The four *"Messengers"* of High Energy Astrophysics

Interplay between the different observations and Perspectives for the Future

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||Stato e Prospettive
della Fisica delle Astroparticelle"

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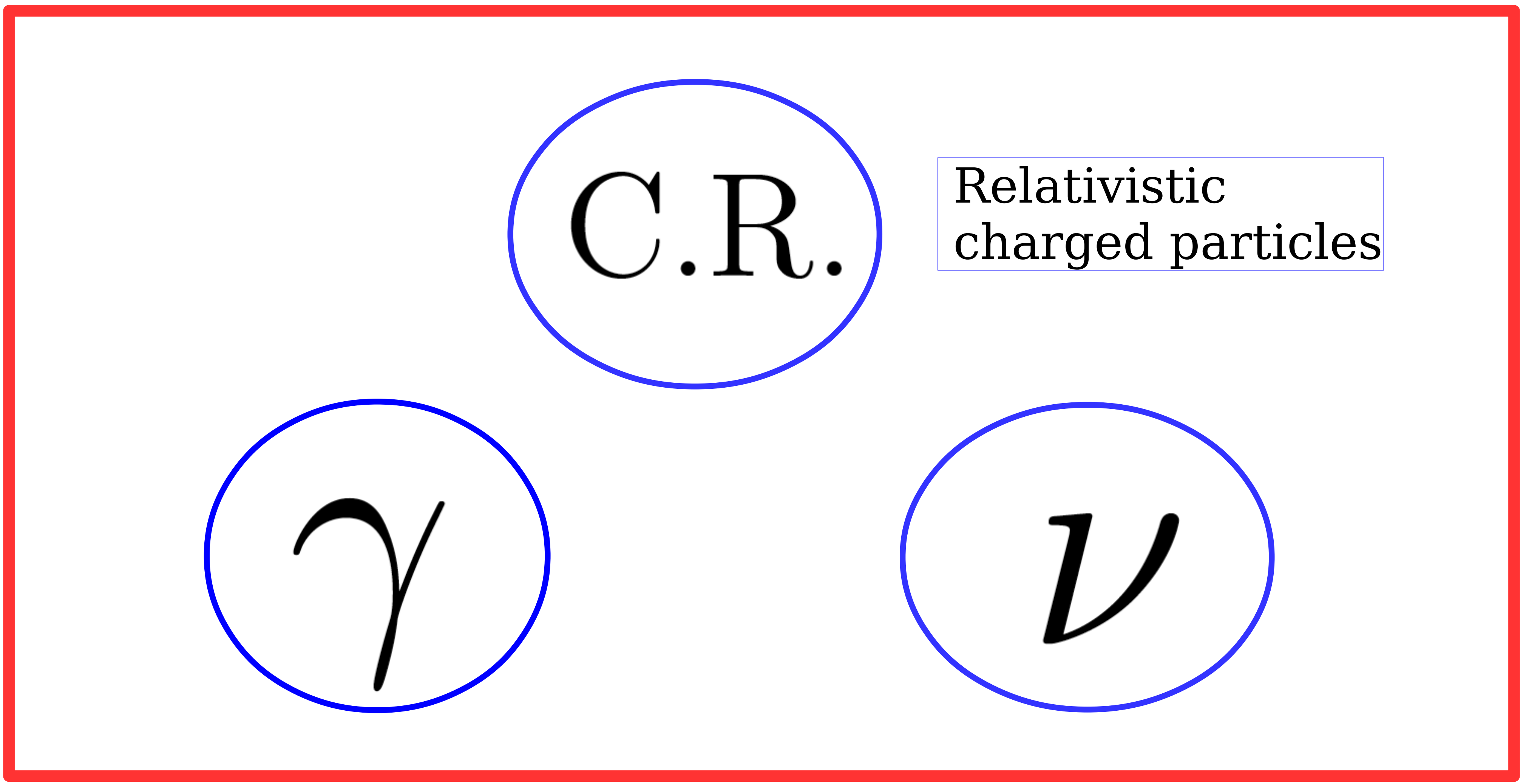
Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

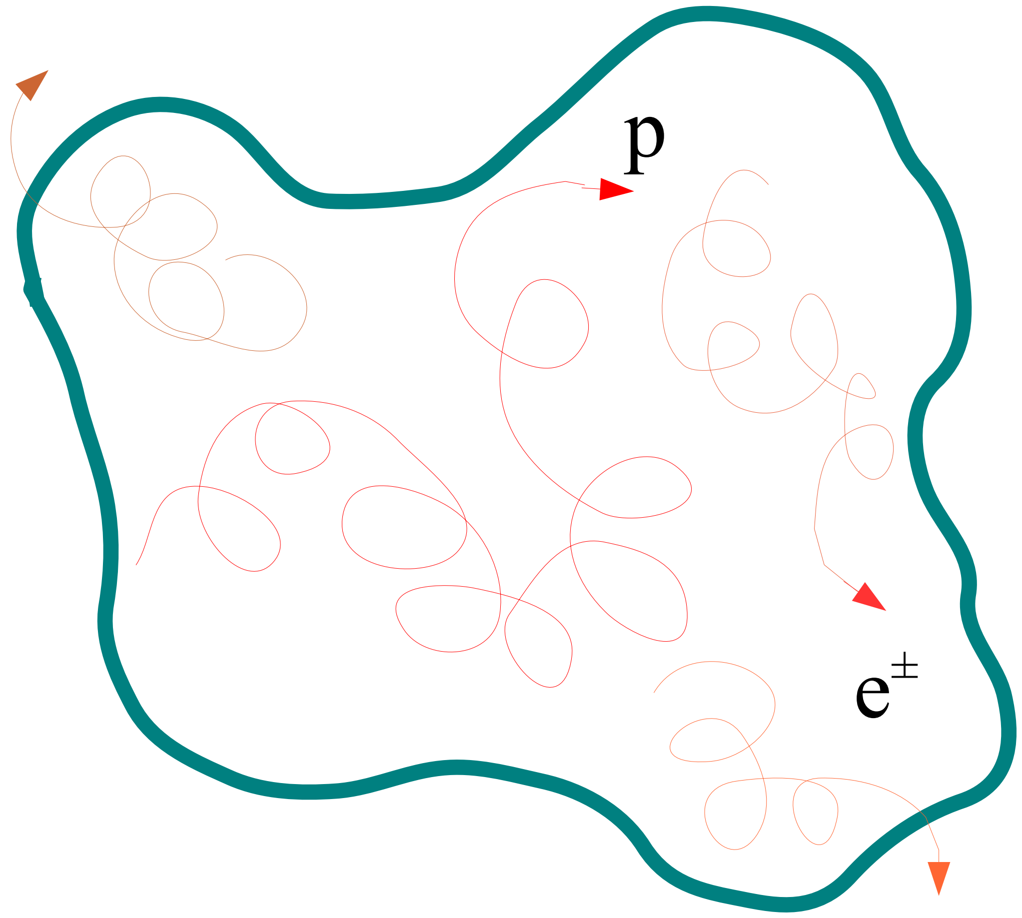
4 Messengers
for the study of the
"High Energy Universe"

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]



Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

Fundamental Mechanism:

Acceleration of Charged Particles

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

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

"Hadronic "

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

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

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

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

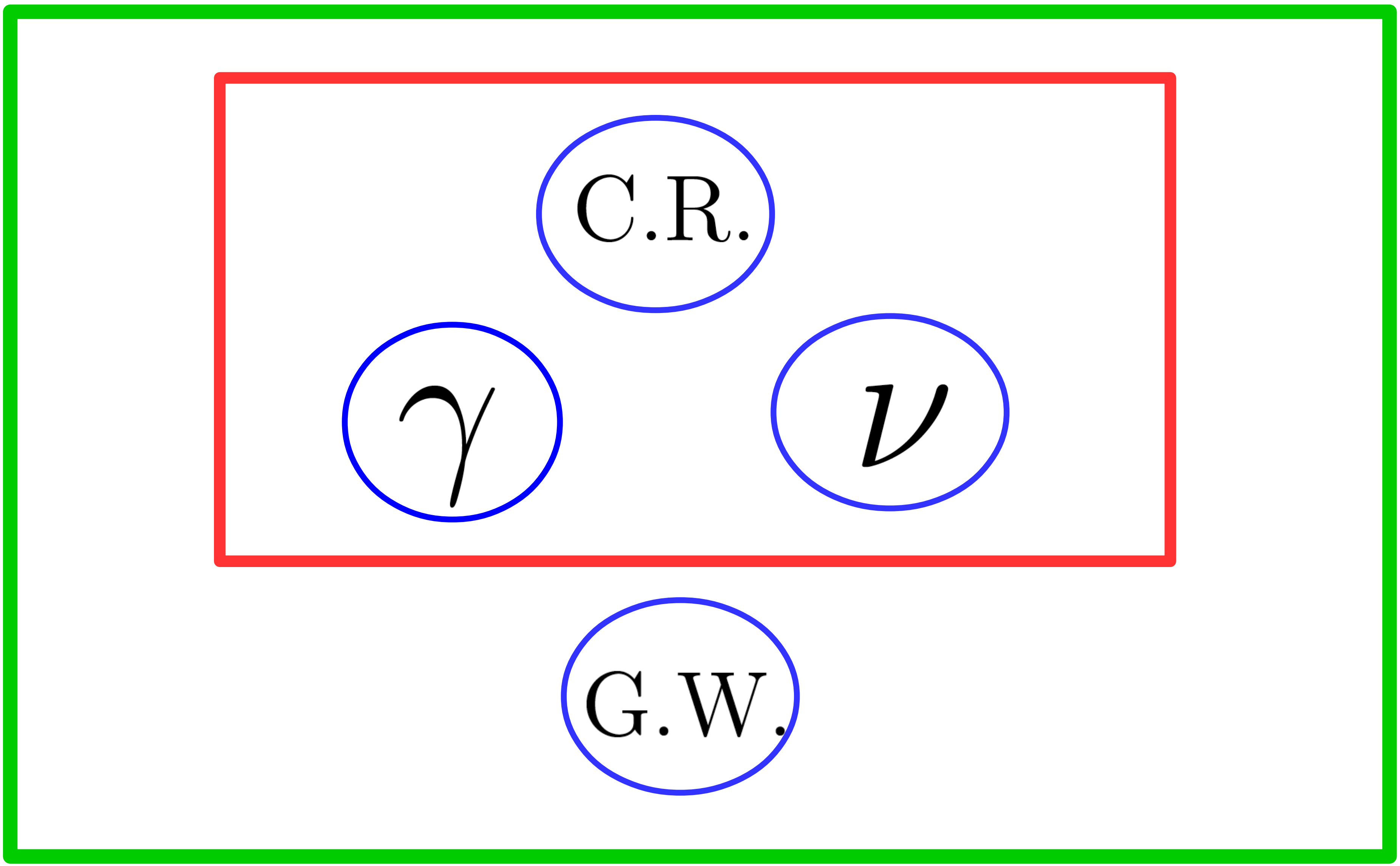
"Leptonic "

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

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

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

Gravitational Waves Studies
Entering a new exciting era with LIGO/VIRGO



Sources are transients

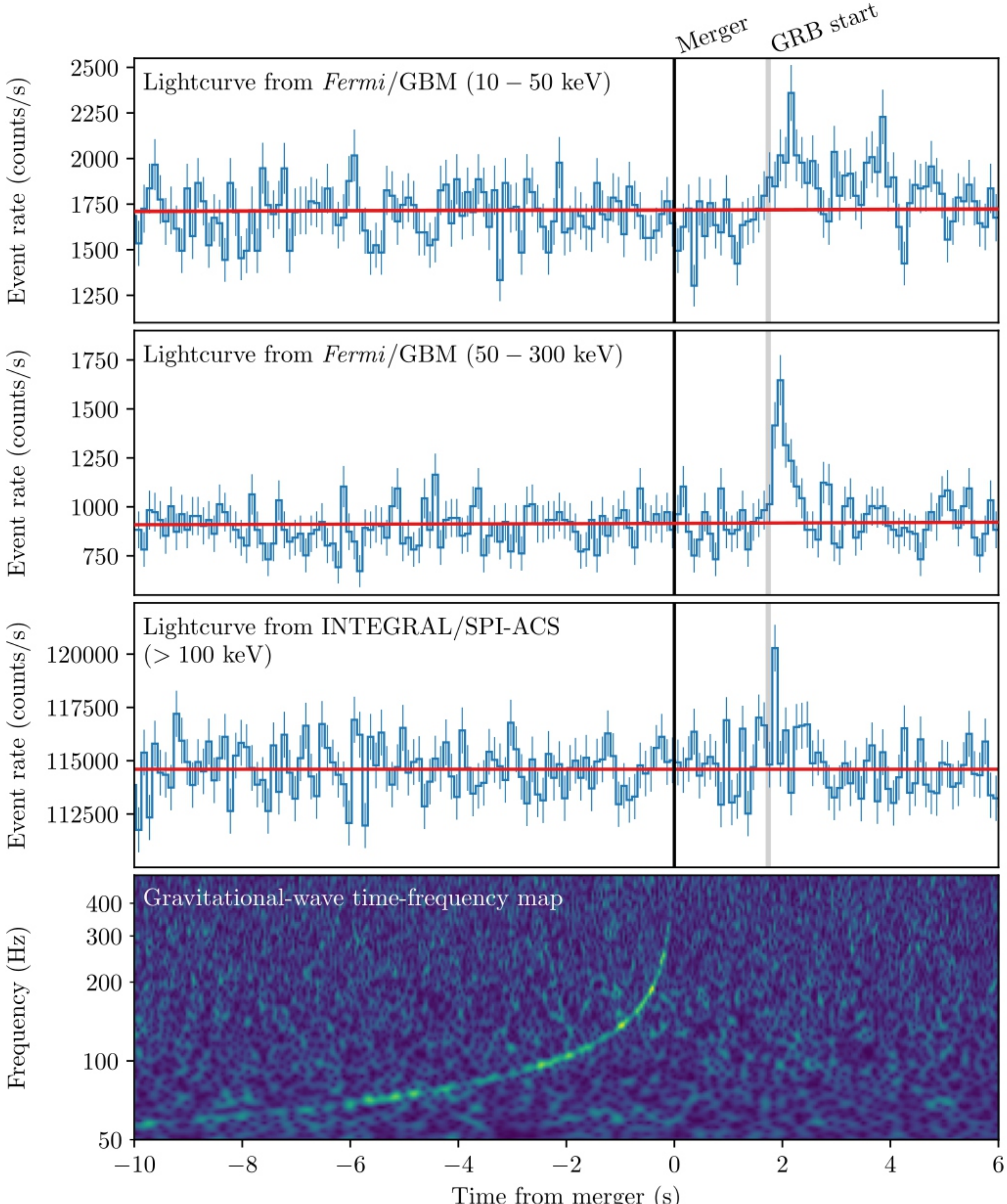
[with a variety of time scales
from a small fraction of a second to thousands of years]

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



GRB 170817A

GW 170817

Non accelerator sources of High Energy Particles

Dark Matter

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

Super Massive Particles

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

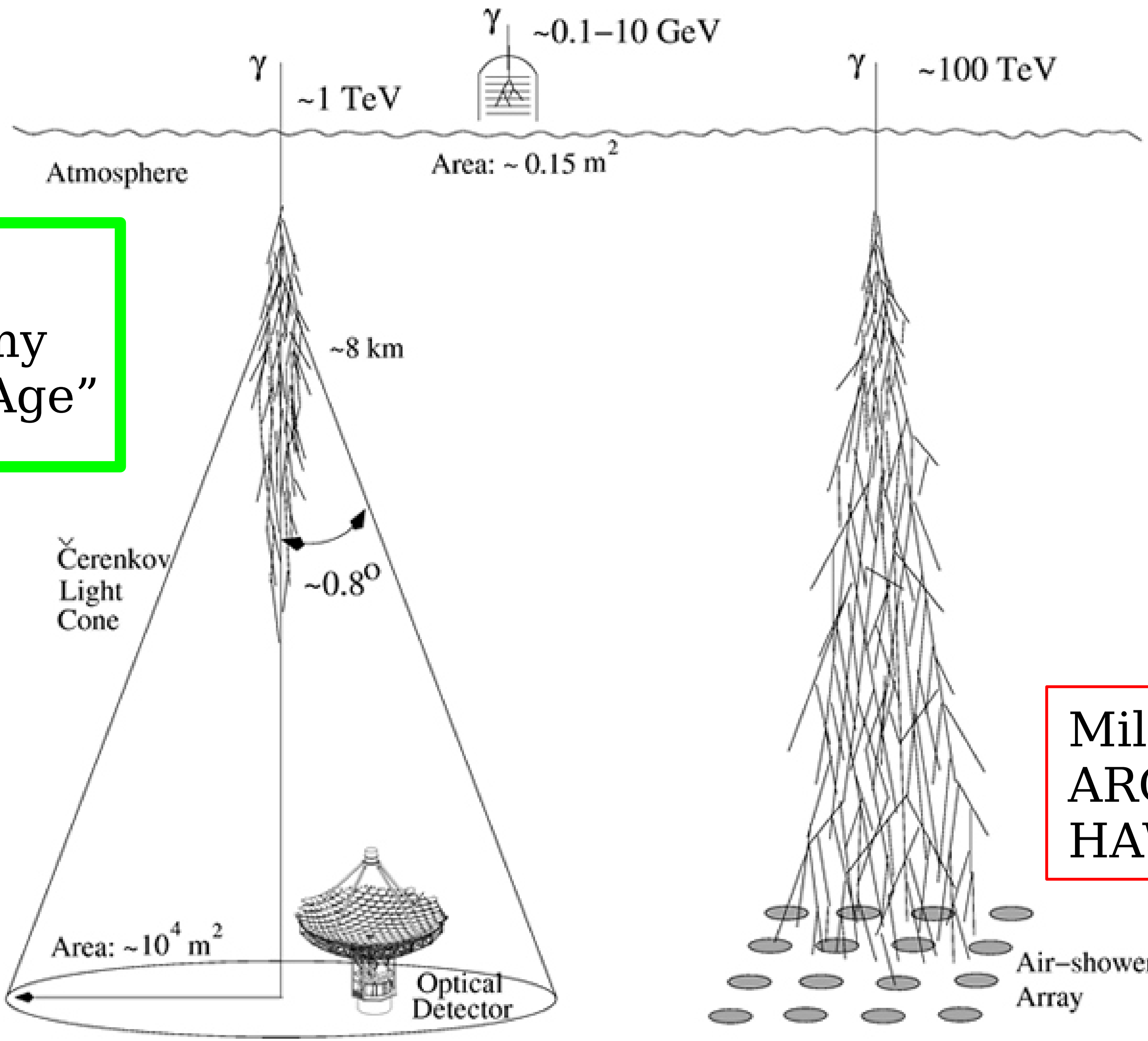
Production of high energy particles
of all types $\gamma\ ,\ \nu\ ,\ e^+\ ,\ e^-\ ,\ p\ ,\ \ldots$

Gamma Rays

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”

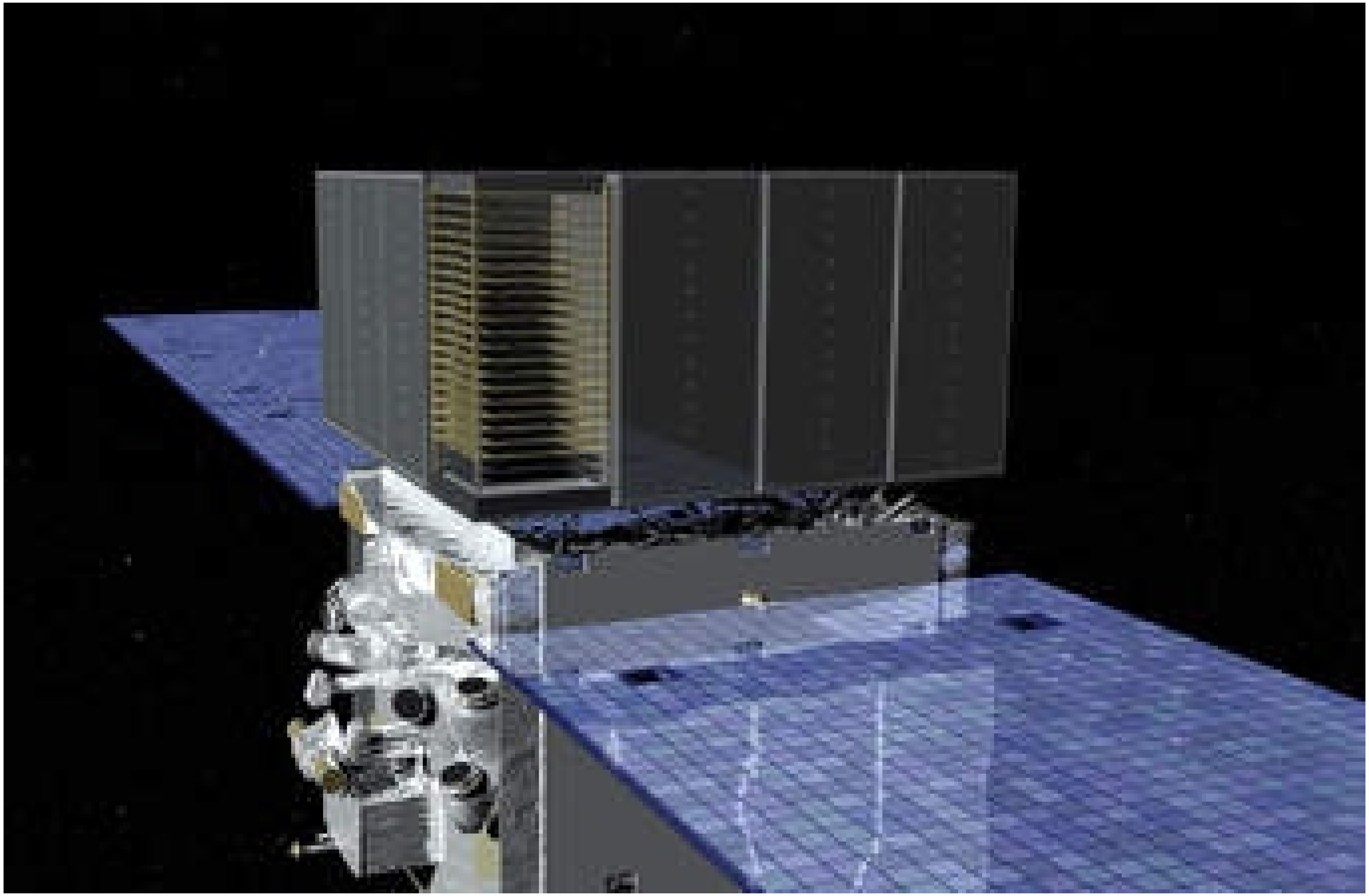


Hess
Magic
Veritas

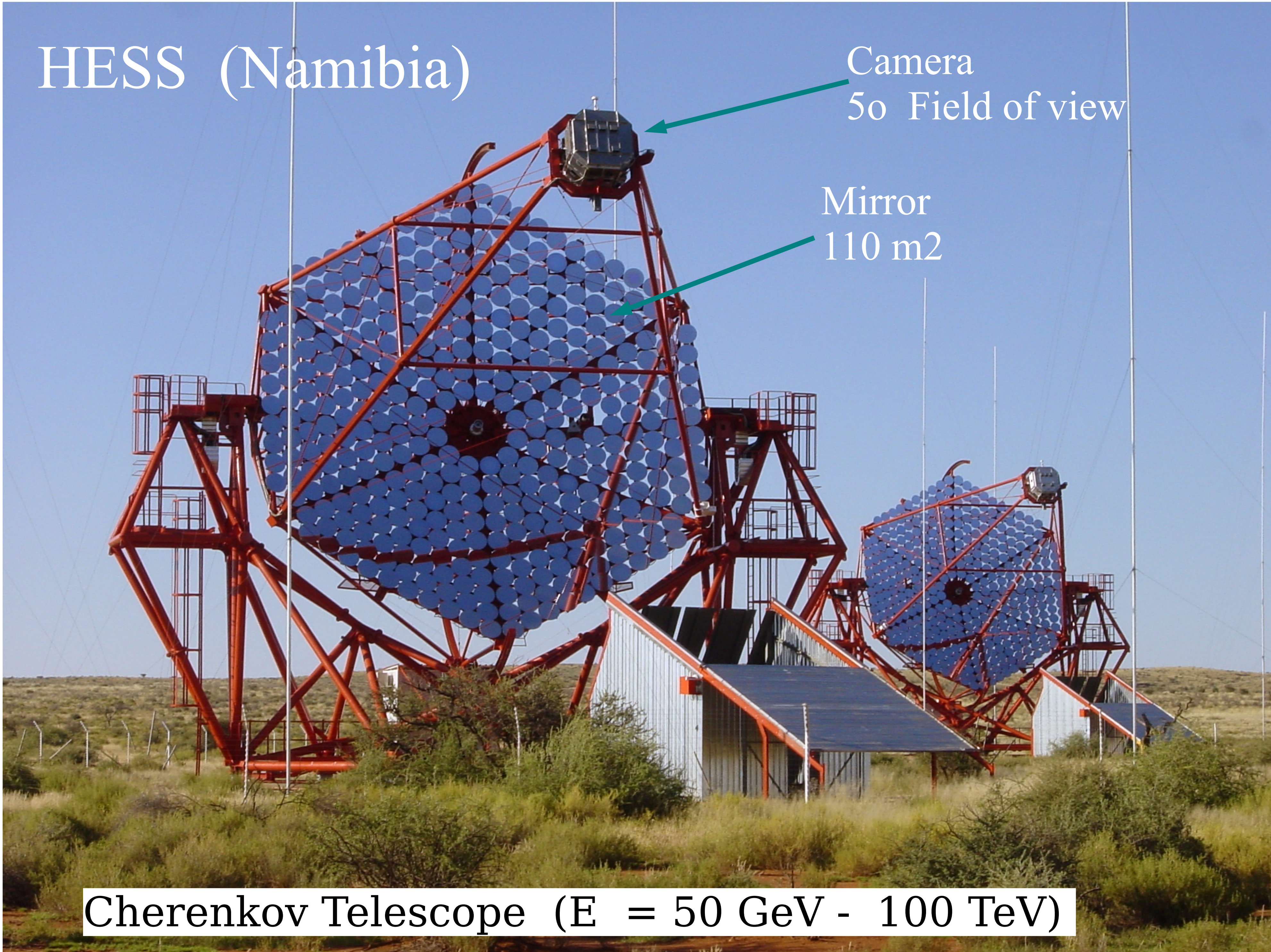
CTA

Milagro
ARGO
HAWC

FERMI Telescope (E > 30 MeV)



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



Cherenkov Telescope (E = 50 GeV - 100 TeV)

Gamma Astronomy has revealed a
a *very rich, fascinating landscape*

- Many sources have been identified
[GeV , TeV ranges]

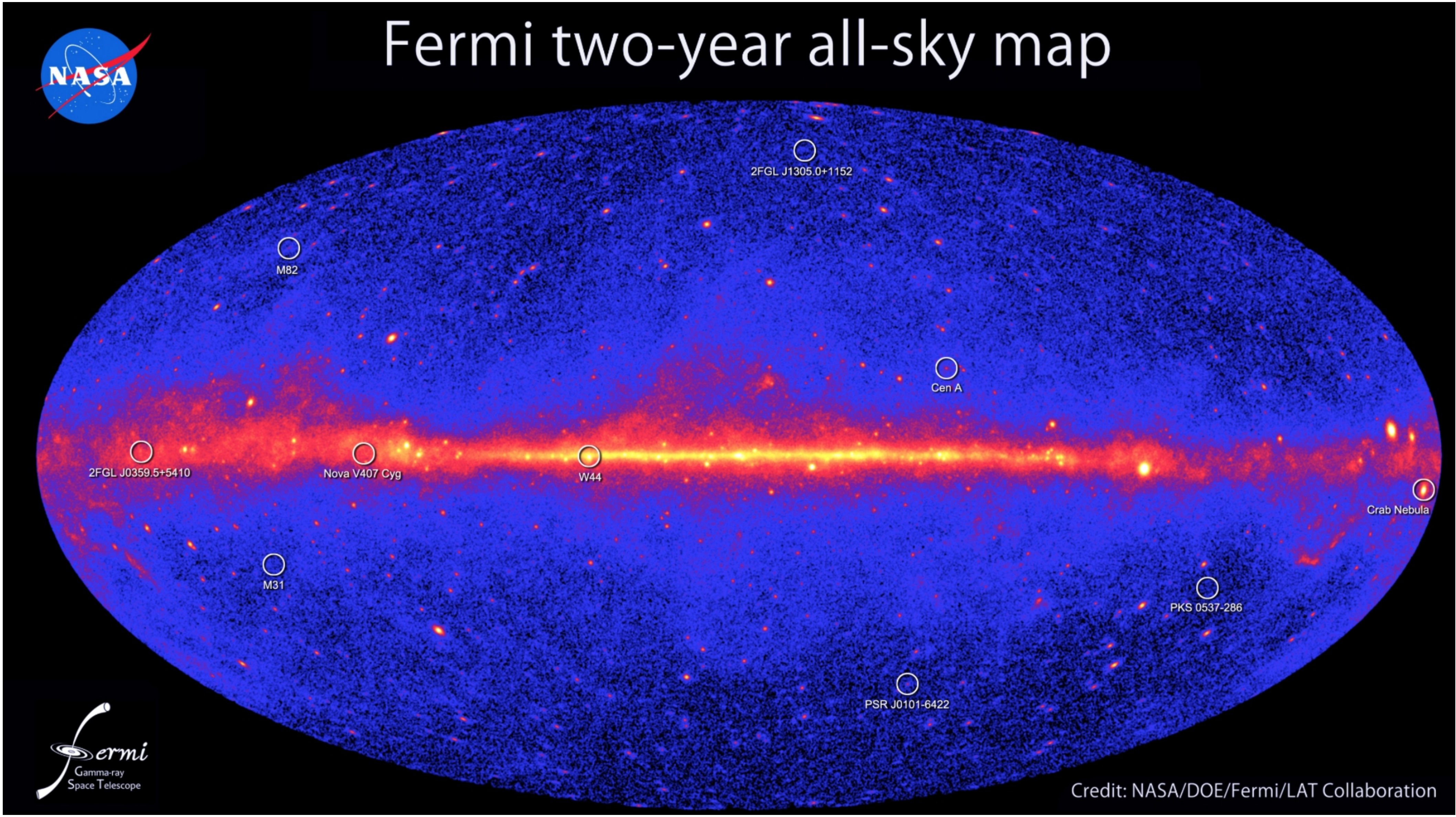
- Several classes of objects
[SNR, Pulsars, PWN, AGN, GRB, ...]

- Probably different acceleration mechanisms.

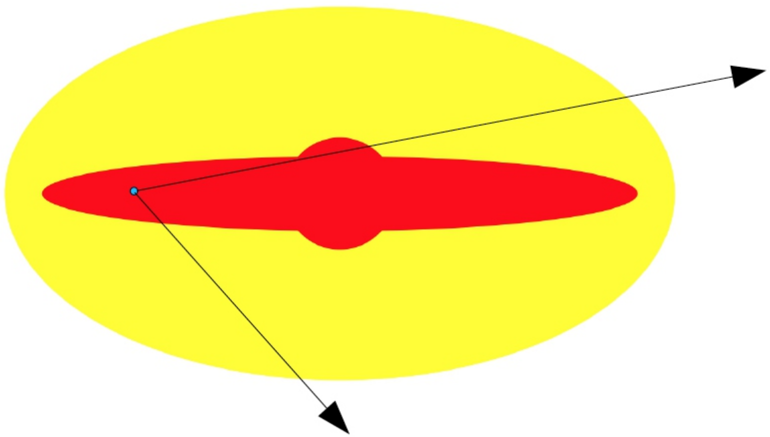
Still developing an understanding
many questions remain open

$E_\gamma \geq 100$ MeV

Gamma Ray Sky

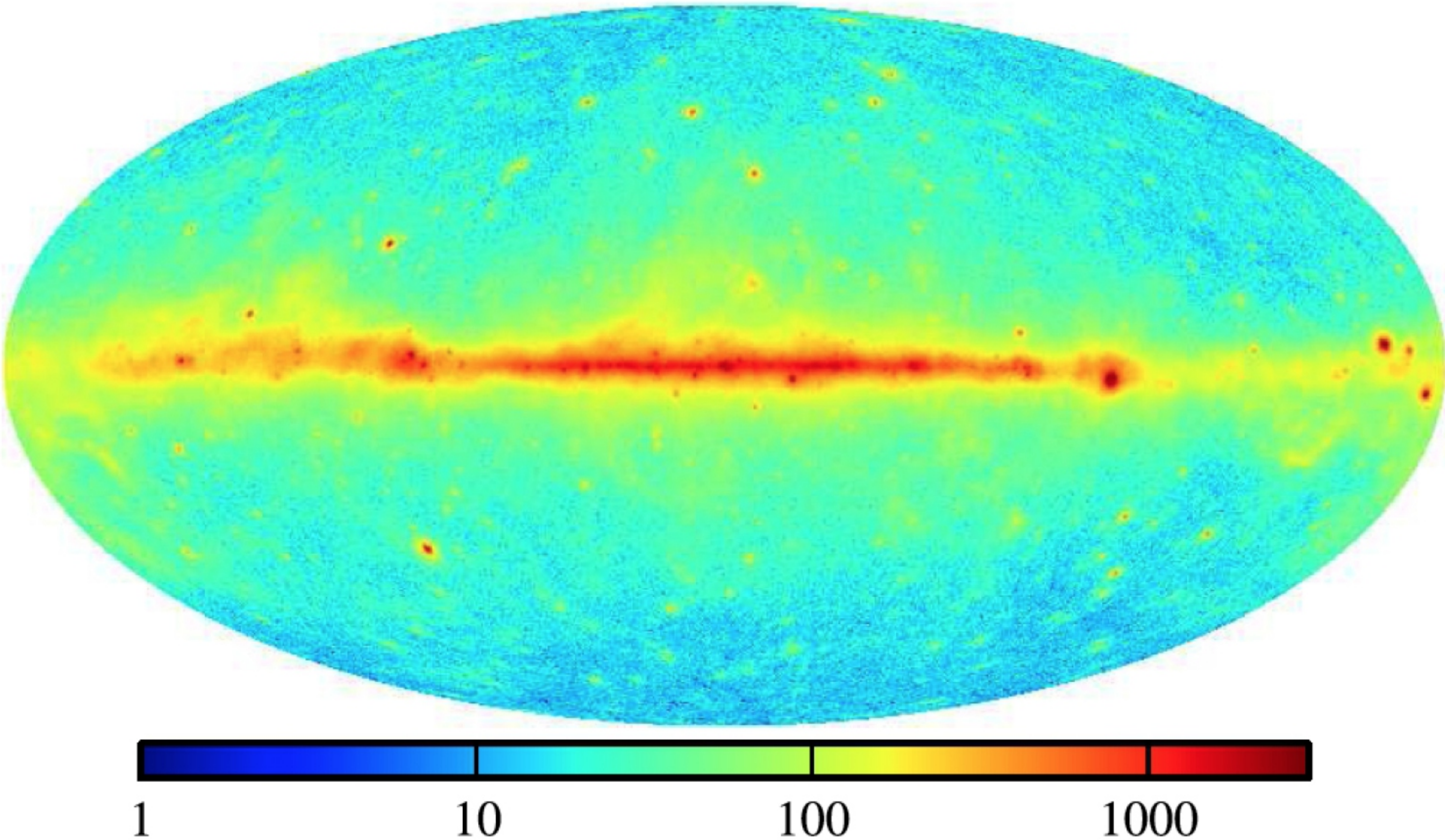


Diffuse Emission



Fermi–LAT counts

Galactic coordinates



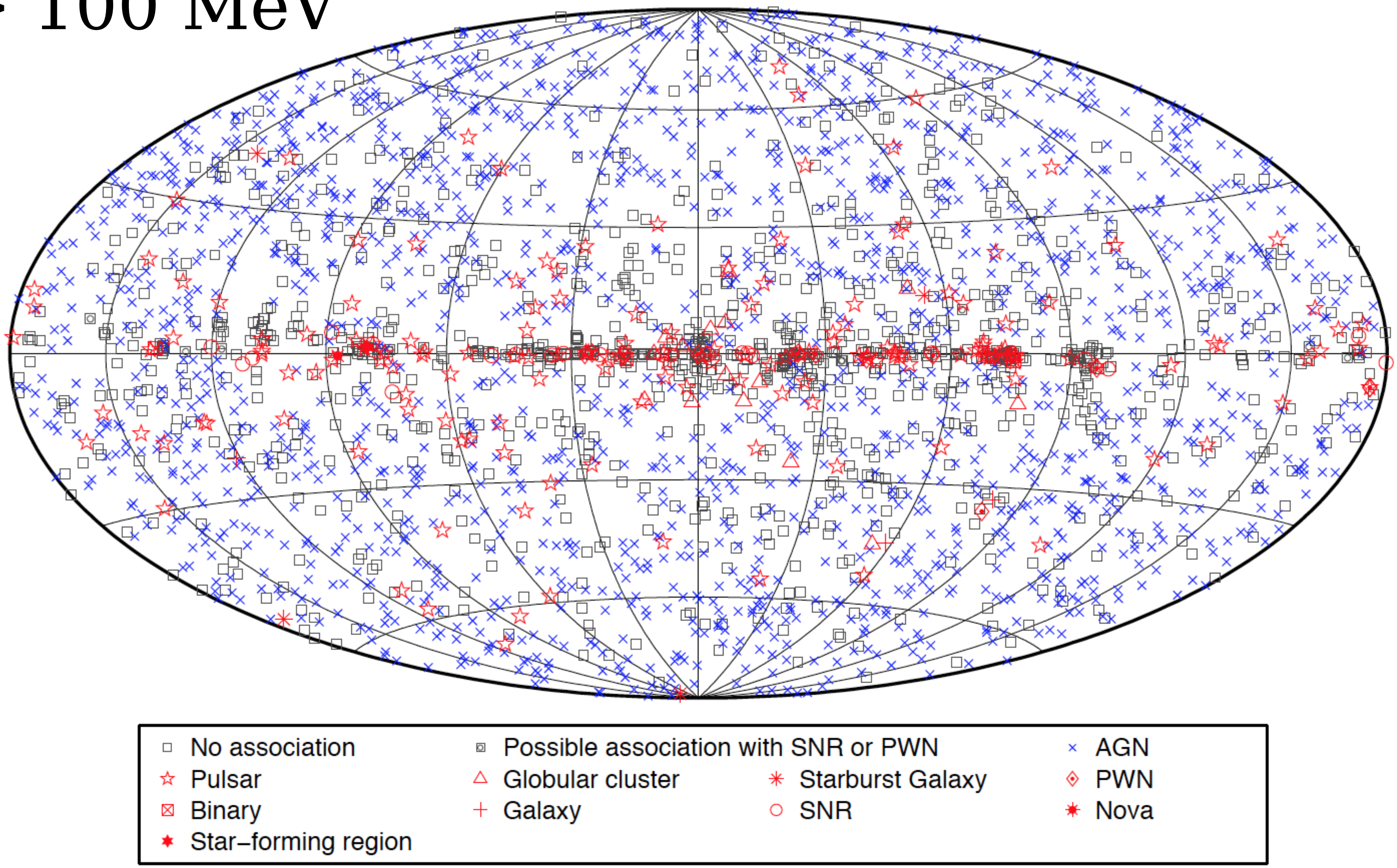
energy range 200 MeV to 100 GeV

Cosmic Ray interactions in the Interstellar Medium

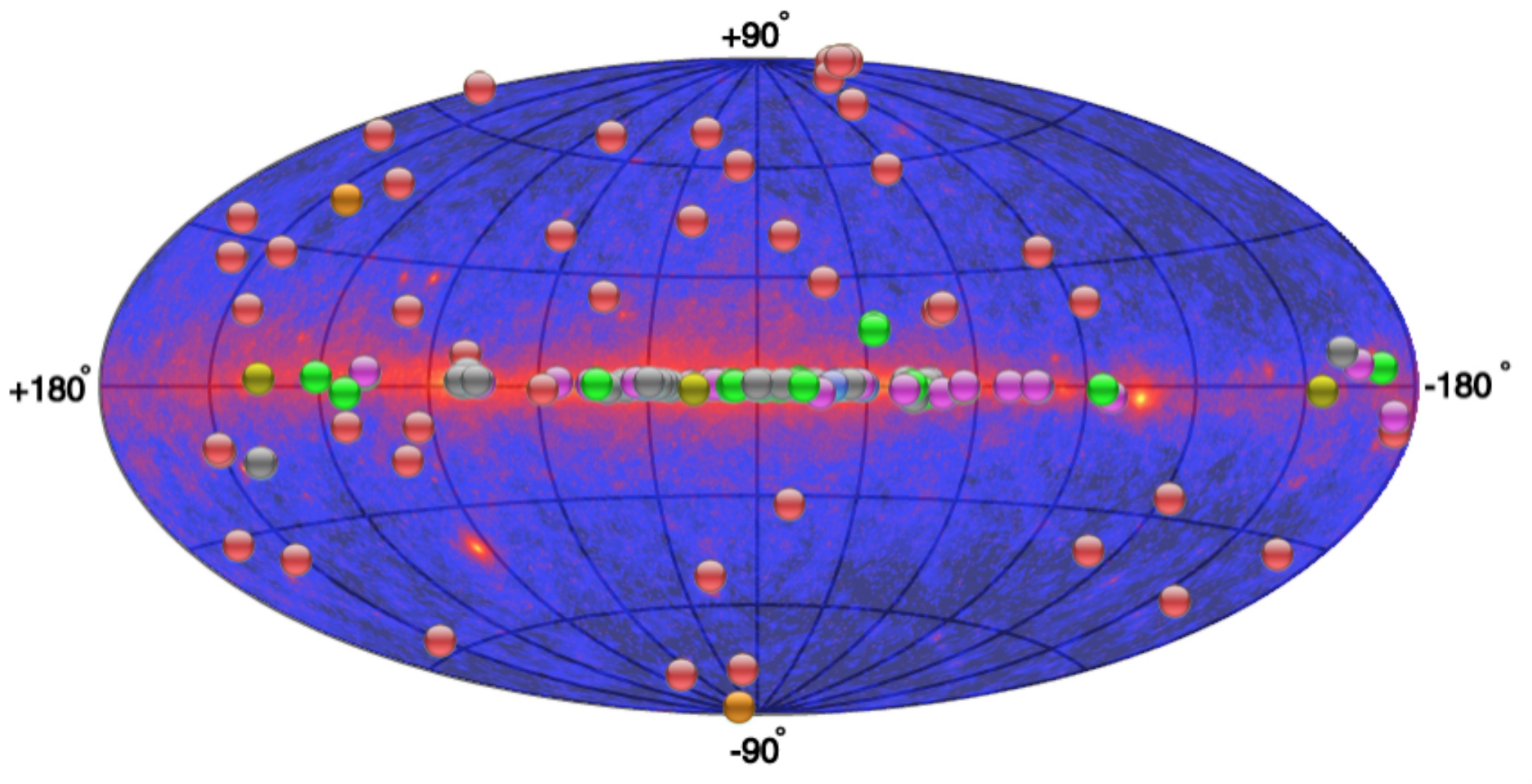
50% of flux
+- 5 degrees
around equator
[Galactic gas]

3rd FERMI Catalog 3034 sources

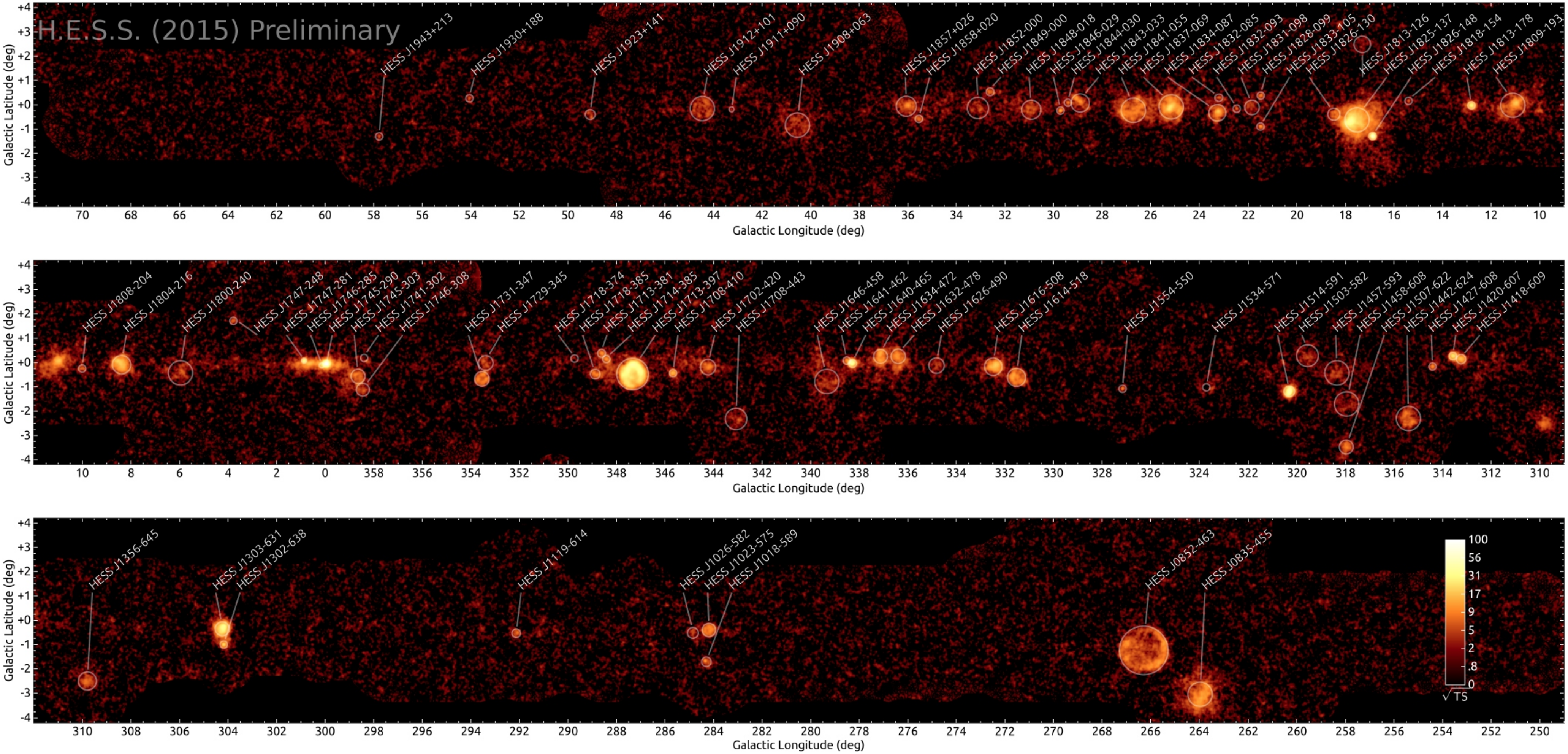
E > 100 MeV



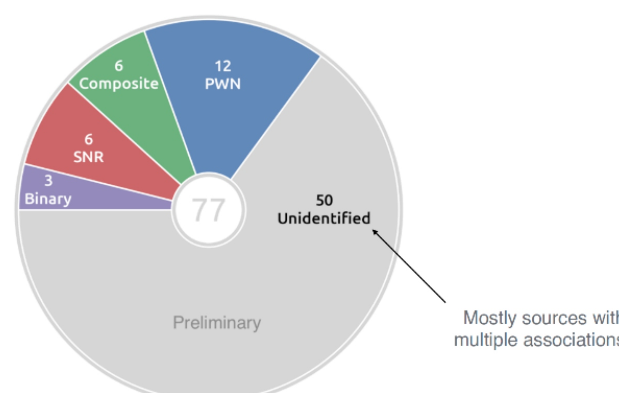
TeV Sky 170 → 200 Sources



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

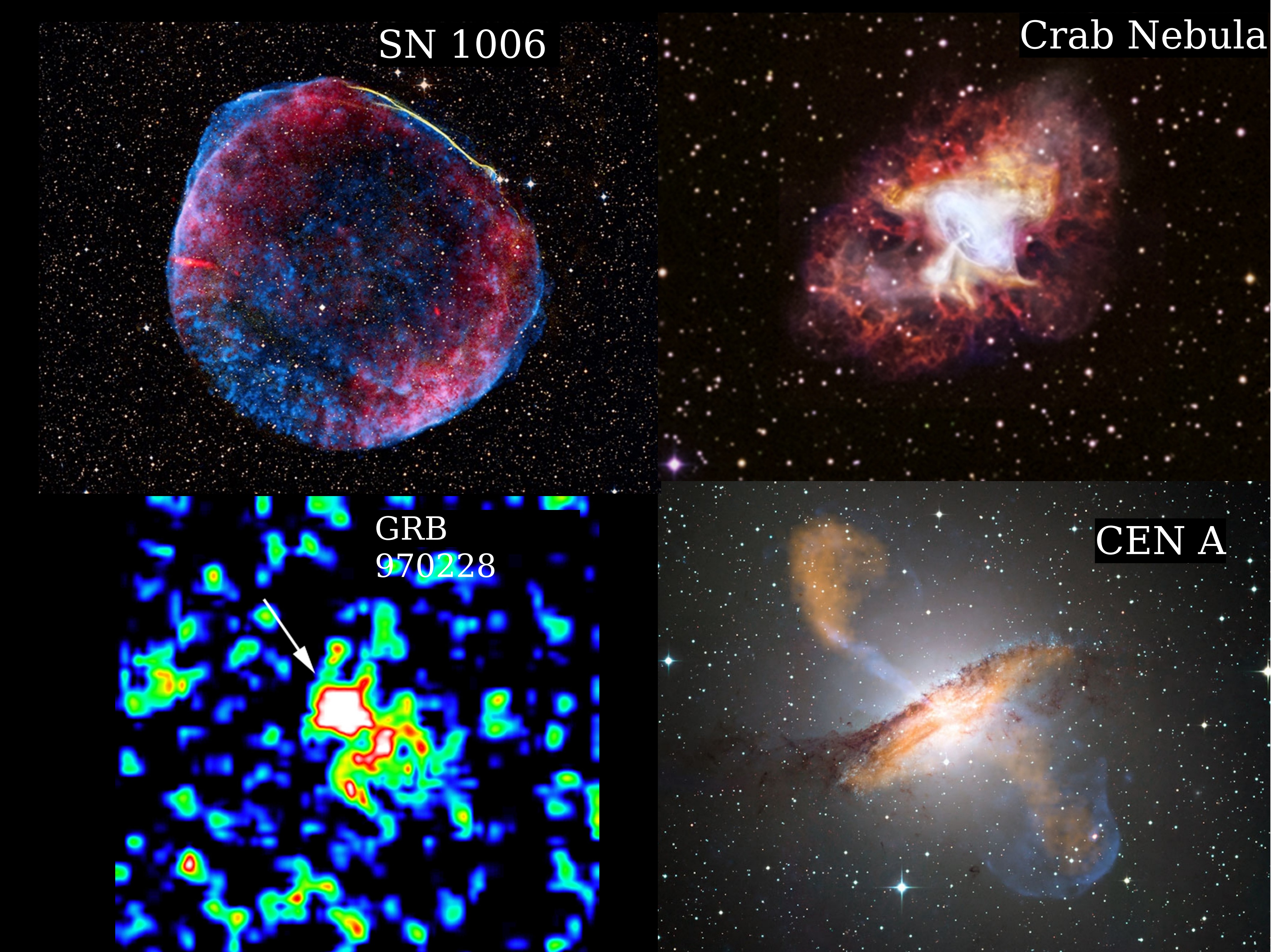


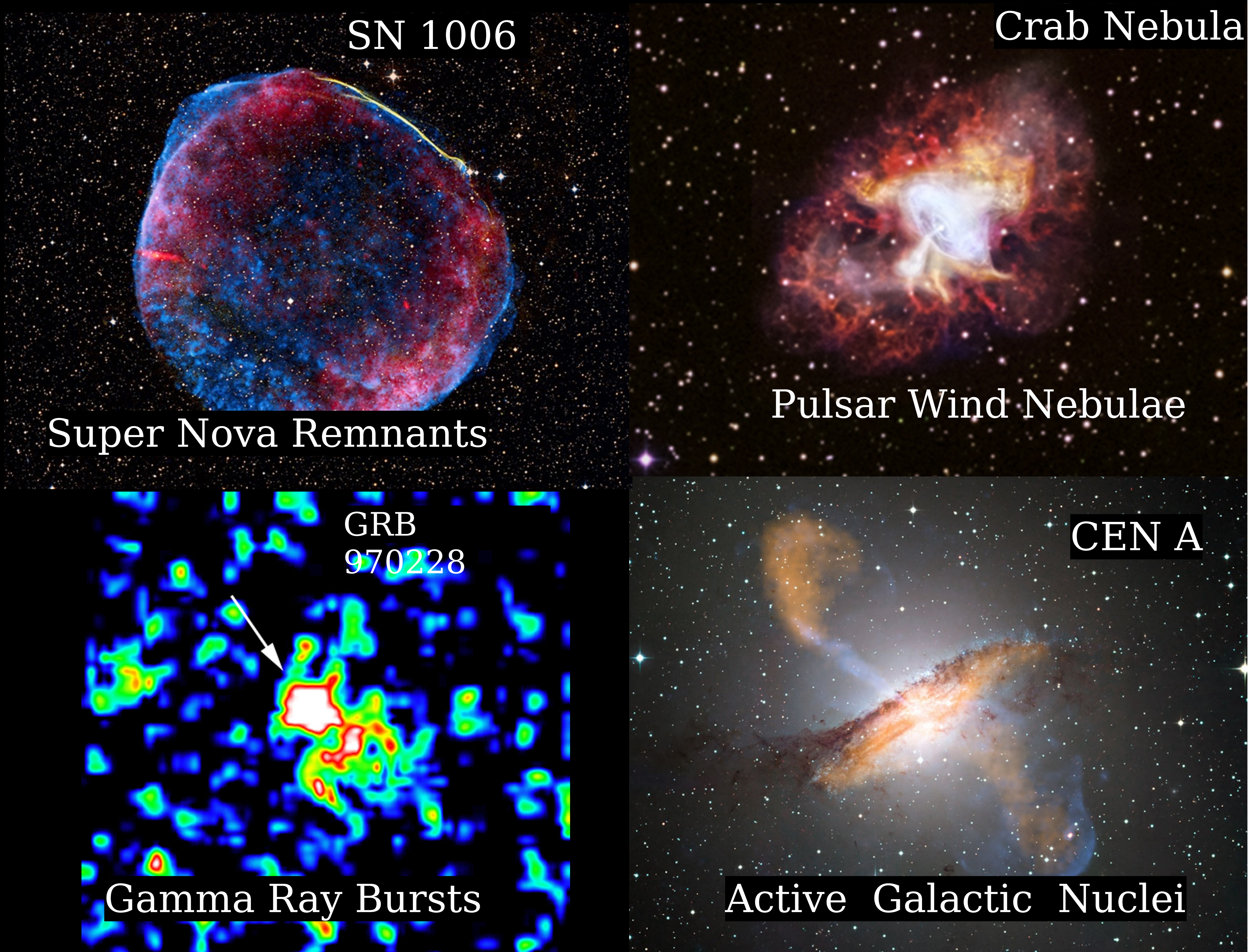
Firm identifications



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

Extraordinary beasts in the sky

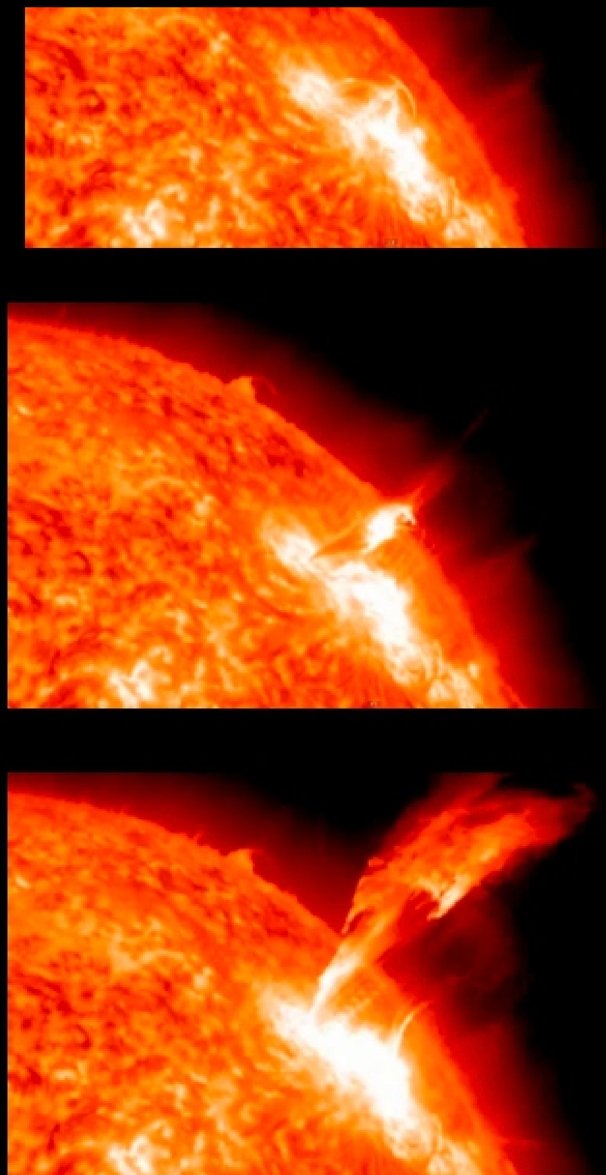

SN 1006
Crab Nebula
GRB
970228
CEN A

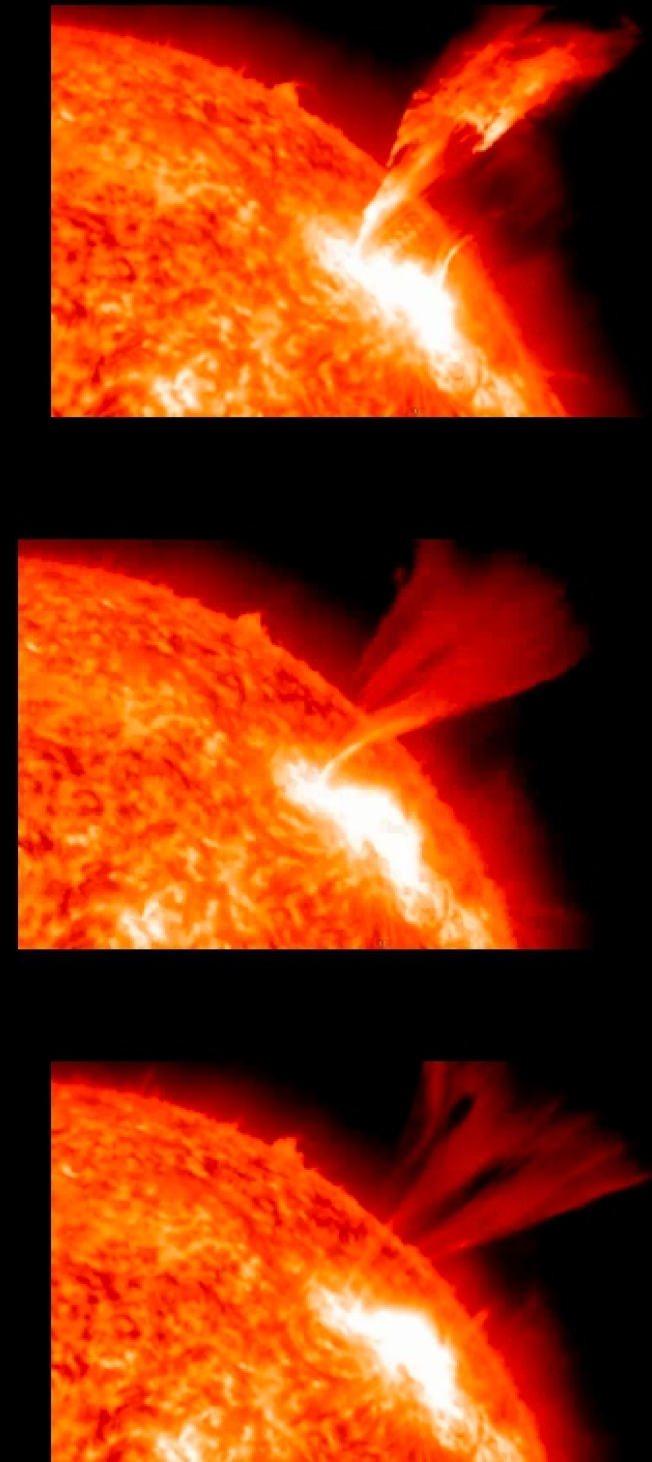

SN 1006
Super Nova Remnants
Crab Nebula
Pulsar Wind Nebulae
GRB
970228
Gamma Ray Bursts
CEN A
Active Galactic Nuclei

Acceleration of Cosmic Rays

[electrically charged particles]

The SUN:
small scale laboratory:
Solar Flare



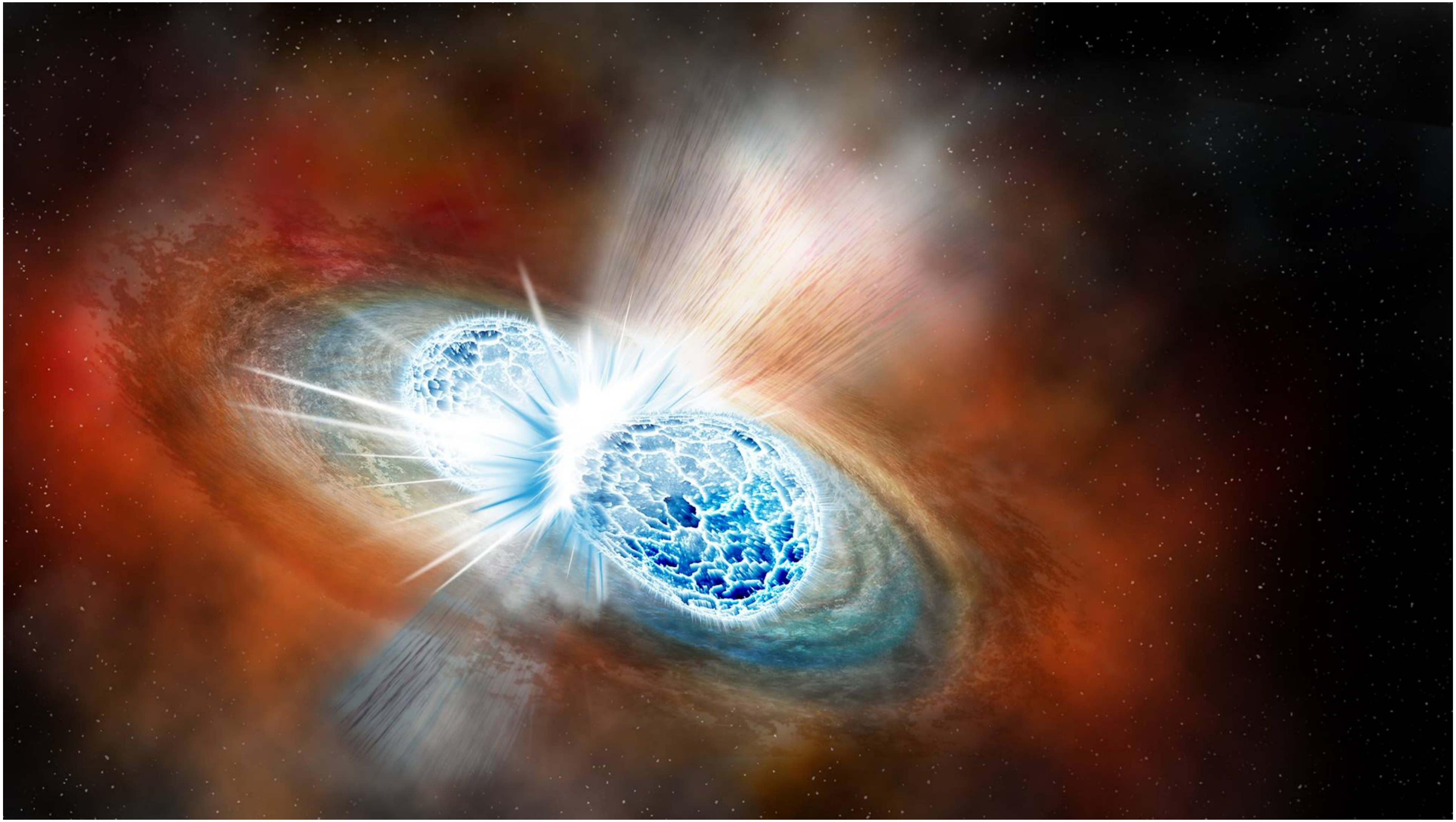


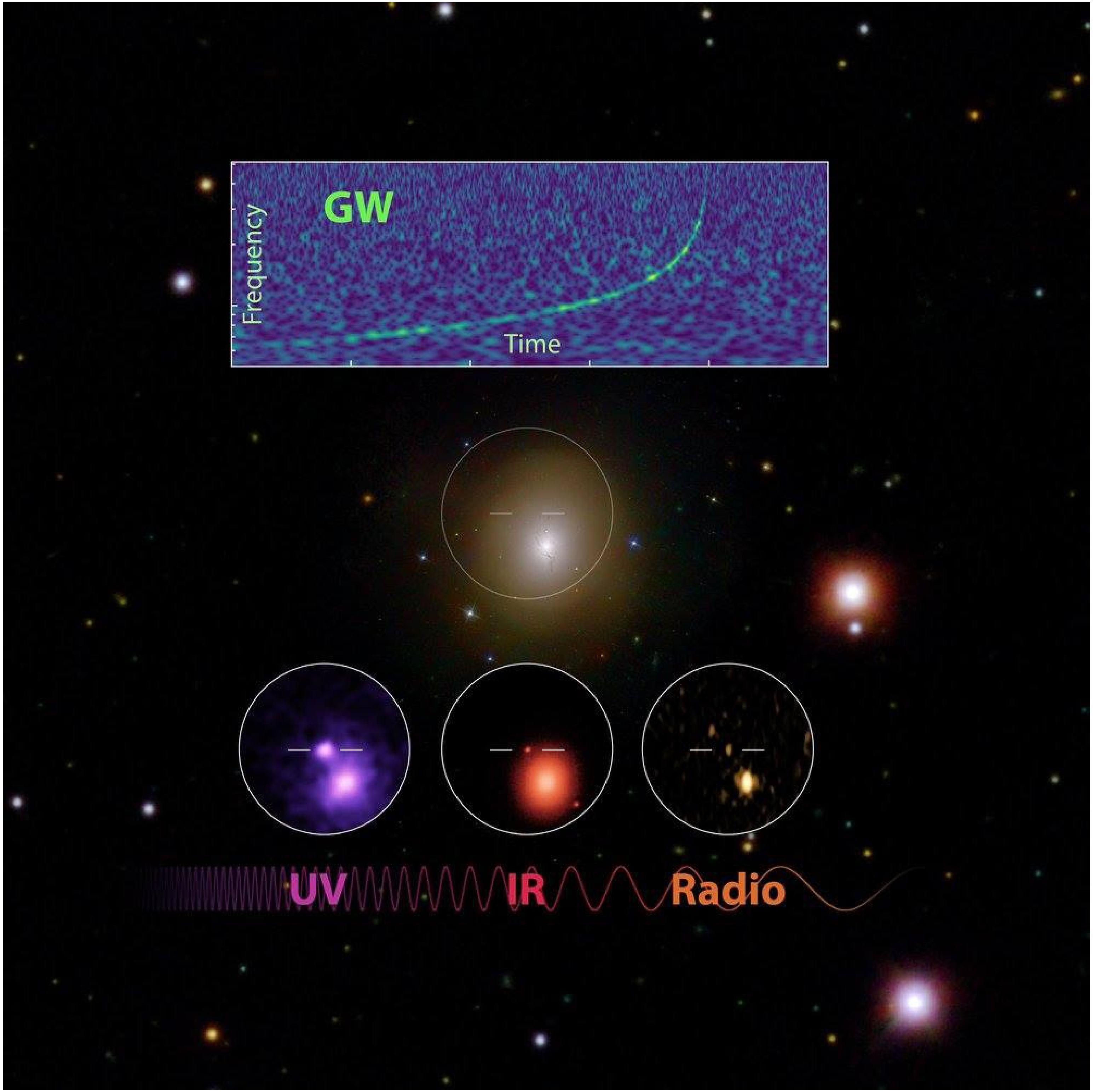
7th march 2011. 20:02 UT

Aurora detected
in Canada same night

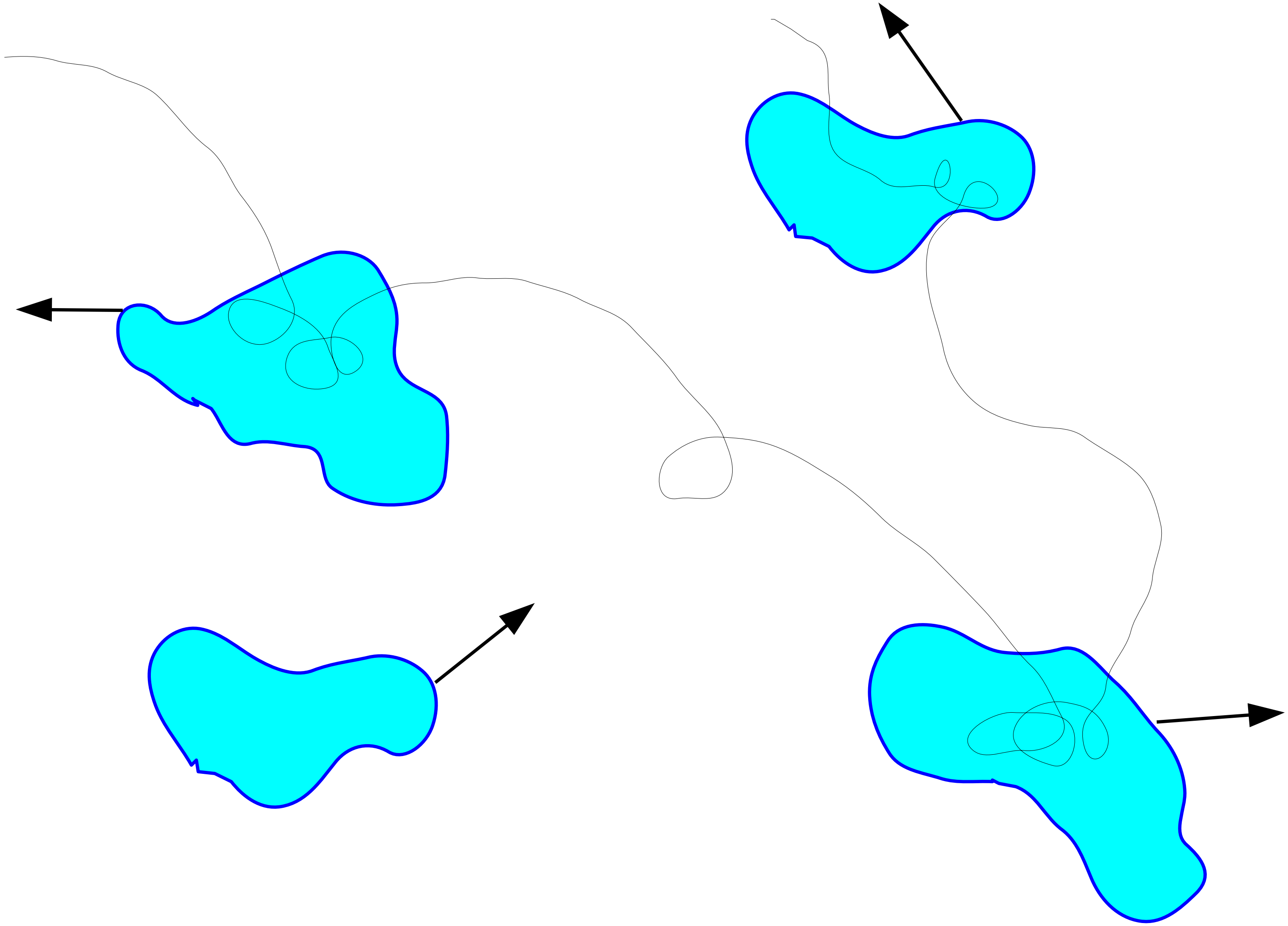
“Analogy”

On a very different scale ......   GW 170817



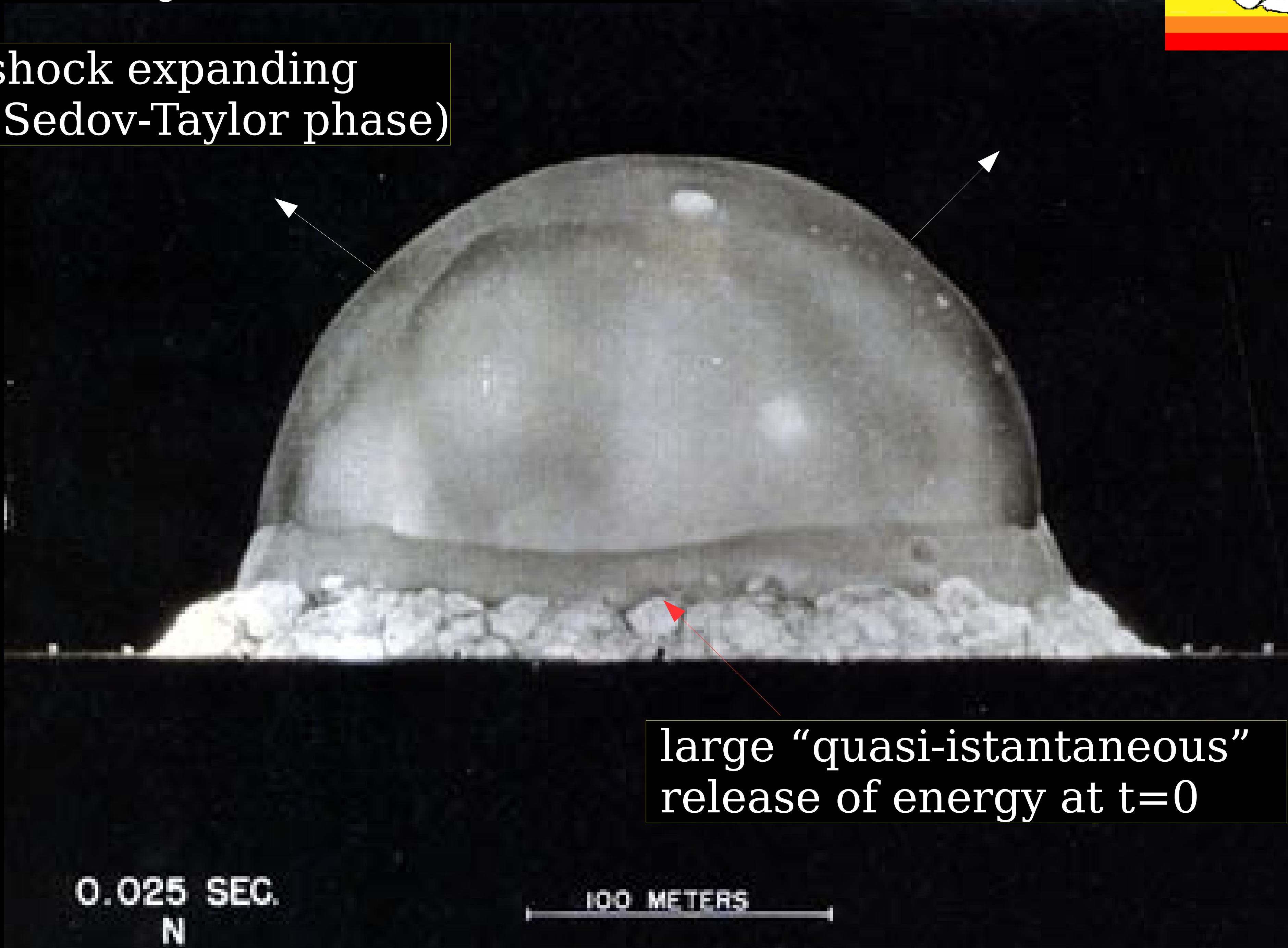

GW
Frequency
Time
UV
IR
Radio

Enrico Fermi original idea



Collisions of charged particles
with moving plasma clouds in the Galaxy
Energy transfer from a macroscopic object to particles

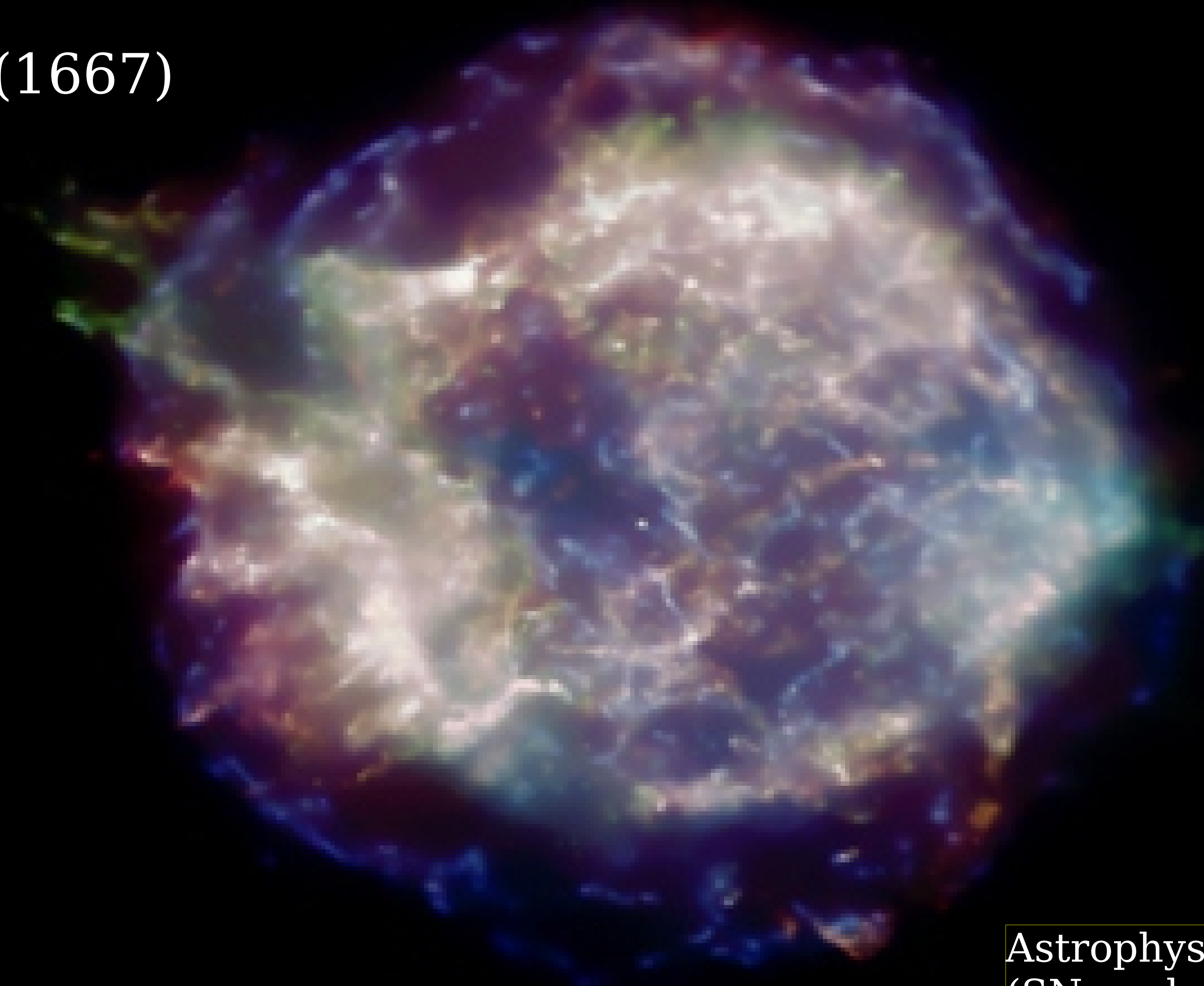
Trinity Test (1945)



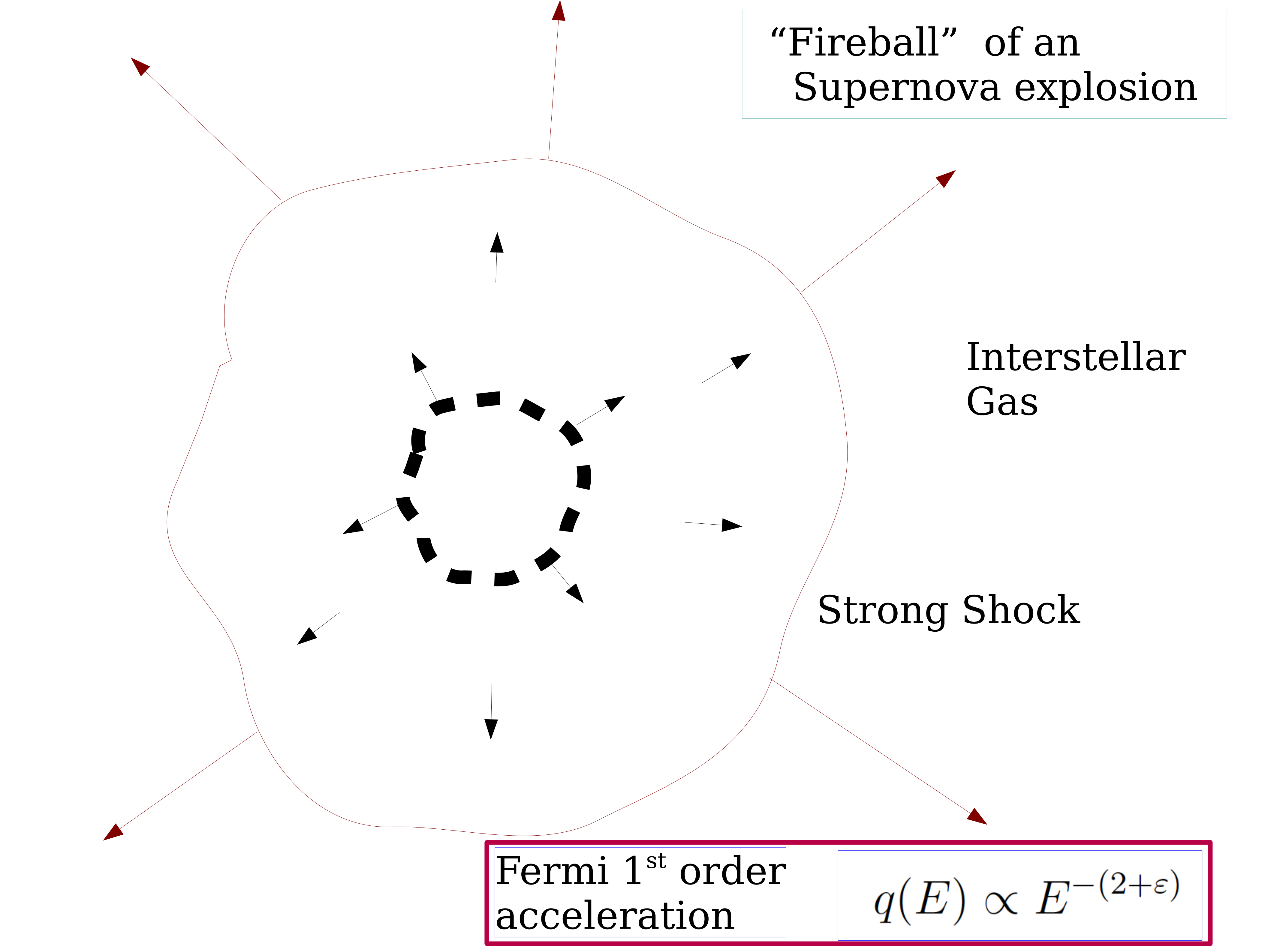
CAS A

(1667)

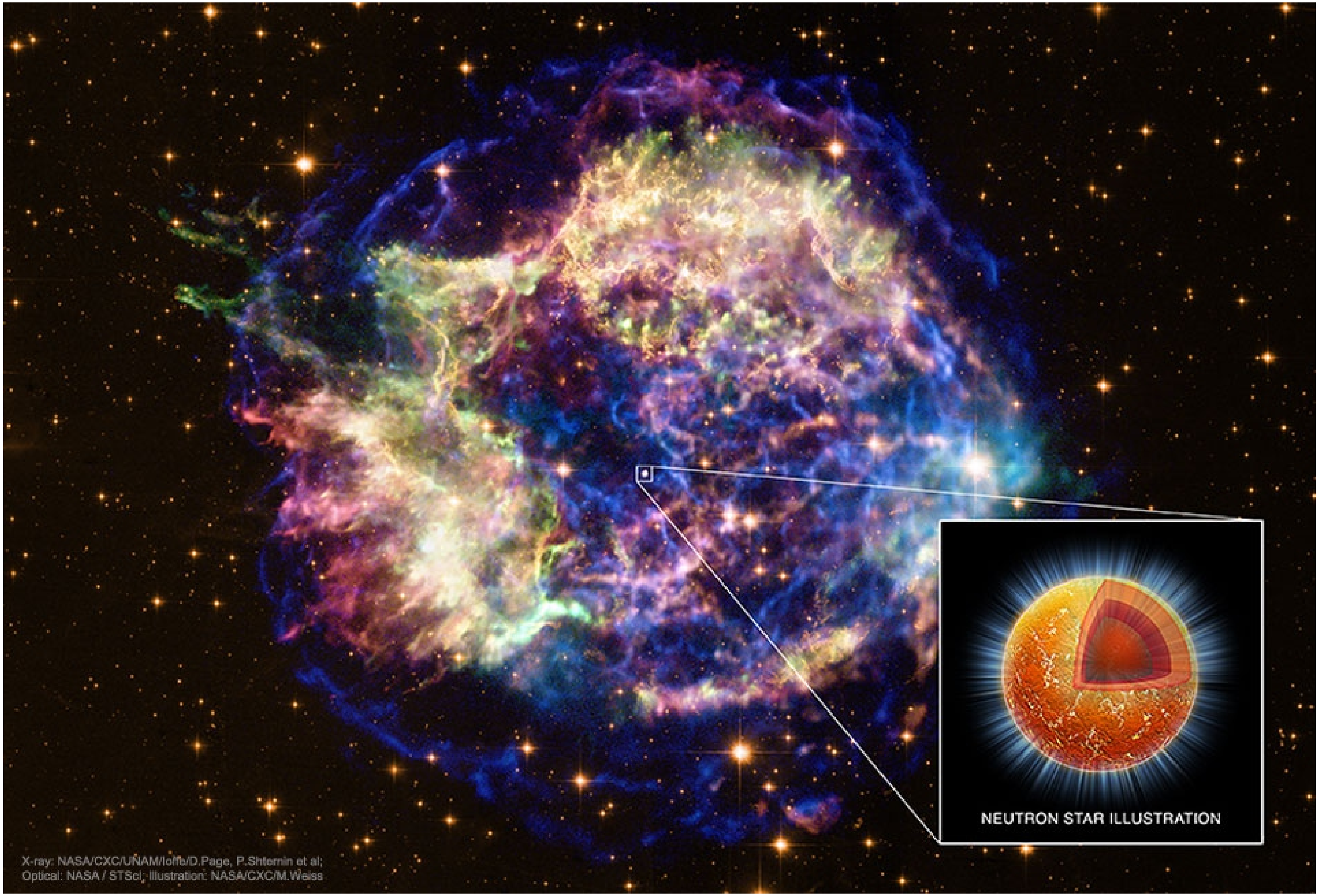
FERMI "1st order acceleration
at strong shocks



Astrophysical shock
(SN explosion)


"Fireball" of an Supernova explosion
Interstellar Gas
Strong Shock
Fermi 1st order acceleration
$q(E) \propto E^{-(2+\varepsilon)}$

Creation of a Neutron Star in a SuperNova explosion



The CRAB Nebula

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

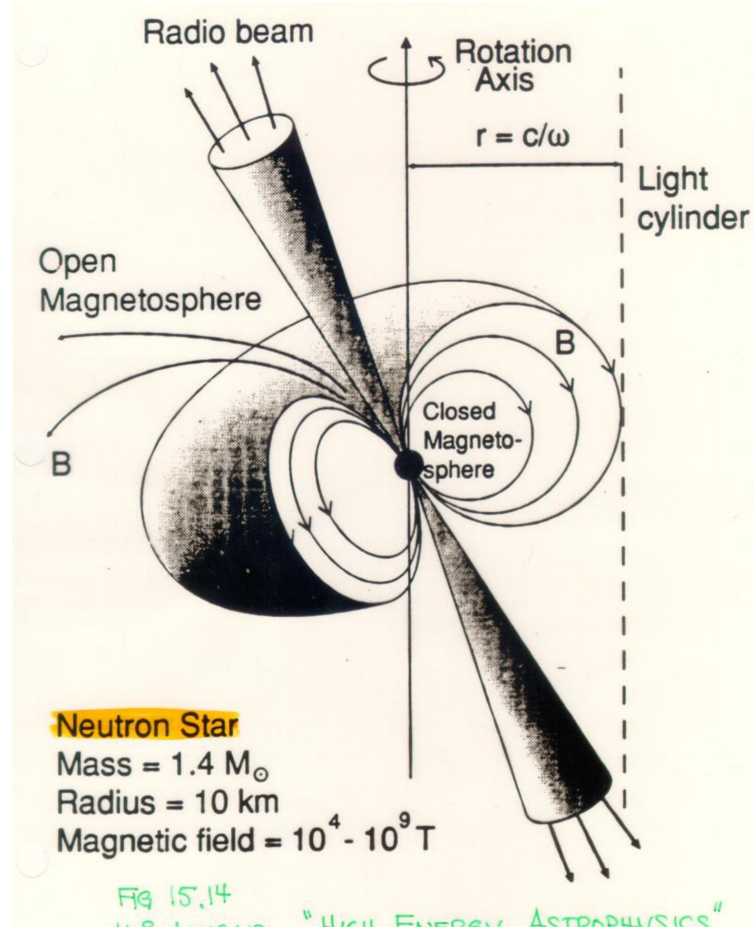
PULSARS

Proposed as possible Accelerators of e+ e-

CRAB Nebula

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

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

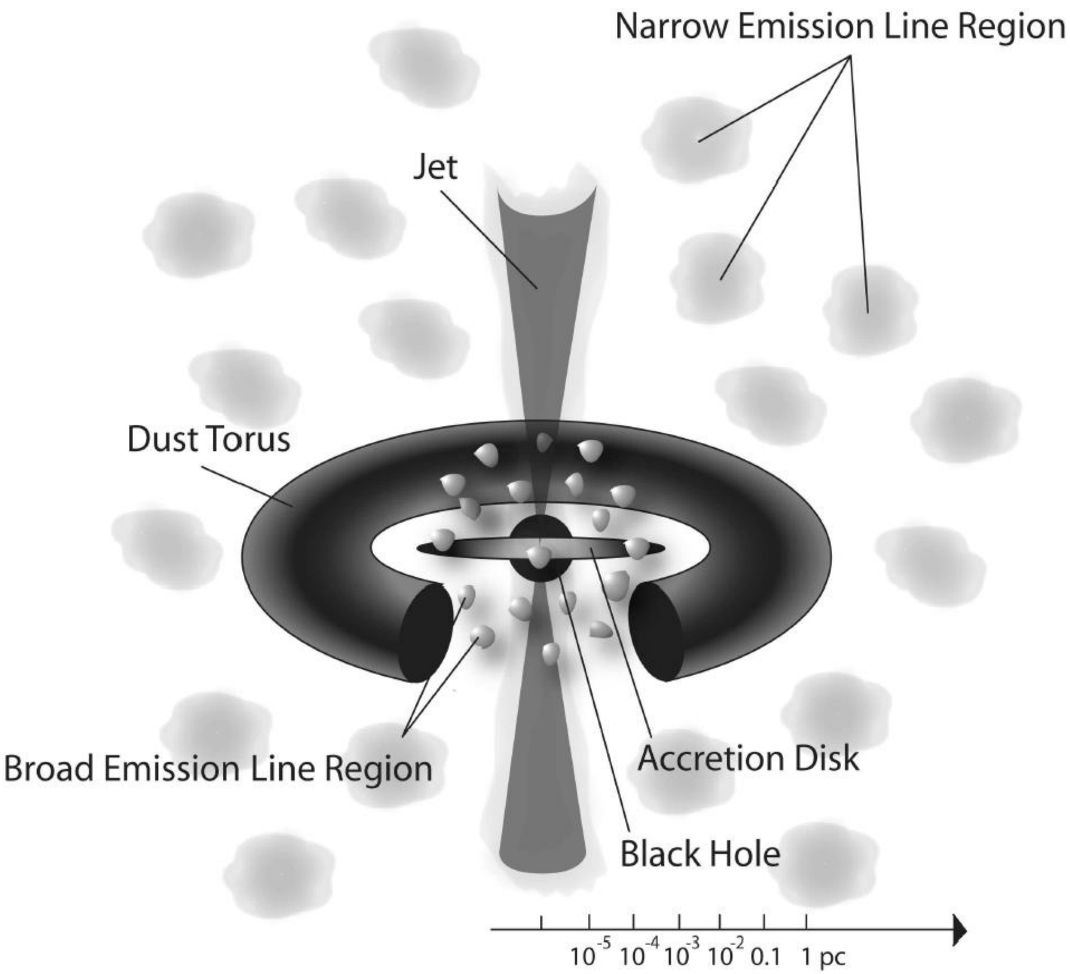


> 100 well identified Pulsars

(3 Pulsar-Wind-Nebulae)

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

ACTIVE GALACTIC NUCLEI

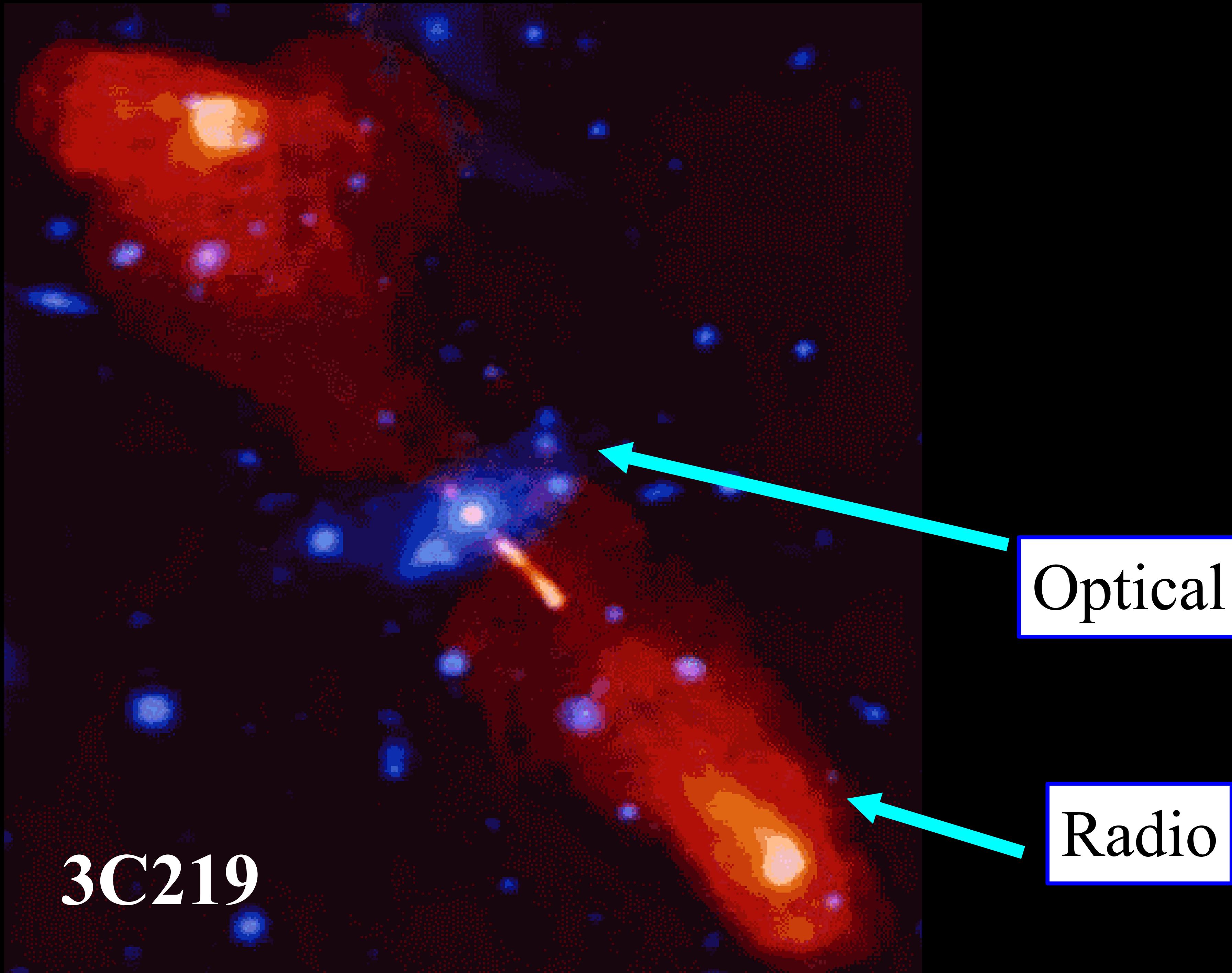


At the center of (probably)
all galaxies
there is a large mass concentration
(millions or even billions
of solar masses).
Mass is very compact
essentially certainly
a SuperMassibe Black Hole

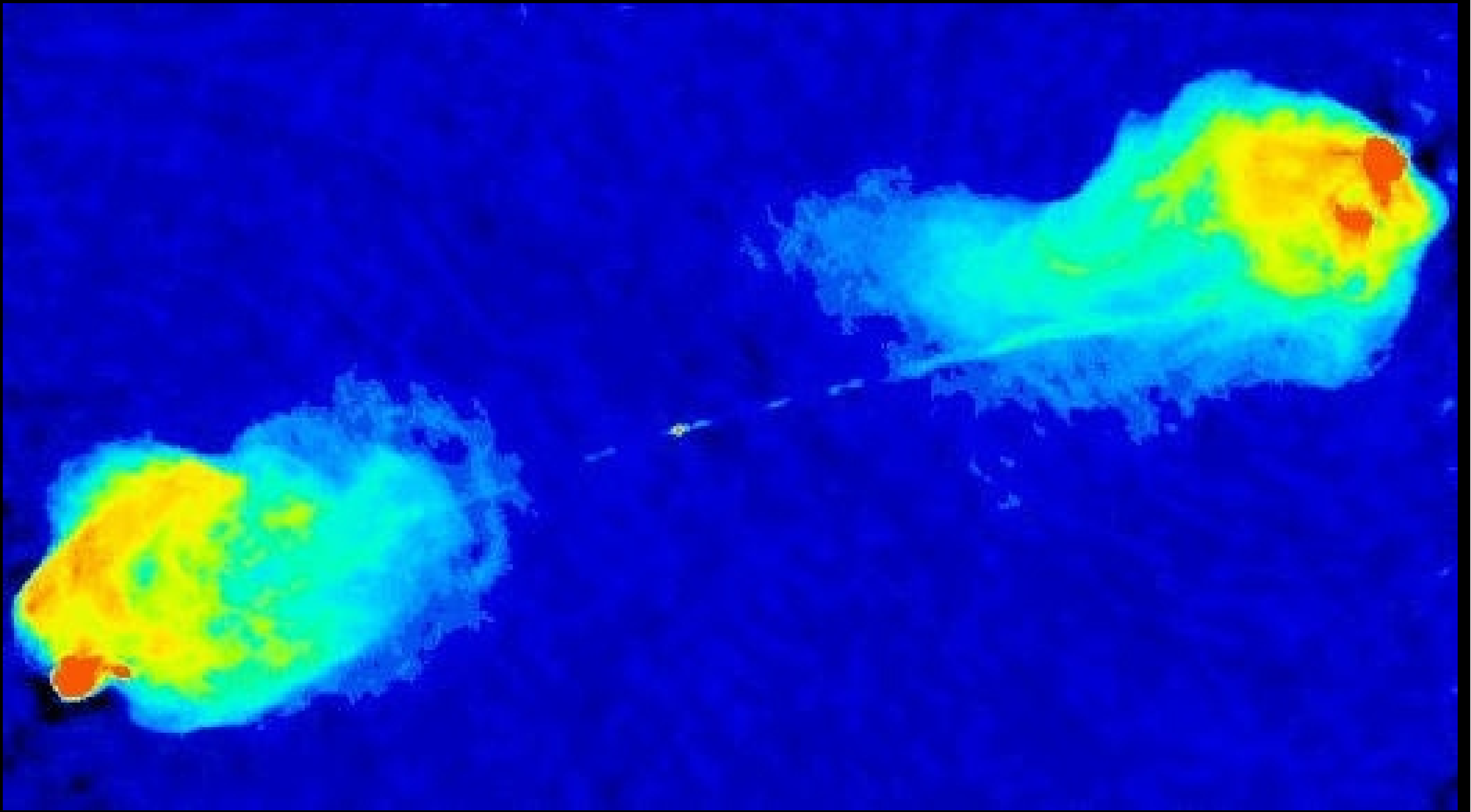
Accretion on the central object
generates radiation
in a very broad spectrum,

The brightest objects
in the Universe.

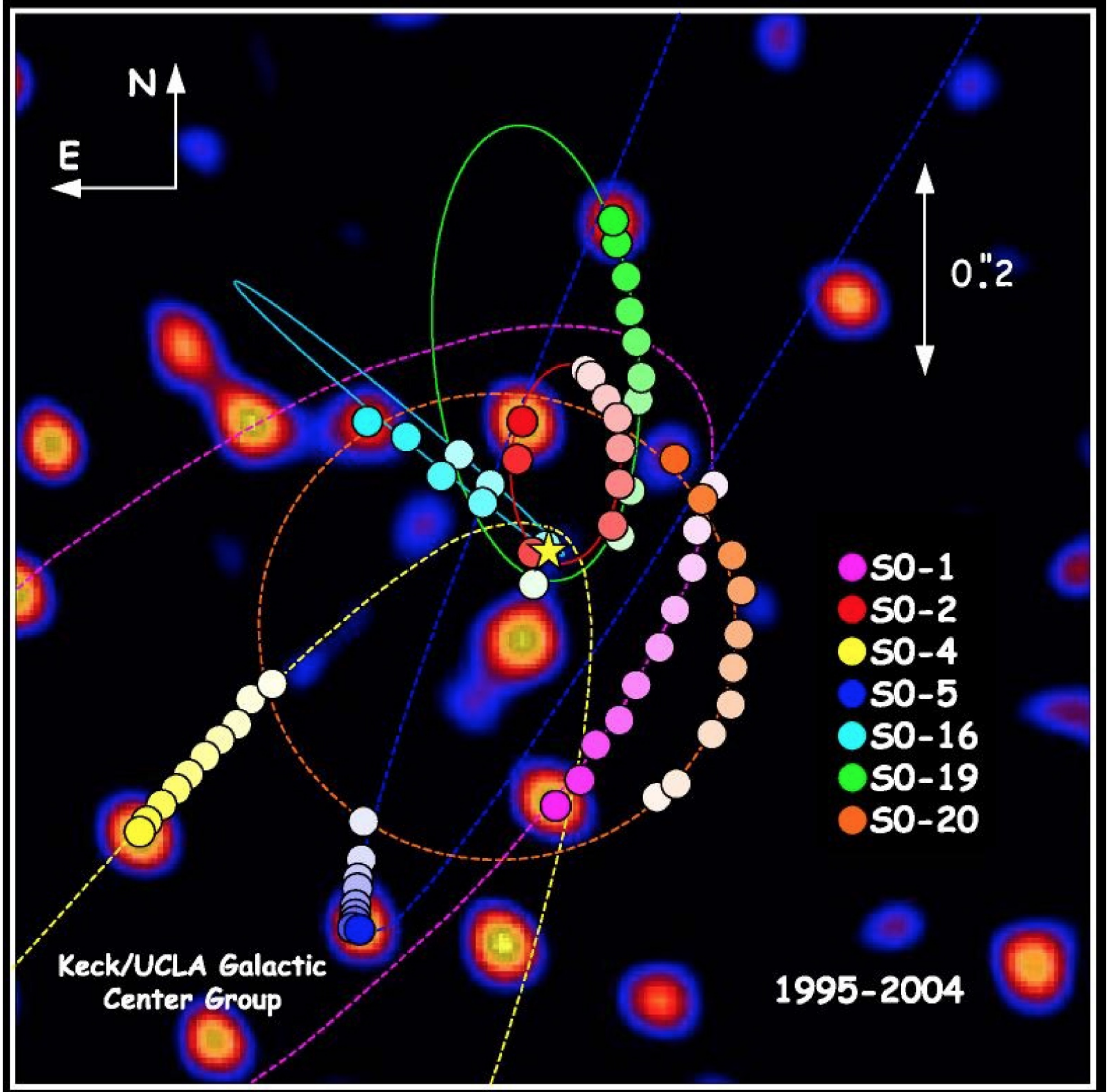
ACTIVE GALACTIC NUCLEI



CYGNUS-A



Galactic Center

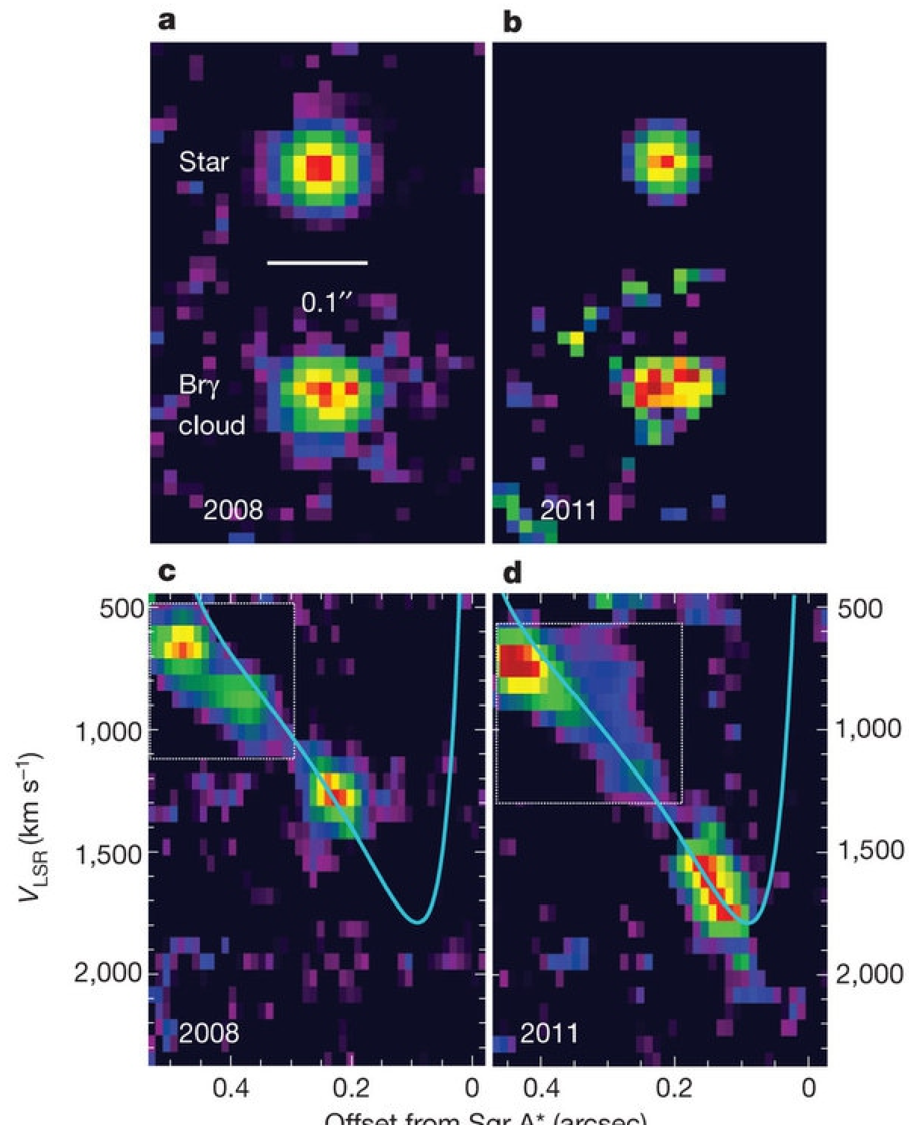


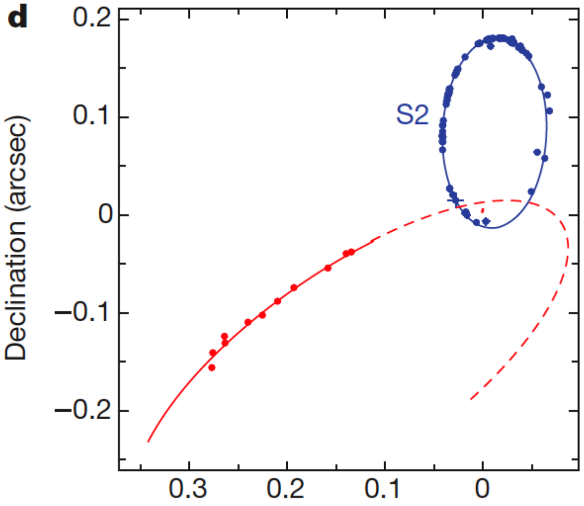
N
E
0."2
S0-1
S0-2
S0-4
S0-5
S0-16
S0-19
S0-20
Keck/UCLA Galactic
Center Group
1995-2004

doi:10.1038/nature10652

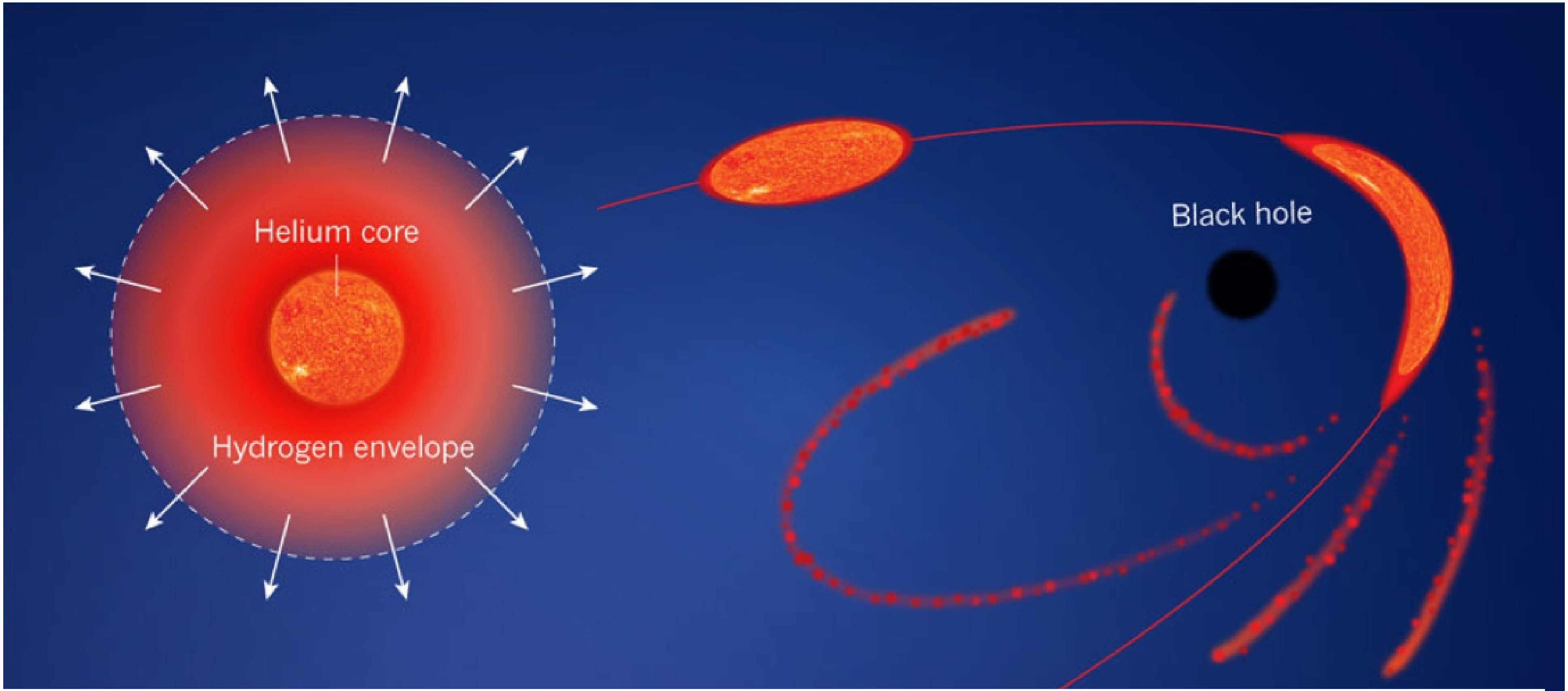
A gas cloud on its way towards the supermassive black hole at the Galactic Centre

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]



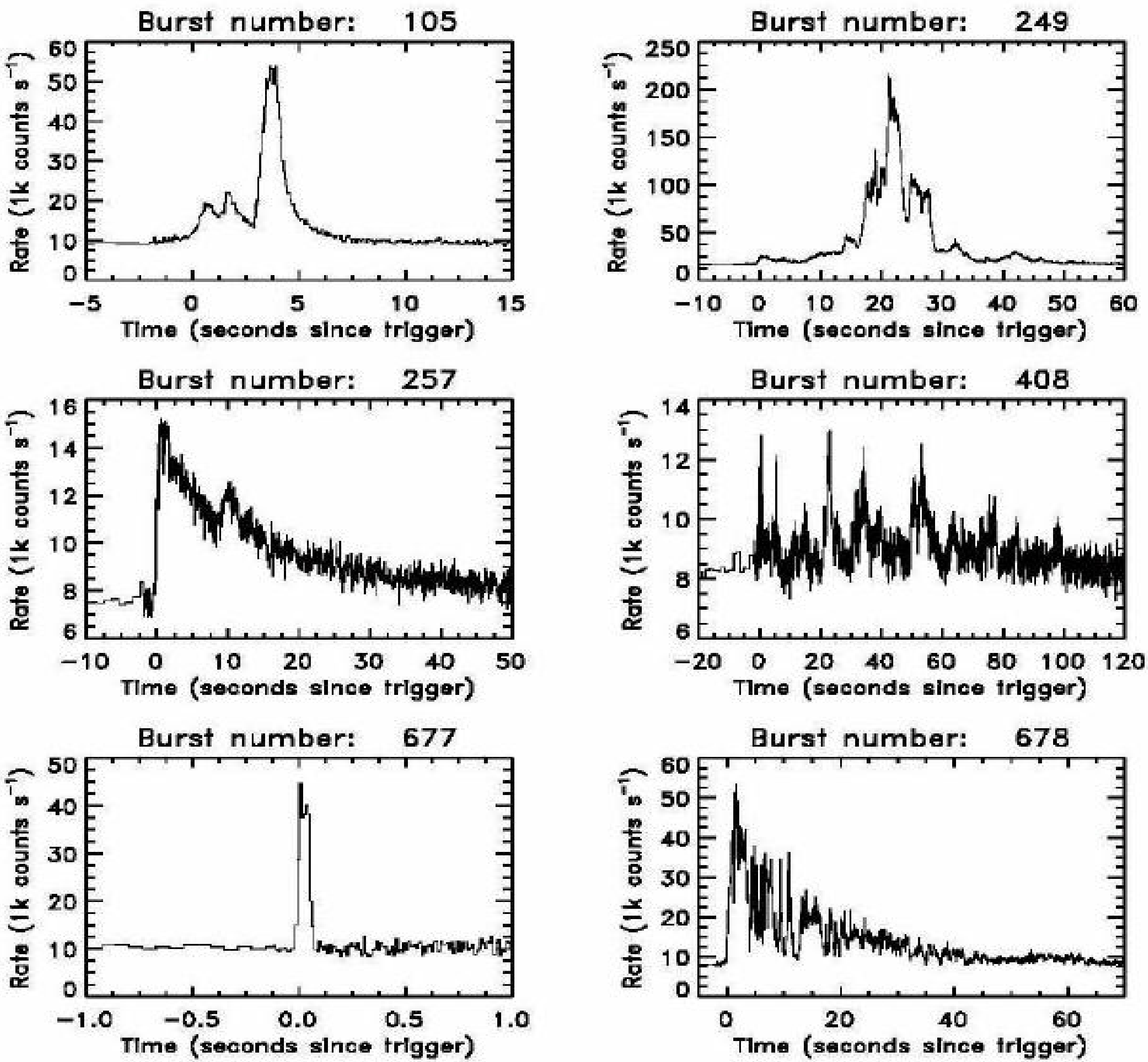


Infalling gas from the disruption of a star.

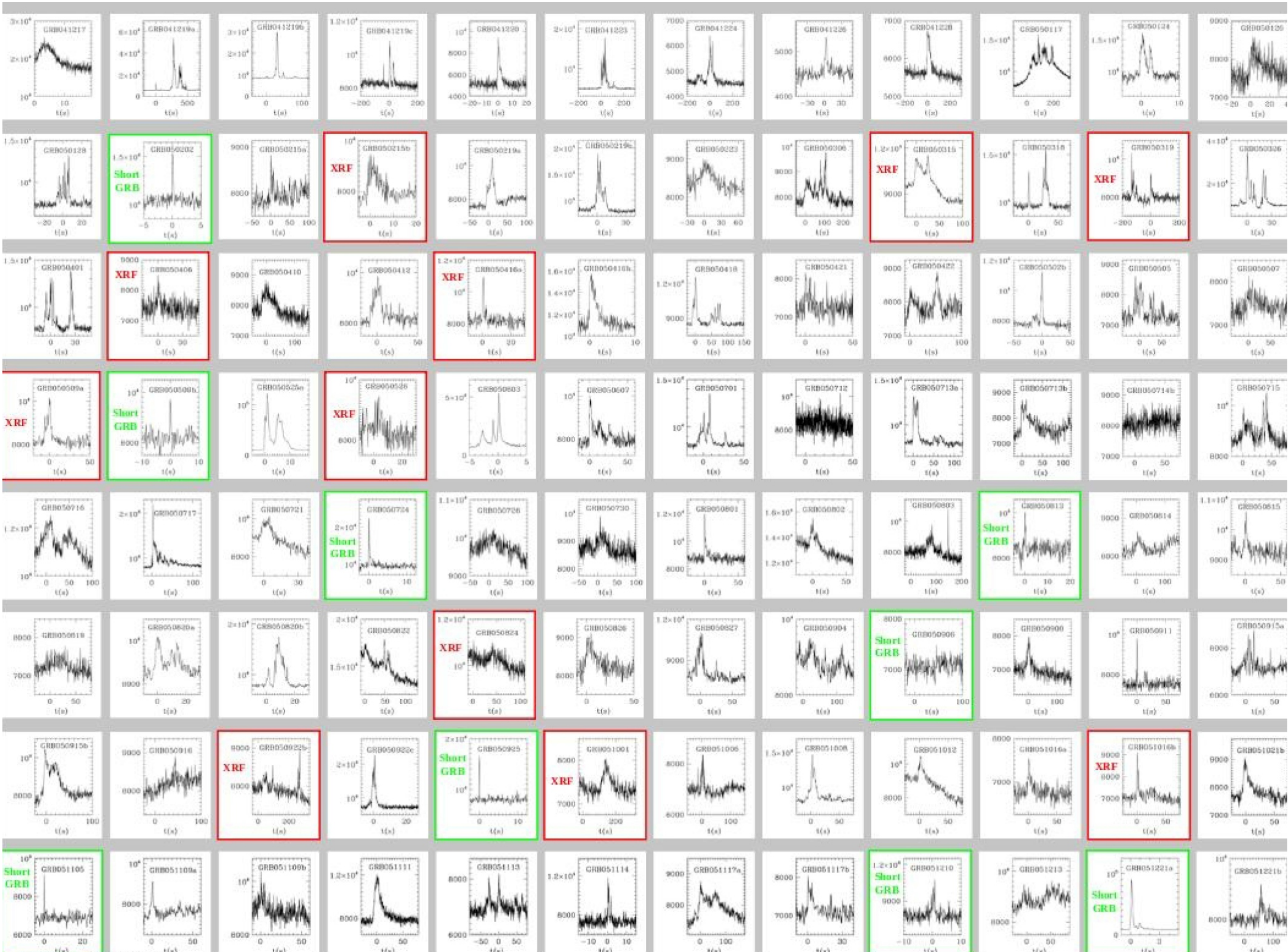


The helium-rich core of a red-giant star that had previously lost its hydrogen envelope moves on an almost parabolic orbit (red) towards a supermassive black hole. The sequence of blobs illustrates the progressive distortion of the star's core due to the tidal pull of the black hole. After the point 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].

GAMMA RAY BURSTS (GRB's)

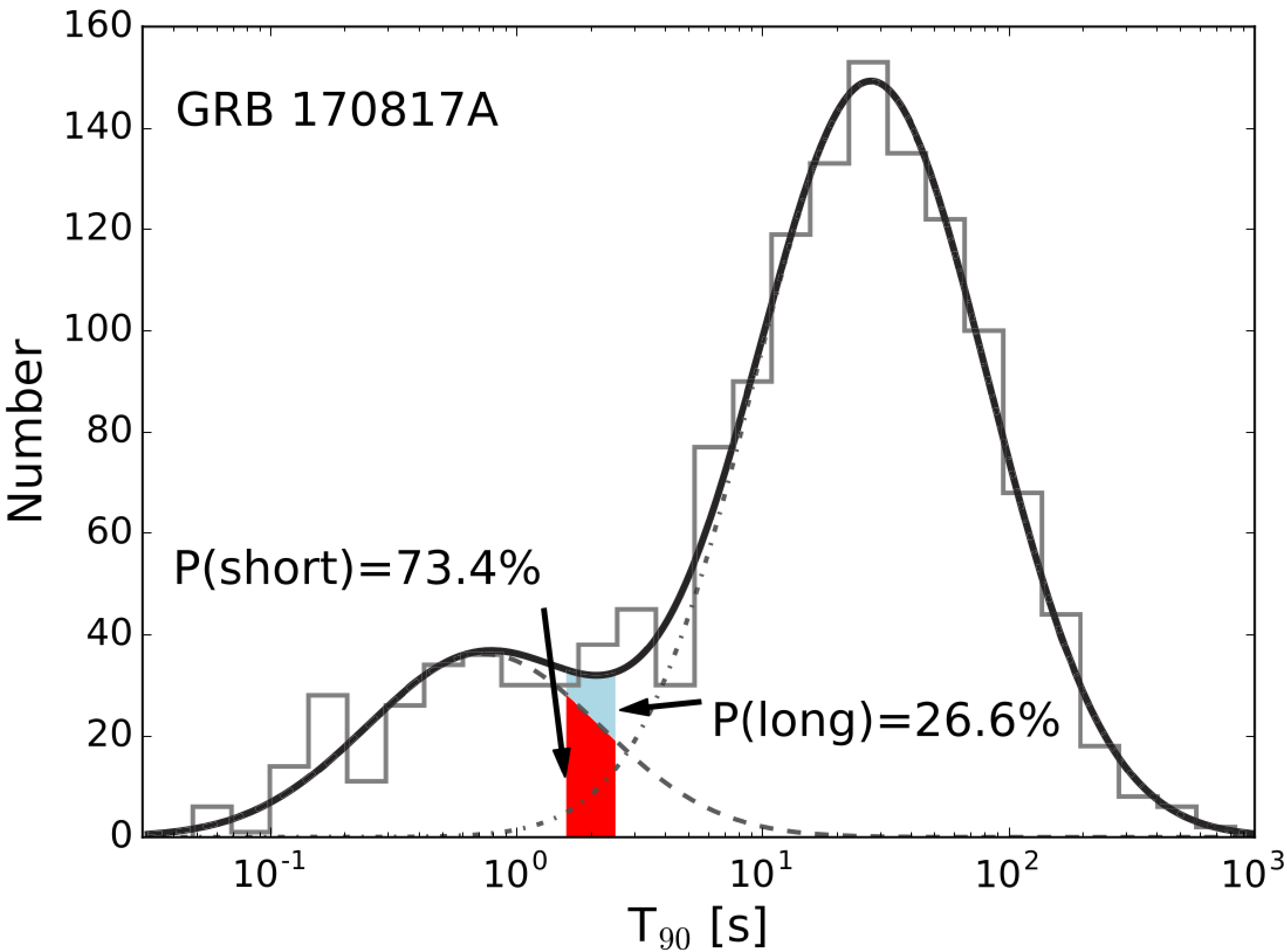


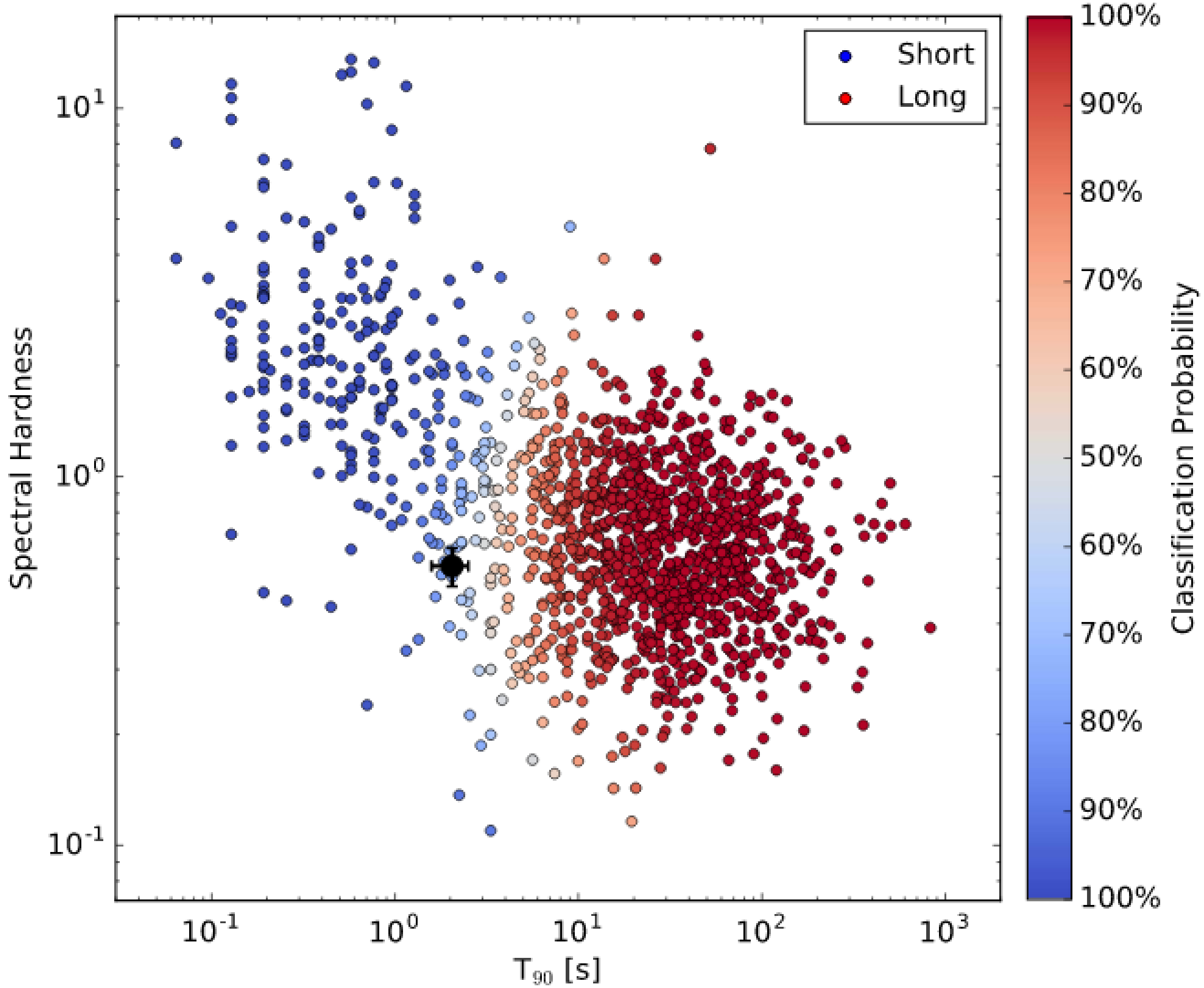
Proposed source
Of the CR



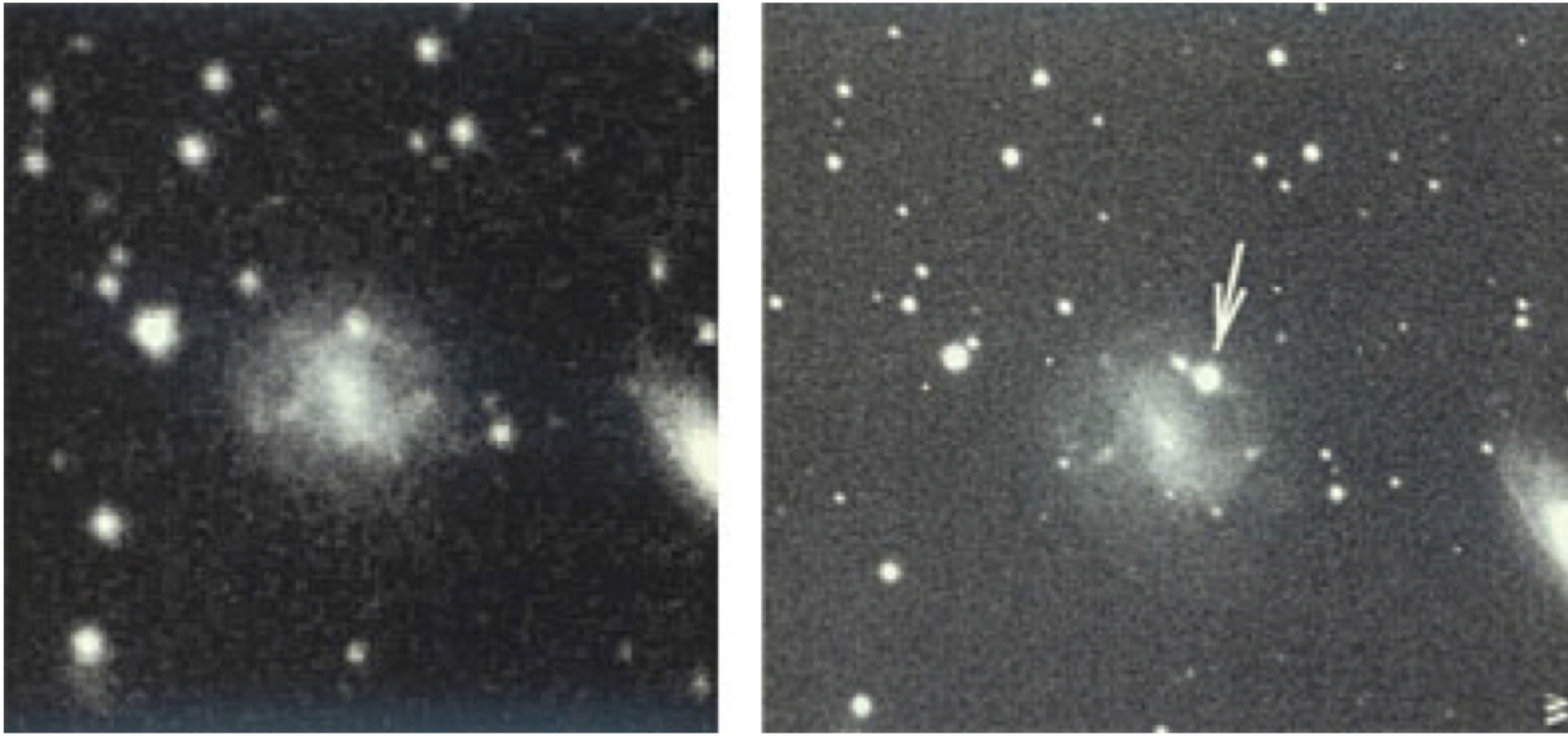
[From N. Gehrels]

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

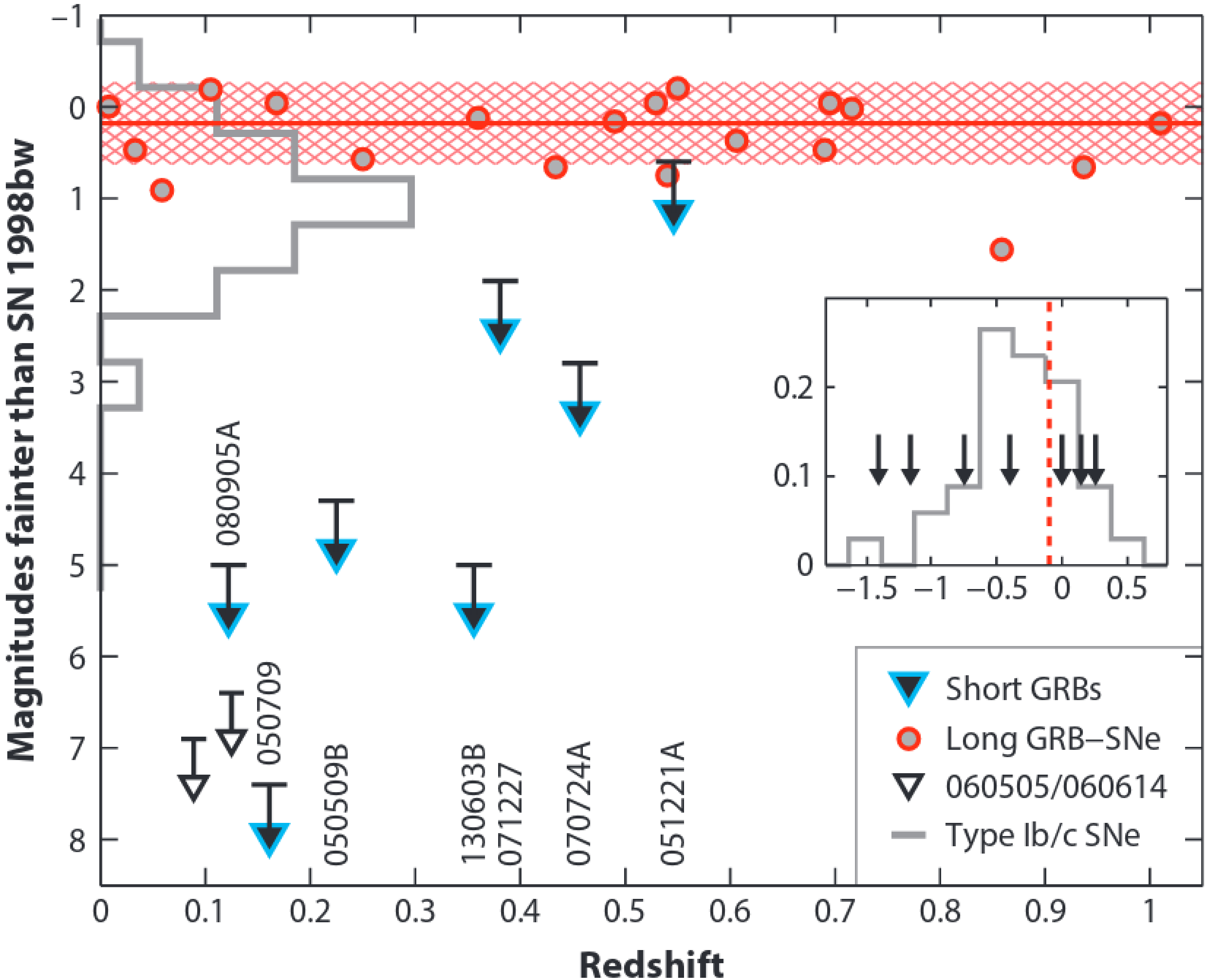




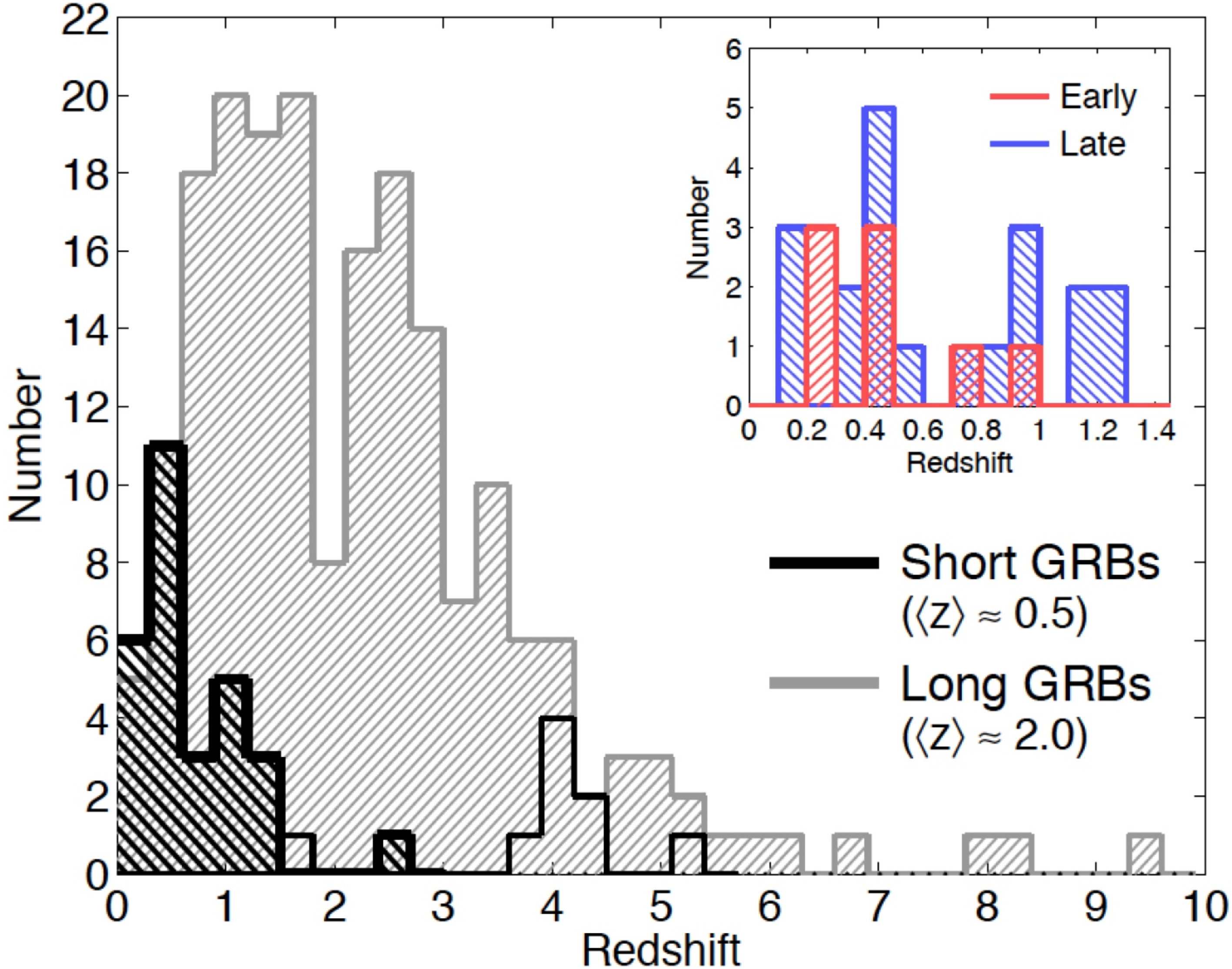
Short
Long
Spectral Hardness
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2
10^3
T_{90} [s]
100%
90%
80%
70%
60%
50%
60%
70%
80%
90%
100%
Classification Probability



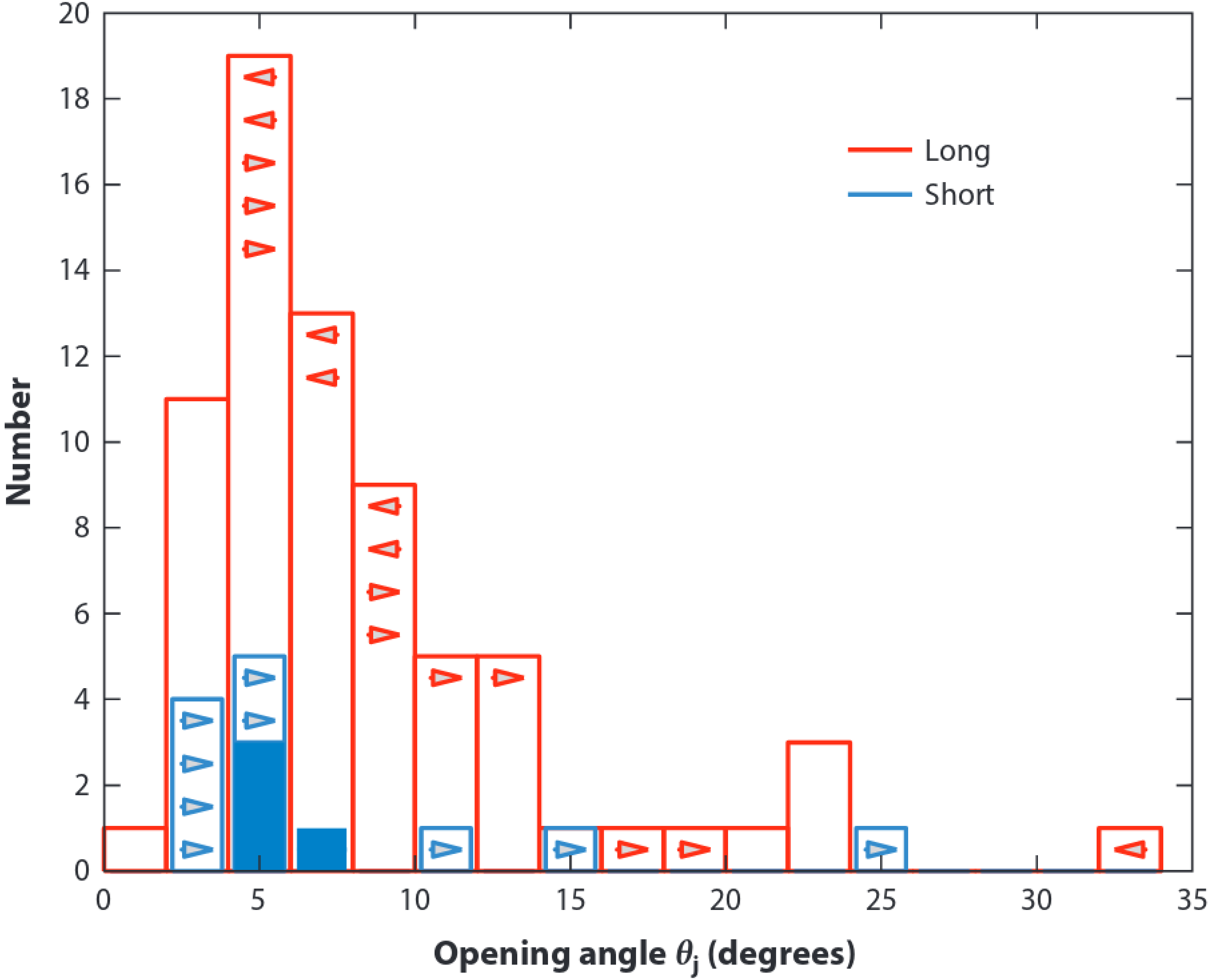
Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.



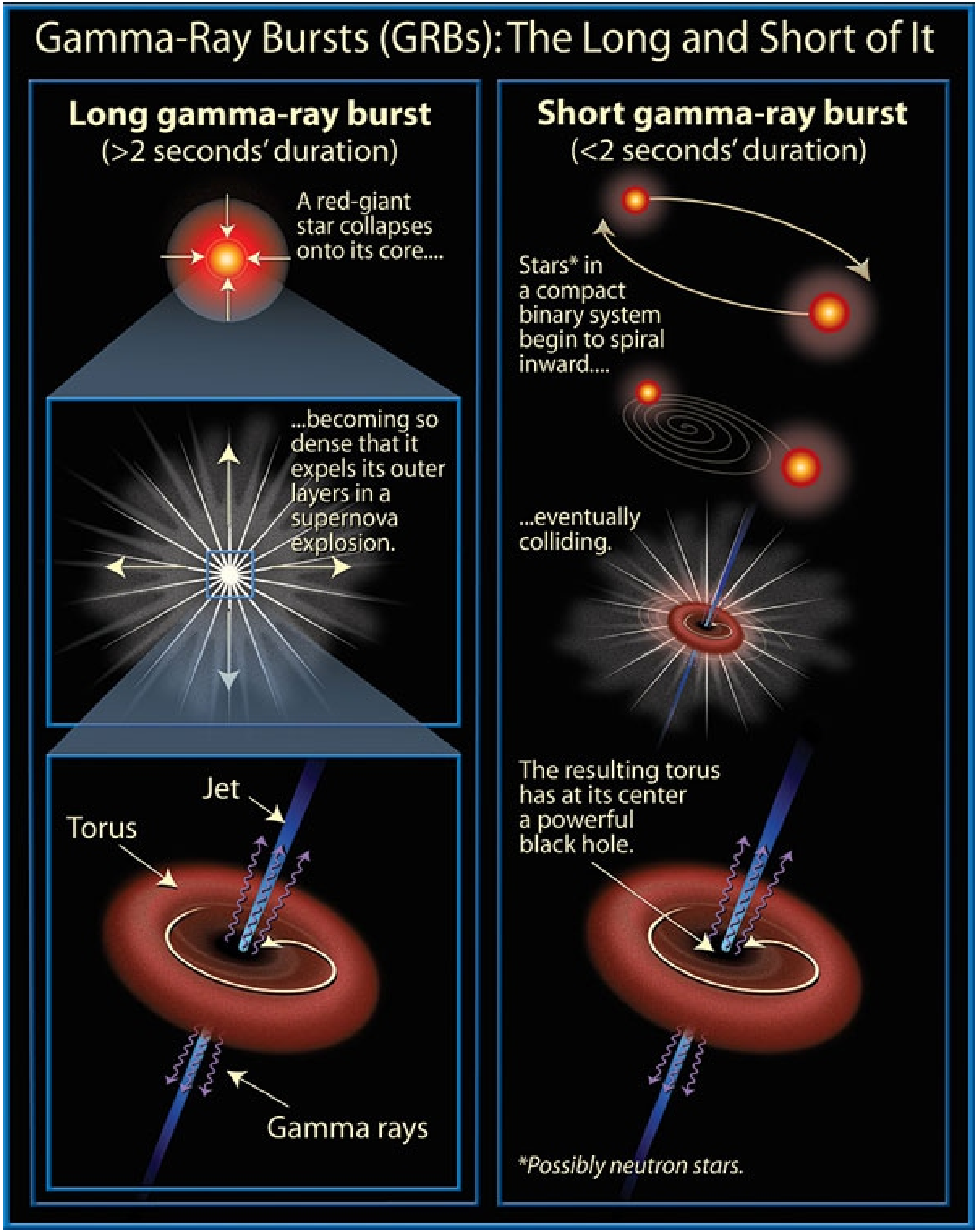
Magnitudes fainter than SN 1998bw
Redshift
080905A
050709
050509B
130603B
071227
070724A
051221A
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe

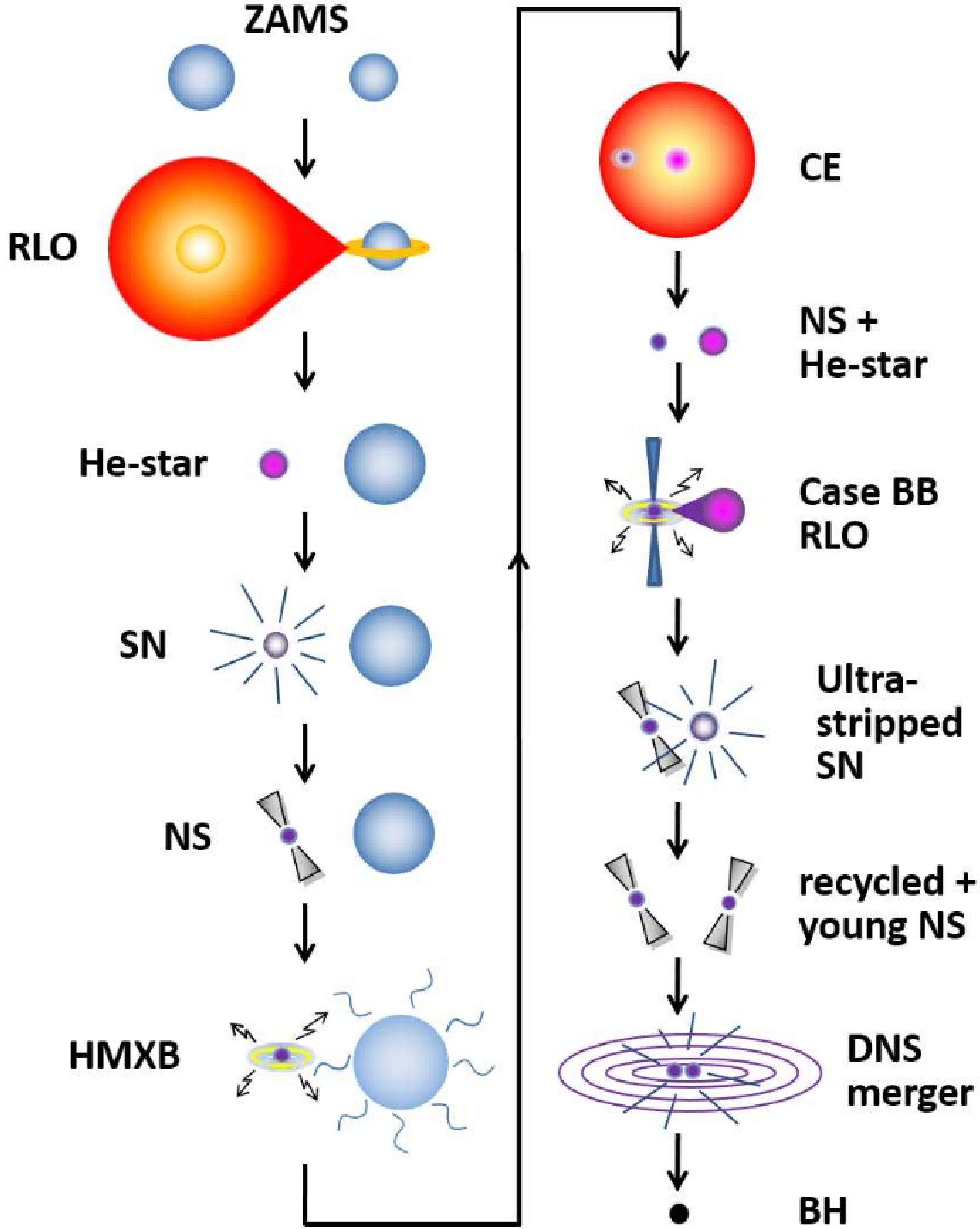


Number
Redshift
Short GRBs
(⟨z⟩ ≈ 0.5)
Long GRBs
(⟨z⟩ ≈ 2.0)
Early
Late
Number
Redshift



Number
20
18
16
14
12
10
8
6
4
2
0
Long
Short
0
5
10
15
20
25
30
35
Opening angle θ_j (degrees)


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.



ZAMS
RLO
He-star
SN
NS
HMXB
CE
NS +
He-star
Case BB
RLO
Ultra-
stripped
SN
recycled +
young NS
DNS
merger
BH

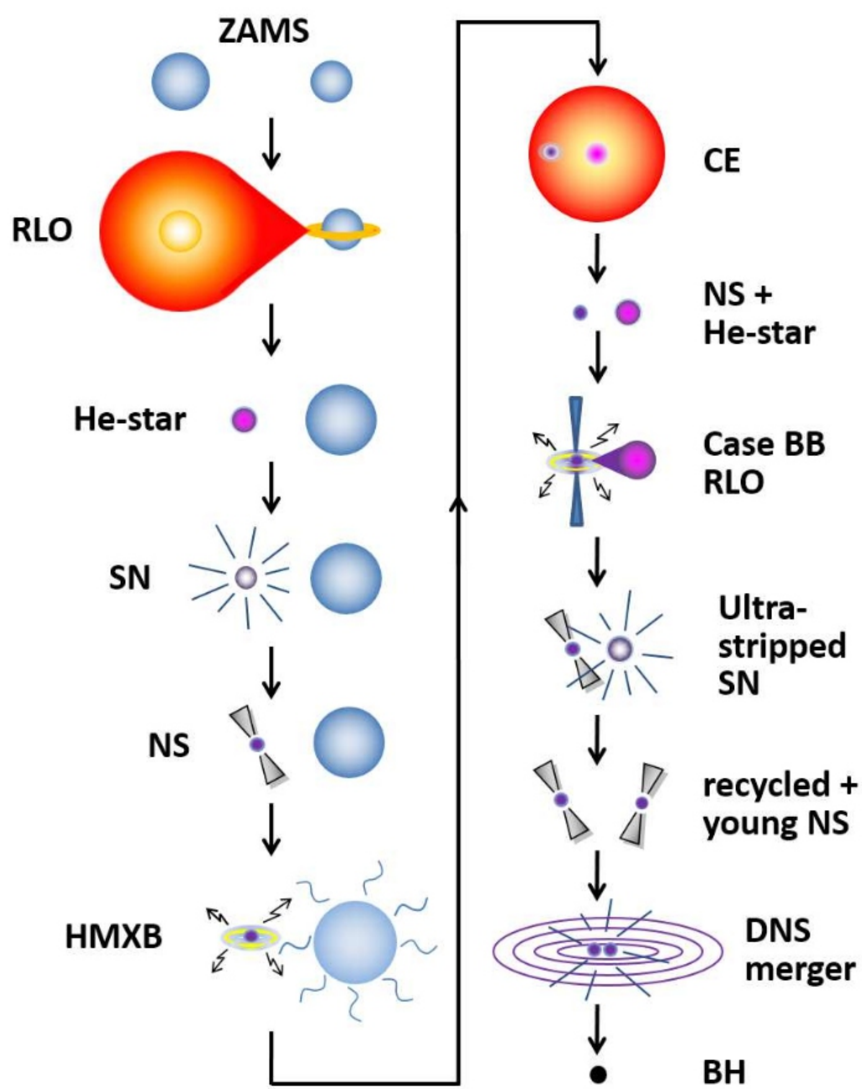


FIG. 1.— Illustration of the formation of a DNS system which merges within a Hubble time and produces a single BH, following a powerful burst of GWs and a short GRB. Acronyms used in this figure: ZAMS: zero-age main sequence; RLO: Roche-lobe overflow (mass transfer); He-star: helium star; SN: supernova; NS: neutron star; HMXB: high-mass X-ray binary; CE: common envelope; BH: black hole.

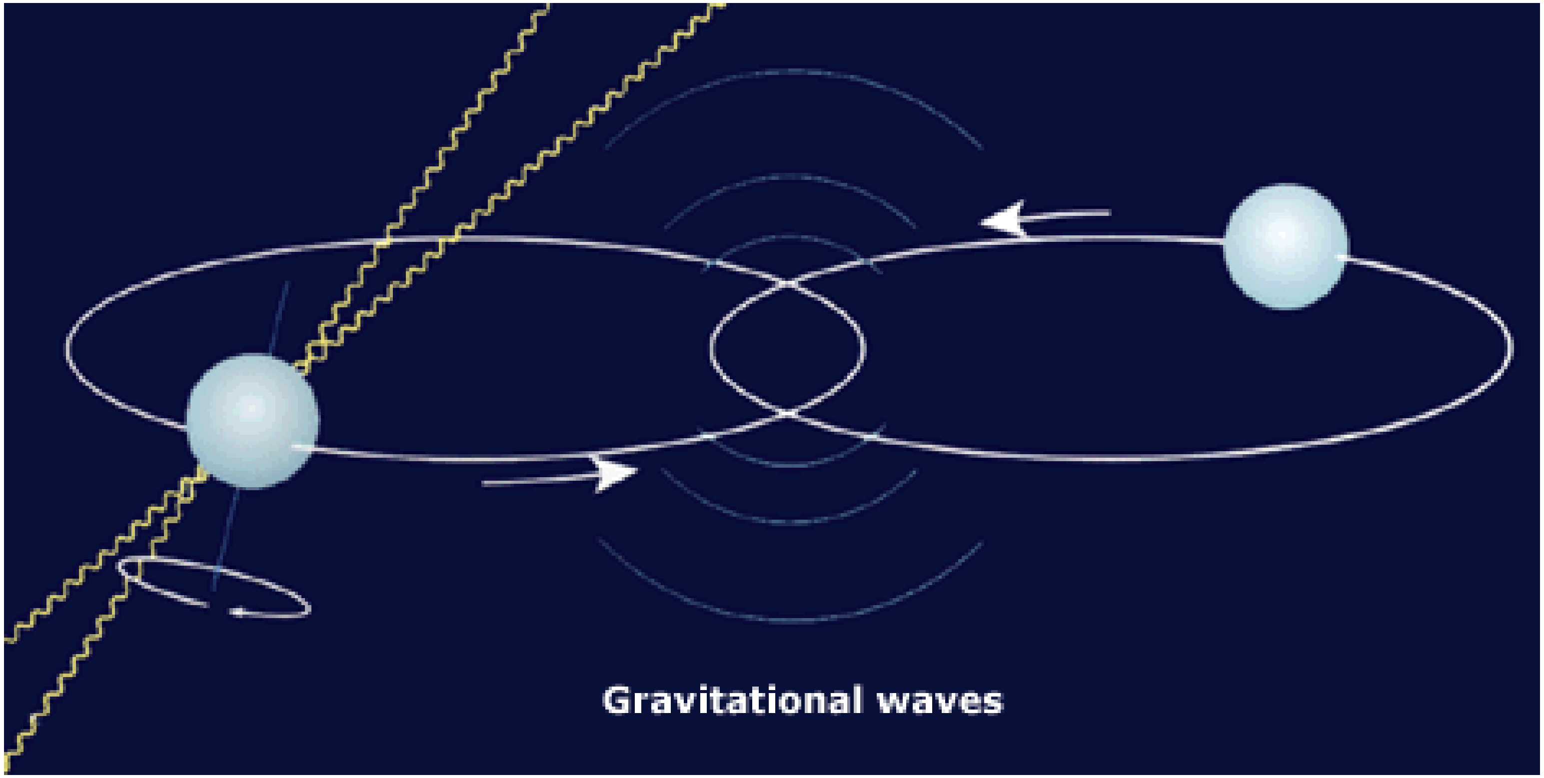
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

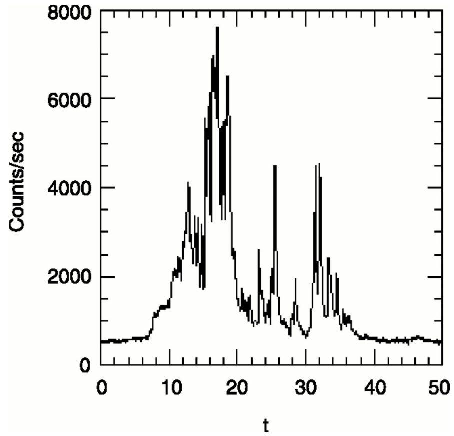
300 Myr
two neutron star coalesce

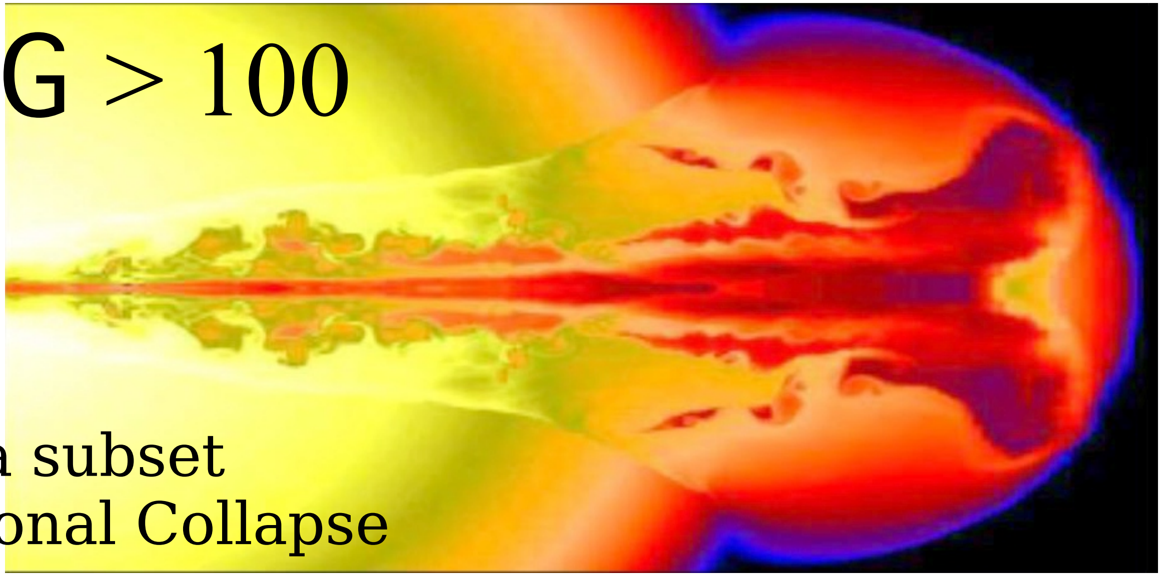
Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

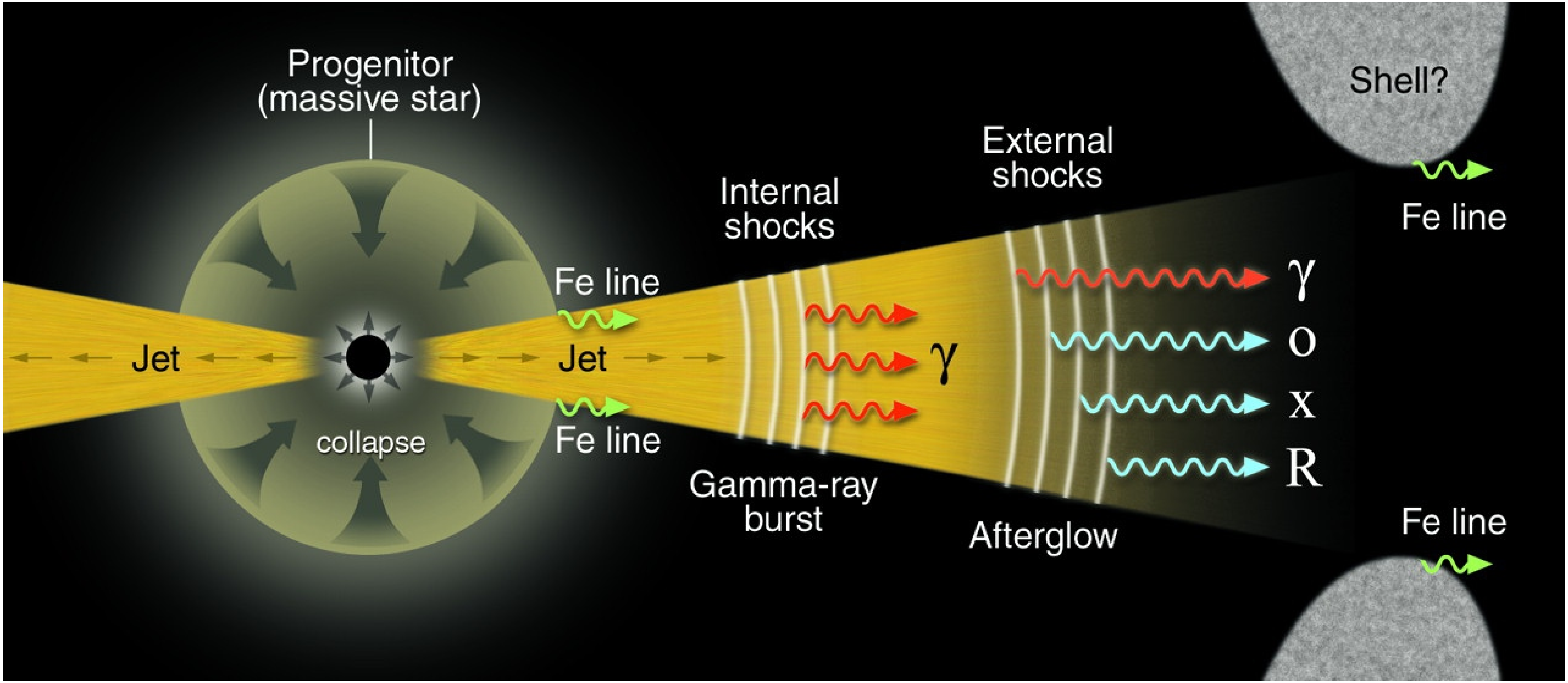
Orbit smaller
3.5 m/year







GRB : associated with a subset
of SN Stellar Gravitational Collapse

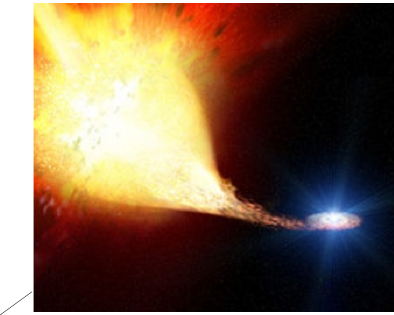


Neutrinos

Relation between the fluxes of

Gamma rays and Neutrinos

from astrophysical sources



Astrophysical source

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

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

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

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

$$\phi_\gamma(E)$$

Earth

$$\phi_{\nu_\alpha}(E)$$

$$\phi_\gamma^{\text{leptonic}}(E) + \phi_\gamma^{\text{hadronic}}(E)$$

Possible absorption in the source
(and in propagation from the source)

Astrophysical source

Flavor oscillations
(good theoretical control)

$$\phi_\gamma(E)$$

Earth

$$\phi_{\nu_\alpha}(E)$$

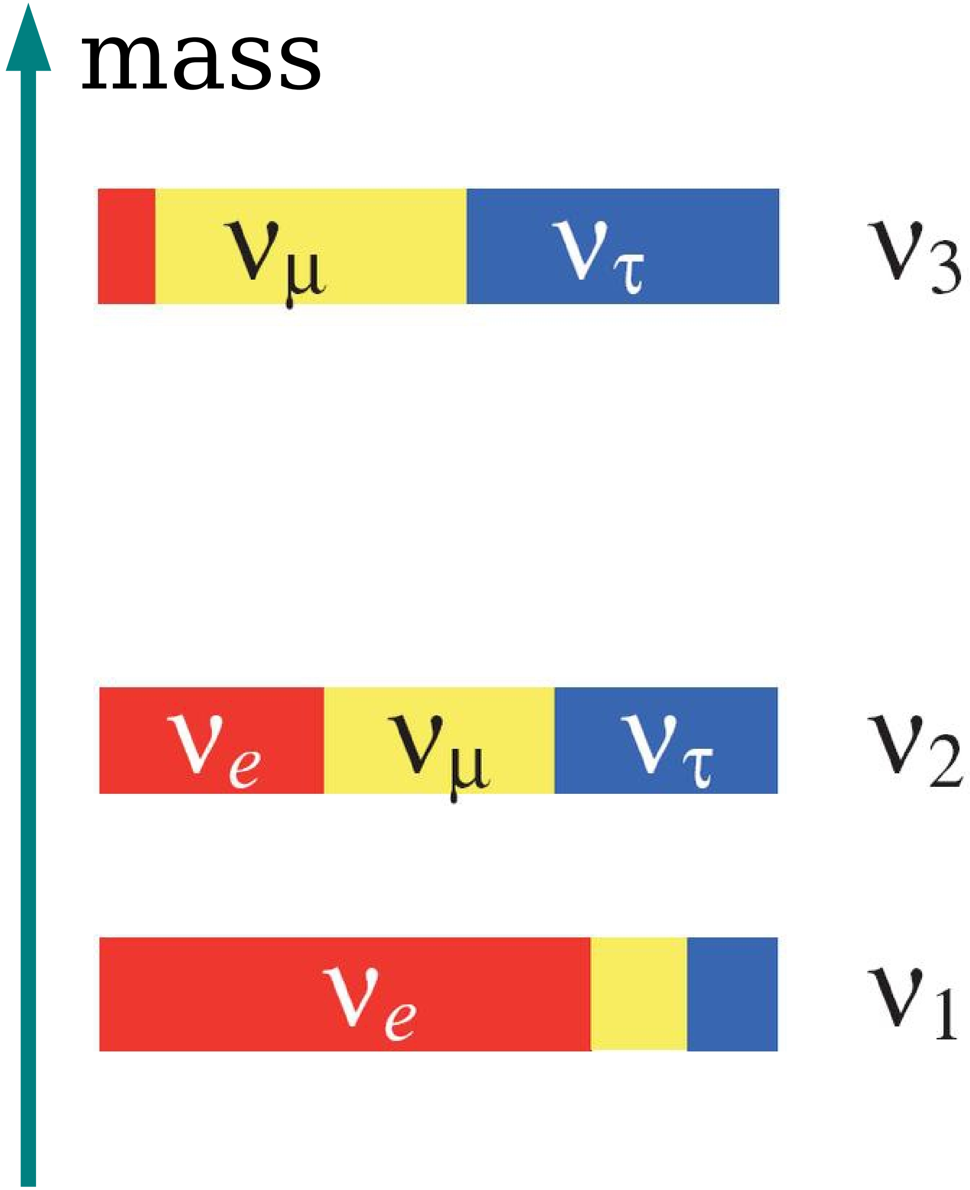
In the absence of absorption
the flux of neutrinos is approximately equal to the flux of gamma ray of *hadronic origin*

Neutrino Flavor, Neutrino masses

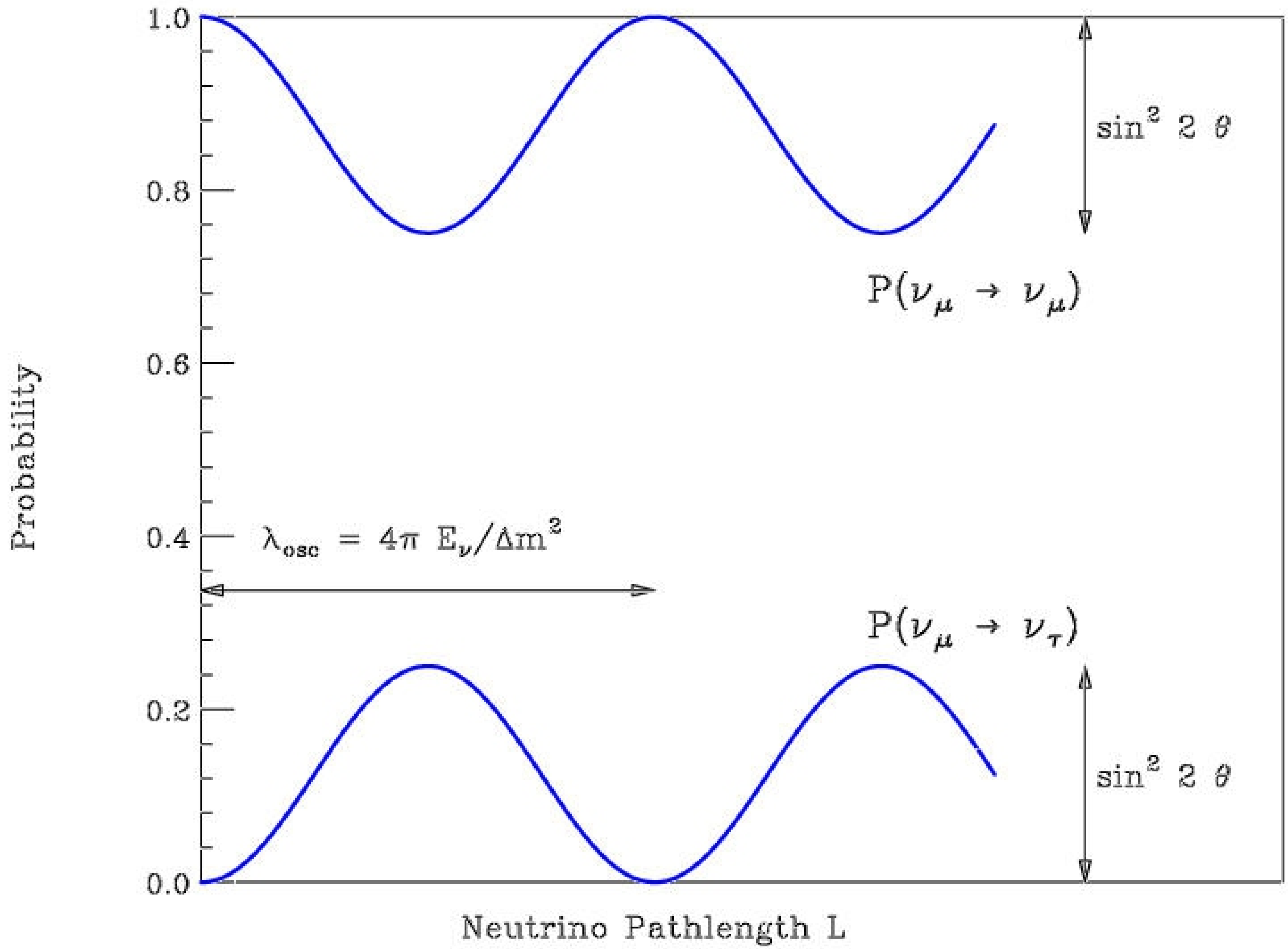
$$\{\ |\nu_e\rangle \quad , \quad |\nu_\mu\rangle \quad , \quad |\nu_\tau\rangle\ \}$$

$$\{\ |\nu_1\rangle \quad , \quad |\nu_2\rangle \quad , \quad |\nu_3\rangle\ \}$$

$$P_{\alpha j} = |\langle\nu_\alpha|\nu_j\rangle|^2$$
$$= |U_{\alpha j}|^2$$



$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta\, \sin^2 \left[1.27\, \Delta m^2 (\mathrm{eV}^2) \frac{L(\mathrm{Km})}{E(\mathrm{GeV})} \right]$$



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

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

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

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

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

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

Oscillating terms average to zero

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

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

$\theta_{13} \simeq 0$

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

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

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

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

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

“Standard mechanism”

$$\begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

much more “astrophysically plausible”

“Muon absorption”

Very high magnetic field

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} v \\ (1-v)/2 \\ (1-v)/2 \end{pmatrix} \approx \begin{pmatrix} 0.2 \\ 0.4 \\ 0.4 \end{pmatrix}$$

“Neutron decay”

Nuclear fragmentation

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1-2\,v \\ v \\ v \end{pmatrix} \approx \begin{pmatrix} 0.6 \\ 0.2 \\ 0.2 \end{pmatrix}$$

Possibility of
"Modifications" of the neutrino flux
during propagation.

Investigate :
Flavor Oscillations
(with very long path-lengths)

[Pseudo-Dirac neutrinos
mass doublets with tiny
mass splitting]

$$z \simeq 1 \qquad \Delta m^2 \approx 10^{-18} \left(\frac{E}{100 \text{ TeV}} \right) \text{ eV}^2$$

Neutrino Decay [with very long lifetimes]

.... (9 orders of magnitude improvement)

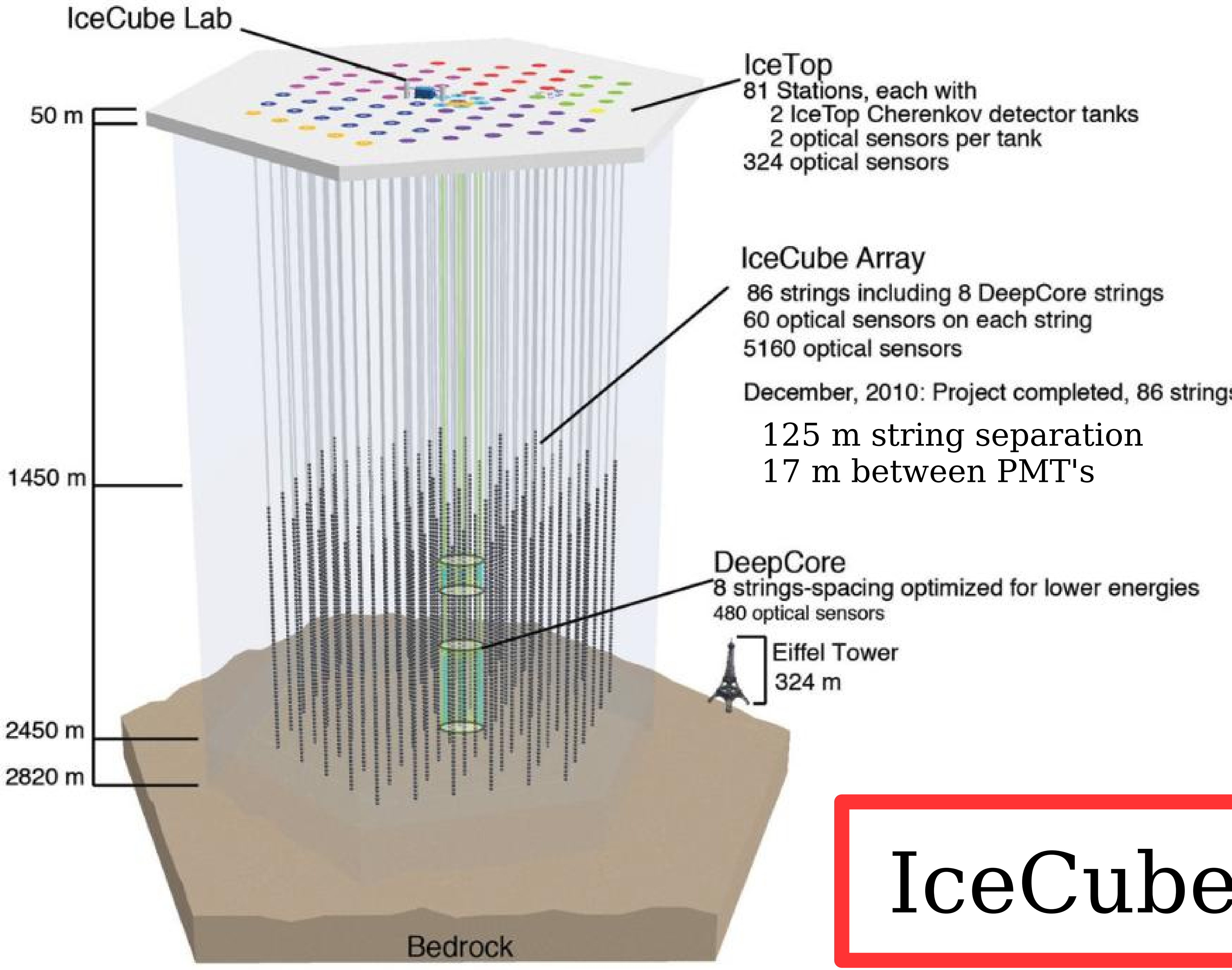
Important difficulty:
Properties of the neutrinos at the source
must be sufficiently well understood.

Neutrino Telescopes

The “Km3” concept

Instrumentation of a large volume
of a transparent medium
(water or ice) with photon detectors (PMT's)

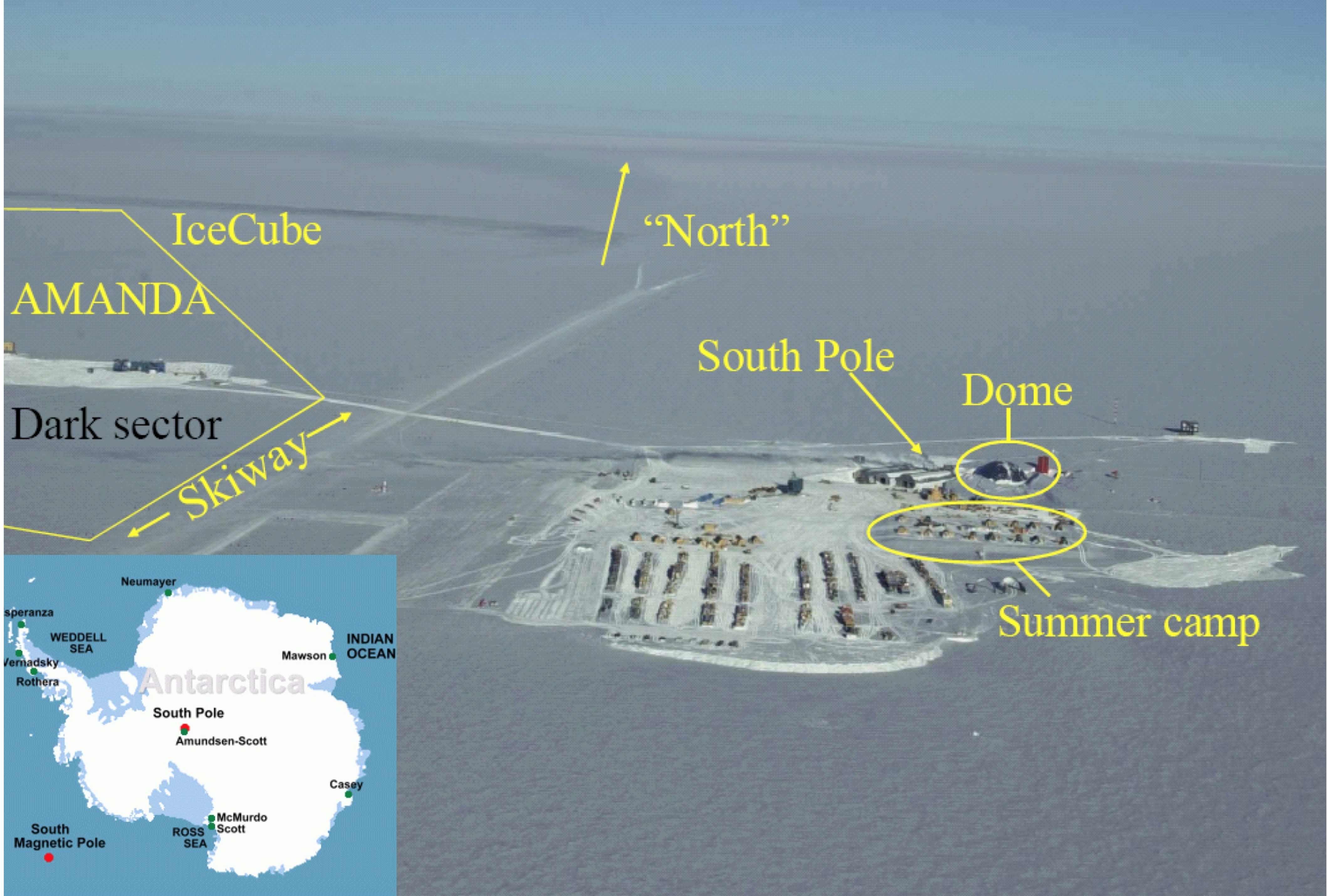
Remarkably difficult challenge
the “implementation” of this idea in a real detector



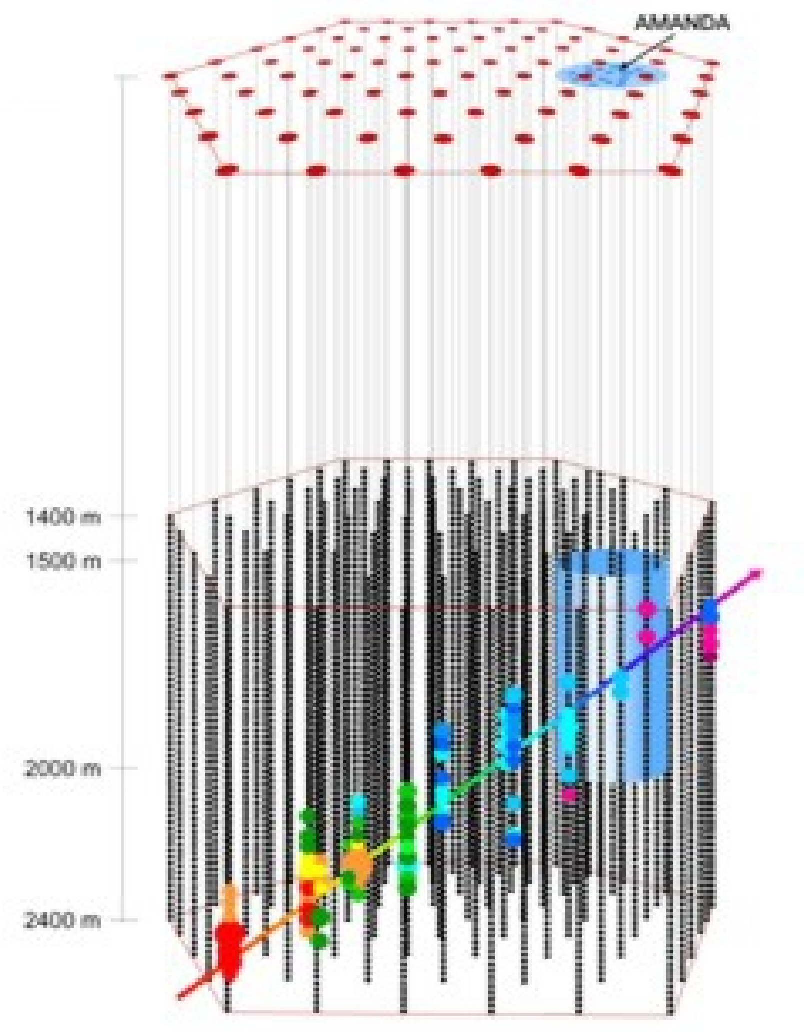
125 m string separation
17 m between PMT's

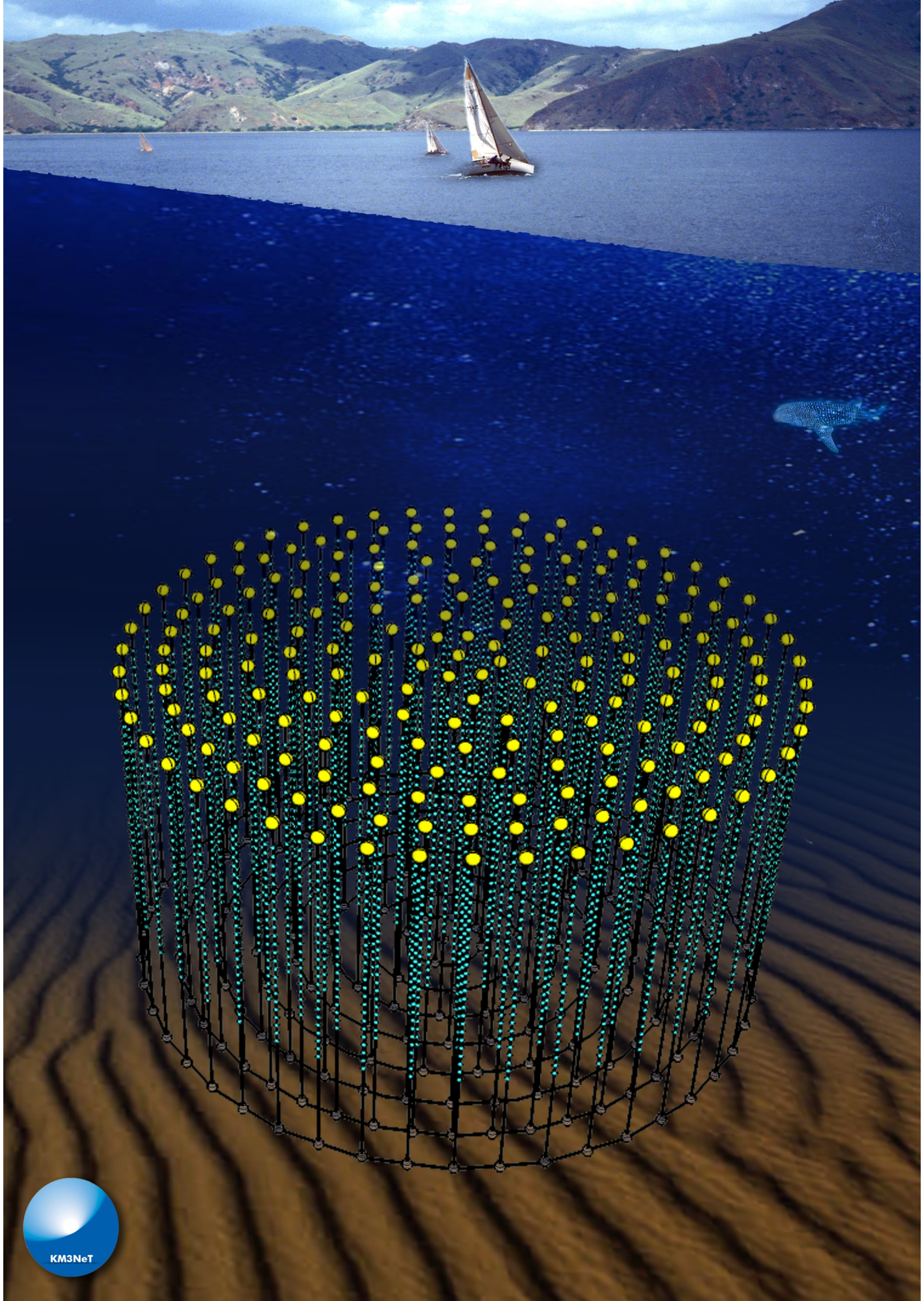
IceCube

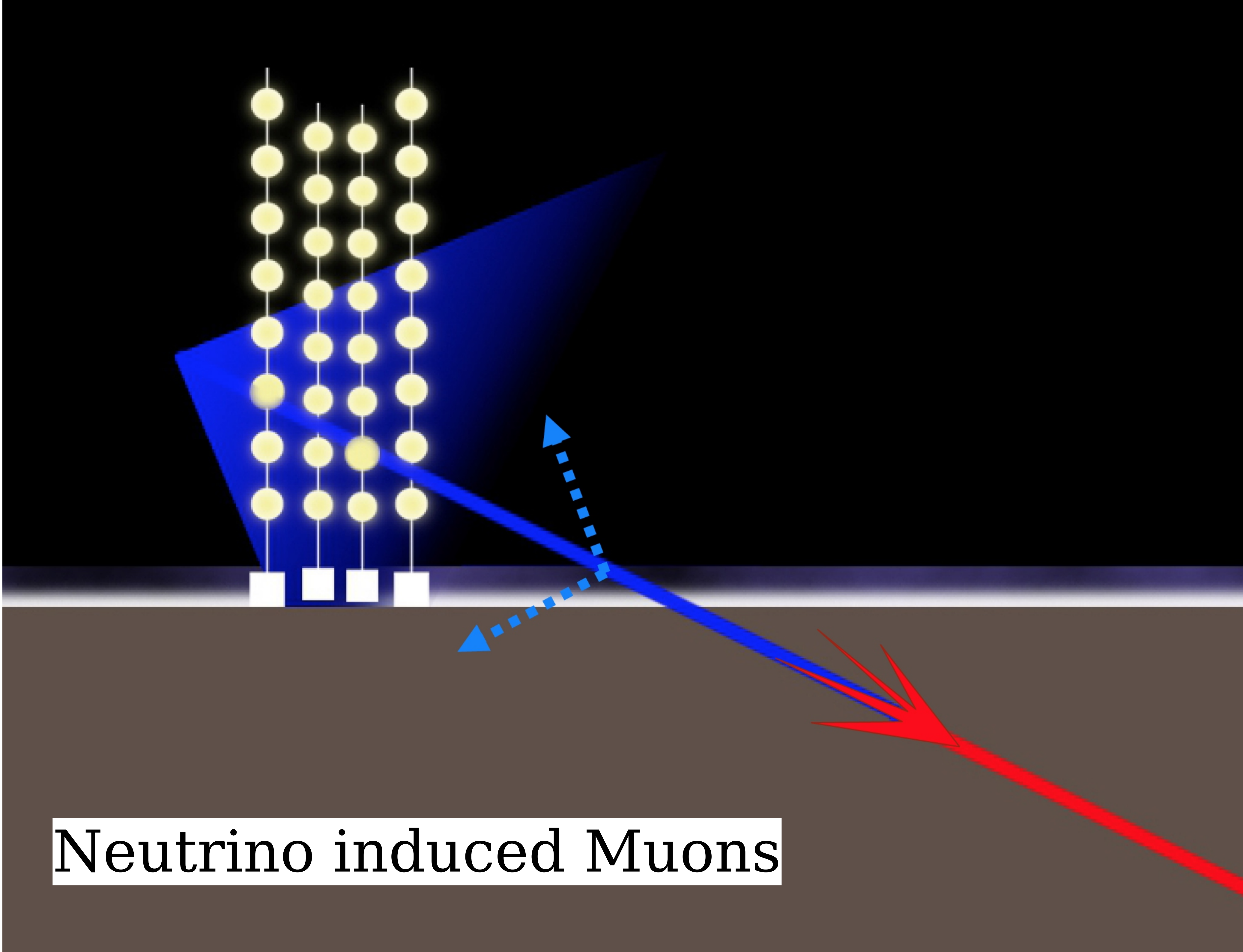
Amundsen-Scott South Pole station



Deployment of the strings

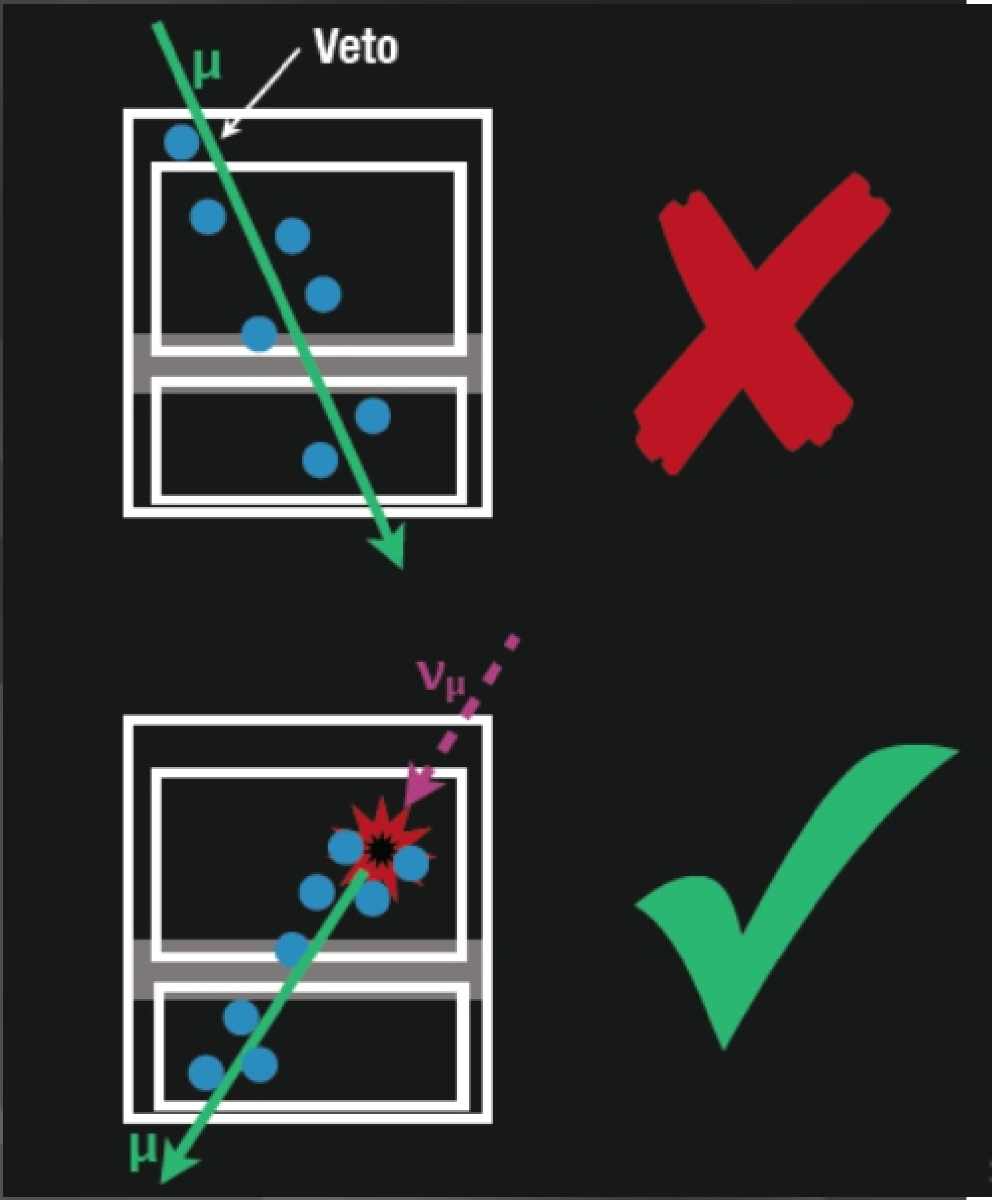



KM3NeT


Neutrino induced Muons

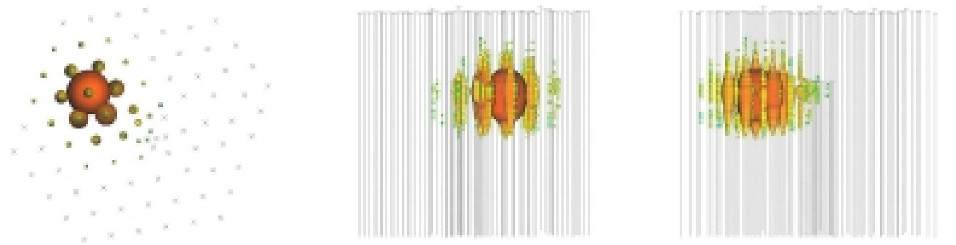
Contained events

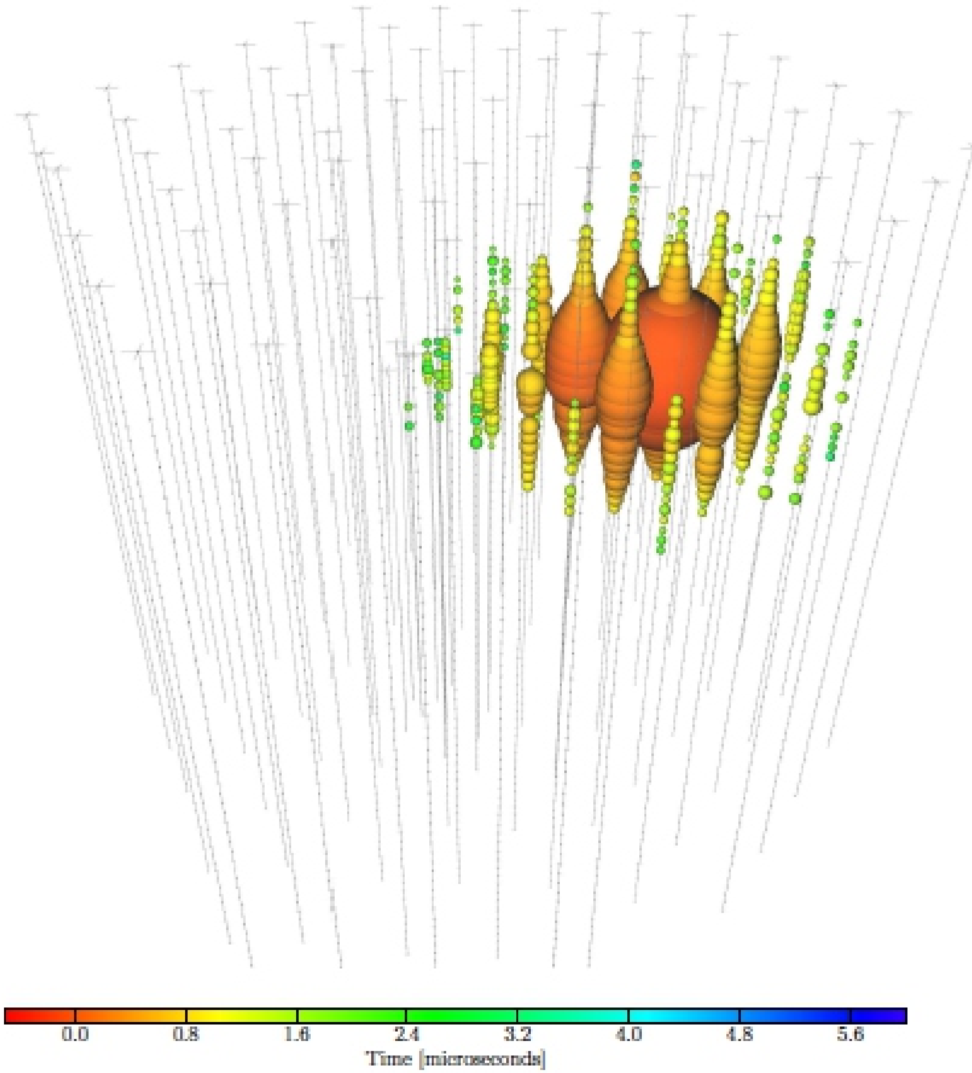
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



loss in statistics is compensated by event definition

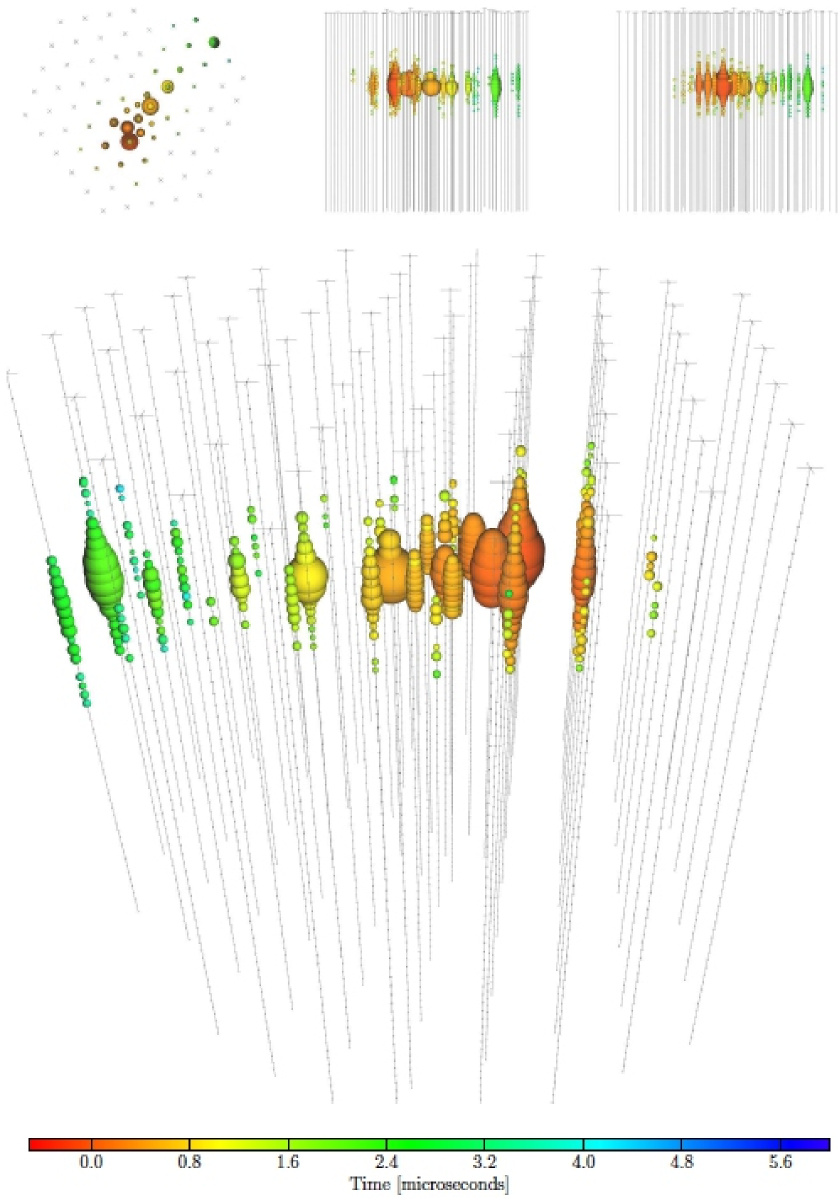
"Shower"





Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	-27.9	265.6	13.2	Shower

“TRACK”

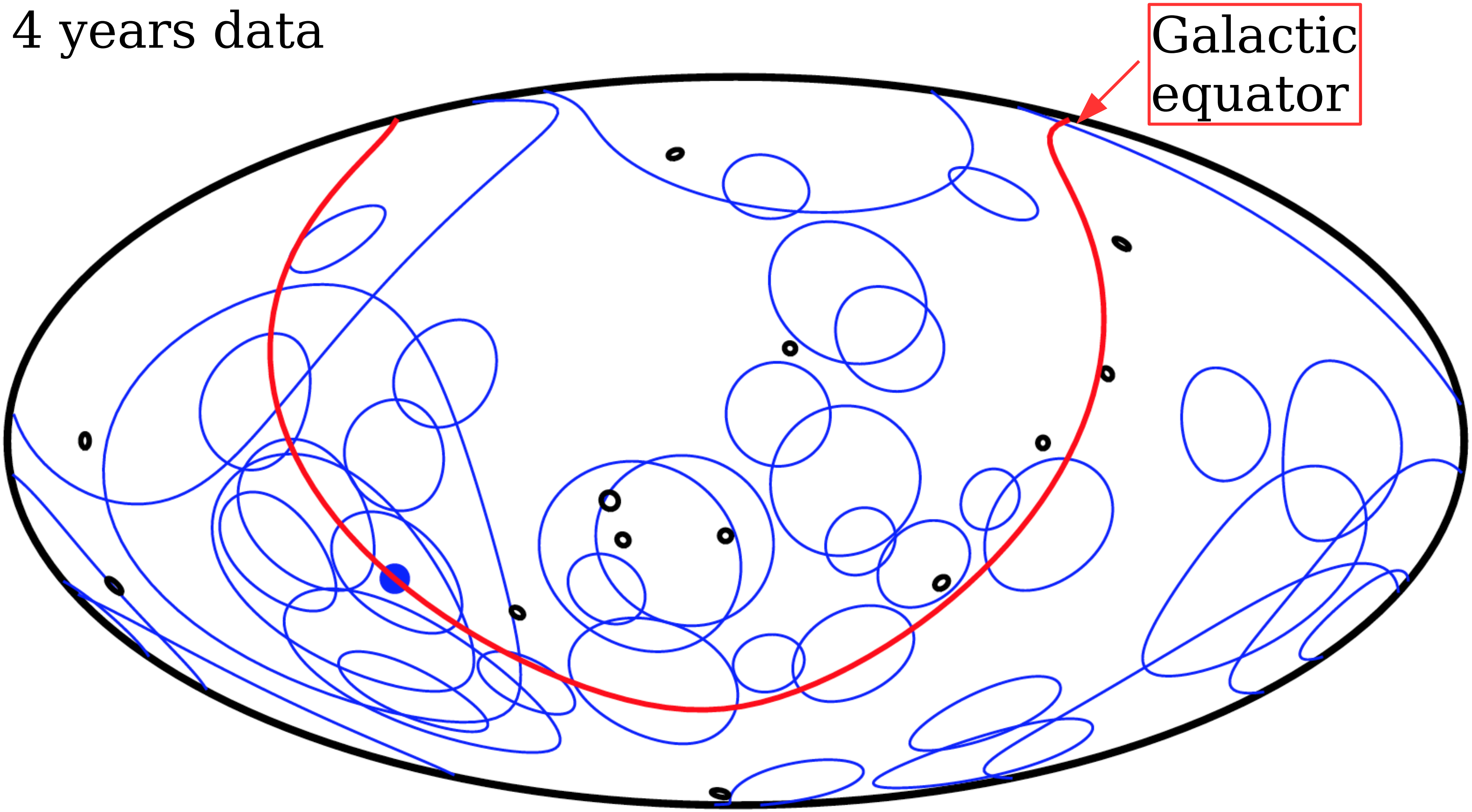


Events with a Muon

Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	-0.4	110.6	$\lesssim 1.2$	Track

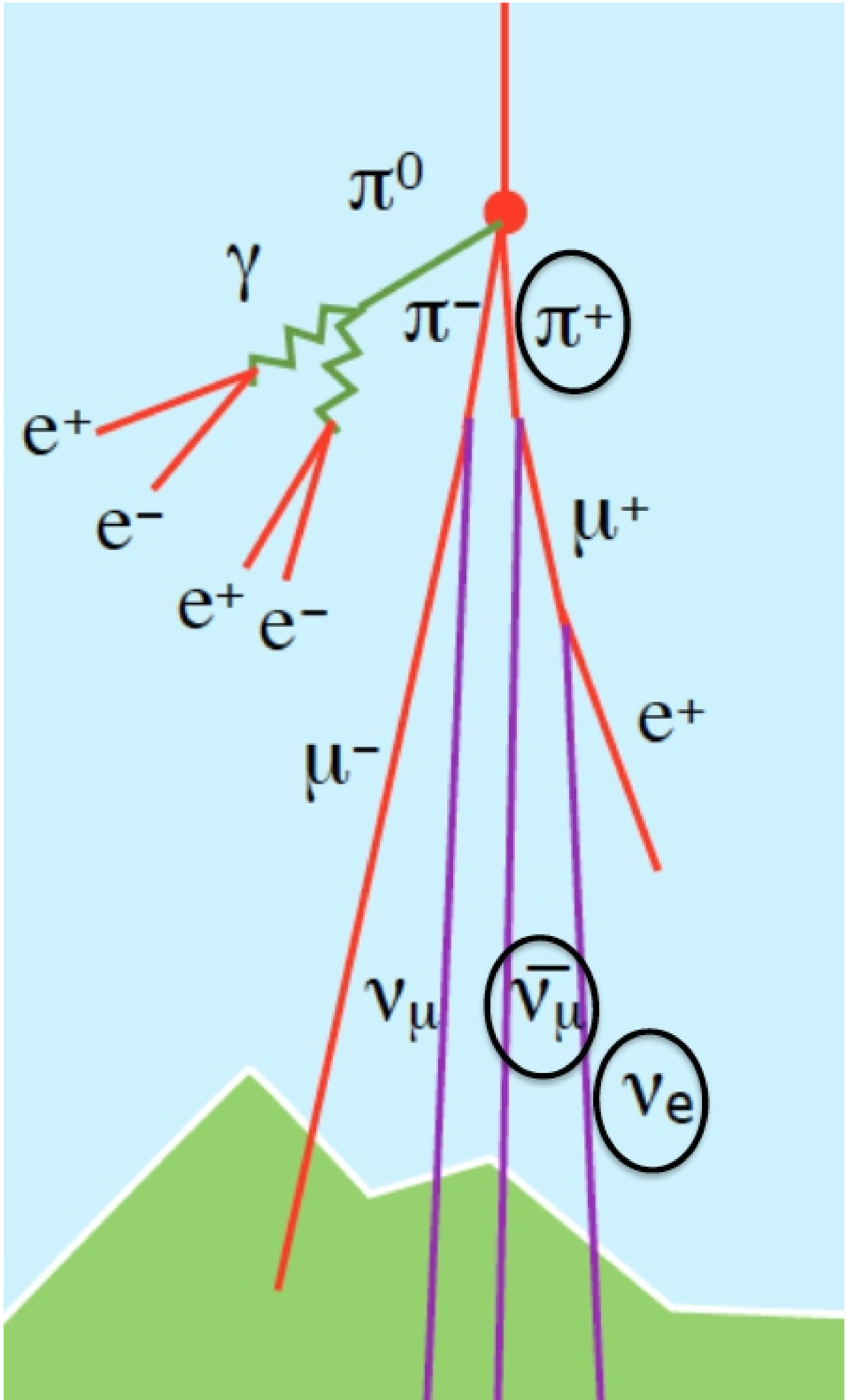
High Energy Starting Events

4 years data



Track [(small) black circles]
Showers [(large) blue circles]

$E_{\rm vis} \gtrsim 30$ TeV



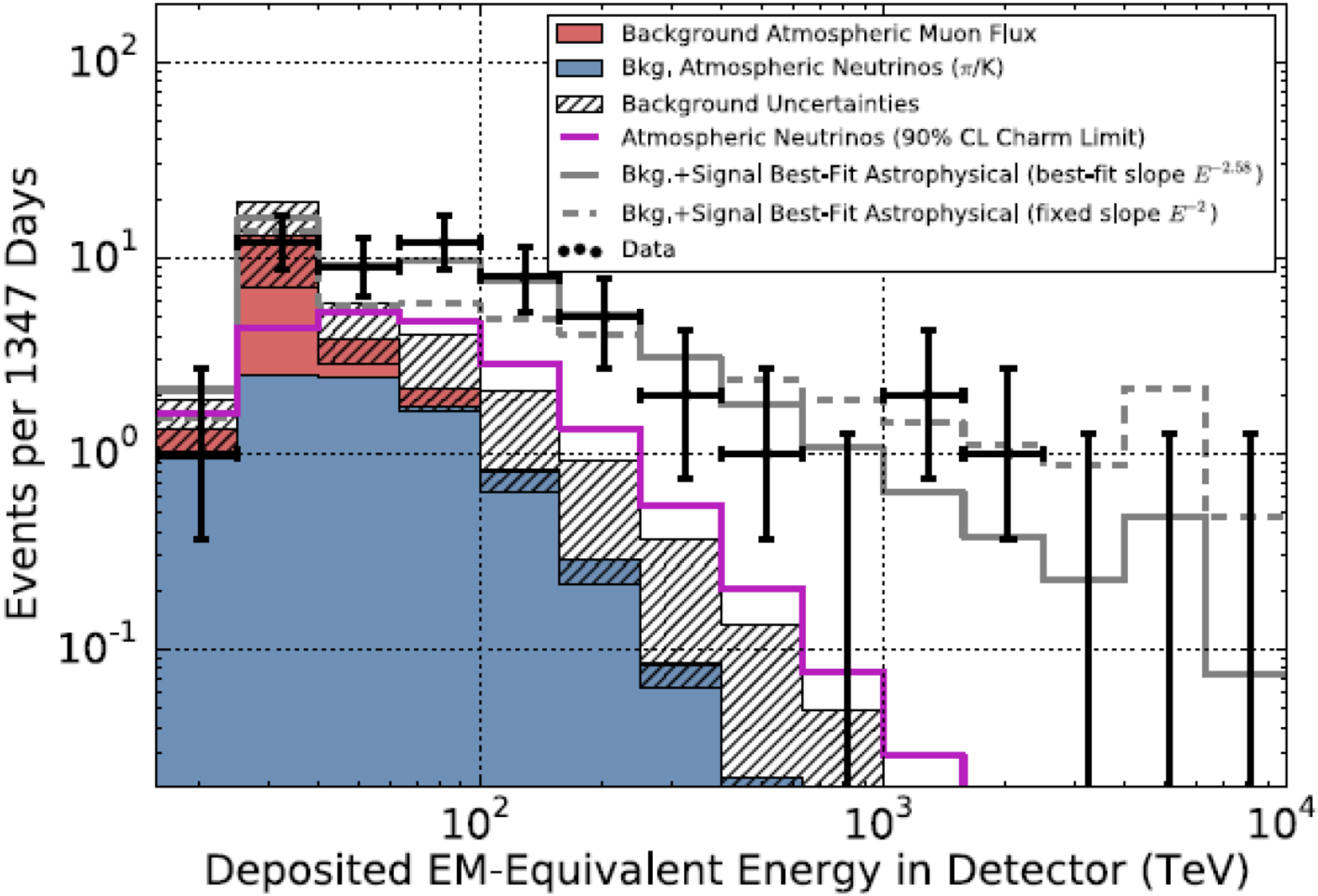
Foreground

to the astrophysical neutrino signal

Atmospheric Neutrinos

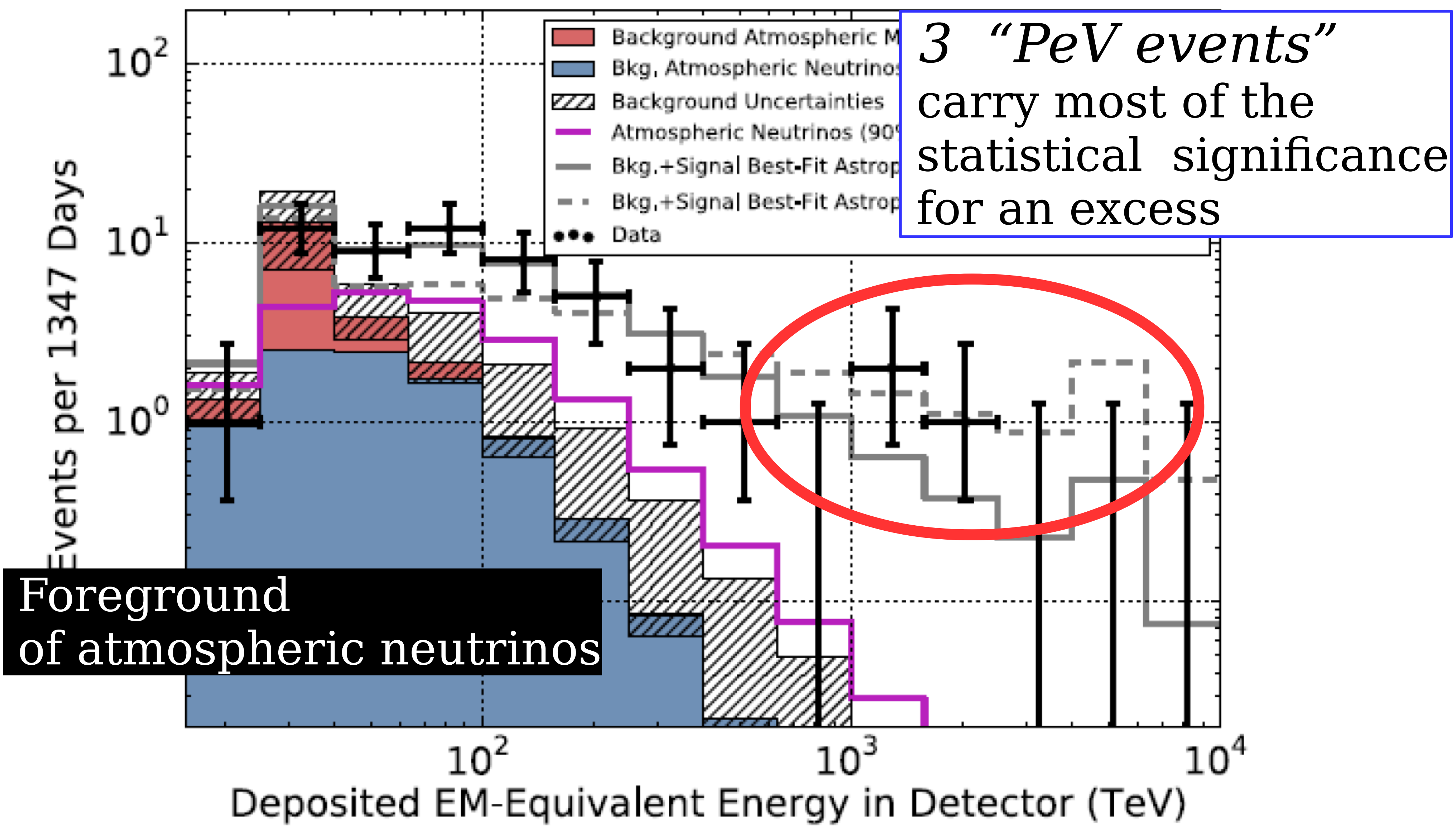
High Energy Starting Events [HESE]

First evidence for an extra-terrestrial h.e. neutrino flux

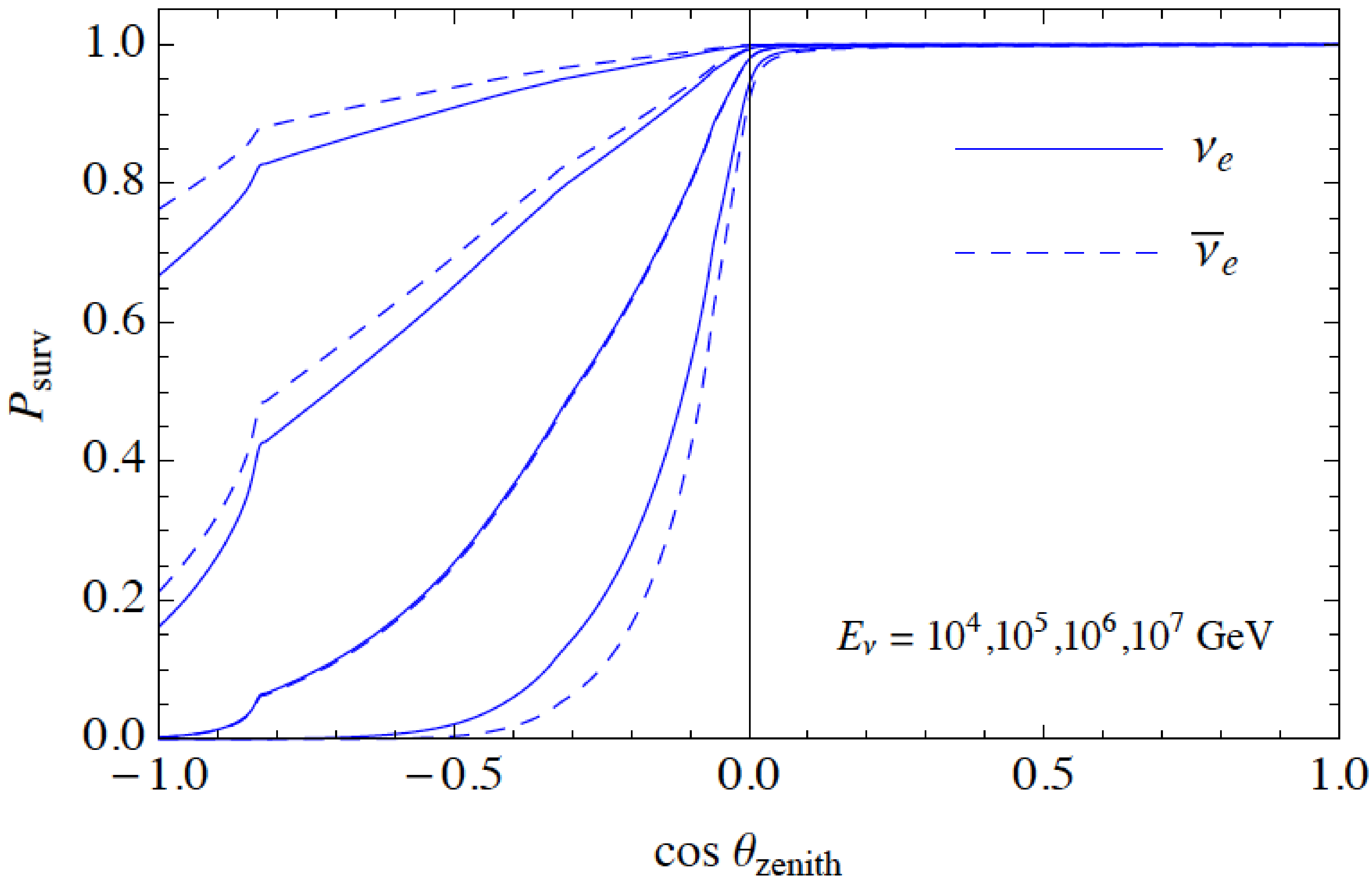


High Energy Starting Events [HESE]

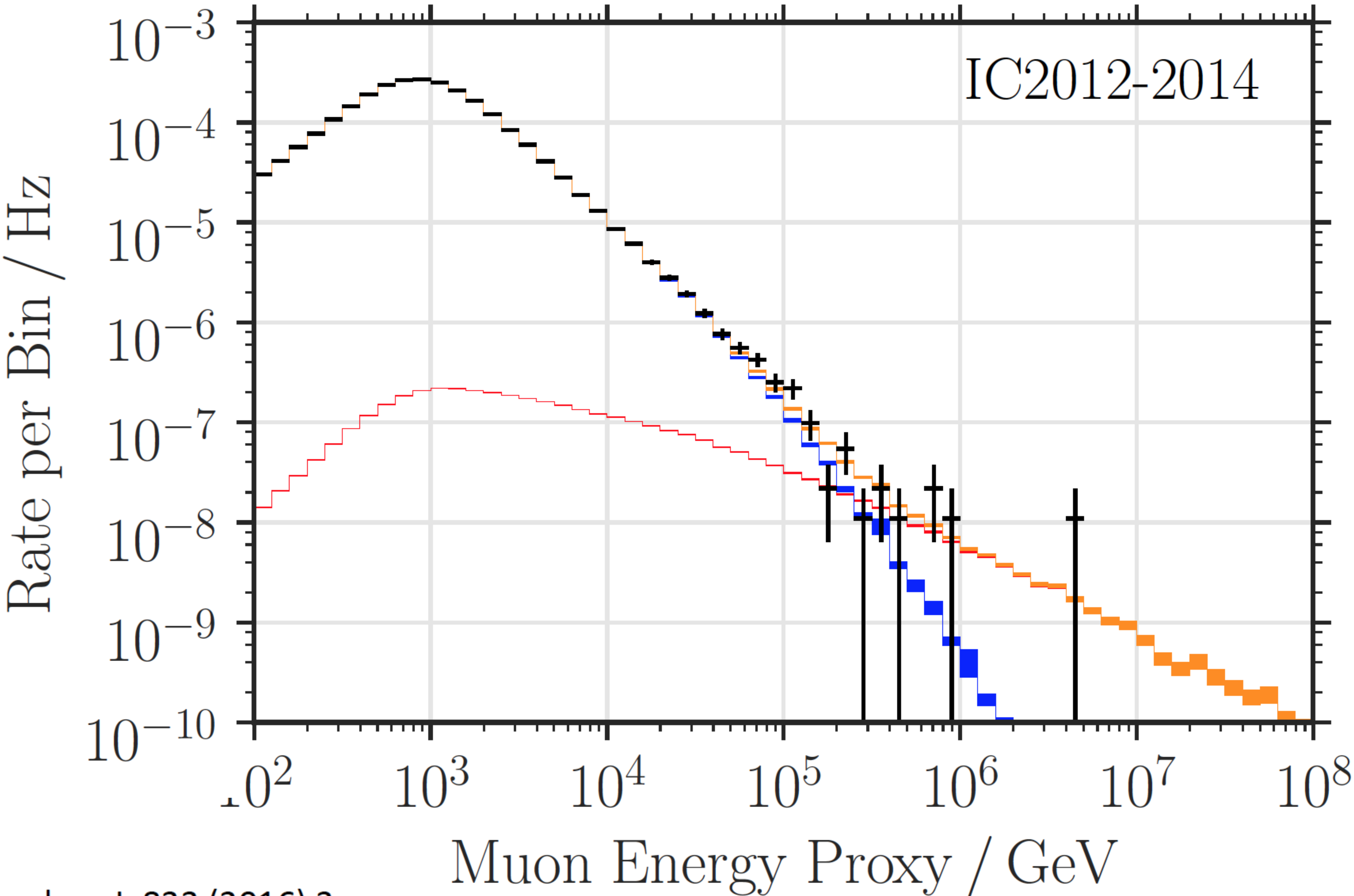
First evidence for an extra-terrestrial h.e. neutrino flux



Absorption of neutrinos in the Earth



Upgoing (neutrino induced) Muons



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Interpretation offered by IceCube collaboration:
(of the HESE events)

There in an excess of neutrino events
over the foreground of atmospheric neutrinos.

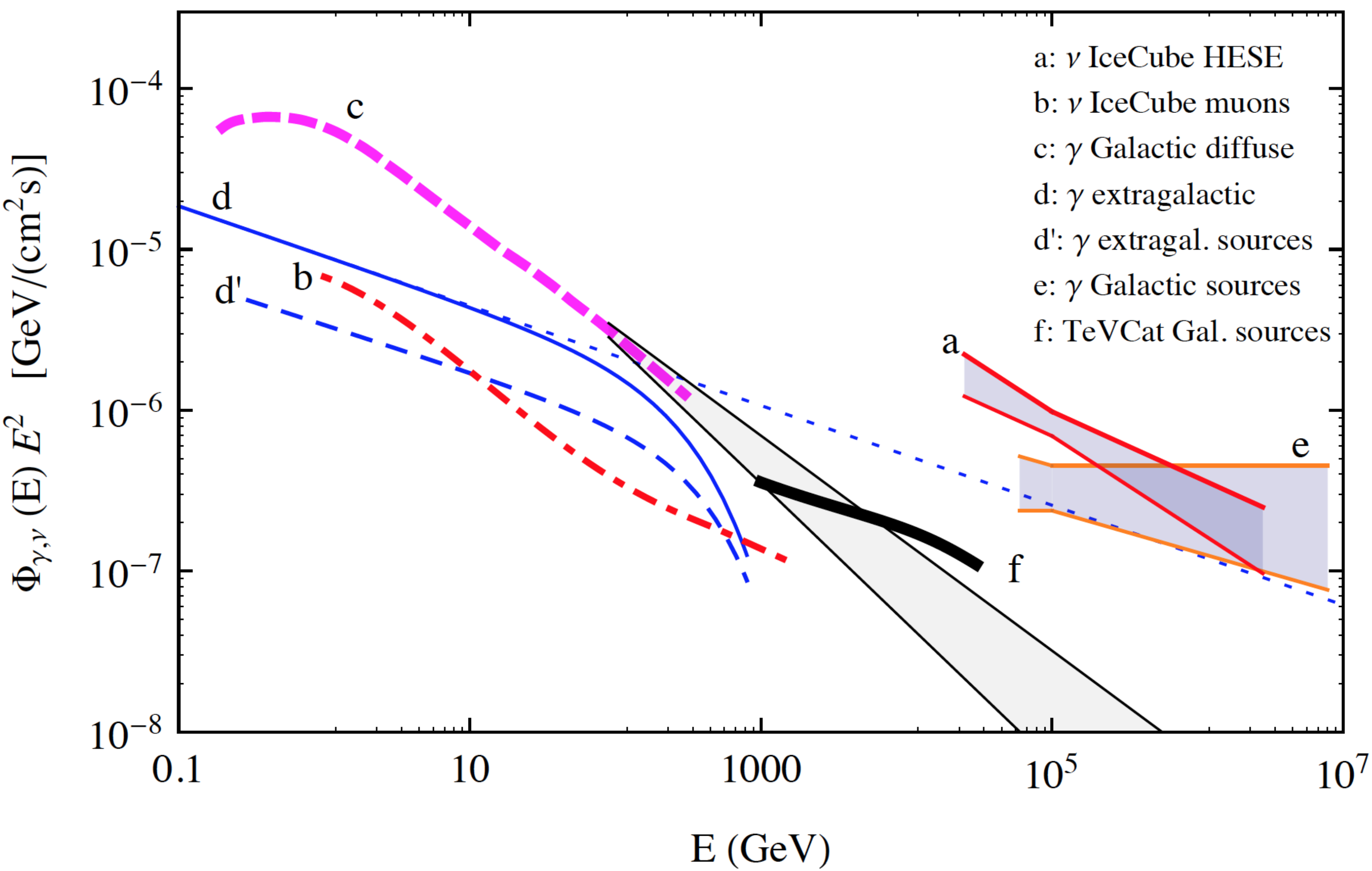
Consistent with an
isotropic (extragalactic) flux

with equal intensity for all 3 flavors (e, mu, tau)
[little sensitivity to the nu/antinu ratio.]

Simple Power Law:

$$\phi_\nu^{\rm astro}(E) = \phi_0 \; E^{-2.50 \pm 0.09}$$

Compare the *Neutrino Signal* to *Gamma Ray fluxes*



$$\phi_\nu^{\rm astro}(E) = \phi_0^{\rm HESE}\ E^{-2.50\pm0.09}$$

$$\phi_\nu^{\rm astro}(E) = \phi_0^{\mu\uparrow}\ E^{-2.13\pm0.13}$$

Spectra are different ?
Possible "solutions" :

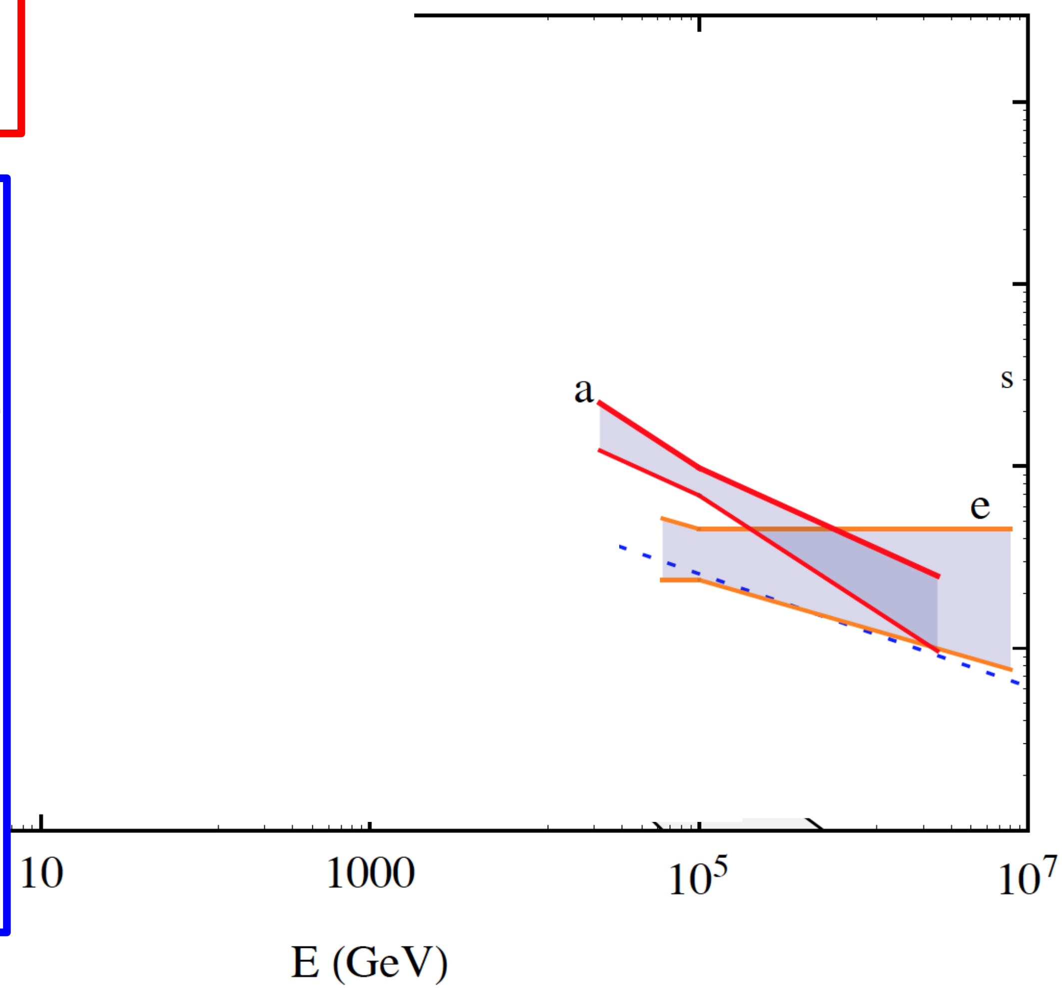
Systematic Effect ?

Break in the Spectrum

Two components
in the spectrum

Anisotropy ?

[Galactic + extragalactic components]



Questions on the IceCube signal:

1. Is the signal of astrophysical neutrinos real ?
   (or is the background/foreground poorly estimated) ?

1a. Could the signal be contaminated by a non negligible contribution of atmospheric neutrinos ?

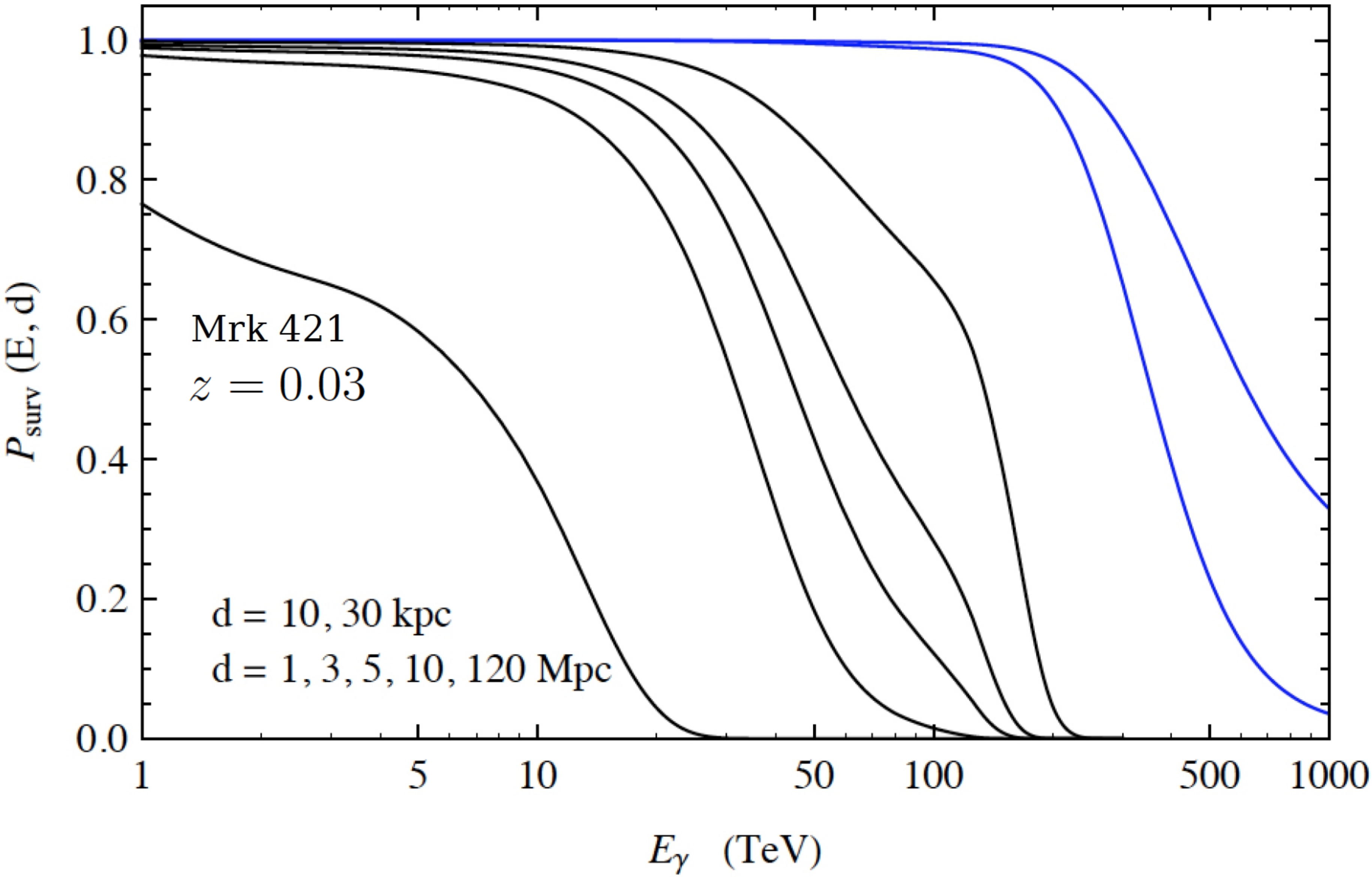
2. Is the signal entirely extragalactic ?
   Or does it contains a non negligible Galactic component ?

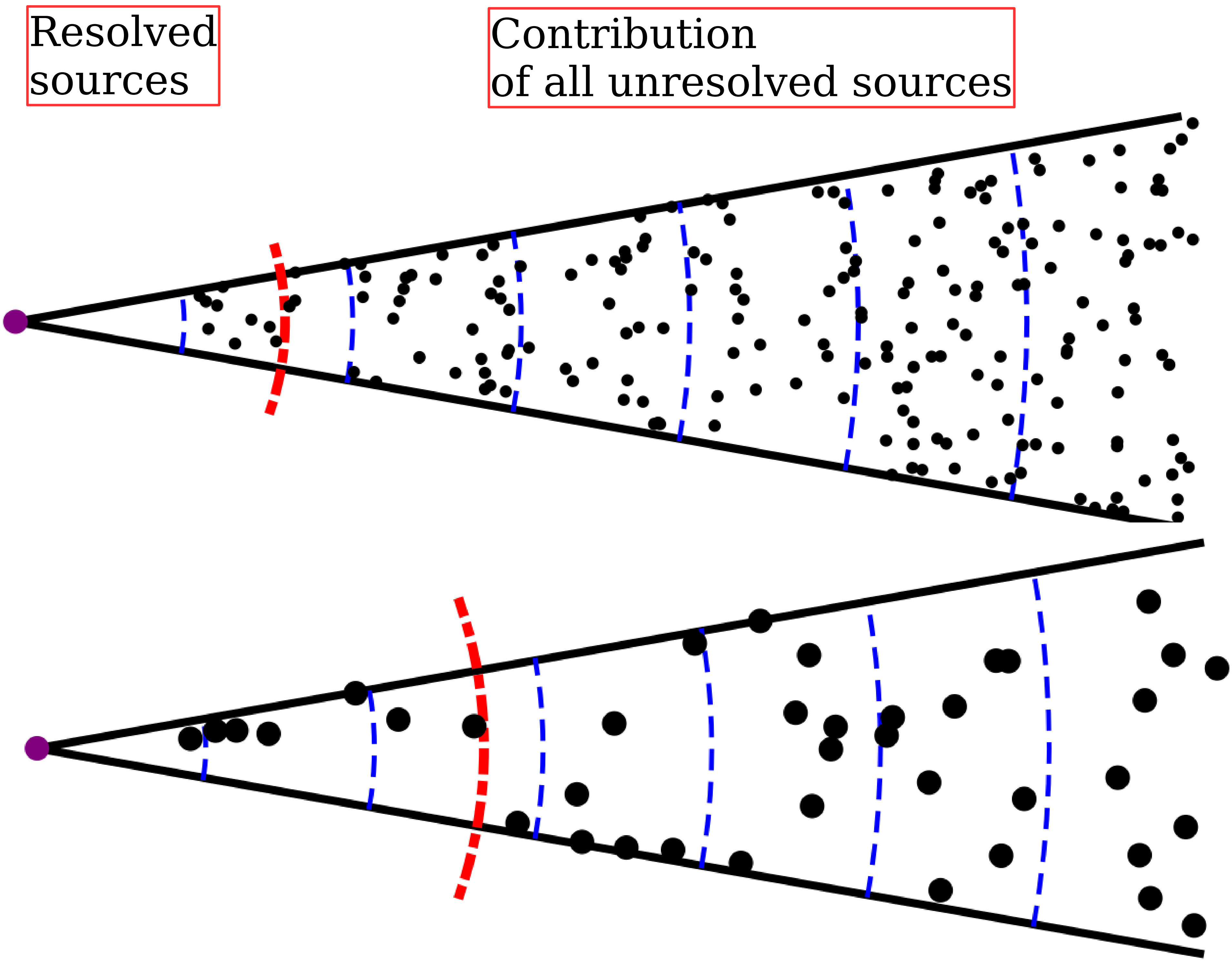
3. If most of the signal is extragalactic, what can we say about the sources ?

3a. If there is a Galactic (perhaps subdominant) component what is its nature ?

Gamma Ray absorption
(intergalactic space)

Astronomy E>100 TeV :
Galactic Astronomy

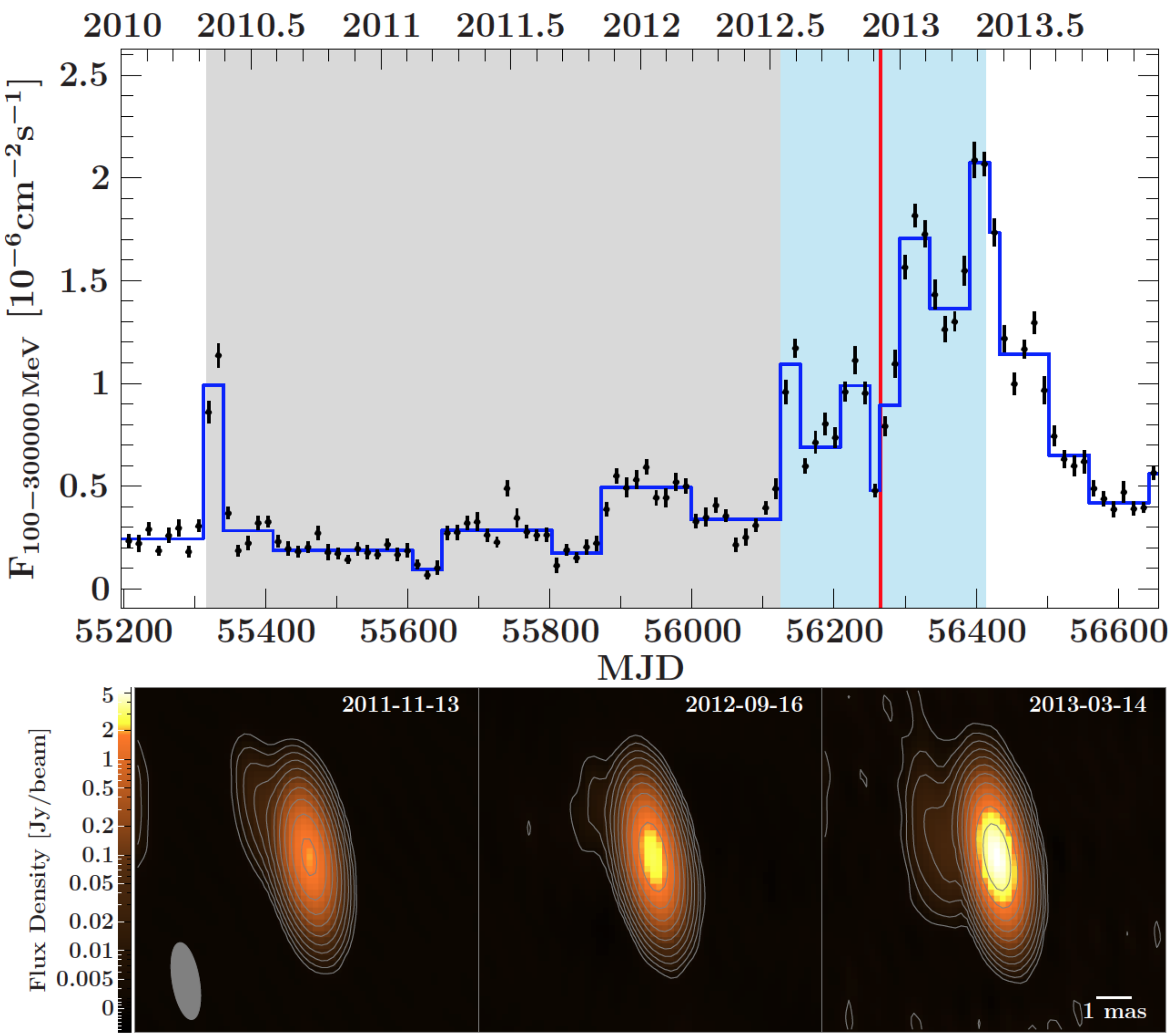




Resolved
sources
Contribution
of all unresolved sources

M. Kadler *et al.*,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,"
Nature Phys. **12**, no. 8, 807 (2016)
[arXiv:1602.02012 [astro-ph.HE]].

γ-ray light curve of PKS B1424−418.

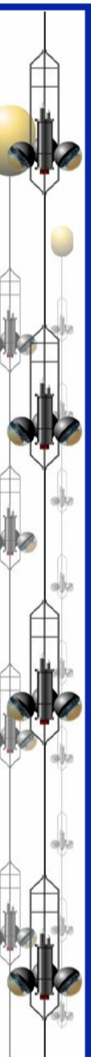


"Intriguing" Coincidence

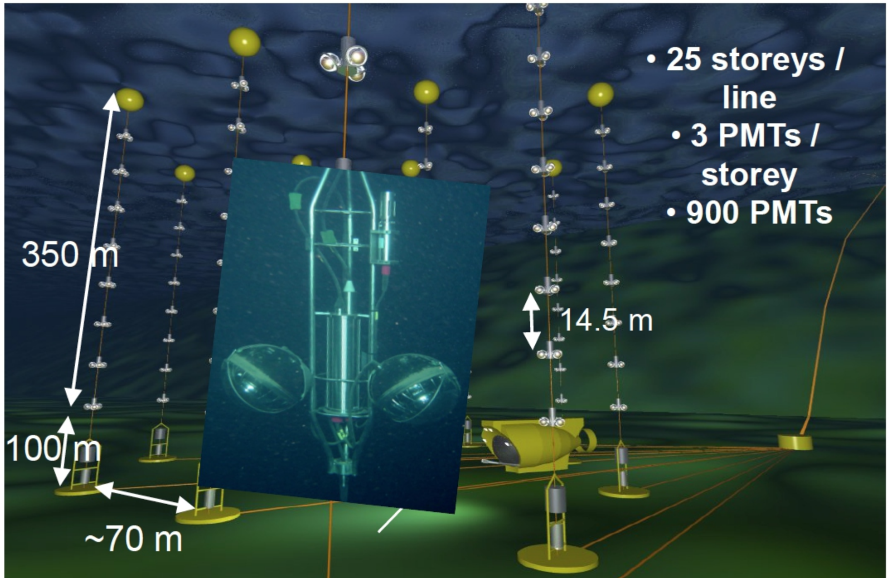
in time

and direction
[error 15 degrees]

Mediterranean Detectors

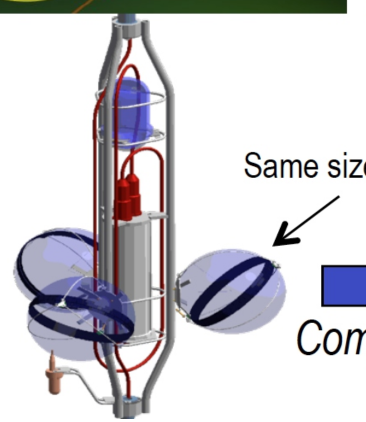


ANTARES Complete since 2008

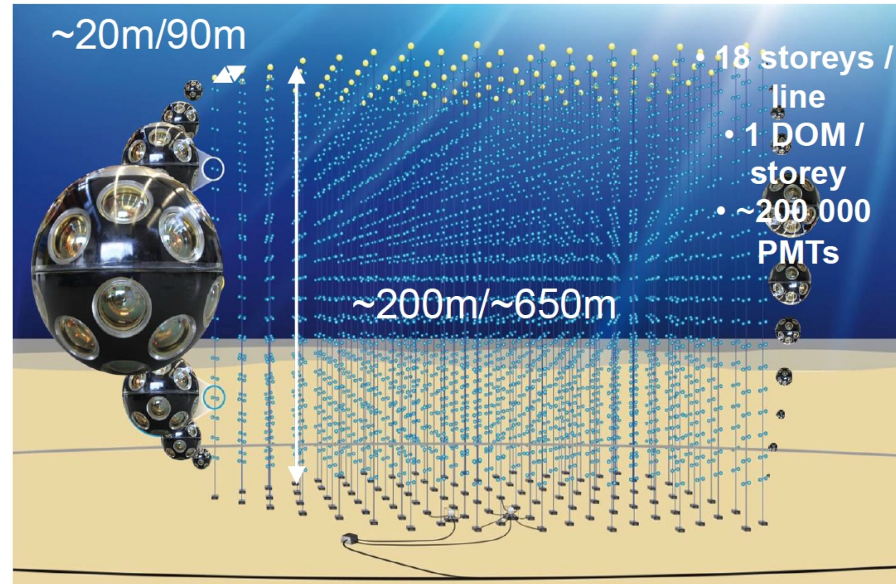


~10 Mton

12 lines
First Generation
First line since 10 years



KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton

Future neutrino telescopes

COSMIC RAYS

Essentially all gamma astronomy and neutrino astronomy
can be seen as observations of Cosmic Rays
in different astrophysical sites

Cosmic Ray Observations at the Earth:

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

Single point, and (effectively) single time.
[Slow time variations,
geological record carries some information]

A *"Local Fog"* that is a terrible nuisance
but also carries very important information

Measurements of Cosmic Rays

as Messengers at the Earth:

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\quad \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

$$\phi_{e^-}(E,\Omega)$$

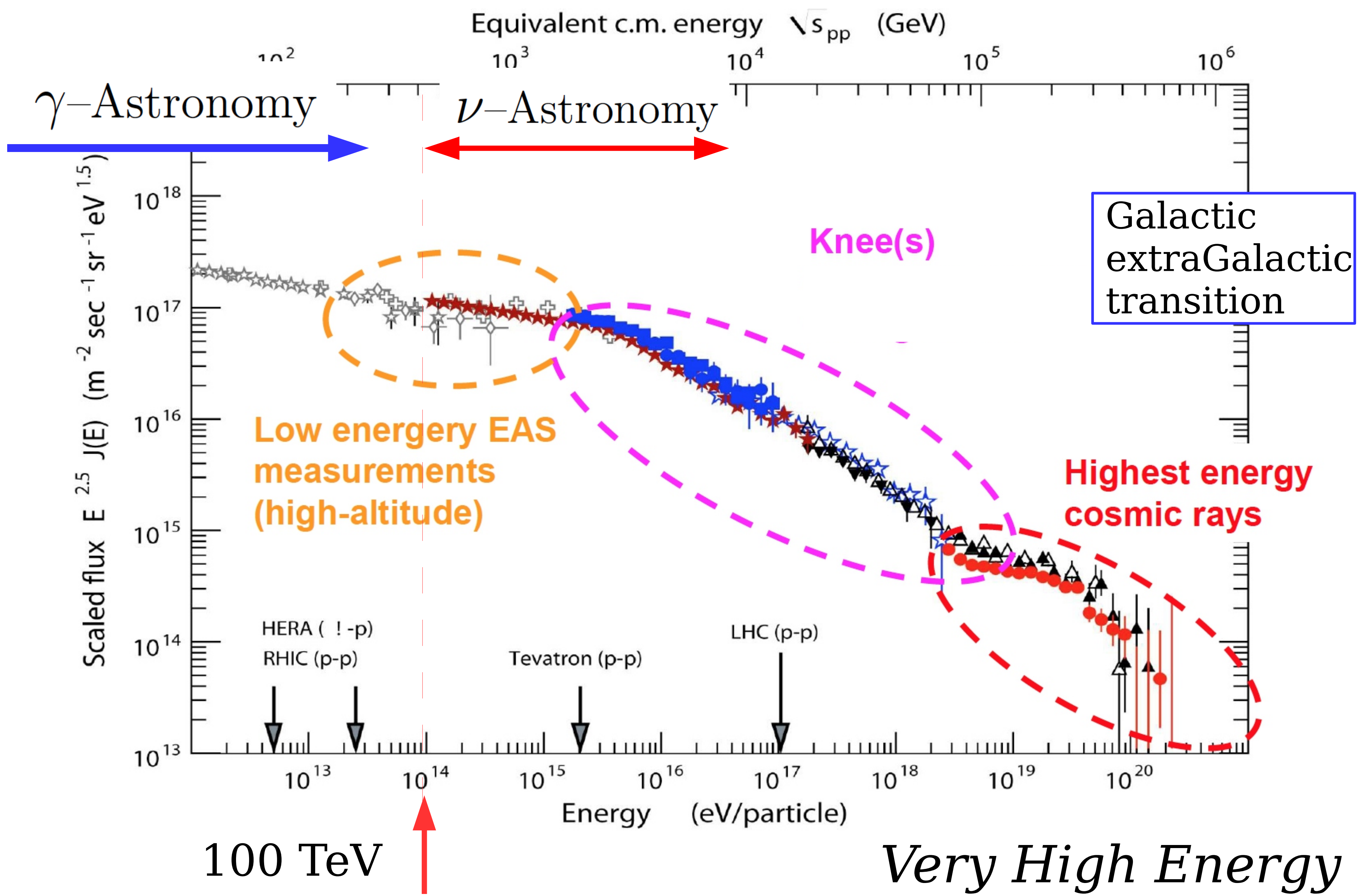
electrons

$$\phi_{e^+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

anti-particles

High Energy CR flux (Indirect Shower Observations)



The CR spectra are *nearly perfectly* isotropic.
but the angular distribution carries information
of great importance

$$\phi(E, \Omega) \simeq \phi(E)$$

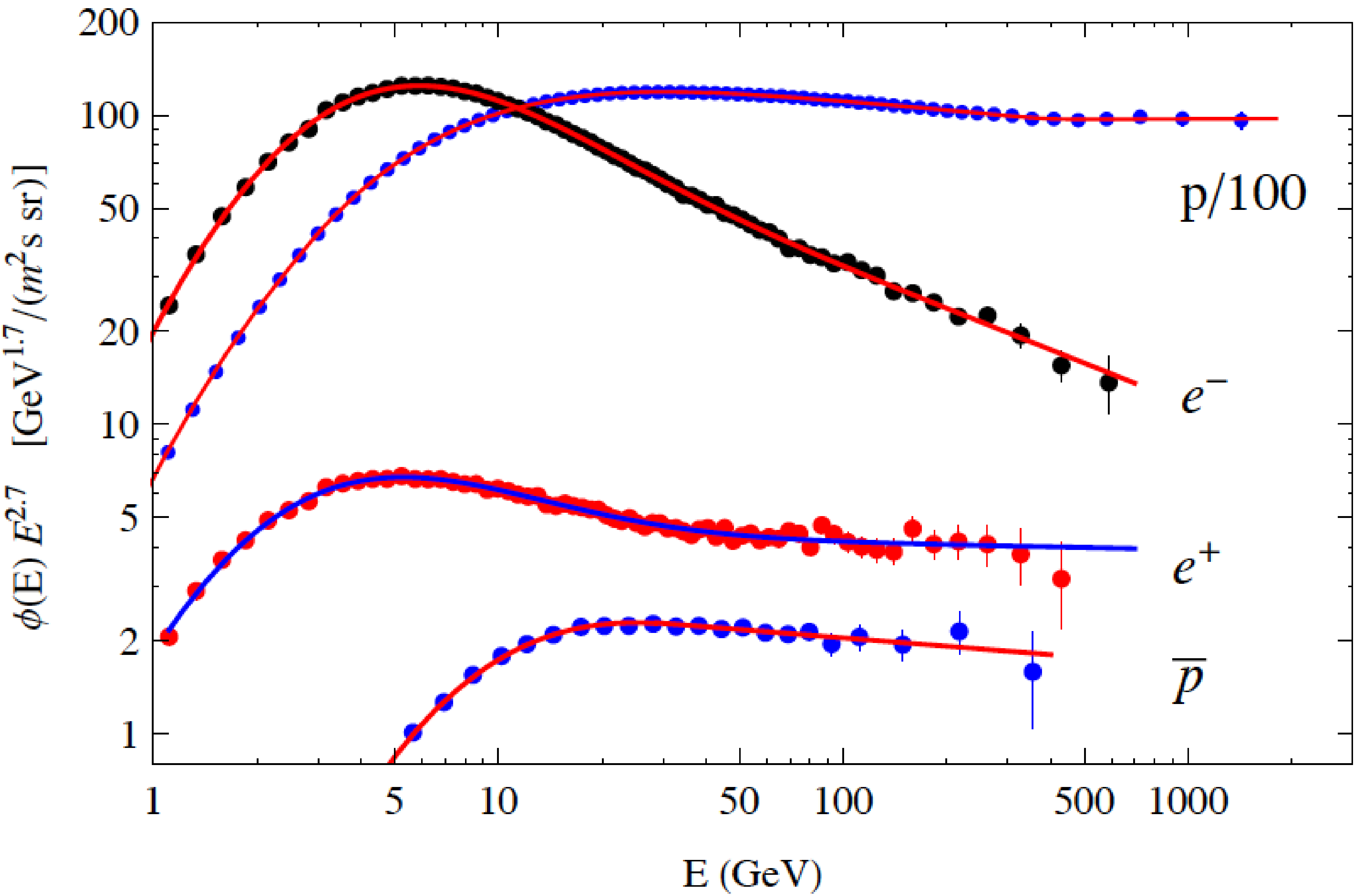
[of course also when the angular distribution is
consistent with exact isotropy [*"The dog that did not bark"*]

The energy spectra
their absolute and relative size,
their *different shapes* for different particle types
carry essential information that we want to understand.

Precision Measurements of AMS02 $E \lesssim 1 \text{ TeV}$

AMS02 measurements:
(antiprotons from AMS days)

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



- Why the proton flux has its shape ?
- Why the electron flux has its shape ?
- Why the positron flux has its shape ?
- Why the $\overline{p}$ flux has its shape ?

Formation of the Cosmic Ray Spectra

$$\phi = \frac{4\,\pi}{\beta\,c}\,n$$

Cosmic Ray Density
at the Sun position

=

"Release"
in Interstellar
Medium

[Injection]

$\otimes$

Propagation
from source to Sun

Secondary particles:

positrons, antiprotons

[in the "conventional picture" :
no DM, no antimatter accelerators)]

Rare Nuclei (Li, Be, B, ...)

"born relativistic"

"Release" = Creation in the interaction of a higher energy particle

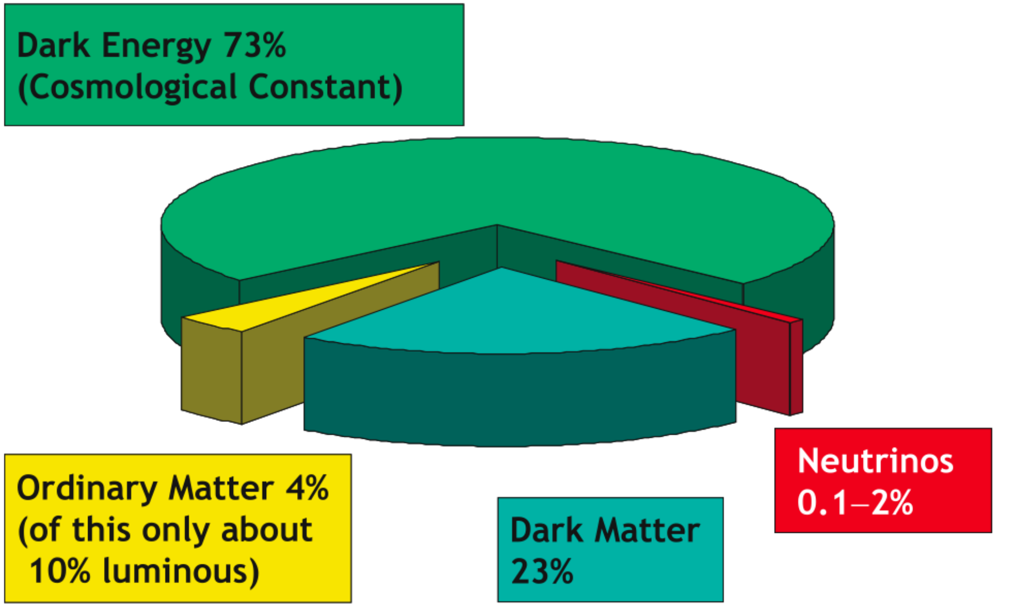
DARK

MATTER

Mysteries of the DARK UNIVERSE

DARK ENERGY :

Drives apart galaxies
and other large scale structures
[The energy of vacuum itself ?]



DARK MATTER:

Holds together galaxies
and other large scale structures
[A new elementary particle ?]

Exist at different scales:
Entire Universe
Clusters of Galaxies
Galaxy

“Conventional mechanism”
for the production of positrons and antiprotons:

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

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

Injections of positrons and anti-protons are intimately connected

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

Relativistic Particles from other sources:

Dark Matter annihilation (or decay).

$$\chi + \overline{\chi} \to \text{secondaries}$$

$$\chi(\overline{\chi}) \to \text{secondaries}$$

$$\chi + \chi \to e^{+} + \overline{p} + \gamma + \nu_j + \ldots$$

$$e^{-} + p + \gamma + \overline{\nu_j} + \ldots$$

Relativistic Particles from other sources:

Dark Matter **annihilation** (or decay).

$$\chi + \overline{\chi} \rightarrow \text{secondaries}$$

$$\chi(\overline{\chi}) \rightarrow$$

Excess of rare (anti)-particles in cosmic rays

Direct imaging of Annihilation (Decay) sites

$$\chi + \chi \rightarrow e^{+} + \overline{p} + \gamma + \nu_j + \ldots$$

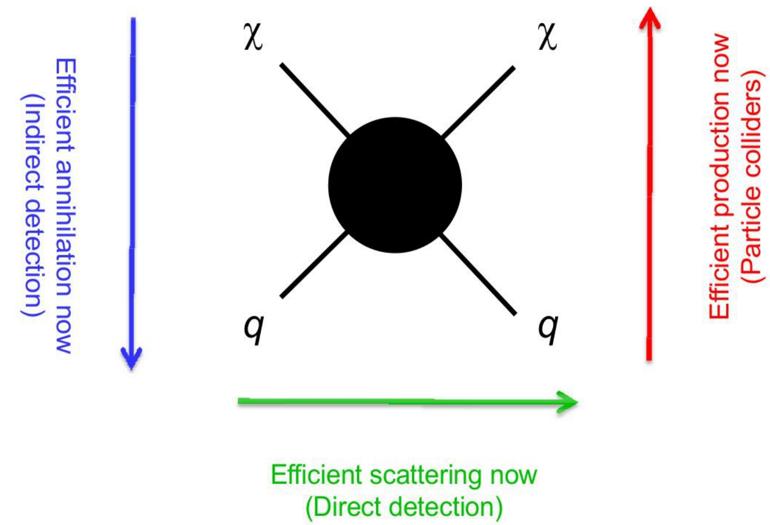
$$e^{-} + p + \gamma + \overline{\nu_j} + \ldots$$

Three roads to the study of the "WIMP" hypothesis:

1. Direct Detection

2. Indirect Detection
   [Observation of annihilation products
   In our own Galaxy]

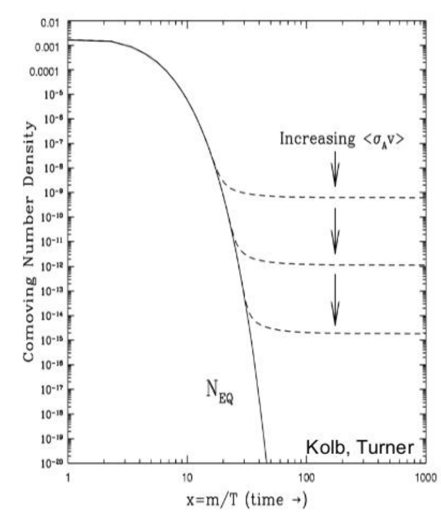
3. Discovery of a new stable particle
   In an accelerator [LHC]

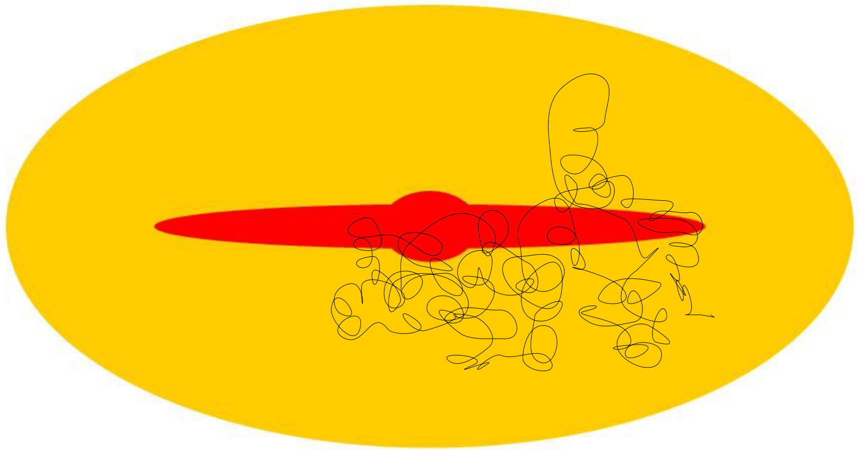


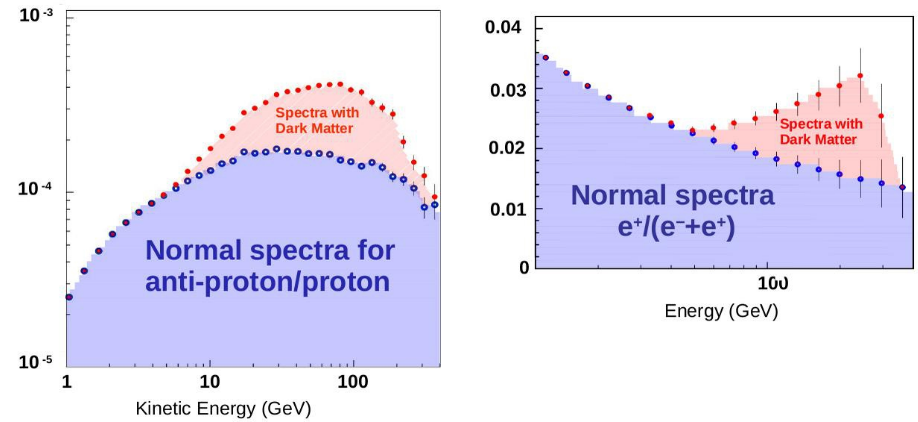
$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle} \right]$$

$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{{M_\chi}^2} \langle \sigma\ v \rangle\ M_\chi$$

$$\chi + \chi \to \gamma \qquad e^+ \qquad \overline{p} \qquad \nu_\alpha$$







SOURCE(s) + Propagation → Observable Cosmic Rays

$$\chi + \chi \rightarrow e^+ + \ldots$$

$$p + p_{\mathrm{ISM}} \rightarrow e^+ \ldots$$

$$p + p_{\mathrm{ISM}} \rightarrow \pi^+ \ldots$$

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

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

Possible
positron accelerators

An understanding of the origin of the
positron and antiproton fluxes is
[seems to me] of central importance for High Energy Astrophysics.

Crucial crossroad for the field.

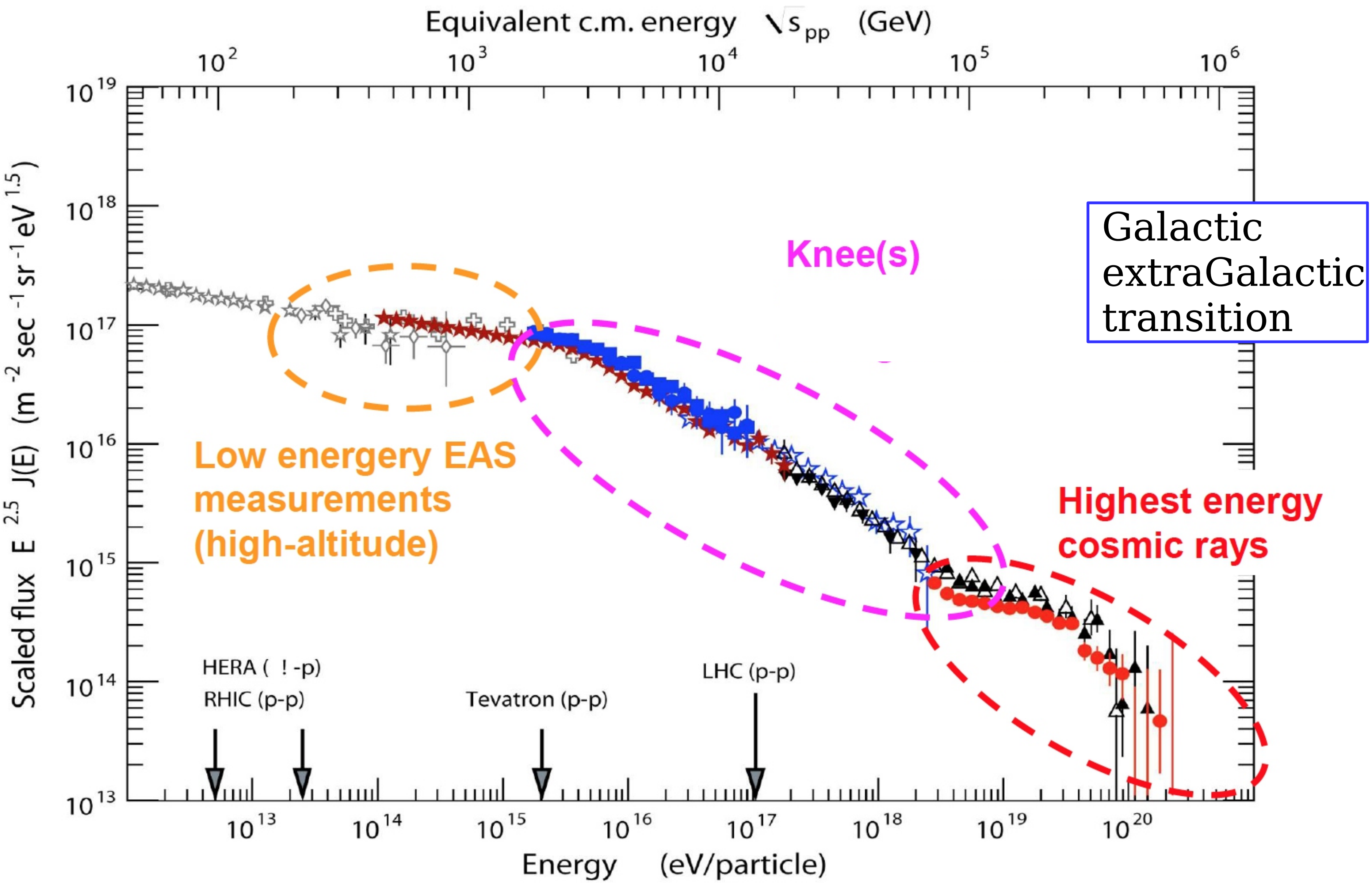
Most commonly accepted view:
The hard positron flux requires an "extra component"
Sources of relativistic positrons [Pulsars, DM annihilation] exist.

The similarity of the antiproton and positron fluxes:

[Constant ratio $e^+/\overline{p} \approx 2$ at high energy (E > 30 GeV)]
[Kinematical suppression of antiprotons at low energy]
suggests a secondary origin for both fluxes.
Viable solution, but the implications are profound.

It is very important to clarify what is the correct explanation

High Energy CR flux



Structures in the Cosmic Ray Energy Spectrum

1. The "Pamela hardening"

2. The break in the $(e^- + e^+)$ spectrum observed by the Cherenkov Telescope

3. The "KNEE" $\log_{10}[E(\mathrm{eV})] \simeq 15.5$

4a. The "Iron Knee" of Kascade Grande 16.92 ± 0.08

4b. The "proton (+Helium) Ankle" 17.08 ± 0.05

4c. The "Second Knee" 17.6 ± 0.2

5. The "ANKLE" 18.6

6. The UHECR suppression 19.4–19.8

The Nature of the "KNEE"
in the Cosmic Ray Spectrum

Accelerator feature

[Maximum energy of acceleration.
implies that all accelerators are similar]

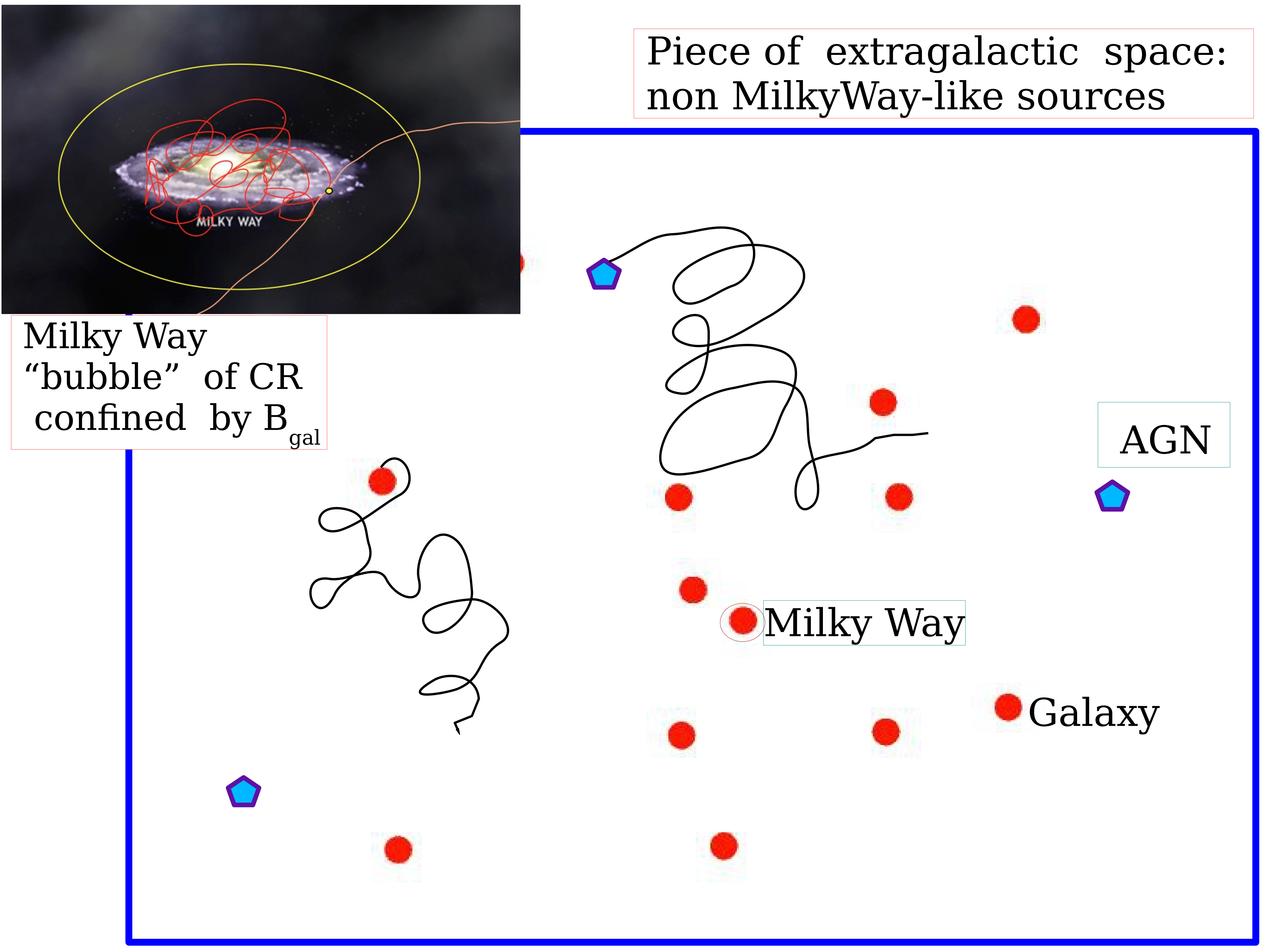
Structure generated by propagation

[implies that the (main) Galactic CR accelerators must be capable to accelerate to much higher energy]

Galactic

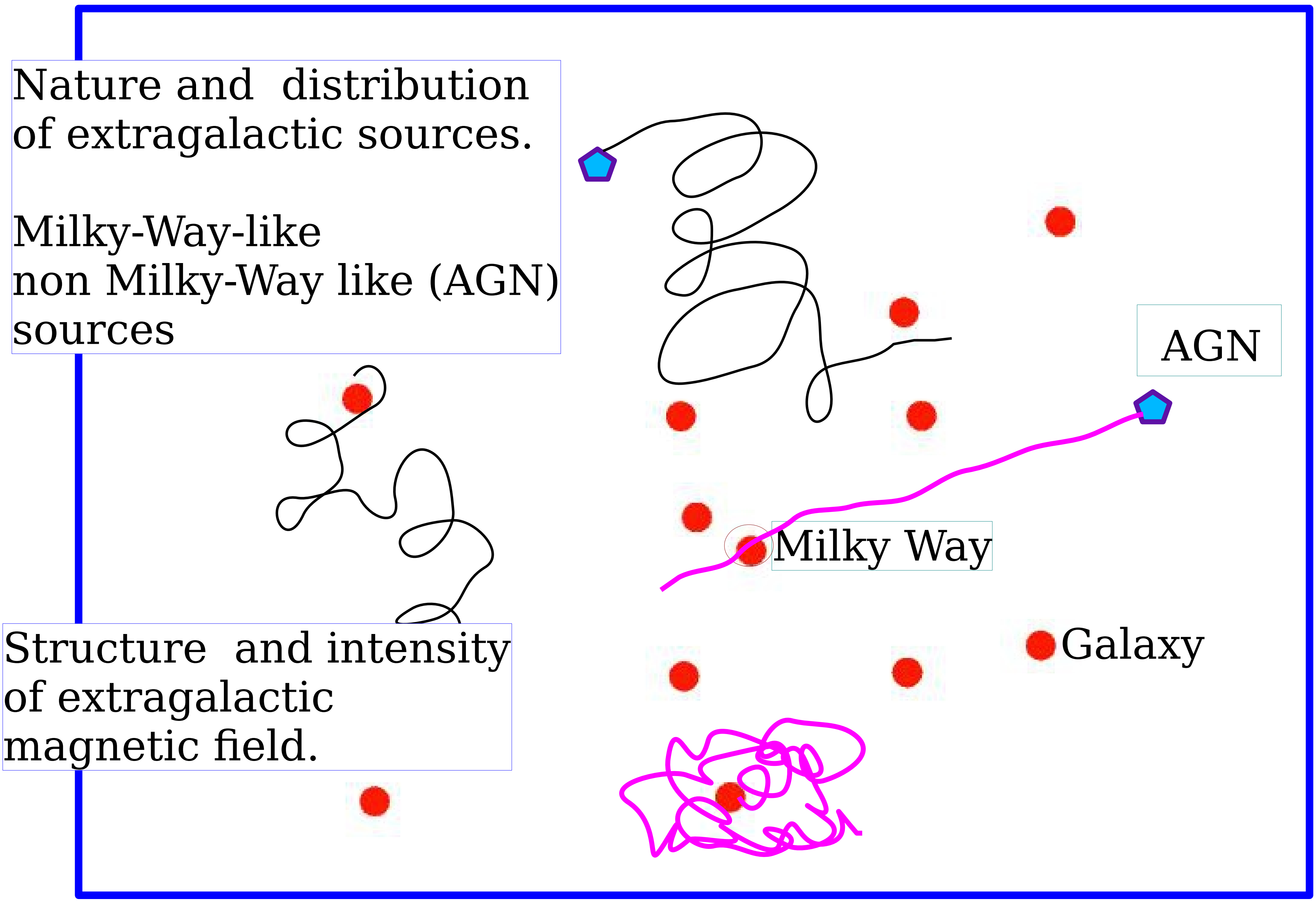
versus

Extra-Galactic CR

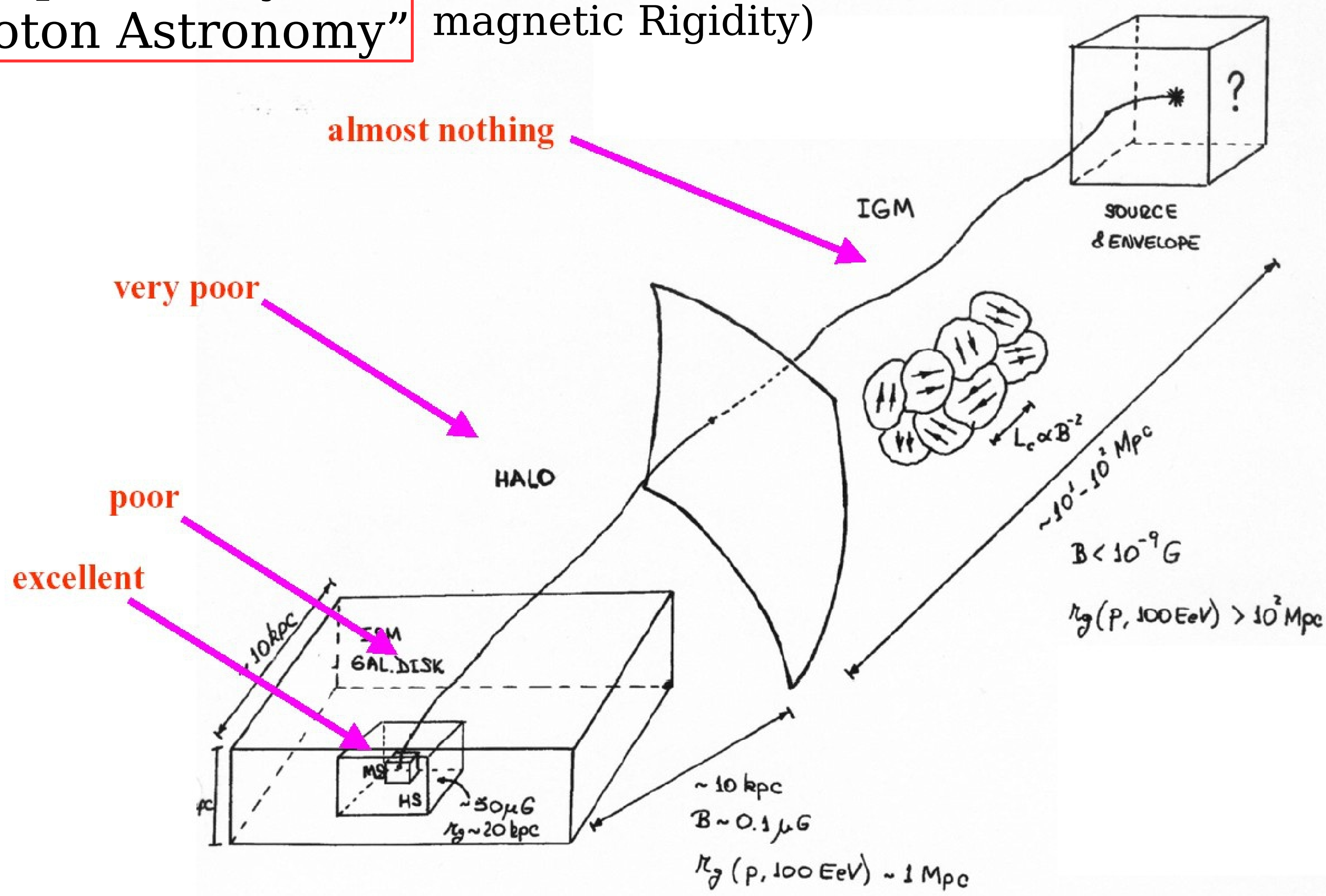


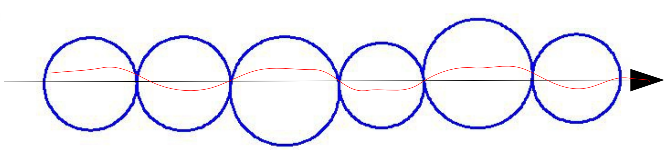
Piece of extragalactic space:
non MilkyWay-like sources
MILKY WAY
Milky Way
“bubble” of CR
confined by B gal
AGN
Milky Way
Galaxy

Piece of extragalactic space:



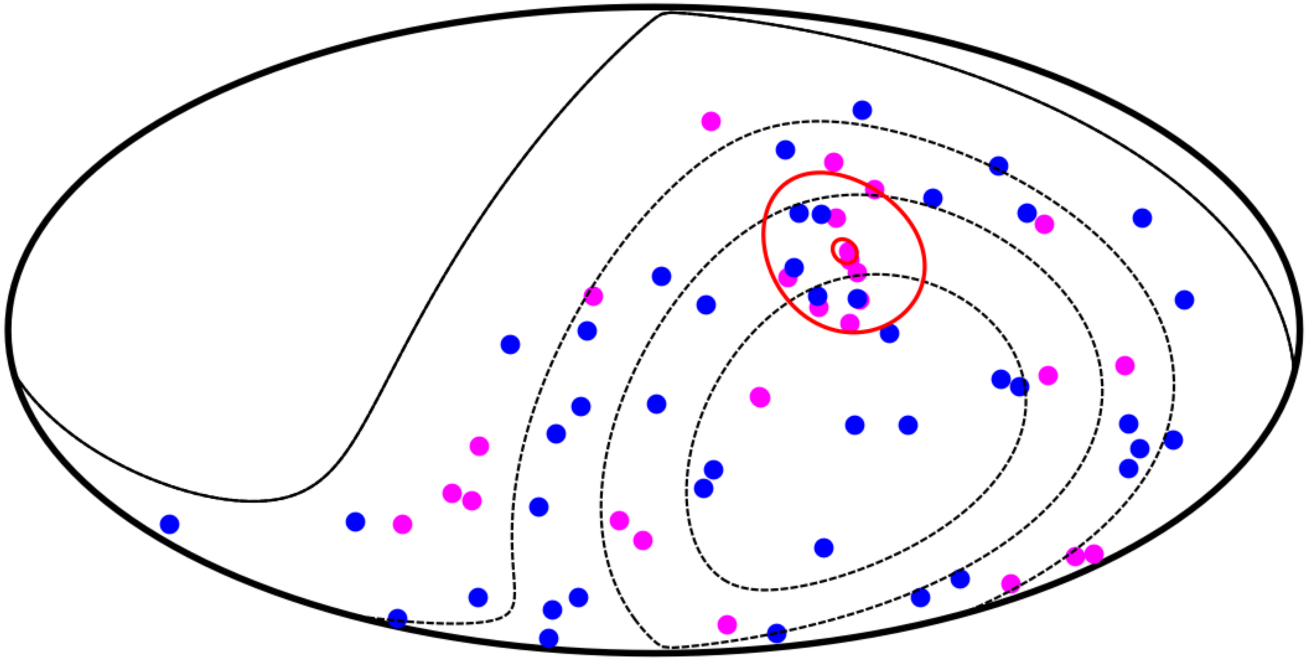
The possibility "proton Astronomy" (at sufficient high magnetic Rigidity)





$$\Delta\theta \simeq 0.53^\circ\ Z \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\left(\frac{\sqrt{D\,d}}{\mathrm{Mpc}}\right)\left(\frac{\langle B\rangle}{nG}\right)$$

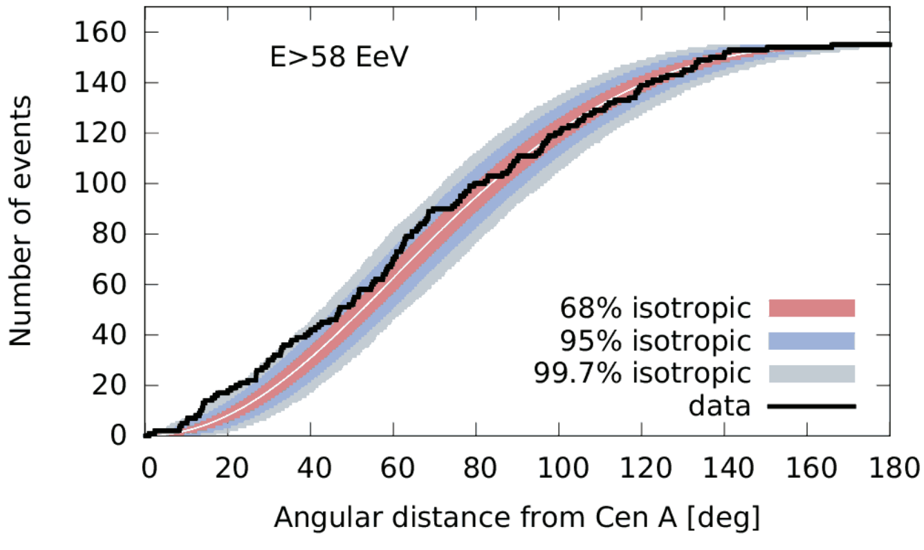
Significant interest in Cen A [closest AGN]



Points: Auger events E > 58 EeV
Red lines:[3, 20] degrees circles around Cen A

Is this the first "image" of an astrophysical object taken with protons ?!

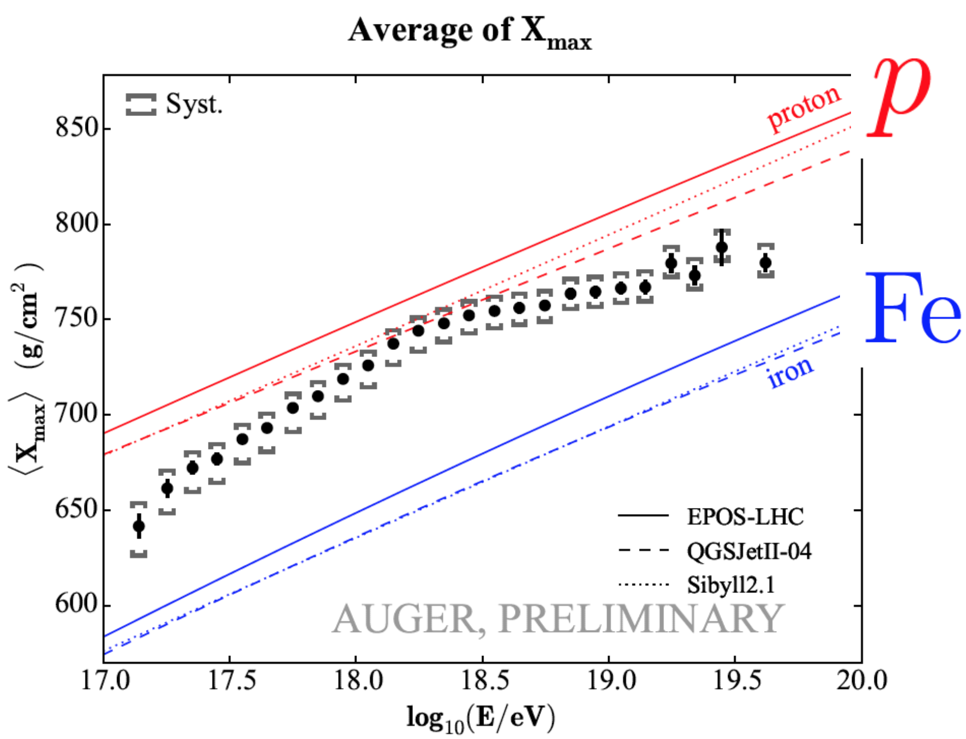
Approximately 3 sigma effect

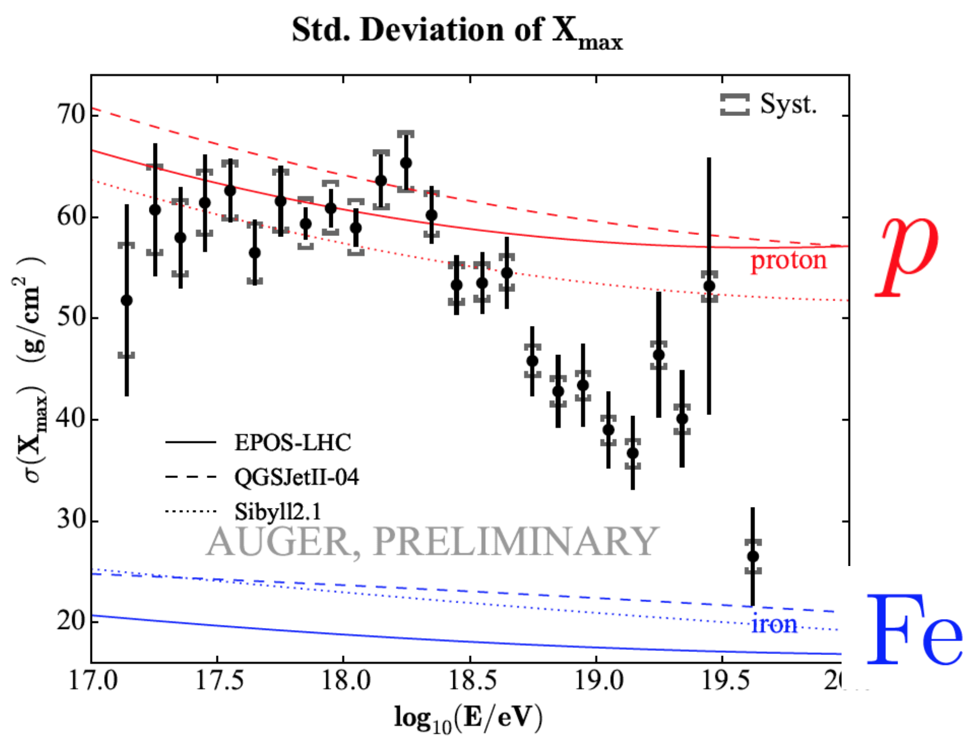


Auger composition study :

Average position of shower Maximum

Dispersion of shower Maximum

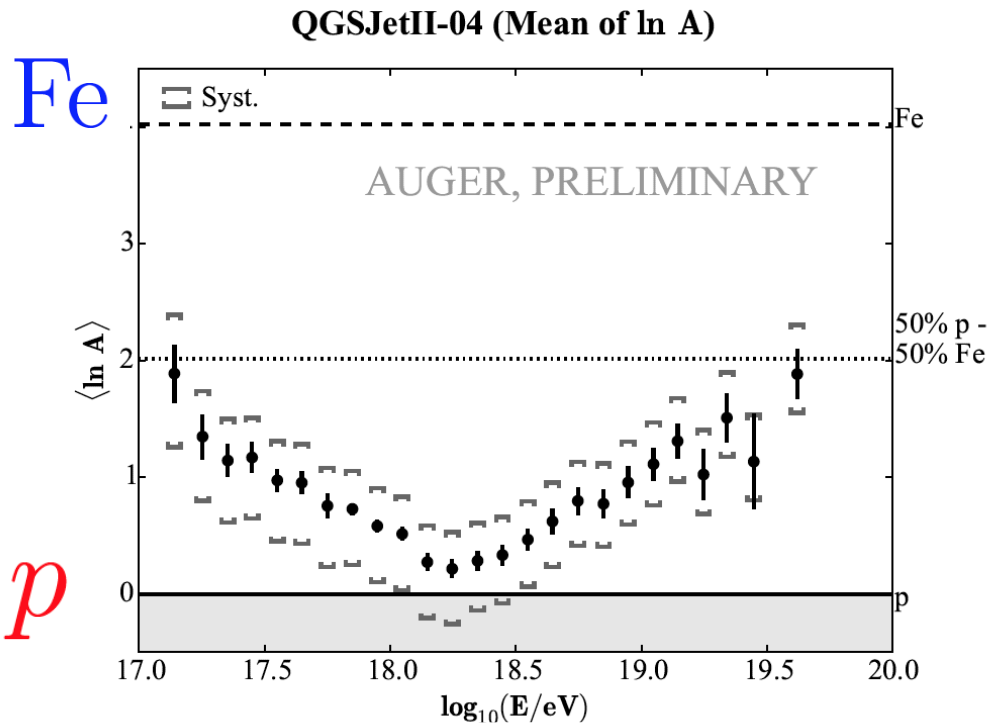


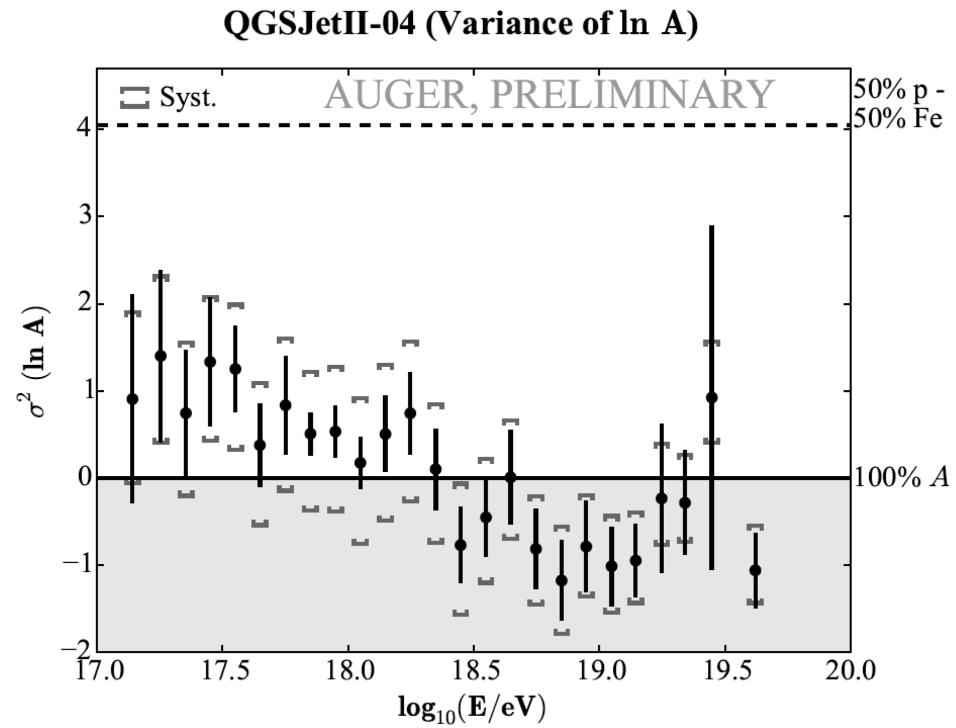


Model dependence QGSJetII-04 [description of Shower development]

$\langle \ln A \rangle$

$\sigma^2 [\ln A]$



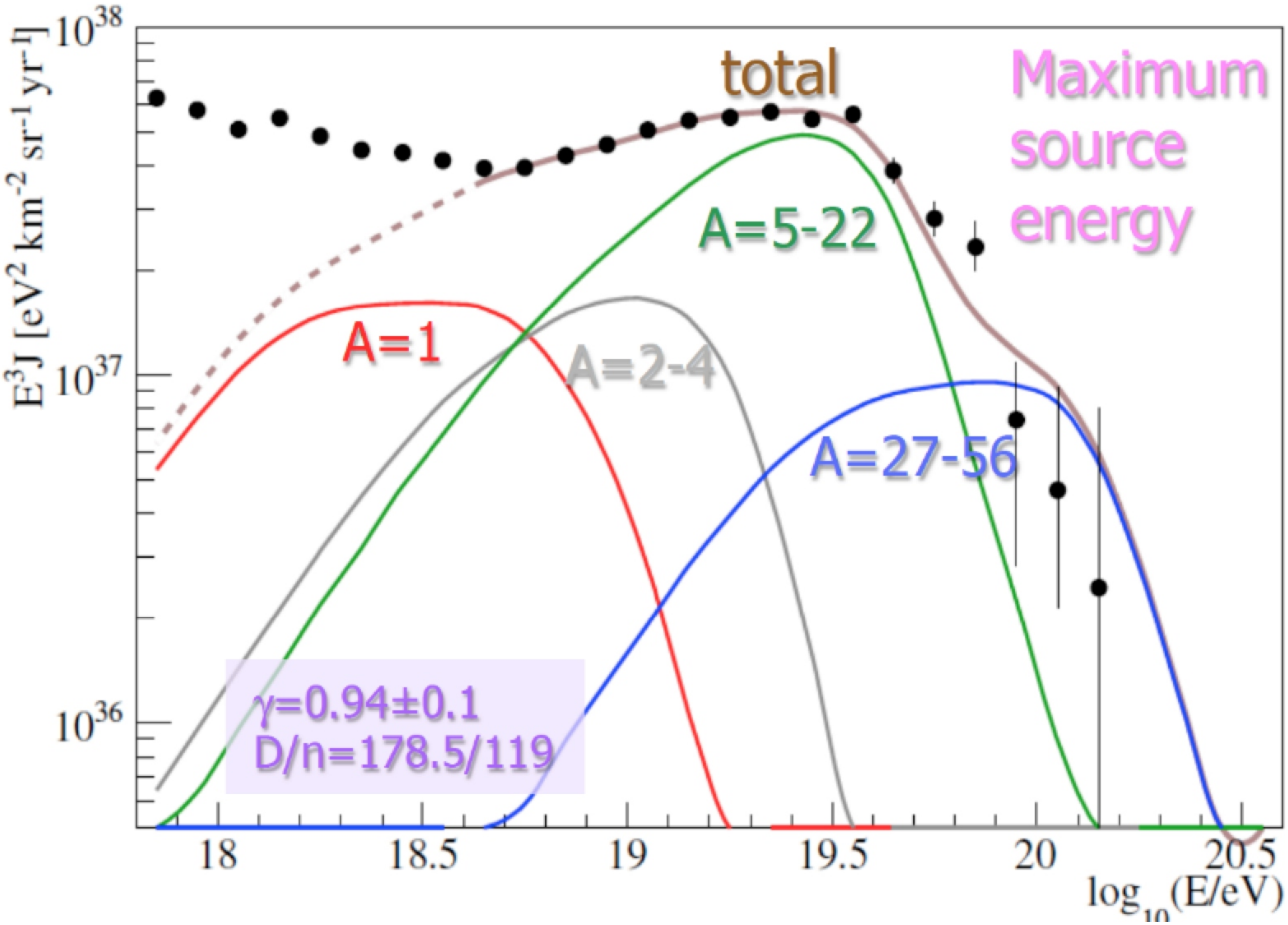


Very light CR population for $E \simeq 10^{18}$ eV

and becoming heavier !

Small dispersion: small range of A contributing to the CR population

Possible Interpretation (Auger at ICRC-2015)



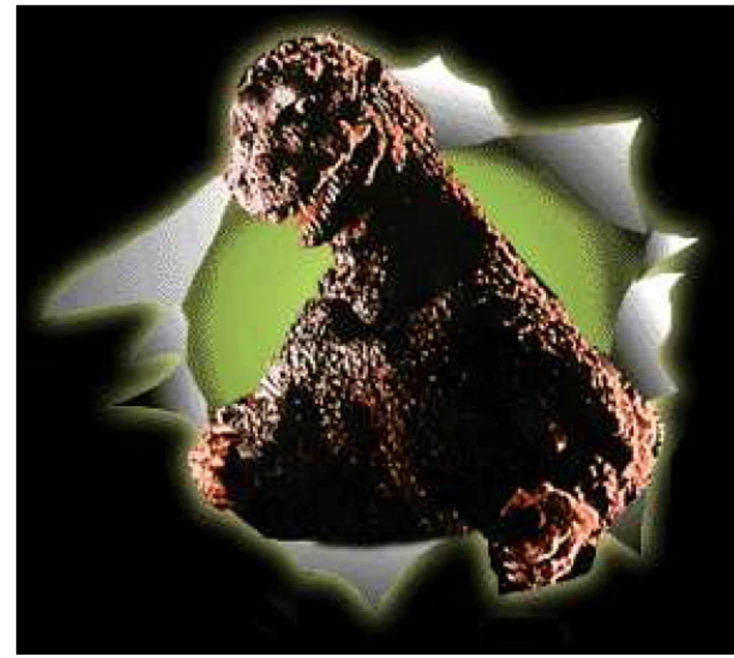
1. Very hard spectra

2. Cutoff is the maximum energy of acceleration in the sources

$$E_{\max}(Z) = Z\ E_p$$

$$M_{\mathrm{GUT}} \sim 10^{15} \div 10^{16}\ \mathrm{GeV}$$

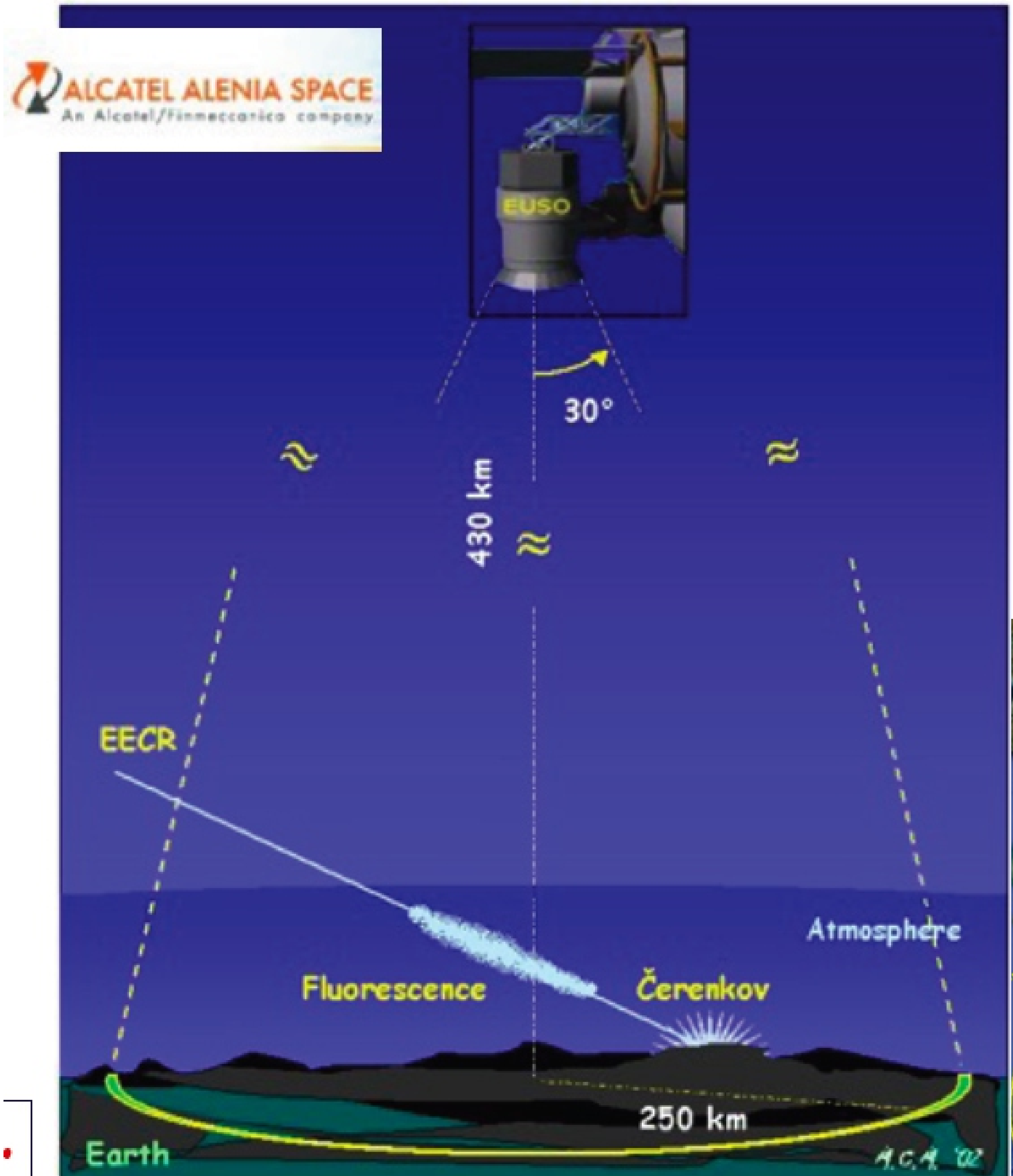
$$M_{\mathrm{GUT}} \sim 10^{24} \div 10^{25}\ \mathrm{eV}$$

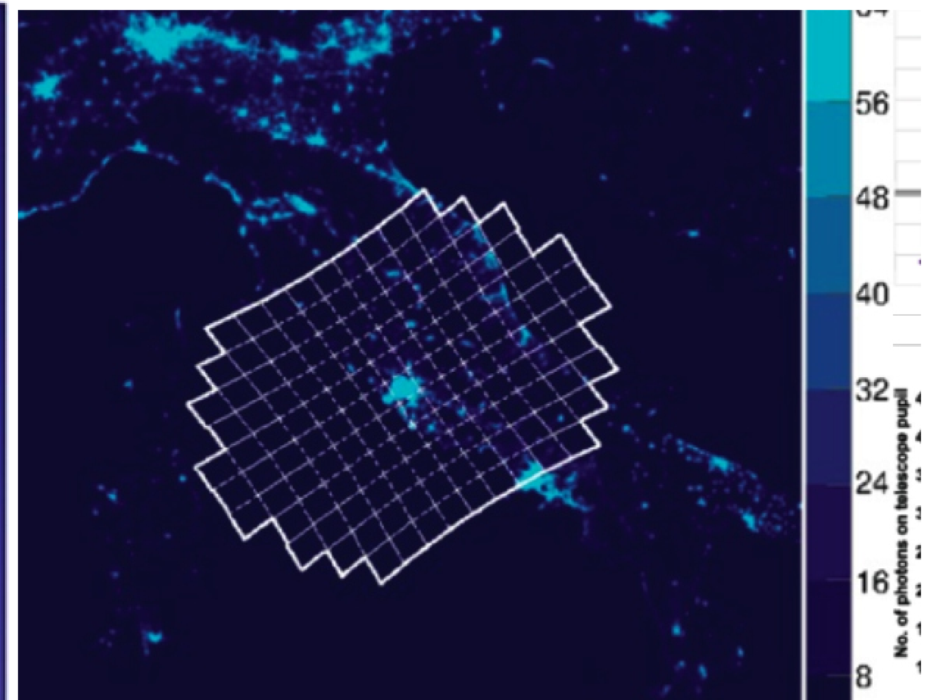


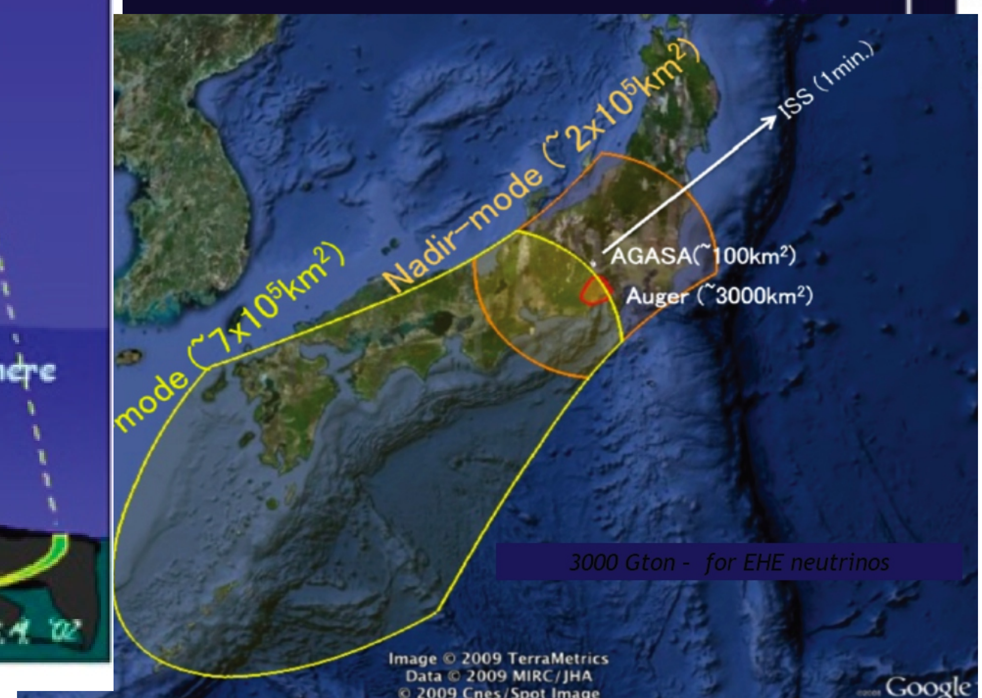
$$M_{\mathrm{Planck}} = \sqrt{\frac{\hbar\, c^5}{G}} \simeq 10^{28}\ \mathrm{eV}$$

Super Massive Particles associated
to these mass scales "WIMPZILLAS"

EUSO concept: Detection of UHCR from space



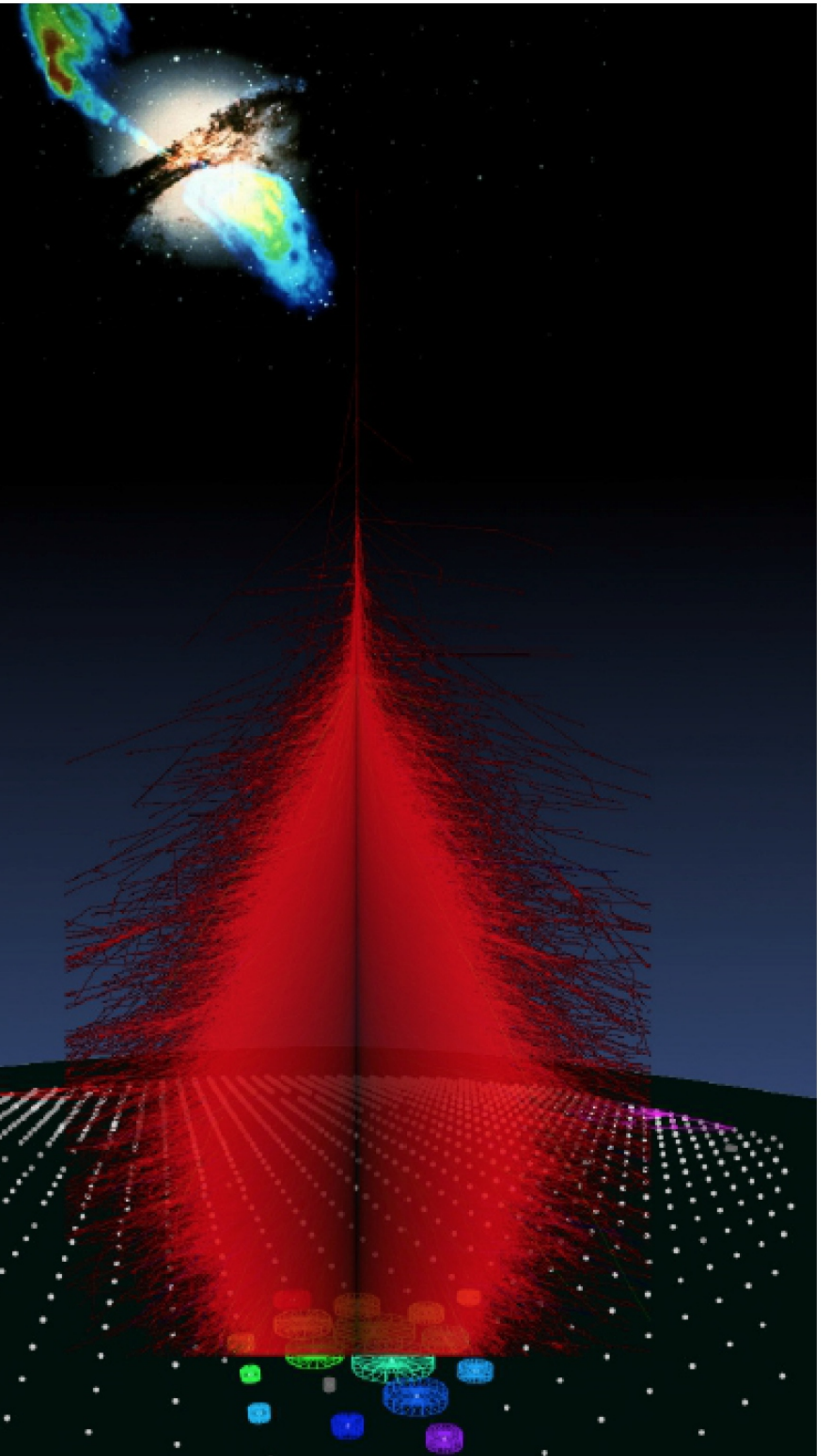




Cosmic Ray Physics
[Astroparticle Physics]

and

HADRONIC INTERACTIONS



the Source

$$E_{\rm lab} \simeq 10^{20}\ \text{eV}$$

$$\sqrt{s} \simeq 430\ \text{TeV}$$

the Shower

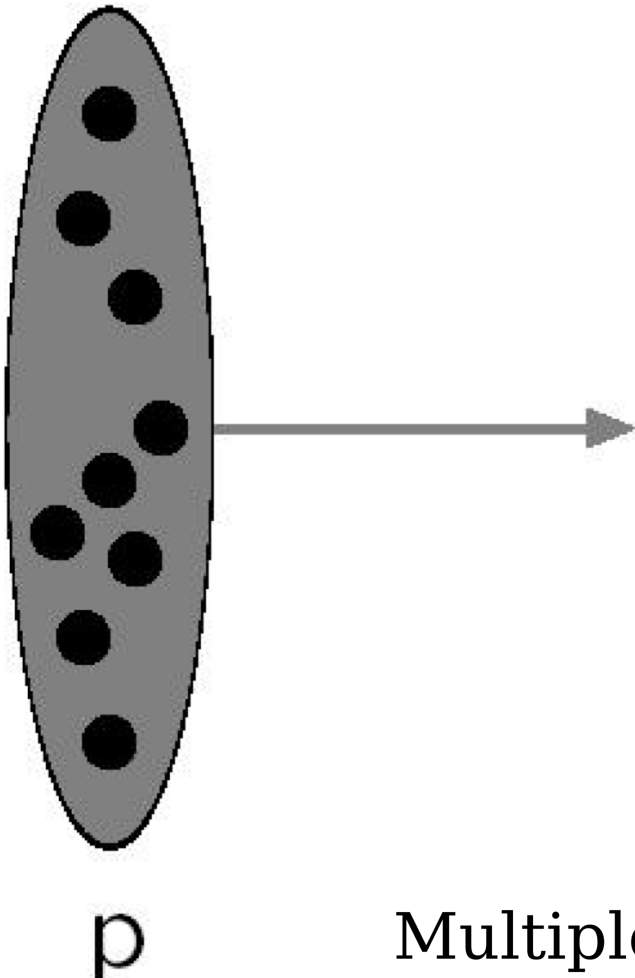
[The estimate of the Energy and Mass of the shower requires the detailed modeling of shower development]

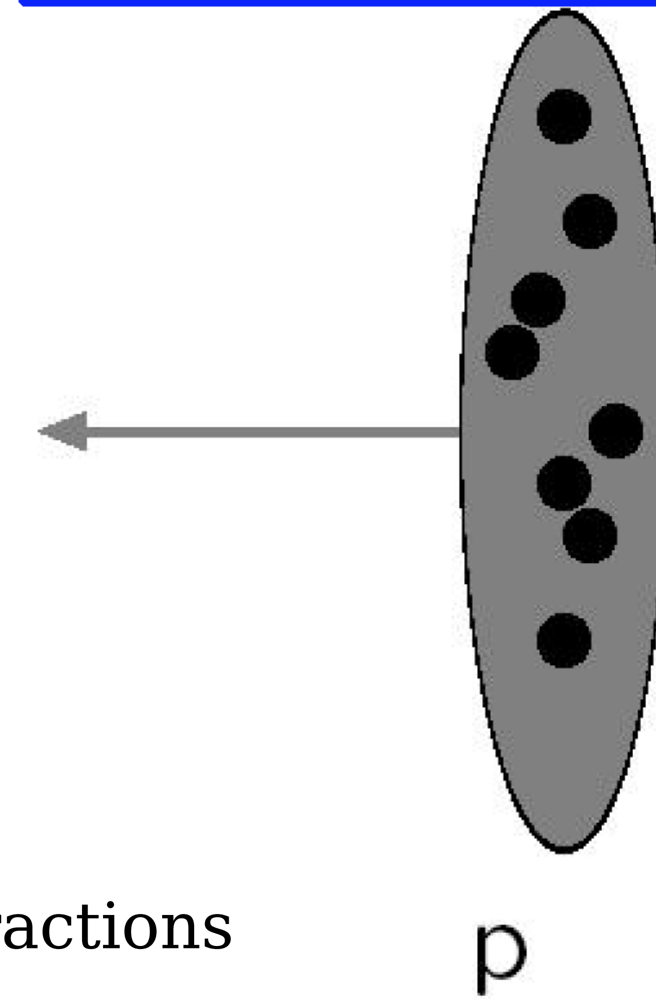
the Data

Hadronic Interactions

QCD

Composite (complex) Objects
Multiple interaction structure





Multiple parton interactions
in the same collision

Great importance of the LHC data

Total, elastic, inelastic cross sections
"Minimum bias" events
Diffractive events
....
[Need all phase space, including the very forward]

Also potentially important measurements at much lower energy (Fixed Target)

Production of positrons:

$$p + p \rightarrow \pi^+ \ldots$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

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

Production of photons :

$$p + p \rightarrow \pi^\circ + \ldots$$

$$\hookrightarrow \gamma \; \gamma$$

Possible and very desirable
a program of measurements of
hadronic cross sections at fixed target energies

Motivations

[1. "Astroparticle Physics" Astroparticle Physics

[2.] Better understanding of QCD

"Bridging the gap between
Hard and Soft regime in hadronic interactions.

Gravitational Waves

..... GW 170817 ..... !!!!

Gravitational Waves

and

High Energy Particles

“Einstein Richest Laboratory”

L. Baiotti and L. Rezzolla,
"Binary neutron-star mergers: a review of Einstein's richest laboratory,"
Reports on Progress of Physics
arXiv:1607.03540 [gr-qc].

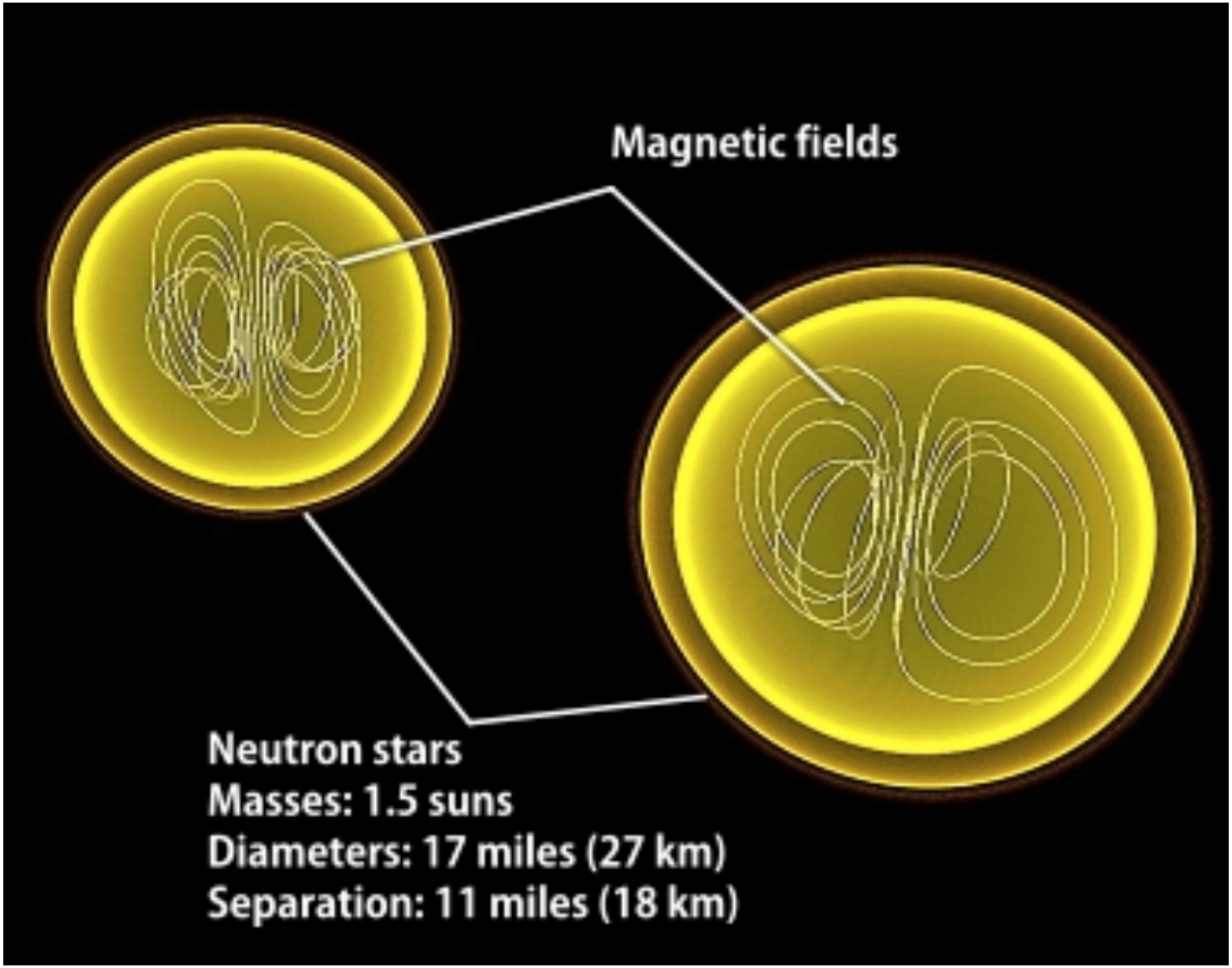
The *merger of binary neutron-stars* systems combines in a single process:

extreme gravity,
copious emission of gravitational waves,
complex microphysics,
and electromagnetic processes that can lead to astrophysical signatures observable at the largest redshifts.

* black-hole formation,
* torus accretion onto the merged compact object,
* *connection with gamma-ray burst engines,*
* ejected material, and its nucleosynthesis.

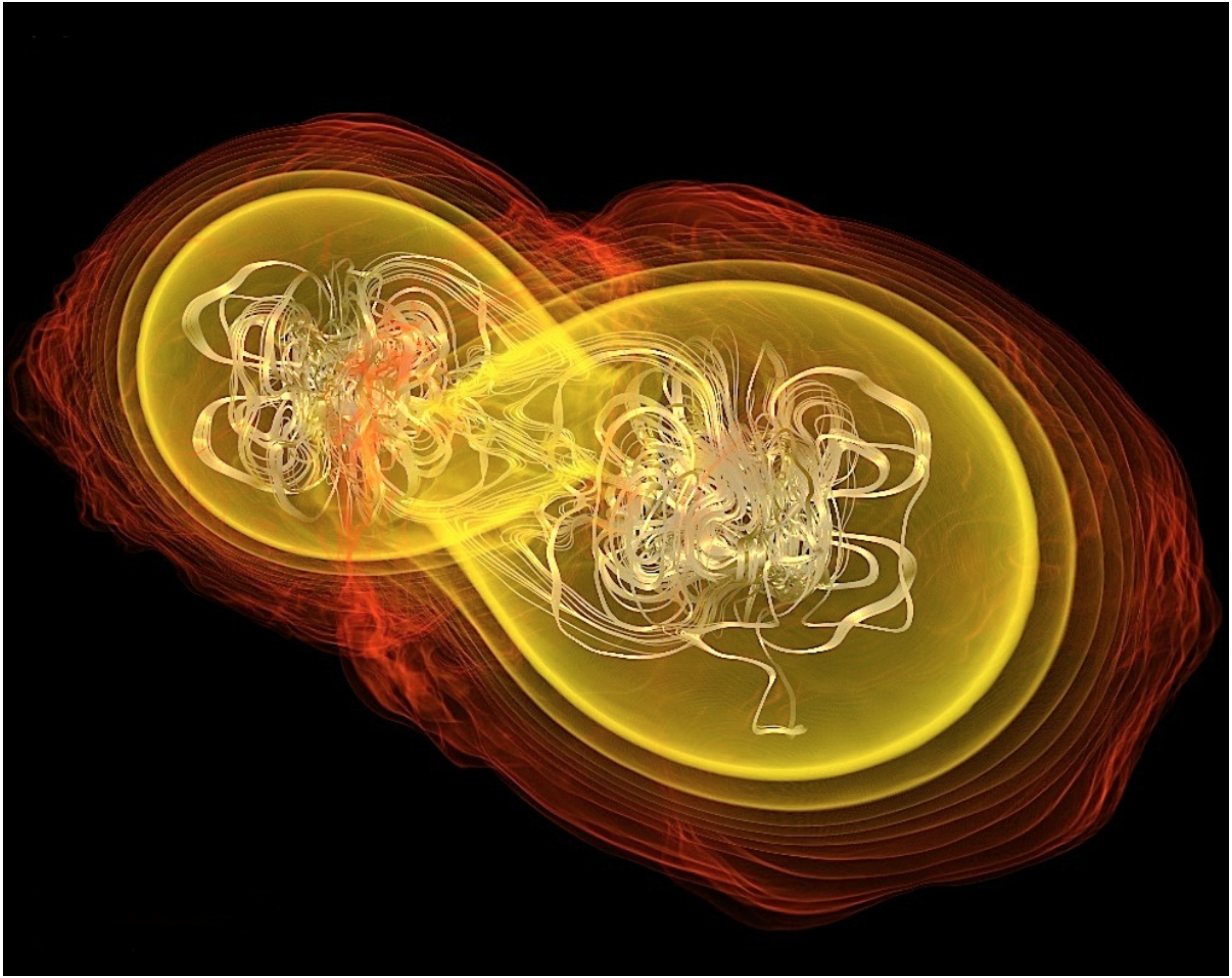
[... This phenomenon] could be considered Einstein's richest laboratory.

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



L. Rezzolla et al. ApJ (2011)

7.5 msec



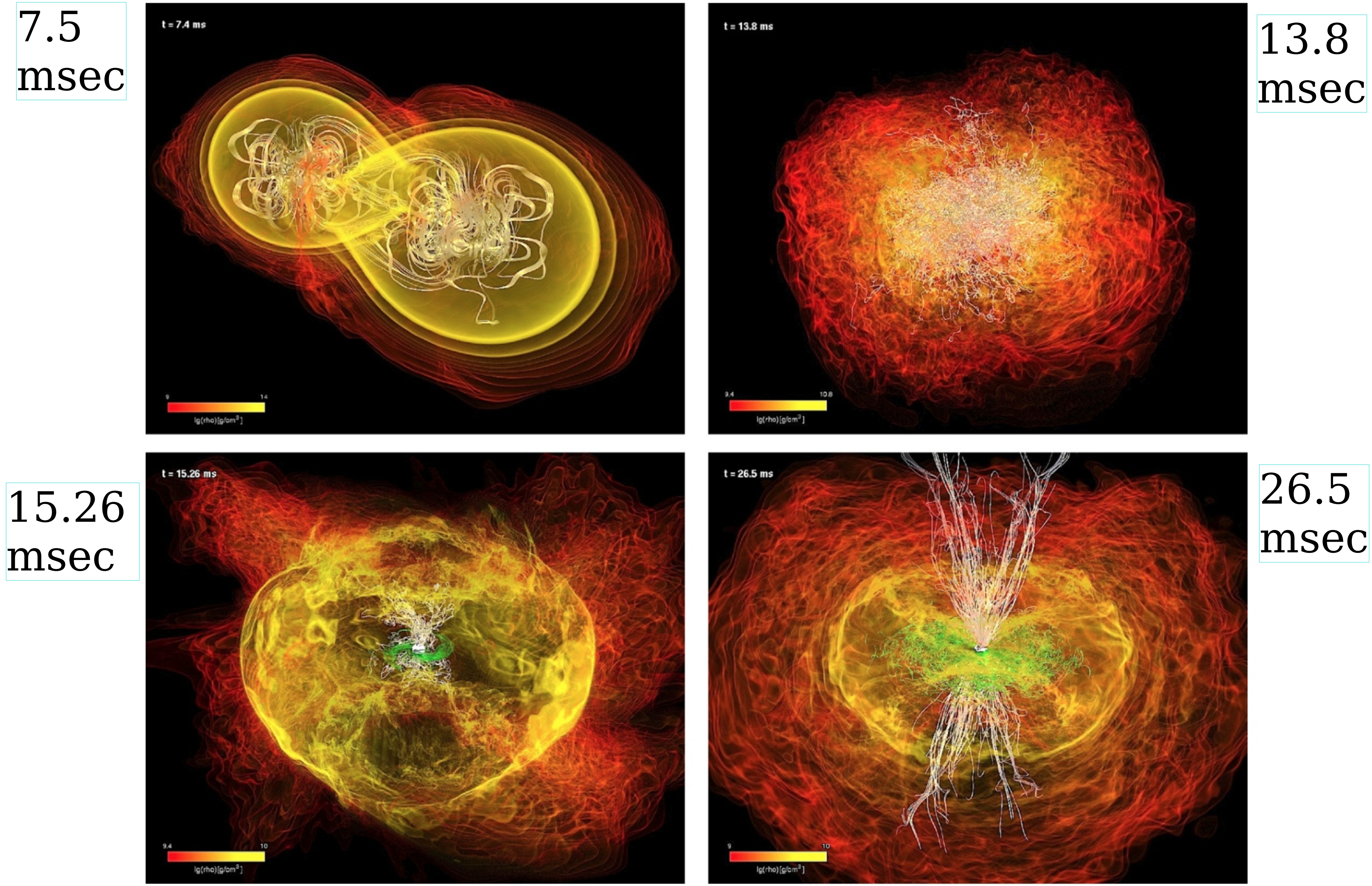


Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t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

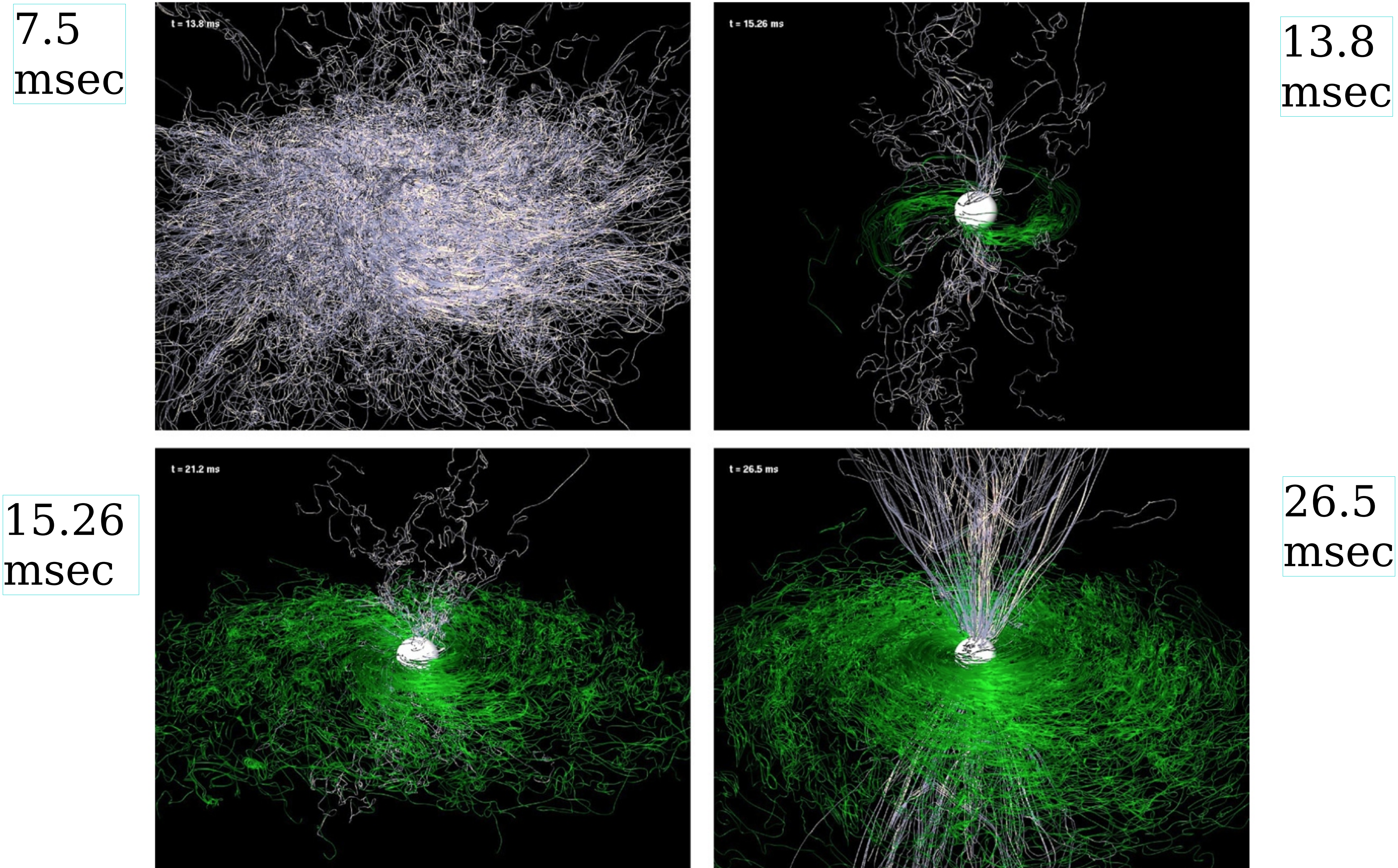
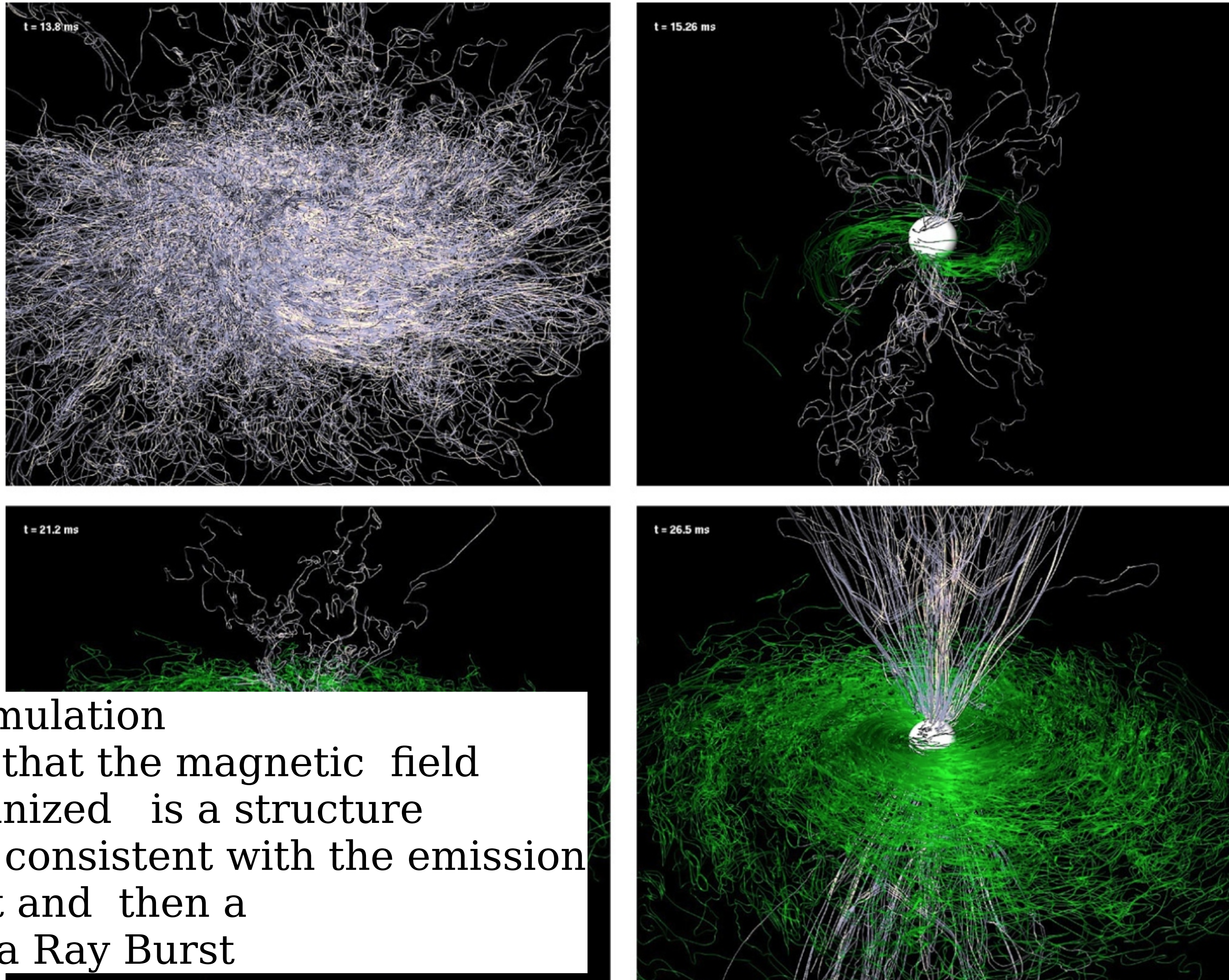


Figure 3. Magnetic-field structure in the HMNS (first panel) and after the collapse to BH (last three panels). Green refers to magnetic-field lines inside the torus and on the equatorial plane, while white refers to magnetic-field lines outside the torus and near the axis. The highly turbulent, predominantly poloidal magnetic-field structure in the HMNS ($t = 13.8$ ms) changes systematically as the BH is produced ($t = 15.26$ ms), leading to the formation of a predominantly toroidal magnetic field in the torus ($t = 21.2$ ms). All panels have the same linear scale, with the horizon diameter being of $\simeq$9 km.

7.5 msec

13.8 msec

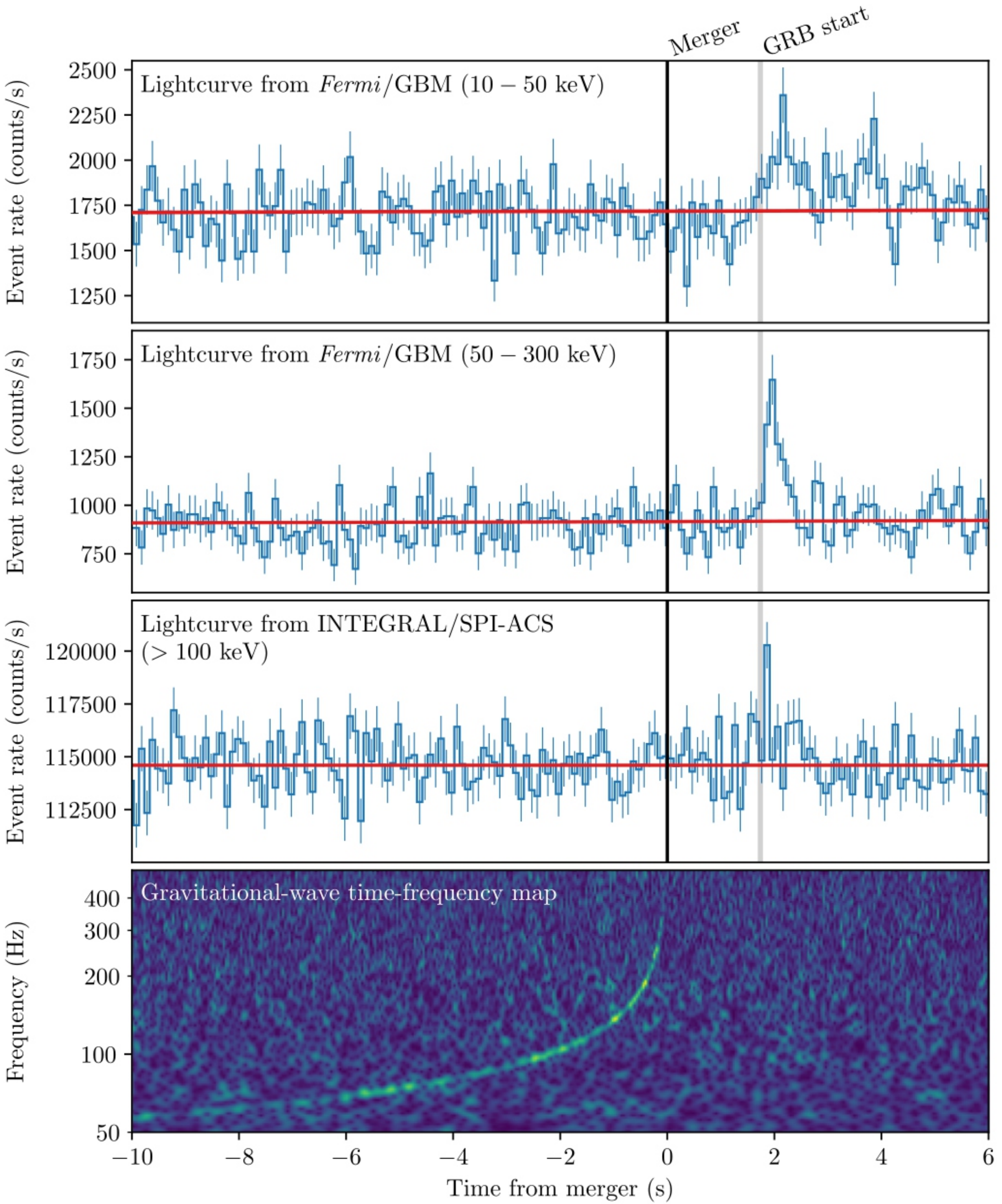


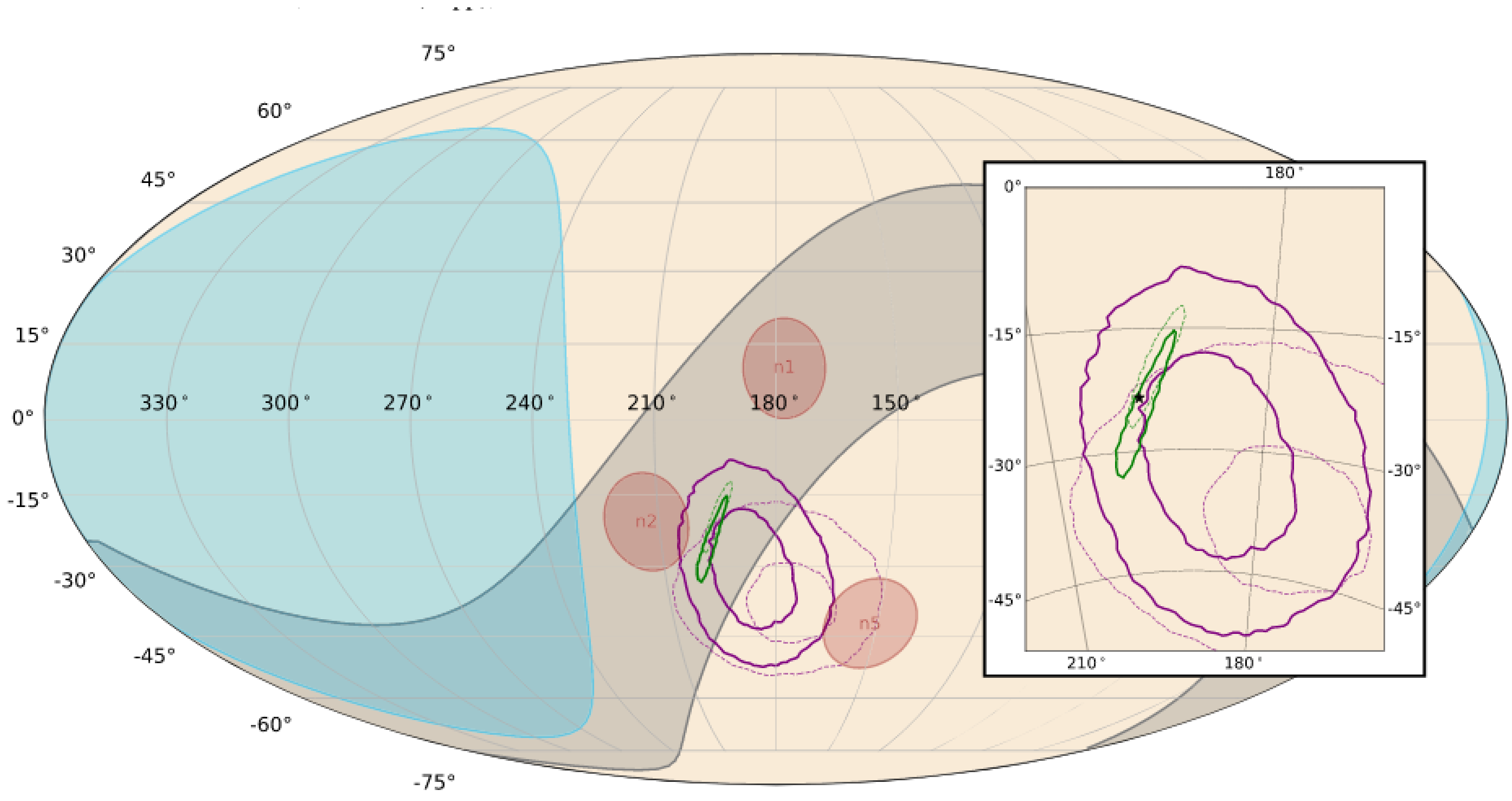
15.26 msec

26.5 msec

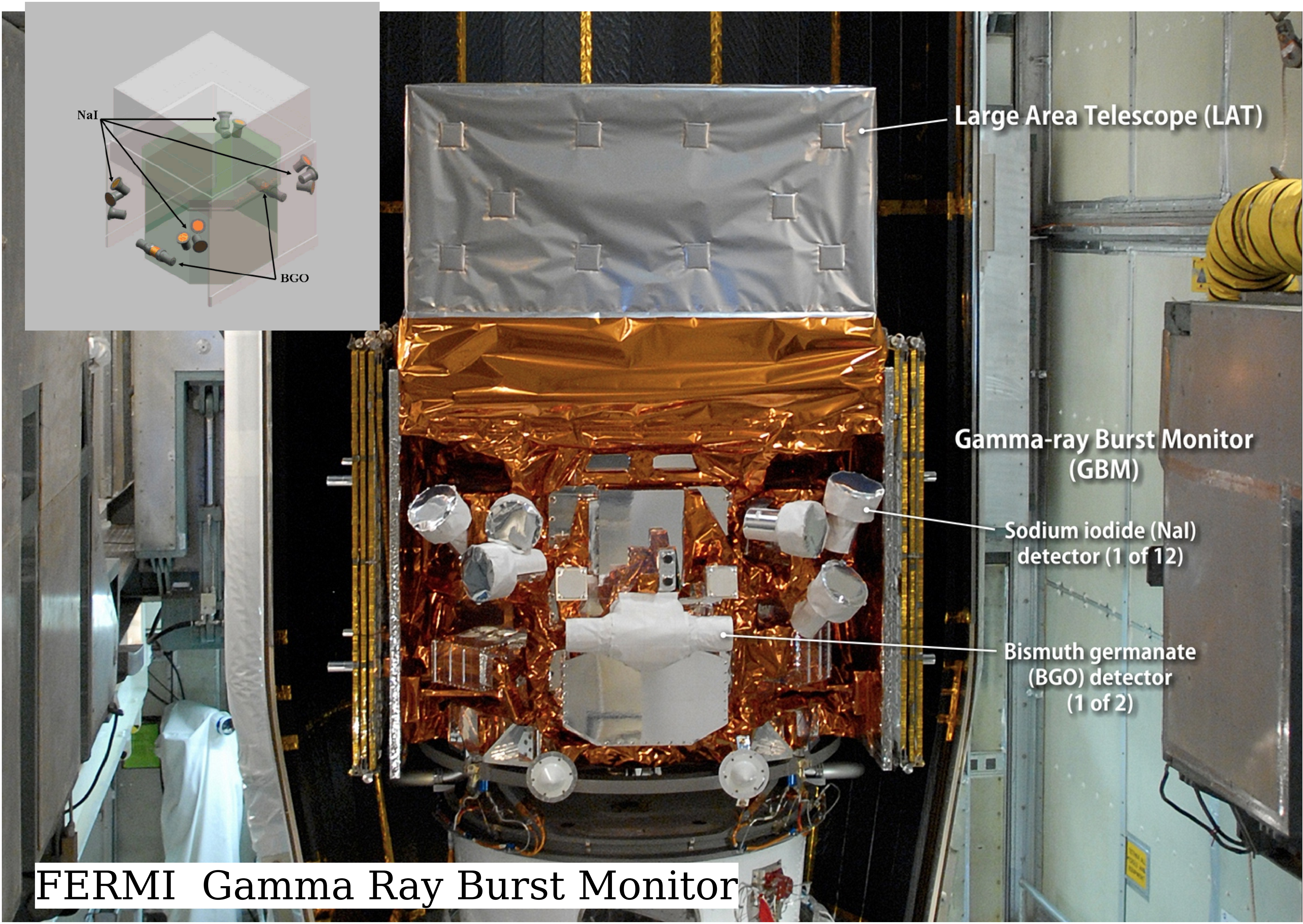
The simulation
shows that the magnetic field
is organized is a structure
that is consistent with the emission
of a jet and then a
Gamma Ray Burst

Figure 3. Magnetic-field structure in the HMNS (first panel) and after the collapse to BH (last three panels). Green refers to magnetic-field lines inside the torus and on the equatorial plane, while white refers to magnetic-field lines outside the torus and near the axis. The highly turbulent, predominantly poloidal magnetic-field structure in the HMNS (t = 13.8 ms) changes systematically as the BH is produced (t = 15.26 ms), leading to the formation of a predominantly toroidal magnetic field in the torus (t = 21.2 ms). All panels have the same linear scale, with the horizon diameter being of $\simeq$9 km.

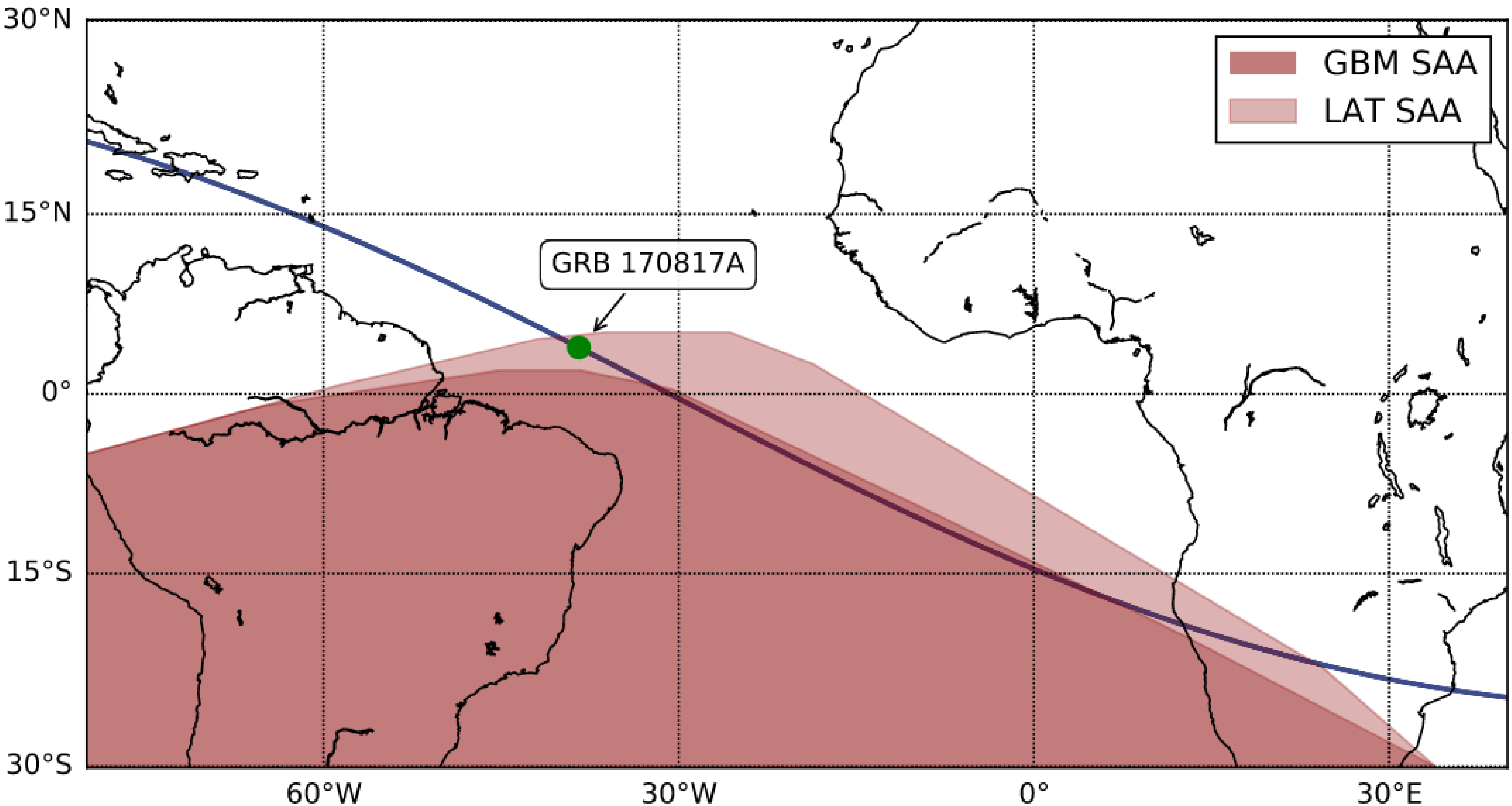

Merger
GRB start
Lightcurve from *Fermi*/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from *Fermi*/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)



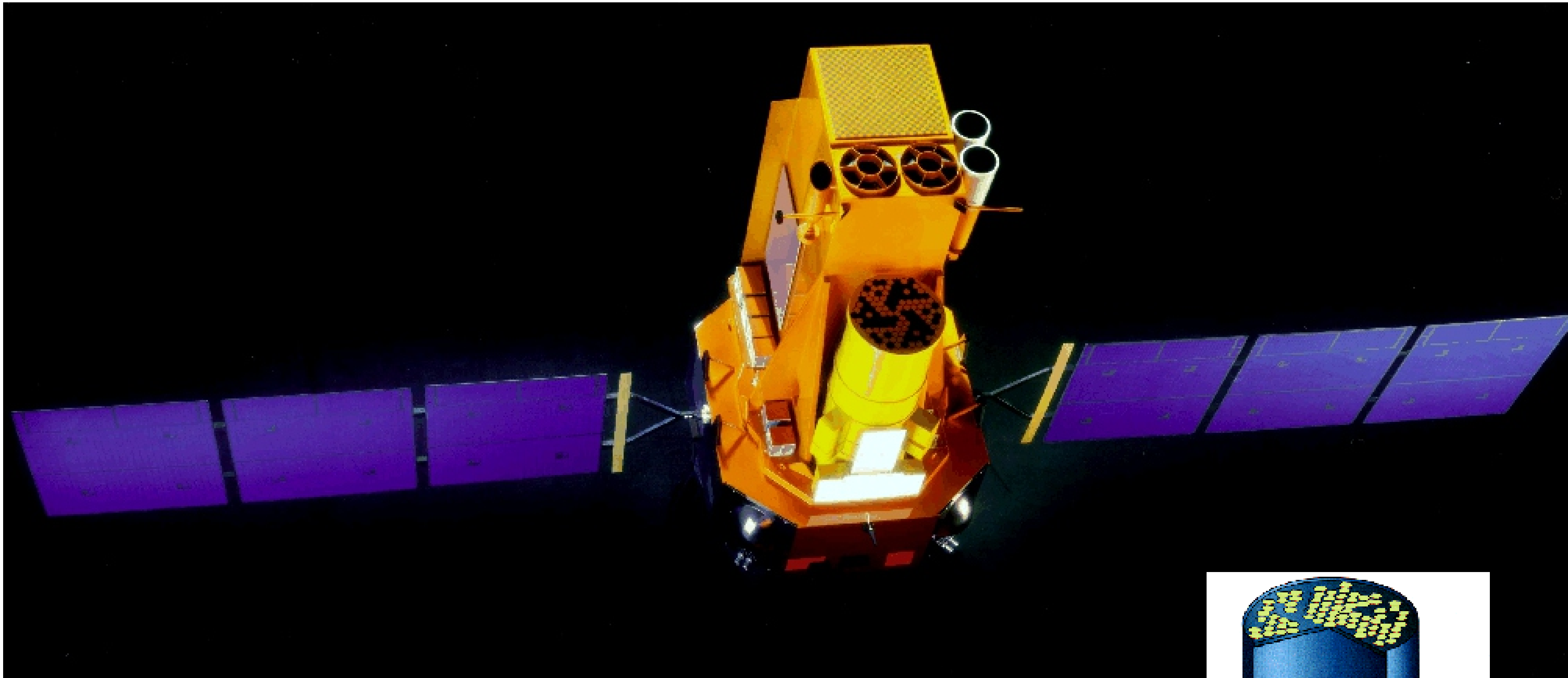
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
330°
300°
270°
240°
210°
180°
150°
n1
n2
n5
0°
180°
-15°
-30°
-45°
210°
180°

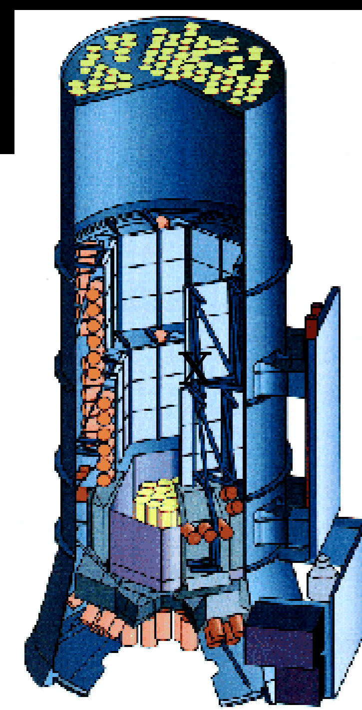


FERMI Gamma Ray Burst Monitor



30°N
15°N
0°
15°S
30°S
60°W
30°W
0°
30°E
GBM SAA
LAT SAA
GRB 170817A





INTEGRAL
SPI-ADC

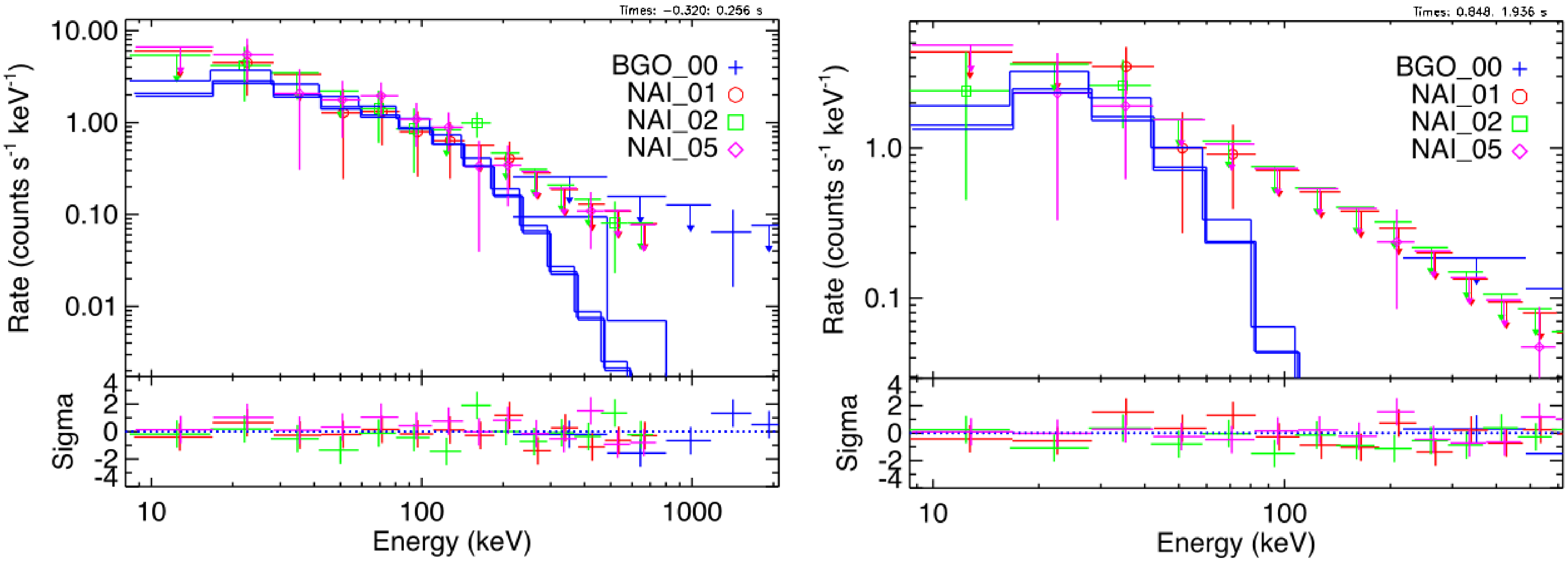
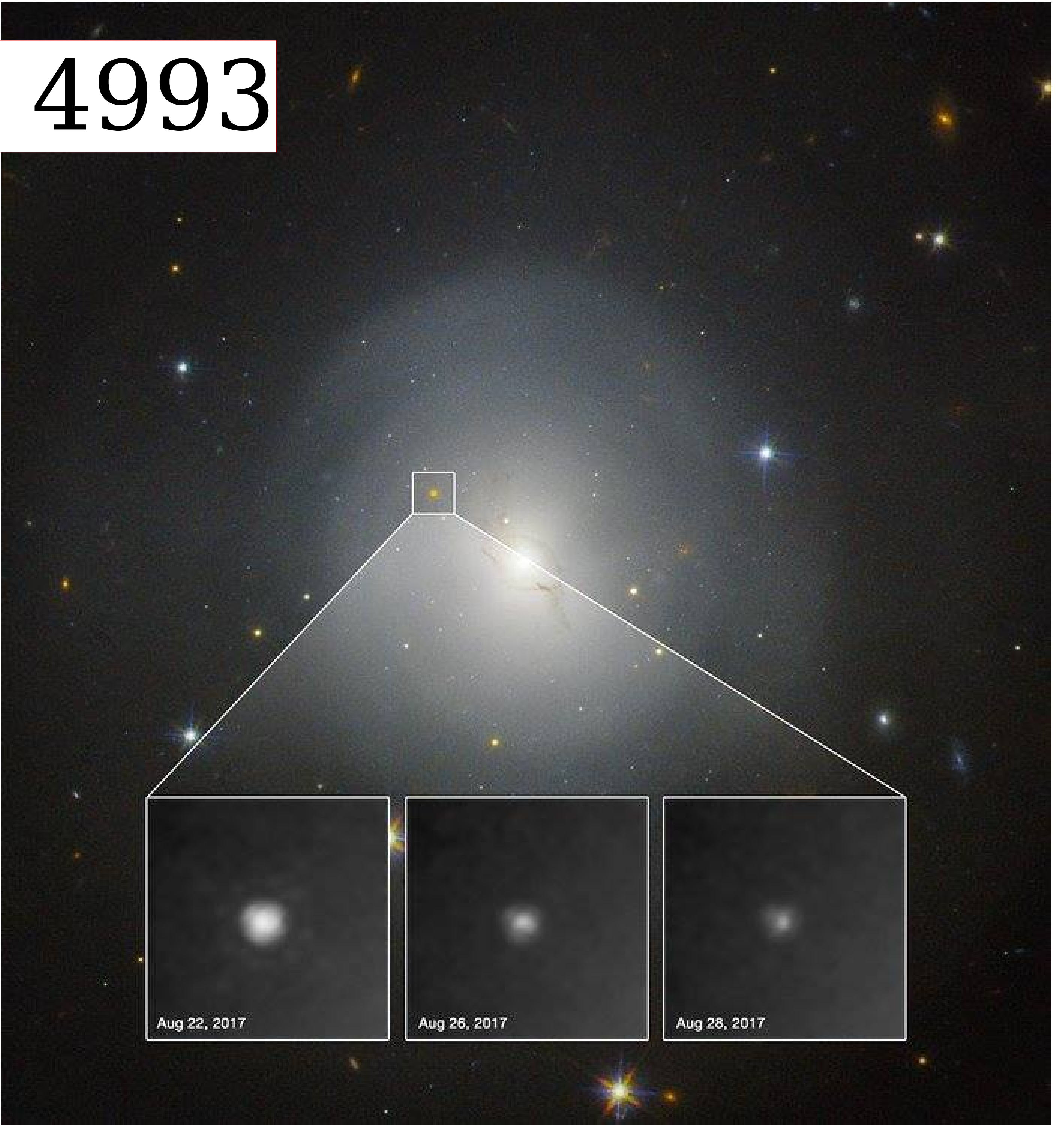
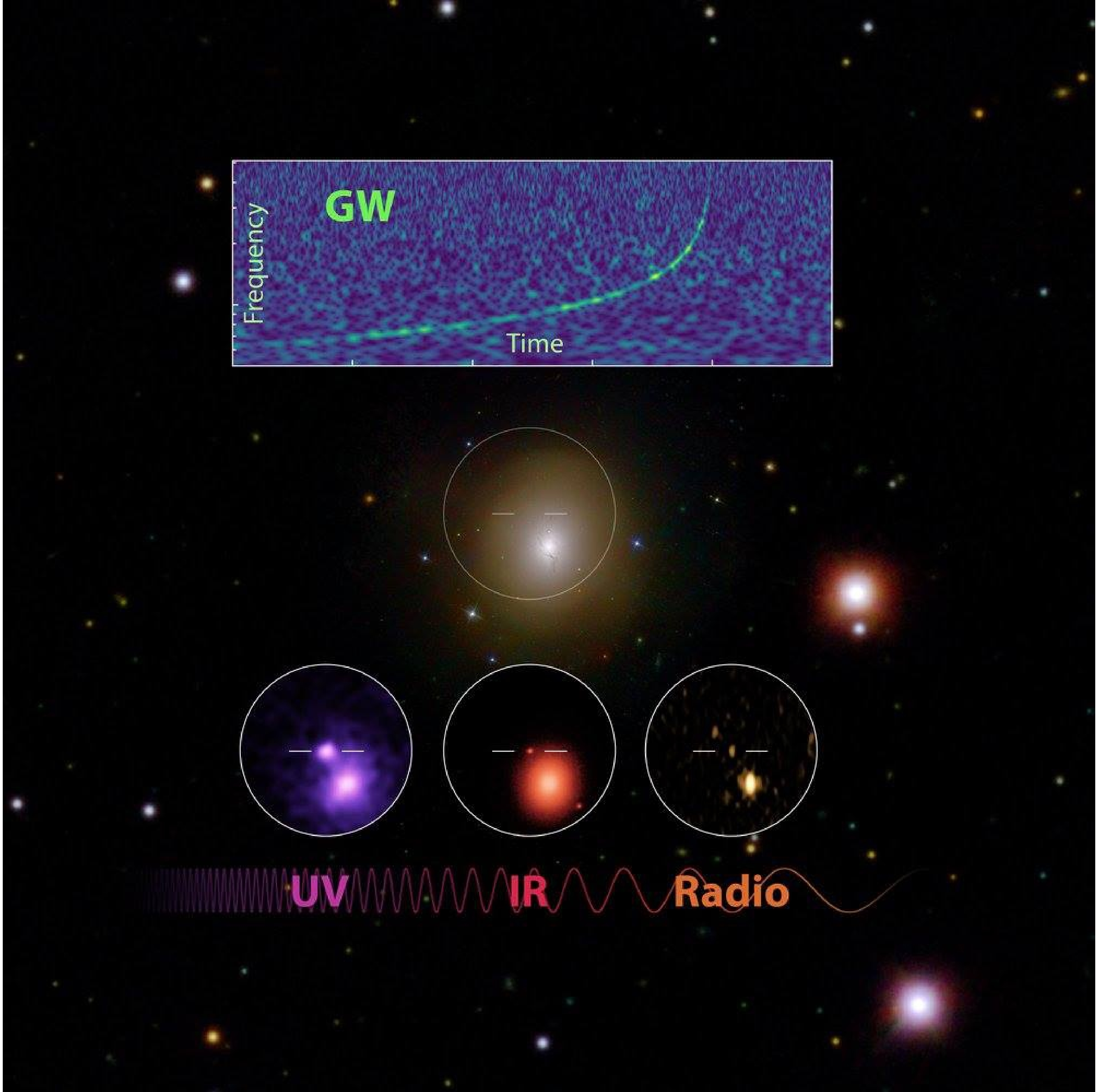


Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model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

NGC 4993




GW
Frequency
Time
UV
IR
Radio

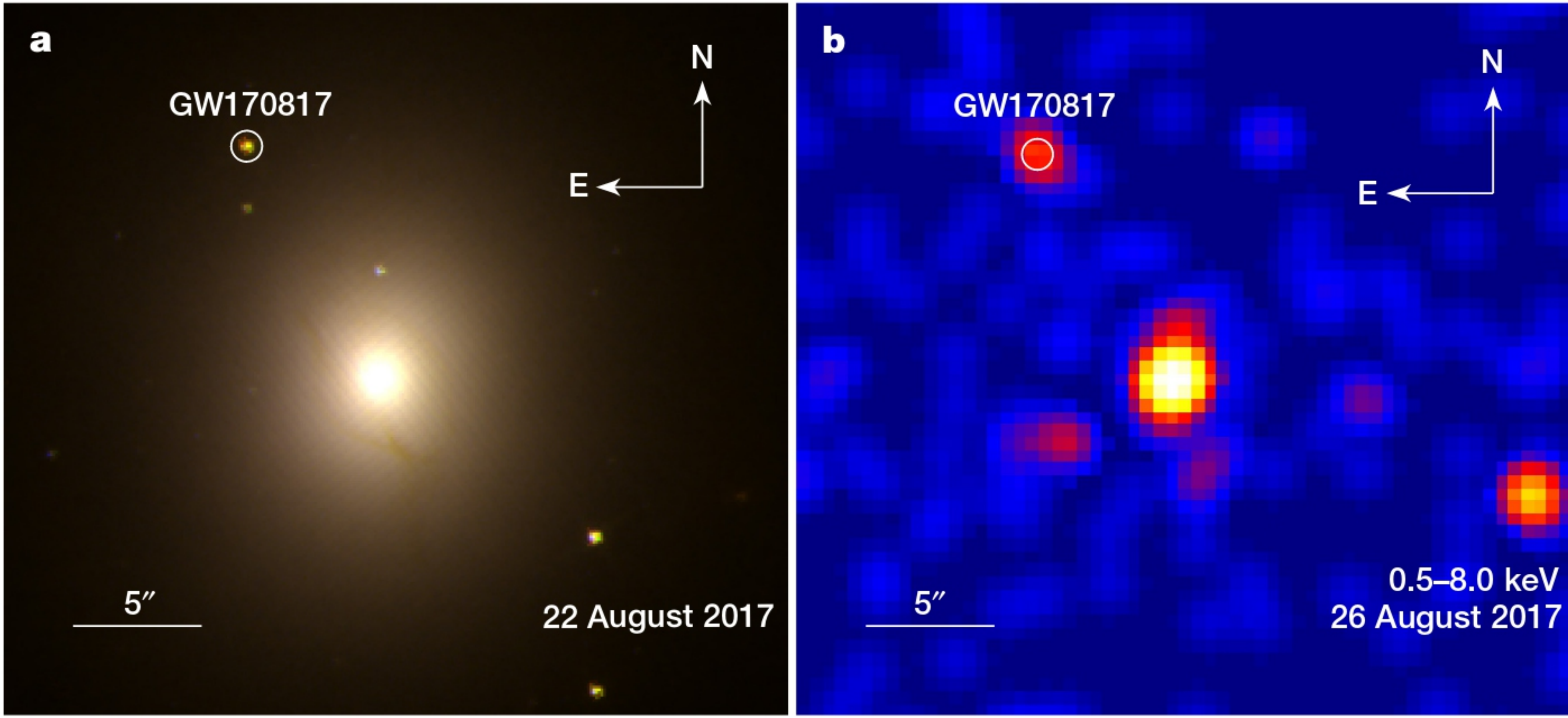
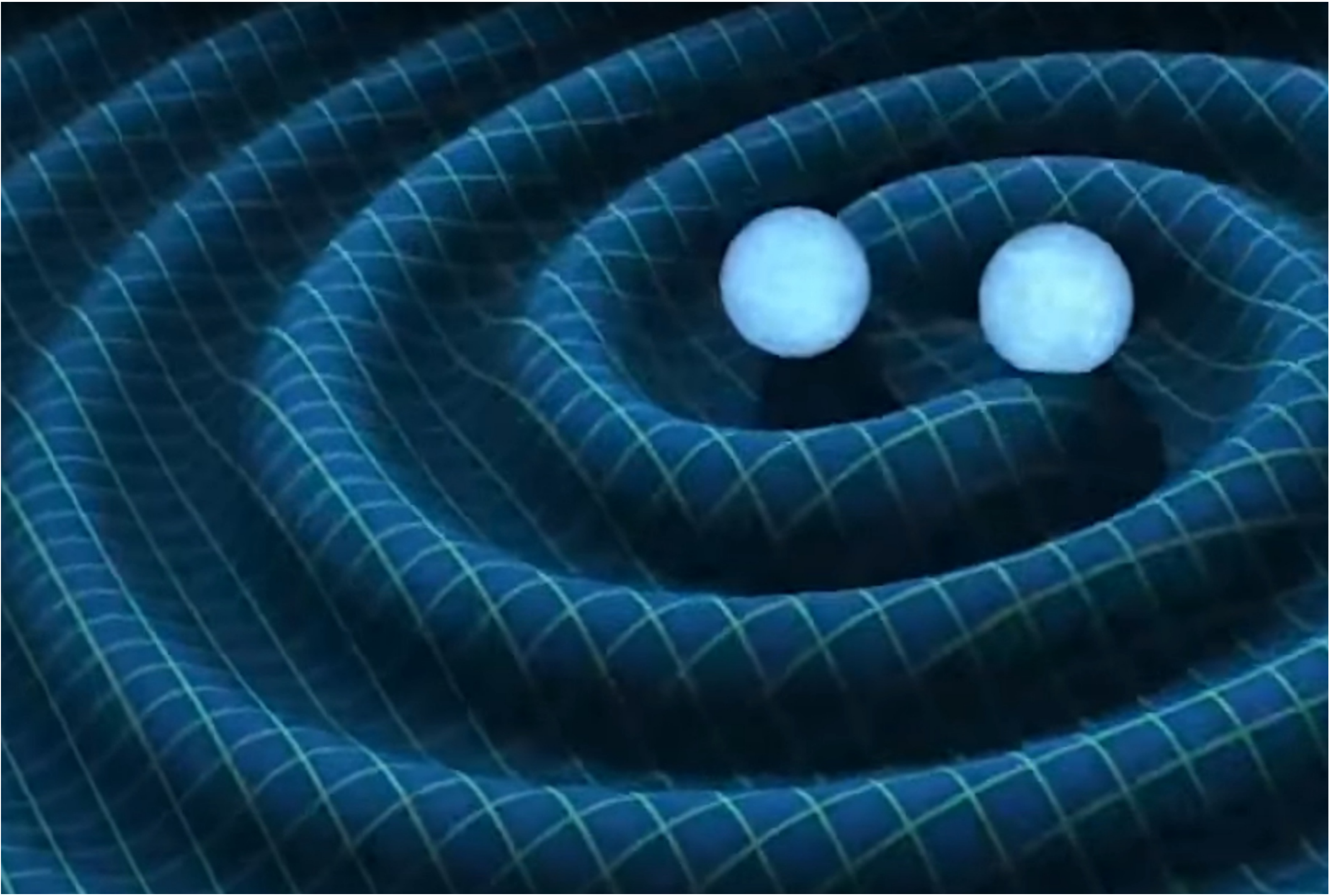
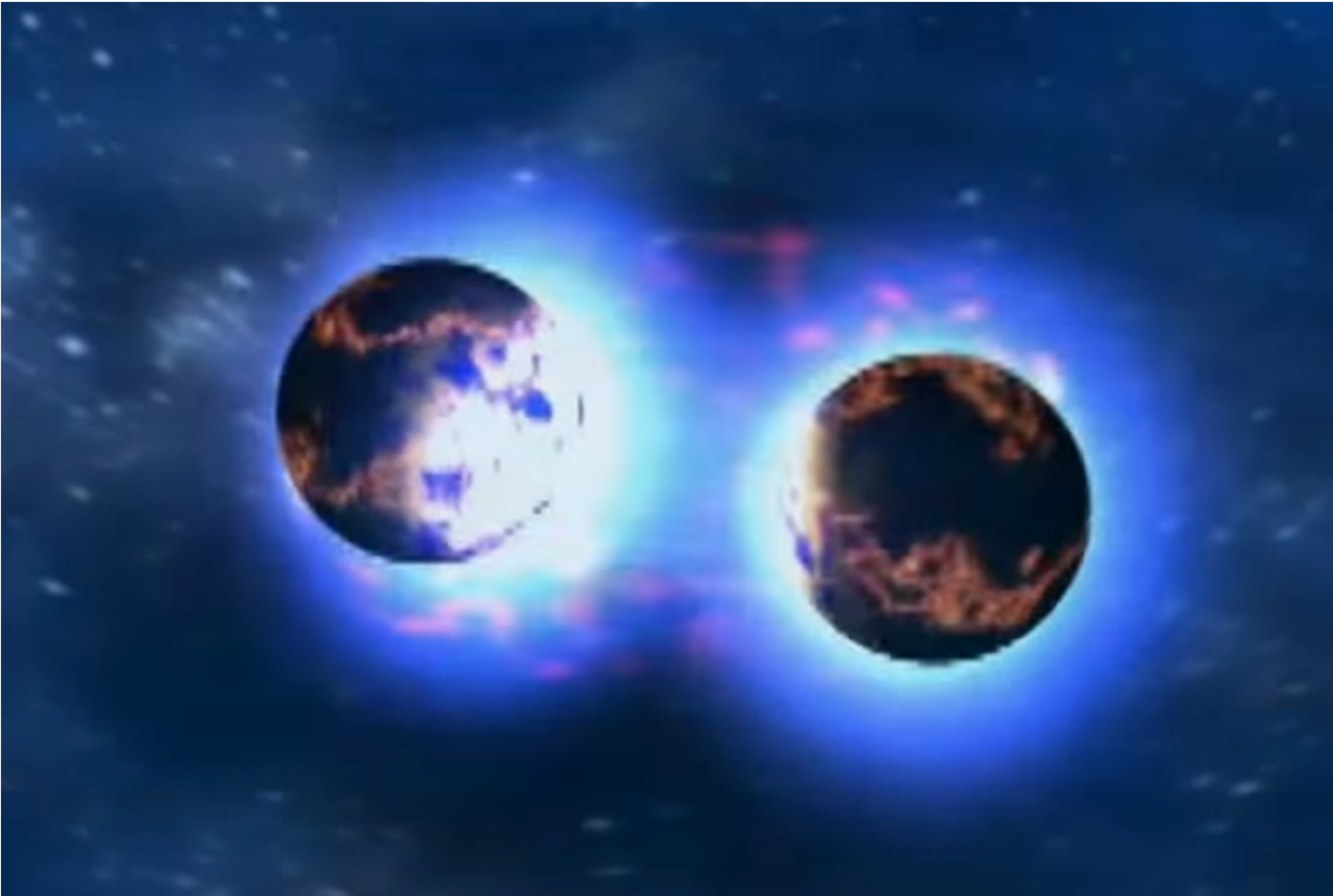
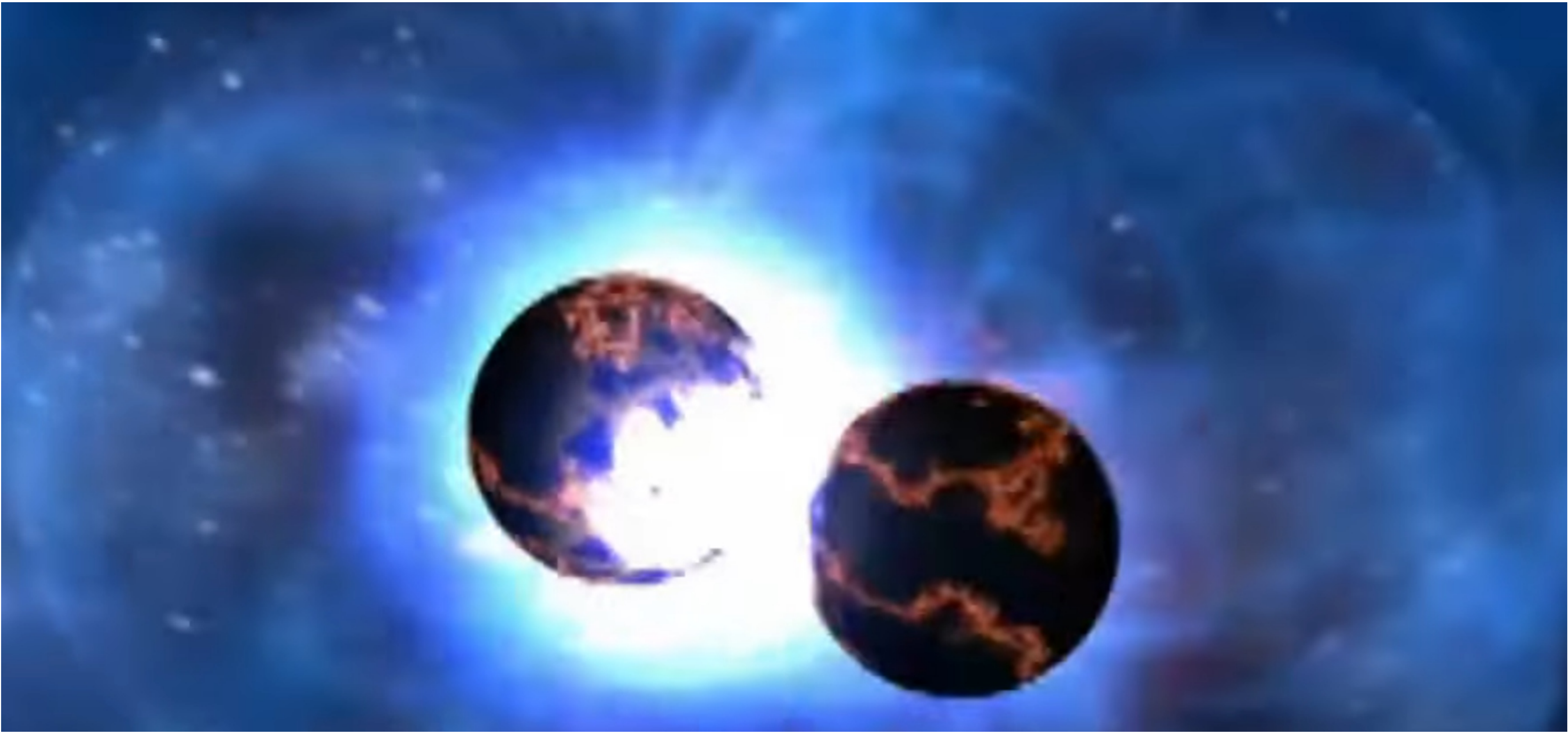
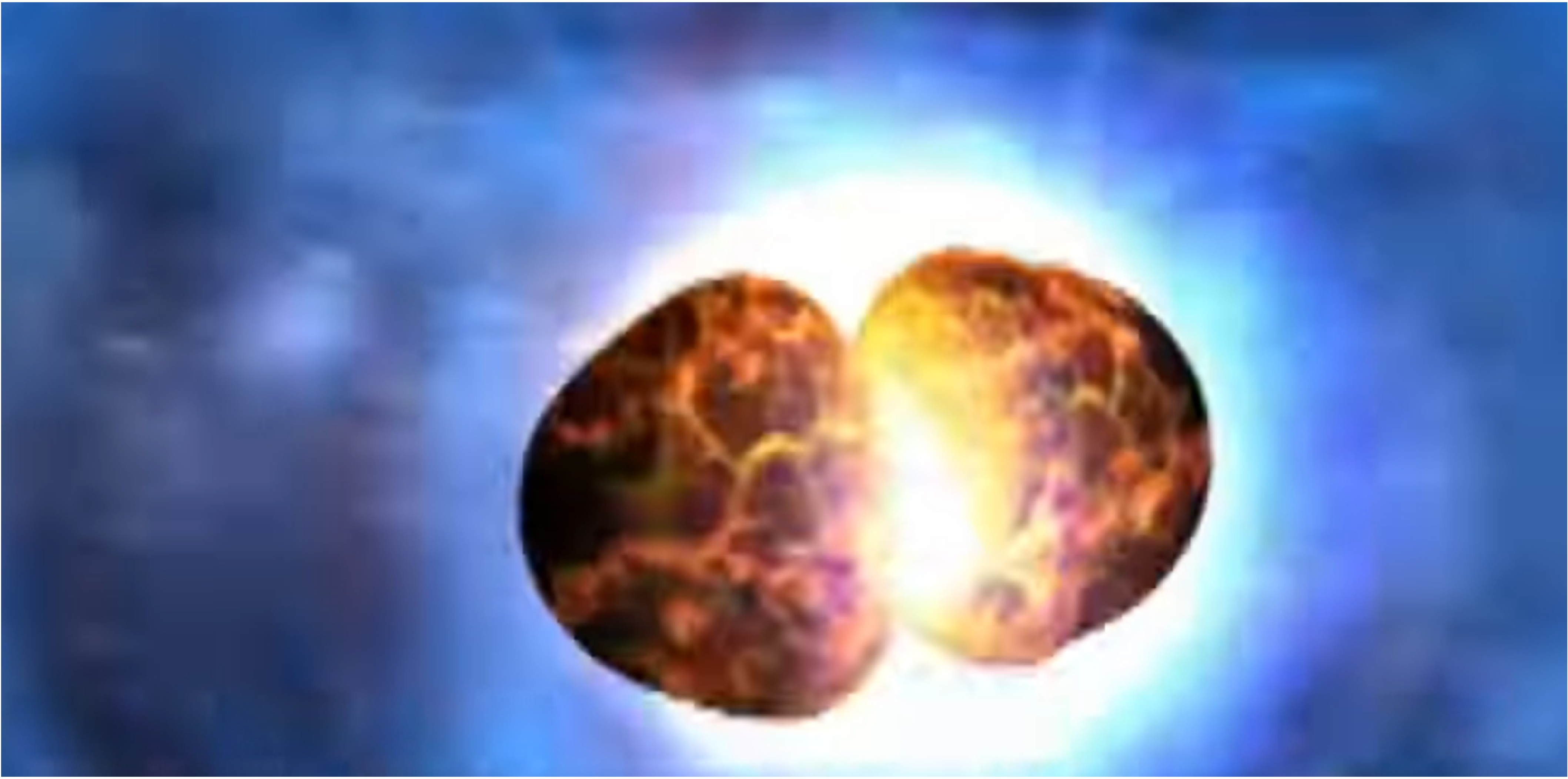


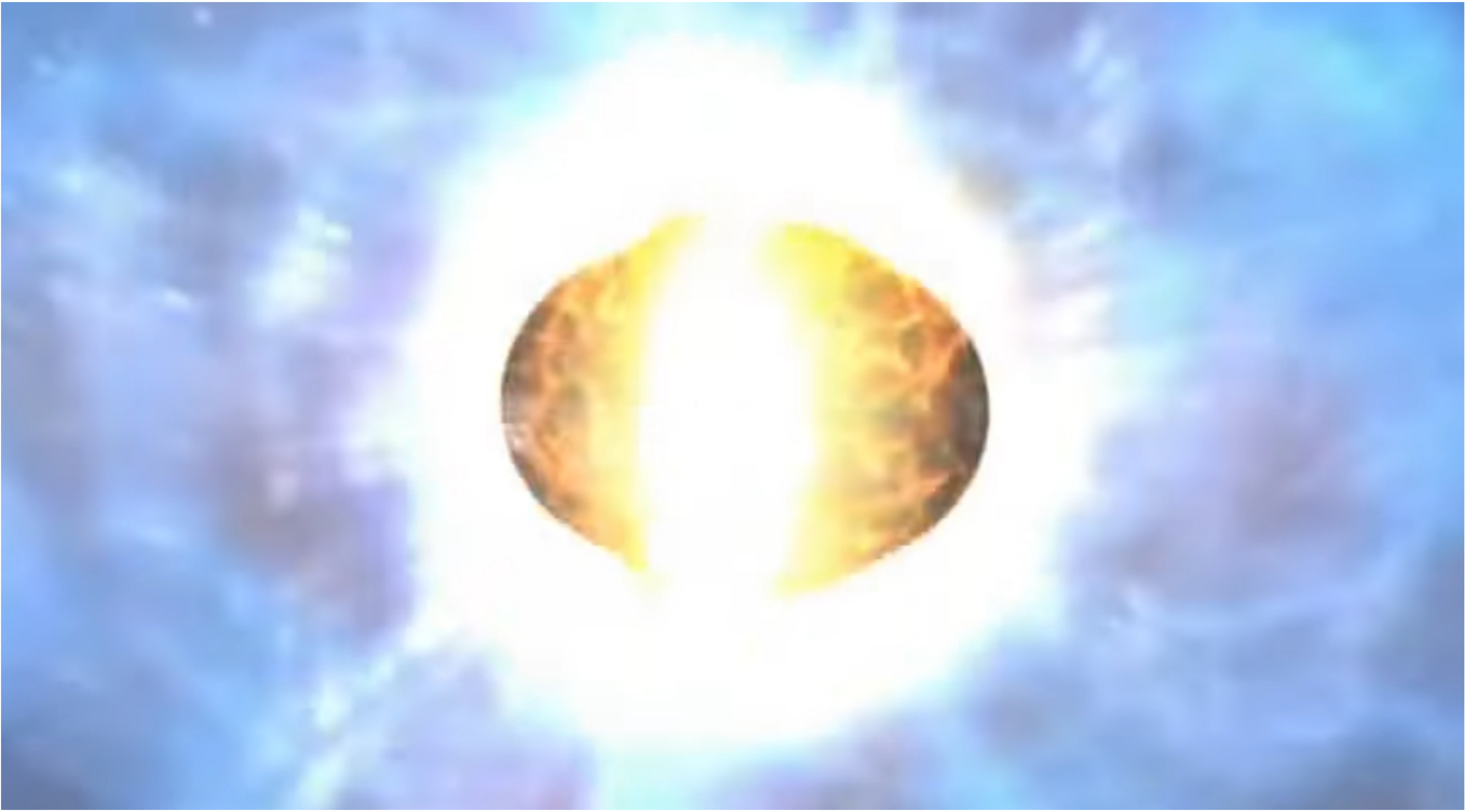
Figure 1 | Optical/infrared and X-ray images of the counterpart of GW170817. a, Hubble Space Telescope observations show a bright and red transient in the early-type galaxy NGC 4993, at a projected physical offset of about 2 kpc from its nucleus. A similar small offset is observed in less than a quarter of short GRBs[5]. Dust lanes are visible in the inner regions, suggestive of a past merger activity (see Methods). **b**, Chandra observations revealed a faint X-ray source at the position of the optical/infrared transient. X-ray emission from the galaxy nucleus is also visible.

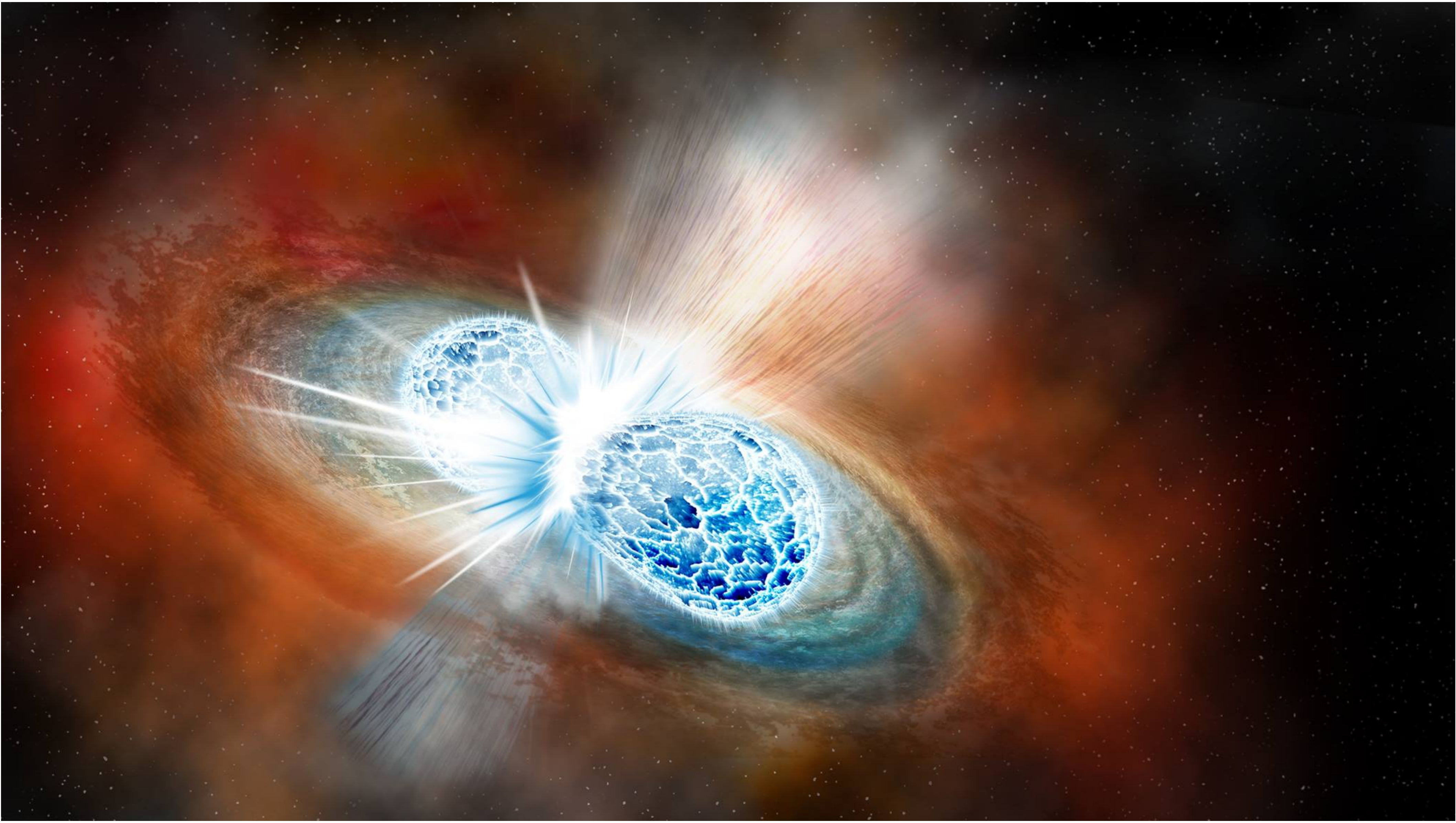


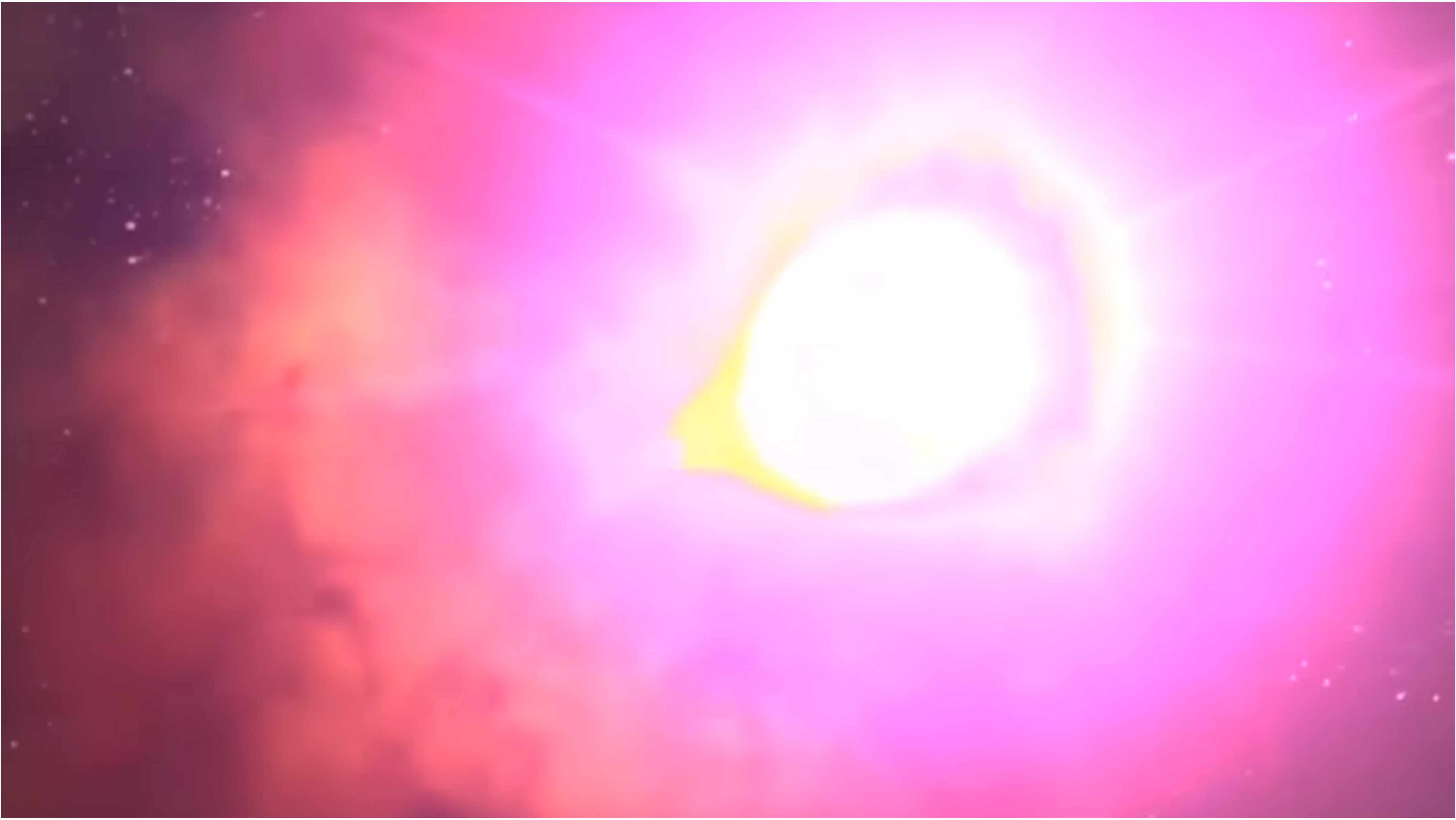


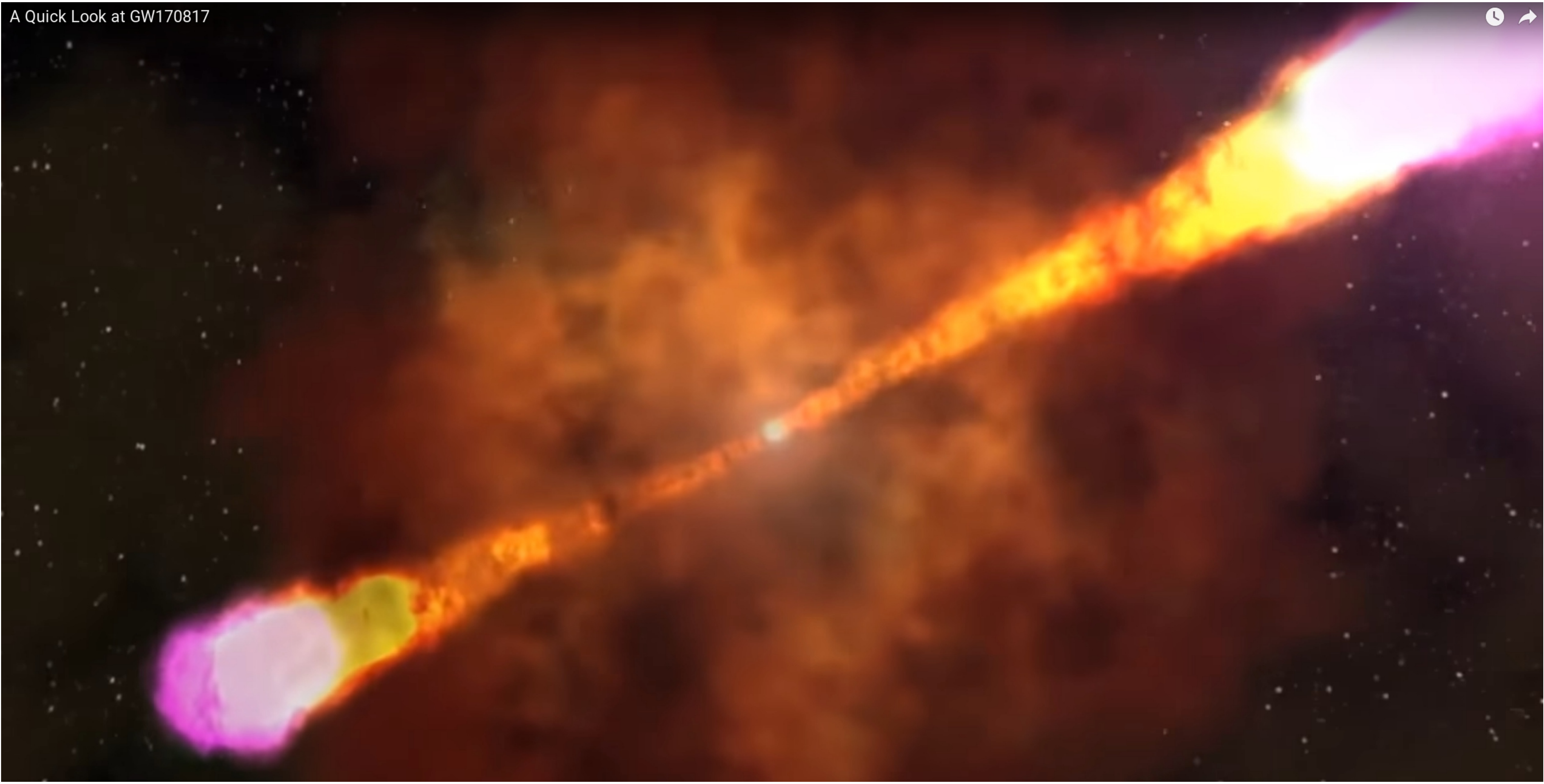


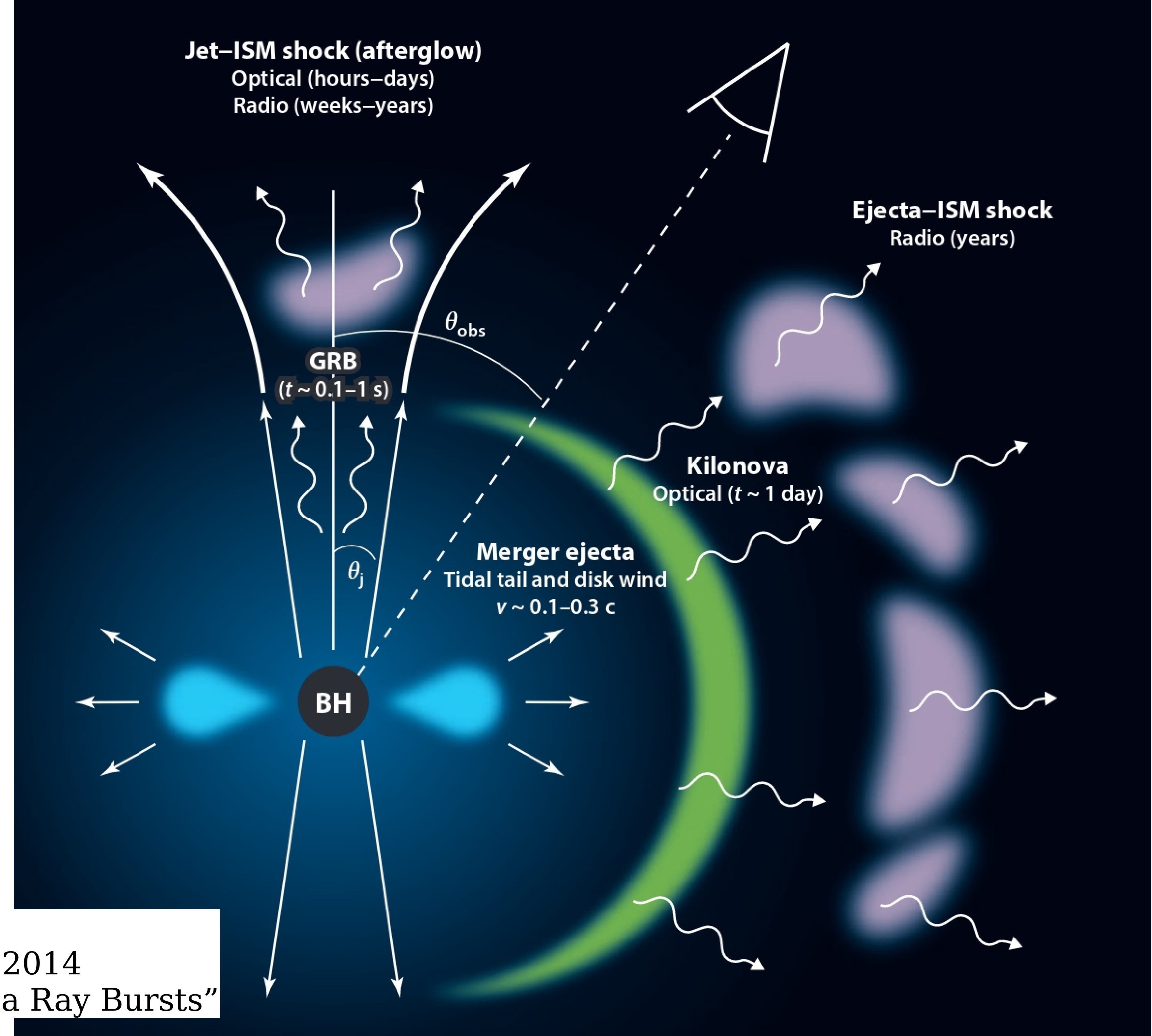




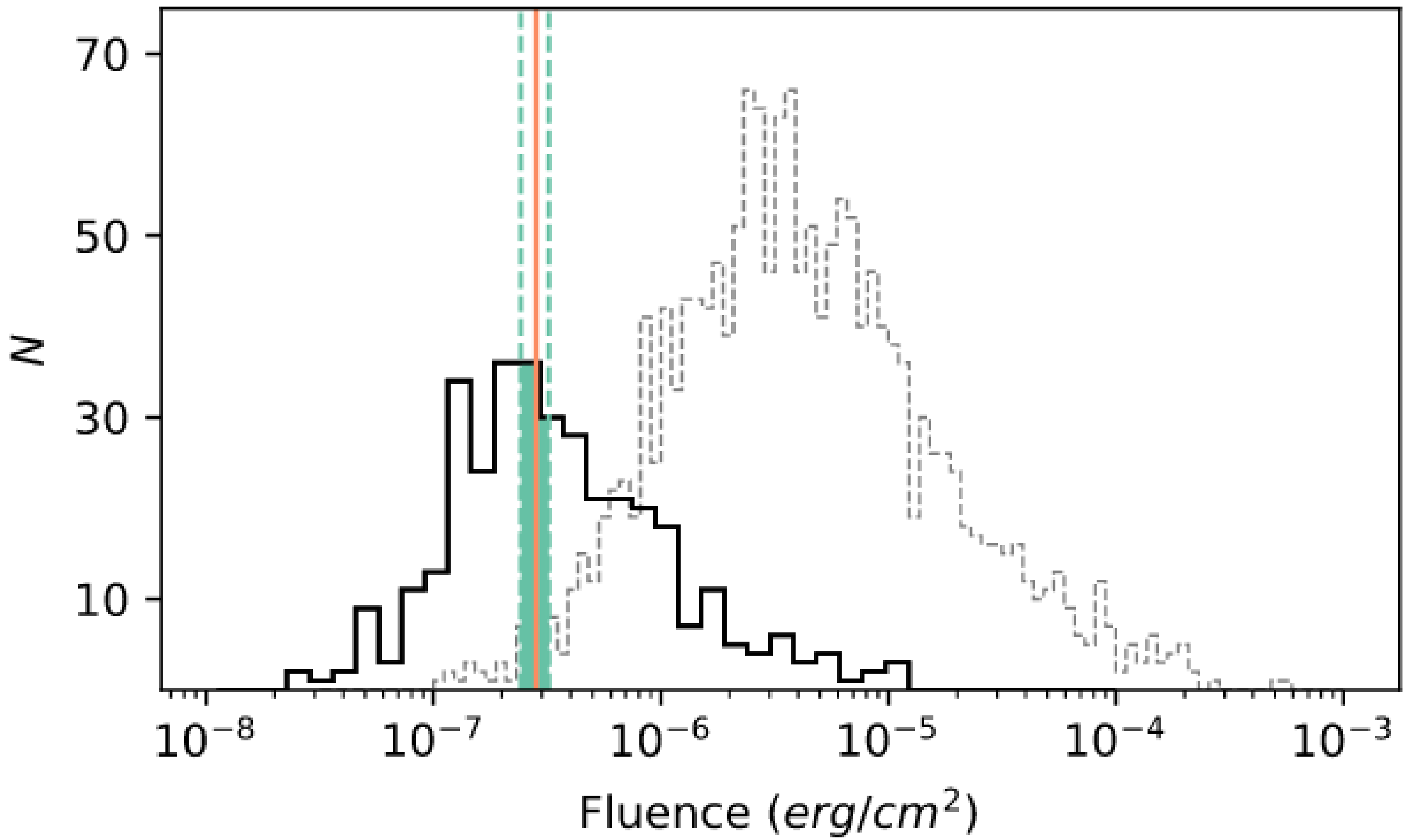





A Quick Look at GW170817



Edo Berger
Ann. Rev AA 2014
“Short Gamma Ray Bursts”



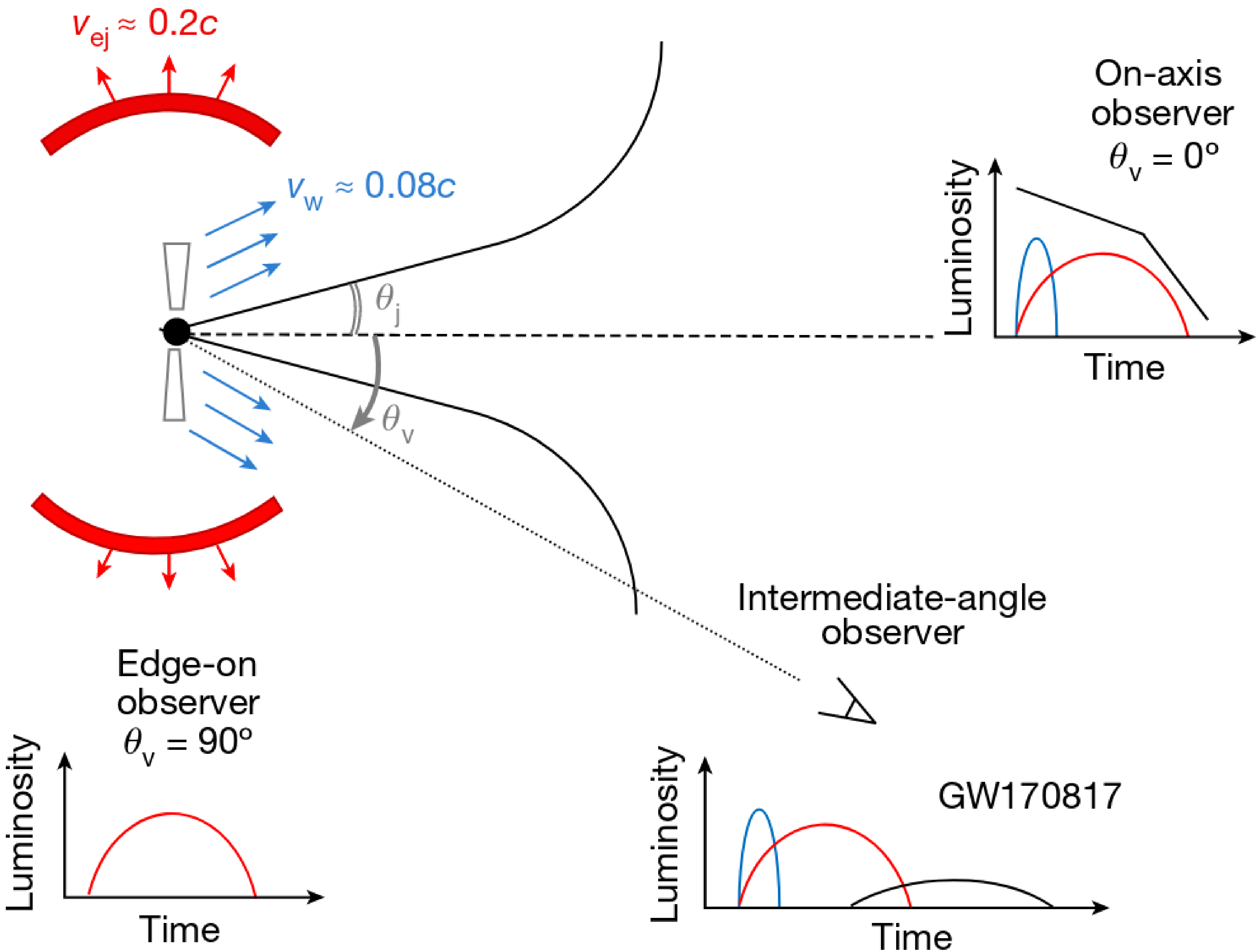
$$\text{Fluence} \simeq 3 \times 10^{-7}\ \text{erg/cm}^2$$

$$E_{\text{iso}} = (4\,\pi\,d^2)\ \text{Fluence} \simeq 3 \times 10^{46}\ \text{erg}$$

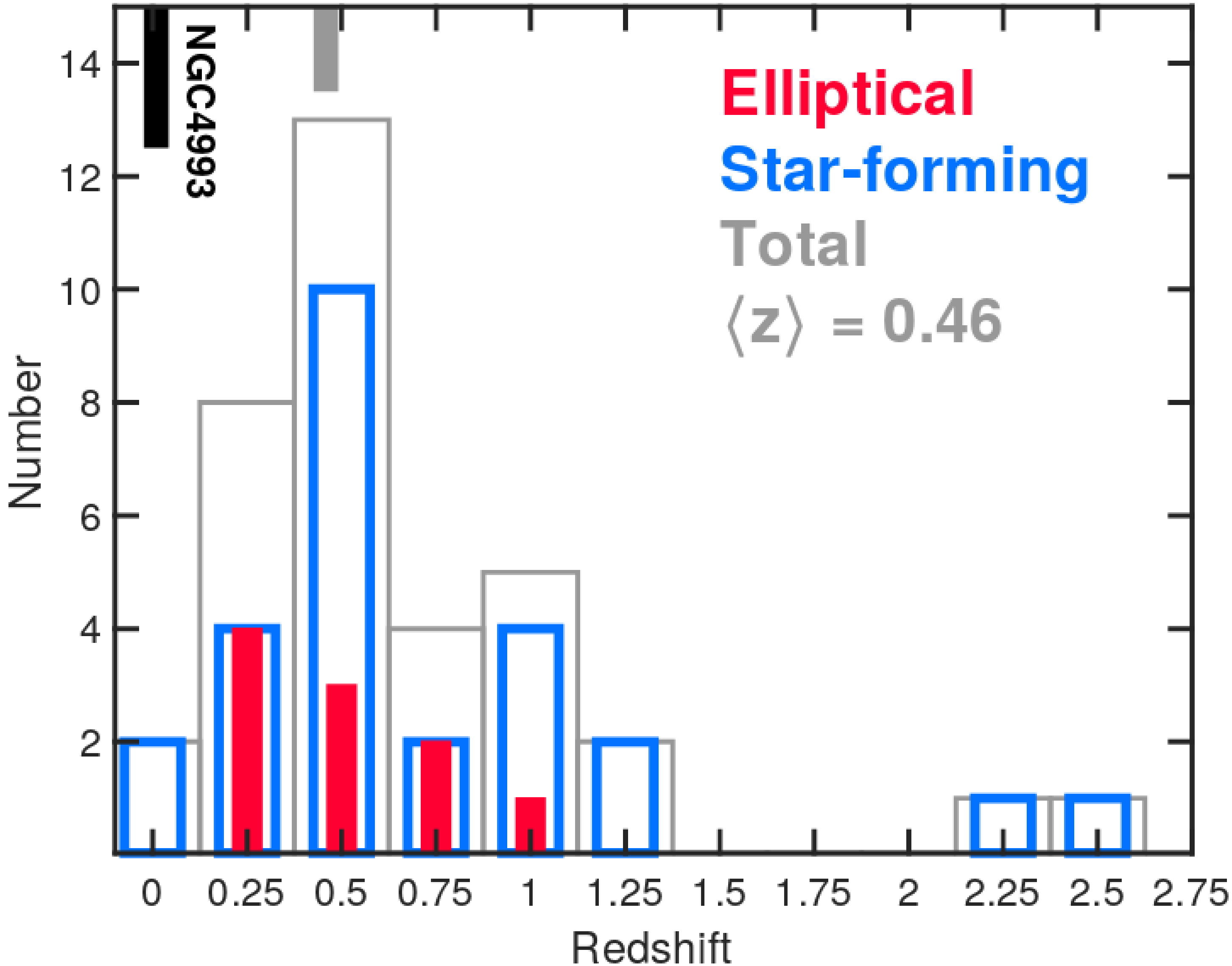
very “faint” Short GRB

$$d = 42.9 \pm 3.2\ \text{Mpc}$$

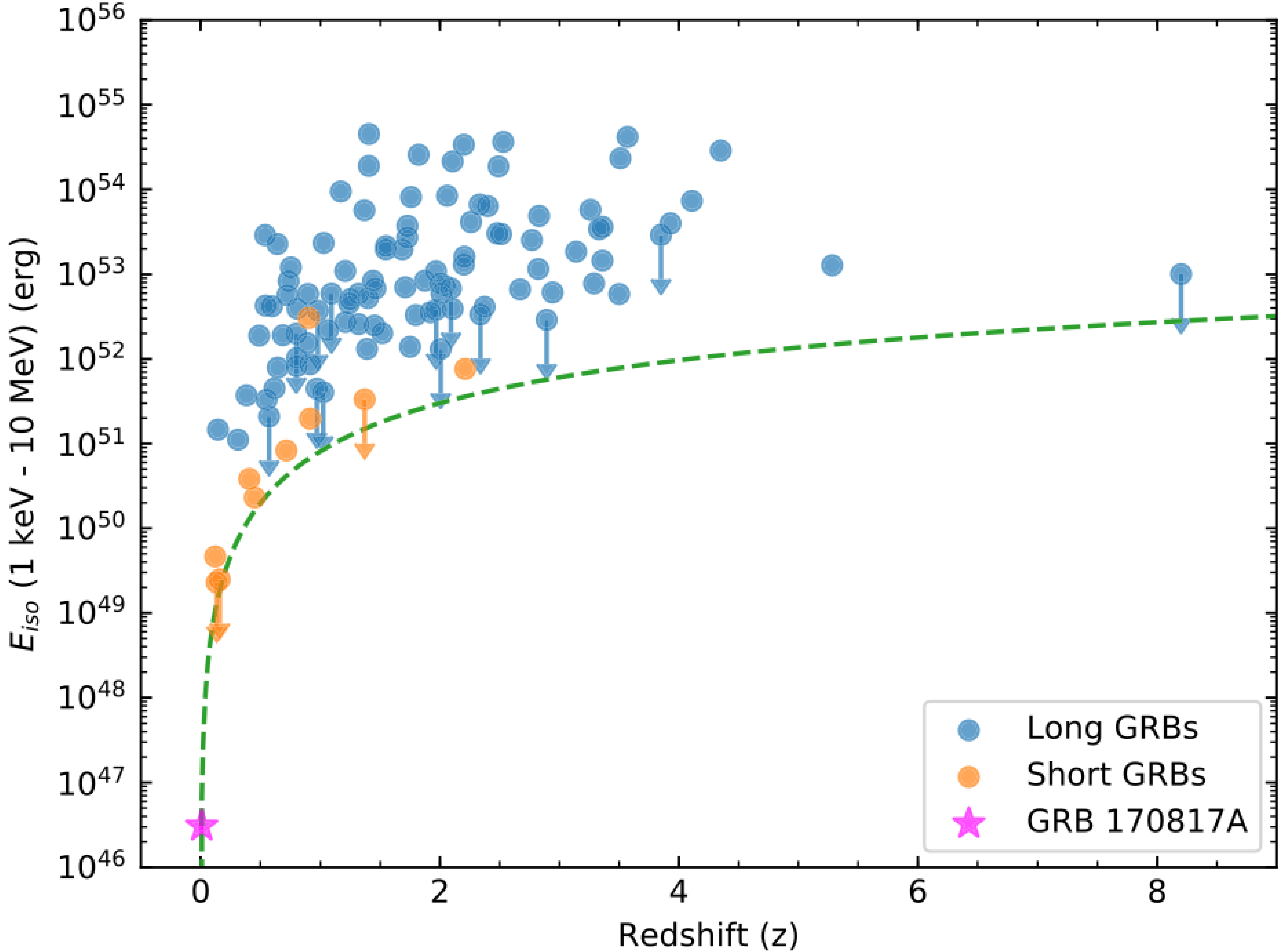
$$d_{\text{GW}} = 40^{+8}_{-14}\ \text{Mpc}$$



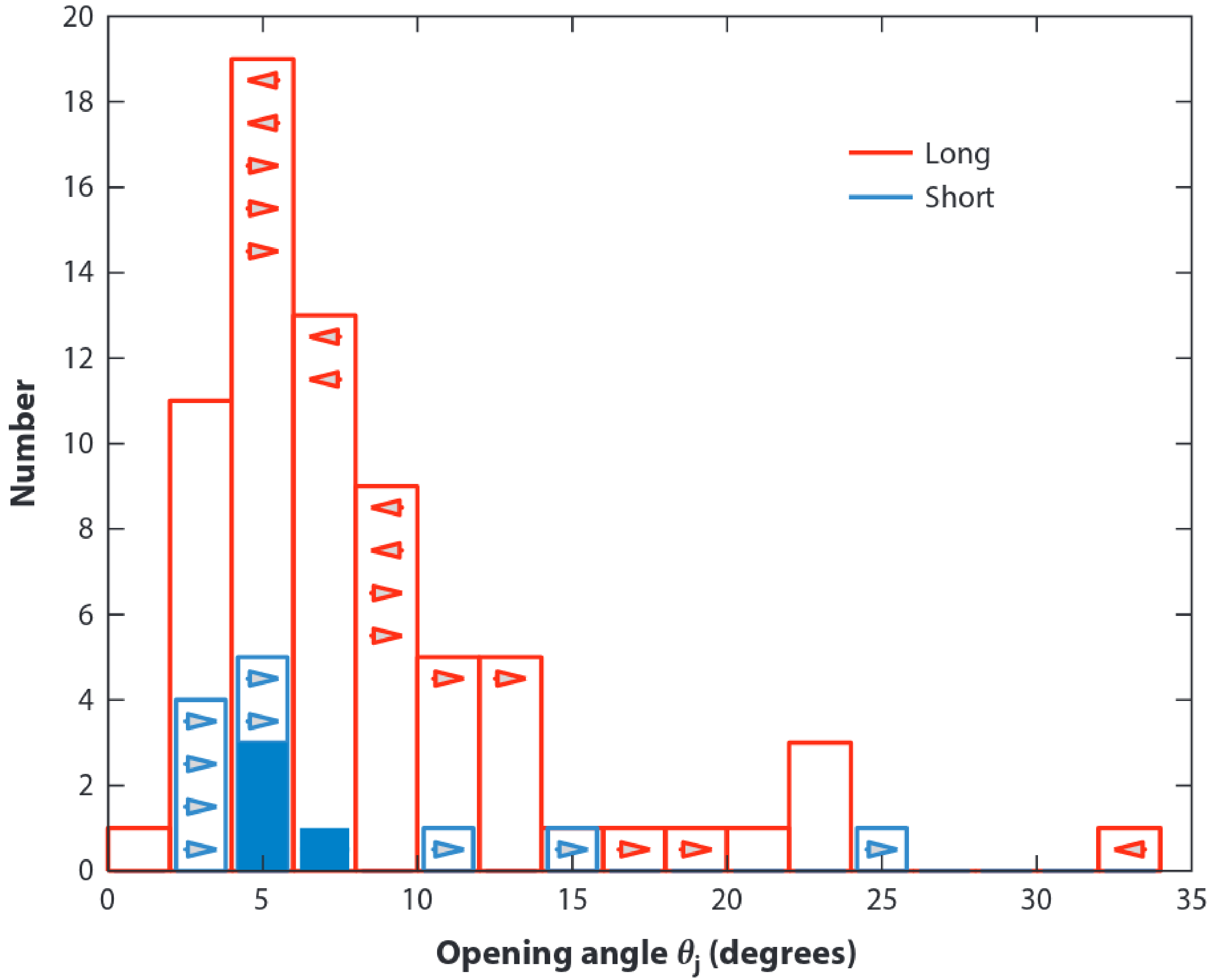
$v_{ej} \approx 0.2c$
$v_w \approx 0.08c$
θ_j
θ_v
On-axis observer
$\theta_v = 0°$
Luminosity
Time
Intermediate-angle observer
GW170817
Luminosity
Time
Edge-on observer
$\theta_v = 90°$
Luminosity
Time

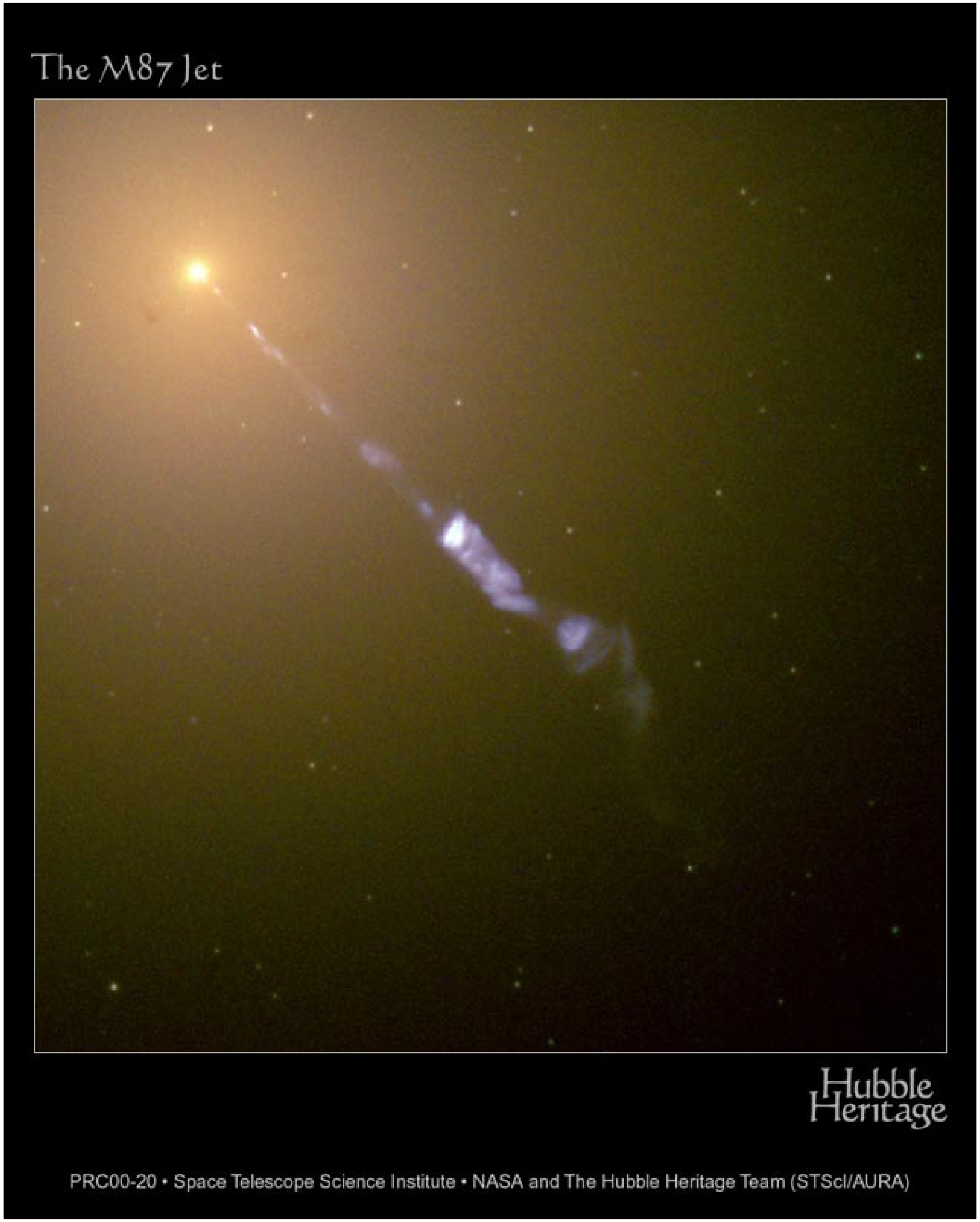


NGC4993
Elliptical
Star-forming
Total
⟨z⟩ = 0.46
Number
Redshift
0
2
4
6
8
10
12
14
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75


E_{iso} (1 keV - 10 MeV) (erg)
10^{56}
10^{55}
10^{54}
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
0
2
4
6
8
Redshift (z)
Long GRBs
Short GRBs
GRB 170817A

Estimate of the angular size of the Short GRB Jet





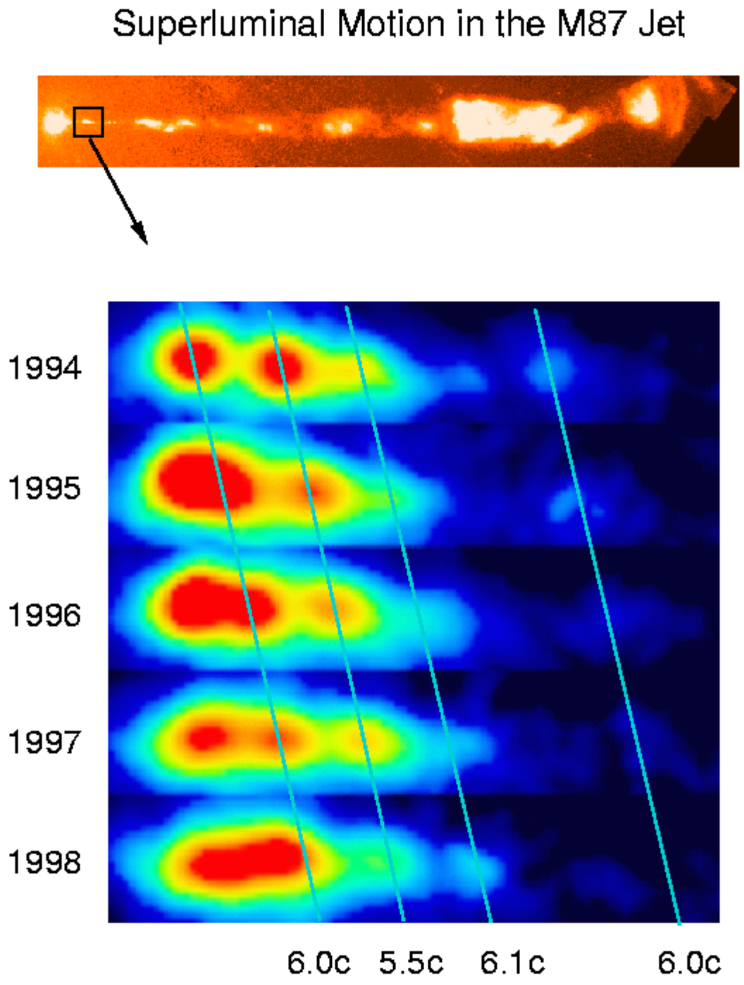
M87 JET

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."

Superluminal Motions



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

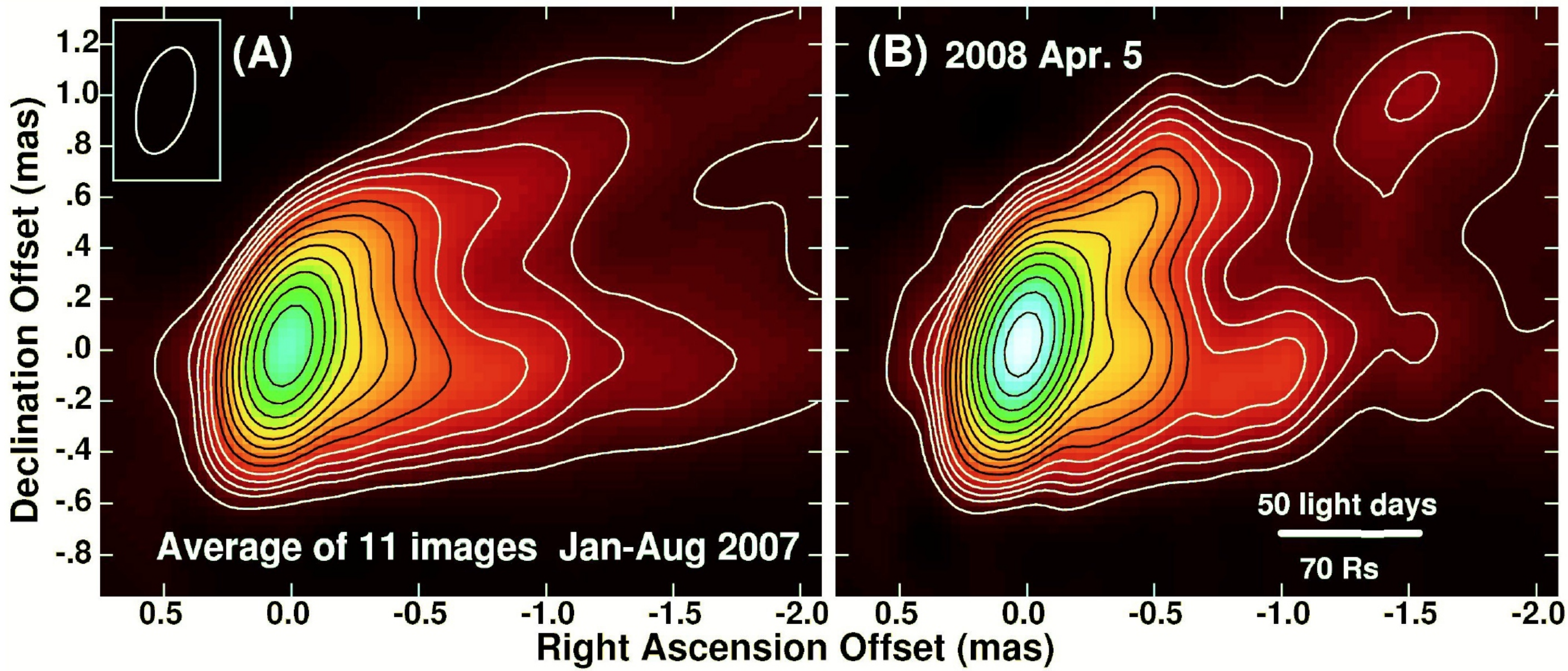
Source moving
on the celestial sphere

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

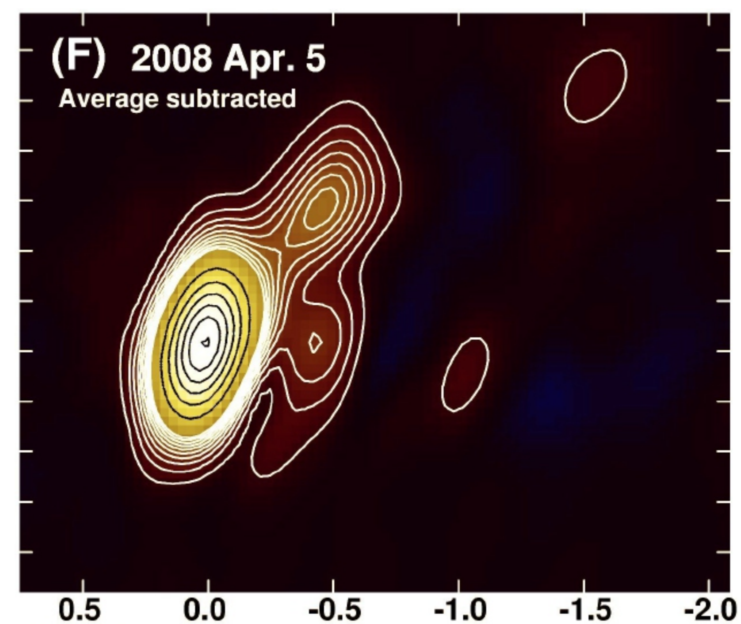
$$\beta_{\perp,{\rm app}} = \frac{\beta\ \sin\theta}{(1-\beta\cos\theta)}$$

$$\Gamma \geq \sqrt{\beta_{\rm app}^2 + 1}$$

$$\theta \approx \Gamma^{-1}$$



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

Observations of M87

2005
2008
2010

HESS
MAGIC
VERITAS

$E \geq 350$ GeV

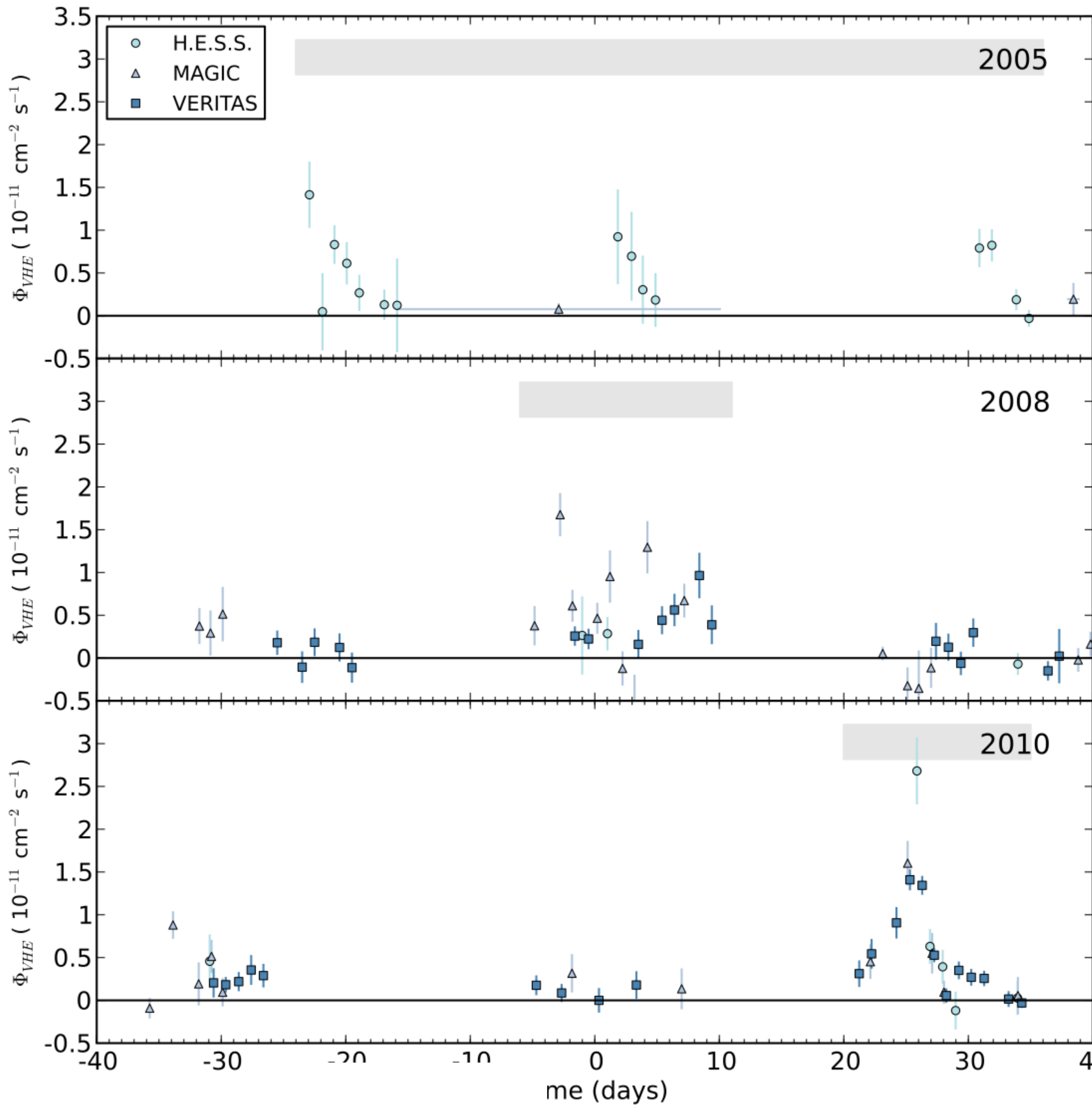


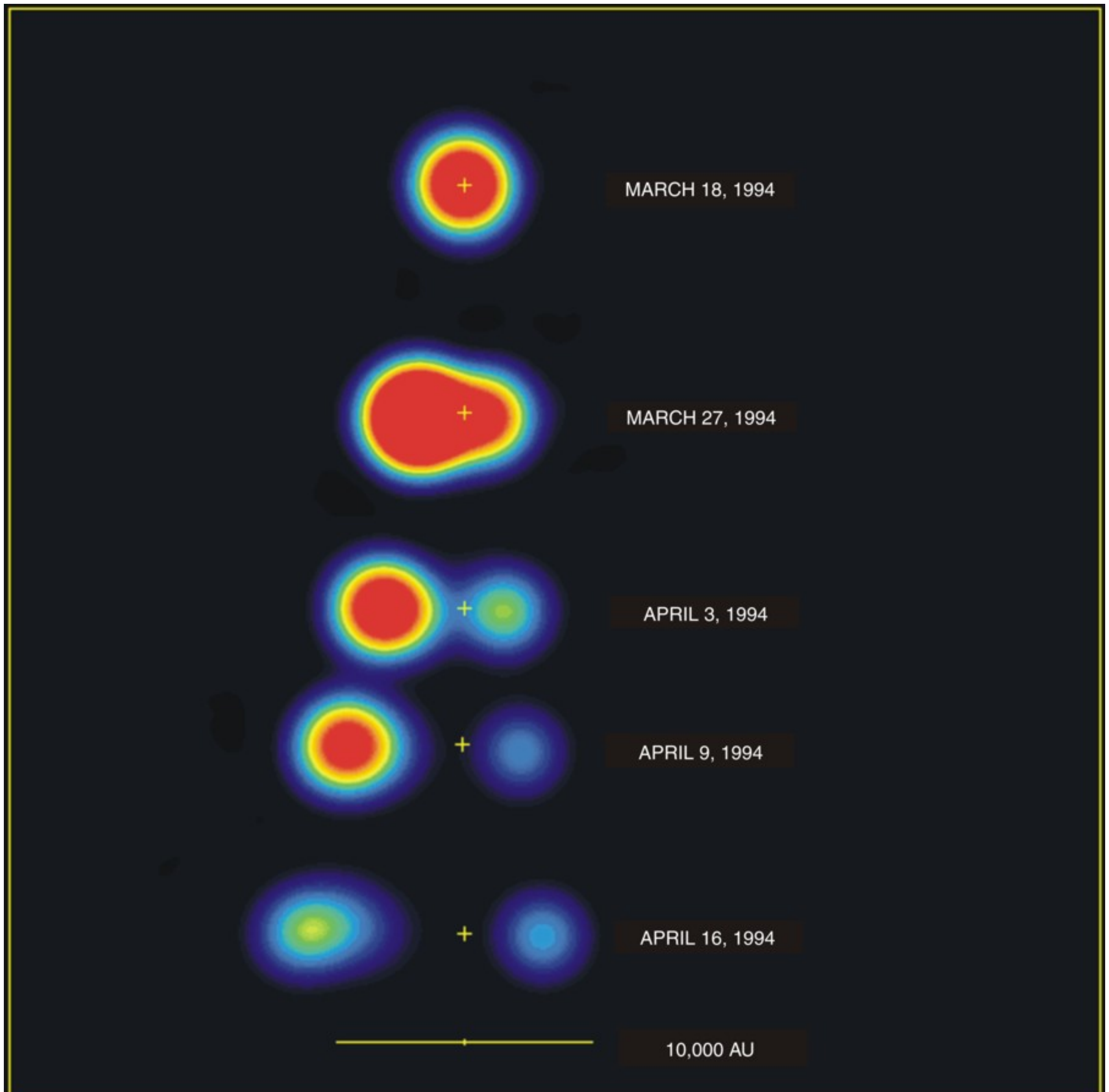
Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500,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

GRS1915+105

Superluminal Motions

in microQuasars

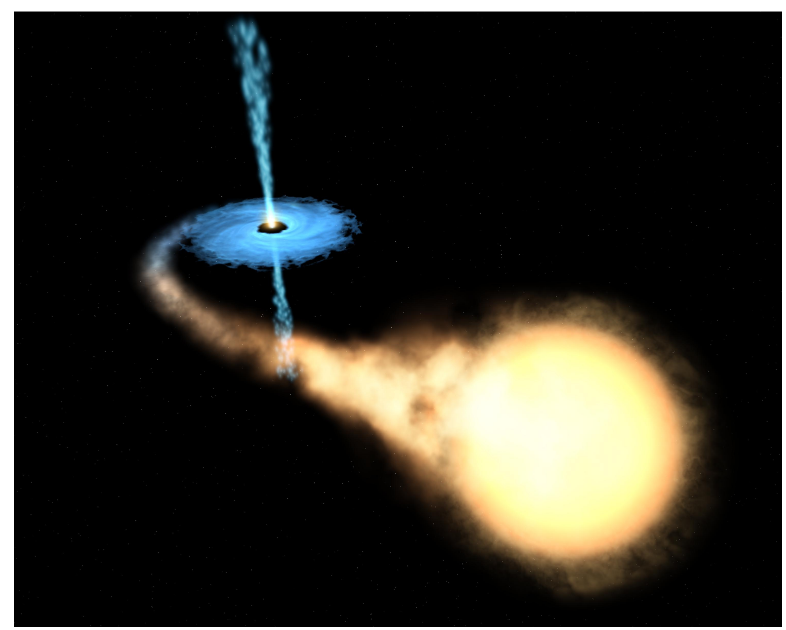
in our Galaxy

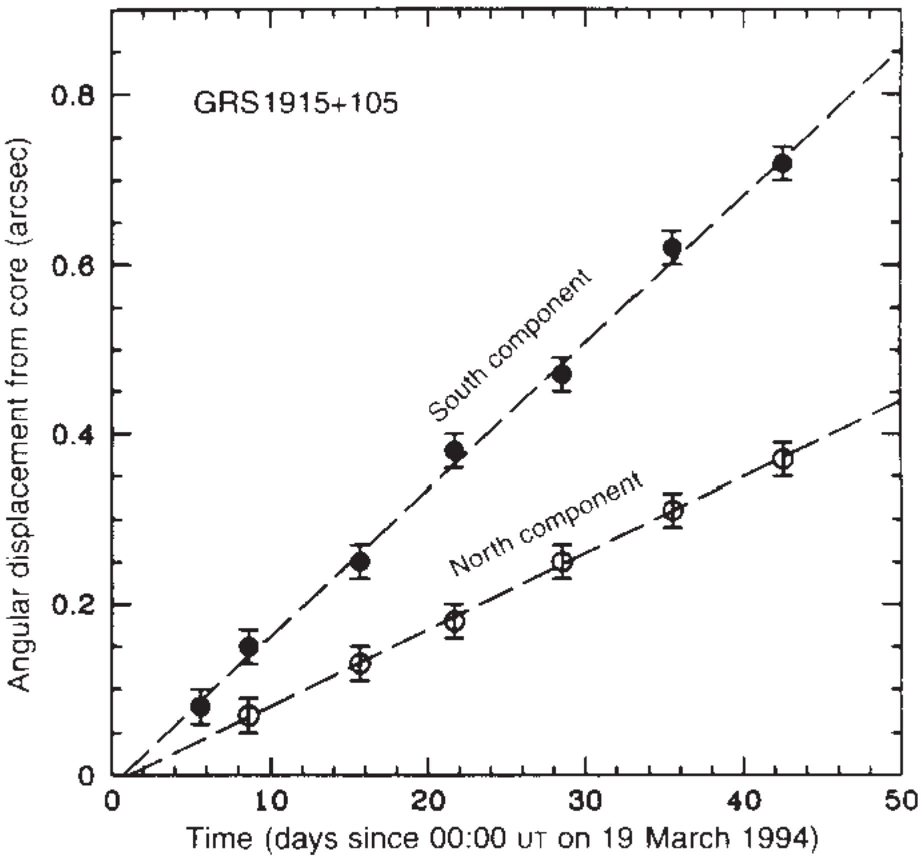


Observations in radio

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

"Two pairs of bright radio condensations"





Angular velocities

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

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

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

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

$$\beta = 0.92 \pm 0.08$$

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

Generation of Relativistic Jets
in several astrophysical sources
associated to Back Holes

Active Galactic Nuclei
Microquasars

Understanding of the mechanisms
that generate the relativistic outflow

Compelling Motivations for "Physics Beyond the Standard Model"

Evidence for Dark Matter
(not a field of the Standard Model)
[Explicit "classic" experimental discrepancy]

Quantization of Gravity

Dark Energy

Inflaton field

Matter/anti-Matter asymmetry

....

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We have “Deep Problems” we want to address
but need new observations, new laboratories to explore
the open questions on the “Boundaries of Science”.

The laboratories to “explore the boundaries”
could be **future accelerators**.

but also [in many cases only] in

Astrophysical objects/environments

and in
Cosmology studies

The study of the “High Energy Universe”
with the four “Messengers” is a very dynamical field
rich in new discoveries and surprises
with an *extraordinary potential.*

It provides “laboratories” to test
our fundamental laws.

It allows tests of what happens close
to the horizons of Black Holes

*It is vital to continue the development
of these studies with more energies and resources*