Status and open problems in Ultra High Energy Cosmic Rays and High Energy Astrophysics

Paolo Lipari
INFN Roma Sapienza

Ultra High Energy Cosmic Rays 2018

Paris, october 12th 2018

[Alan Watson 8/oct/2018]

Val L. Fitch,
"Elementary particle physics: the origins,"
Rev. Mod. Phys. **71**, S25 (1999).

"Those who became interested in cosmic rays tended to be rugged individualist, to be iconoclastic and to march to the drummer in their own heads rather than some distant one"

…. continuation of the text :

After all, this was the period when nuclear physics was coming into its own, it was the fashionable subject, it was the subject that had the attention of the theorists, it was the subject for which great accelerators were being built.

The cosmic-ray explorers eschewed all that and found their satisfactions in what might be called
the backwater of the time.

Cecil Powell [1953, meeting Bagnères–de–Bigorre]

"Gentlemen, we have been invaded...
the accelerators are here"

The present :
still plenty of interesting personalities .....

but no *"Backwater of Physics"*

Cosmic Ray Science has merged in
the broader field of

Multi-messenger
High energy Astrophysics

A vibrant field of fundamental interest

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

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

"High Energy Universe"

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

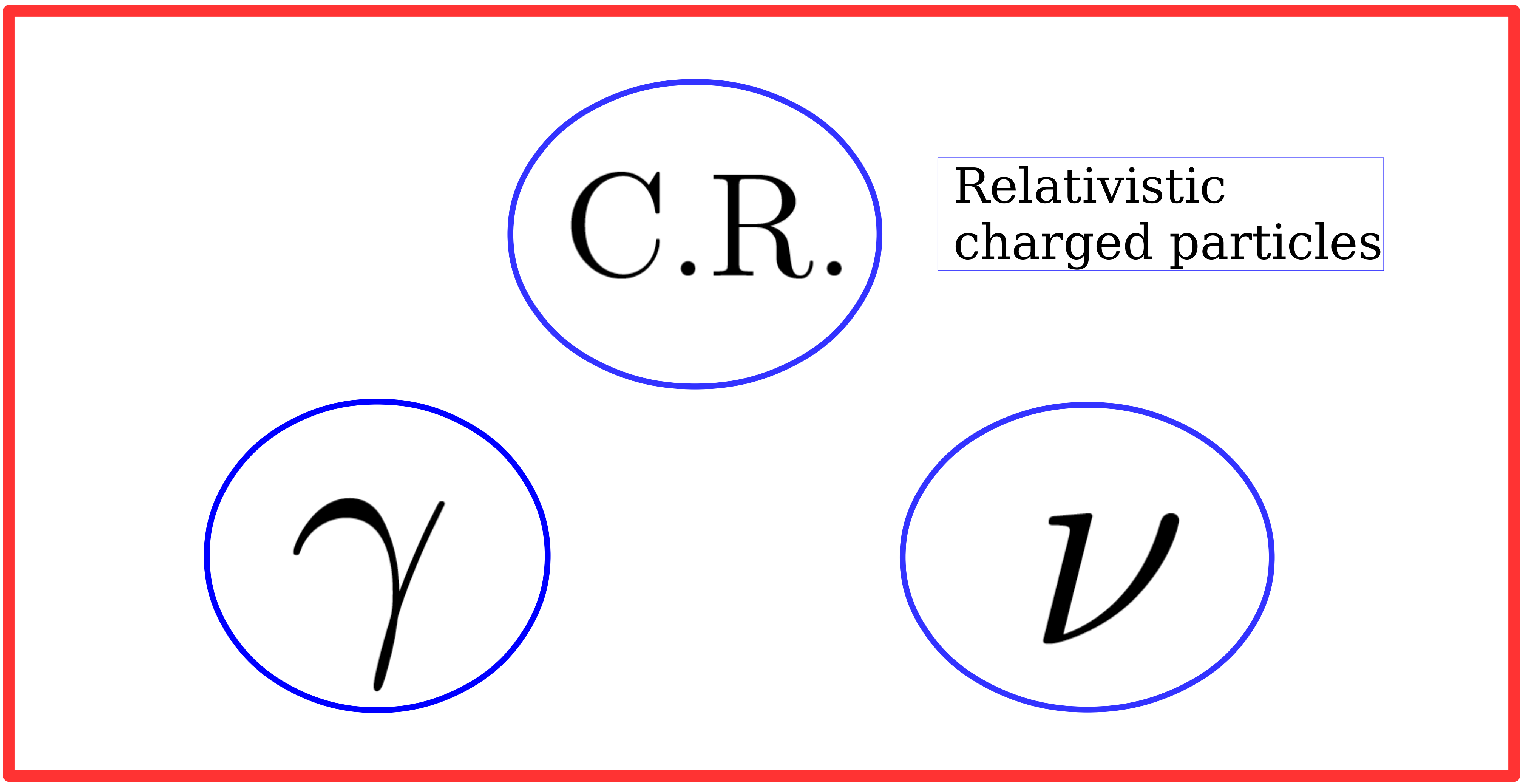
This field is one of the most significant and fascinating "Frontiers" in Science today.

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

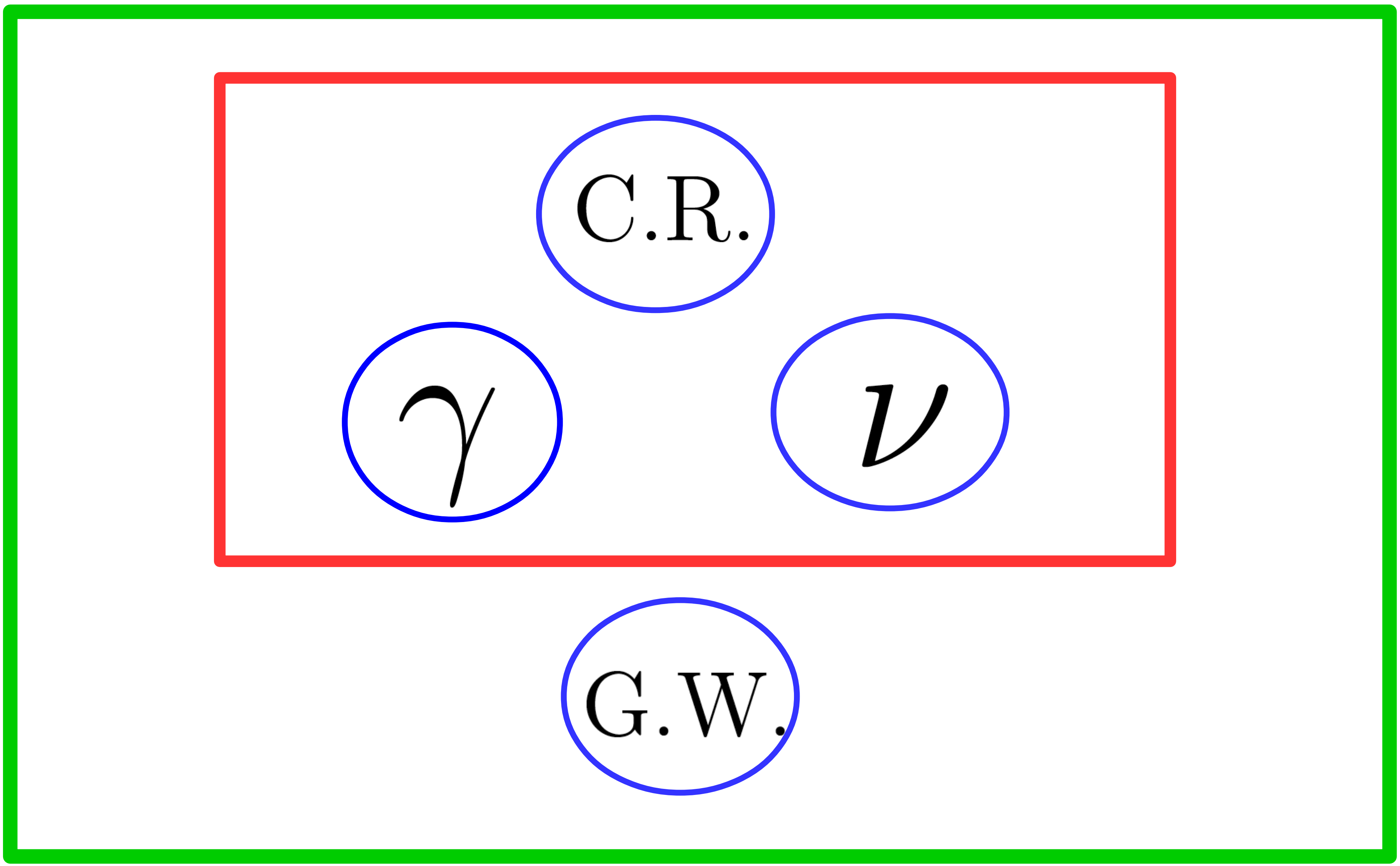
2. The sources of the High Energy radiation can be the "laboratories" where we test *(in conditions that are not achievable in "Earth based laboratories")* our Fundamental Laws of Physics.

Three messengers are “inextricably” tied together

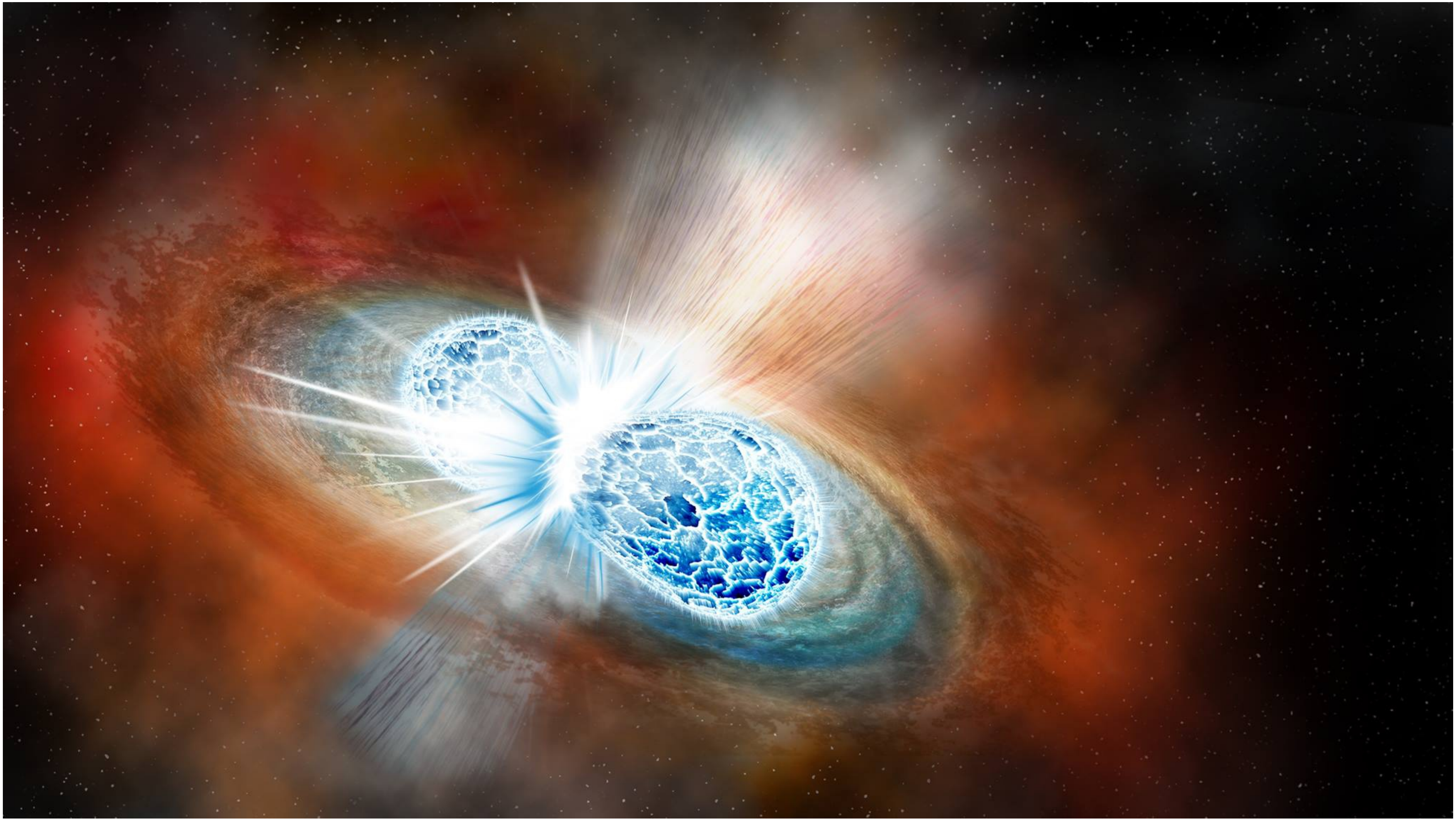
[Cosmic Rays, Gamma Rays, High Energy Neutrinos
can really be considered as three probes that study the
same underlying physical phenomena]

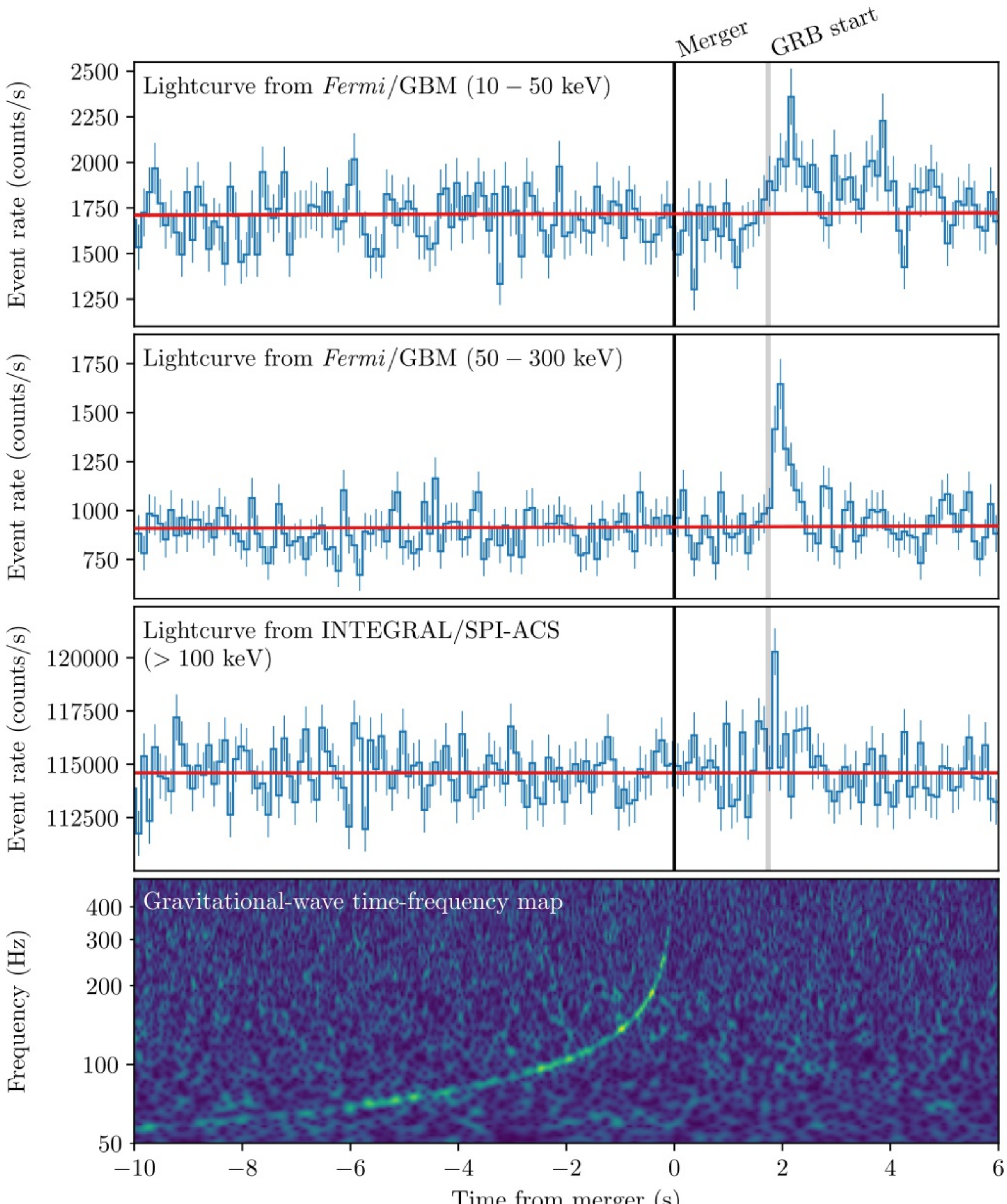


Gravitational Waves Observations
Entering a new exciting era with LIGO/VIRGO



GW 170817 GRB 170817A





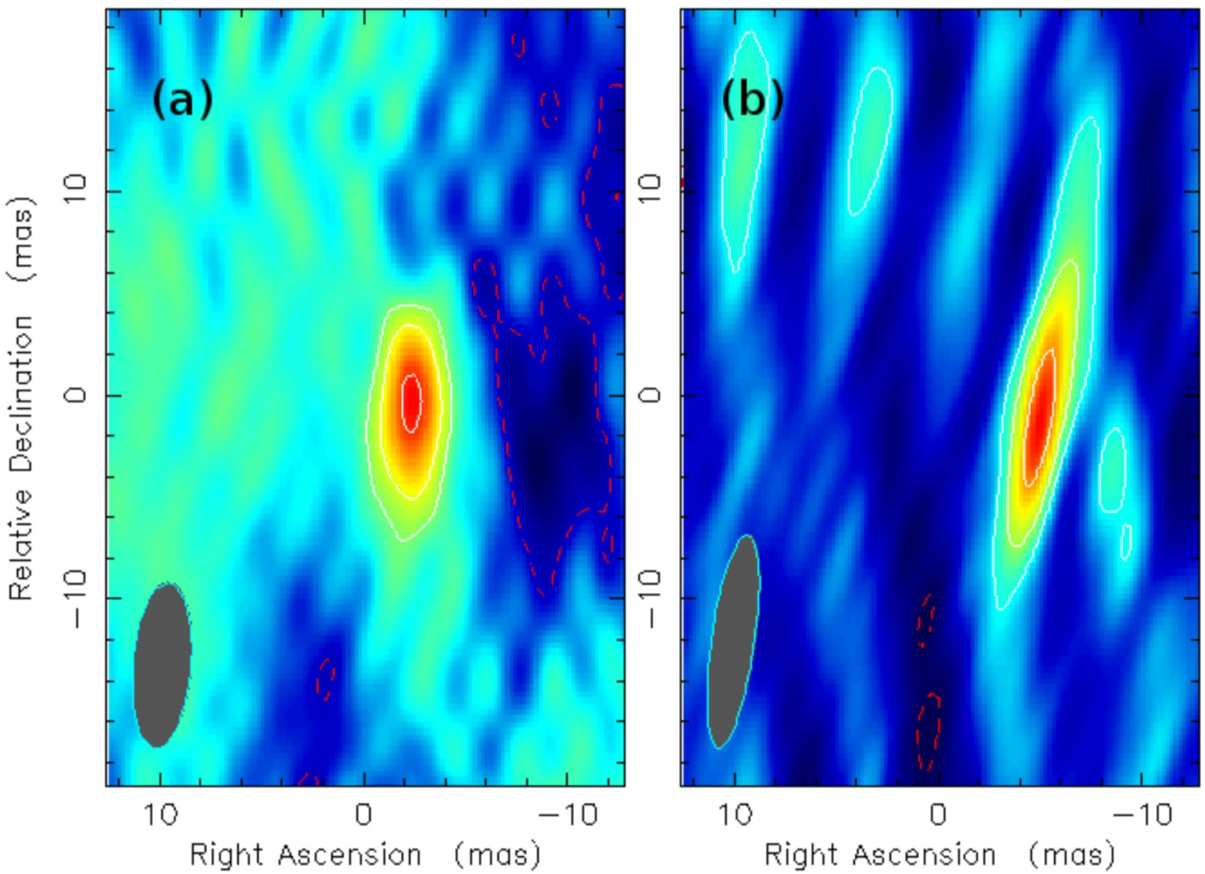
GRB 170817A

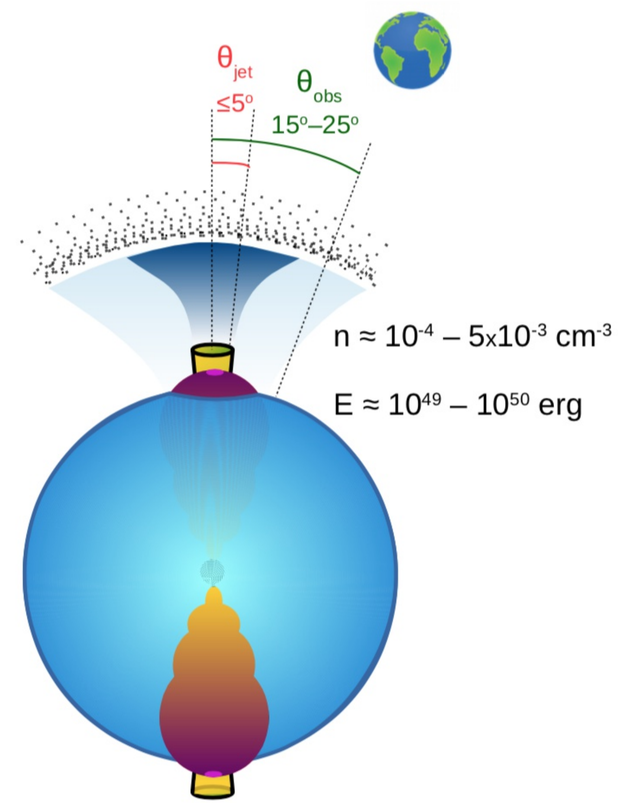
17/08/2017

Neutron stars merger

Extraordinary event !

GW 170817



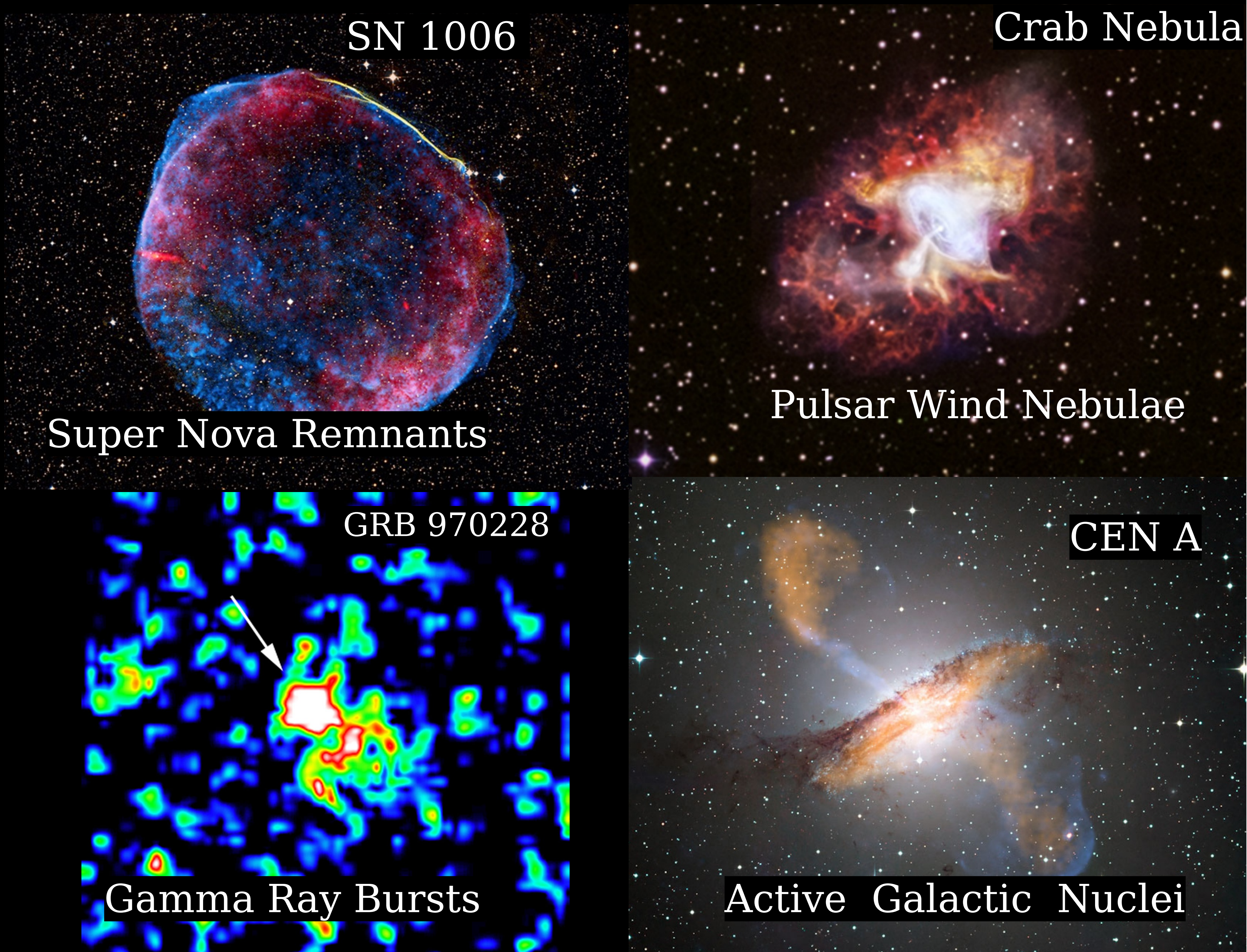


Superluminal motion
Detected in radio [240 days]
2.7 mas displacement

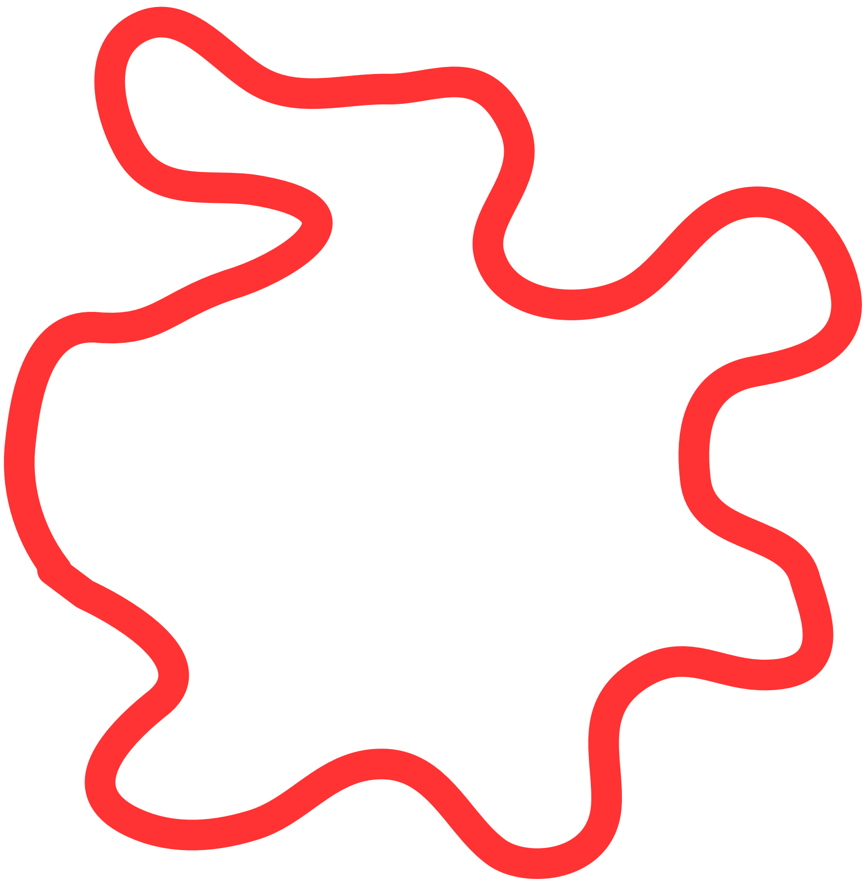
“High Energy Sources”

Discovery of several classes
of astrophysical objects/events that are capable
of accelerating particles to relativistic energies

[Strange and wonderful beasts in the Sky]


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

High Energy Source



$n_{\mathrm{gas}}(\vec{x}, t)$

$\vec{B}(\vec{x}, t)\, \vec{E}(\vec{x}, t)$

$n_\gamma(\varepsilon, \hat{u}_\gamma, \vec{x}, t)$

Structure

$N_p(E, \vec{x}, t)$

$N_A(E, \vec{x}, t)$

$N_e(E, \vec{x}, t)$

Relativistic Particles

Emission of photons and Neutrinos

$$[p + \text{gas}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \text{gas}] \to \pi^\pm \ (K) \to \nu$$

$$[p + \gamma_{\text{soft}}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \gamma_{\text{soft}}] \to \pi^\pm \ (K) \to \nu$$

$$[e + \gamma_{\text{soft}}] \to e + \gamma$$

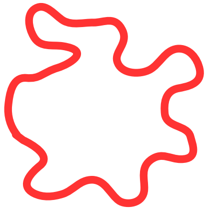
$$[e + \text{gas}] \to e + \gamma$$

$$[e + \vec{B}] \to e + \gamma_{\text{syn}}$$

(p, He, ...A, ...)

“hadronic emissions”

“Leptonic emissions”



Emission of photons and Neutrinos

$$[p + \mathrm{gas}] \to \pi^0 \ (\eta) \to \gamma$$

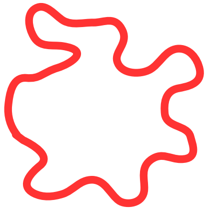
$$[p + \mathrm{gas}] \to \pi^\pm \ (K) \to \nu$$

$$[p + \gamma_{\mathrm{soft}}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \gamma_{\mathrm{soft}}] \to \pi^\pm \ (K) \to \nu$$

(p, He, ...A, ...)

“hadronic emissions”



Simple clear connection between emissions

Neutrino

and

Gamma Ray

But:

Gamma absorption in source
Gamma absorption in space
Leptonic mechanisms

Emission of photons and Neutrinos

$$[p + \mathrm{gas}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \mathrm{gas}] \to \pi^\pm \ (K) \to \nu$$

$$[p + \gamma_{\mathrm{soft}}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \gamma_{\mathrm{soft}}] \to \pi^\pm \ (K) \to \nu$$

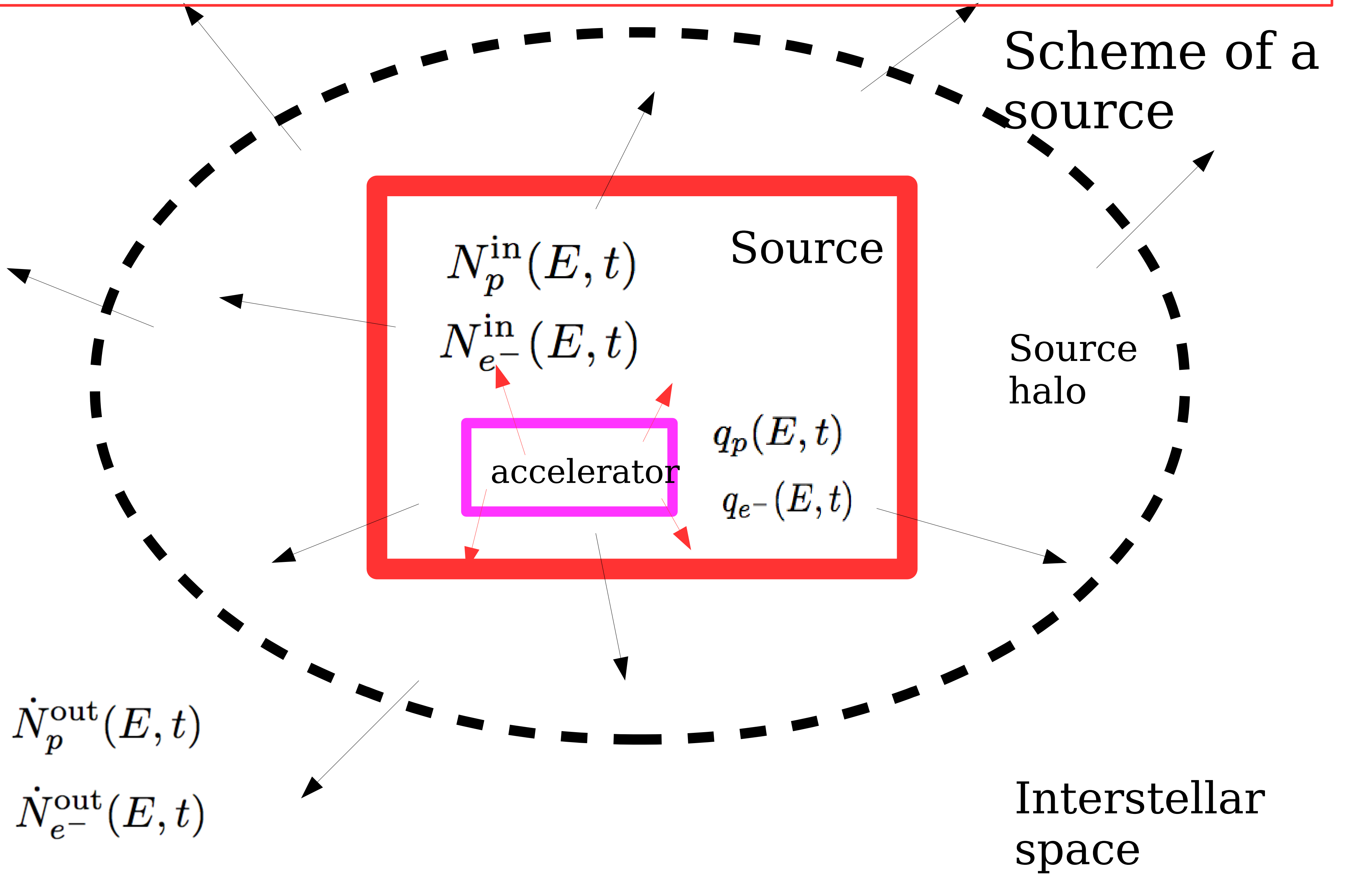
$$[e + \gamma_{\mathrm{soft}}] \to e + \gamma$$

$$[e + \mathrm{gas}] \to e + \gamma$$

$$[e + \vec{B}] \to e + \gamma_{\mathrm{syn}}$$

Understanding the “co-acceleration of protons and electrons a fundamental problem

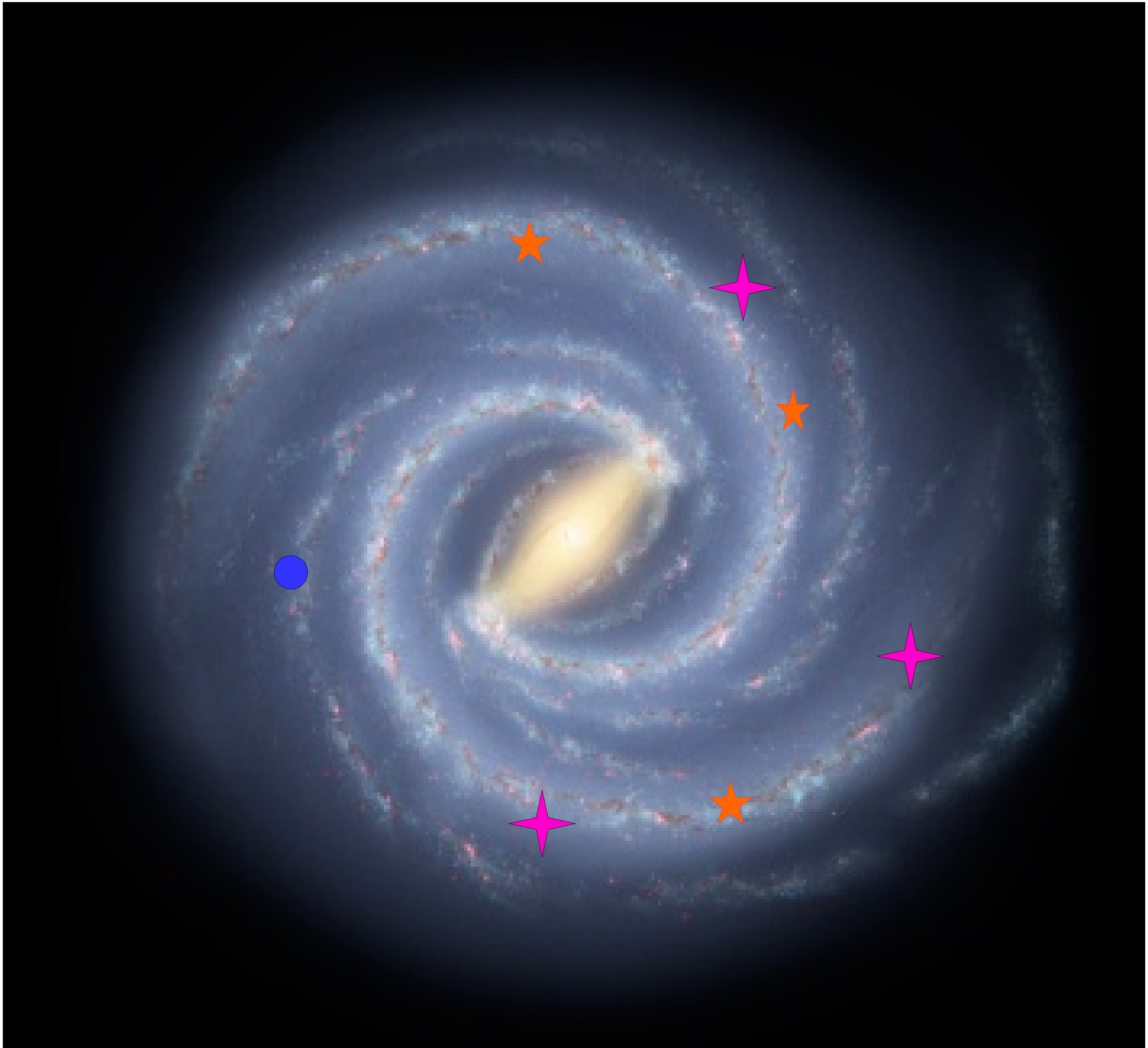
Emission of Cosmic Rays from the Sources requires "escape"

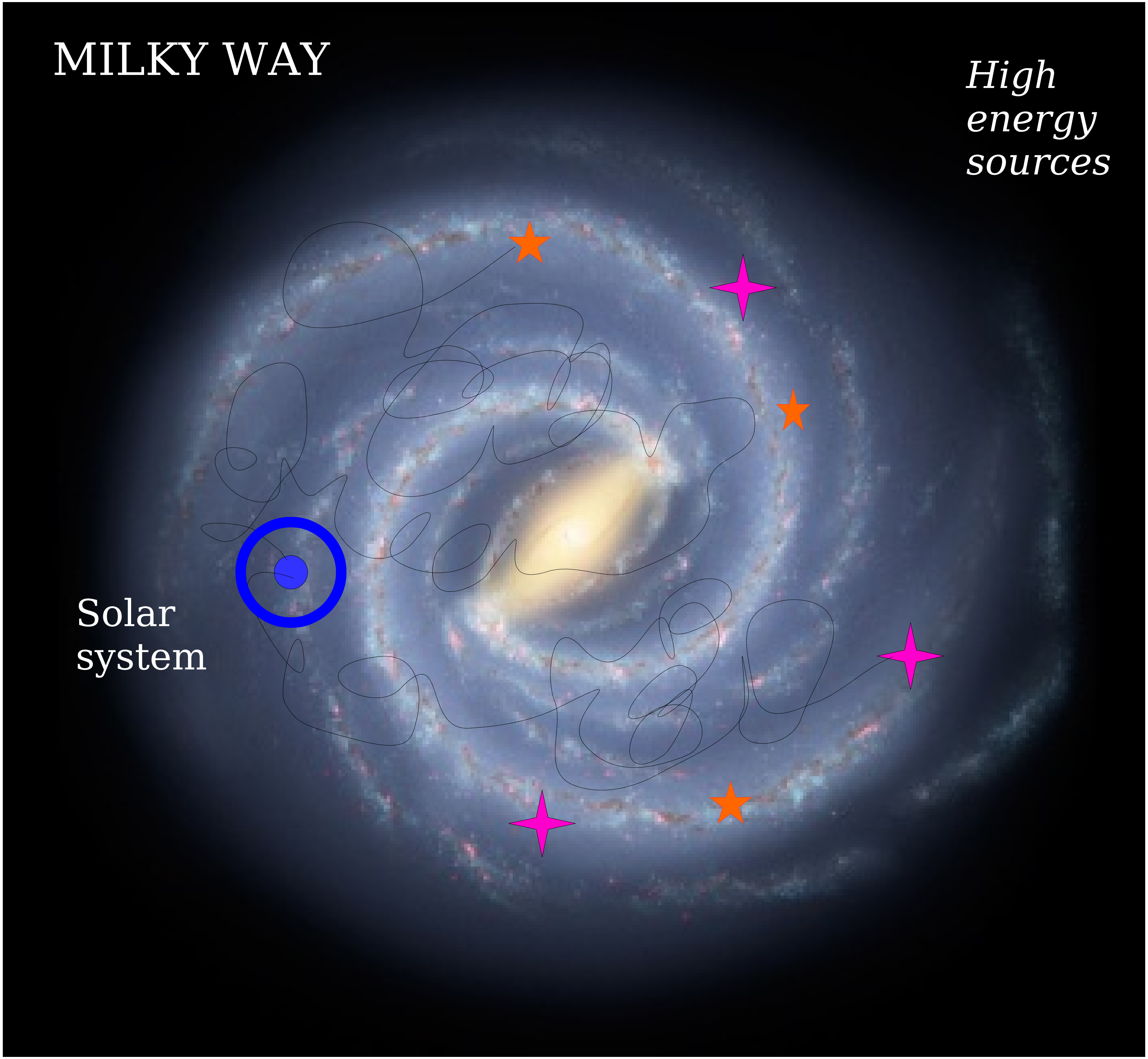


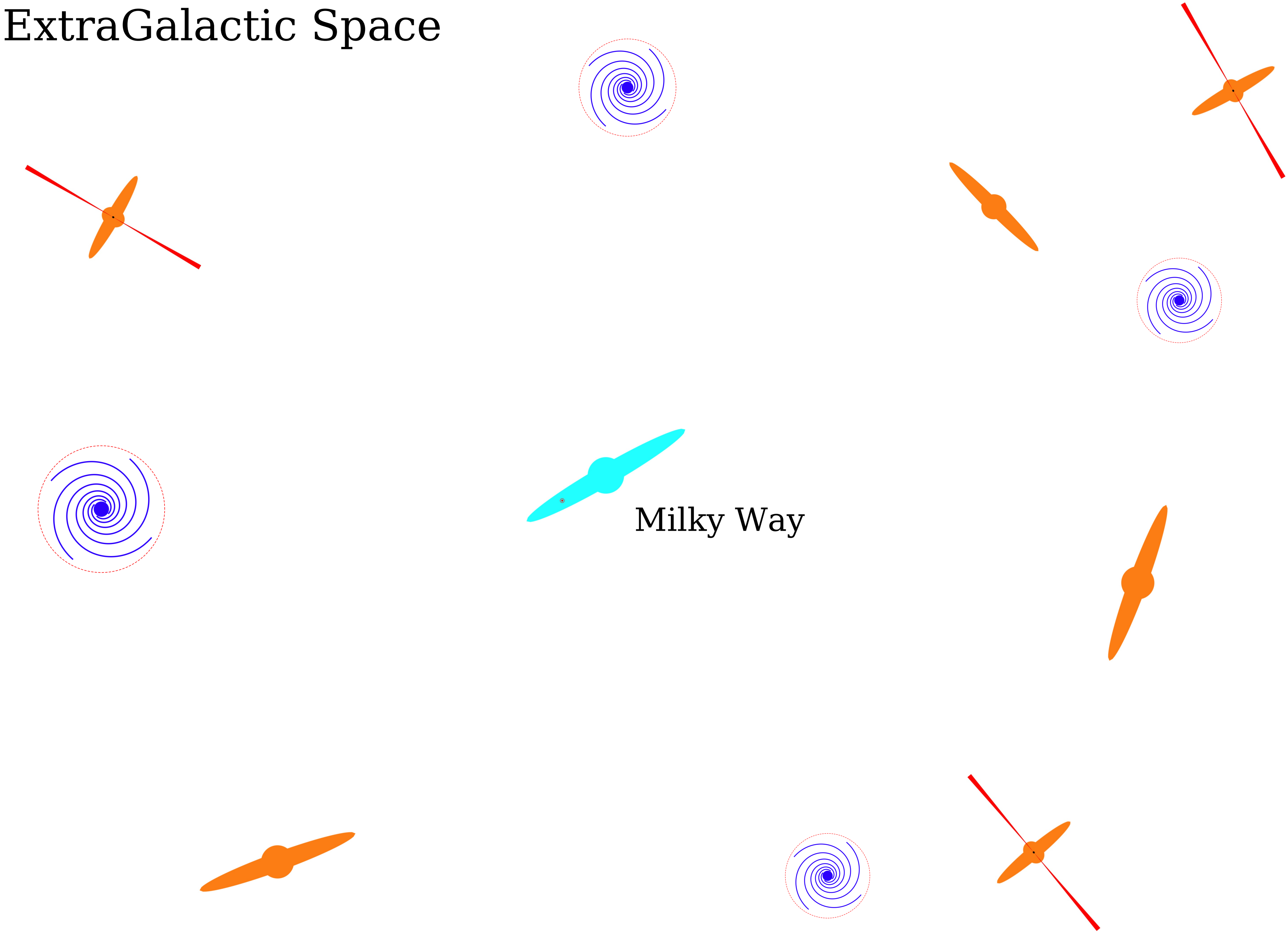
COSMIC RAYS

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

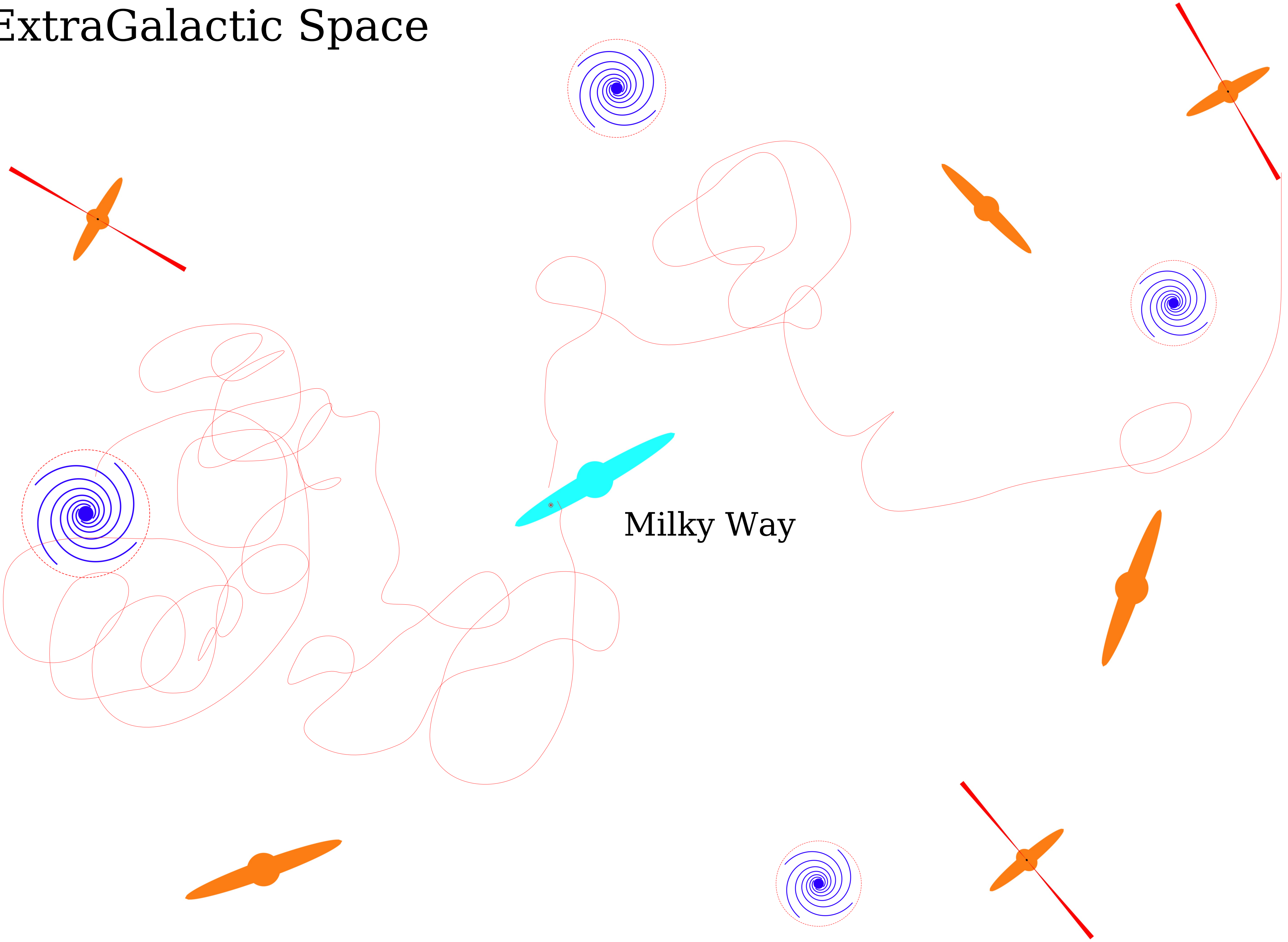
Measurement at
single point, and (effectively) single time.
[slow time variations,
geological record carries some information]

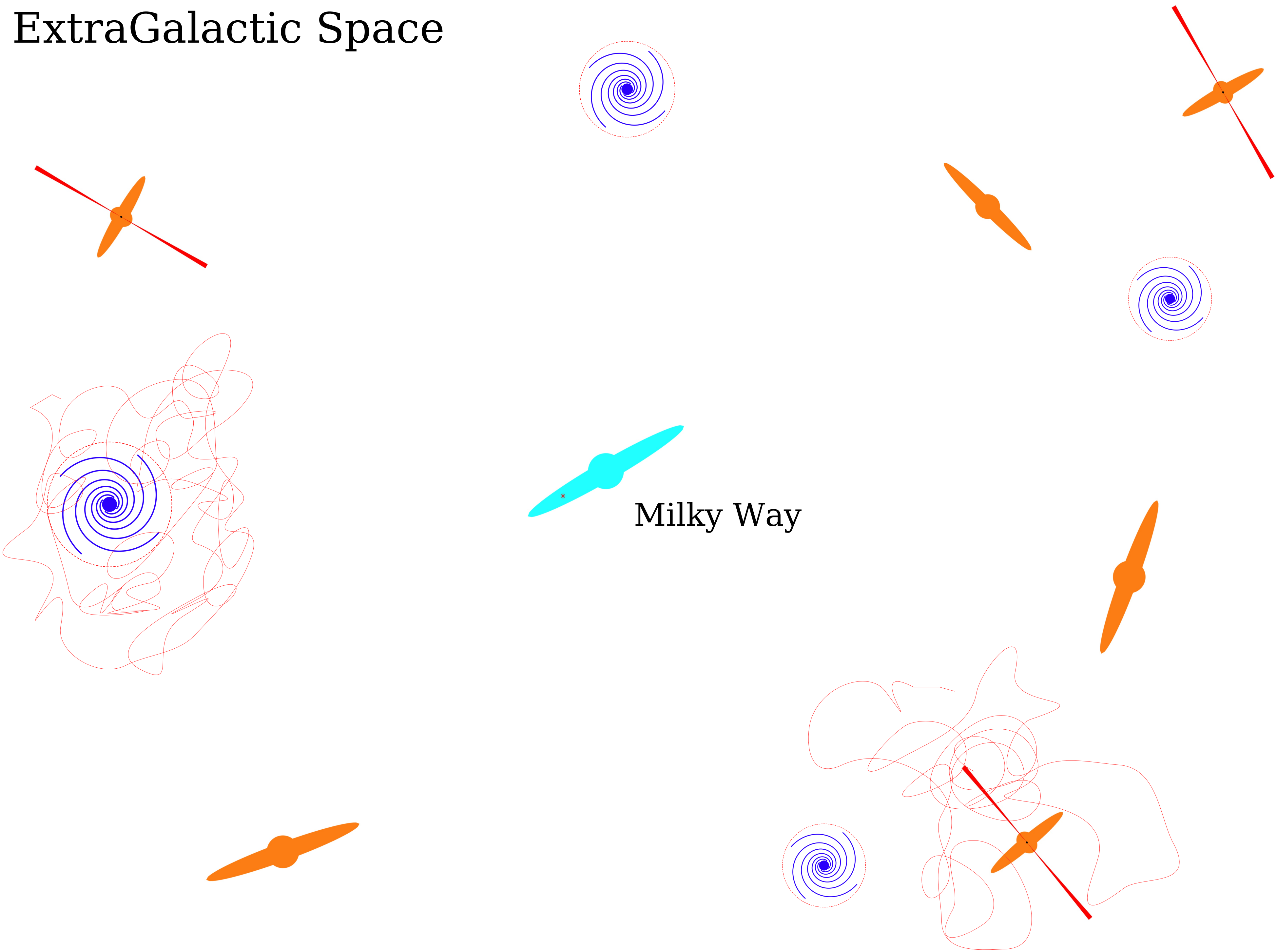



MILKY WAY
High
energy
sources
Solar
system


ExtraGalactic Space
Milky Way

ExtraGalactic Space

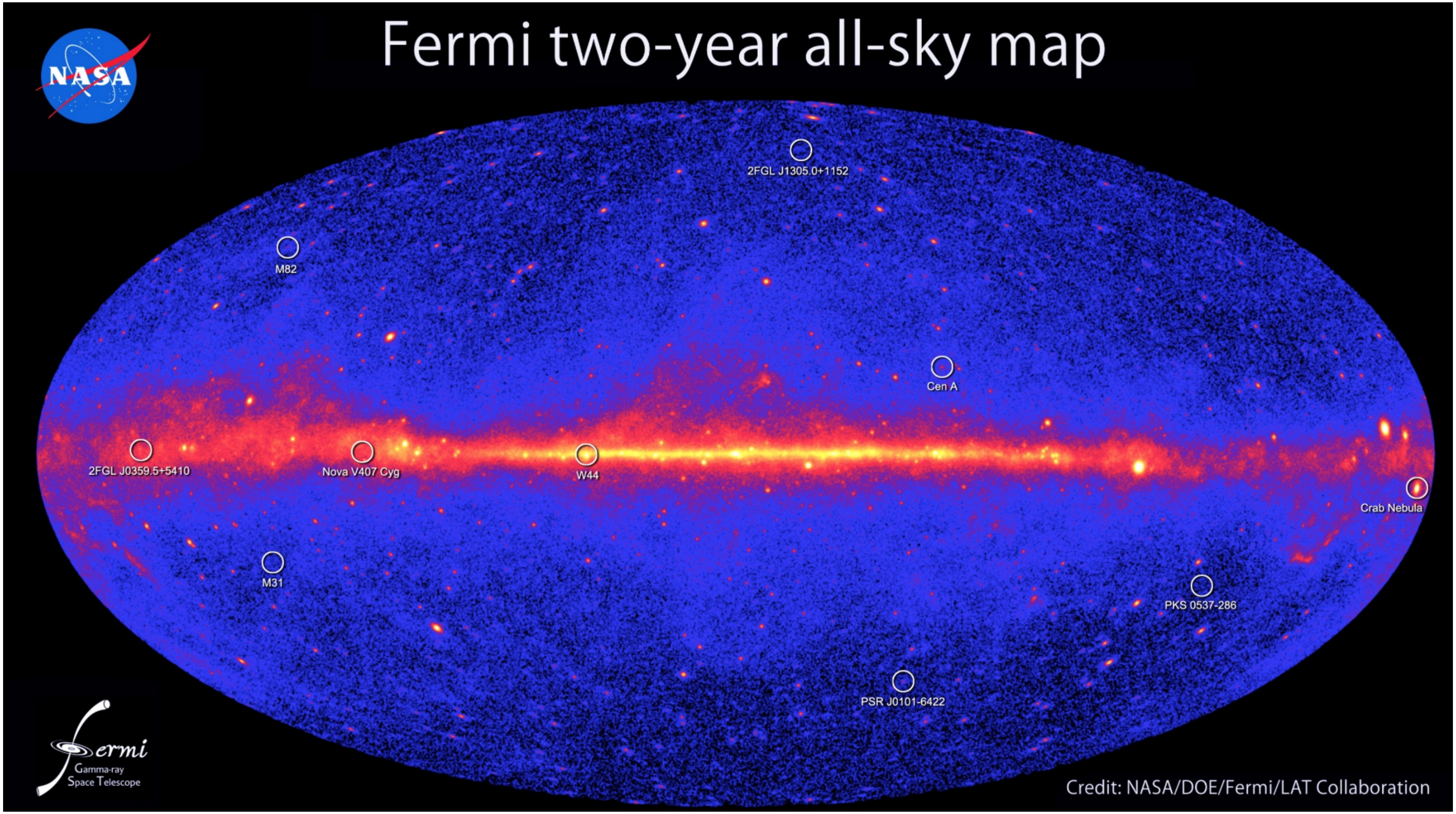



ExtraGalactic Space
Milky Way

GAMMA ASTRONOMY

$E_\gamma \geq 100$ MeV

Gamma Ray Sky



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

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

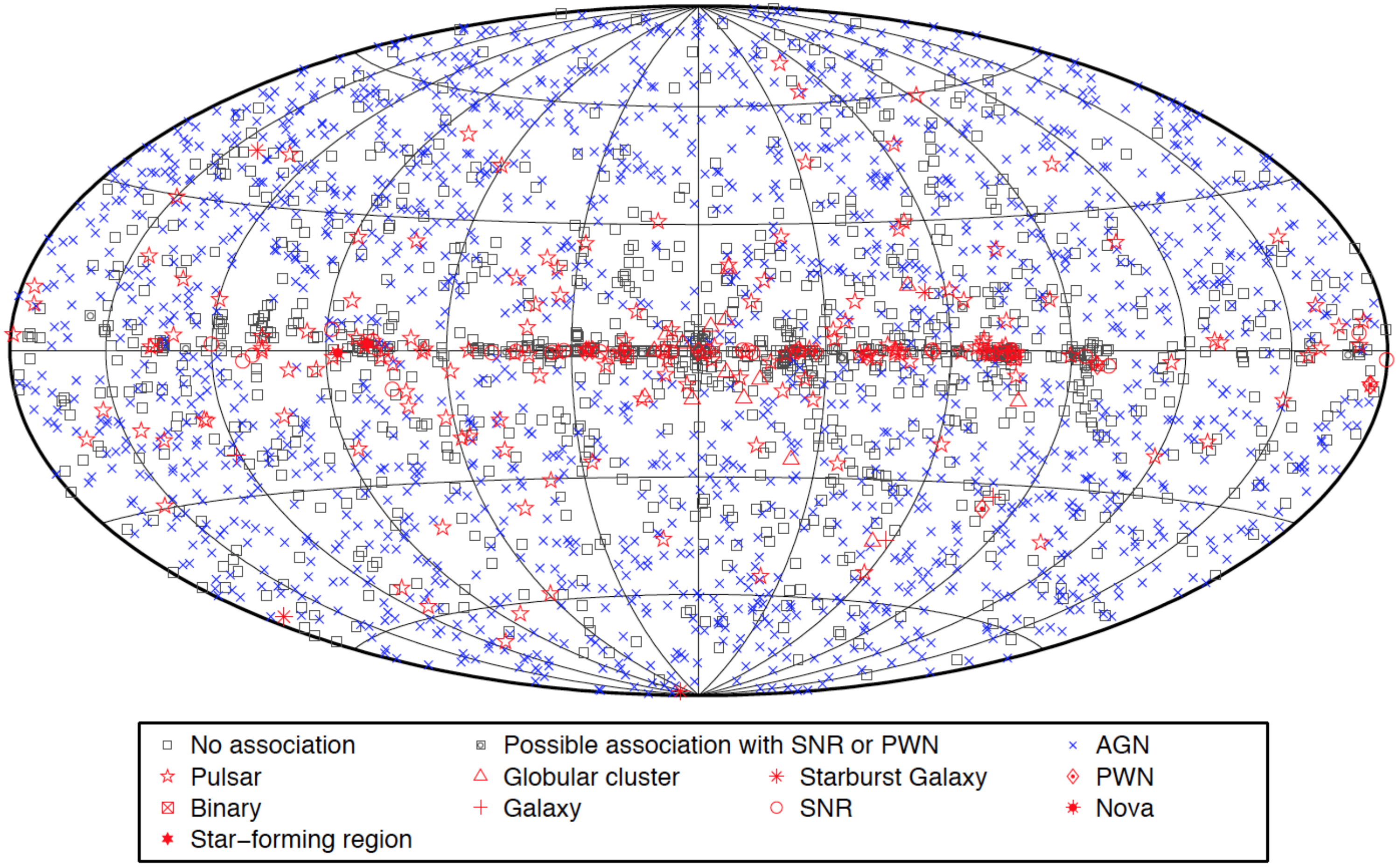
- Several classes of objects [SNR, Pulsars, PWN, AGN, GRB, ...]

- Probably different acceleration mechanisms.

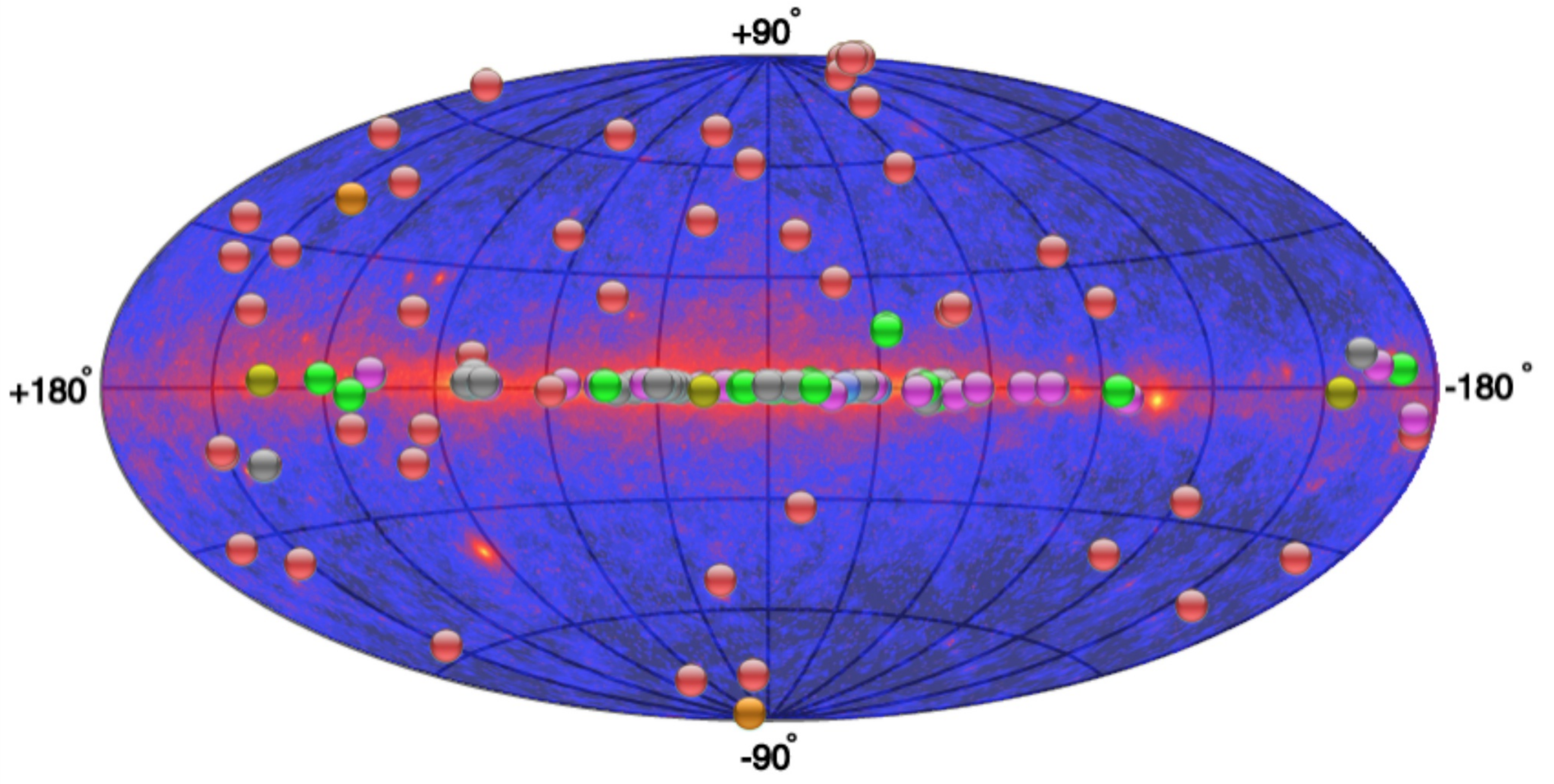
Still developing an understanding
many questions remain open

3rd FERMI Catalog 3034 sources

E > 100 MeV



TeV Sky 170 → 200 Sources



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

Components of the Gamma Ray flux (0.1 – 1000 GeV)

$$\boxed{\begin{aligned}\phi_\gamma(E,\Omega) = &\sum_{j\in\{\text{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Galactic}}_{\text{diffuse}}(E,\Omega)\\ &+ \sum_{j\in\{\text{extragal.}\}} \phi_j(E,\Omega_j) + \phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega)\end{aligned}}$$

$$\phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega) = \phi^{\text{extragal.}}_{\text{unresolved sources}}(E) + \phi^{\text{extragal.}}_{\text{diffuse}}(E,\Omega)$$

Components of the Gamma Ray flux (0.1 – 1000 GeV)

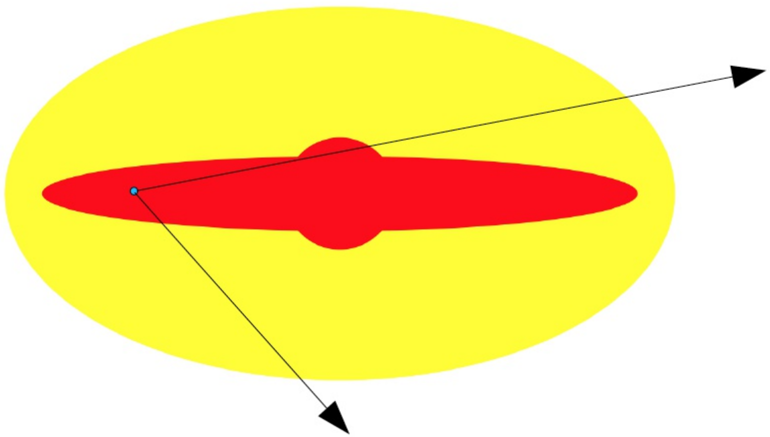
$$\phi_\gamma(E,\Omega) = \sum_{j\in\{\text{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Galactic}}_{\text{diffuse}}(E,\Omega)$$

$$+ \sum_{j\in\{\text{extragal.}\}} \phi_j(E,\Omega_j) + \phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega)$$

$$\phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega) = \phi^{\text{extragal.}}_{\text{unresolved sources}}(E) + \phi^{\text{extragal.}}_{\text{diffuse}}(E,\Omega)$$

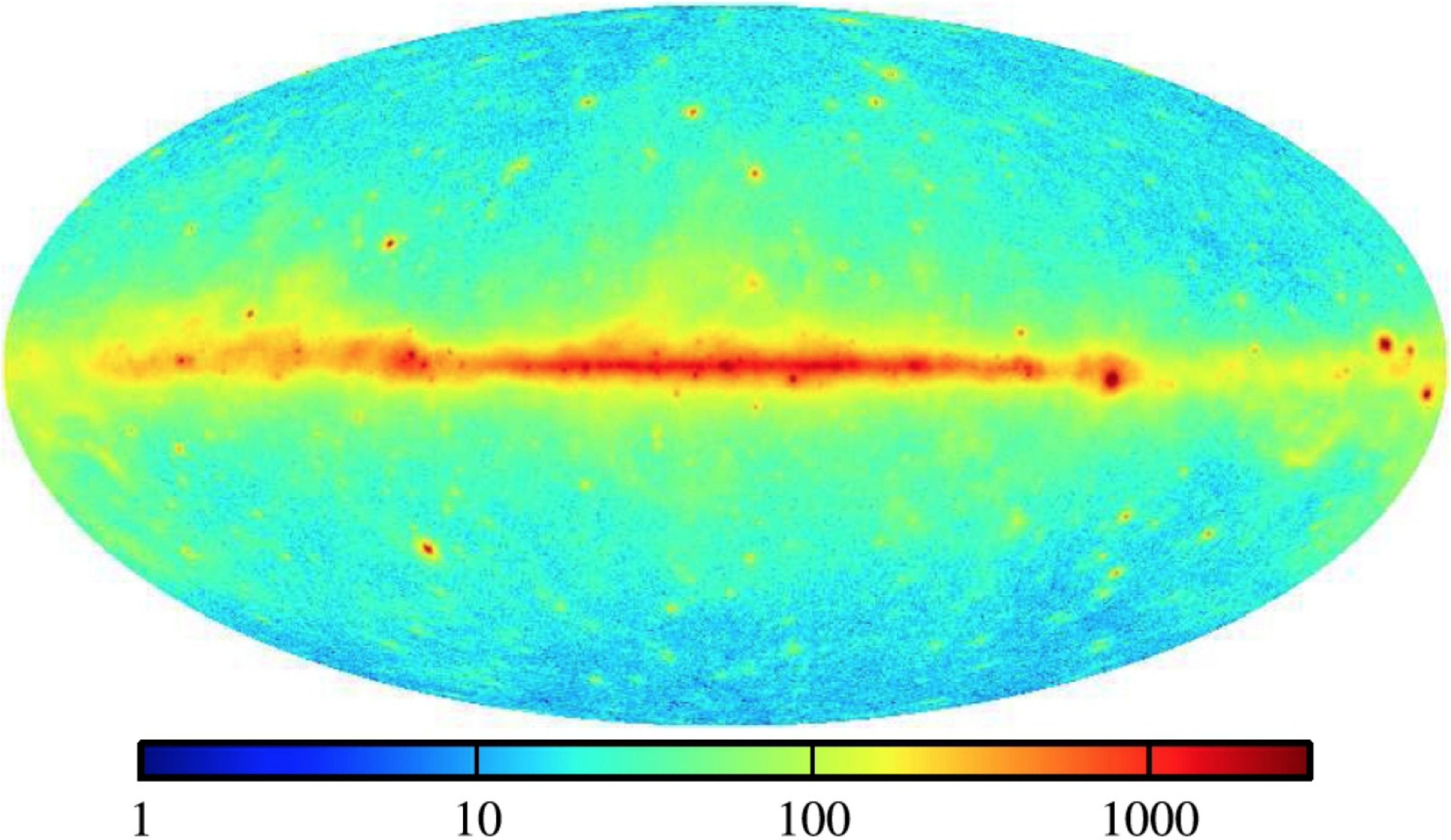
Note : The Neutrino sky will have the same 5 components (perhaps in different proportions)

Diffuse Emission



Fermi–LAT counts

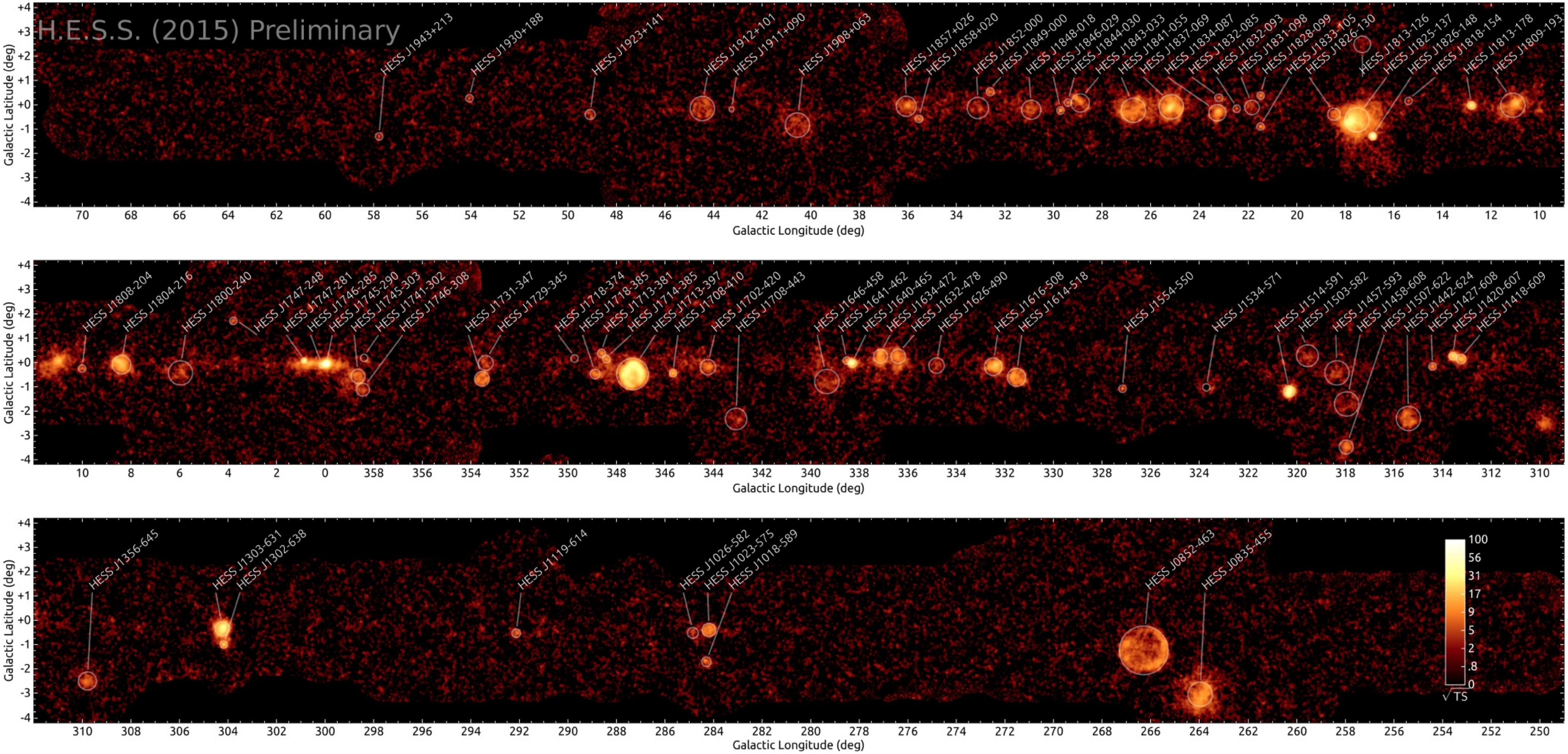
Galactic coordinates



energy range 200 MeV to 100 GeV

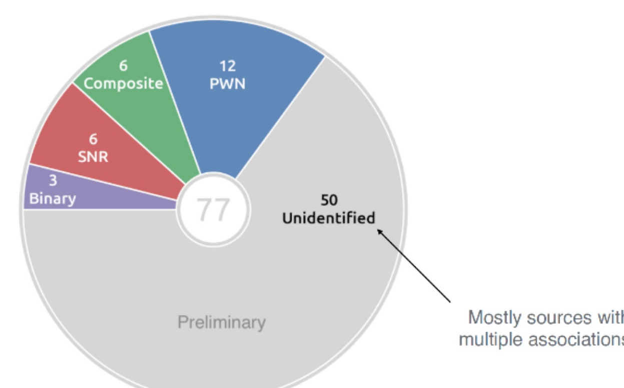
Cosmic Ray interactions in the Interstellar Medium

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



Firm identifications

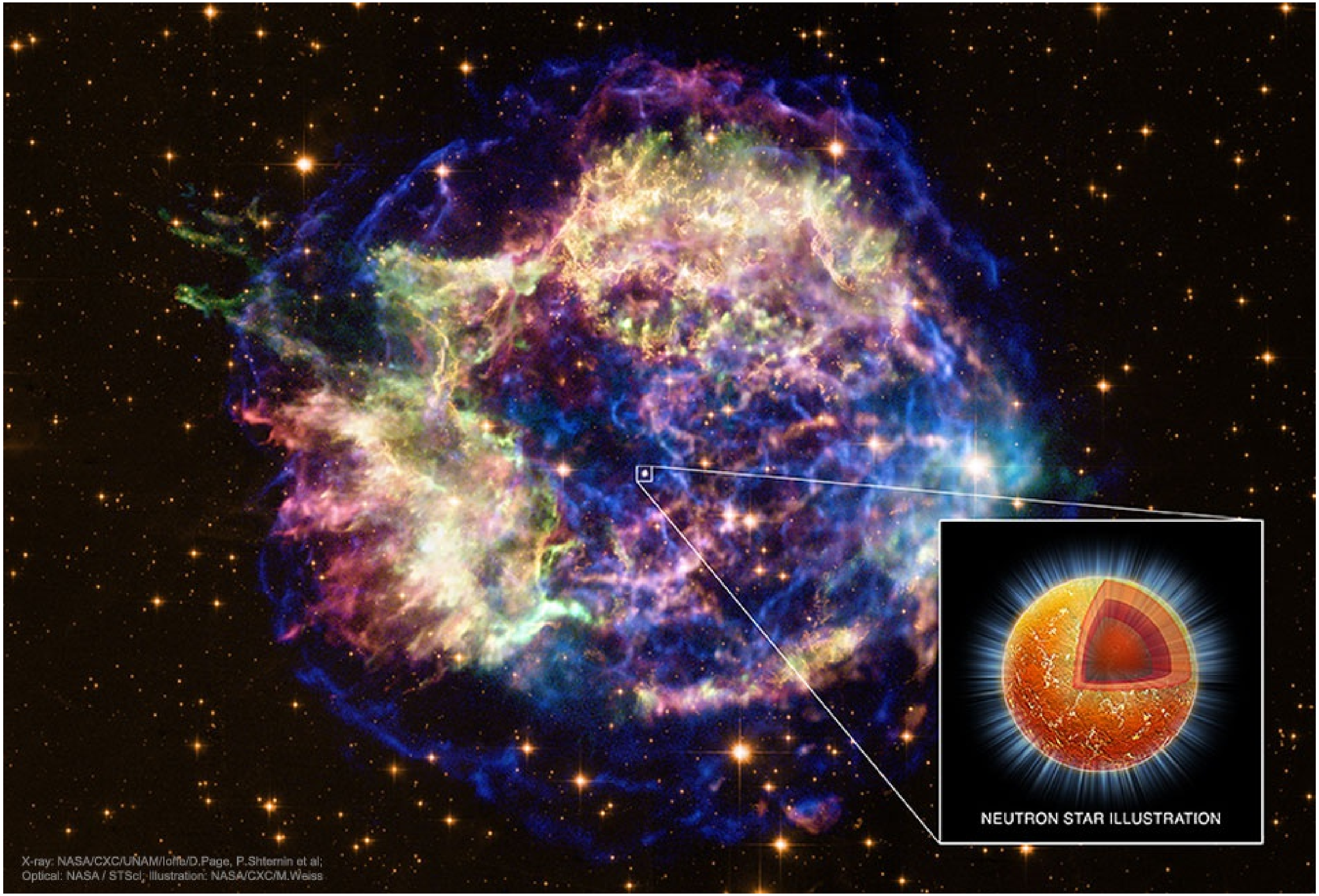
HESS survey of Galactic Plane [ICRC 2015] 77 "firm identifications"

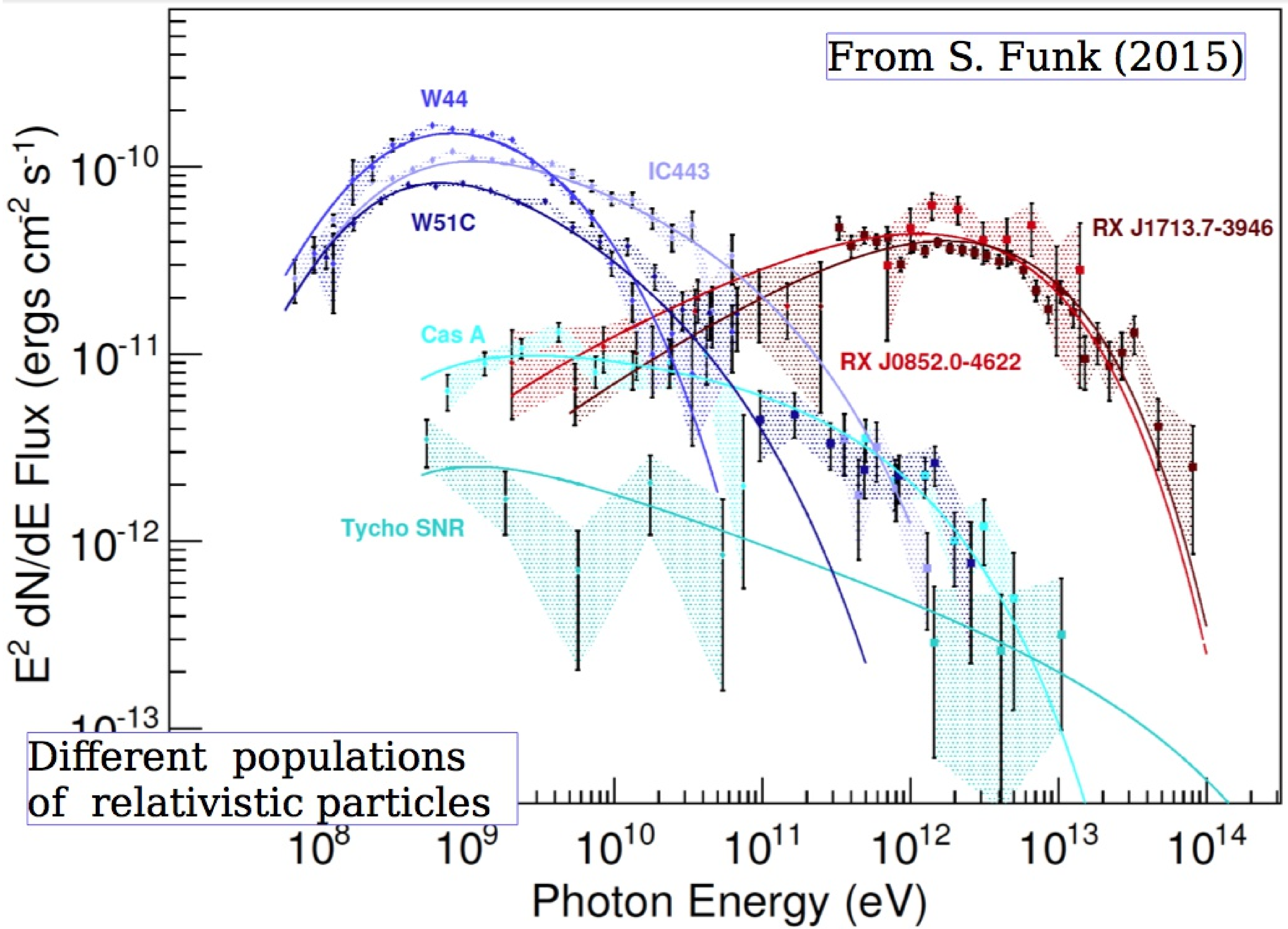


The SuperNova “Paradigm”

Most of the Galactic Cosmic Rays are accelerated in the Shock Waves of SN explosions

Creation of a Neutron Star in a SuperNova explosion





From S. Funk (2015)
W44
IC443
W51C
RX J1713.7-3946
Cas A
RX J0852.0-4622
Tycho SNR
E² dN/dE Flux (ergs cm⁻² s⁻¹)
Photon Energy (eV)
Different populations
of relativistic particles

Note:

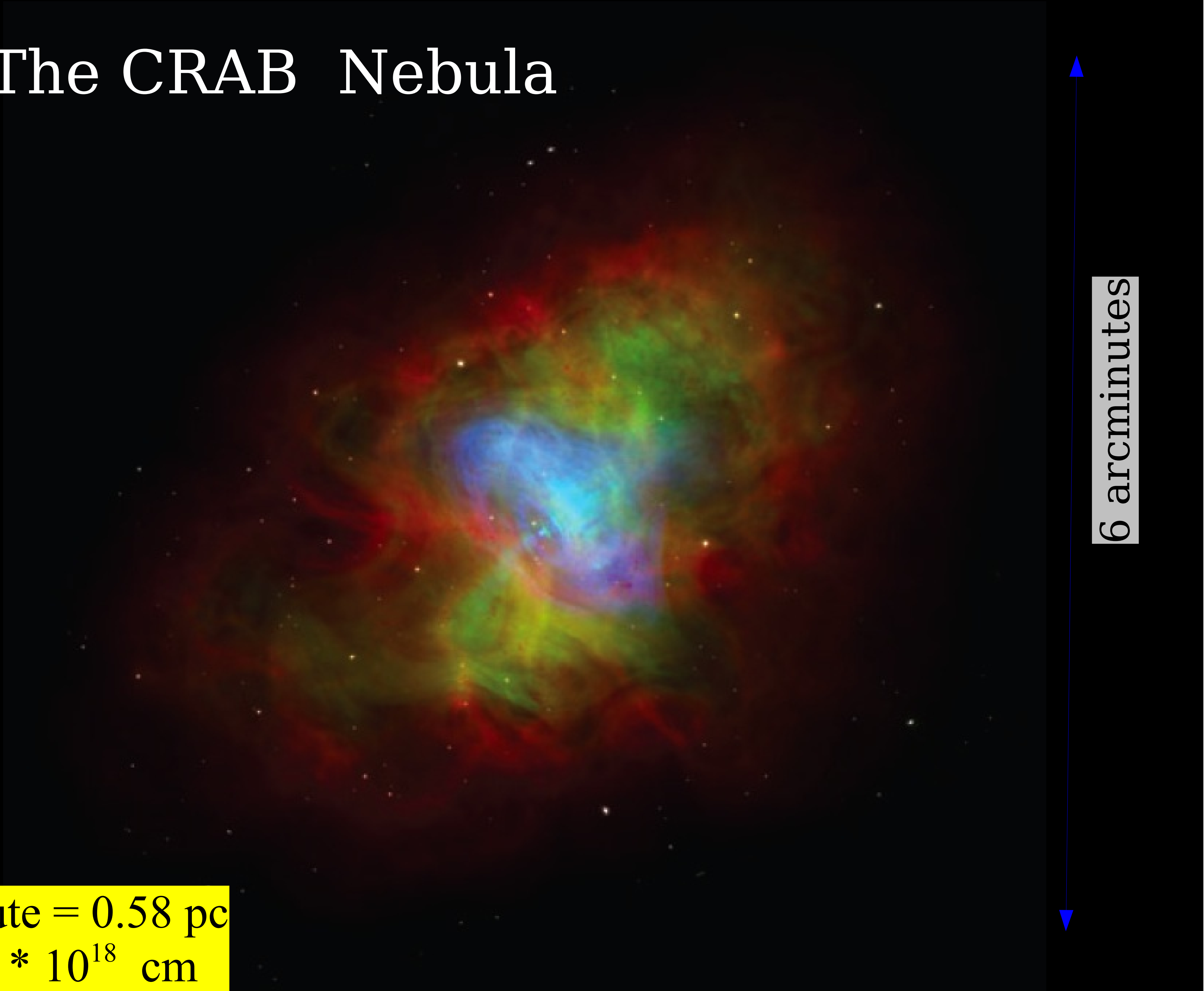
The Cosmic Ray observations
are an important *“boundary” conditions*
to study SNR acceleration
[or in fact any mechanism that is the
Main source of the Galactic Cosmic Rays]

Energy Balance

Spectral shape

Maximum energy

The CRAB Nebula



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

A very interesting chapter:

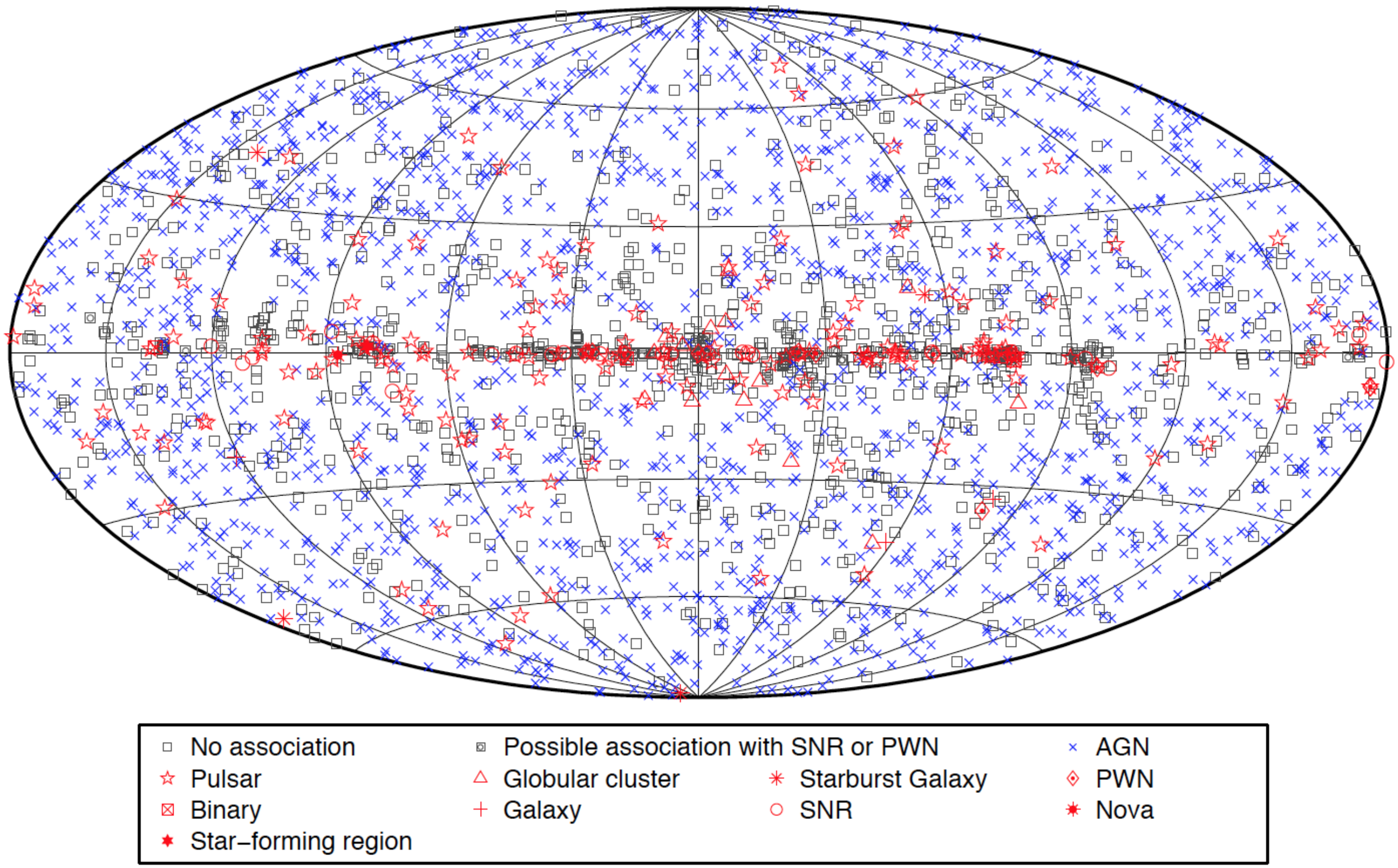
PULSARS

Different Mechanisms for particle acceleration

Acceleration of positrons ?

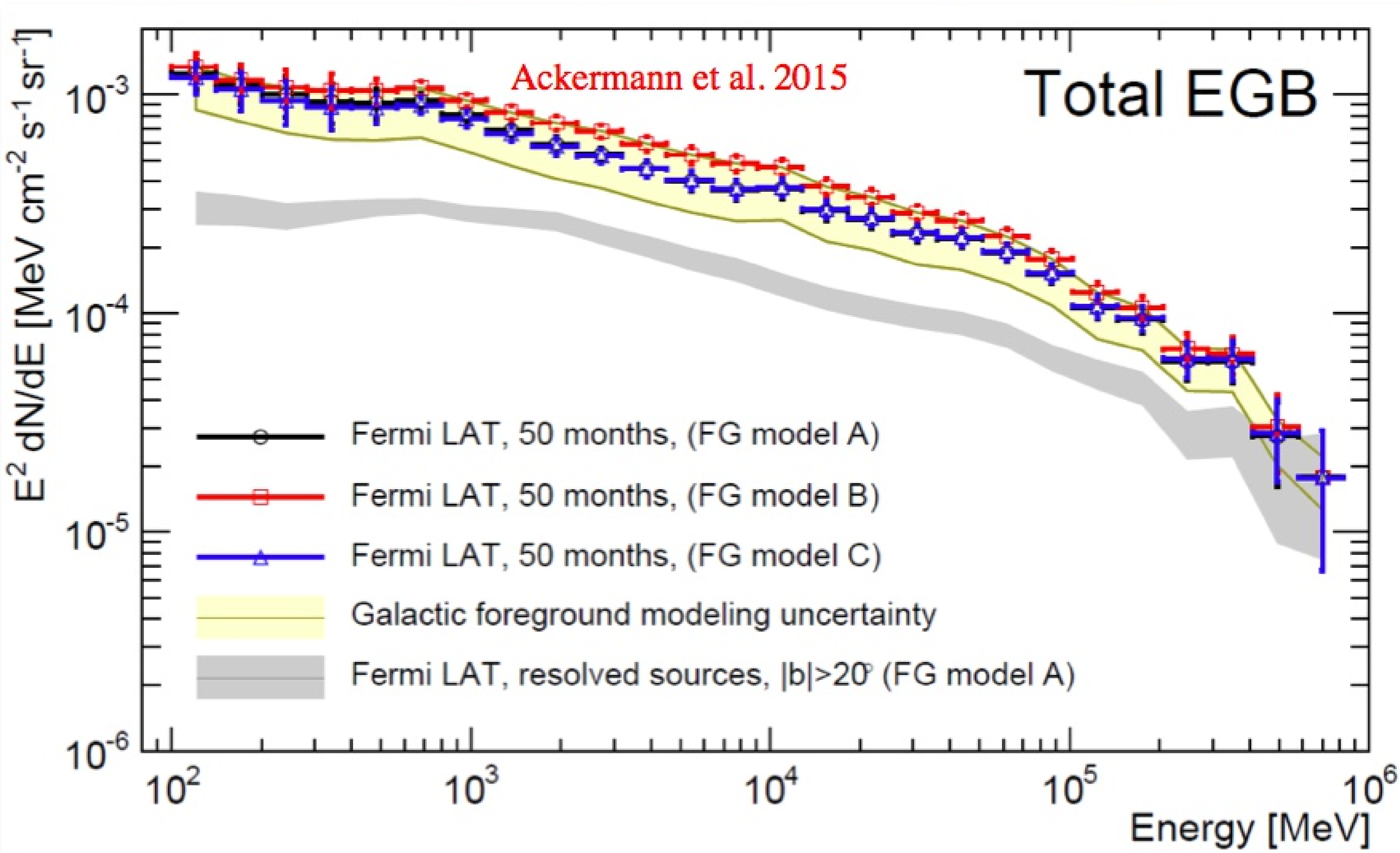
Extragalactic gamma ray sky

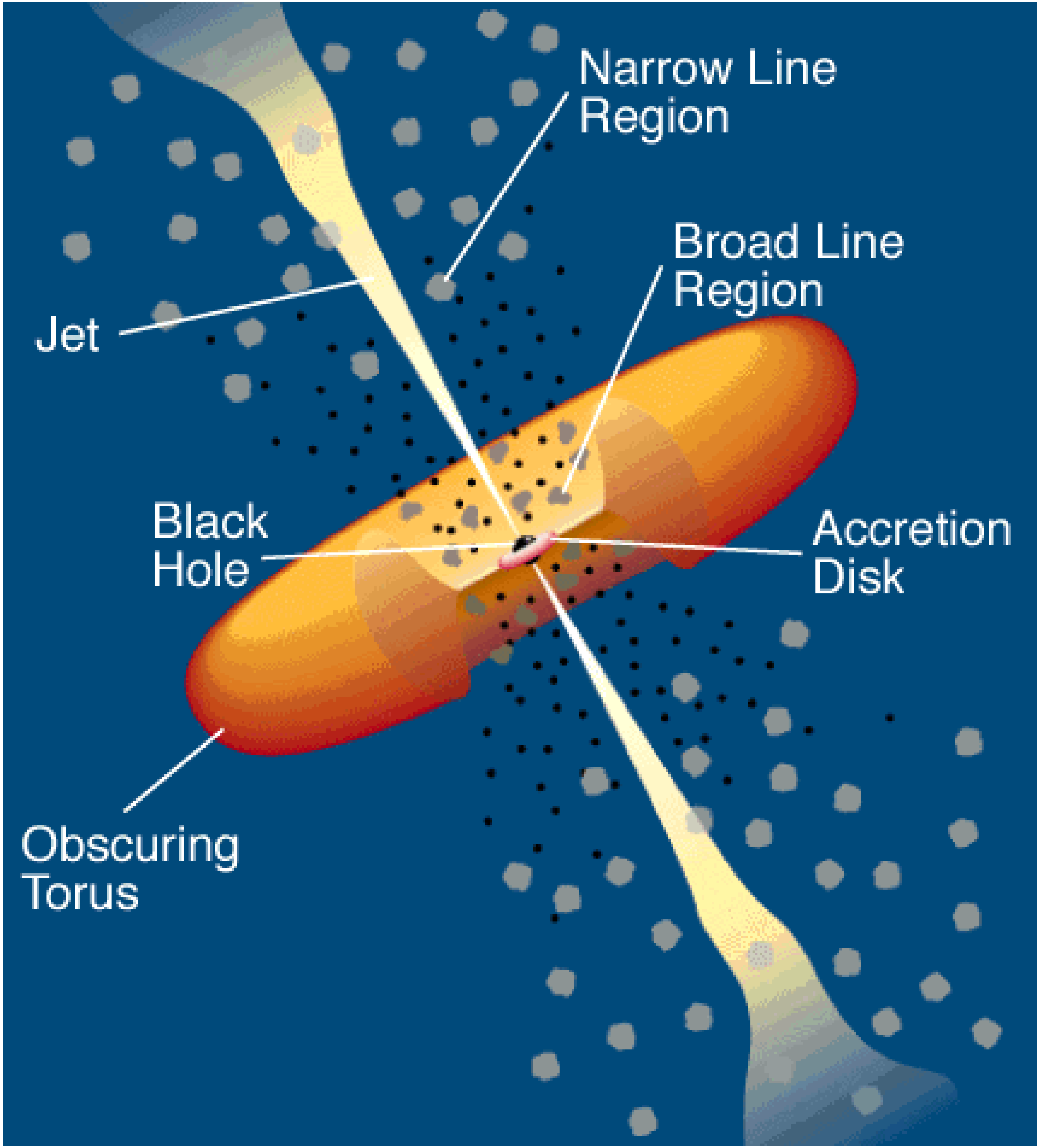
Dominated by Blazars (AGN's)

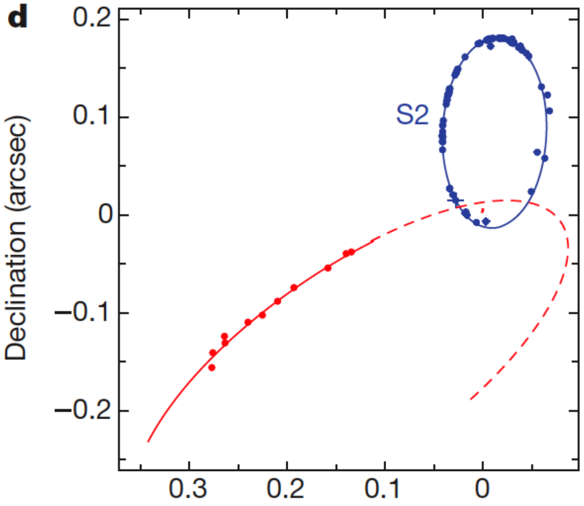


Total Extragalactic Gamma-ray Background

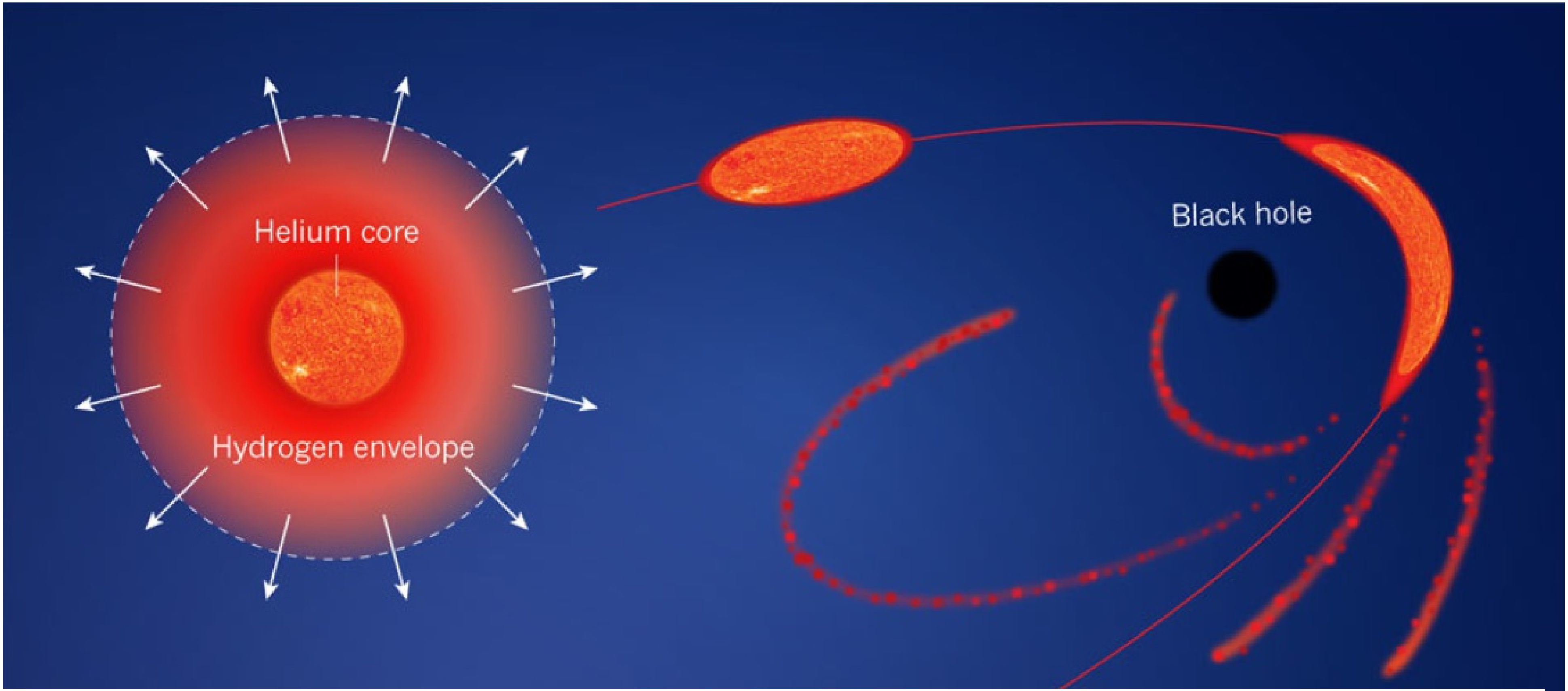
Systematic uncertainty from Galactic foreground represented by yellow band




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

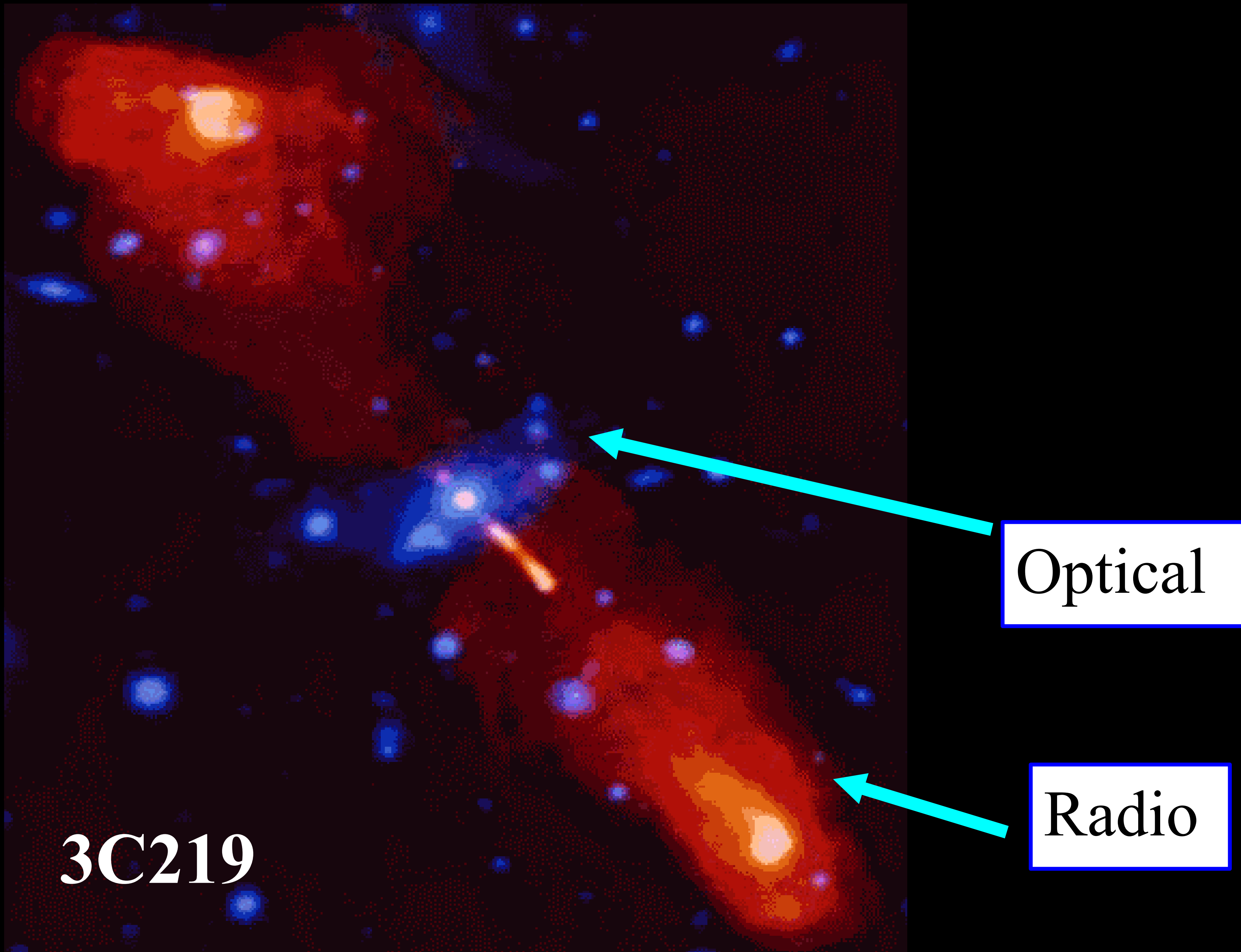


Infalling gas
from the disruption of a star.

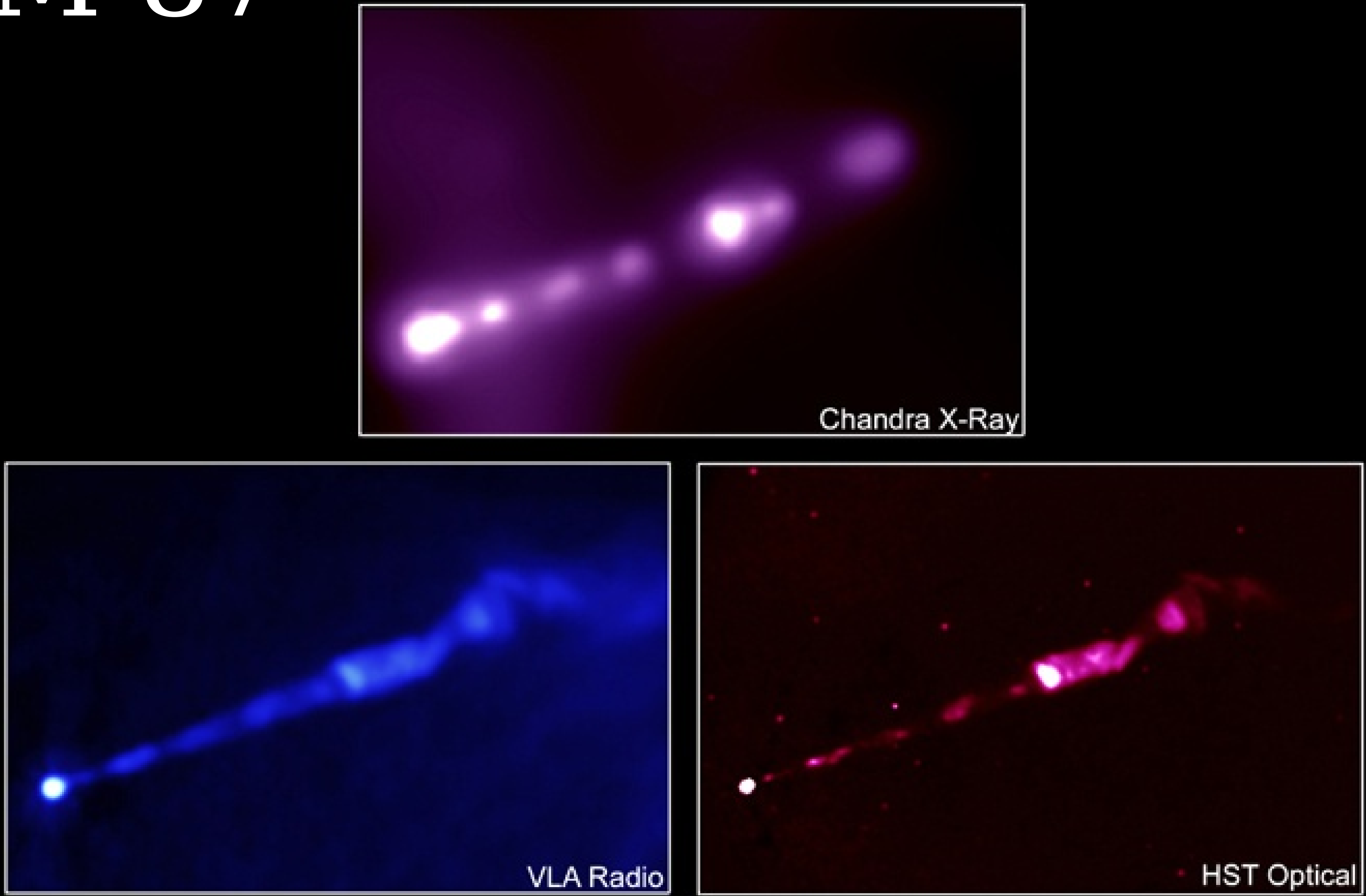


The helium-rich core of a red-giant star that had previously lost its hydrogen envelope moves on an almost parabolic orbit (red) towards a supermassive black hole. The sequence of blobs illustrates the progressive distortion of the star's core due to the tidal pull of the black hole. After the point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

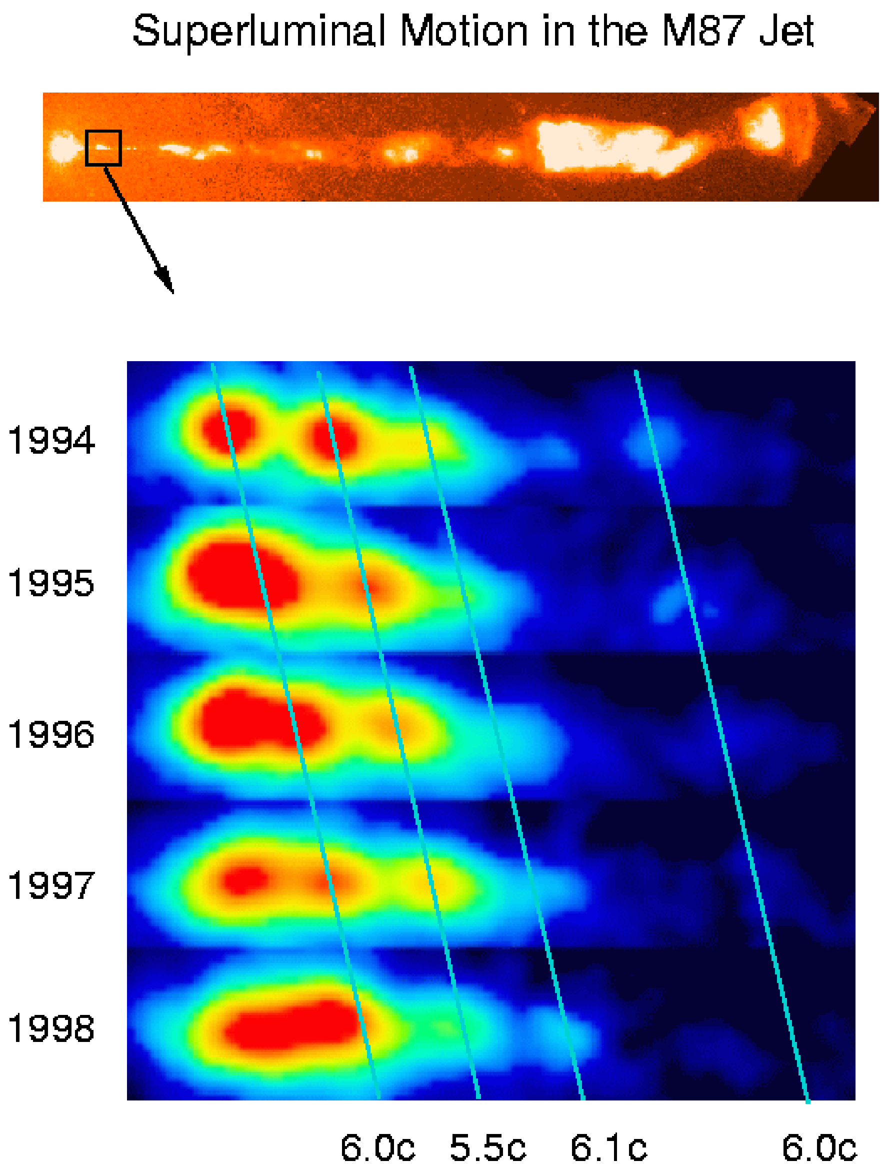
ACTIVE GALACTIC NUCLEI



M 87



Superluminal Motions

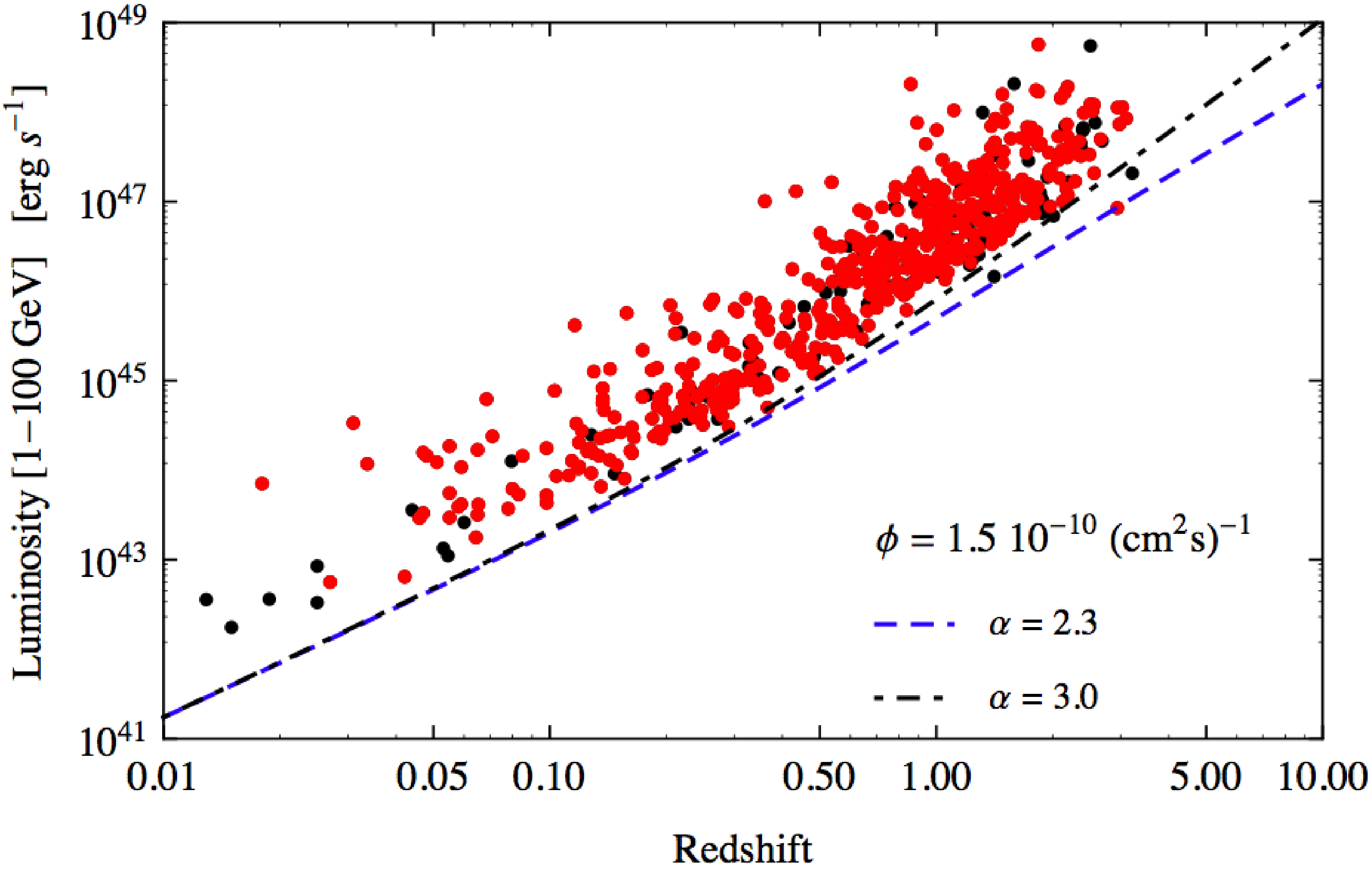


Source moving
on the celestial sphere

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

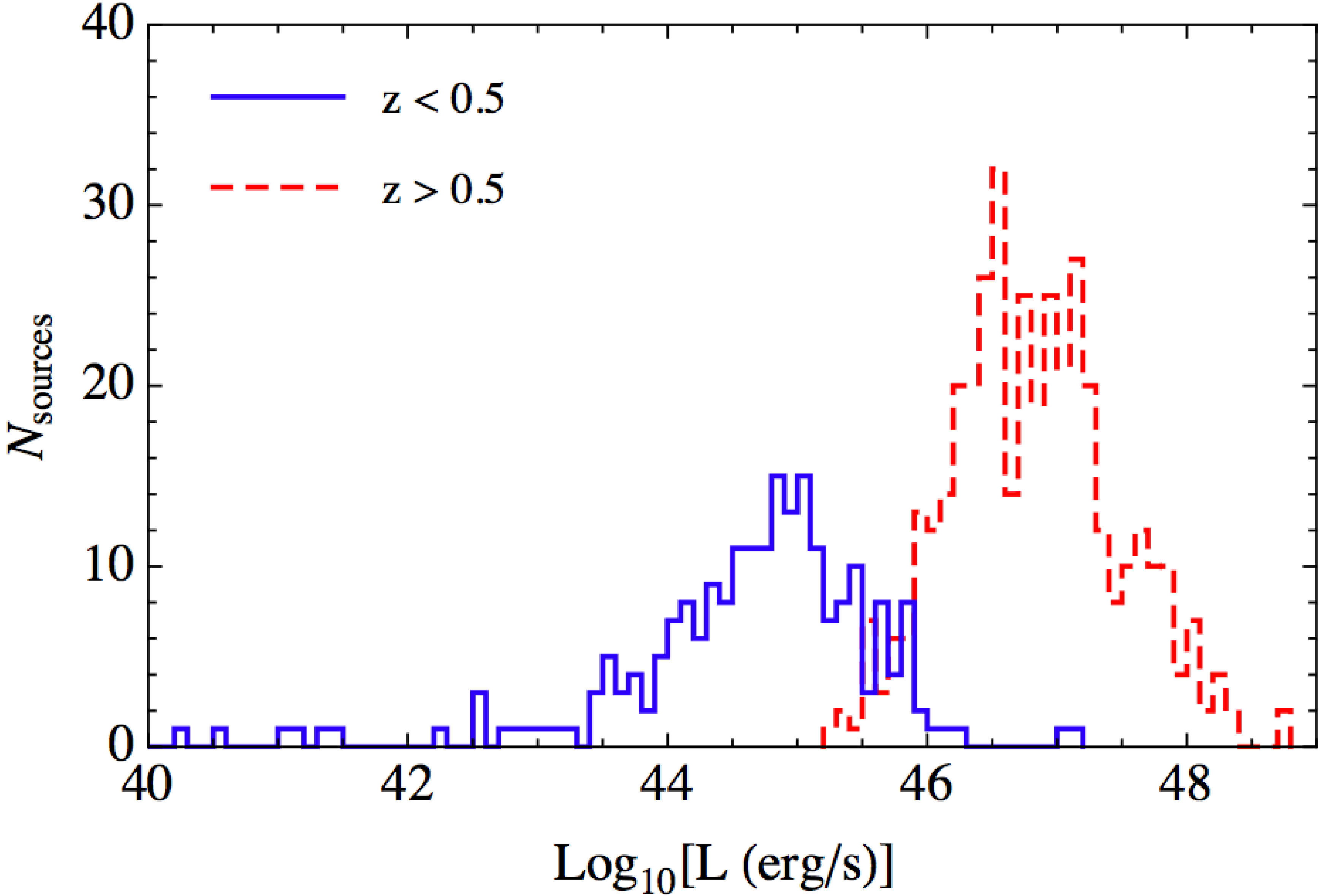
M87 :

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

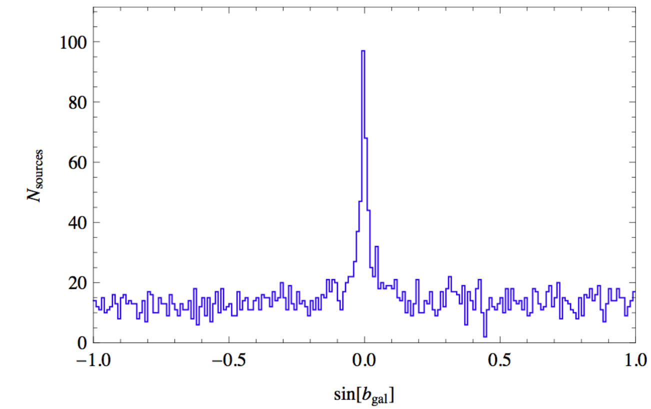


Blazars in the 2LAC FERMI catalog
(1121 objects)
618 with redshift known

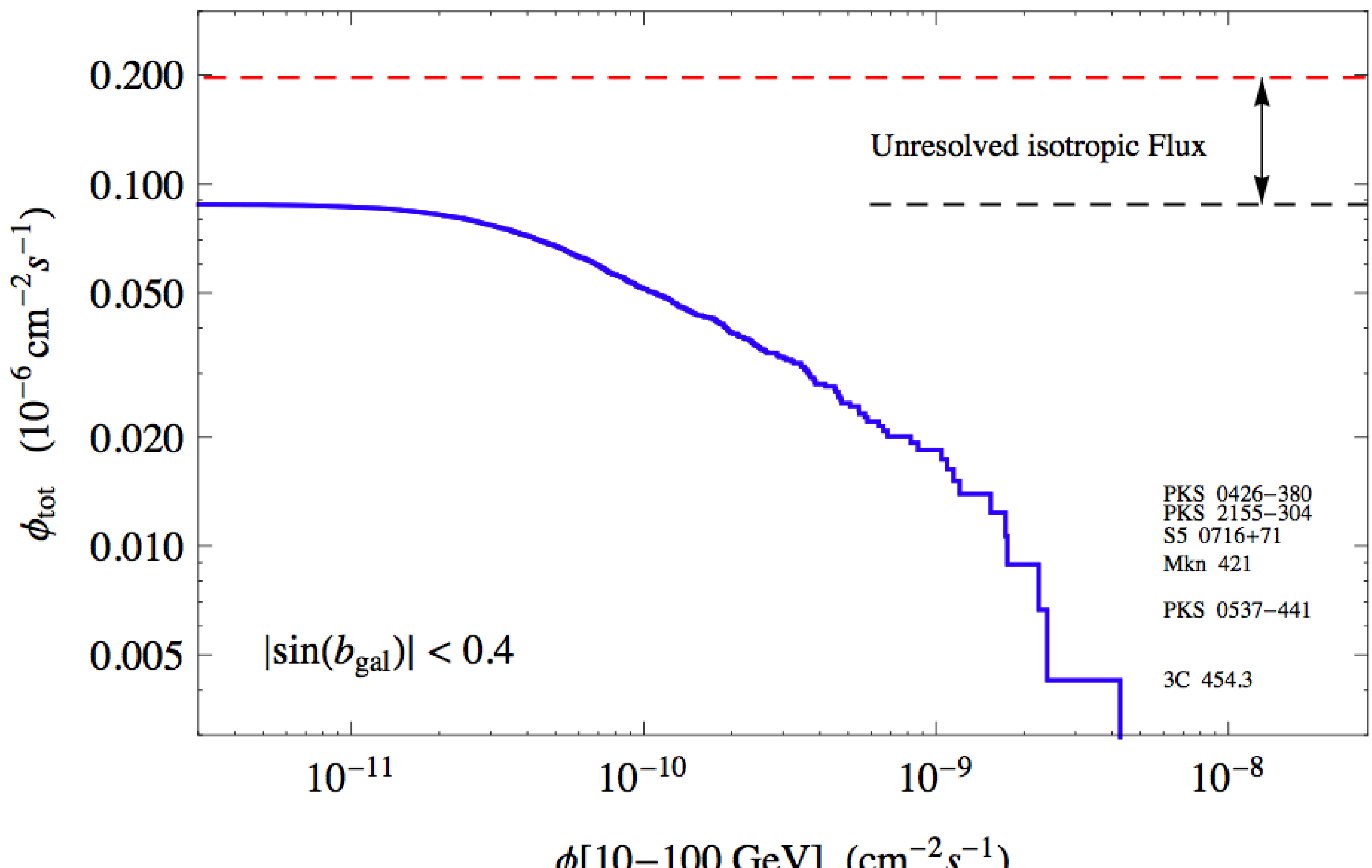
Very broad distribution of luminosity



Luminosity [1-100 GeV]

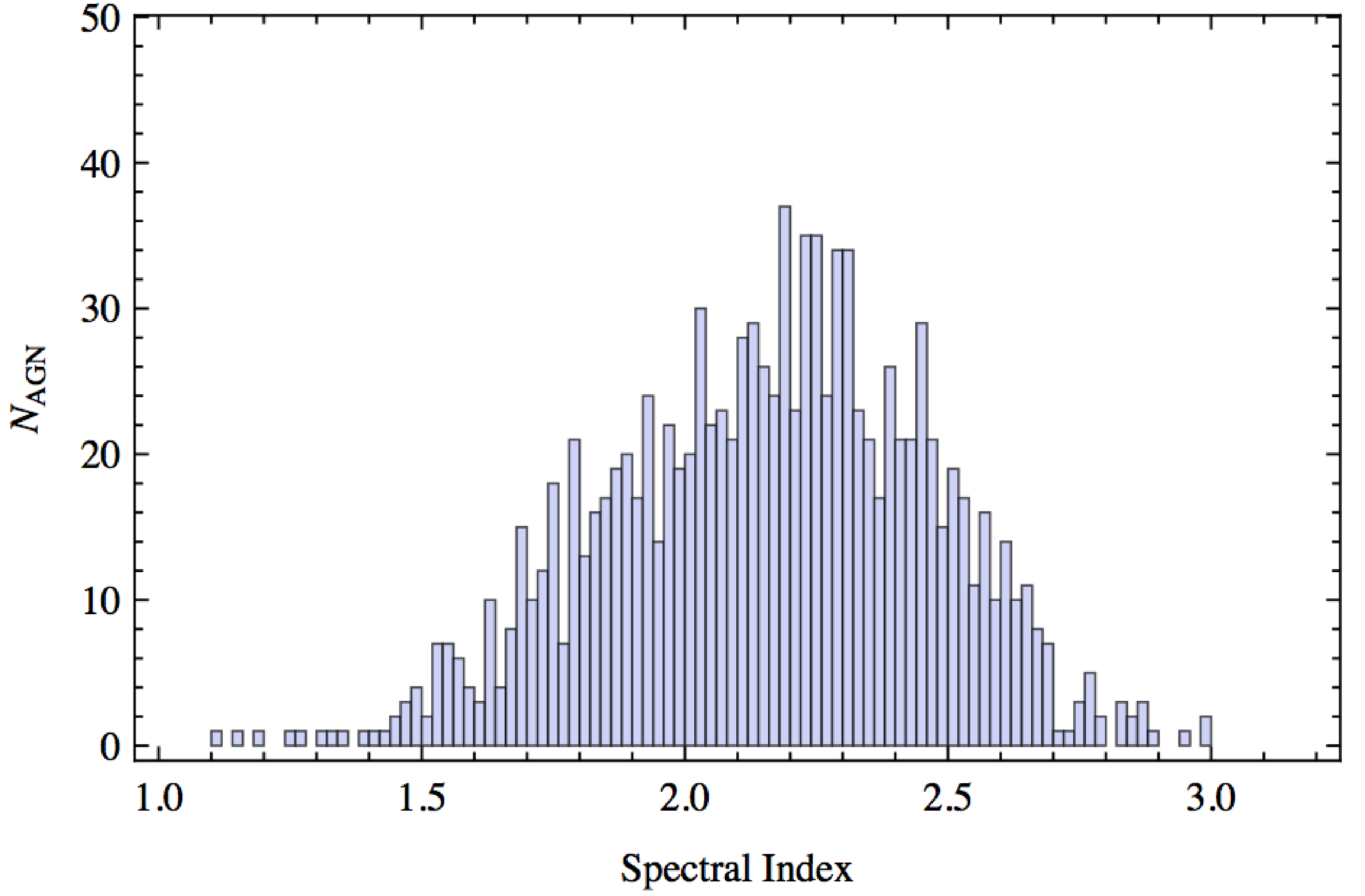


N_{sources}
100
80
60
40
20
0
−1.0
−0.5
0.0
0.5
1.0
$\sin[b_{\mathrm{gal}}]$

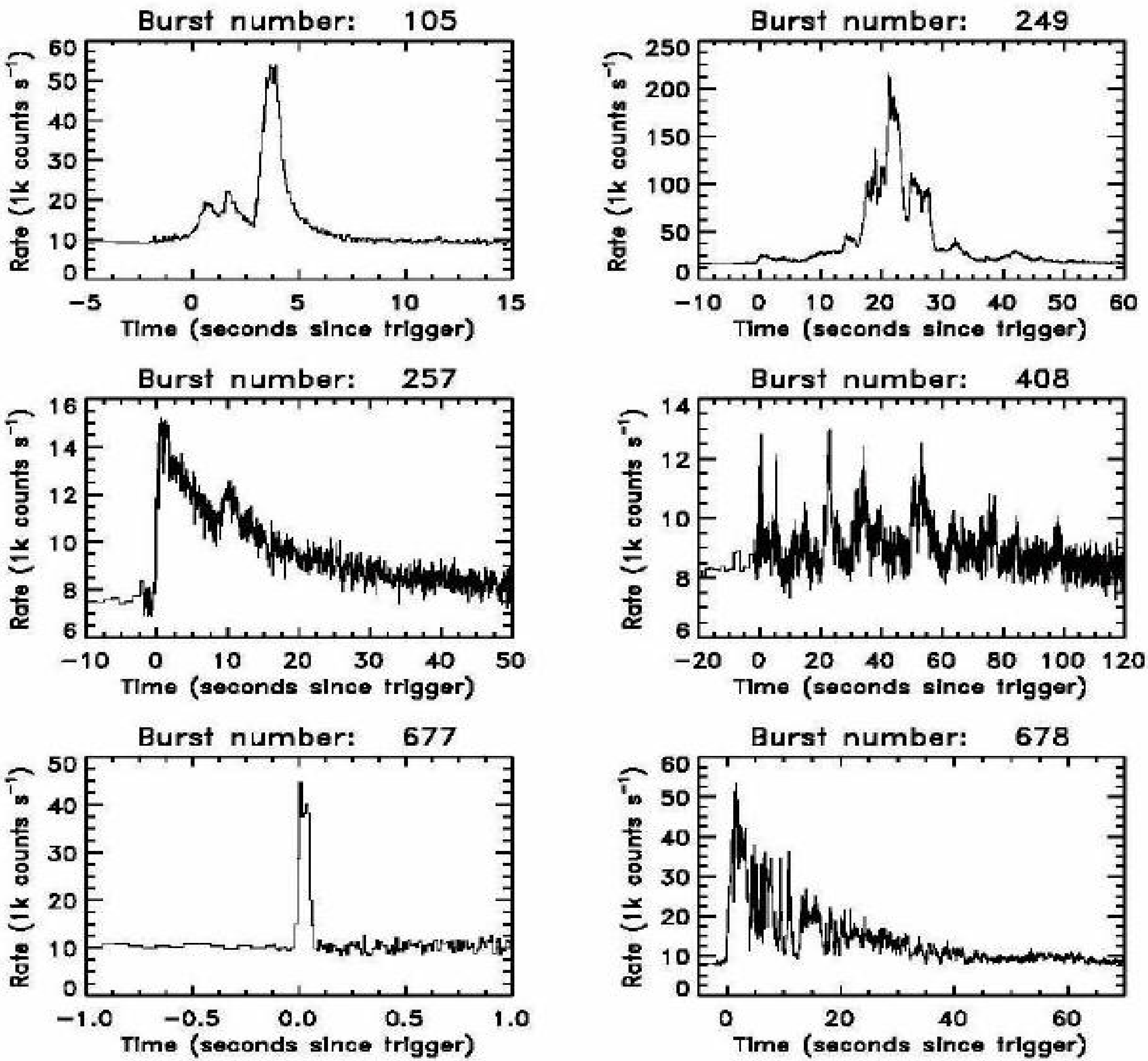


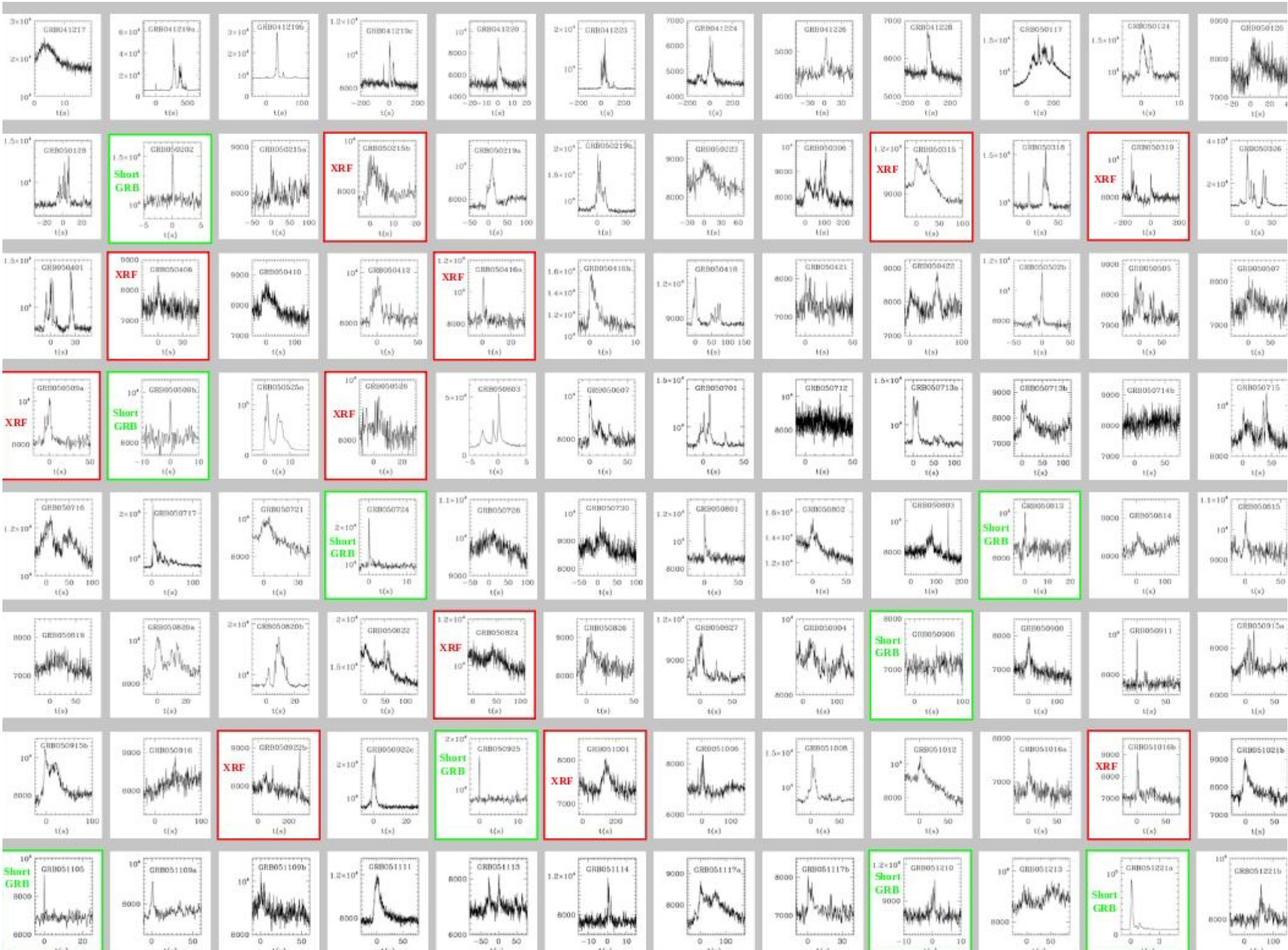
0.200
0.100
0.050
0.020
0.010
0.005
ϕ_{tot} $(10^{-6}\mathrm{cm}^{-2}s^{-1})$
Unresolved isotropic Flux
PKS 0426−380
PKS 2155−304
S5 0716+71
Mkn 421
PKS 0537−441
3C 454.3
$|\sin(b_{\mathrm{gal}})| < 0.4$
10^{-11}
10^{-10}
10^{-9}
10^{-8}
ϕ[10−100 GeV] $(\mathrm{cm}^{-2}s^{-1})$

Spectral Index of the Blazars in the FERMI 2LAC catalog.



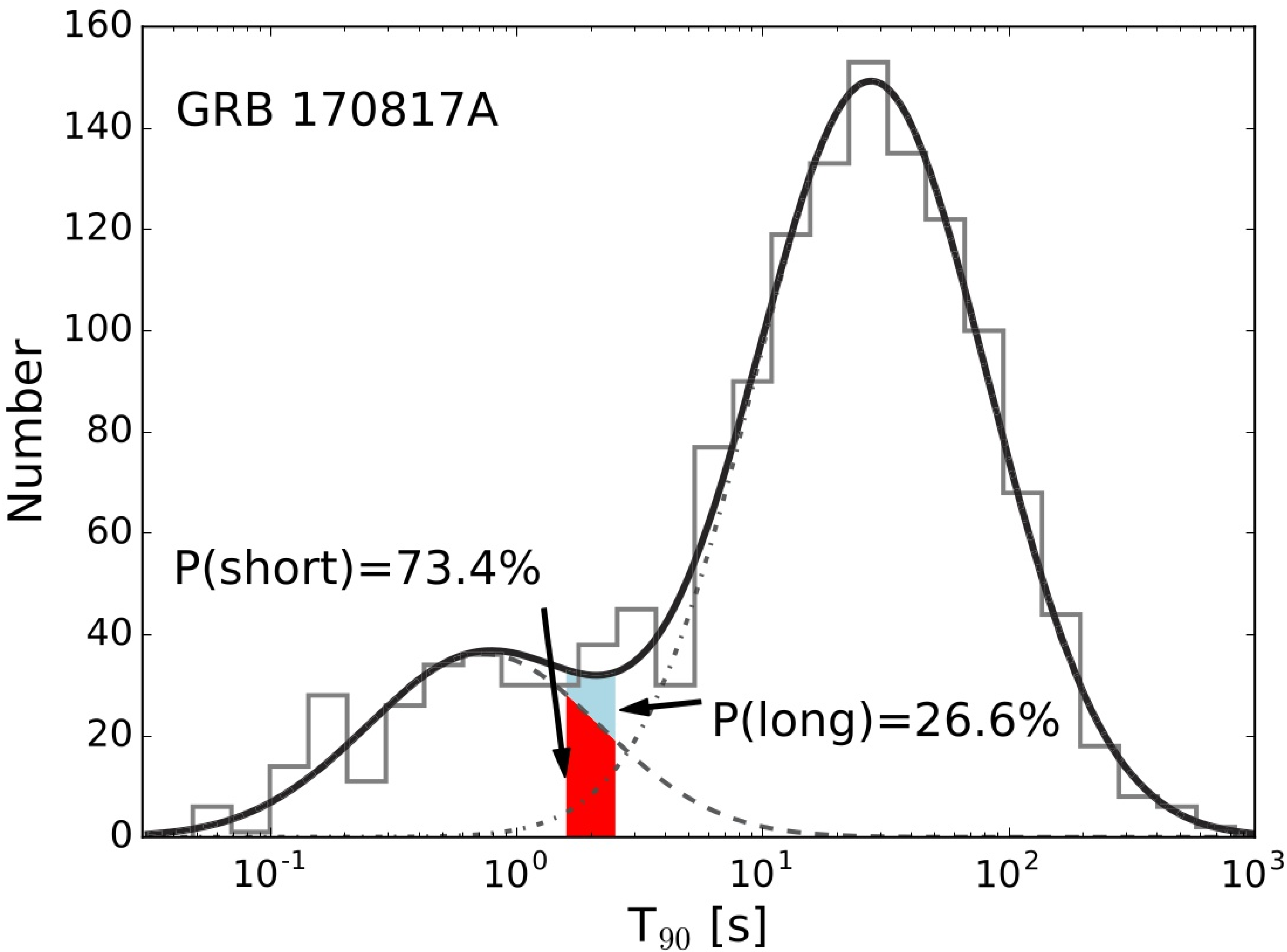
GAMMA RAY BURSTS (GRB's)

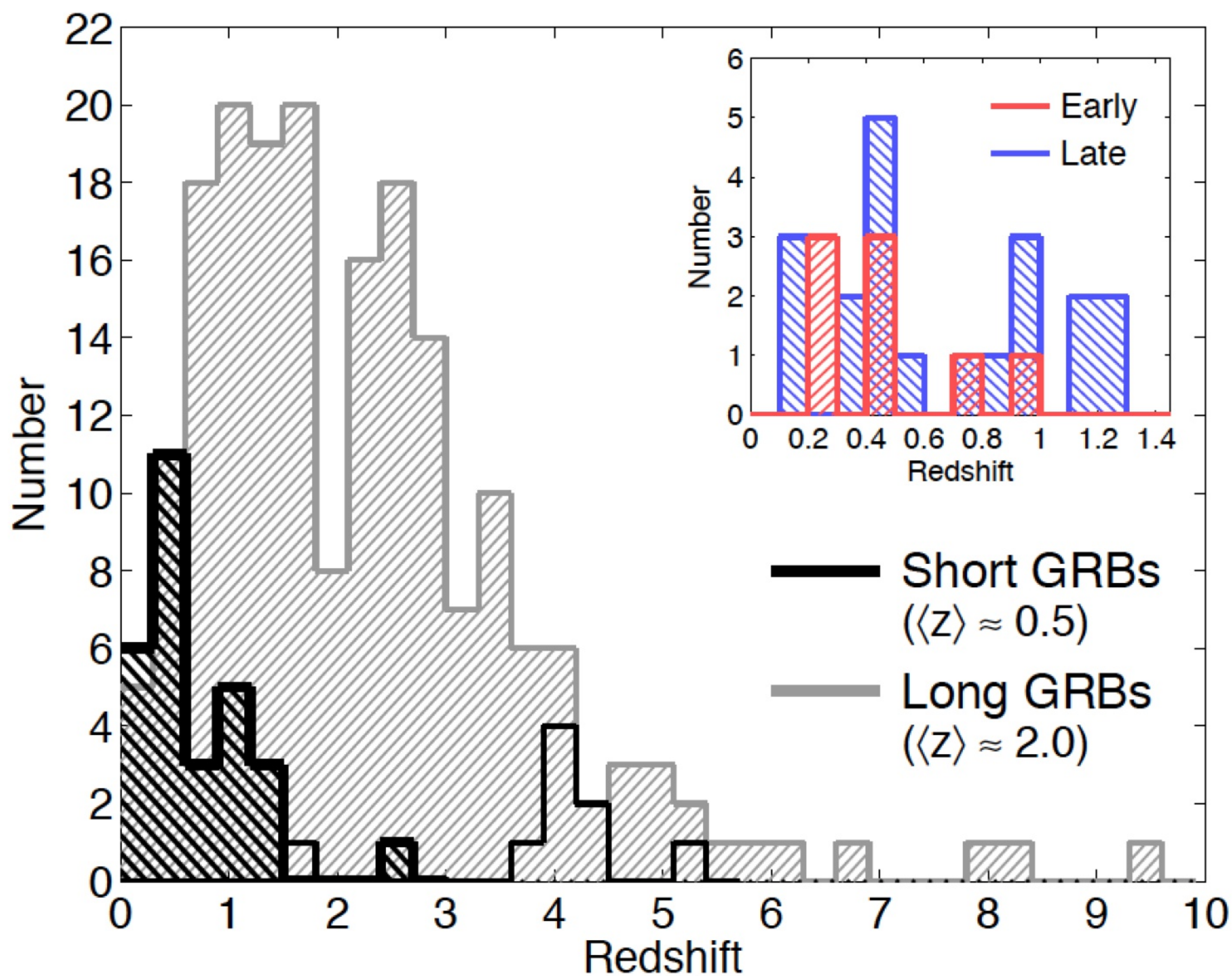




[From N. Gehrels]

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





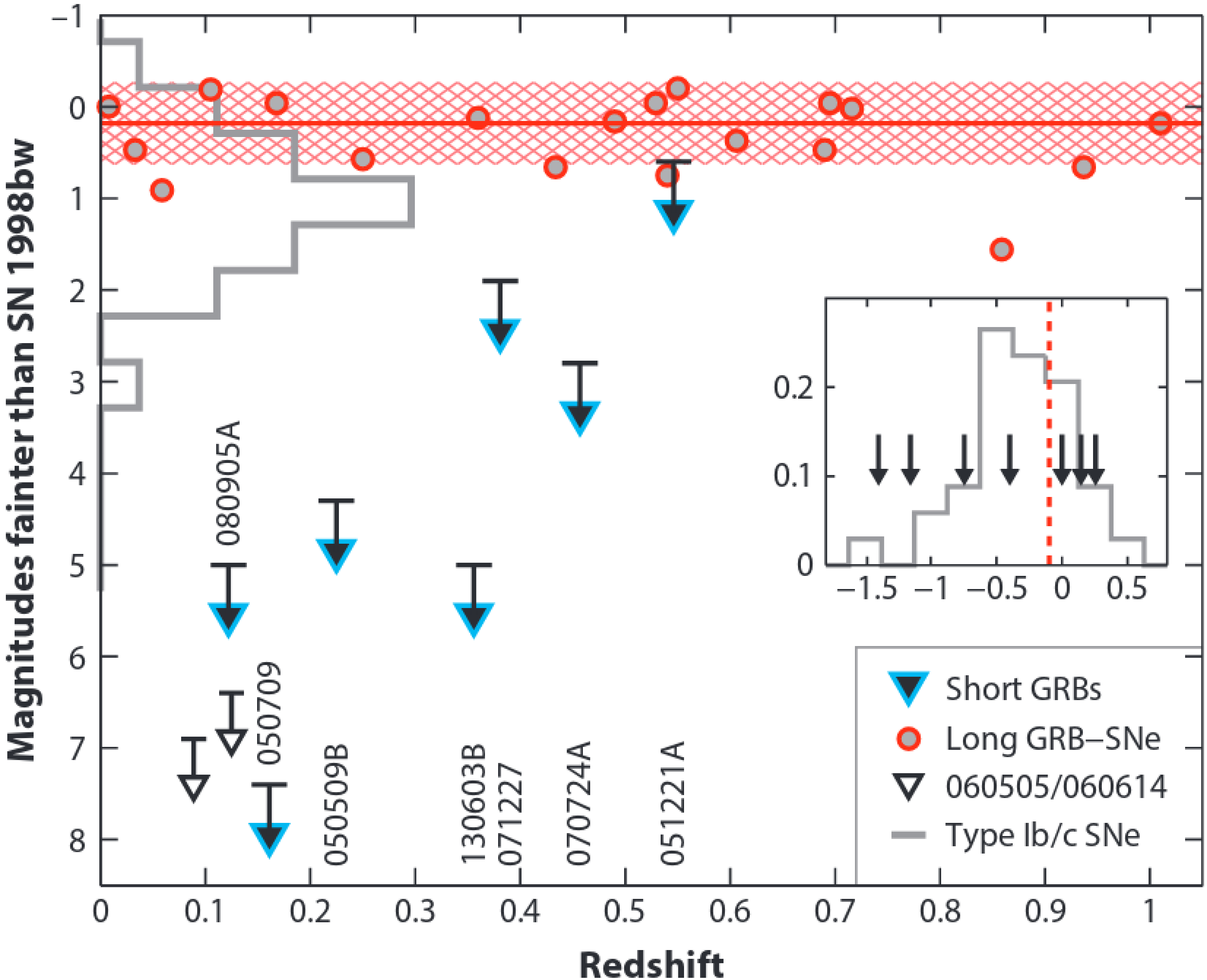
Number
Redshift
Short GRBs
(⟨z⟩ ≈ 0.5)
Long GRBs
(⟨z⟩ ≈ 2.0)
Early
Late

Association Long GRB's with SN explosions

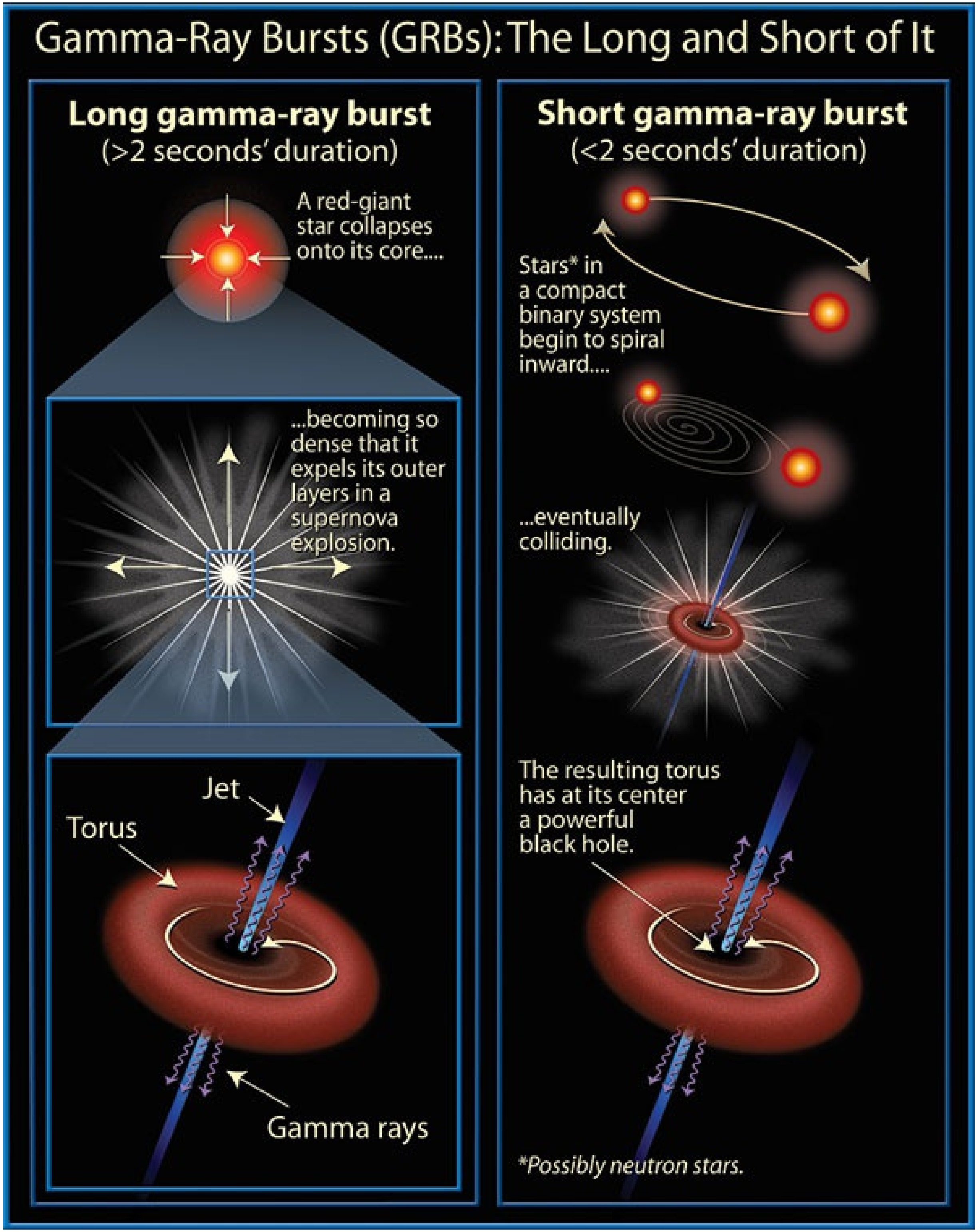
Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.

SN 1998bw

GRB 980425



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


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

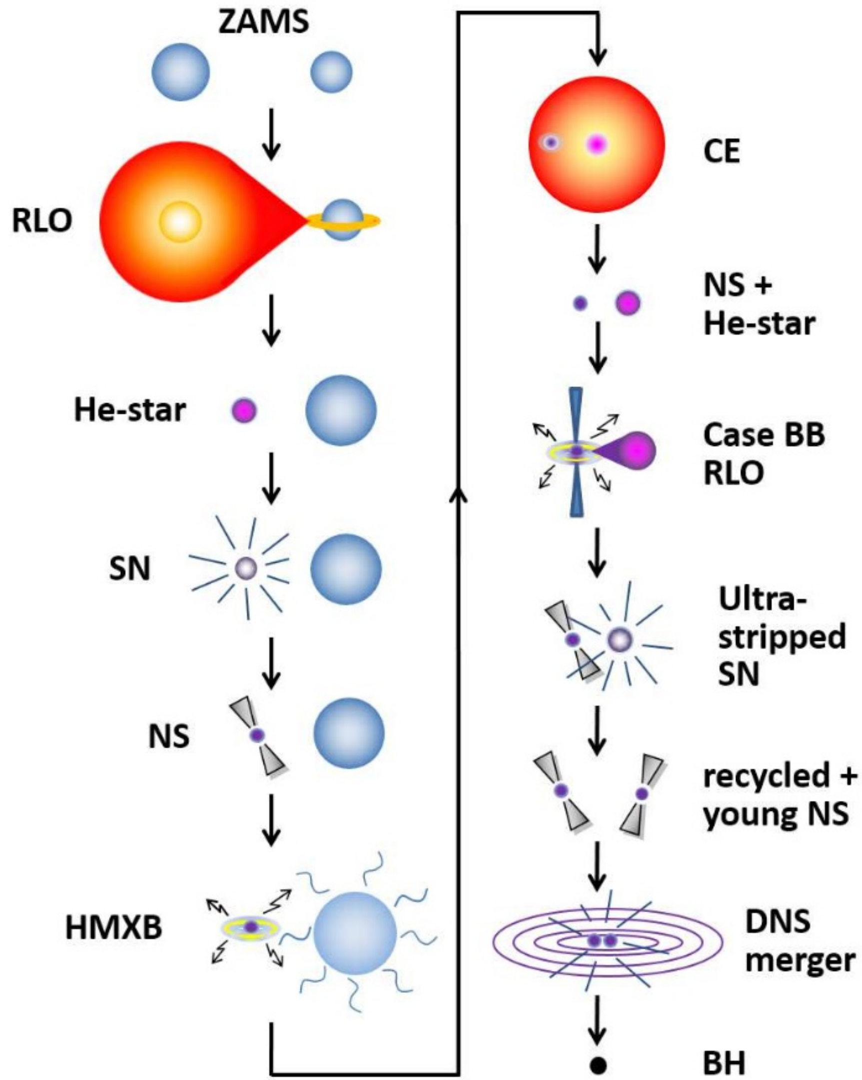


FIG. 1.— Illustration of the formation of a DNS system which merges within a Hubble time and produces a single BH, following a powerful burst of GWs and a short GRB. Acronyms used in this figure: ZAMS: zero-age main sequence; RLO: Roche-lobe overflow (mass transfer); He-star: helium star; SN: supernova;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

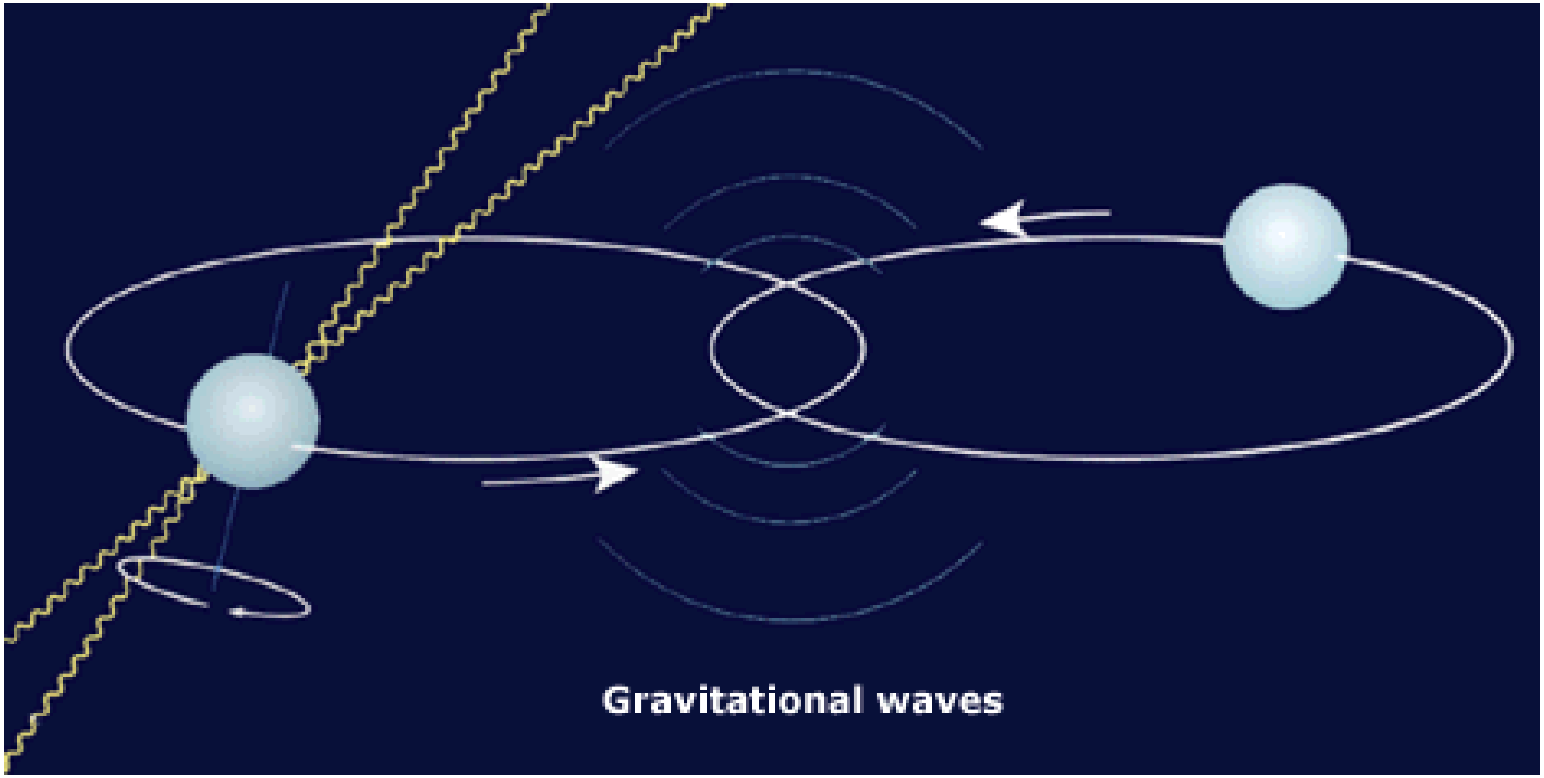
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

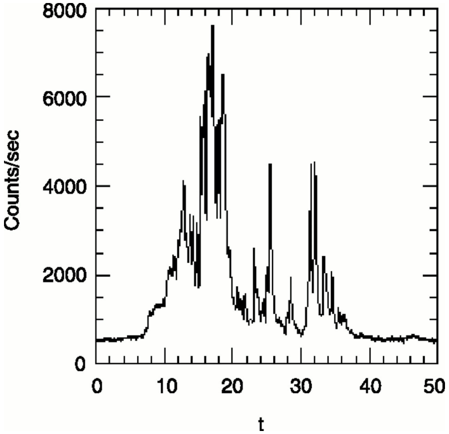
300 Myr
two neutron star coalesce

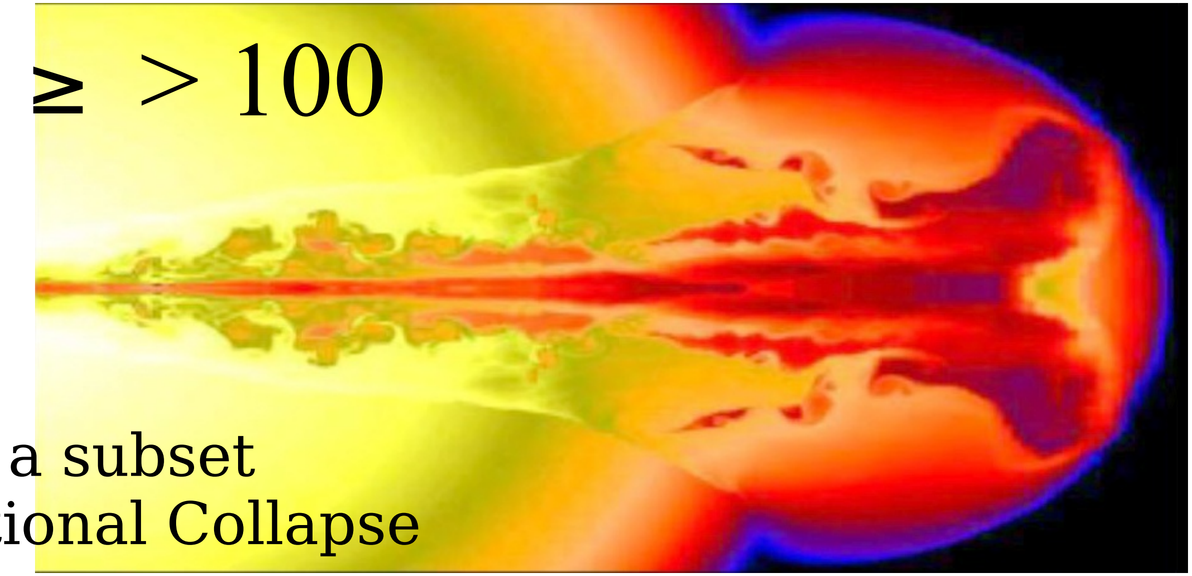
Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

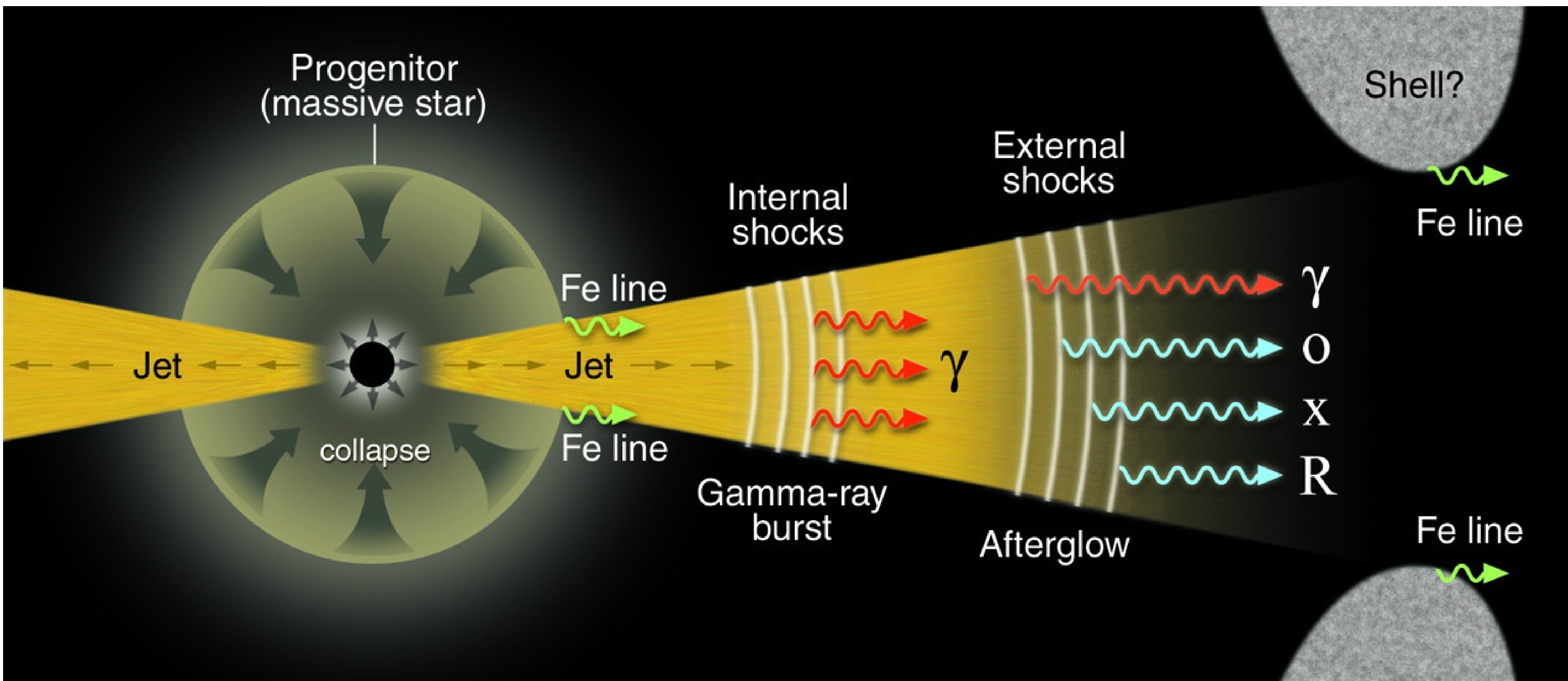
Orbit smaller
3.5 m/year







GRB : associated with a subset
of SN Stellar Gravitational Collapse

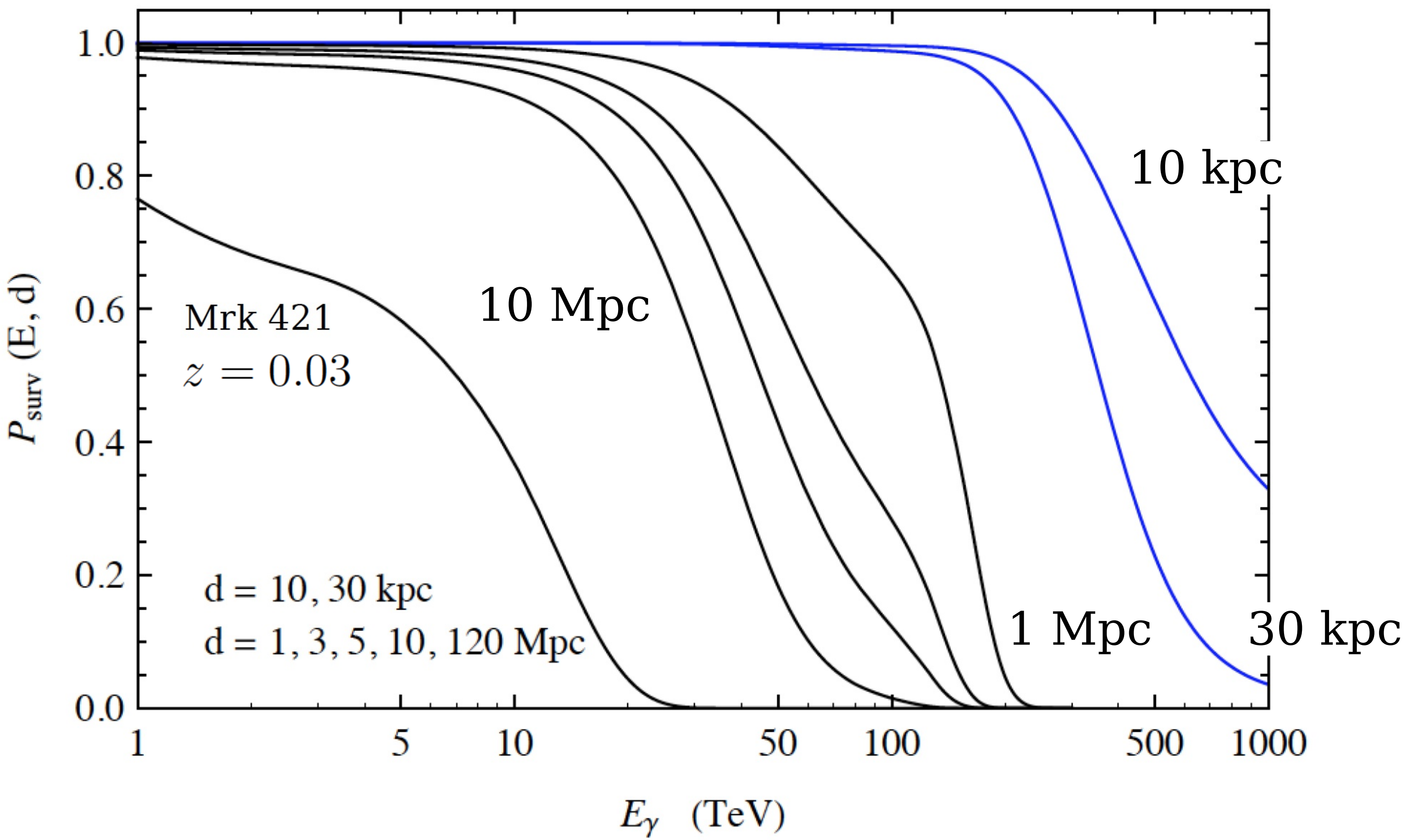


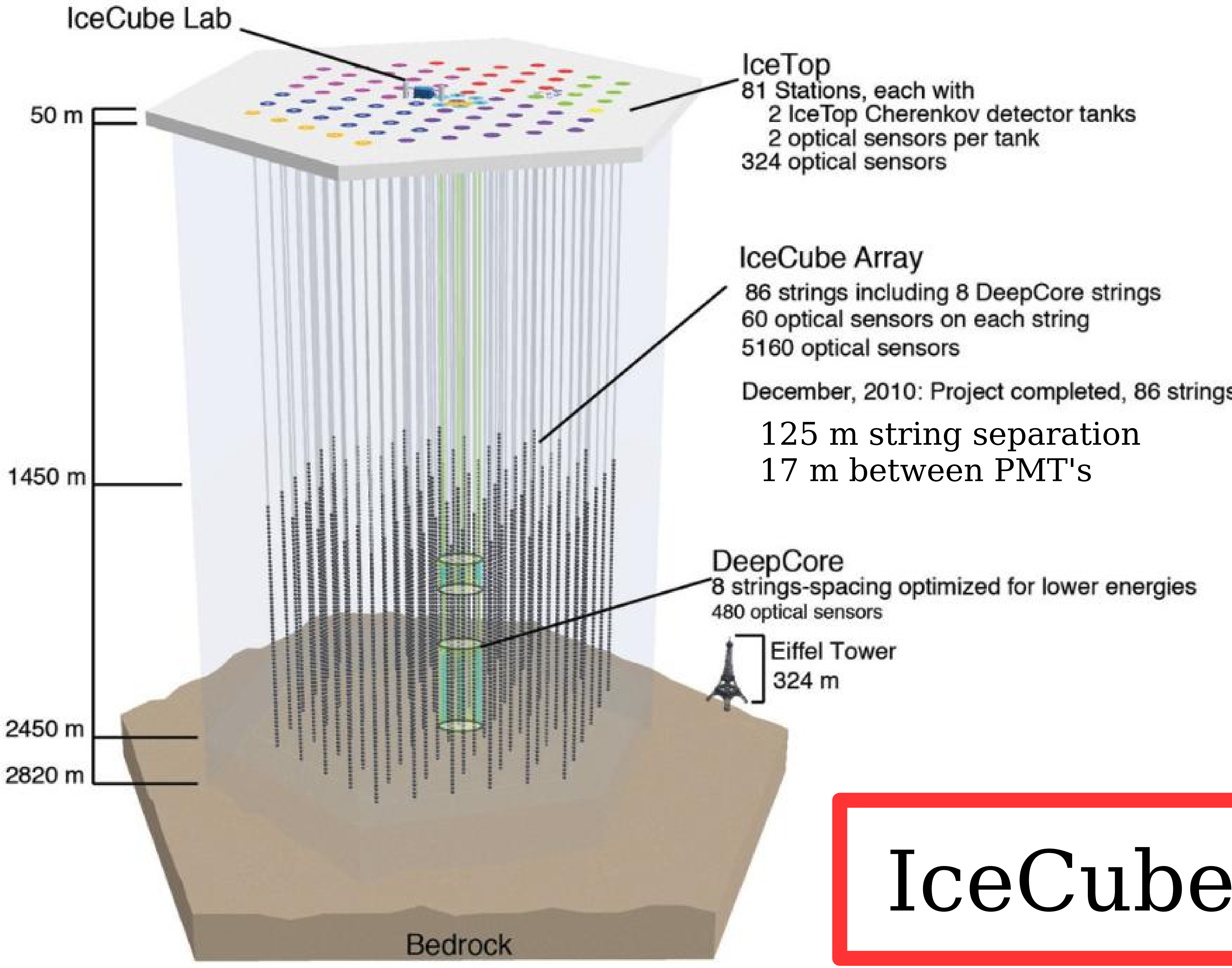
Neutrinos

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

Gamma Ray absorption
(intergalactic space)

Astronomy E>100 TeV :
Galactic Astronomy





125 m string separation
17 m between PMT's

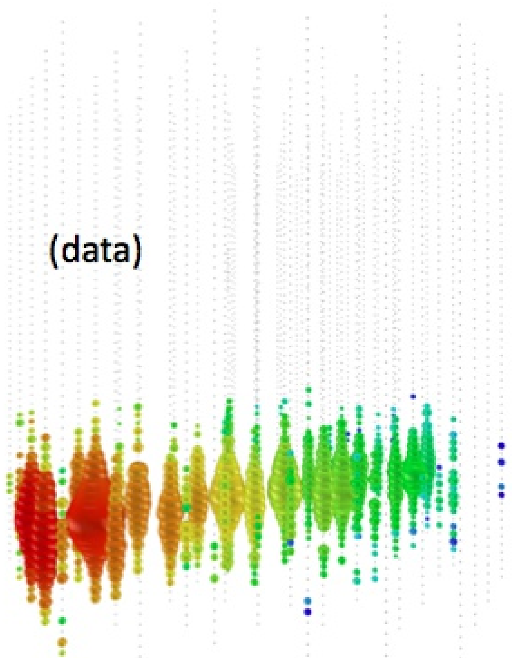
IceCube

$$
\begin{aligned}
\phi_{\nu_\alpha}(E,\Omega) = {} & \boxed{\phi_{\nu_\alpha}^{\text{atm. standard}}(E,\Omega) \\ + \phi_{\nu_\alpha}^{\text{atm. charm}}(E,\Omega)} \\
& + \boxed{\phi_{\nu_\alpha}^{\text{astro. extragalactic}}(E,\Omega) \\ + \phi_{\nu_\alpha}^{\text{astro. Galactic}}(E,\Omega)}
\end{aligned}
$$

Types of events and interactions

Charged-current ν_μ

(data)



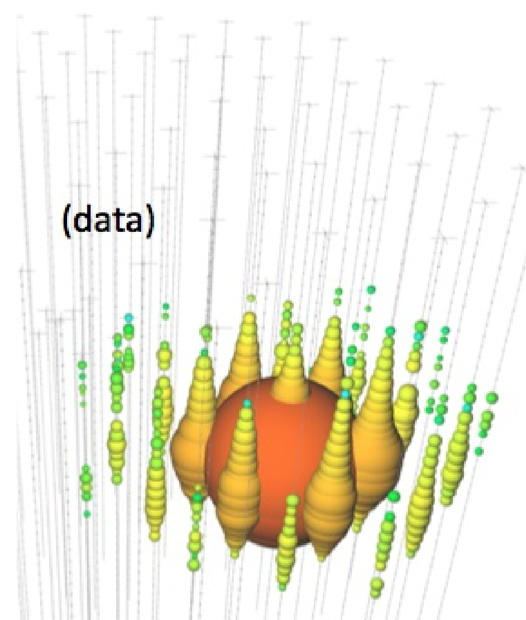
Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

Neutral-current / ν_e

(data)

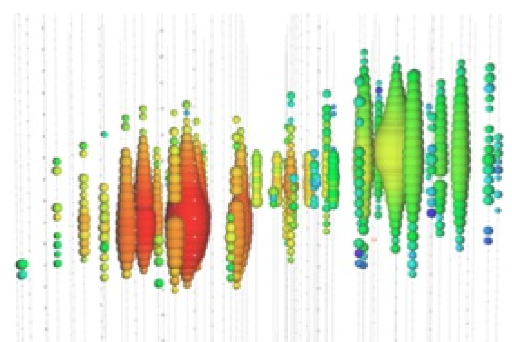


Isolated energy deposition
(cascade) with no track

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

Charged-current ν_τ

(simulation)



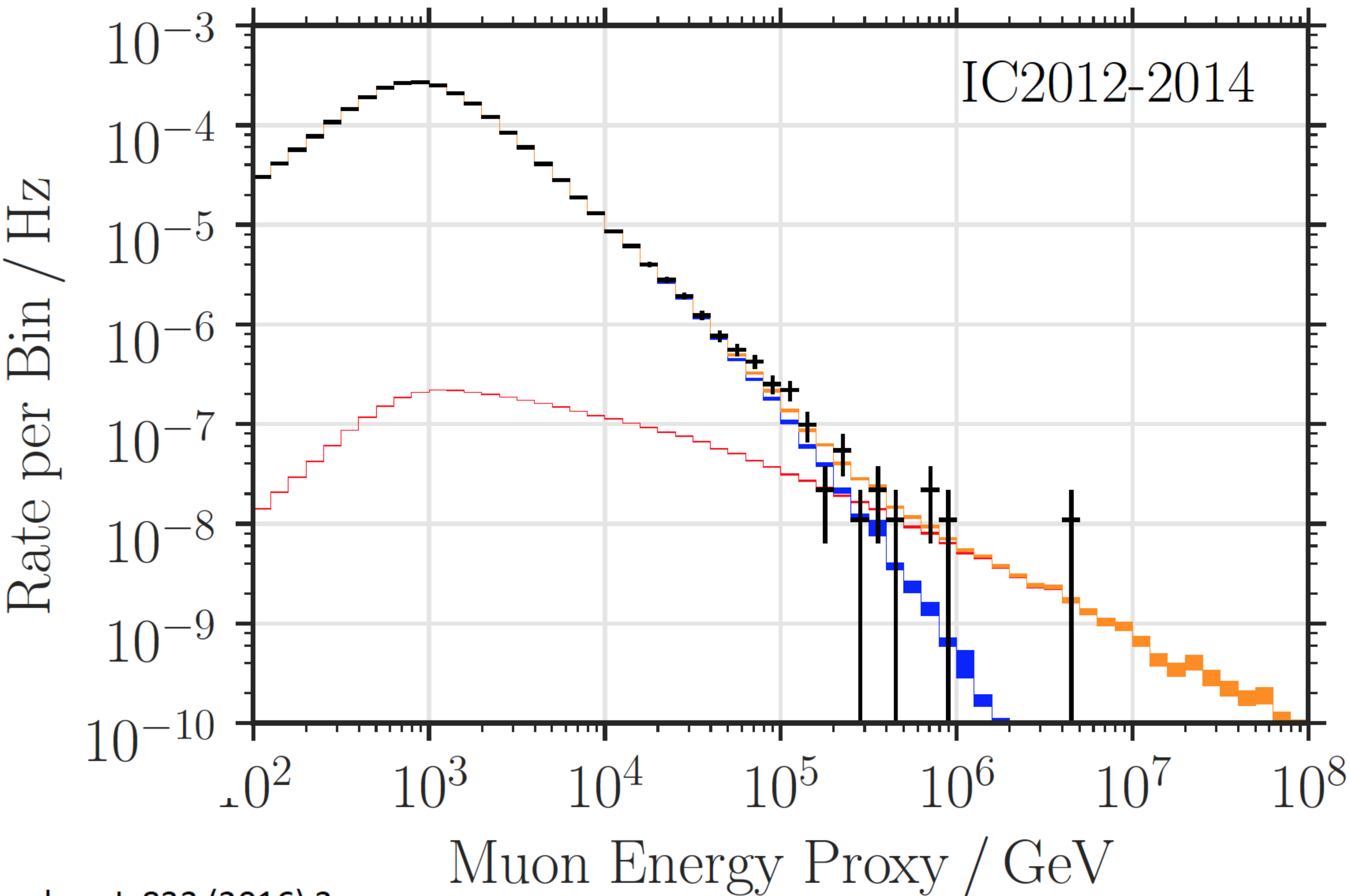
"Double-bang"

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

ID: above~ 100 TeV
(two methods)

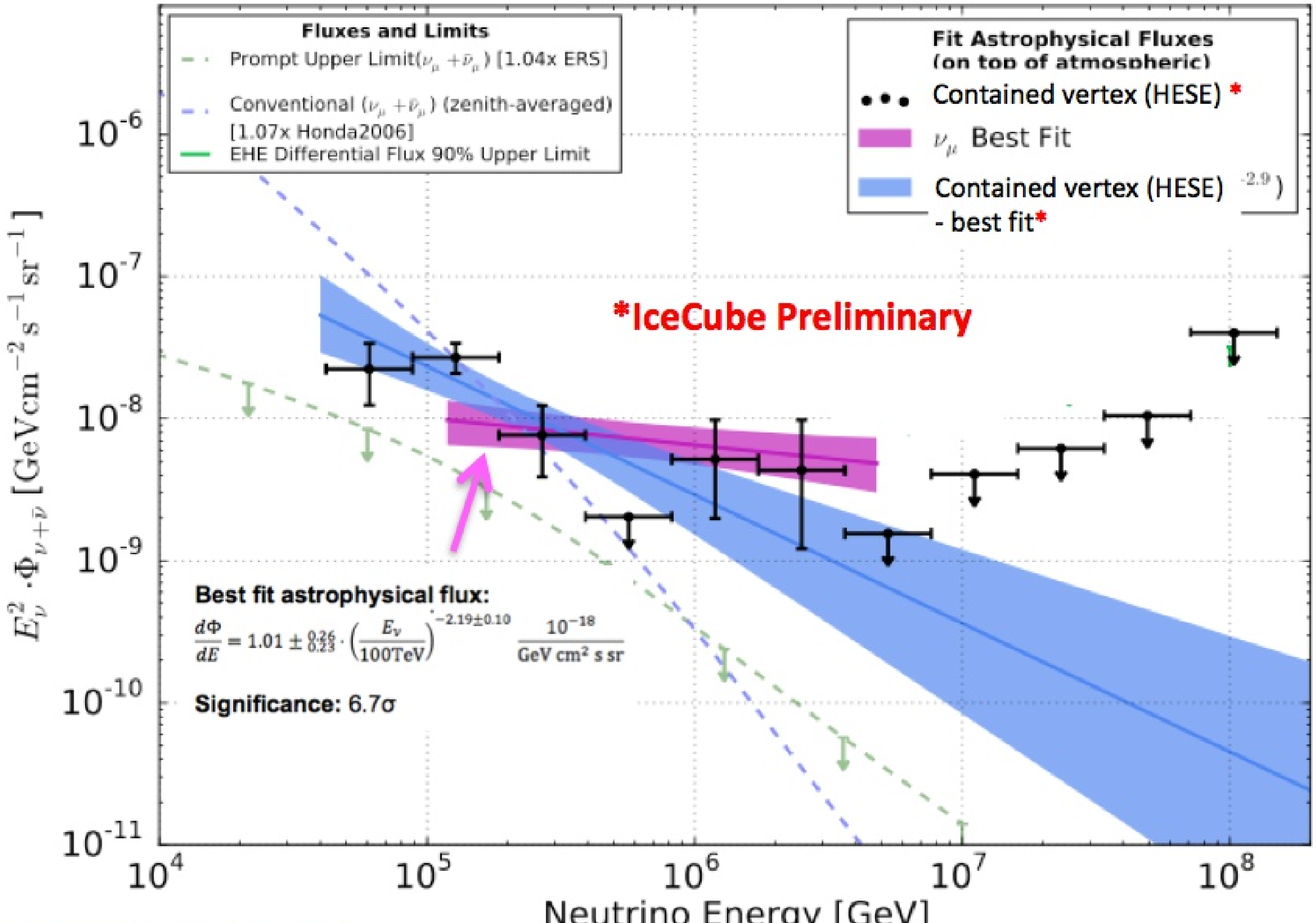
Early  Late

Upgoing (neutrino induced) Muons



Astrophys. J. 833 (2016) 3

Energy spectrum with these event samples:
1.) upgoing muon neutrinos 2.) contained vertex events



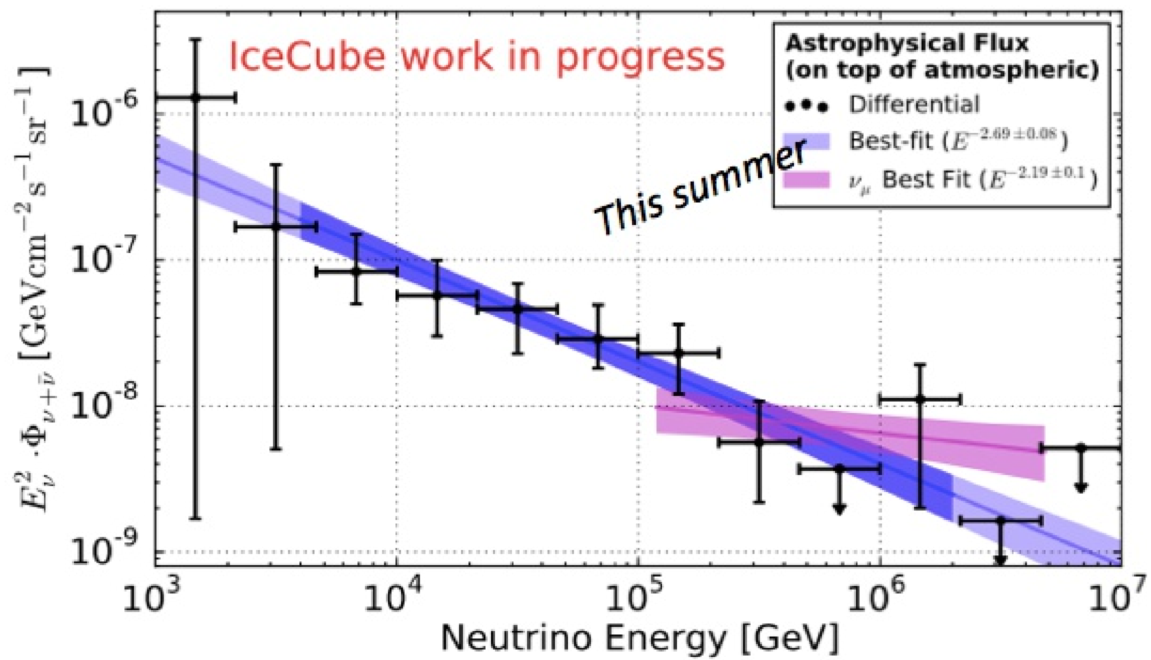
ICRC 2017: Kopper, Wandkowsky for IceCube C.
ICRC 2017: Haack for IceCube C.

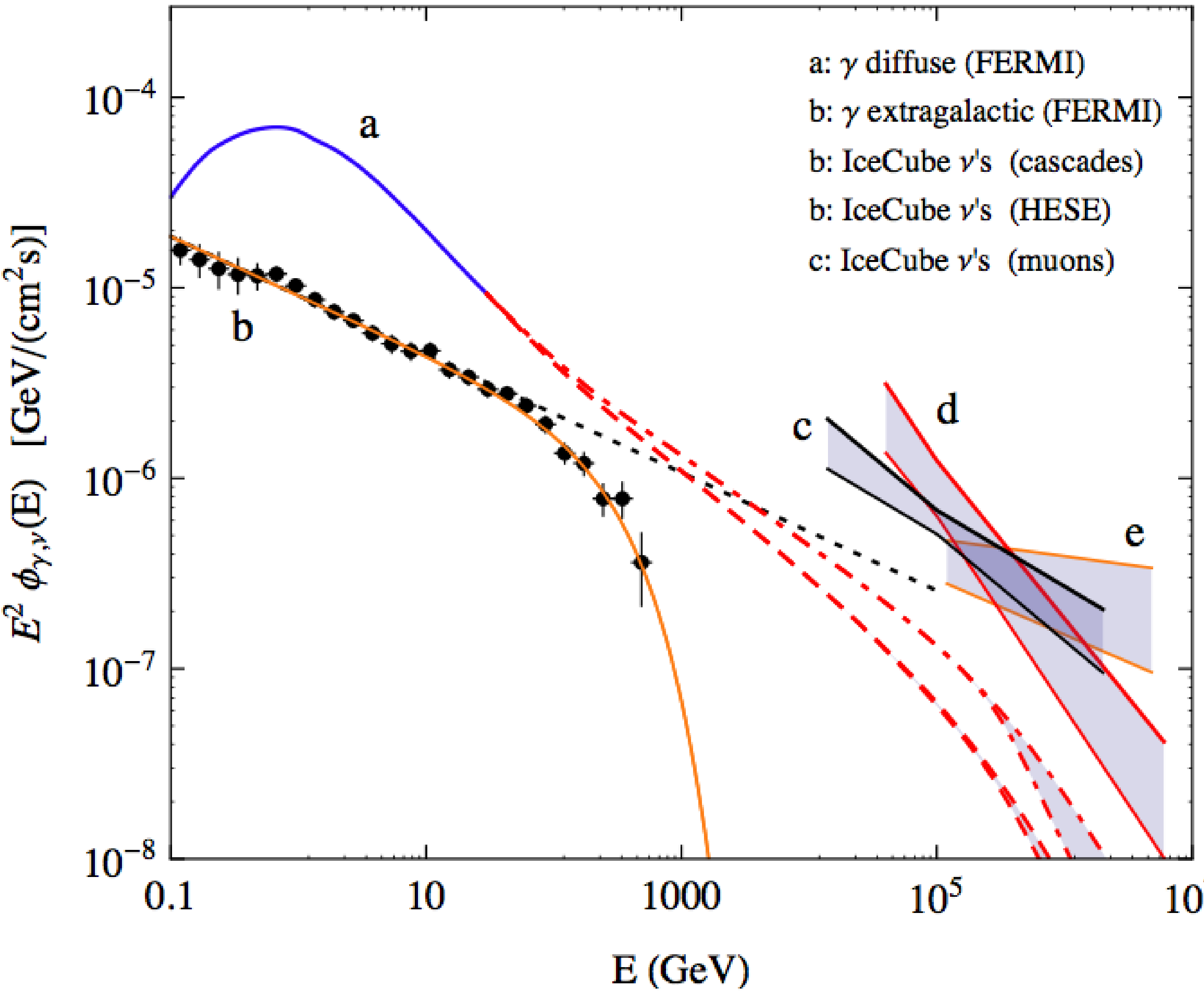
Low-threshold starting events (2010-2016)

7-yr unfolding

Systematics not included yet!

- Unfolding to neutrino energy:
  - assume isotropic flux, $\nu_e:\nu_\mu:\nu_\tau=1:1:1$, $\nu:\bar{\nu}=1:1$
  - compatible with through-going muons in sensitive energy range





a: γ diffuse (FERMI)
b: γ extragalactic (FERMI)
b: IceCube ν's (cascades)
b: IceCube ν's (HESE)
c: IceCube ν's (muons)
a
b
c
d
e
$E^2\,\phi_{\gamma,\nu}(E)$ [GeV/(cm^{2}s)]
E (GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.1
10
1000
10^5
10^7

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 ?

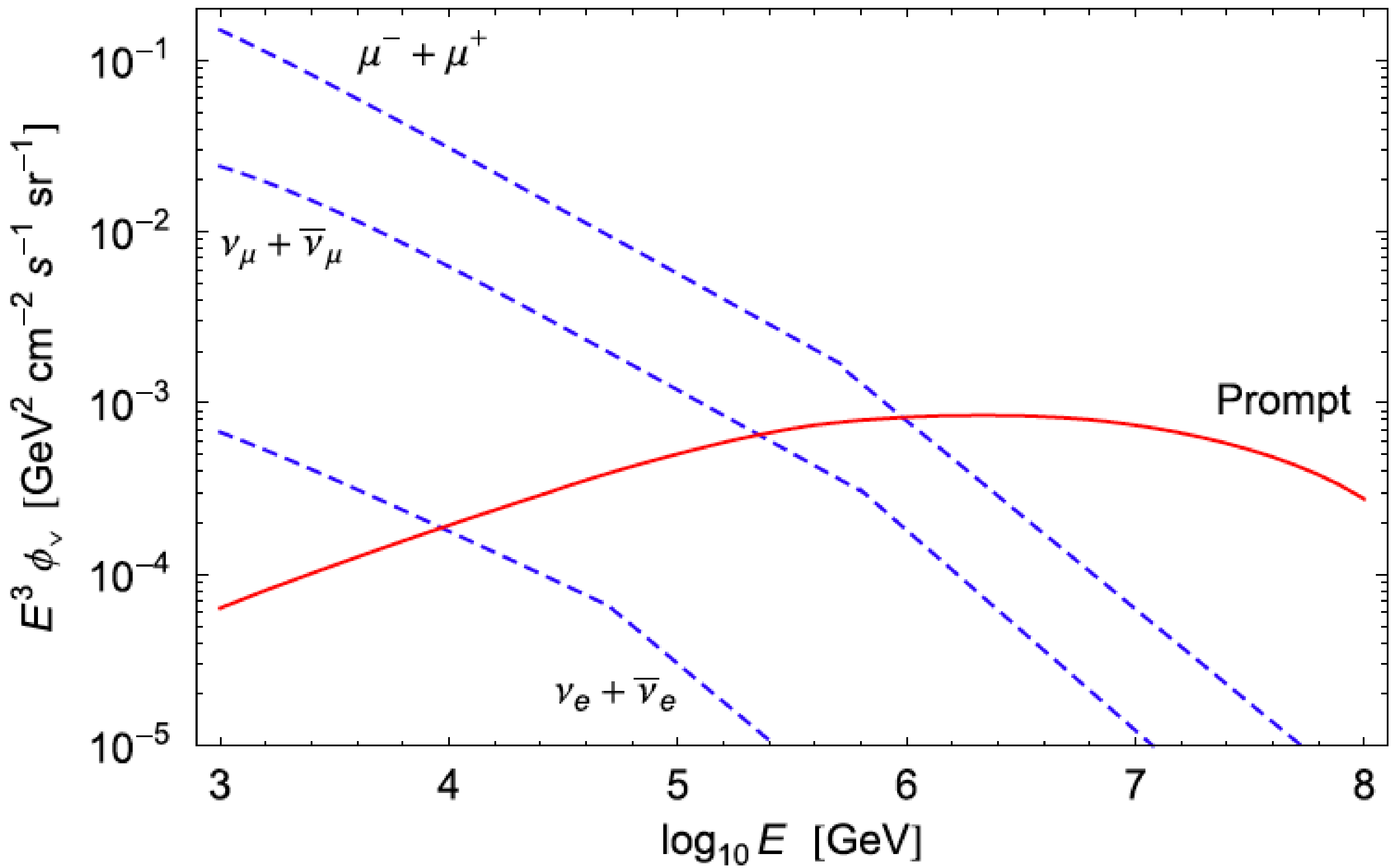
3a. If there is a Galactic (perhaps subdominant) component what is its nature ?

PHYSICAL REVIEW D 78, 043005 (2008)

Prompt neutrino fluxes from atmospheric charm

Rikard Enberg,[1] Mary Hall Reno,[2] and Ina Sarcevic[1,3]

Calculation used as reference by IceCube



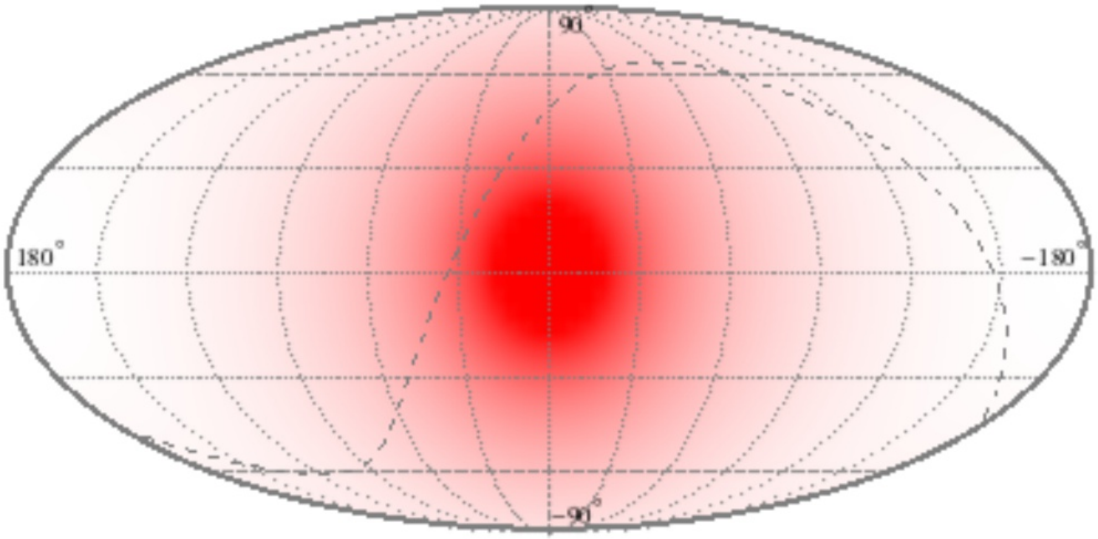
Note: Uncertainties = *Primary Flux * Charm production*

Does the IceCube signal have a Galactic component ?

There are models where the signal is *entirely* of Galactic origin.

A. Esmaili and P. D. Serpico,
"Are IceCube neutrinos unveiling PeV-scale decaying dark matter?,"
JCAP **1311**, 054 (2013)
[arXiv:1308.1105 [hep-ph]].

Expected angular distribution distribution

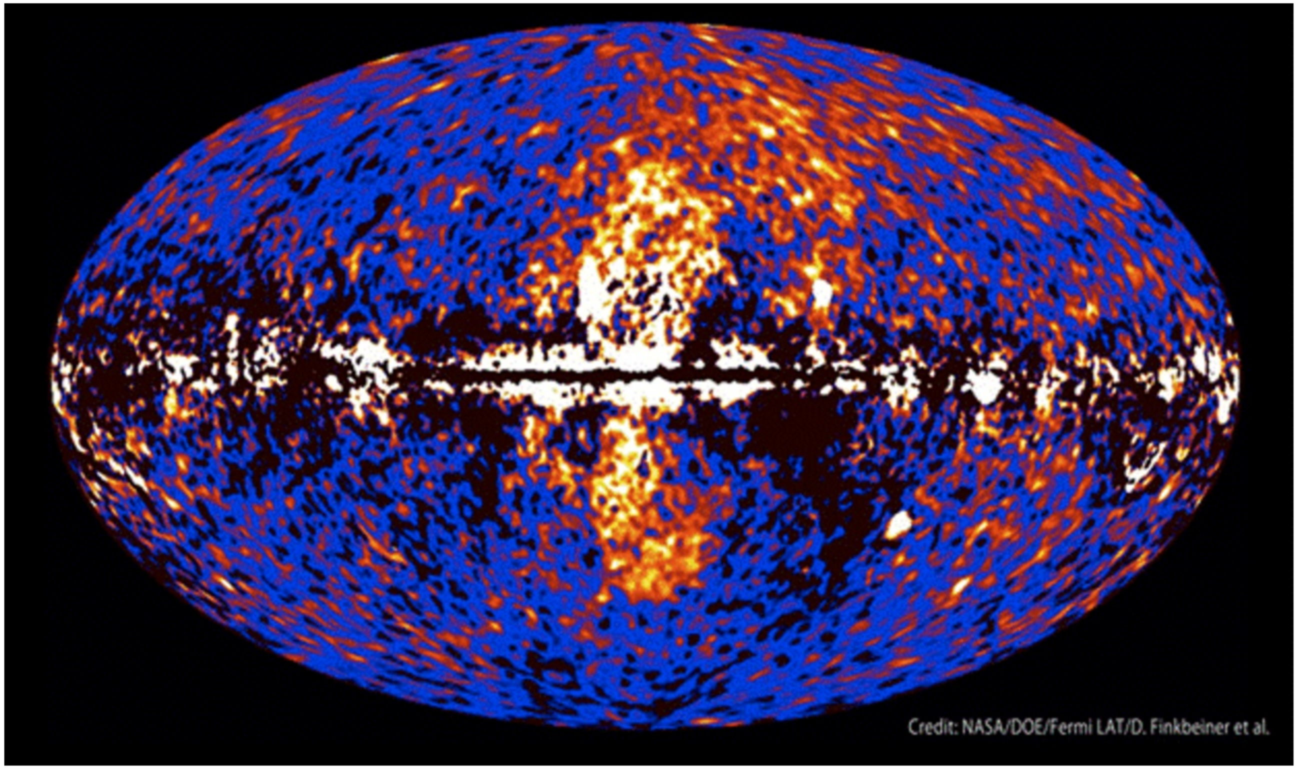


(a) PDF of DM decay

A. M. Taylor, S. Gabici and F. Aharonian,
"Galactic halo origin of the neutrinos detected by IceCube,"
Phys. Rev. D **89**, no. 10, 103003 (2014)
doi:10.1103/PhysRevD.89.103003 [arXiv:1403.3206 [astro-ph.HE]].

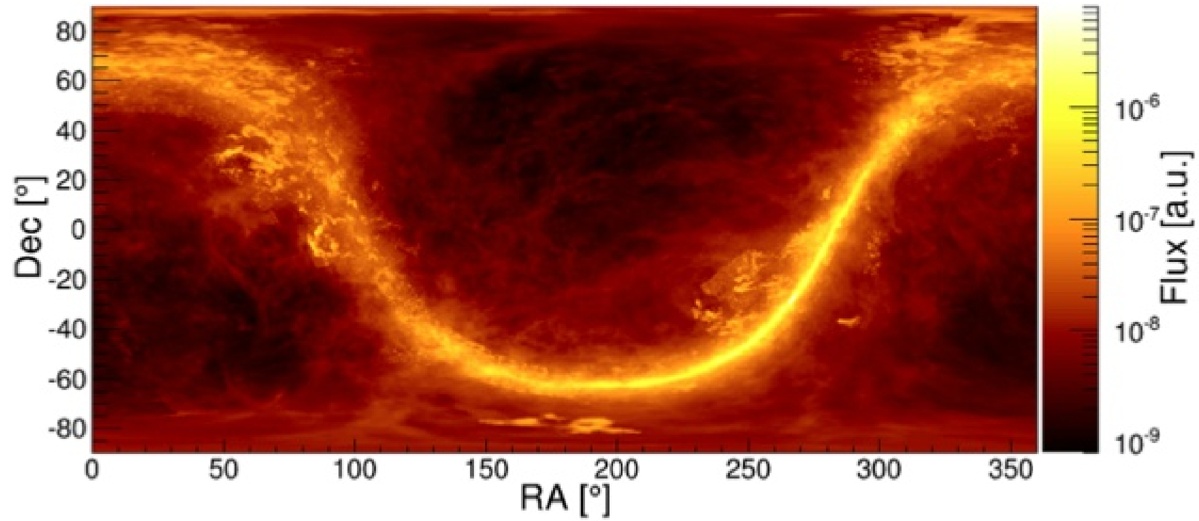
Very large (100 kpc) halo of cosmic rays

[Inspired (to a large extent) by the observations of the "Fermi Bubbles"]



What fraction of the cosmic neutrino flux comes from the Milky Way?

Galactic contribution (from disk)?



Gamma ray skymap of FERMI satellite data in equatorial coordinates:

Answer: < 16%

Compared to best fit spectrum in this energy range ($E^{-2.5}$ flux)

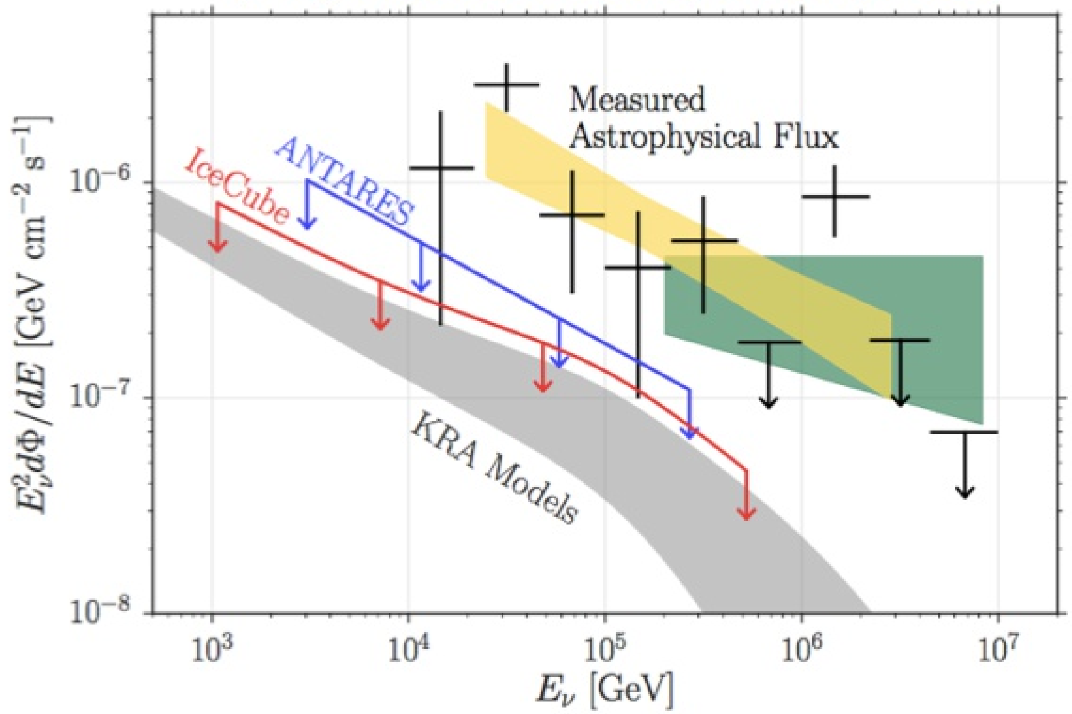
arXiv:1707.0341

Can we see the diffuse galactic neutrino flux?

Answer: Not yet.

Possible improvements by using more info from Southern Sky:
- Cascade channel
- Optimized starting muon channel using atmospheric self-veto (ESTES)

(Integrated over whole sky for comparison)



arXiv:1707.0341

Table 2. Summary of results for both Galactic plane analysis methods for each of the three models.

	ps-template method				diffuse-template method		
Spatial Template	n_s	p-value	Sensitivity $\phi_{90\%}$	Upper Limit $\phi_{90\%}$	p-value	Sensitivity $\phi_{90\%}$	Upper Limit $\phi_{90\%}$
Fermi-LAT π^0-decay, $E^{-2.5}$	149	37%	2.97×10^{-18}	3.83×10^{-18}	7.0%	3.16×10^{-18}	6.13×10^{-18}
KRA-γ (50 PeV)	98	29%	79%	120%	6.9%	95%	170%
Ingelman & Thunman	169	41%	220%	260%	19.8%	260%	360%

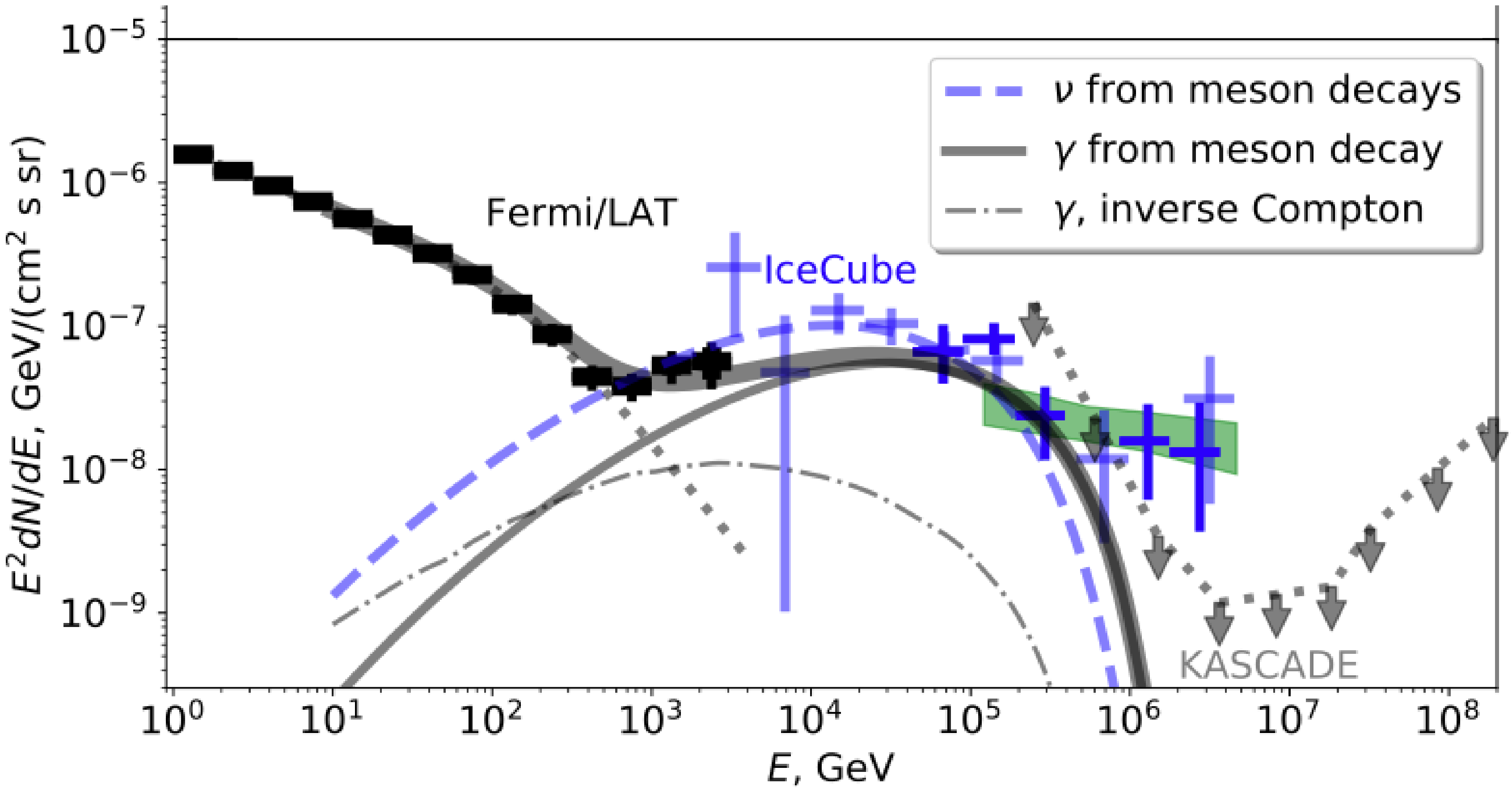
NOTE—Best-fit number of signal events n_s. Fluxes are integrated over the full sky and parameterized as $d\phi_{\nu_\mu+\bar{\nu}_\mu}/dE = \phi_{90\%} \cdot (E/100\text{ TeV})^{-2.5}$ GeV^{-1} cm^{-2} s^{-1} with 90% confidence level upper limits and median sensitivities quoted for $\phi_{90\%}$ or as a percentage relative to the model prediction.

arXiv:1802.09983v1

A *"daring, ambitious and controversial"* paper

Discovery of the multi-messenger gamma-ray counterpart of the IceCube neutrino signal

A. Neronov[1], M. Kachelrieß[2] and D. V. Semikoz[3,4]



The *“excess of gamma rays”*
that, according to Neronov, Kachelriess & Semikoz,
emerge as sharp hardening of the flux around 1 TeV
appears at large Galactic Latitudes $|b| > 20^{\circ}$
and is *consistent with being isotropic*
[the flux on the Galactic disk is consistent
with “standard” expectation]

Note: An hadronic background contamination effect
would result in an isotropic effect.

Possible interpretations ?
1. DM decay model is disfavored
   (but perhaps not excluded)

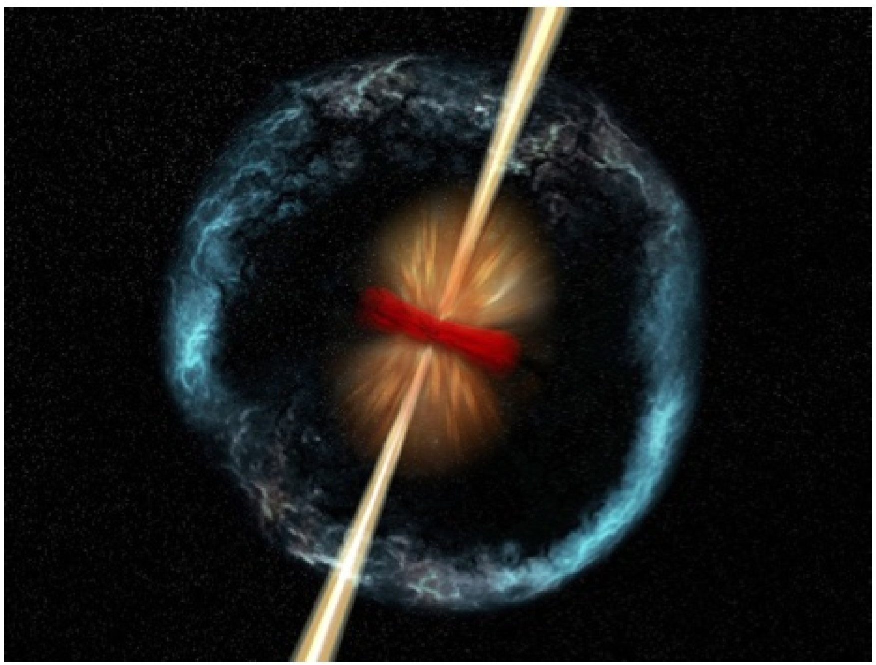
2. Large Galactic halo “*a la* Taylor, Gabici and Aharonian” [?]

The result must be verified independently
(and *“certified”* by the FERMI team)

Its is either wrong or very important

What fraction of the cosmic neutrino flux comes from prompt GRB?

Gamma Ray Bursts



807 GRB's monitored for prompt neutrino emission at TeV to PeV energy range.

Illustration credit: NASA/CXC/M.Weiss

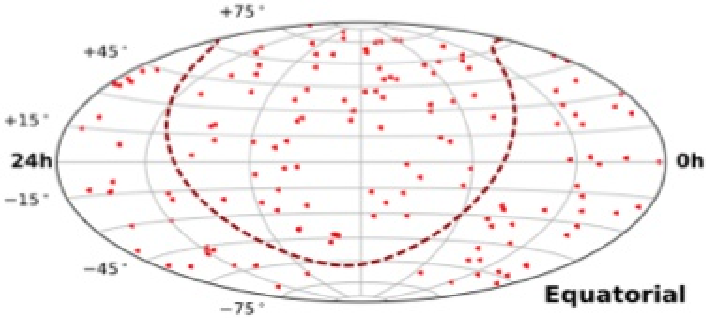
Answer: < 1%

Ref: arxiv: 1702.06868

What fraction of the cosmic neutrino flux comes from Fermi blazars?

Active Galaxies - Blazars

AGN with supermassive black hole, with Jet pointing at us.

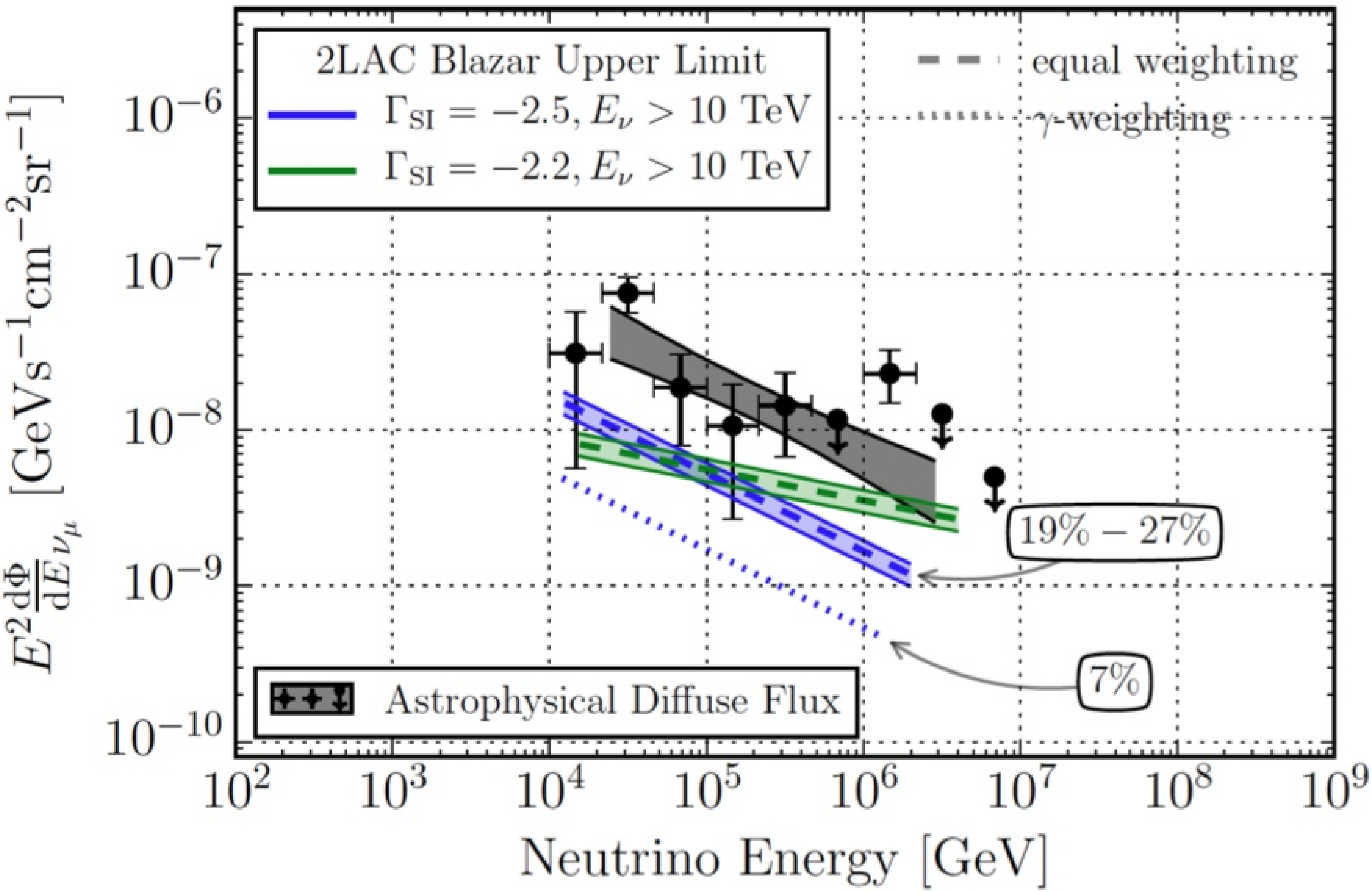


Fermi reports that ~85% of the gamma rays from the "diffuse" gamma ray flux originate fro blazars.

Answer: only a small fraction (< 6% to 27%) of events from Fermi blazar catalogues.

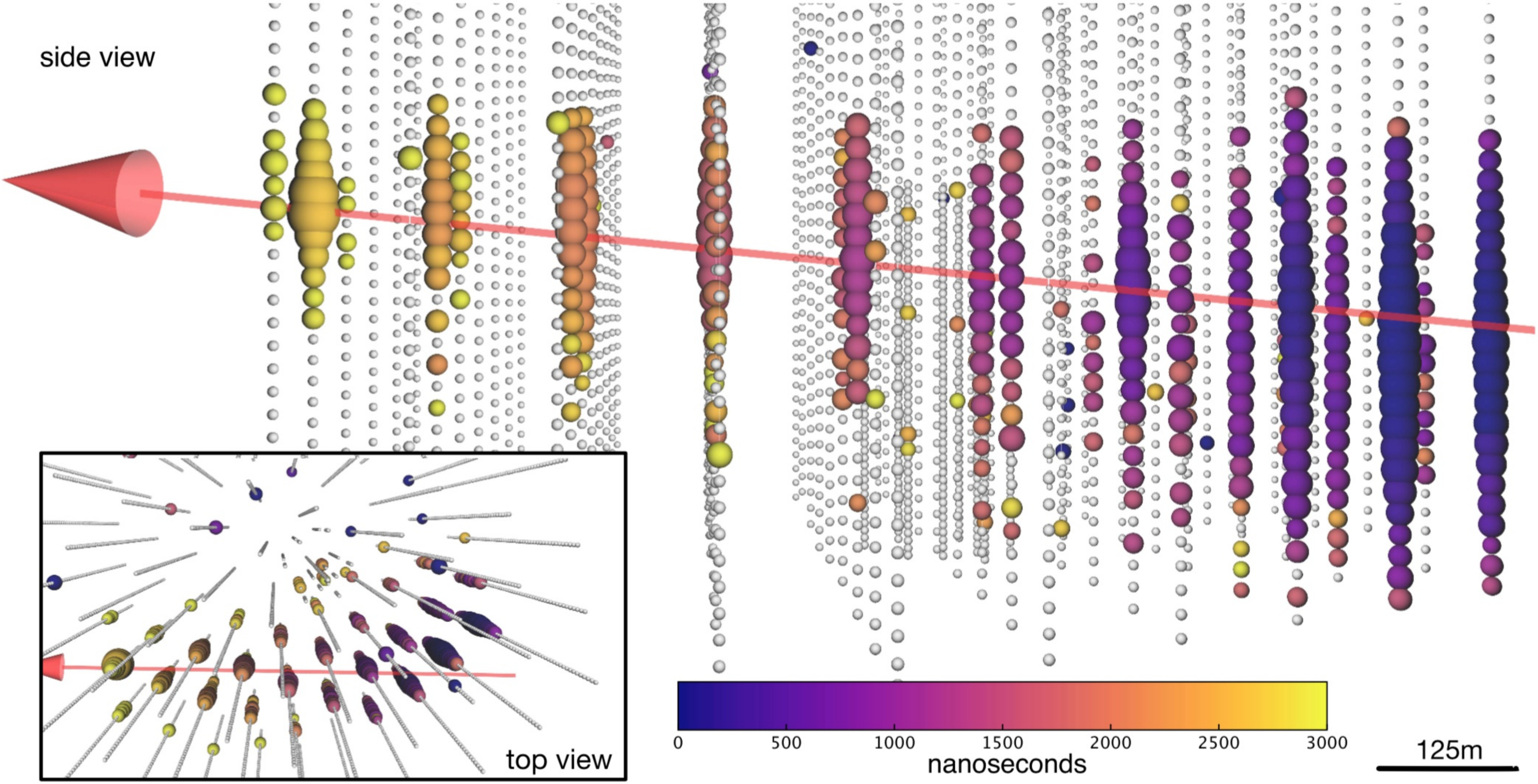
(Some assumptions, eg assume energy spectrum, apply.
Ref: - Astrophys. J **835**, 45 (2017)
- ICRC 2017, Huber for IceCube C.

IceCube study of correlations with the FERMI 2LAC



Neutrinos from Blazars

22 /sept/ 2017



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

(Muon entering the detector:

IceCube GCN 21916 17/09/23

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

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

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

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

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

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

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

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

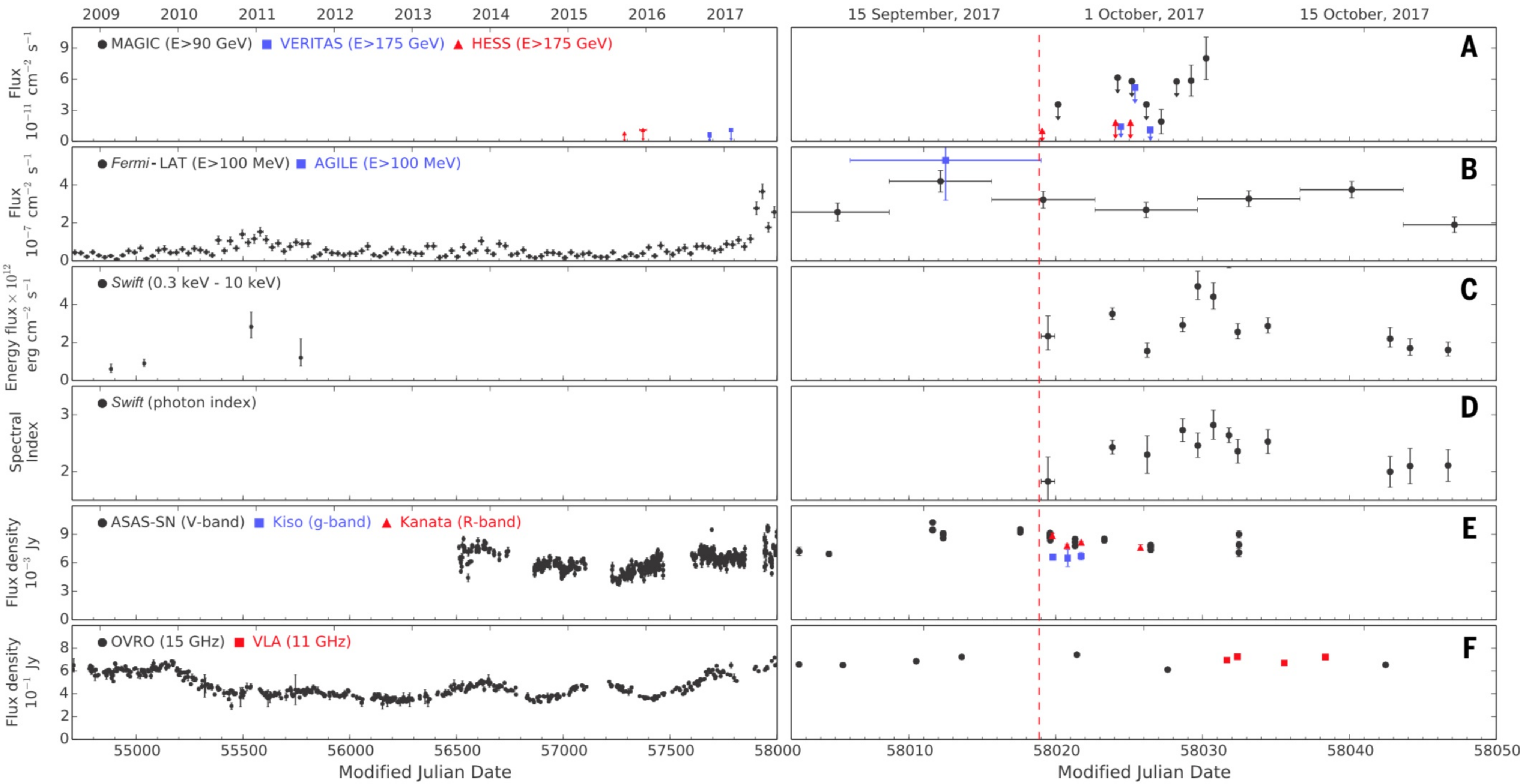
ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
*on **28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

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

…. Great source of excitement ……

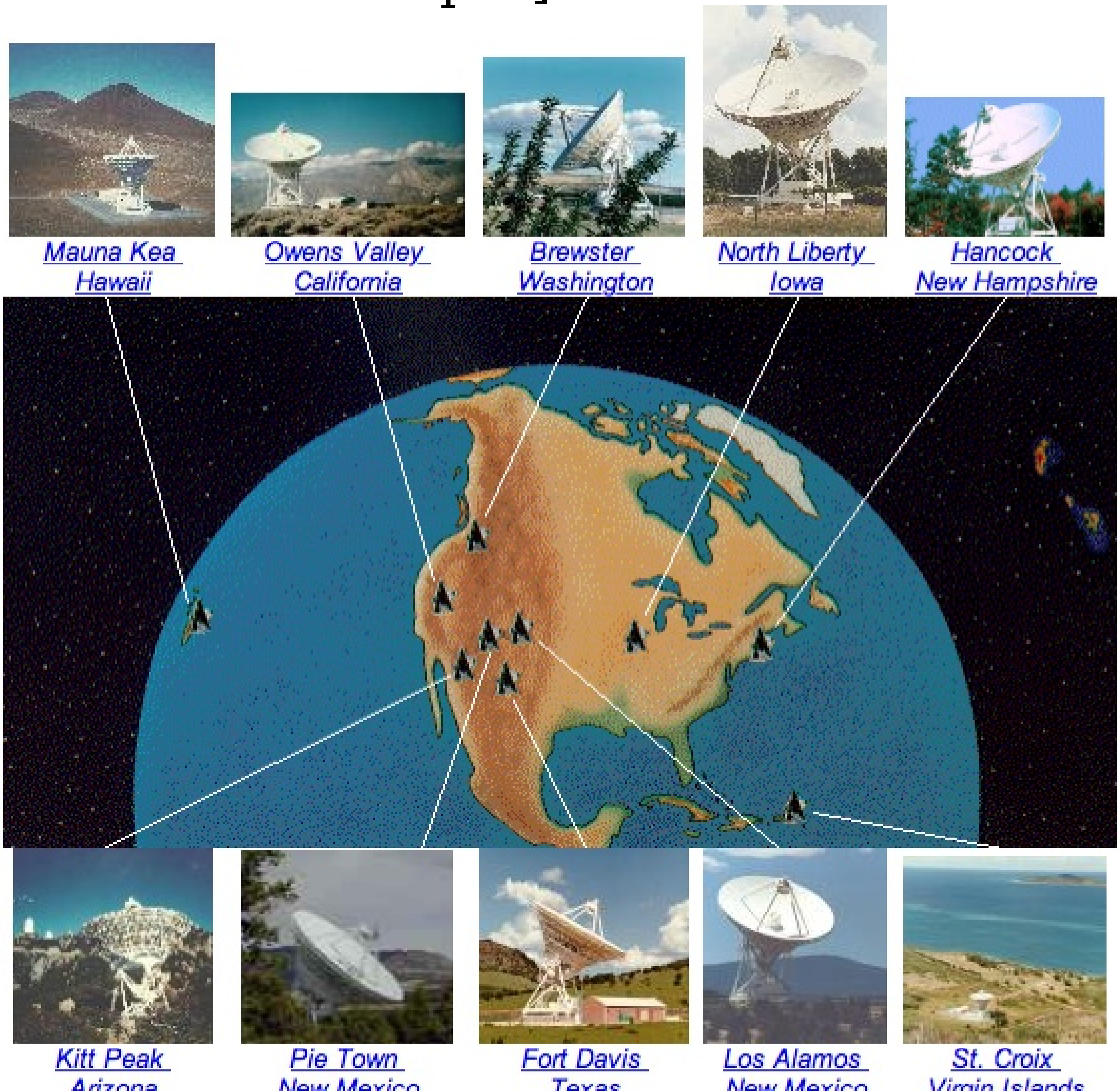
Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS …..]

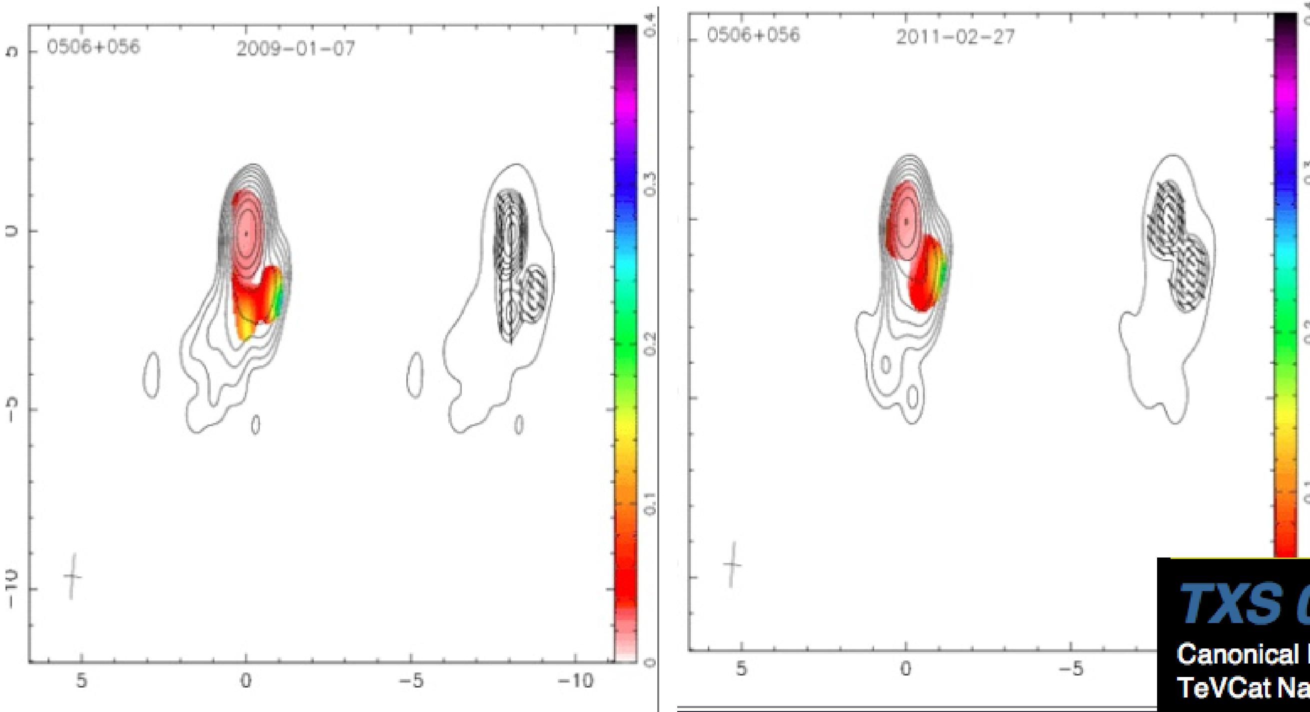


2009
2010
2011
2012
2013
2014
2015
2016
2017
15 September, 2017
1 October, 2017
15 October, 2017
MAGIC (E>90 GeV)
VERITAS (E>175 GeV)
HESS (E>175 GeV)
Flux 10^{-11} cm^{-2} s^{-1}
A
Fermi-LAT (E>100 MeV)
AGILE (E>100 MeV)
Flux 10^{-7} cm^{-2} s^{-1}
B
Swift (0.3 keV - 10 keV)
Energy flux × 10^{12} erg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

Very Long Baseline Array (VLBA)
[ensemble of 10 radio telescopes]

8000 km
baseline





TXS 0506+056

$$z = 0.3365 \pm 0.0010$$

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

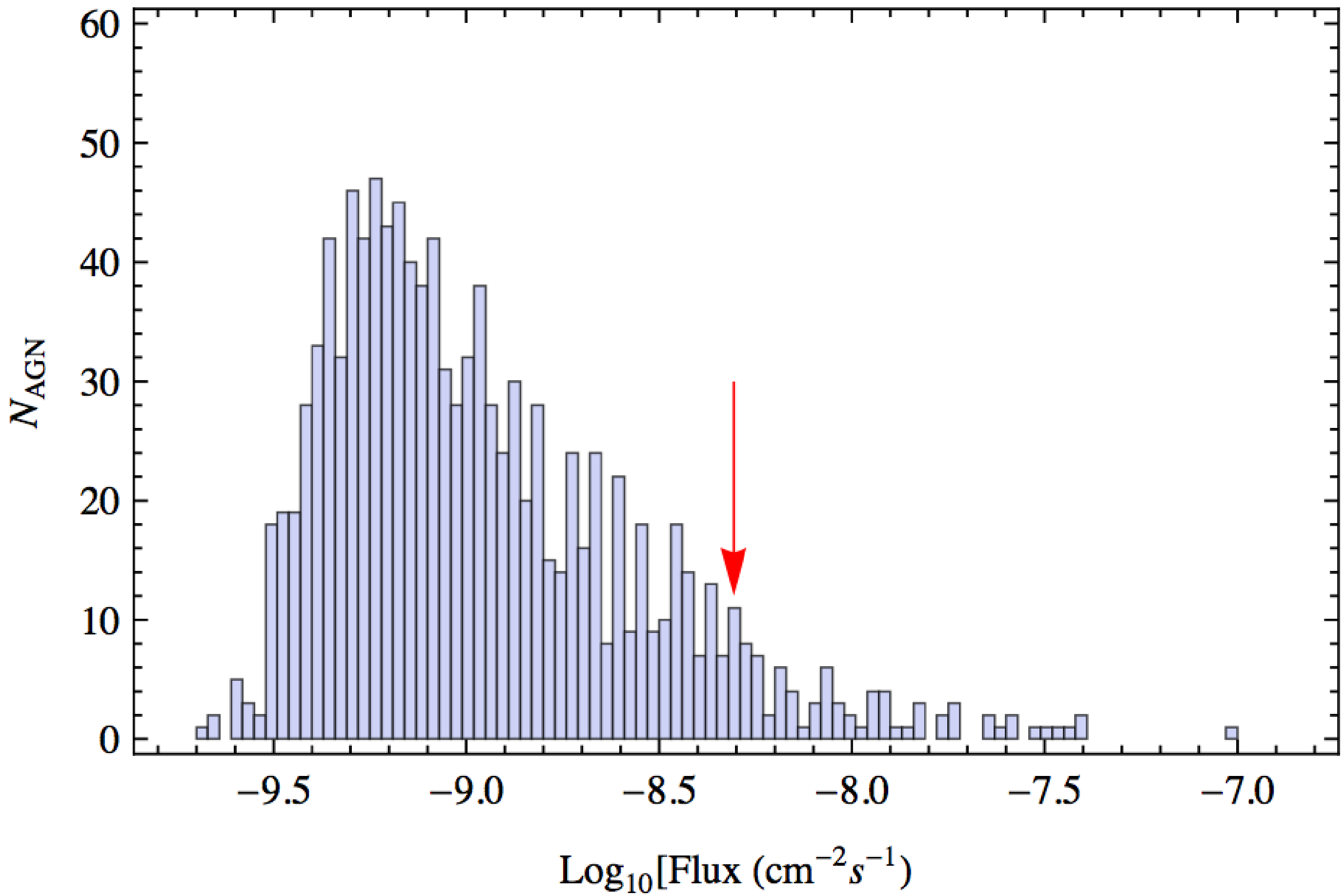
$$d = 706 \ \text{Mpc}$$

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

TXS 0506+056

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 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:	

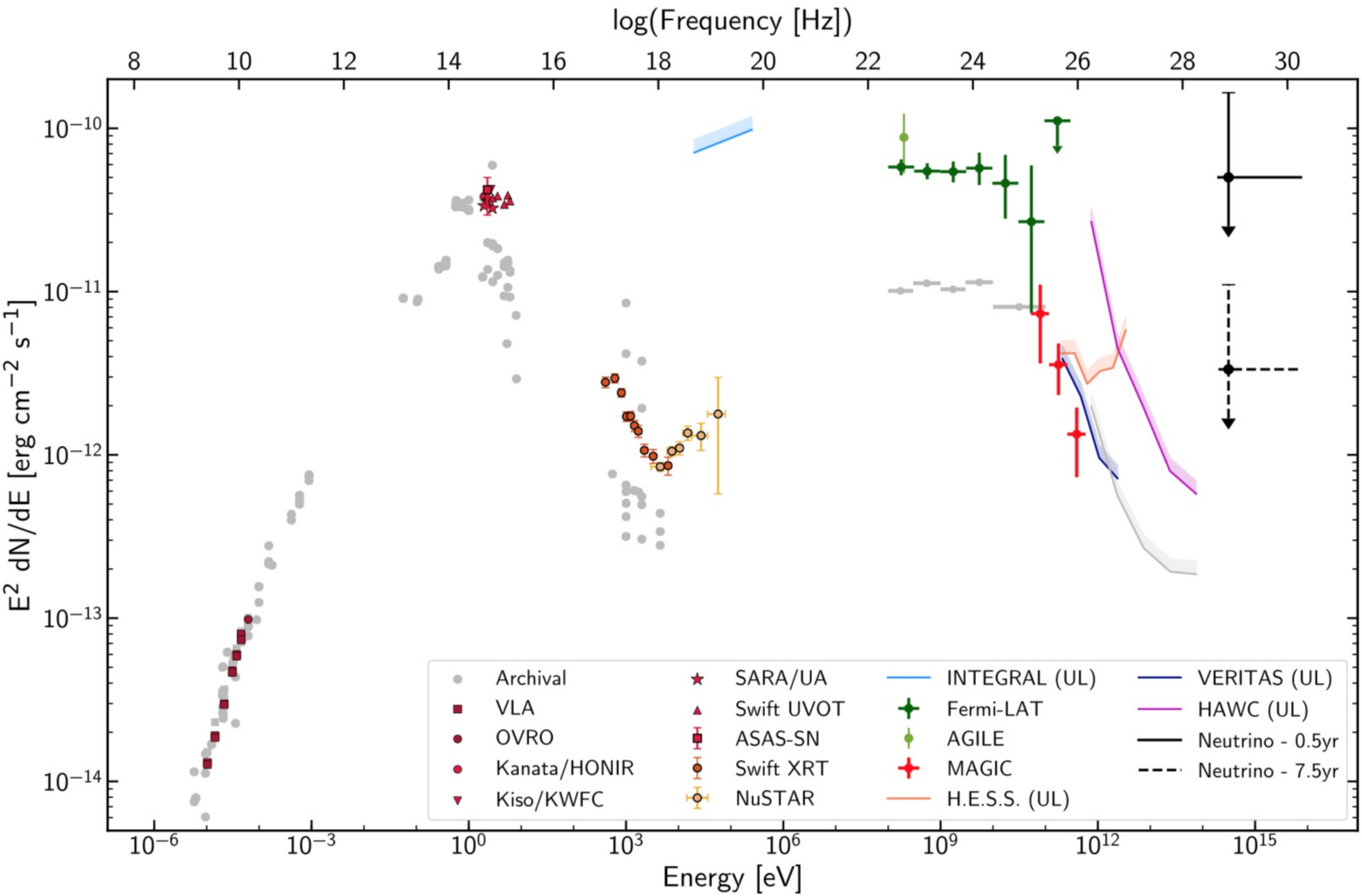
The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916. Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for 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.



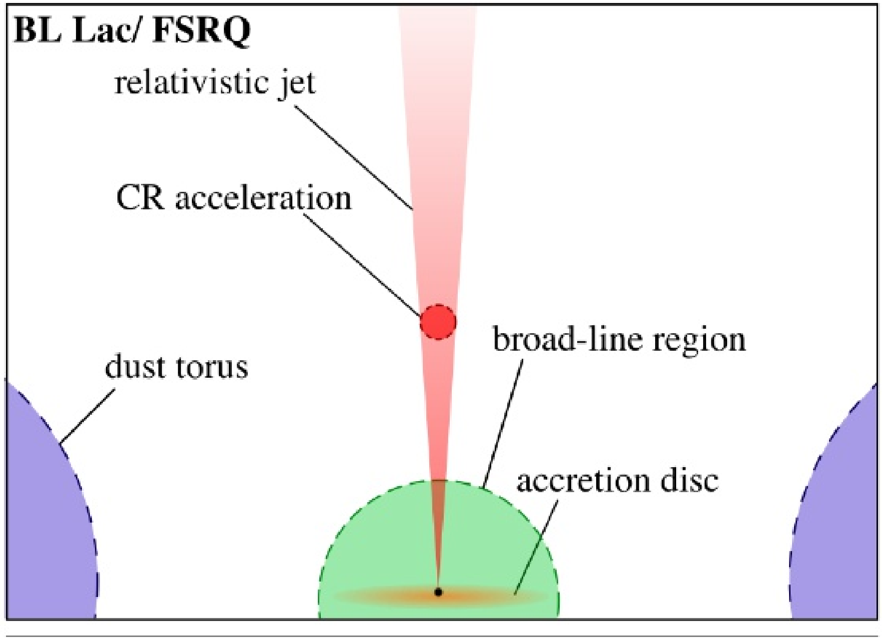
$$\alpha = 2.059 \pm 0.042$$

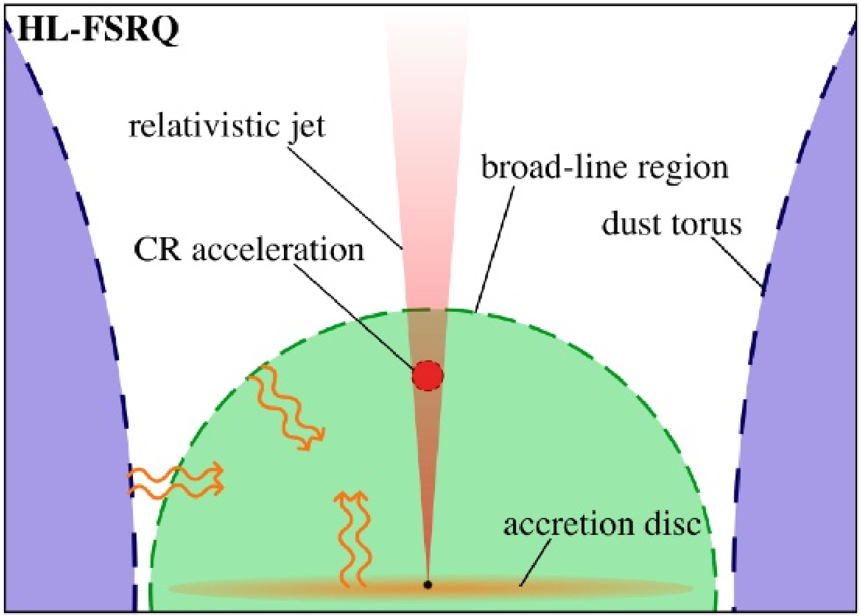
$$\Phi_\gamma[1 \div 100 \text{ GeV}] = 4.94 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$$

$$L(E) = \phi_\gamma(E) \times E^2 \simeq 4.5 \times 10^{45} \ \frac{\text{erg}}{\text{s}}$$

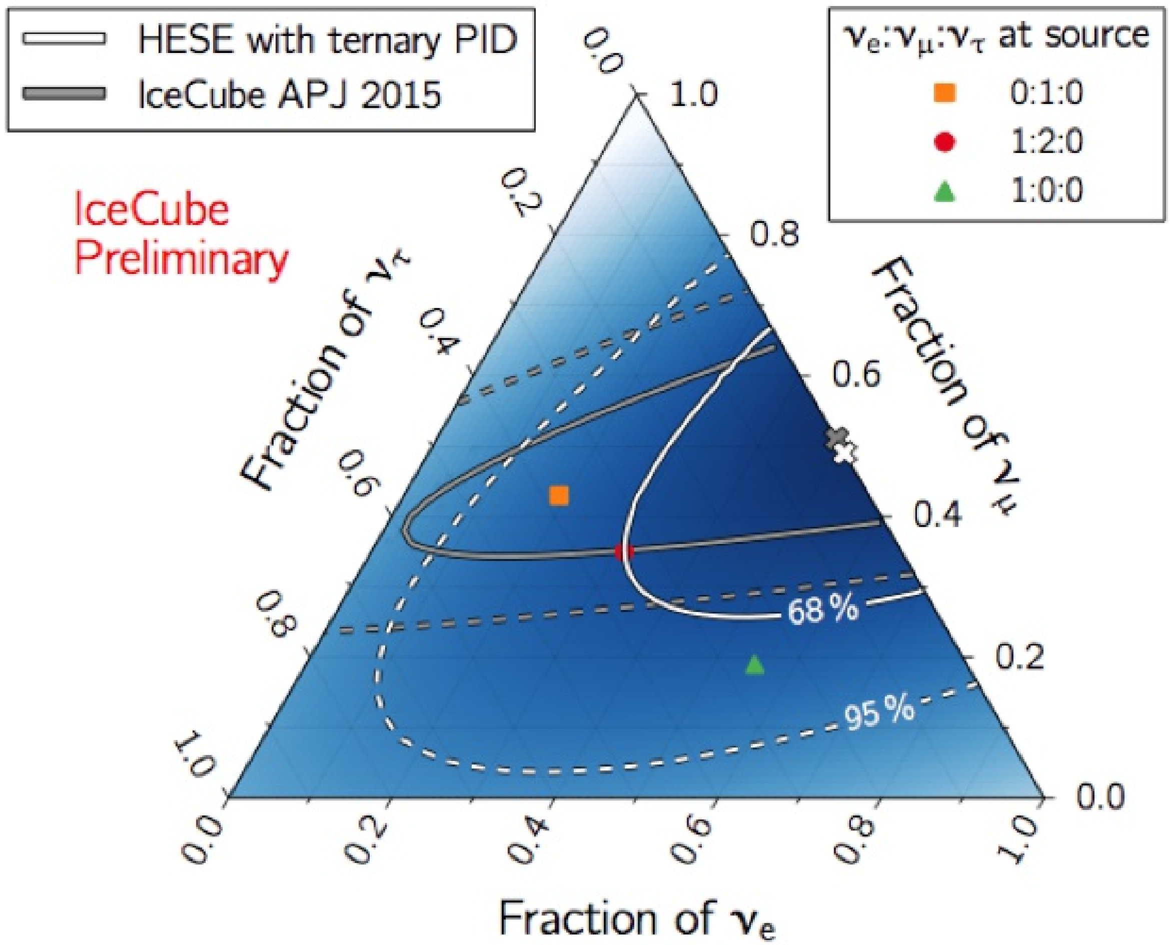


log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Energy [eV]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr


BL Lac/ FSRQ
relativistic jet
CR acceleration
broad-line region
dust torus
accretion disc


HL-FSRQ
relativistic jet
broad-line region
dust torus
CR acceleration
accretion disc

Tau neutrino search - Flavor ratio



- Tau neutrinos seen: **0**
- Expected: ~2.83 events*
- Compatible with statistical fluctuation (9%).

$$f_{\nu_e} = 0.51^{+0.12}_{-0.13}$$

$$f_{\nu_\mu} = 0.49^{+0.12}_{-0.13}$$

$$f_{\nu_\tau} = 0.00^{+0.16}_{-0.00}$$

Usner et al. (IceCube Coll.), ICRC 2017

*Using HESE 3 year fit with E^-2.3 spectrum.

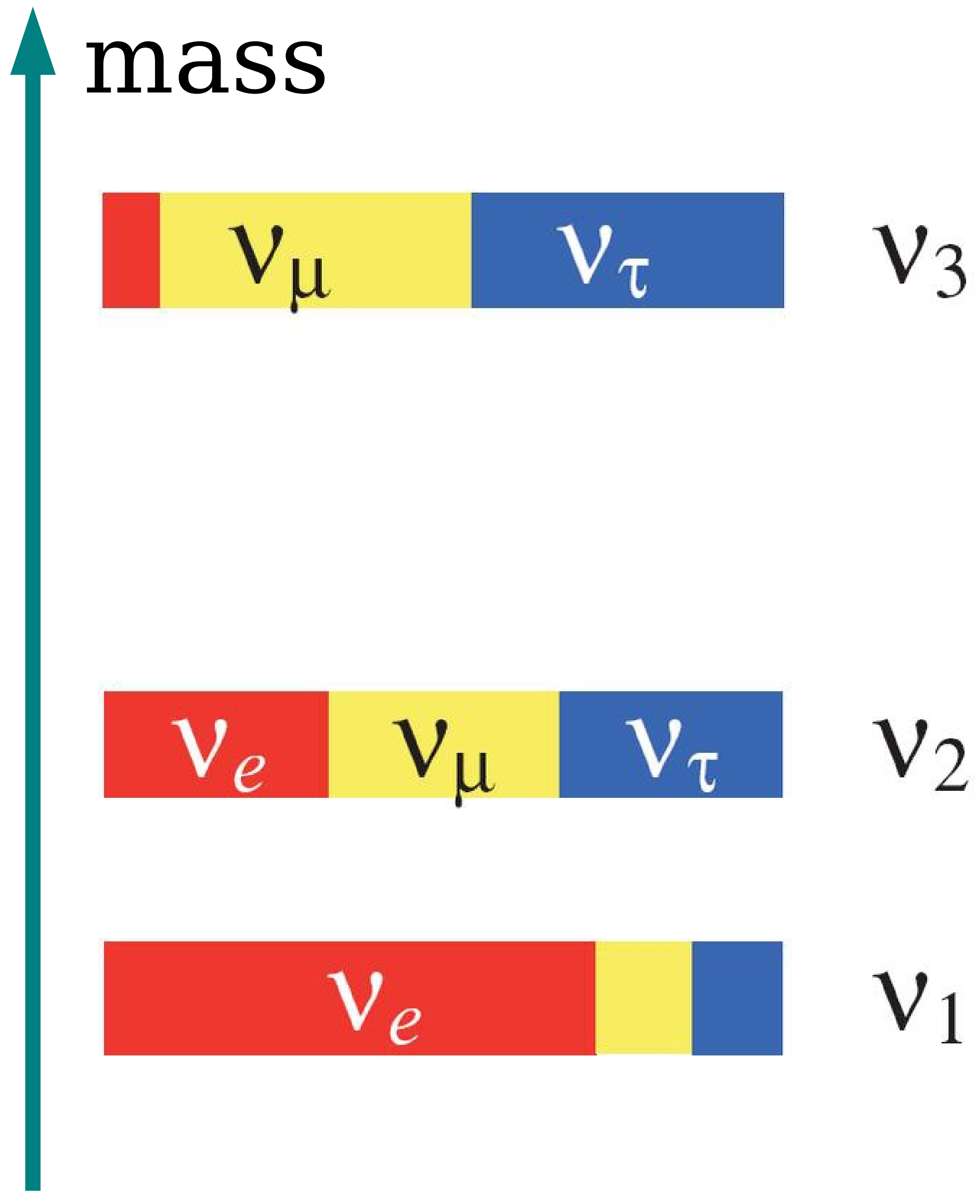
Phys. Rev. Lett. 113 (2014) 101101.

Neutrino Flavor, Neutrino masses

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

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

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



$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) &= \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} \; |U_{\beta j}|^2 \; |U_{\alpha j}|^2 \\
&\cancel{+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)} \\
&\cancel{+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)}
\end{aligned}
$$

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

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

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

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

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

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

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

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

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

“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]

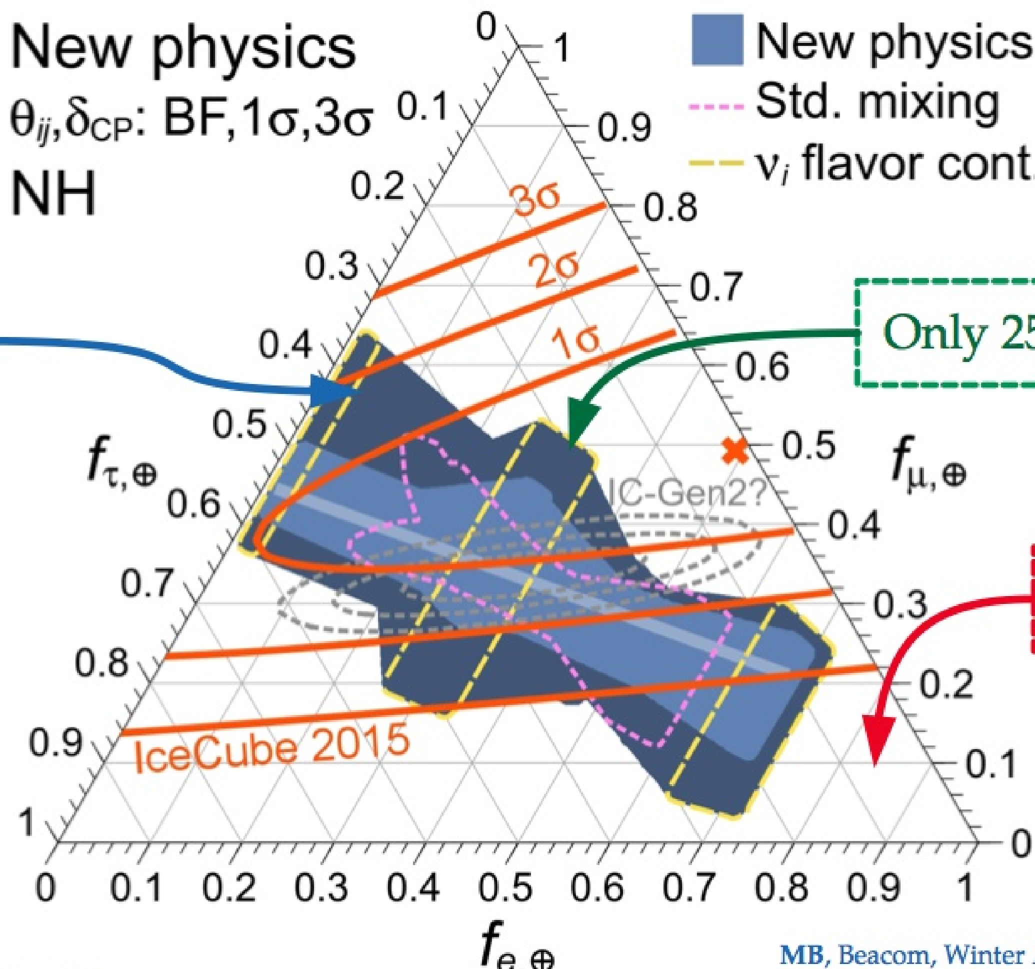
$$z \simeq 1 \qquad \Delta m^2 \approx 10^{-18} \left(\frac{E}{100 \text{ TeV}} \right) \text{eV}^2$$

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.

Flavor ratios accessible with decay-like physics



Region of all linear combinations of ν_1, ν_2, ν_3

Only 25% of parameter space

What lives outside?

MB, Beacom, Winter *PRL* 2015

Fundamental physics with HE astrophysical Neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
  n = +1: CPT-even Lorentz violation

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} \, (E/\text{PeV})^{-n} \, (L/\text{Gpc})^{-1} \, \text{PeV}^{1-n}$

- Improvement over current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from:
  - Spectral shape
  - Angular distribution
  - Flavor information

  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

COSMOGENIC NEUTRINOS

Intimately related to UHECR

Study the Redshift dependence
(and the composition)
of the source of UHECR

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]

Spectra nearly (but not exactly !)
perfectly isotropic

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

Measurements of **Cosmic Rays**

as Messengers at the Earth:

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

protons+ nuclei

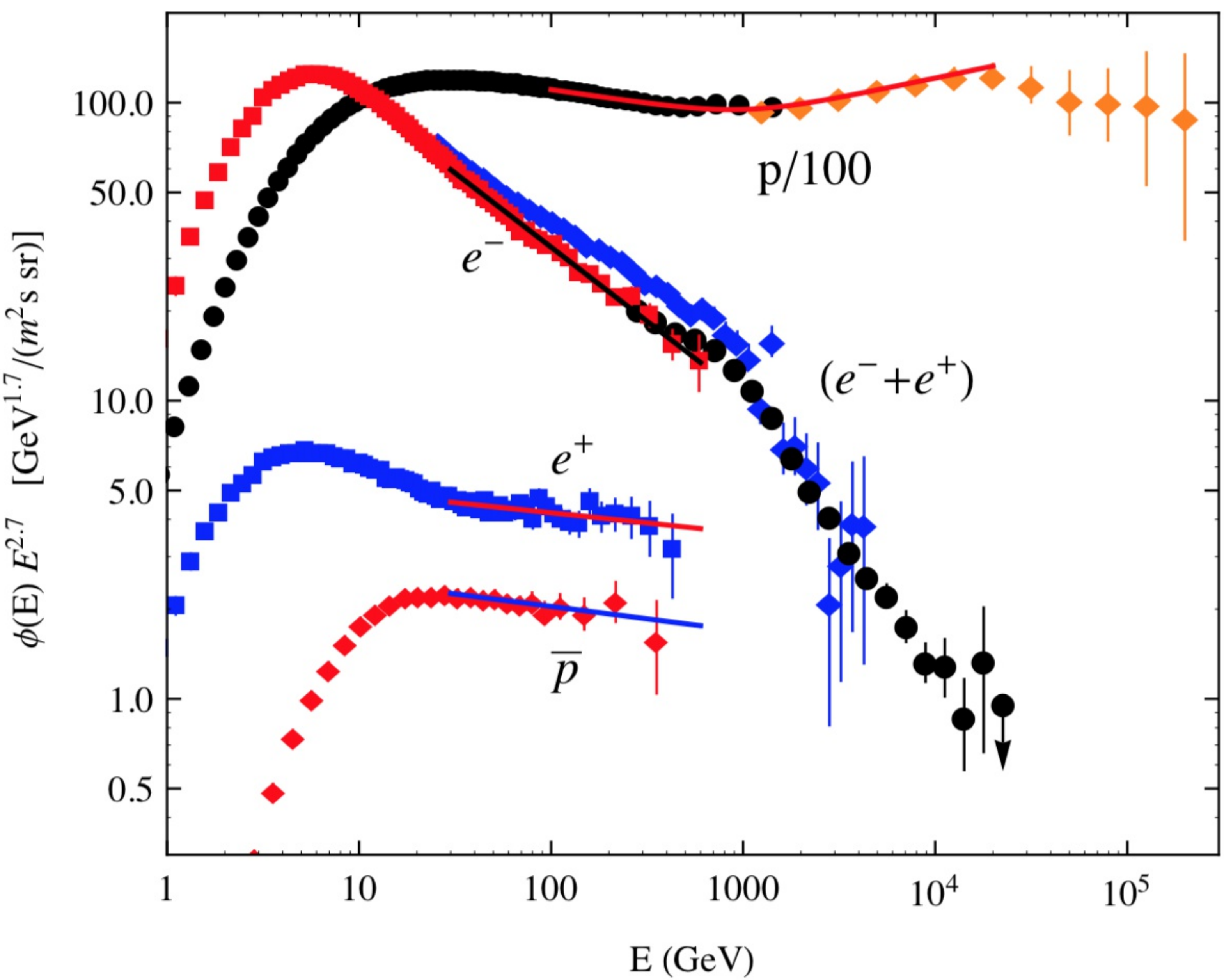
$$\boxed{\phi_{e^-}(E,\Omega)}$$

electrons

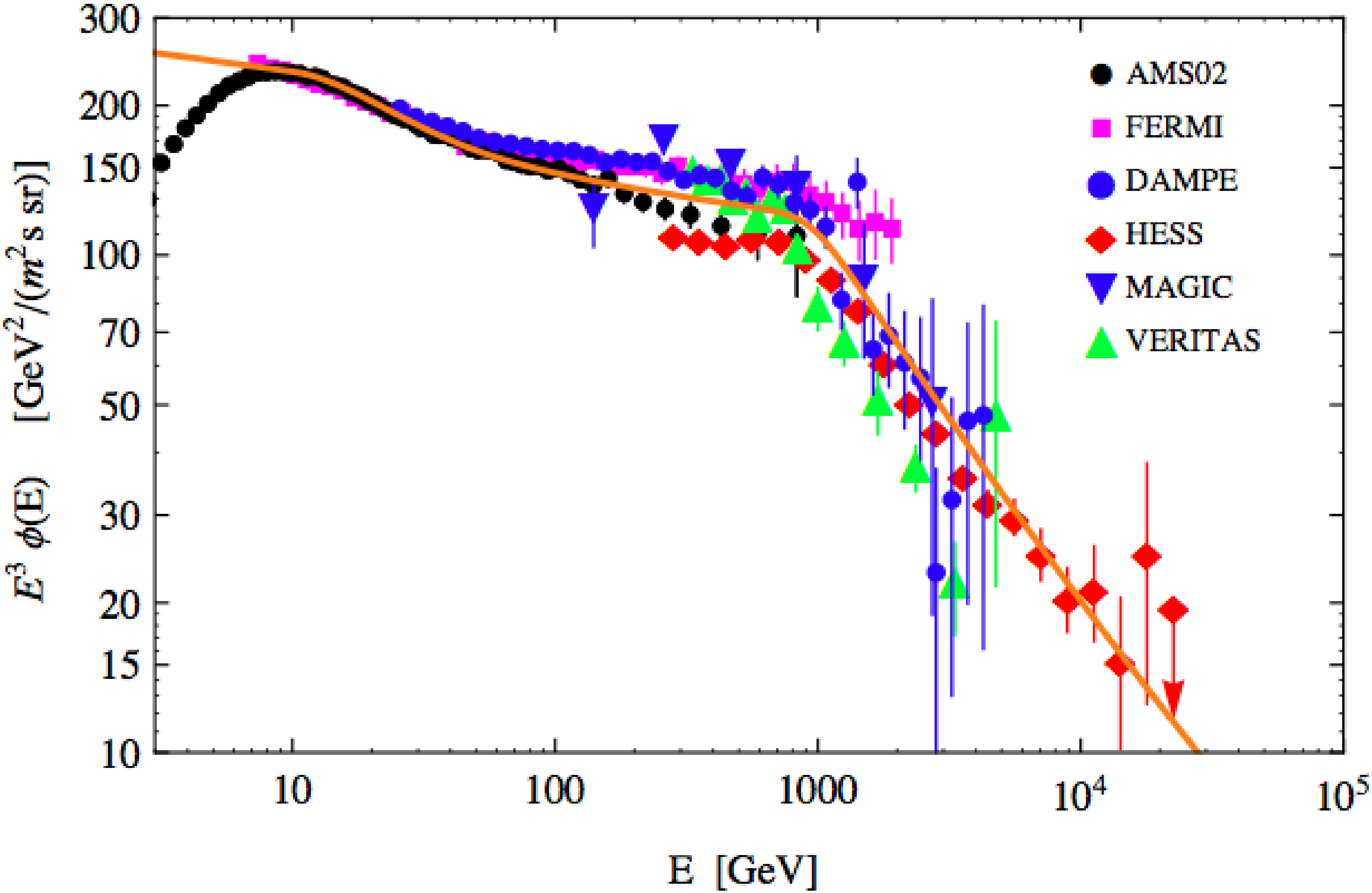
$$\boxed{\phi_{e^+}(E,\Omega)} \qquad \boxed{\phi_{\overline{p}}(E,\Omega)}$$

anti-particles

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



New data release (ICRC-2017) by HESS
Publication of DAMPE (chinese satellite)



Formation of the COSMIC RAYS spectra

$$\phi_j(E, \vec{x}, t) \iff q_j(E, \vec{x}, t)$$

Propagation

Observable fluxes (directly at the Earth)

Propagation

Spectra released in interstellar space by the CR sources

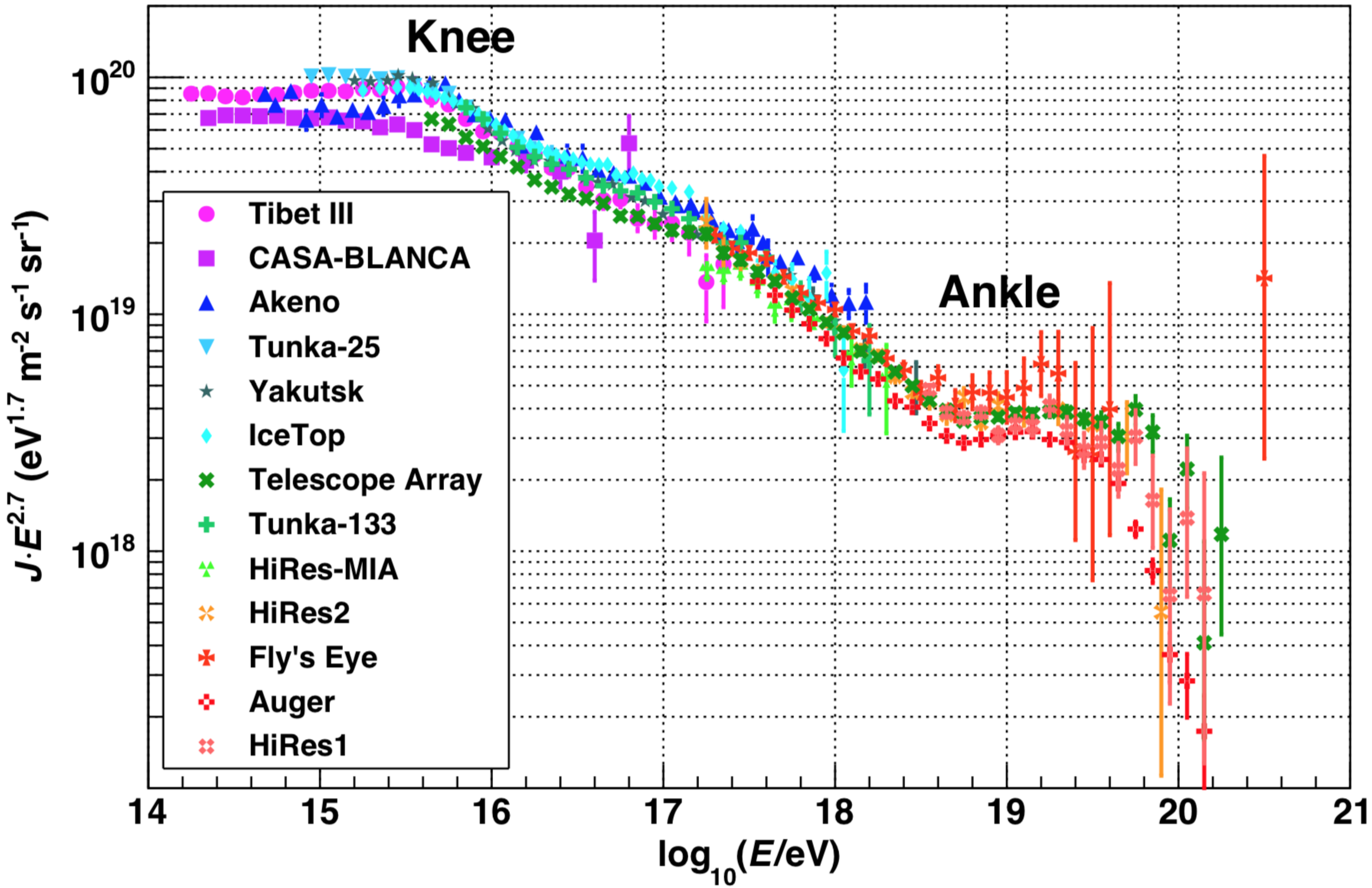
In my opinion:

Understanding the shapes of the CR spectra
In the 1-GeV 10-TeV range is a fundamental problem
and there are several important questions open.

Is there a “non-standard” positron source

How are electrons accelerated ?

[recent discussion :
P.L. astro-ph/1810.03195]



Knee
Ankle
Tibet III
CASA-BLANCA
Akeno
Tunka-25
Yakutsk
IceTop
Telescope Array
Tunka-133
HiRes-MIA
HiRes2
Fly's Eye
Auger
HiRes1
$J \cdot E^{2.7}$ (eV$^{1.7}$ m^{-2} s^{-1} sr^{-1})
10^{20}
10^{19}
10^{18}
14
15
16
17
18
19
20
21
$\log_{10}(E/\mathrm{eV})$

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"	$\log_{10}[E(\text{eV}] \simeq$ 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]

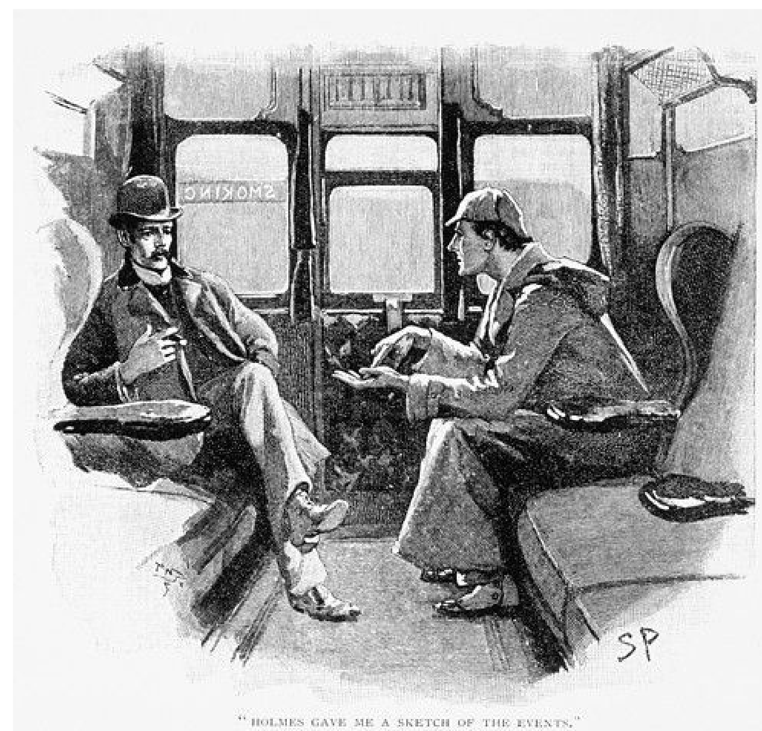
Galactic

versus

Extra-Galactic CR

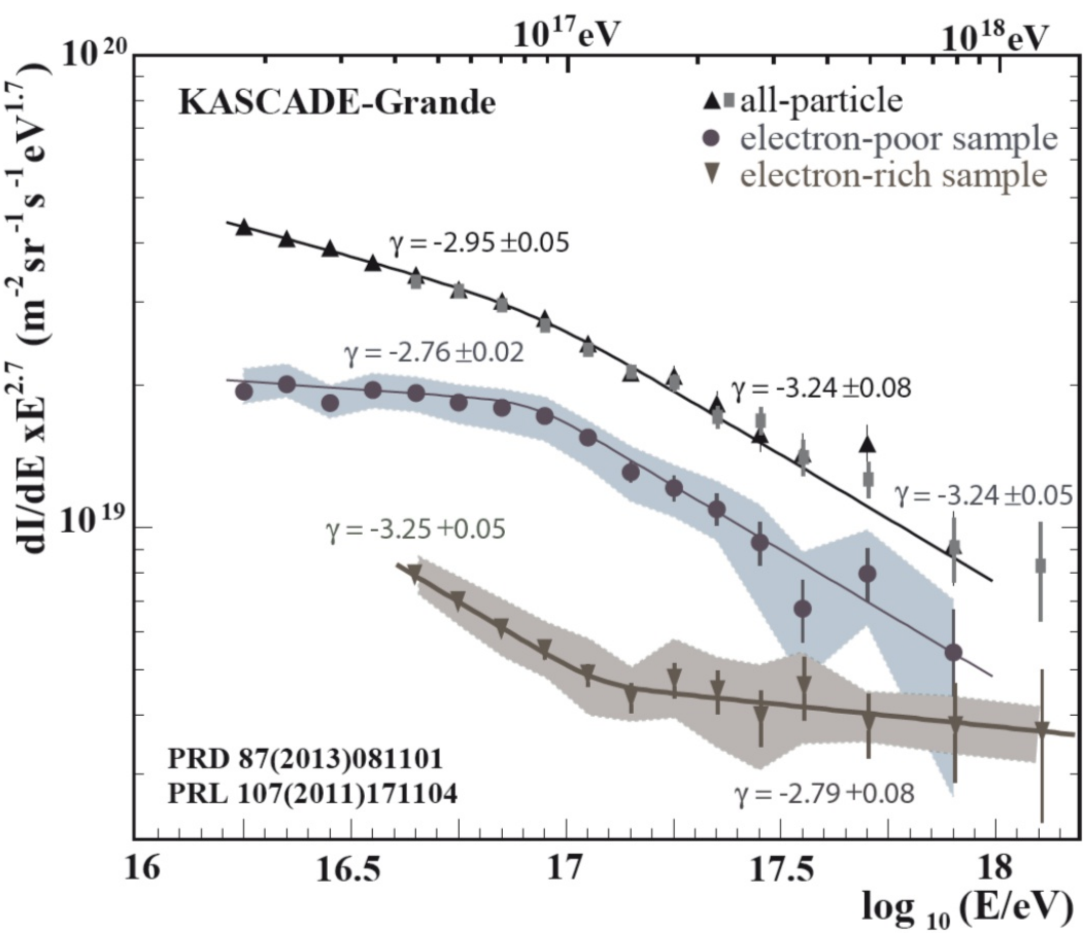
The dogs that did not bark: at the *Galactic/extragalactic Transition:*

[1] The “hardening”
[2] The anisotropy



“HOLMES GAVE ME A SKETCH OF THE EVENTS.”

KASCADE-Grande
energy spectra of mass groups



- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**
- **slope change from γ = -3.25 to γ = -2.79!**

Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

Conclusions – open points

- Light and heavy knee established
- Light ankle probably there
- Difficult to compare experiments due to different observables
  what is contribution of MHz-Radio?
- Yet no conclusive result due to insufficient hadronic interaction models
- Continuation in improving hadronic interaction models required
- Still problem: absolute mass scale
- Confrontation of the data with astrophysical models still challenging
- Future: (mass dependent) Anisotropy studies
- Future: Multi-messenger Analyses (cosmic rays, γ-rays, neutrinos)
- IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, PAO, NEVOD, HAWC?
- Global Data Centre for Astroparticle Physics envisaged

Conclusions – open points

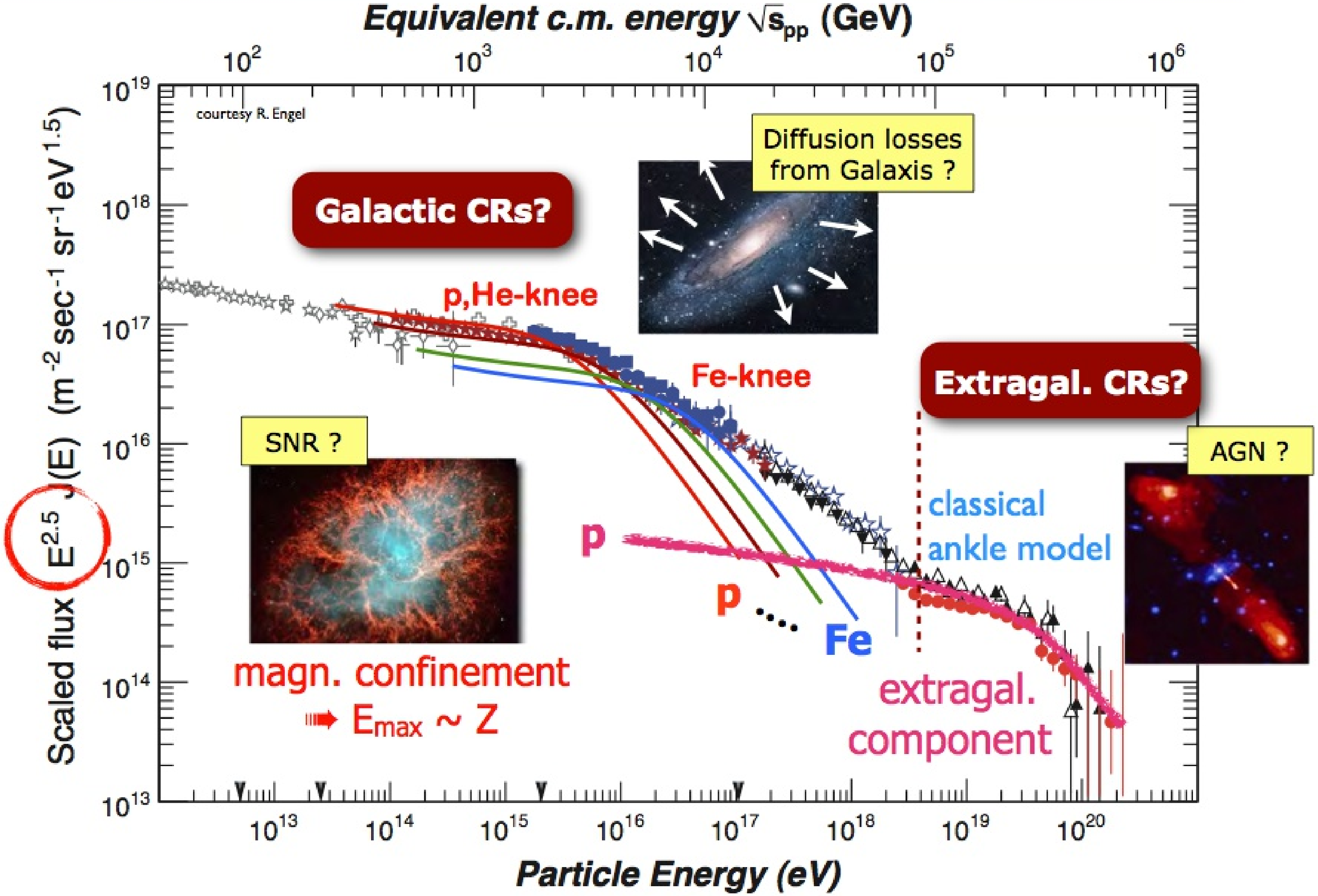
- Light and heavy knee established
- Light ankle probably there
- ferent observables
- hadronic interaction models
- tion models required
-

Light Ankle:

Extragalactic component ?
Crucial piece of the puzzle

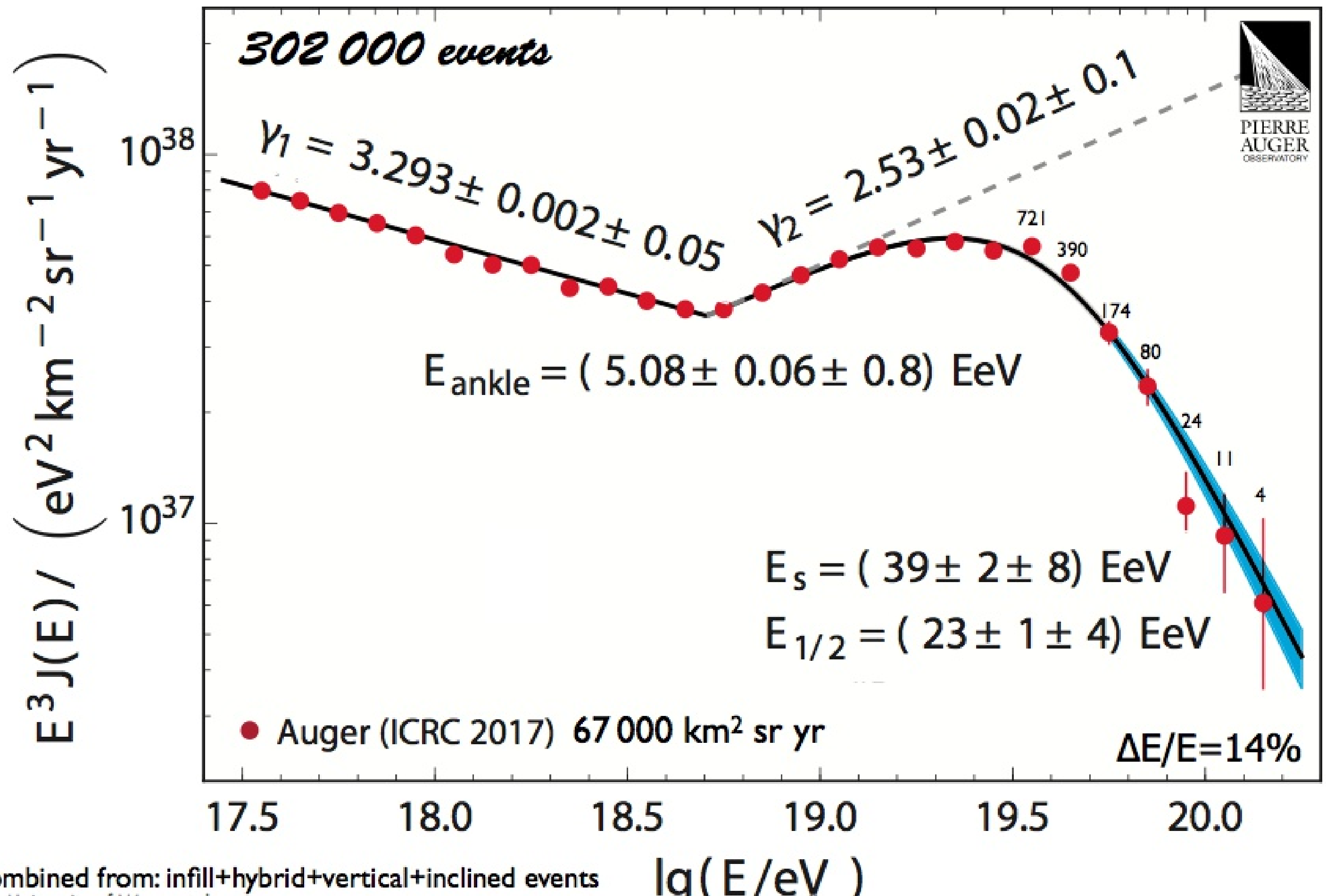
- Confrontation of the data with astrophysical models still challenging
- Future: (mass dependent) Anisotropy studies
- Future: Multi-messenger Analyses (cosmic rays, γ-rays, neutrinos)
- IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, PAO, NEVOD, HAWC?
- Global Data Centre for Astroparticle Physics envisaged

Features of CR spectrum



End of the CR-Spectrum (0°-80°)

F. Fenu (Auger) @ ICRC2017 arXiv:1708.06592
Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239



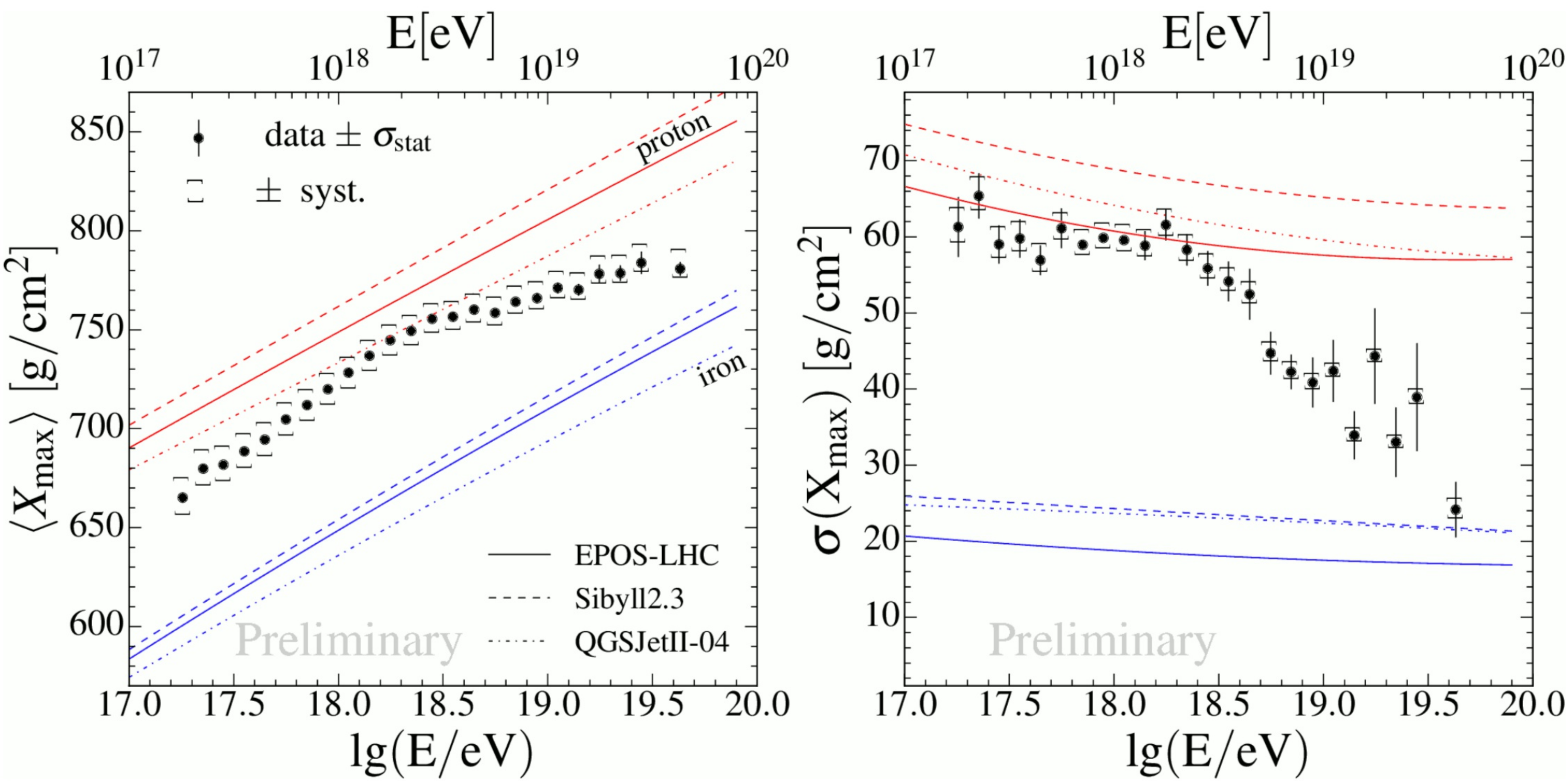
combined from: infill+hybrid+vertical+inclined events

A Result of fundamental importance:

Evidence (obtained by AUGER)
for a composition dominated
by medium mass-number Nuclei
at the highest energy

If this result is correct it is a very important
Piece in the puzzle of High Energy emission

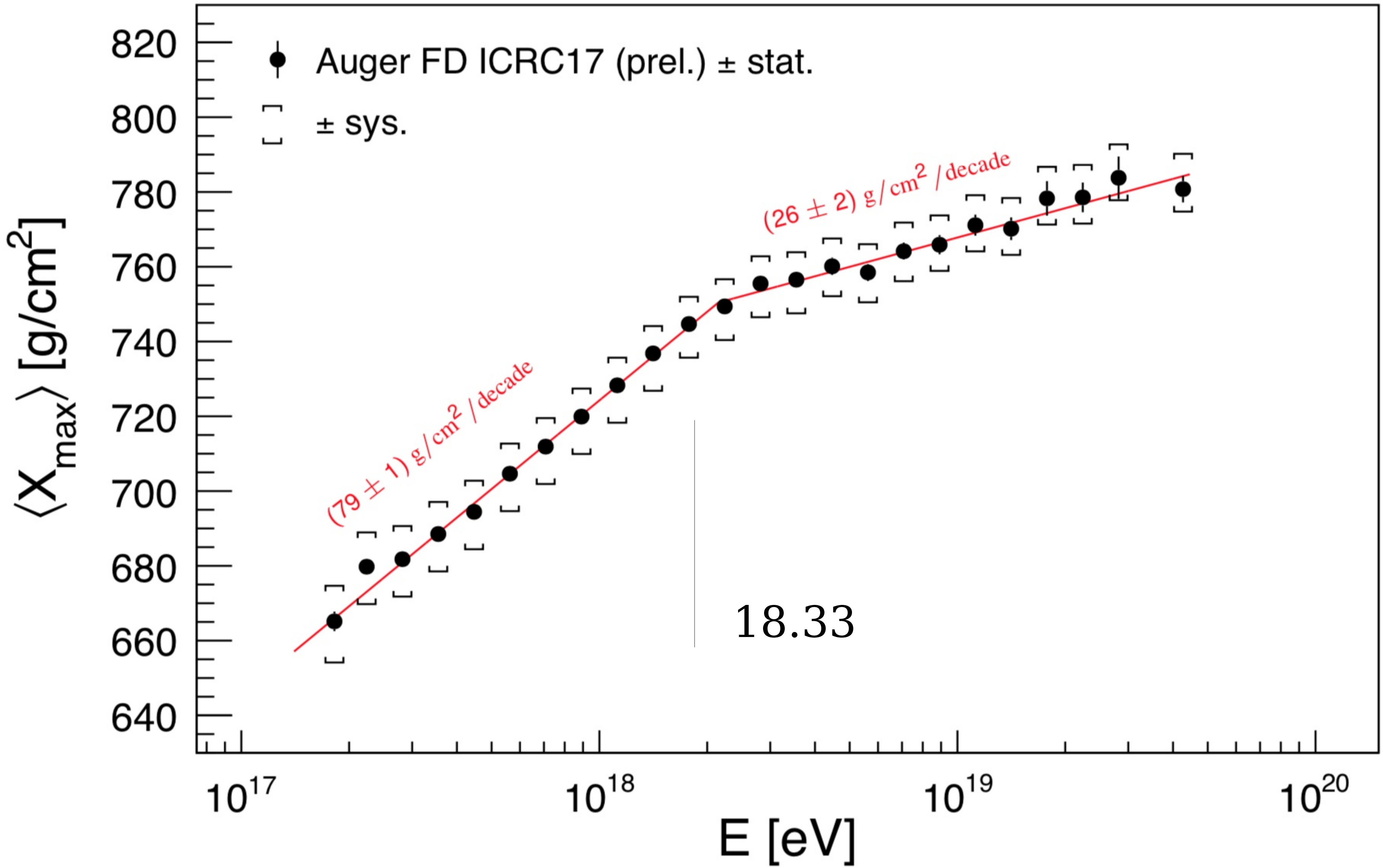
A new crucial piece of the puzzle
of the high energy sources
With many surprising features.



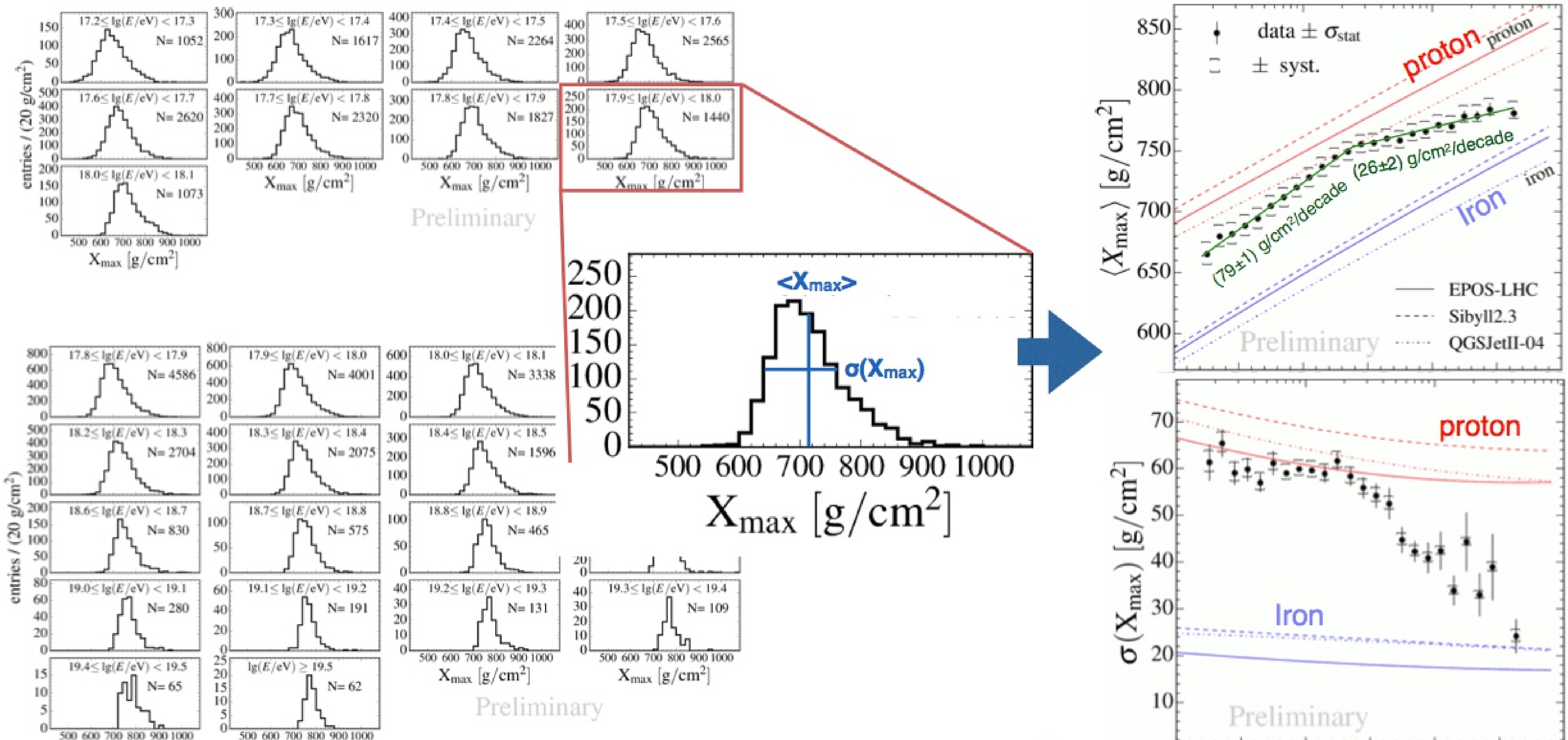
E[eV]
10^{17}
10^{18}
10^{19}
10^{20}
$\langle X_{max} \rangle$ [g/cm^2]
data $\pm$ σ_{stat}
$\pm$ syst.
proton
iron
EPOS-LHC
Sibyll2.3
QGSJetII-04
Preliminary
lg(E/eV)
$\sigma(X_{max})$ [g/cm^2]
Preliminary
lg(E/eV)

Average Shower Maximum vs. Energy

Pierre Auger Coll., PRL 2011, PRD 2014; update at ICRC17



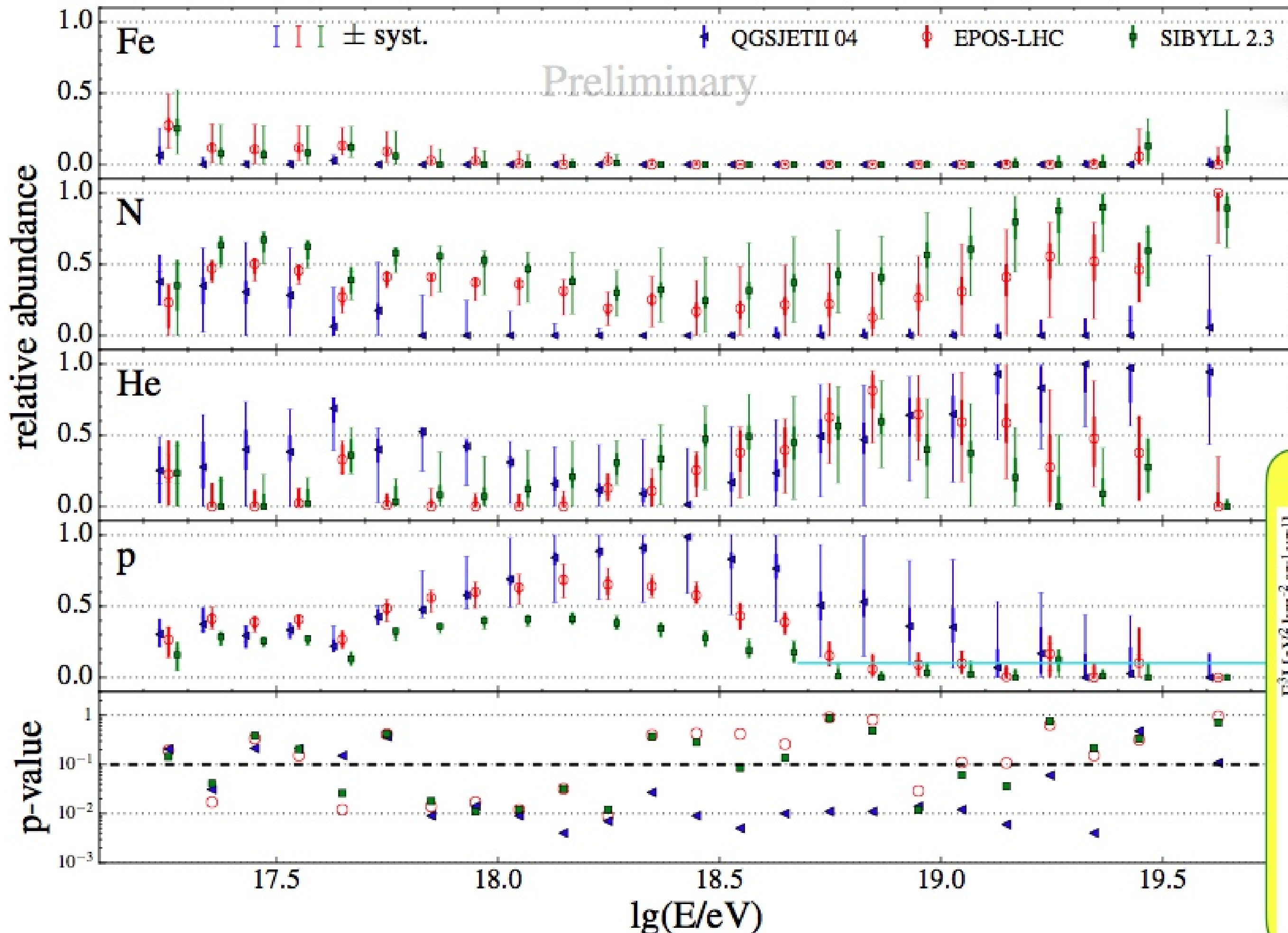
X_{max} Distributions



Bellido (Auger) @ ICRC2017 ; arXiv:1708.06592

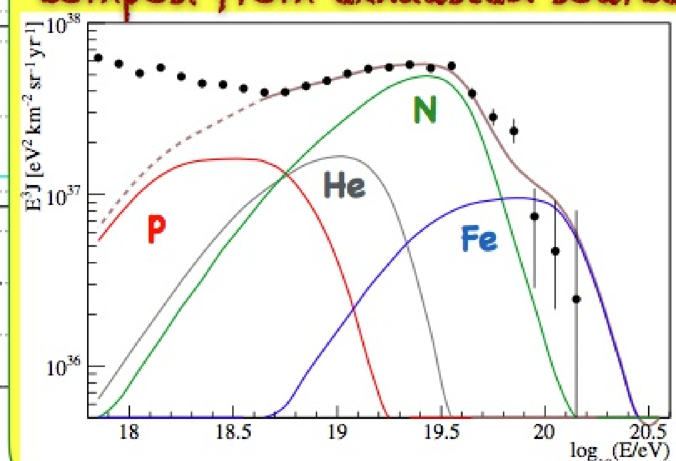
Mass Fractions from Auger

Bellido (Auger) @ ICRC2017 ;
arXiv:1708.06592

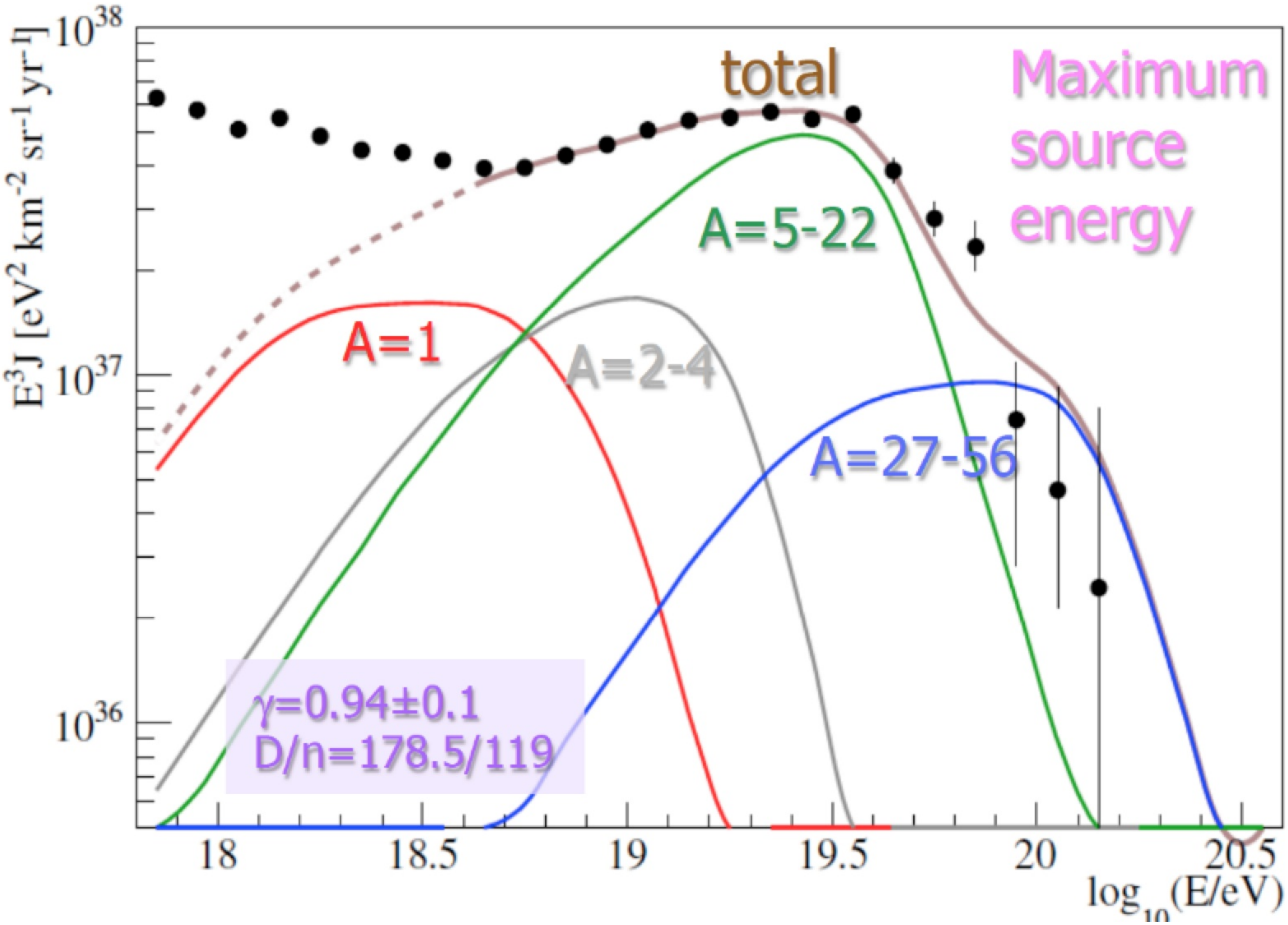


remember....

compos. from exhausted sources ?



Possible Interpretation (Auger at ICRC-2015)



1. Very hard spectra

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

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

Results presented at the 35th ICRC

[V. de Souza, PoS (ICRC2017) 522]

Comparison of $X_{\max}$ distributions measured by Auger and TA

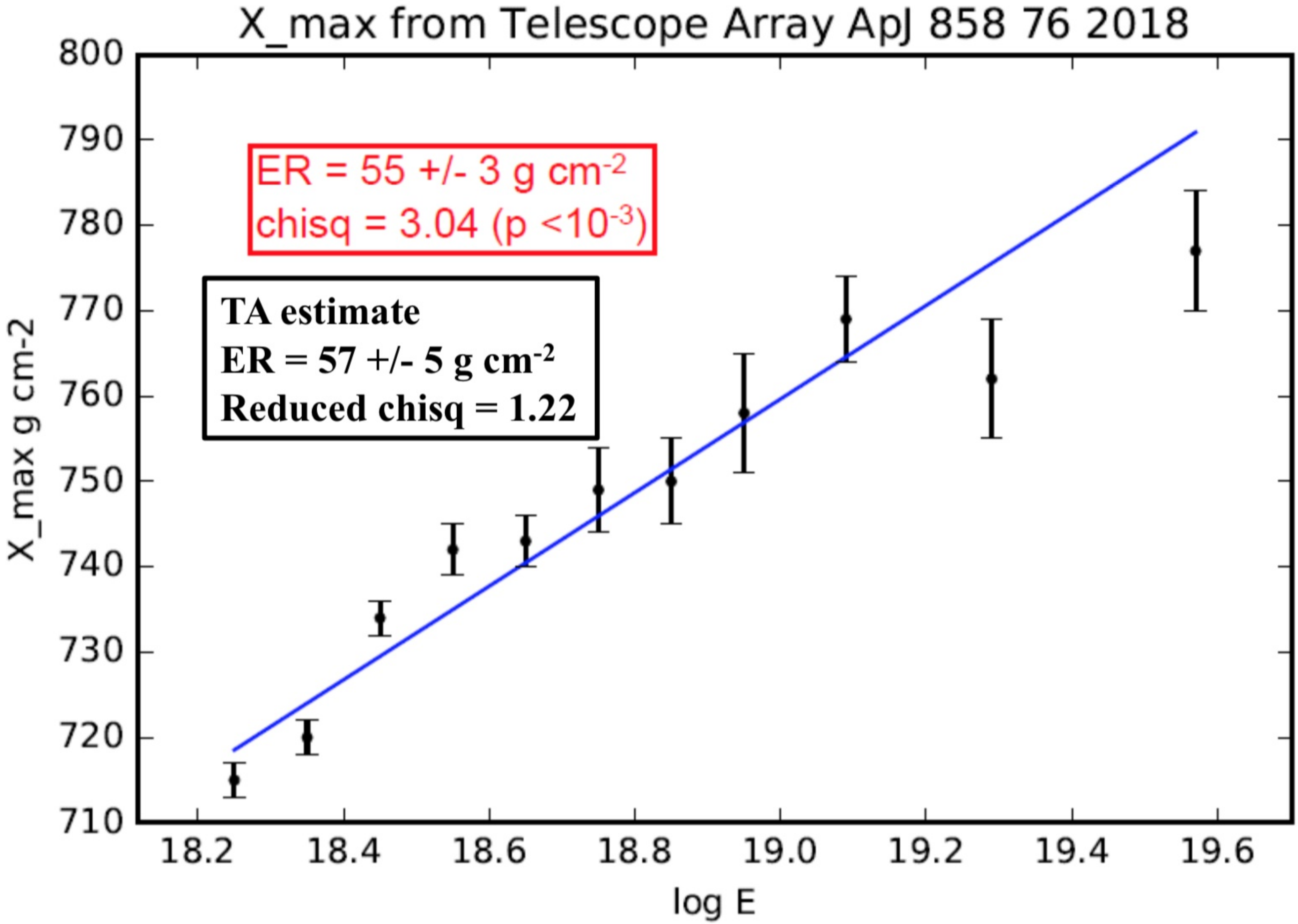
"At the current level of statistics and understanding of systematics, the TA data is consistent with the proton models used in this paper for energies less than 10^{19} eV and it is also consistent with the AugerMix composition"

“At the current level of statistics and understanding of systematics, the TA data is consistent with the proton models used in this paper for energies less than 10^{19} eV and it is also consistent with the AugerMix composition”

....
This is for me (but I think also for everybody)
a very disappointing statement.

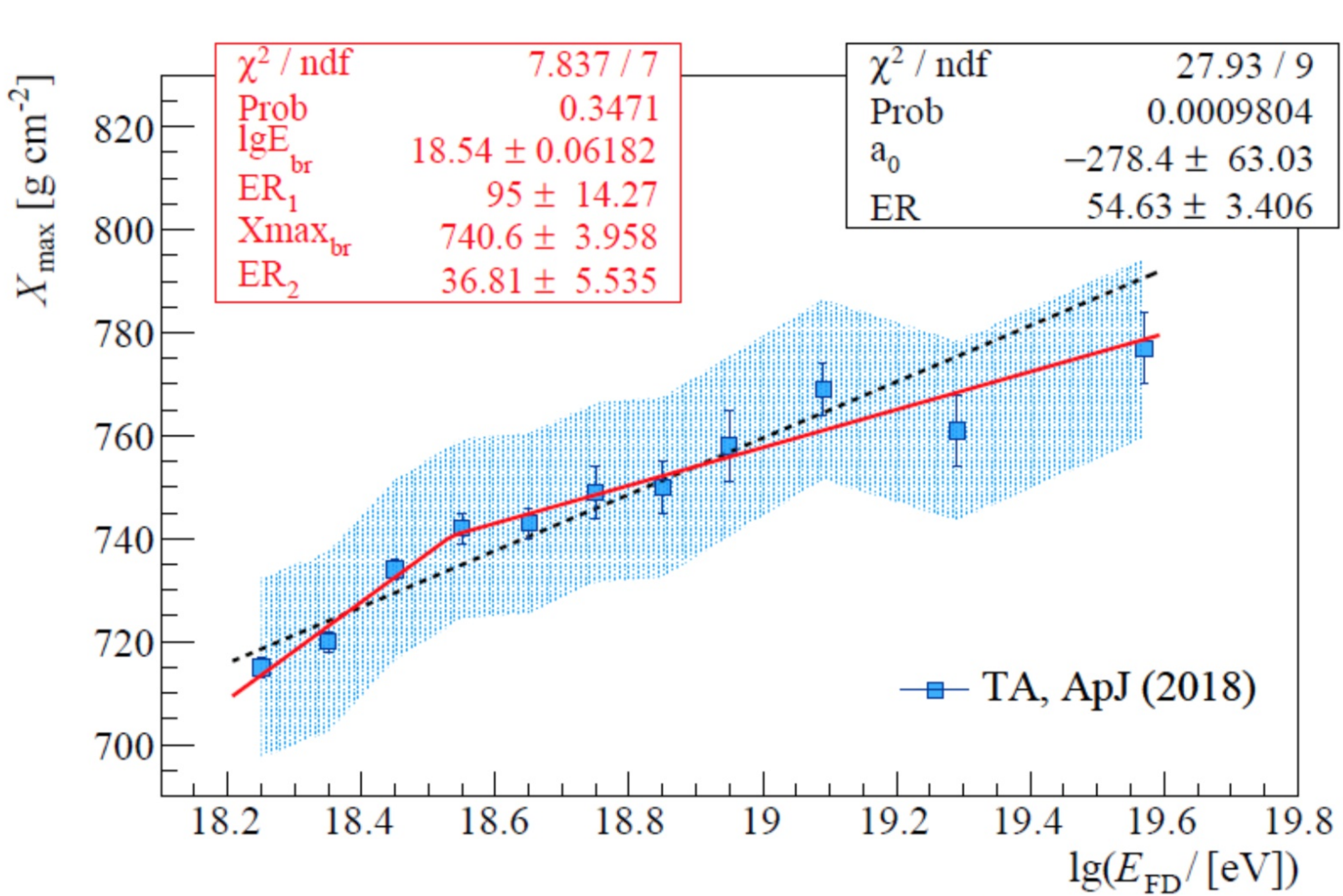
No conflict between experiments `(good !)
but no confirmation (or support)
for a result of crucial importance (bad !)

Is it possible (I ask myself) that
Telescope Array cannot discriminate
(in the (Log) energy range 18.33 – 19.0
between elongation rates of
(55 +- 5) and (26 +-2) ?



X_max from Telescope Array ApJ 858 76 2018
ER = 55 +/- 3 g cm-2
chisq = 3.04 (p <10-3)
TA estimate
ER = 57 +/- 5 g cm-2
Reduced chisq = 1.22
X_max g cm-2
log E
800
790
780
770
760
750
740
730
720
710
18.2
18.4
18.6
18.8
19.0
19.2
19.4
19.6

Search for a break: plot by Alexey Yushkov – thanks!



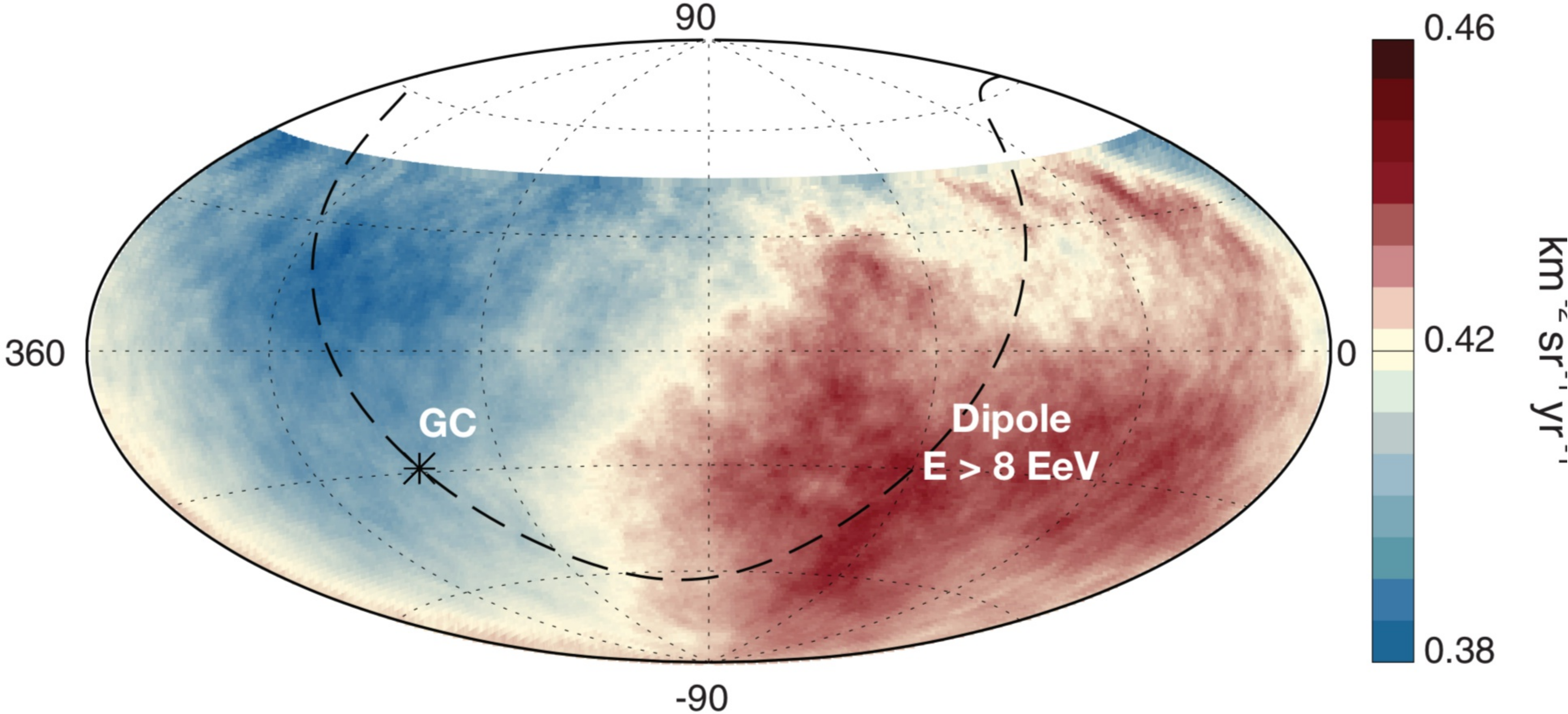
Note: break point is close to the ankle

Anisotropies

Large-scale analysis: reconstruction of the dipole

Amplitude: 6.5$^{+1.3}_{-0.9}$%

Right ascension: 100˚±10˚, Declination: -24˚±13˚



The direction of the dipole lies ≈ 125˚ from the Galactic Center

Origin hard to explain with a Galactic origin

Large-scale analysis: o

Study of a possible evolution of the first ha

[Auger Coll. arXiv 1808.03579, just ac

Dividing the E > 8 EeV bin i

Energy [EeV]	events	a_1^α	b_1^α			
8 - 16	24,070	-0.011 ± 0.009	0.044 ± 0.00			
16 - 32	6,604	0.007 ± 0.017	0.050 ± 0.01			
≥ 32	1,513	-0.03 ± 0.04	0.05 ± 0.04	0.06	115 ± 35	0.26

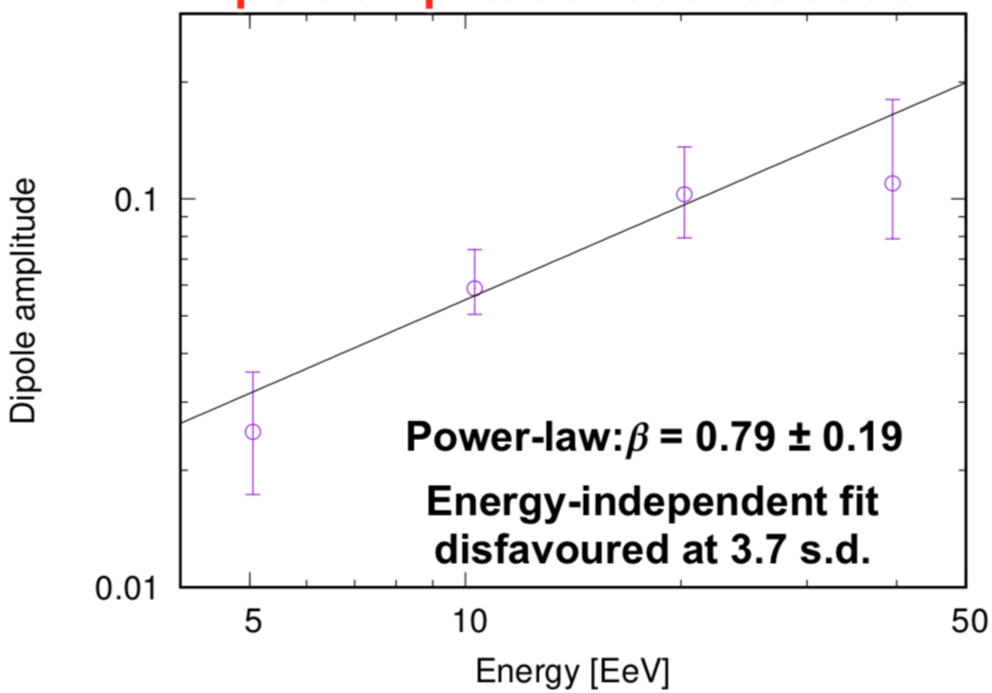
Obviously
Very important !

But:

What does it mean ?

Constant phase in spite of a (naturally) more limited significance of the amplitude

Dipole amplitude reconstruction



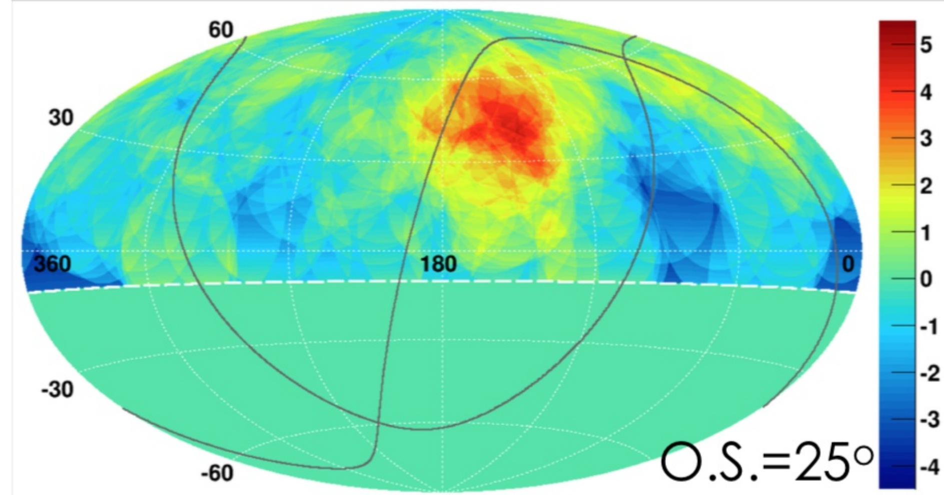
Indication of an increase of the dipole amplitude vs energy

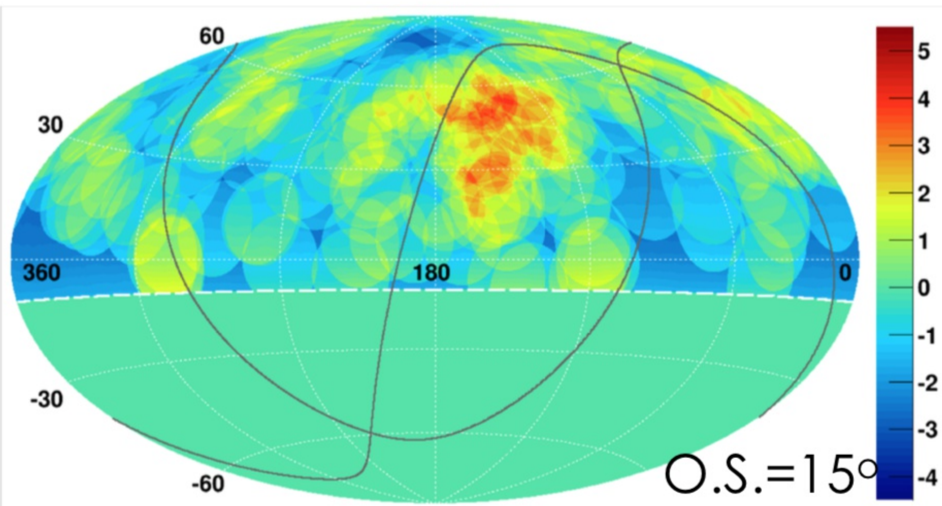
Constant direction

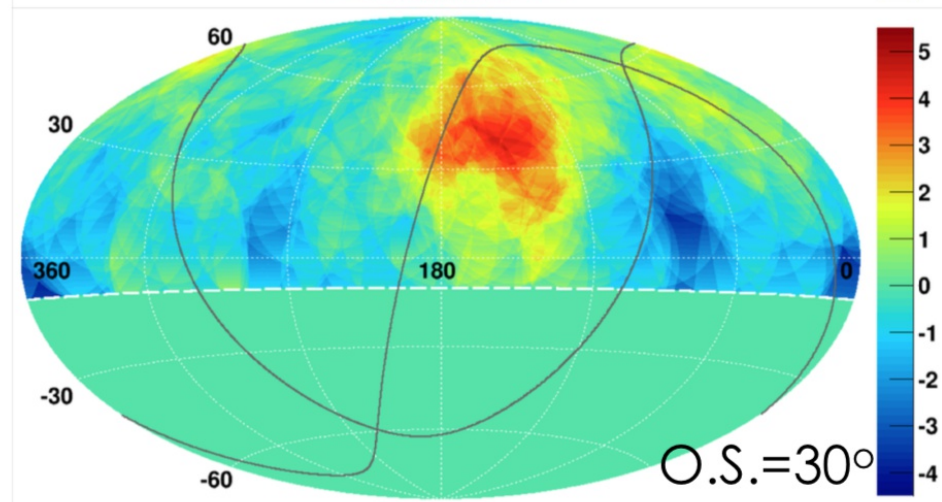
Angular Scan (>57EeV,10 years)

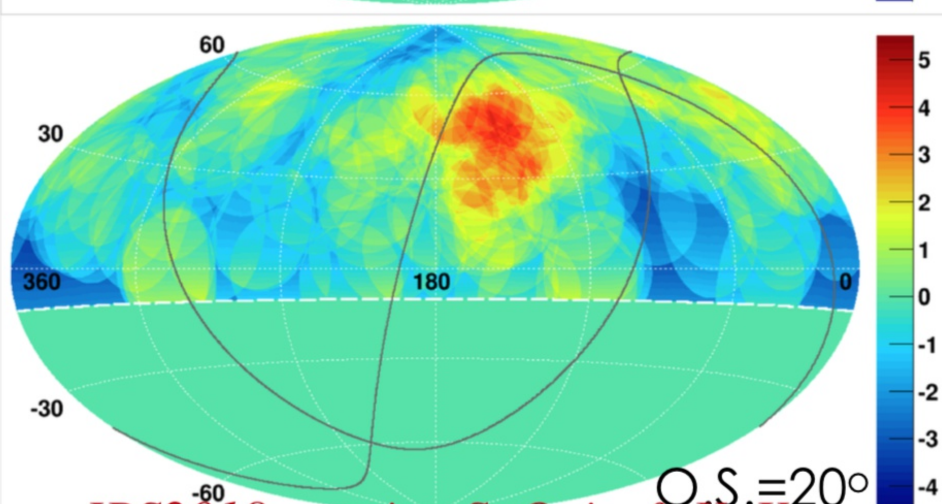
Preliminary

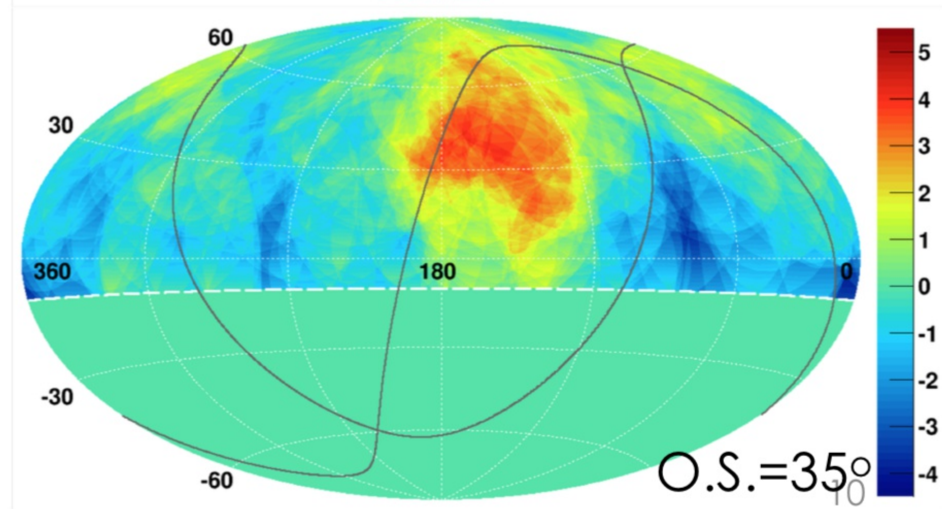
O.S. : oversampling radius











From JPS2018 meeting S. Ogio & K. Kawata

≈ 5500 UHECRs exploited (≈ 90000 km² sr y)

[Auger Coll. ApJL 853 (2018) L29]

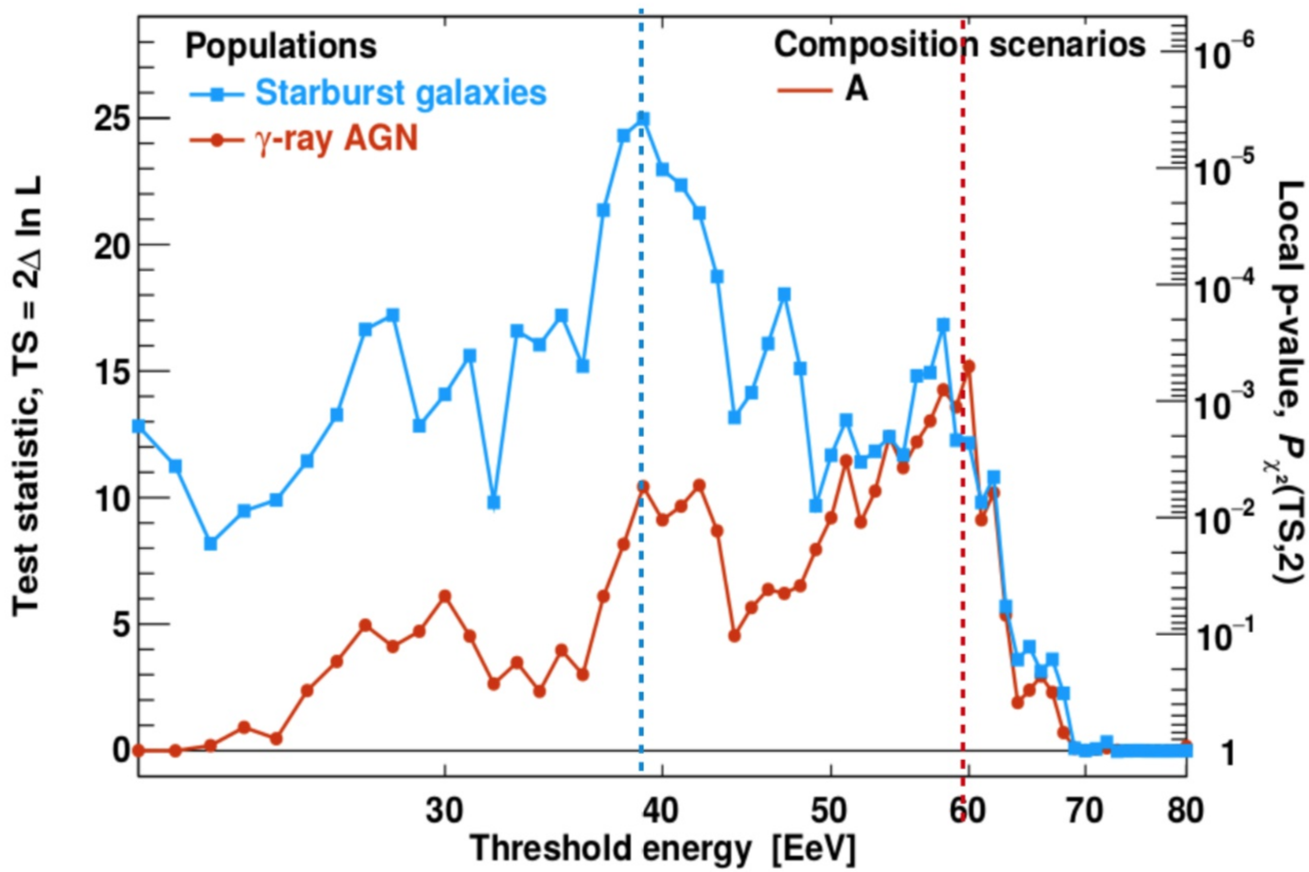
AGNs

TS is maximum for E > 60 EeV (177 events)

SBGs

TS is maximum for E > 39 EeV (894 events)

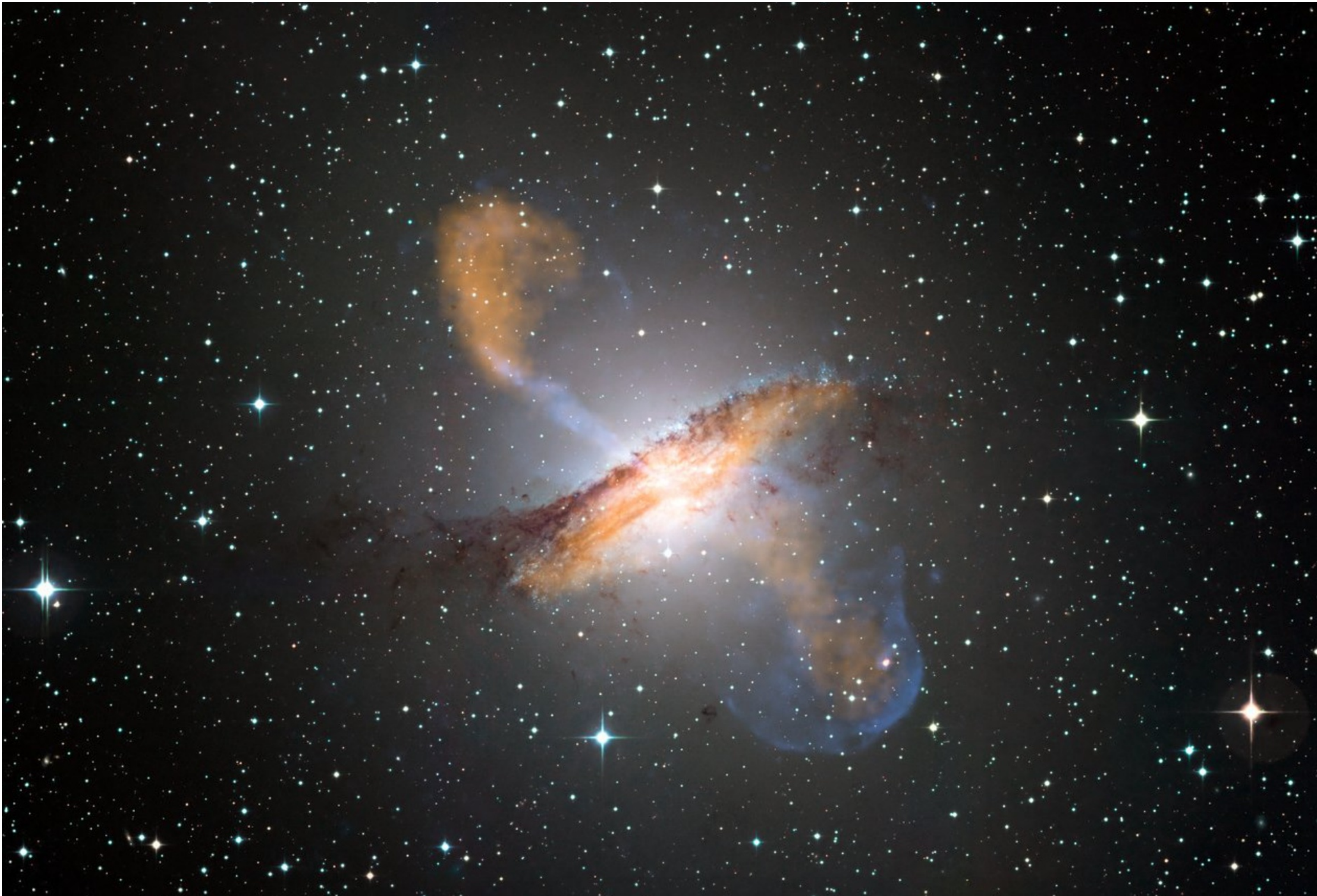
TS as a function of energy threshold



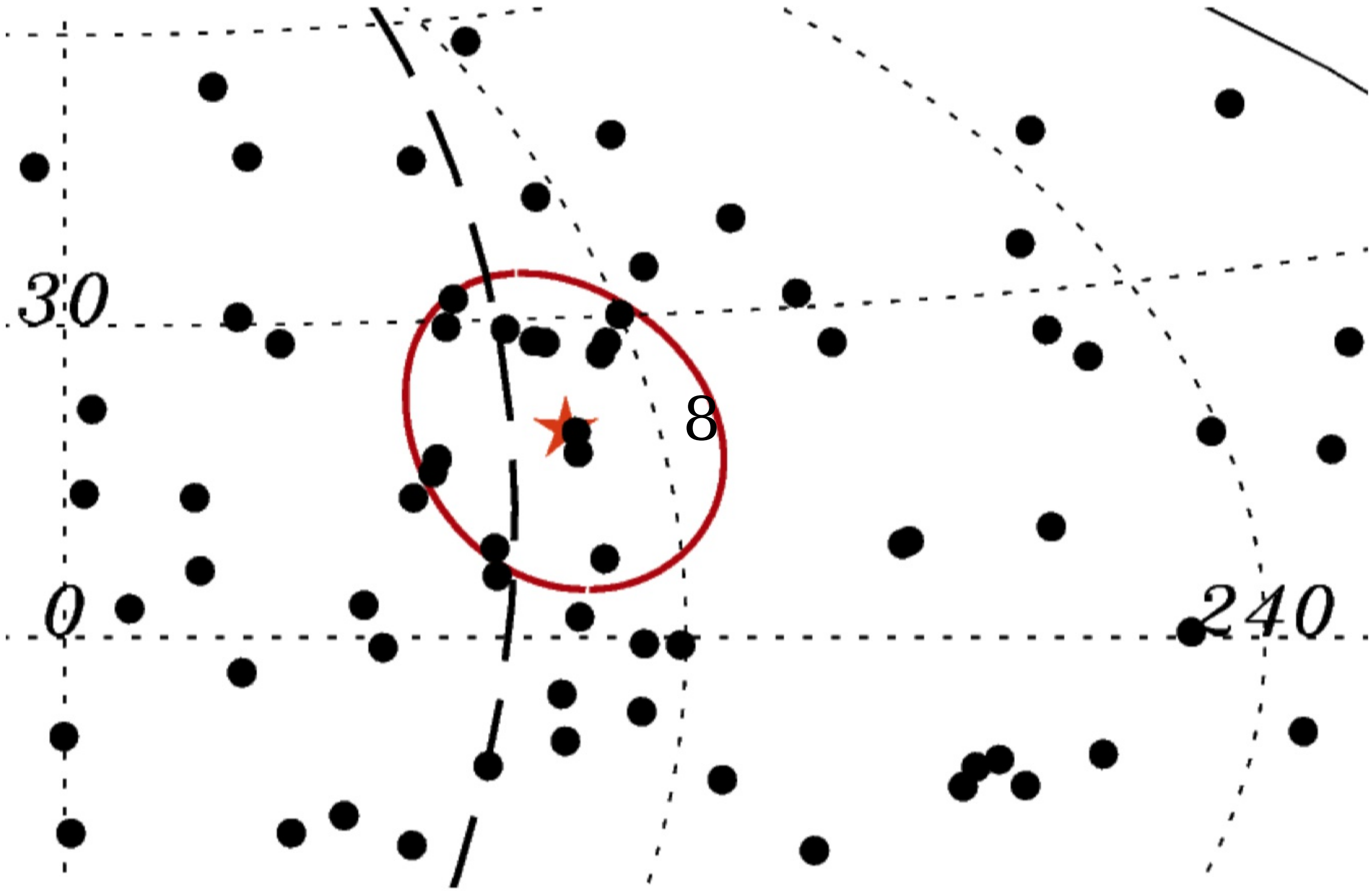
Star Burst Galaxies   (?!)

Final Stages of stellar evolution ?

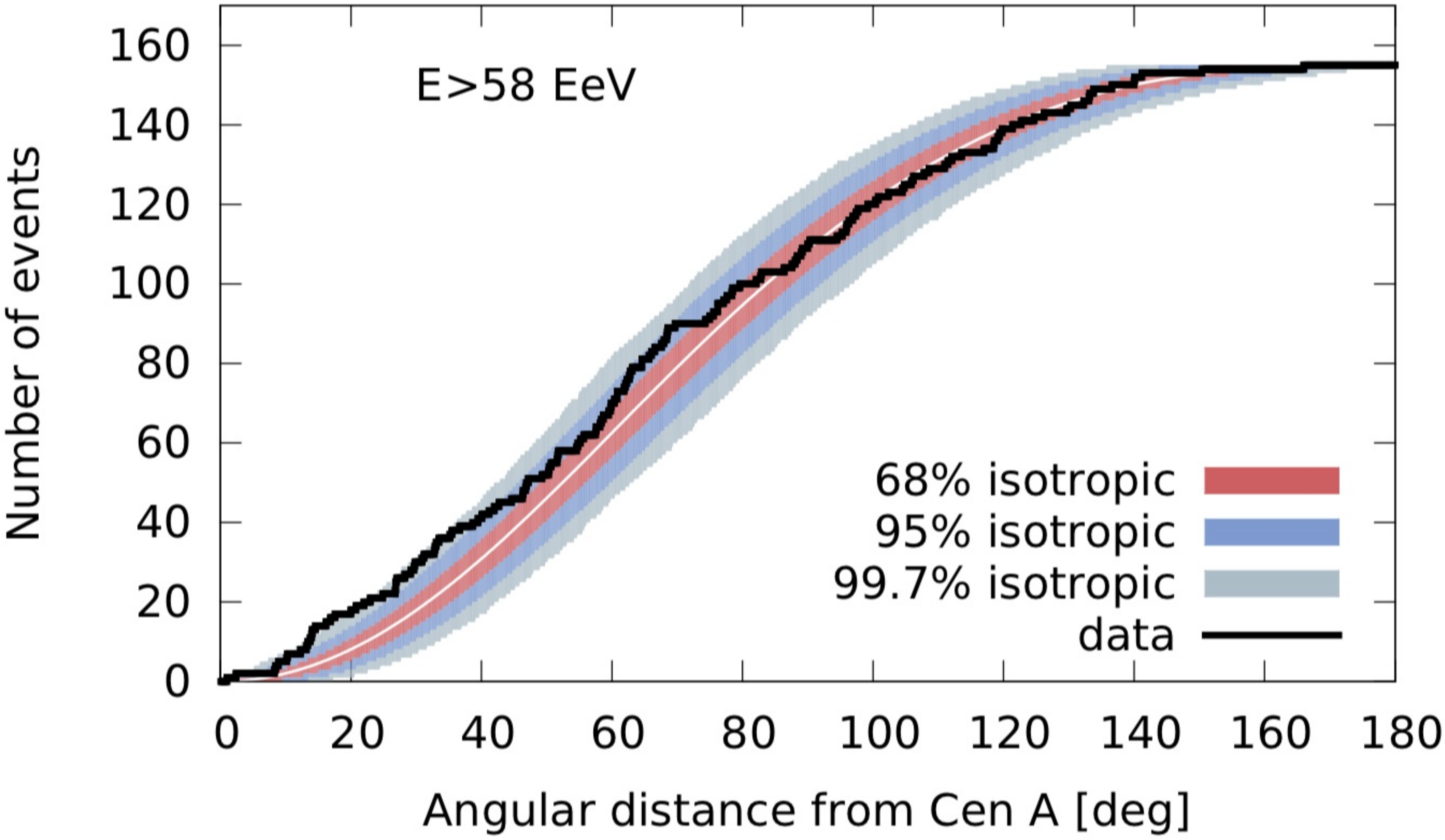
Collective effect due to
Galactic Wind generated by the ensemble
of SN explosions ?



CEN A   (excess as reported in 2014 by Auger)



Possible excess from CEN A

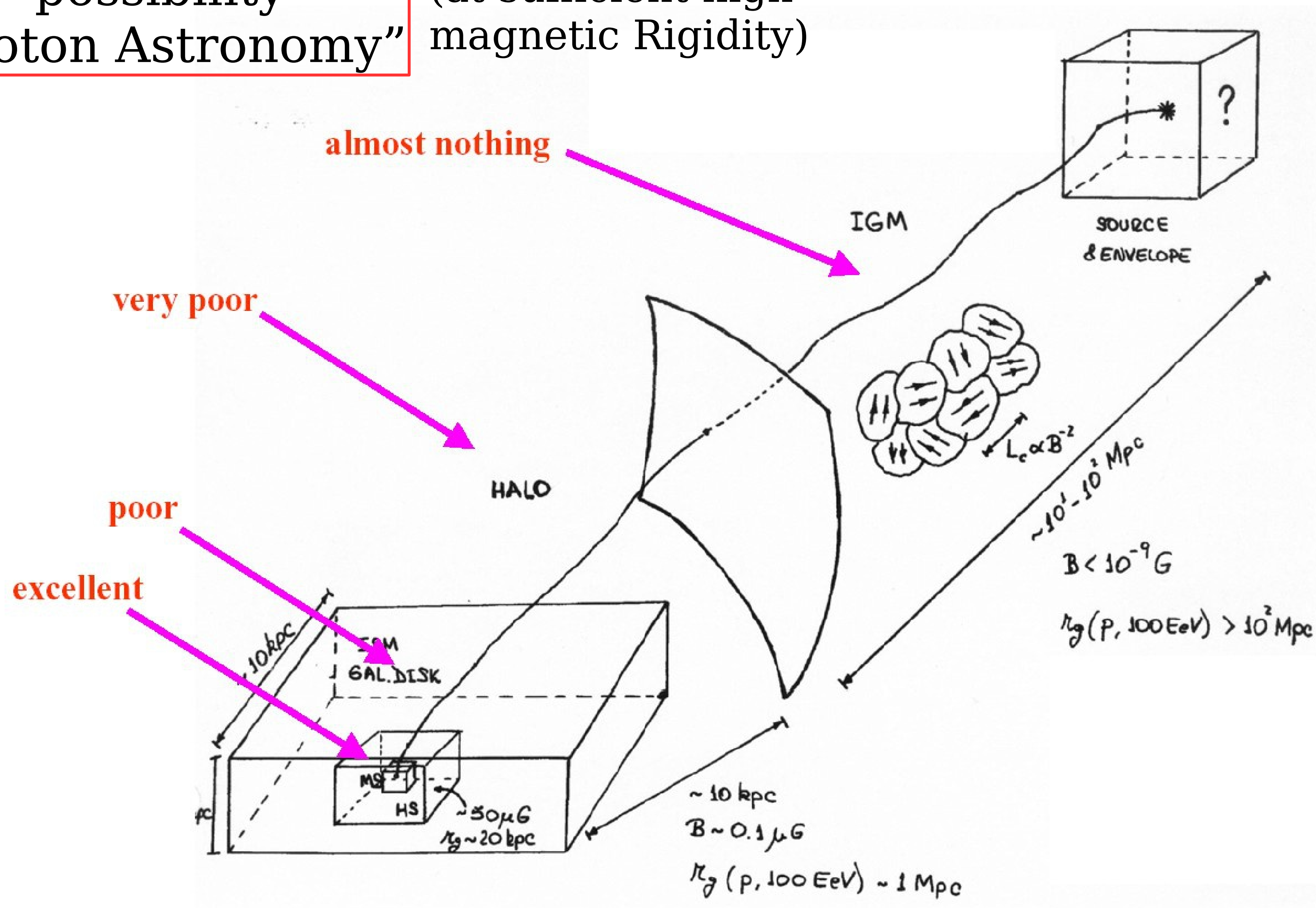


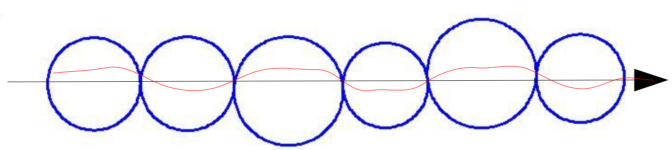
MAGNETIC

FIELDS

Galactic and extragalactic

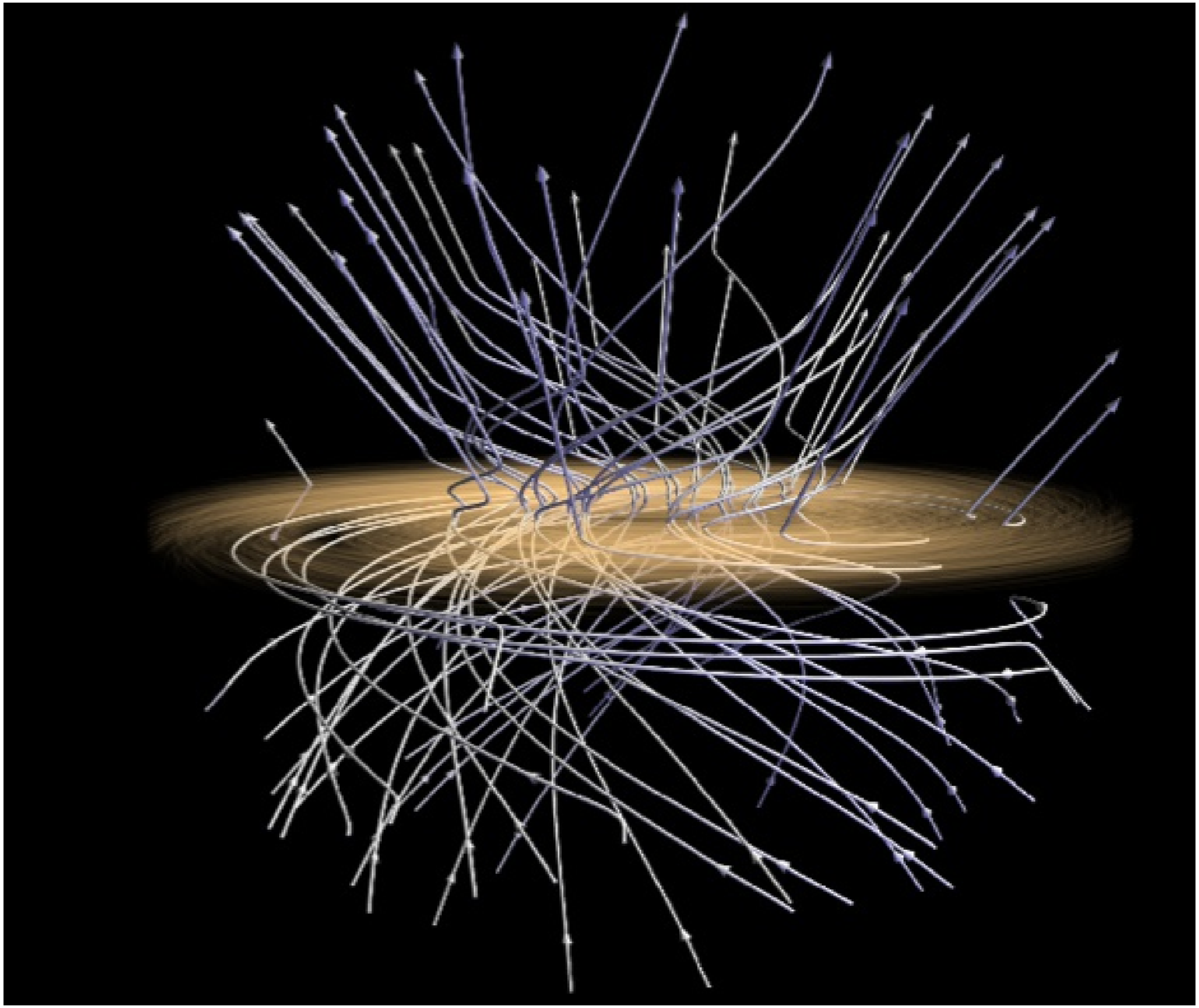
The possibility "proton Astronomy" (at sufficient high magnetic Rigidity)





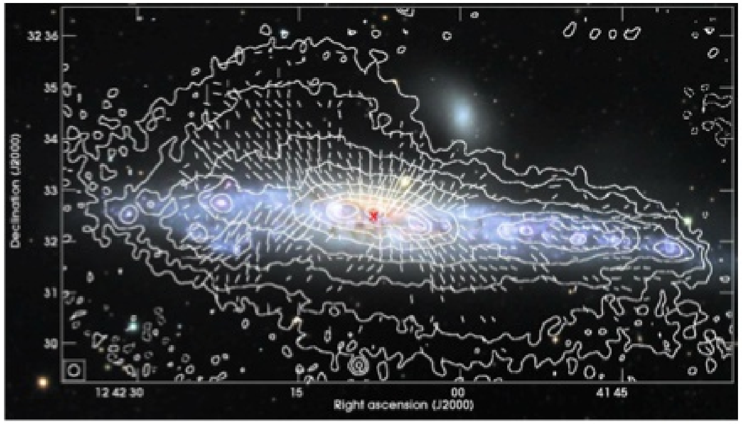
$$\Delta\theta \simeq 0.53^\circ \; Z \; \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \left(\frac{\sqrt{D\, d}}{\mathrm{Mpc}}\right) \left(\frac{\langle B \rangle}{nG}\right)$$

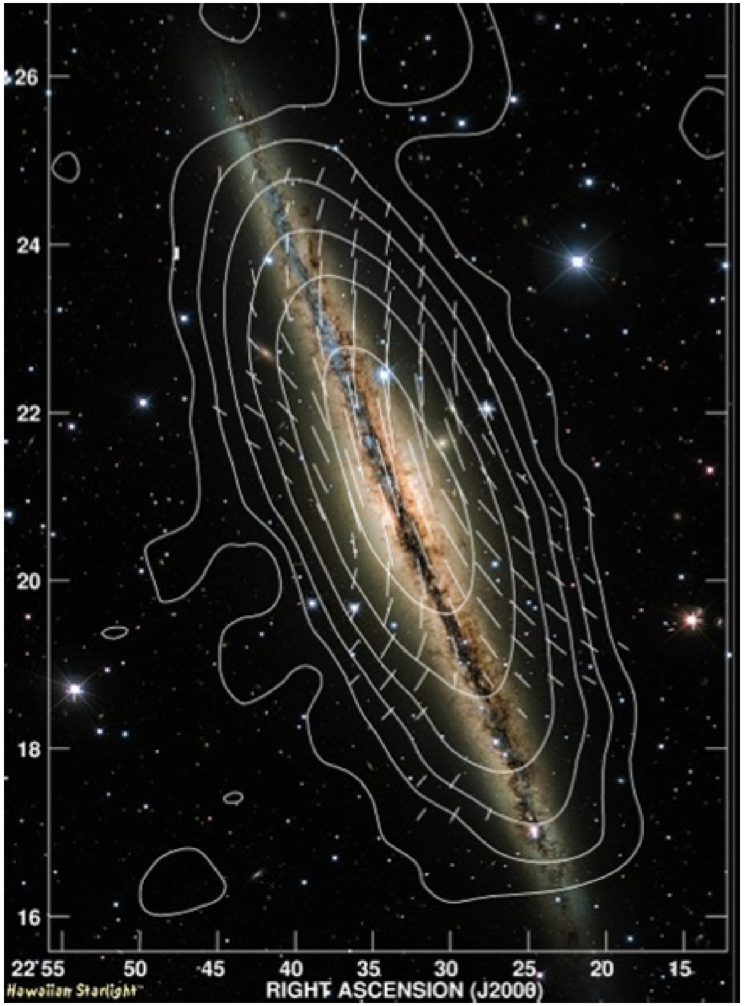
Structure of the Milky Way Magnetic Field



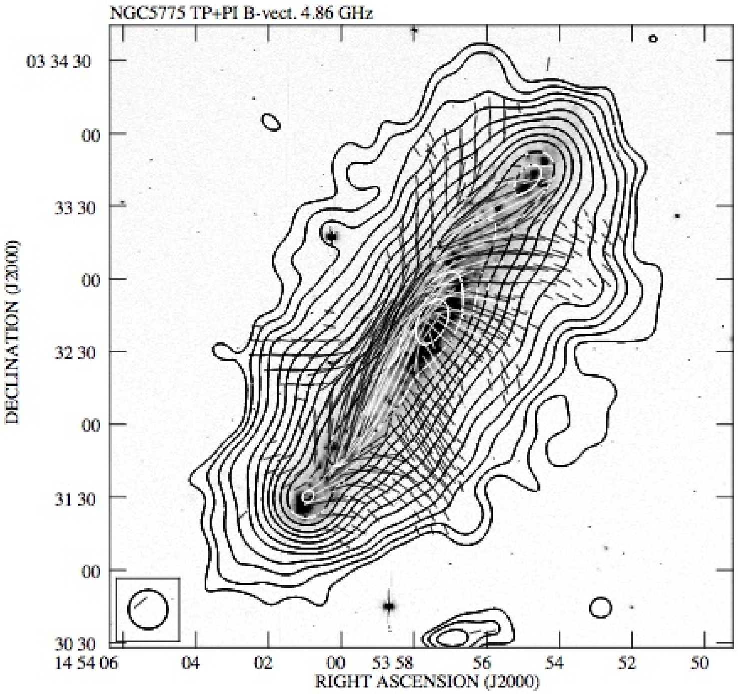
X-field

NGC 4631, M. Krause, arXiv:1401.1317





NGC891, M. Krause MPIfR



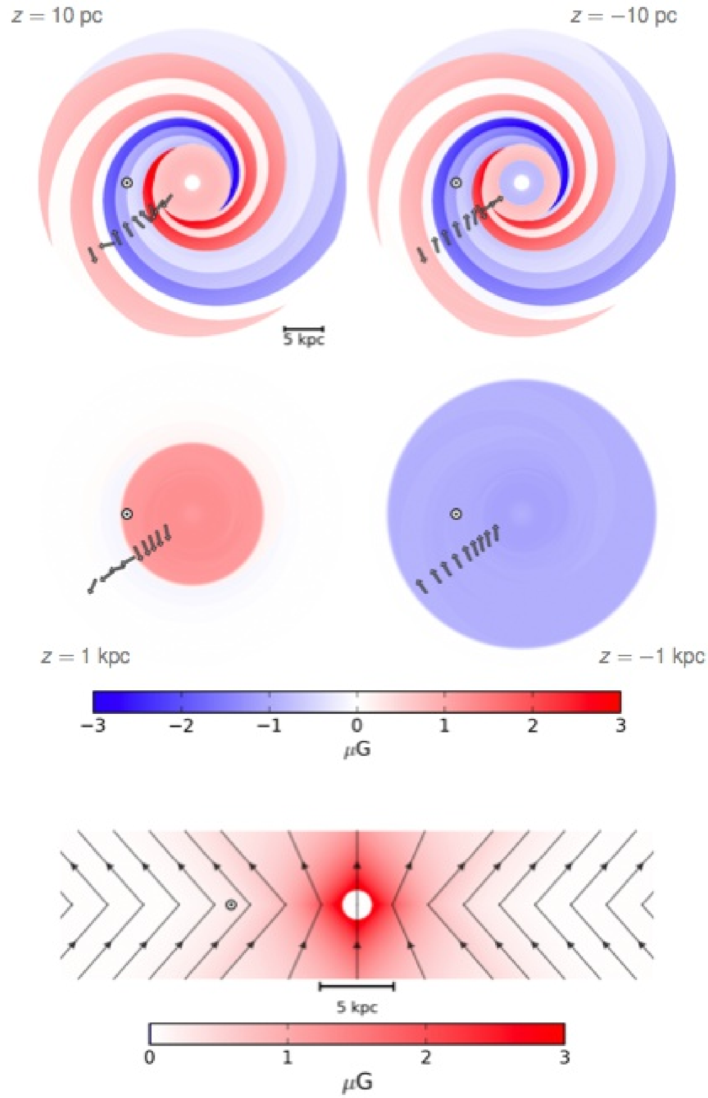
NGC 5775, M. Krause, arXiv:1401.1317

Jansson&Farrar Global Magnetic Field Model (JF12)

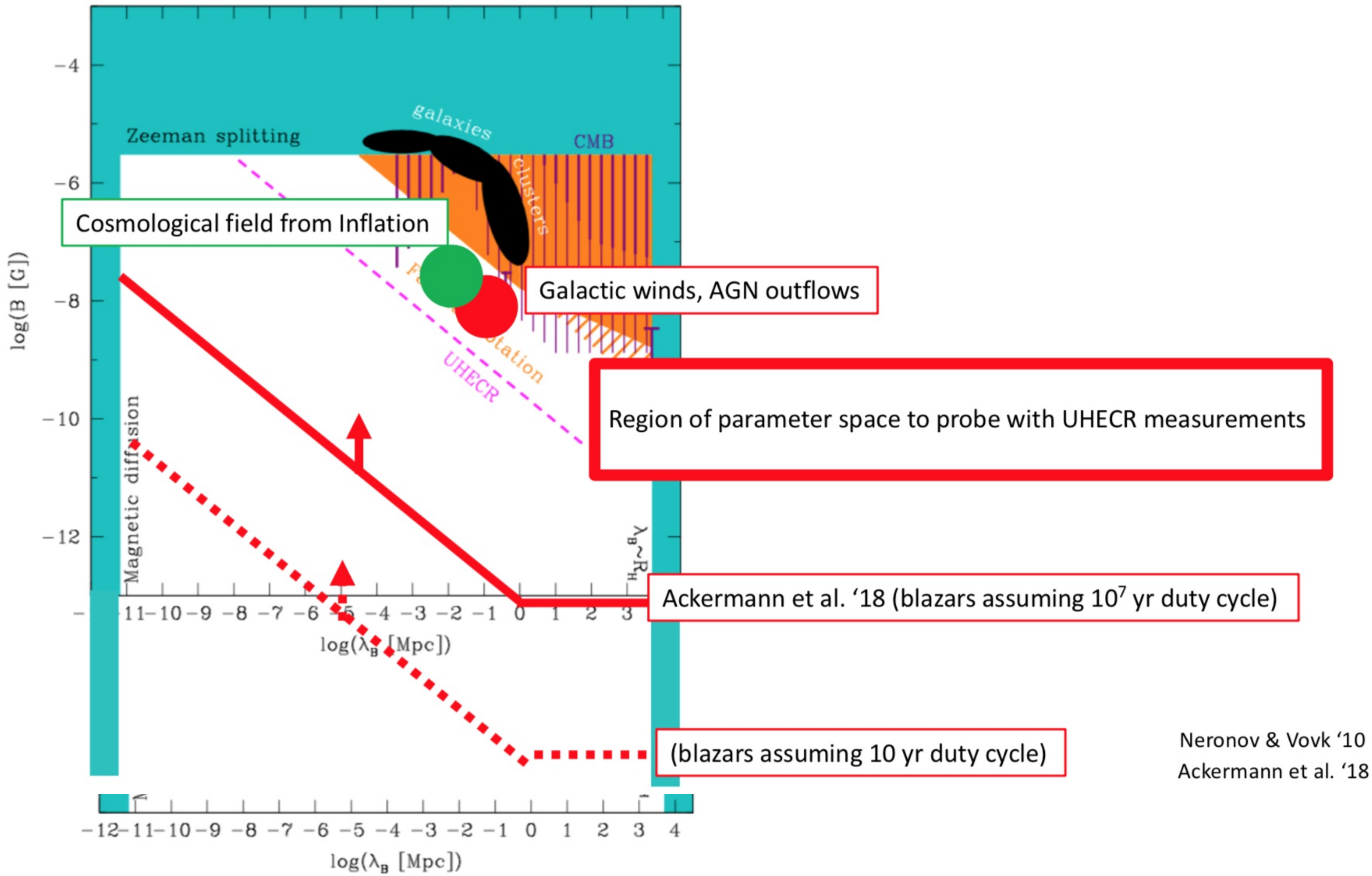
three (divergence-free!) components:

- disk field, ($h \lesssim 0.4$ kpc)
- toroidal halo field ($h_{\rm scale} \sim 5.3$ kpc)
- "X-field" (halo)

- regular field[a]: 21 parameters
- random field[b]: 13 parameters
- striation: 1 parameter
- CR electron norm.: 1 parameter



[a] R. Jansson & G.F. Farrar, ApJ **757** (2012) 14
[b] R. Jansson & G.F. Farrar, ApJ **761** (2012) L11



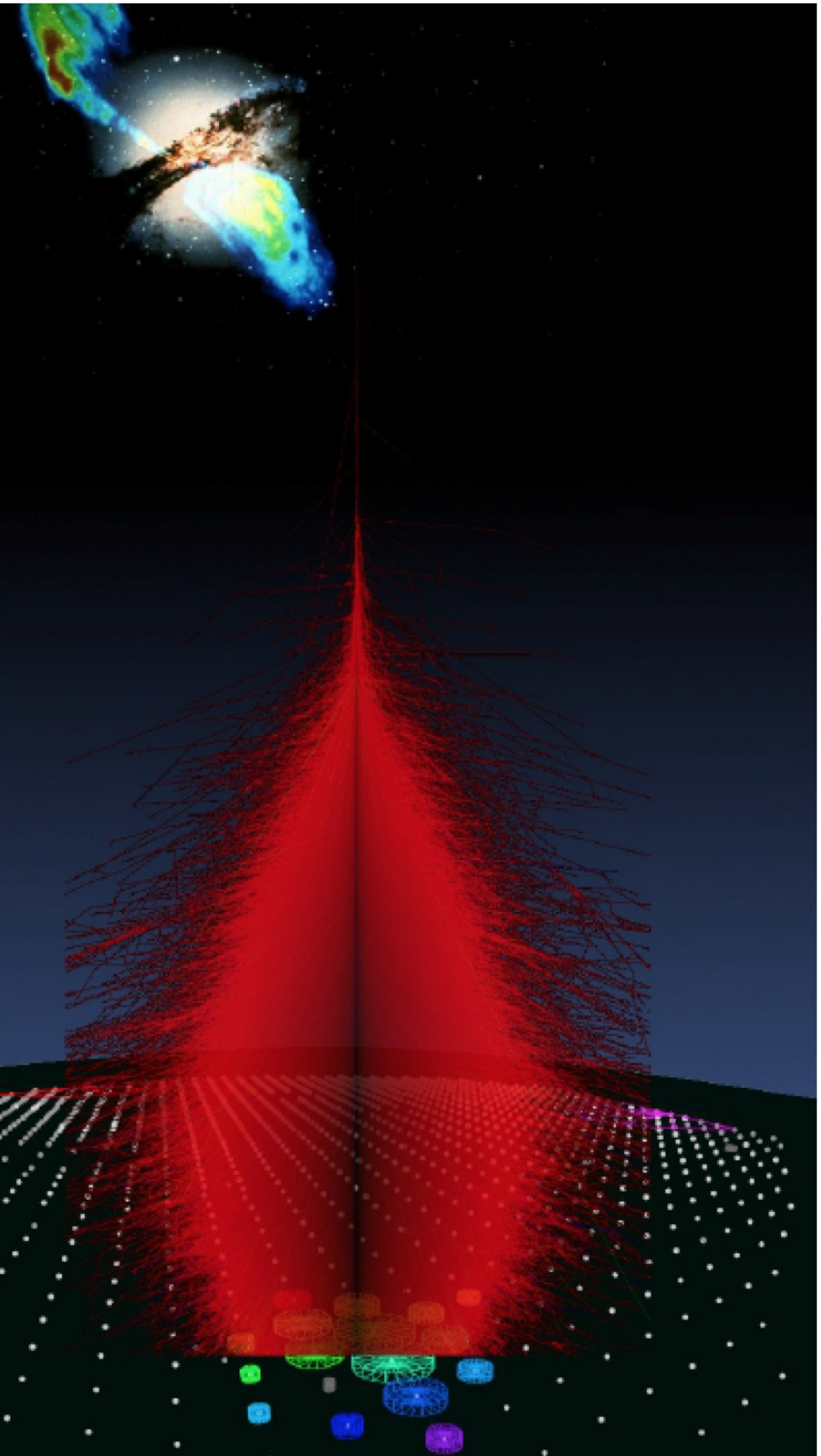
Extragalactic magnetic field

[Andrii Neronov 10/oct/2018]

Cosmic Ray Physics
[Astroparticle Physics]

and

HADRONIC INTERACTIONS



the Source

$$E_{\mathrm{lab}} \simeq 10^{20}\ \mathrm{eV}$$

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

the Shower

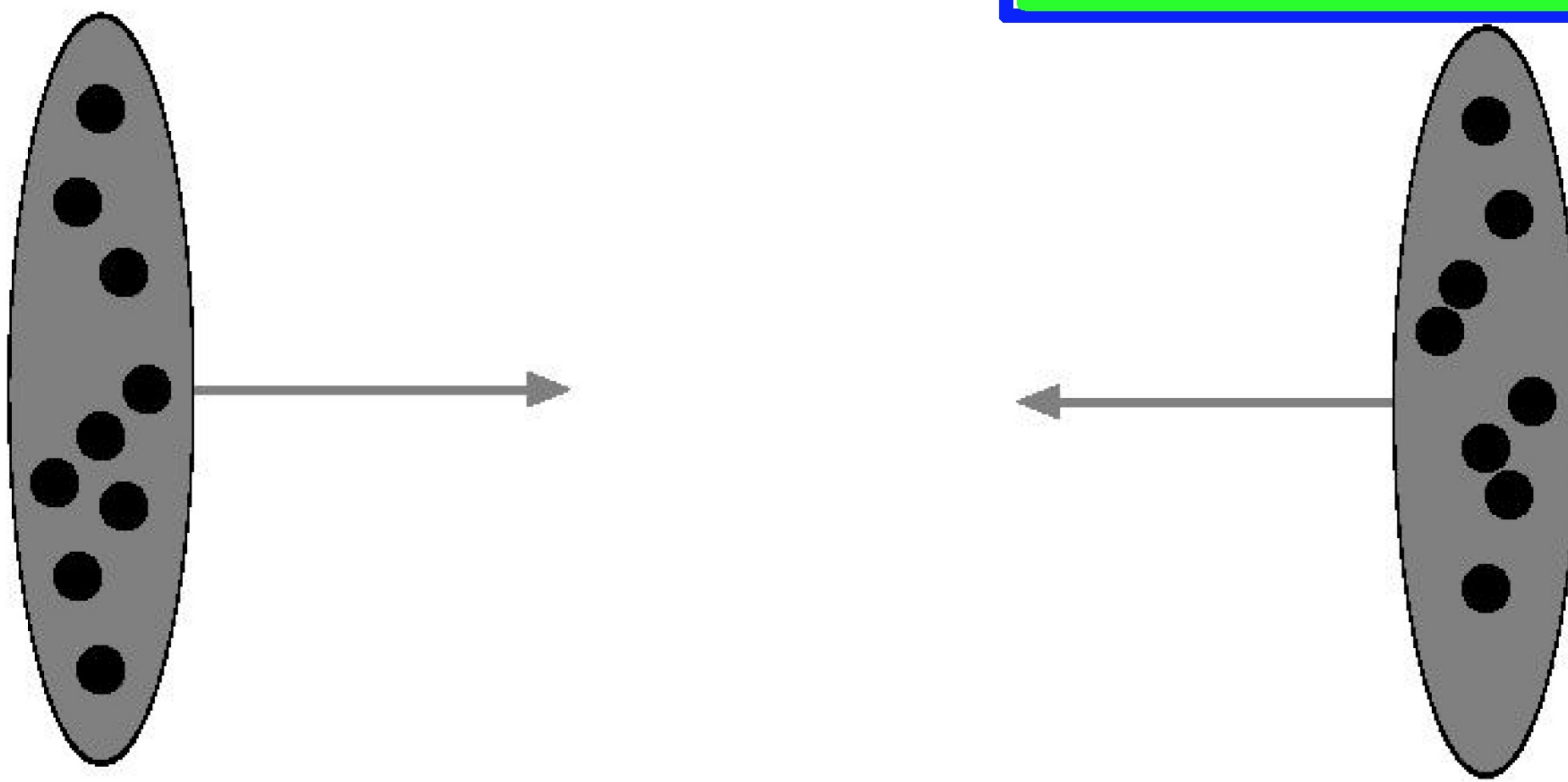
[The estimate of the Energy and Mass of the shower requires the detailed modeling of shower development]

the Data

Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



p

Multiple parton interactions
in the same collision

p

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)

Where are we with the modeling of Hadronic Interactions ?

How large are the uncertainties ?

What are the perspectives to make them smaller ?

What is the impact for present and future studies ?

my opinion:

Uncertainties on hadronic interactions are still large (and possibly/probably underestimated).

Dedicated efforts (experimental and theoretical) can significantly reduce these uncertainties.
This a very important and valuable program for
High energy astrophysics
and
Particle Physics

However: necessary to construct Observational programs that *"minimize"* the dependence on hadronic interactions [multiple variables, self consistency, ...]

Open Problems for Cosmic Ray Astrophysics

Ensemble of Galactic sources:

[*] What is the shape of the source spectrum
[*] What is the source spectrum for *electrons*
[*] Do positron accelerator exist ?
[*] What is the maximum energy of Galactic sources
[*] What generates the "Knee"
[*] Do different classes of object contribute to the flux
[*] What classes of objects ?

Ensemble of extragalactic sources:

[*] What is the shape of the extragalactic source spectrum
[*] What is the maximum energy
[*] More than one class of events ?
[*] Source identification [CR astronomy]
....

Strategies for future CR studies

Two main directions:

[1.] Highest Energies, Very large Exposures

pursue the dream of Cosmic Ray Astronomy
[look for surprises, exotic, …]

[2.] Lower energies [TeV - EeV]
Higher statistics
Better control of systematics
Redundant measurements.
Clarify open problems
Knee, Ankle, Galactic/extragalactic, ….