High Energy Astrophysics:

Theory challenges Experiment,

what can we learn

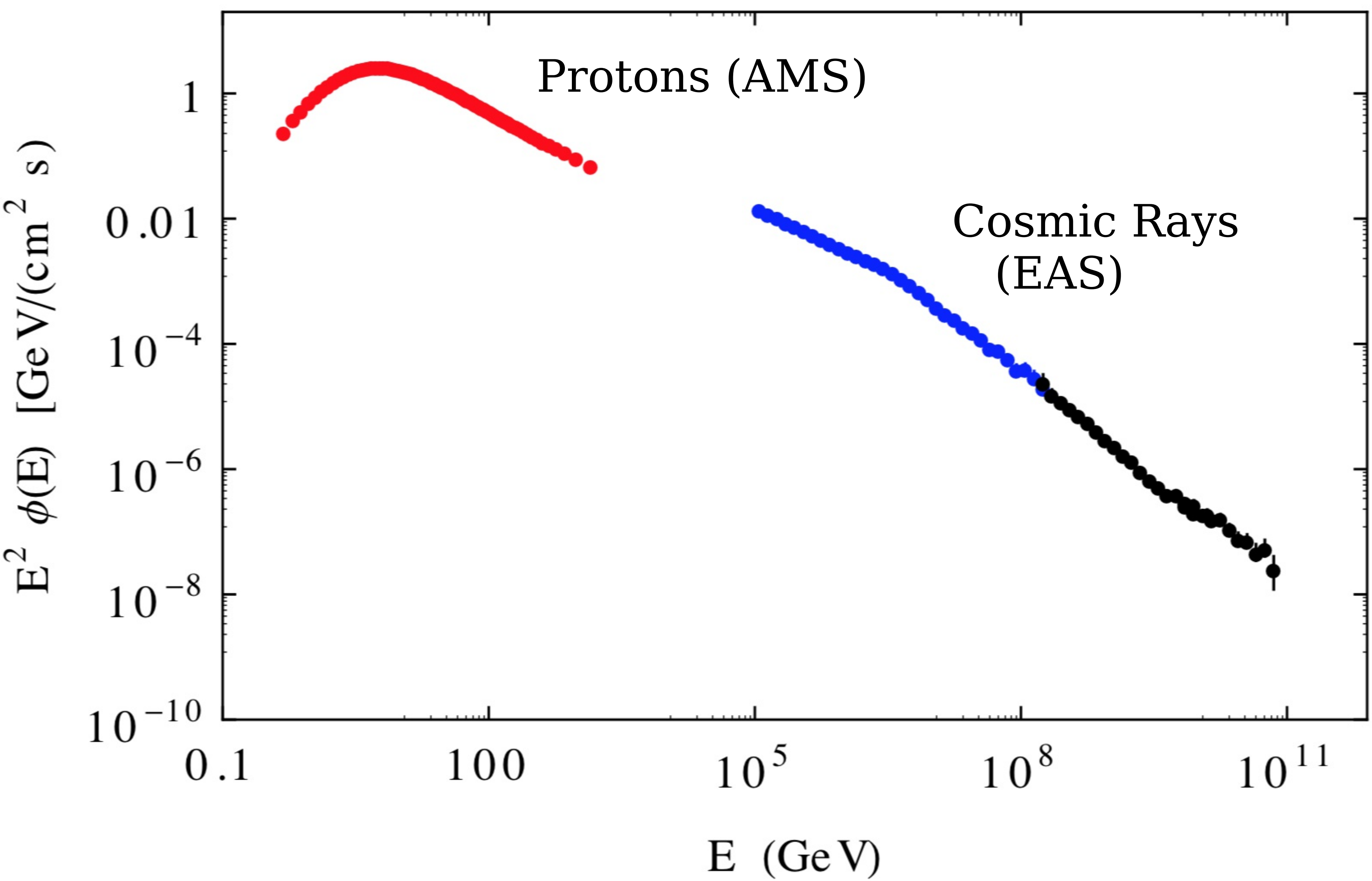
with better observations.

Paolo Lipari (INFN Roma Sapienza)
“Workshop Neutrino Telescopes”
Venezia, 18th march 2019

1. Where we are now in our understanding of the “High Energy Universe” .

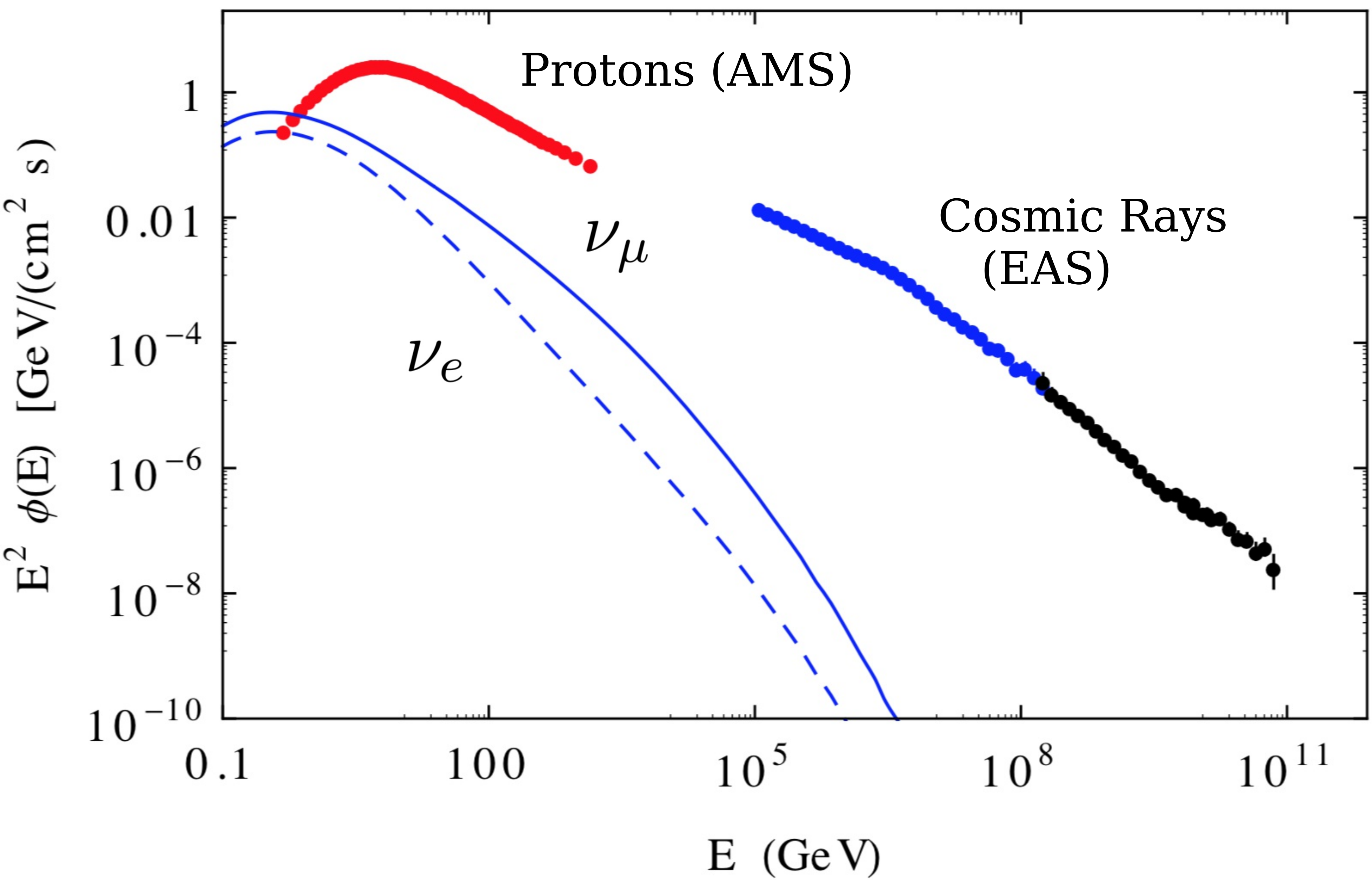
2. Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

3. Open problems in the *ASTROPHYSICS* of the “High Energy Universe"



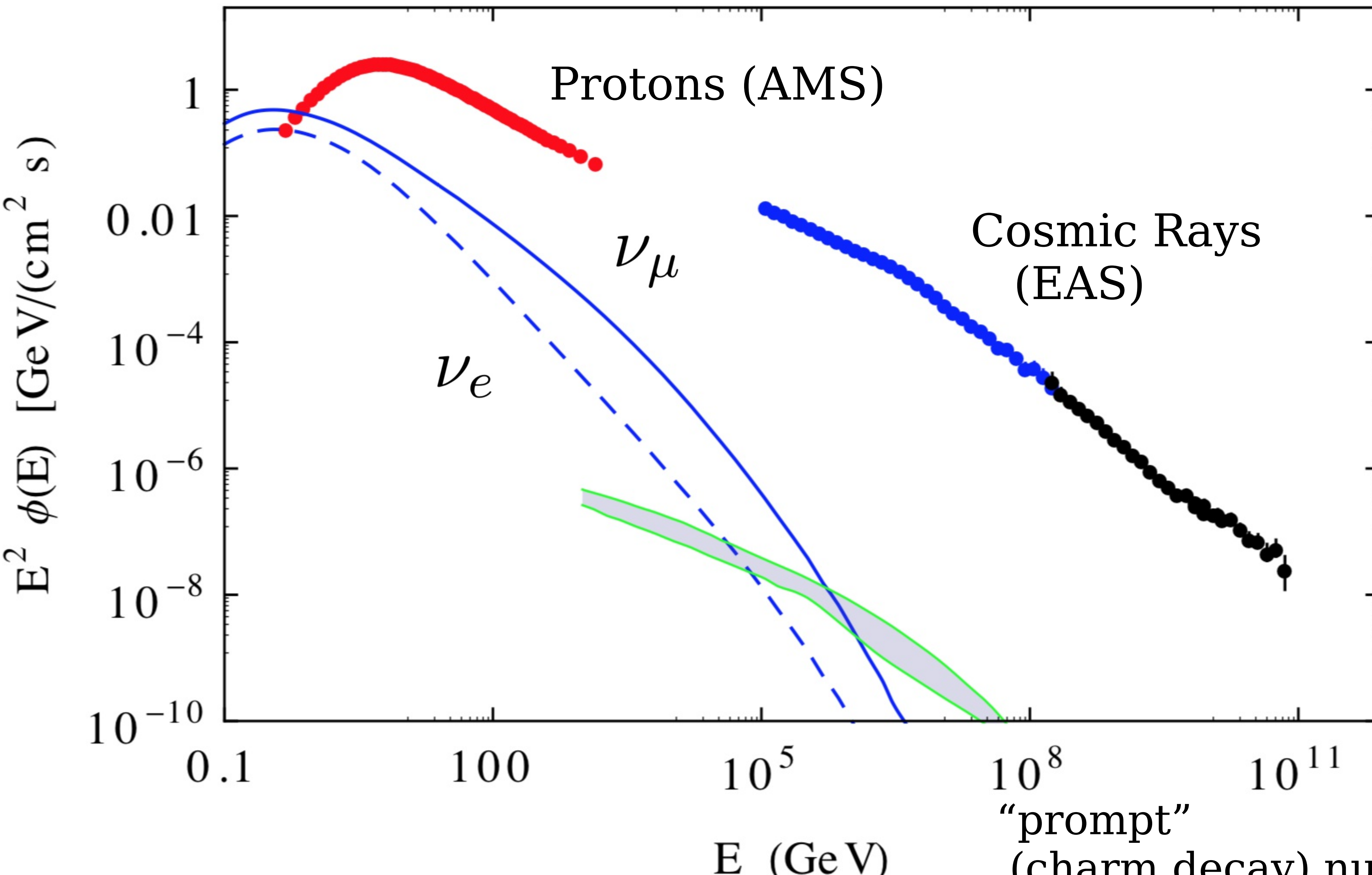
(Angle integrated Spectra)

Atmospheric Neutrinos (pi/K decay)



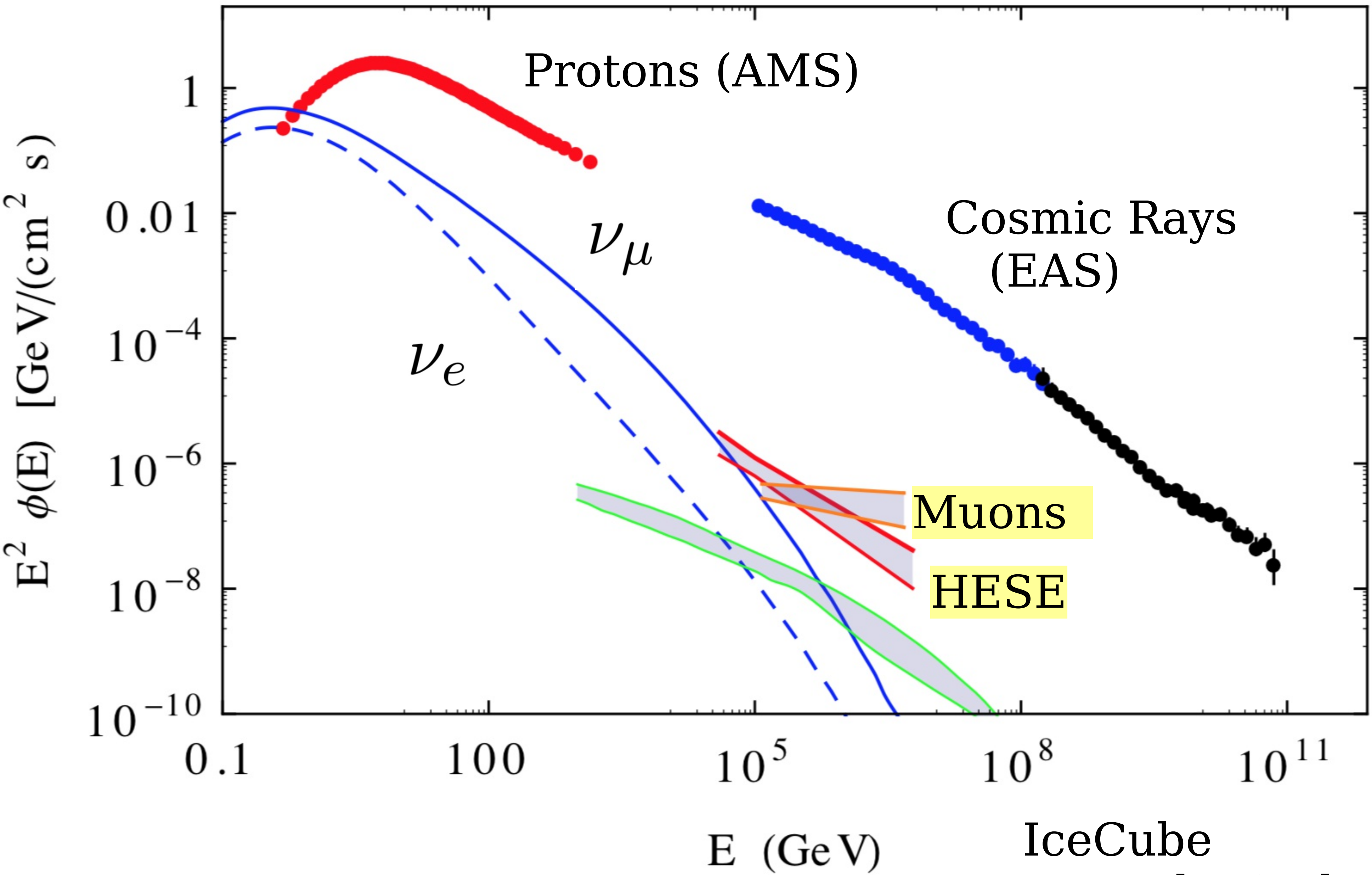
(Angle integrated Spectra)

Atmospheric Neutrinos (pi/K decay)



"prompt"
(charm decay) nu's

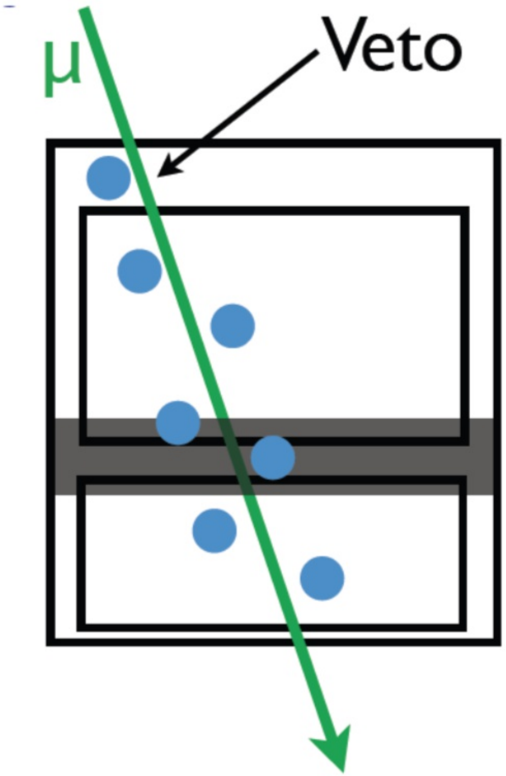
(Angle integrated Spectra)

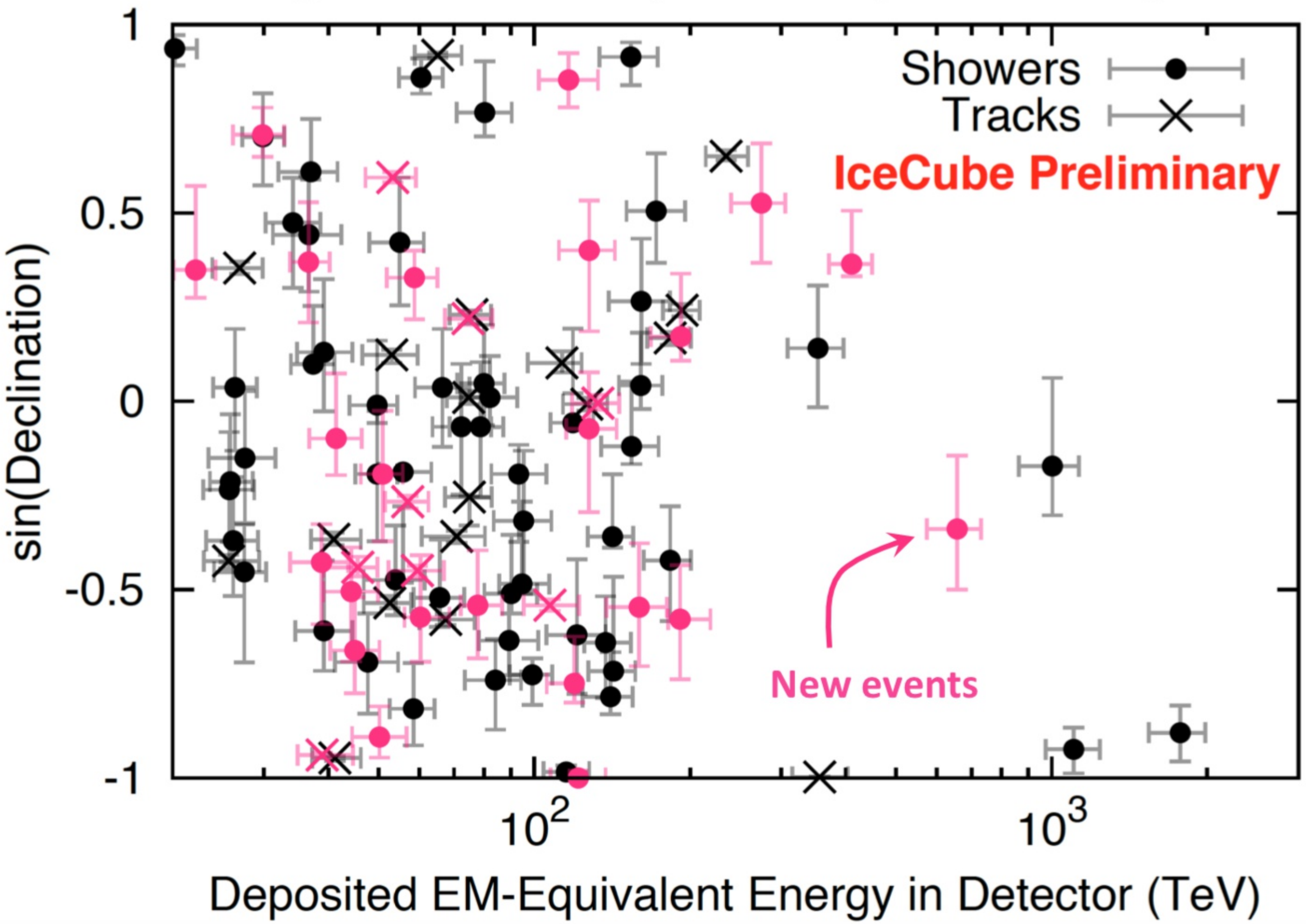


IceCube
Astrophysical
signal

(Angle integrated Spectra)

High-Energy Starting Events (HESE) – 7.5 yr





Prior result 6 years ICRC 2017 arXiv:1710.01191

Updates to calibration and ice optical properties

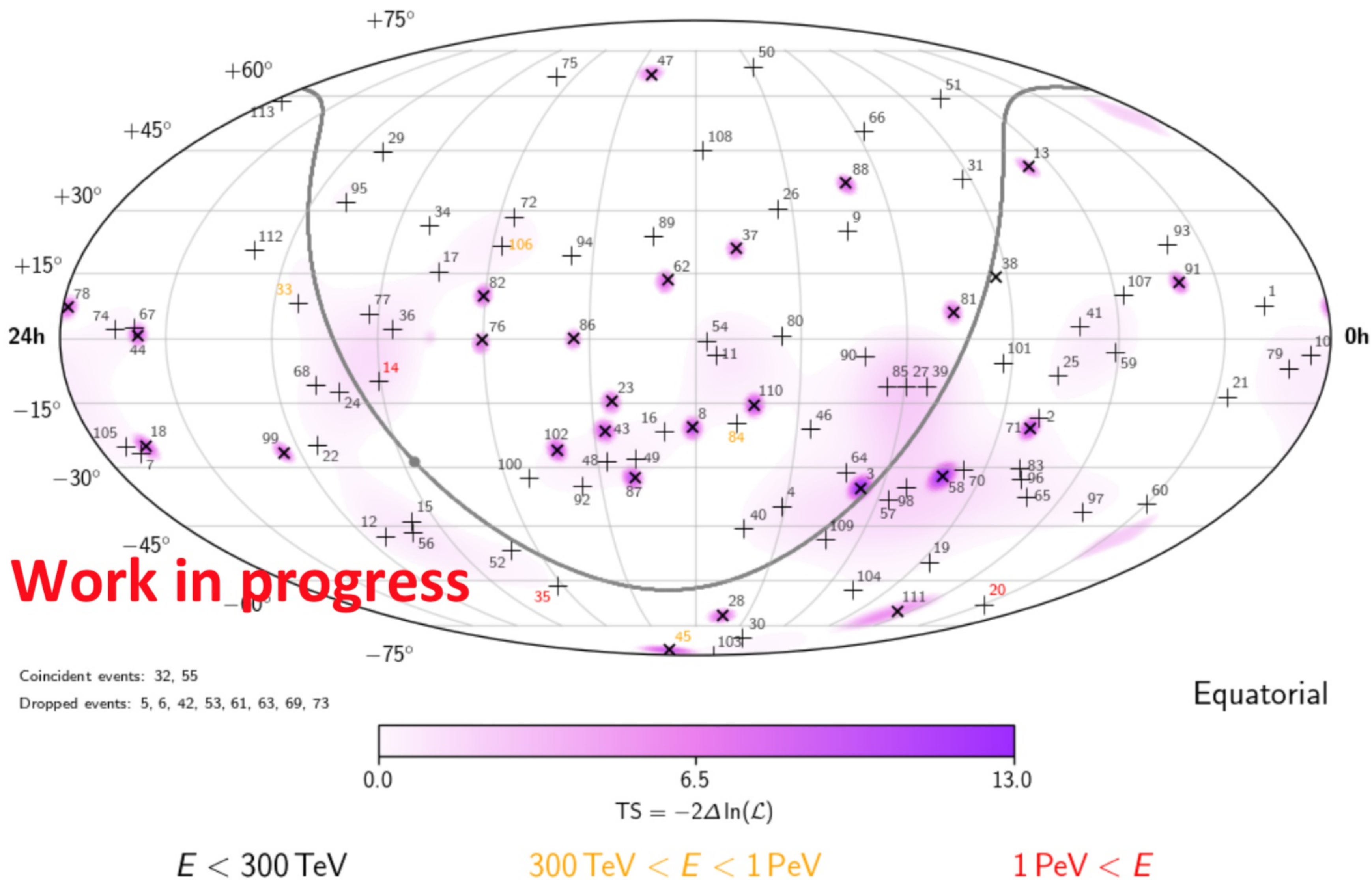
103 events, with 60 events >60 TeV

→ Changes to RA, Dec, energy

IceCube. Nature volume 551 (2017) 596

Poster #175. Wandkowsky et al. (IceCube)

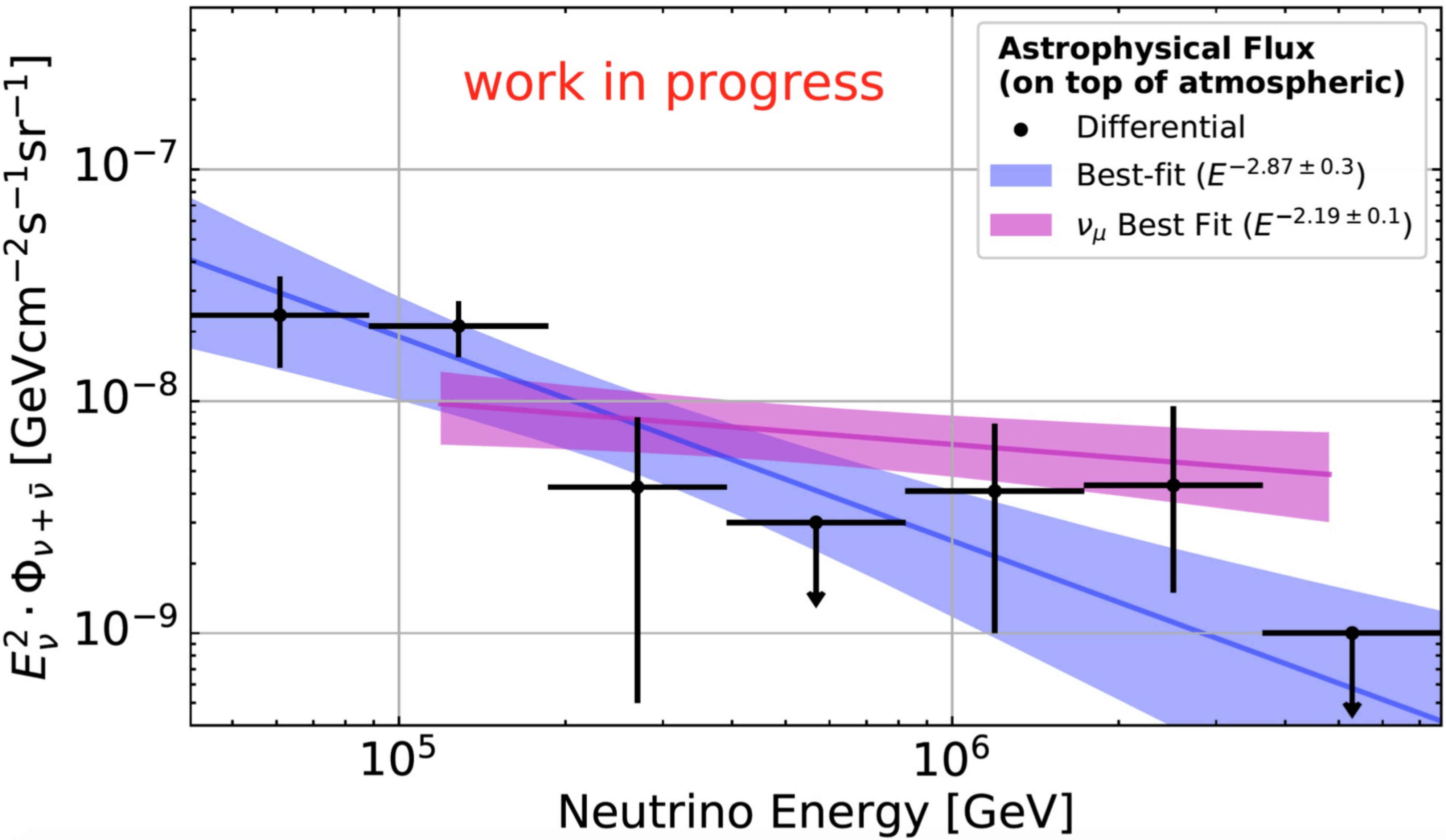
High-Energy Starting Events (HESE) – 7.5 yr

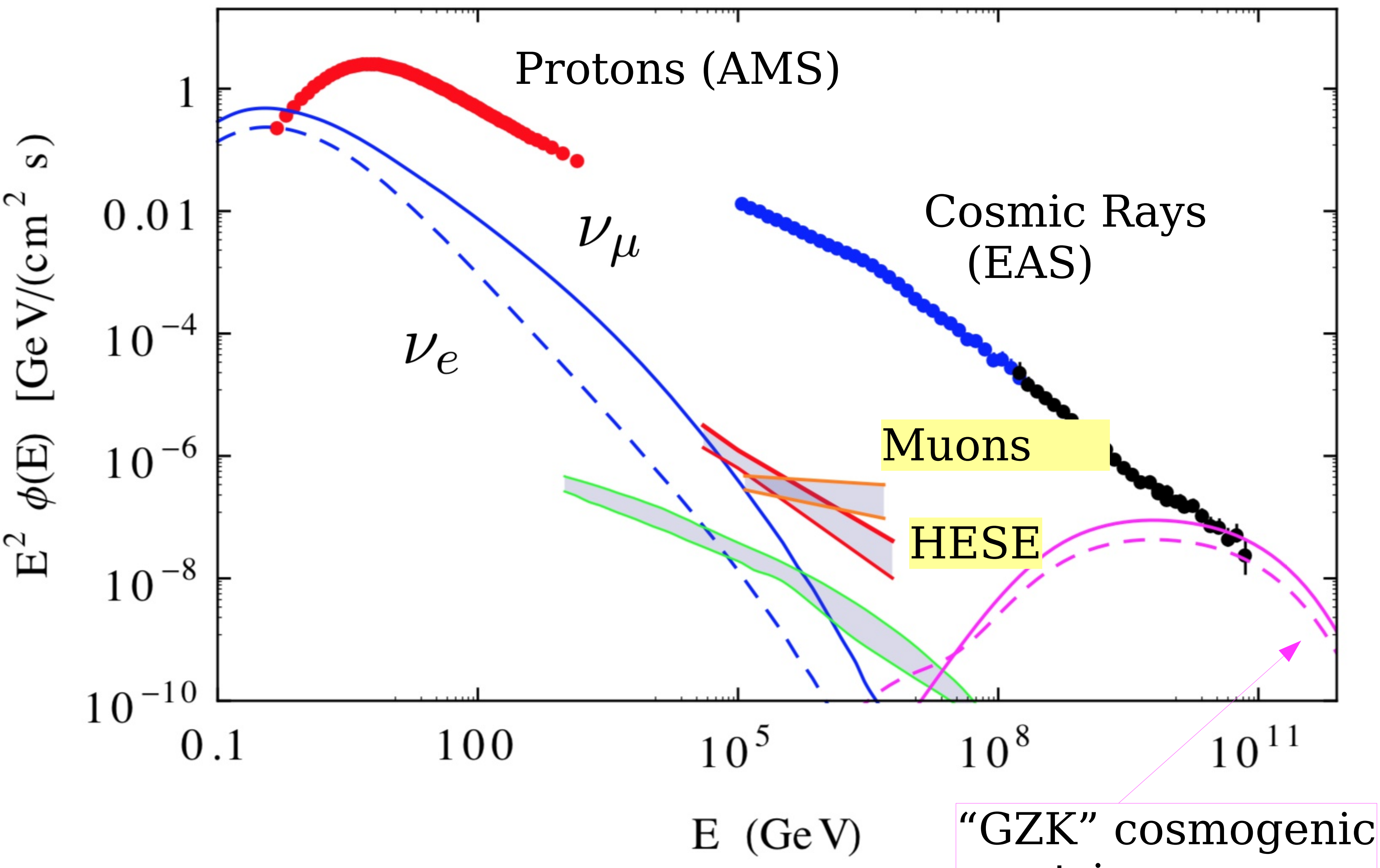


No evidence for point sources, nor a correlation with the galactic plane

Poster #175. Wandkowsky et al. (IceCube)

High-Energy Starting Events (HESE) – 7.5 yr

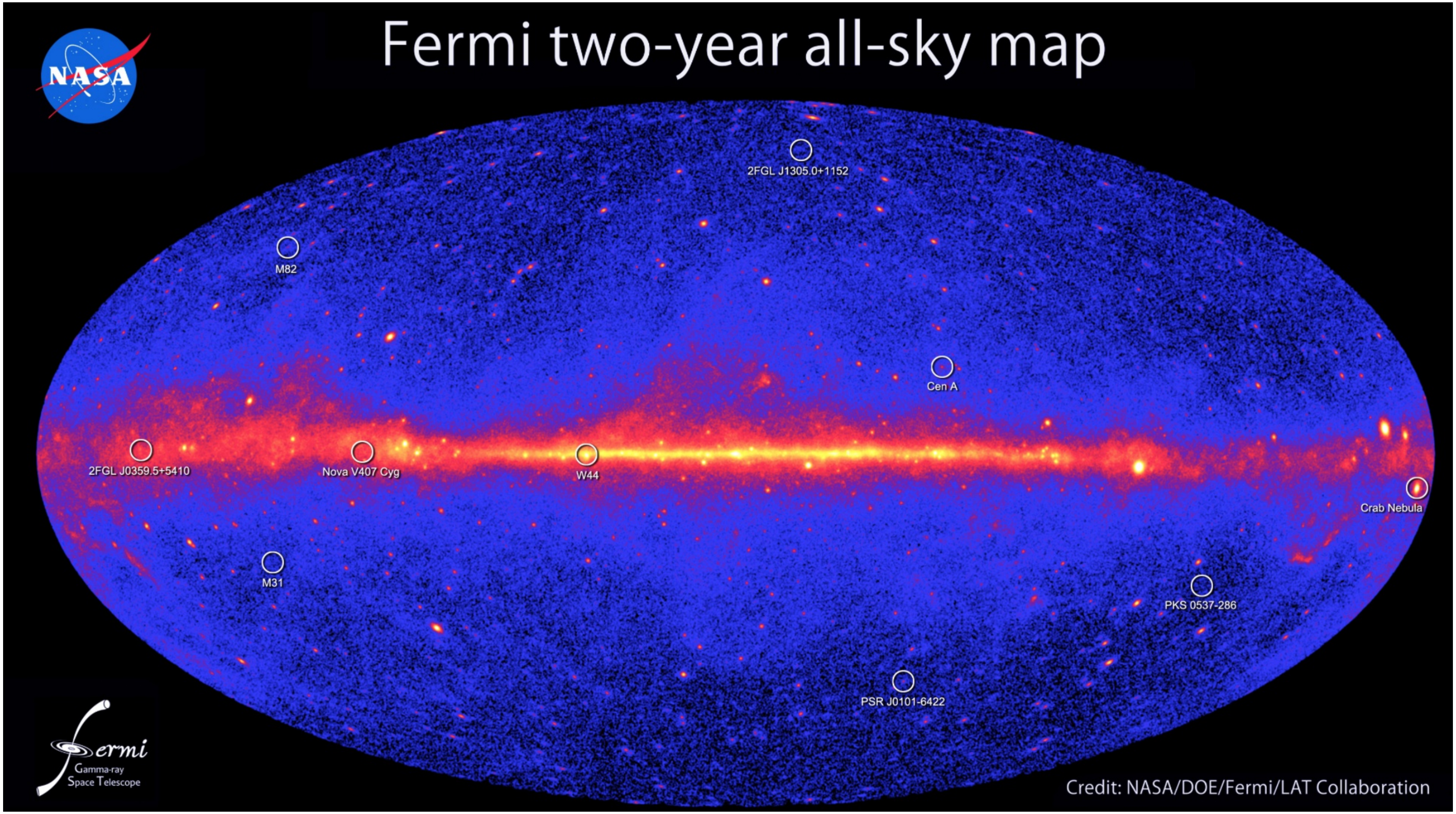




(angle integrated Spectra)

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

Gamma Ray Sky



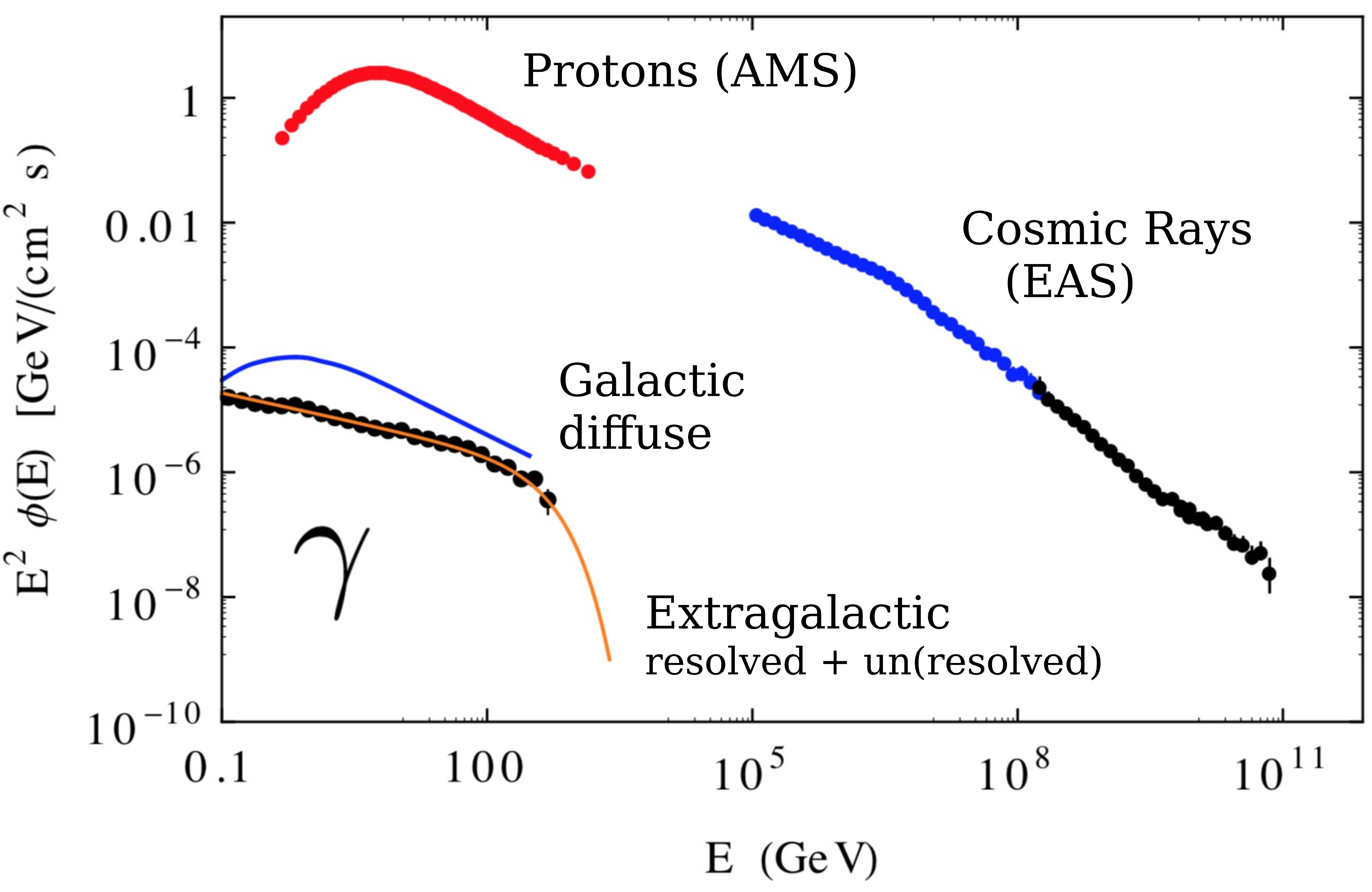
2008 - ...

Fermi Satellite

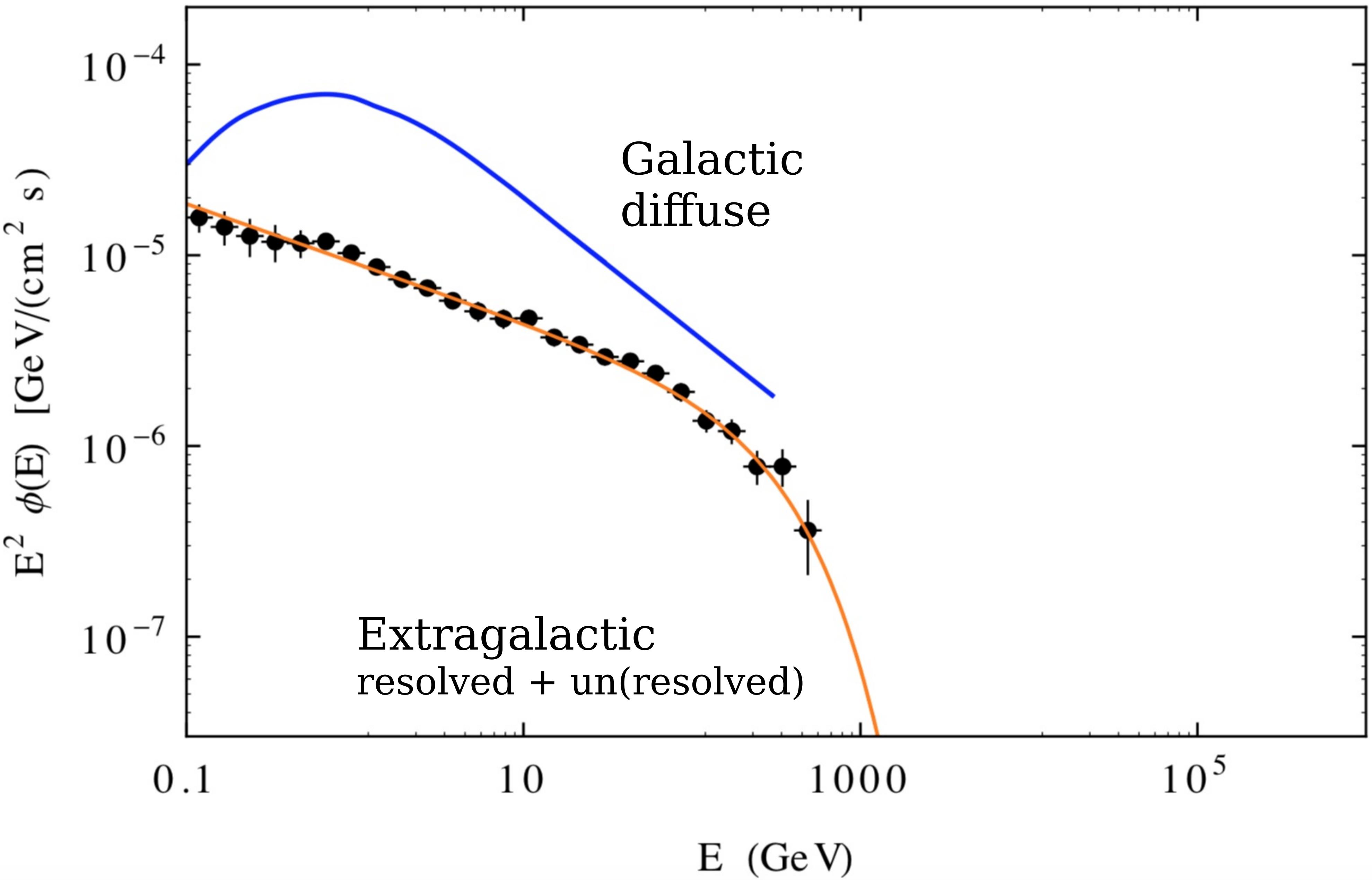
LAT: 10 MeV - 300 GeV
BGO: ....
GBM: 10 keV-1 MeV

> 5000 sources 50 MeV - 1 TeV
> 5000 GRBs

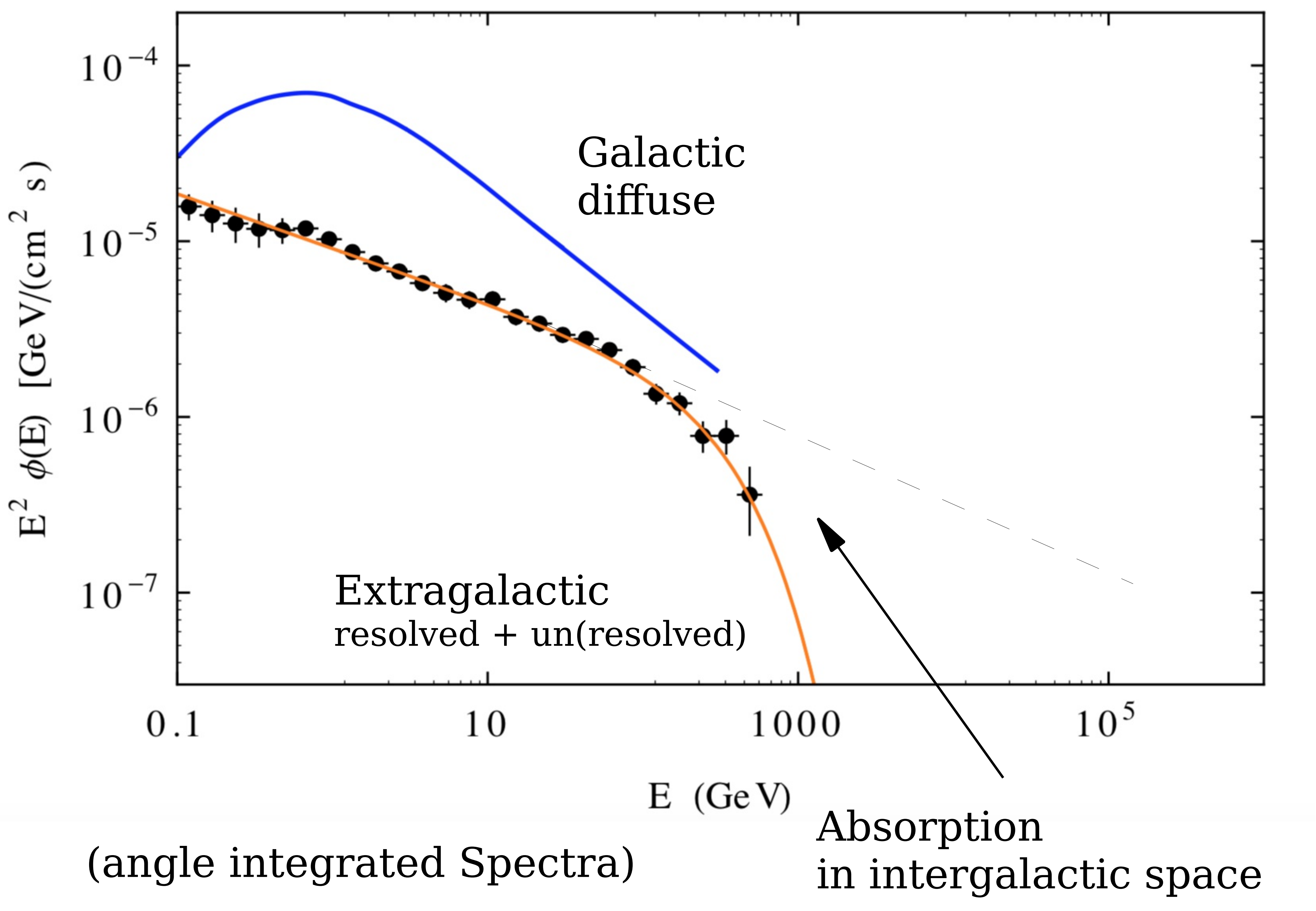
≈ 1 m² 2.5 sr
LAT: 10 MeV - 300 GeV

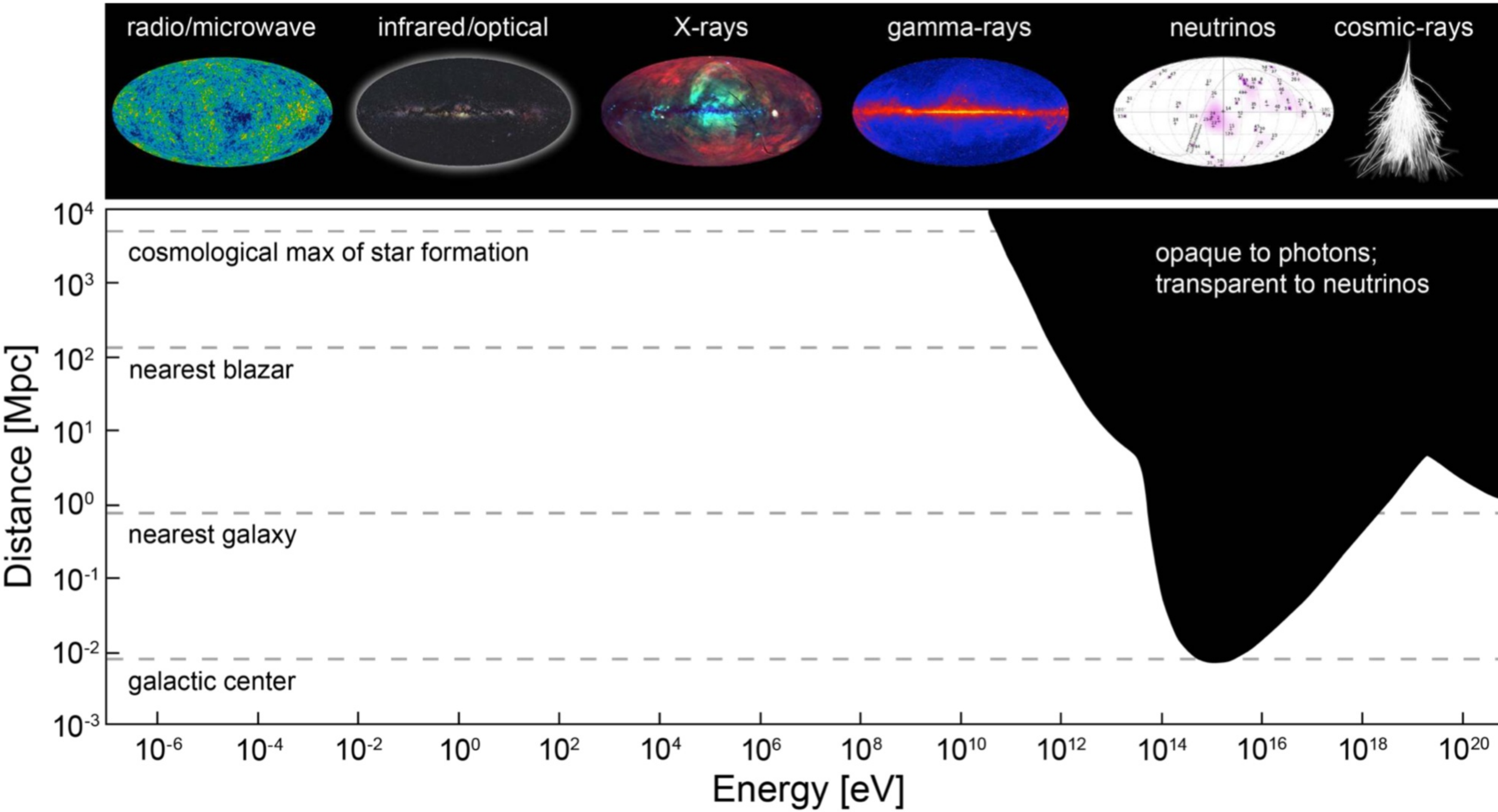


(angle integrated Spectra)

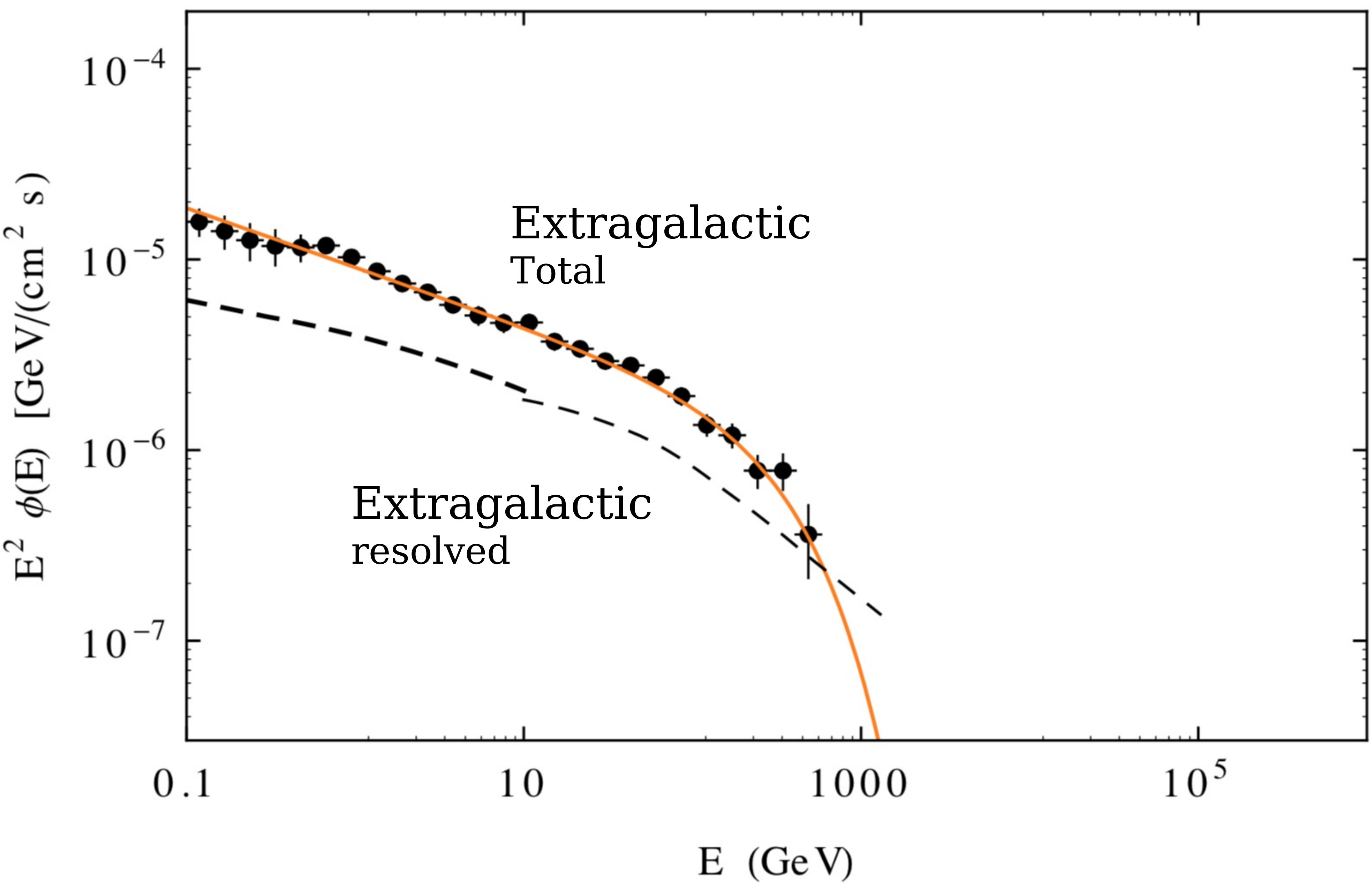


(angle integrated Spectra)


Galactic
diffuse
Extragalactic
resolved + un(resolved)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.1
10
1000
10^5
$E^2\ \phi(E)$ [GeV/(cm^2 s)
E (GeV)
Absorption
in intergalactic space
(angle integrated Spectra)

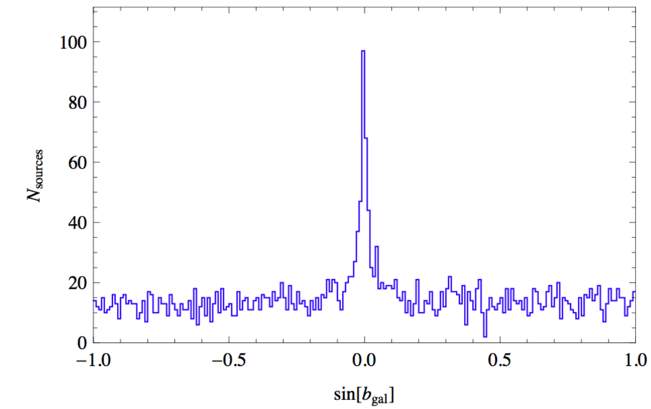


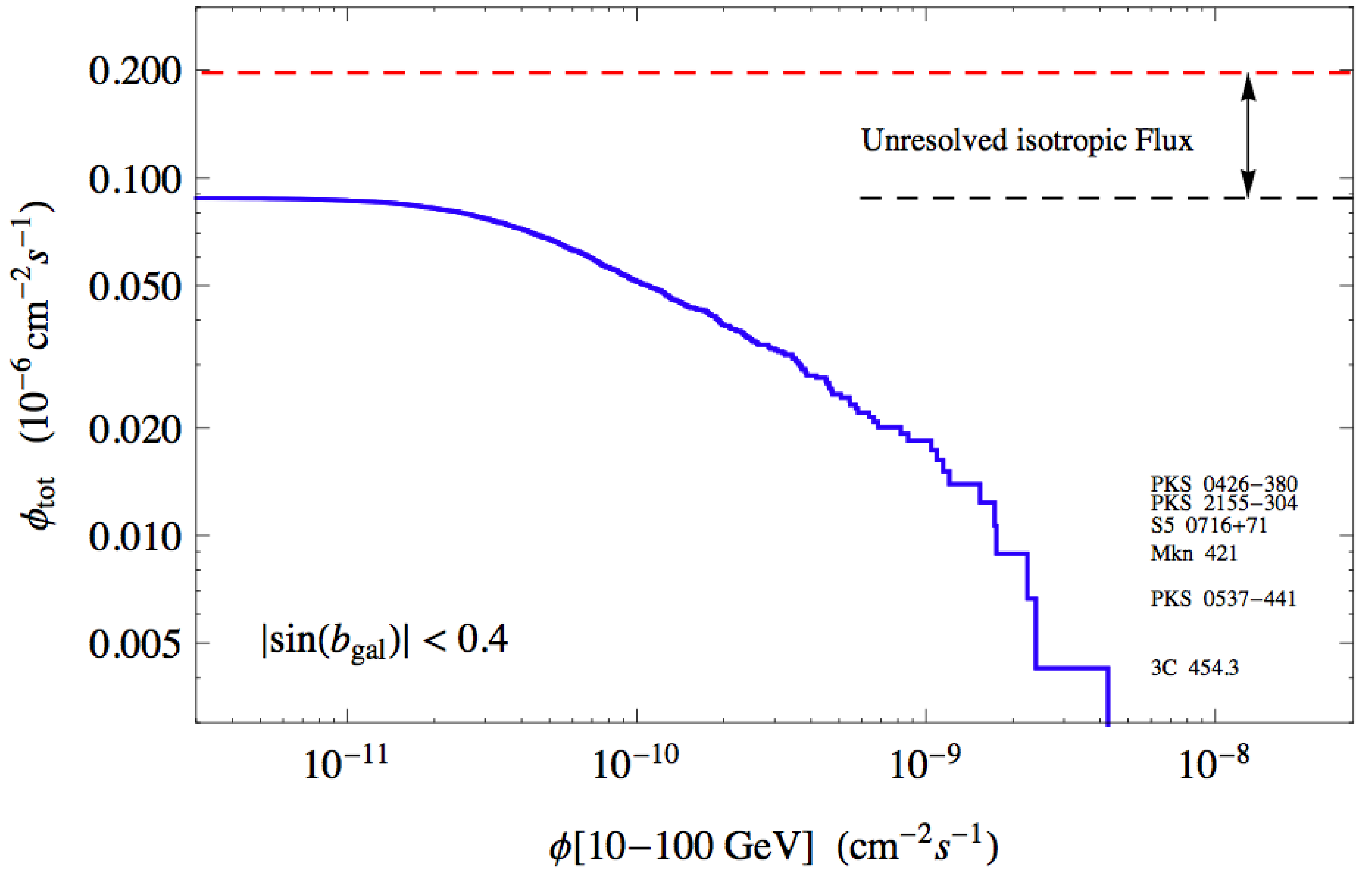
radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
cosmological max of star formation
opaque to photons;
transparent to neutrinos
nearest blazar
nearest galaxy
galactic center
Distance [Mpc]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6} 10^{-4} 10^{-2} 10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}
Energy [eV]



Extragalactic
Total
Extragalactic
resolved
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E^2\ \phi(E)$ [GeV/(cm^2 s)
0.1
10
1000
10^5
E (GeV)

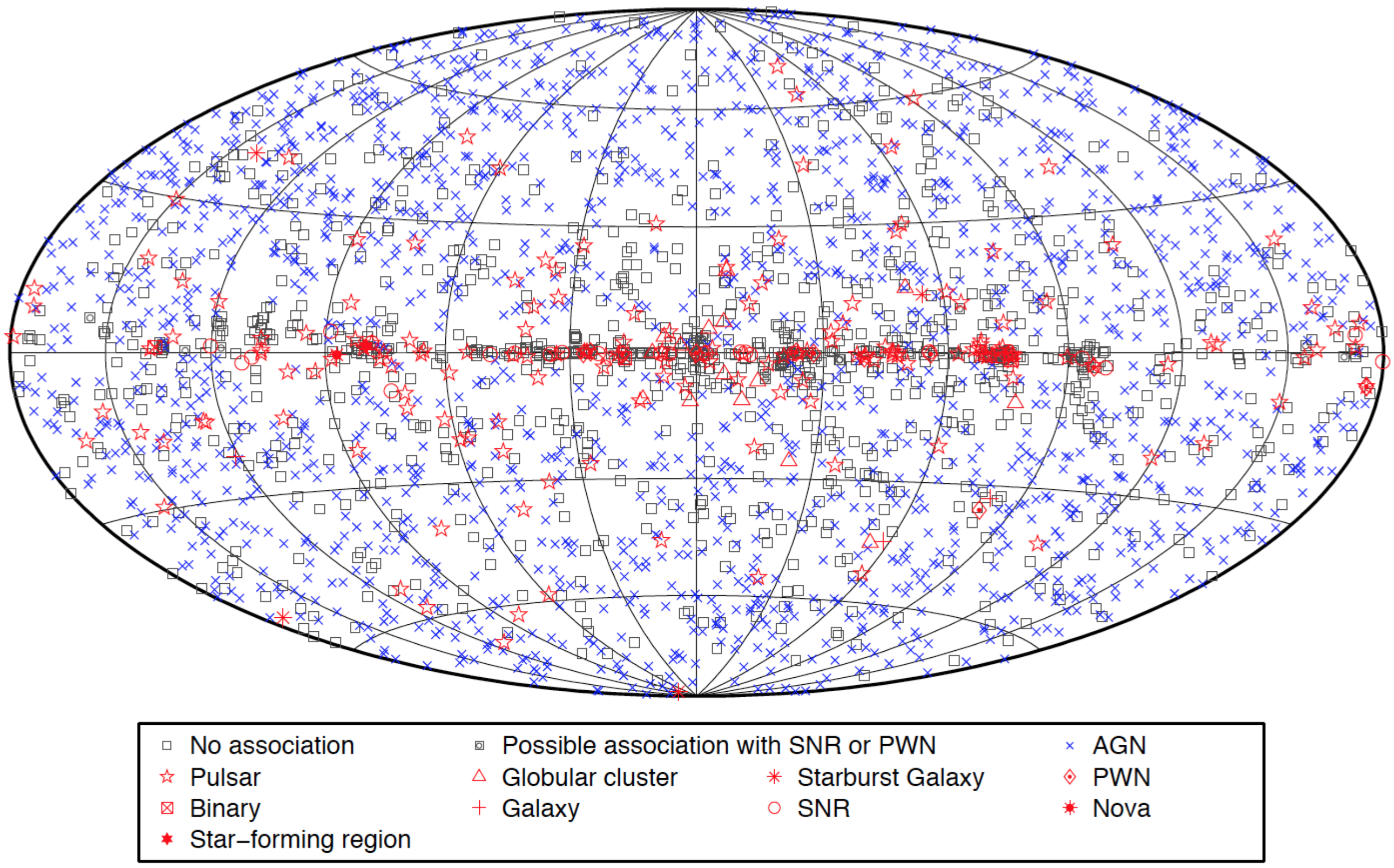
Extragalactic gamma ray sky
Dominated by BLAZARS

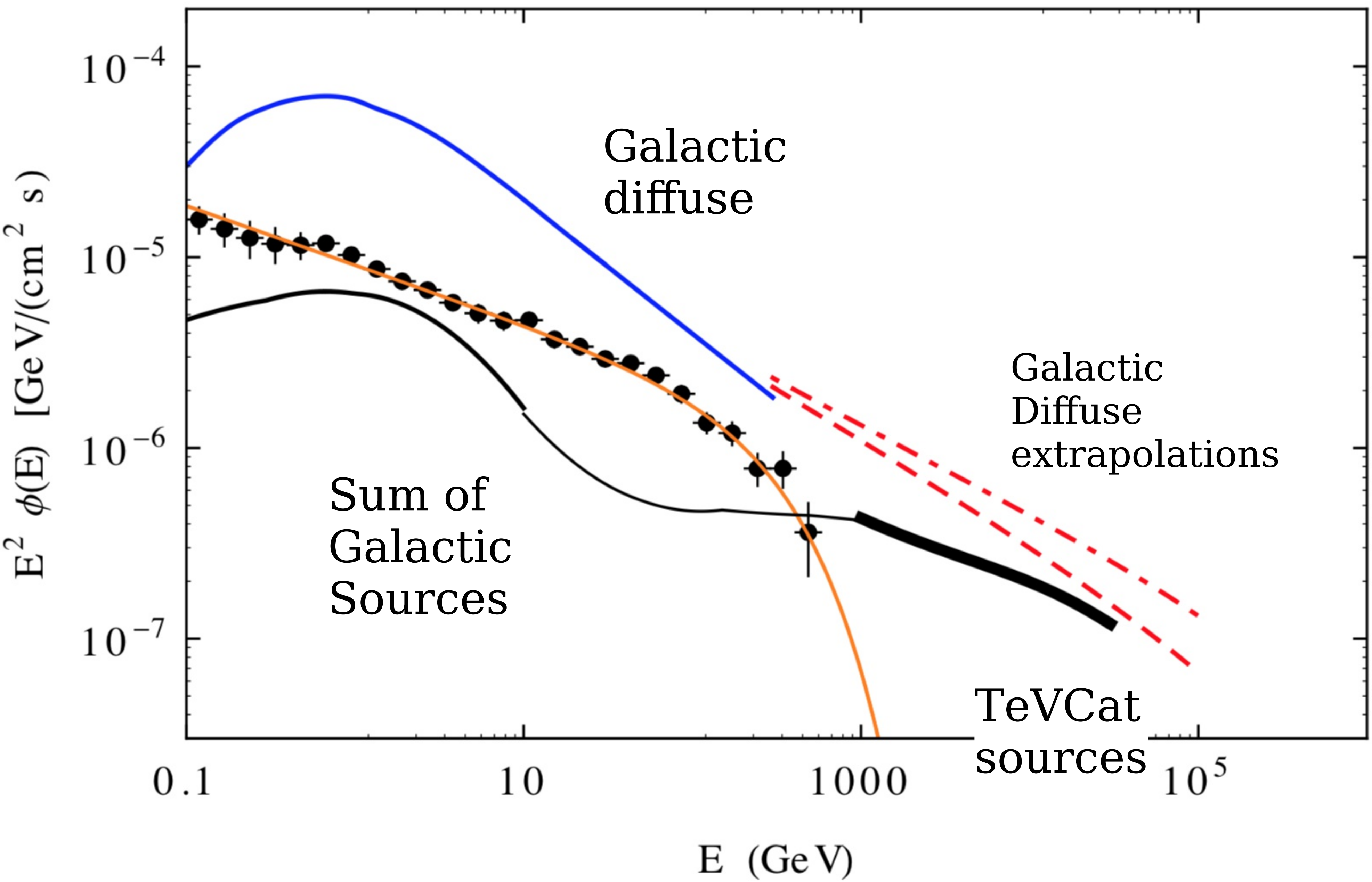


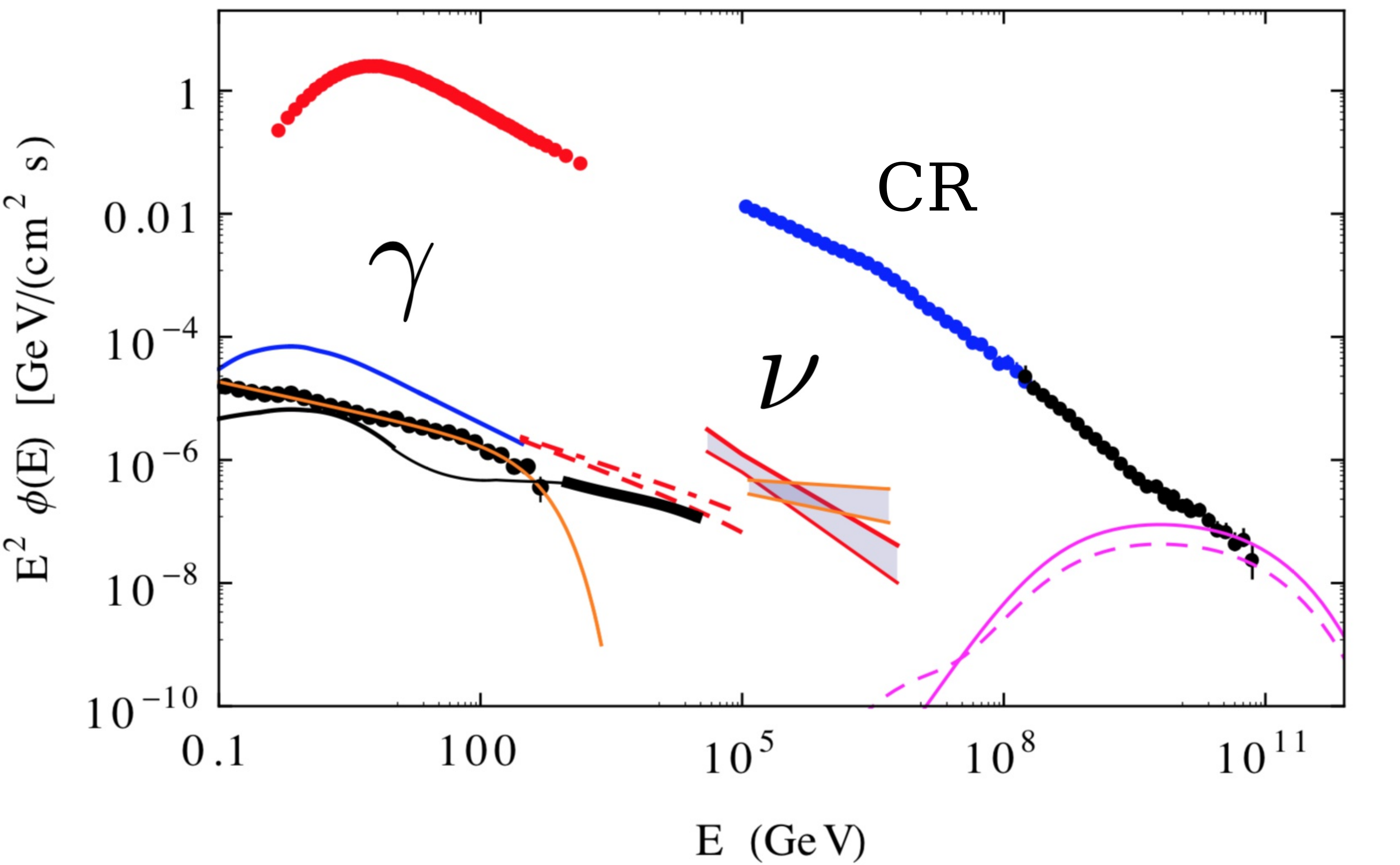


3rd FERMI Catalog 3034 sources

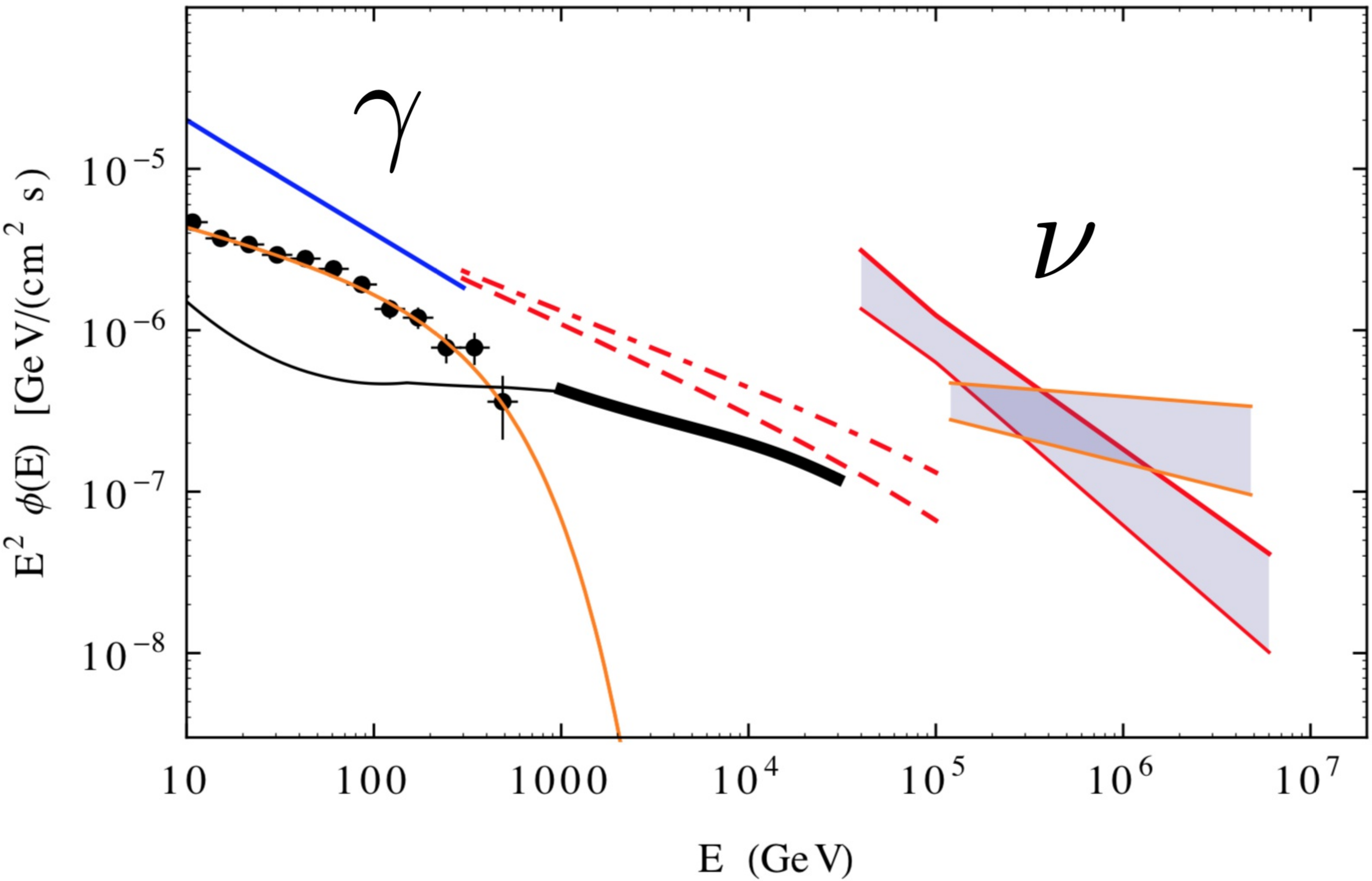
E > 100 MeV



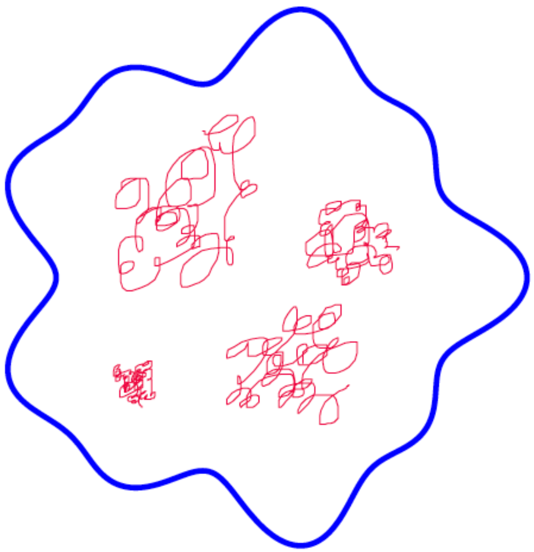

10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E^2\ \phi(E)\ [\mathrm{GeV/(cm^2\ s)}]$
Galactic diffuse
Galactic Diffuse extrapolations
Sum of Galactic Sources
TeVCat sources
0.1
10
1000
10^5
E (GeV)



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



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



Population of relativistic protons: $N_p(E_p)$

Average density of the medium: n

Emission Rates of Photons and Neutrinos:

$$\dot{N}_{\nu,\gamma}(E) = \int_E^\infty dE_p \; N_p(E_p) \; [\sigma_{pp}(E_p)\, c\, n] \; \frac{dN_{\gamma,\nu}(E, E_p)}{dE}$$

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

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

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

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

Simple relation between neutrino and gamma-ray emissions

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 "

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

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

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

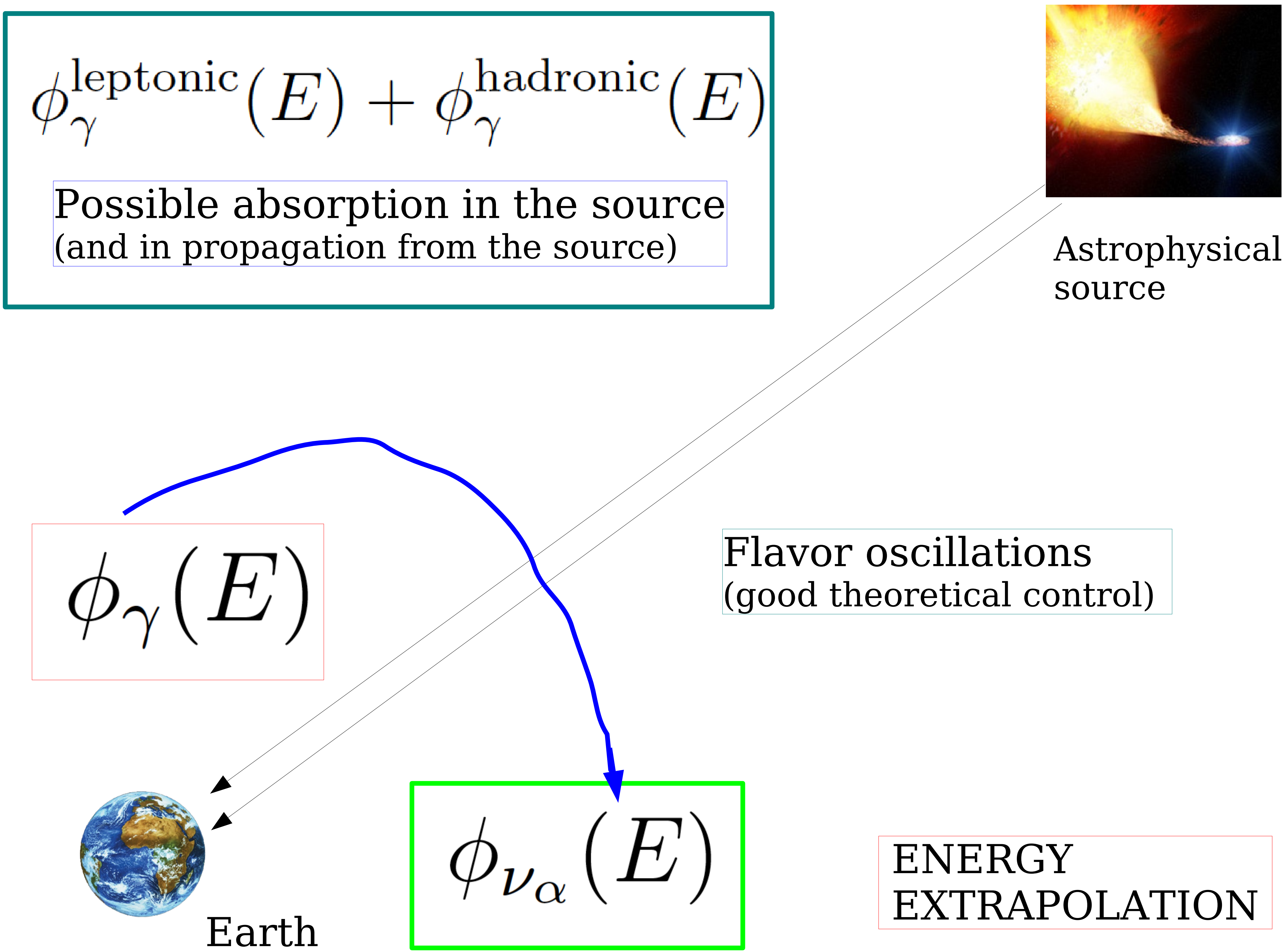
$$\hookrightarrow e^+ \ \nu_e \ \overline{\nu}_\mu$$

"Leptonic "

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

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

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



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

2. Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

Observed a (small but important) event rate of very high energy neutrinos with very long path-lengths.

~ 10 HESE ev./yr

$E \gtrsim 30$ TeV

A very valuable tool for Particle Physics

2. Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

Very High Energy $\sim$ PeV

10^6 GeV

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

10^{27} cm

Very large (astrophysical) uncertainties about source spectra

Flavor Oscillation, Neutrino Decay $\sim k \; L/E$

$k = \Delta m^2$ $k = m_\nu/\tau_\nu$

$$\left(\frac{L}{E}\right)_{\rm atmo} \simeq \left(\frac{2 \; R_\oplus}{1 \; \rm GeV}\right) \simeq 10^9 \; \frac{\rm cm}{\rm GeV}$$

$$\left(\frac{L}{E}\right)_{\odot} \simeq \left(\frac{1 \; \rm AU}{1 \; \rm MeV}\right) \simeq 10^{16} \; \frac{\rm cm}{\rm GeV}$$

$$\left(\frac{L}{E}\right)_{\rm astro} \simeq \left(\frac{\rm Gpc}{10 \; \rm TeV}\right) \simeq 3 \times 10^{23} \; \frac{\rm cm}{\rm GeV}$$

$$\left(\frac{L}{E}\right)_{\rm SN} \simeq \left(\frac{10 \; \rm kpc}{10 \; \rm MeV}\right) \simeq 3 \times 10^{24} \; \frac{\rm cm}{\rm GeV}$$

New Physics effects

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

$n = 0$

$n = 1$ Lorentz invariance violations

Study very favorable with Astrophysical Neutrinos

Three topics about Particle Physics with Astrophysical Neutrinos

A. Neutrino Cross section

B. Neutrino Flavor evolution

C. New Neutrino Interactions

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

Neutrino Cross Section at High Energy

IceCube Collaboration,
“Measurement of the multi-TeV neutrino cross section
with IceCube using Earth absorption”,
Nature **551**, 596 (2017)
[arXiv:1711.08119 [hep-ex]].

M. Bustamante and A. Connolly,
“Extracting the Energy-Dependent Neutrino-Nucleon Cross Section
above 10 TeV Using IceCube Showers,” ”
Phys. Rev. Lett. **122**, no. 4, 041101 (2019)
[arXiv:1711.11043 [astro-ph.HE]].

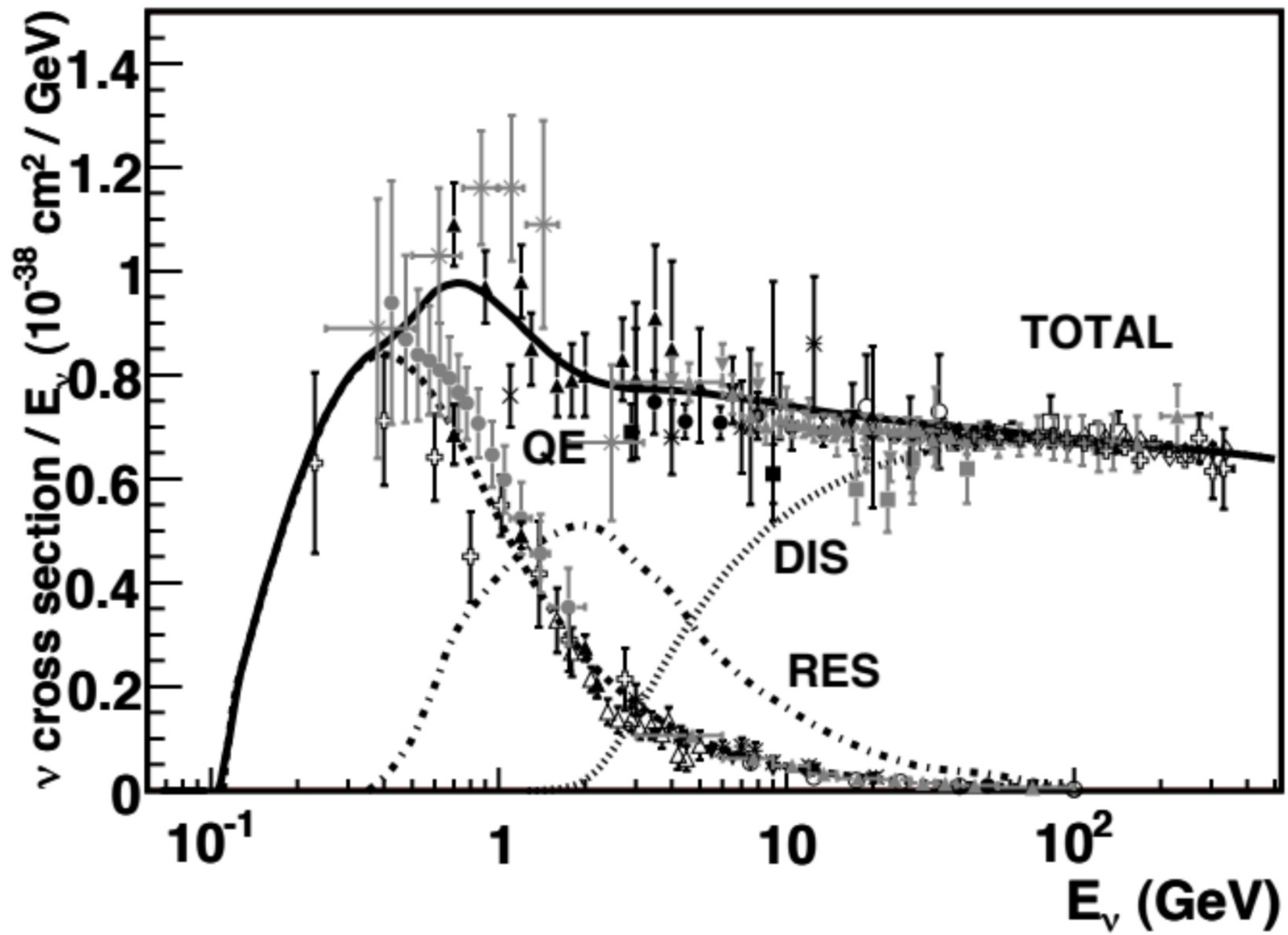
This meeting:

Subir Sarkar
“High Energy Neutrino Cross Sections’
Thursday 21/03/2019 12:20

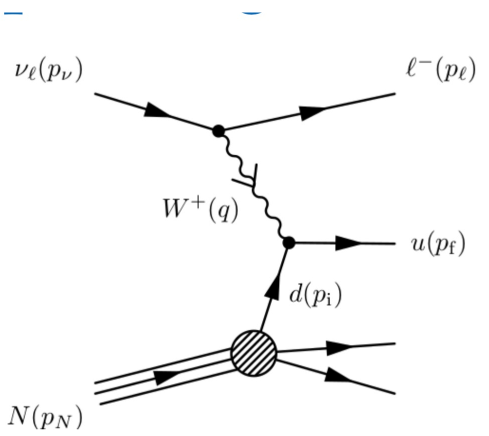
Andrea Donini
“Earth Tomography with neutrinos”
Thursday 21/03/2019 12:50

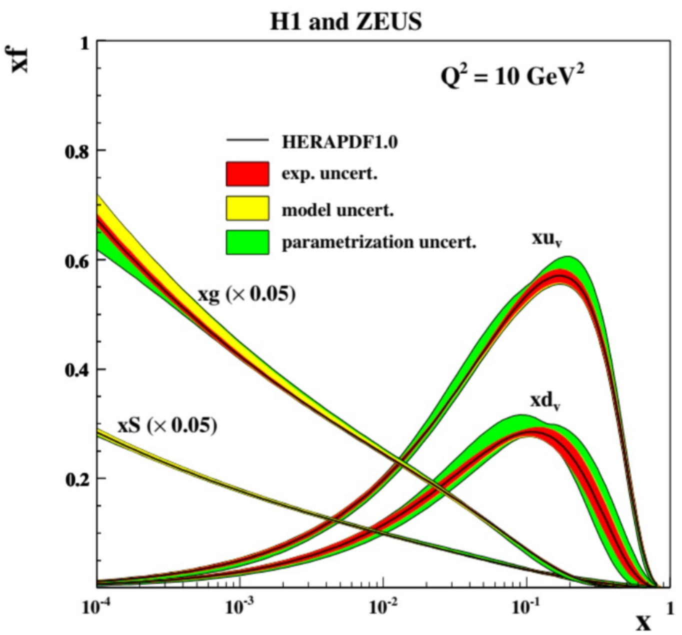
Particle Data Book
summary of measurements

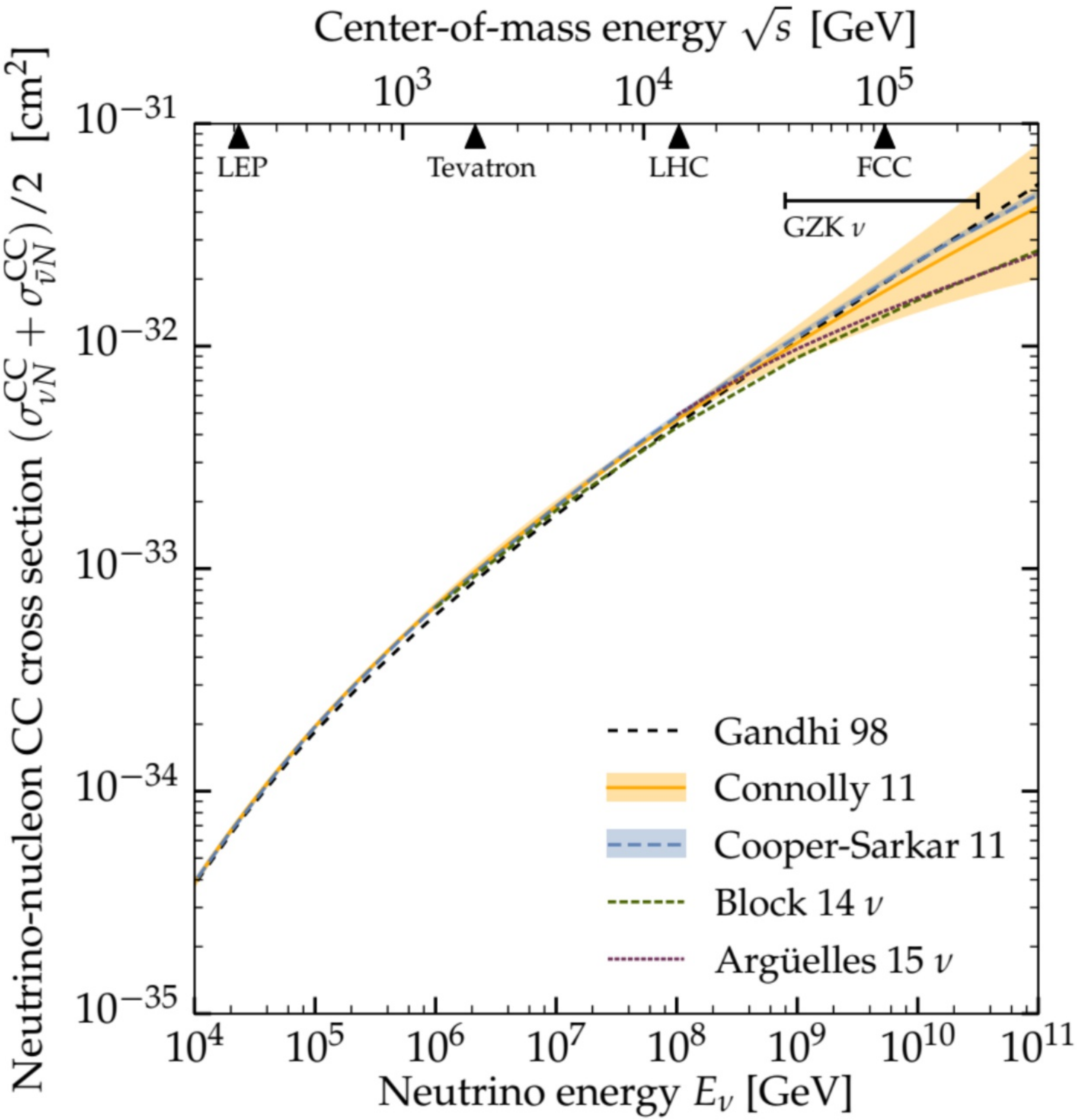
$$\sigma_{\nu_\mu}(E)$$

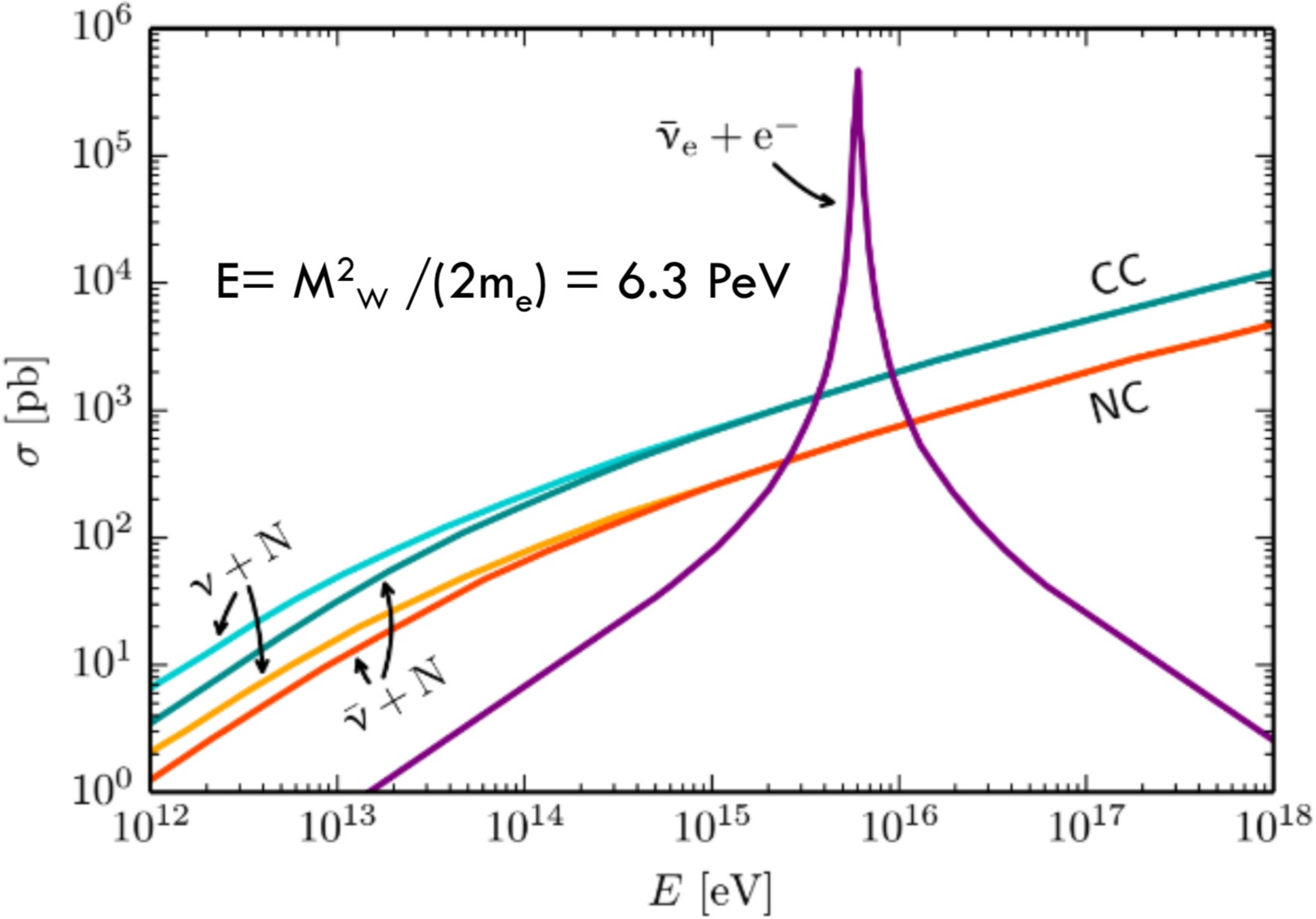


Standard Model calculation of the (DIS) neutrino cross section









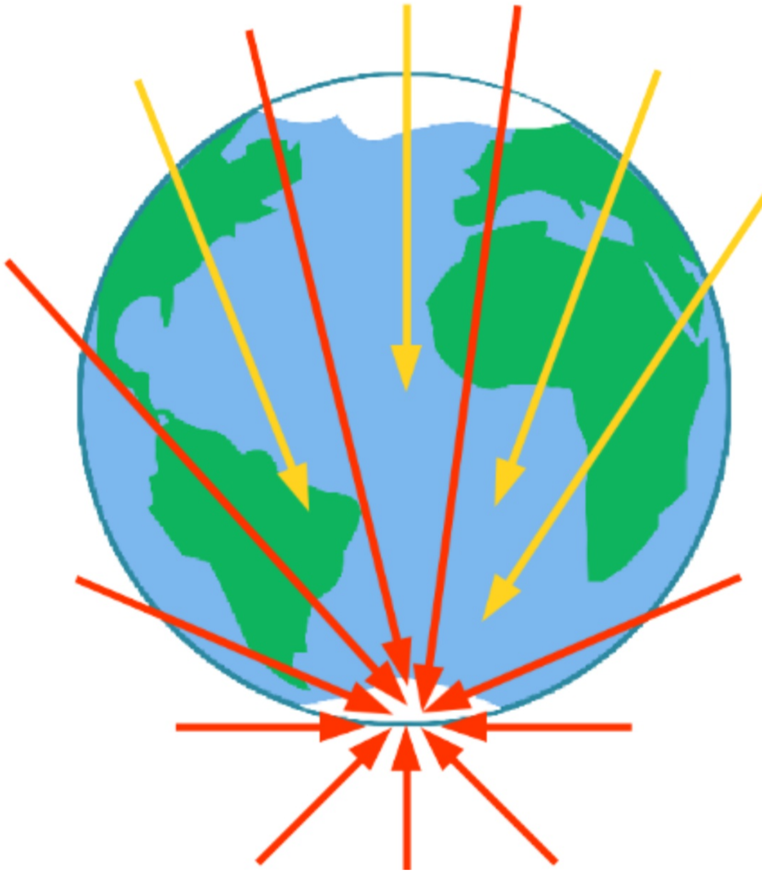
$$\overline{\nu}_e + e^- \to W^- \to \ldots$$

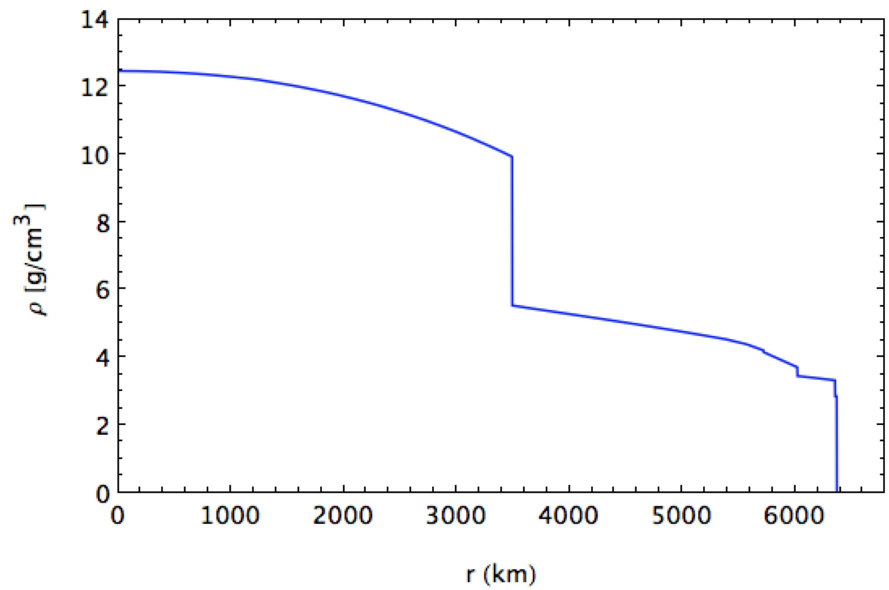
"Glashow Resonance"

$$(p_{\overline{\nu}_e} + p_e)^2 = M_W^2$$

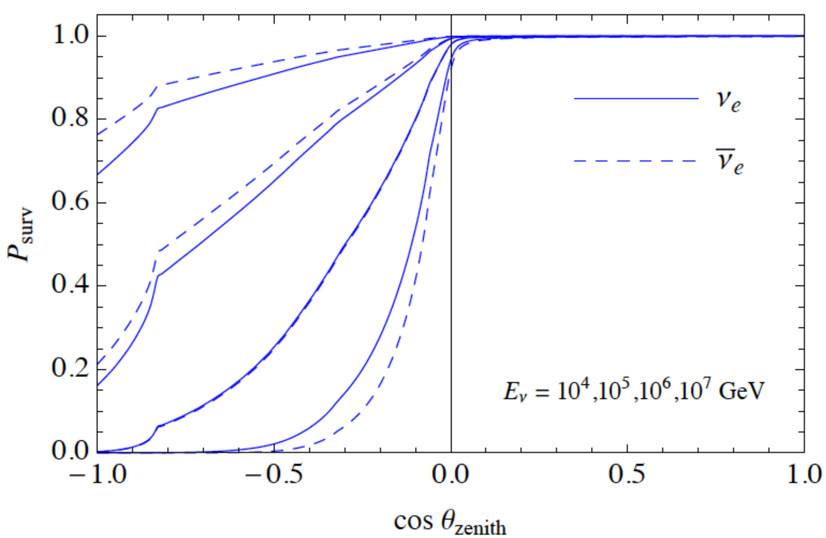
$$m_e^2 + 2\, m_e\, E_{\overline{\nu}} = M_W^2$$

$$E^* = \frac{M_W^2 - m_e^2}{2\, m_e} \simeq 6.4 \text{ PeV}$$





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

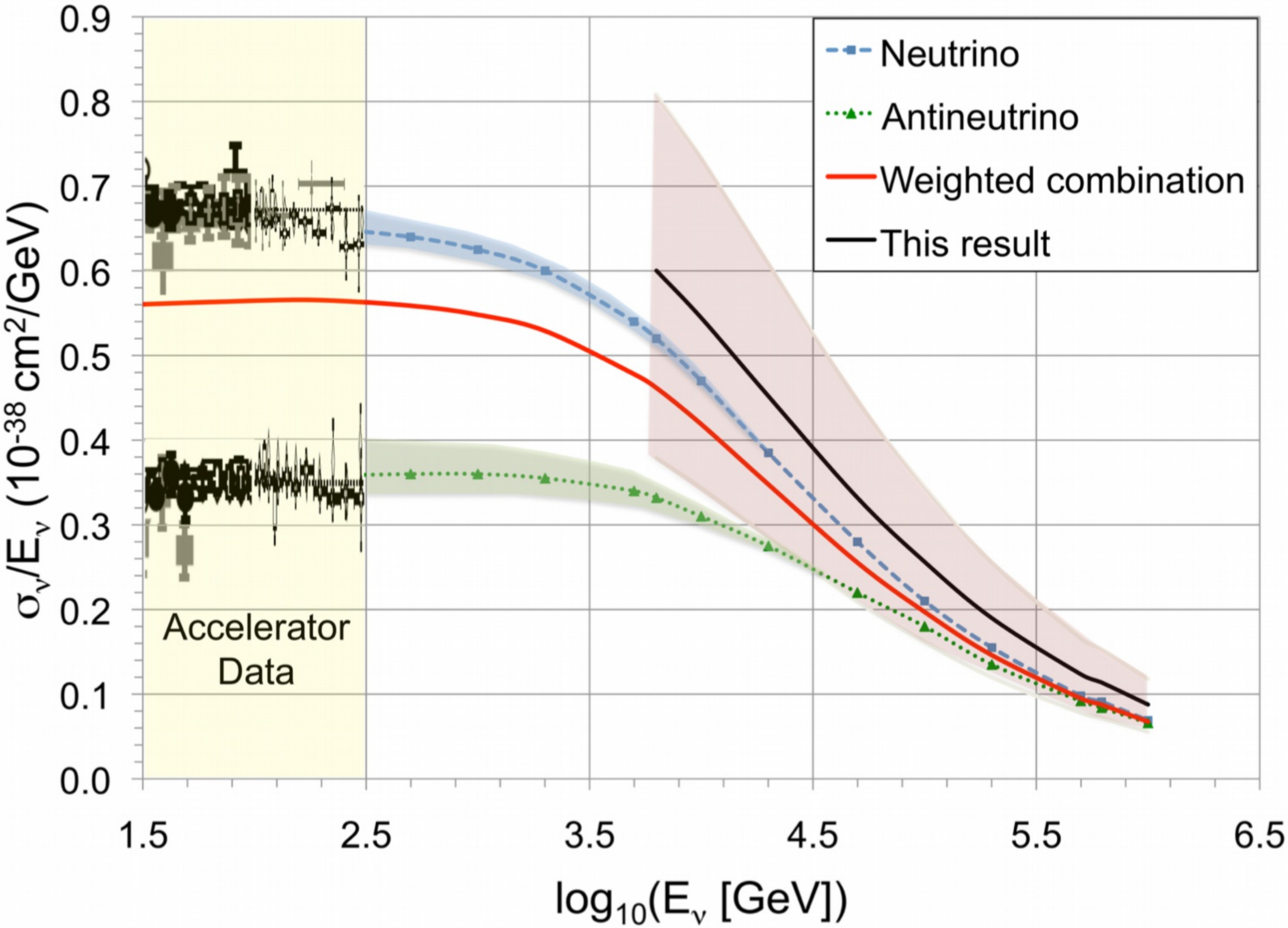


$$\tau = \frac{X}{m_p}\,\sigma_\nu$$

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

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

IceCube result



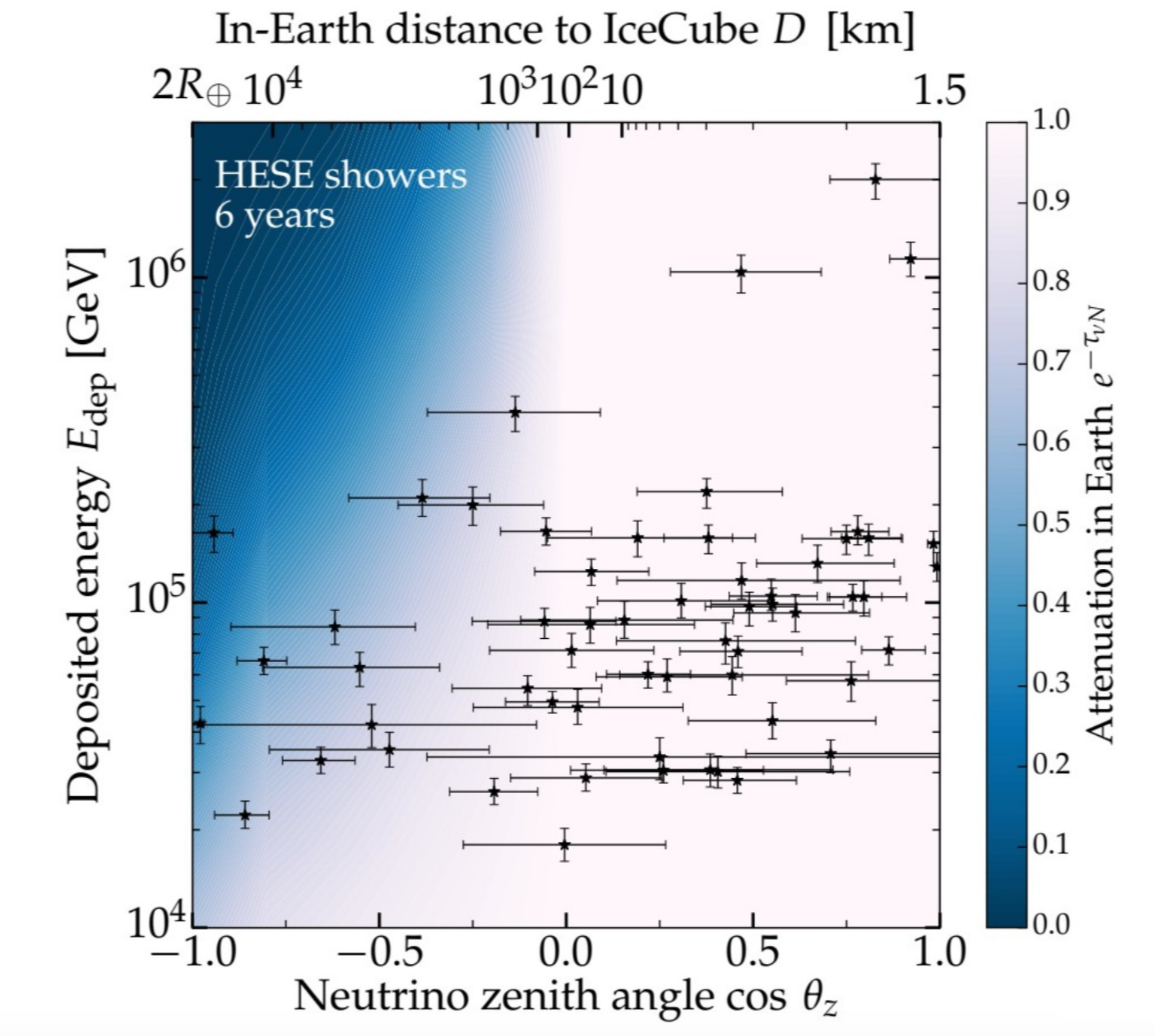
Based on up-going muons

$$E_\mu \gtrsim 6\ \mathrm{TeV}$$

$$\frac{\sigma_{\rm obs}}{\sigma_{\rm SM}} \simeq 1.30^{+0.21}_{-0.19}\ (\mathrm{stat.})\ {}^{+0.39}_{-0.43}\ (\mathrm{syst.})$$

M. Bustamante and A. Connolly,
"Extracting the Energy-Dependent Neutrino-Nucleon Cross Section above 10 TeV Using IceCube Showers," "
Phys. Rev. Lett. **122**, no. 4, 041101 (2019)
[arXiv:1711.11043 [astro-ph.HE]].

IceCube Showers



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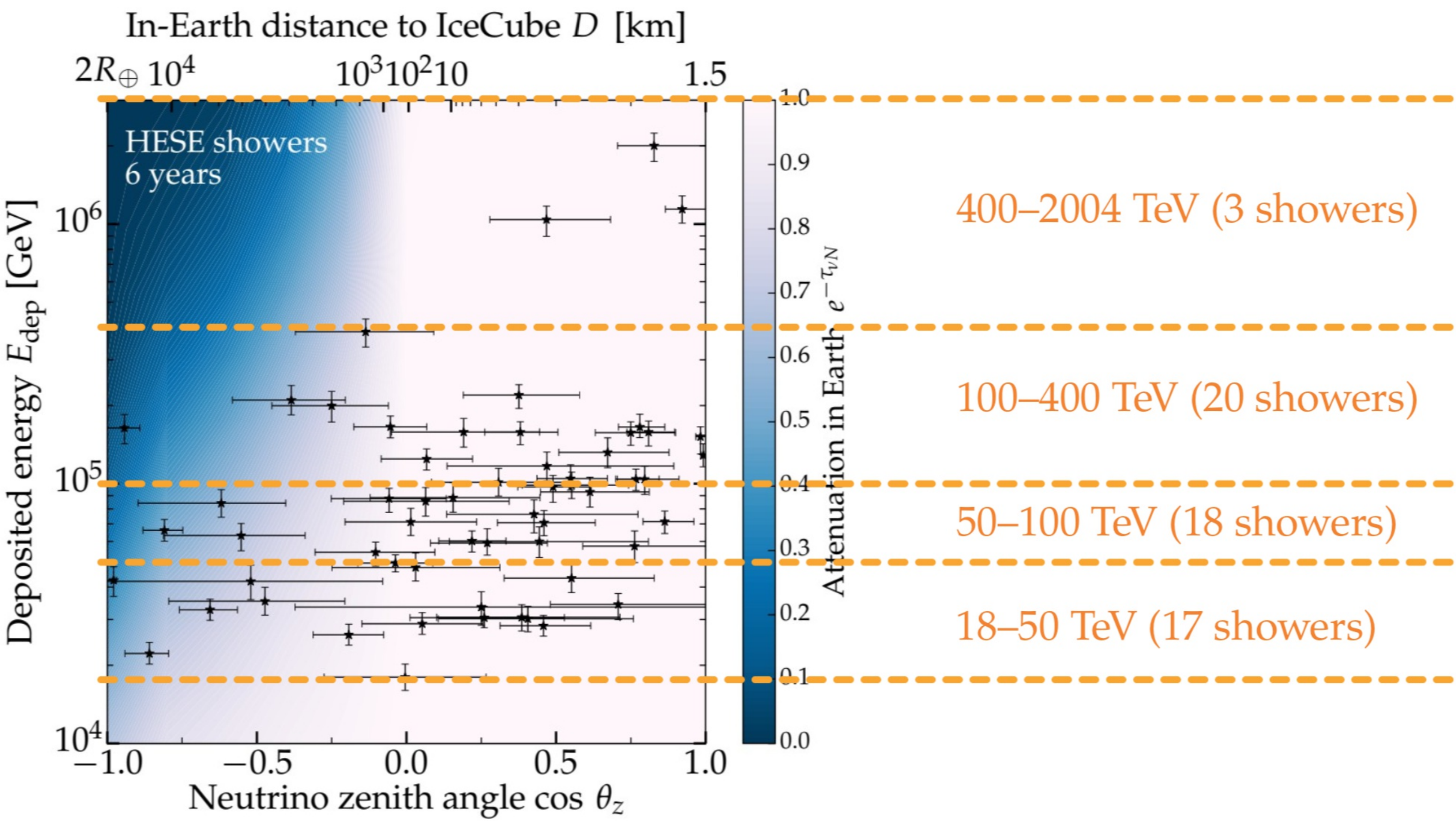
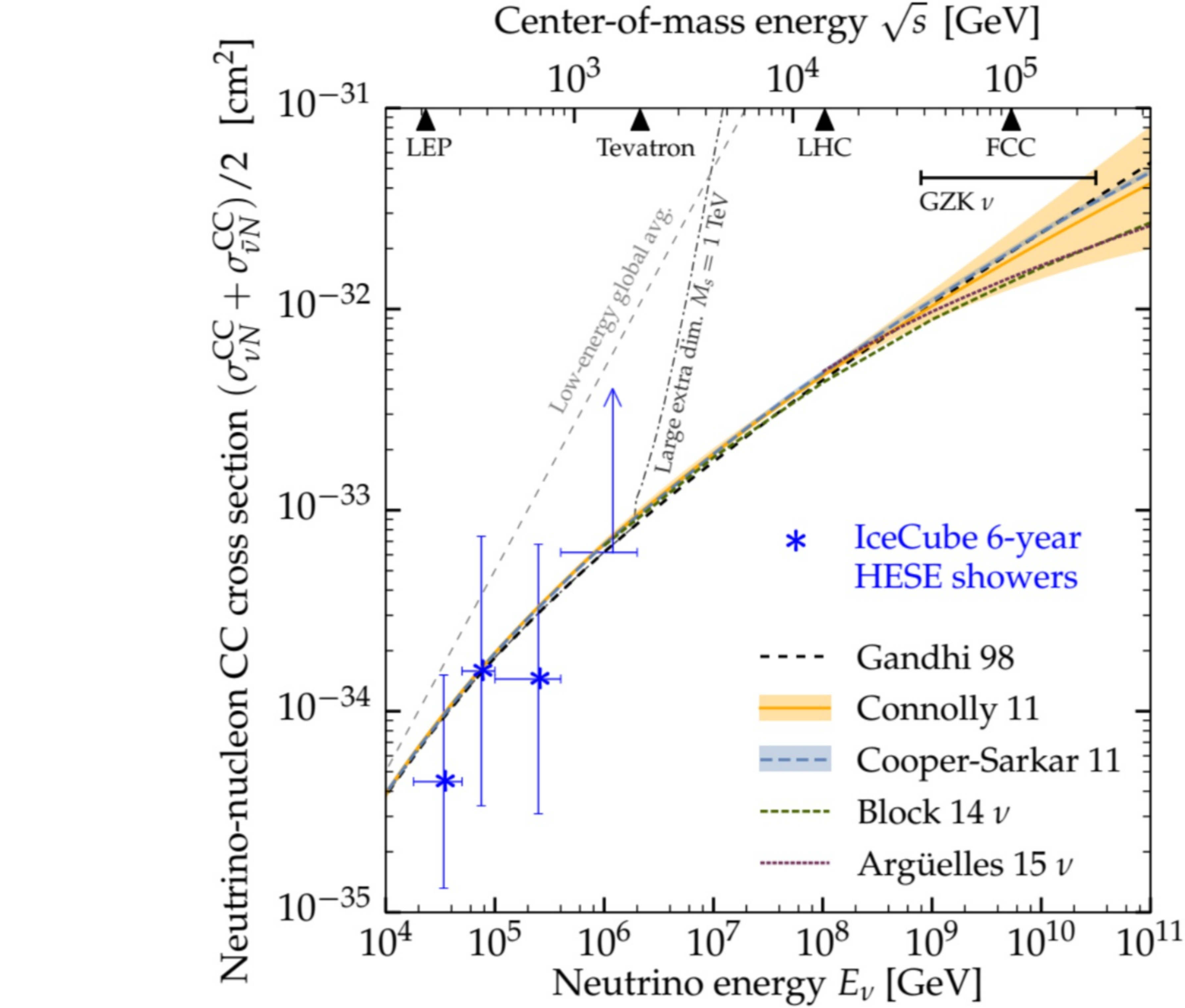
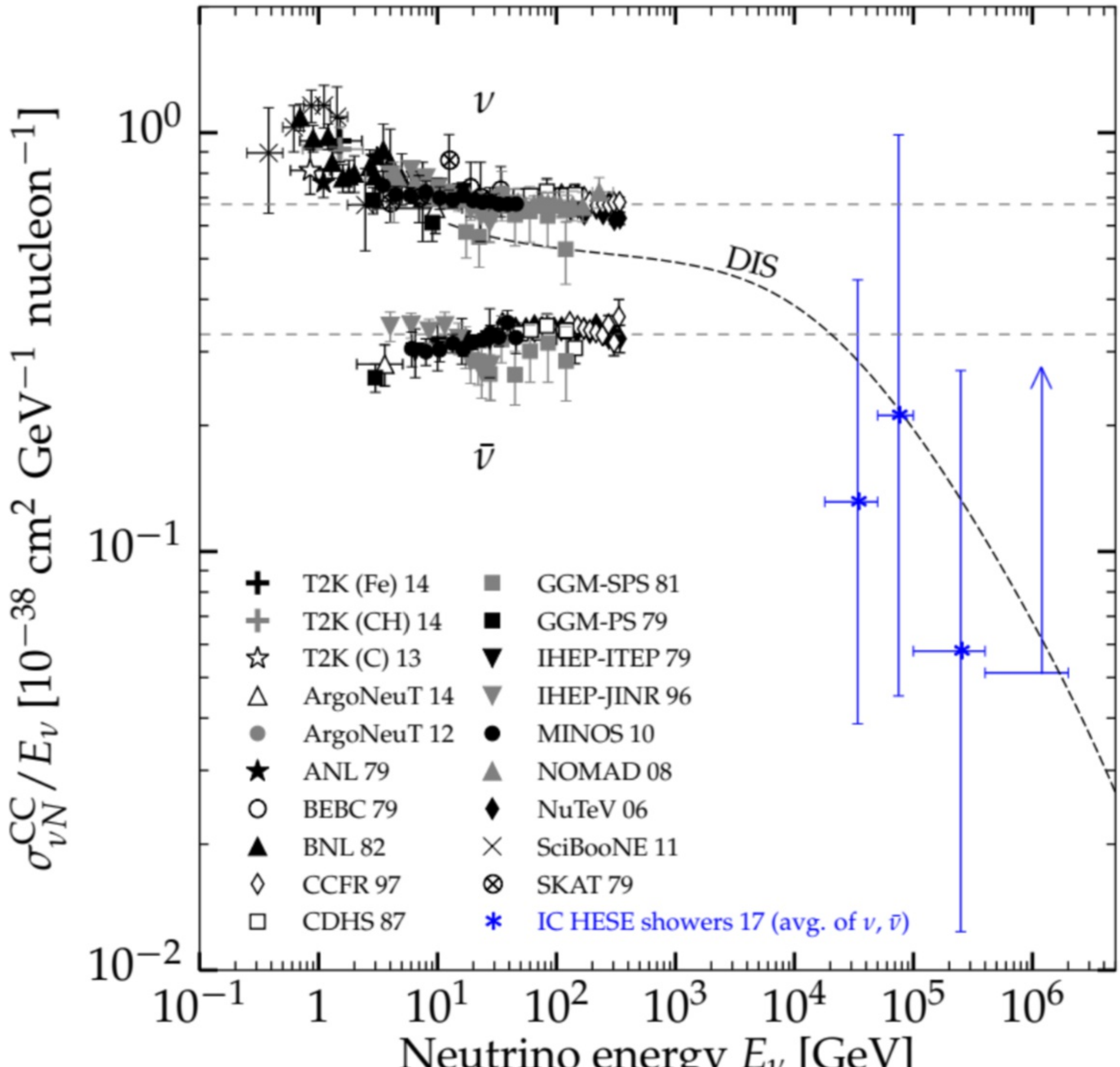
IceCube Showers





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



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

Astro2020 Science White Paper

Papers presented for the
Astrophysics 2020 decadal survey of NASA

M. Ackermann *et al.*,
"Fundamental Physics with High-Energy Cosmic Neutrinos,"
arXiv:1903.04333 [astro-ph.HE].

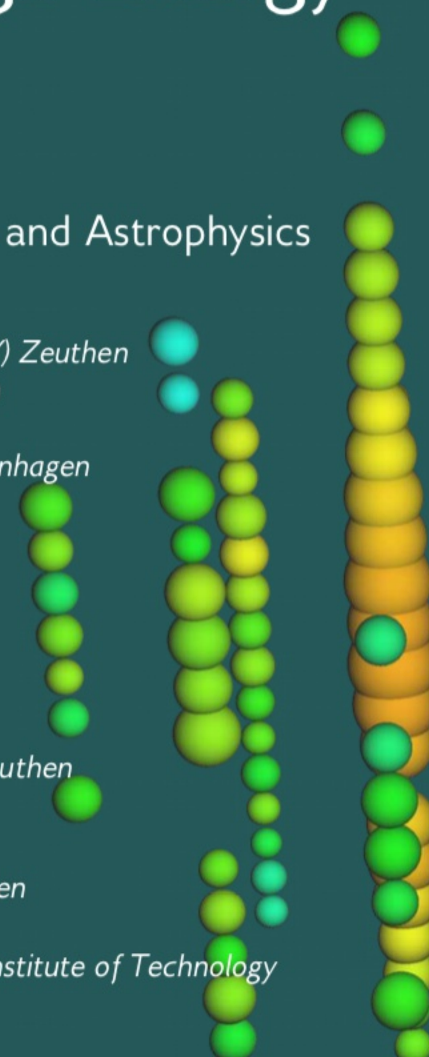
M. Ackermann *et al.*,
"Astrophysics Uniquely Enabled by Observations of
High-Energy Cosmic Neutrinos,"
arXiv:1903.04334 [astro-ph.HE].

Astro2020 Science White Paper

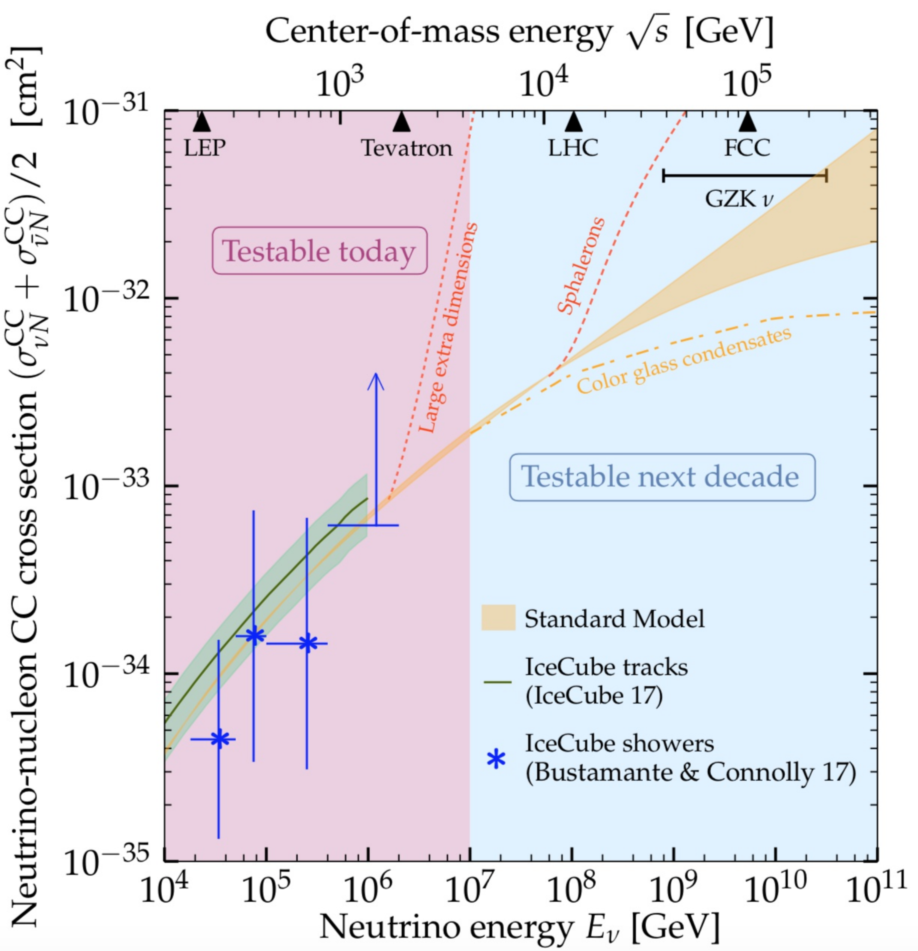
Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos

Thematic Area: Multi-Messenger Astronomy and Astrophysics

Markus Ackermann, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Markus Ahlers[*], *Niels Bohr Institute, University of Copenhagen*
Luis Anchordoqui, *City University of New York*
Mauricio Bustamante, *Niels Bohr Institute, University of Copenhagen*
Amy Connolly, *The Ohio State University*
Cosmin Deaconu, *University of Chicago*
Darren Grant, *Michigan State University*
Peter Gorham, *University of Hawaii, Manoa*
Francis Halzen, *University of Wisconsin, Madison*
Albrecht Karle[†], *University of Wisconsin, Madison*
Kumiko Kotera, *Institut d'Astrophysique de Paris*
Marek Kowalski, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Miguel A. Mostafa, *Pennsylvania State University*
Kohta Murase[‡], *Pennsylvania State University*
Anna Nelles[§], *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Angela Olinto, *University of Chicago*
Andres Romero-Wolf[¶], *Jet Propulsion Laboratory, California Institute of Technology*
Abigail Vieregg[‖], *University of Chicago*
Stephanie Wissel, *California Polytechnic State University*



At the EeV scale, measuring the cross section to within an order of magnitude could distinguish between SM predictions and BSM modifications; see Fig. 2. This target is achievable with tens of events in the PeV–EeV energy range. Detection will be challenging, since the flux is expected to decrease fast with energy and the cross section is expected to grow with energy, making the Earth opaque to neutrinos. Facing significant uncertainties in the predicted flux of cosmogenic neutrinos [119–123], we advocate for the construction of larger neutrino observatories to boost the chances of discovering and collecting a sufficiently large number of cosmogenic neutrinos.



B. Neutrino Propagation

Standard Flavor Oscillations (in vacuum)

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

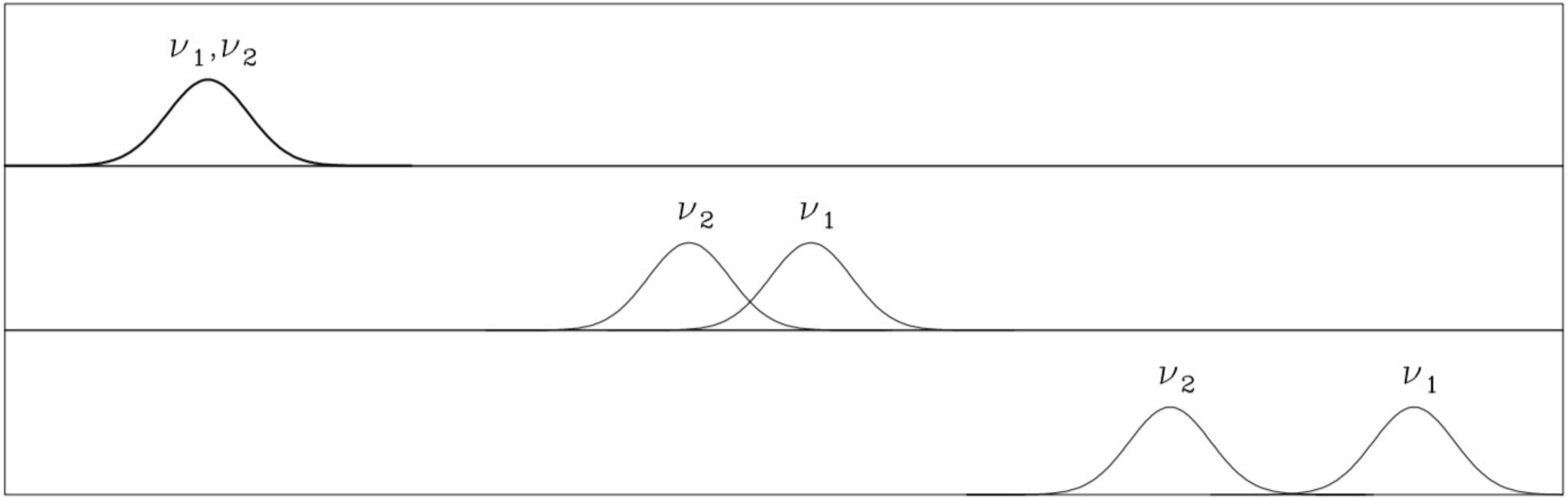
$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) &= \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \, \frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2 \\
&+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\cos\left(\frac{\Delta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

Oscillation terms vanish in two cases:

1. Decoherence of the neutrino mass states

2. Average in length/energy

Decoherence



Astrophysical extragalactic neutrinos arrive at the detector as mass eigenstates

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

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

Neutrino Flavor at the source.

[usual “benchmark examples”]

1. “Standard Production”

$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{1,\ 2,\ 0\}$$

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

2. “Muon damped"

$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{0,\ 1,\ 0\}$$

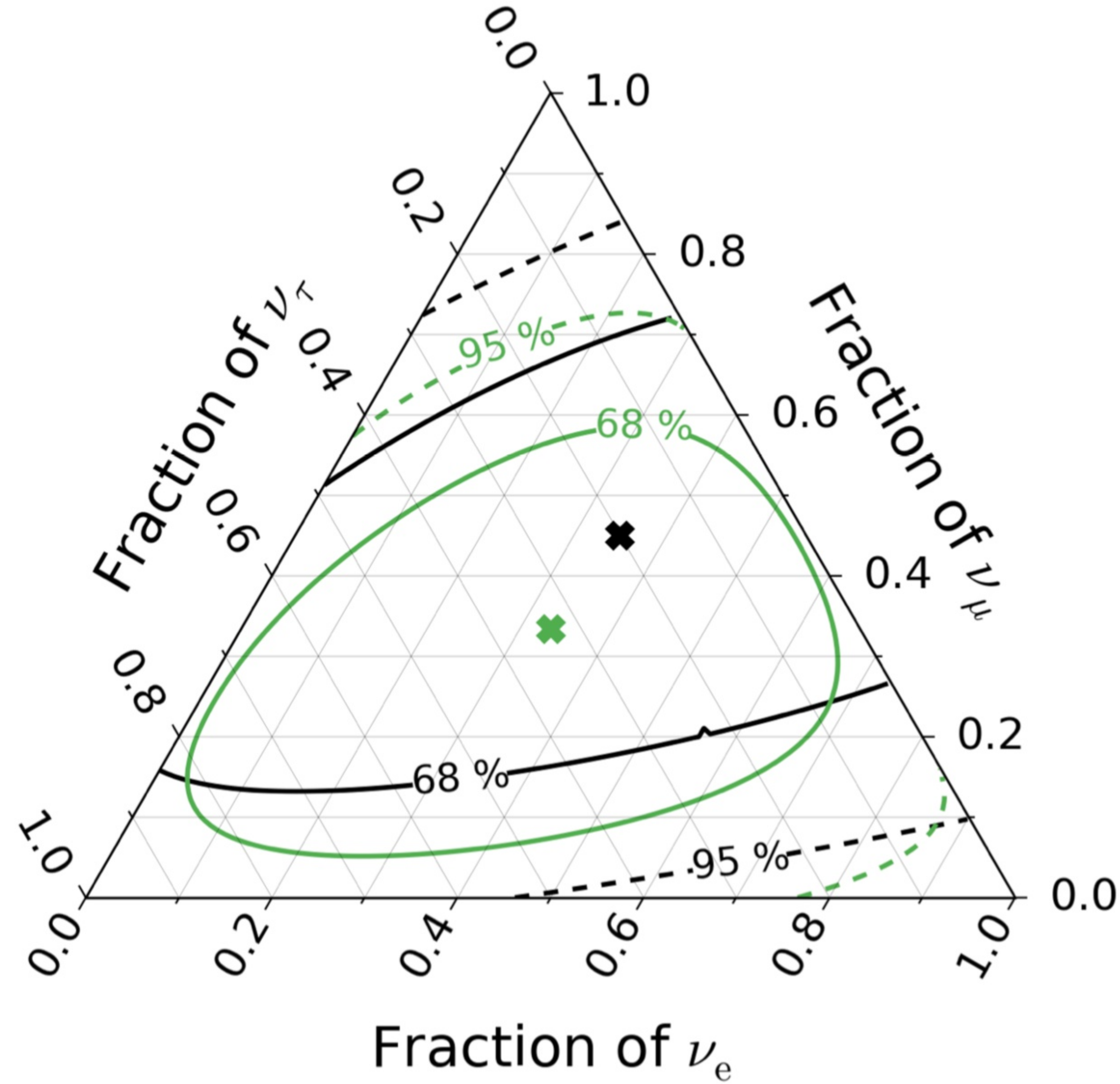
$$-\frac{dE}{dt} = \frac{4}{9}\frac{e^4\,B^2}{m^4}\,E^2$$

$$E_{\rm syn} = \frac{3}{2}\frac{m^{5/2}}{e^2\,B\,\sqrt{\tau}} = \frac{5.8\times 10^{18}\ {\rm eV}}{B_{\rm Gauss}}$$

3. Neutron decay

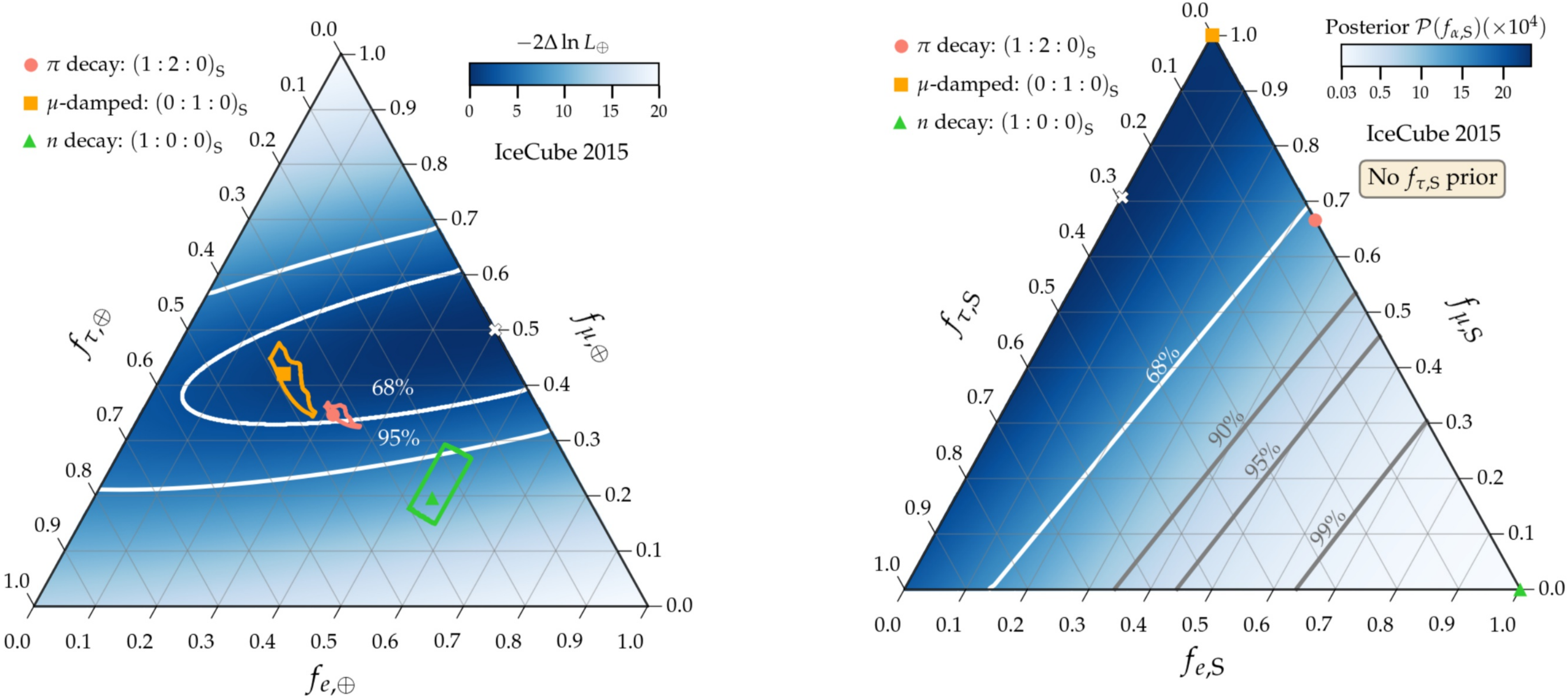
$$\{f_e,\ f_\mu,\ f_\tau\}_s \approx \{1,\ 0,\ 0\}$$

Difficult to produce neutrons without charged pions



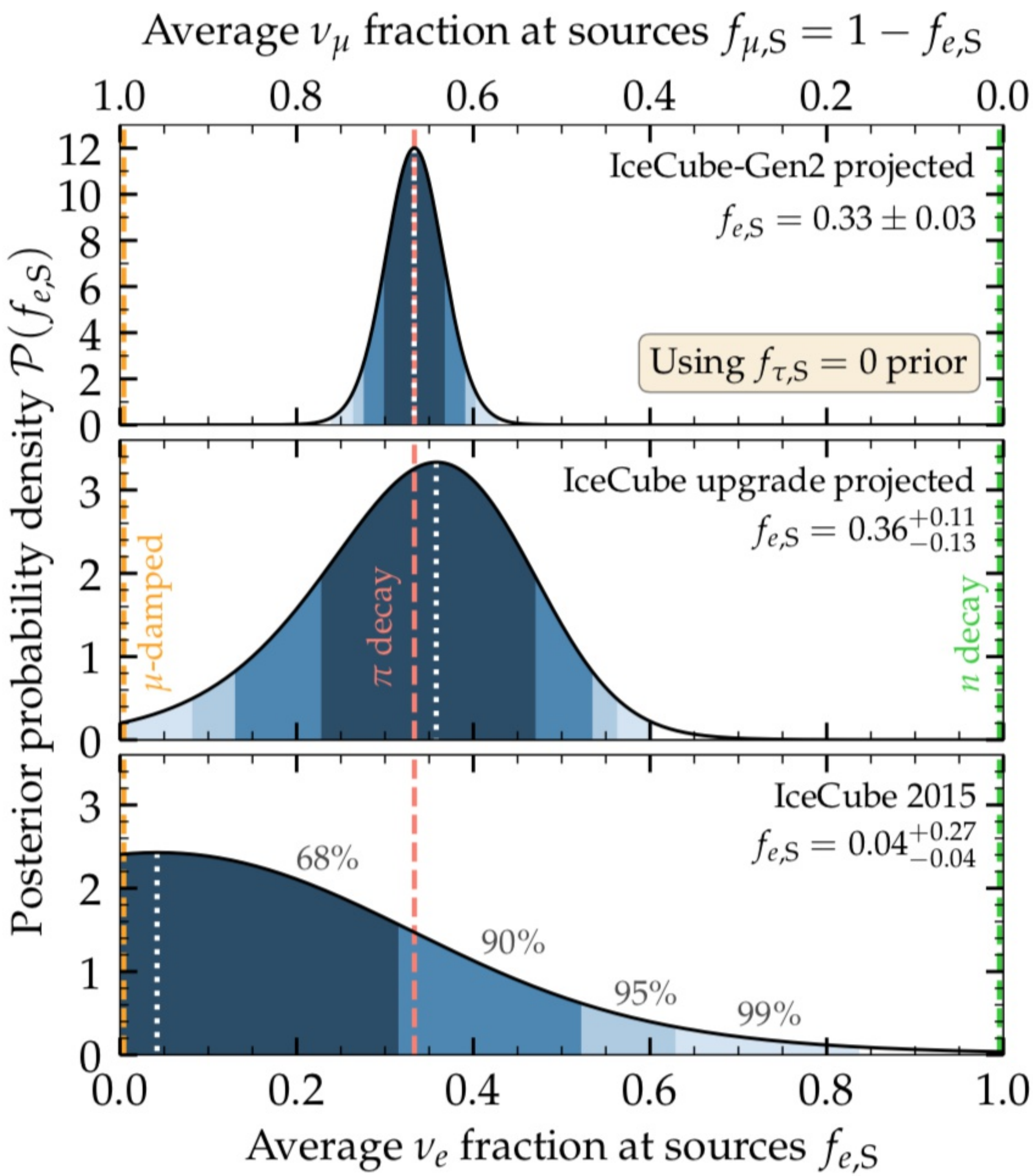
Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
95 %
68 %
68 %
95 %
0.0
0.2
0.4
0.6
0.8
1.0

Flavor content inferred from track/shower ratio

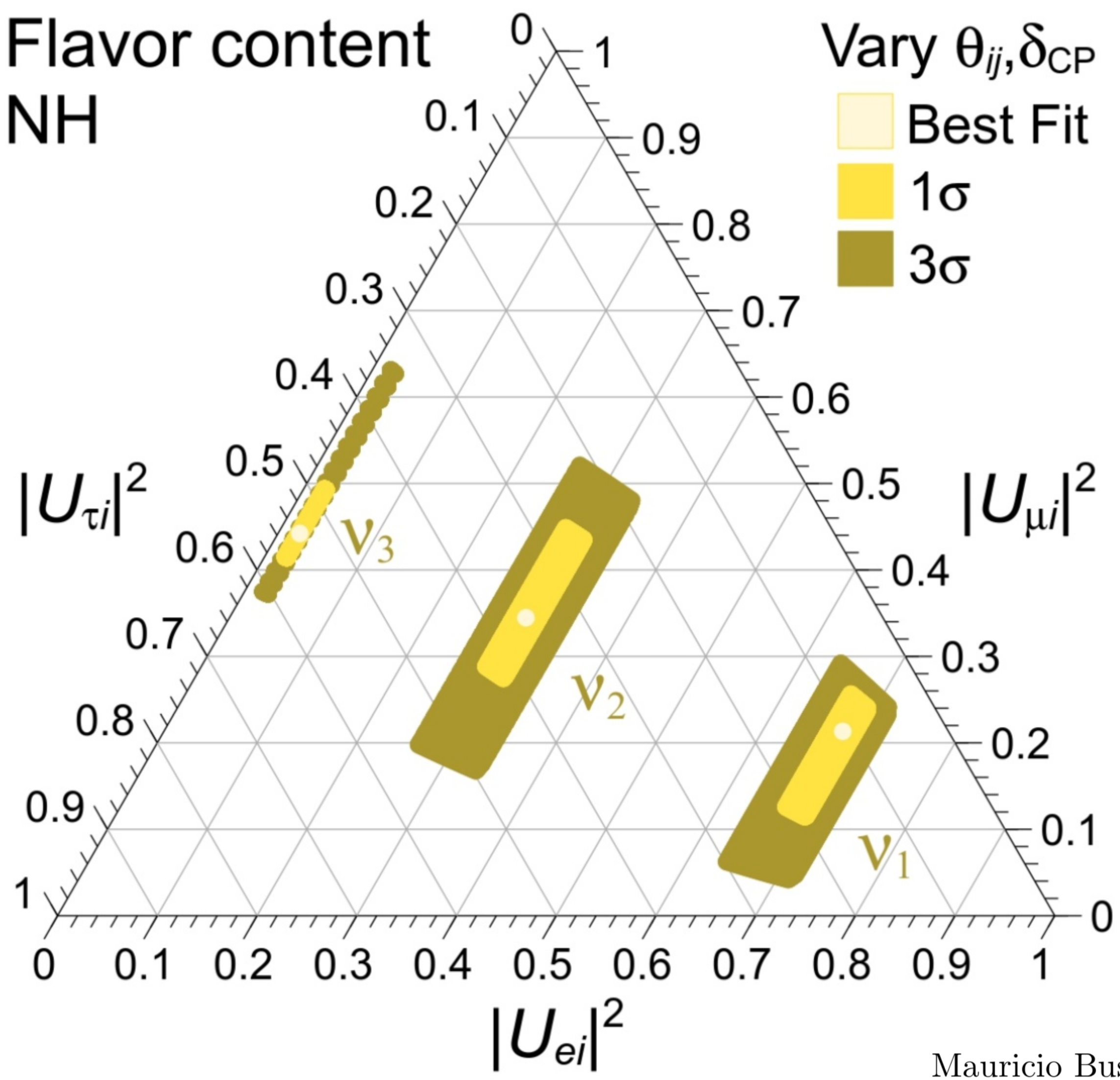


M. Bustamante and M. Ahlers,
"Inferring the flavor of high-energy astrophysical neutrinos at their sources,"
arXiv:1901.10087 [astro-ph.HE].

Projected sensitivity for more data



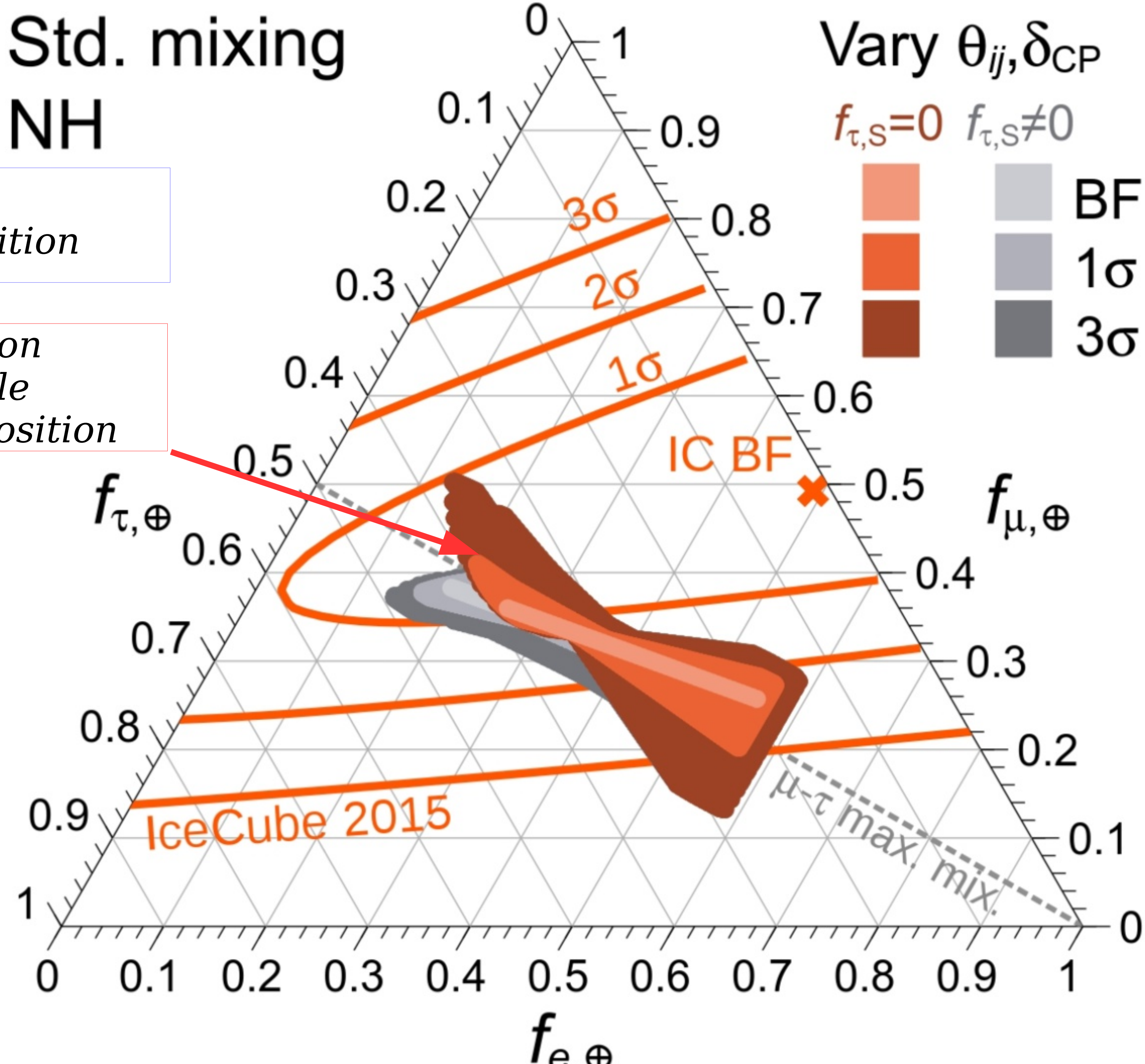
Potential to study non-standard neutrino propagation properties

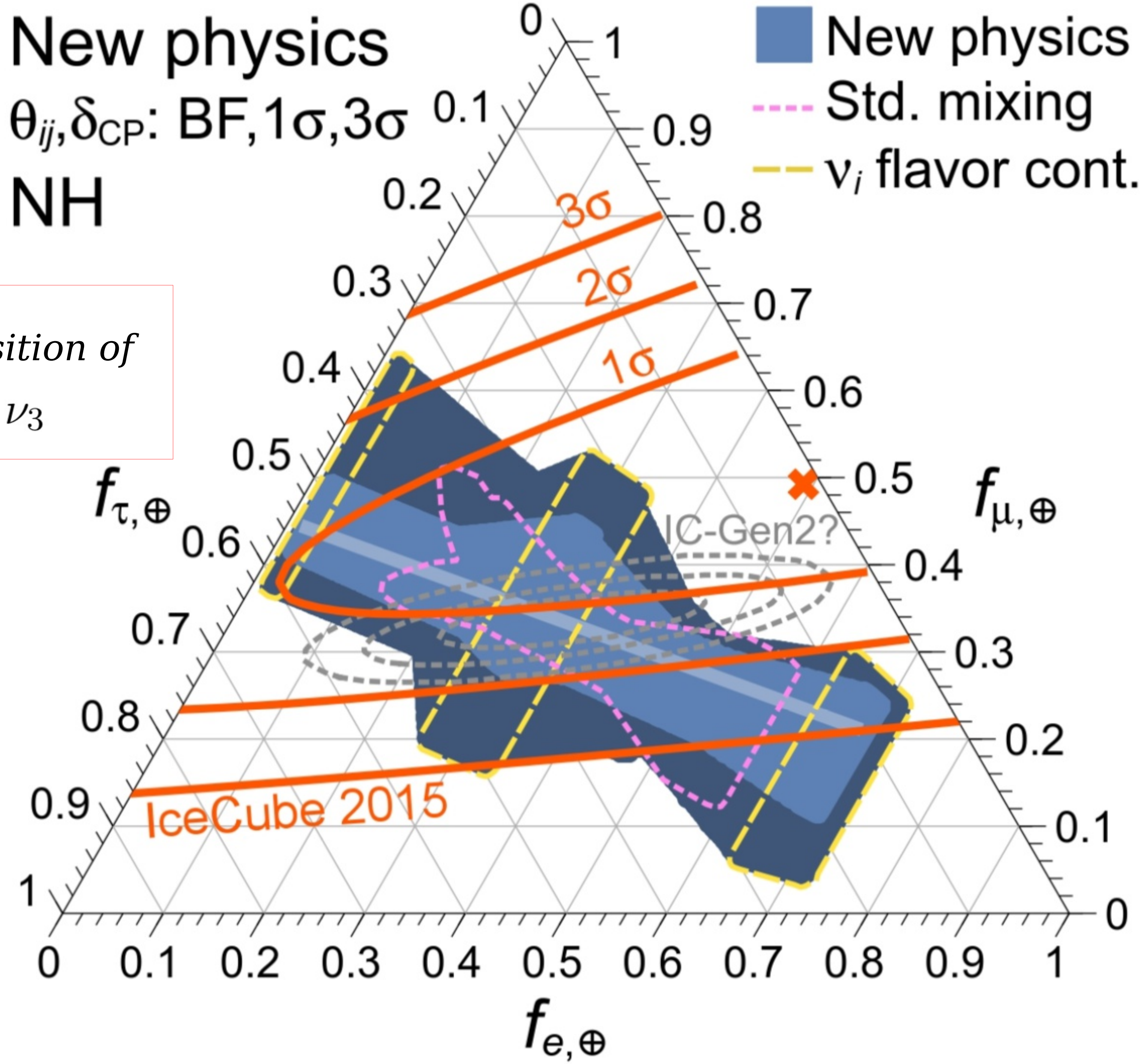


Mauricio Bustamante, John F. Beacom, and Walter Winter, "Theoretically palatable flavor combinations of astrophysical neutrinos", Phys. Rev. Lett. 115, 161302 (2015), arXiv:1506.02645 [astro-ph.HE].

Arbitrary initial condition

Allowed region for observable Flavor composition



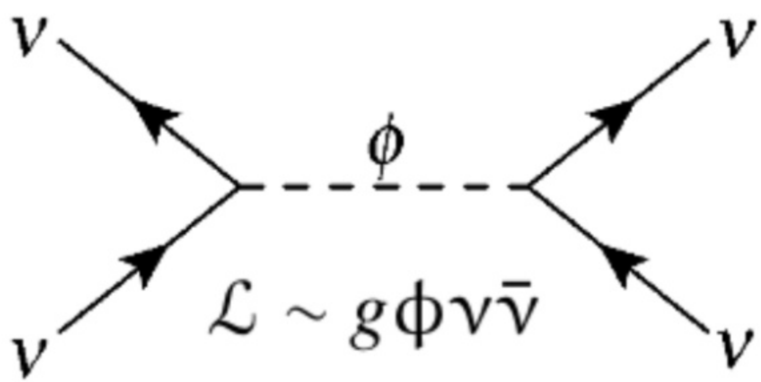


General superposition of

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

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

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



$$\mathcal{L} \sim g\phi\nu\bar{\nu}$$

$$\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}$$

$$E_{\rm res} = \frac{M^2}{2m_\nu}$$

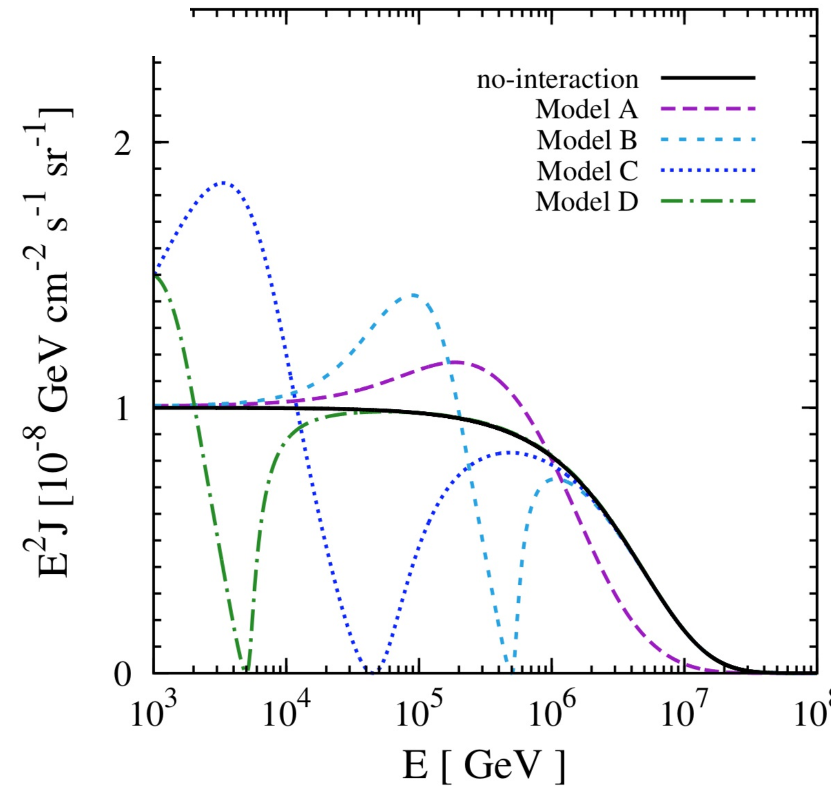


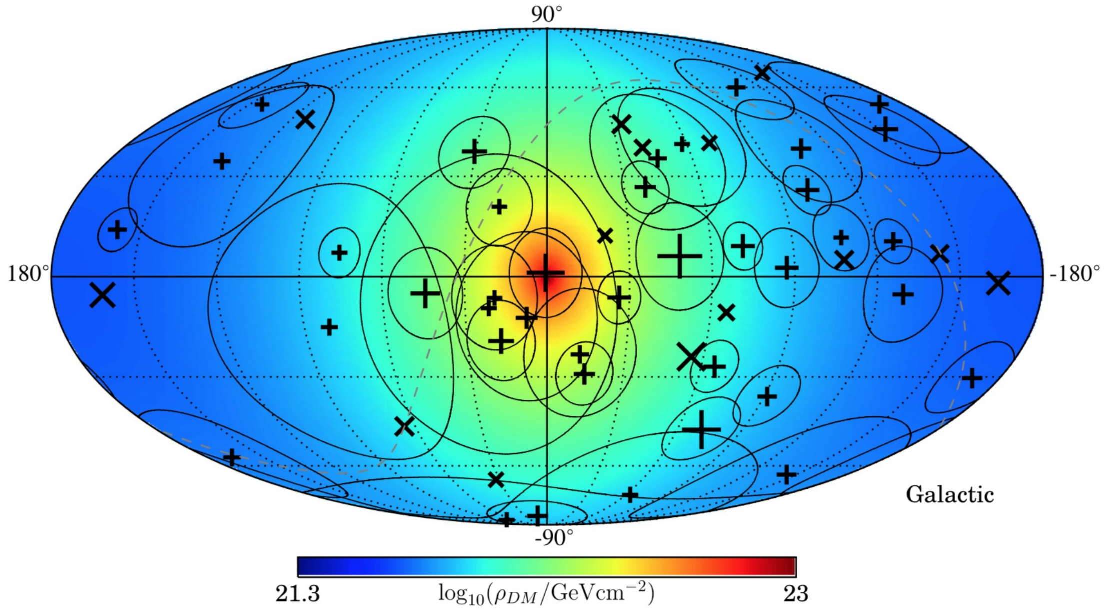
TABLE I. Parameters for the benchmark scenarios.

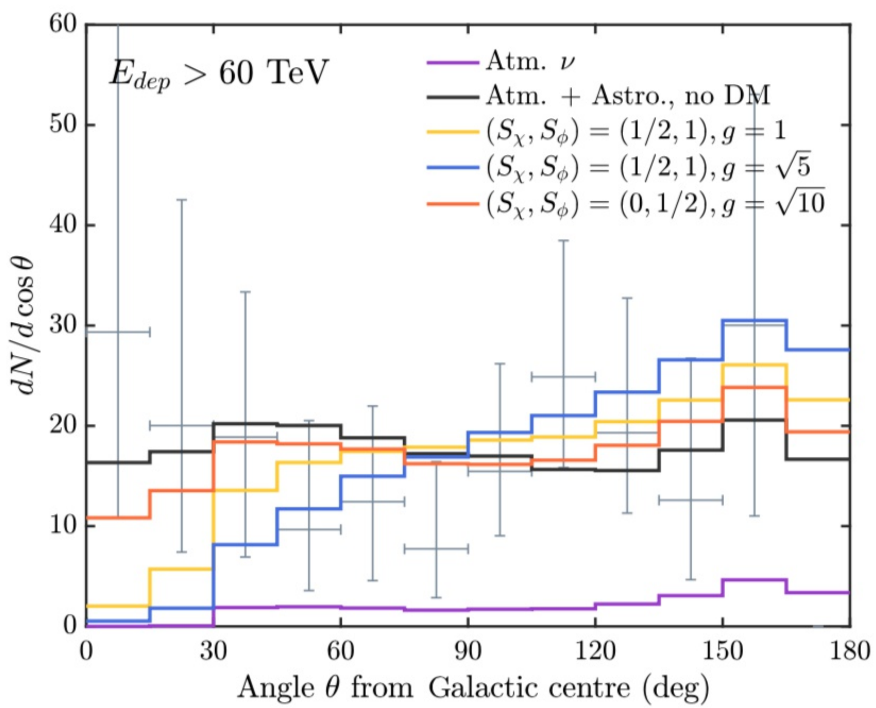
	A	B	C	D
g	0.3	0.03	0.03	0.01
M [MeV]	100	10	3	1
τ (1 PeV)	~ 0.7	~ 0.6	~ 0.2	~ 0.002
$E_{\rm res}$ [PeV]	50	0.5	0.045	0.005

Neutrino-DM interactions

(Absorption feature in the direction of the Galactic Center)

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





3. Open Problems in the *ASTROPHYSICS* of the High Energy Universe

The last decade of studies in High Energy Astrophysics has yielded an extraordinary amount of data and revealed a wealth of new phenomena

But…

Many crucial and fundamental problems remain open, and still poorly understood.

What are the main sources of
the Galactic Cosmic Rays ?

What is their maximum energy ?

When extragalactic cosmic rays
start to dominate the spectrum ?

What are the sources of the
extragalactic cosmic rays.

What is the relation between
proton and electron acceleration

Physical mechanisms in
SN explosions, Pulsars, AGN jets
GRB (short and long), ...

....

CTA

10x more sensitive than current instruments

+ much wider energy coverage and field of view

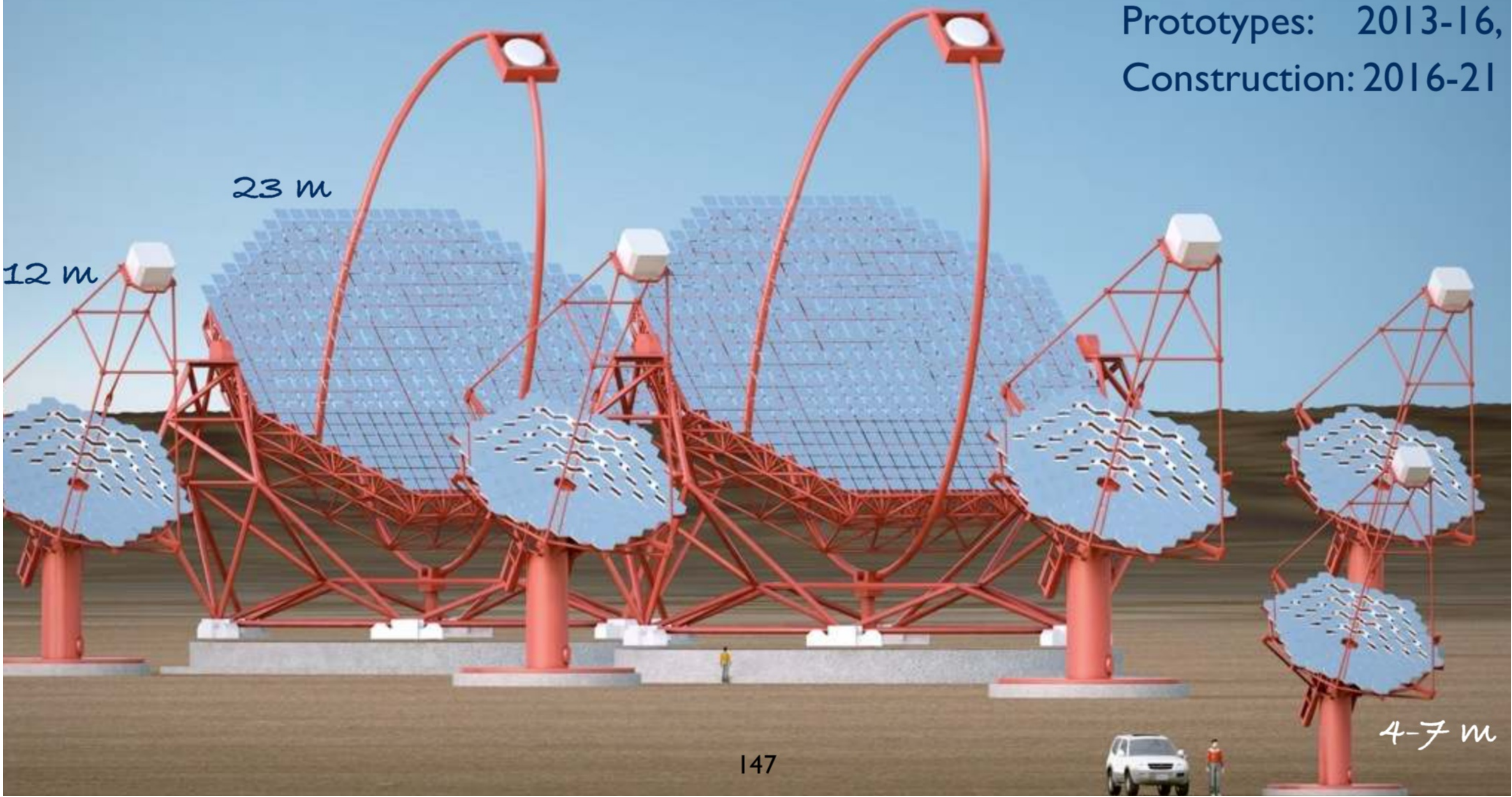
substantially better angular and energy resolution

telescopes: ~100 (3 sizes)

Design: 2008-12,

Prototypes: 2013-16,

Construction: 2016-21



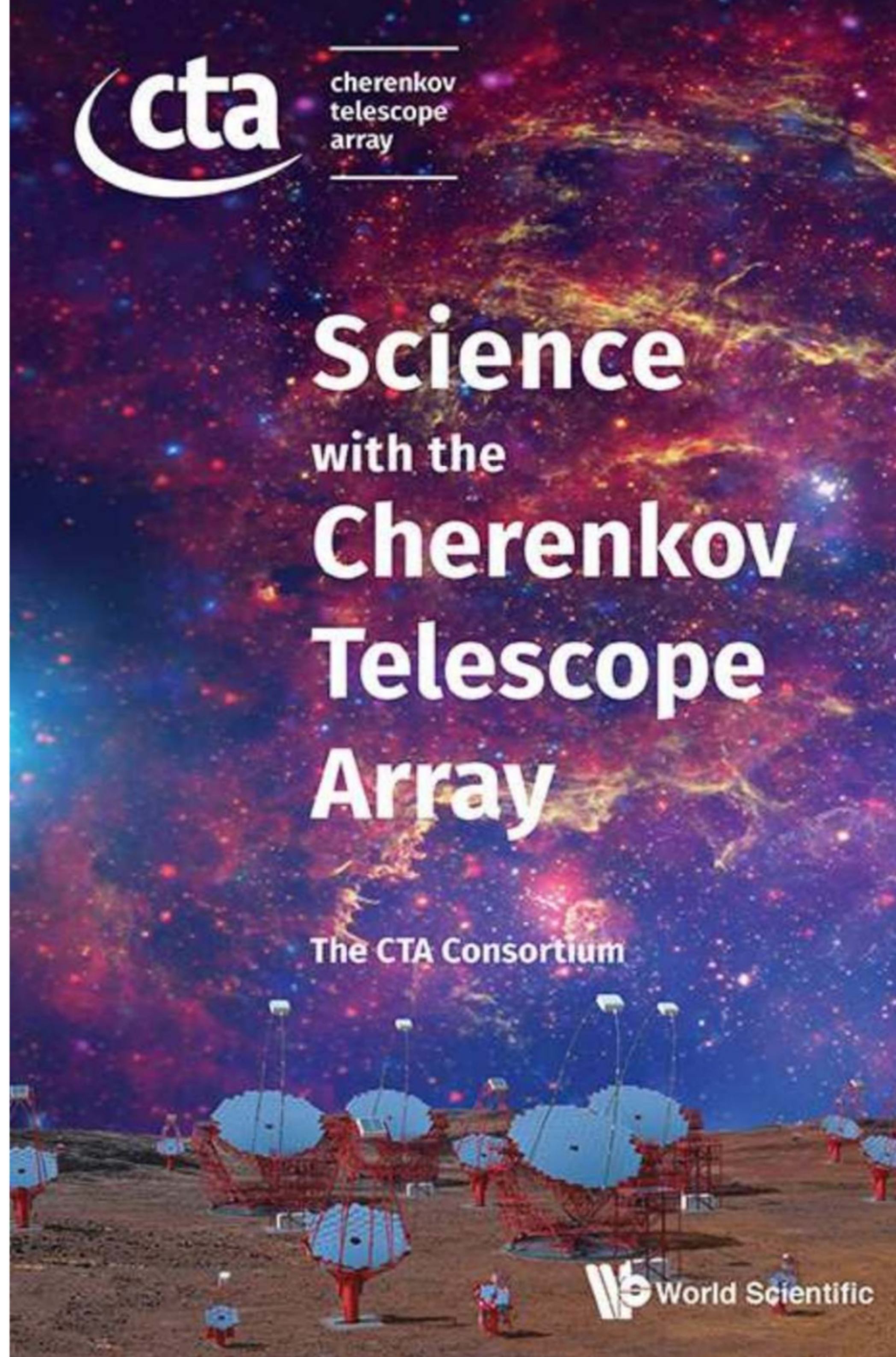
Key Science Projects

arXiv 1709.07997   2017

World Scientific 2019
https://doi.org/10.1142/10986

210 pages

Contents



Theme 1: Understanding the Origin and Role of Relativistic Cosmic Particles

- What are the sites of high-energy particle acceleration in the universe?
- What are the mechanisms for cosmic particle acceleration?
- What role do accelerated particles play in feedback on star formation and galaxy evolution?

Theme 2: Probing Extreme Environments

- What physical processes are at work close to neutron stars and black holes?
- What are the characteristics of relativistic jets, winds and explosions?
- How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?

Theme 3: Exploring Frontiers in Physics

- What is the nature of dark matter? How is it distributed?
- Are there quantum gravitational effects on photon propagation?
- Do axion-like particles exist?

Understanding the High Energy Sources

Dynamics of matter under large acceleration
(and extreme conditions)

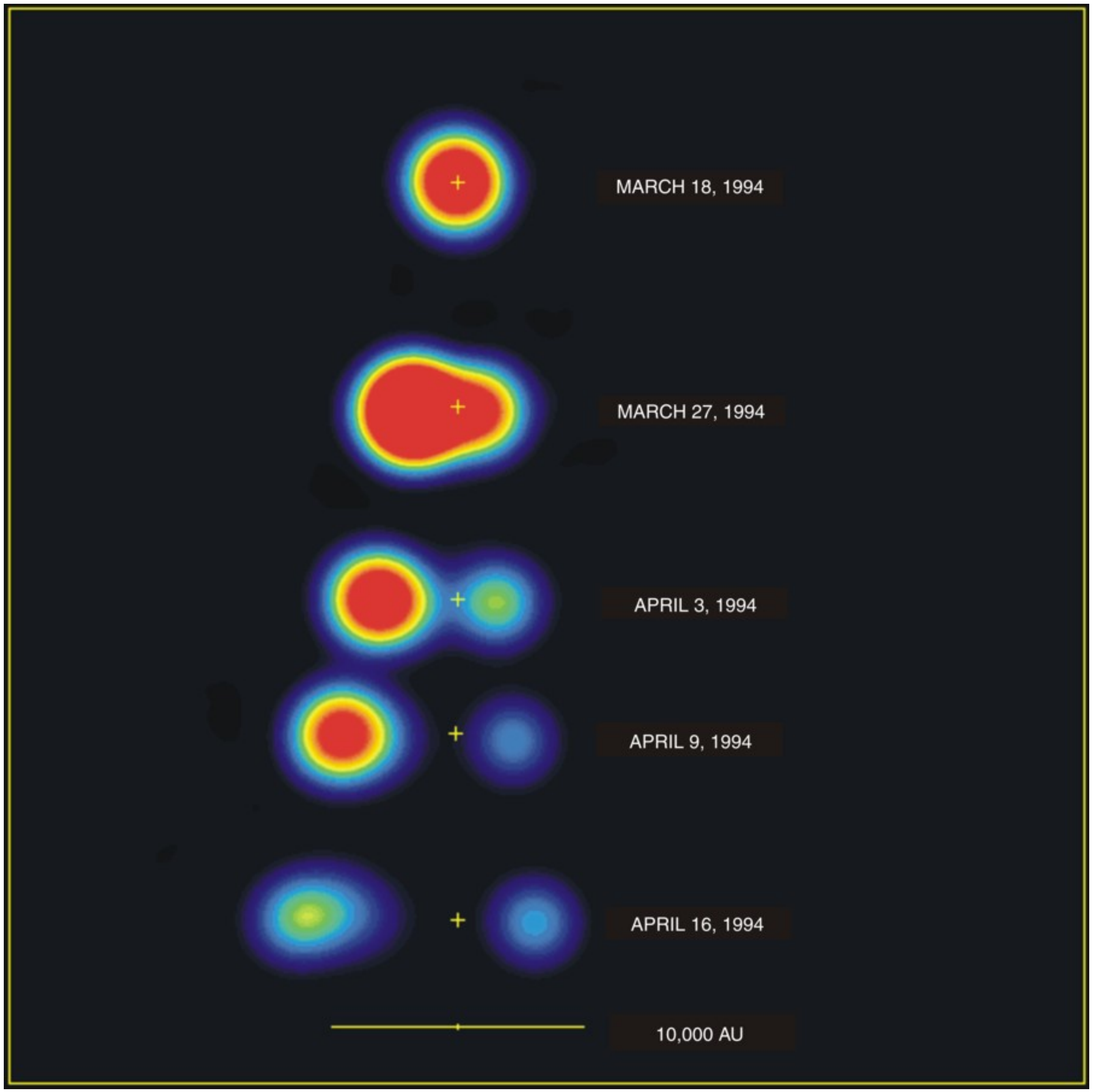
Generation of Electromagnetic Fields

Acceleration of charged particles
(up to Relativistic energies)

Radiation Mechanisms for
relativistic particles
(protons, nuclei, electrons, positrons,...)
inside (or near) the sources

Superluminal Motions in microQuasars in our Galaxy

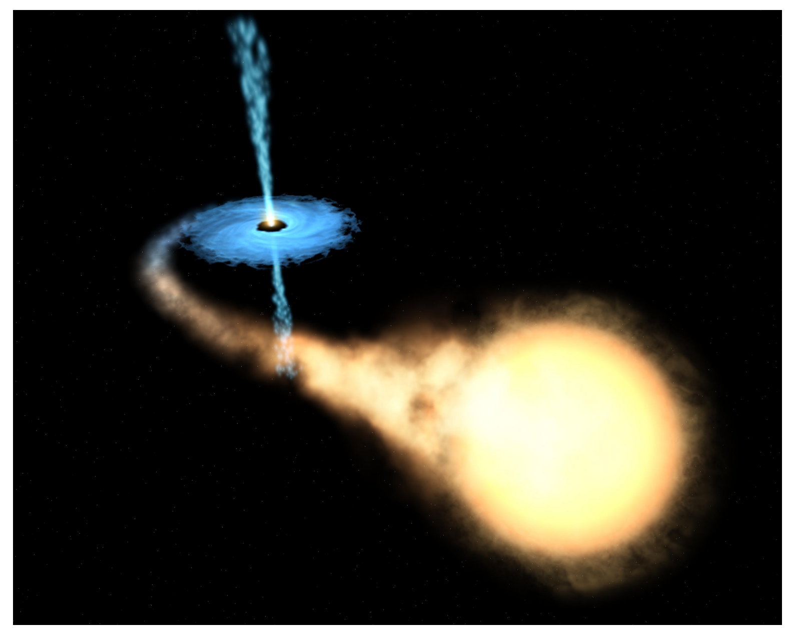
GRS1915+105

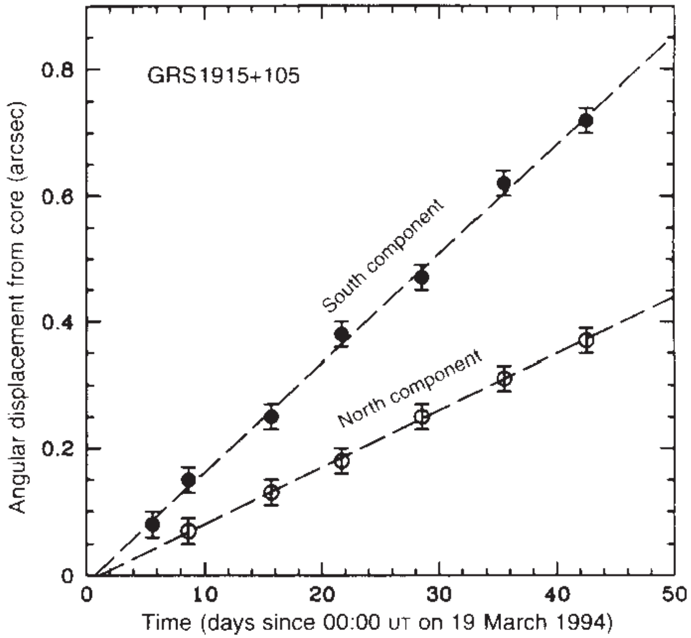


Observations in radio

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

"Two pairs of bright radio condensations"





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

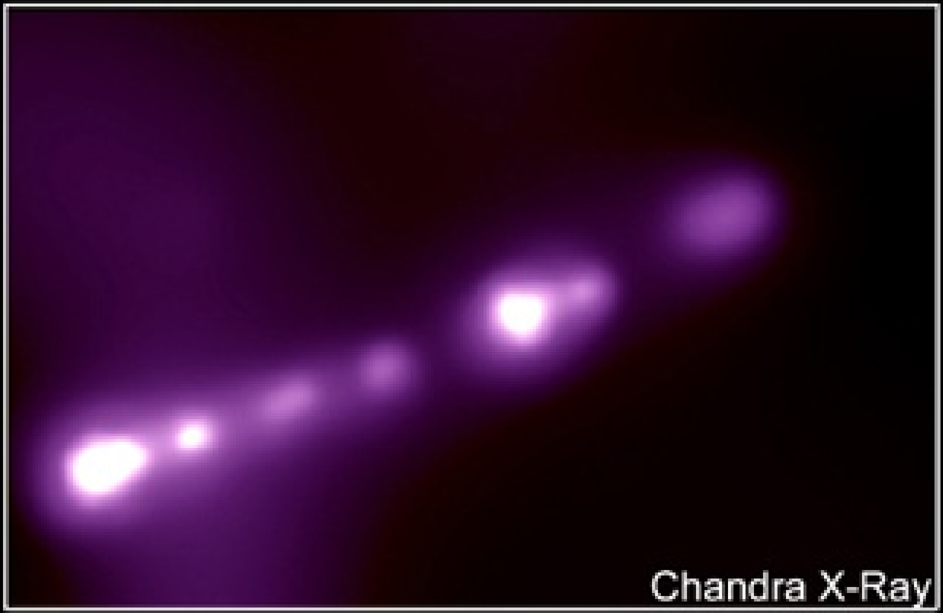
$$\mu_r \simeq 9.0 \pm 0.1 \ \frac{\text{mas}}{\text{day}}$$

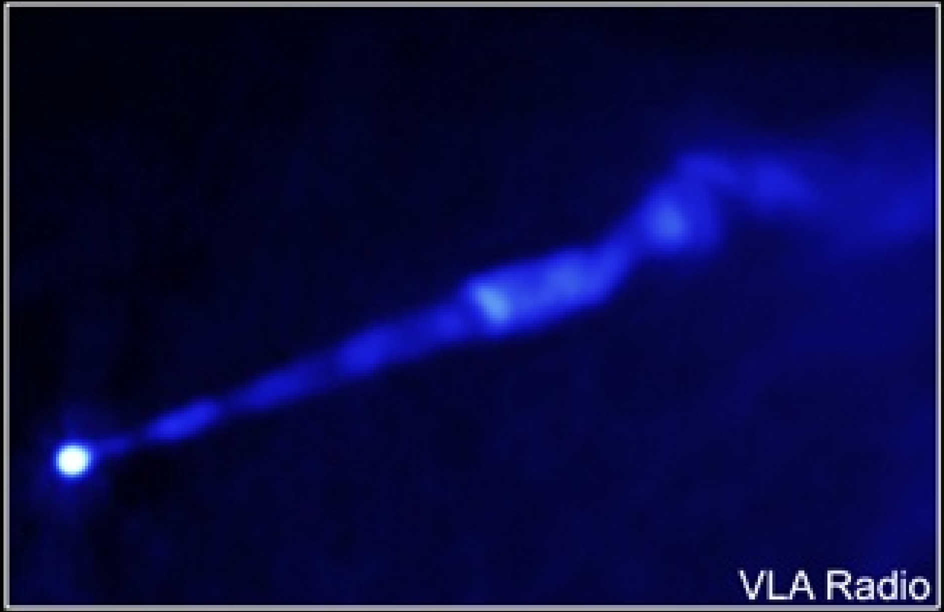
$$\boxed{\mu_{a,r} = \frac{\beta \ \sin\theta}{1 \pm \beta \ \cos\theta} \frac{c}{D} \qquad D = 12.5 \pm 1.5 \text{ kpc}}$$

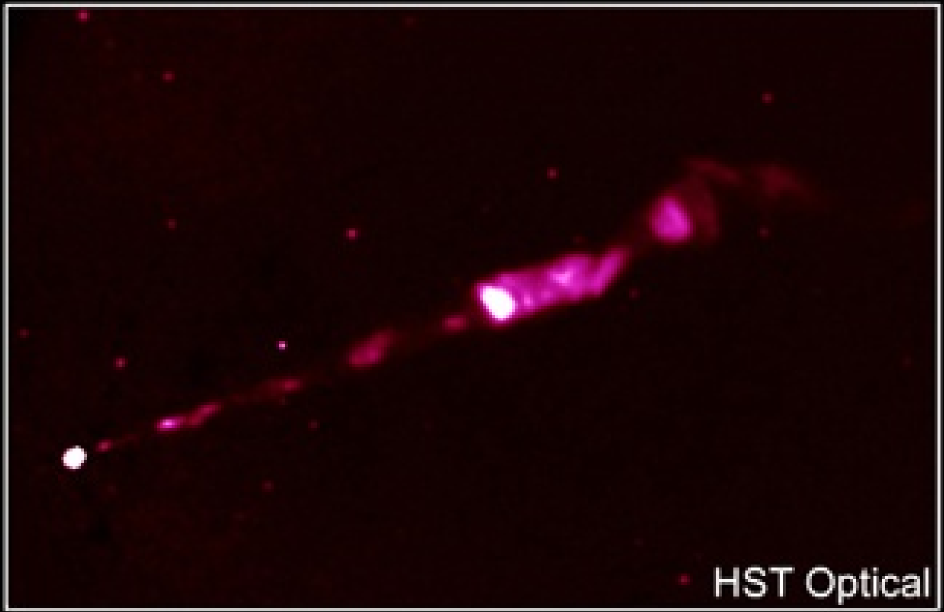
$$\beta = 0.92 \pm 0.08$$

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

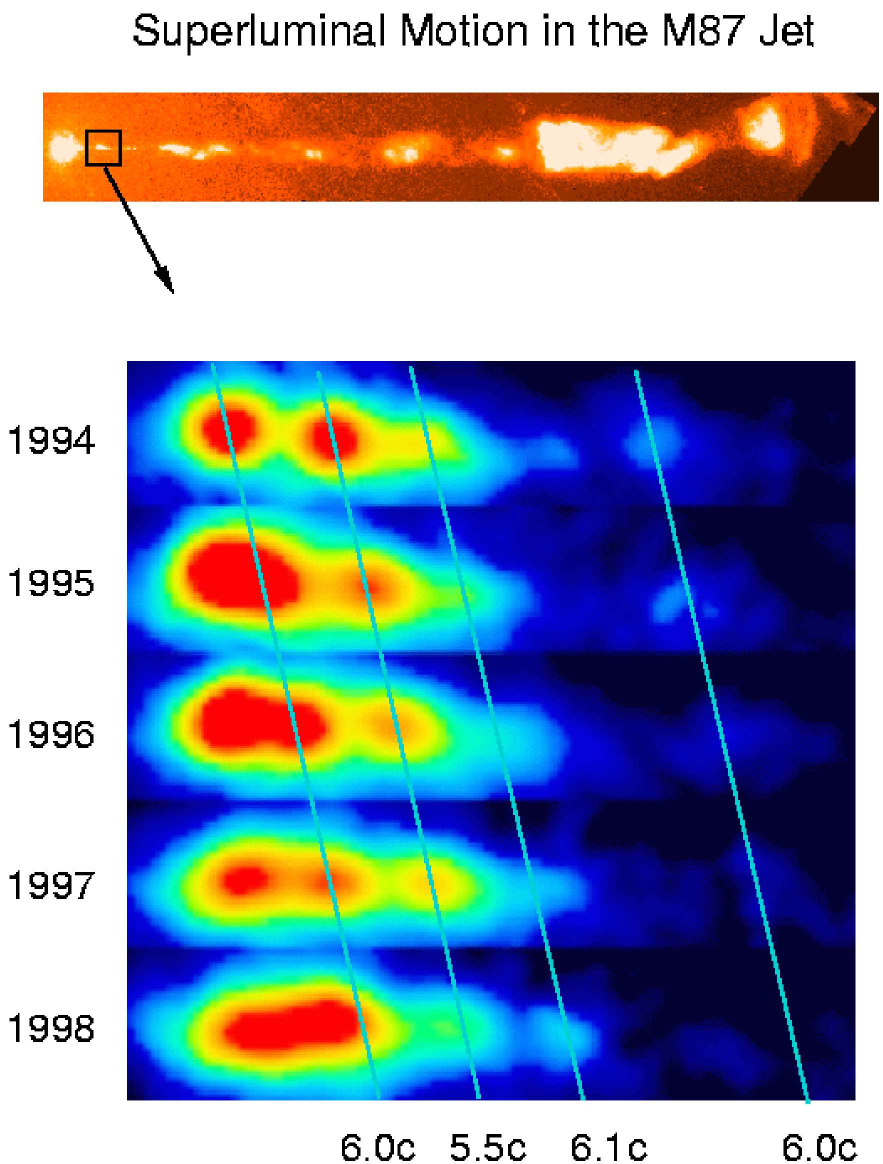
M 87







Superluminal Motions

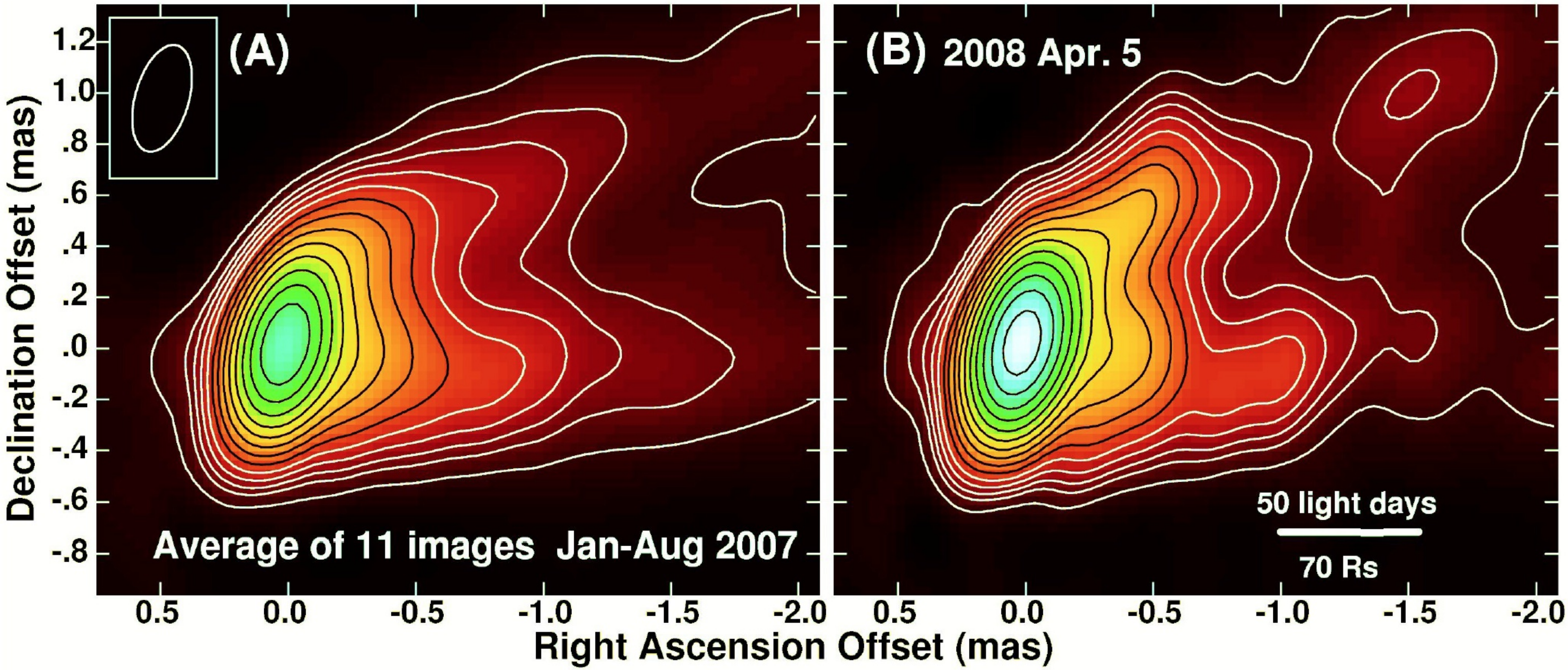


Source moving
on the celestial sphere

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

M87 :

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

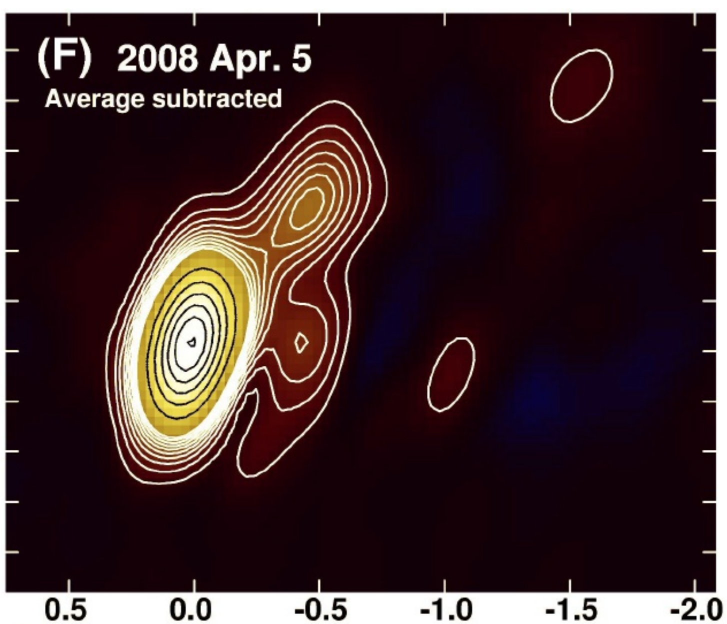


VLBA radio images of M87 at 43 GHz

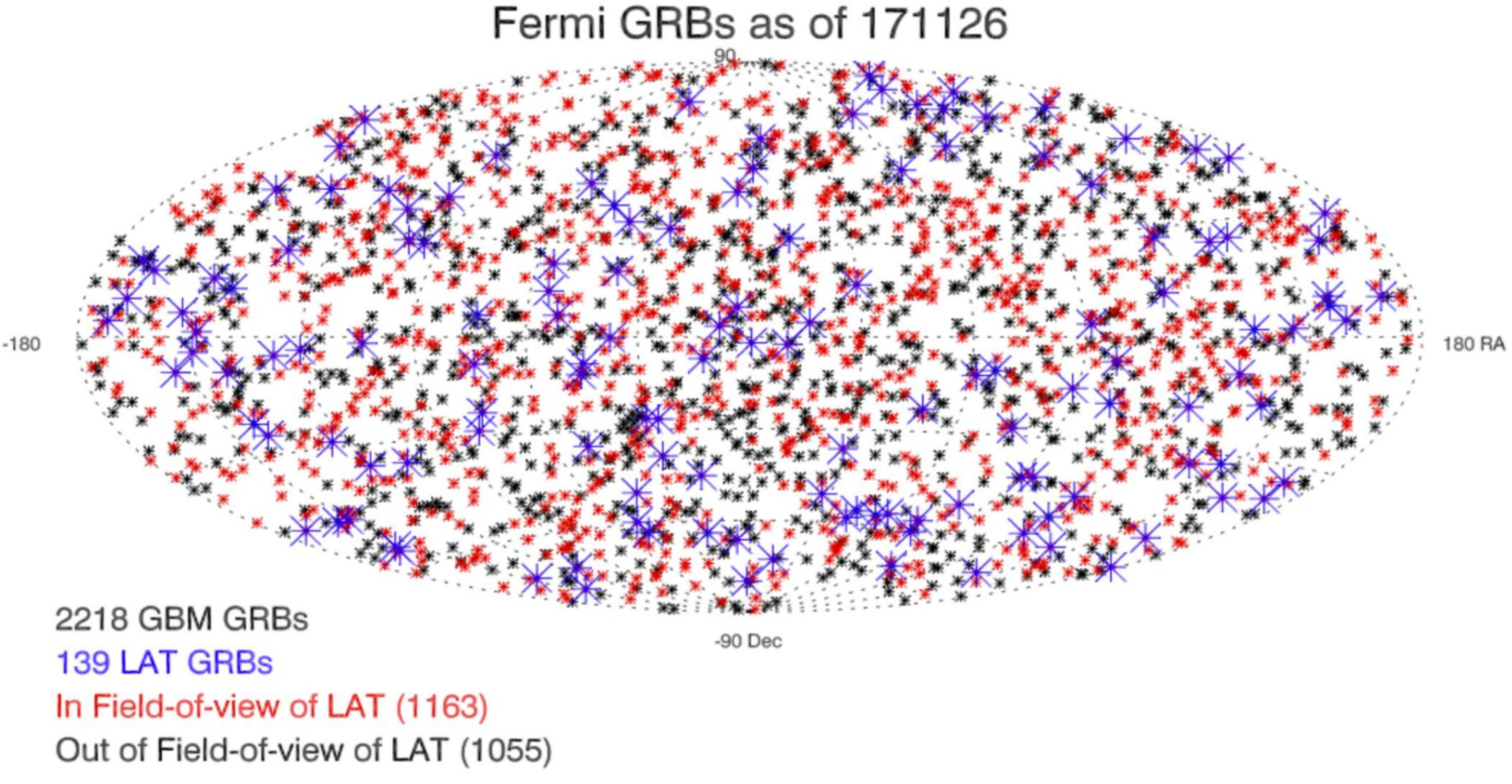
Science 24 Jul 2009:
Vol. 325, Issue 5939, pp. 444-448
DOI: 10.1126/science.1175406

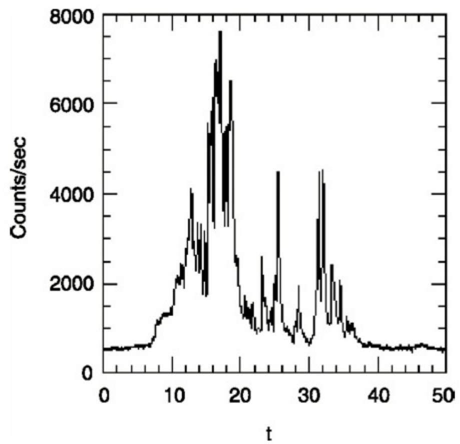
Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

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

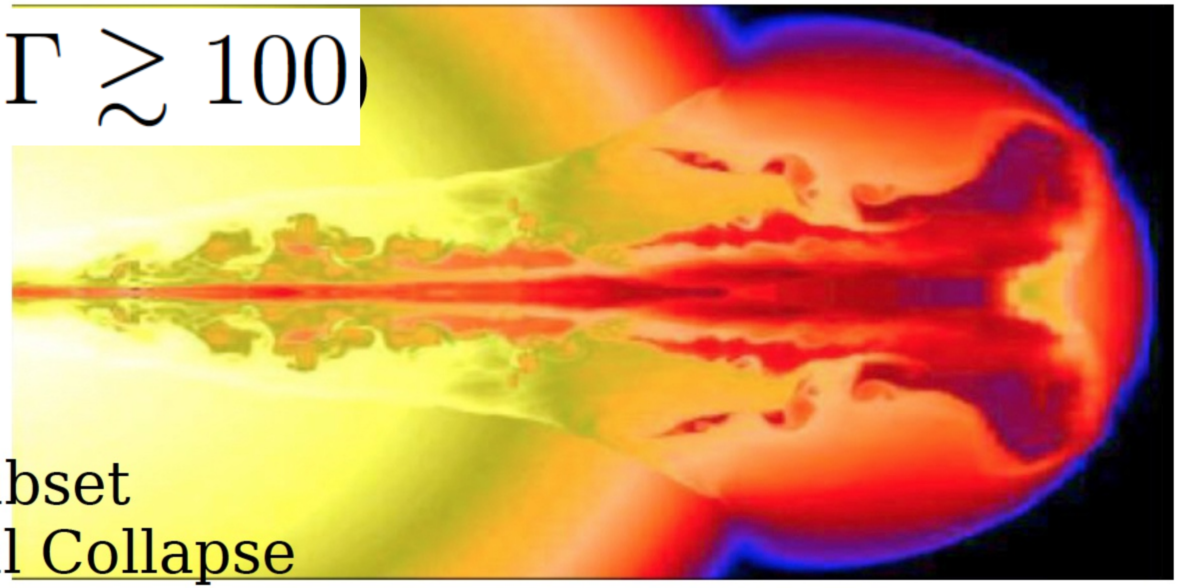


Gamma Ray Bursts

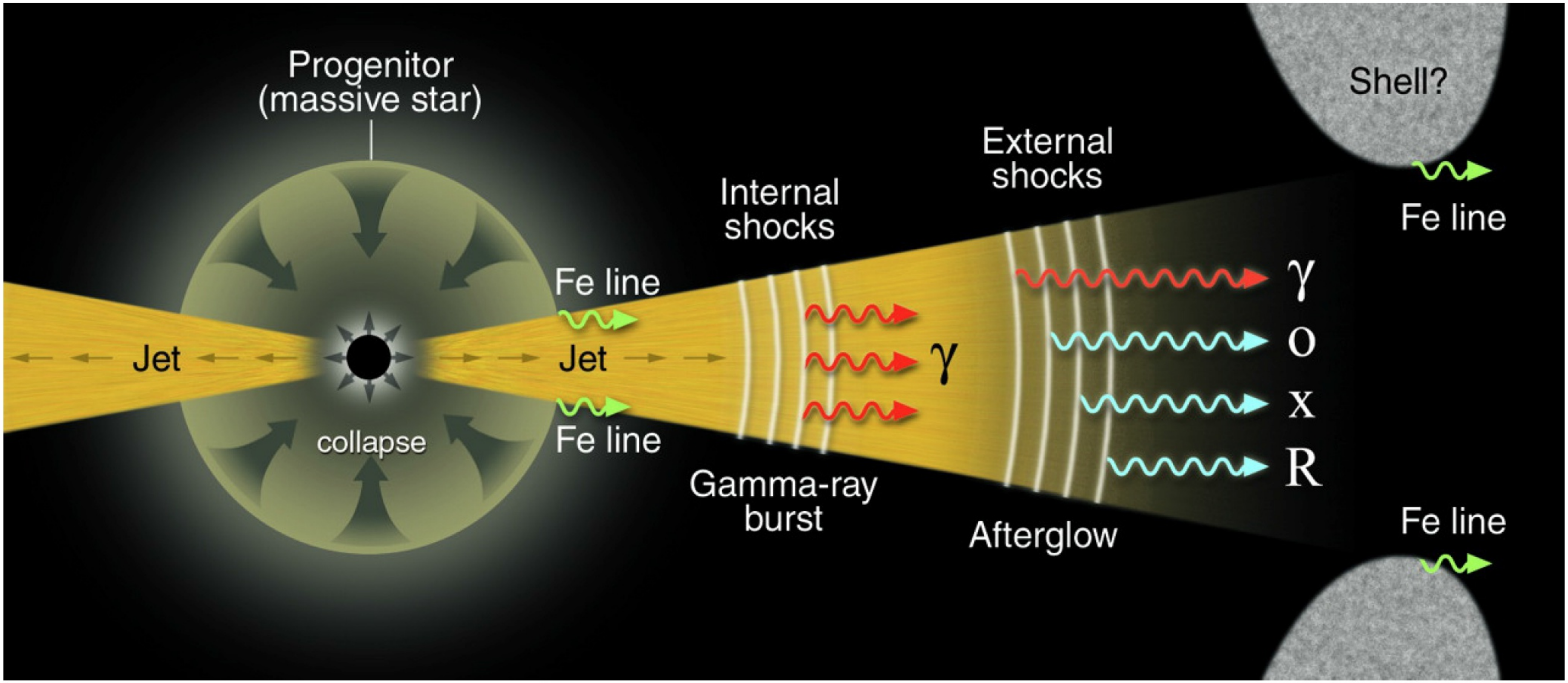




$\Gamma \gtrsim 100$

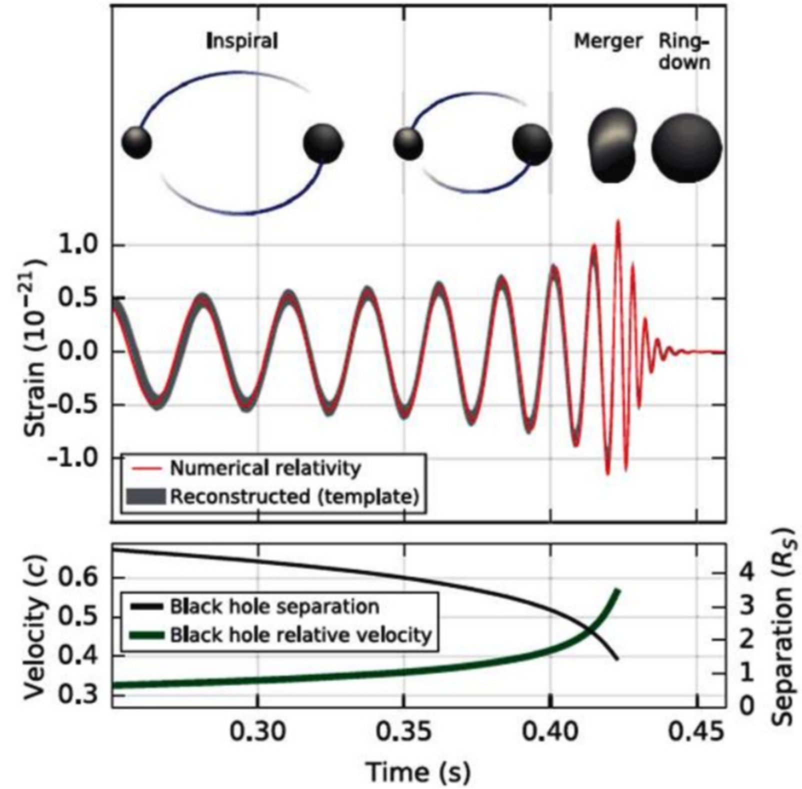


GRB : associated with a subset
of SN Stellar Gravitational Collapse



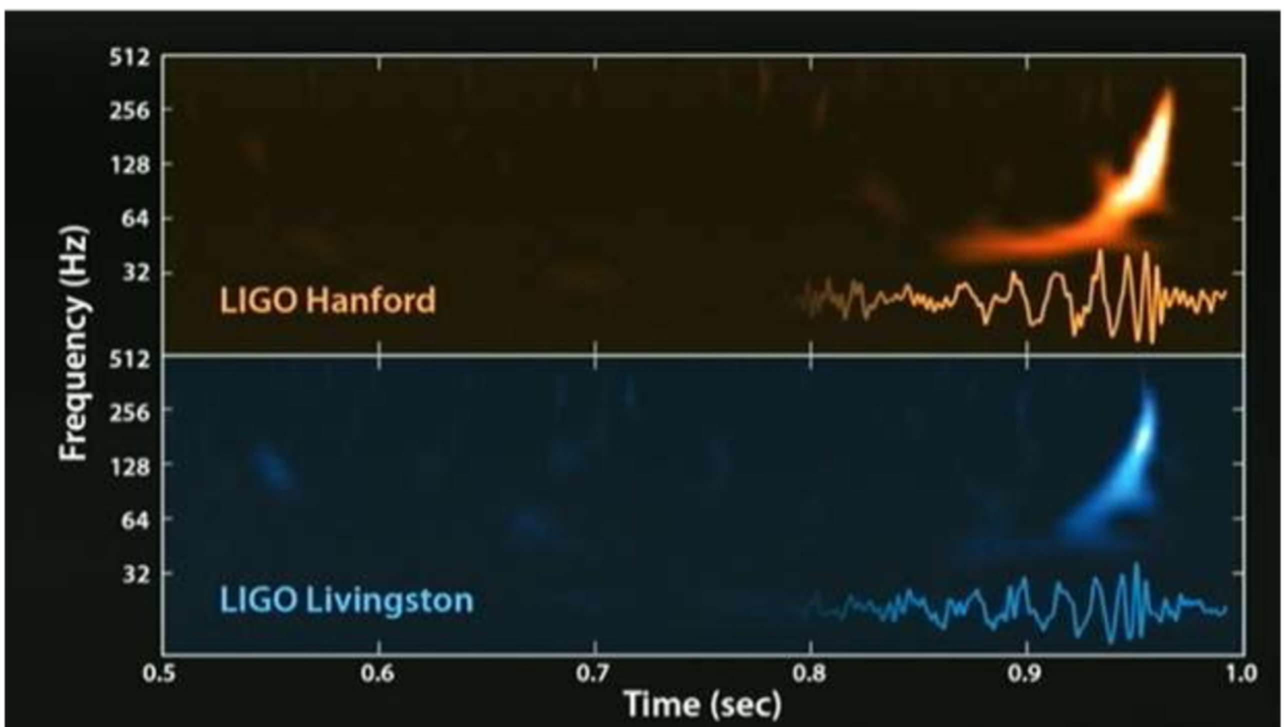
Gravitational Waves:

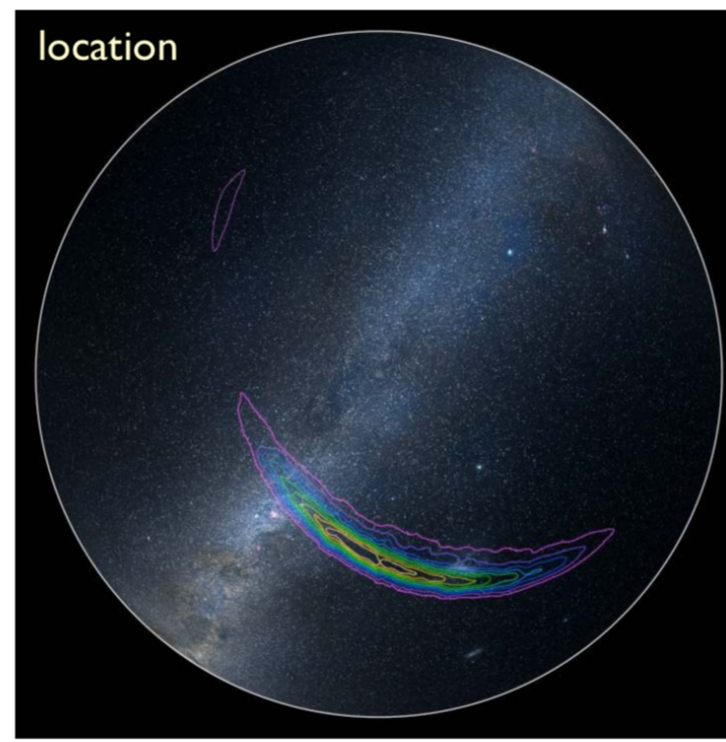
event GW150914 : Merger of two black holes
29 and 36 solar masses
1.3 x 10^9 light years away



New messenger in the multi-messenger approach
to high-energy astrophysics.

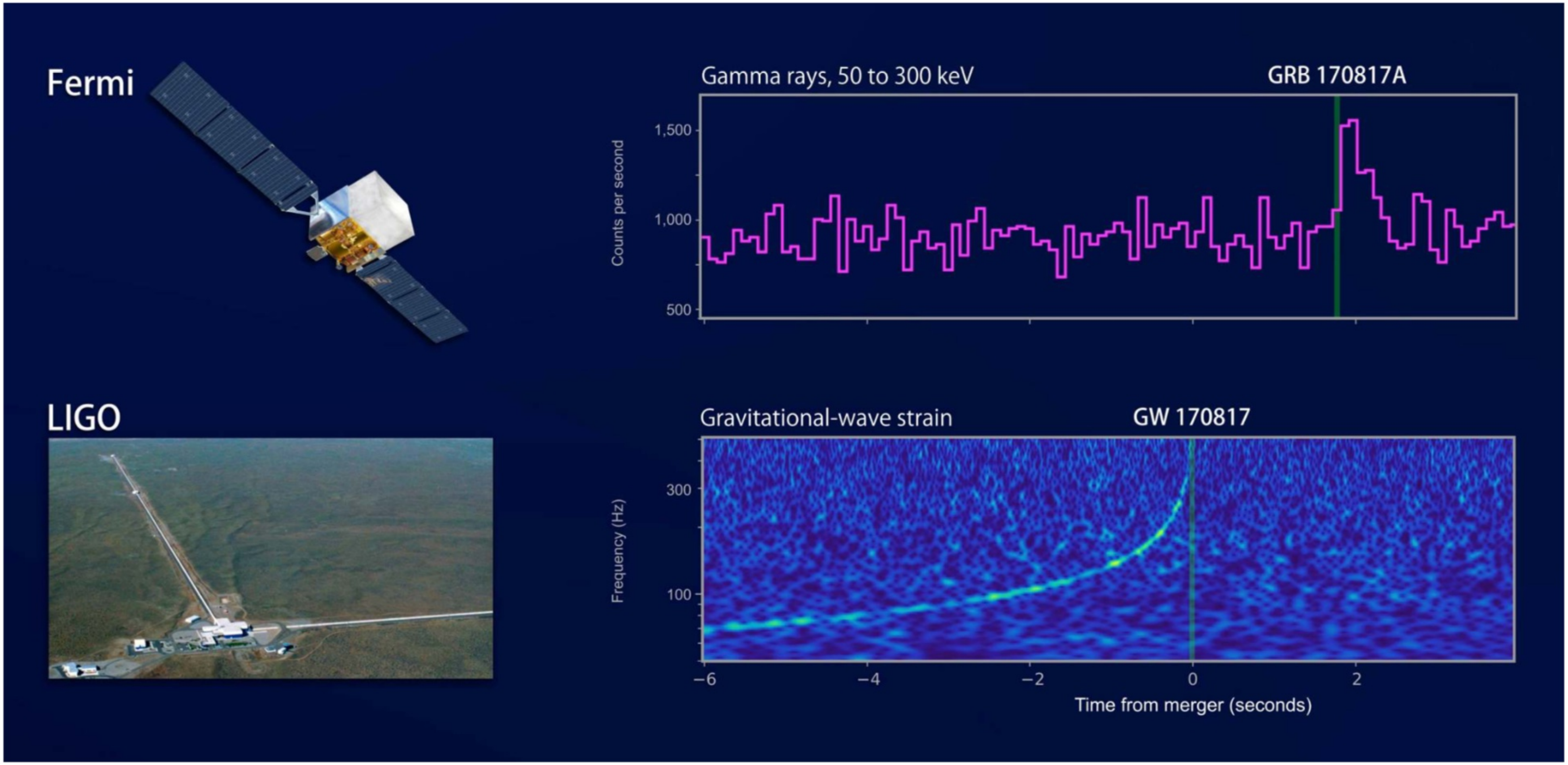
Do grav. events produce also other measurable outputs
(light, neutrinos, gamma rays)? Some might …

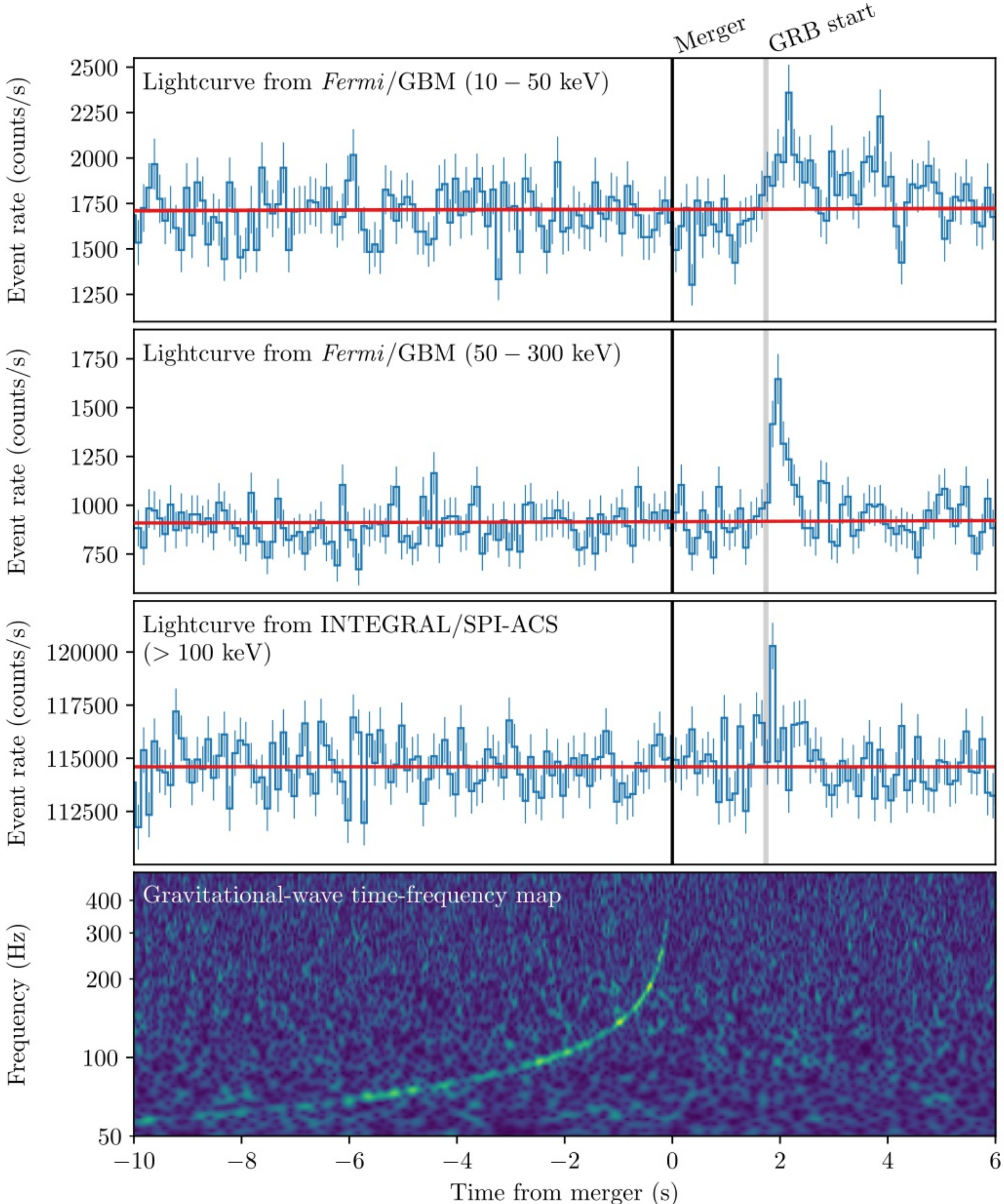




Another first: neutron star merger (NS-NS)

2017: LIGO detected the first binary Neutron-Star merger: GW170817 - this time with an electro magnetic counterpart





GRB 170817A

GW 170817

7.5 msec

13.8 msec

15.26 msec

26.5 msec

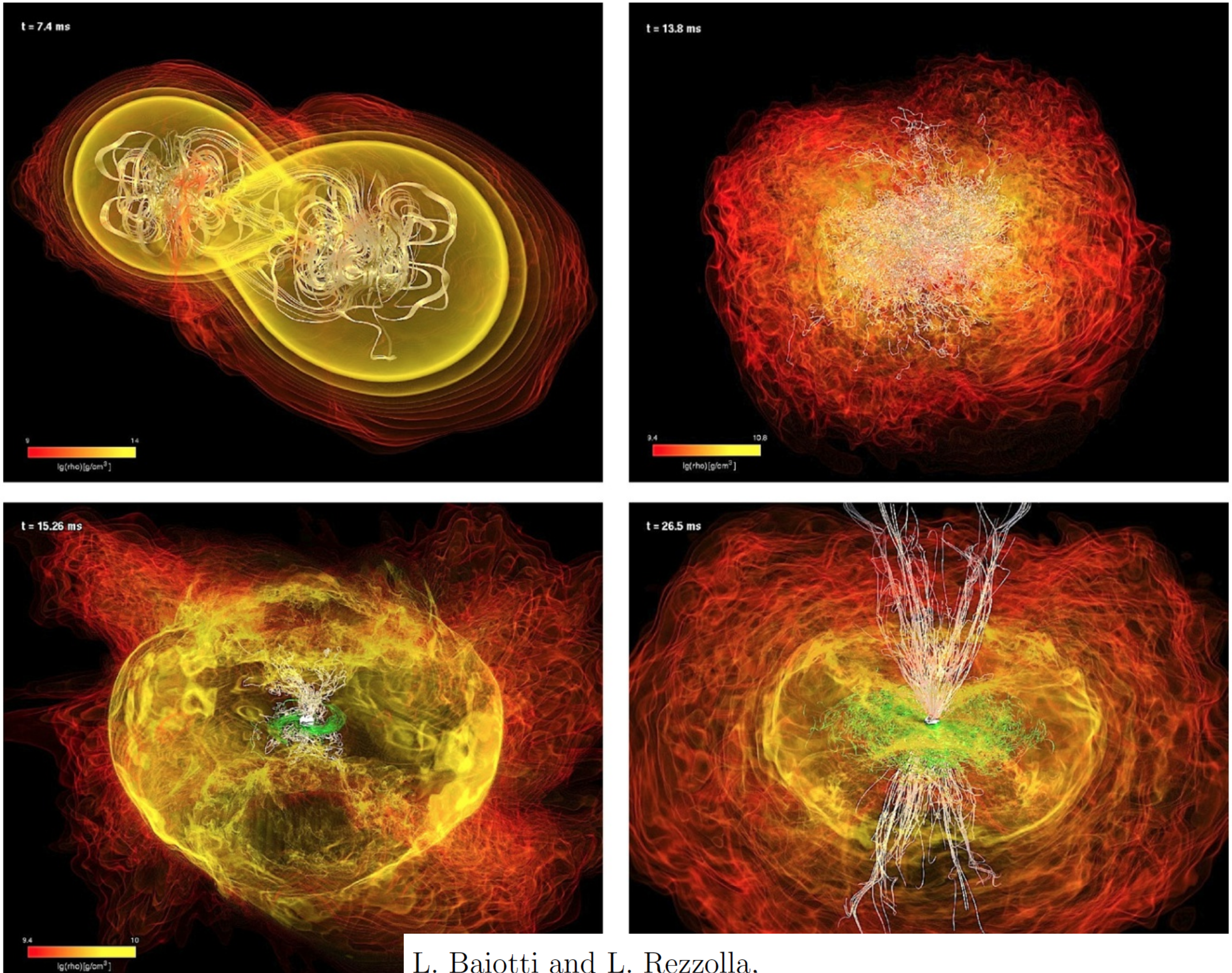


Figure 1. Snapshots at representative times of the evolu
the density, over which the magnetic-field lines are supe
to BH (t = 13.8 ms), while those in the lower row to th
in the torus and on the equatorial plane, while white lin
size of ~90/170 km, while the horizon has a diameter

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].

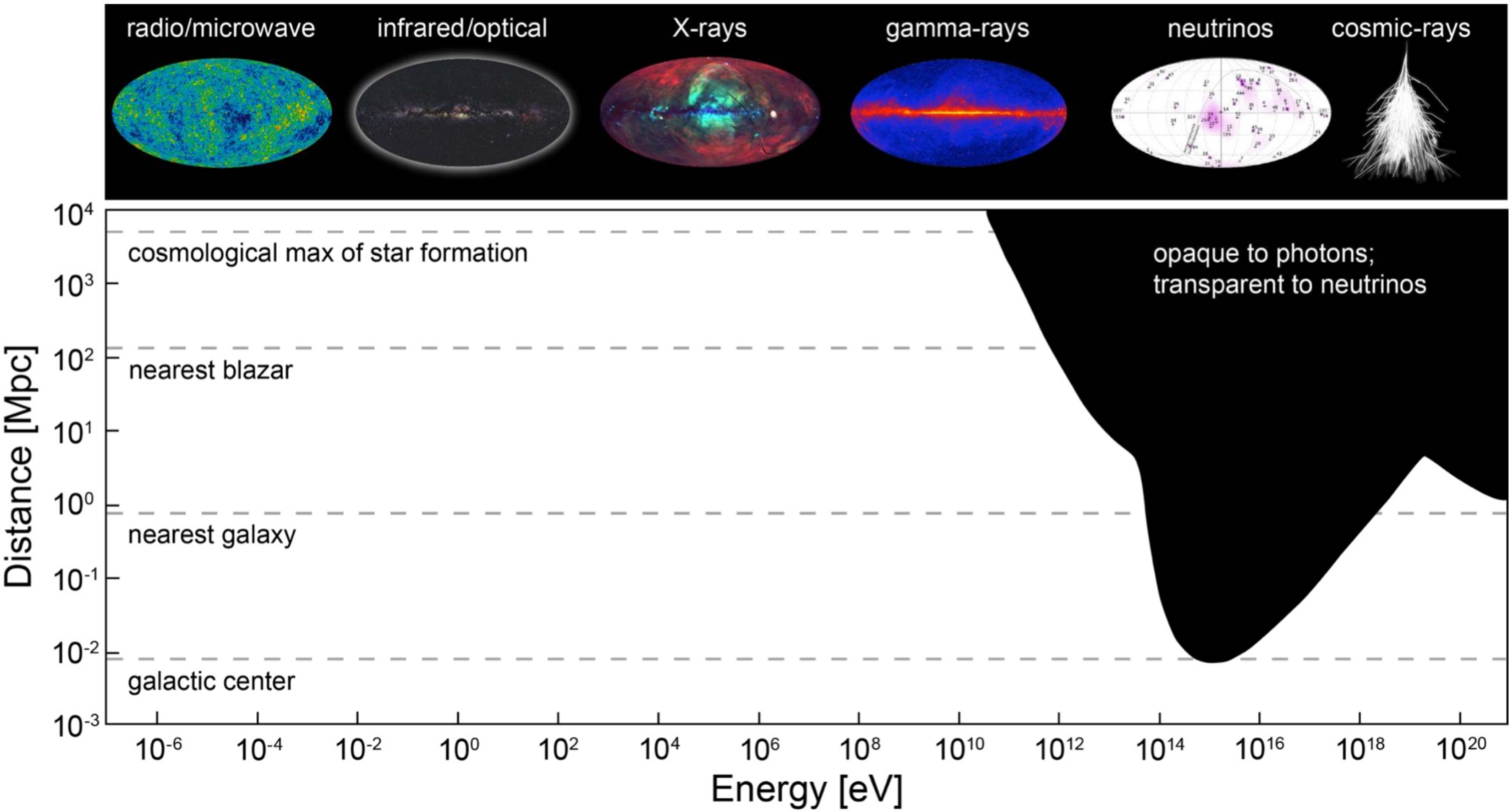
Role of Neutrinos in Multi-Messenger Astrophysics:

1. Clarify the nature and properties of the extragalactic neutrino signal observed by IceCube.

2. Contribute to the understanding of the Galactic Sources.

3. Explore the EeV $(10^{18}\ \mathrm{eV})$ energy range Measure (or put strong limits) on cosmogenic neutrinos

The High energy region of highest interest because of photon absorption $E \gtrsim 10\ \mathrm{TeV}$



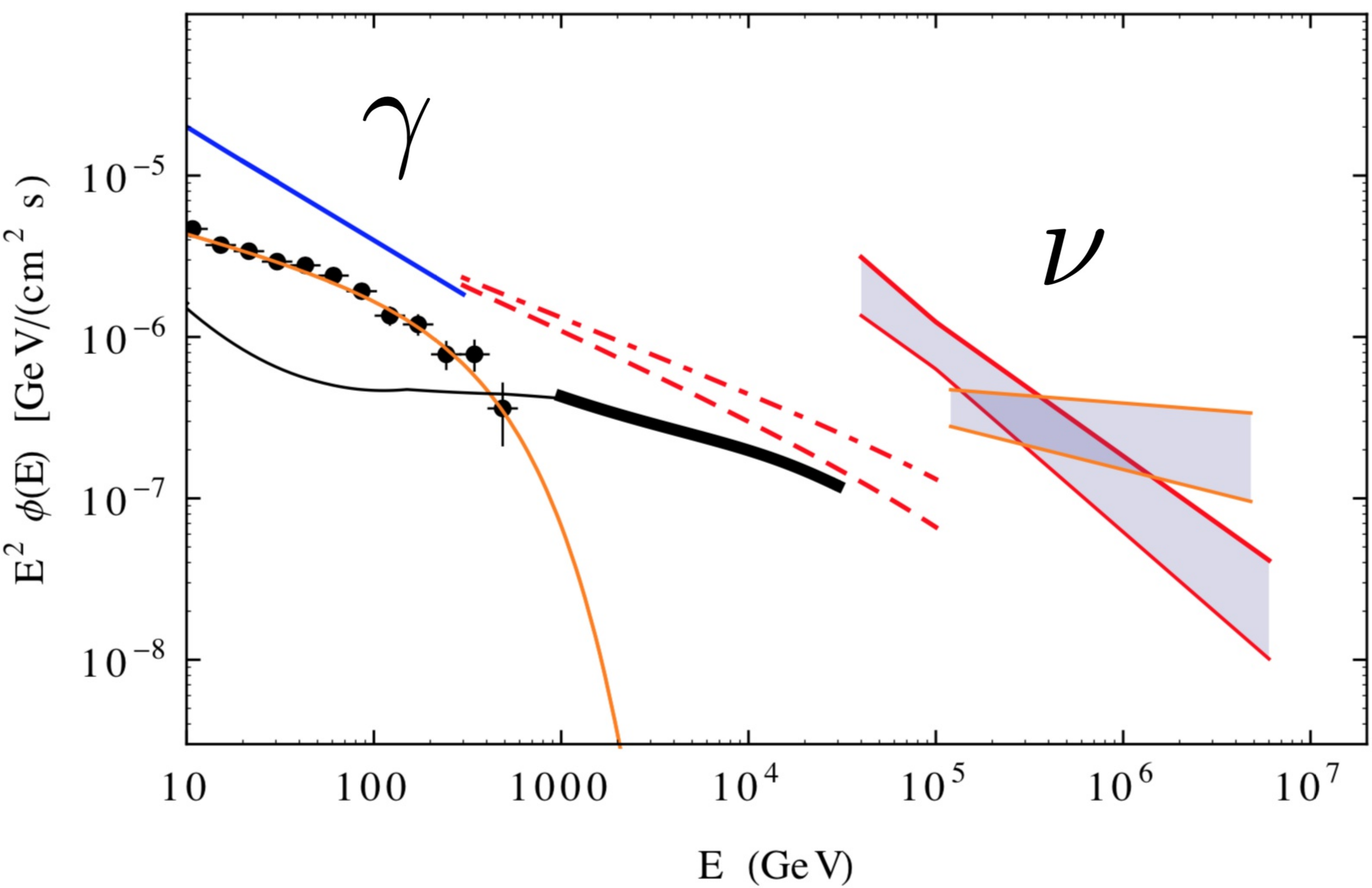
Clarify the nature and properties
of the extragalactic neutrino signal
observed by IceCube.

[a] Precision measurement of
Energy Spectrum

Is there a break ?
Is there a cutoff ?

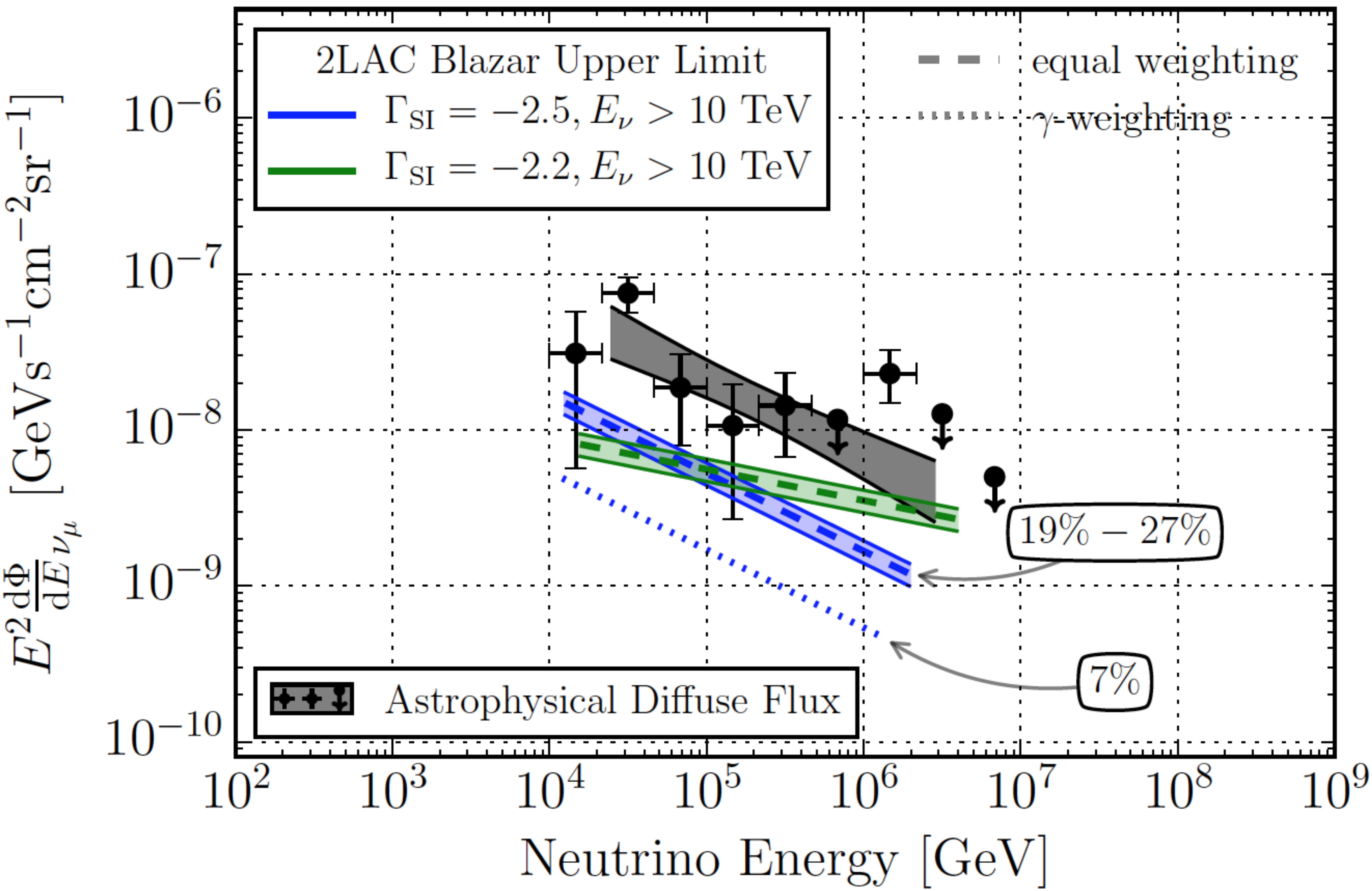
[b] Determine the flavor composition at the Earth

[c] Identify the Source Population
responsible for the diffuse neutrino emission



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

IceCube study of correlations with the FERMI 2LAC



Blazars only subdominant as the origin of the IceCube signal

~~A~~ The neutrino event in IceCube

TXS 0506+56

High-energy, through going track

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

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

Coincident observations by Fermi-LAT and MAGIC

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

ATel #10791; *Yasuyuki T. Tanaka*
Daniel Kocevski (NASA/MS

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B.*
cester), and F. E. Marshall
e collaboration:

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DE*
(OSU), T. W.-S. Holoien, B. J
(Diego Portale

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.*
AR), M. Tavani (INAF/IAPS, and Univ.
-Bo), P. Munar-Adrover, G. Minervini,
DA-Brera), I. Donnarumma (ASI), V.
(CIFS and INAF/IAPS), M. Cardillo
tti, M. Trifoglio (INAF/IASF-Bo), A.
tti (INAF/IASF-Mi), A. Chen (Wits
onte, Y. Evangelista, M. Feroci, F.
Soffitta, S. Sabatini, V. Vittorini
ENEA-Frascati), G. Di Cocco, F.
(INAF/IASF-Bo), A. Pellizzoni, M.
llini, E. Vallazza (INFN Trieste), F.
rselli, P. Picozza (INFN and Univ.
ia), P. Lipari, D. Zanello (INFN and

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; *D. B. Fox (PSU), J. J*
(U. Leicester), C. F. Turley (PSU
Osborne (U. Leicester), M.

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara,*
ki, S. Nakahira, W. Iwakiri,
N), N. Kawai, S. Sugita, T.
), A. Yoshida, T. Sakamoto,
U), H. Tsunemi, T. Yoneyama
on U.), Y. Ueda, T. Hori, A.

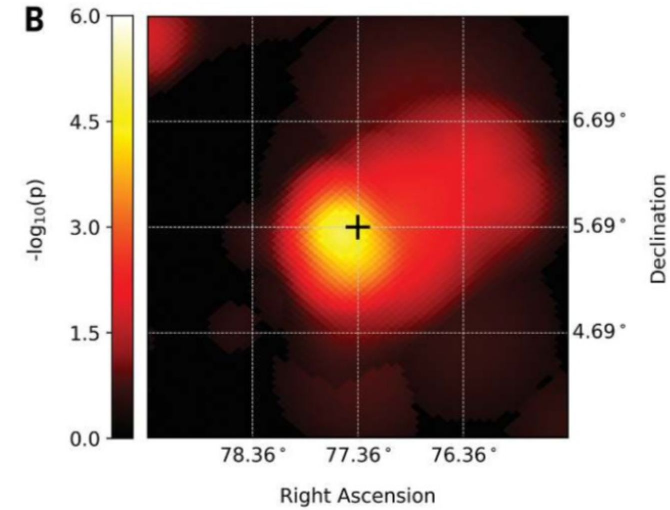
VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

Science 361 (2018) no.6398, eaat1378

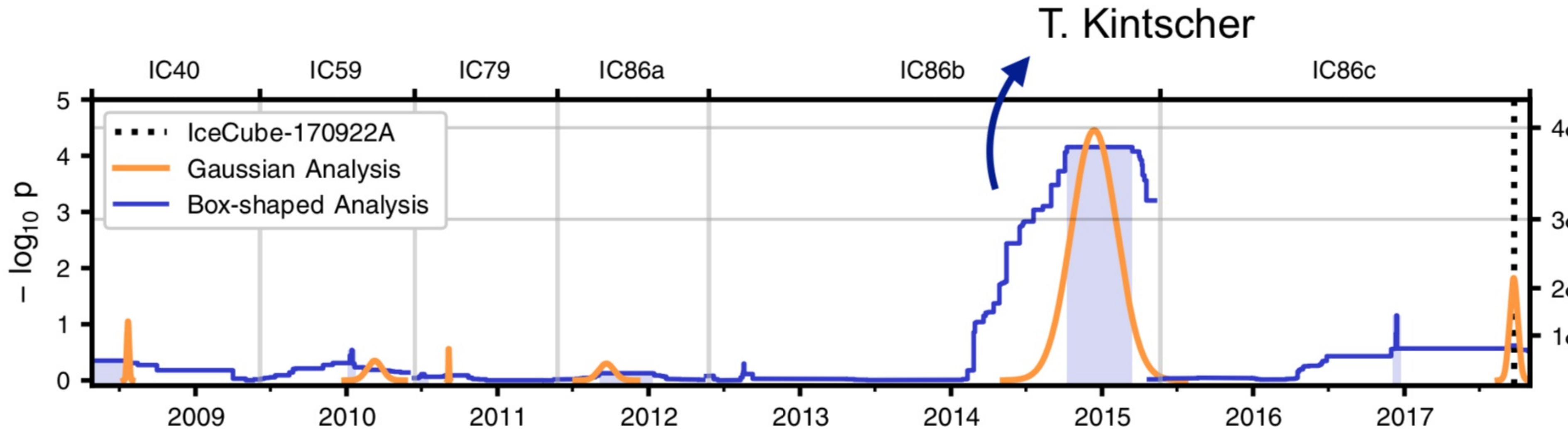
IC170922A / TXS 0506+56

First evidence for a neutrino point source



Archival search

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



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

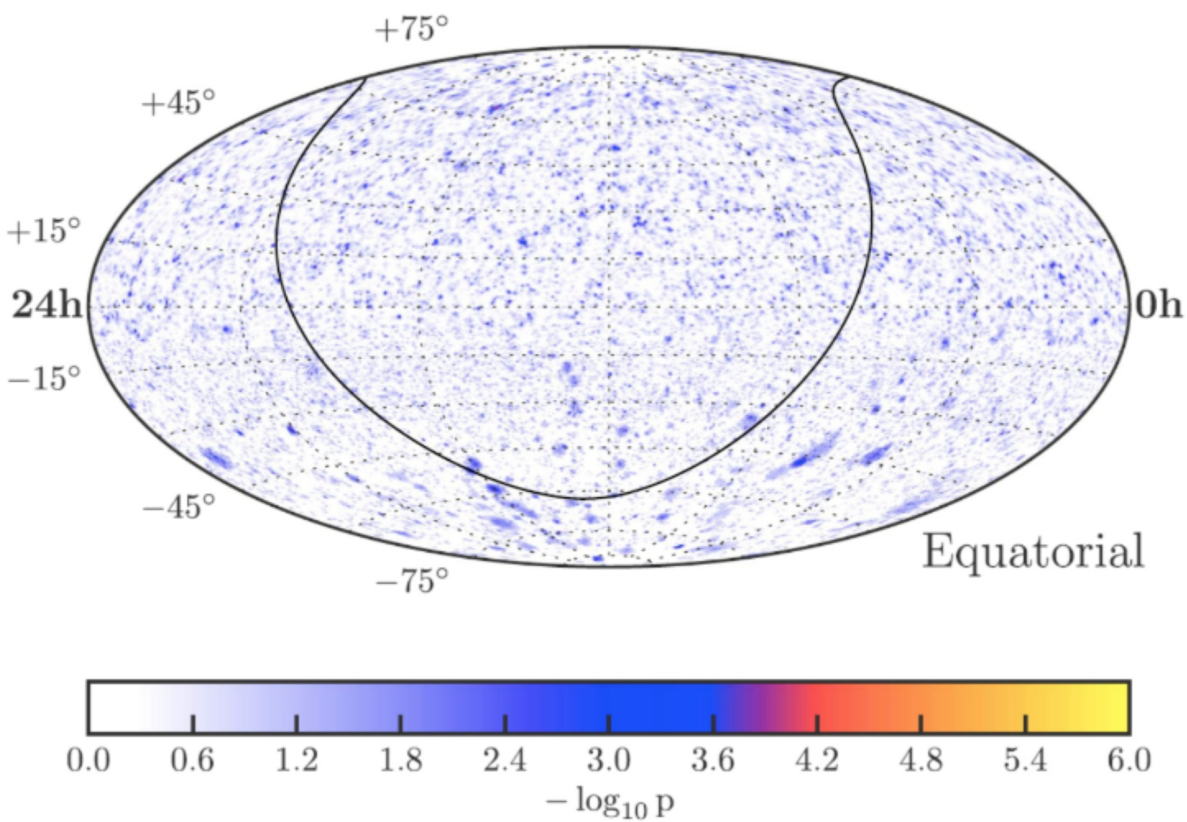
Inconsistent with background-only hypothesis at the 3.5σ level

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

Search for Galactic Point Sources

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

IceCube - Point Sources – 7 years

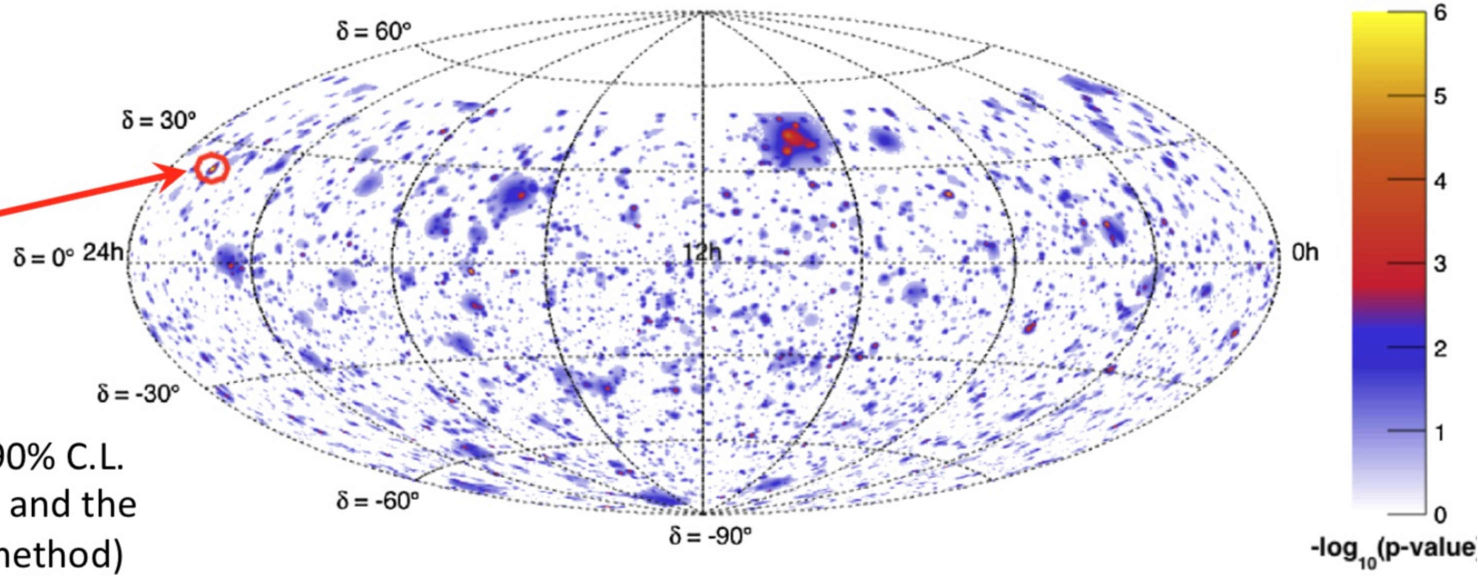


No significant PS reported

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

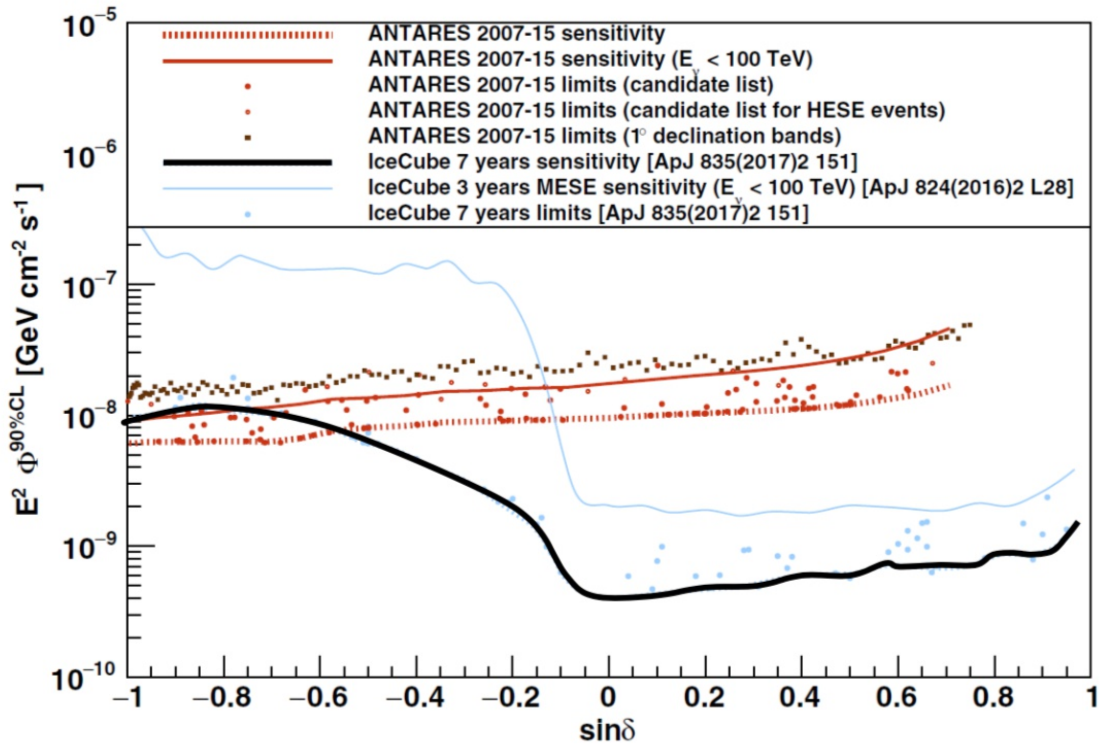
ANTARES – Point Sources

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



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

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



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

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

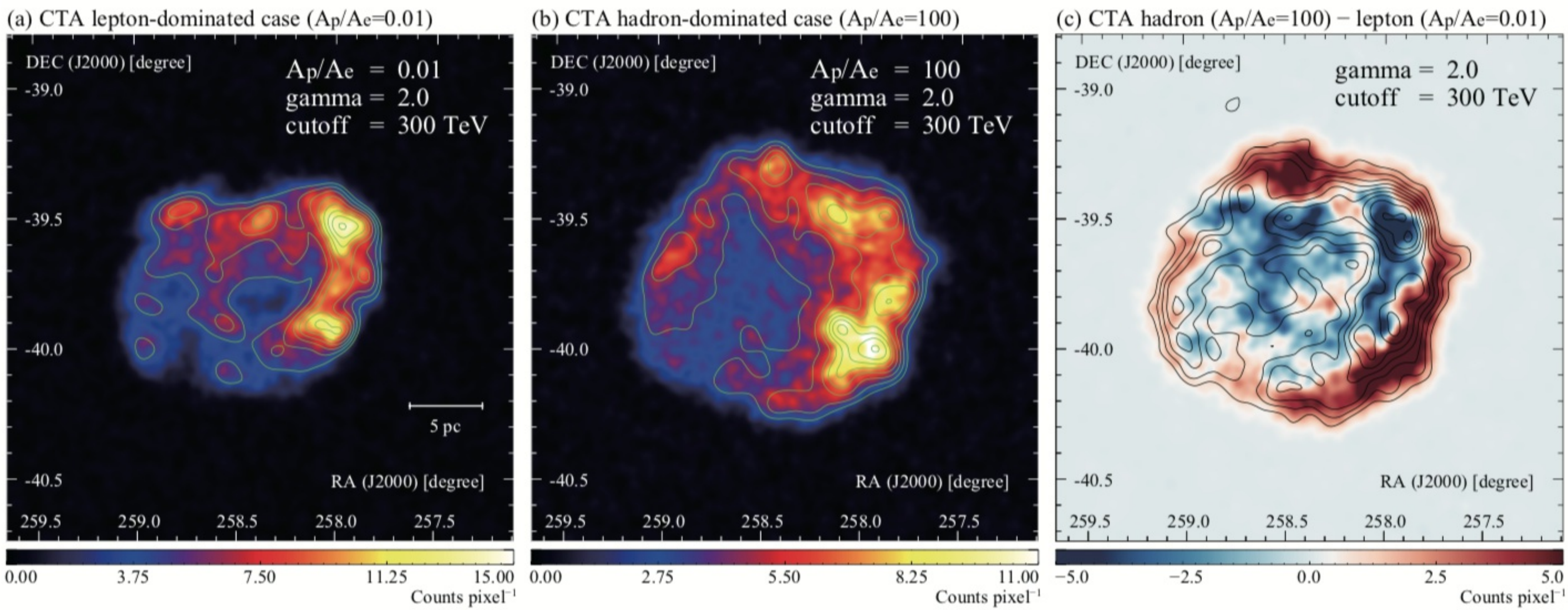
Search for Galactic Point Sources

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

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

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

Morphology studies have the potential to establish the presence/absence of correlation between gas in the source and the gamma ray emission



F. Acero *et al.* [CTA Consortium],
"Prospects for Cherenkov Telescope Array Observations of the Young Superngva Remnant RX J1713.7–3946",
Astrophys. J. **840**, no. 2, 74 (2017)
[arXiv:1704.04136 [astro-ph.HE]].

“Signature” of the hadronic mechanism:

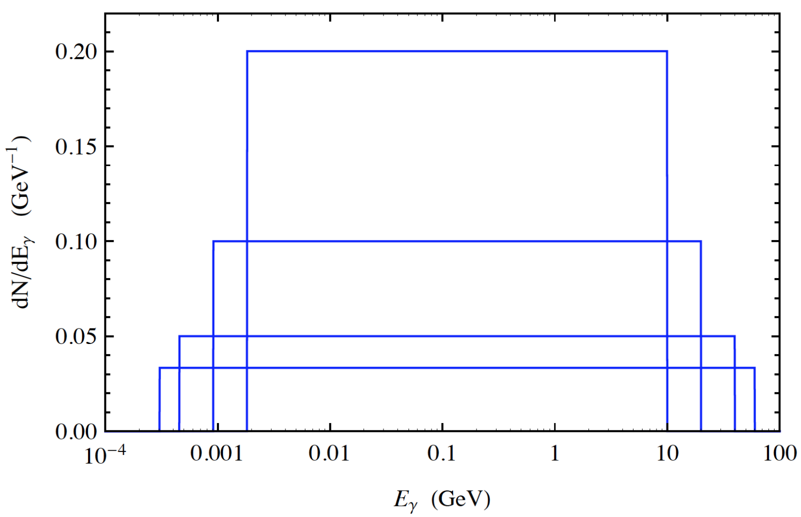
The mass m_{π° leaves its “imprint”

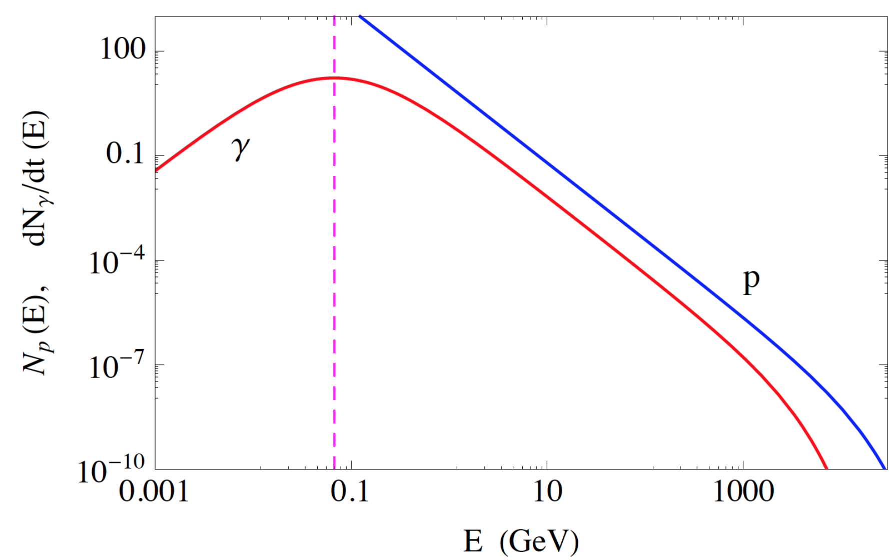
on the photon spectrum

$$E_{\gamma,\min} = E_\pi \, (1 - \beta_\pi)$$

$$E_{\gamma,\max} = E_\pi \, (1 + \beta_\pi)$$

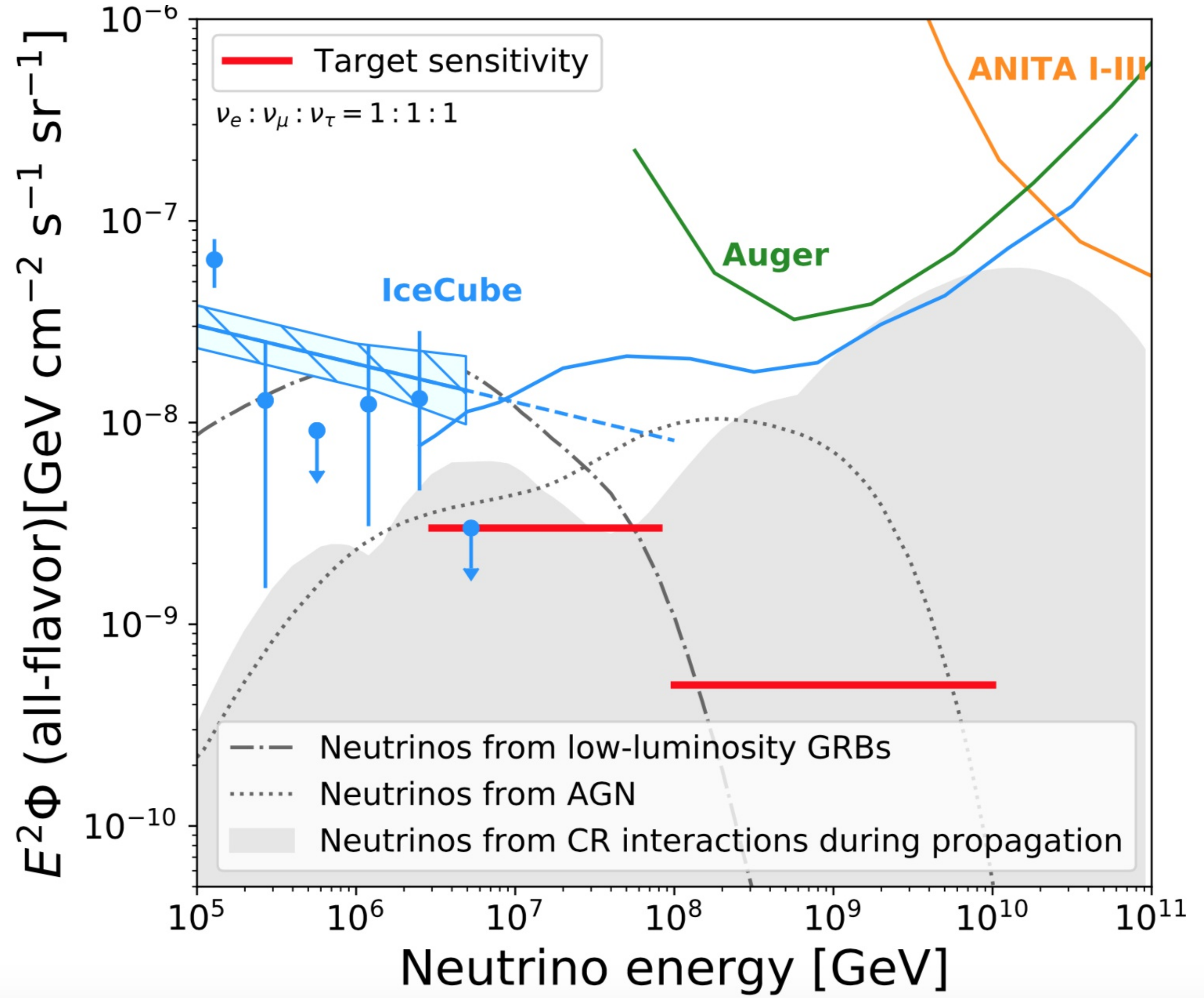
Spectrum symmetric around $E_\gamma = \dfrac{m_{\pi^\circ}}{2}$



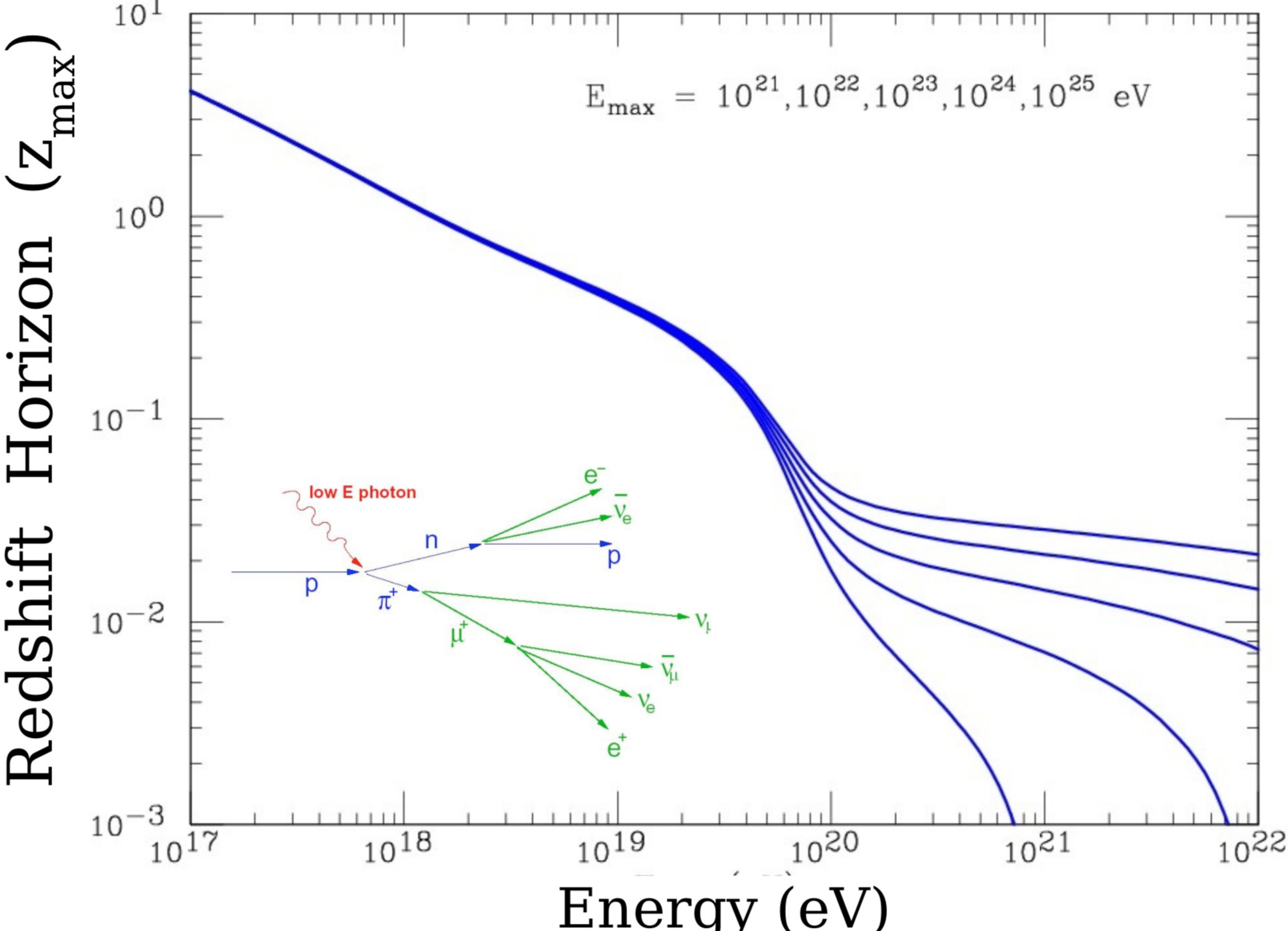


$$E_{\pi,\min}(E_\gamma) = E_\gamma + \frac{m_\pi^2}{4\,E_\gamma} = \frac{m_\pi}{2} \left[\frac{2E_\gamma}{m_\pi} + \frac{m_\pi}{2\,E_\gamma}\right]$$

Very strong case to develop Neutrino telescopes beyond the "beaded string - km3 concept" aiming at the EeV range [Radio the technique with this potential]



"Horizon" (in time) for protons



Conclusions:

- Multi-messenger studies of the High Energy Universe is a vibrant exciting field that explore the most "extreme environment" in the present universe [where *Gravity and Particle Physics meet]*.

- High Energy Neutrino Astronomy is a crucial element in this field. The current detectors are barely "scratching the surface" [but this is already exciting]

- "One order of magnitude more data" in the 30 TeV – 10 PeV energy range can be of enormous help in clarifying the "puzzles" about the IceCube signal [and very likley solidy identify the main source(s)]
  ... *and provide very interesting Particle Physics studies*

- The EeV range strongly suggests the development of new detector concepts