Black Hole system *(and test General Relativity)*



GW150914

1st Catalog of Gravitational-Wave transients



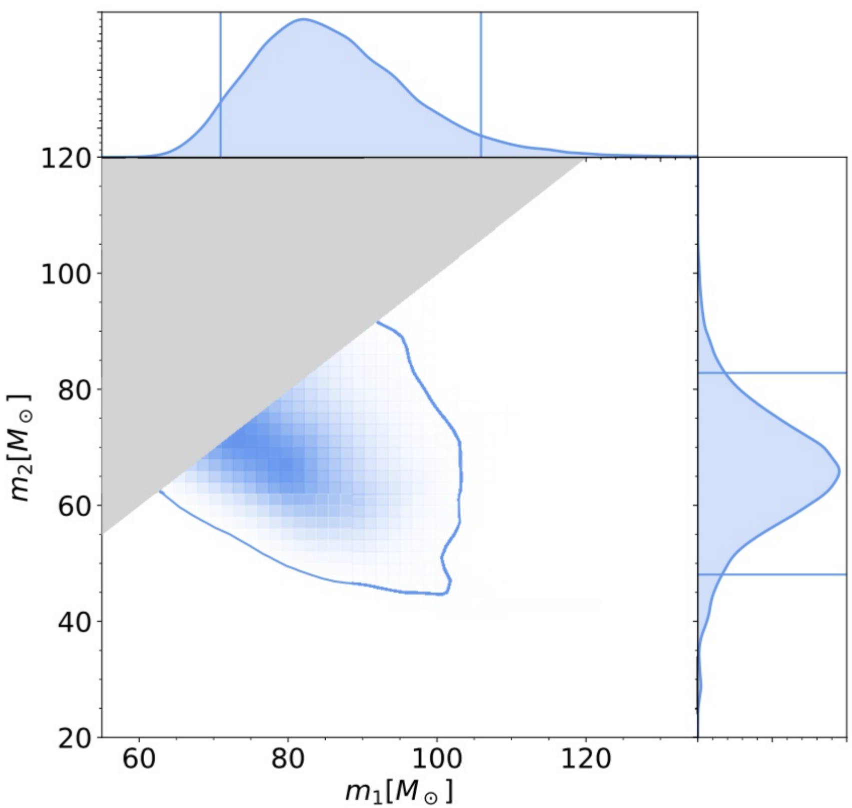


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 30 May 2020; revised 19 June 2020; accepted 9 July 2020; published 2 September 2020)

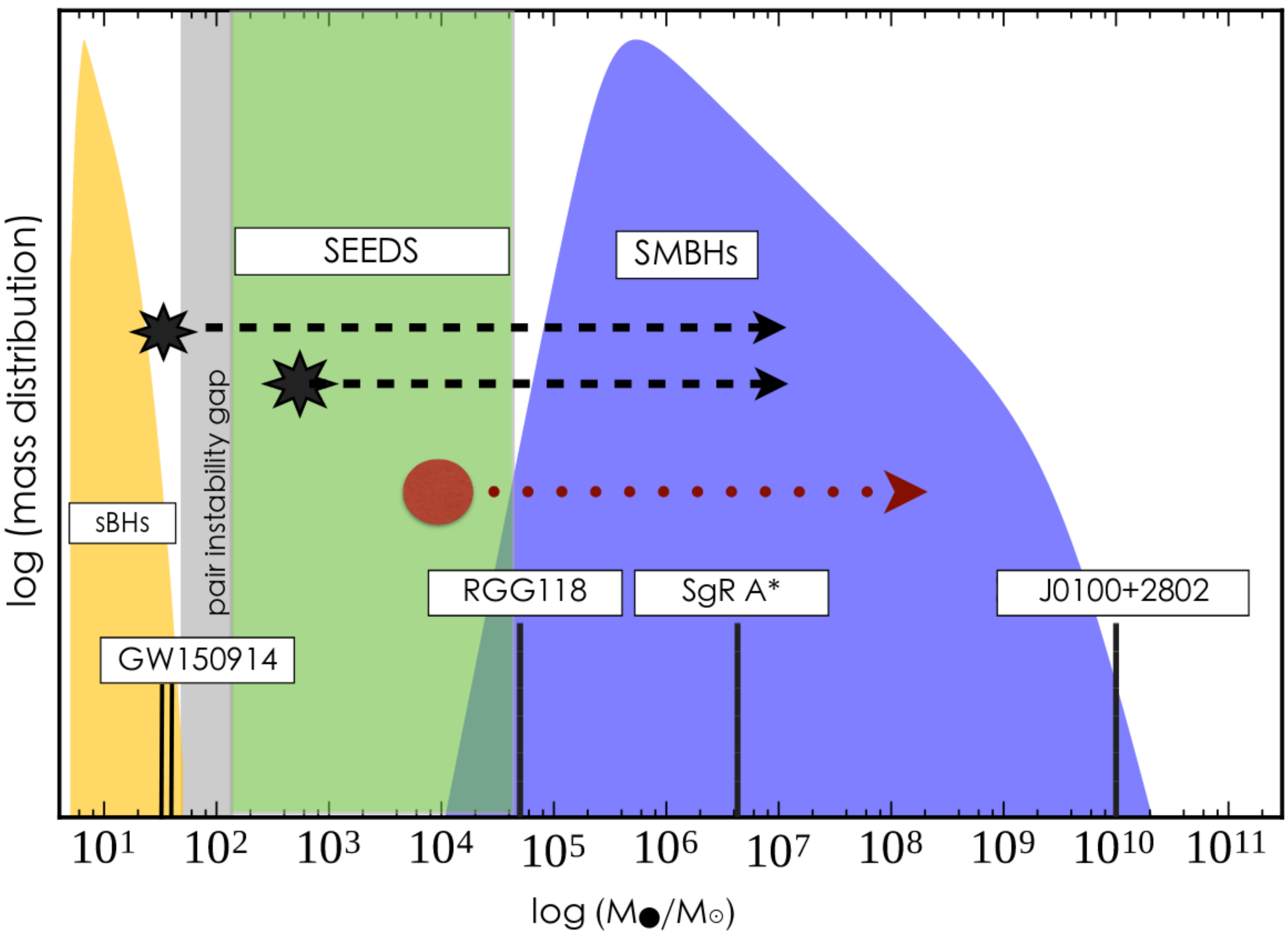


$85^{+21}_{-14}\ M_\odot$

$66^{+17}_{-18}\ M_\odot$

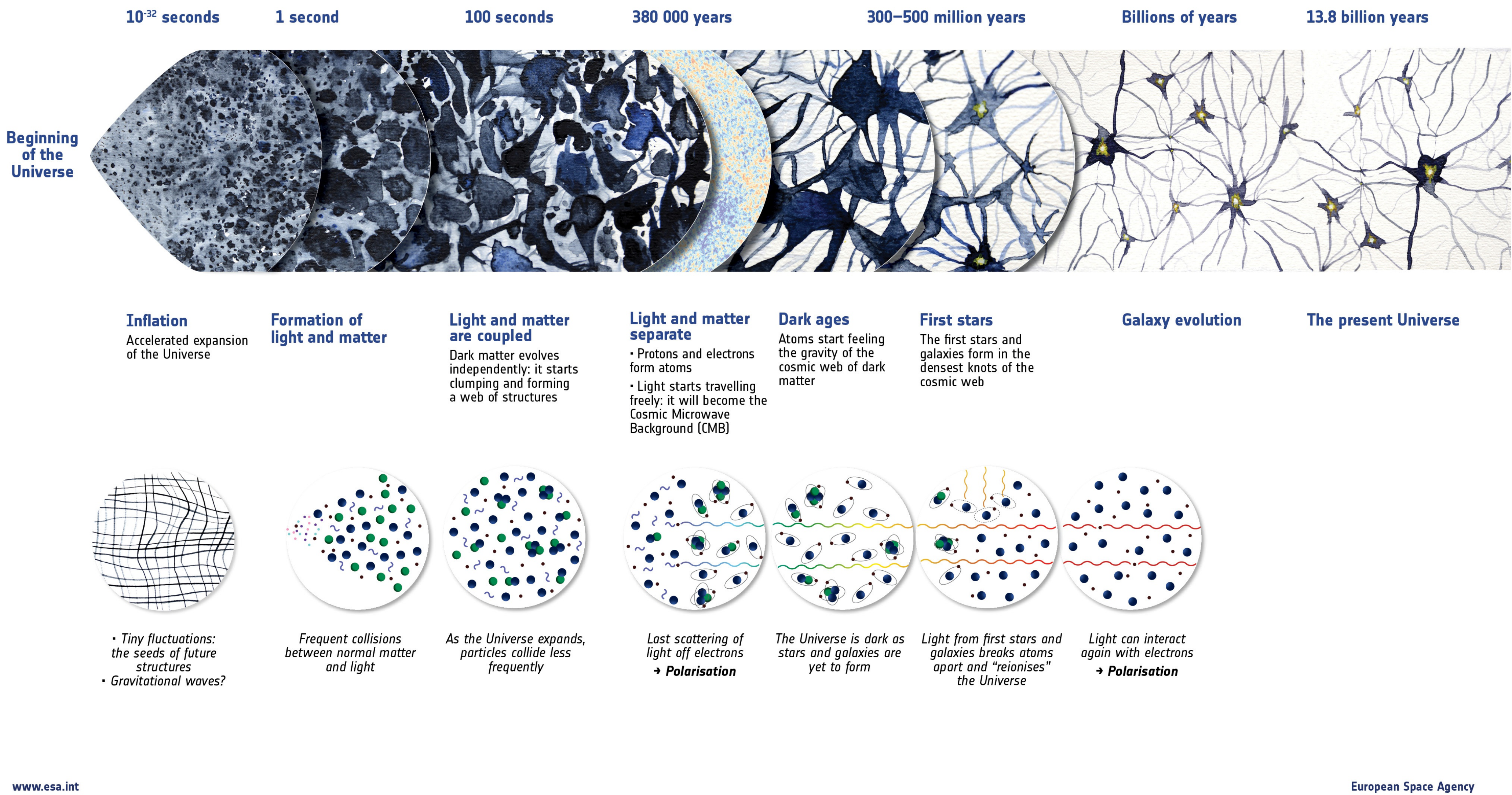
$142^{+28}_{-16}\ M_\odot$

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].

COSMOLOGICAL HISTORY

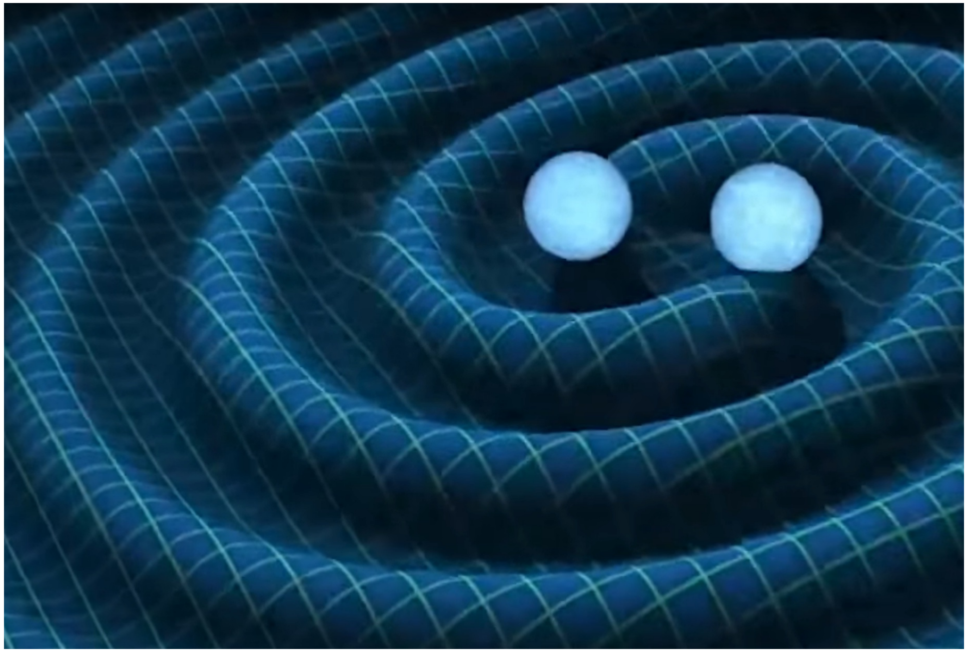


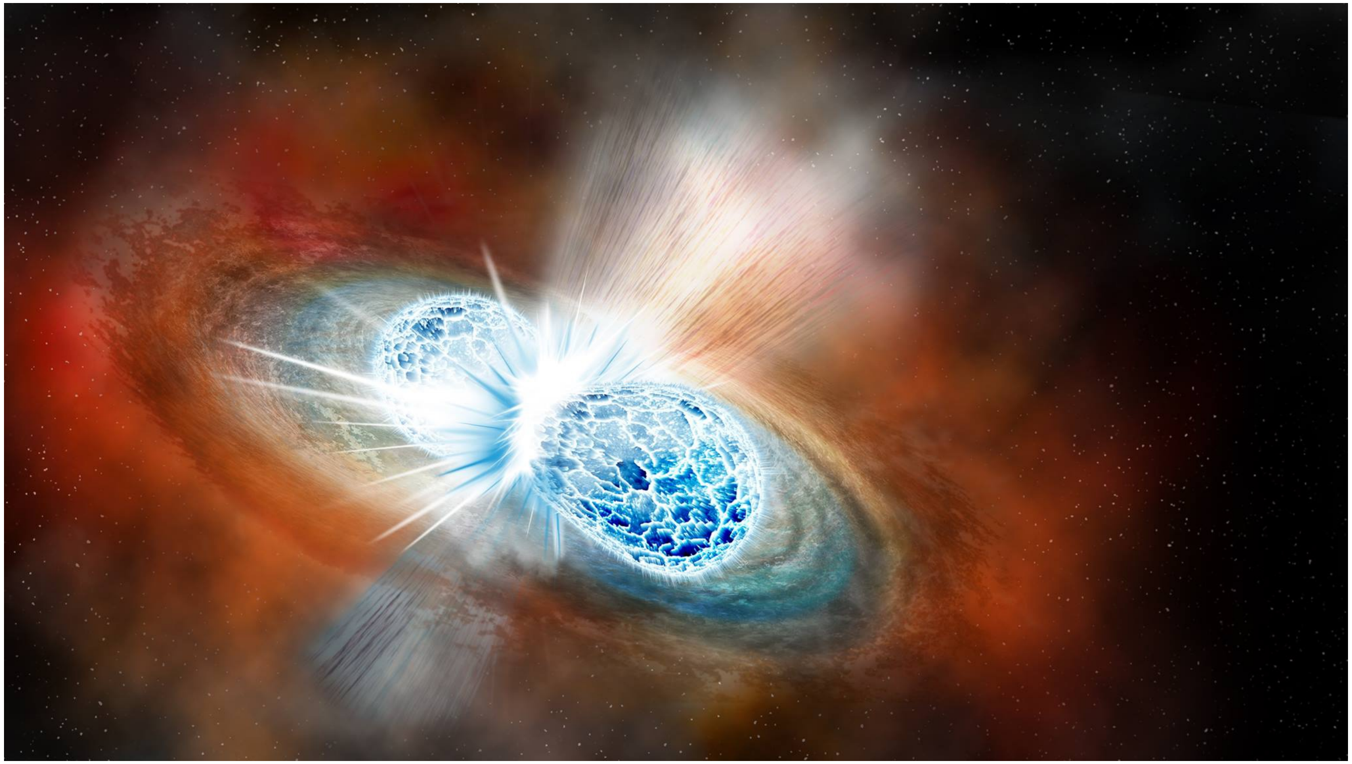
Credit NASA, ESA

- 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 over-density
can modify the dynamics of the merger)





GW 170817

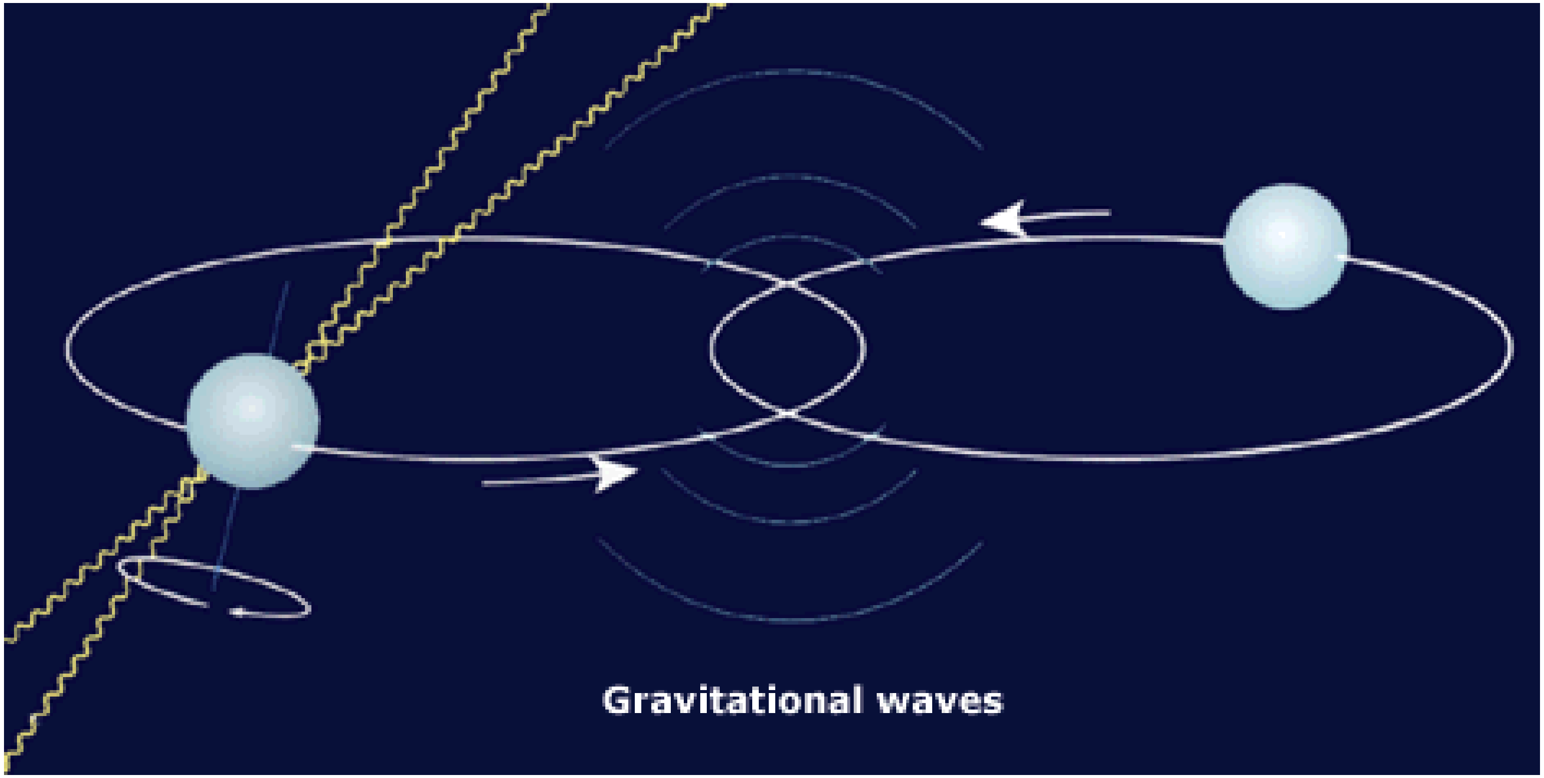
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

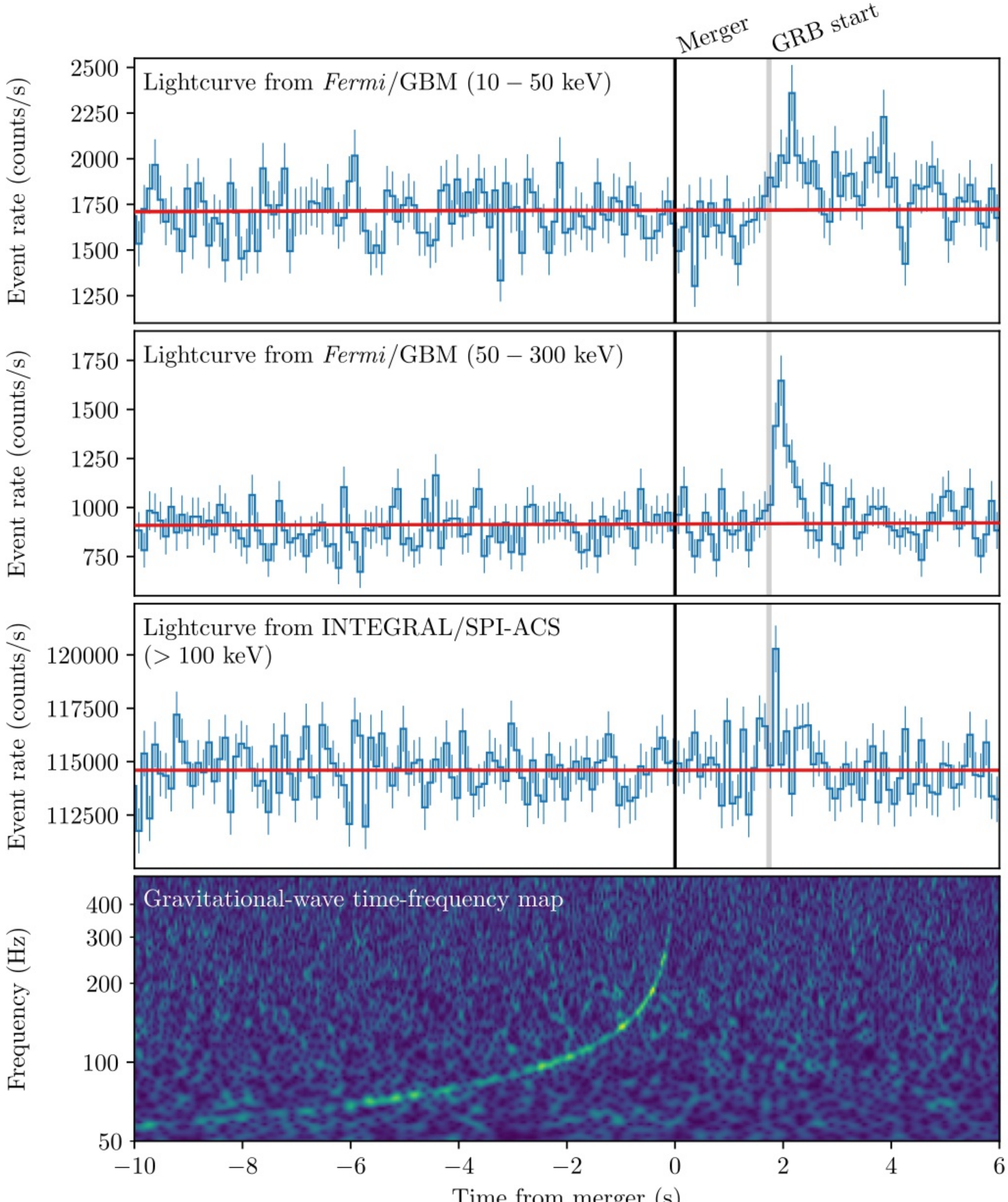
300 Myr
two neutron star coalesce

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

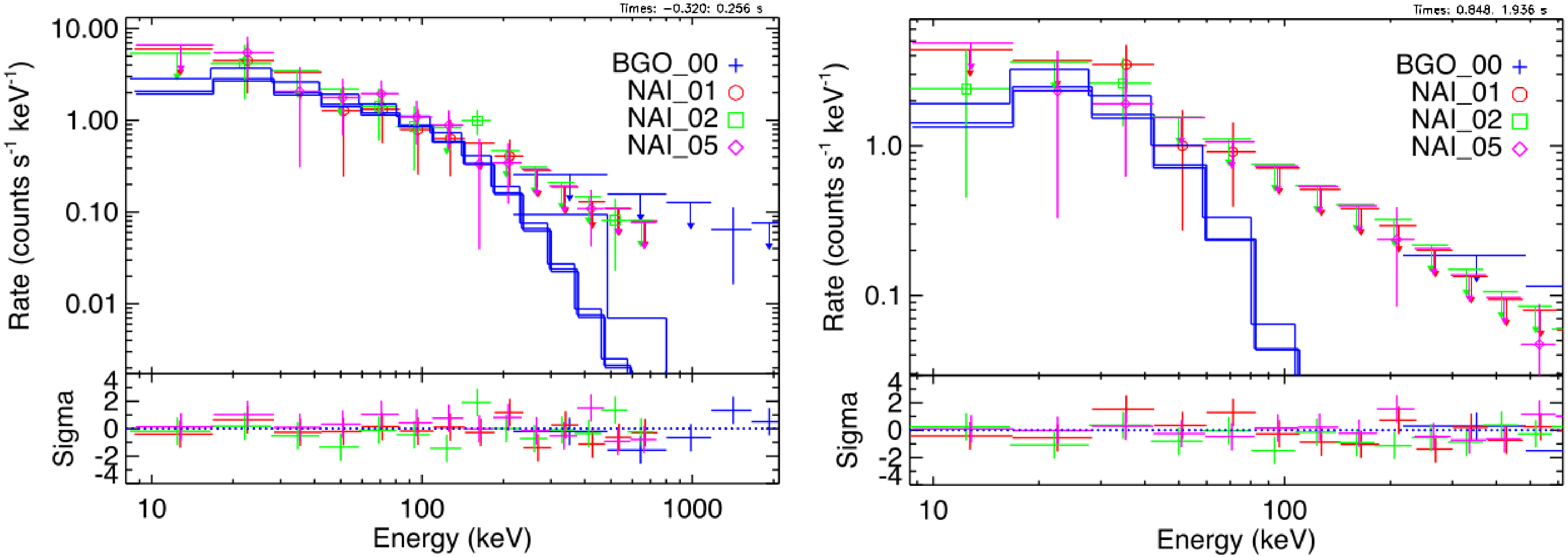
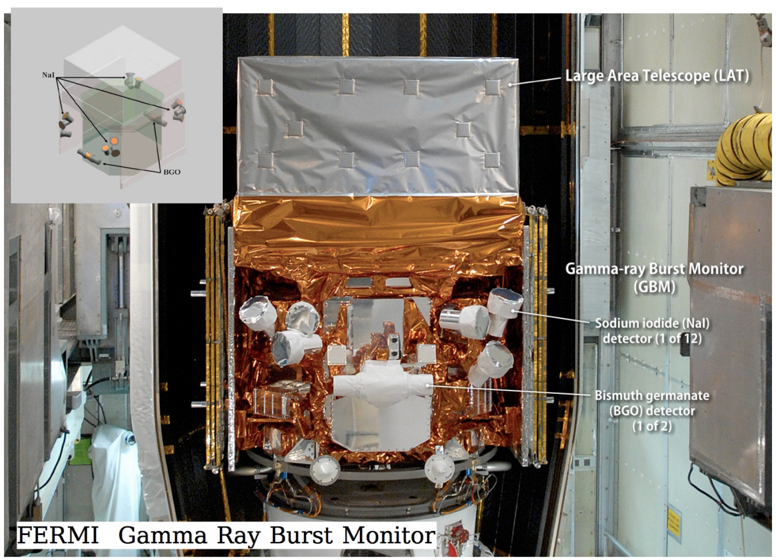


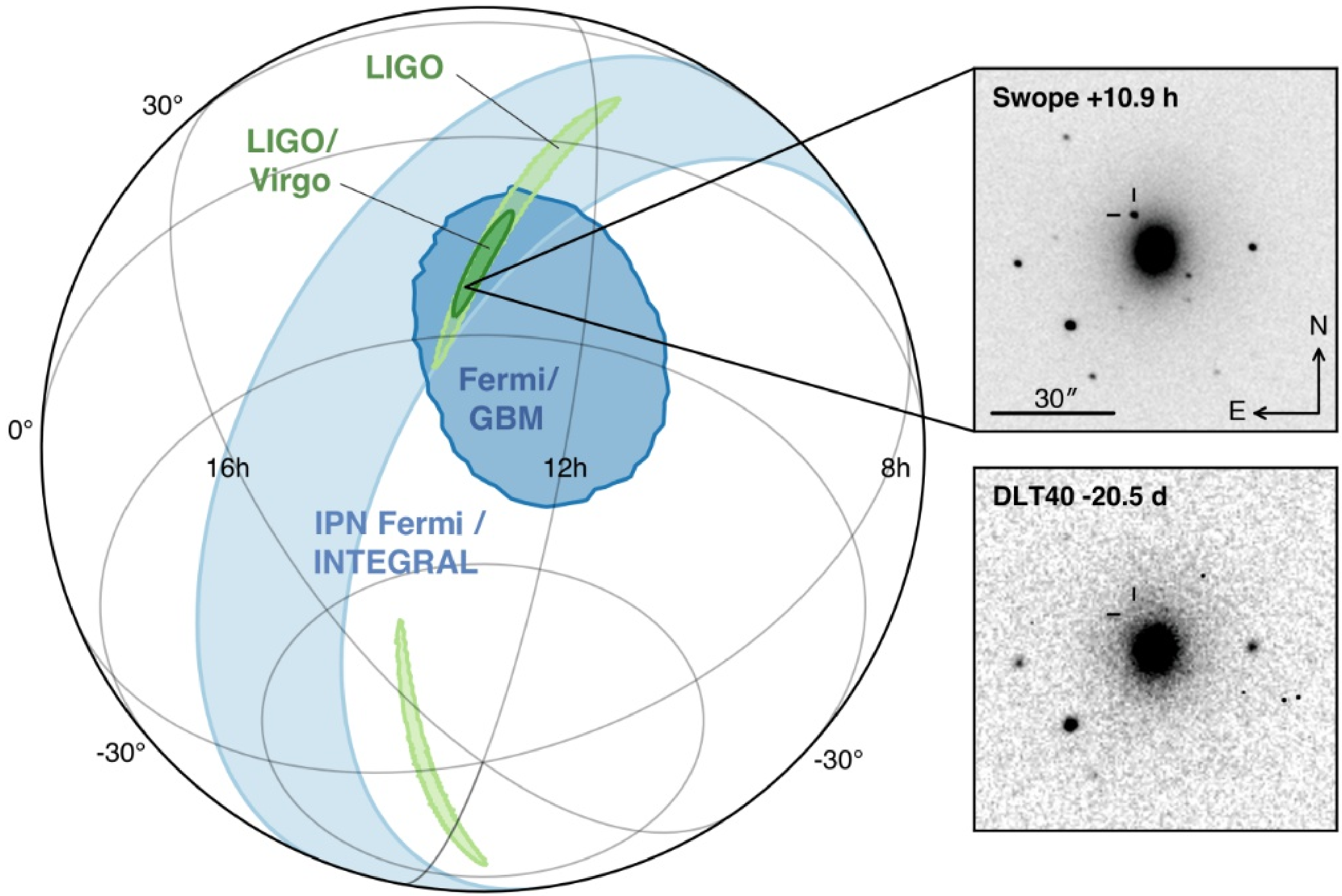
Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model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

INTEGRAL
SPI-ADC

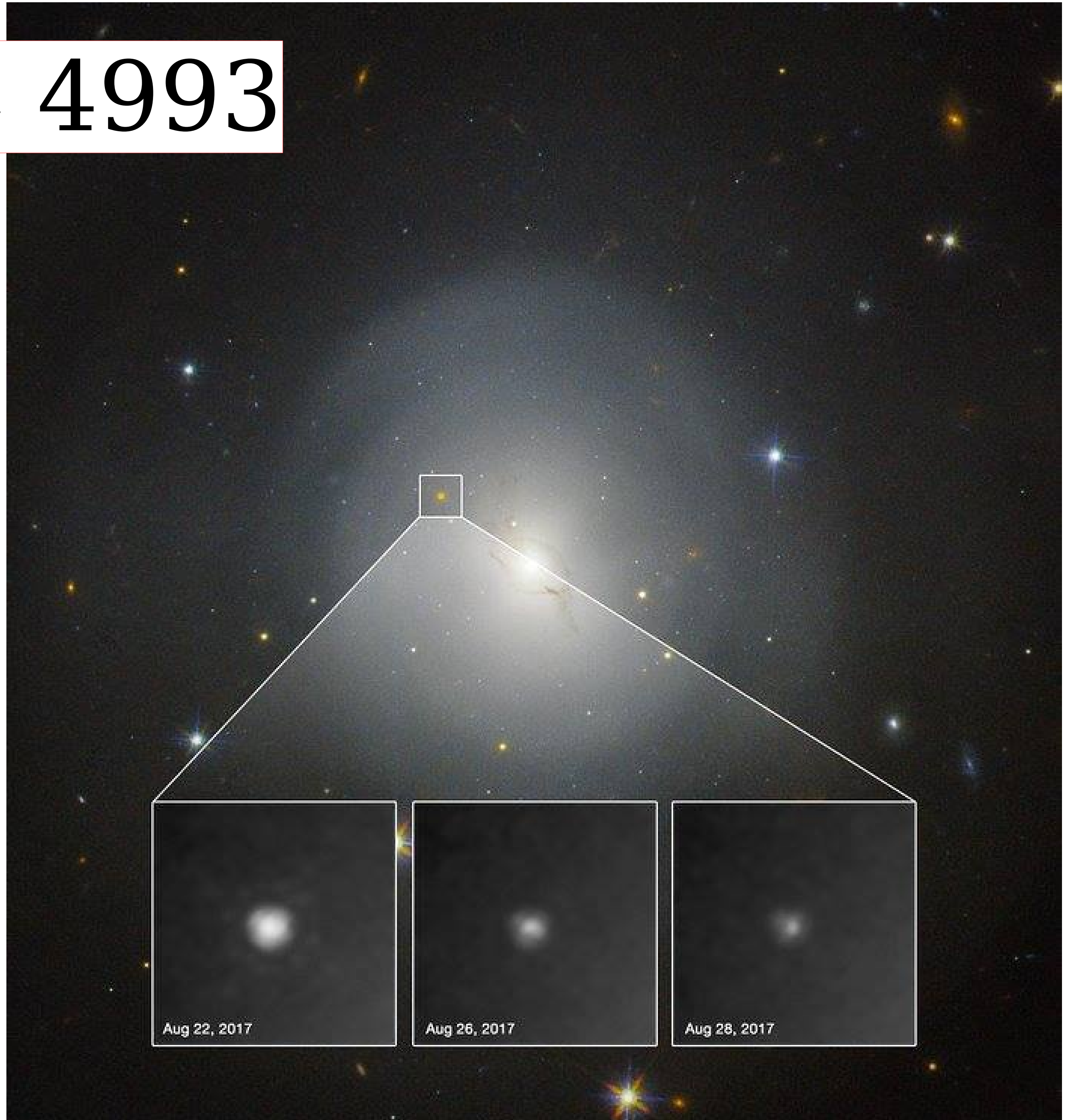


The multi-messanger sky localization of GW170817

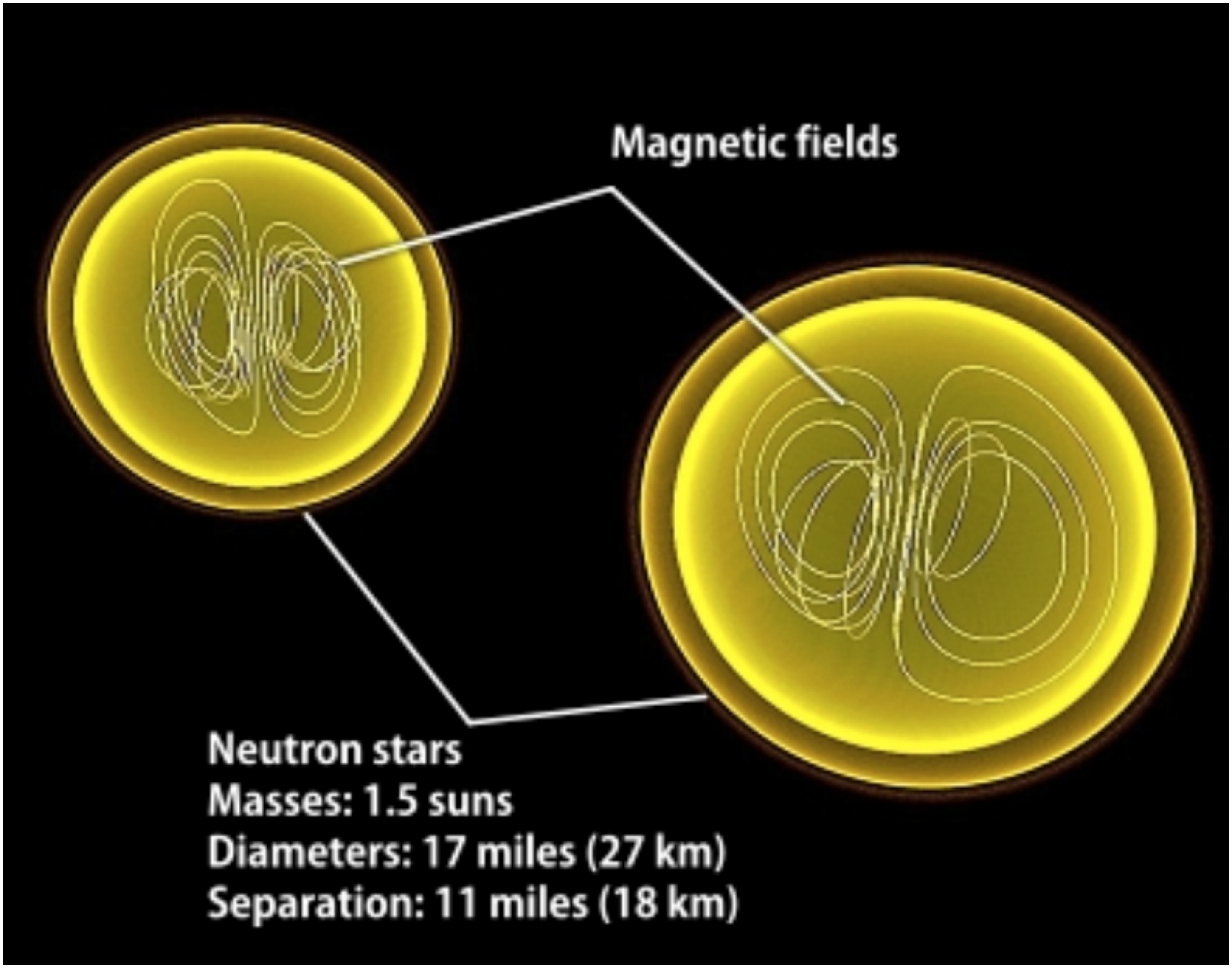
identification of the host galaxy.



NGC 4993



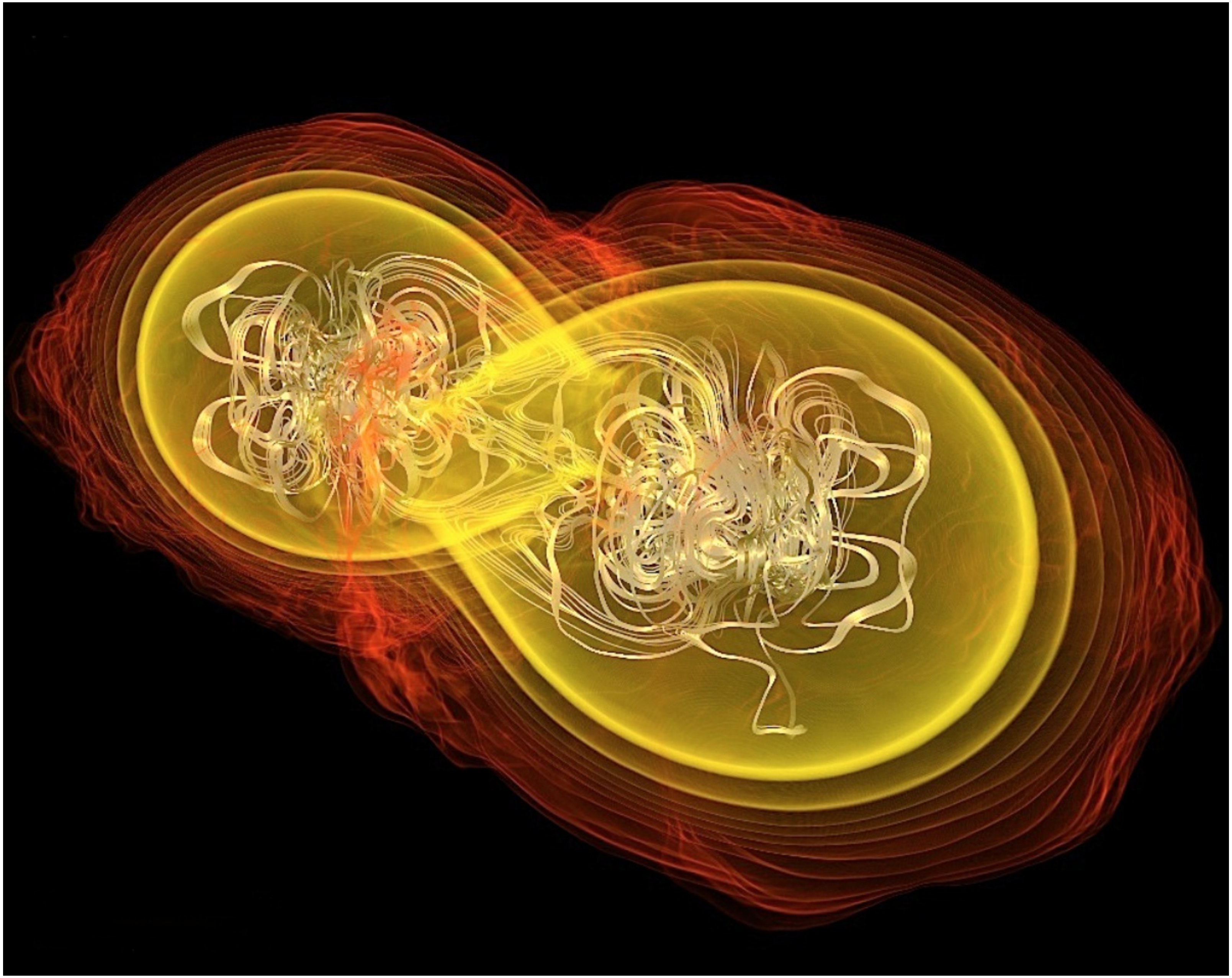
Numerical Simulation [35 msec] of merging of 2 neutron stars



L. Rezzolla et al. ApJ (2011)

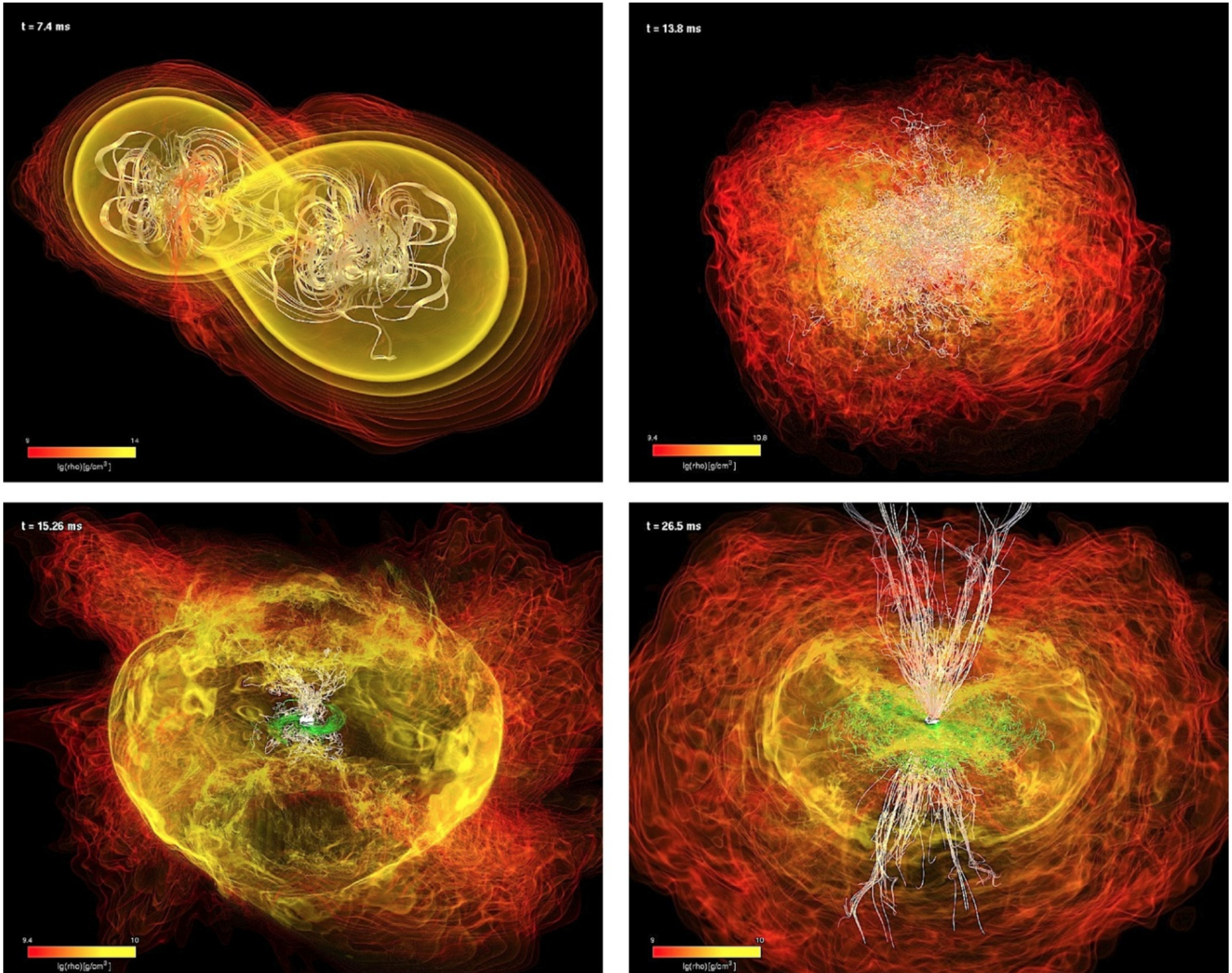
THE MISSING LINK: MERGING NEUTRON STARS NATURALLY PRODUCE JET-LIKE STRUCTURES AND CAN POWER SHORT GAMMA-RAY BURSTS

7.5 msec



7.5 msec

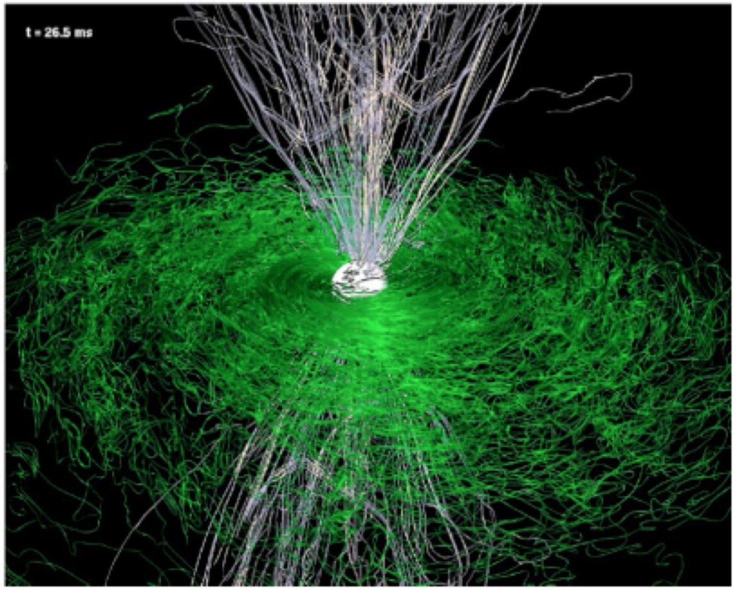
13.8 msec



15.26 msec

26.5 msec

Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t = 7.4$ ms) and before the collapse to BH ($t = 13.8$ ms), while those in the lower row to the evolution after the formation of the BH ($t = 15.26$ ms, $t = 26.5$ ms). Green lines sample the magnetic field in the torus and on the equatorial plane, while white lines show the magnetic field outside the torus and near the BH spin axis. The inner/outer part of the torus has a size of $\sim 90/170$ km, while the horizon has a diameter of $\simeq 9$ km.



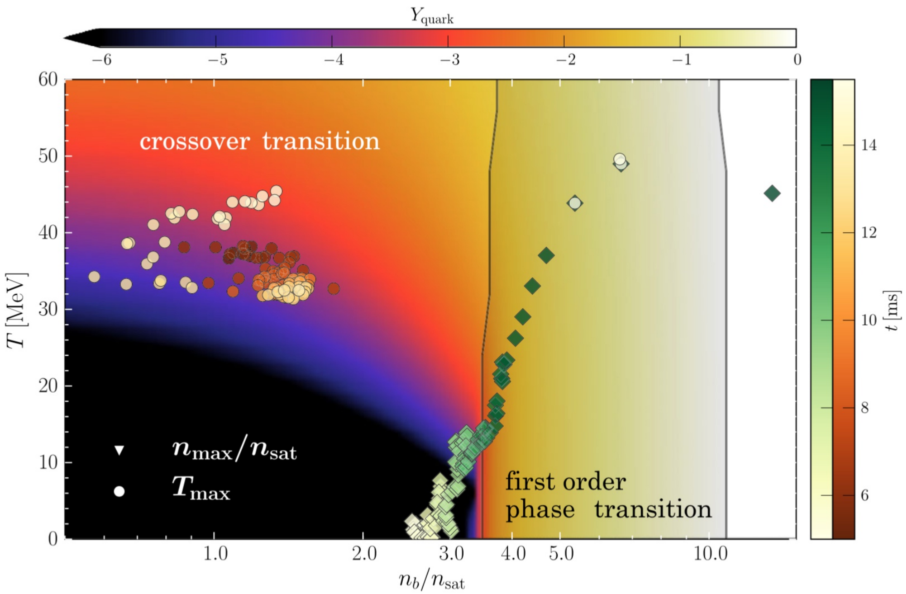
The simulation
shows that the magnetic field
is organized is a structure
that is consistent with the emission
of a jet and then a
Gamma Ray Burst

The *merger of binary neutron-stars* systems combines
in a single process:

Extreme gravity,
Black Hole formation
Copious emission of gravitational waves,
Complex microphysics,
Electromagnetic processes that can lead to *Gamma-Ray-Burst*
Ejected material, and its nucleosynthesis.

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]].

$$\{n_B, T\}$$

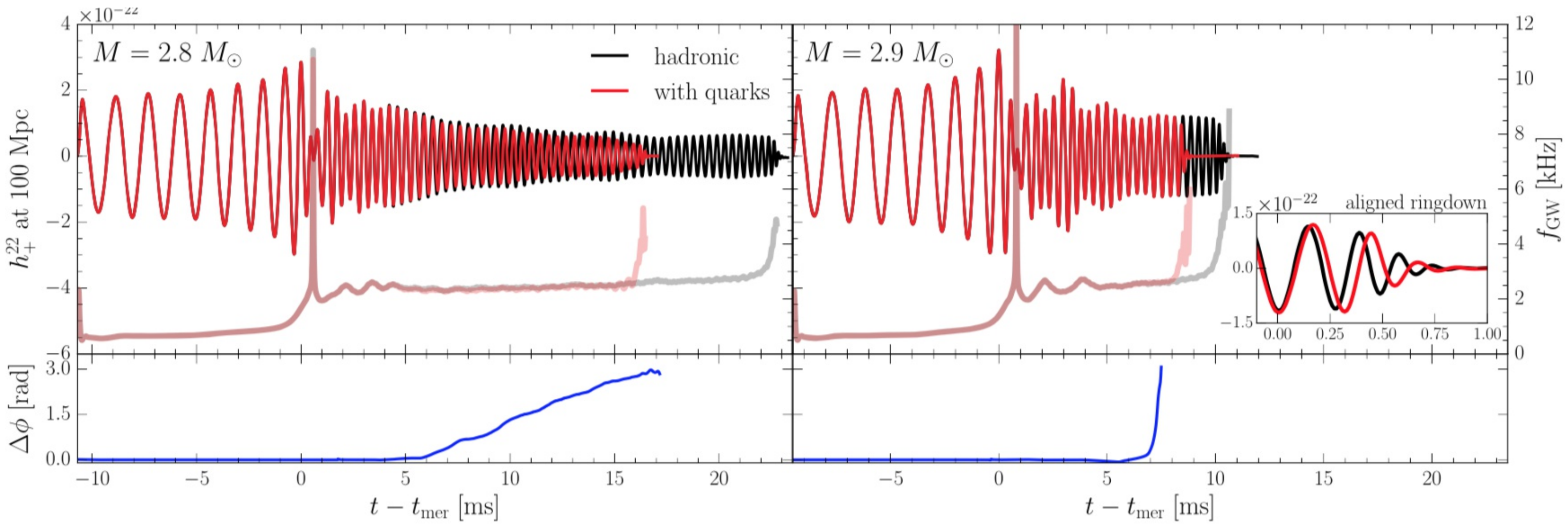


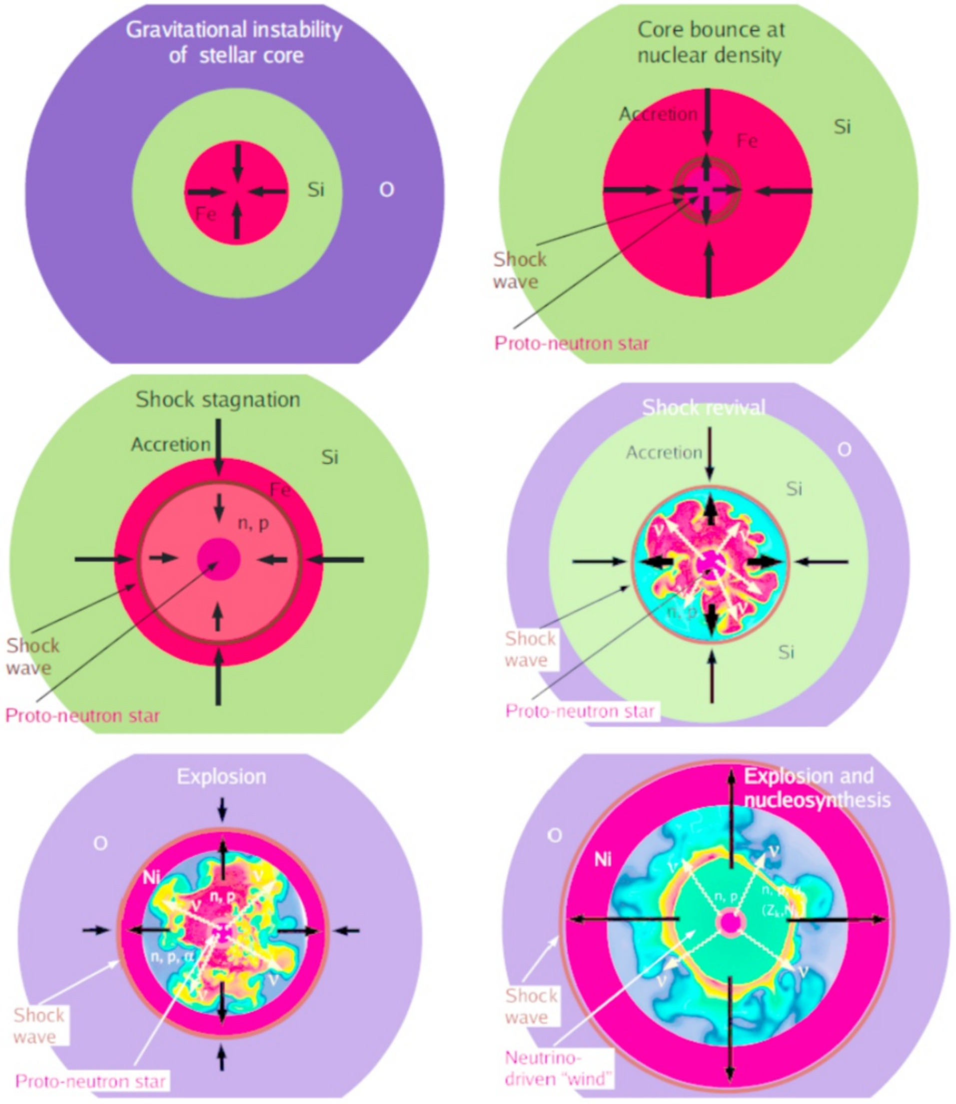
FIG. 4. Properties of the GW emission for the low- (left-hand panels) and high-mass binaries (right-hand panels). The top panels report the strain h_+^{22} for the two EOSs, together with the instantaneous GW frequency $f_{\rm GW}$ (semitransparent lines). The bottom panels show the phase difference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

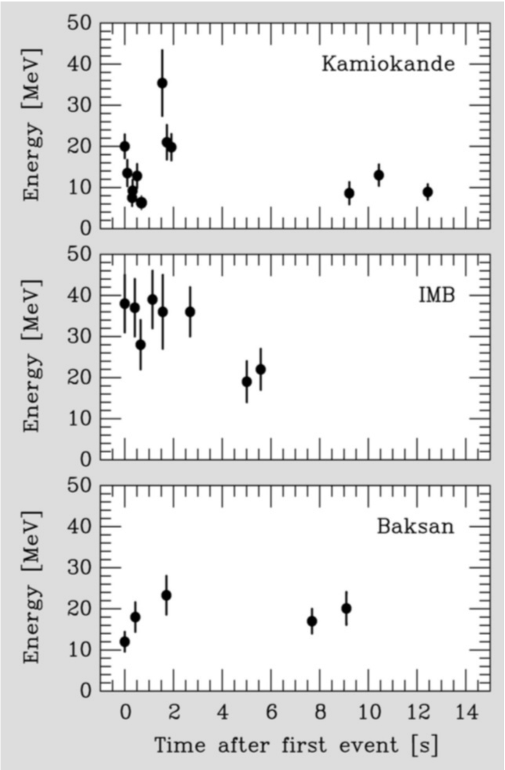
C. J. Horowitz *et al.*,
"r-Process Nucleosynthesis:
Connecting Rare-Isotope Beam Facilities with the Cosmos,"
arXiv:1805.04637 [astro-ph.SR].

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.

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

SuperNova Neutrinos





The future

This line of research

[the study of the "High Energy Universe" with multi-messengers (CR, gamma, neutrinos, GW) observations]

has great interest, great potential
and should be pursued energetically by the INFN
(and more in general by the community of particle physicists).

This is a field that has been
“dominated by the observers”

Cosmic Rays

Pulsars

Quasars

Jets of Active Galactic Nuclei

Gamma Ray Bursts

Large mass Black Hole mergers

[....]

just to list
the “big surprises”

(and there are
many “small" ones)
....

there is no reason
to think the
“surprises”
are finished

Theorists and “modelers” have always had several steps
behind trying to “catch up” with the new results

It is obviously essential to construct a plan of future observations, and this is not easy because of the "complexity" (multi-component based) of the field.

Gamma Observations [MeV, GeV, TeV, PeV, ...]

Neutrino Observations [Solar, SN, TeV, PeV, EeV]

Cosmic Rays [GeV, TeV, PeV, EeV]

Gravitational Waves

4 messengers, and also a *very broad energy range*

that can only be covered
using different techniques
and different detectors

Choosing priorities is obviously necessary but not easy (and several considerations play a role).

Here I have avoided discussing the question of selecting "priorities" for future projects.

One comment is that [in my opinion]
the are *important scientific goals* and *valid motivations* for future observations *for all four messengers*

Because of the nature of these studies,
(and the potential for surprises)

It is desirable to construct a "broad" program that covers all four messengers, and different experiments

Motivations for this line of research

1. Understanding the nature, the structure
   and the properties of the astrophysical accelerators

2. Use these astrophysical objects/transients
   as “laboratories” to test fundamental laws

3. Study the propagation of the messengers ν γ
   across astrophysical distances [Galactic,extragalactic]
   to perform fundamental physics tests.

4. Dark Matter studies

5. Cosmology studies

Is this "just astrophysics ? I
I think it is an important task for
"fundamental physics

1. Understanding the nature, the structure and the properties of the astrophysical accelerators

2. Use these astrophysical objects/transients as "laboratories" to test fundamental laws

3. Study the propagation of the messengers ν γ across astrophysical distances [Galactic,extragalactic] to perform fundamental physics tests.

4. Dark Matter studies

5. Cosmology studies

Very important to construct an harmonious program that combine future accelerators and multi-messenger astrophysics