High Energy Sources
and
Multi-Messenger High Energy Astrophysics

Part 2.

Paolo Lipari (INFN, Roma)

Amaldi Research Center

Roma, March 11th , 2021

Outline of talk

Gamma Ray Observations

- Classes of sources
  - AGN
  - GRB
  - other sources

Neutrino Observations

Cosmic Ray Observations

Conclusions

“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.

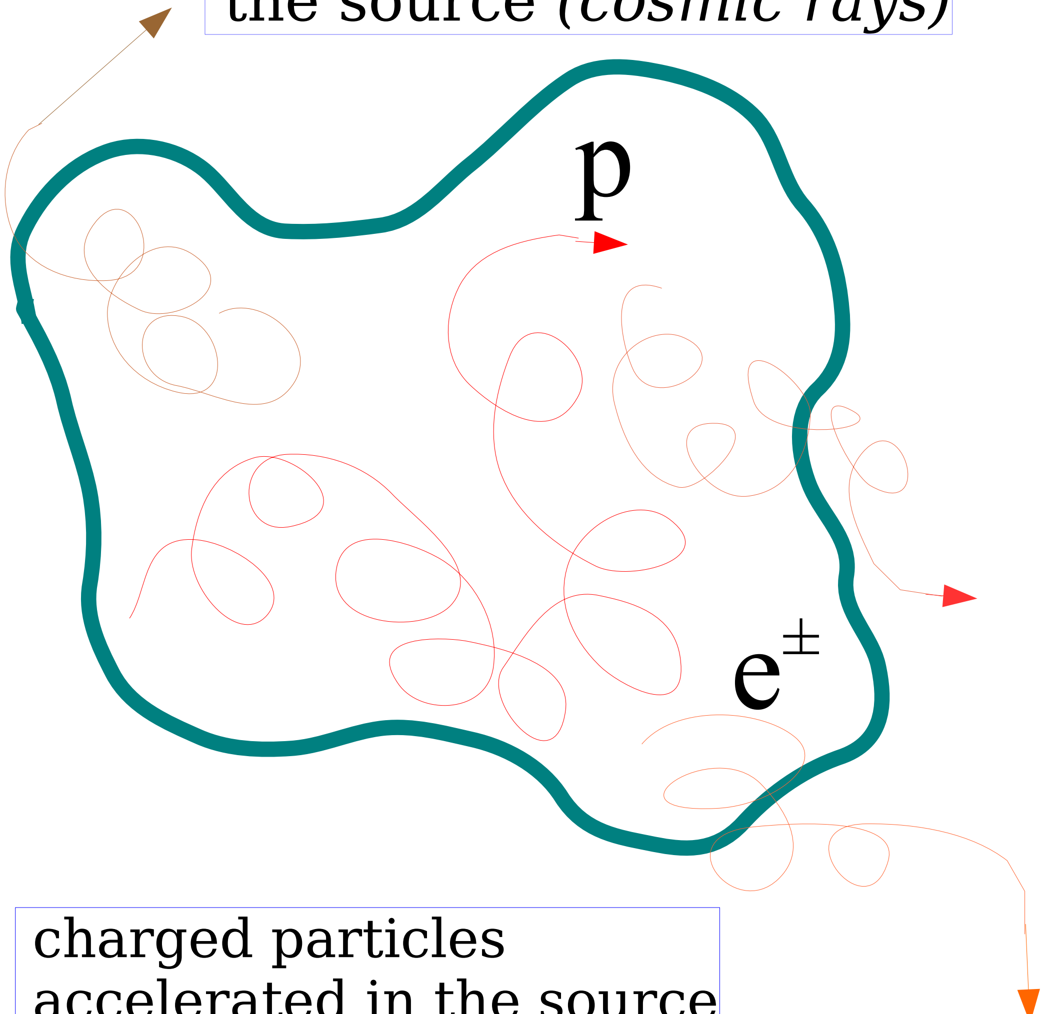
4 Messengers

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

Cosmic Ray Source

particles escaping
the source *(cosmic rays)*



charged particles
accelerated in the source

Interactions with gas and
radiation fields *(photons, neutrinos)*

Hadronic emission

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

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

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

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

Leptonic emission

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

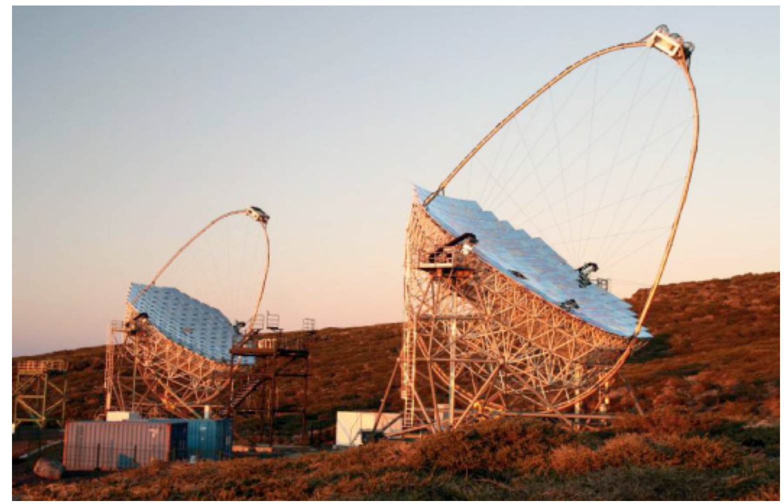
$$e^{\pm} \; Z \to e^{\pm} \; \gamma \; Z$$

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

Gamma Rays

Space $E_\gamma \simeq 0.1 \div 100$ TeV

Cherenkov $E_\gamma \simeq 0.1 \div 100$ TeV

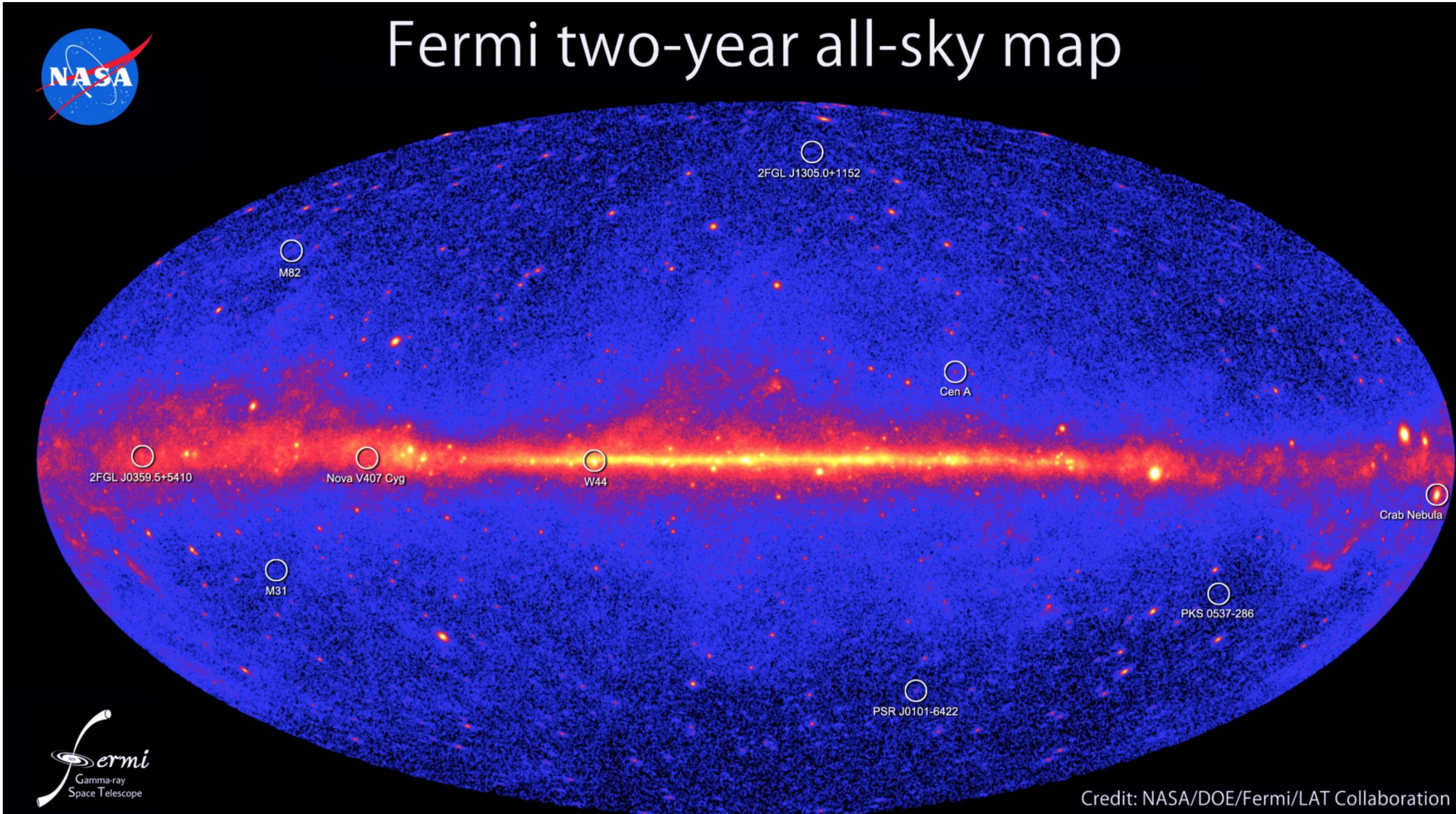


Ground Array

$E_\gamma \lesssim 30$ PeV

$E_\gamma \geq 100$ MeV

Gamma Ray Sky

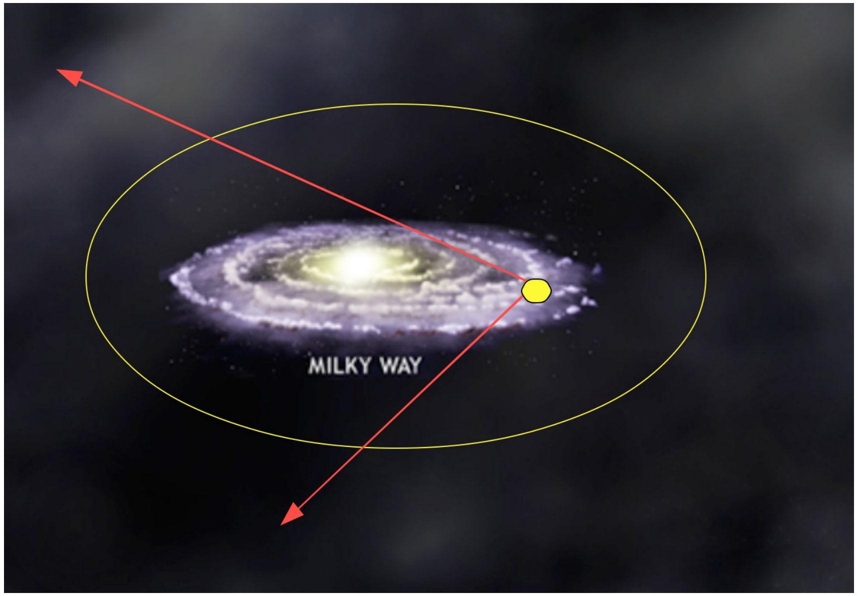


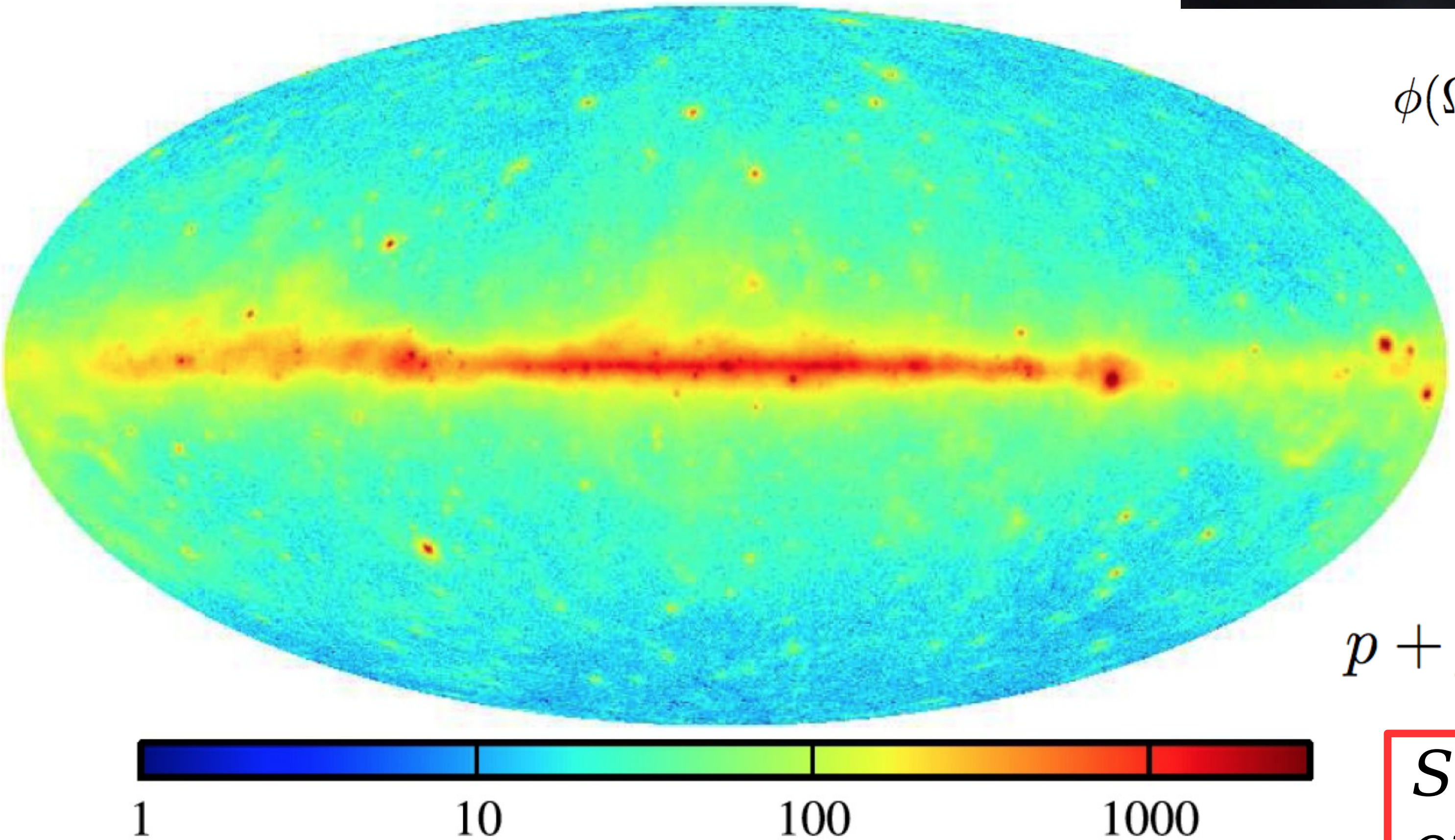
Diffuse flux + Ensemble of (quasi)-point like sources

Diffuse Emission

Fermi–LAT counts

Galactic coordinates





energy range 200 MeV to 100 GeV

$$\phi(\Omega) \propto \int d\ell \; n_{\rm cr}(\vec{\ell}) \; n_{\rm ism}(\vec{\ell})$$

Integral
over line of sight

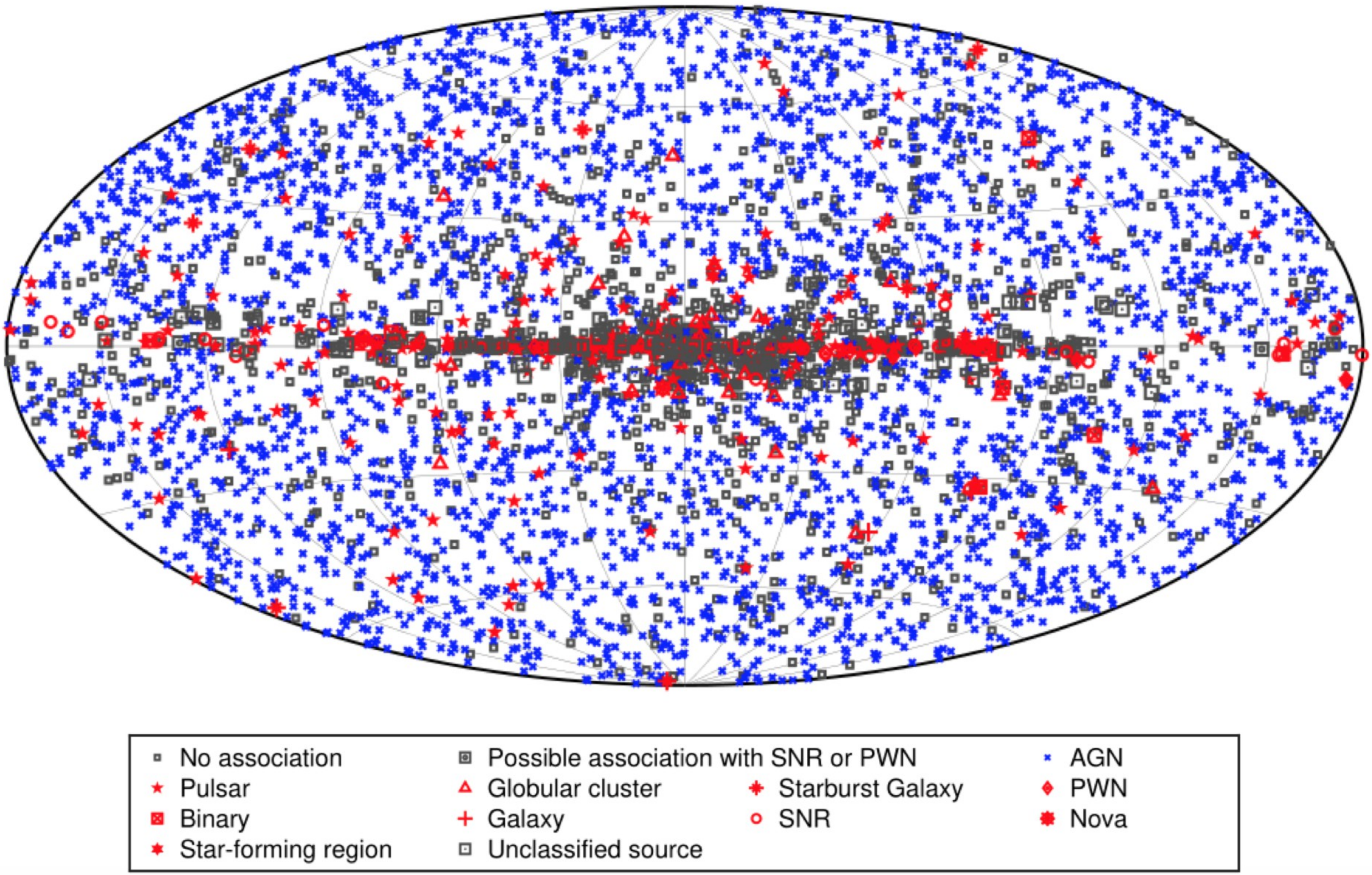
[(CR density) *
(gas density)]

$$p + p_{\rm ISM} \to \pi^\circ \to \gamma \;\; \gamma$$

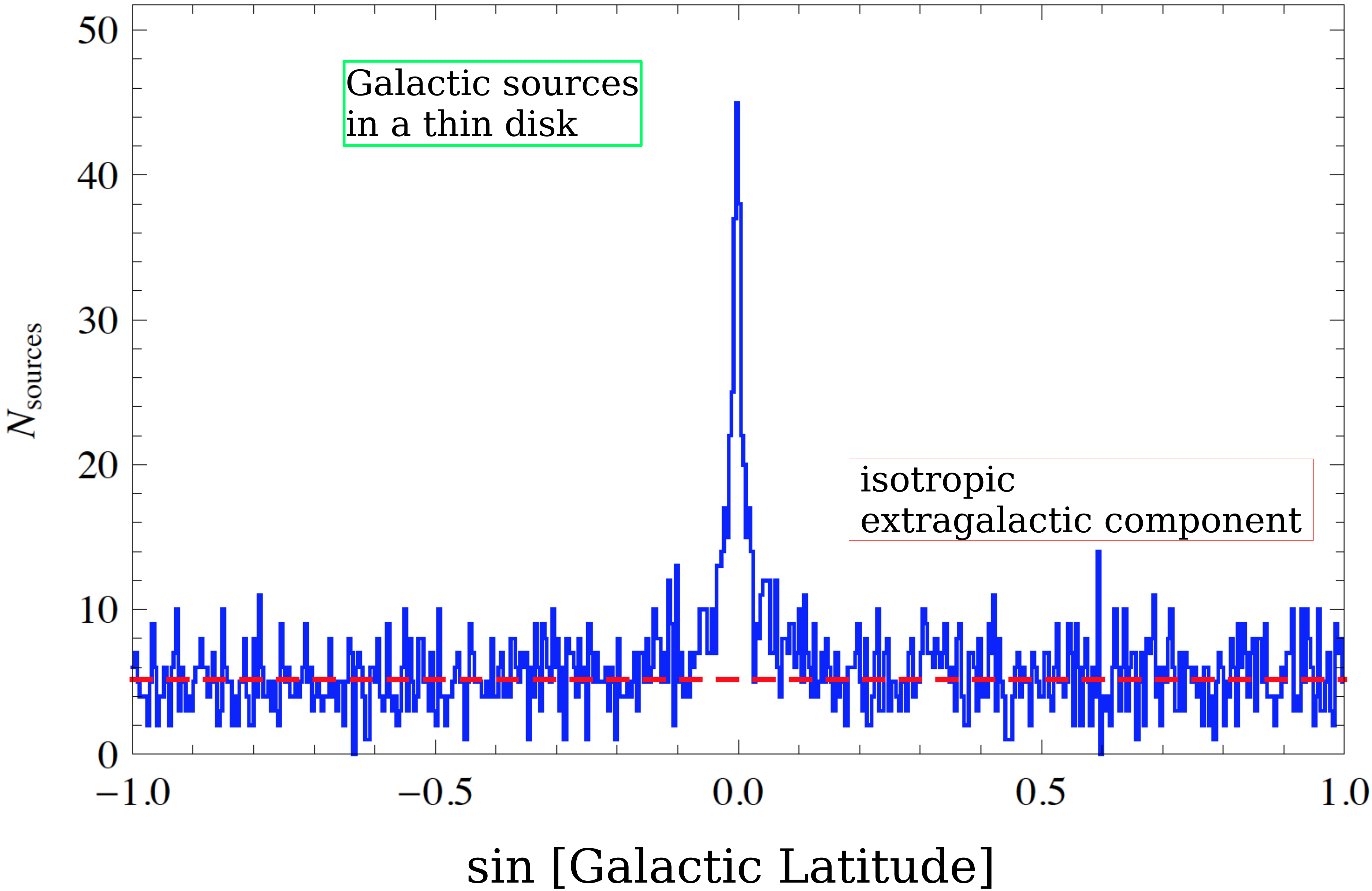
Study distribution of Cosmic Rays in the Galaxy

FERMI 4th Catalog (5064 sources)

Equal Area
Sky projection



3034 3rd catalog sources



Classes of Sources

[Fermi sources associated with known objects]

72% of sources

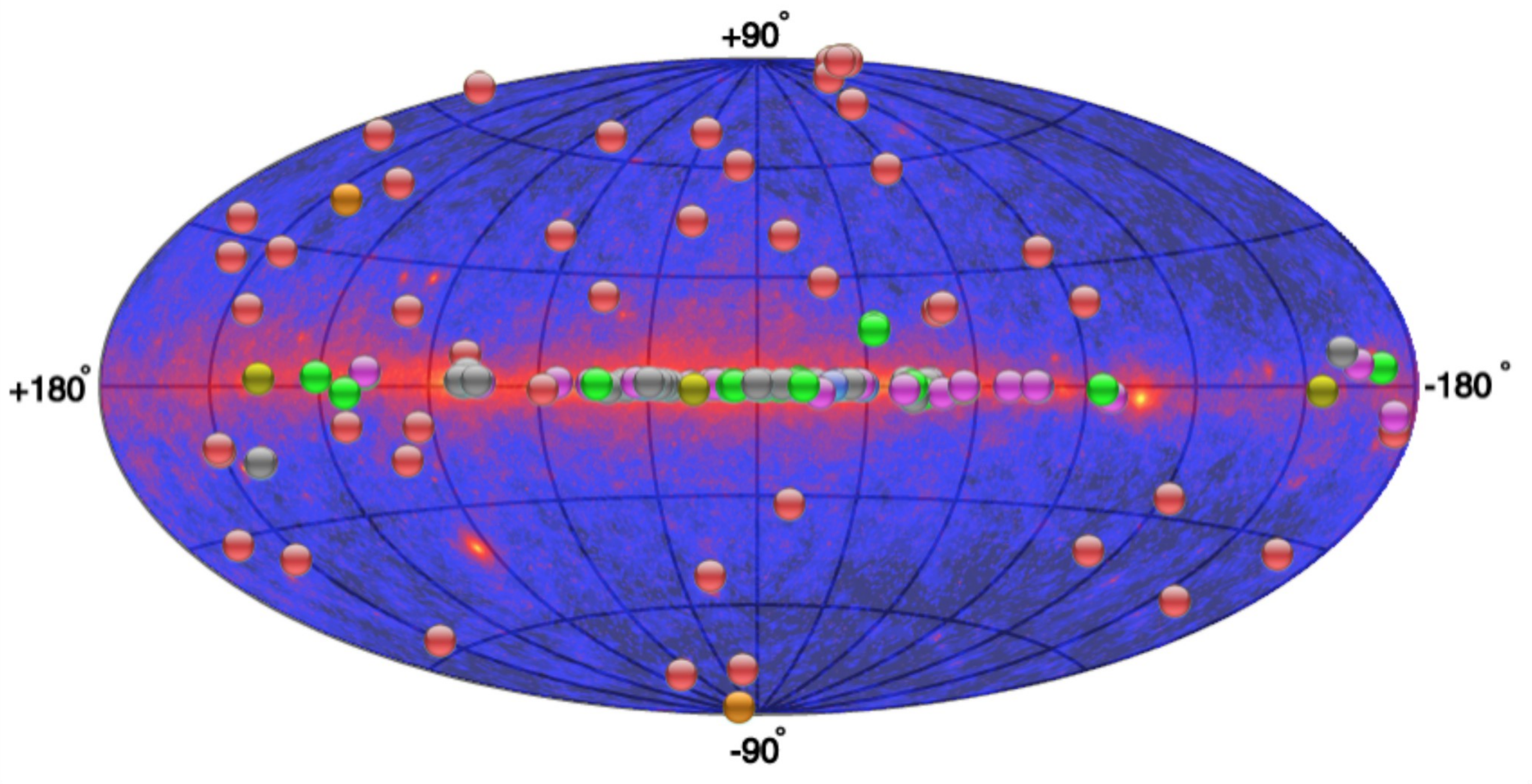
extragalactic

Active Galactic Nuclei (AGN)	3208	88%
(AGN of "Blazar" class	3137	86%)
Galaxies (Normal)	4	
Galaxies (Star Forming)	7	

Galactic

Pulsars	239	6.5%
SuperNova Remnants (SNR)	40	1.1%
SNR + Pulsar Wind Nebulae	108	3.0%
Globular Clusters (many ms Pulsars [?])	30	
Accreting Binary Stars	11	
Novae	1	

TeV Sky 170 → 200 Sources



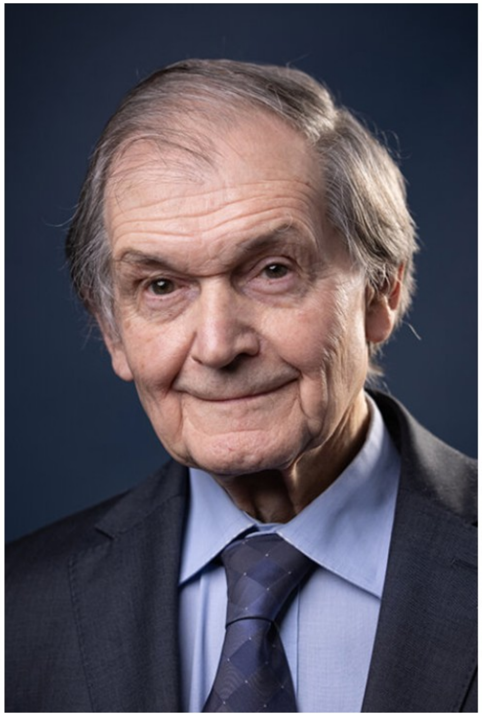
blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky

Super Massive Black Holes
(at the center of Galaxies)

Active Galactic Nuclei

(powered by mass accretion)

The Nobel Prize in Physics 2020



© Nobel Prize Outreach. Photo: Fergus Kennedy

Roger Penrose

Prize share: 1/2

© Nobel Prize Outreach. Photo: Bernhard Ludewig

Reinhard Genzel

Prize share: 1/4

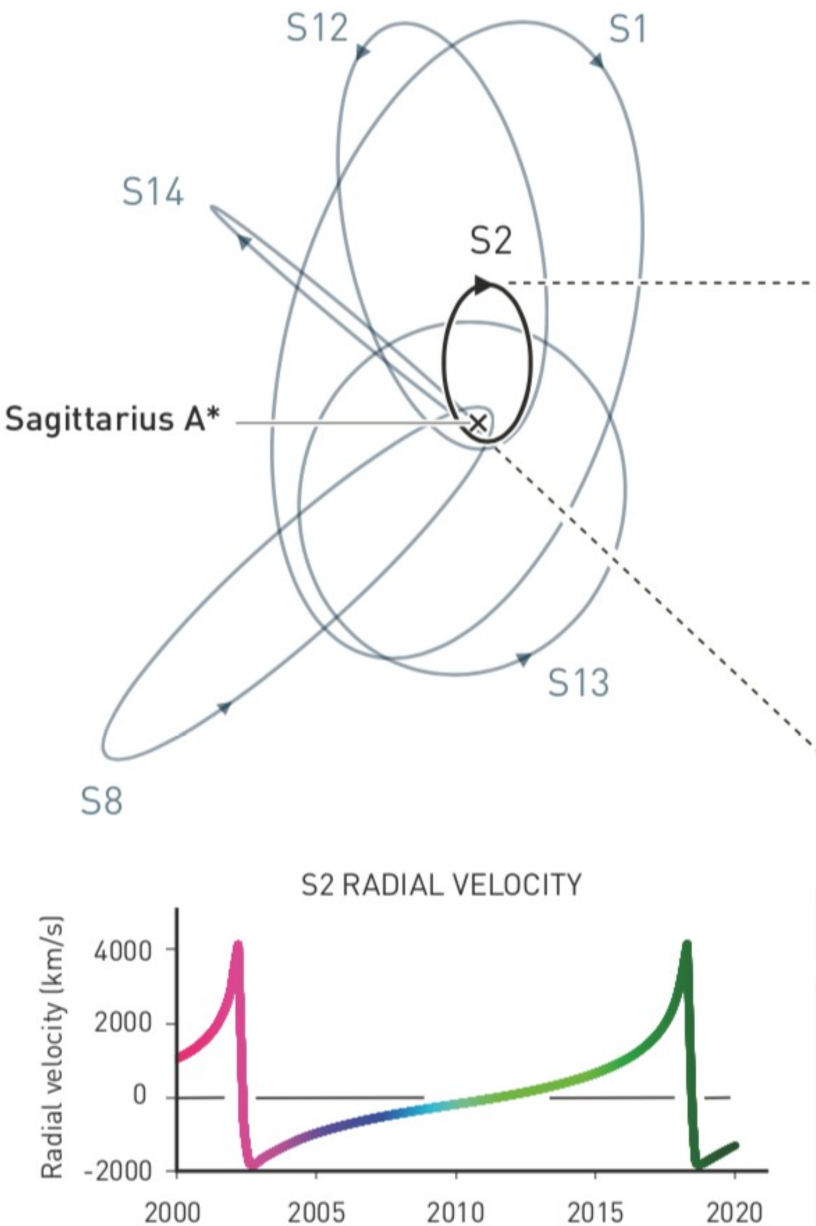
© Nobel Prize Outreach. Photo: Annette Buhl

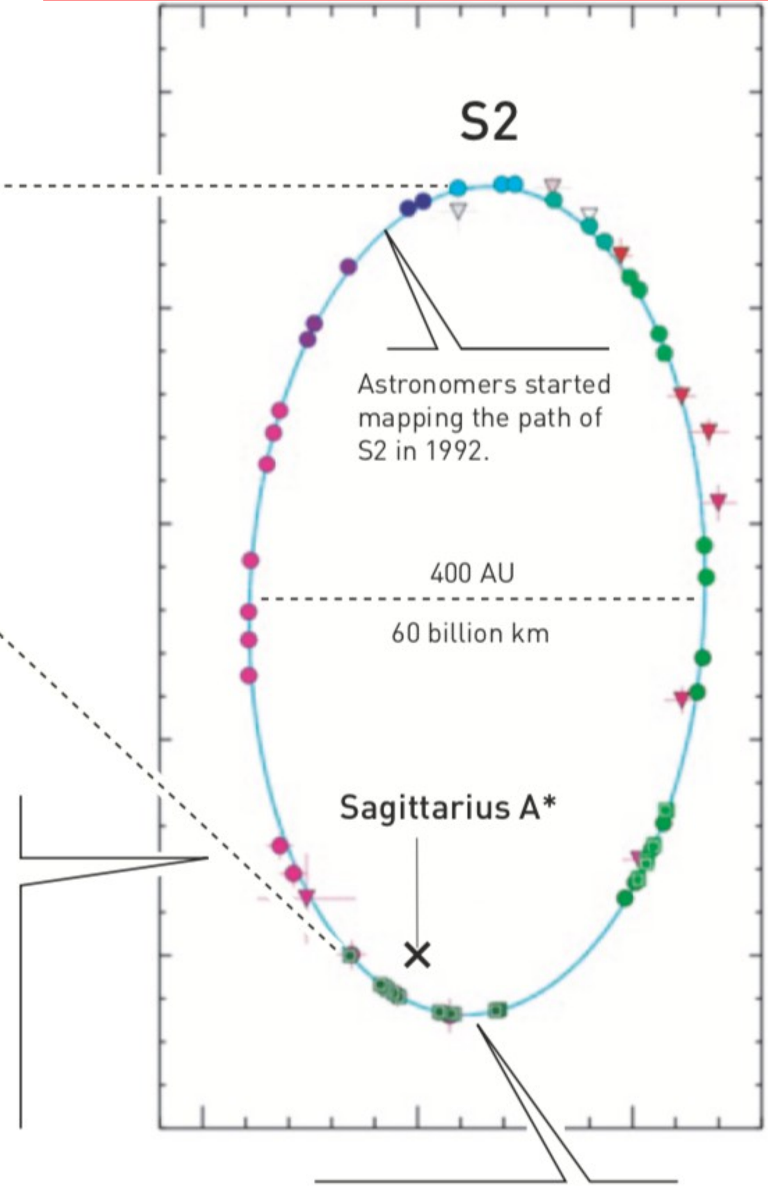
Andrea Ghez

Prize share: 1/4

Penrose	For the discovery that black hole formation is a robust prediction of the general theory of relativity
Genzel Ghez	For the discovery of a supermassive compact object at the centre of our Galaxy

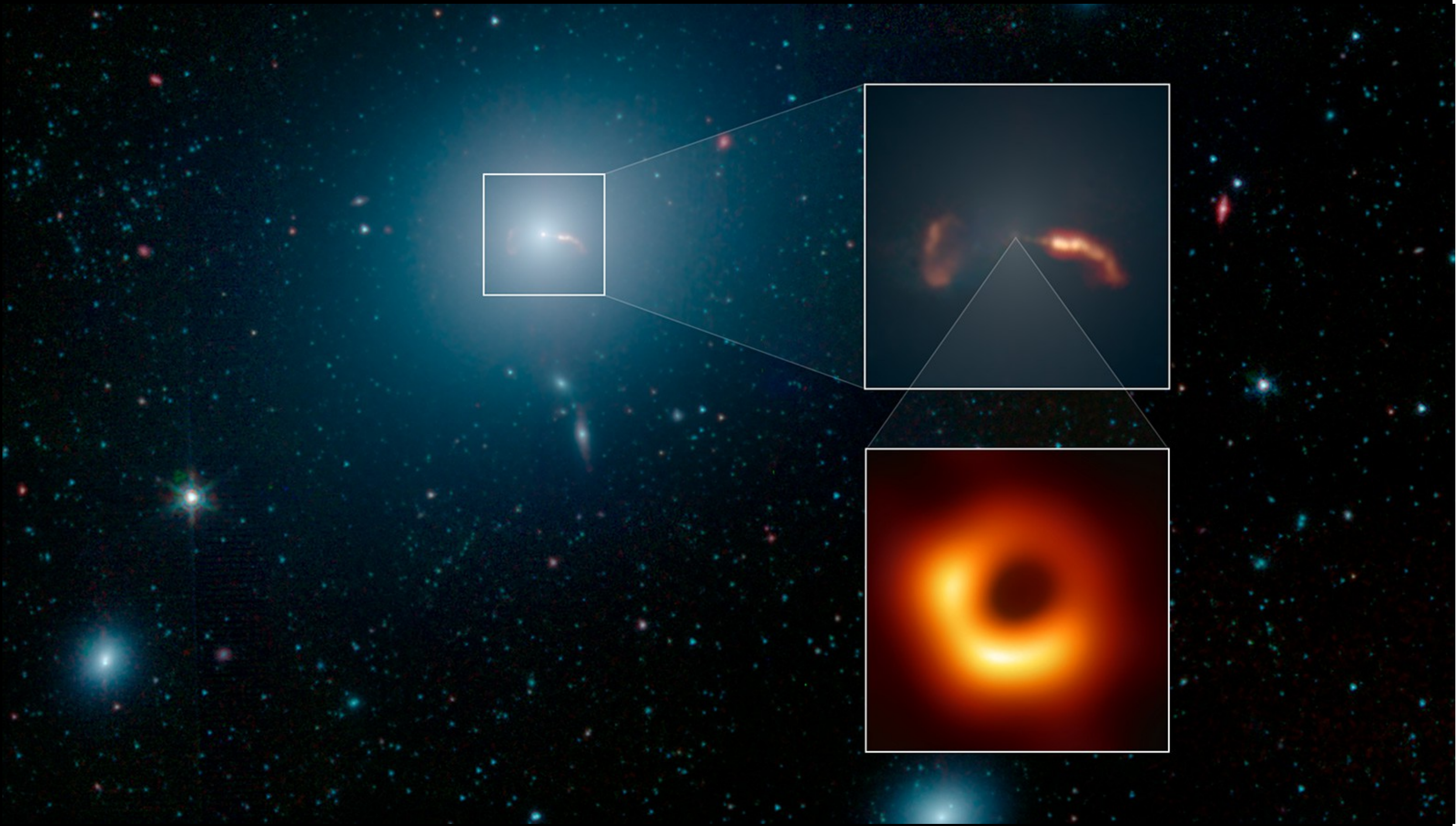
Supermassive object at the Milky Way center





Closest to SgrA*
in 2002 and 2018
(maximum velocity)

M87 (d=17 Mpc)

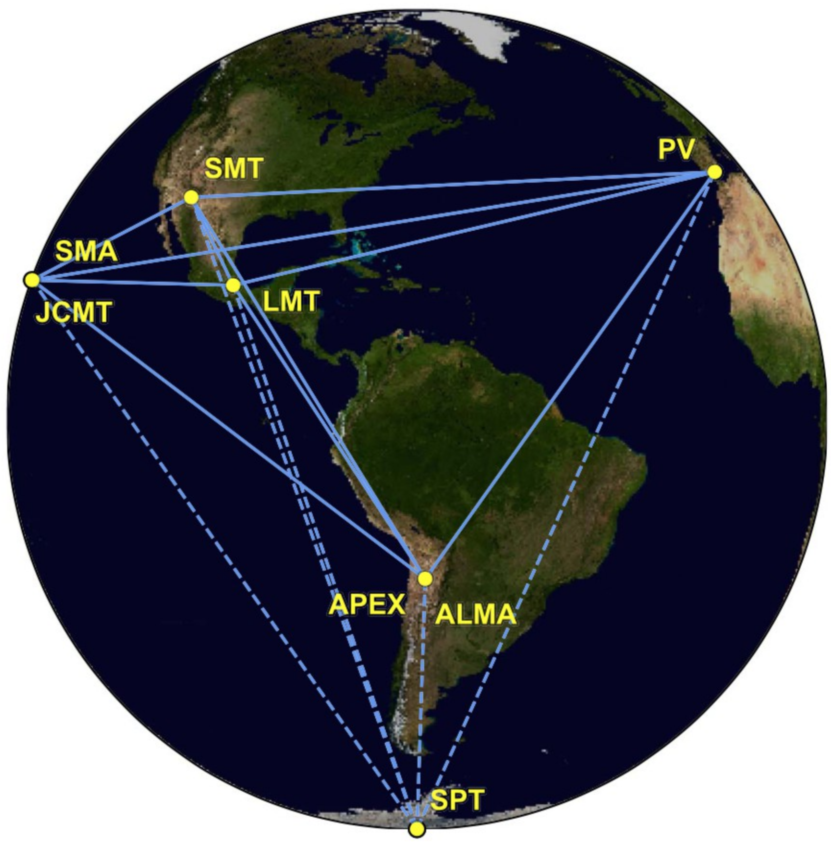


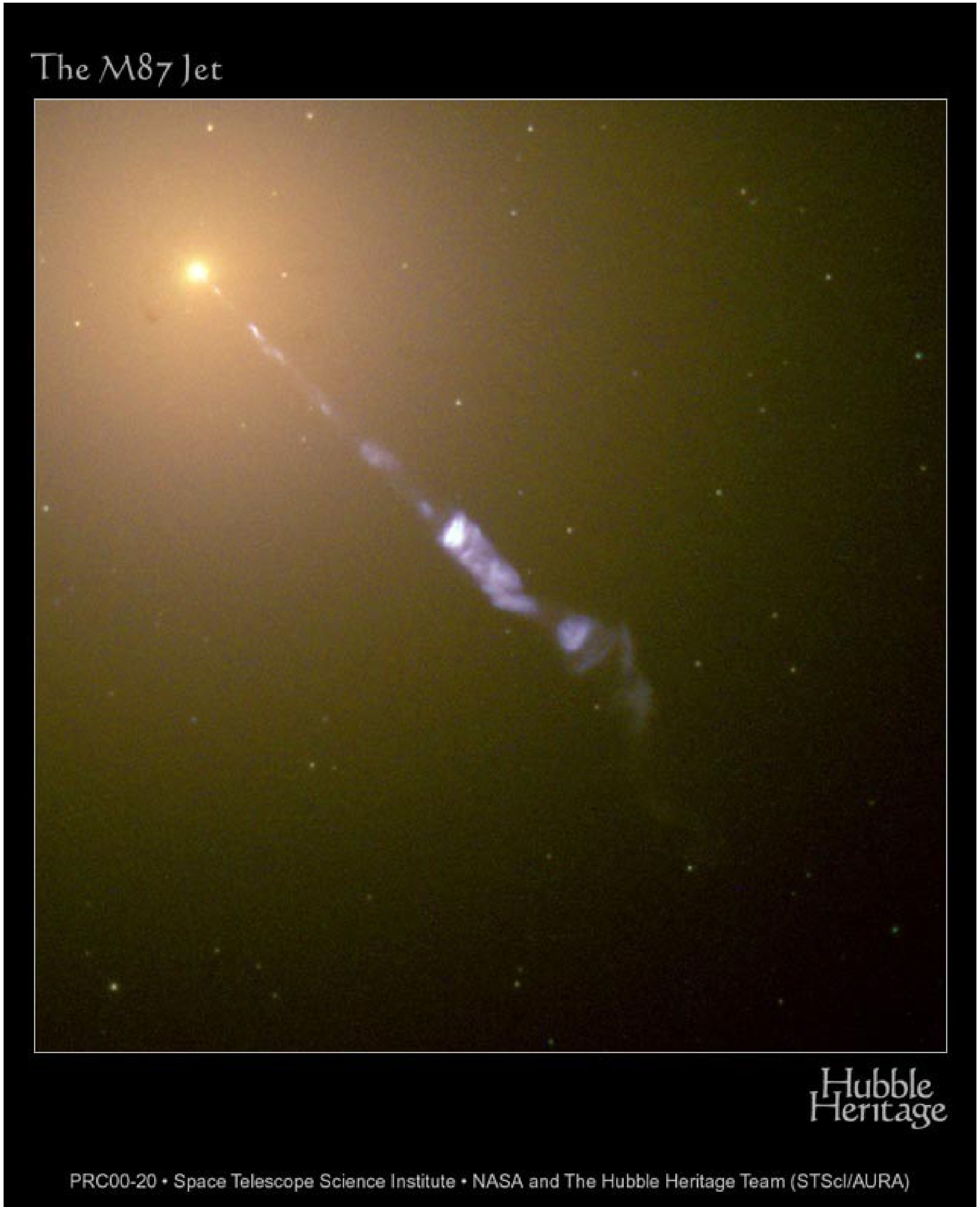
The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10

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



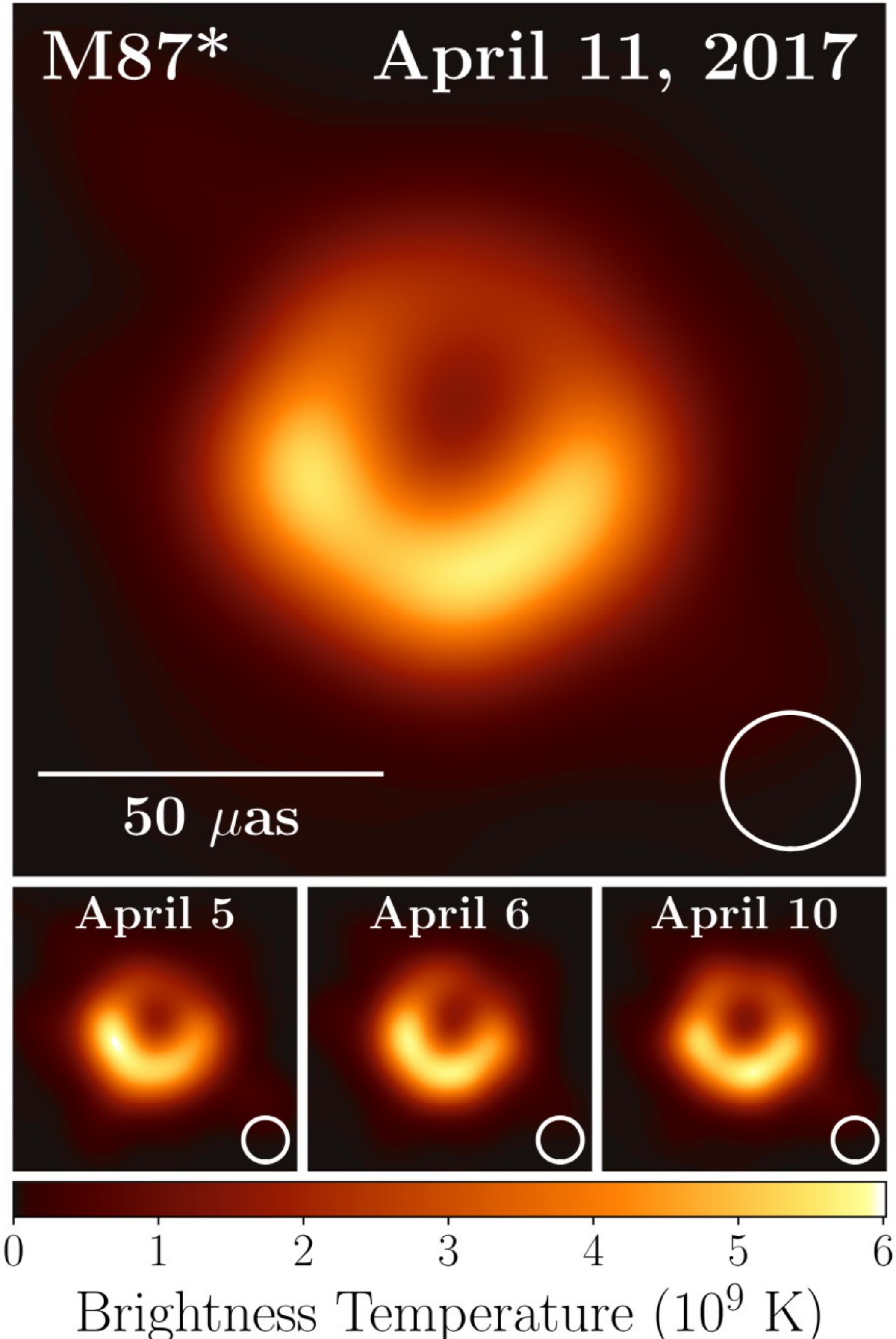


M87 JET

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."



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

Schwarzschild radius

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

Photon capture radius

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

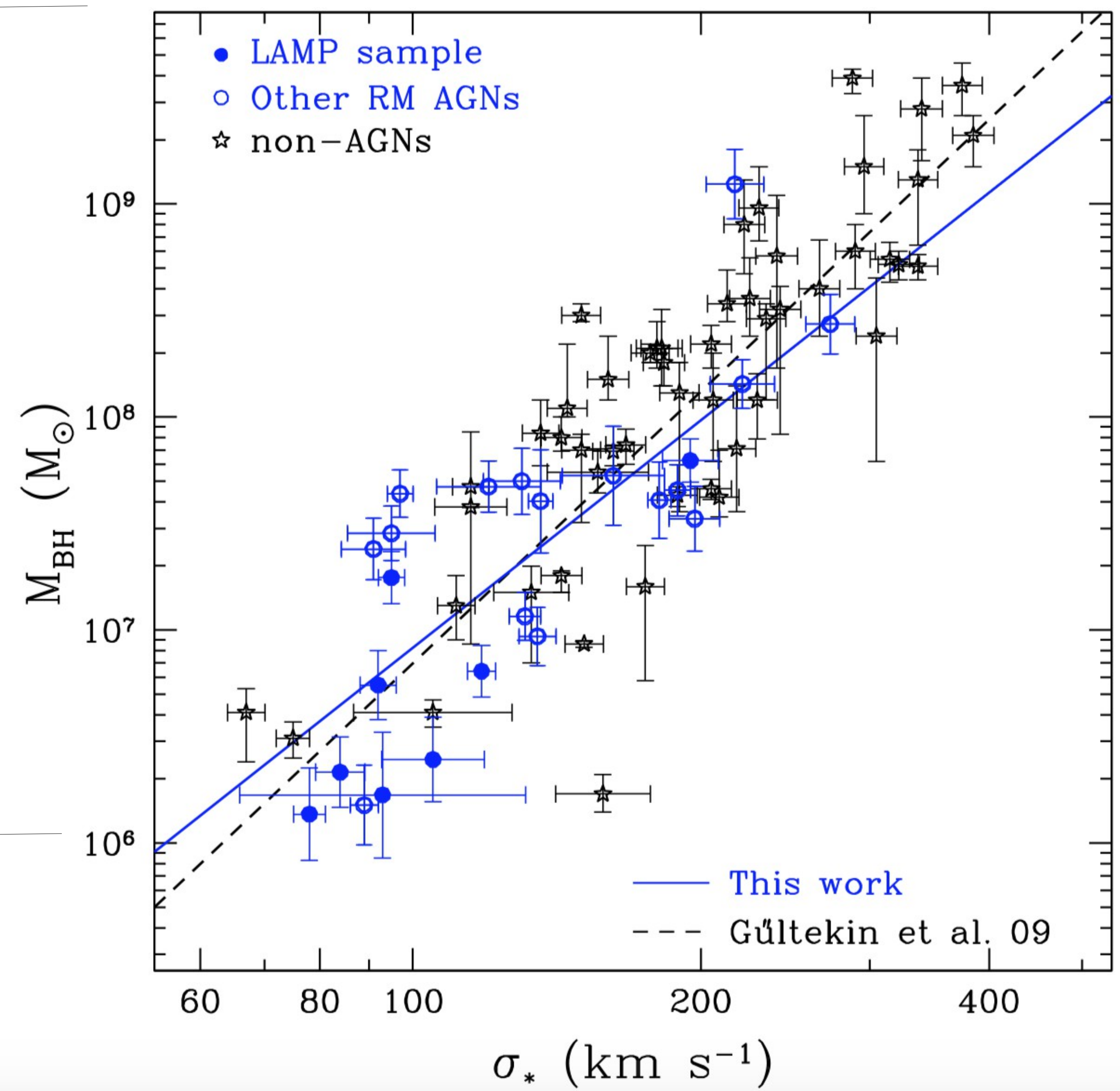
$$d = 16.8 \pm 0.8\ \text{Mpc}$$

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

AGN SMBH masses B.Peterson [2014]

$10^{10}\ M_\odot$

$10^{6}\ M_\odot$



Sloan Digital Survey of Quasars (283,033 objects)

Largest mass

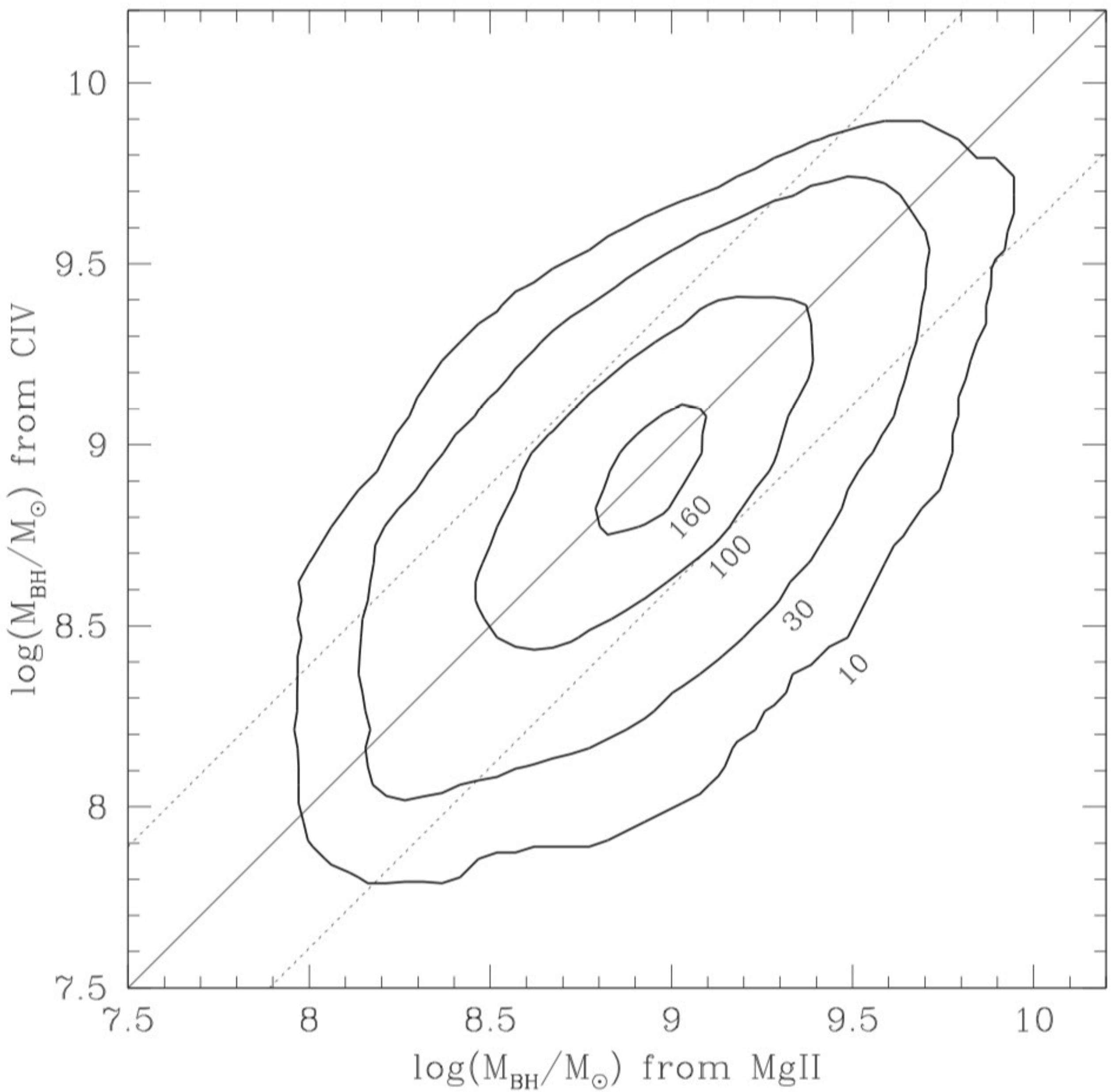
SDSS J140821.67+025733.2
(at z = 2.055)

$$M \approx 1.96 \times 10^{11}\ M_\odot$$

Largest Luminosity

SDSS J155152.46+191104.0
(at z = 2.850)

$$L \simeq 4.7 \times 10^{14}\ L_\odot$$



Active Galactic Nuclei (AGN)

Complicated (and also controversial) classification in different types. A real “Zoo” of different objects

Seyferth Galaxies
Radio Galaxies
.....
Quasars
BL-Lac Objects

Emission Associated to accretion to a SuperMassive Black Hole at the galaxy center

Accretion Power

$$\Delta E \approx \frac{G\, M\, \Delta m}{r_{\rm min}}$$

Energy Released by mass Δm

Approaching massive object of mass M

to a minimum distance $r_{\rm min}$

$$\eta = \frac{\Delta E}{\Delta m\, c^2} \approx \frac{1}{2\,(r_{\rm min}/R_S)}$$

"efficiency"
(fraction of rest-mass energy that can be released)

$$\eta \simeq 0.06 \div 0.42$$

Schwarzschild radius

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

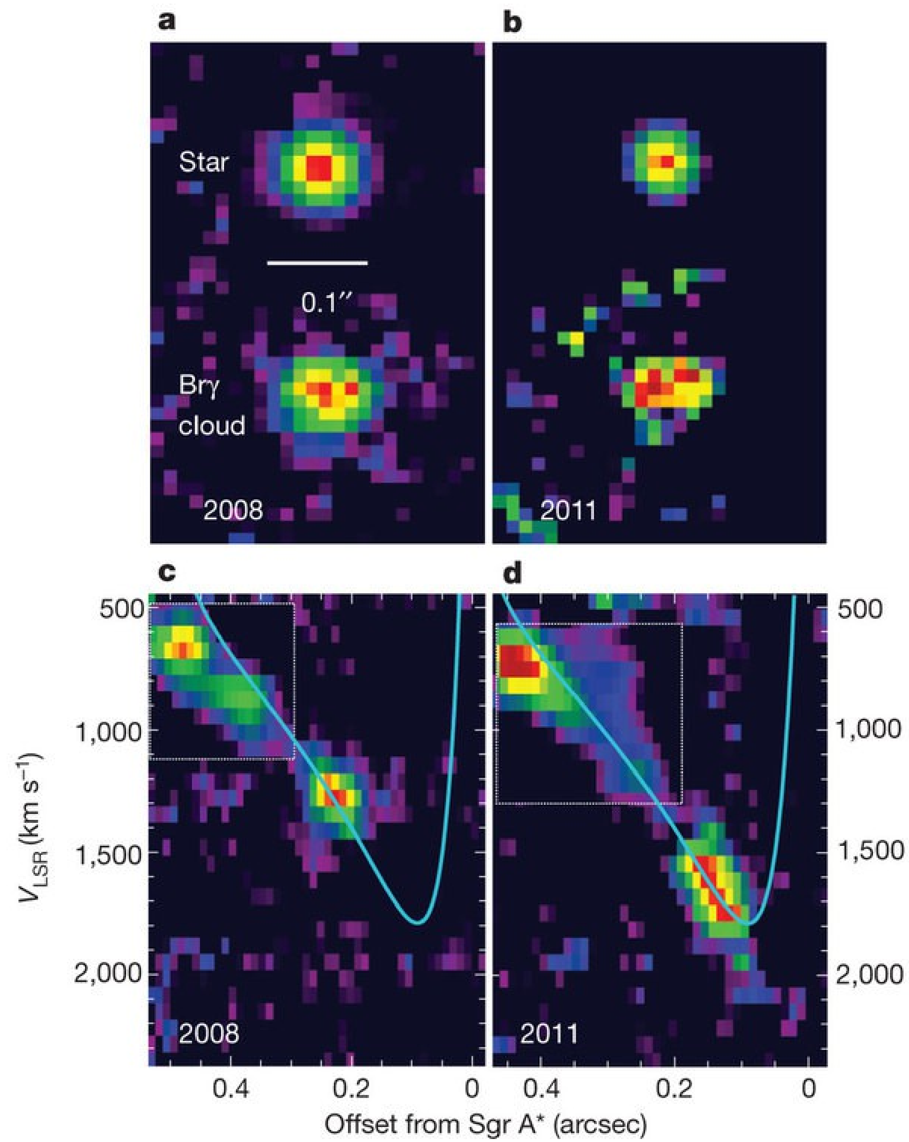
$$\dot{M} = 1\ M_\odot\ {\rm yr}^{-1}$$

$$L \simeq 10^{46}\ {\rm erg/s} \simeq 3 \times 10^{12}\ L_\odot$$

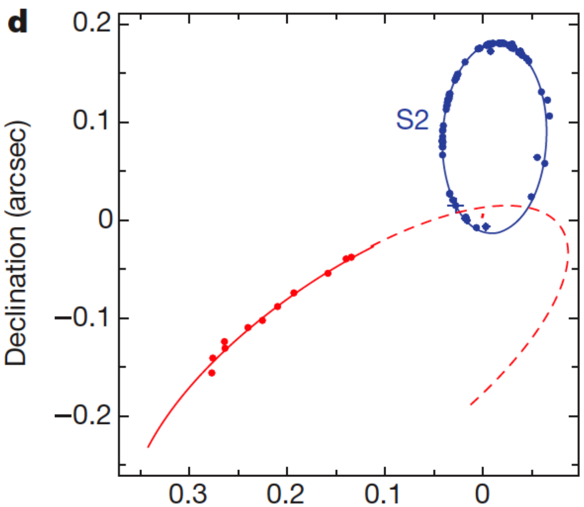
doi:10.1038/nature10652

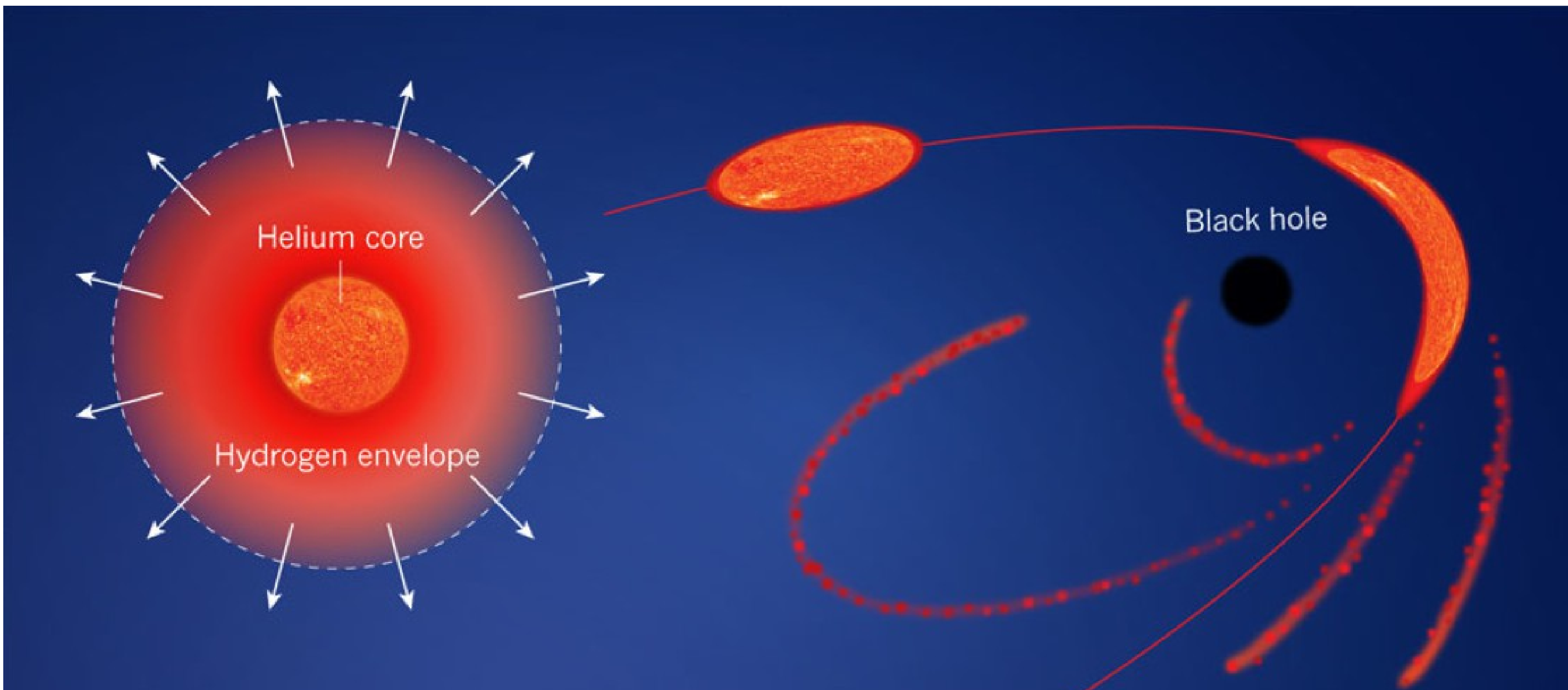
A gas cloud on its way towards the supermassive black hole at the Galactic Centre

S. Gillessen[1], R. Genzel[1,2], T. K. Fritz[1], E. Quataert[3], C. Alig[4], A. Burkert[4,1], J. Cuadra[5], F. Eisenhauer[1], O. Pfuhl[1], K. Dodds-Eden[1], C. F. Gammie[6] & T. Ott[1]



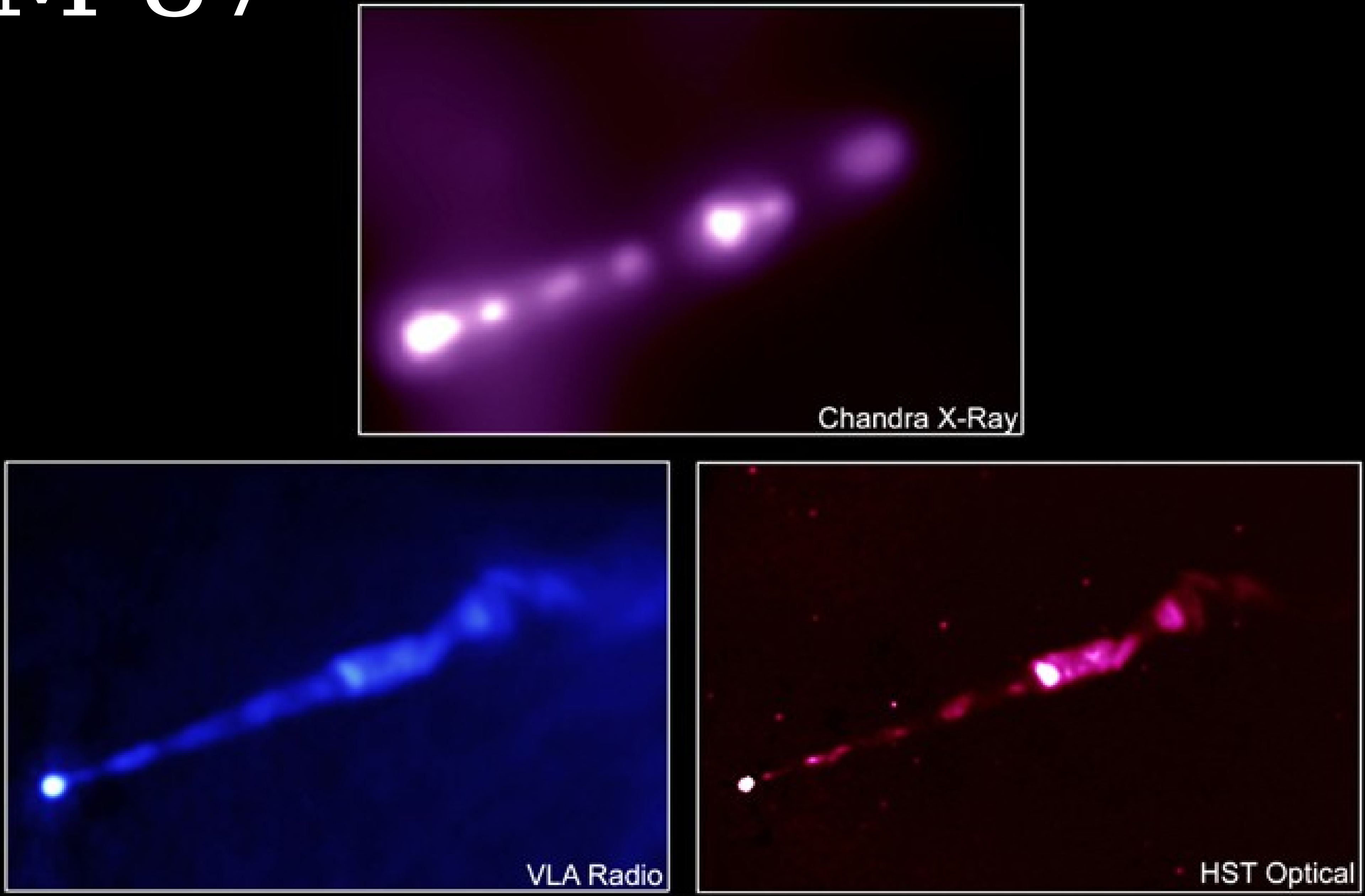
Infalling gas
from the disruption of a star.





The helium-rich core of a red-giant star that had previously lost its hydrogen envelope moves on an almost parabolic orbit (red) towards a supermassive black hole. The sequence of blobs illustrates the progressive distortion of the star's core due to the tidal pull of the black hole. After the point of closest approach to the black hole, the core is completely disrupted, with part of the resulting debris being expelled from the system and part being launched into highly eccentric orbits, eventually falling onto the black hole. Accretion of this debris gives rise to the intense ultraviolet–optical flare that has been observed by Gezari and colleagues[1].

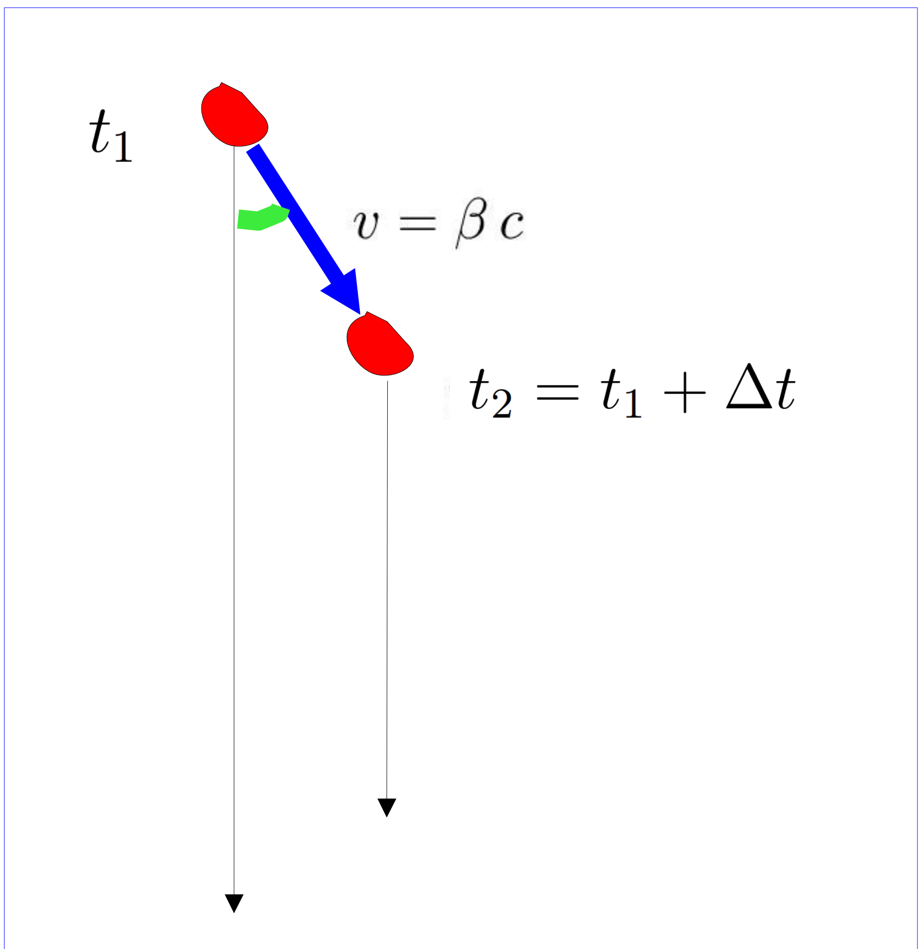
M 87



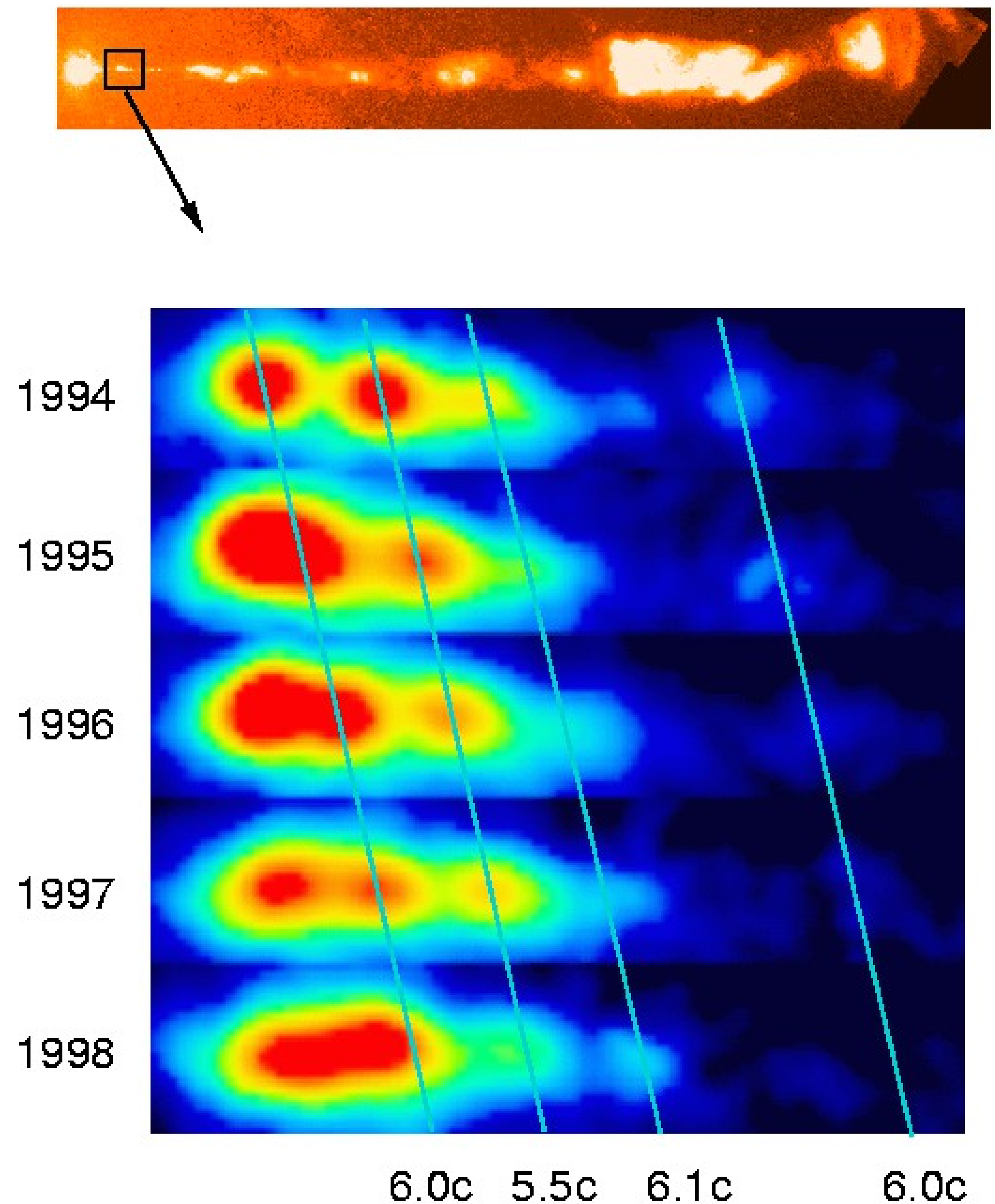
First astrophysical “jet” [1913 Heber Curtis]

Superluminal Motion

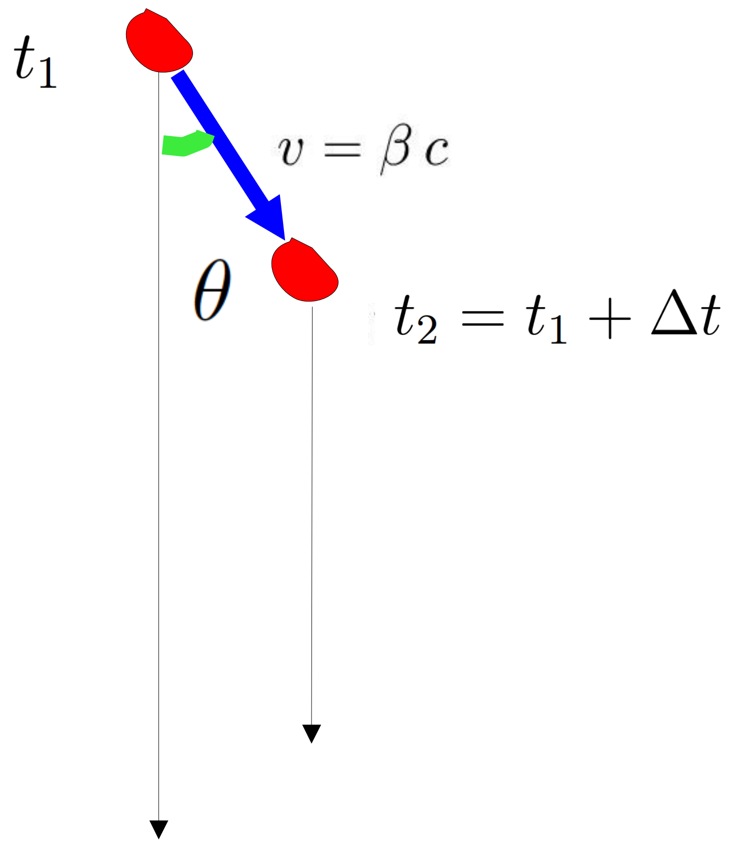
$$v_{\perp,\mathrm{app}} = \frac{L\,(\varphi_2 - \varphi_1)}{\Delta t_{\mathrm{obs}}}$$



Superluminal Motion in the M87 Jet



Moving Source



$$t_1^{\rm obs} = t_1 + \frac{L}{c}$$

$$t_2^{\rm obs} = t_1 + \frac{L - c\,\beta\,\cos\theta\,\Delta t}{c}$$

$$\Delta t_{\rm obs} = \Delta t\,(1 - \beta\,\cos\theta)$$

$$\varphi_2 = \varphi_1 + \frac{c\,\beta\,\sin\theta\;\Delta t}{L}$$

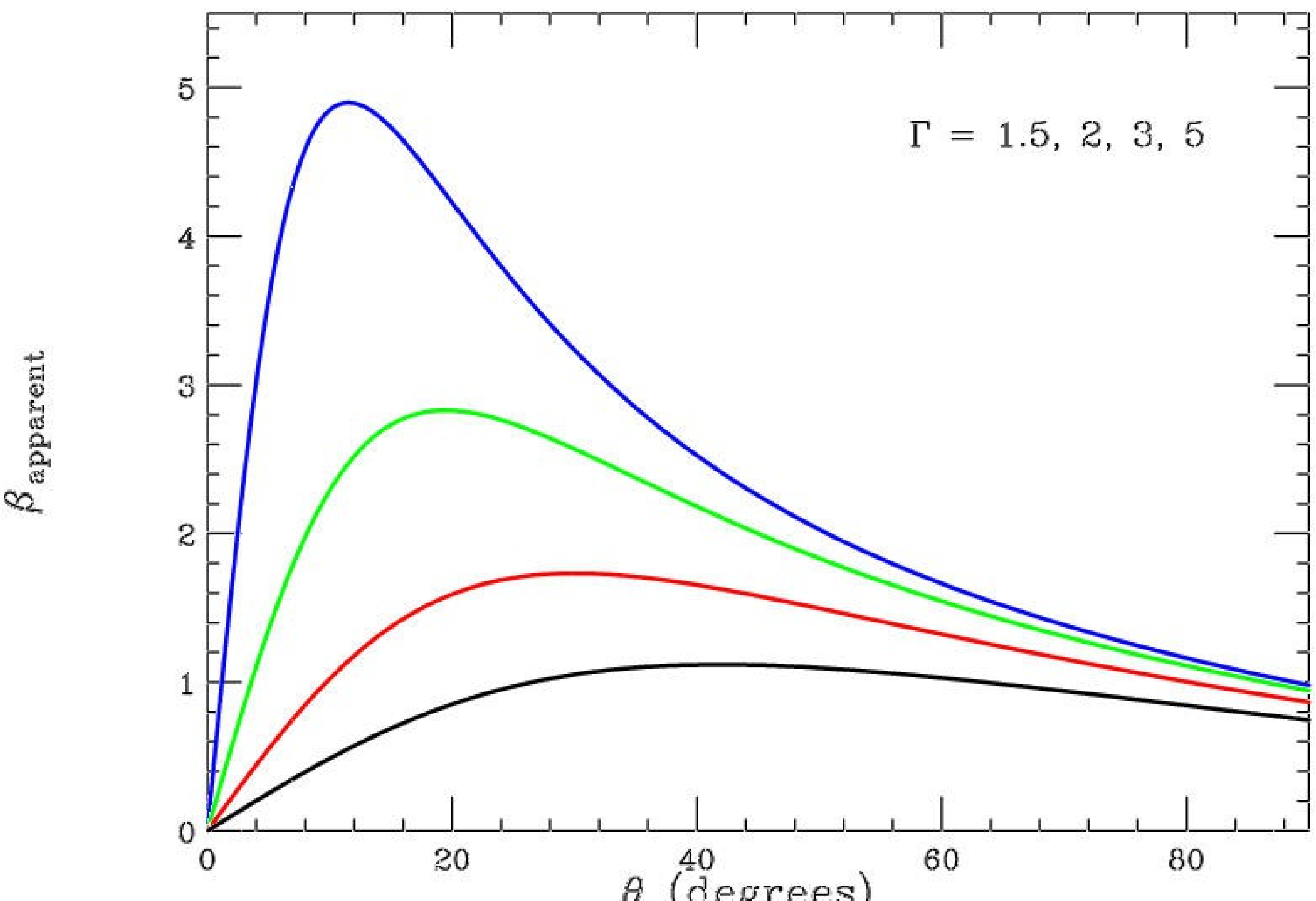
$$\Delta t_{\rm obs} = \Delta t\,(1 - \beta\,\cos\theta)$$

$$\beta_{\perp,{\rm app}} = \frac{L\,(\varphi_2 - \varphi_1)}{c\,\Delta t_{\rm obs}} = \frac{\beta\;\sin\theta}{(1 - \beta\cos\theta)}$$

$$\beta_{\rm apparent} = \frac{r}{c}\,\frac{\Delta\Omega}{\Delta t_{\rm obs}} = \frac{\beta\,\sin\theta}{[1-\beta\,\cos\theta]}$$

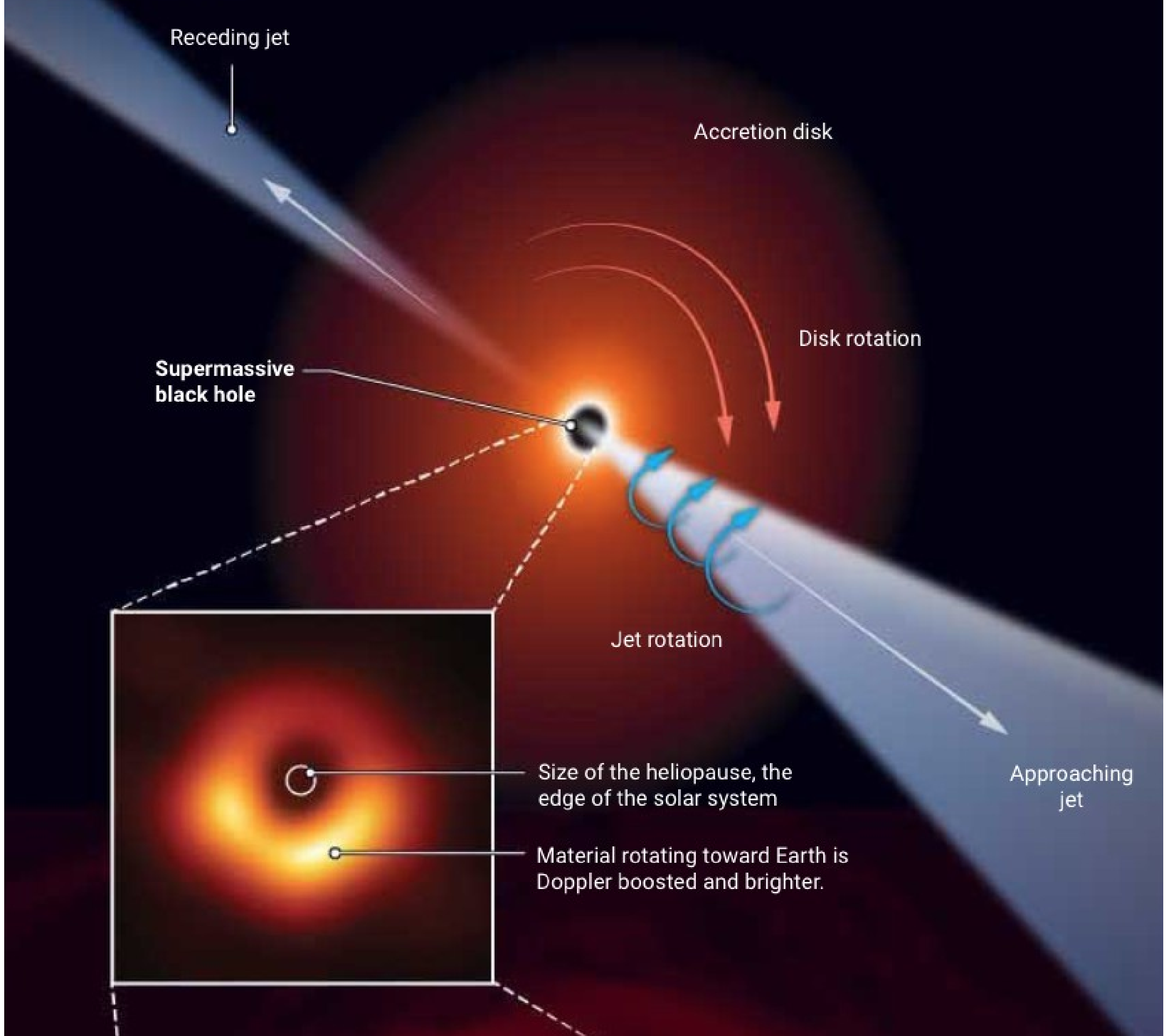
$$\theta = \cos^{-1}\beta \simeq \frac{1}{\gamma}$$

$$\beta_{\rm apparent} \to \beta\gamma$$



Strange beast

The Event Horizon Telescope (EHT) team took 2 years to produce an image of the black hole at the center of nearby galaxy Messier 87 (M87), which feeds on a swirling disk of bright matter. Its gravity is so strong that photons orbit it, creating a bright ring. Gravitational lensing magnifies the black hole's event horizon into a larger dark shadow, which may be partially filled by material in front of the hole.

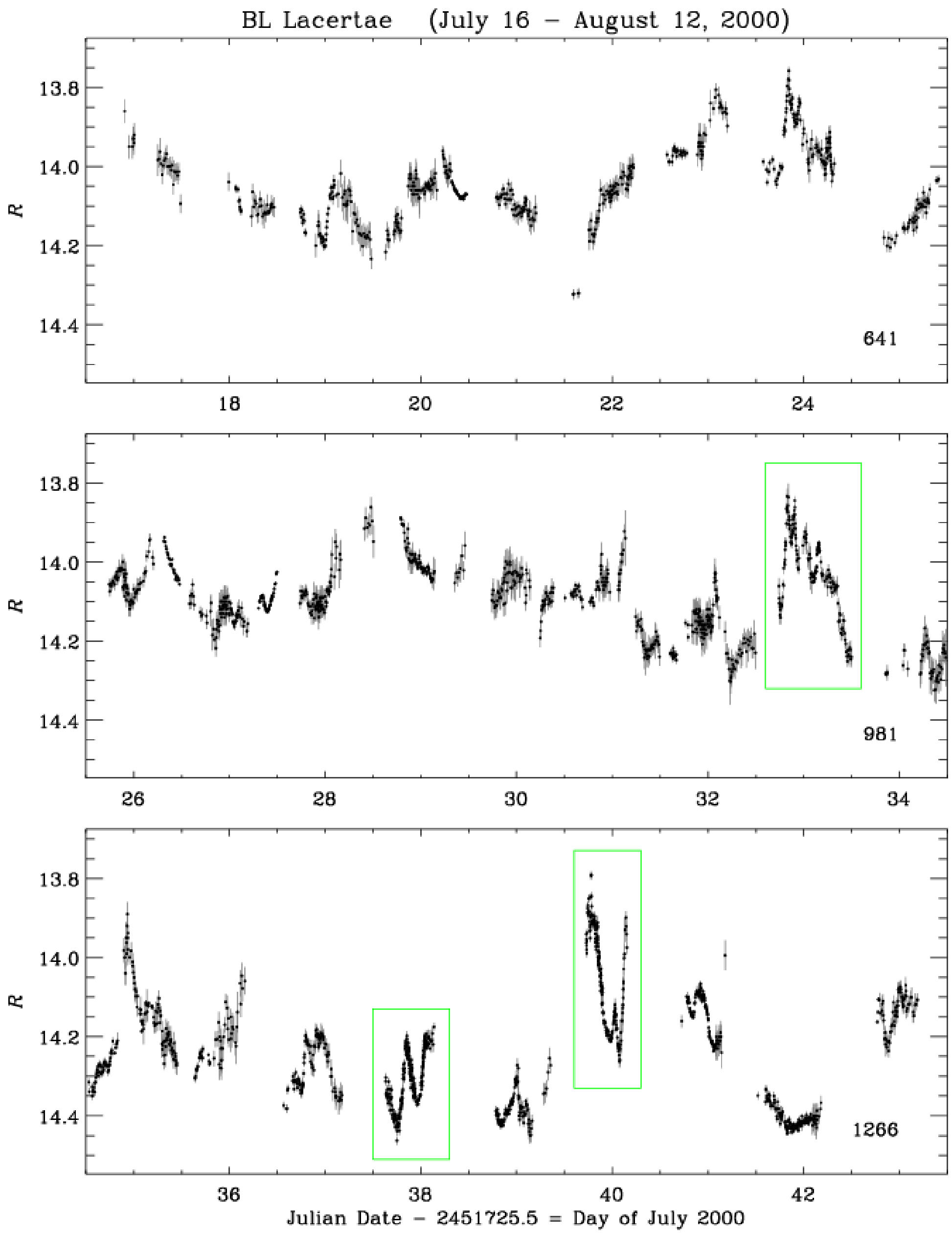


BL Lacertae

"Variable star"
(classified and names in 1929)

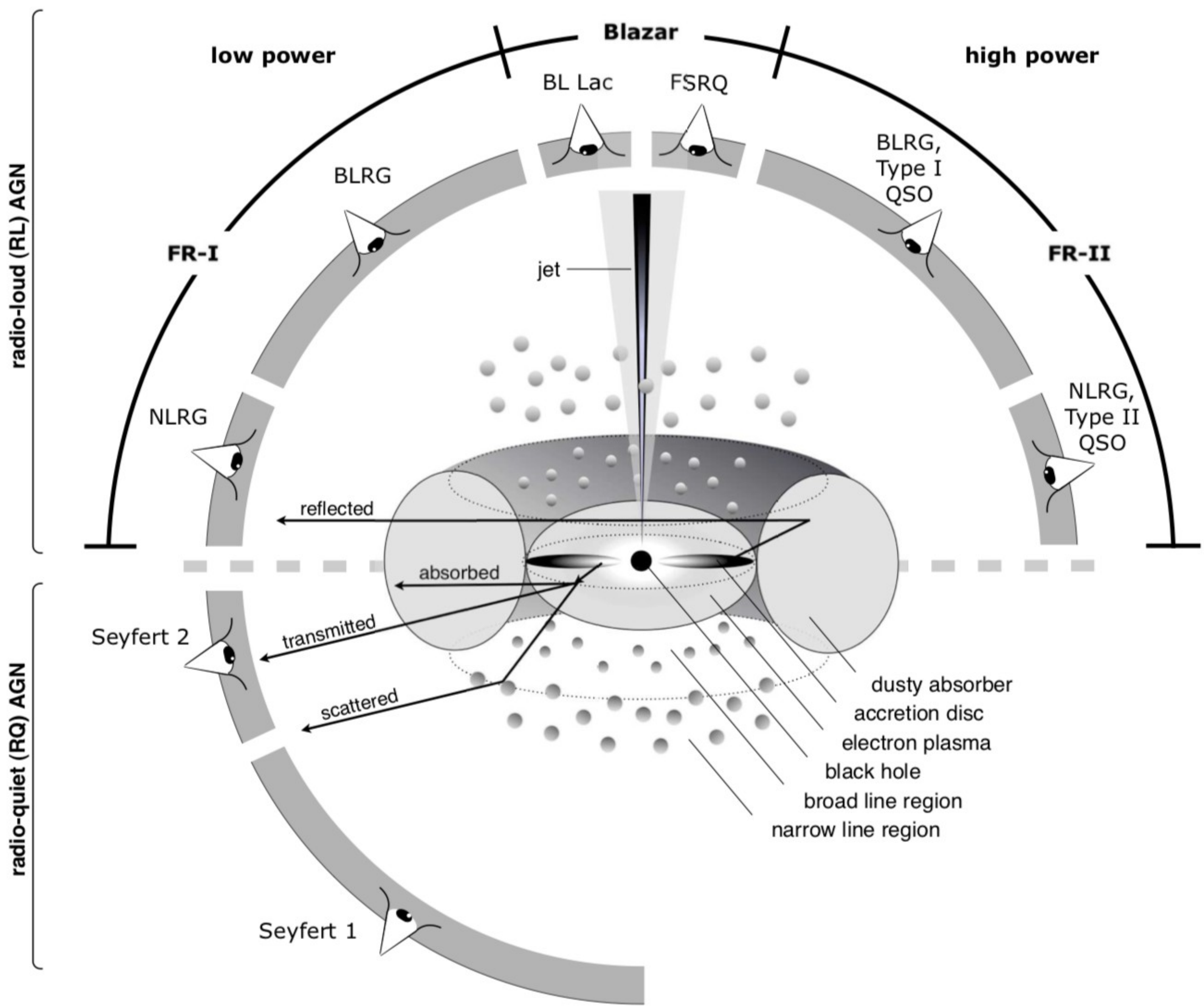
1968 associated with radio source.
AGN at z = 0.07

Whole Earth Blazar Telescope (WEBT) Very rapid variation



"BLAZARS" :

Quasars, BL-Lac Objects
Brightests, most variable AGN
(jets pointing to observer)



radio-loud (RL) AGN
radio-quiet (RQ) AGN
low power
Blazar
high power
BL Lac
FSRQ
BLRG
BLRG,
Type I
QSO
FR-I
FR-II
jet
NLRG
NLRG,
Type II
QSO
reflected
absorbed
transmitted
scattered
Seyfert 2
Seyfert 1
dusty absorber
accretion disc
electron plasma
black hole
broad line region
narrow line region

Observations of M87

2005
2008
2010

HESS
MAGIC
VERITAS

$E \geq 350$ GeV

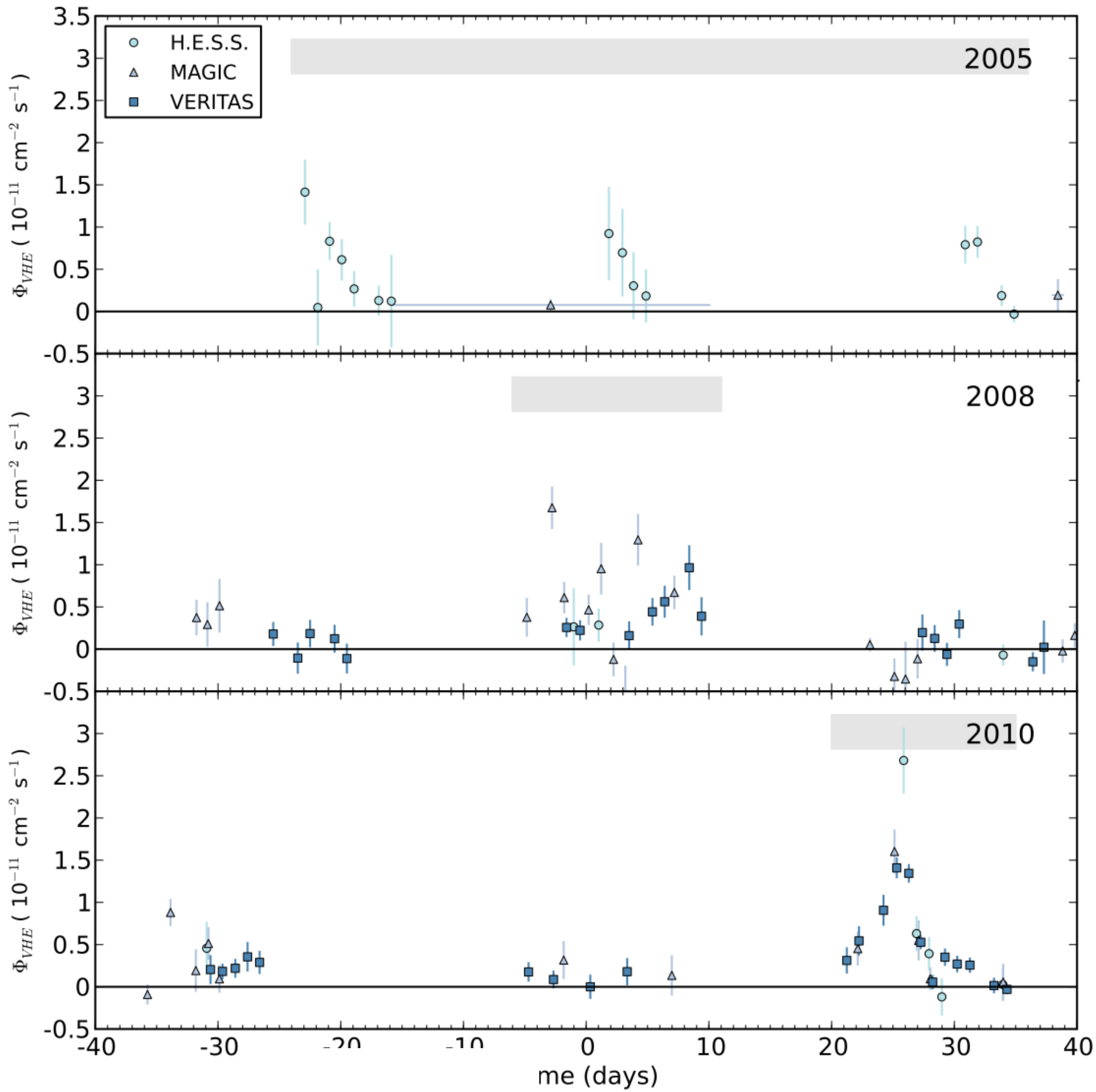
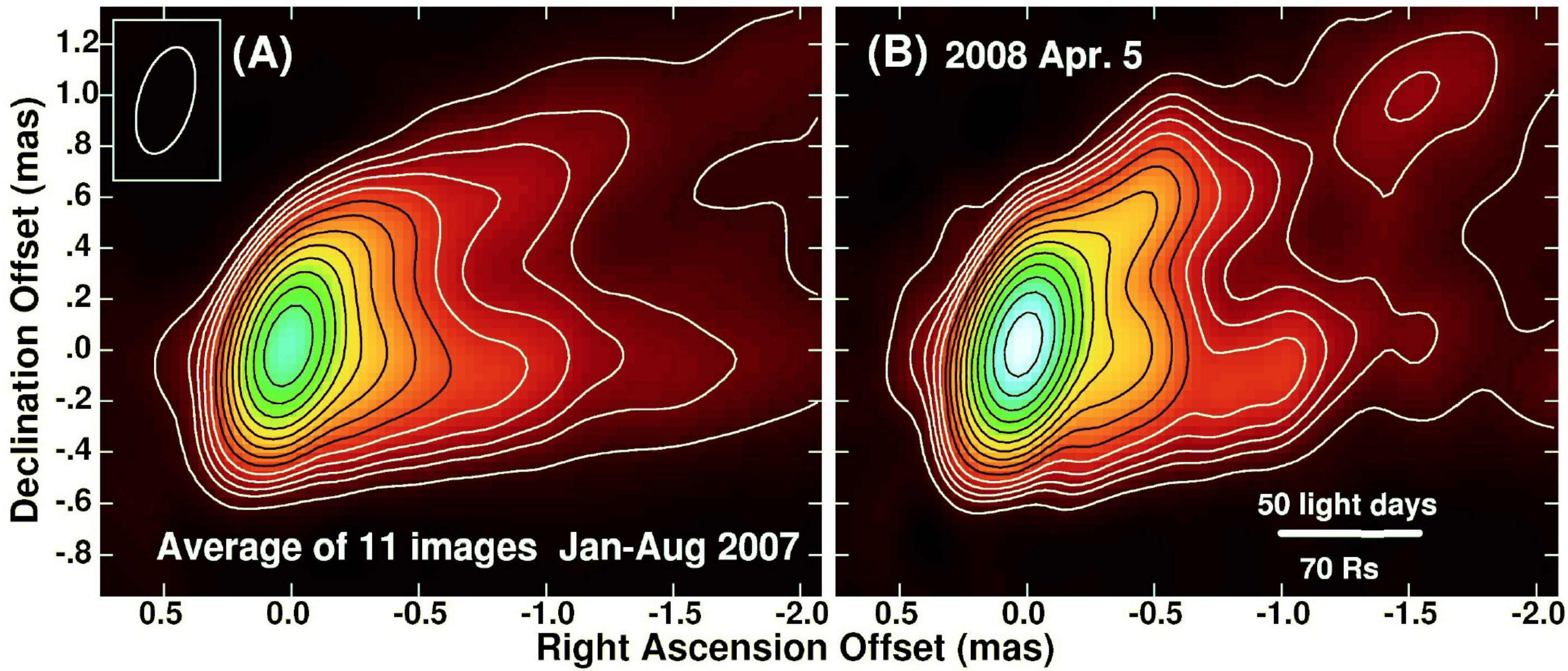
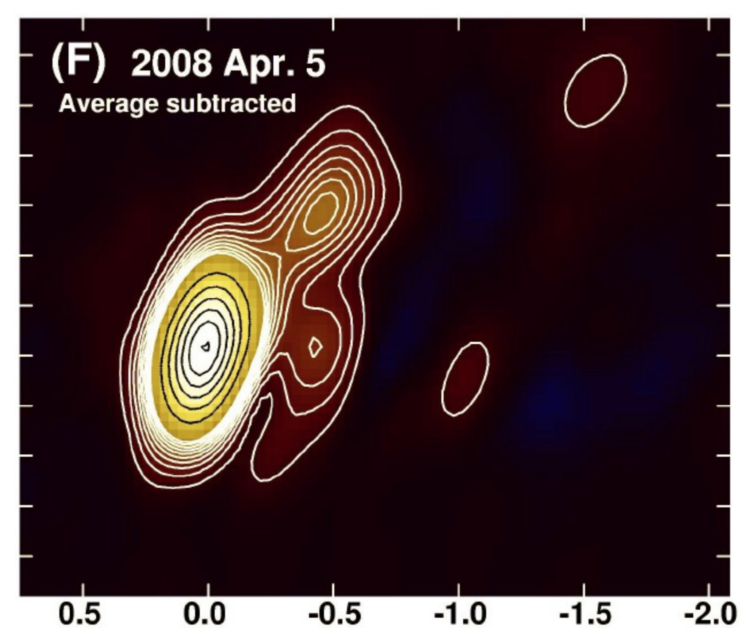


Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500,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



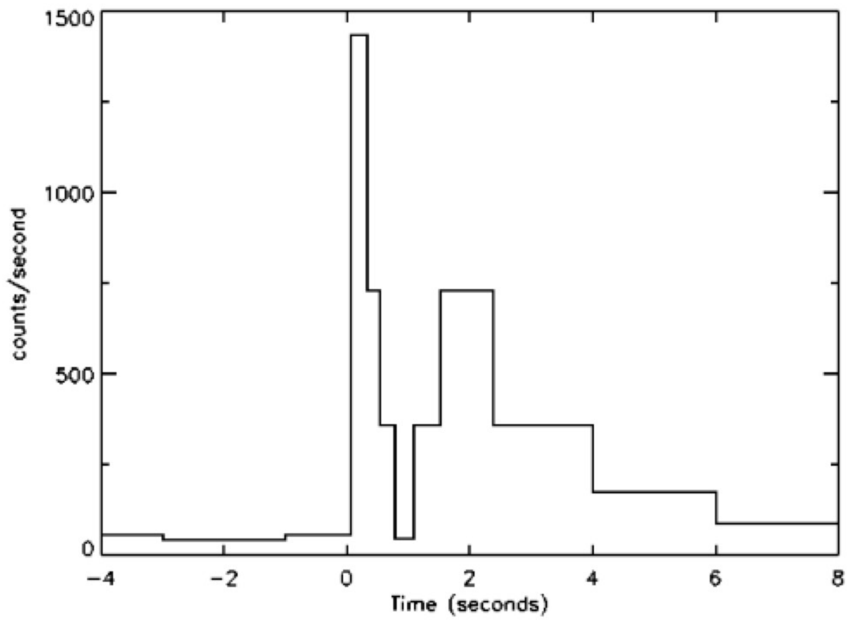
Science 24 Jul 2009:
Vol. 325, Issue 5939, pp. 444-448
DOI: 10.1126/science.1175406

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

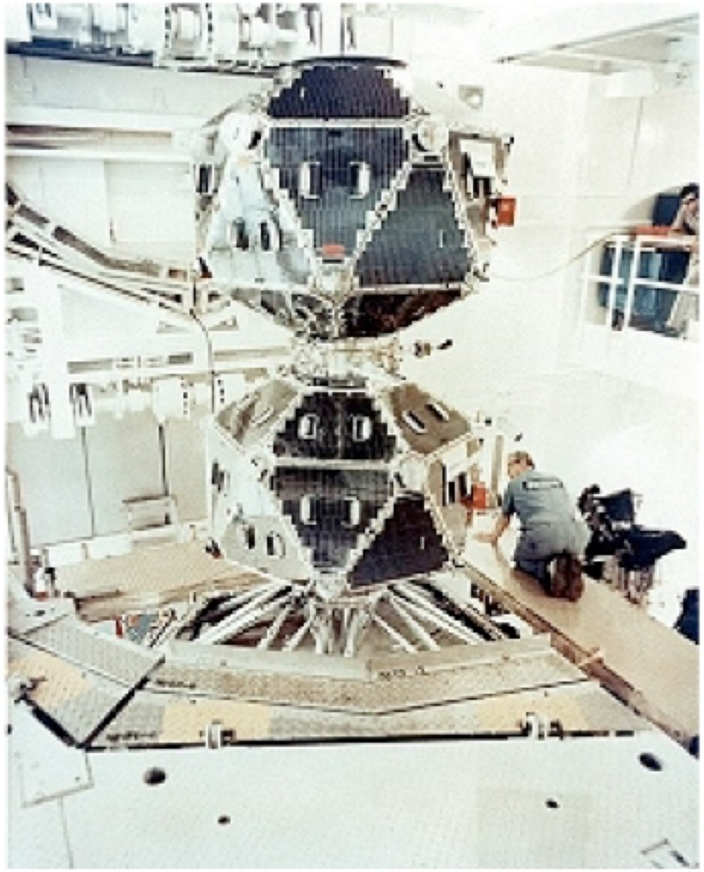
The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration

Gamma Ray Bursts (GRB)

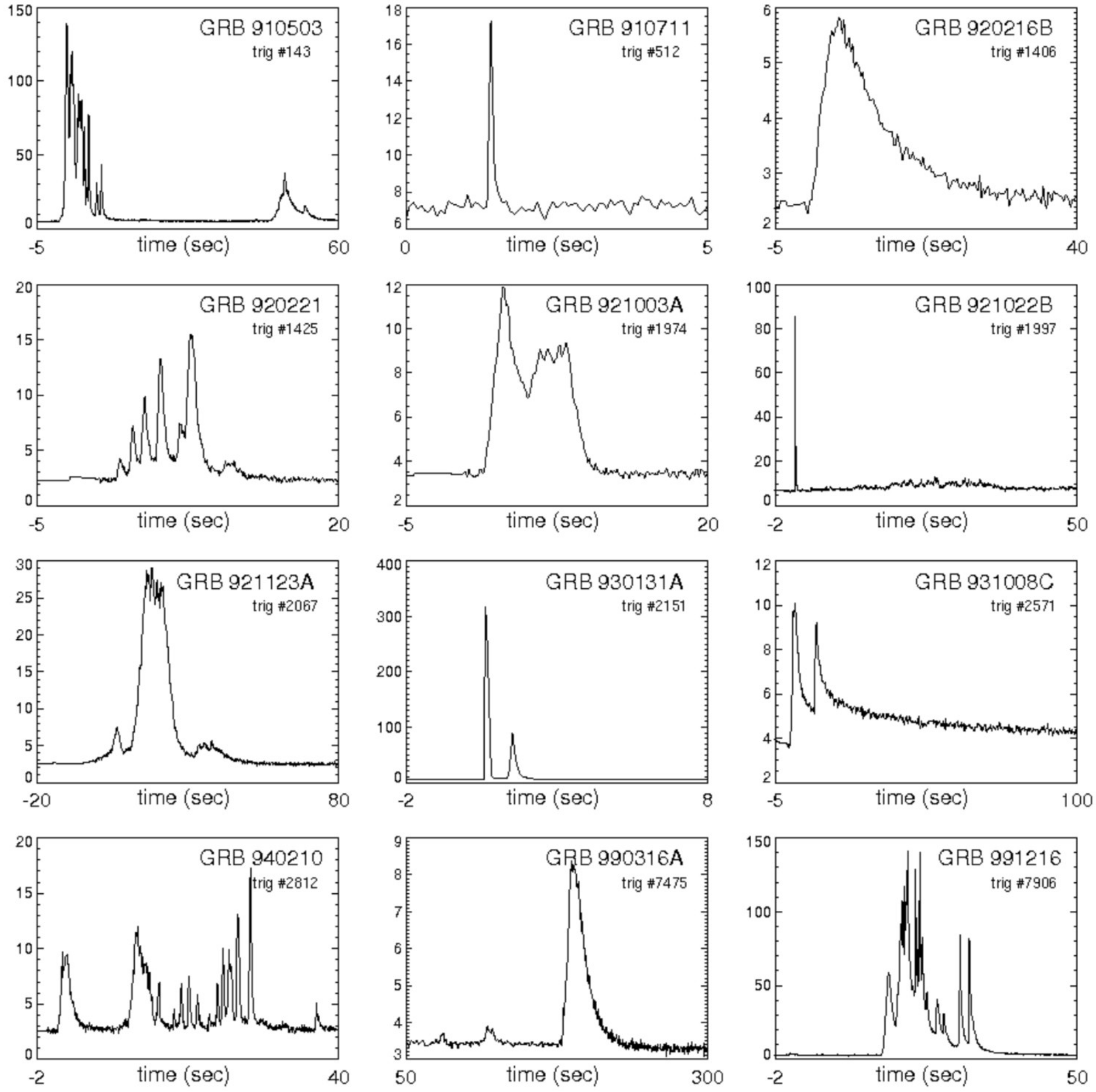
1st GRB 2nd July 1967

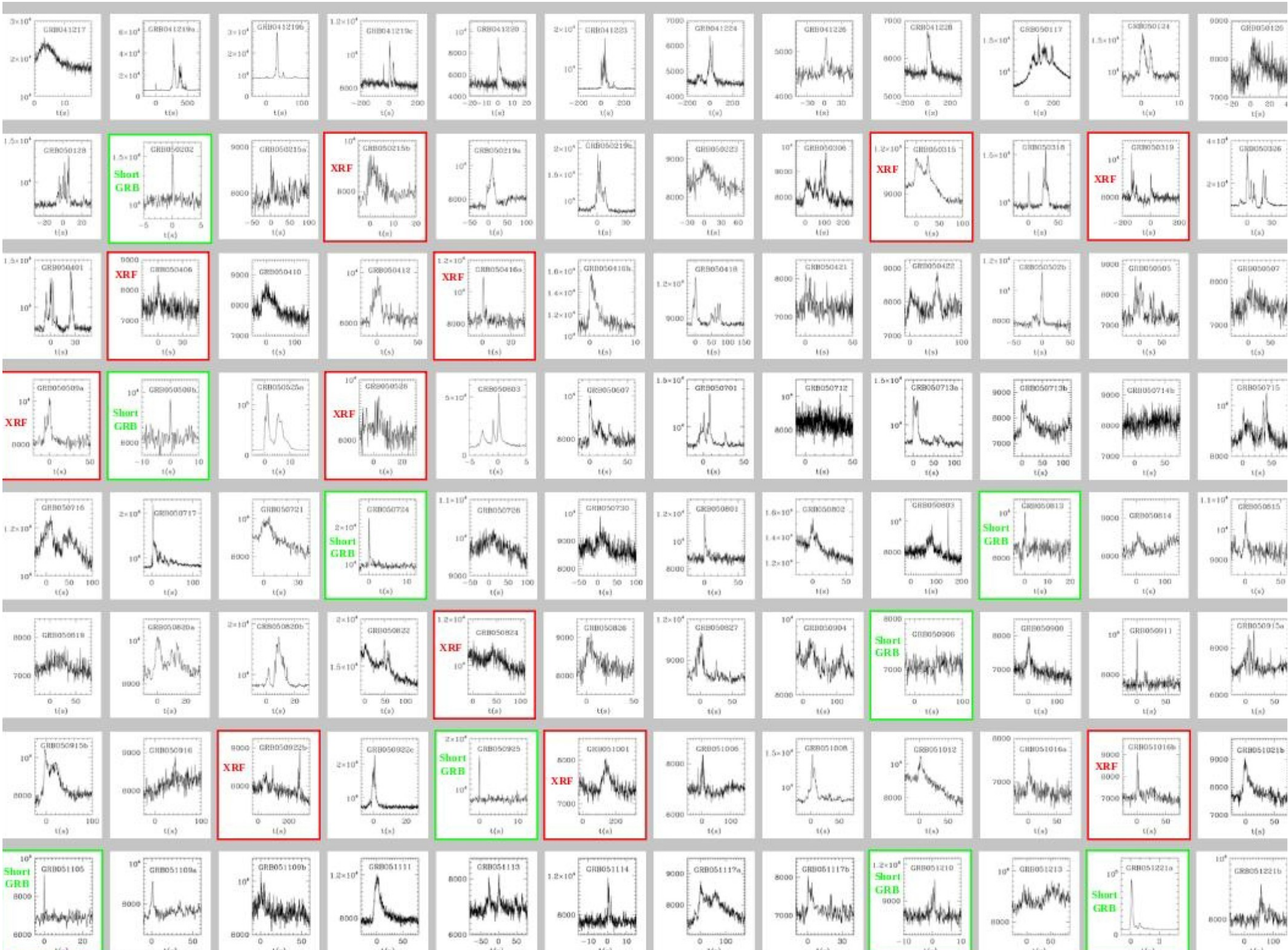


VELA satellite



Examples of GRB time profiles (from BATSE 1991-2000)

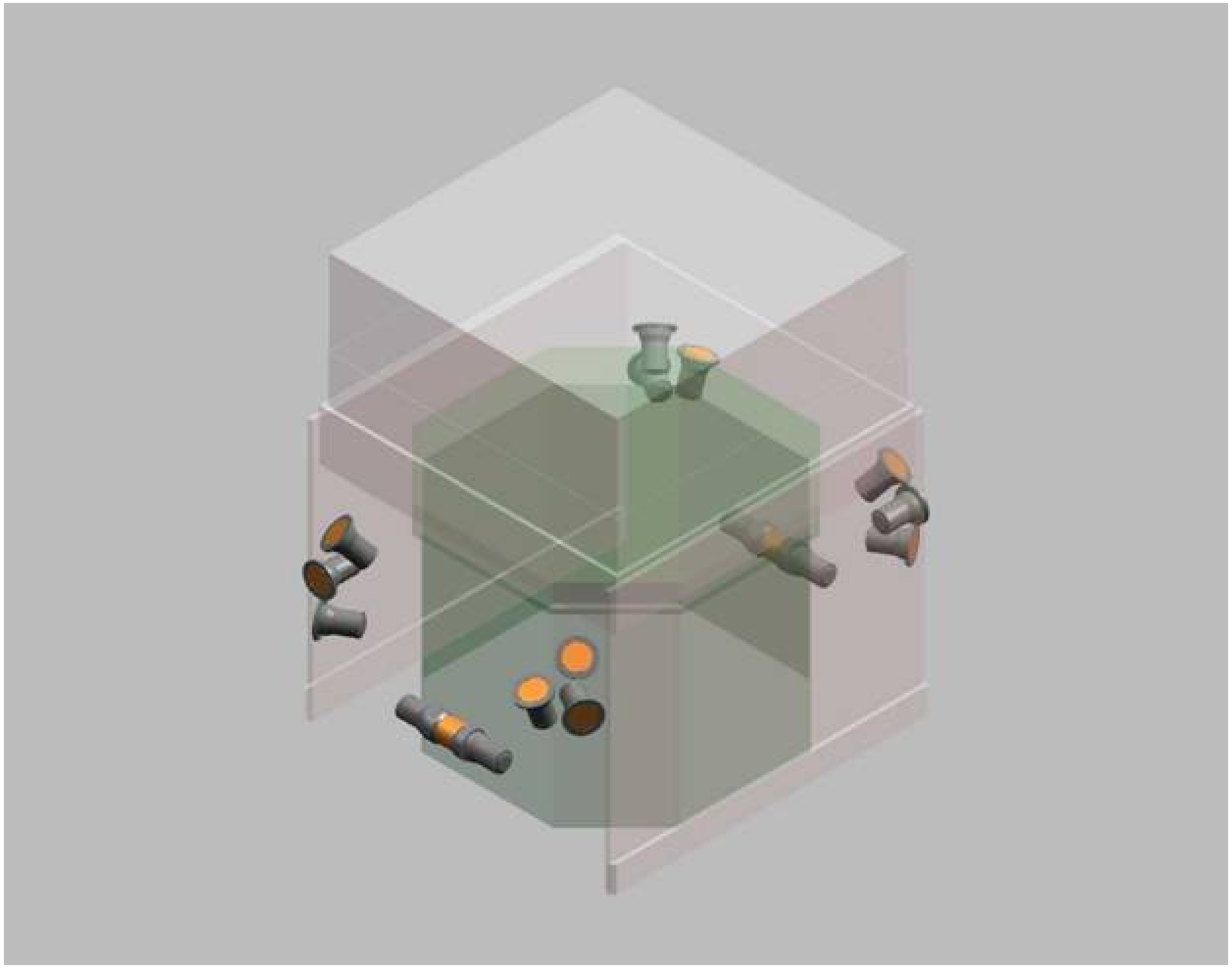




[From N. Gehrels]

Fermi Telescope

Gamma Burst Monitor (GBM)

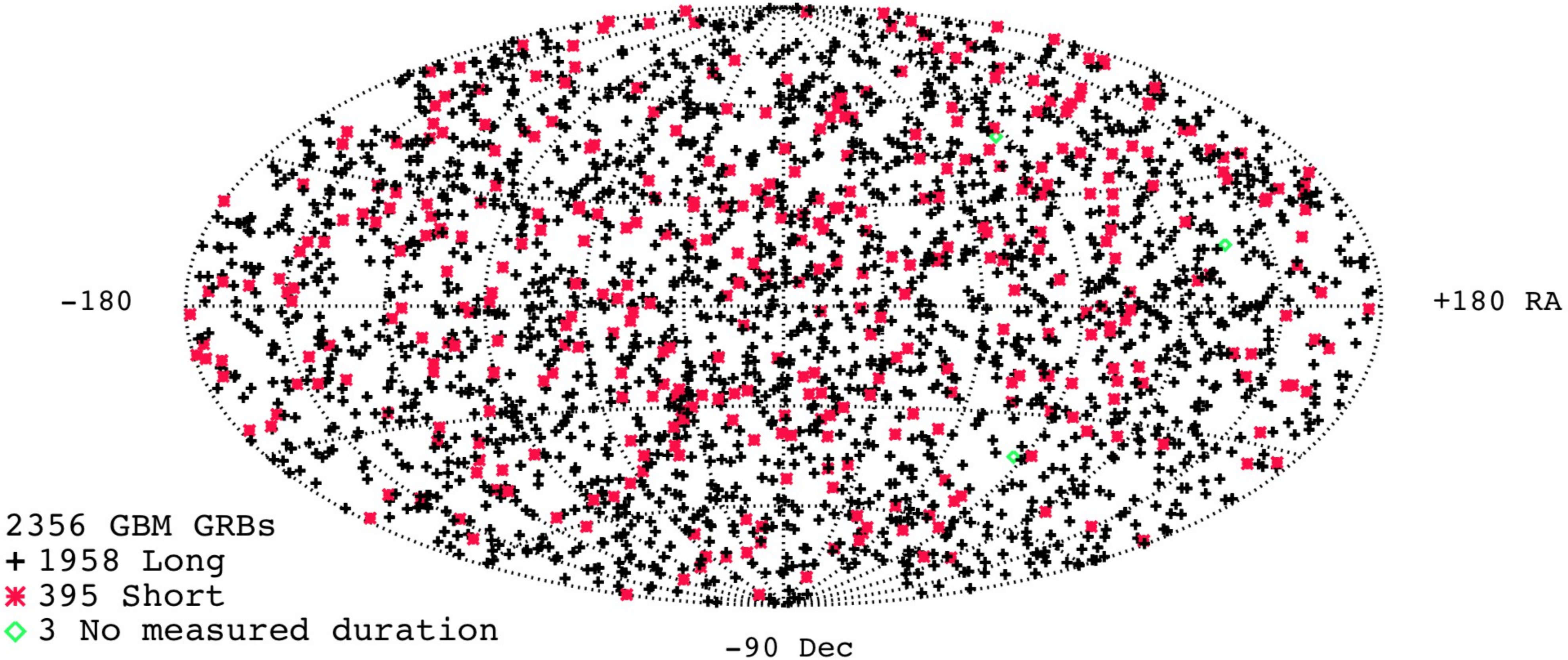


Direction of burst from comparison of rates of different detectors

12 NaI scintillators (10 KeV – 1 MeV)
2 BGO scintillators (150 KeV - 30 MeV)

FERMI satellite Gamma Ray Burst Monitor (GBM)

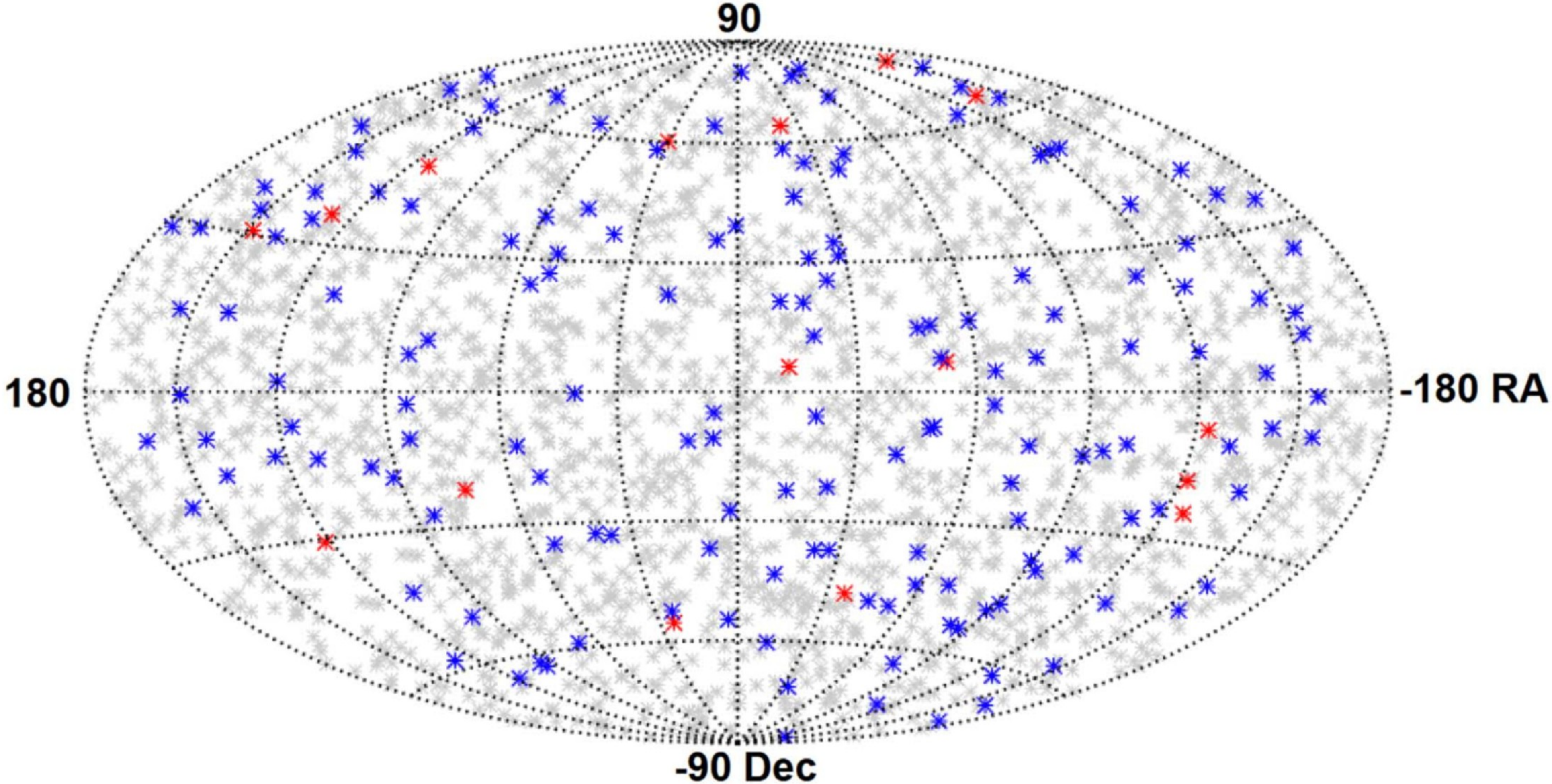
10 years catalog 1998-2008 [50-300 KeV]



Isotropic distribution

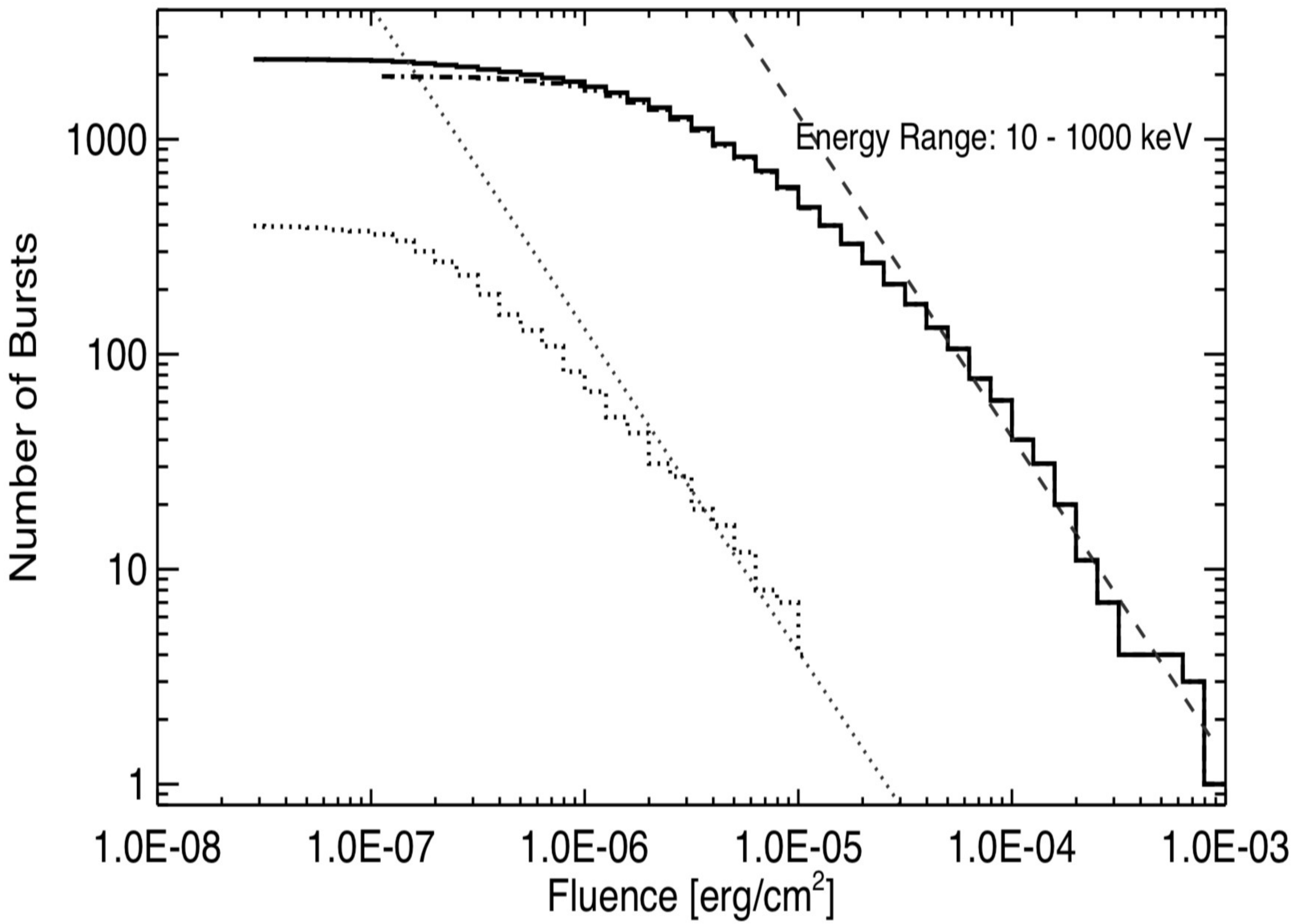
2nd FERMI-LAT GRB catalog (2008/ July/14 – 2018/July/31)

[0.1 – 100 GeV]

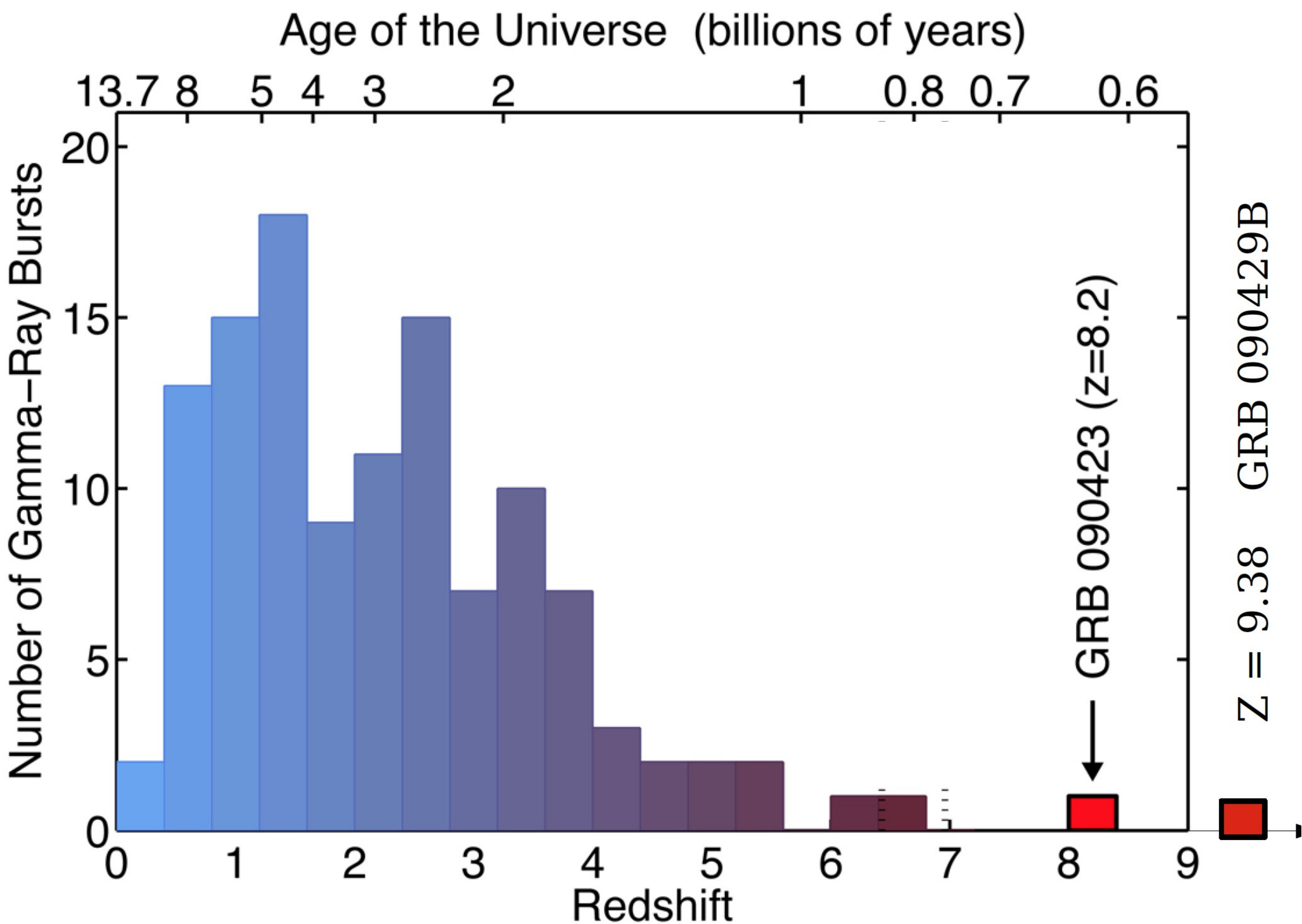


2357 GBM GRBs (gray asterisks)

(160 + 16) long (short) LAT-detected GRB

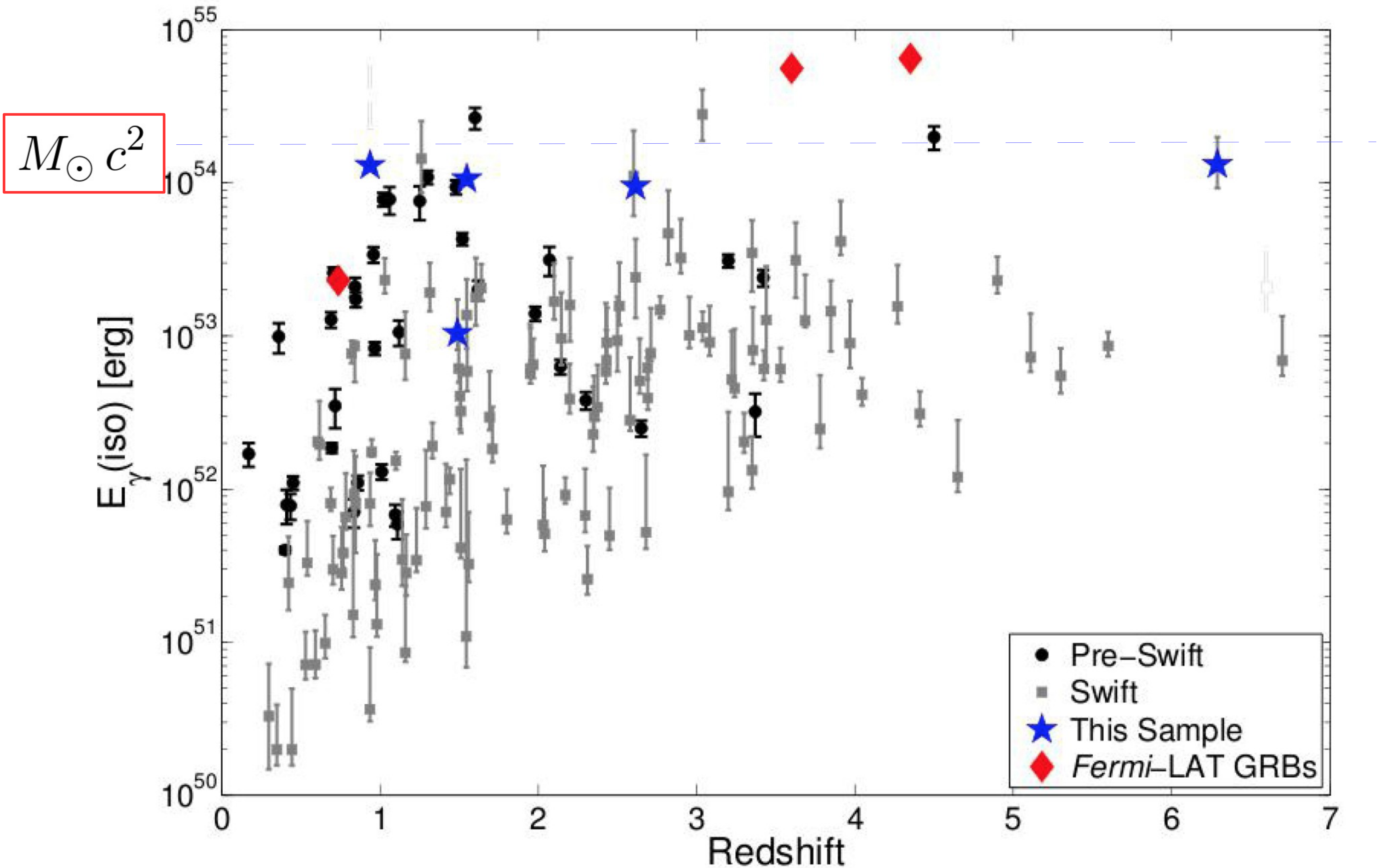


Energy Range: 10 - 1000 keV
1000
100
10
1
Number of Bursts
1.0E-08
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
Fluence [erg/cm2]



Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma–Ray Bursts
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
Redshift
GRB 090423 (z=8.2)
GRB 090429B
Z = 9.38

Extraordinary Large (beamed) Energy Output



GRB 130427A

Science

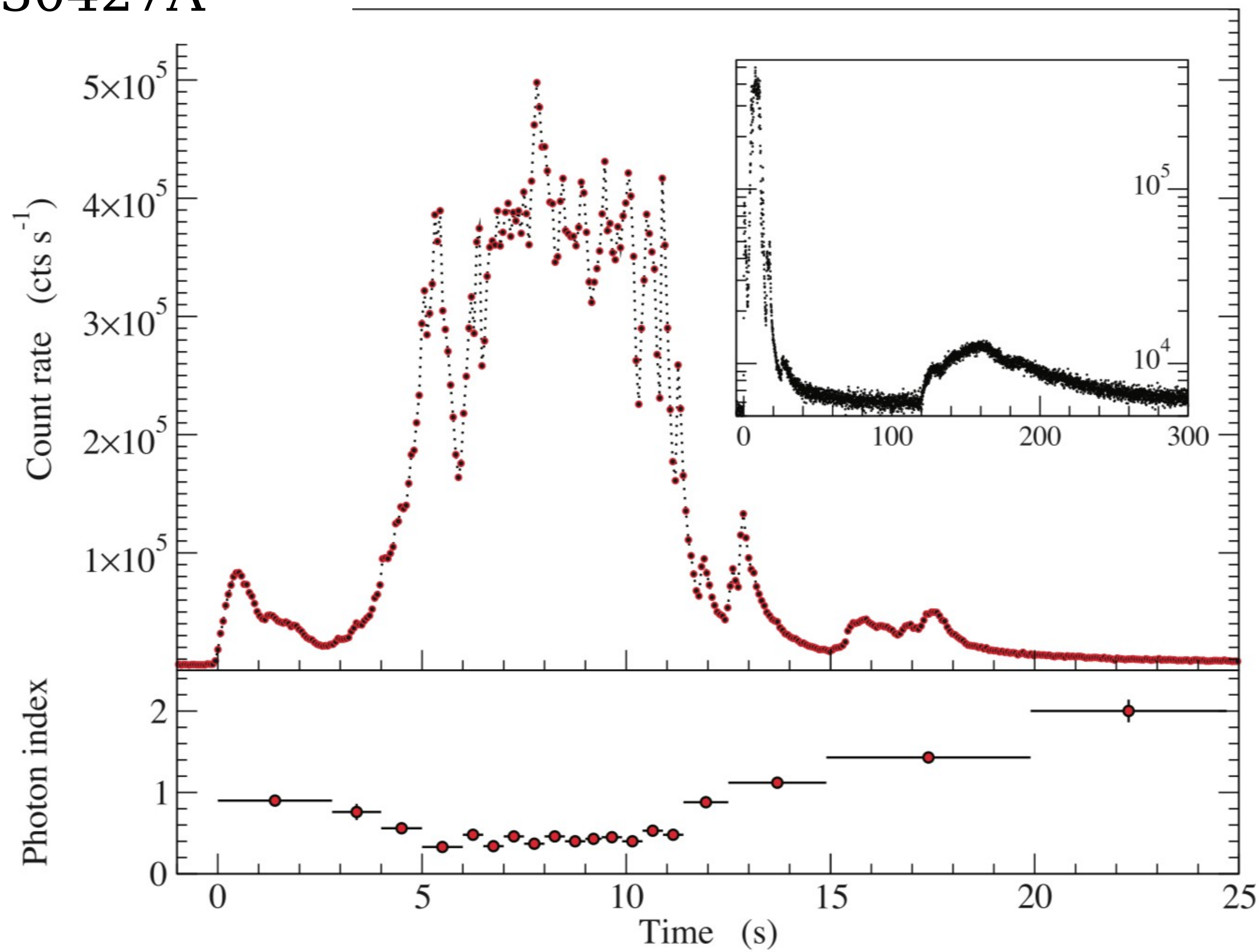
3rd January 2014

GRB 130427A: A Nearby Ordinary Monster

Fermi paper lower limit on Lorentz Factor of outflow

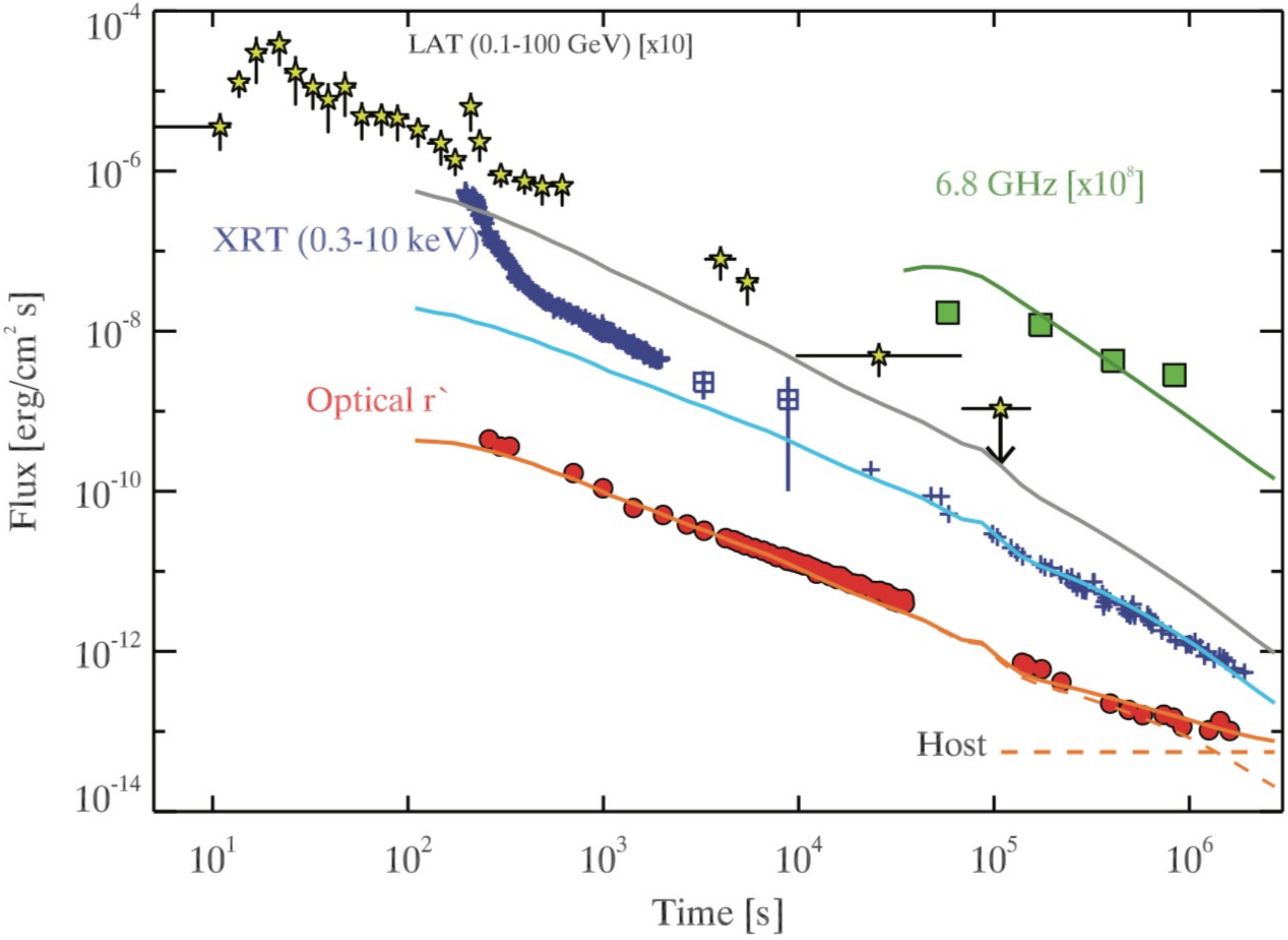
$$\Gamma_{\rm min} = 455^{+16}_{-13}$$

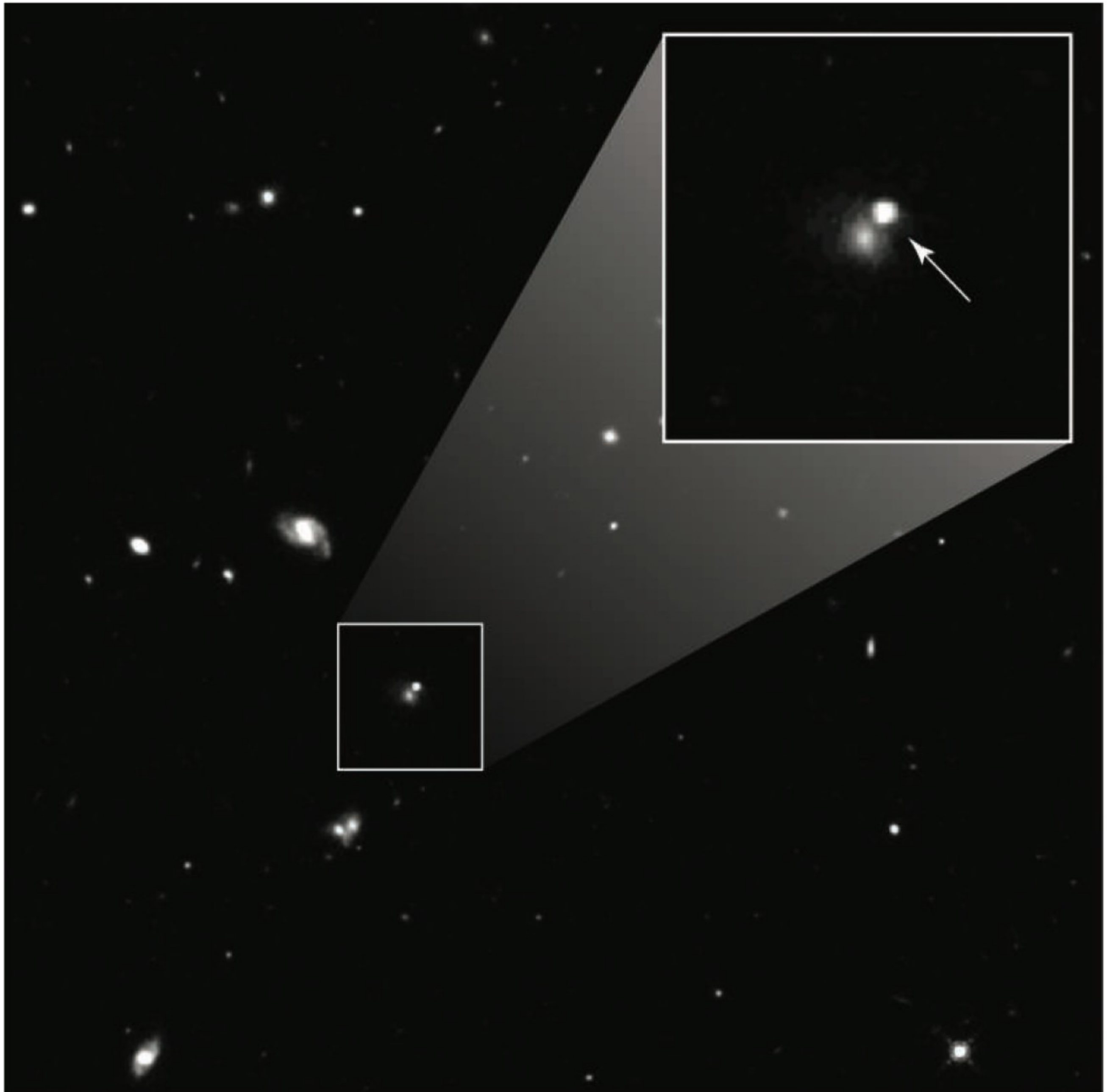
GRB 130427A



Time profile [SWIFT (Bat)] [15-350 keV]

Afterglow of GRB 130427A





Hubble
Space Telescope

Detection
of SN 2013 cq
and its host galaxy

[at z = 0.3399]

GRB 0.83''
from center if Galaxy
(4 kpc)

Why do we think that GRB are "jet like" with a very large relativistic velocity ?

$\Delta t_{\rm obs}$ Duration

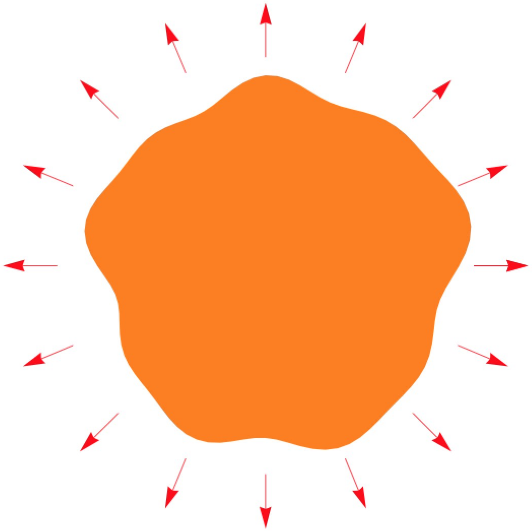
$\mathcal{F}$ energy fluence

$\mathrm{erg}/(\mathrm{cm}^2\,\mathrm{s})$

GRB event
(assume no beaming)

size of source

$$R \simeq \Delta t_{\rm obs}\, c$$



At the "explosion" time
enormous photons density in source

$$n_\gamma \approx \frac{4\,\pi\, d^2\;\mathcal{F}}{\langle \varepsilon \rangle}\;\frac{1}{R^3}$$

The source is not transparent

Opacity $\tau \approx R\, n_\gamma\, \sigma_{\gamma\gamma} \approx \dfrac{4\,\pi\, d^2\;\mathcal{F}}{\langle\varepsilon\rangle\;(\Delta t_{\rm obs}\, c)^2}\;\sigma_{\gamma\gamma}$

Parameters of GRB139427A $\tau \approx 10^{12}$

enormous opacity
system "thermalized"
with Black body emission

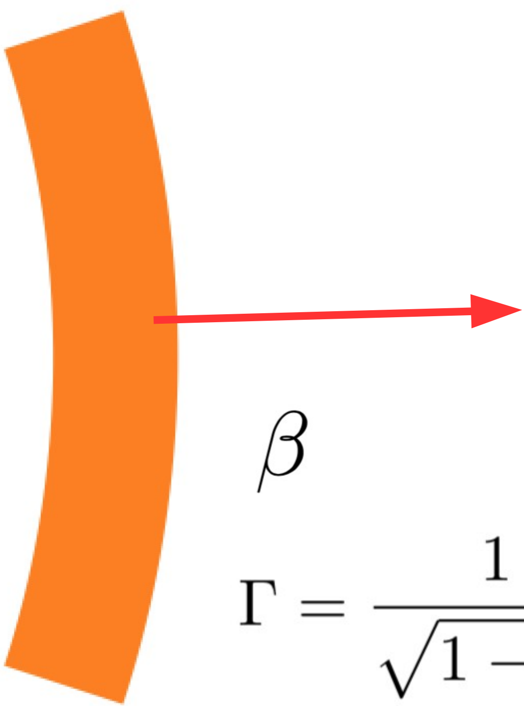
How can one reduce the opacity ? $\tau \lesssim 1$

$$\tau \approx \frac{4\,\pi\, d^2\ \mathcal{F}}{\langle\varepsilon\rangle\ (\Delta t\, c)^2}\ \sigma_{\gamma\gamma}$$

Relativistic beaming $\Gamma \gtrsim 1200$

$$(\Delta t)_{\rm obs} \simeq\ \Delta t\ (1-\beta) \approx \Delta t\ \frac{1}{2\Gamma^2}$$

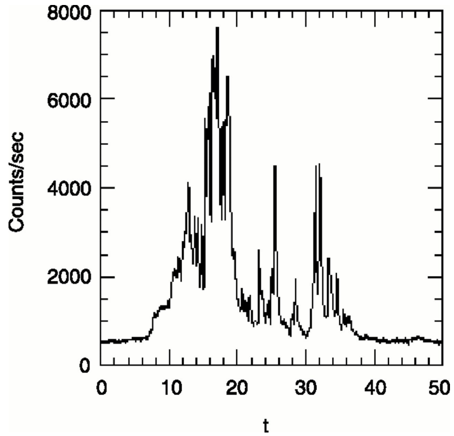
$$\Delta t_{\rm obs} \simeq 10\ \text{sec} \qquad\qquad \Delta t \gtrsim 1\ \text{yr}$$



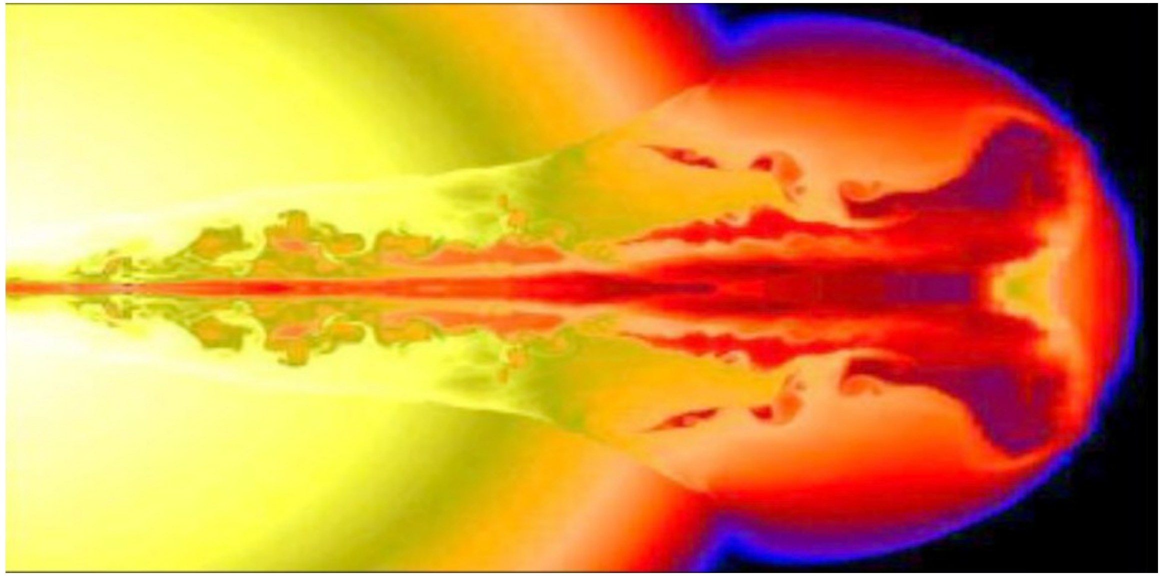
β

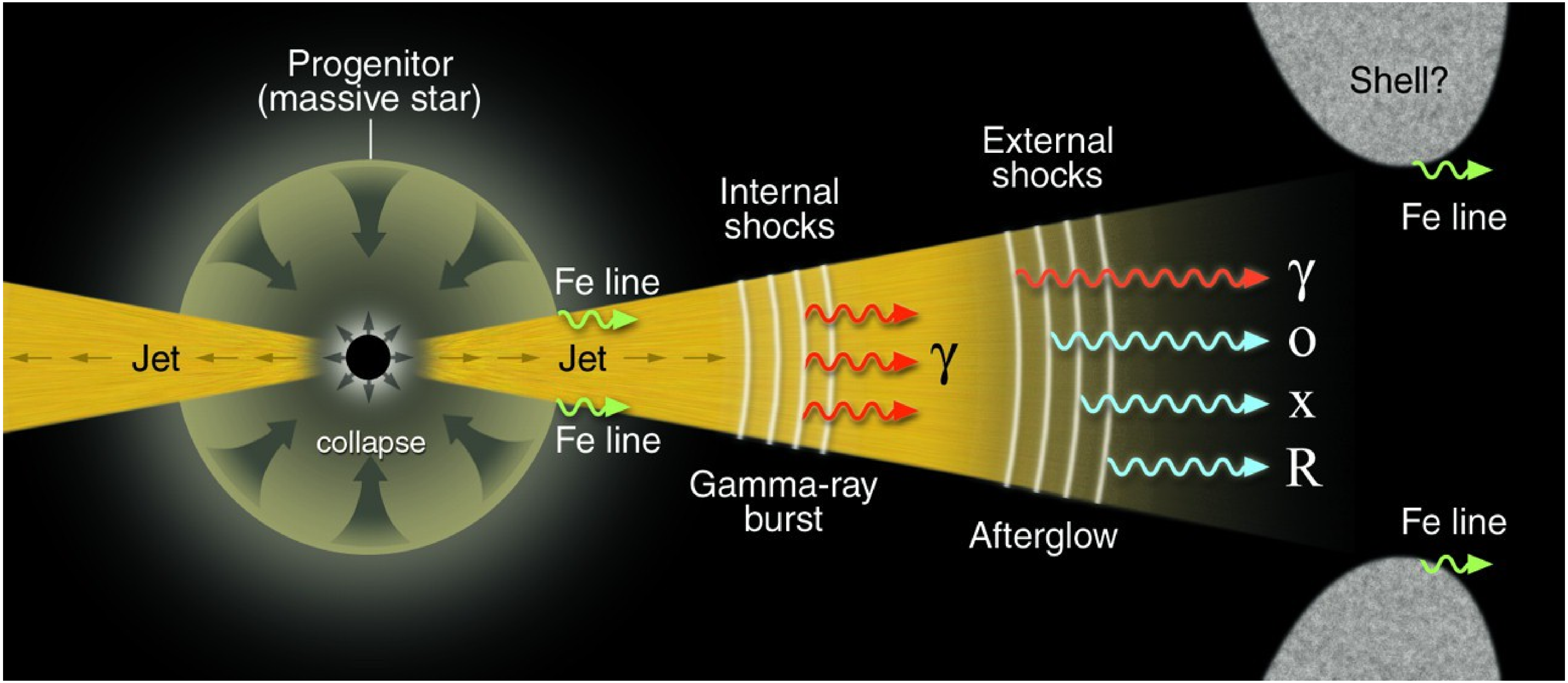
$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

[all energies in source frame
lower (fewer photons above threshold)



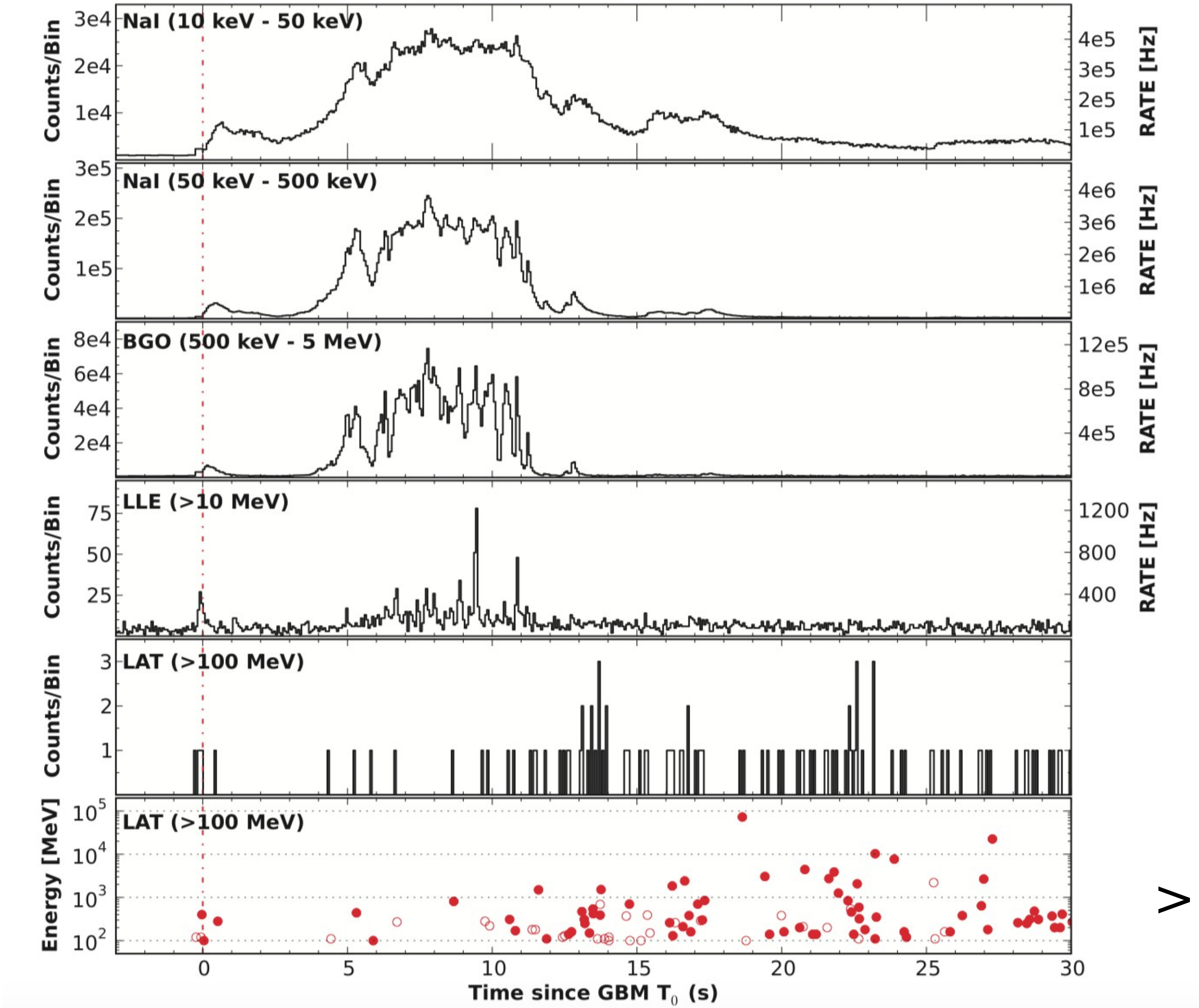
8000
6000
4000
2000
0
Counts/sec
0
10
20
30
40
50
t





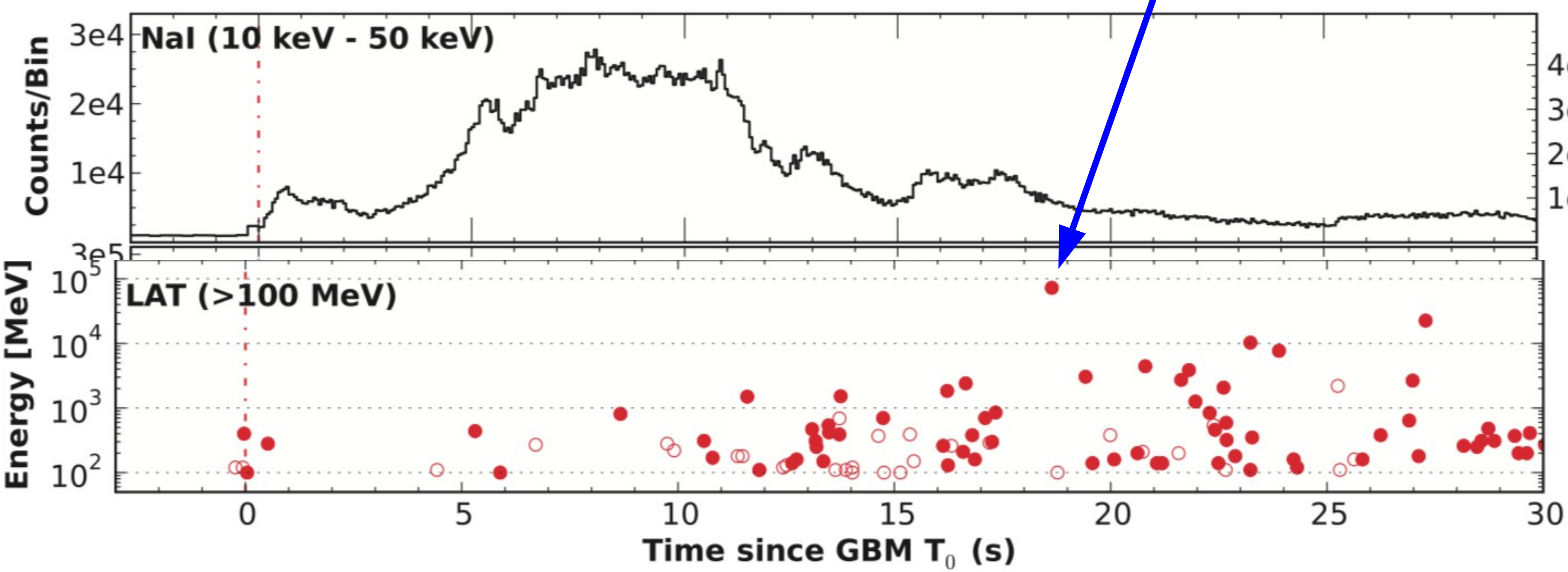
Progenitor
(massive star)
collapse
Jet
Jet
Fe line
Fe line
Internal shocks
Gamma-ray burst
γ
External shocks
Afterglow
γ
o
x
R
Shell?
Fe line
Fe line

FERMI Observations of GRB 130427A

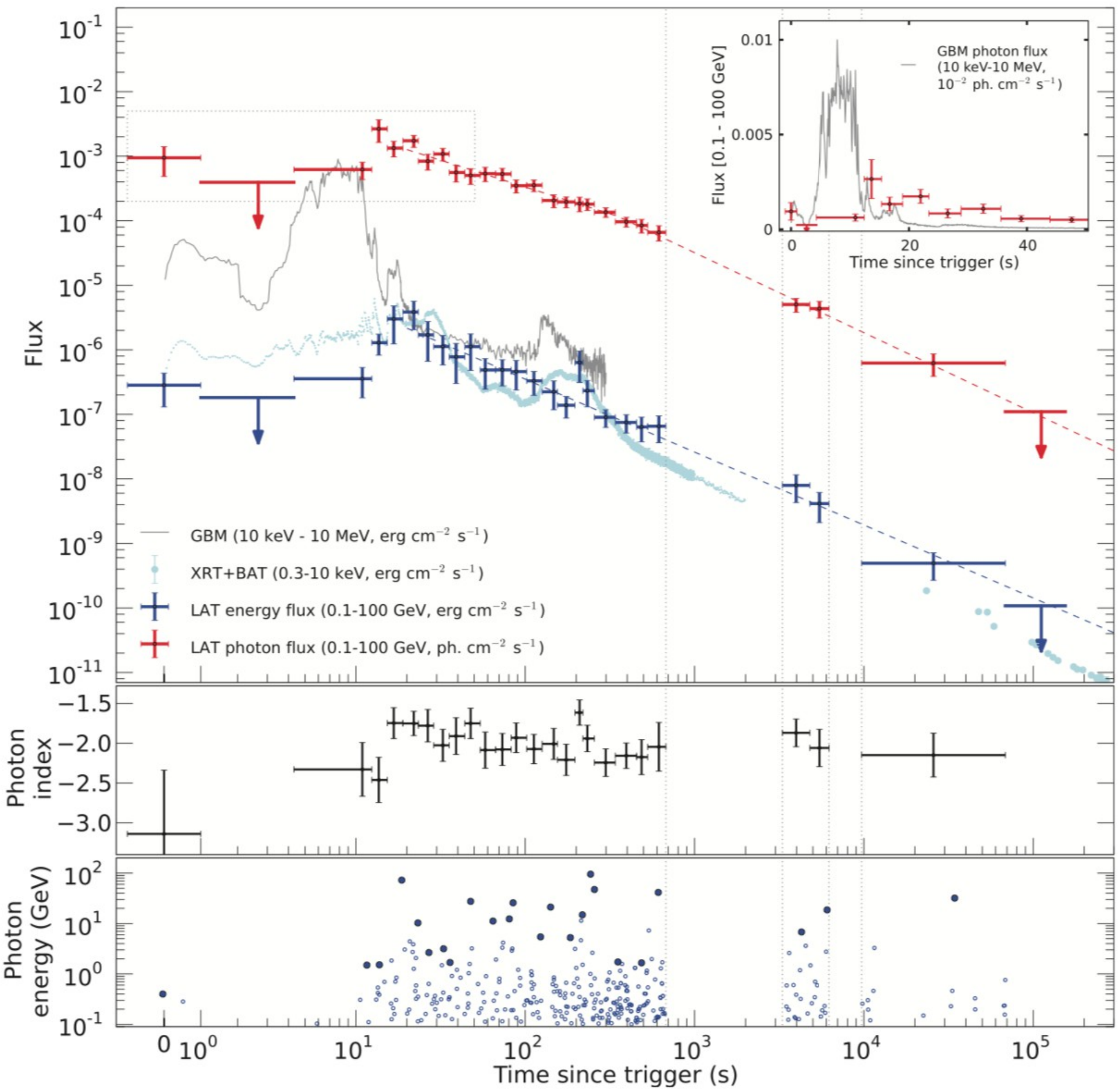


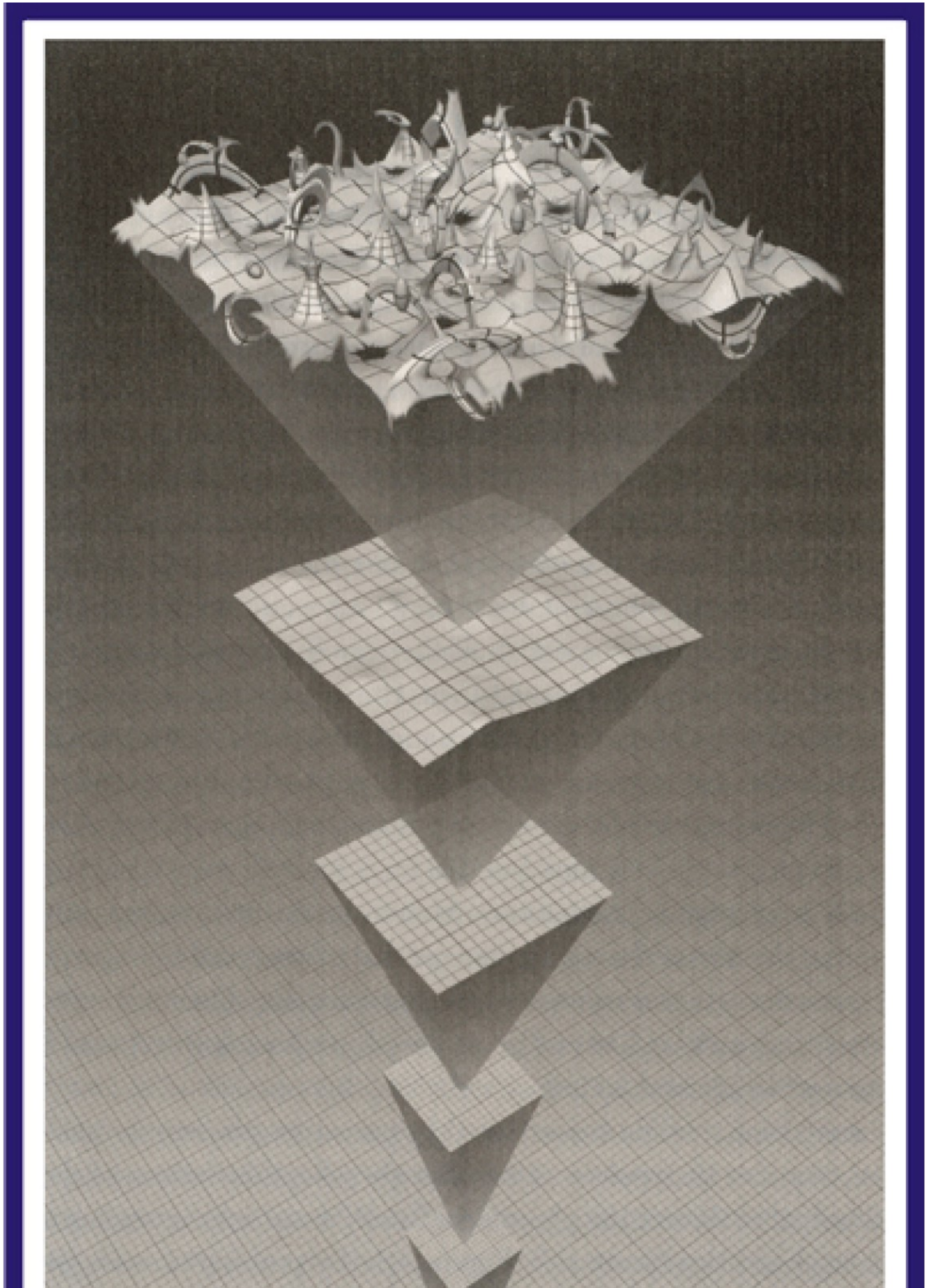
> 100 MeV

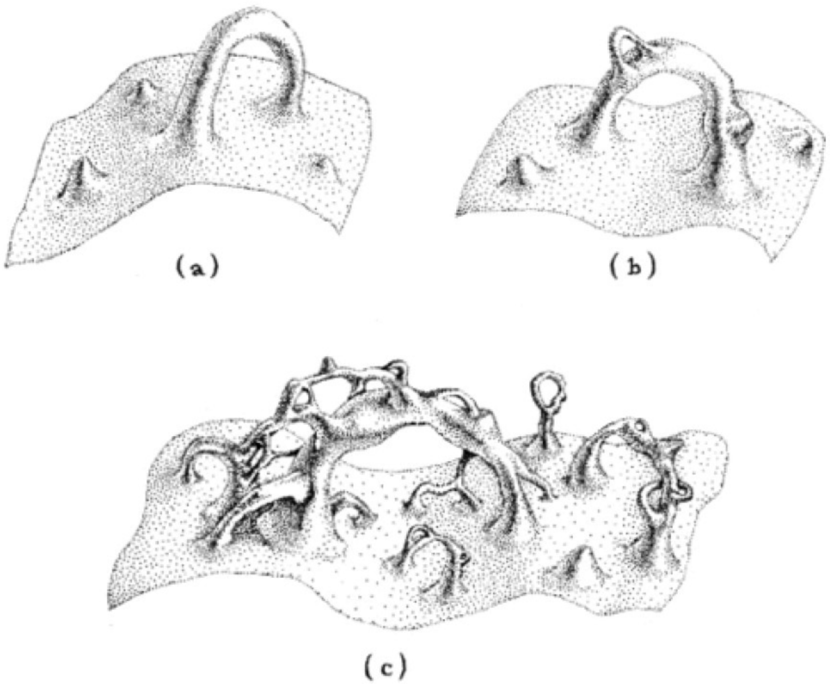
95 GeV photon
(at observation.
128 GeV at the source)



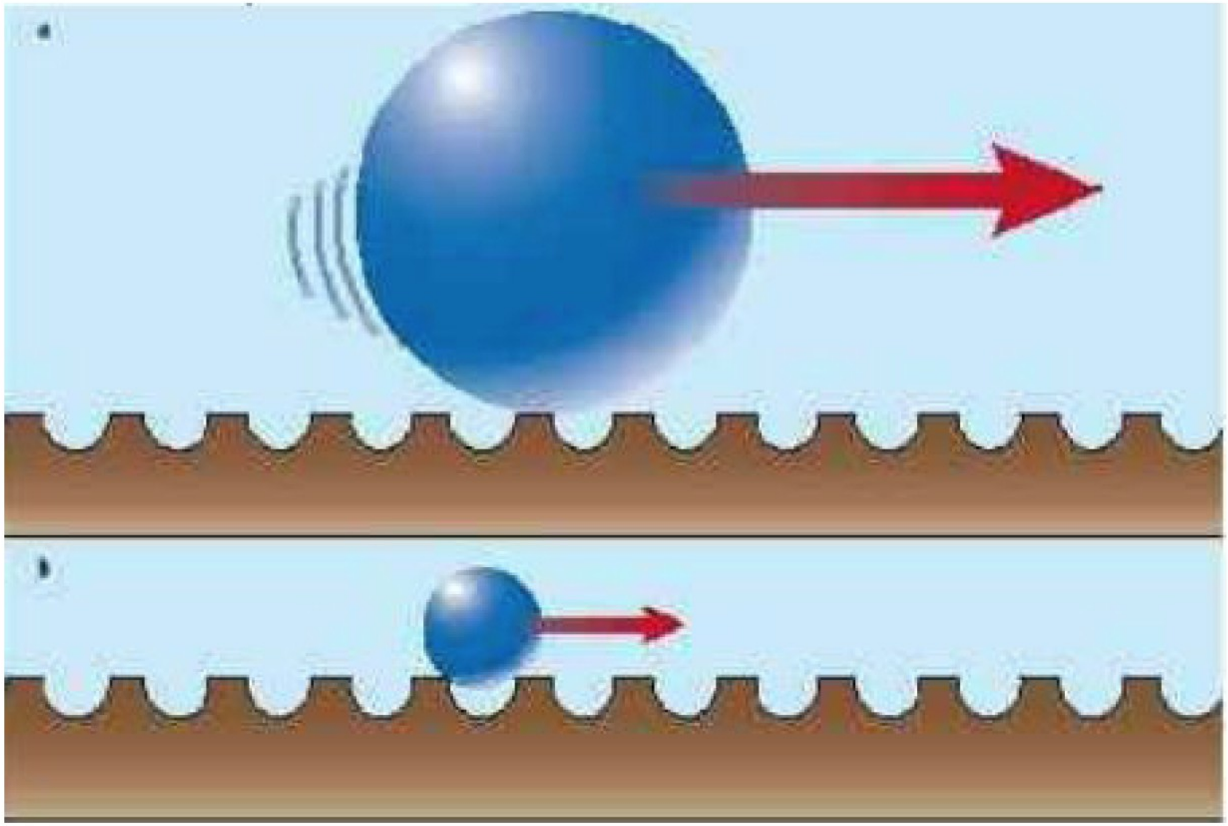
Fermi Observations during Afterglow







Quantum Gravity effects
[space-time granularity]



$$E_{\text{Planck}} = \sqrt{\frac{\hbar\, c^5}{G_{\text{Newton}}}}$$

$$\simeq 1.22 \times 10^{19}\ \text{GeV}$$

$$L_{\text{Planck}} = \frac{\hbar\, c}{E_{\text{Planck}}}$$

$$\simeq 1.62 \times 10^{-33}\ \text{cm}$$

$$v_\gamma \simeq c\ \left(1 - \xi\, \frac{E}{E_{\text{Planck}}} + \ldots\right)$$

$$v_\gamma \simeq c\ \left(1 - \frac{E}{E_{\text{QG}}} + \ldots\right)$$

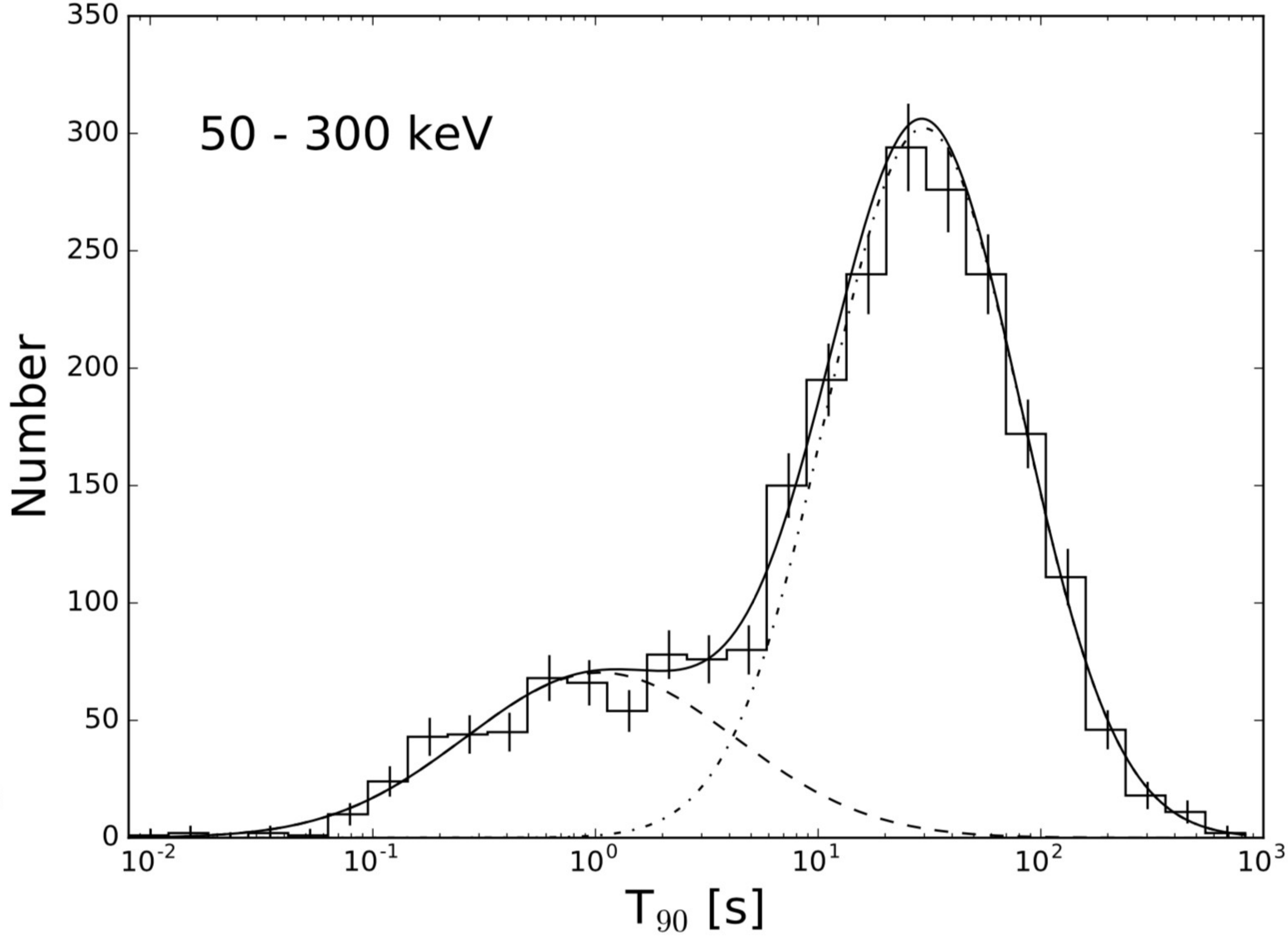
GBM time-duration distribution

T[90% of fluence]

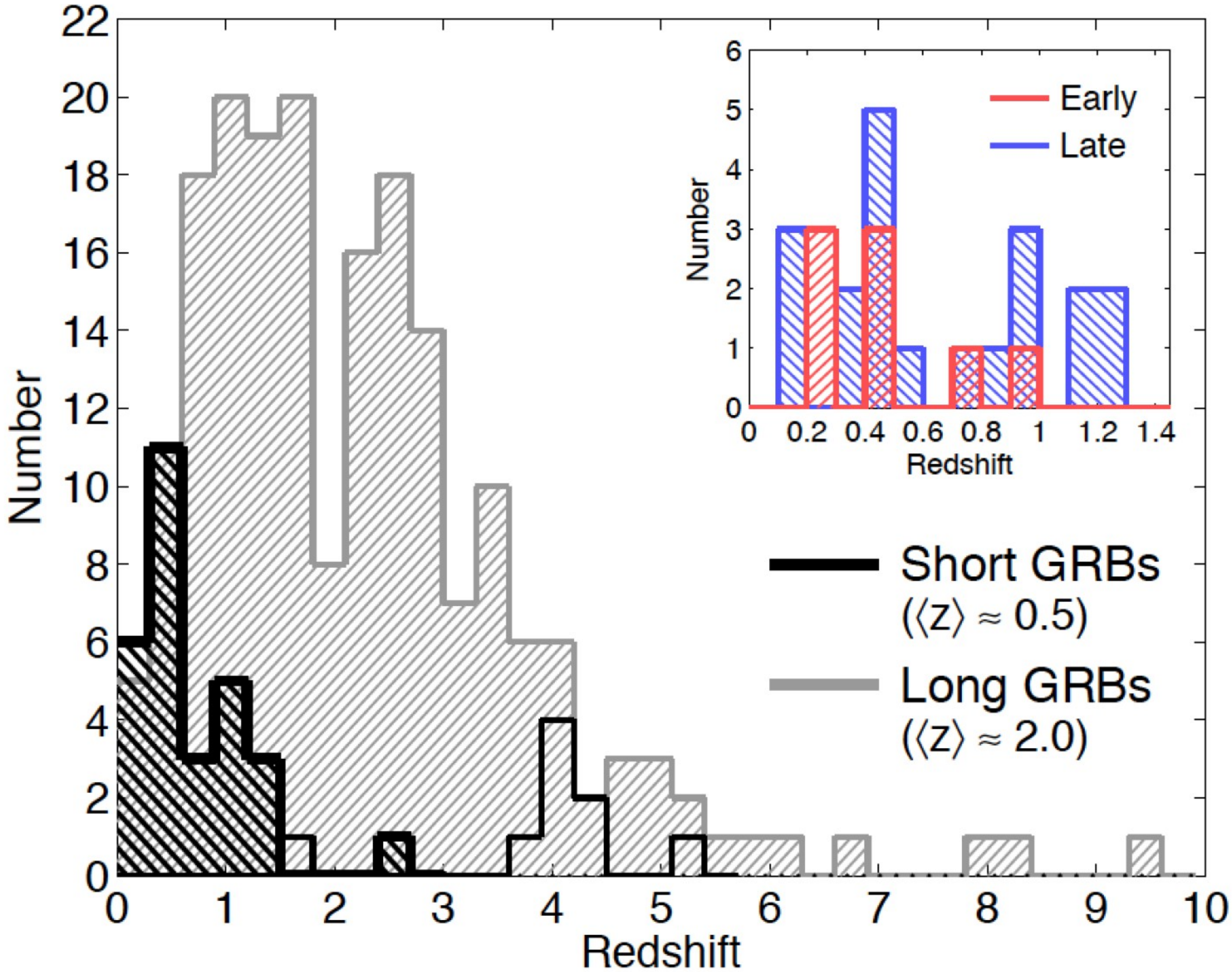
LogNormal distribution fits

$$10^{\langle \log T \rangle} = 1.05 \text{ sec}$$

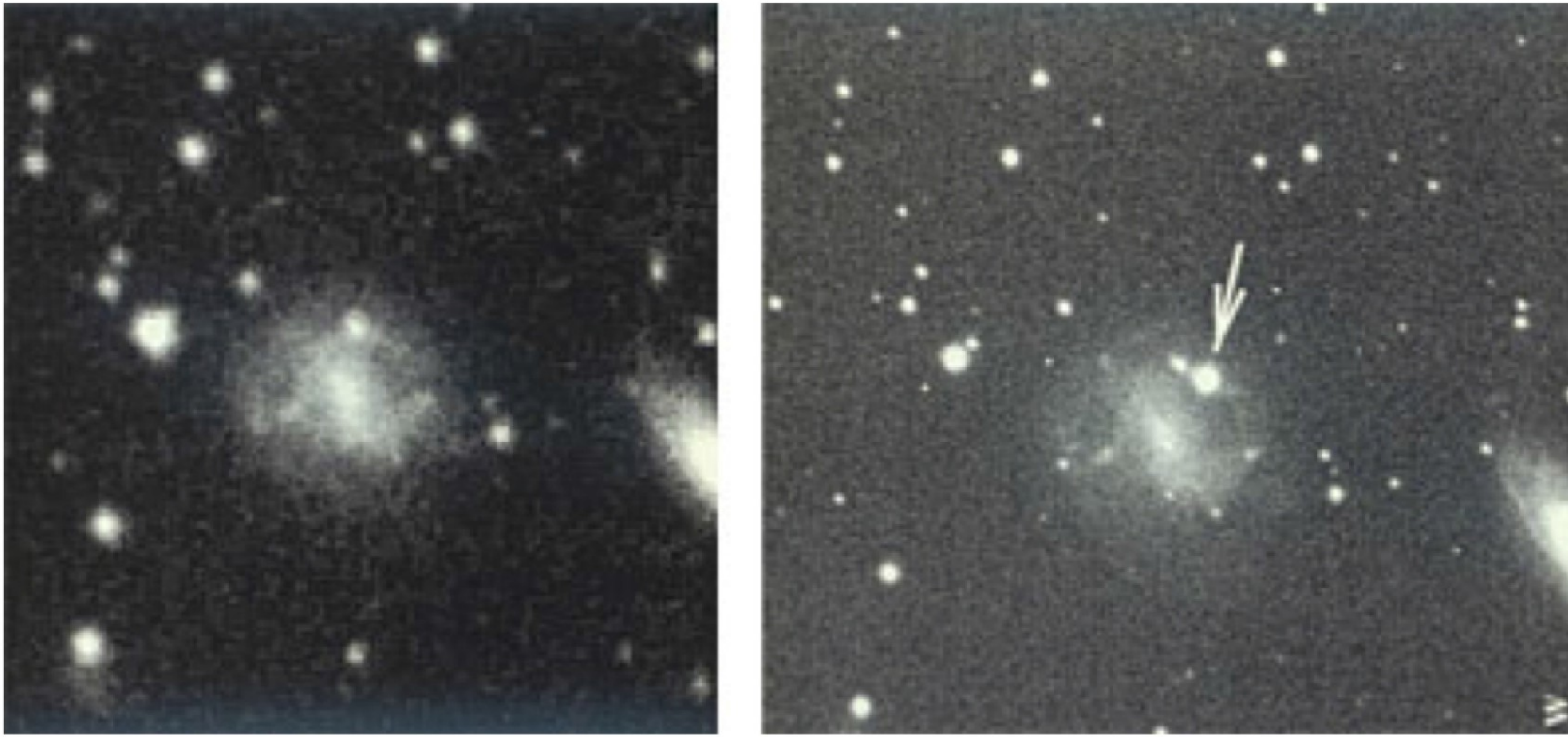
$$10^{\langle \log T \rangle} = 29.9 \text{ sec}$$



Short versus Long GRB's

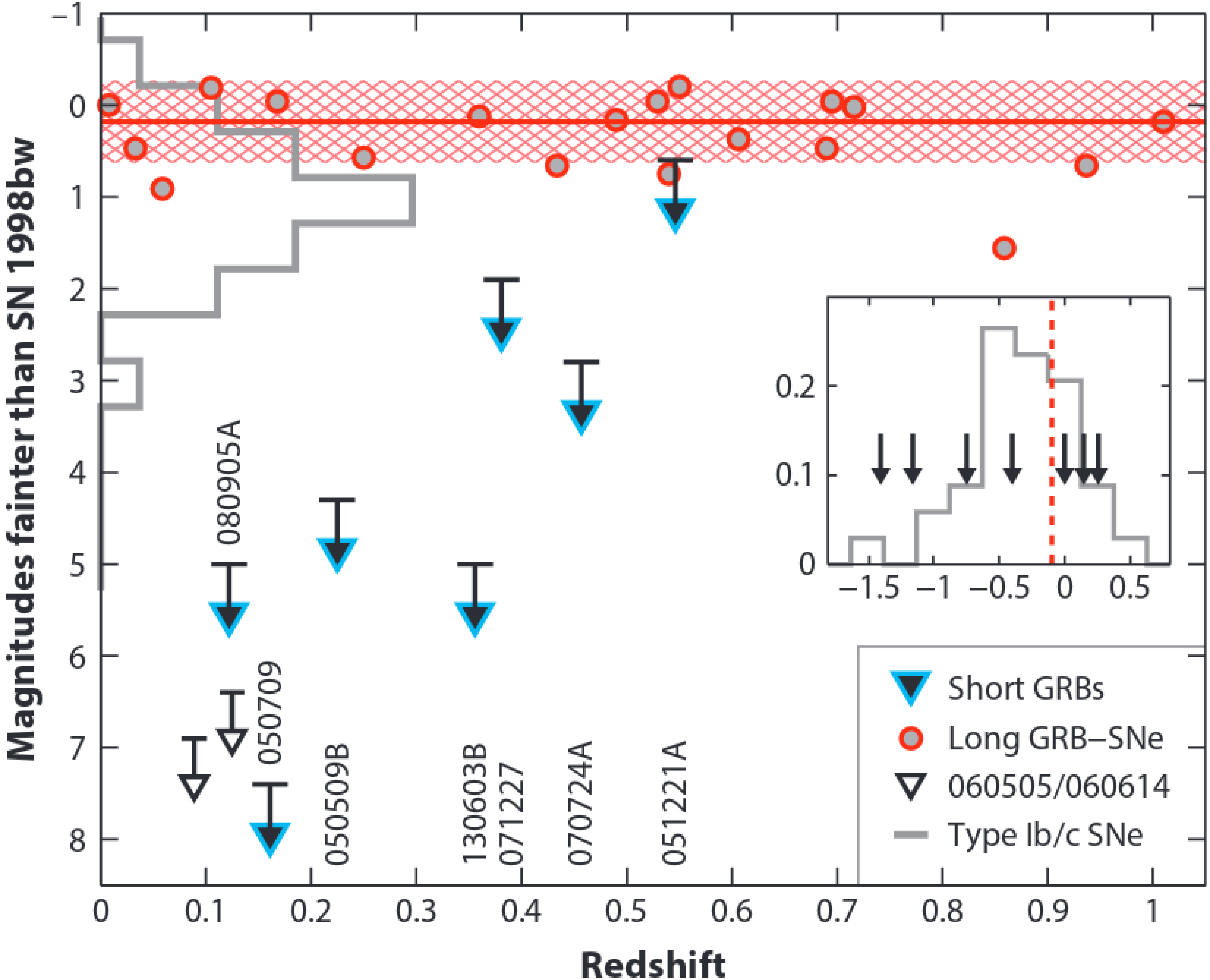


Association Long GRB's with SN explosions



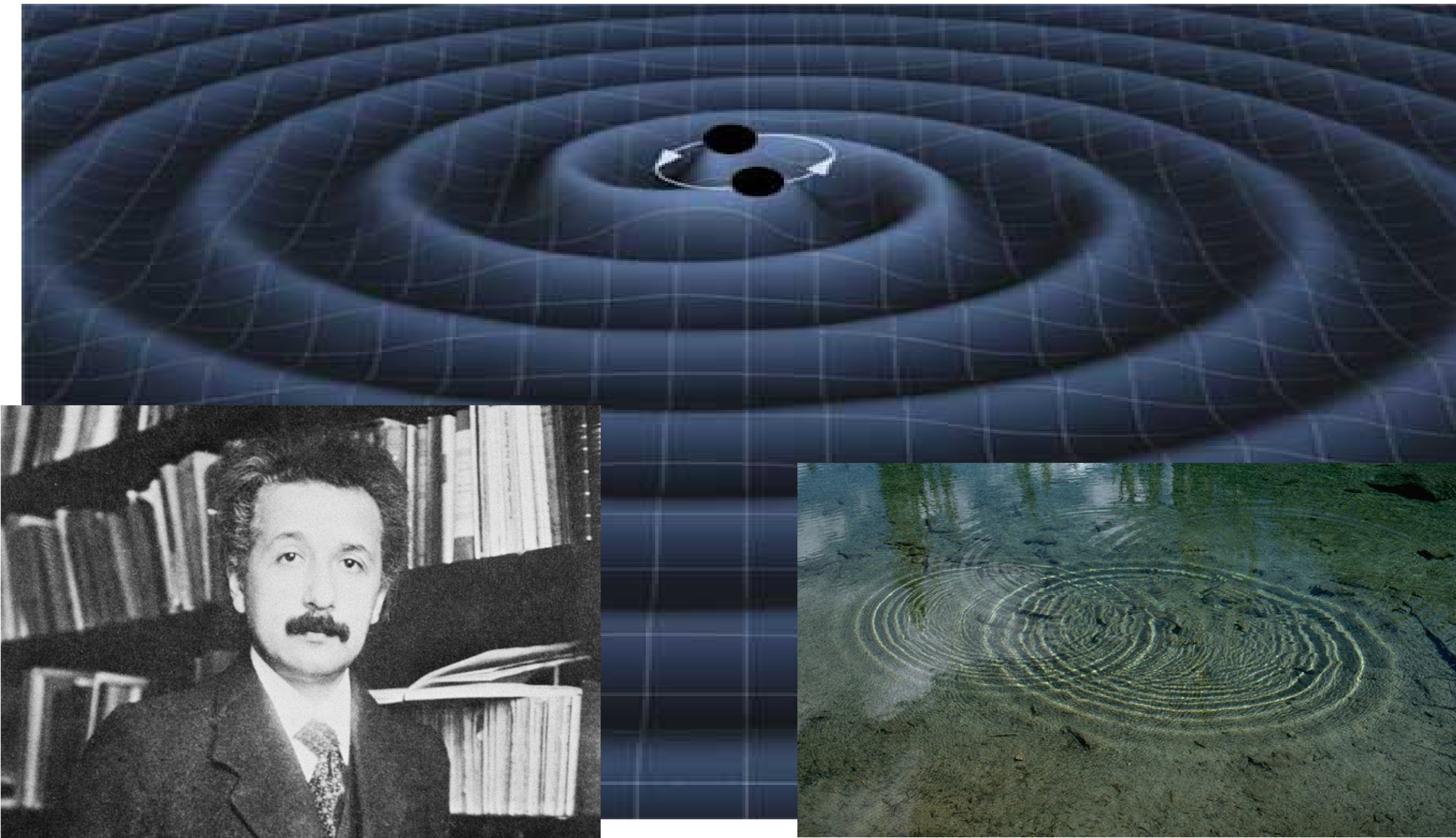
Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.

SN 1998bw GRB 980425

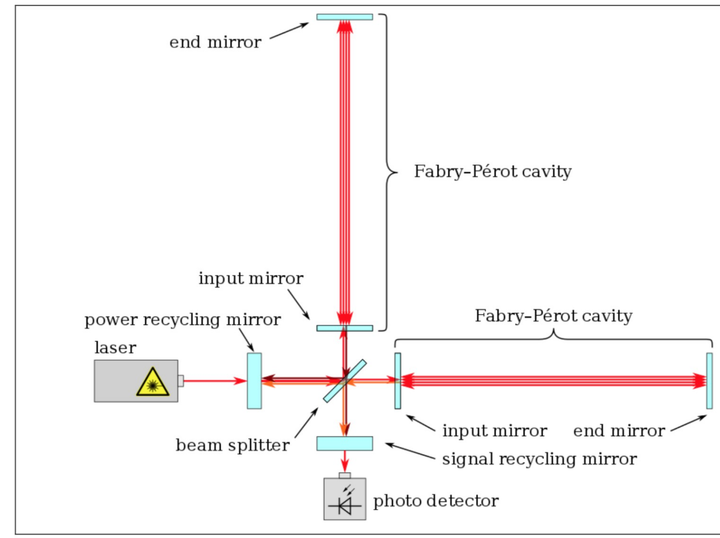


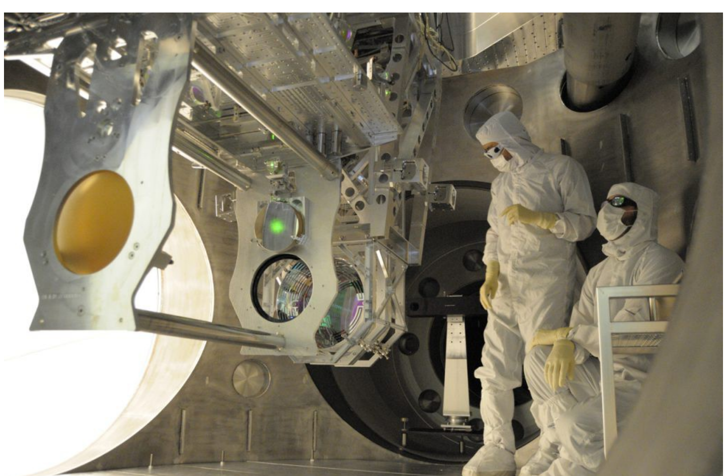
Magnitudes fainter than SN 1998bw
Redshift
−1
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
080905A
050709
050509B
130603B
071227
070724A
051221A
0.2
0.1
0
−1.5
−1
−0.5
0
0.5
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe

Gravitational Waves



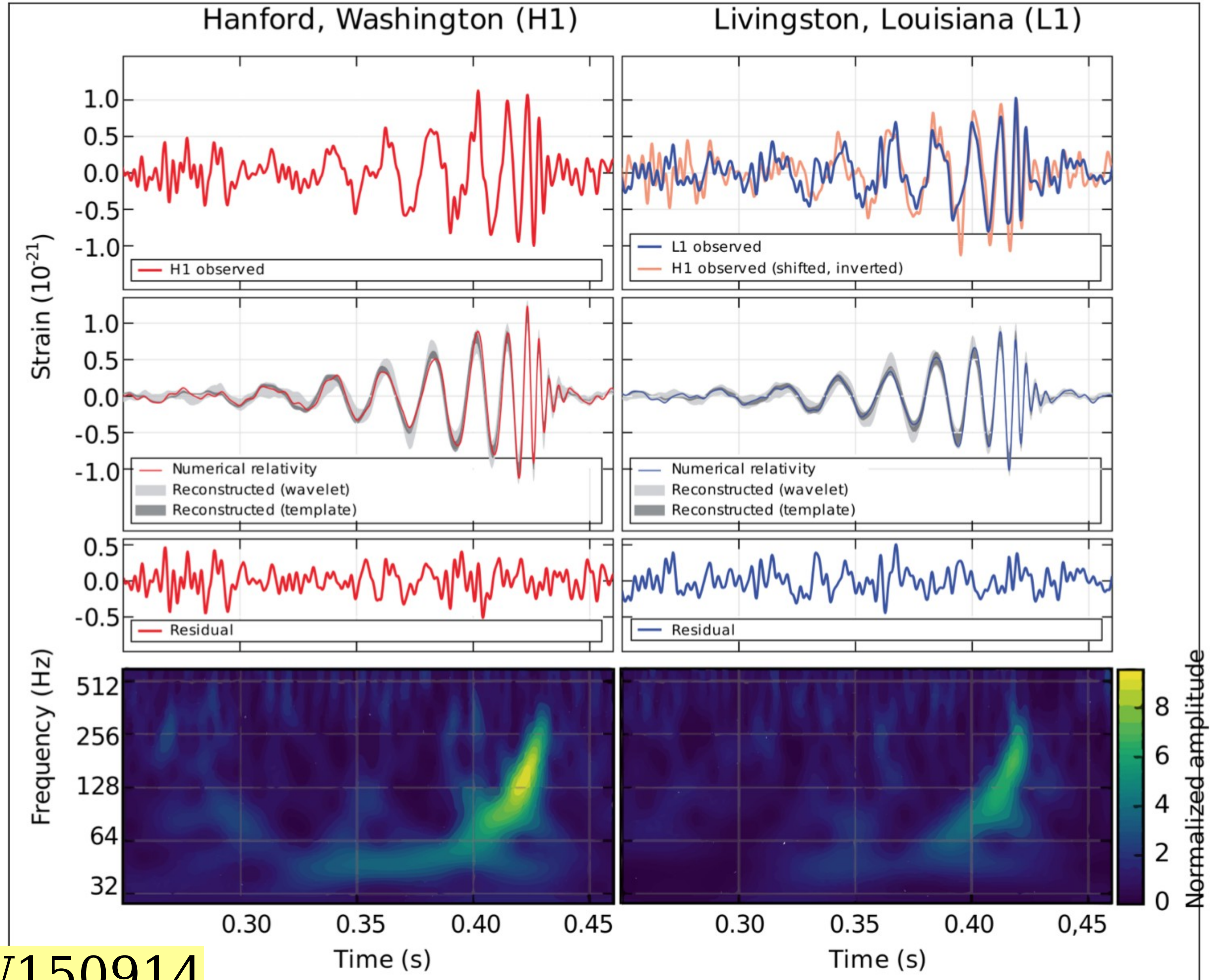
VIRGO


end mirror
Fabry–Pérot cavity
input mirror
power recycling mirror
Fabry–Pérot cavity
laser
beam splitter
input mirror
end mirror
signal recycling mirror
photo detector



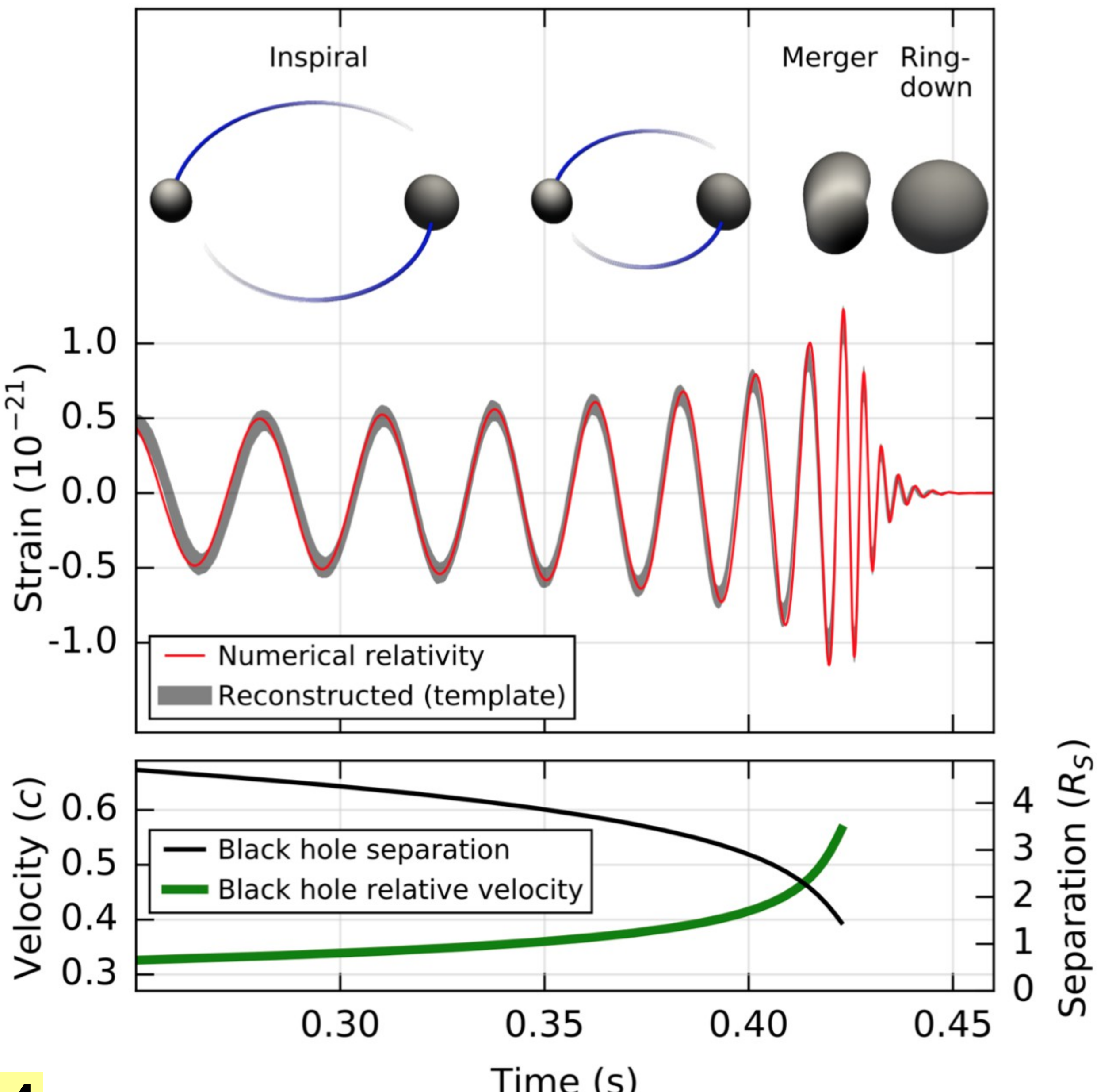
LIGO
Hanford
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston
Observatory

LIGO


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)
512
256
128
64
32
Normalized amplitude
Time (s)
0.30
0.35
0.40
0.45

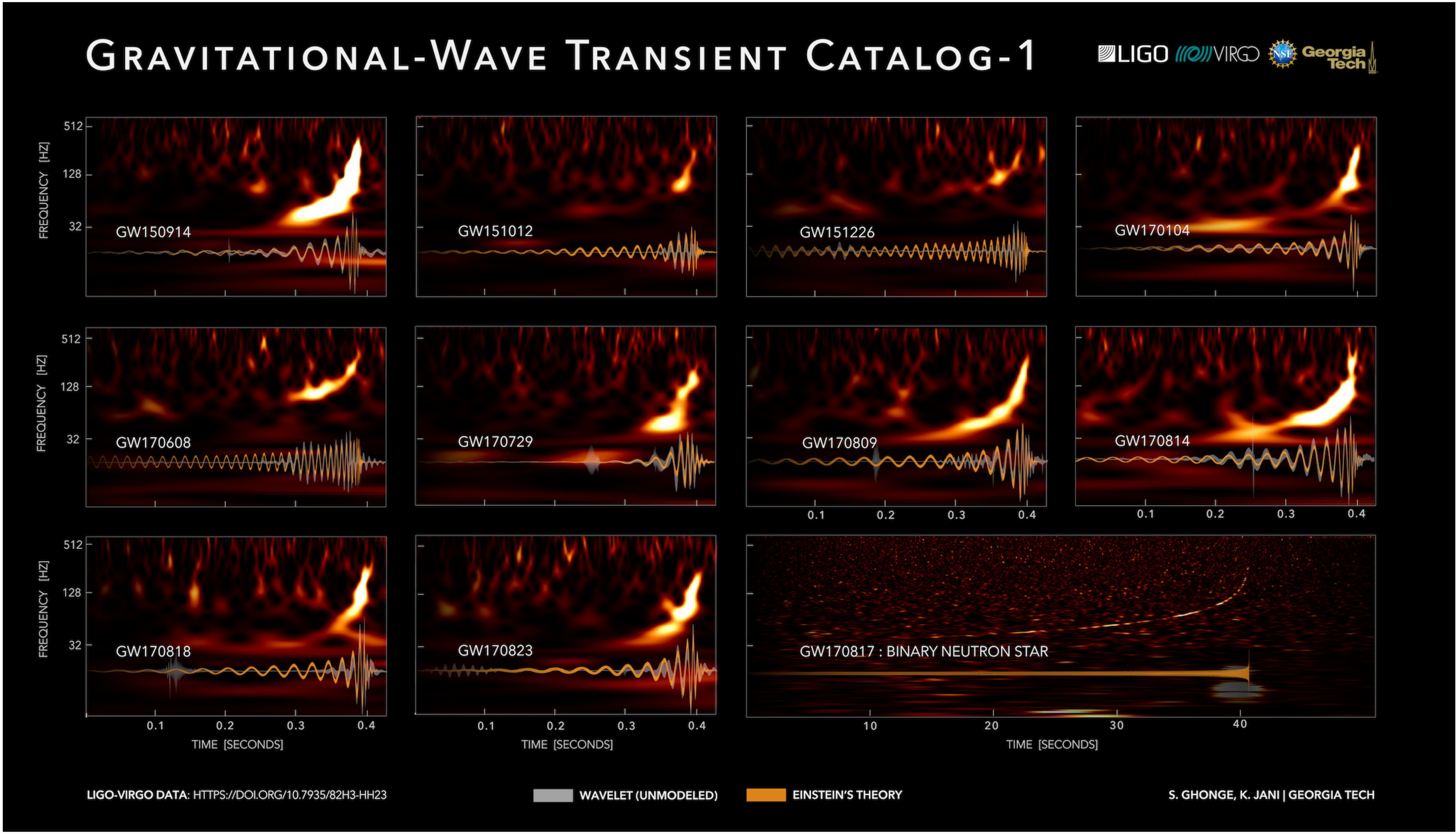
GW150914

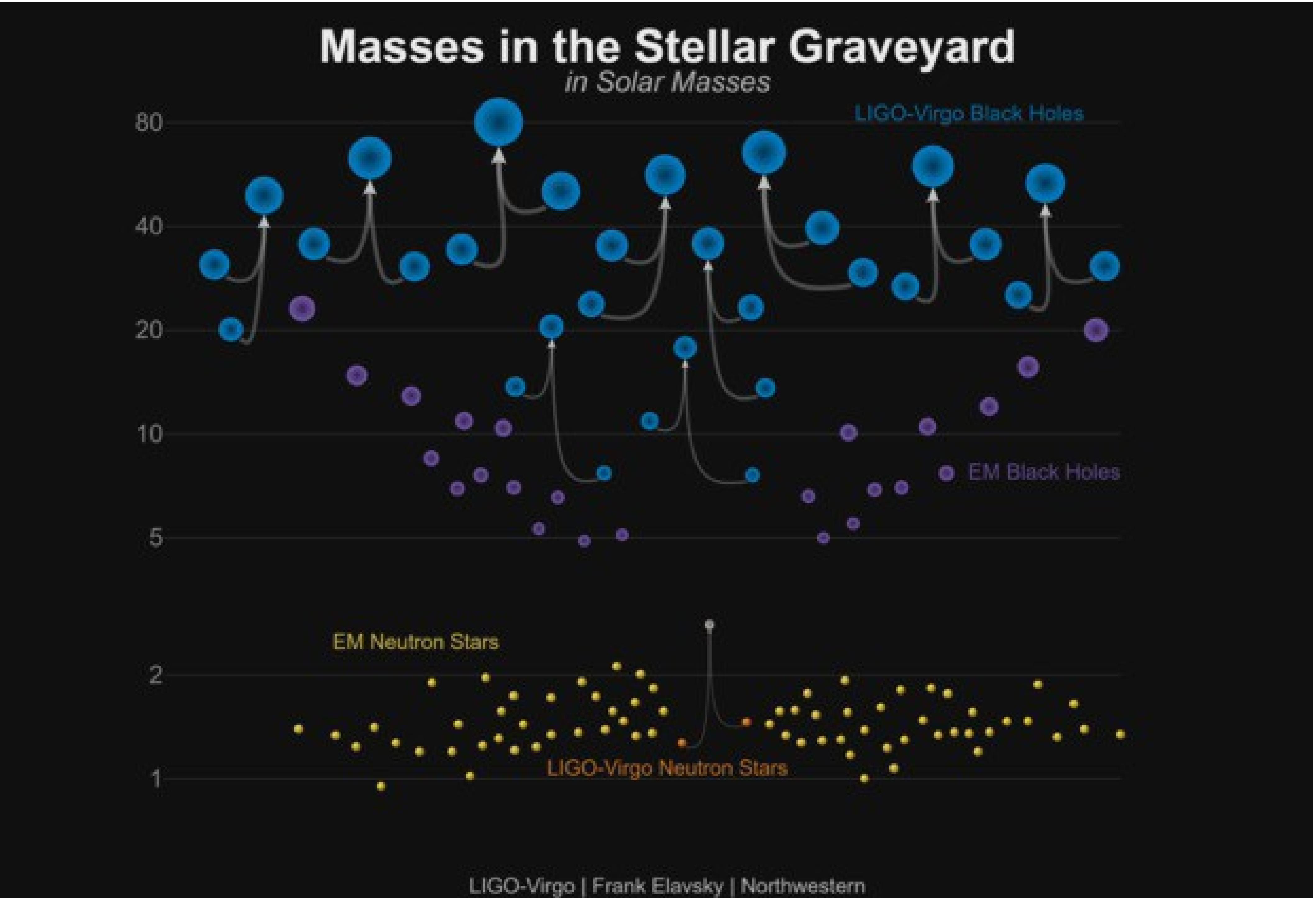
Wave form allows to reconstruct the parameters of the Binary Black Hole system *(and test General Relativity)*



GW150914

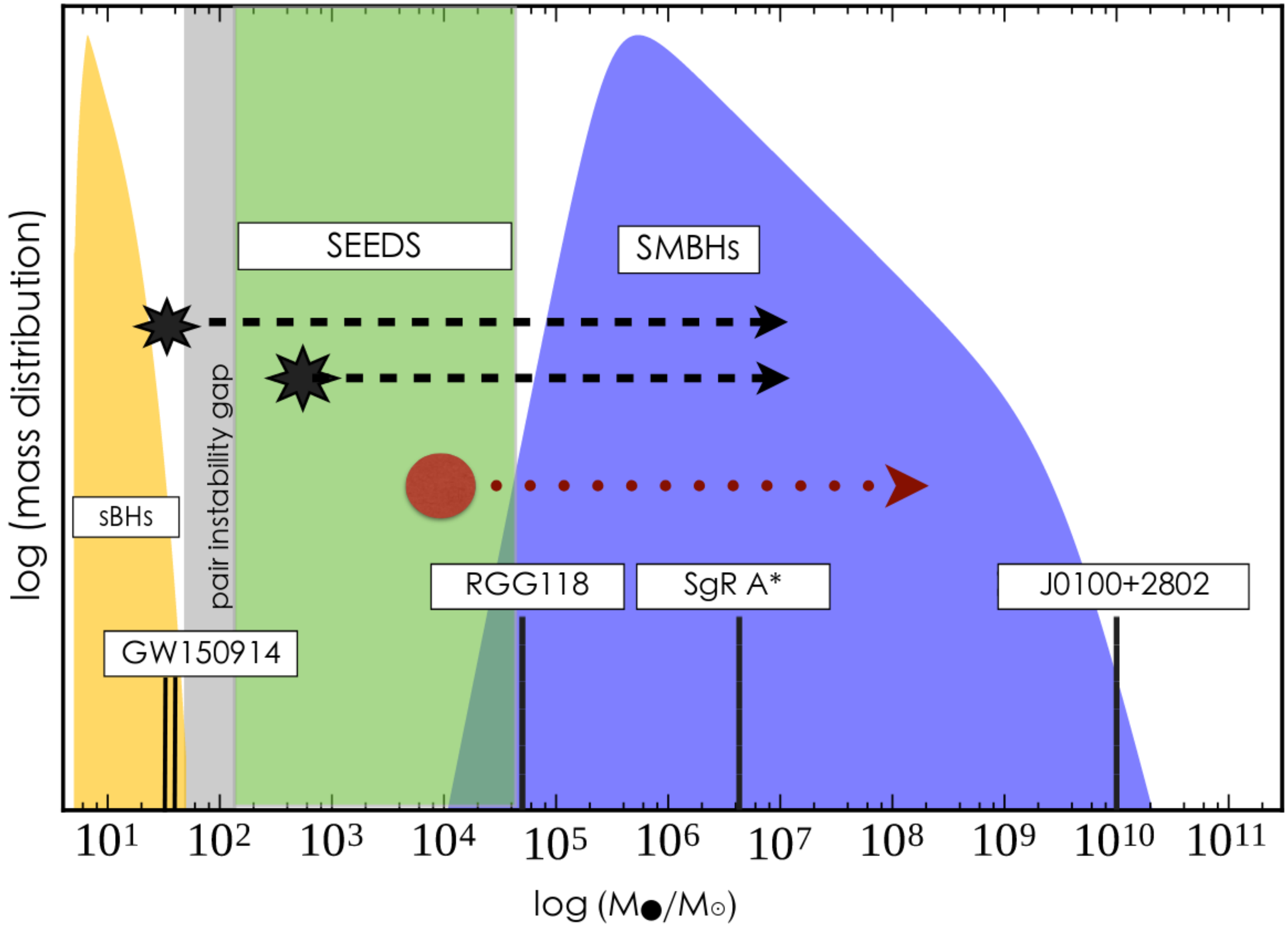
1^{st} Catalog of Gravitational-Wave transients





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].

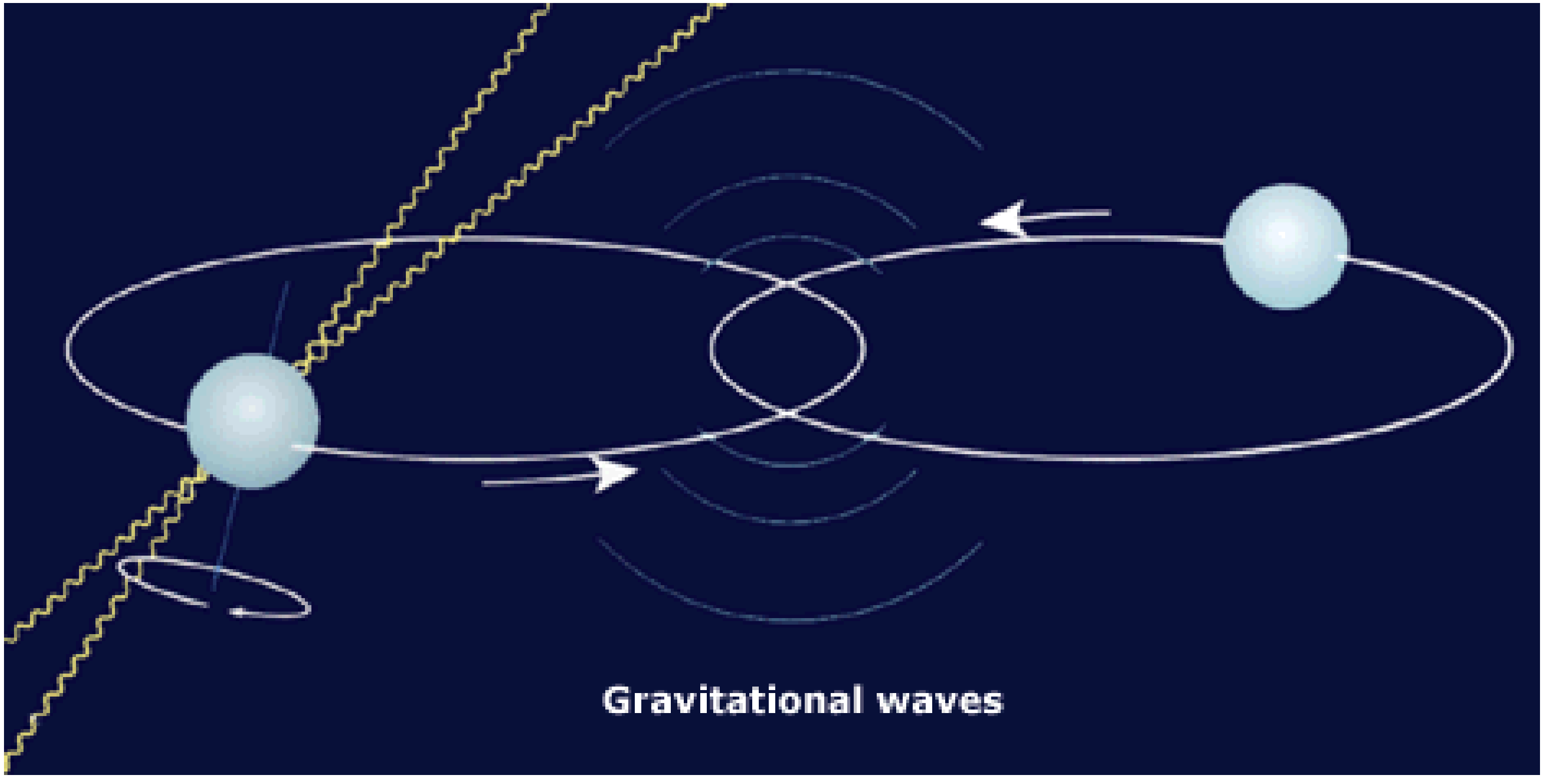
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

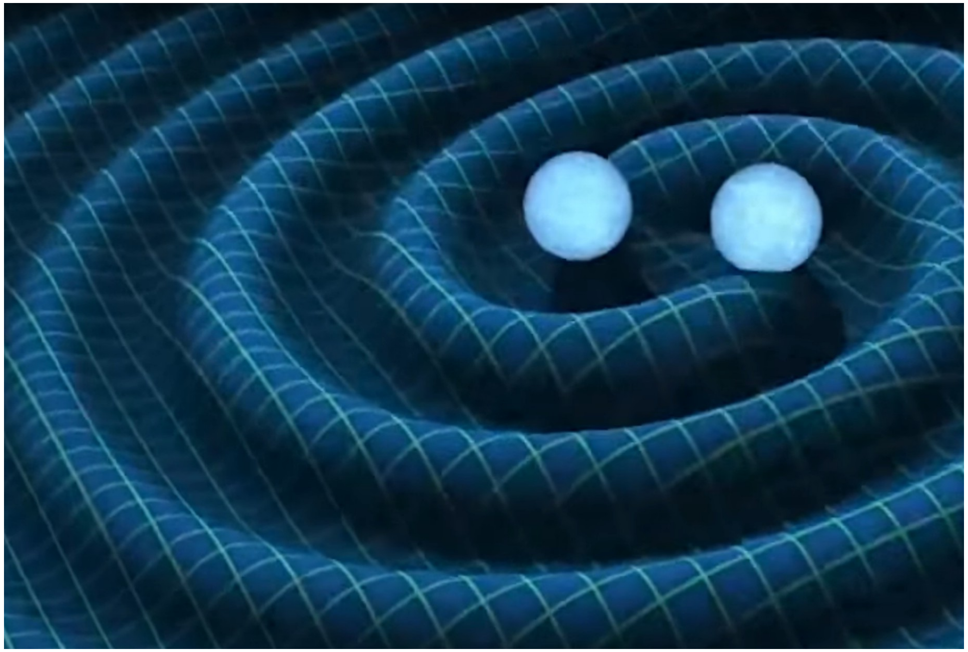
300 Myr
two neutron star coalesce

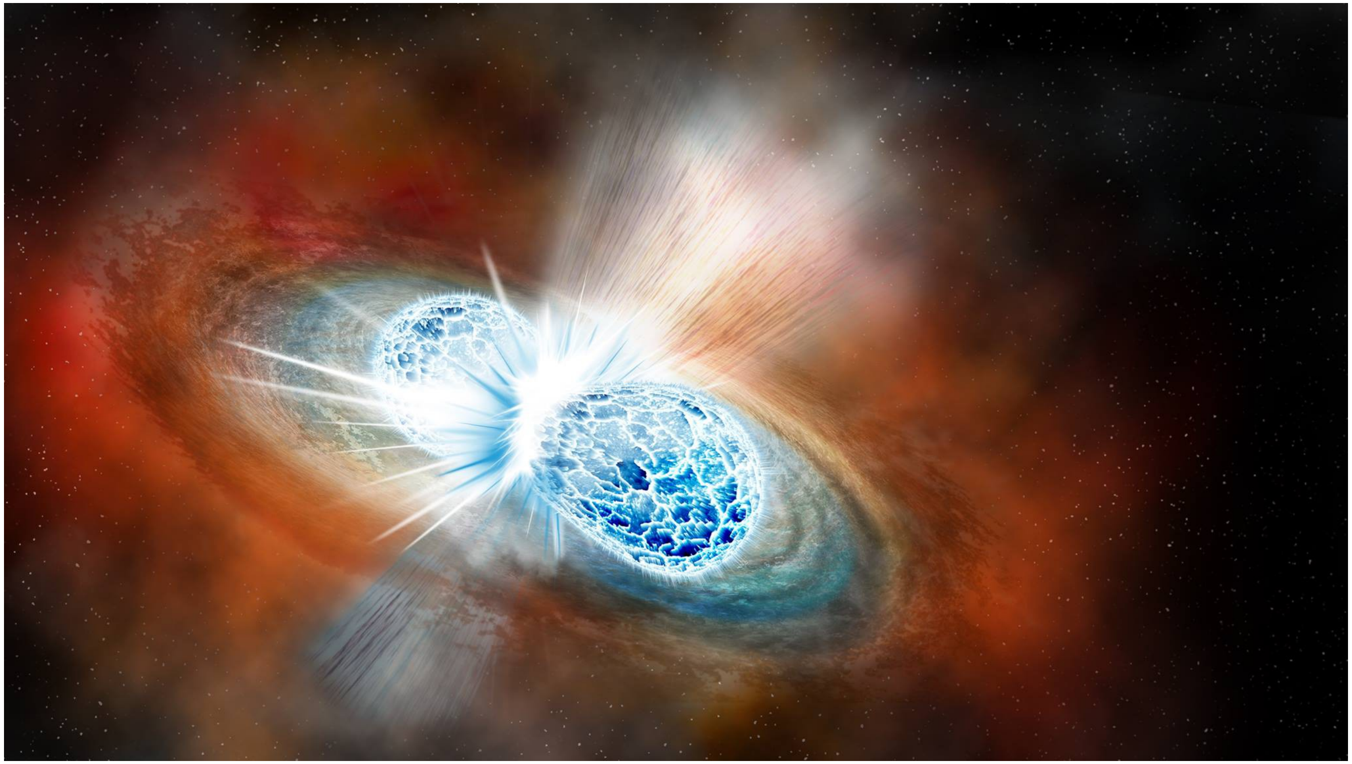
Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

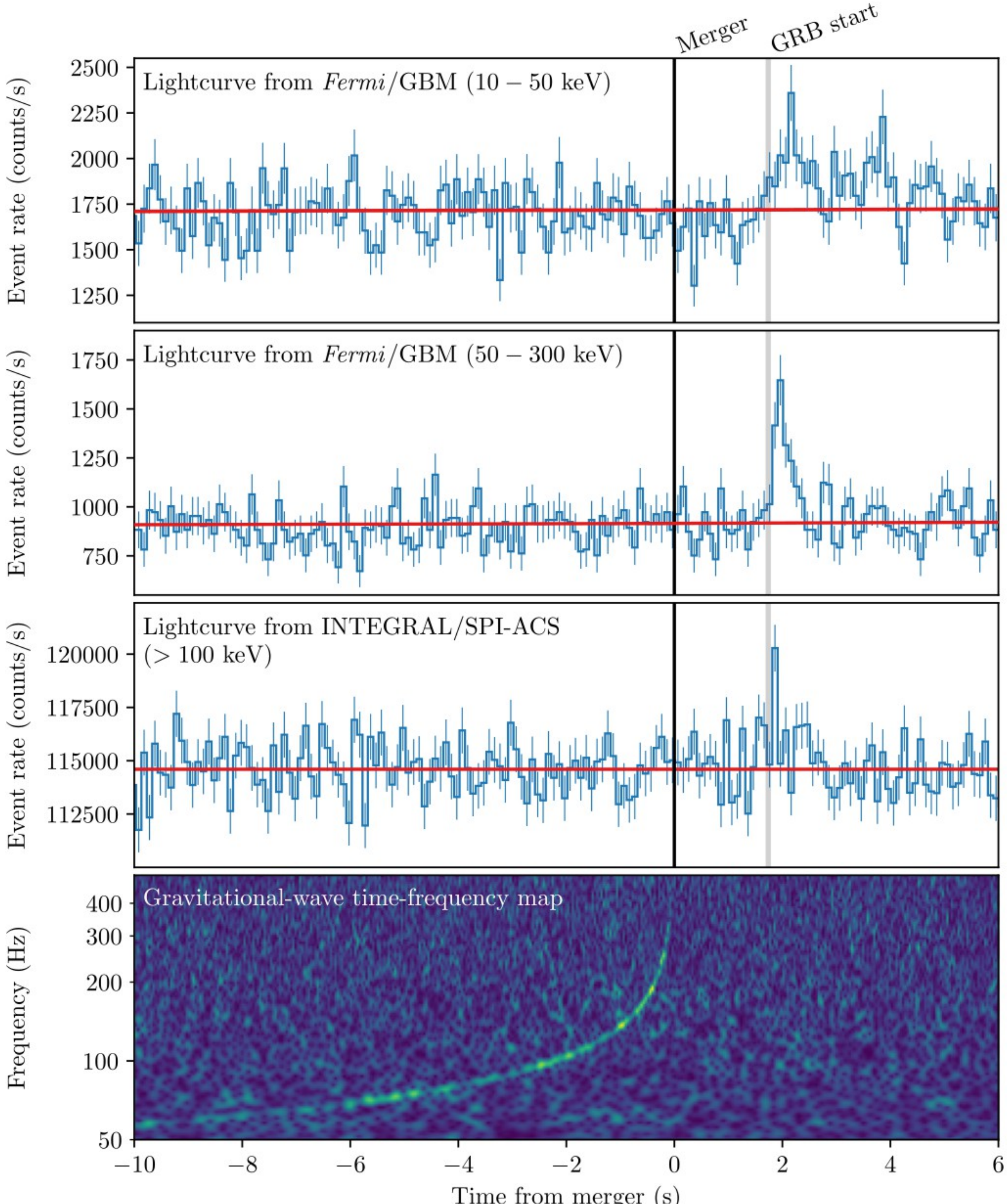
Orbit smaller
3.5 m/year







GW 170817



GRB 170817A

GW 170817

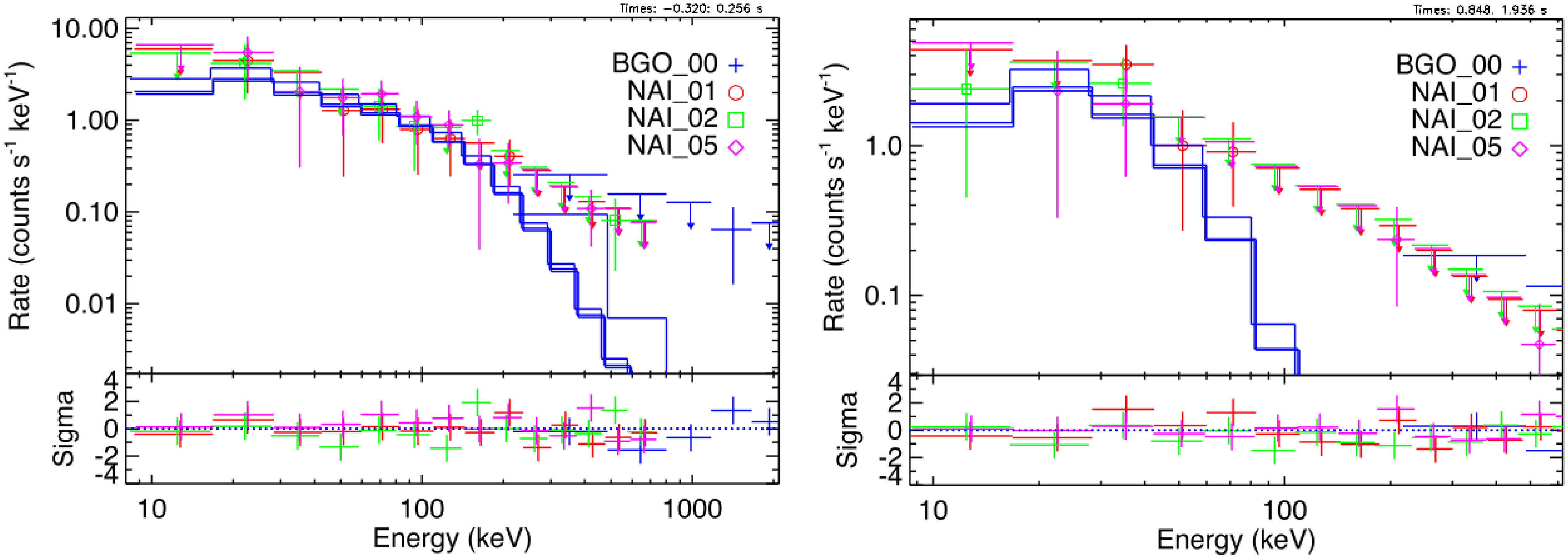
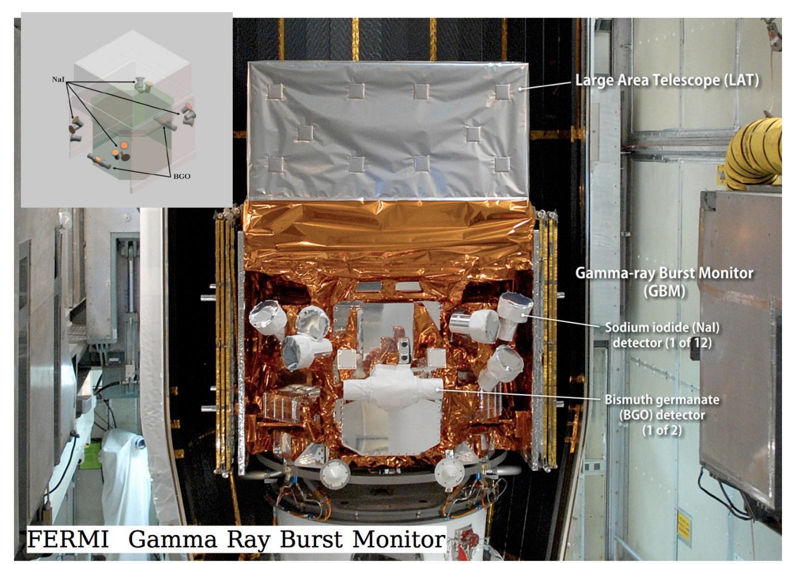
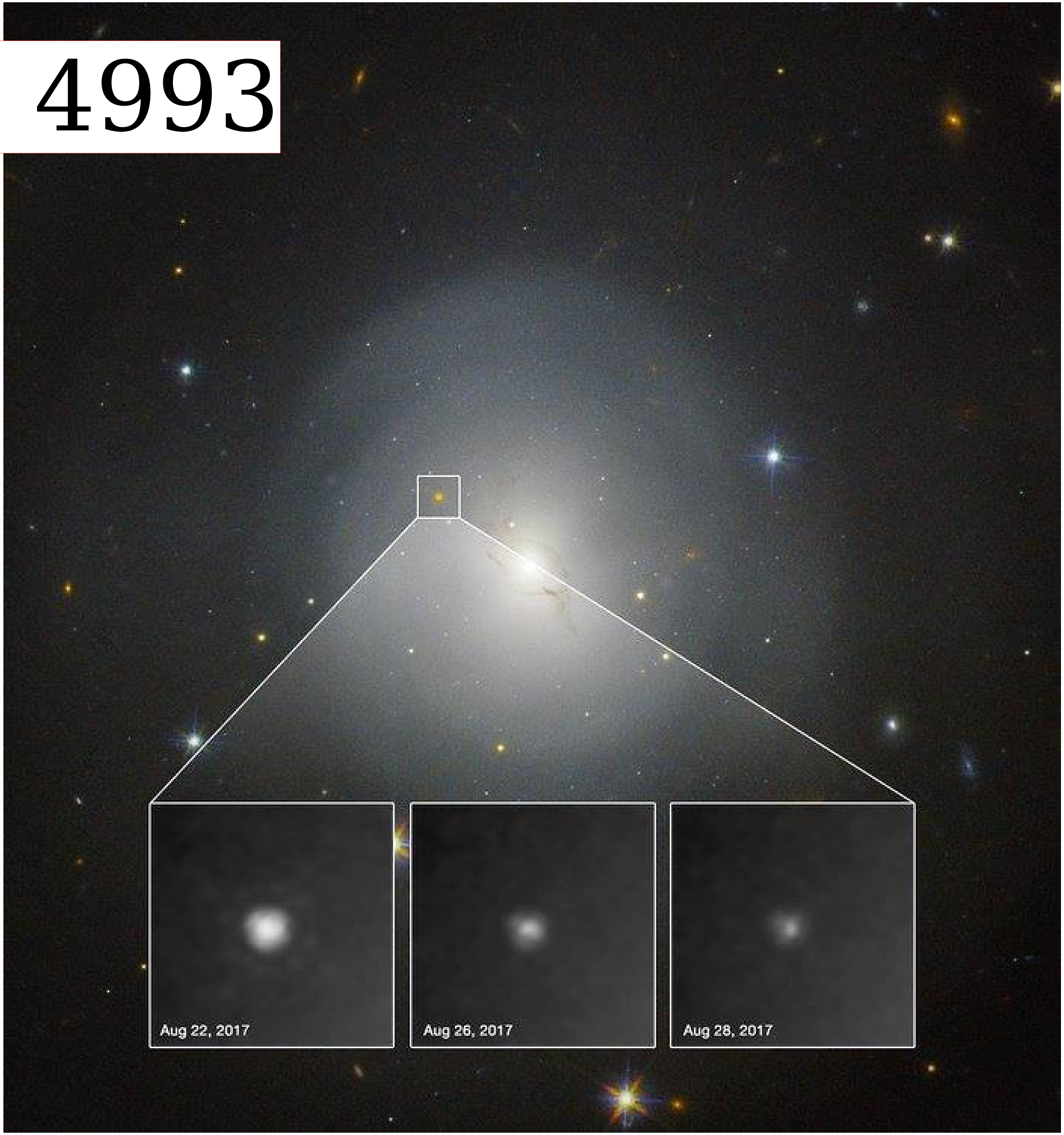


Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model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

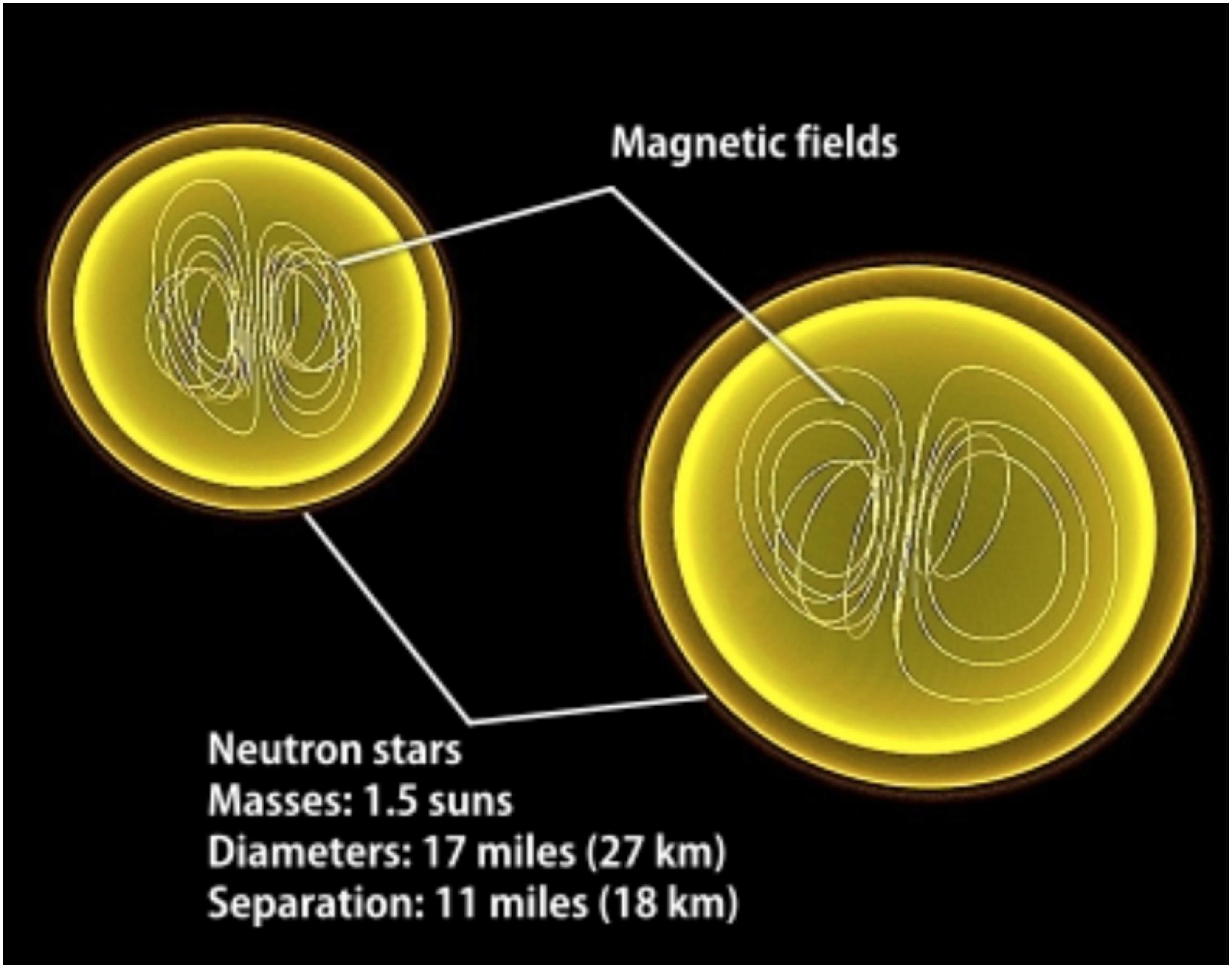
INTEGRAL
SPI-ADC



NGC 4993



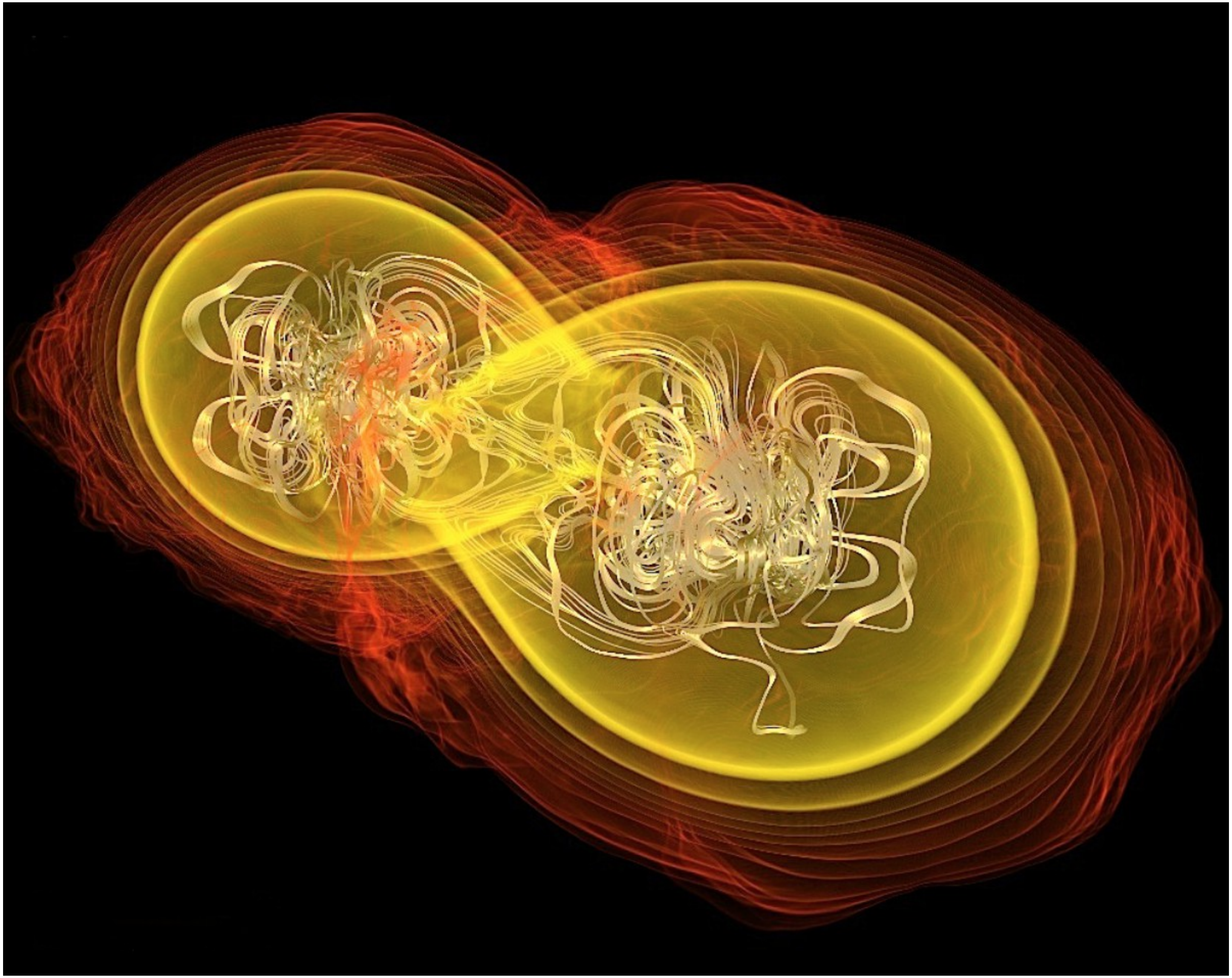
Numerical Simulation [35 msec] of merging of 2 neutron stars



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

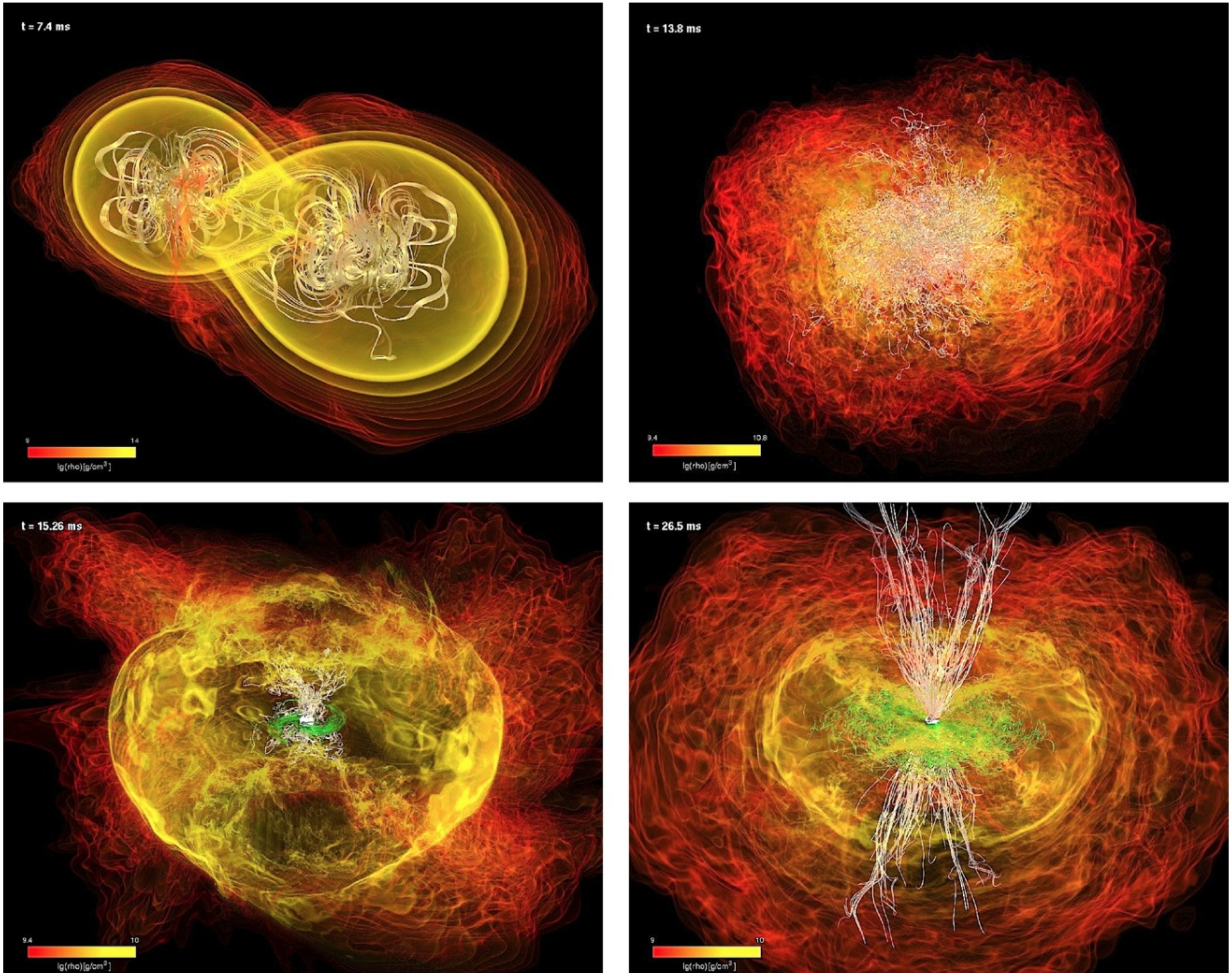
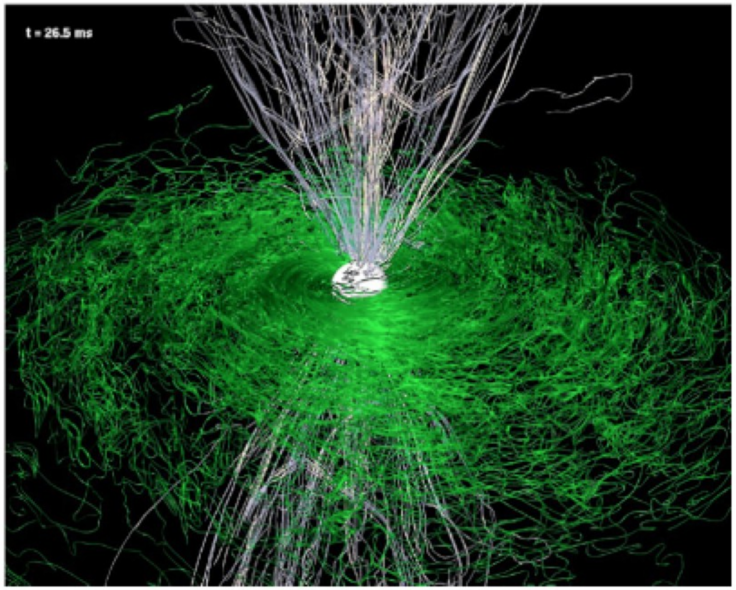


Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t = 7.4$ 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.

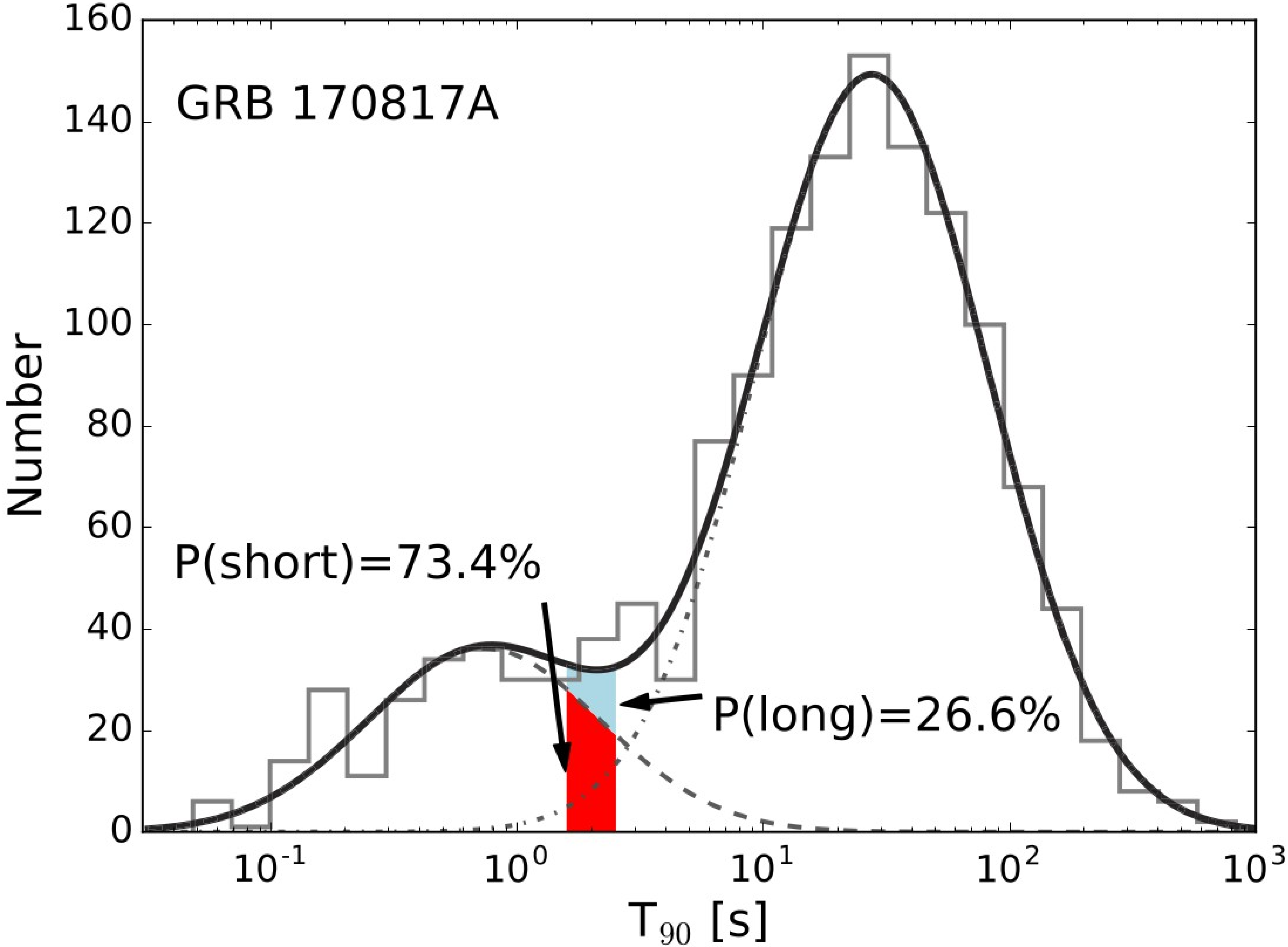


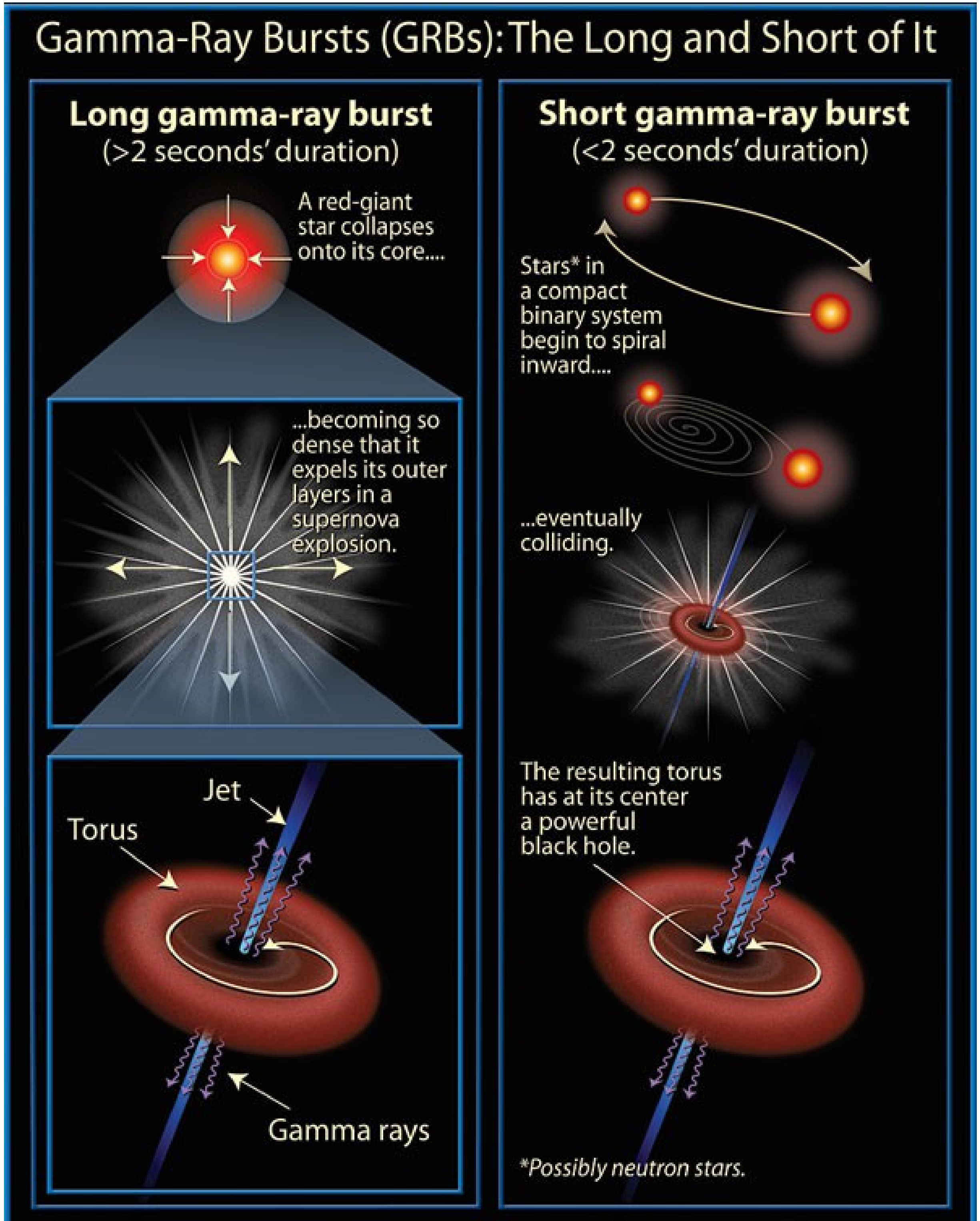
The simulation
shows that the magnetic field
is organized is a structure
that is consistent with the emission
of a jet and then a
Gamma Ray Burst

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.

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





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.

Classes of Sources

[Fermi sources associated with known objects]

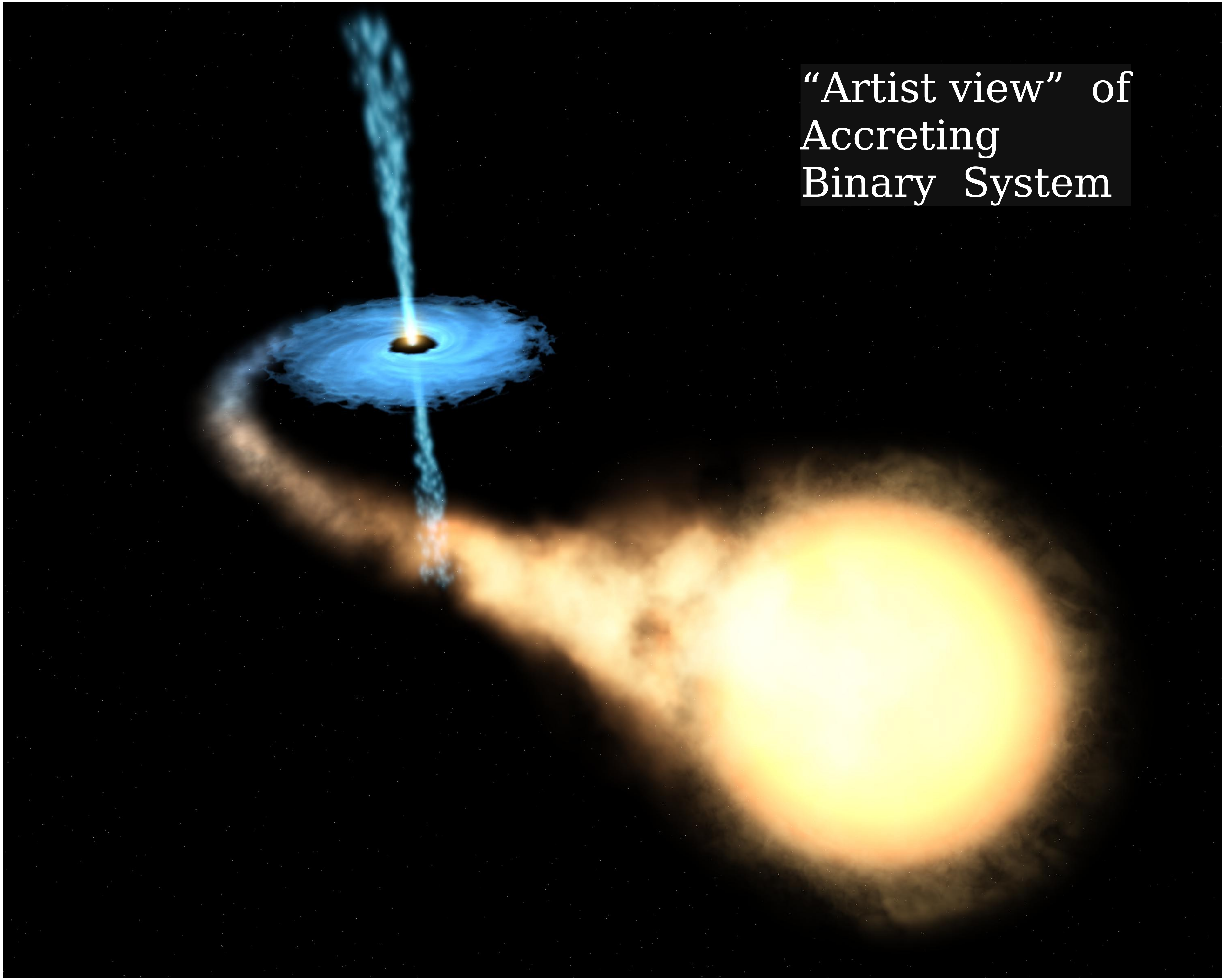
72% of sources

extragalactic

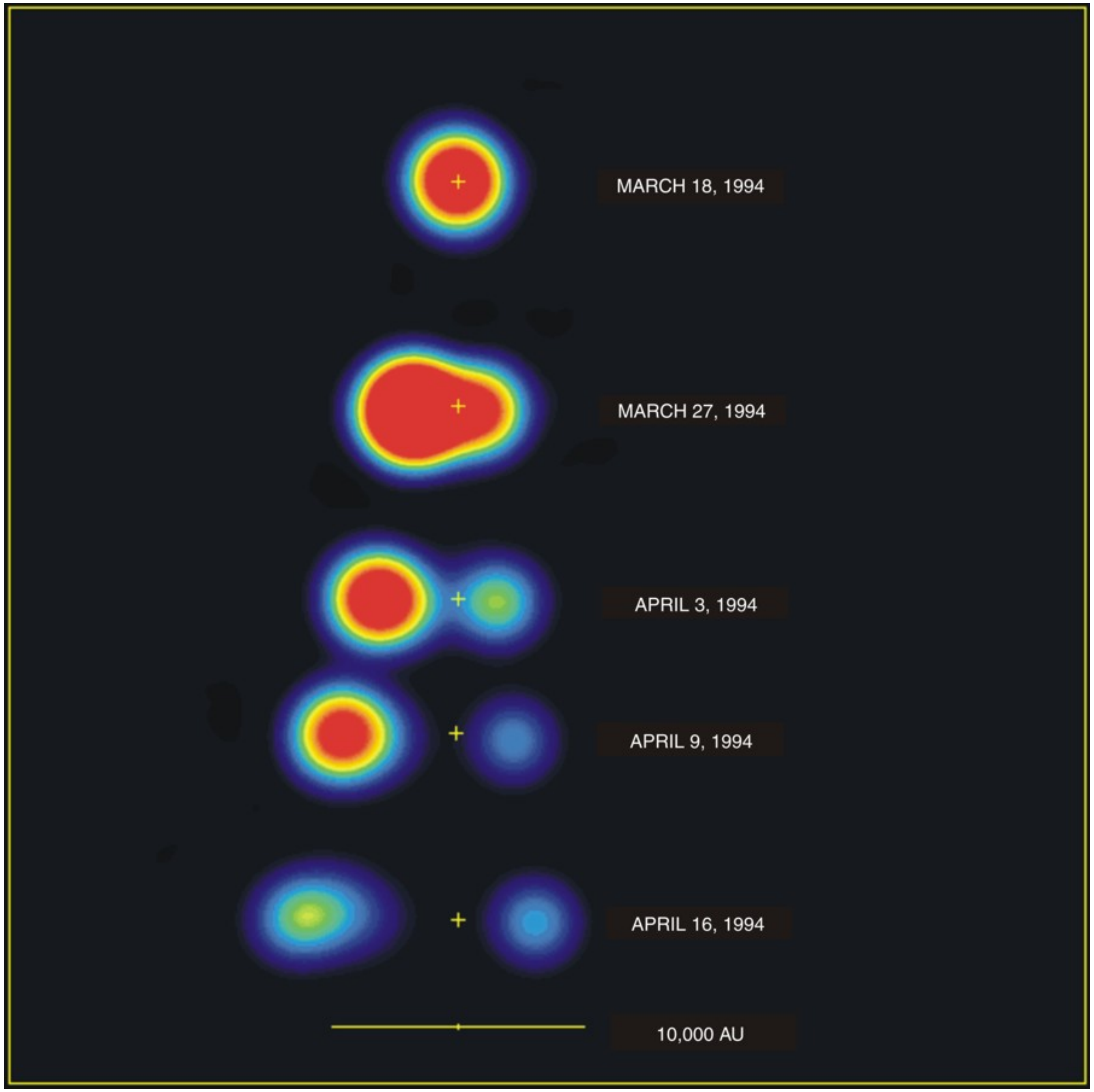
Active Galactic Nuclei (AGN)	3208	88%
(AGN of "Blazar" class	3137	86%)
Galaxies (Normal)	4	
Galaxies (Star Forming)	7	

Galactic

Pulsars	239	6.5%
SuperNova Remnants (SNR)	40	1.1%
SNR + Pulsar Wind Nebulae	108	3.0%
Globular Clusters (many ms Pulsars [?])	30	
Accreting Binary Stars	11	
Novae	1	


“Artist view” of
Accreting
Binary System

Superluminal Motions in microQuasars in our Galaxy

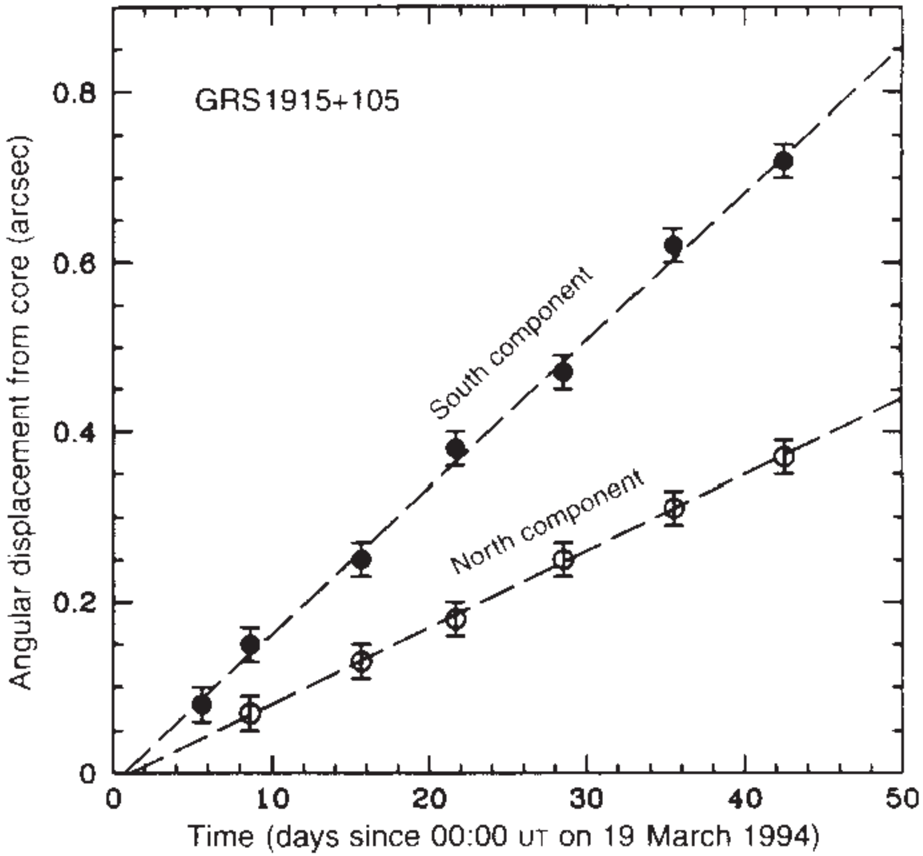


GRS1915+105

Observations in radio

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

"Two pairs of bright radio condensations"



Angular velocities

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

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

$$\beta = 0.92 \pm 0.08$$

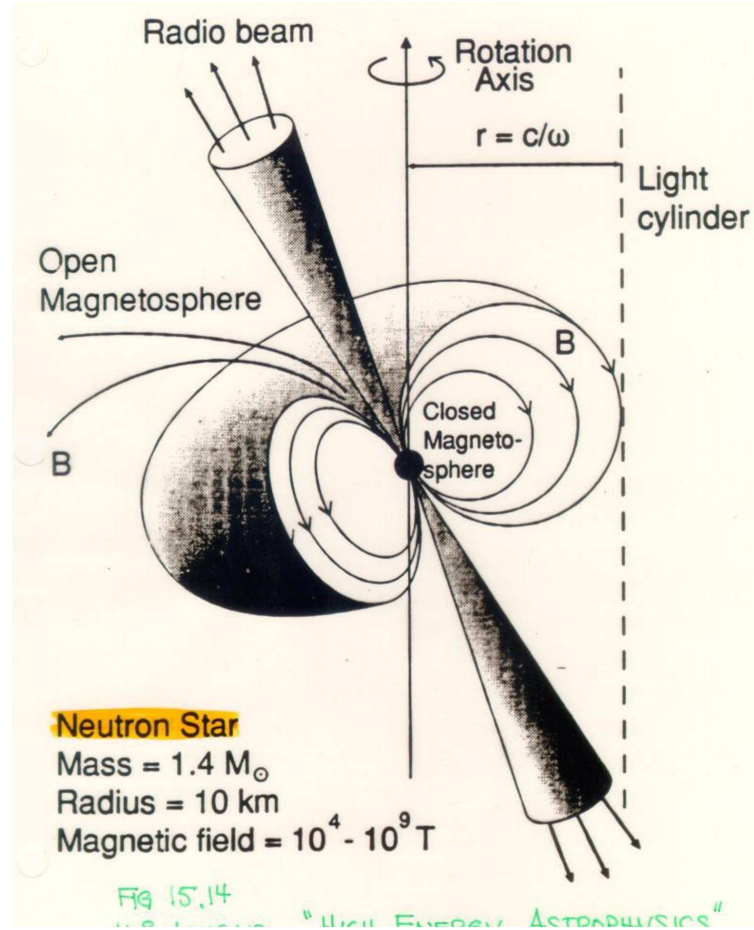
$$\theta = (70 \pm 2)^\circ$$

$$\mu_{a,r} = \frac{\beta \ \sin\theta}{1 \pm \beta \ \cos\theta} \ \frac{c}{D}$$

$$D = 12.5 \pm 1.5 \text{ kpc}$$

PULSARS

Proposed as possible Accelerators of e+ e-



CRAB Nebula

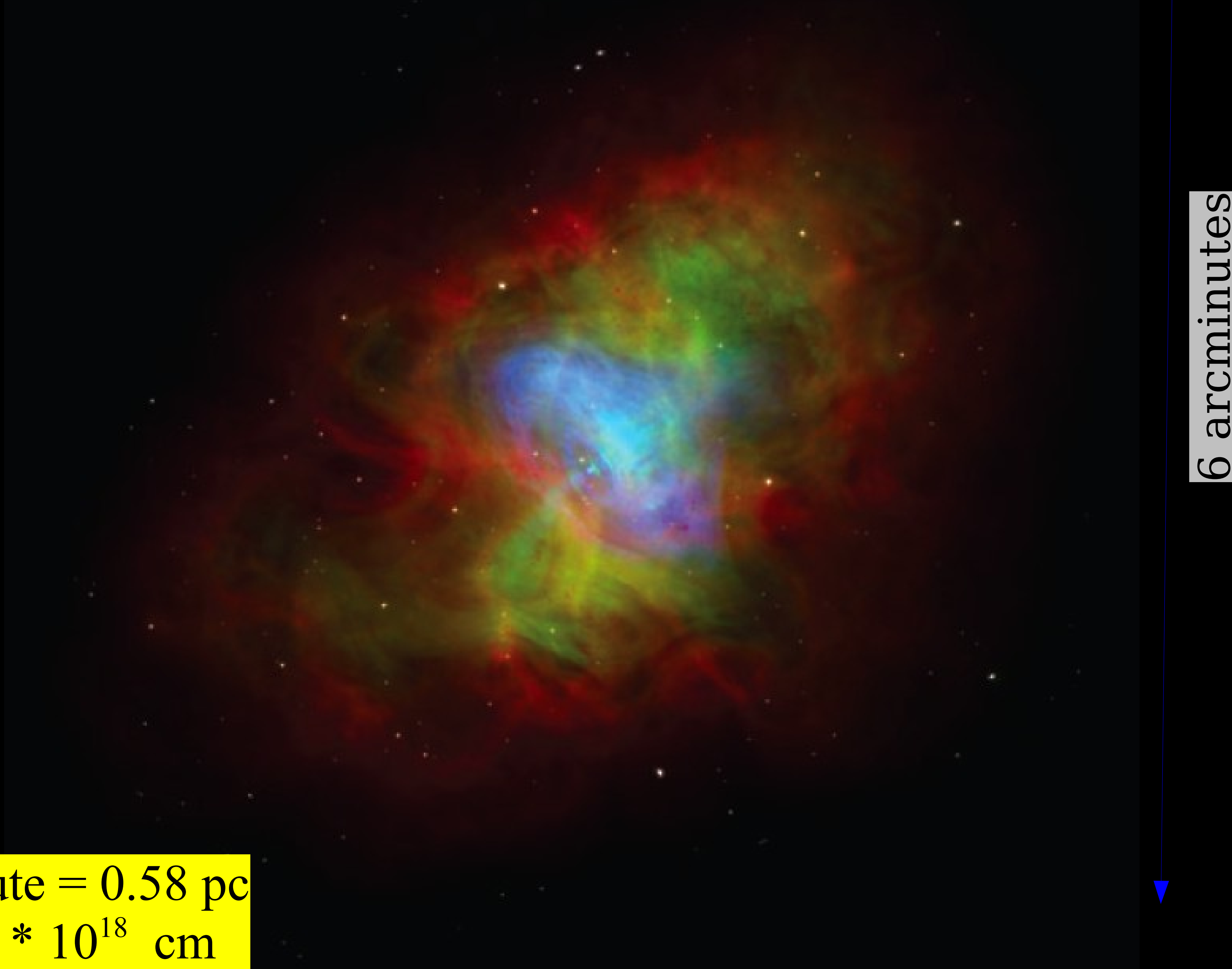
$P_{\text{Crab}} = 0.0334\ \text{s}$

$(\Delta P_{\text{Crab}})_{\text{year}} = 13.2 \times 10^{-6}\ \text{s}$

> 100 well identified Pulsars
(3 Pulsar-Wind-Nebulae)

Very large variation in the fraction of Spin Down Energy going into gamma Rays

The CRAB Nebula

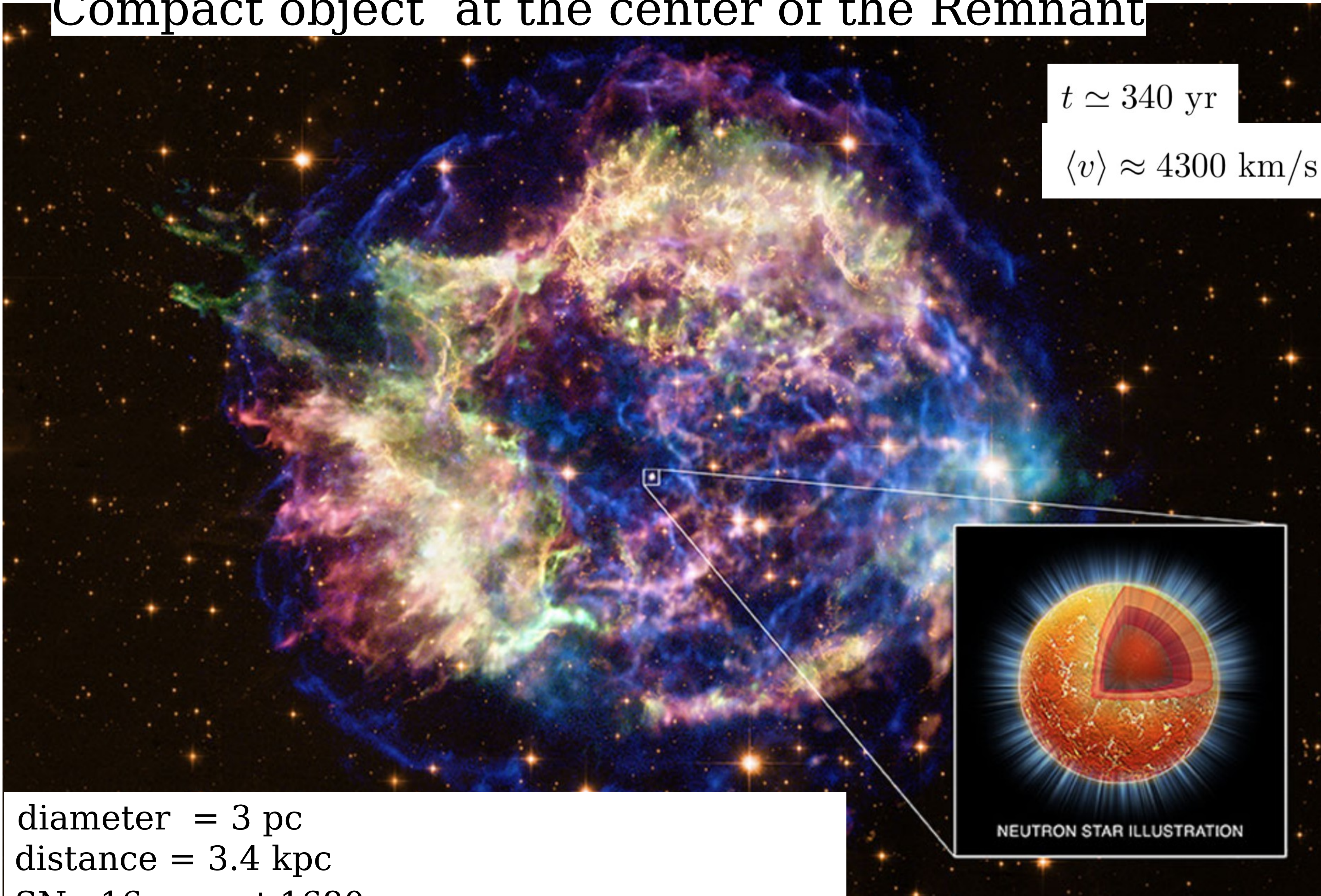


1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

Compact object at the center of the Remnant

$t \simeq 340$ yr

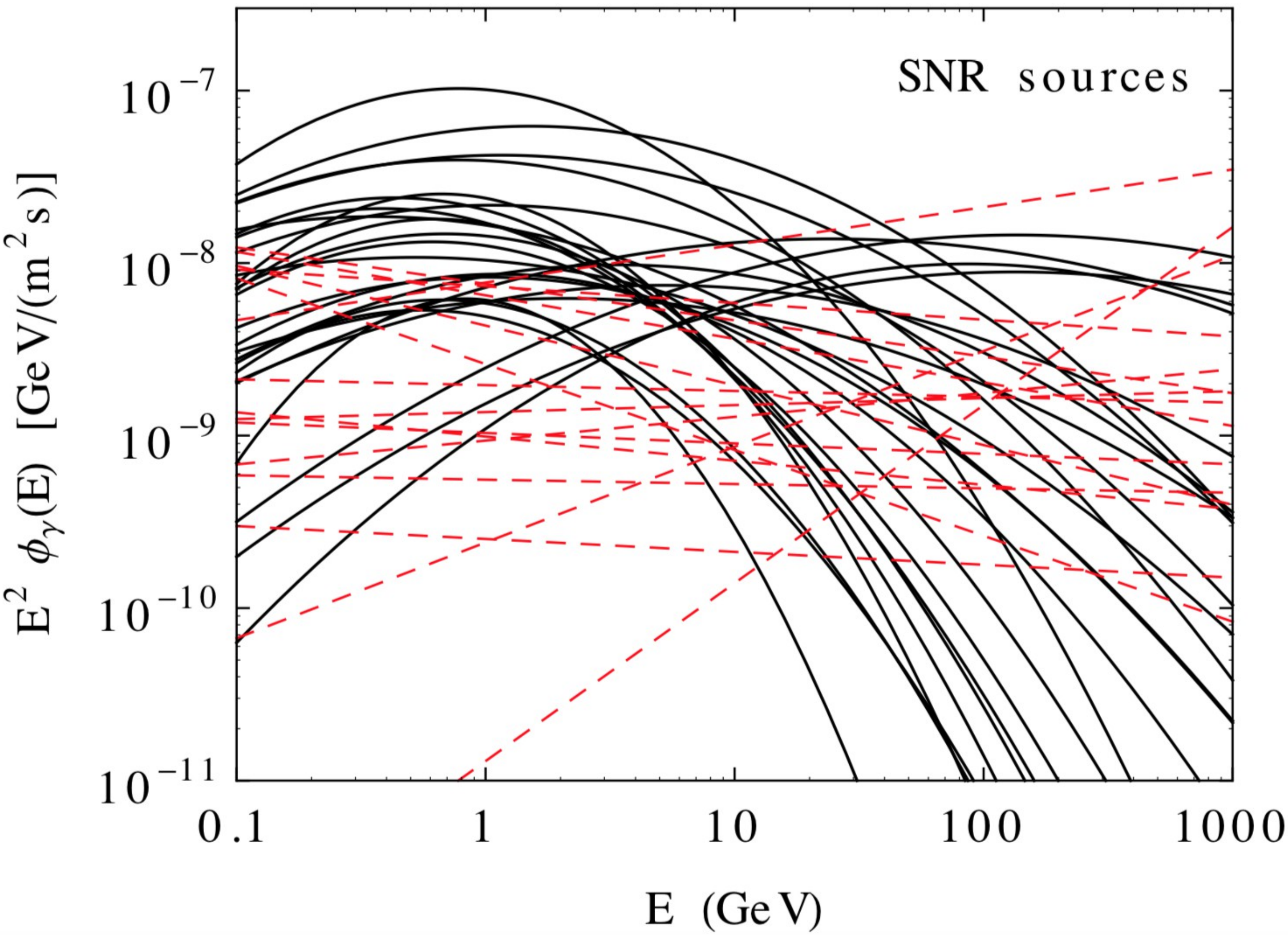
$\langle v \rangle \approx 4300$ km/s



diameter = 3 pc
distance = 3.4 kpc
SN : 16 august 1680 [Astronomer Royal John Flamsteed]

Fits to the FERMI sources associated
with Supernova Remnants

Are SNR the
main sources of
Galactic Cosmic Rays ?



Dark Matter

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

"Dark Matter"
Cornelia Parker
Tate Gallery London

This is obviously a problem of GREAT importance
[for many is THE CENTRAL problem]

It is intimately related to
the study of the High Energy Universe

[but very little discussion in this seminar.....]

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

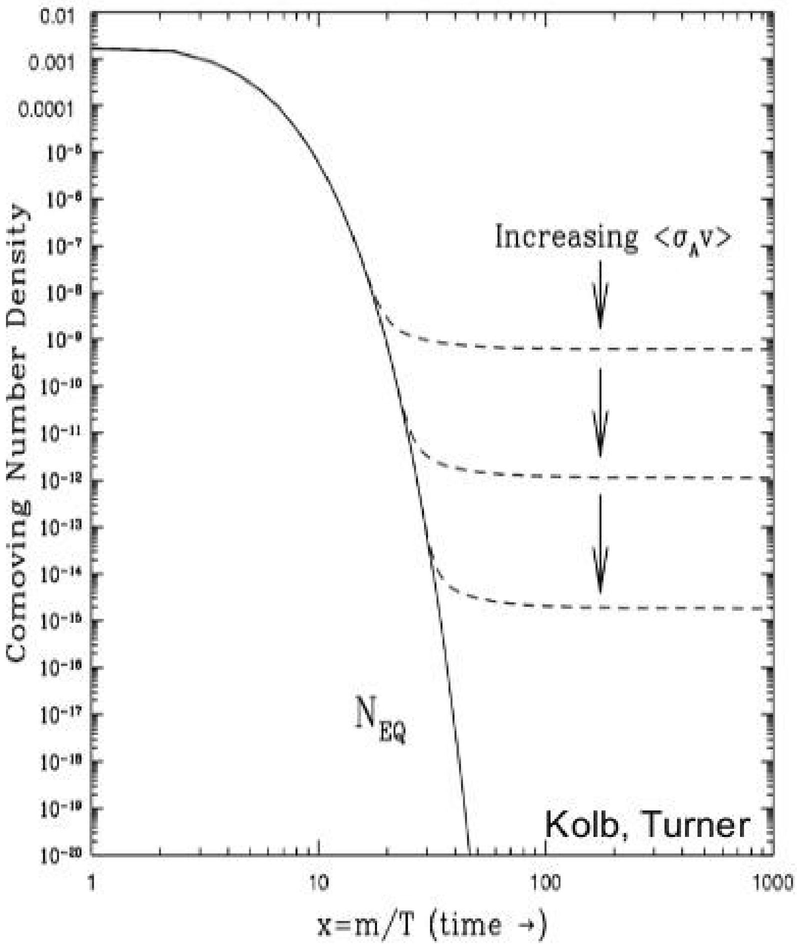
The presence of DM can be
important for the structure of
astrophysical sources
[for example galactic nuclei]

Weakly Interacting Massive Particle

Thermal Relic

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

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



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

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:

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

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

No evidence for Dark Matter signal
in gamma ray studies

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]].

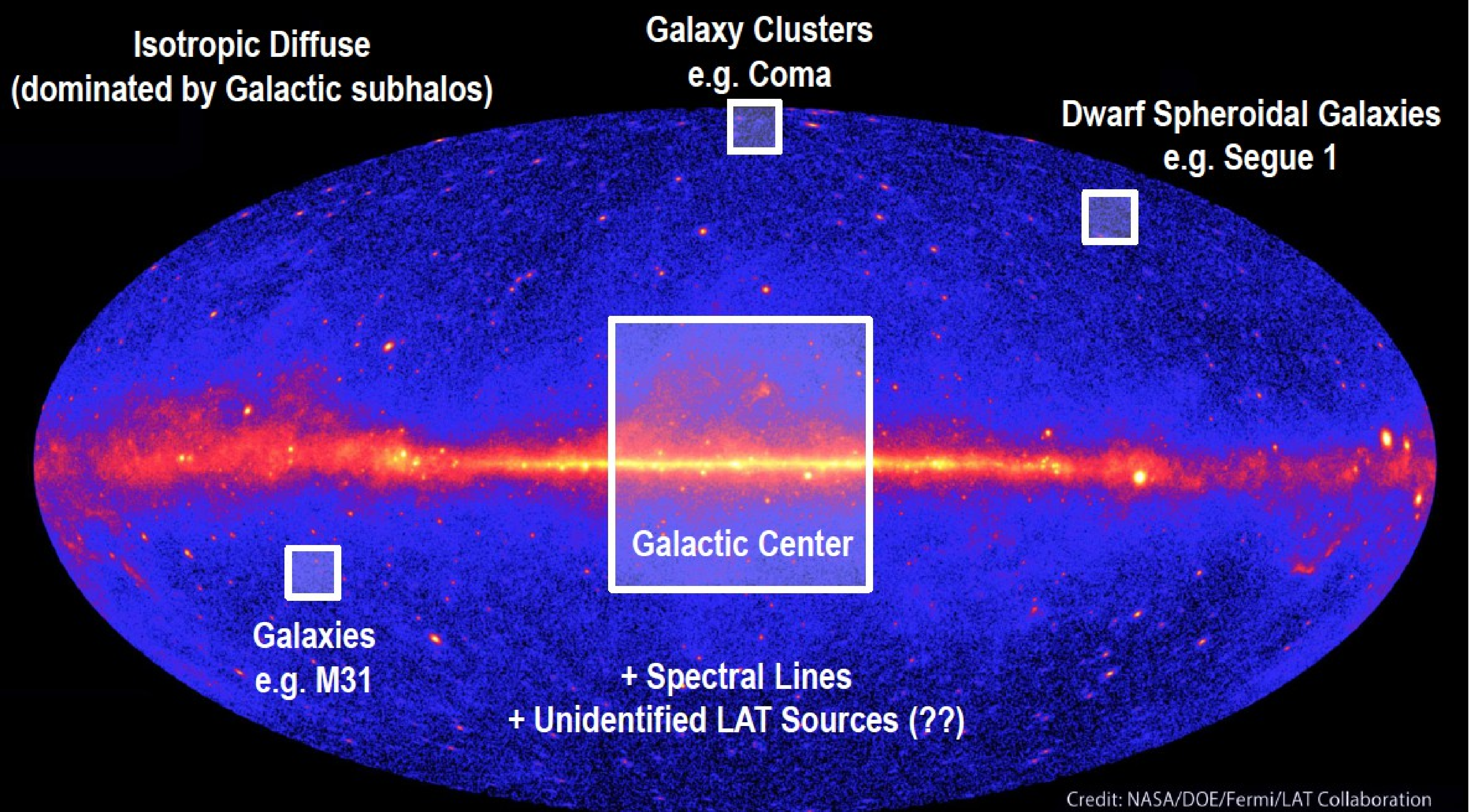
M. Ackermann *et al.* [Fermi-LAT Collaboration],
"Searching for Dark Matter Annihilation from Milky Way
Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,"
Phys. Rev. Lett. **115**, no. 23, 231301 (2015)
[arXiv:1503.02641 [astro-ph.HE]].

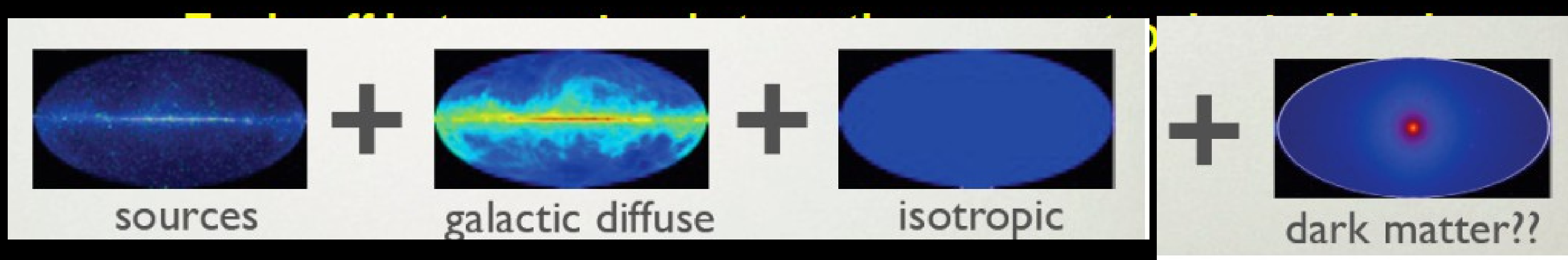
M. Ackermann *et al.* [Fermi-LAT Collaboration],

"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]].


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??

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 > 1TeV

Hadronic emission

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

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

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

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

Leptonic emission

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

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

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

Gamma Ray emission

Neutrino emission

Approximately same size
(and spectral shape)

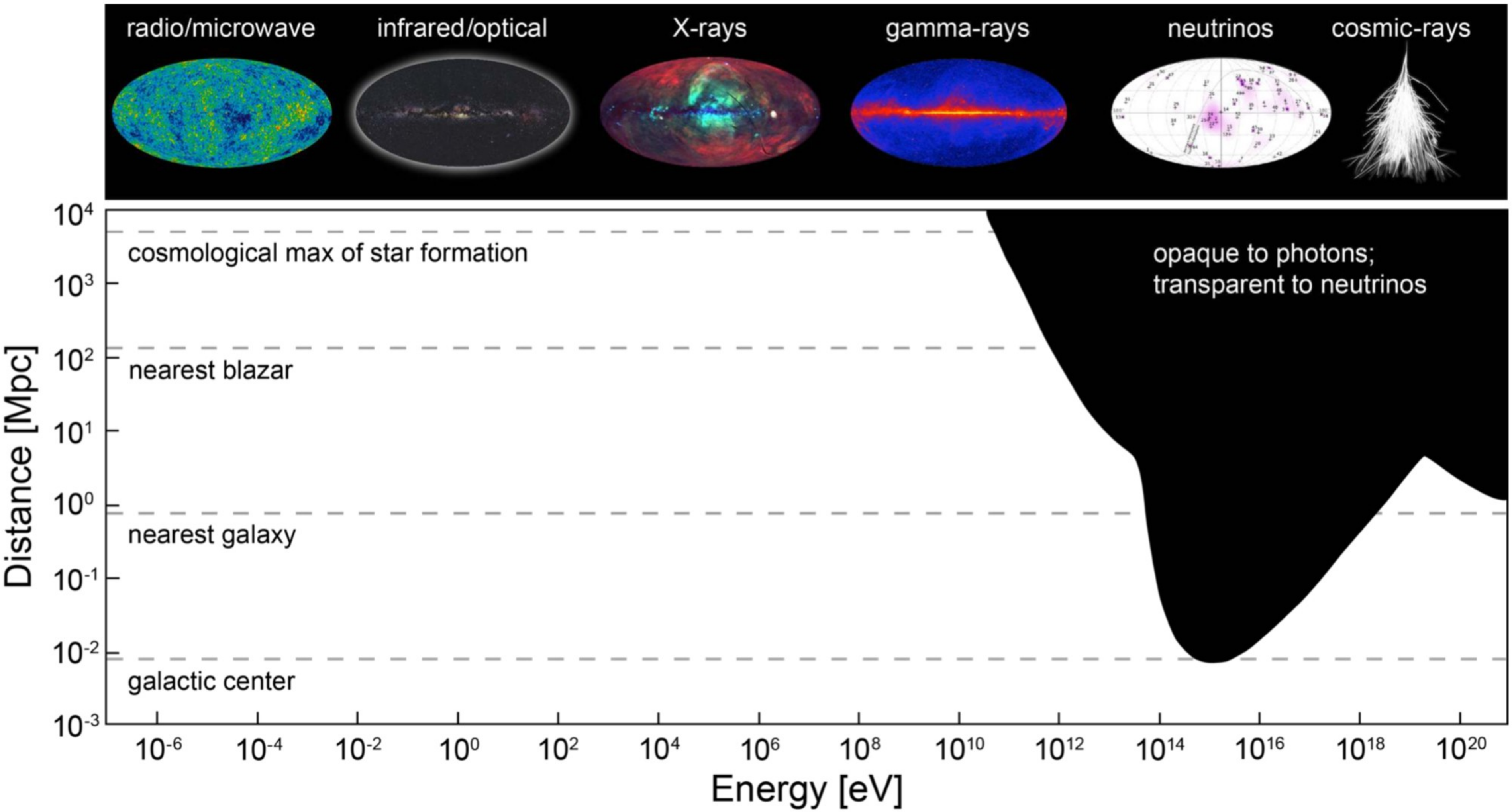
for hadronic mechanism

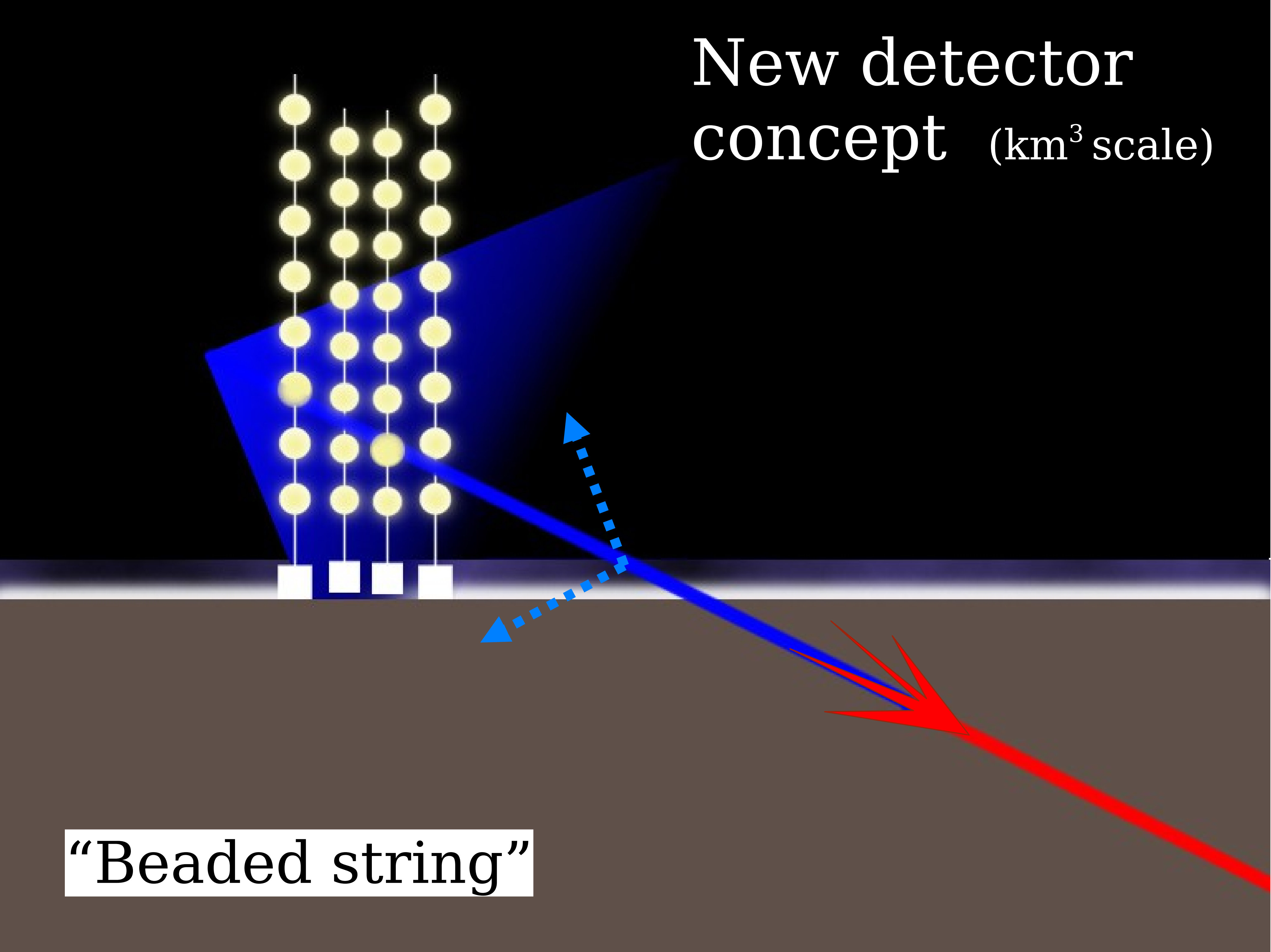
Neutrino not-absorbed

Gamma rays
suffer absorption
inside the source
in propagation

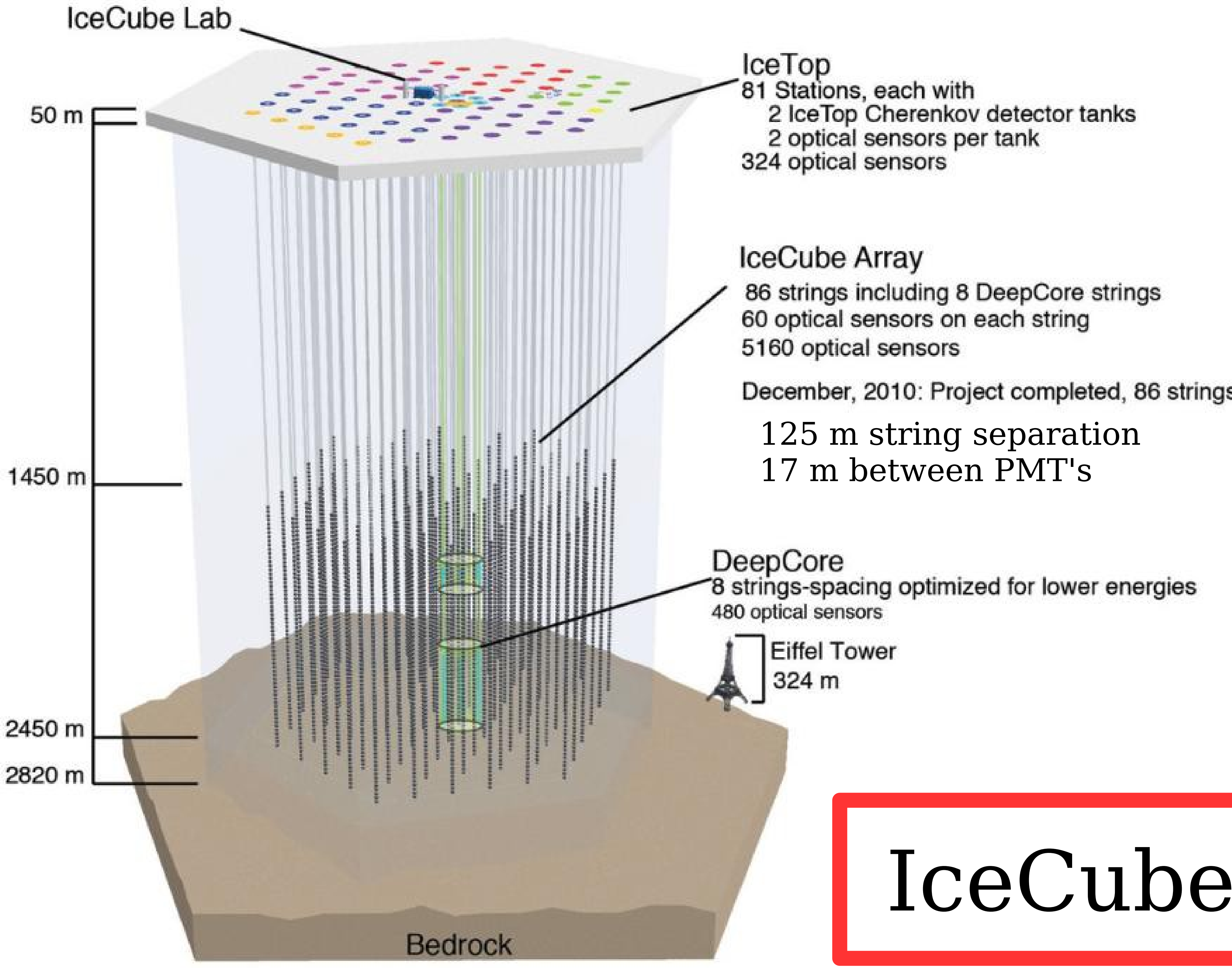
The High energy region of highest interest because of photon absorption

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

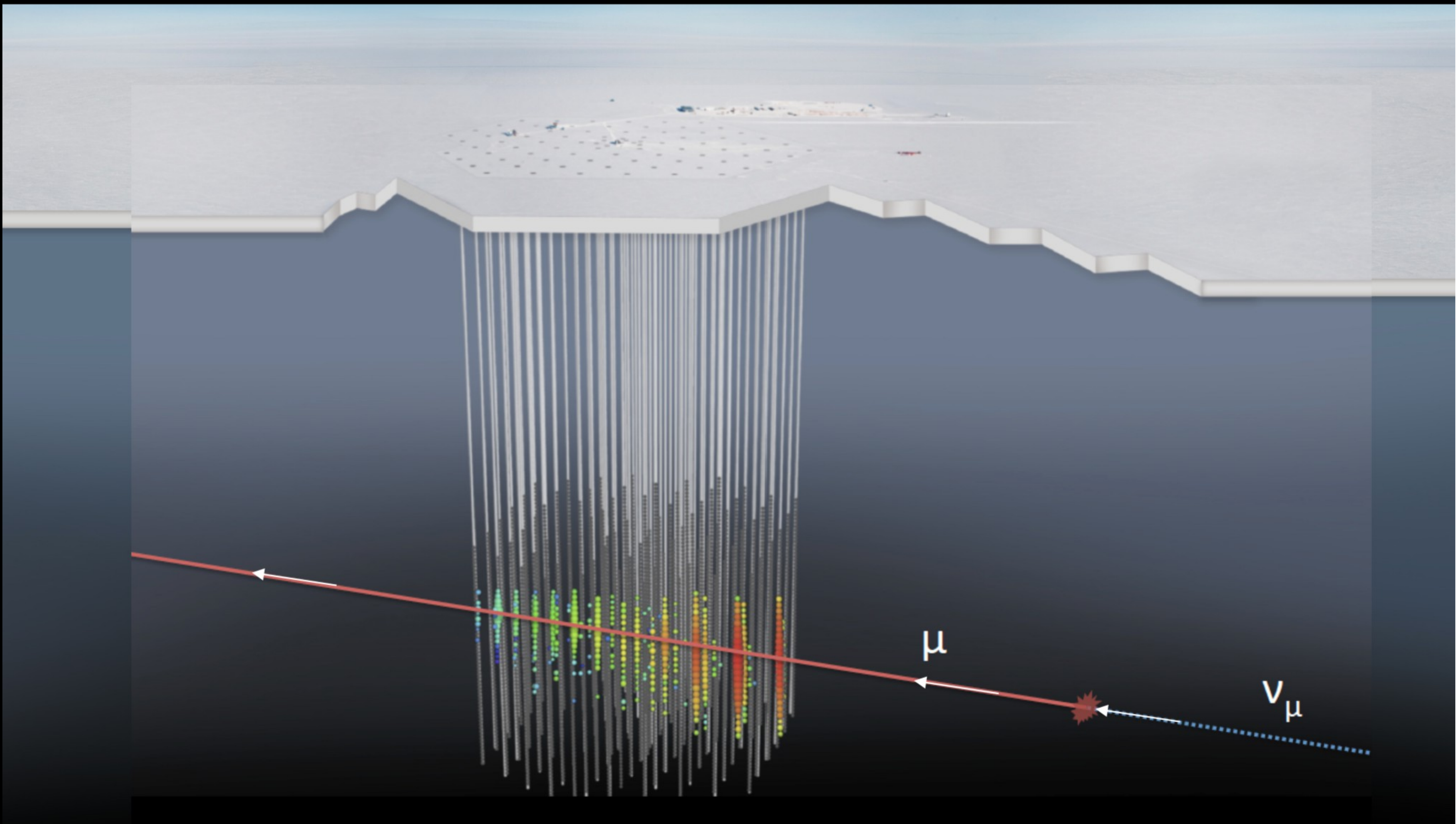


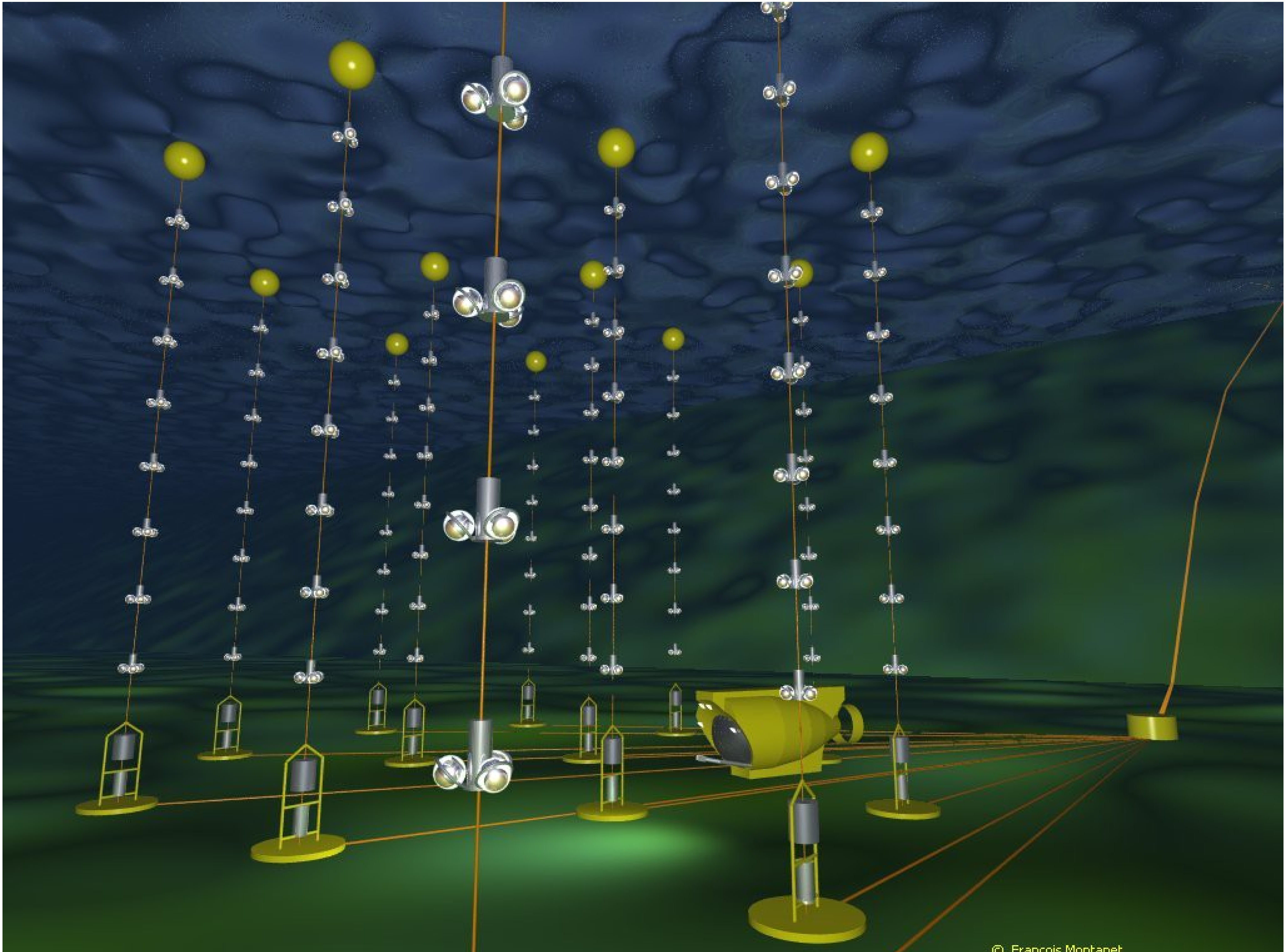

New detector
concept (km^3 scale)
"Beaded string"

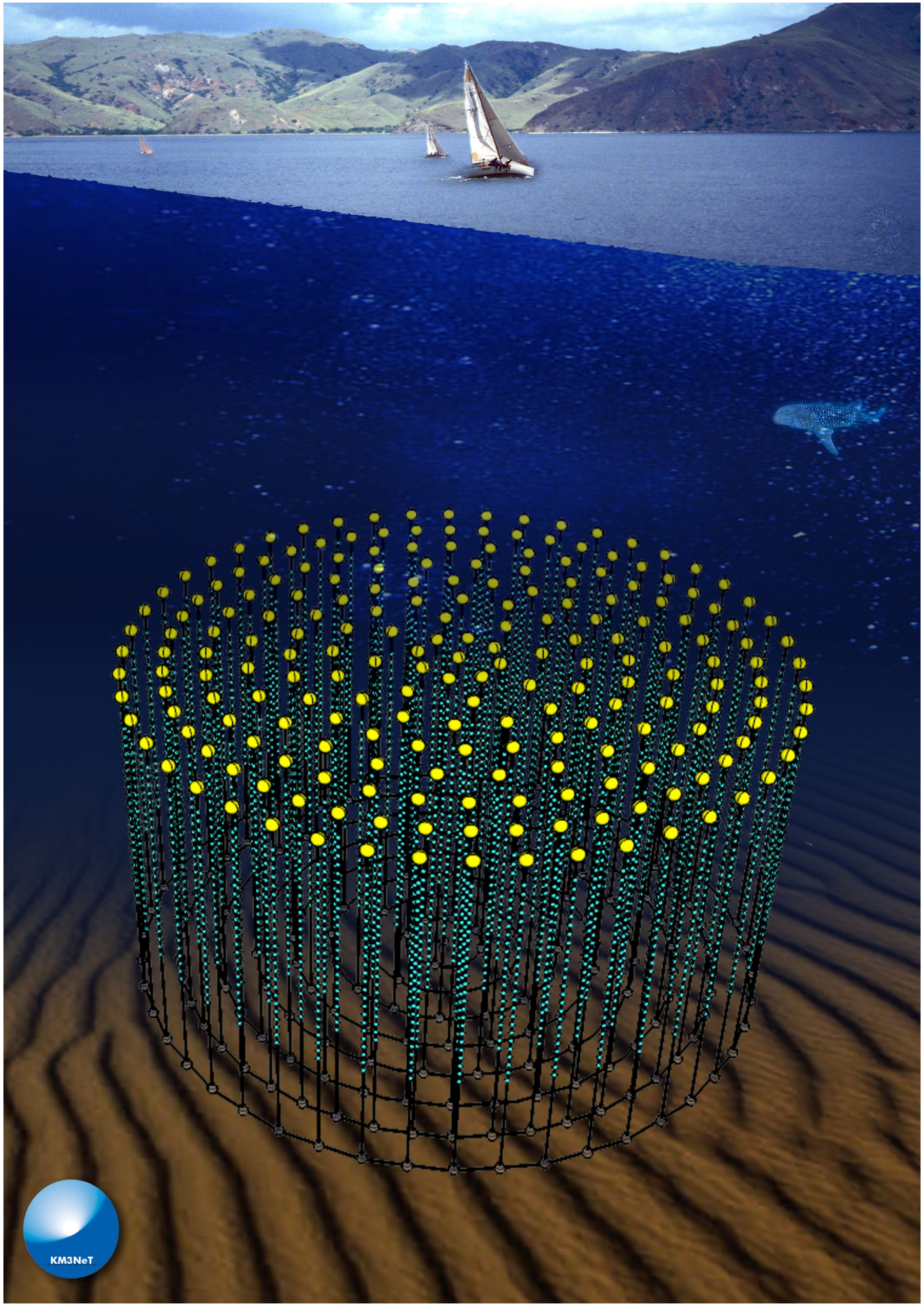
IceCube



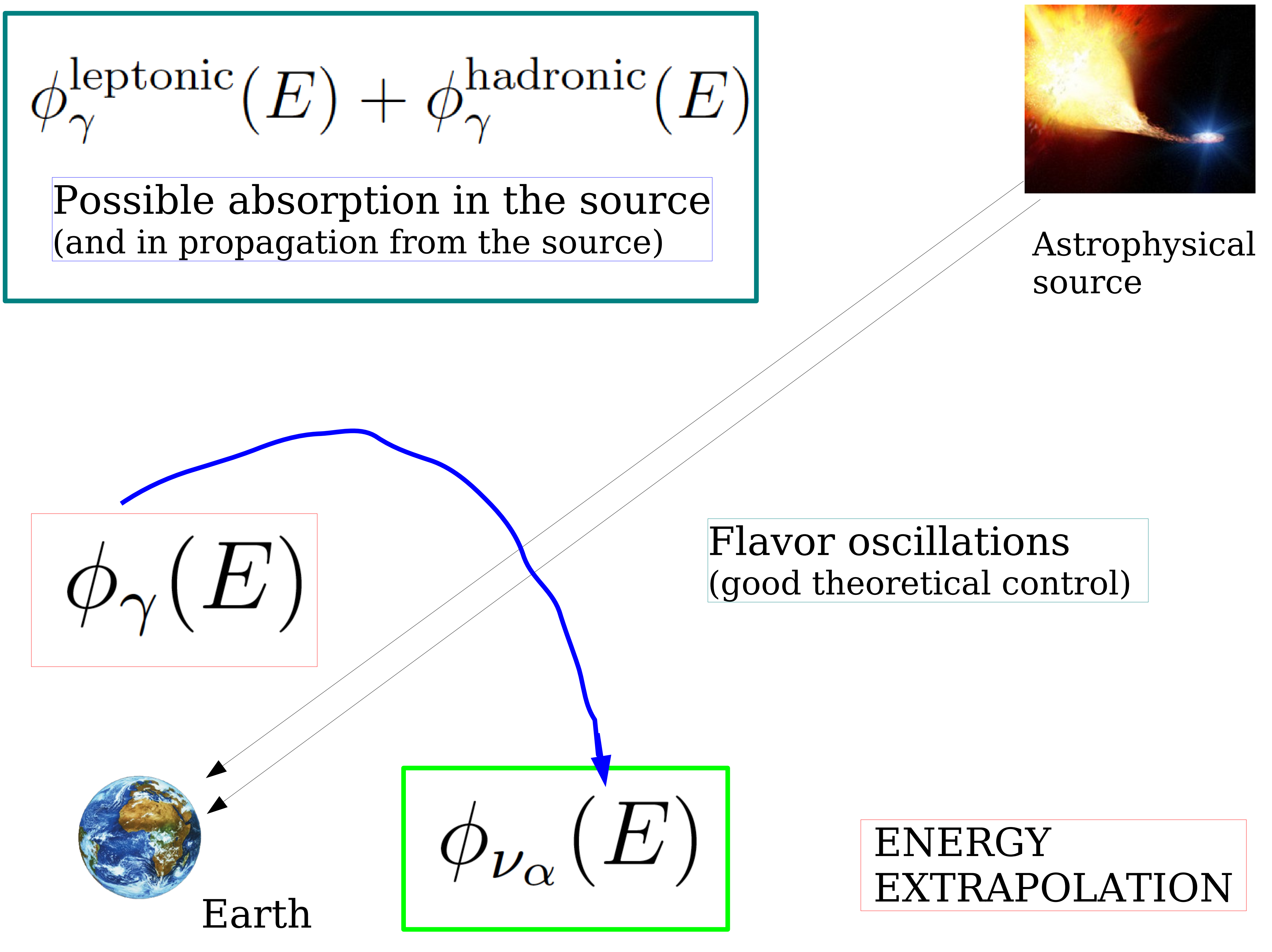
125 m string separation
17 m between PMT's


μ
ν μ


© François Montanet



Artist view of KM3NET

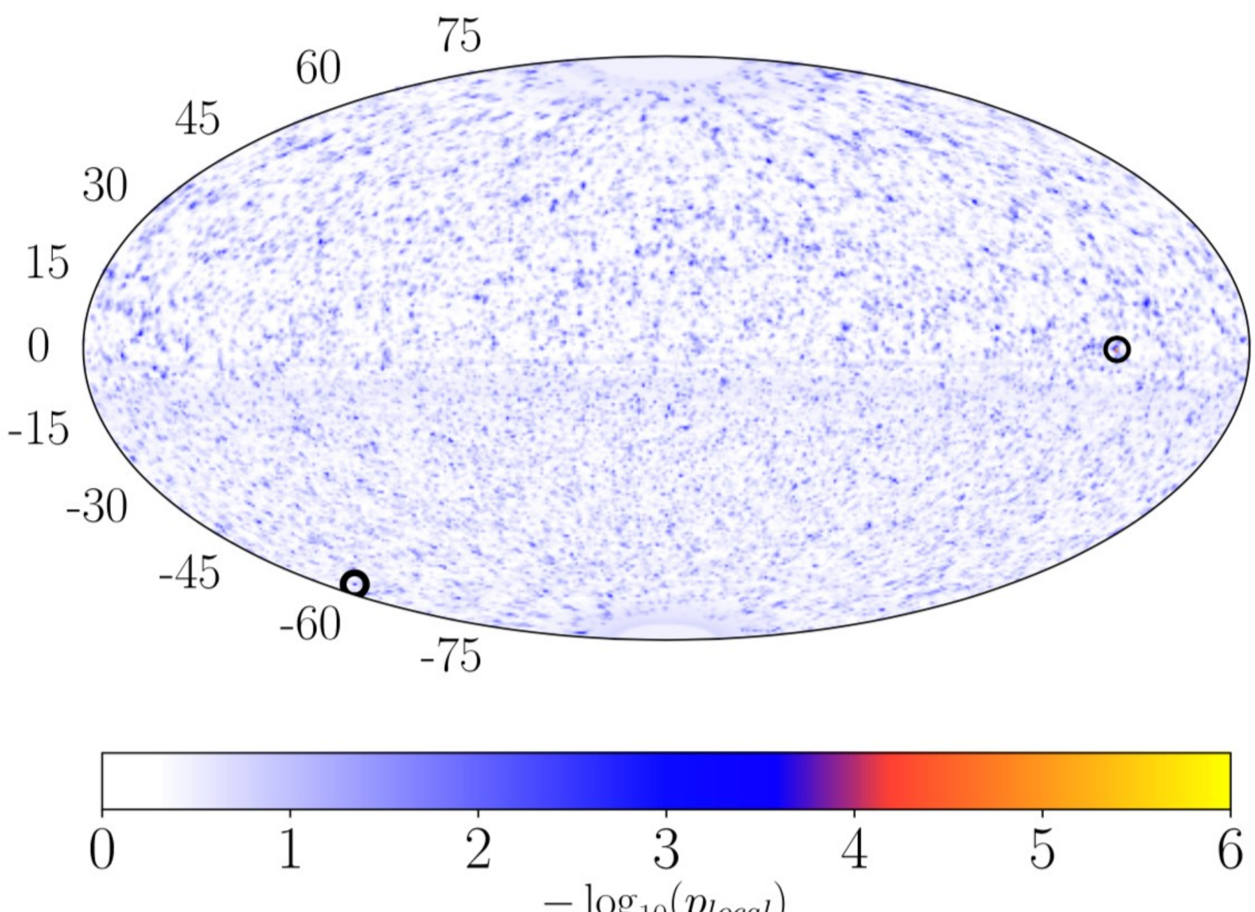


$\phi_\gamma^{\text{leptonic}}(E) + \phi_\gamma^{\text{hadronic}}(E)$
Possible absorption in the source
(and in propagation from the source)
Astrophysical source
$\phi_\gamma(E)$
Flavor oscillations
(good theoretical control)
Earth
$\phi_{\nu_\alpha}(E)$
ENERGY EXTRAPOLATION

Search for Neutrino Point Sources

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

IceCube 10 years search

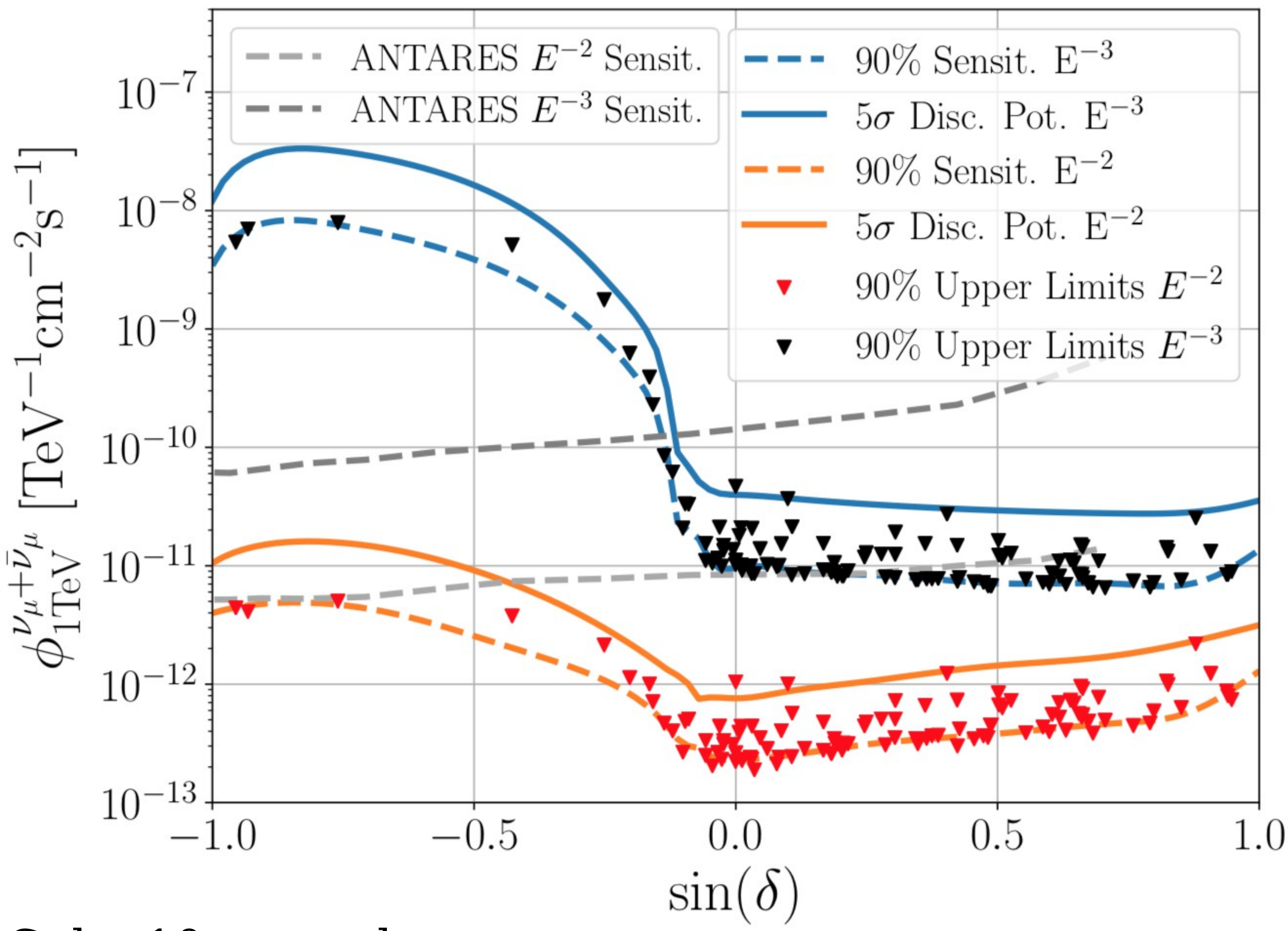


Two most significant excesses

2 AGN

NGC 1068
(2.9 sigma)

TXS 0506+056
(3.3 sigma)



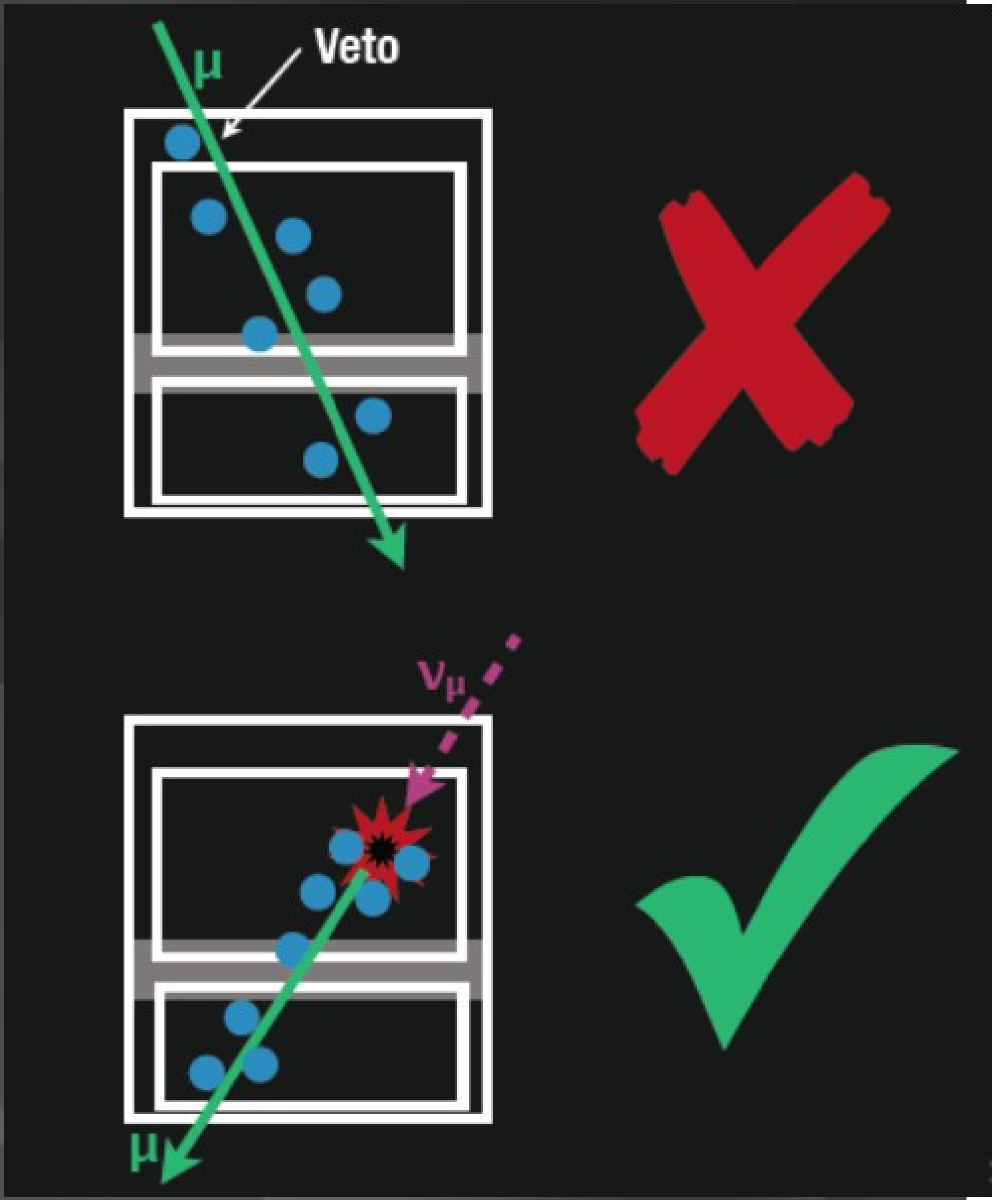
IceCube 10 years data

[from Catalog of potential sources]

$E_\nu \gtrsim 1$ TeV

Starting events

- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

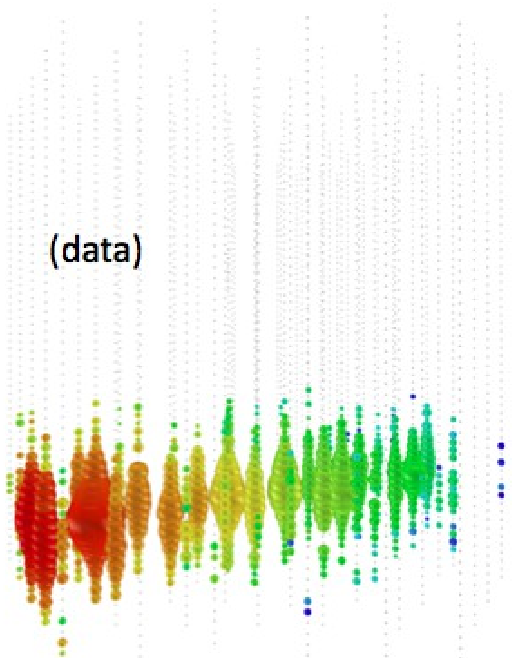


loss in statistics is compensated by event definition

Types of events and interactions

Charged-current ν_μ

(data)



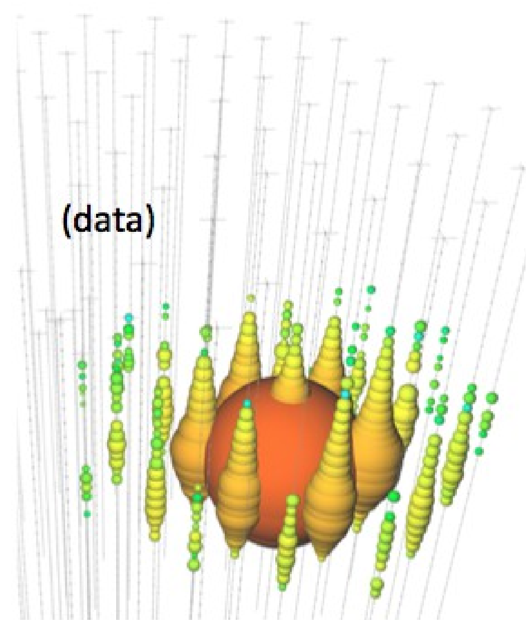
Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

Neutral-current / ν_e

(data)



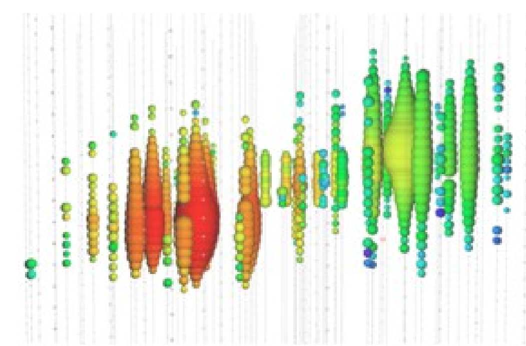
Isolated energy deposition (cascade) with no track

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

Early  Late

Charged-current ν_τ

(simulation)

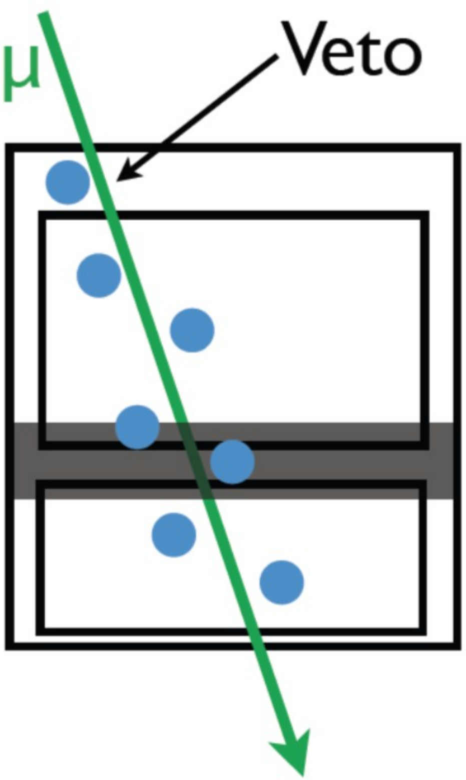


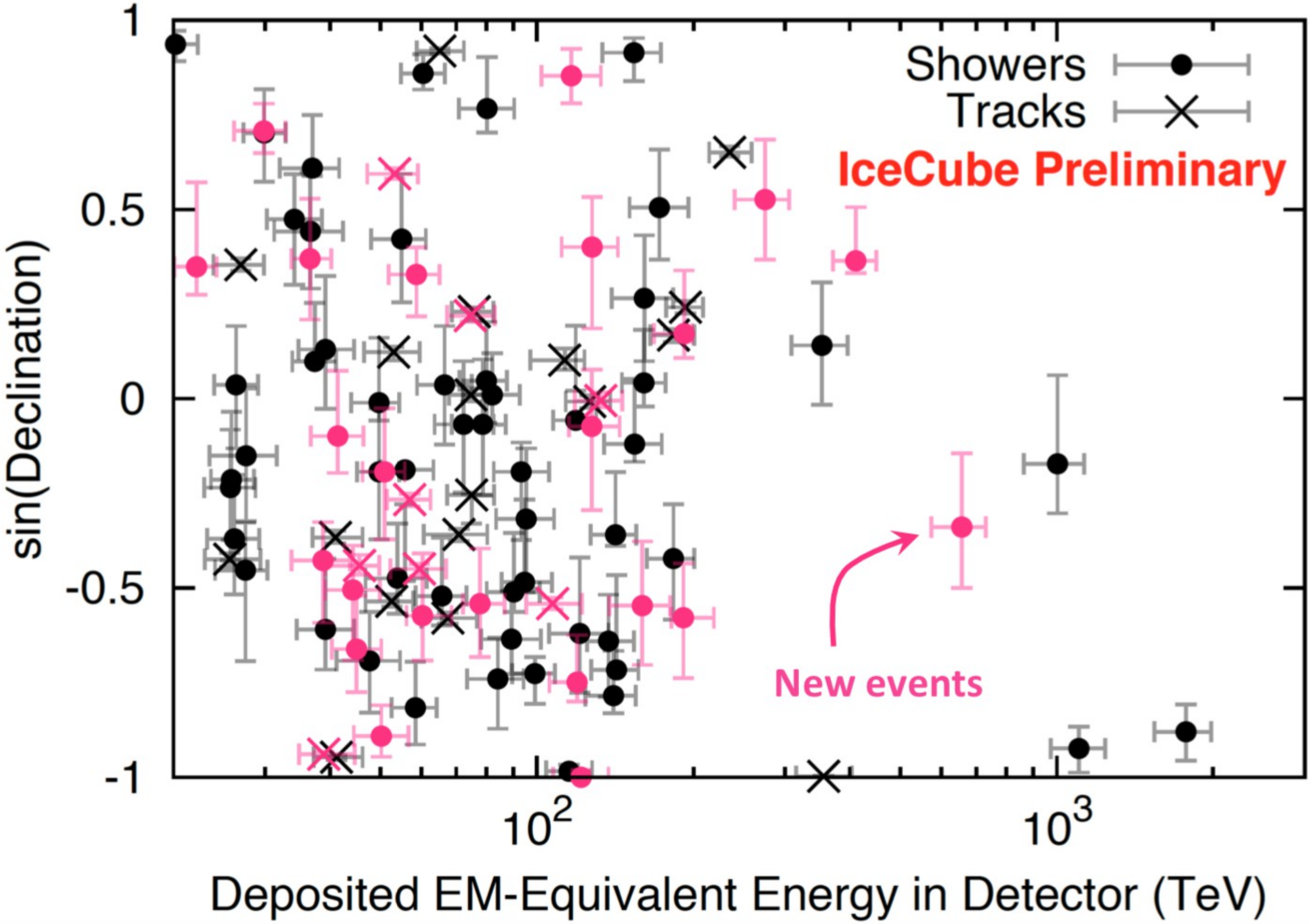
"Double-bang"

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

ID: above~ 100 TeV
(two methods)

High-Energy Starting Events (HESE) – 7.5 yr





Prior result 6 years ICRC 2017 arXiv:1710.01191

Updates to calibration and ice optical properties

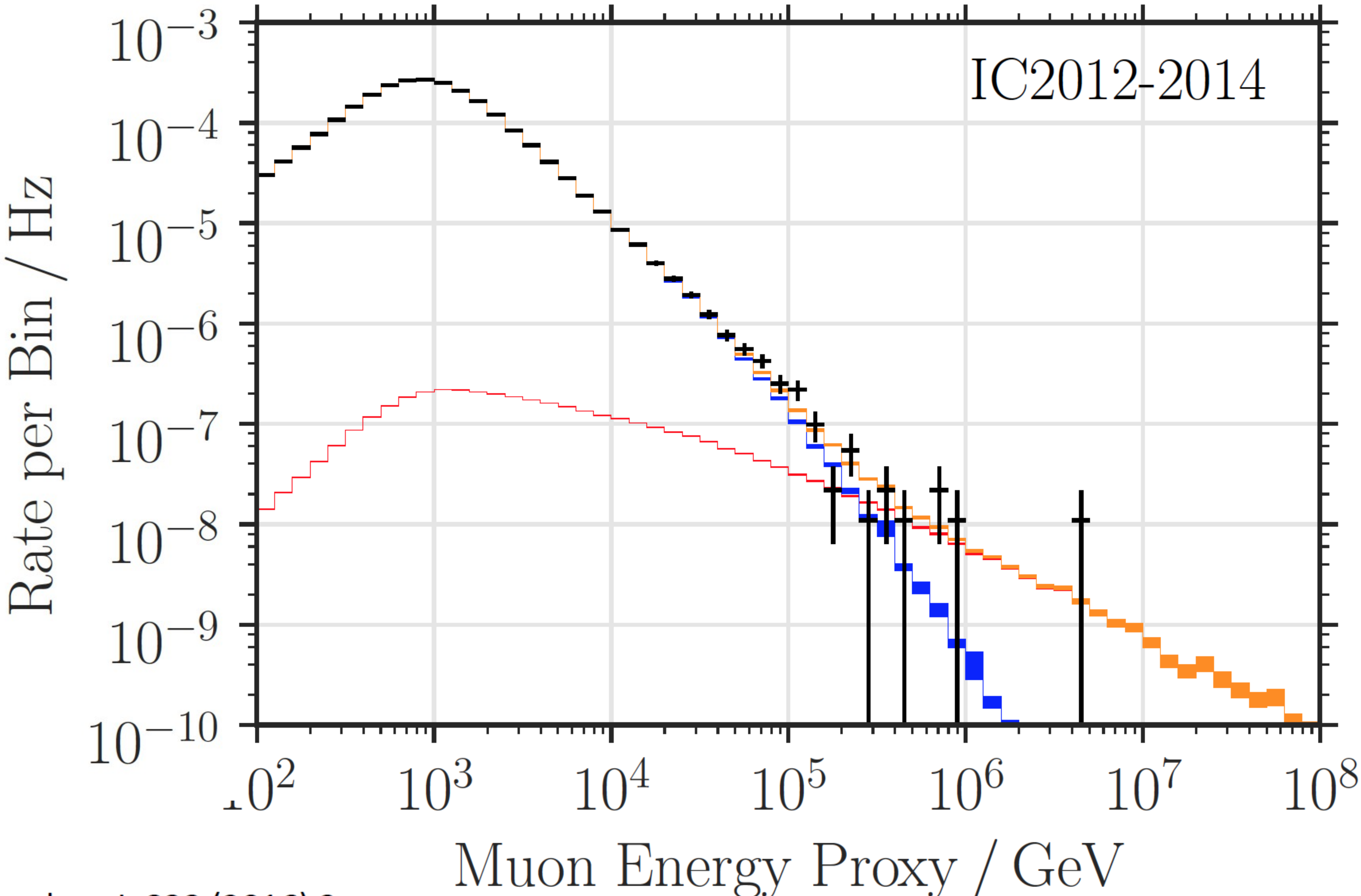
103 events, with 60 events >60 TeV

→ Changes to RA, Dec, energy

IceCube. Nature volume 551 (2017) 596

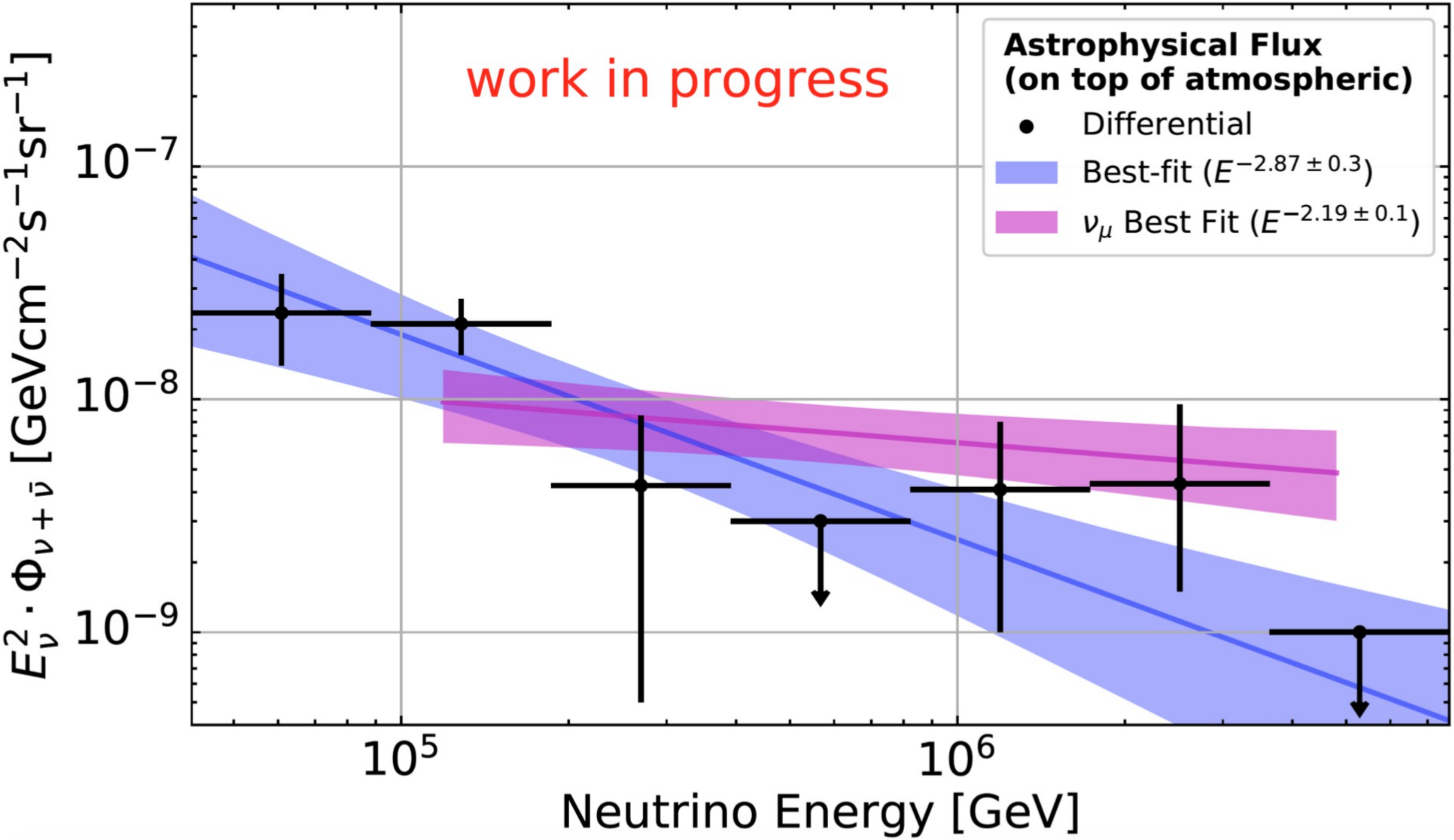
Poster #175. Wandkowsky et al. (IceCube)

Upgoing (neutrino induced) Muons



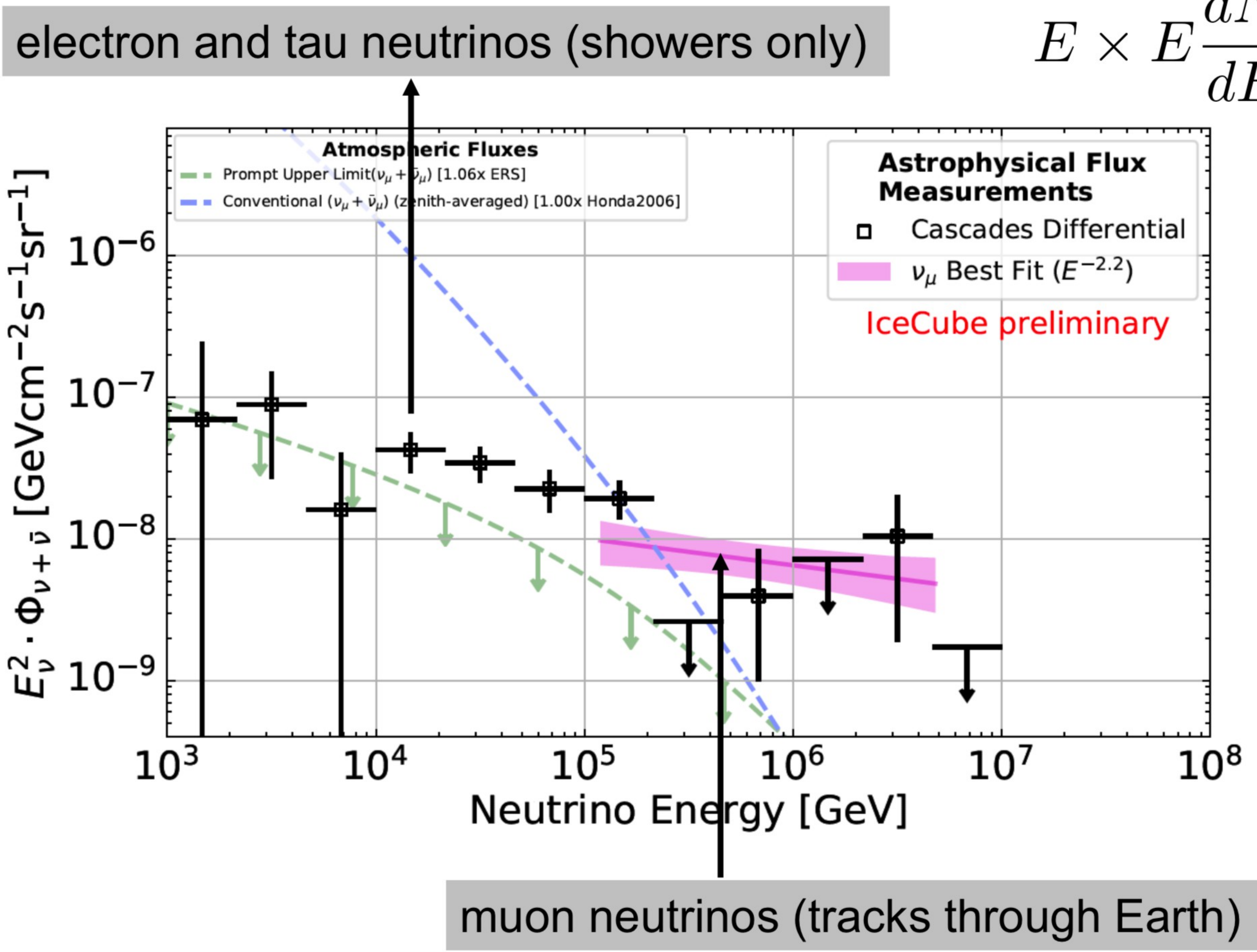
Astrophys. J. 833 (2016) 3

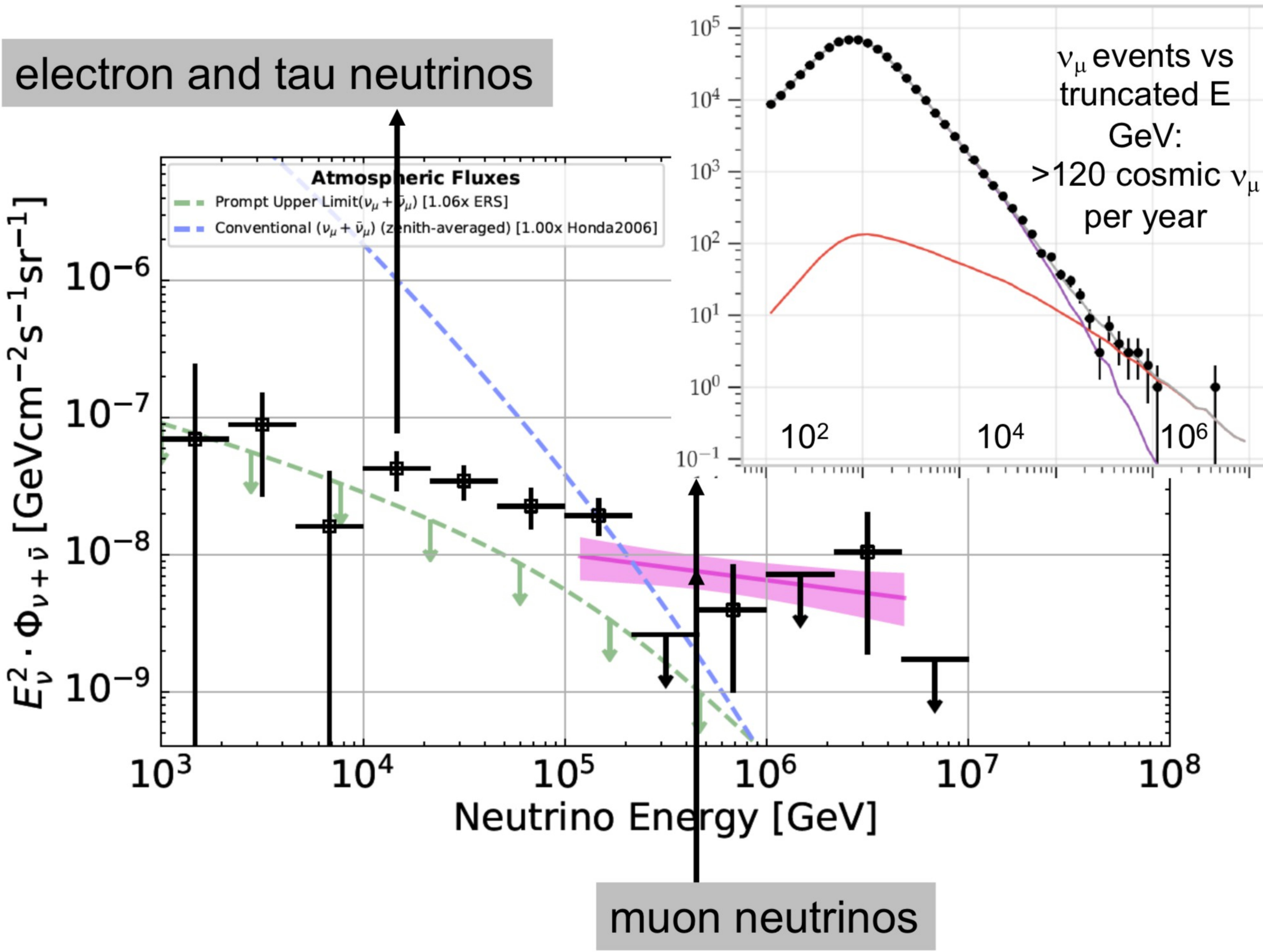
High-Energy Starting Events (HESE) – 7.5 yr



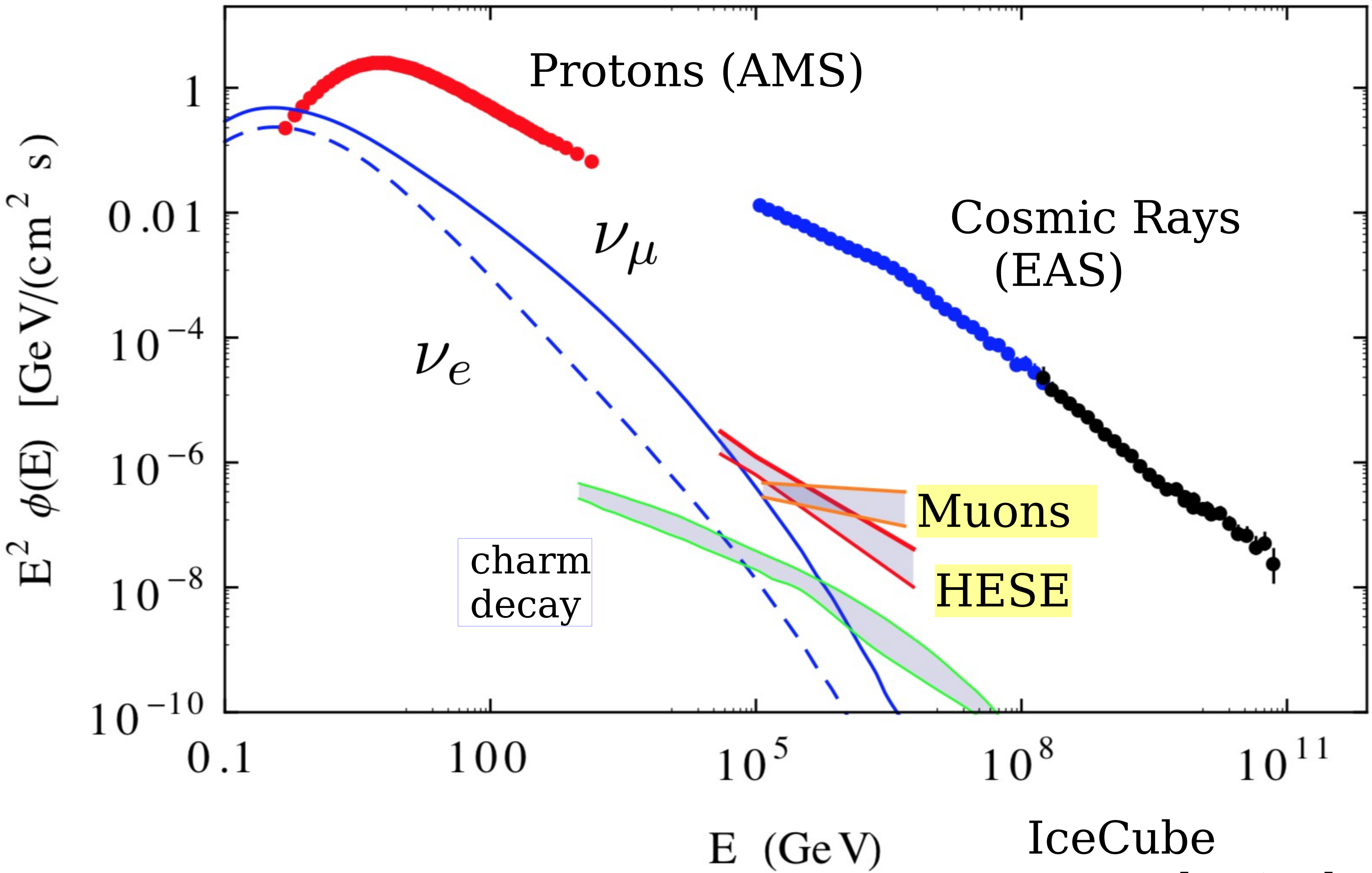
Ignacio Taboada: Neutrino 2018

$$E \times E\frac{dN}{dE}$$




electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
ν_μ events vs truncated E GeV:
>120 cosmic ν_μ per year
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^2
10^4
10^6
muon neutrinos

Signal from the ensemble of extragalactic sources



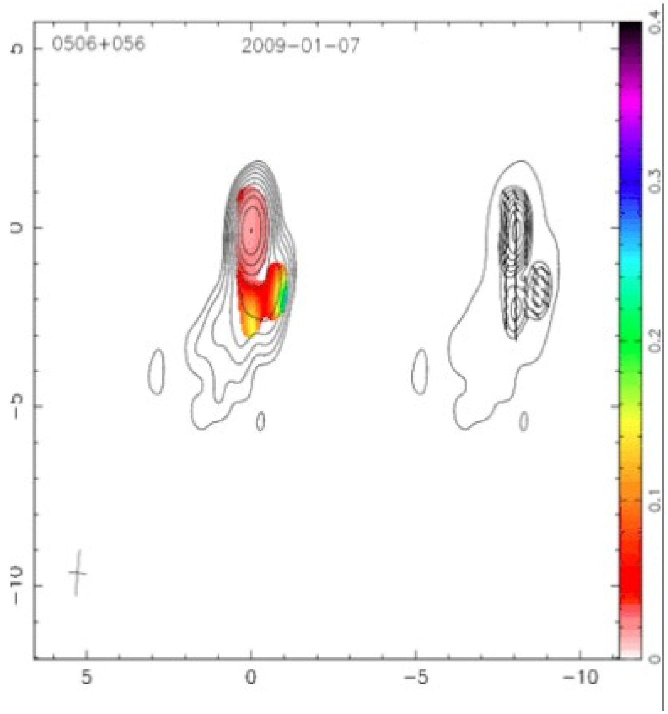
(Angle integrated Spectra)

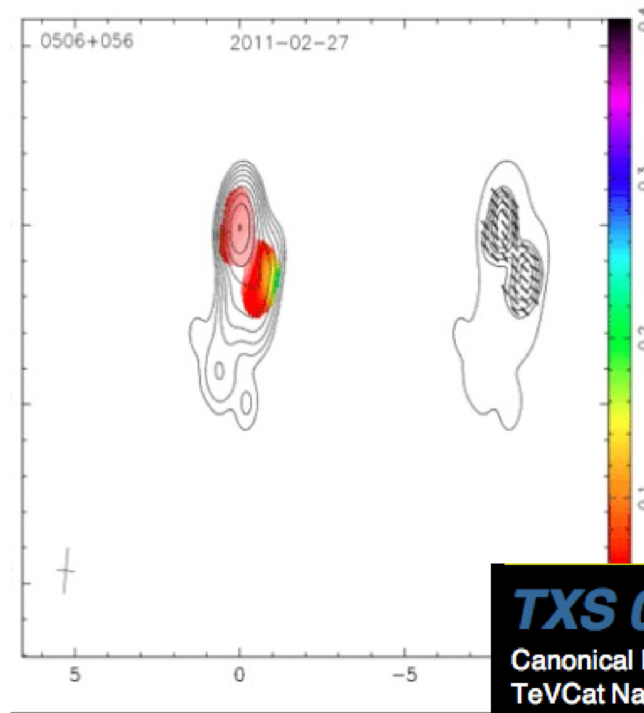
IceCube
Astrophysical
signal

Evidence
of neutrino
emission from a

BLAZAR

TXS 0506+056





TXS 0506+056

$$z = 0.3365 \pm 0.0010$$

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

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

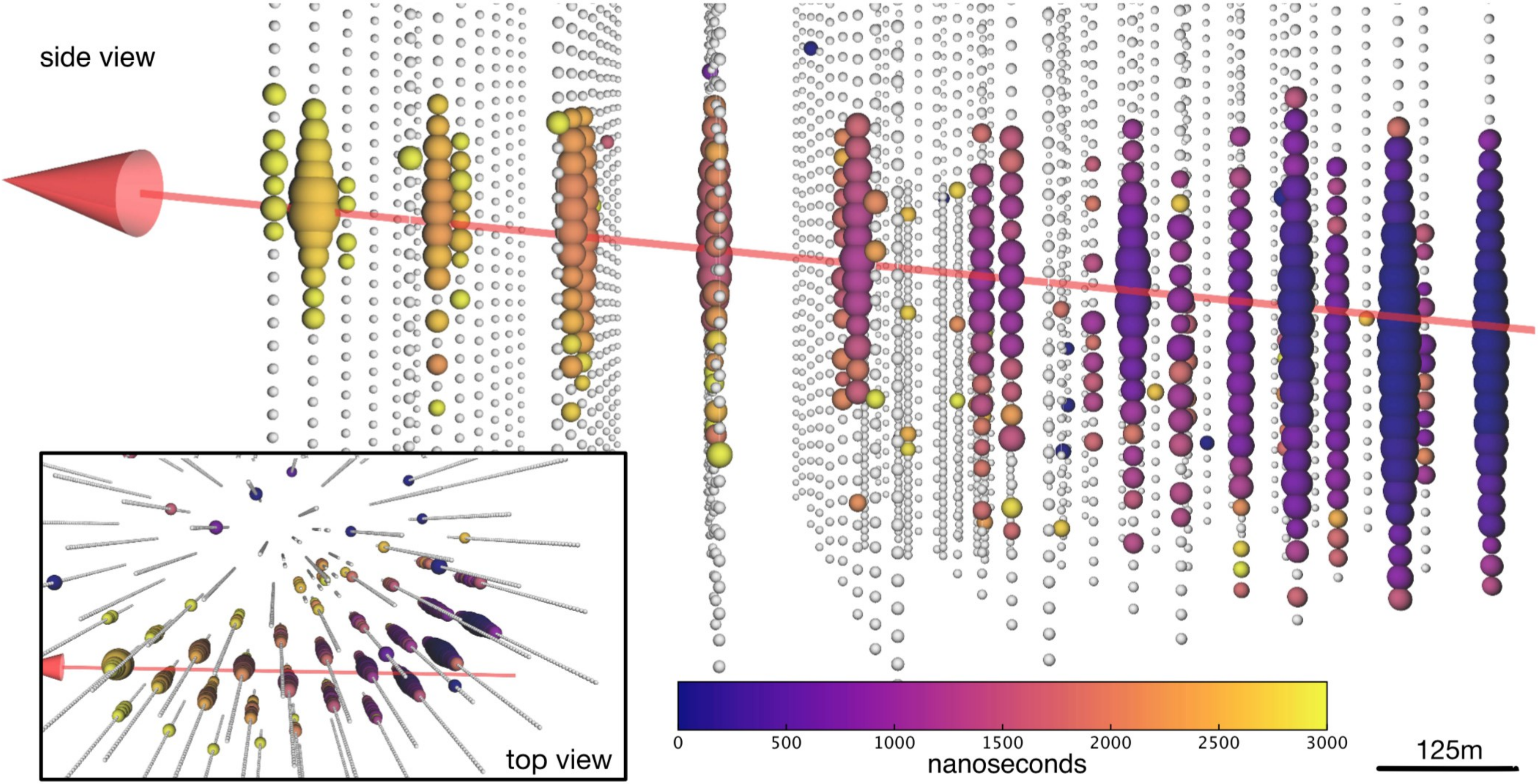
$$\beta_{\text{app}} = \frac{\dot{\Omega}\, d}{c} = 3.7 \pm 0.9$$

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

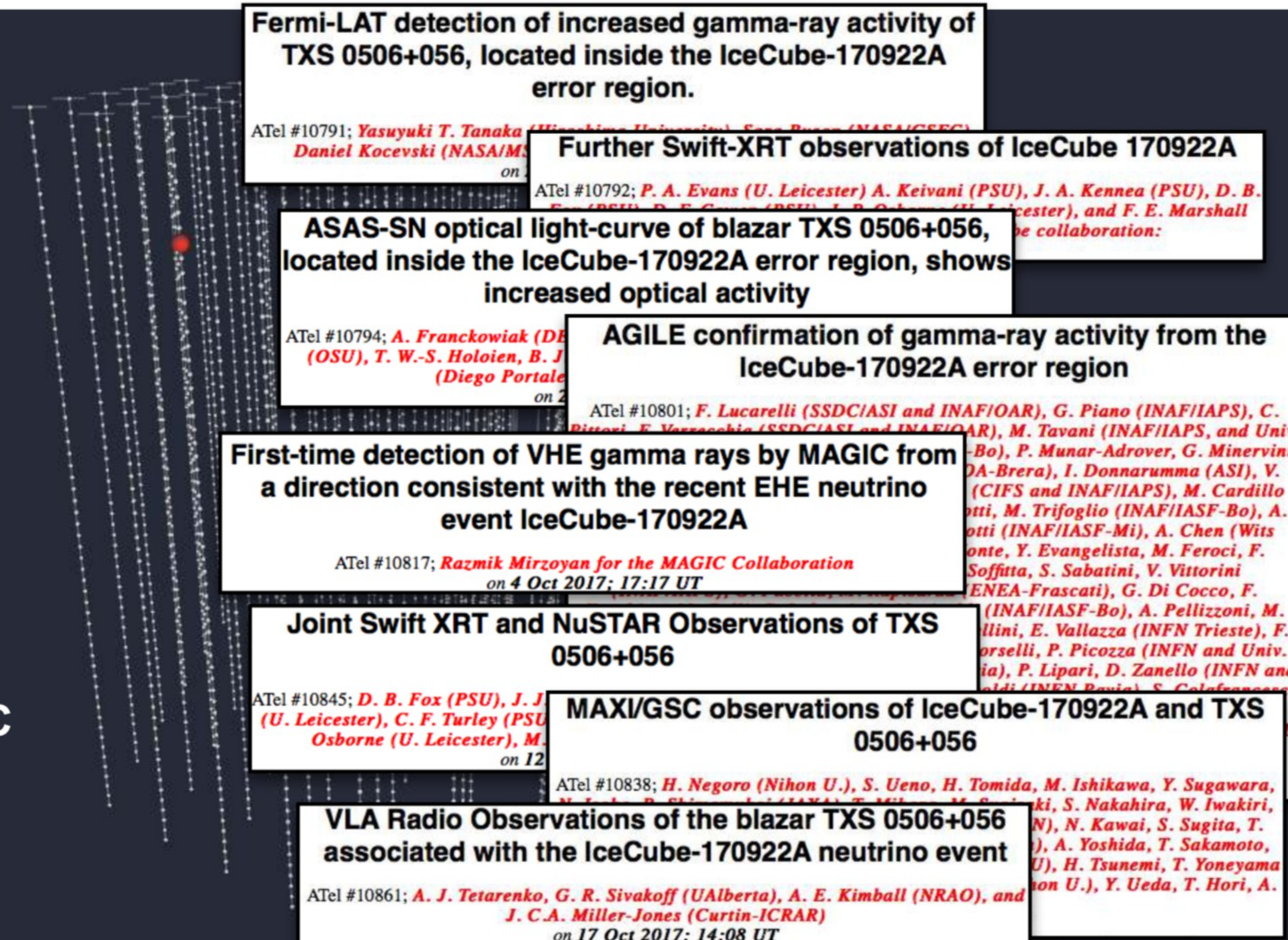
```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

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
```

~~A~~ The 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

Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams *†

Individual astrophysical sources previously detected in neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017 we detected a high-energy neutrino, IceCube-170922A, with an energy of ∼290 terra–electronvolts. Its arrival direction was consistent with the location of a known γ-ray blazar TXS 0506+056, observed to be in a flaring state. An extensive multi-wavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the first detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

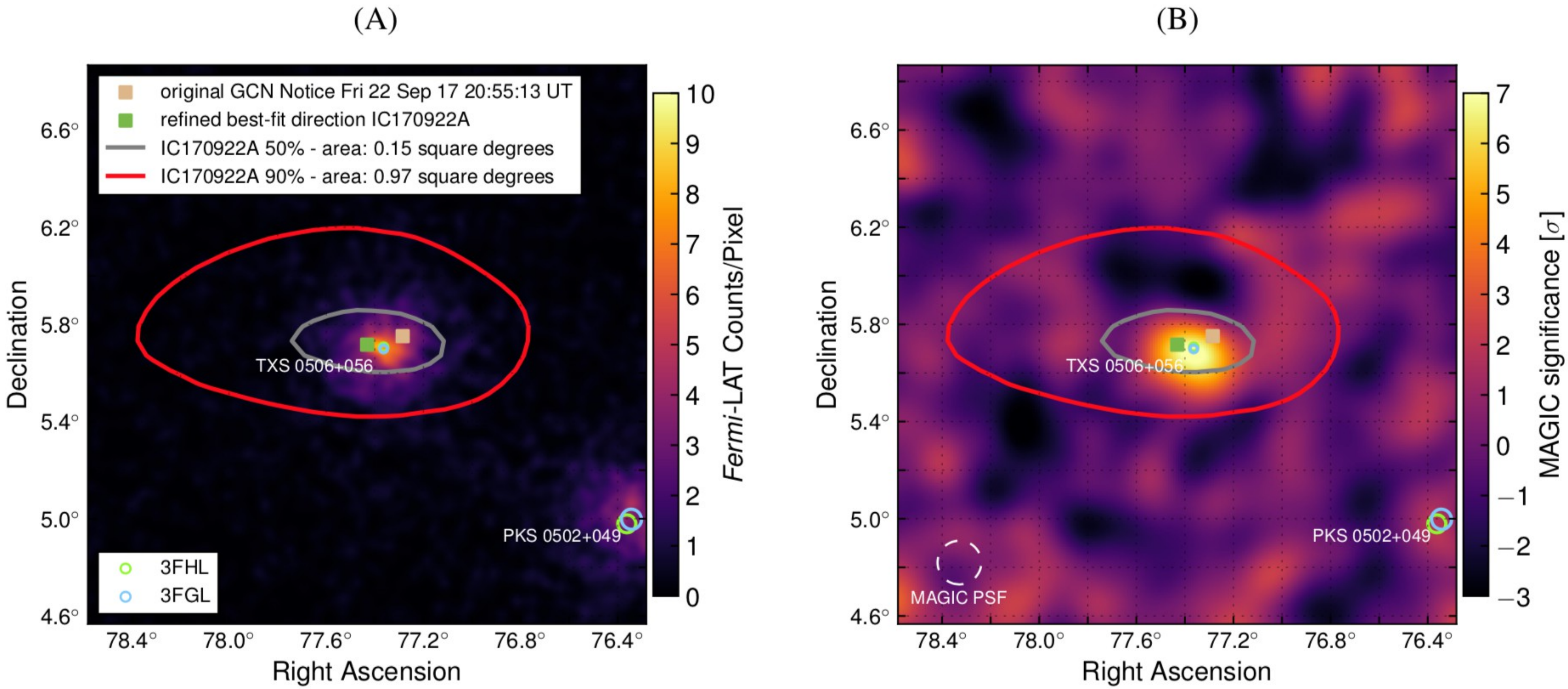


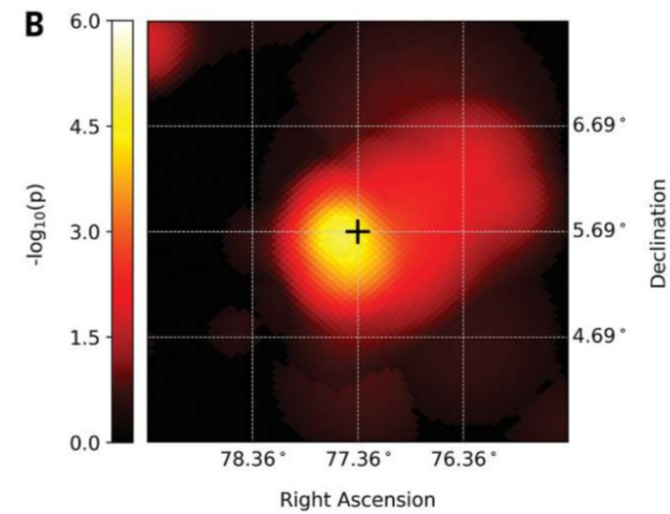
Figure 2: ***Fermi*-LAT and MAGIC observations of IceCube-170922A's location.** Sky position of IceCube-170922A in J2000 equatorial coordinates overlaying the γ-ray counts from *Fermi*-LAT above 1 GeV (A) and the signal significance as observed by MAGIC (B) in this region. The tan square indicates the position reported in the initial alert and the green square indicates the final best-fitting position from follow-up reconstructions (*18*). Gray and red curves show the 50% and 90% neutrino containment regions, respectively, including statistical and systematic errors. *Fermi*-LAT data are shown as a photon counts map in 9.5 years of data in units of counts per pixel, using detected photons with energy of 1 to 300 GeV in a 2° by 2° region around TXS0506+056. The map has a pixel size of 0.02° and was smoothed with a 0.02 degree-wide Gaussian kernel. MAGIC data are shown as signal significance for γ-rays above 90 GeV. Also shown are the locations of a γ-ray source observed by *Fermi*-LAT as given in the *Fermi*-LAT Third Source Catalog (3FGL) (*23*) and the Third Catalog of Hard *Fermi*-LAT Sources (3FHL) (*24*) source catalogs, including the identified positionally coincident 3FGL object TXS 0506+056. For *Fermi*-LAT catalog objects, marker sizes indicate the 95% C.L. positional uncertainty of the source.

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events with respect to atmospheric backgrounds at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are the first identifiable sources of the high-energy astrophysical neutrino flux.

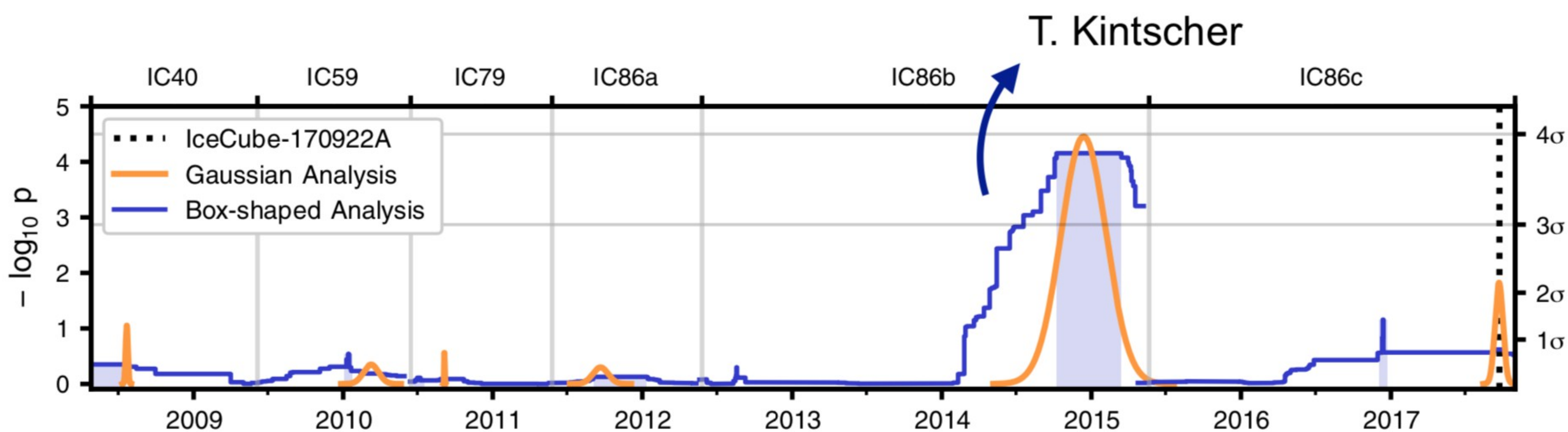
IC170922A / TXS 0506+56

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!

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

Oscillations of Astrophysical Neutrinos

Expected flavor composition

[Standard mechanism of production]

$$\nu_e \simeq \nu_\mu \simeq \nu_\tau$$

Oscillation lengths:

short for astrophysical distances

$$L_{\rm osc}^{(12)} \simeq 108 \left(\frac{E}{10^{20}\ \text{eV}} \right) \text{pc}$$

$$L_{\rm osc}^{(23)} \simeq L_{\rm osc}^{(13)} \simeq 3.2 \left(\frac{E}{10^{20}\ \text{eV}} \right) \text{pc}$$

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) = \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2$$

$$= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2$$

$$+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

$$+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

$$X_{\text{source}} \gg E / |\Delta m^2_{jk}|$$

Oscillating terms average to zero

$$\langle P(\nu_\alpha \to \nu_\beta) \rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

$$\simeq \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

$$\theta_{13} \simeq 0$$

$$\theta_{23} \simeq 45^\circ$$

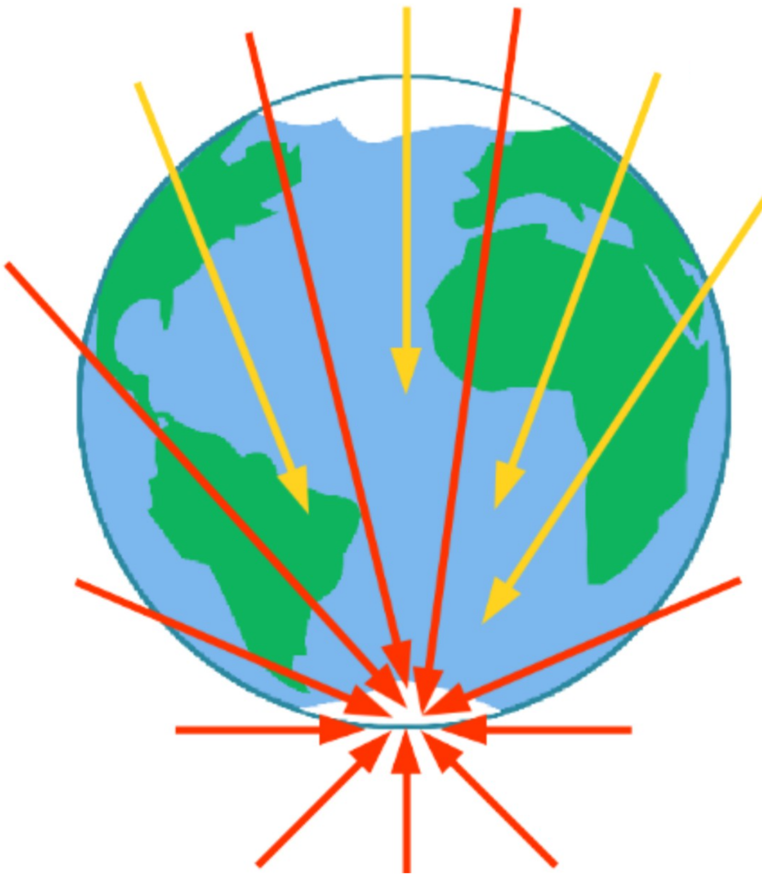
$$v = \cos^2\theta_{12} \sin^2\theta_{12} \simeq 0.2$$

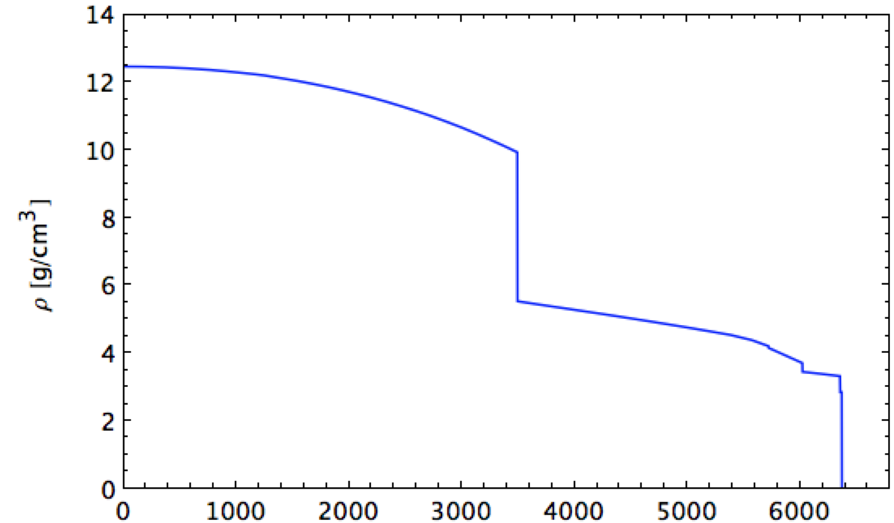
$$\begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

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

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

Measure Cross section



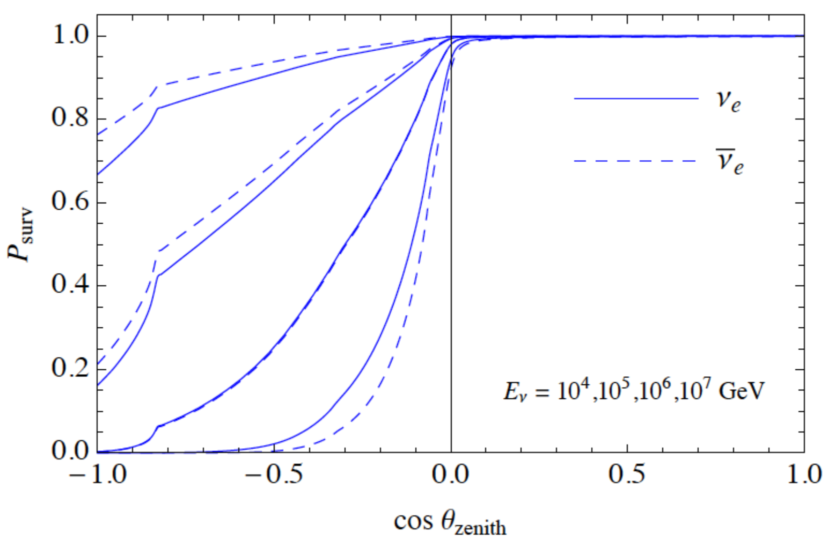


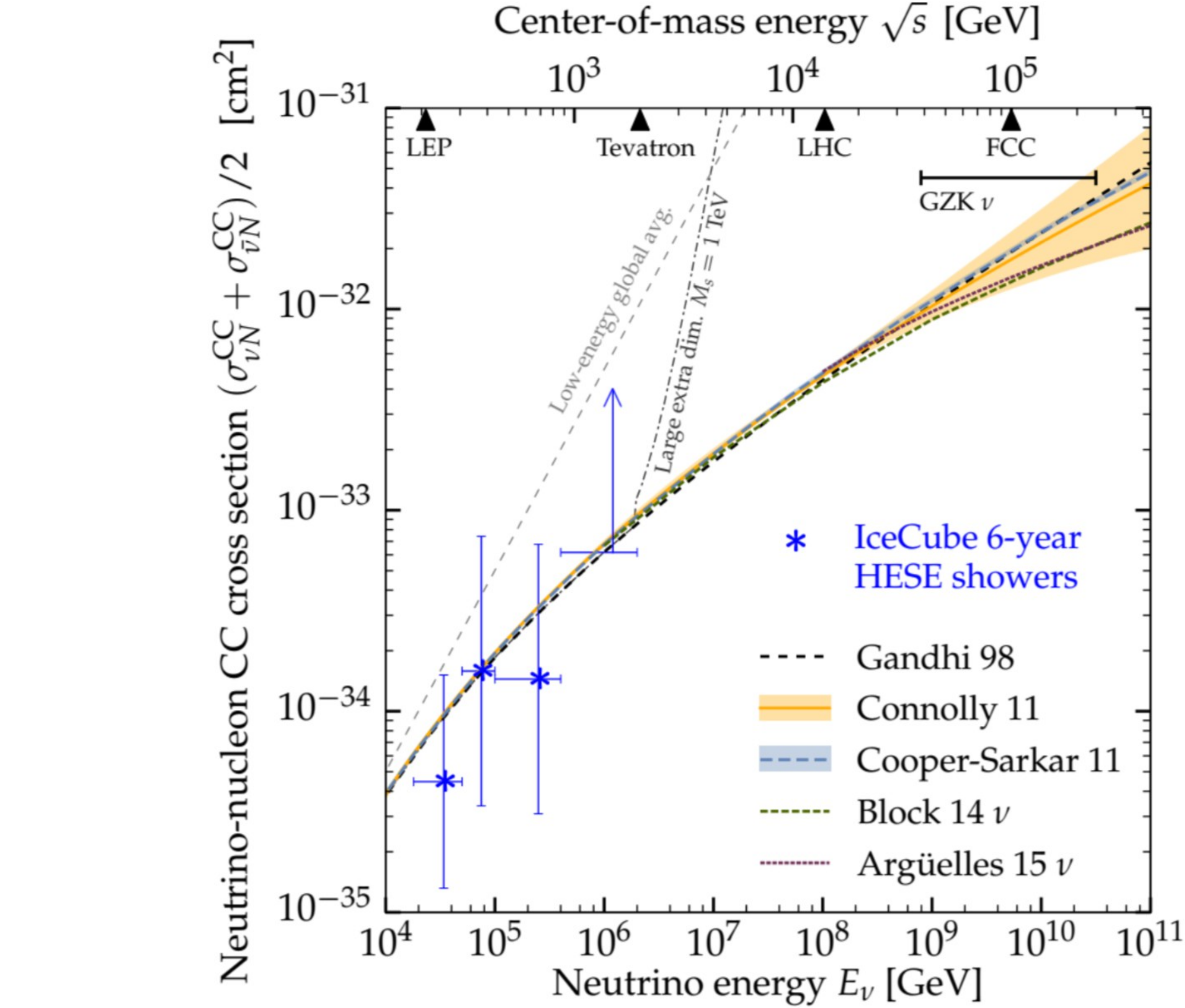
$$P_{\rm surv} = e^{-\tau(E,\Omega)}$$

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

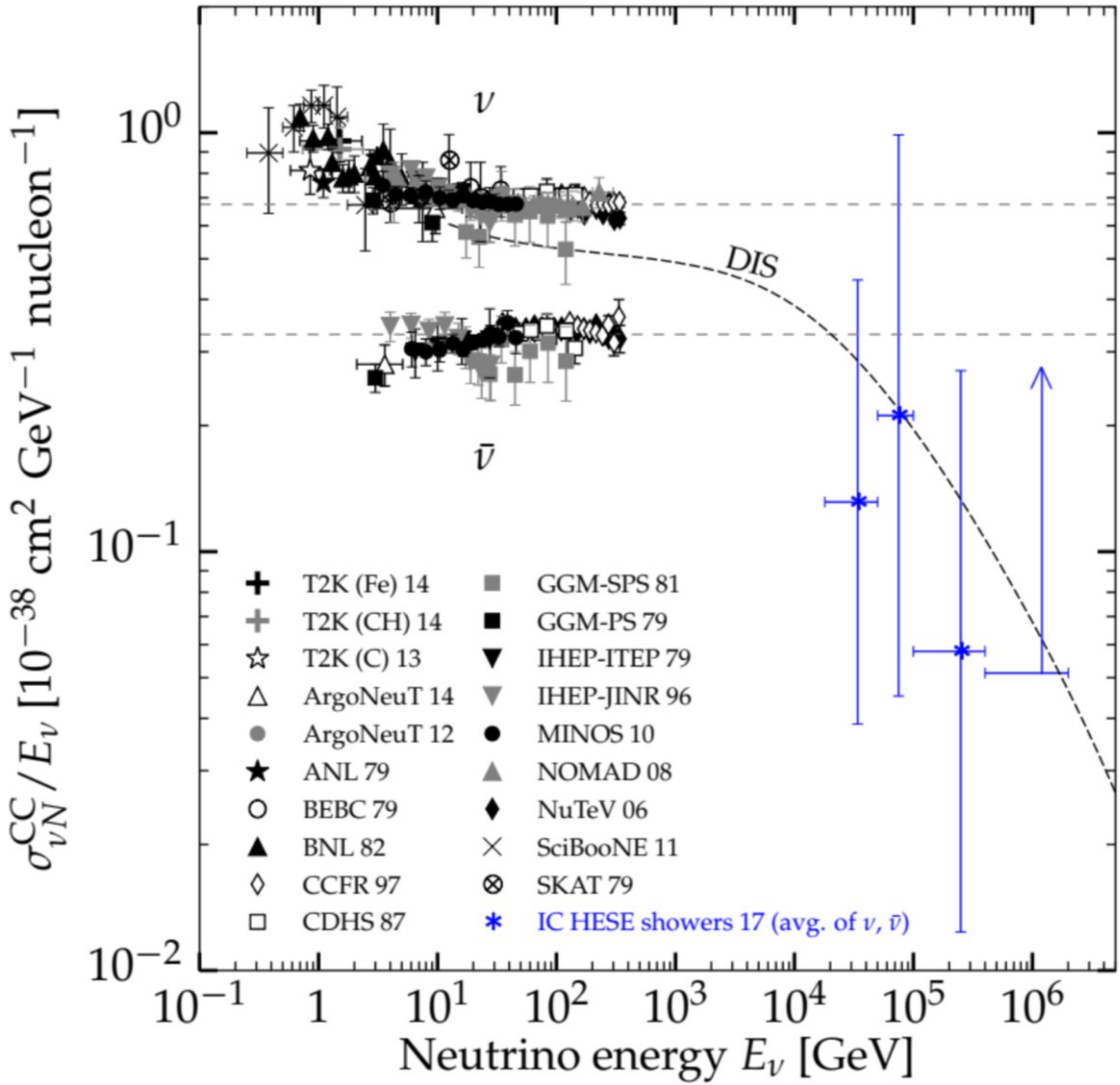
$$\frac{X_\oplus}{m_p} \simeq 6.5\ {\rm nb}^{-1}$$

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





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]

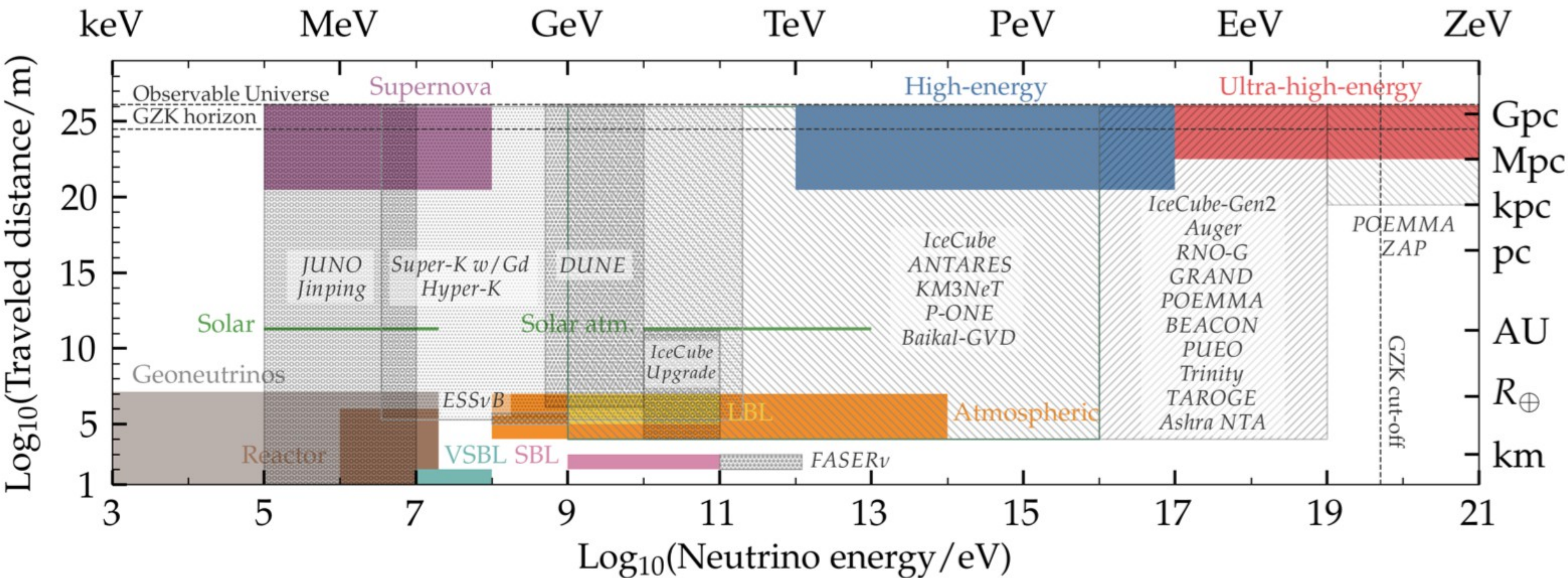


ν
$\bar{\nu}$
DIS
10^0
10^{-1}
10^{-2}
$\sigma^{CC}_{\nu N}/E_\nu$ [10^{-38} cm^2 GeV^{-1} nucleon^{-1}]
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
10^6
Neutrino energy E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
IC HESE showers 17 (avg. of ν, $\bar{\nu}$)

New Physics effects

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

Study very favorable with Astrophysical Neutrinos



Cosmic Neutrino Probes of Fundamental Physics

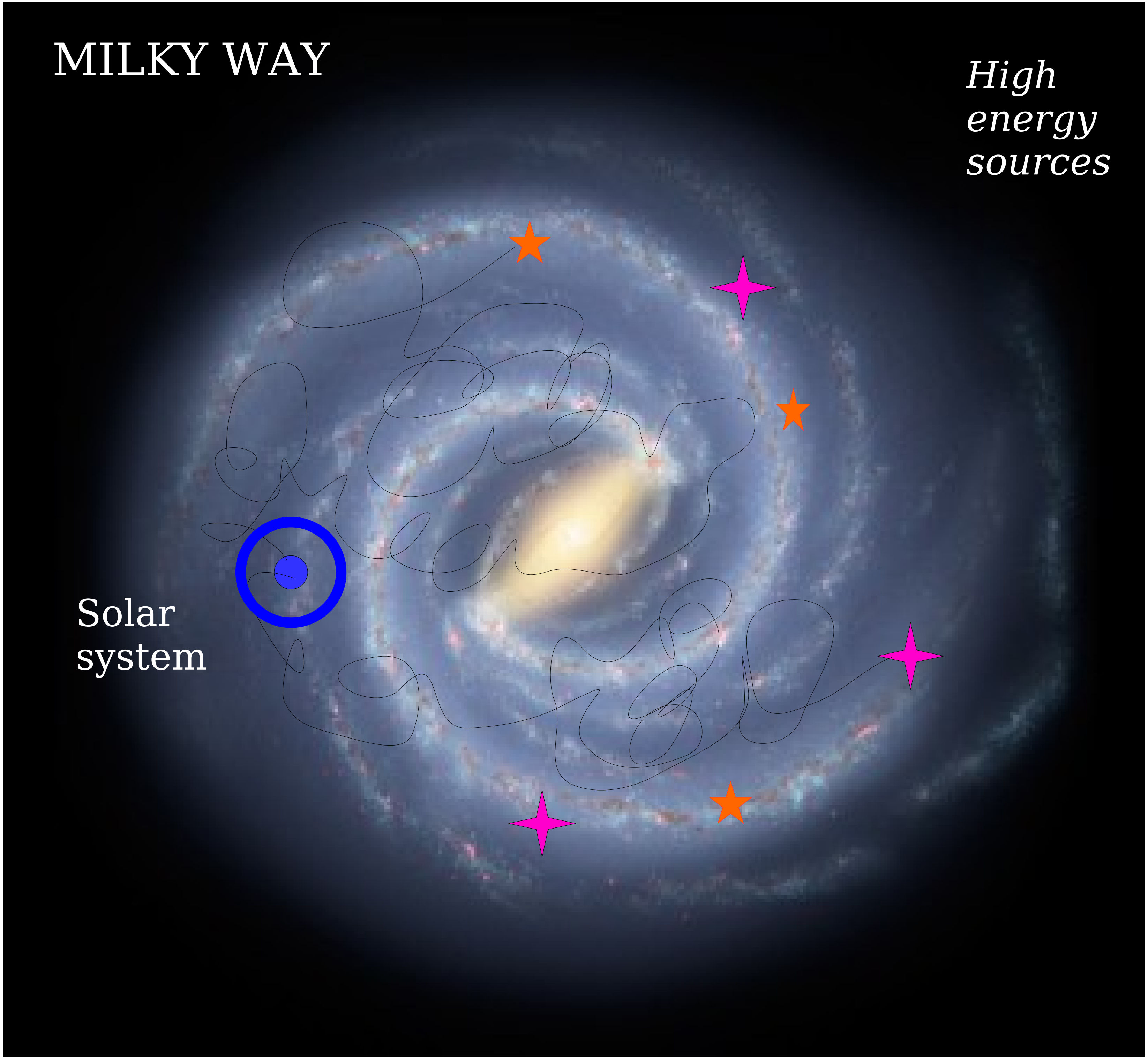
LoI Snowmass 2021

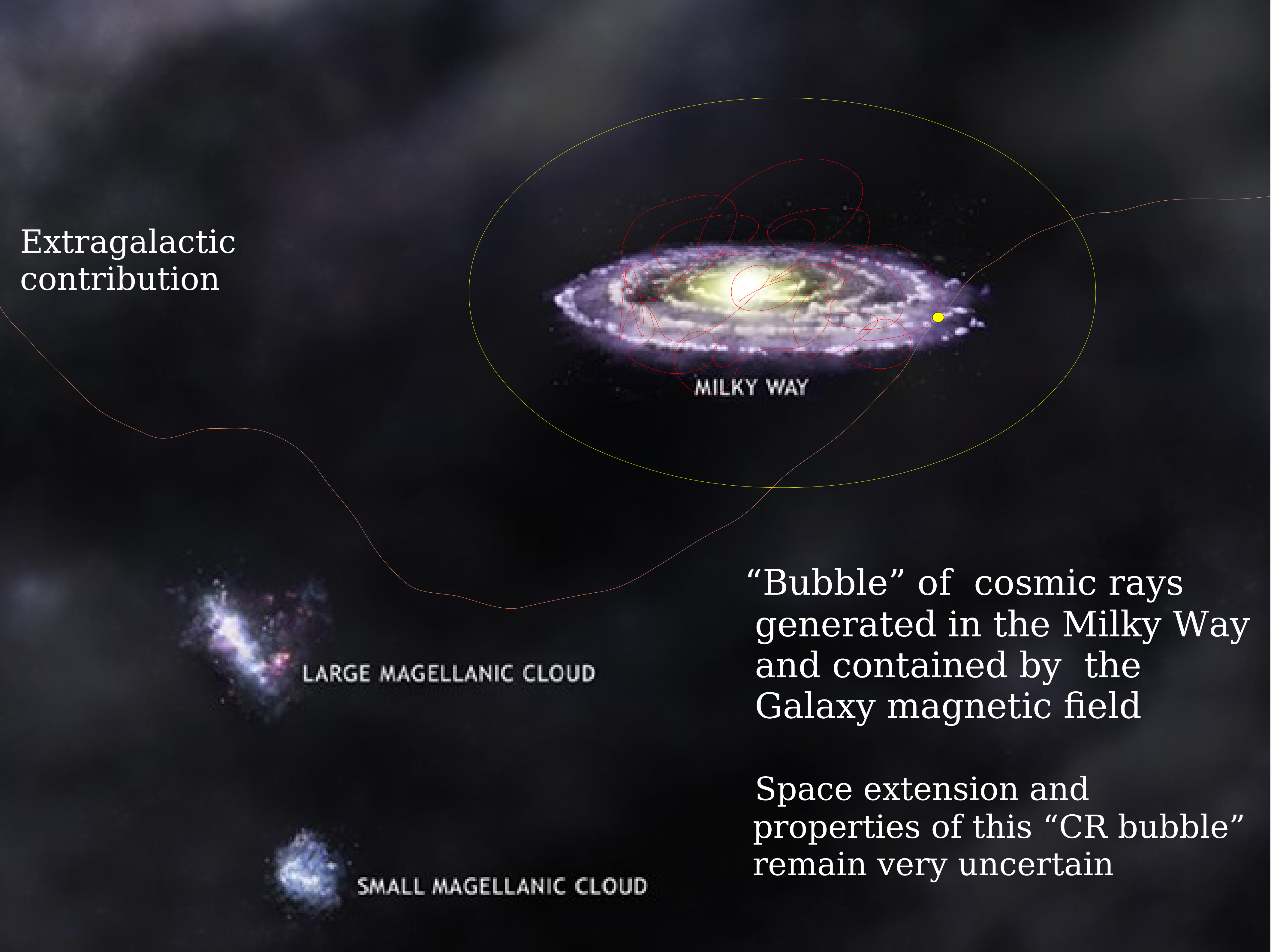
COSMIC RAYS

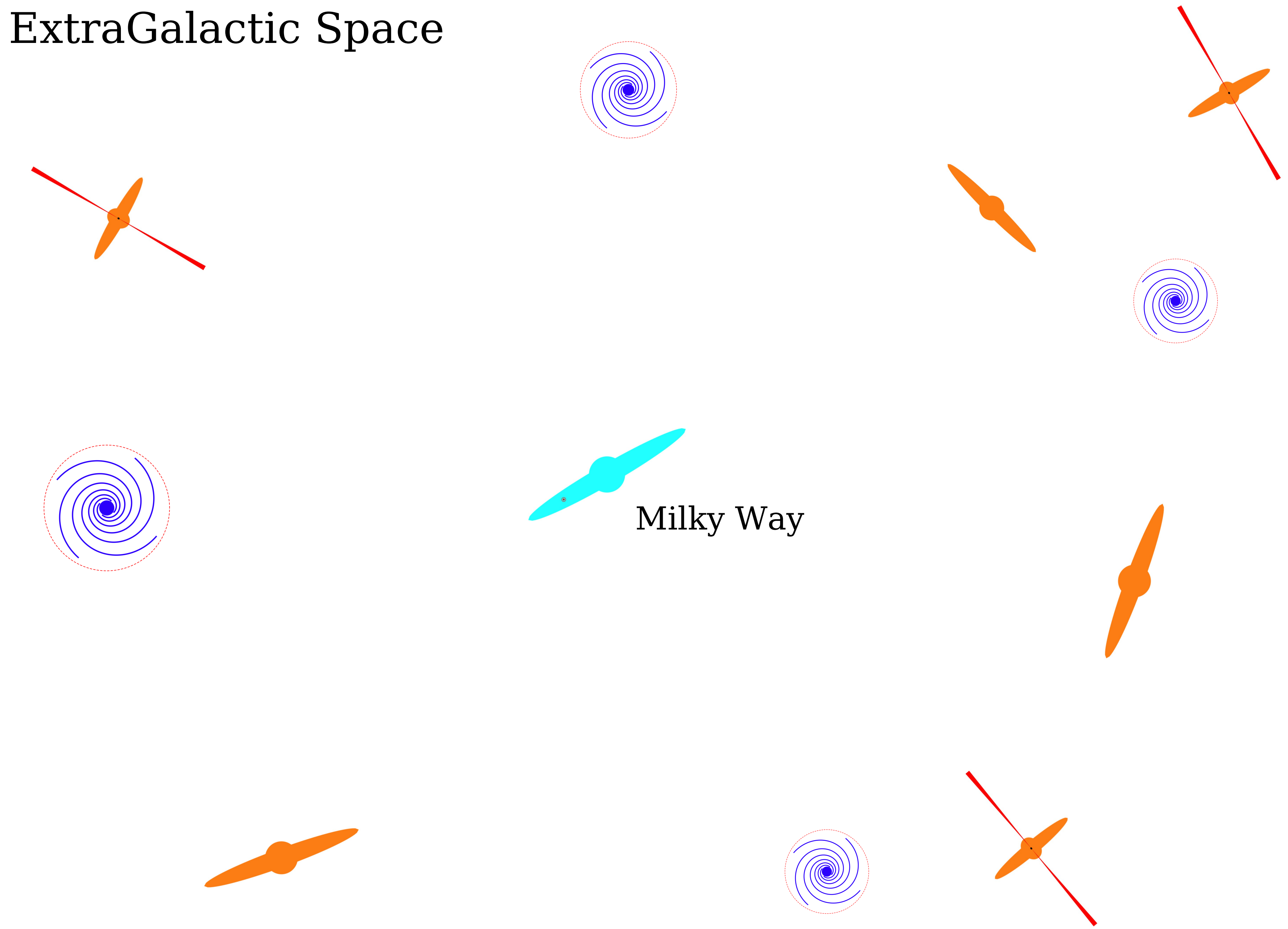
Space and time integrated average of particles
generated by many sources in the Galaxy
and in the universe, *also shaped by propagation effects*.

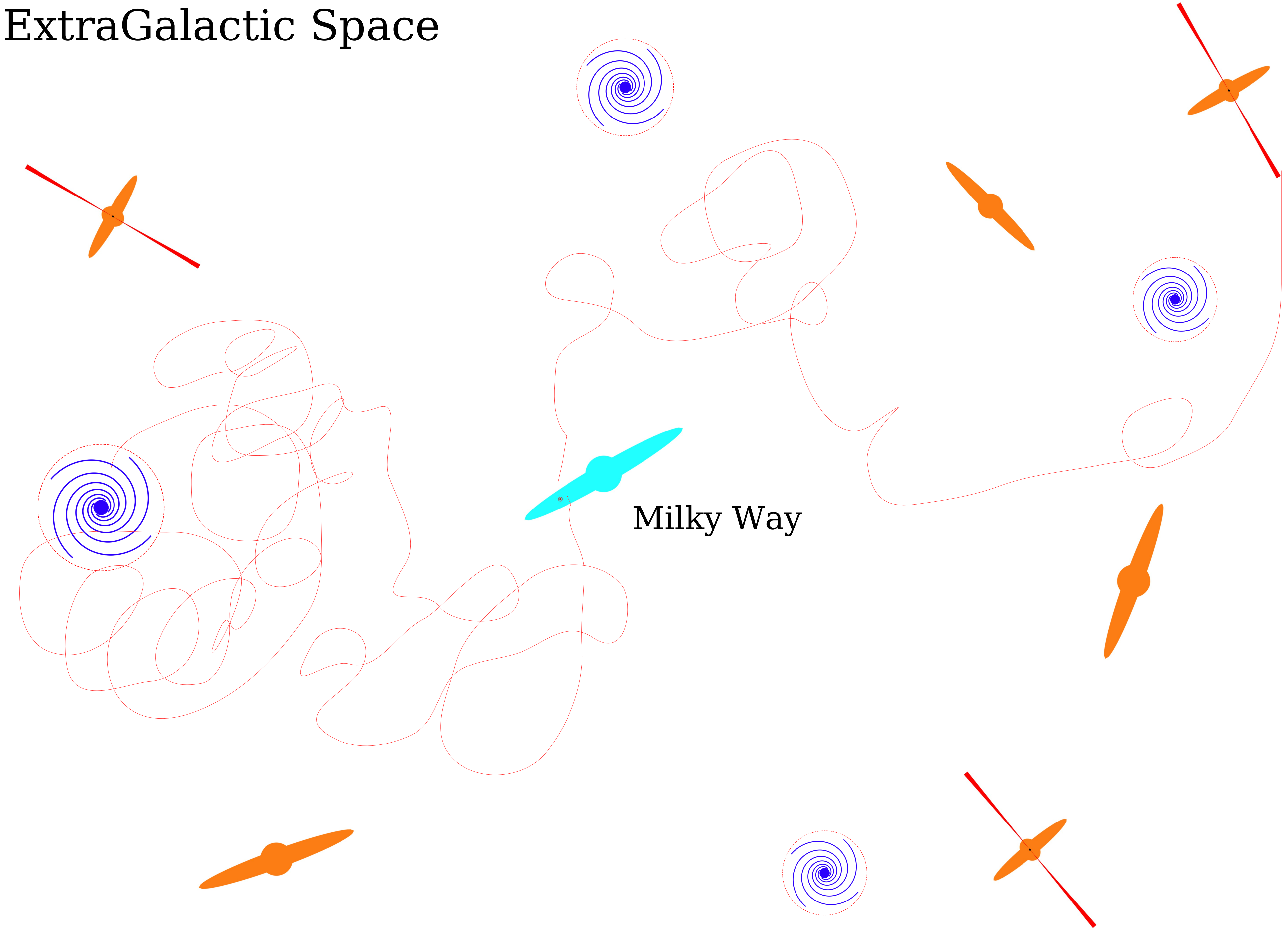
Measurement at
single point, and (effectively) single time.

[slow time variations,
geological record carries some information]

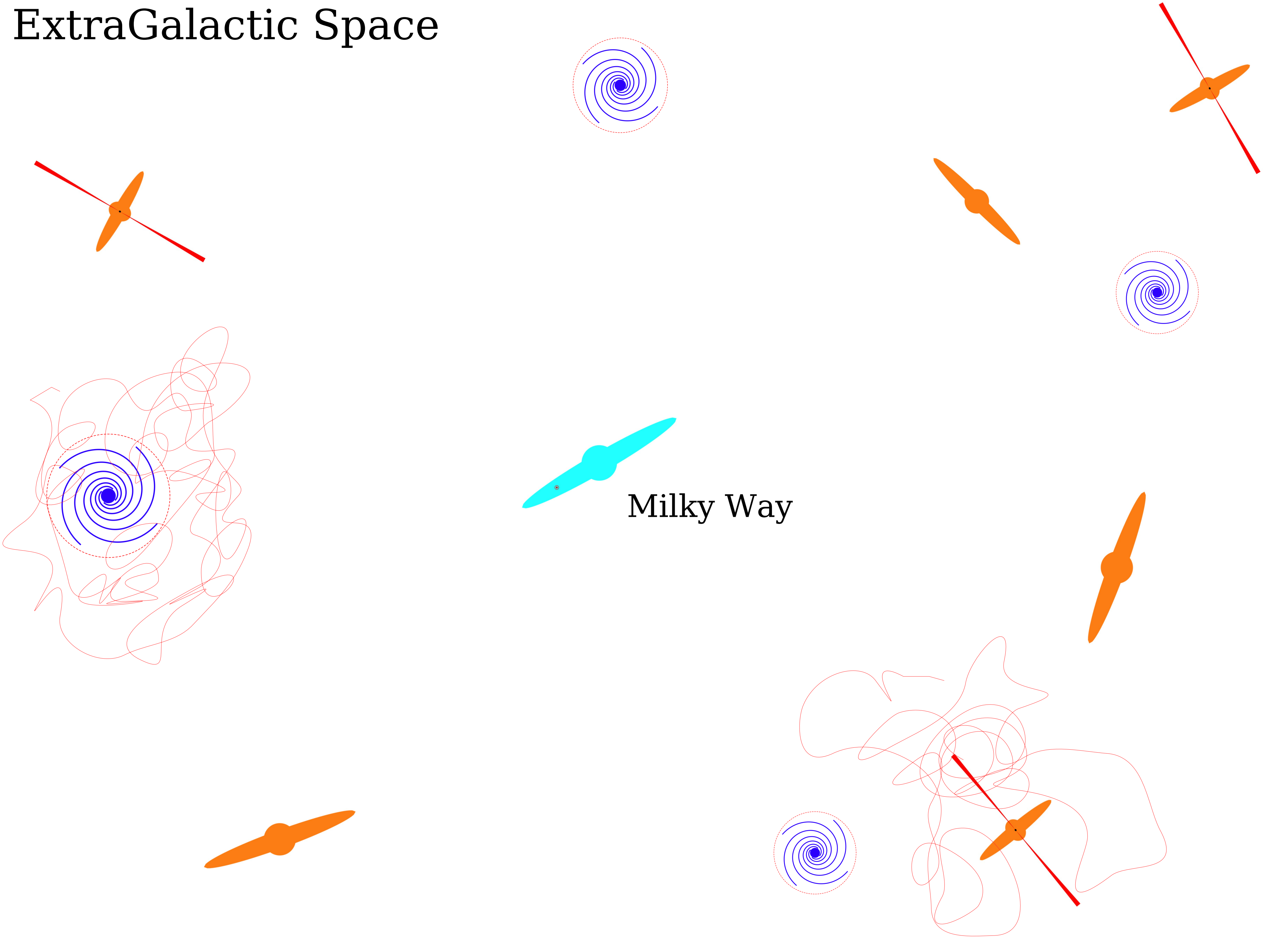

MILKY WAY
High energy sources
Solar system


Extragalactic contribution
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


ExtraGalactic Space
Milky Way


ExtraGalactic Space
Milky Way

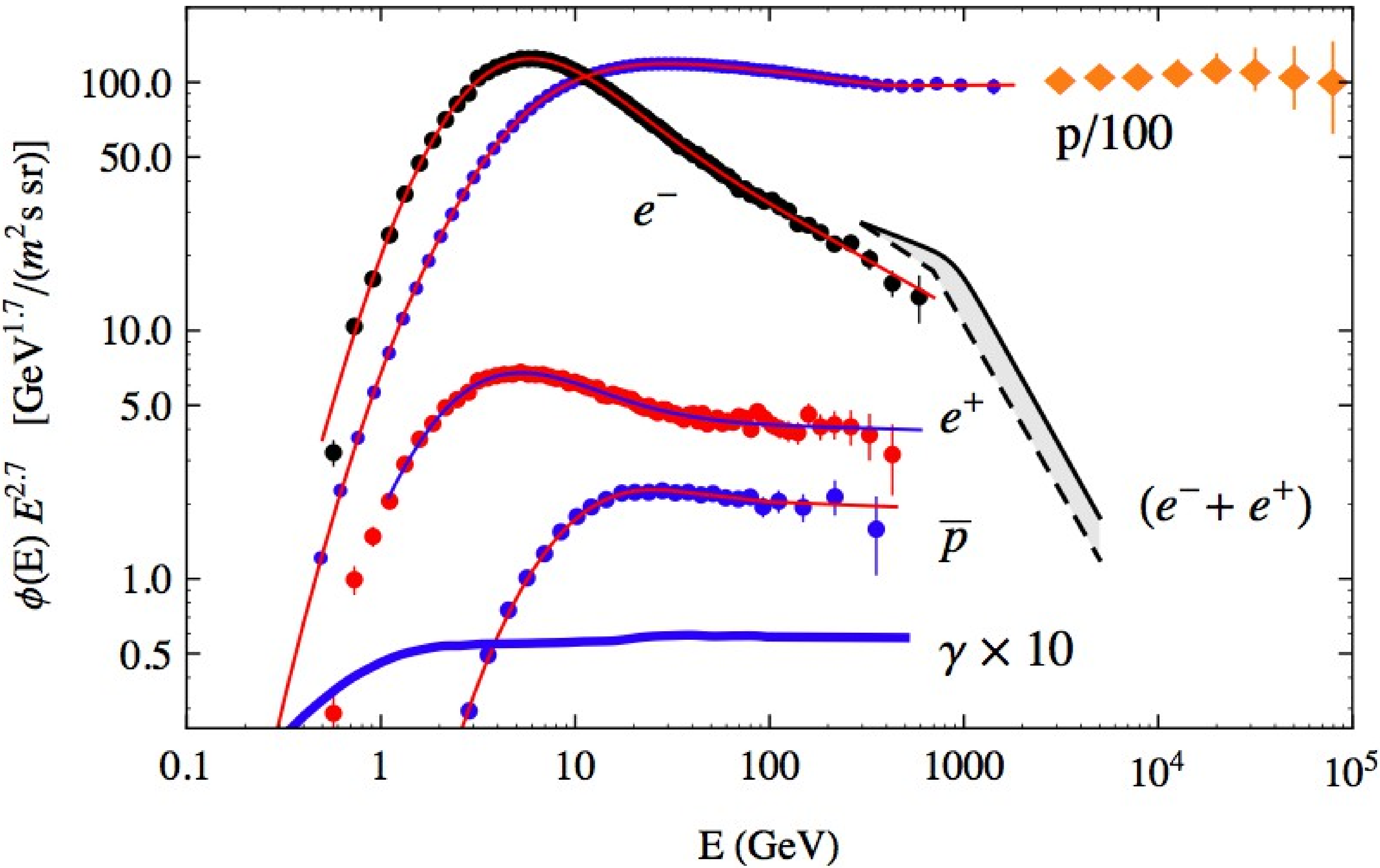
ExtraGalactic Space



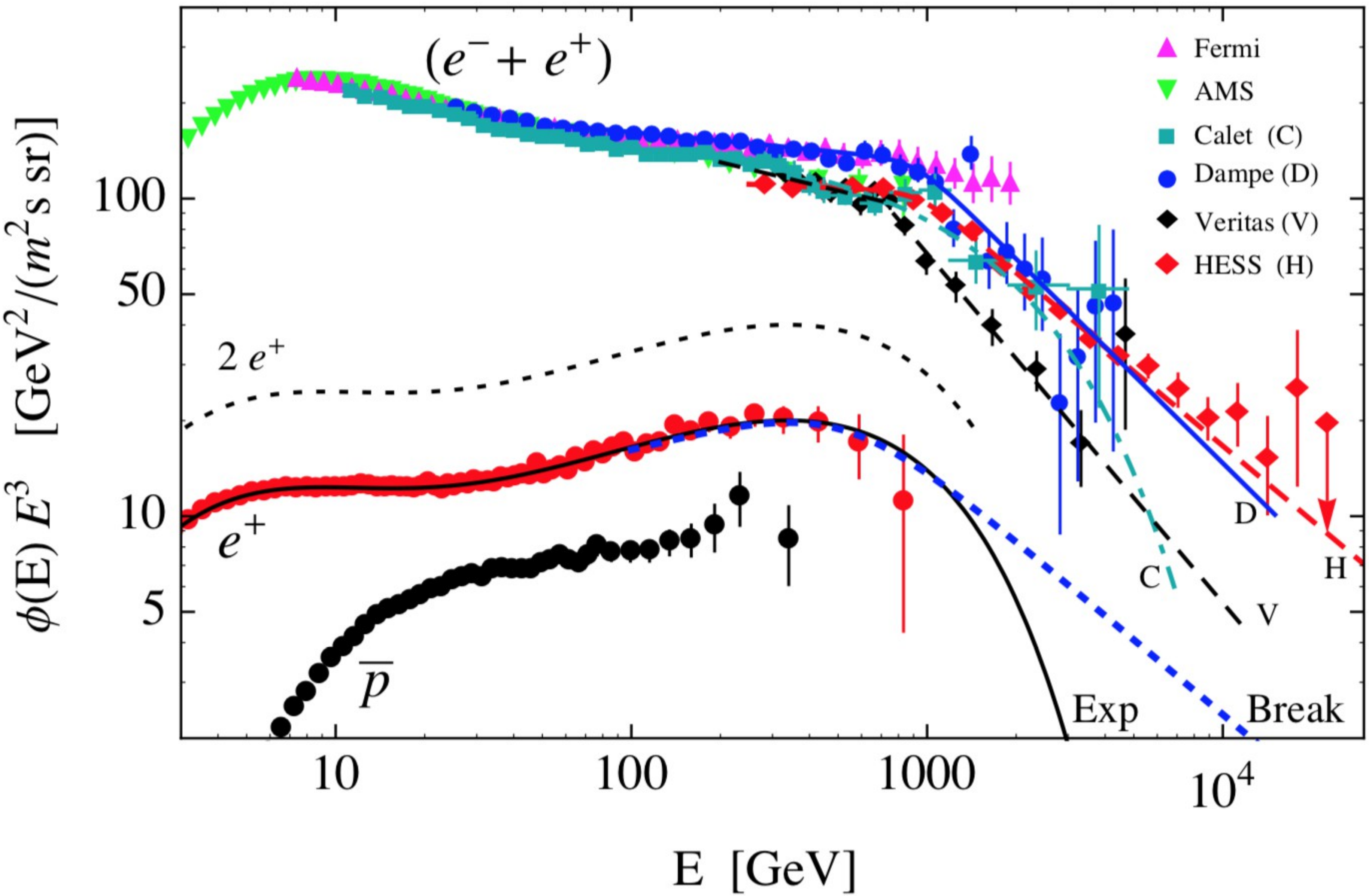
Cosmic Ray Spectra
AMS02

$p \quad e^- \quad e^+ \quad \overline{p}$

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
H
C
V
Exp
Break
$\phi(E)\,E^3$ [GeV^2/(m^2s sr)]
100
50
10
5
10
100
1000
10^4
E [GeV]

“Conventional mechanism”

for the production of positrons and antiprotons:

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

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

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

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

“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

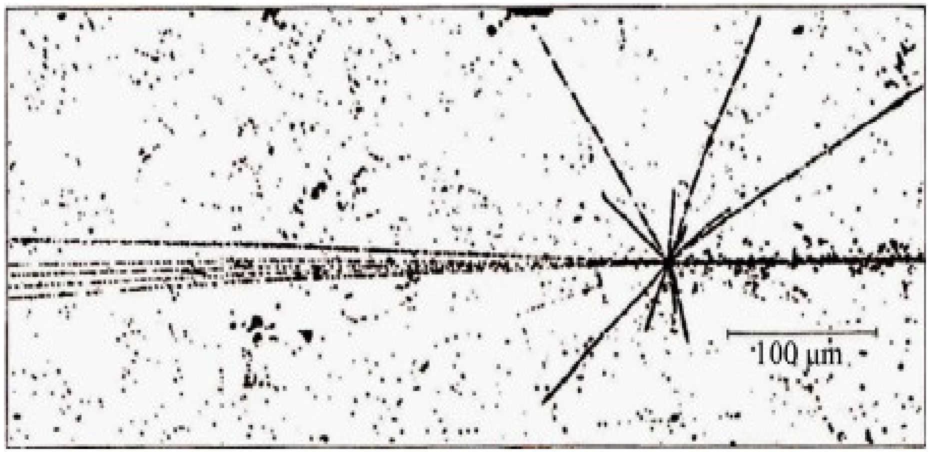
Fundamental QCD Lagrangian density

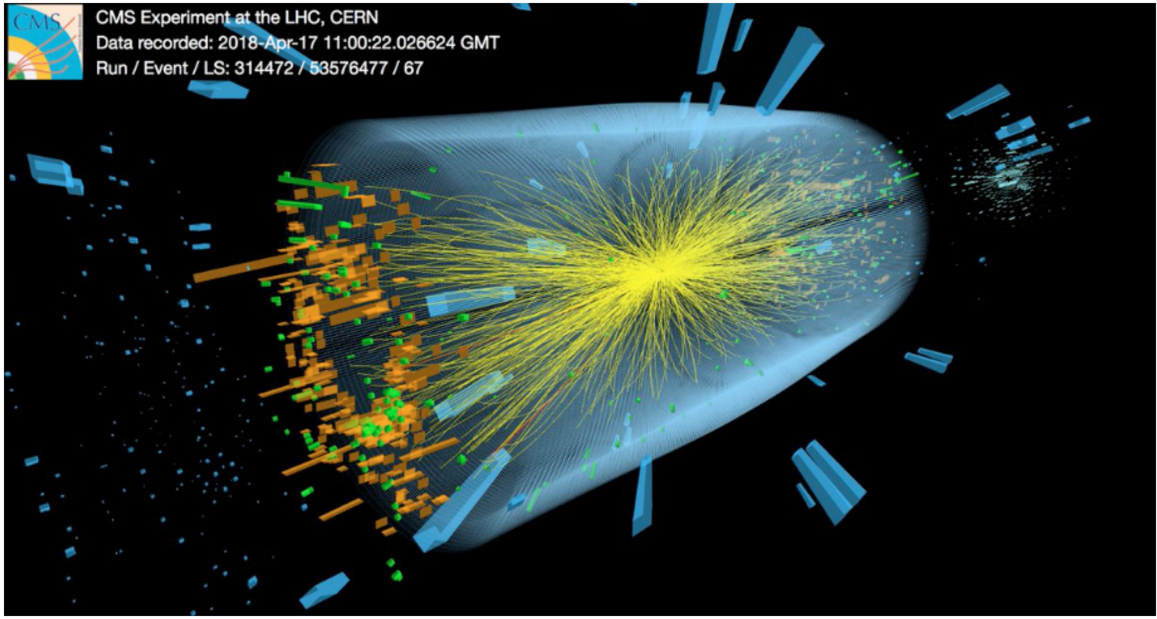
(in terms of quarks and gluon fields)

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

$$D_\mu = \partial_\mu - ie_s\sum_A t^A g^A_\mu$$

Multi-particle production



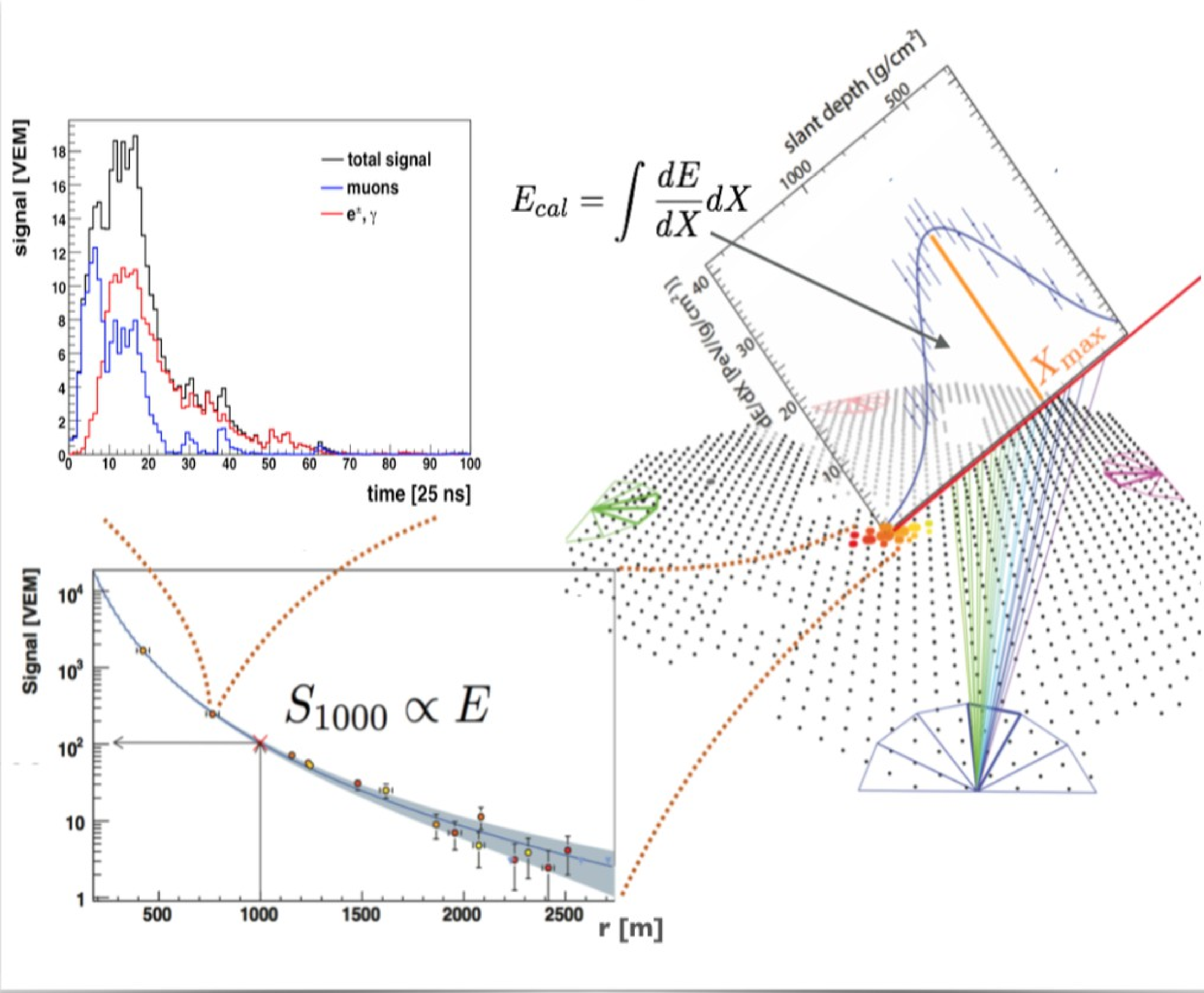


Study of Ultra High Energy Cosmic Rays
(interpretation of the observations
of Cosmic Ray showers in the atmosphere)

requires an *extrapolation of LHC data*

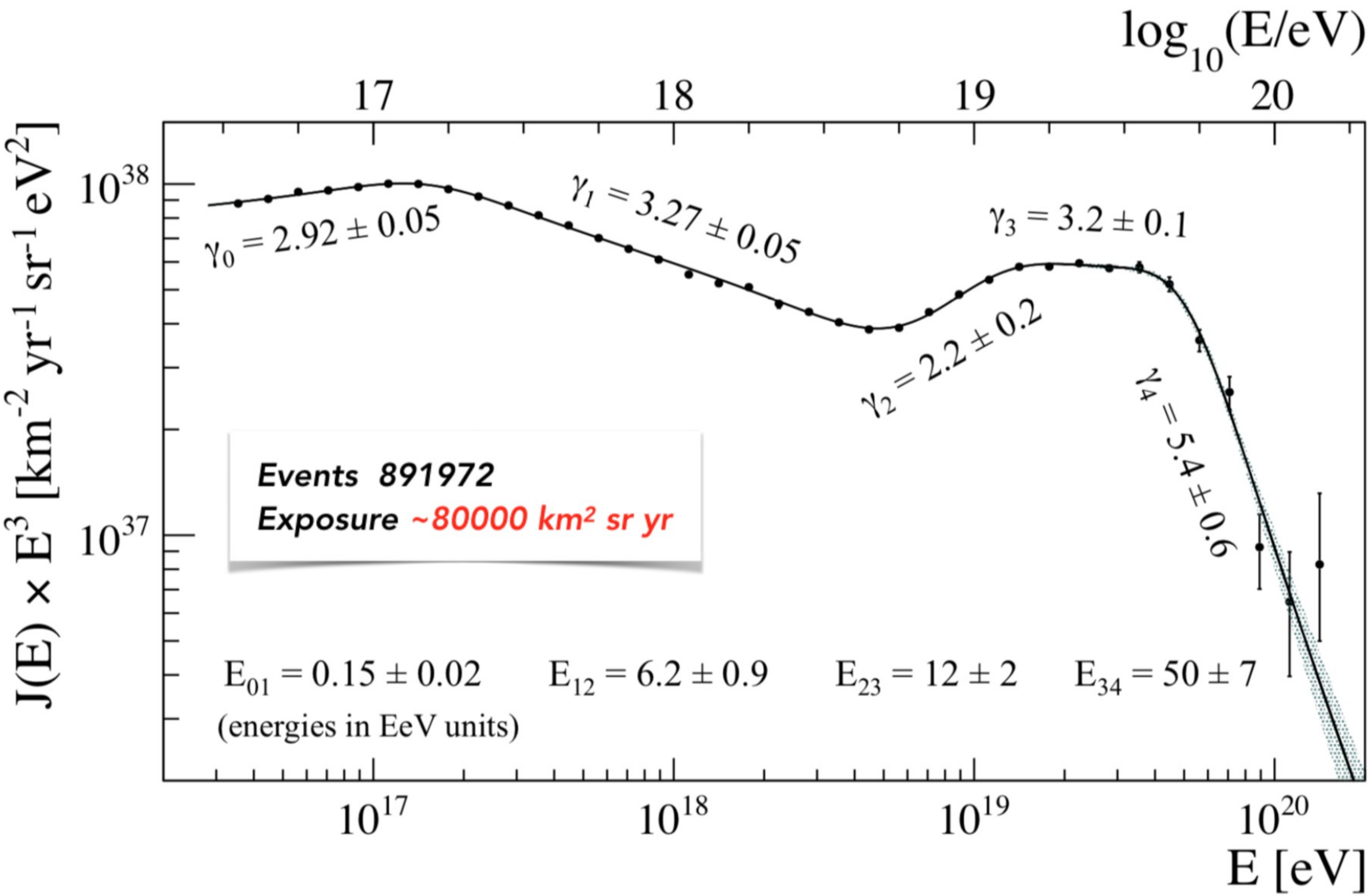
laboratory energy (proton primary)	c.m. energy (nucleon-nucleon collisions)
$E \gtrsim 10^{17}$ eV	$\sqrt{s} \gtrsim 13.7$ TeV
$E = 10^{20}$ eV	$\sqrt{s} \simeq 433$ TeV

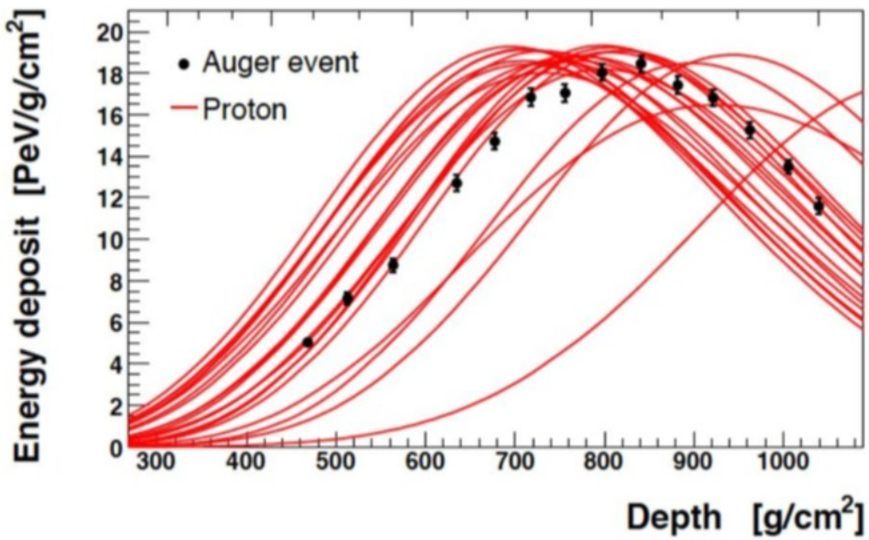
Precise description of *interactions at lower energy*
is also essential to correctly describe
very high energy showers



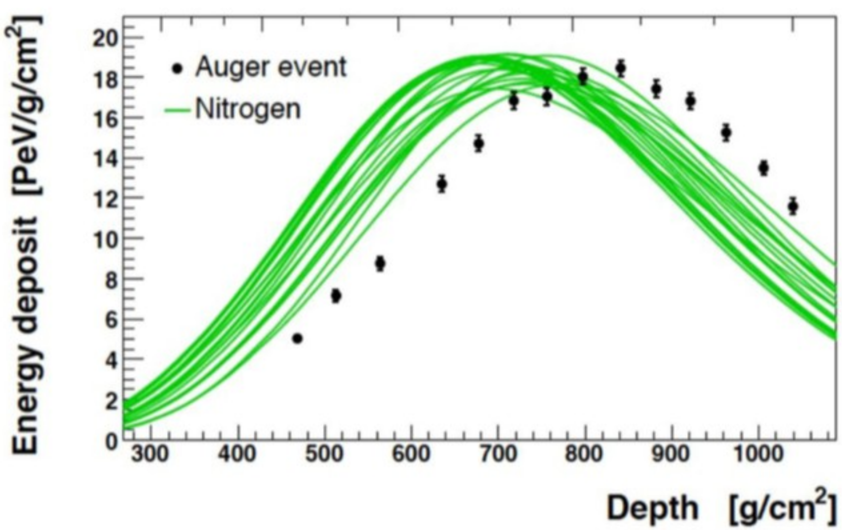
signal [VEM]
total signal
muons
e±, γ
time [25 ns]
$E_{cal} = \int \frac{dE}{dX} dX$
slant depth [g/cm²]
1000
500
dE/dX [PeV/(g/cm⁻²)]
X_{max}
Signal [VEM]
$S_{1000} \propto E$
r [m]

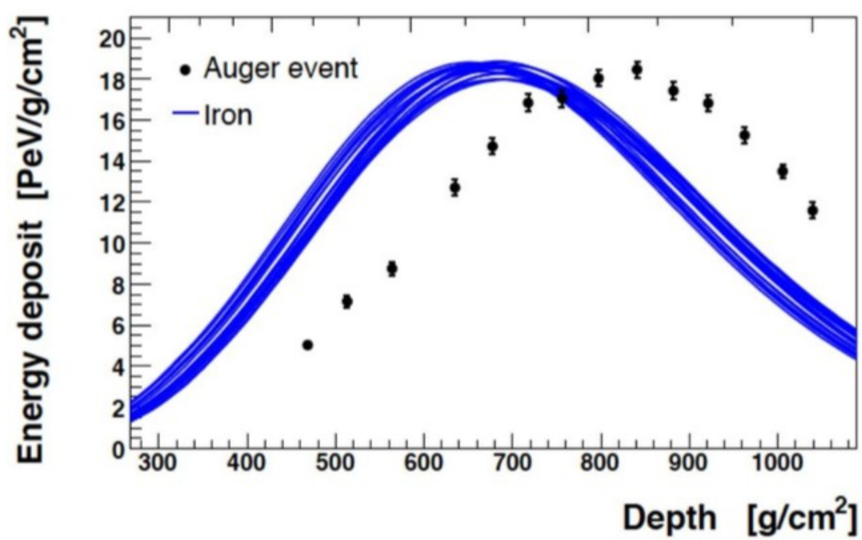
The energy spectrum



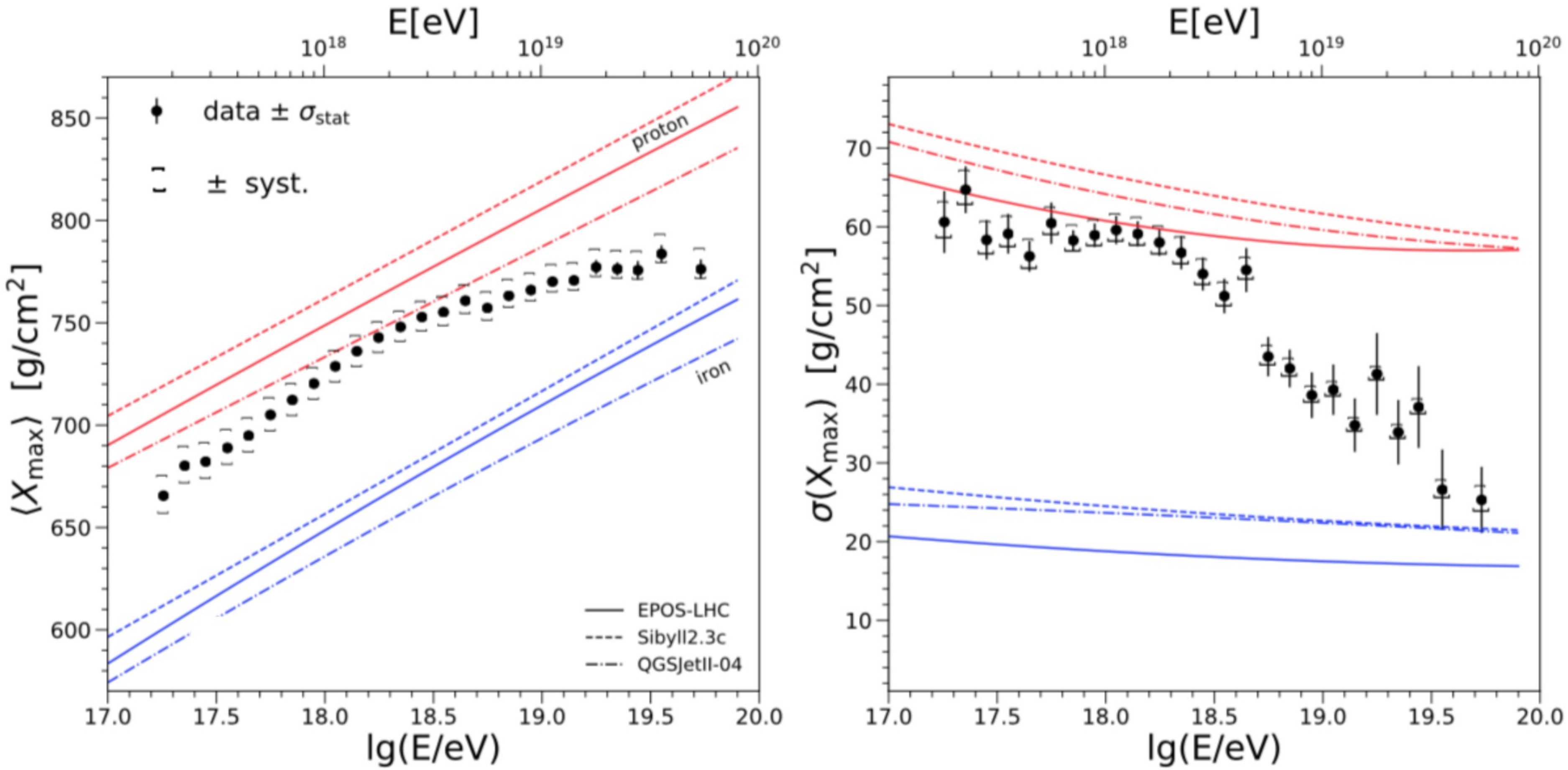


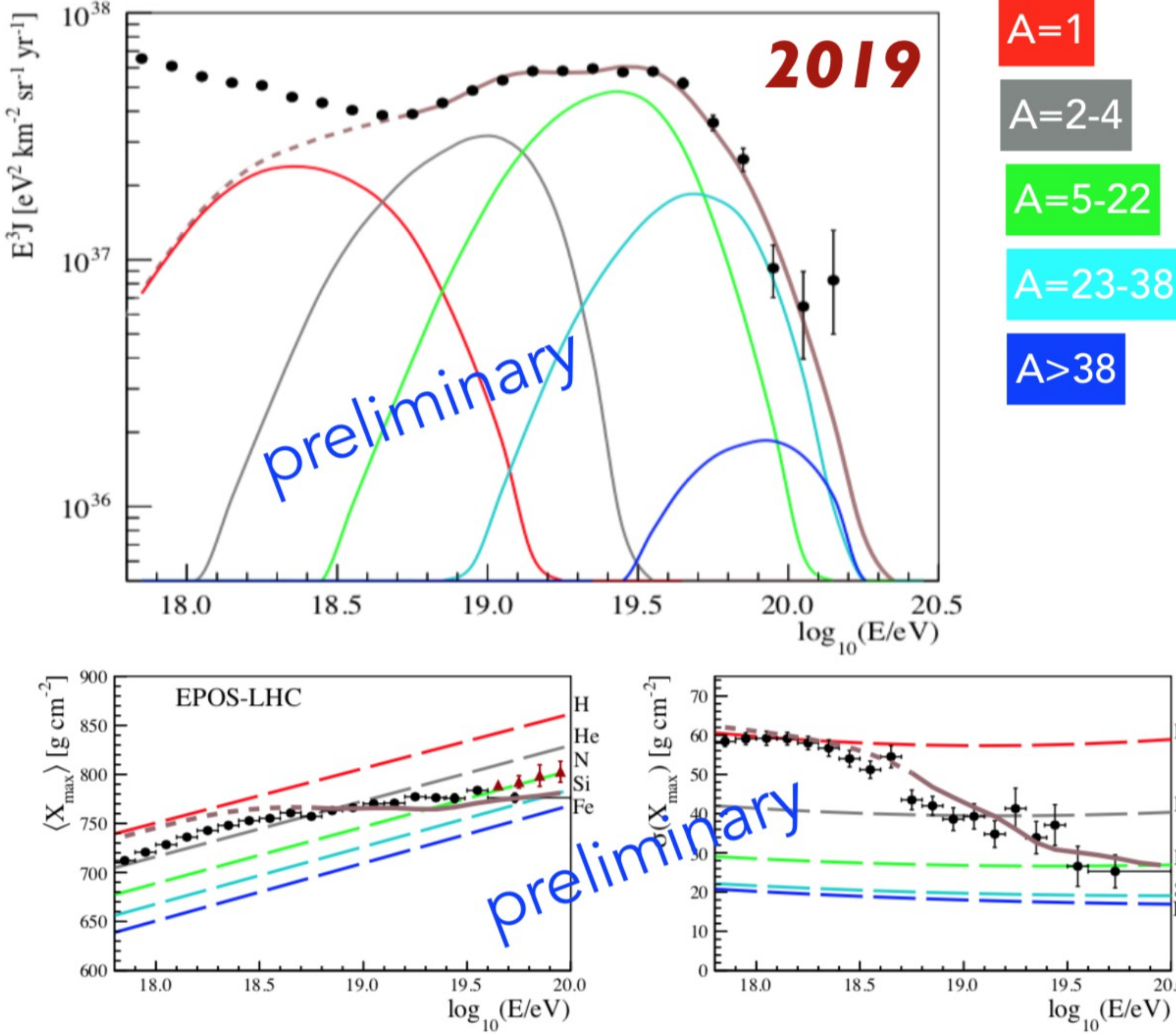
$$E \simeq 10^{20}\ \mathrm{eV}$$



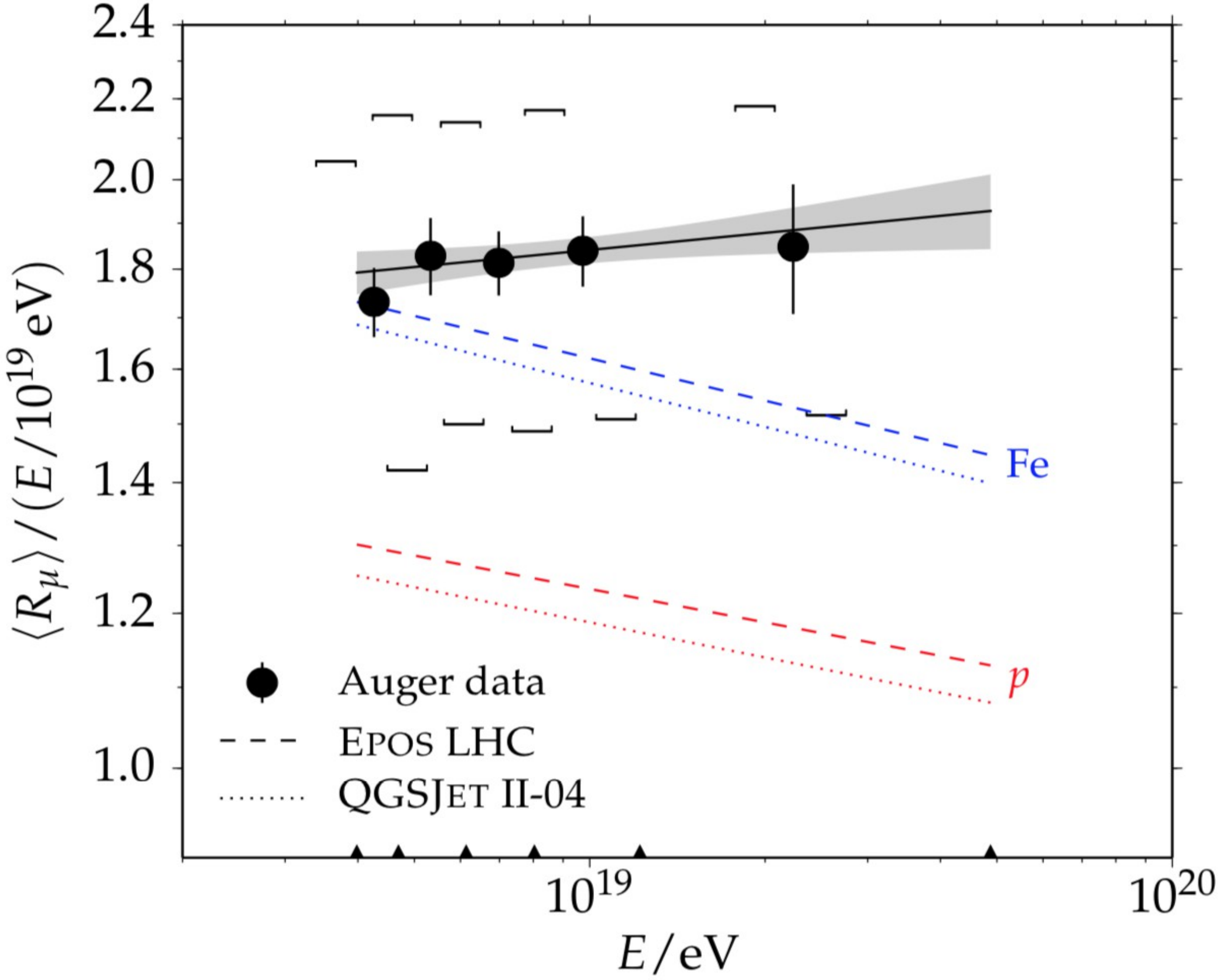


Auger Observation of the Maximum of the shower development




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]
10^38
10^37
10^36
18.0
18.5
19.0
19.5
20.0
20.5
log10(E/eV)
EPOS-LHC
⟨Xmax⟩ [g cm^-2]
H
He
N
Si
Fe
σ(Xmax) [g cm^-2]
preliminary

The “Muon problem” in Ultra High Energy Cosmic Rays



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