Very-high-energy gamma-rays and neutrinos: the search for PeVatrons

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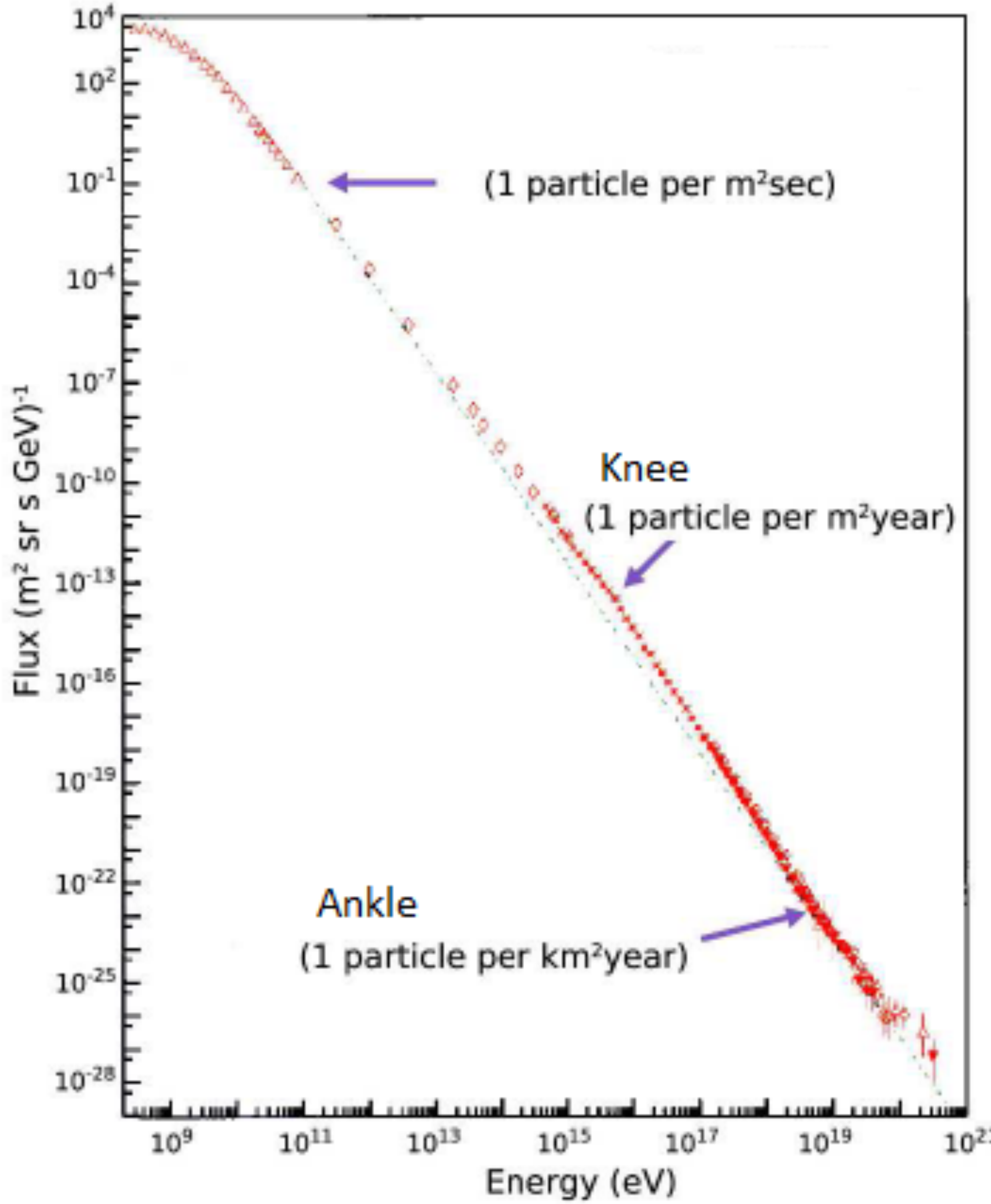
20/04/2017

TRIESTE - IFAE 2017

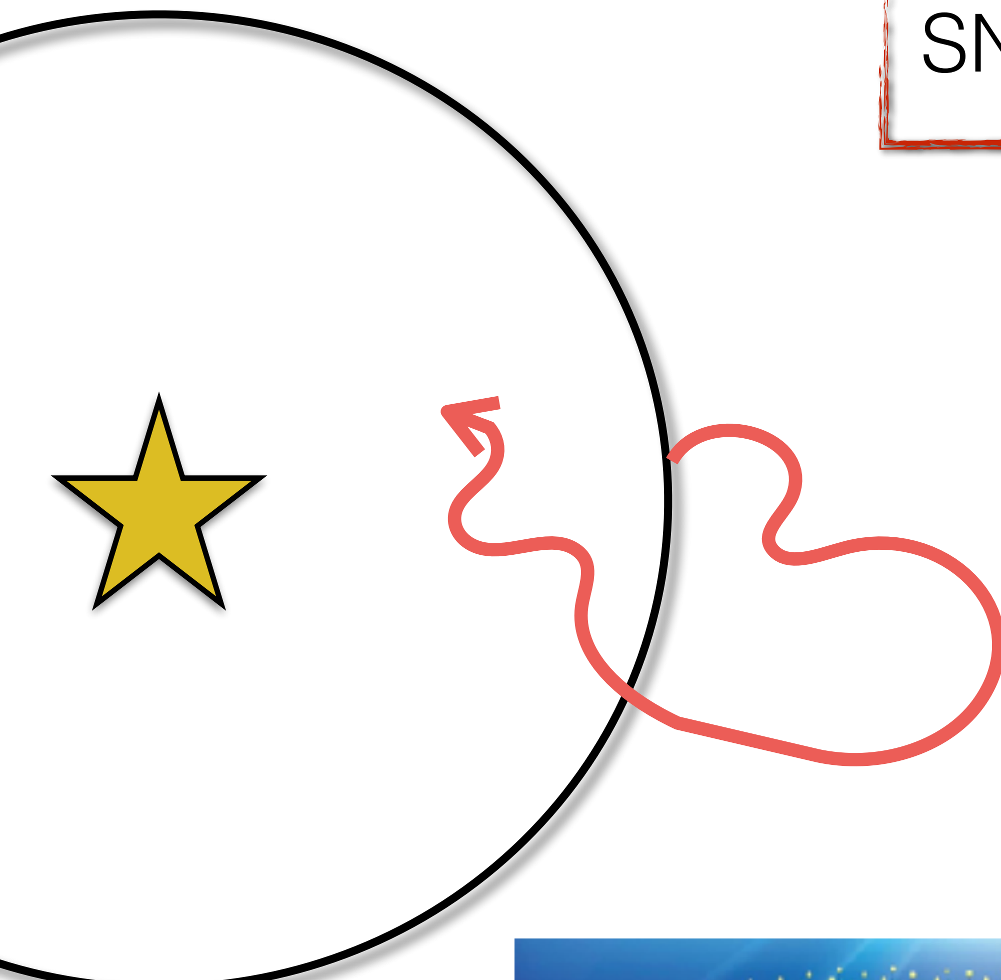
How much do we know about CRs?



The SNR paradigm for the origin of CRs

Enough power in SN explosions to explain CRs

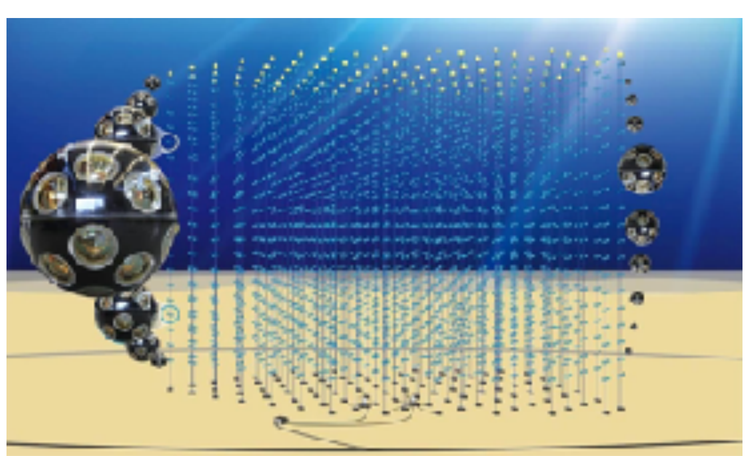
SNR shocks -> acceleration sites

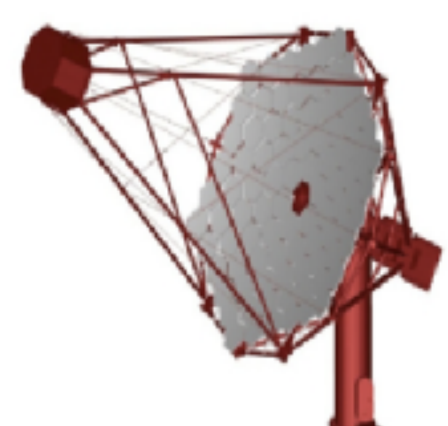


Diffusive Shock Acceleration

pp interaction -> γ-rays and ν

Cherenkov telescopes



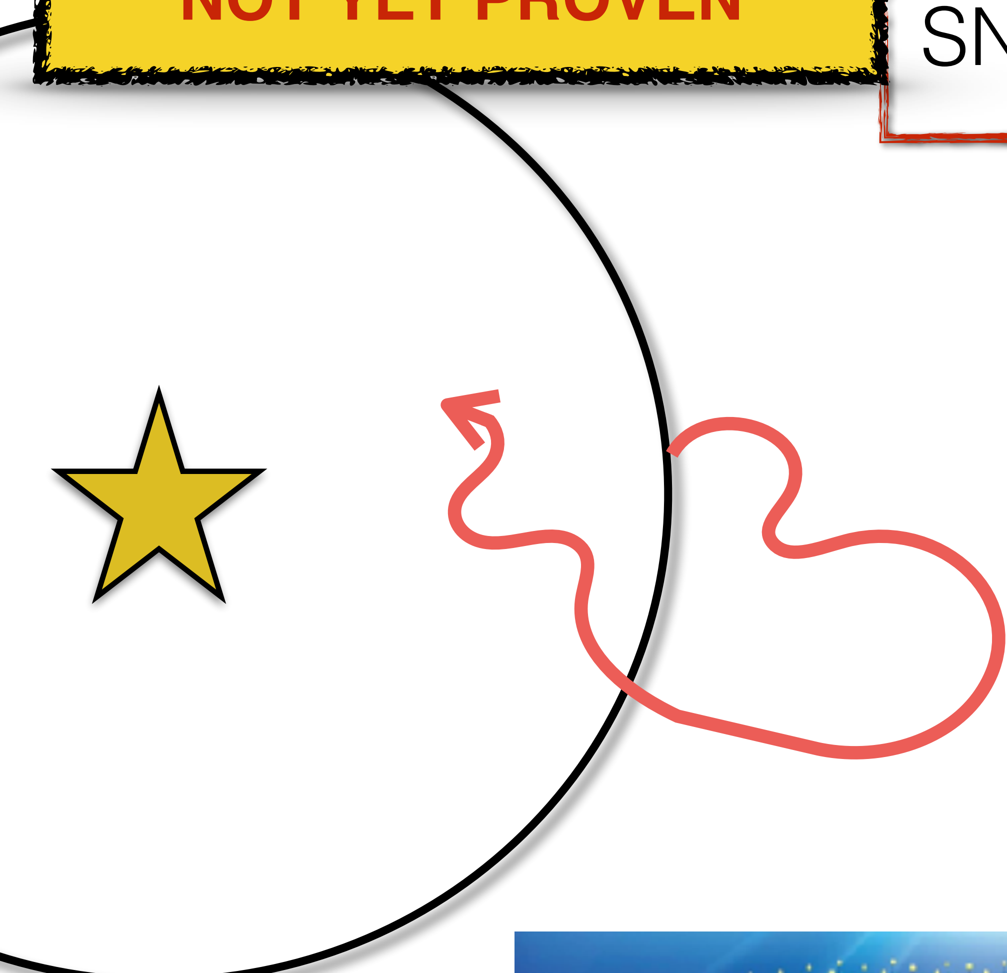


The SNR paradigm for the origin of CRs

Enough power in SN explosions to explain CRs

NOT YET PROVEN

SNR shocks -> acceleration sites



Diffusive Shock Acceleration

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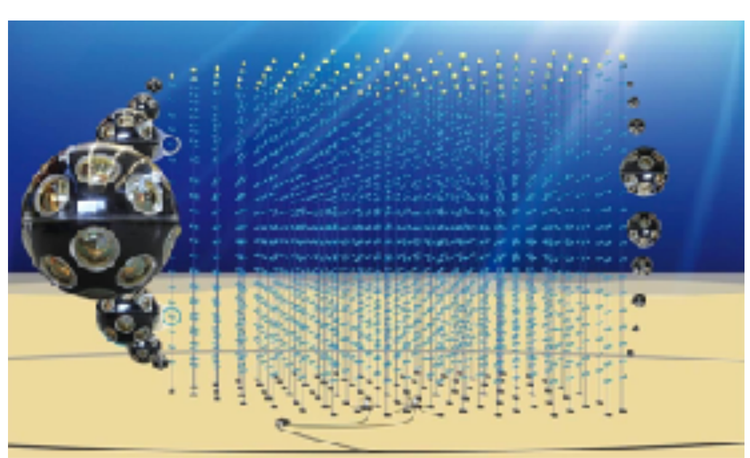
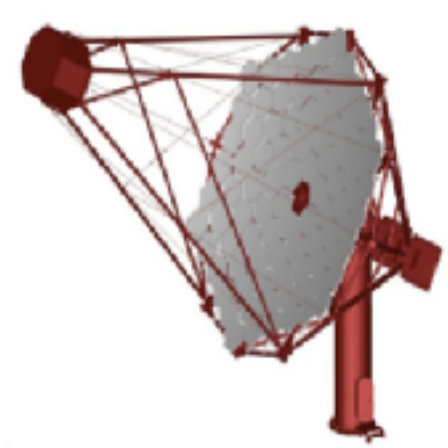
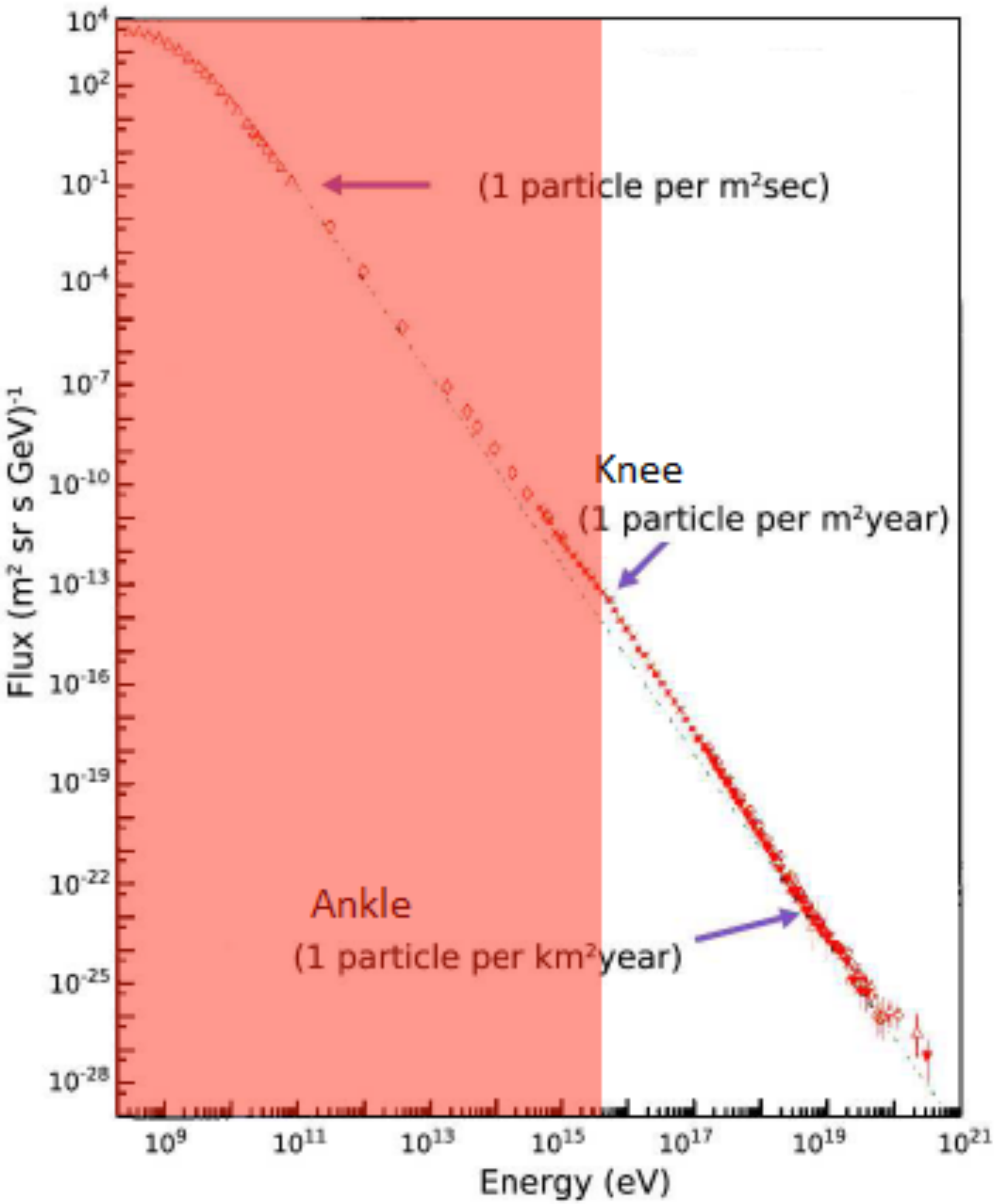






Are SNRs proton PeVatrons?

Hillas criterium

$$E_{max} \simeq v_s R B$$

shock speed — **radius** — **magnetic field**

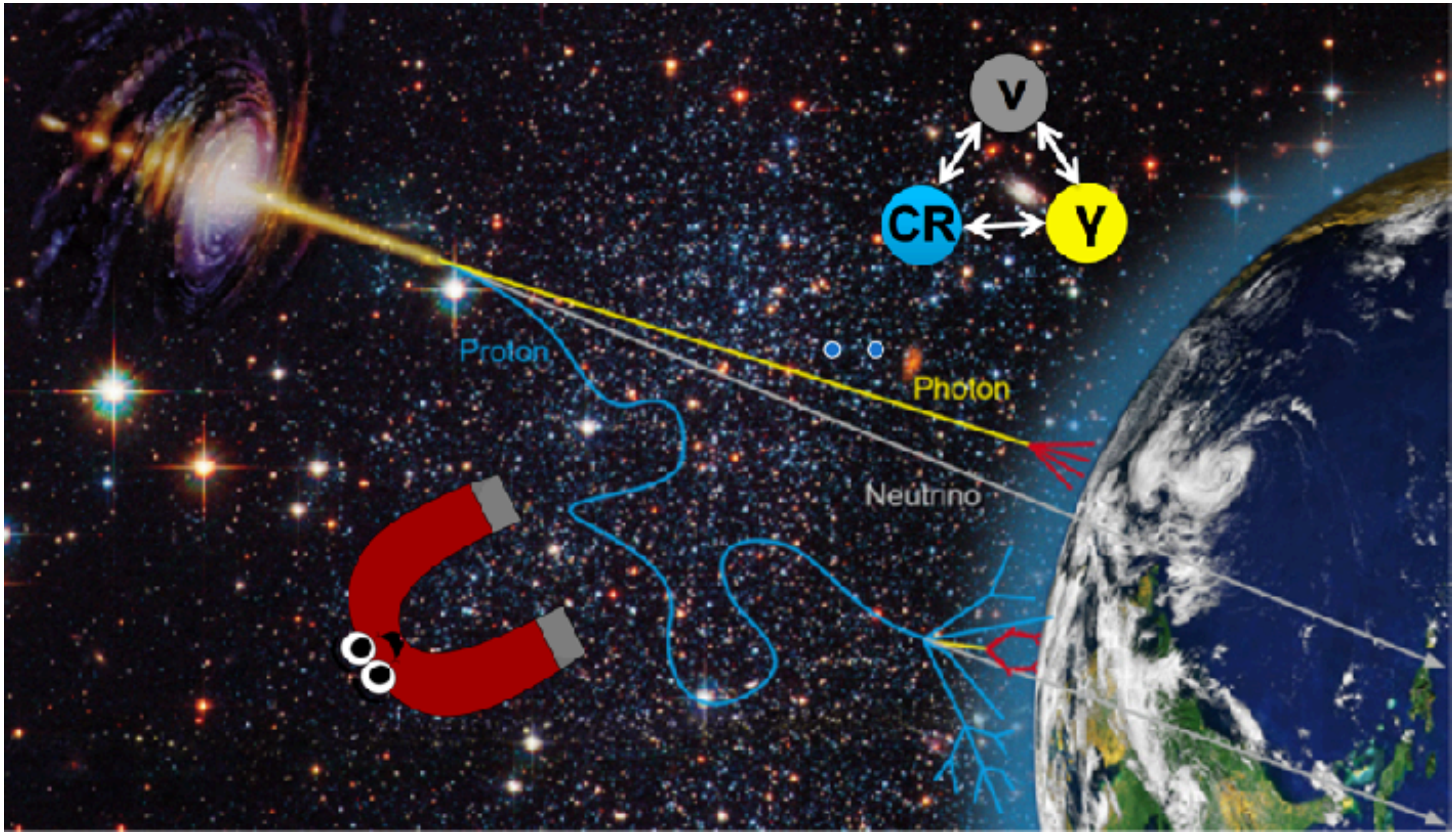
$$E_{max} \simeq 1 \underbrace{\left(\frac{v_s}{10^3 Km/s}\right)}_{3} \underbrace{\left(\frac{R}{pc}\right)}_{3} \underbrace{\left(\frac{B}{\mu G}\right)}_{10} TeV$$

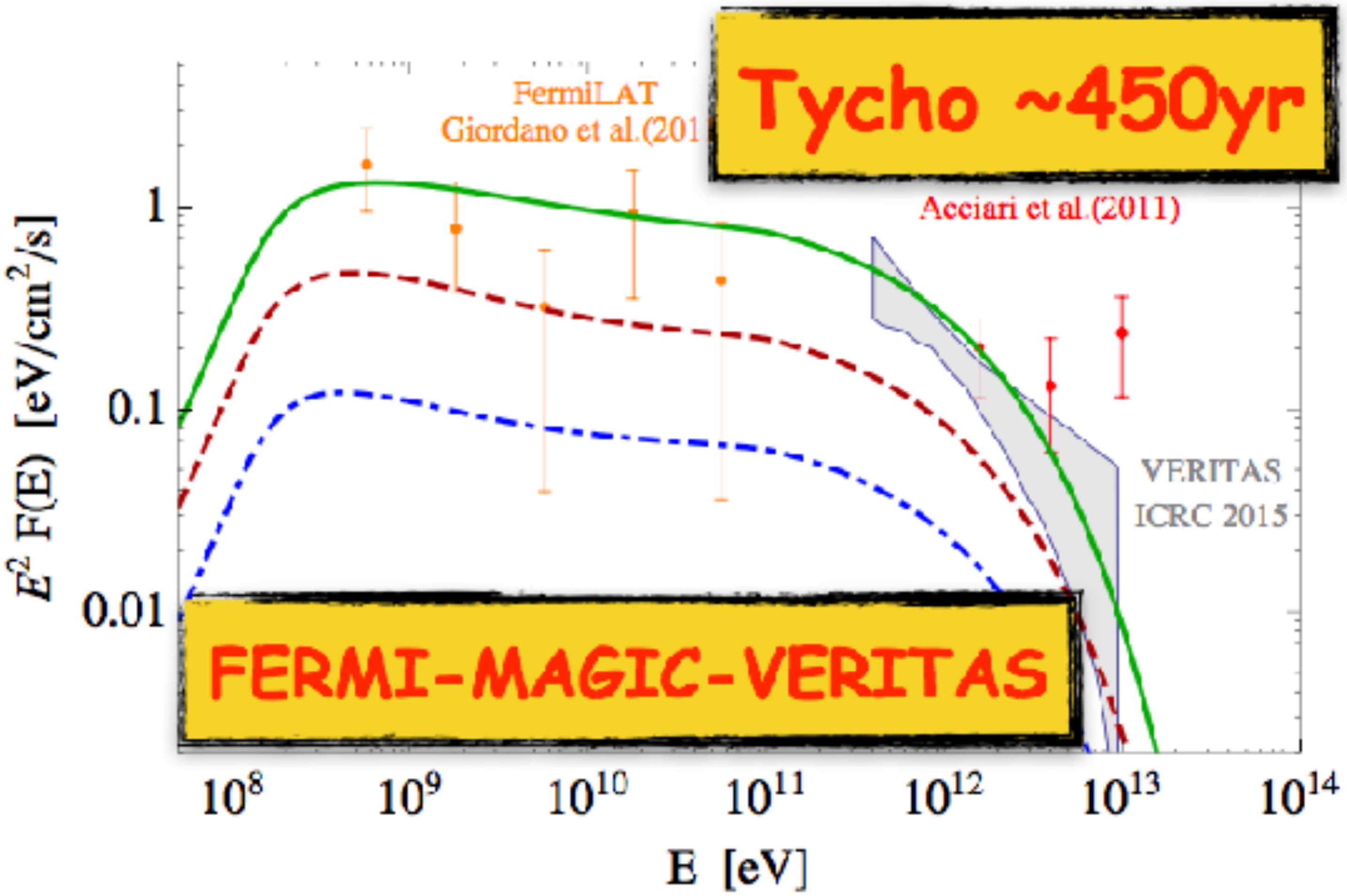
$$\boxed{E_{max} \simeq 100\,\mathrm{TeV}}$$

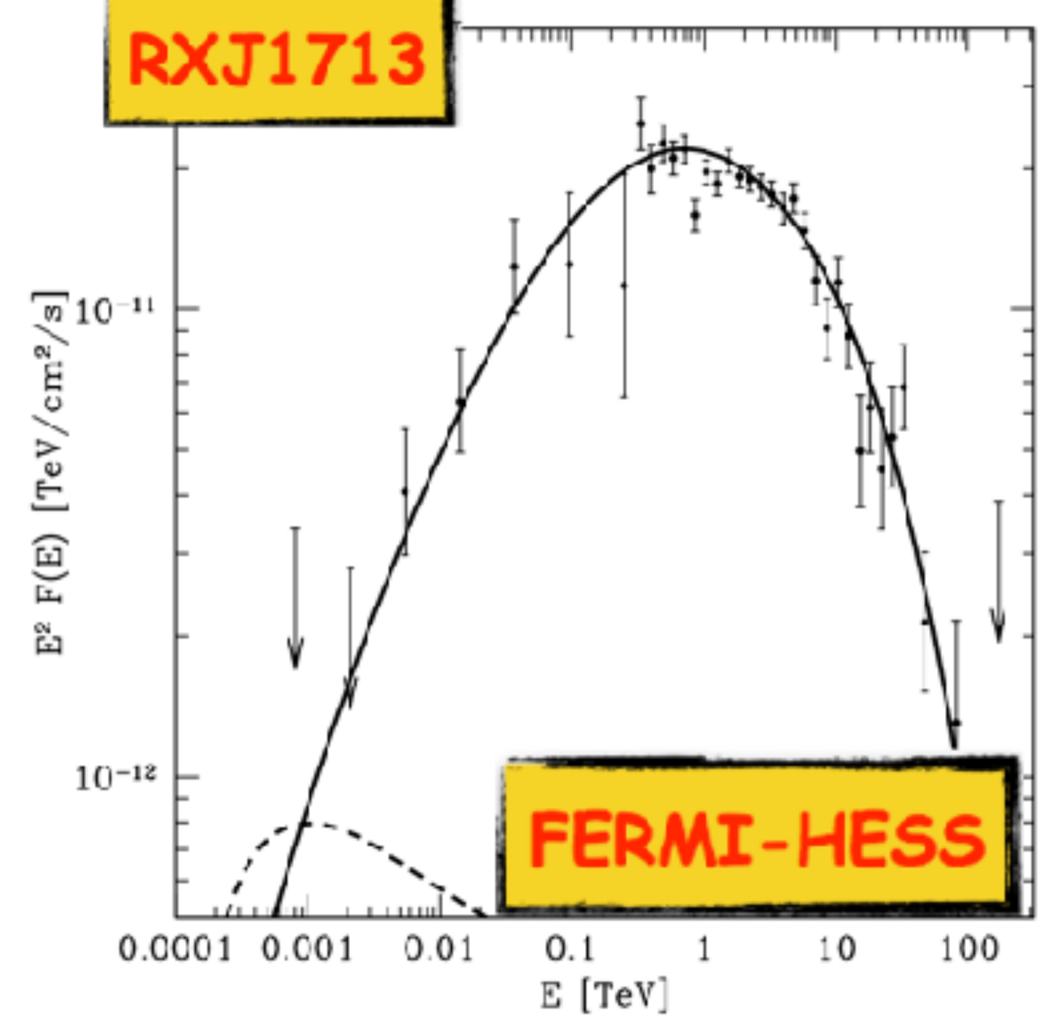
The multi-messenger search for PeVatrons

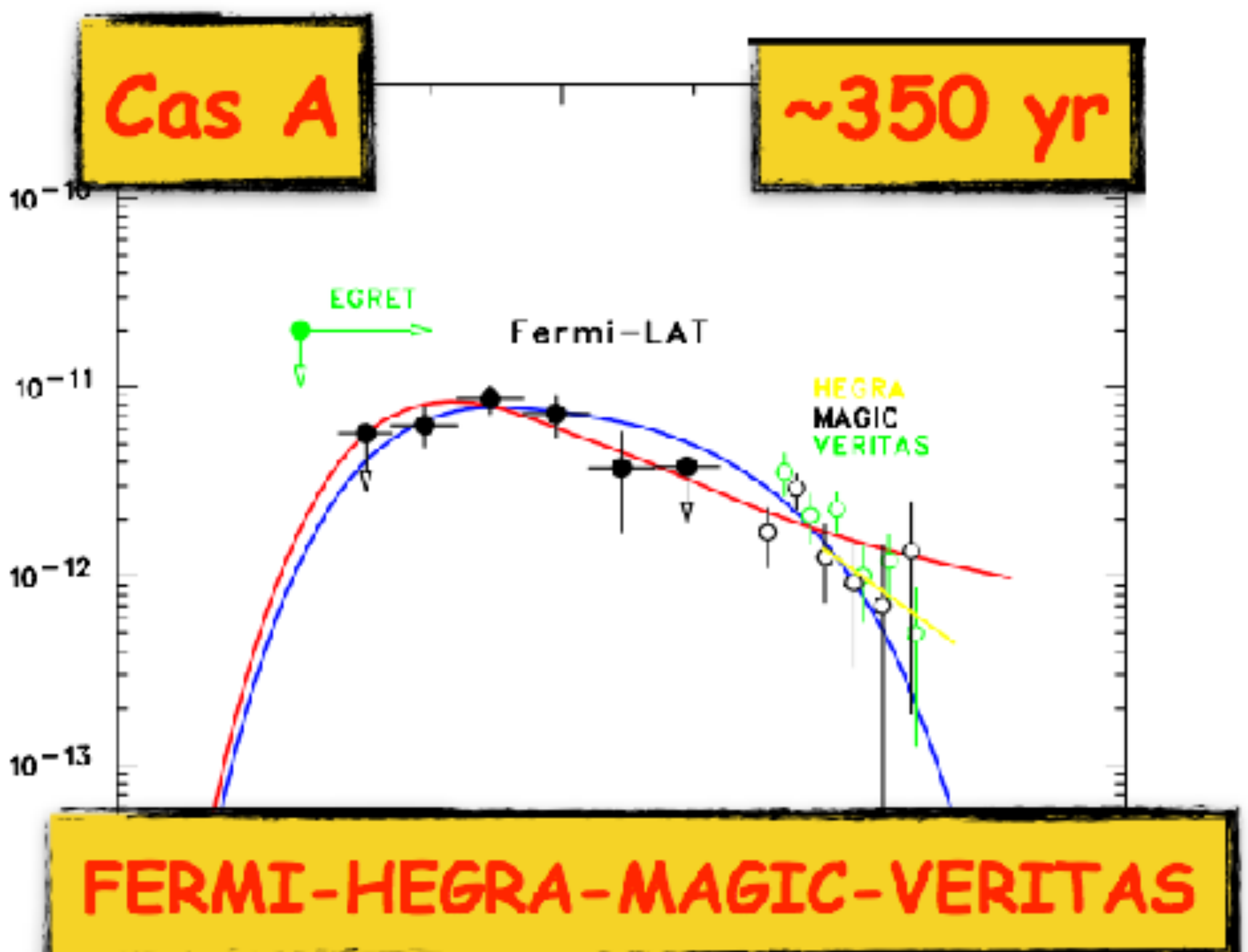
<u>Observational signature</u>

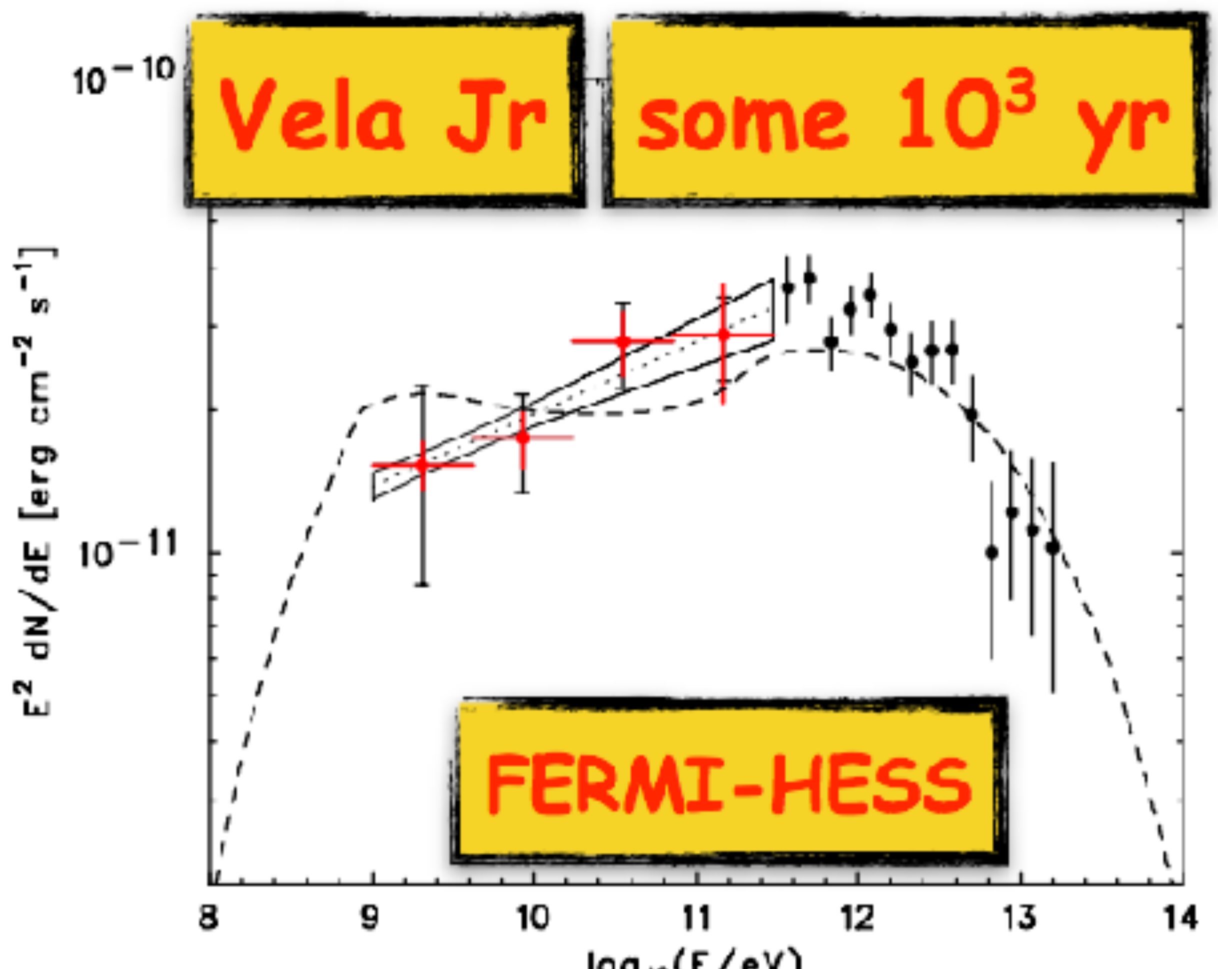
γ-ray and/or ν emission extending unattenuated in the multi-TeV domain:
$E_P = 1$ PeV -> $E_\gamma = 100$ TeV and $E_\nu = 50$ TeV

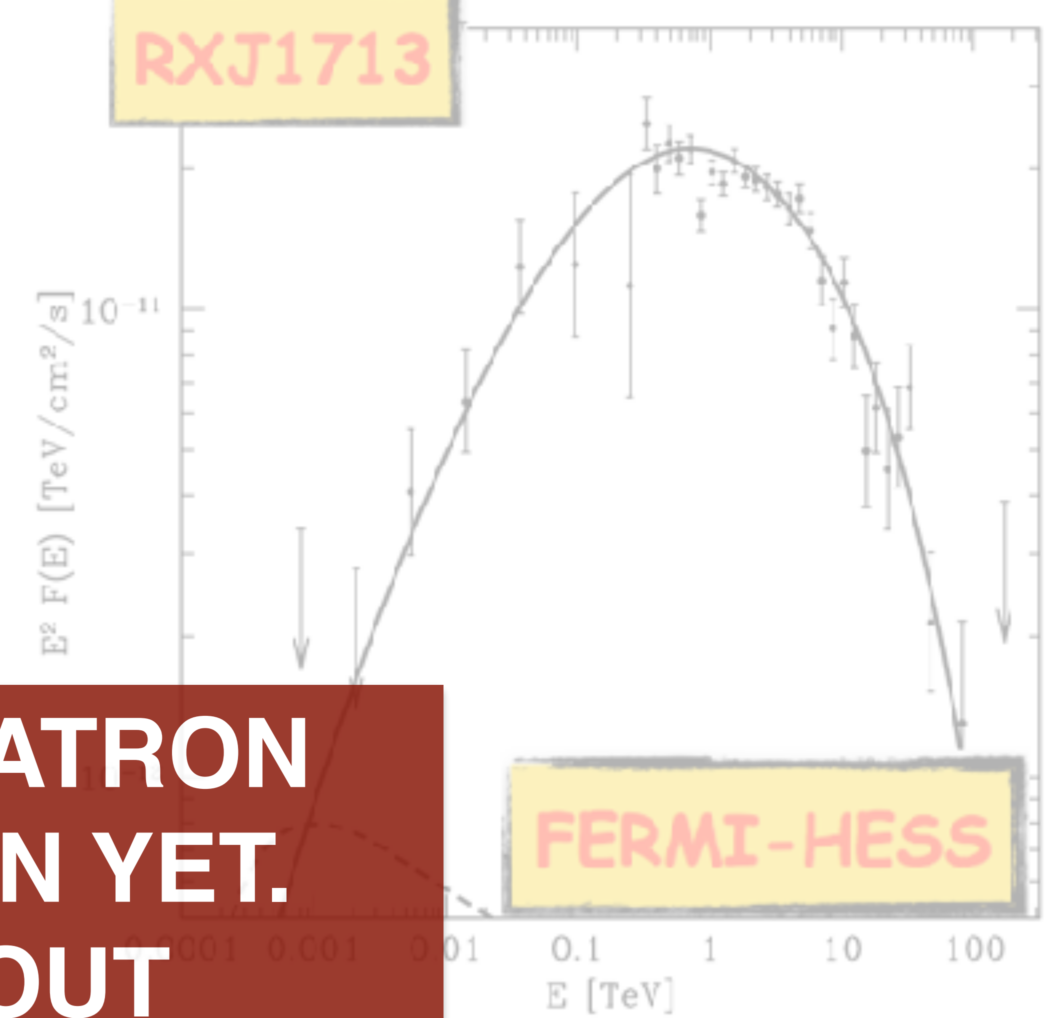



Tycho ~450yr
FermiLAT
Giordano et al.(201
Acciari et al.(2011)
VERITAS
ICRC 2015
FERMI-MAGIC-VERITAS
E^2 F(E) [eV/cm^2/s]
E [eV]

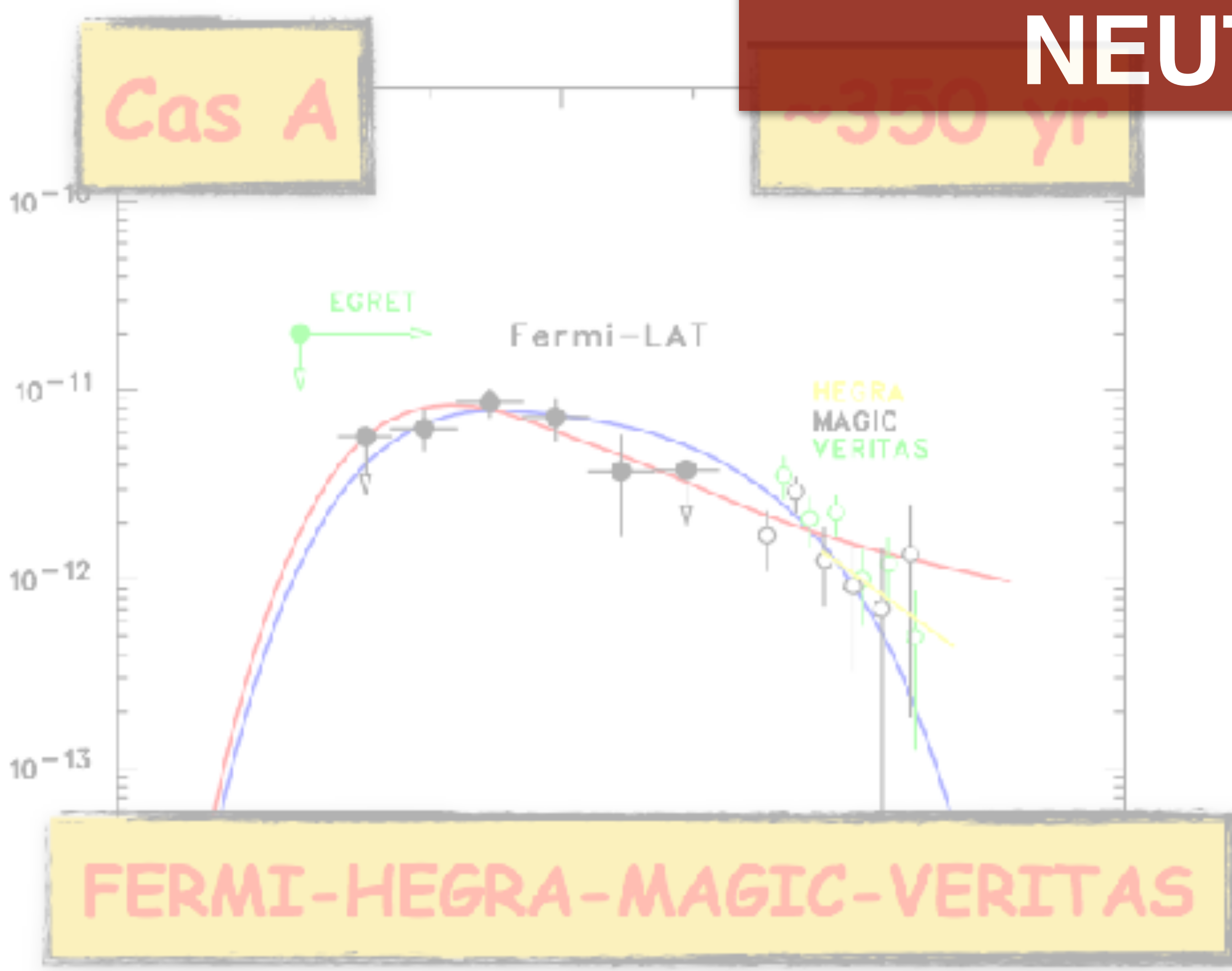

RXJ1713
FERMI-HESS
E^2 F(E) [TeV/cm^2/s]
E [TeV]

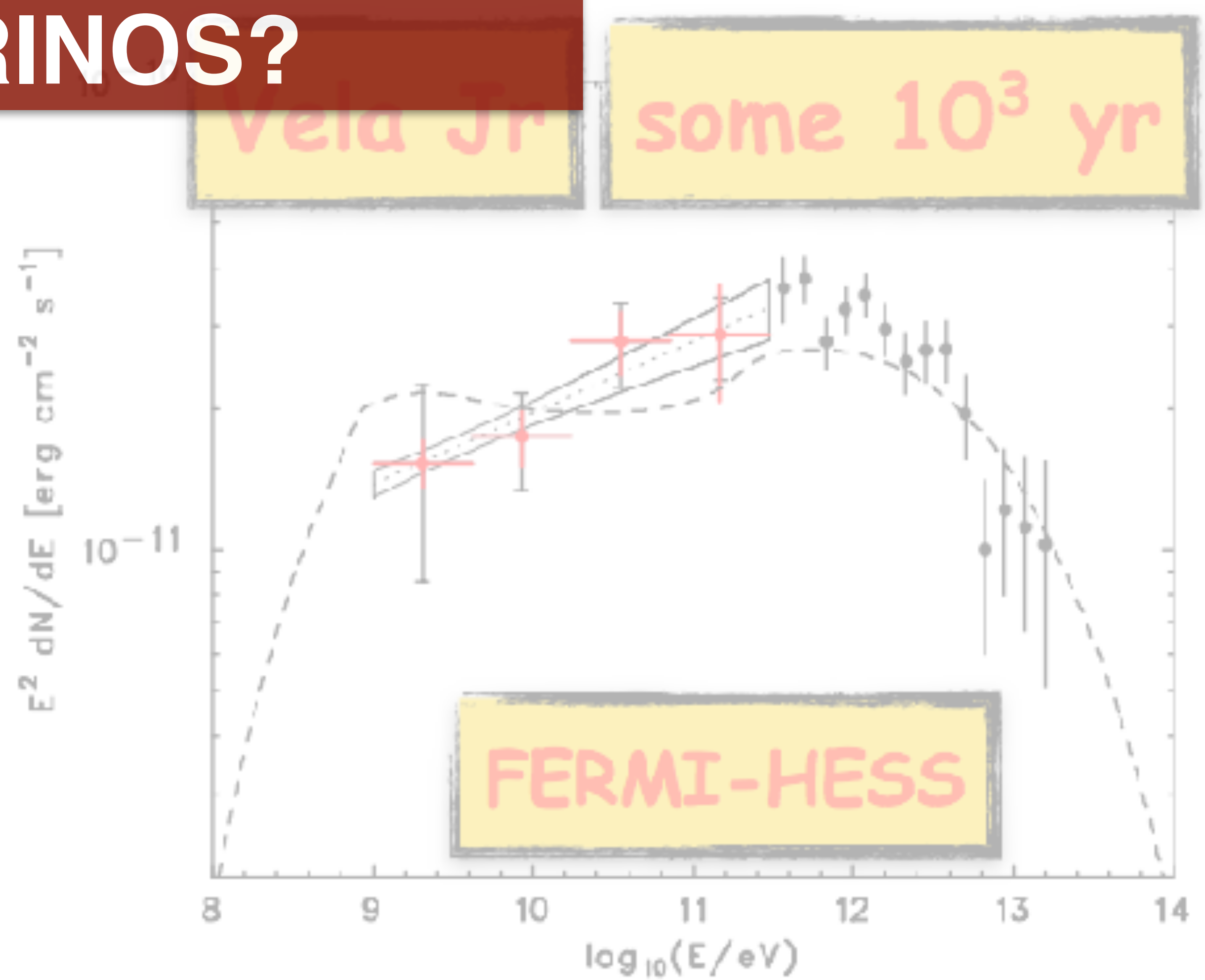

Cas A
~350 yr
EGRET
Fermi-LAT
HEGRA
MAGIC
VERITAS
FERMI-HEGRA-MAGIC-VERITAS


Vela Jr
some 10^3 yr
FERMI-HESS
E^2 dN/dE [erg cm^{-2} s^{-1}]
log$_{10}$(E/eV)

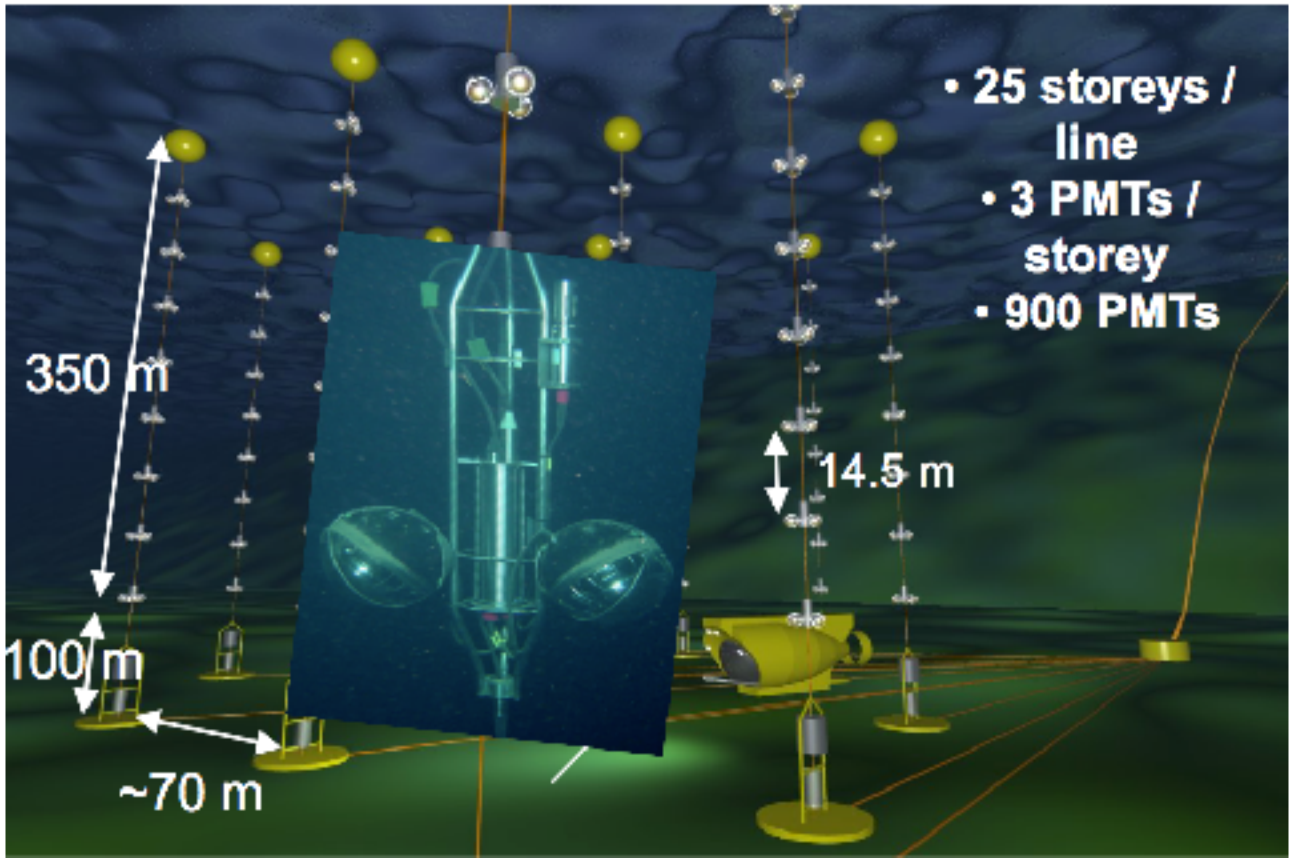


NO SNR-PEVATRON ASSOCIATION YET. WHAT ABOUT NEUTRINOS?

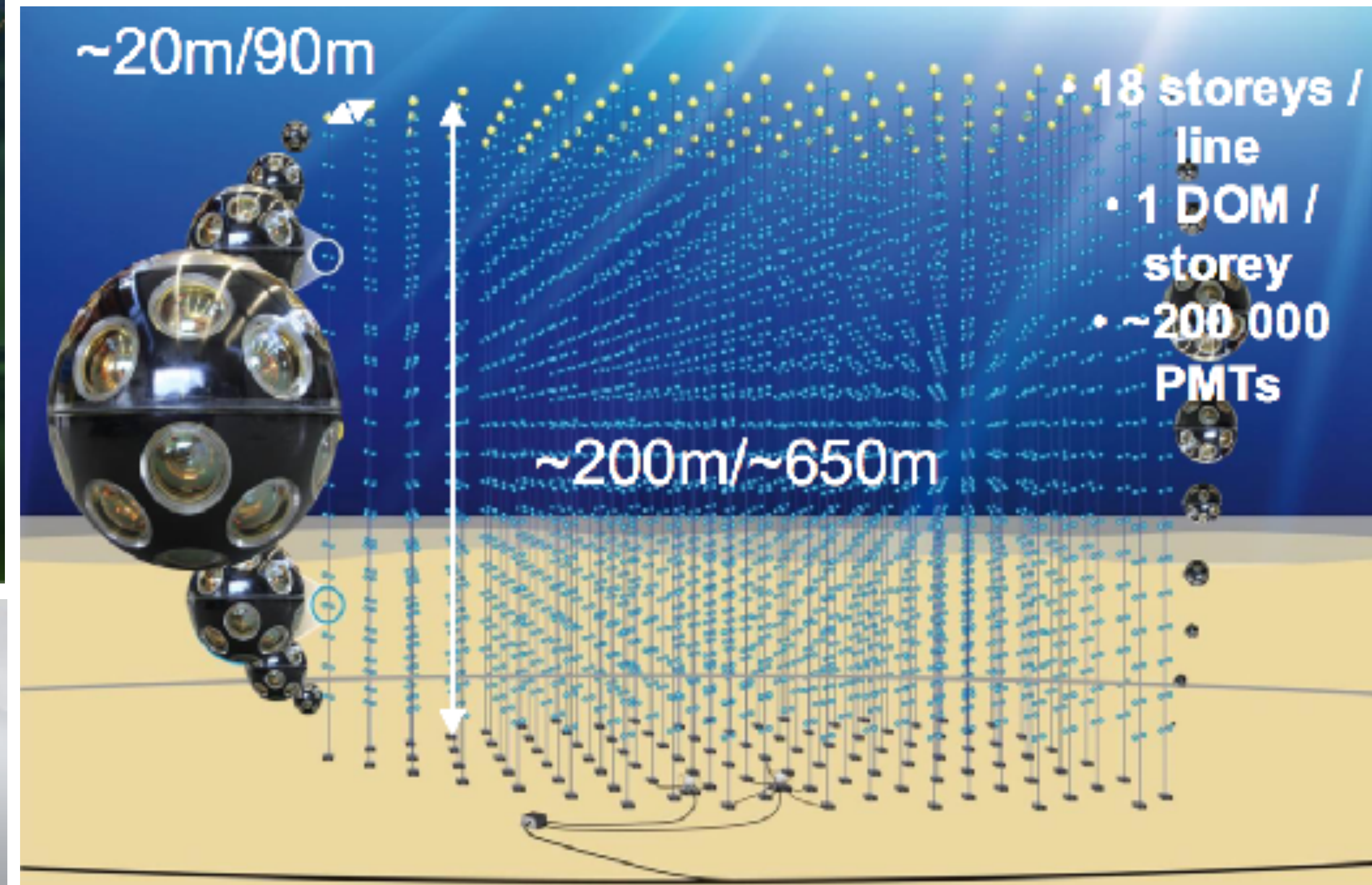




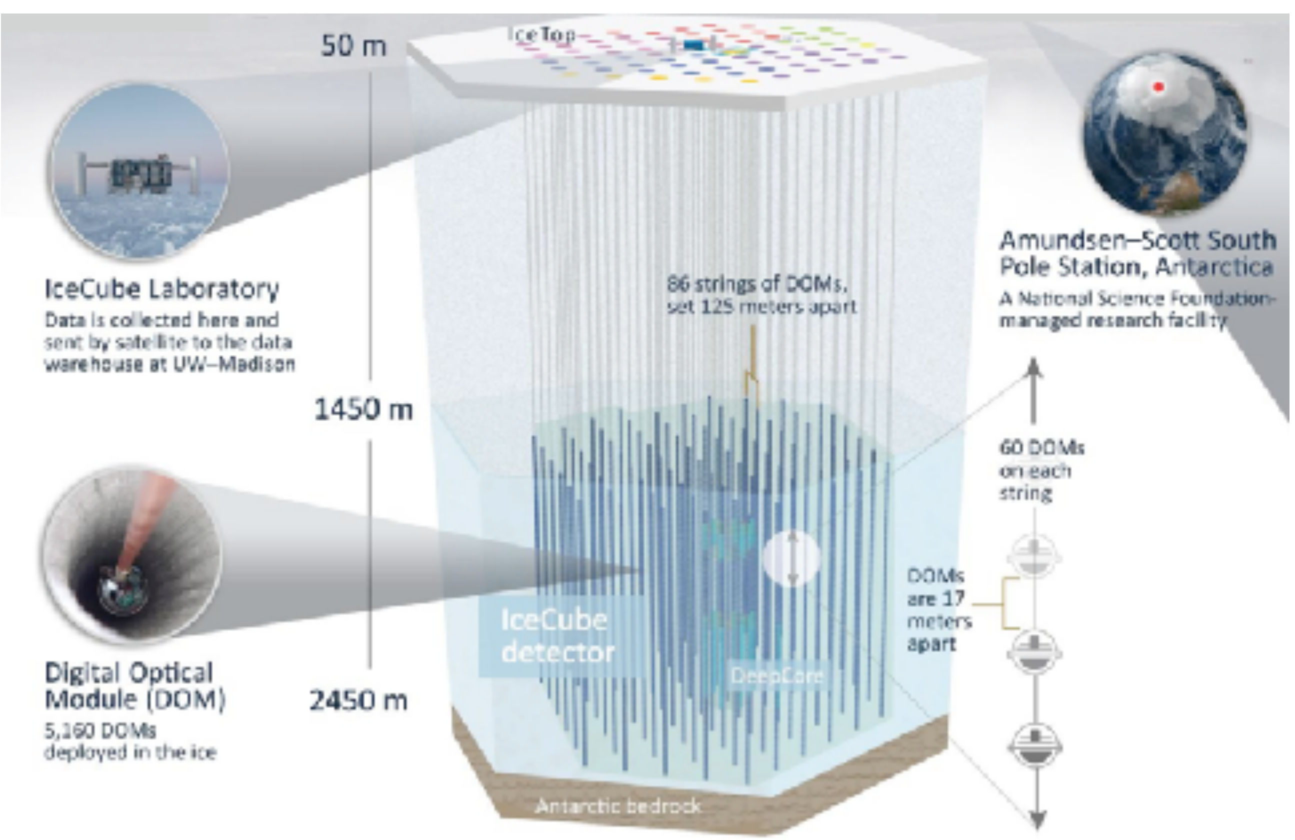
Under operation neutrino telescopes



ANTARES completed since 2008
0.01 Km^3
http://antares.in2p3.fr



Under construction KM3NeT
few Km^3
http://www.km3net.org

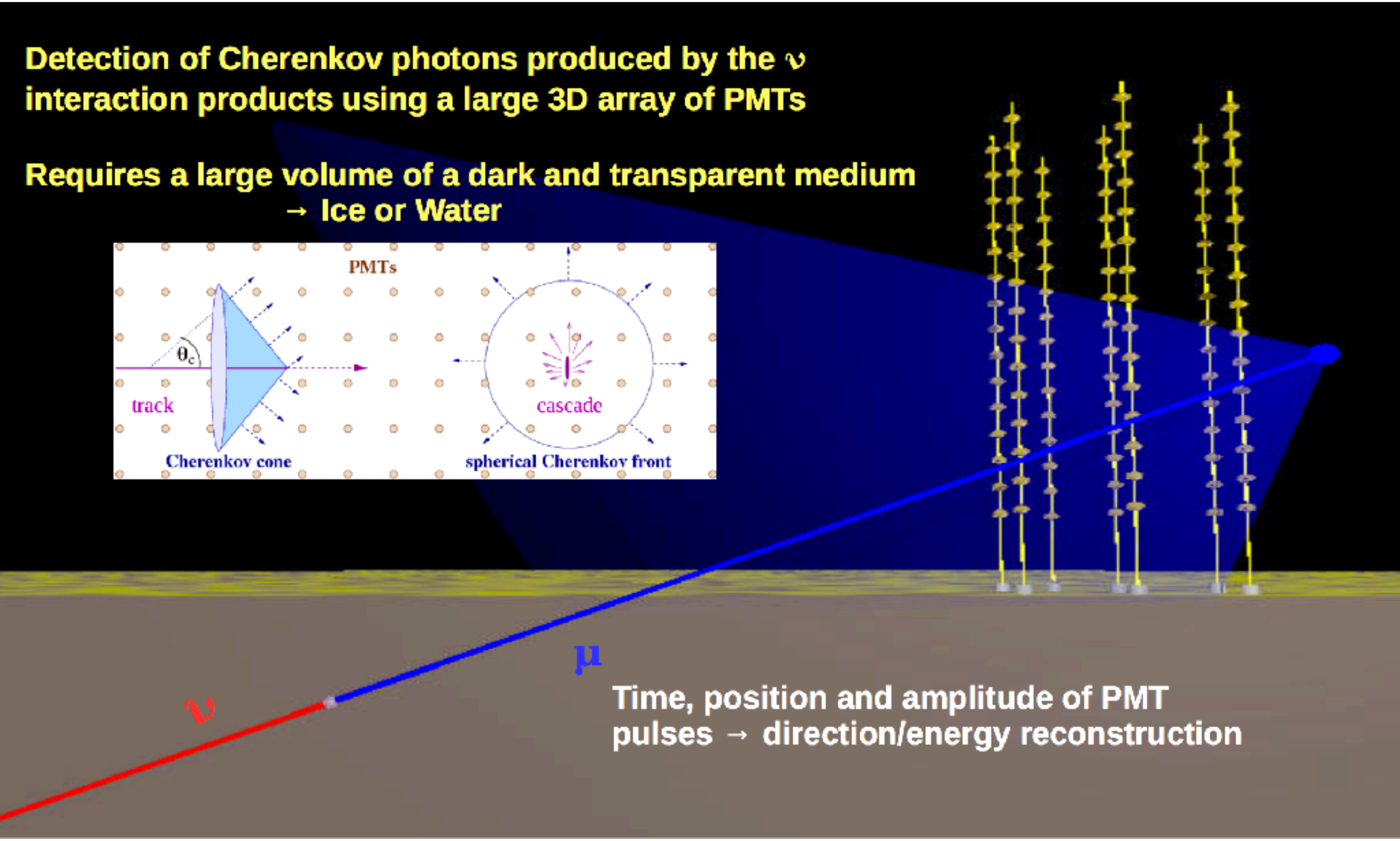


IceCube completed since 2010
1 Km^3
https://icecube.wisc.edu

How do we detect neutrinos

Detection of Cherenkov photons produced by the ν interaction products using a large 3D array of PMTs

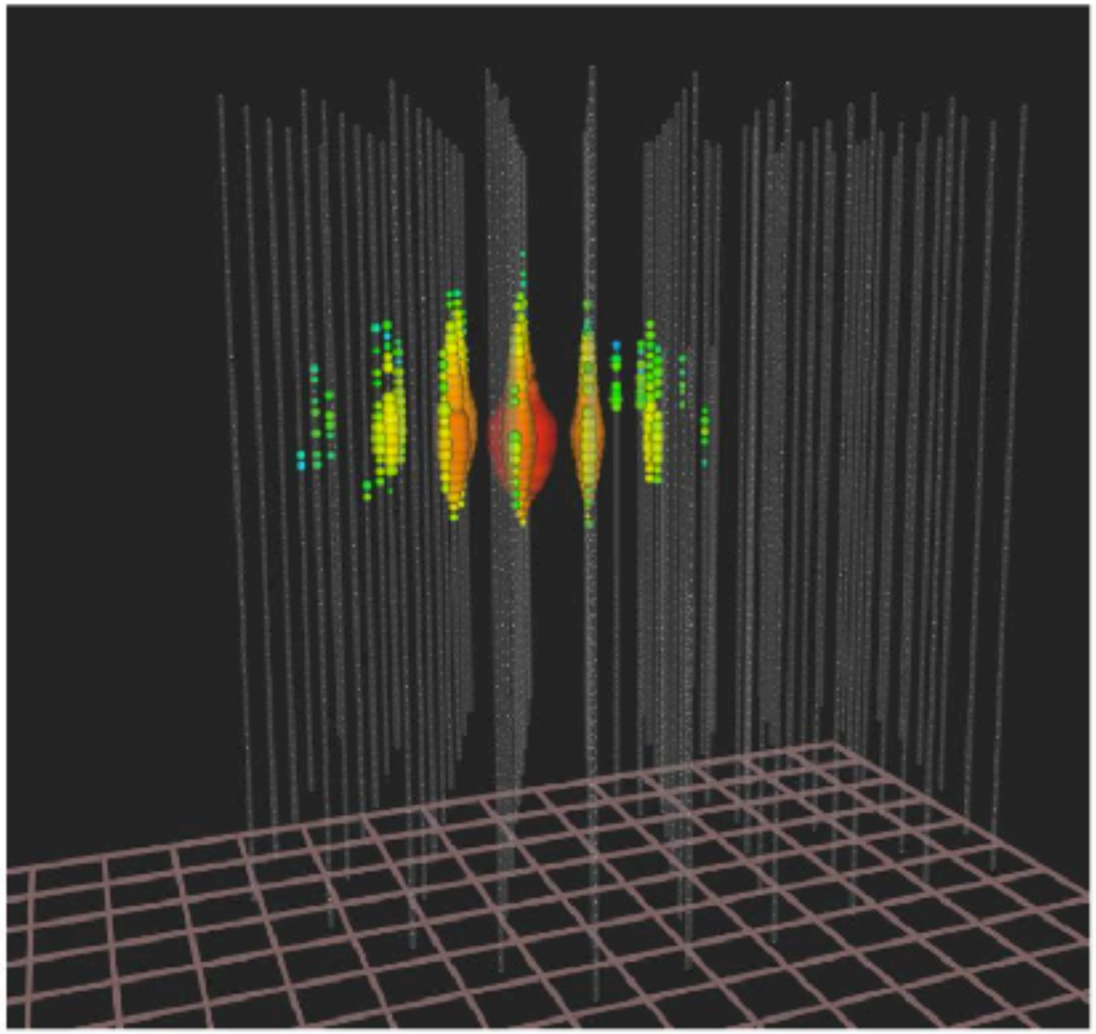
Requires a large volume of a dark and transparent medium → Ice or Water



Time, position and amplitude of PMT pulses → direction/energy reconstruction

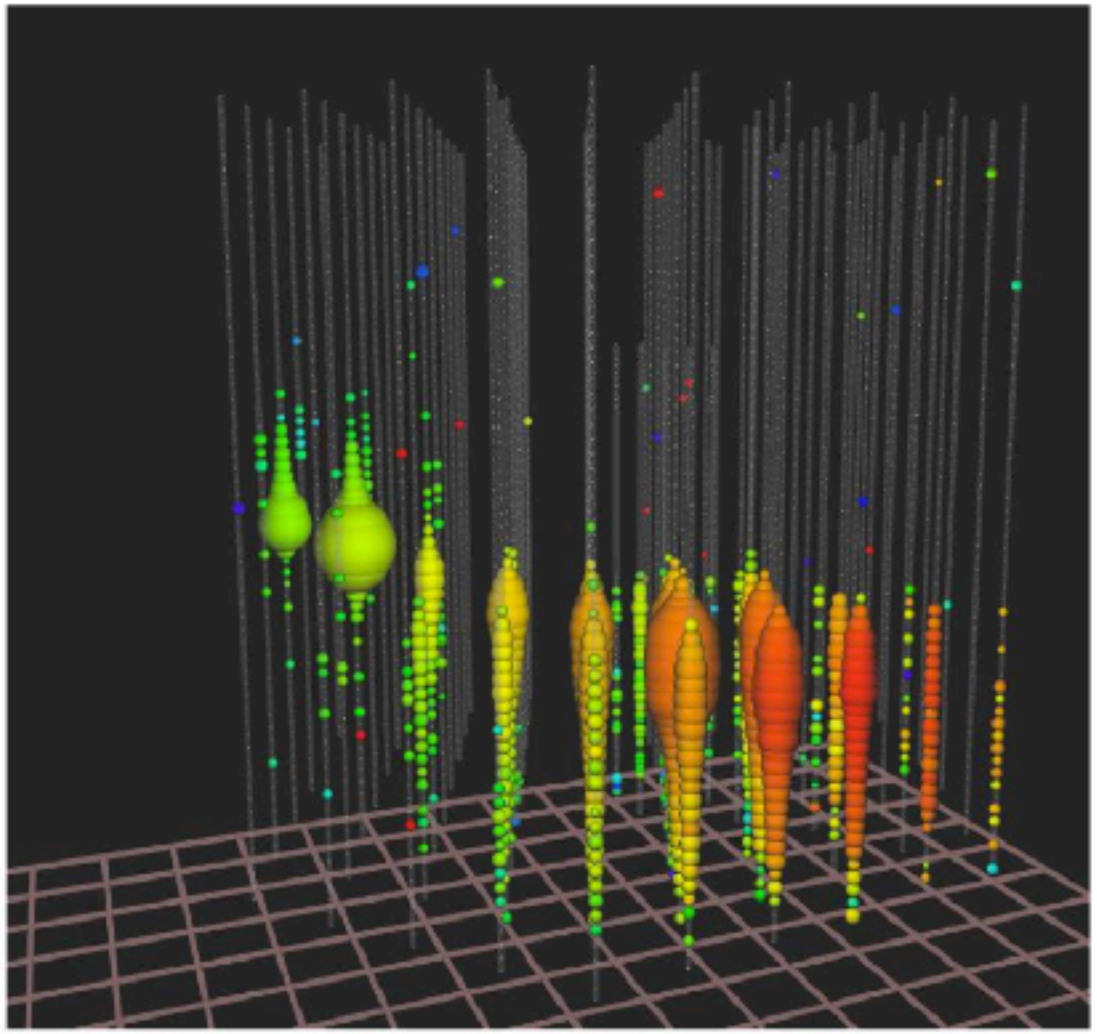
Neutrino event topology

Isolated neutrinos interacting in the detector



Calorimetry + all flavors

Up-going muon tracks



Astronomy: angular resolution

Neutrino event topology

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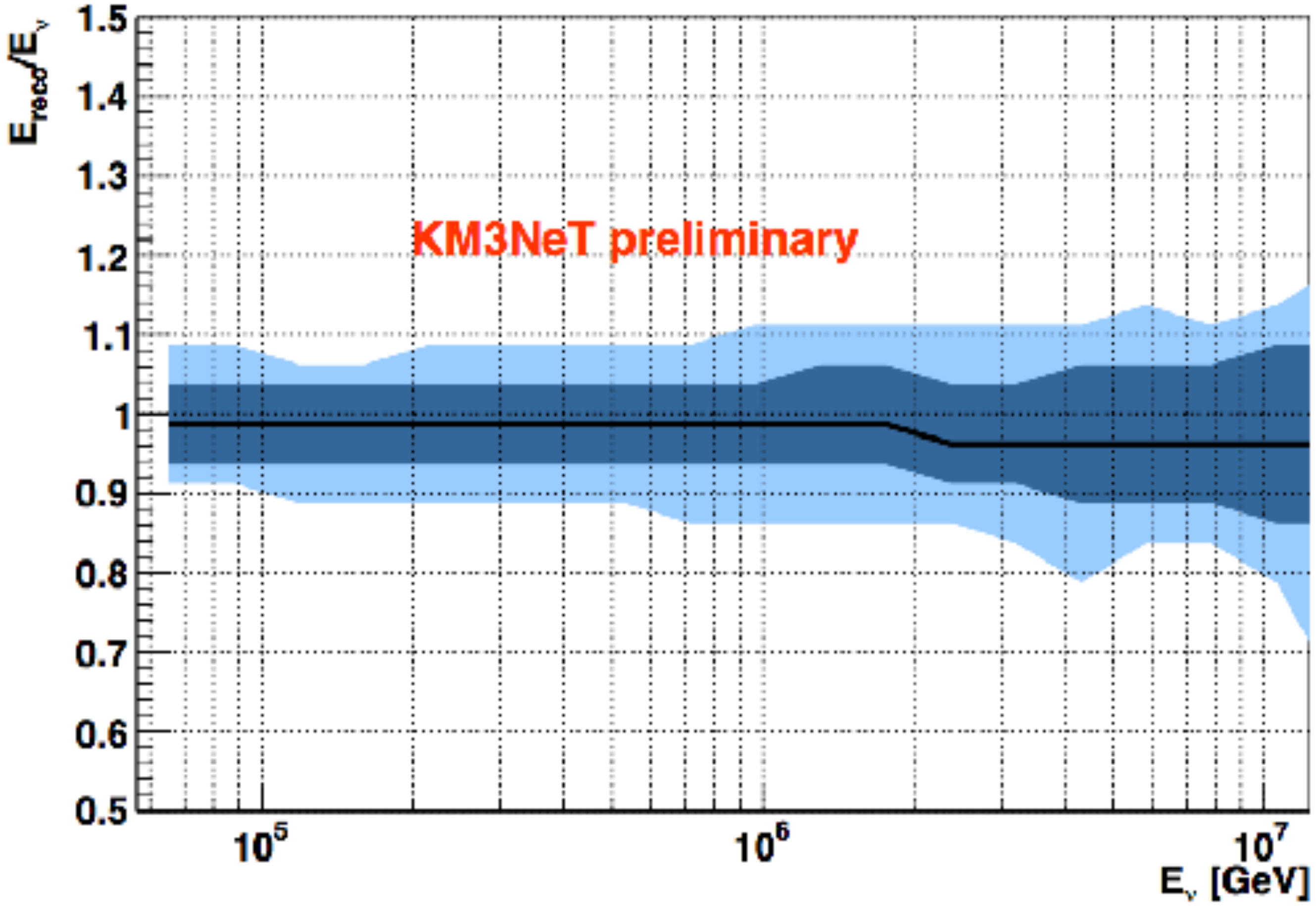

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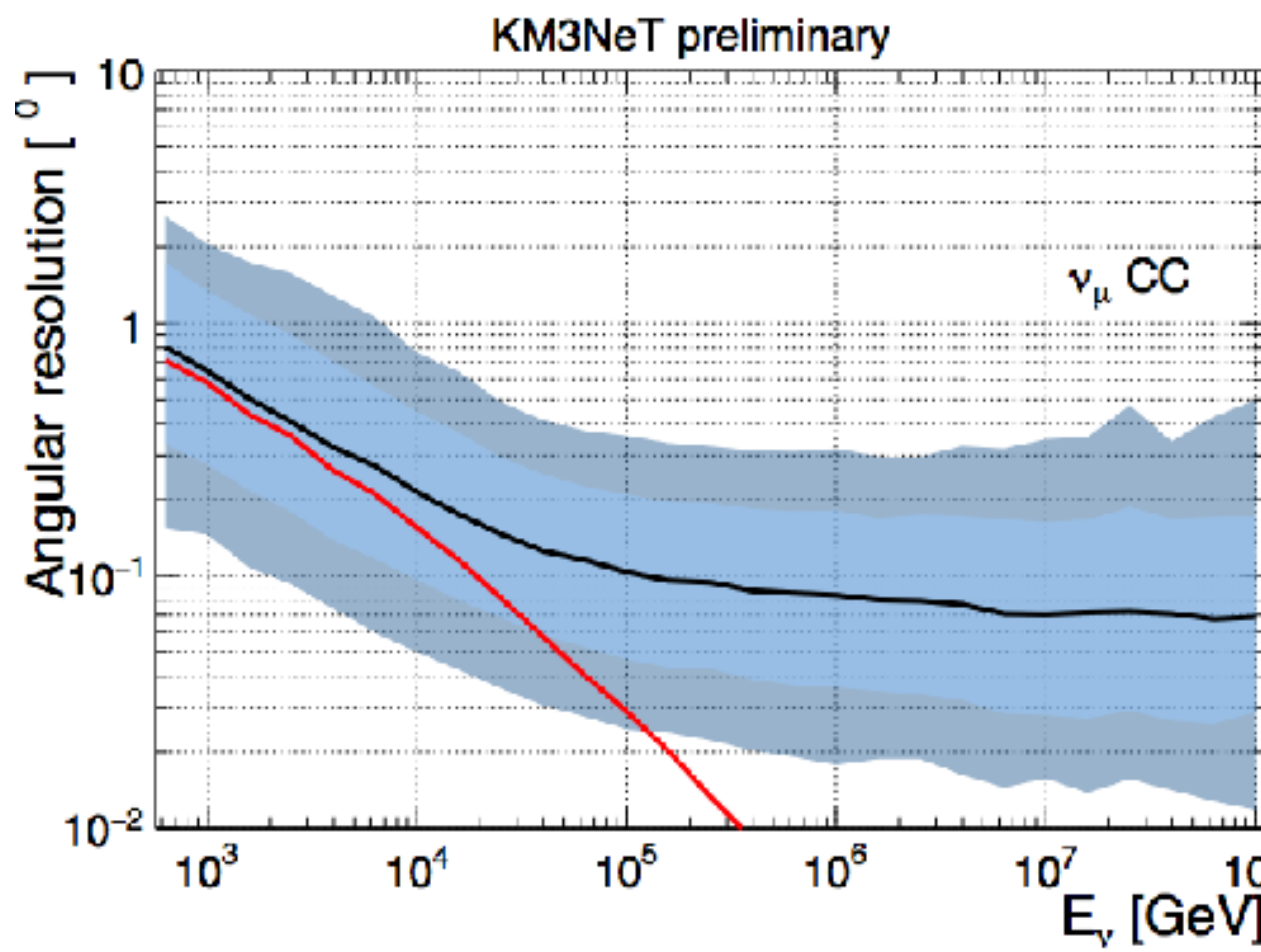
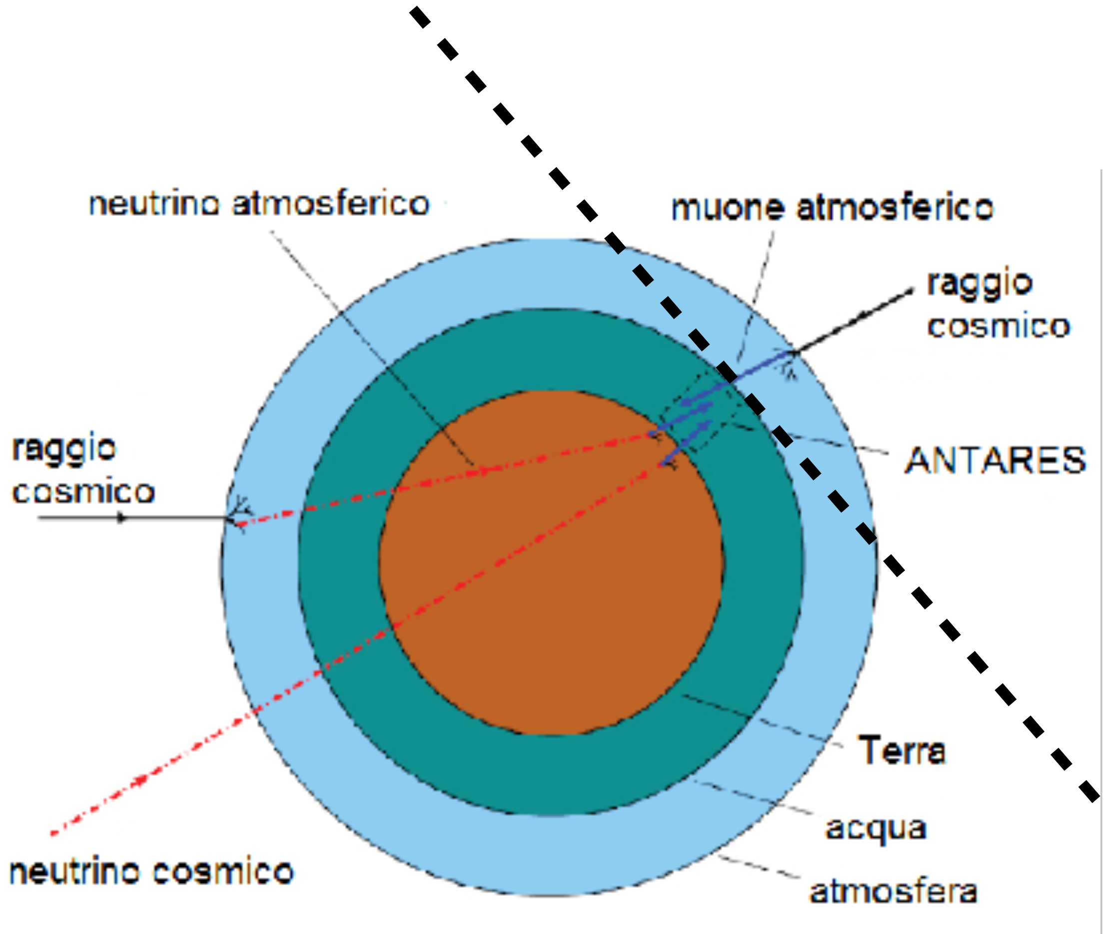
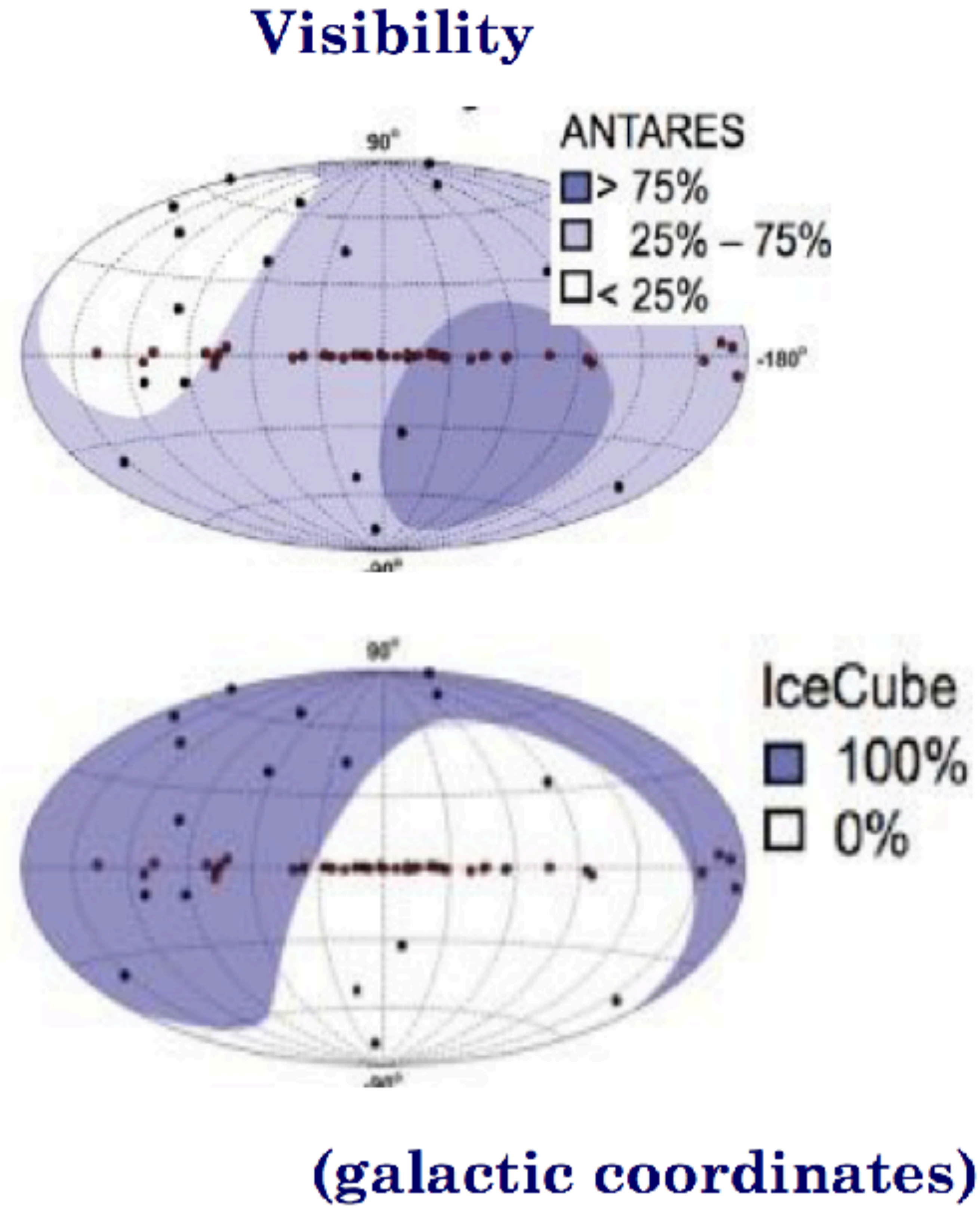


Astronomy: angular resolution

Adrian-Martinez et al. [KM3NeT Coll.], J. Phys. G: Nucl. Part. Phys. 43 (2016)

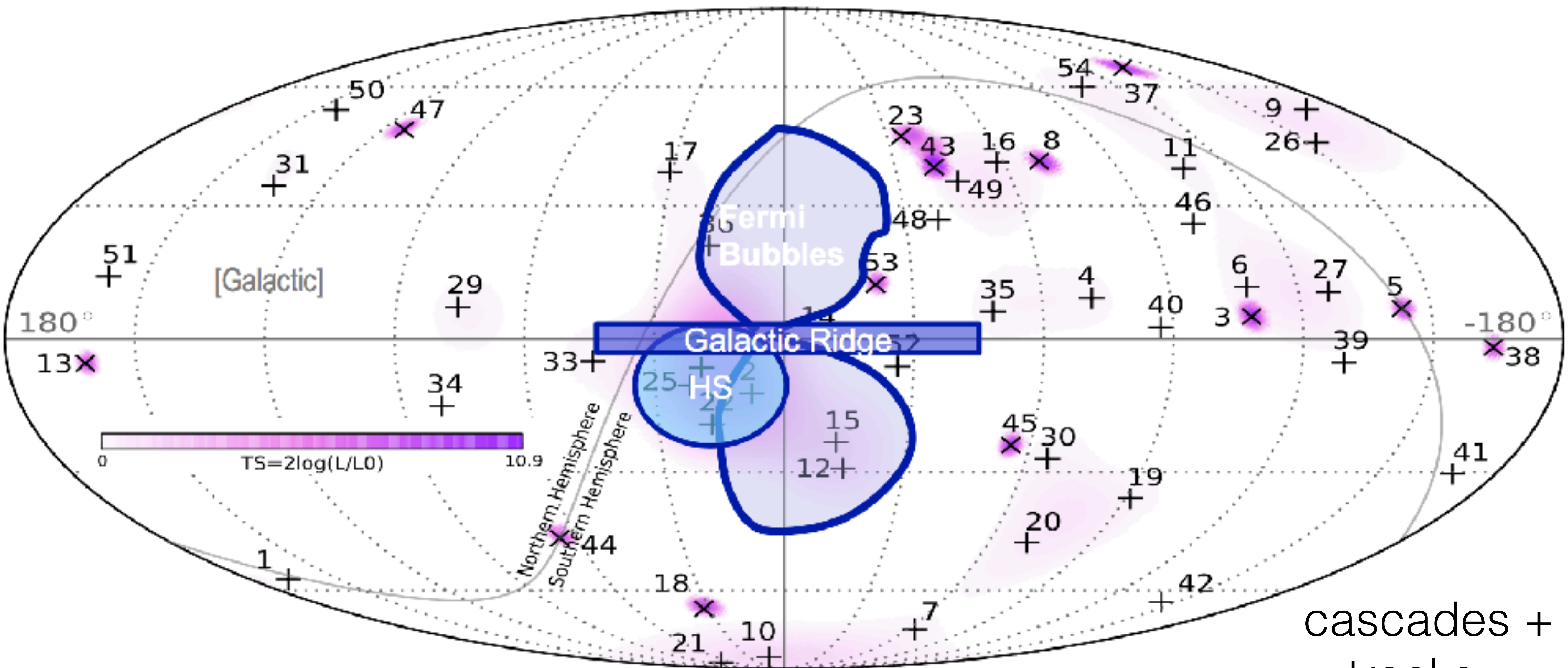
A complementary view of the sky





The IceCube signal

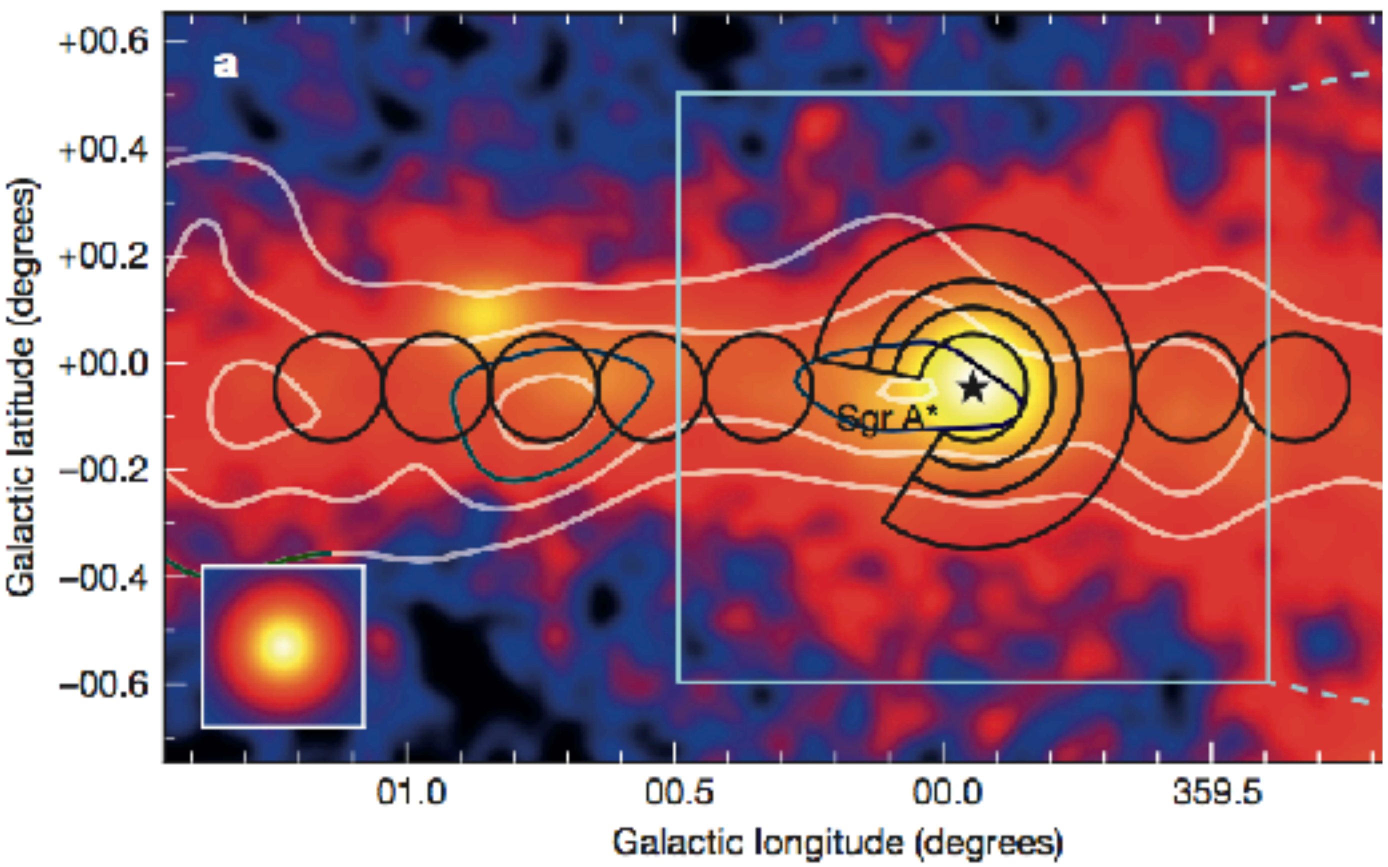
4 years of HESE (all flavors): sources not yet identified

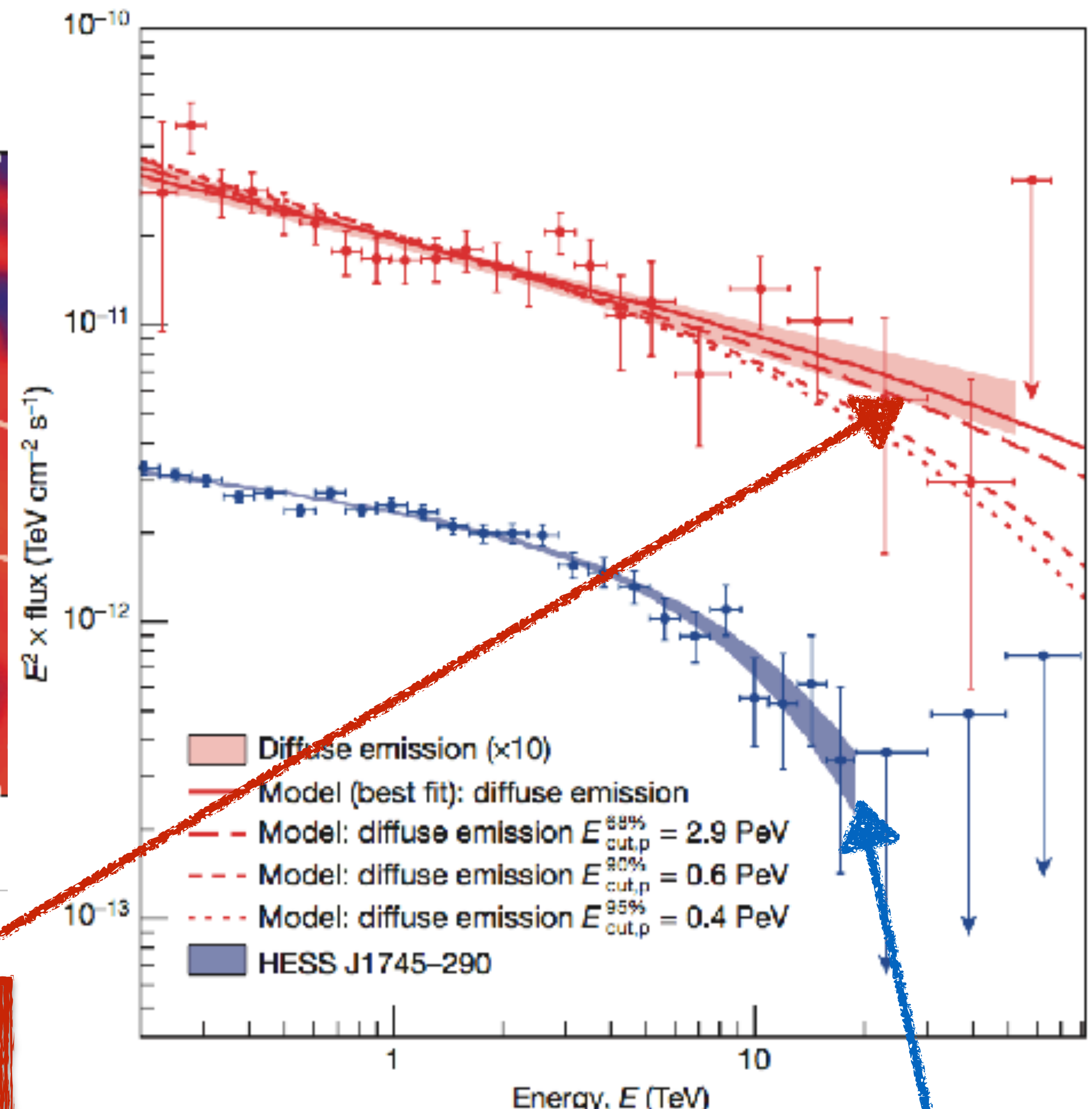


cascades +
tracks x

Compatible with isotropy
Moderate excess from the Southern Sky (not yet at 3σ level):
Fermi Bubbles? Galactic Ridge?

A proton PeVatron in the Galactic Center?





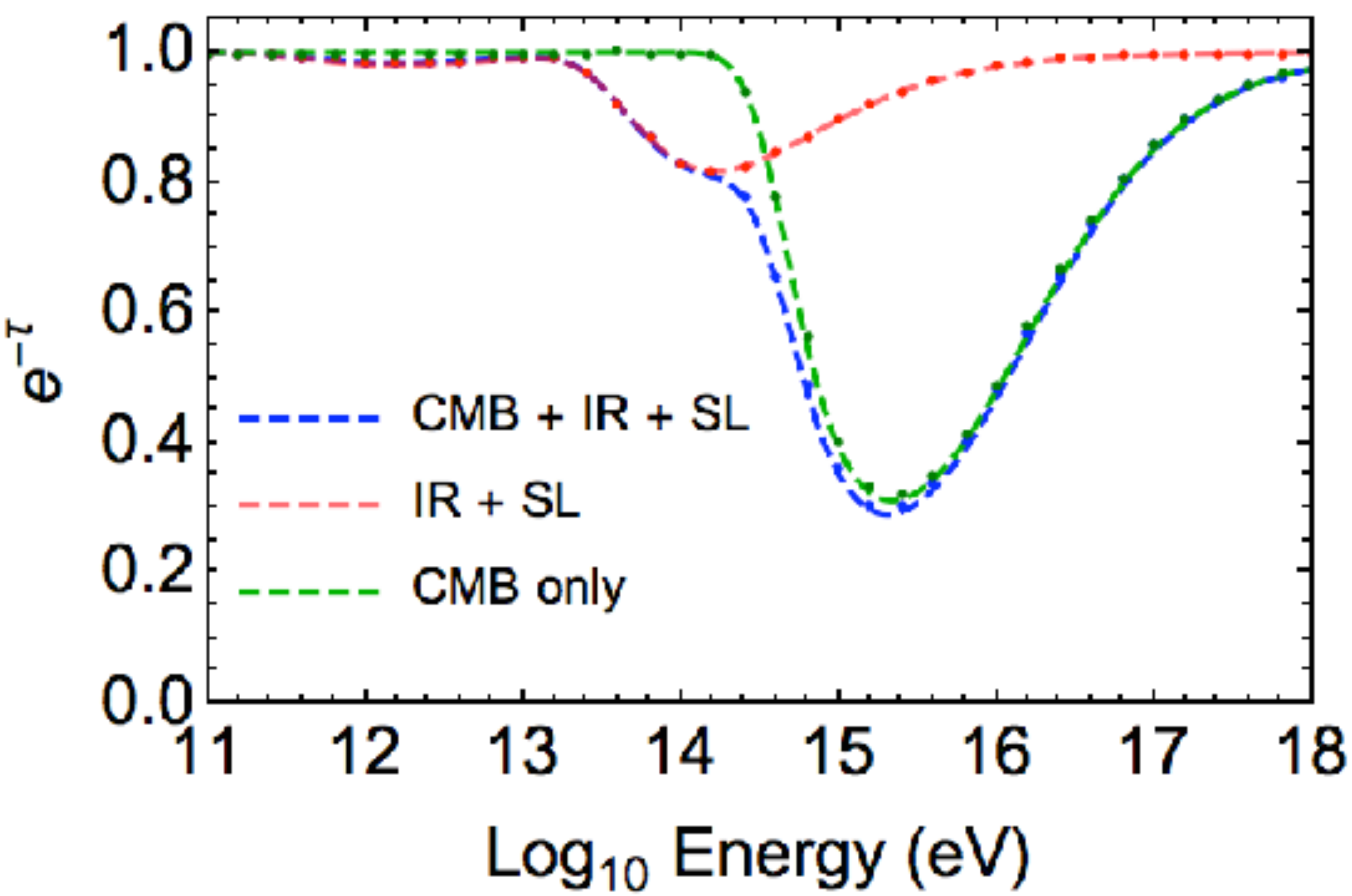
Diffuse emission from the GC without a perceivable cutoff

Point source emission with a 10 TeV cut-off

Aharonian *et al.* [HESS Coll.], Nature 531 (2016) 476

The effect of radiation fields

The observed γ-ray spectrum is not the same as the emitted one: absorption from radiation fields has to be taken into account in the propagation from the source to the Earth.



$$\gamma\gamma \longrightarrow e^{+}e^{-}$$

Celli, Palladino and Vissani,
Eur. Phys. J. C (2017) **77**: 66

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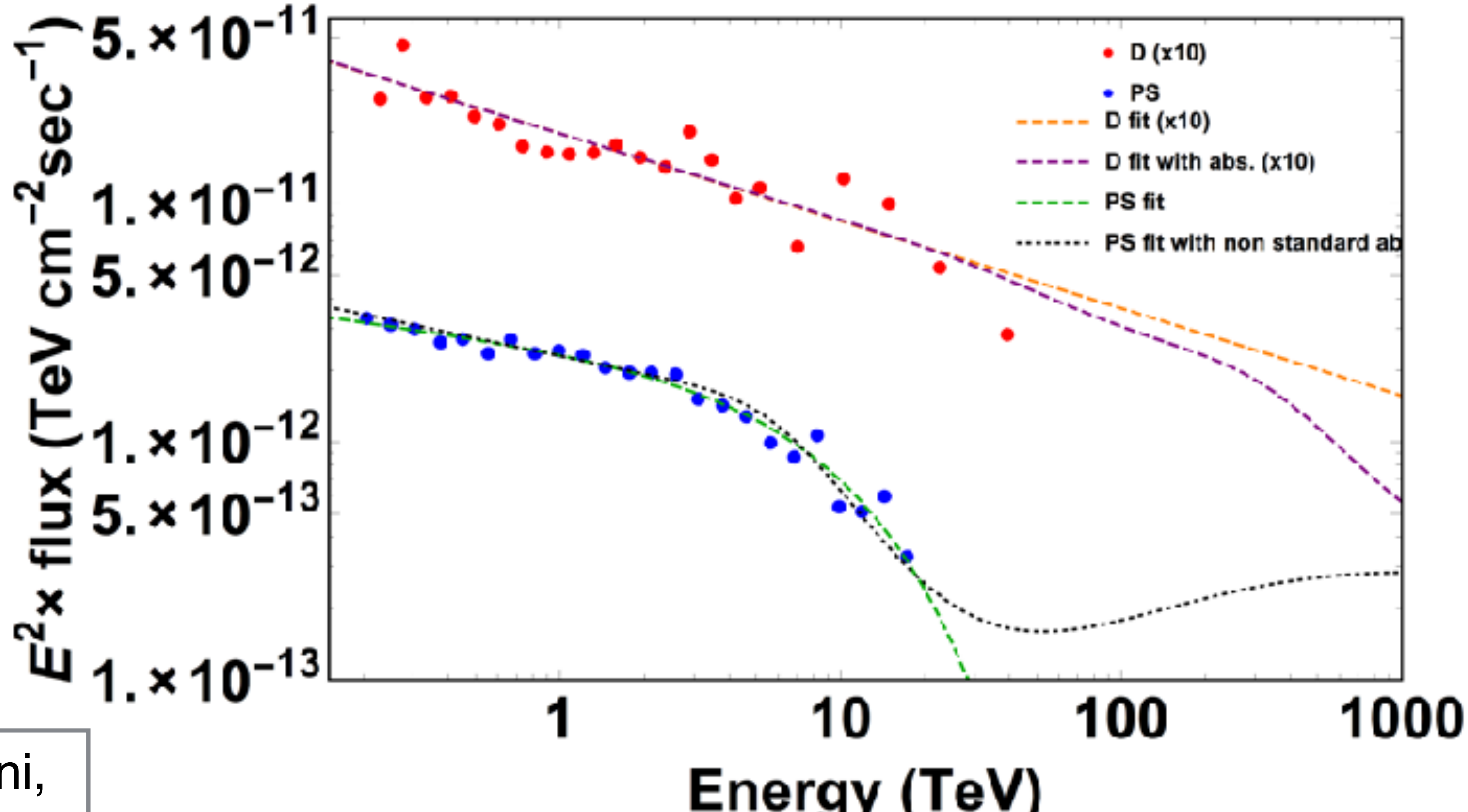

Celli, Palladino and Vissani, Eur. Phys. J. C (2017) **77**: 66

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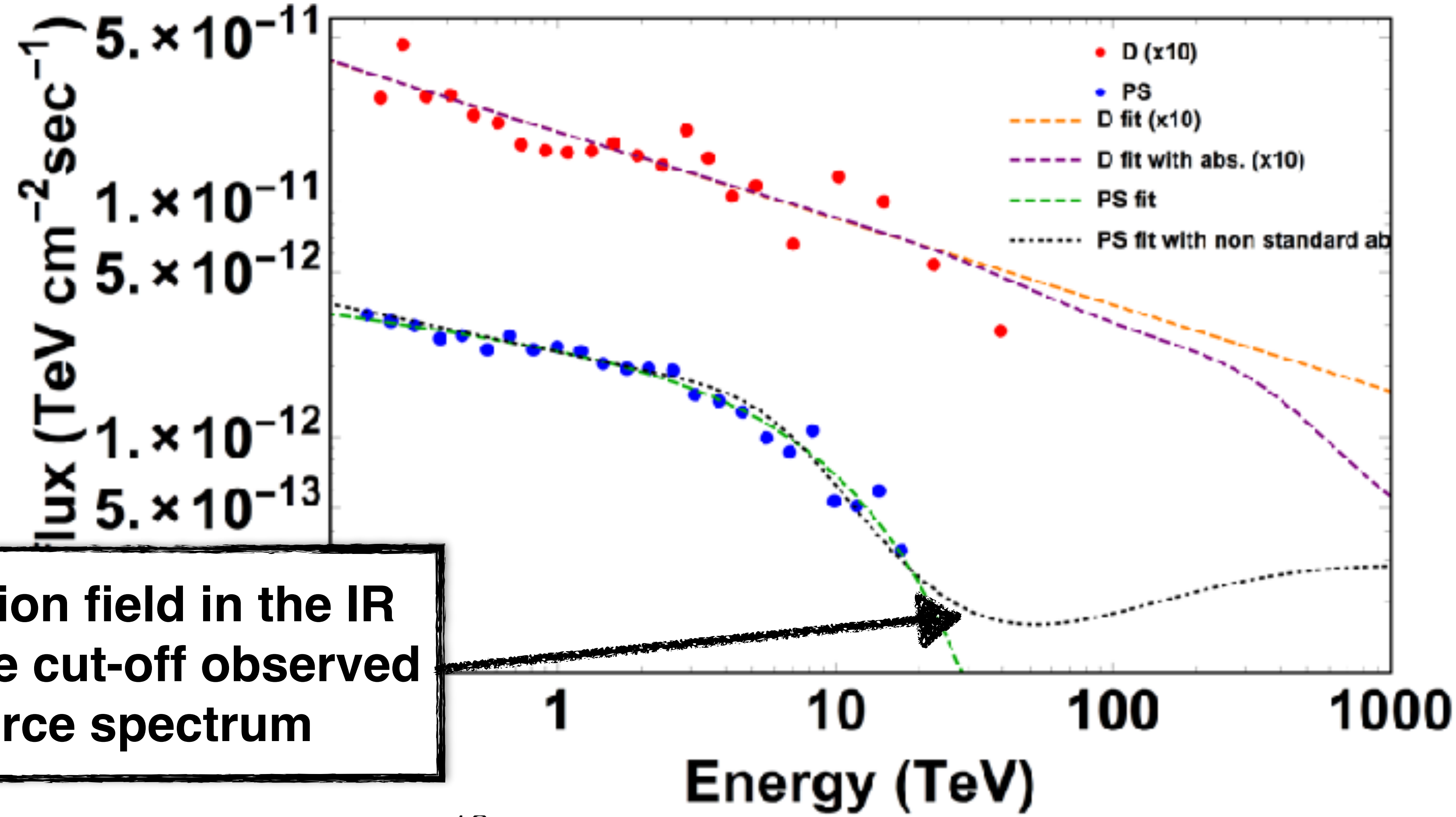
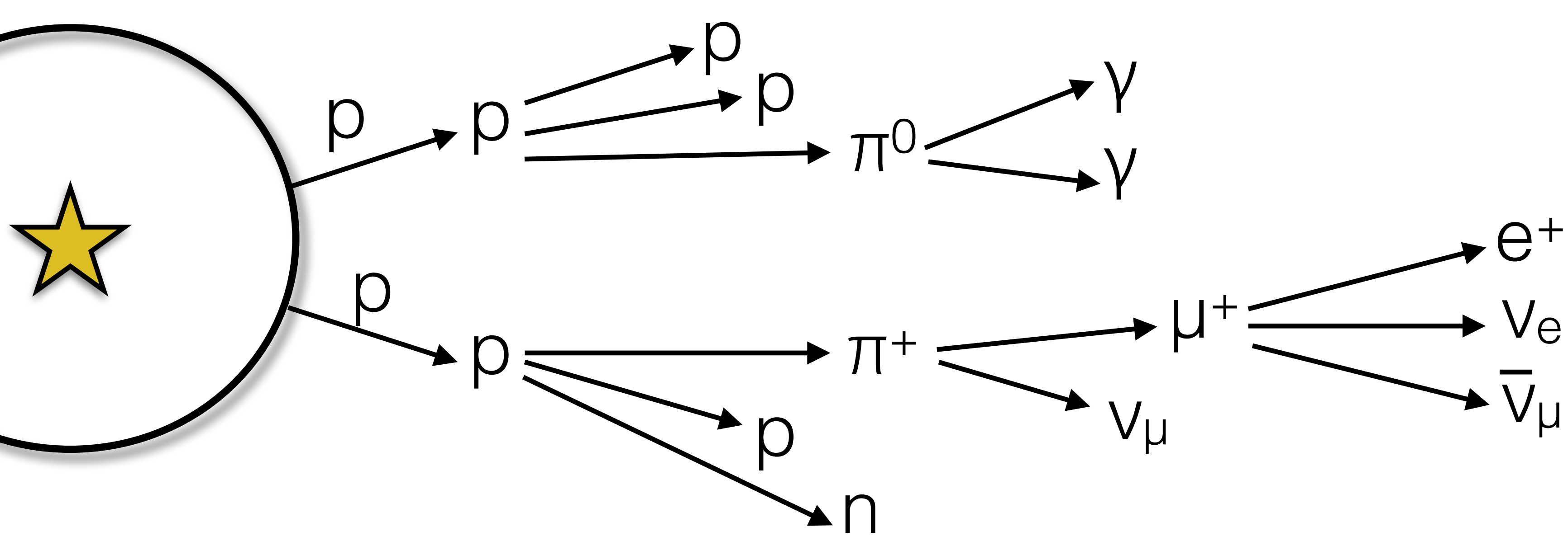


An unknown radiation field in the IR might be causing the cut-off observed in the point source spectrum

Muon neutrino fluxes from the GC

Villante and Vissani,
Phys. Rev. D78 (2008)103007



100% hadronic origin

pp interaction with target gas (CMZ)

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Villante and Vissani,
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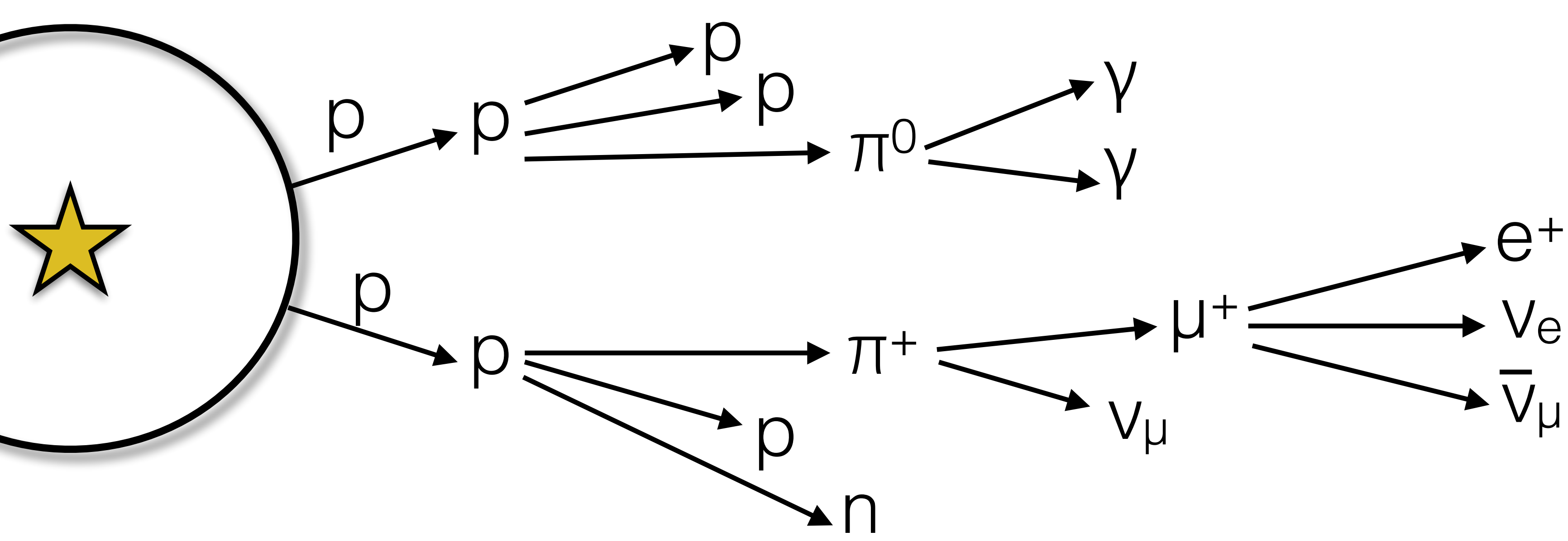


100% hadronic origin

pp interaction with target gas (CMZ)

GAMMA-RAY FLUXES

PS:

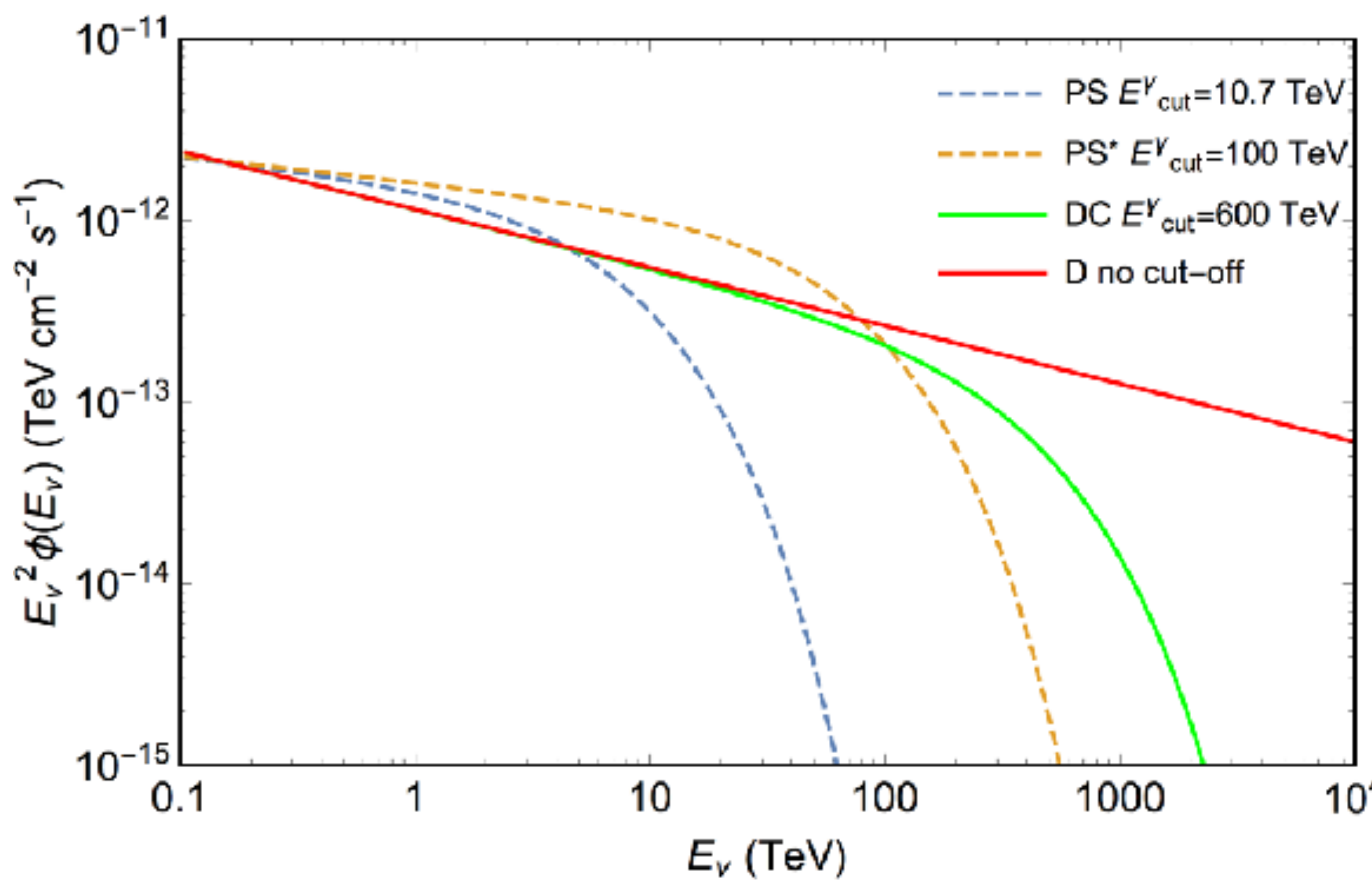
γ=2.14

ϕ_0(1TeV)=2.55x10^{-12} TeV^{-1} cm^{-2} s^{-1}

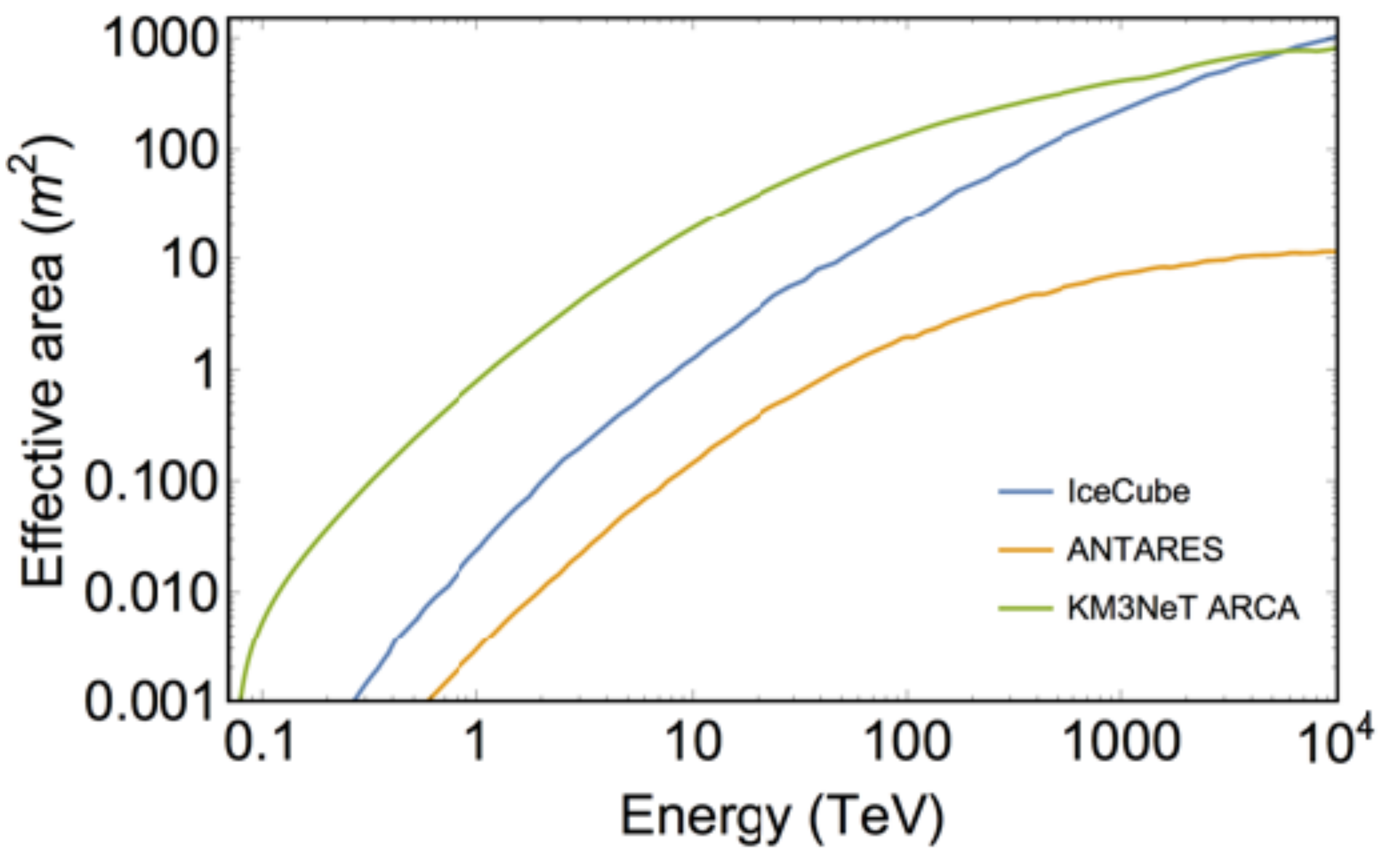
DIFFUSE:

γ=2.32

ϕ_0(1TeV)=1.92x10^{-12} TeV^{-1} cm^{-2} s^{-1}



Event rates in neutrino telescopes



δ_{GC}=-29.01°

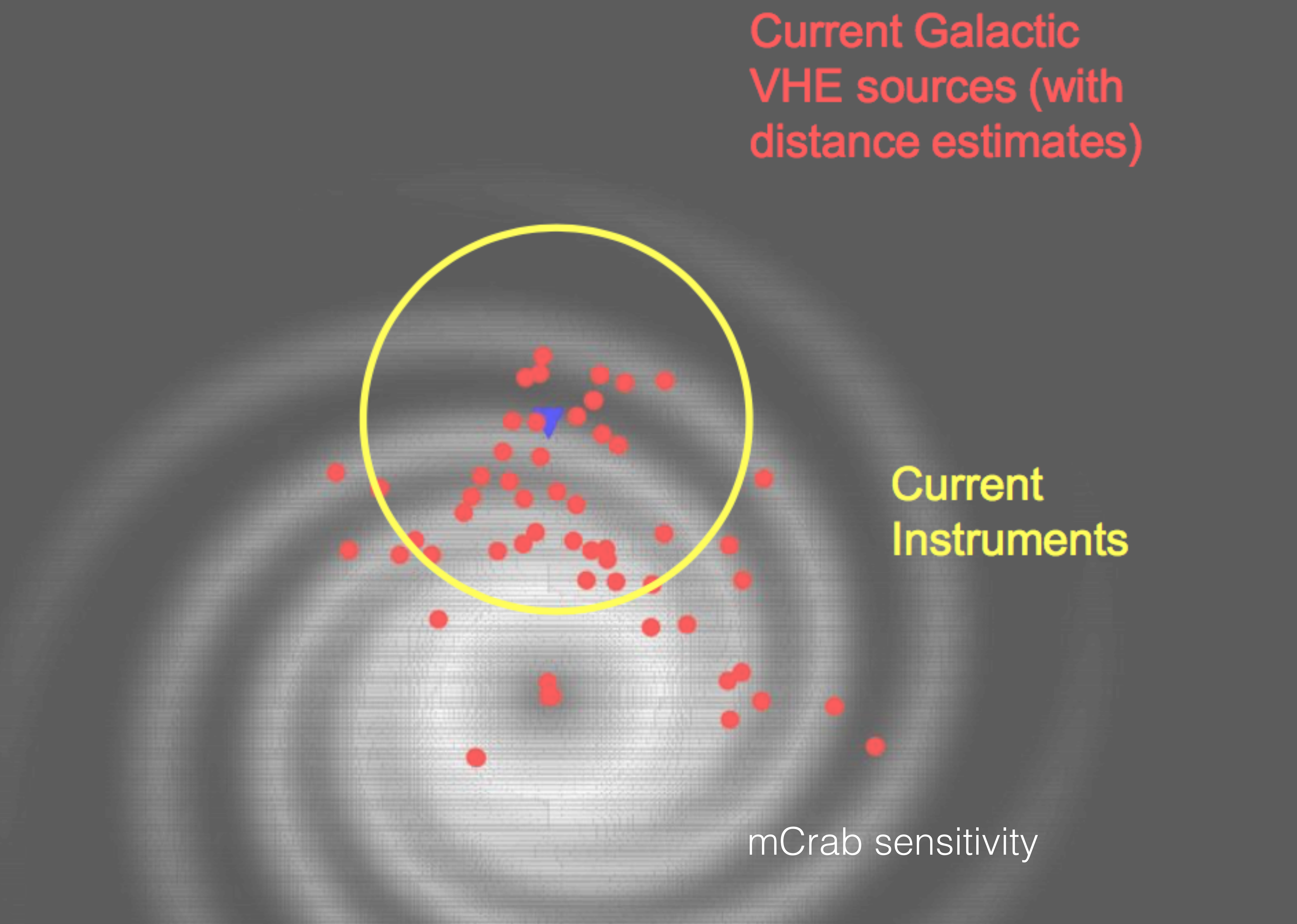
IceCube: PS, -30° < δ < 0°
ANTARES: PS, -45° < δ < 0°
ARCA: PS, 2 building blocks

68% of the signal below 100 TeV

	ANTARES (evts/year)	ARCA (evts/year)	IceCube (evts/year)
PS E_γ=10.7 TeV	0,006	1,1	0,05
PS* E_γ=100 TeV	0,02	2,1	0,15
D NO CUTOFF	0,01	1,4	0,13
DC E_γ=600 TeV	0,01	1,3	0,10

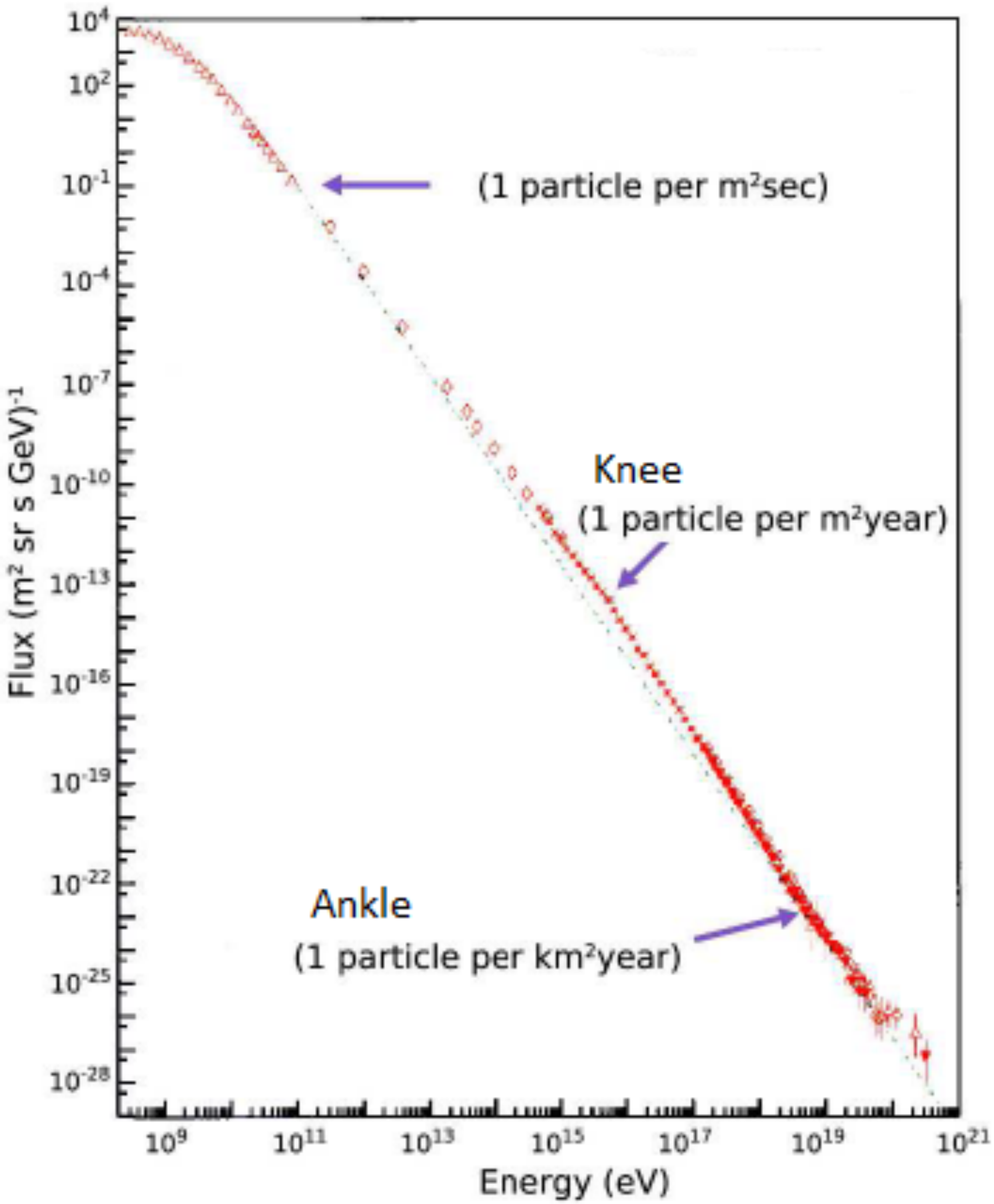
Conclusions

- Acceleration mechanisms at the source (as well as the origin of cosmic rays) are still poorly understood;
- A multi-messenger approach is fundamental to disentangle leptonic from hadronic processes;
- The search for PeVatrons is a key science project in both gamma-ray and neutrino communities: the investigation of galactic source emissions makes the case for a gamma-ray Southern observatory and a Northern neutrino telescope;
- Neutrino astronomy is a promising field (we might see a different sky from the gamma one), but several data-taking years are necessary in a cubic kilometer detector to detect point-like sources.


Current Galactic VHE sources (with distance estimates)
Current Instruments
mCrab sensitivity

BACKUP SLIDES

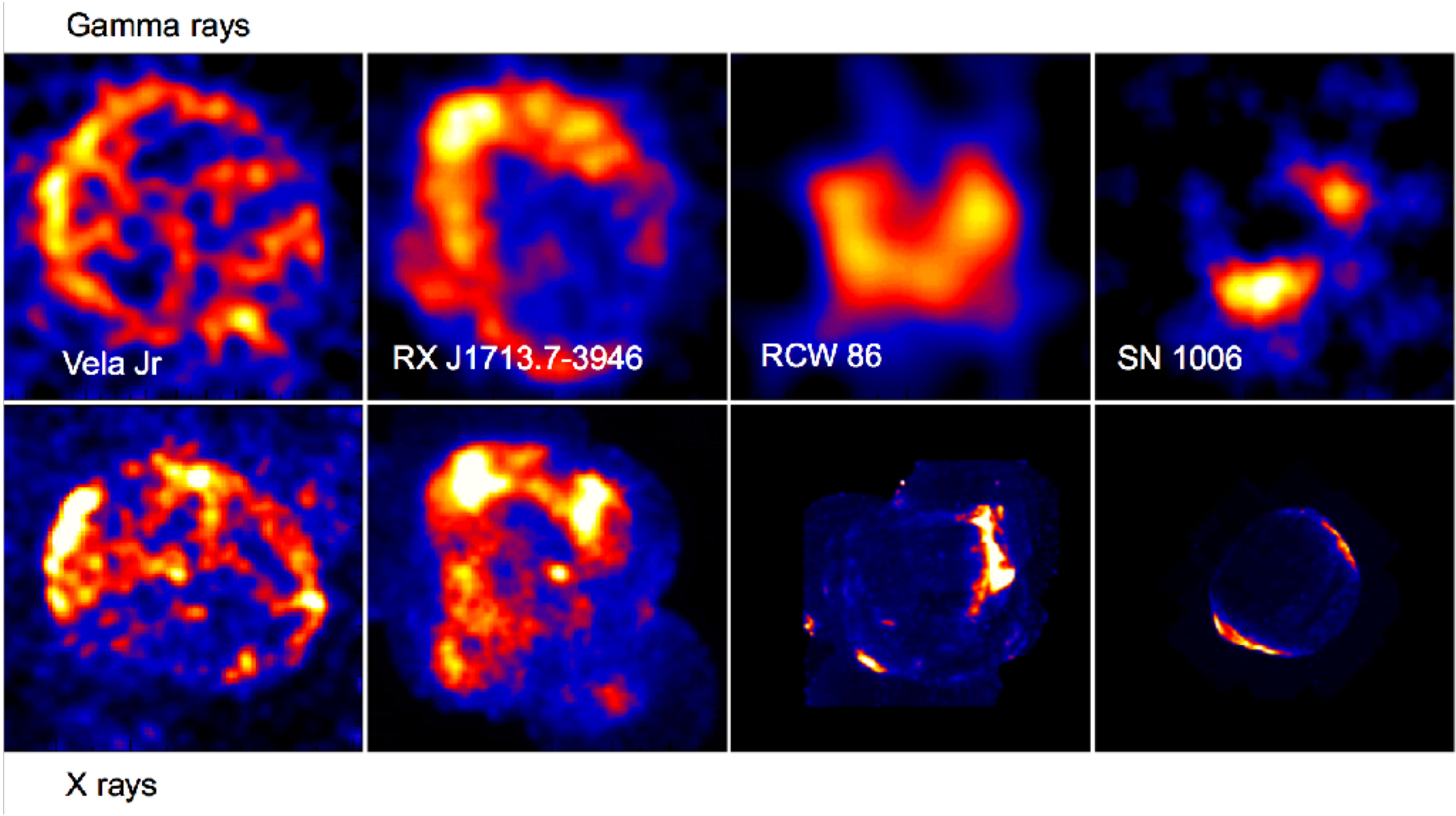
The SNR paradigm for the origin of CRs



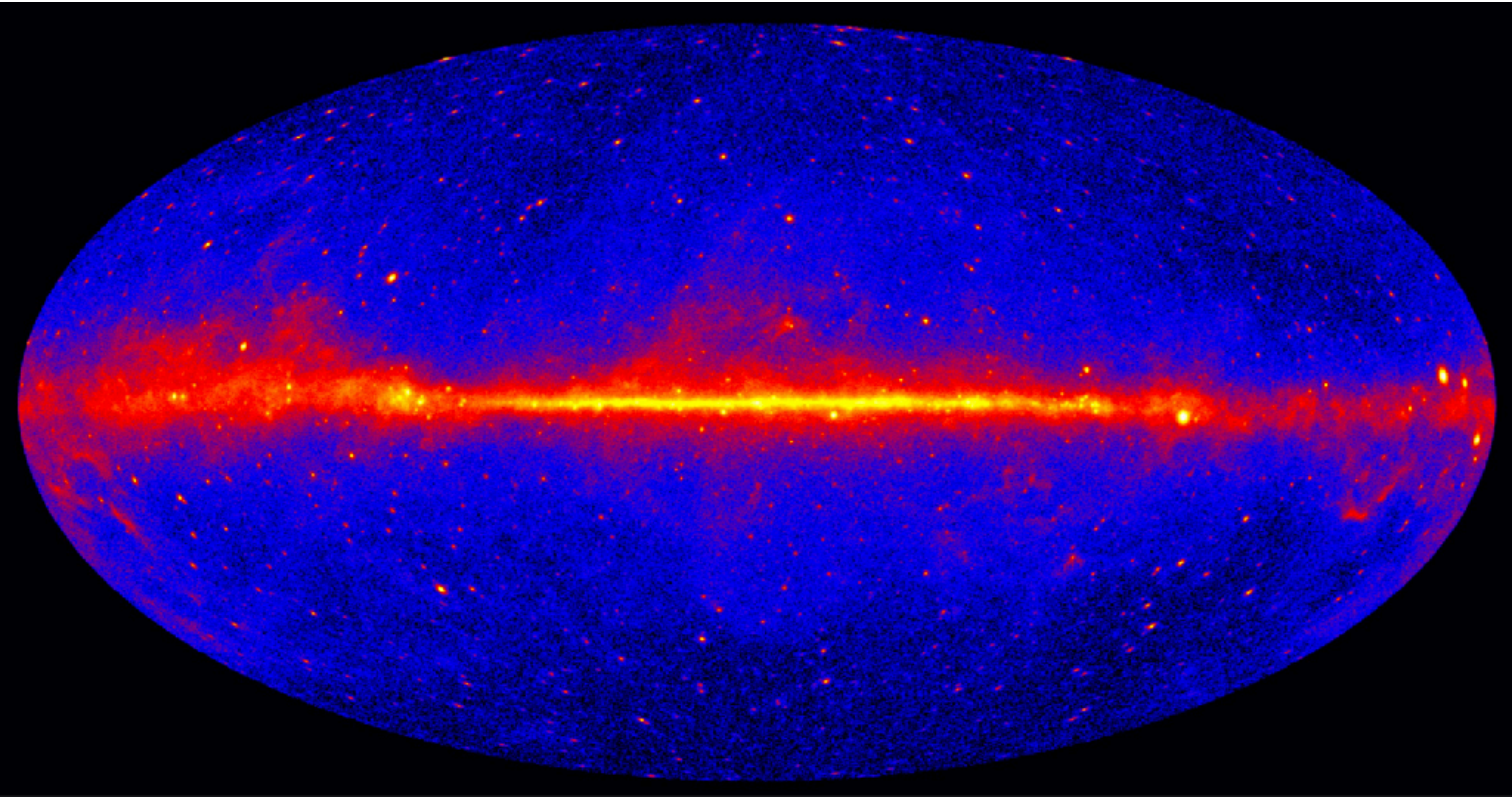
$$
\begin{aligned}
U_{CR} &= 0.5\,\mathrm{eV/cm^3} \\
V &= 400\,\mathrm{kpc^3} \\
\tau_{res} &= 5 \times 10^6\,\mathrm{years} \\
P_{CR} &\simeq \frac{U_{CR} V}{\tau_{res}} \simeq 10^{40}\,\mathrm{erg/s}
\end{aligned}
$$

$$
\begin{aligned}
E_{SN} &= 10^{51}\mathrm{erg} \\
R_{SN} &= 0.03\,\mathrm{year}^{-1} \\
P_{SN} &= R_{SN} E_{SN} \simeq 10^{41}\,\mathrm{erg/s} \\
&\longrightarrow \xi = 10\%
\end{aligned}
$$

A variety of SNRs observed until now



The Fermi LAT sky…



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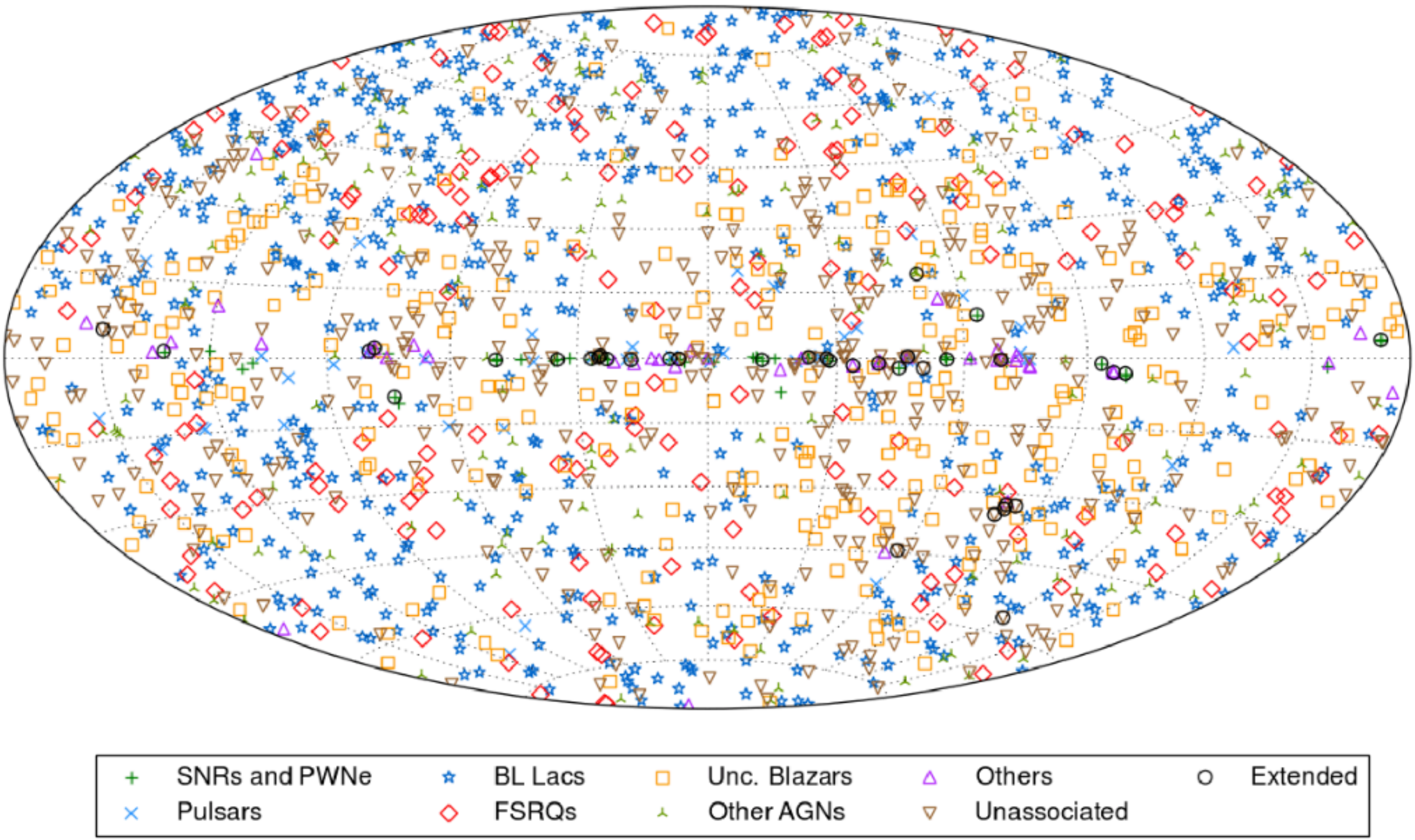


Known radiation fields

Rad. field	T_i (eV)	ξ_i	L_i (kpc)	$n_{\gamma,i}$ (cm^{-3})	E_i (TeV)
CMB	$2.35 \cdot 10^{-4}$	1	8.3	410.7	1111
IR	$3.10 \cdot 10^{-3}$	$1.55 \cdot 10^{-4}$	4.1	146.0	84.23
SL	$3.44 \cdot 10^{-1}$	$1.47 \cdot 10^{-11}$	2.4	19.0	0.26

Porter, Moskalenko, Strong, Orlando and Bouchet, Astrophys. J. 682 (2008) 400

and unknown

The absorption observed in the PS emission at the GC position might be due to a radiation field with

$T=1.3\times10^{-2}$ eV

$\xi=1$, $L=0.07$ pc, $n=7\times10^{7}\ \mathrm{cm}^{-3}$

$\xi=0.02$, $L=3.5$ pc, $n=1.4\times10^{6}\ \mathrm{cm}^{-3}$

Absorption and scattering: water vs ice

	acqua marina (Mar Mediterraneo) $\lambda = 473(375)\,nm$	acqua (Lago di Baikal) $\lambda = 480\,nm$	ghiaccio (Polo Sud) $\lambda = 400\,nm$
λ_a	$60 \pm 10(26 \pm 3)\,m$	$20 - 24\,m$	$110\,m$
λ_s^{eff}	$270 \pm 30(120 \pm 10)\,m$	$200 - 400\,m$	$20\,m$

Tabella 3.2. Parametri della propagazione della luce in acqua e ghiaccio.

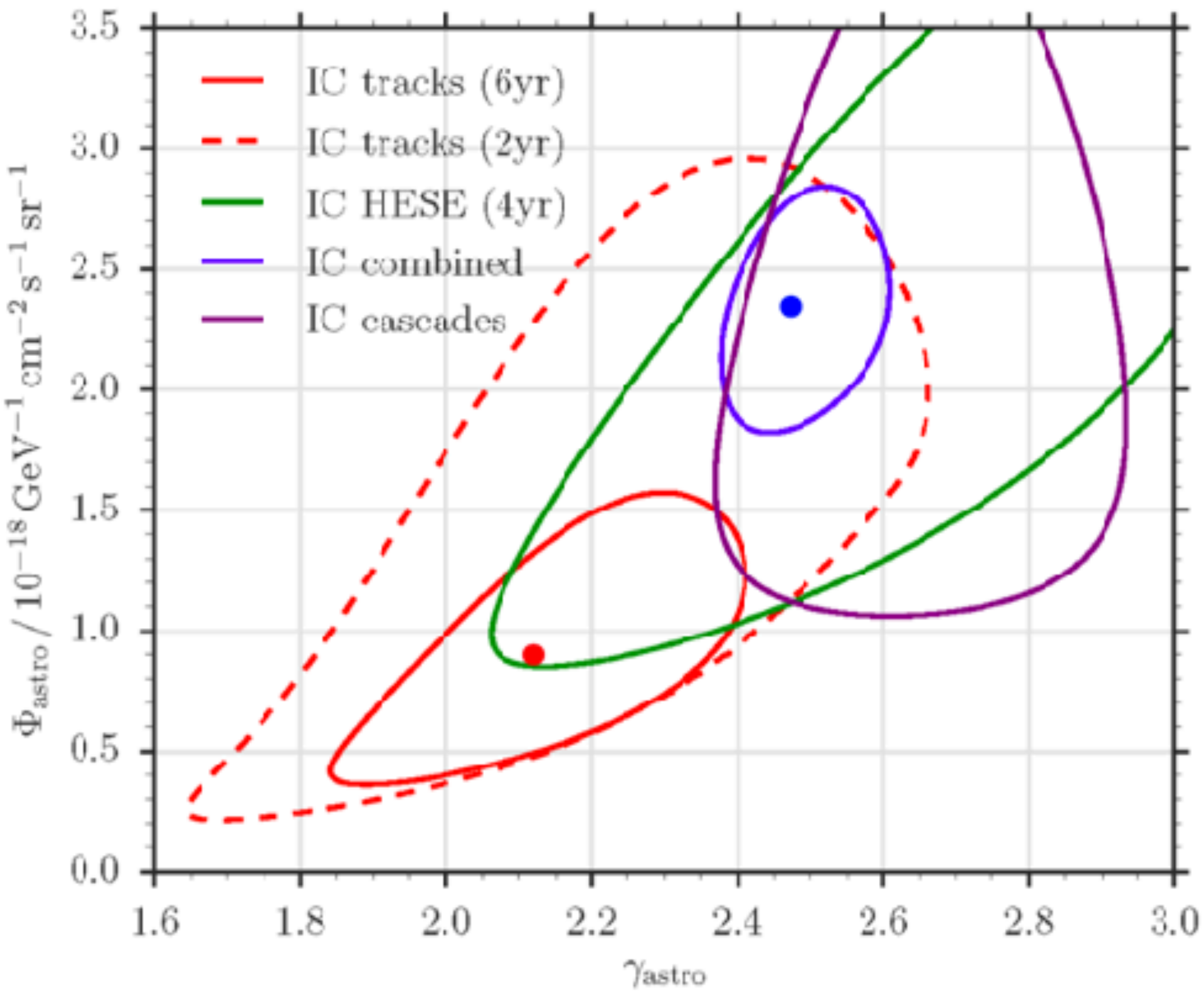
$$^{40}\text{K} \rightarrow {}^{40}\text{Ca} + e^- + \bar{\nu}_e$$

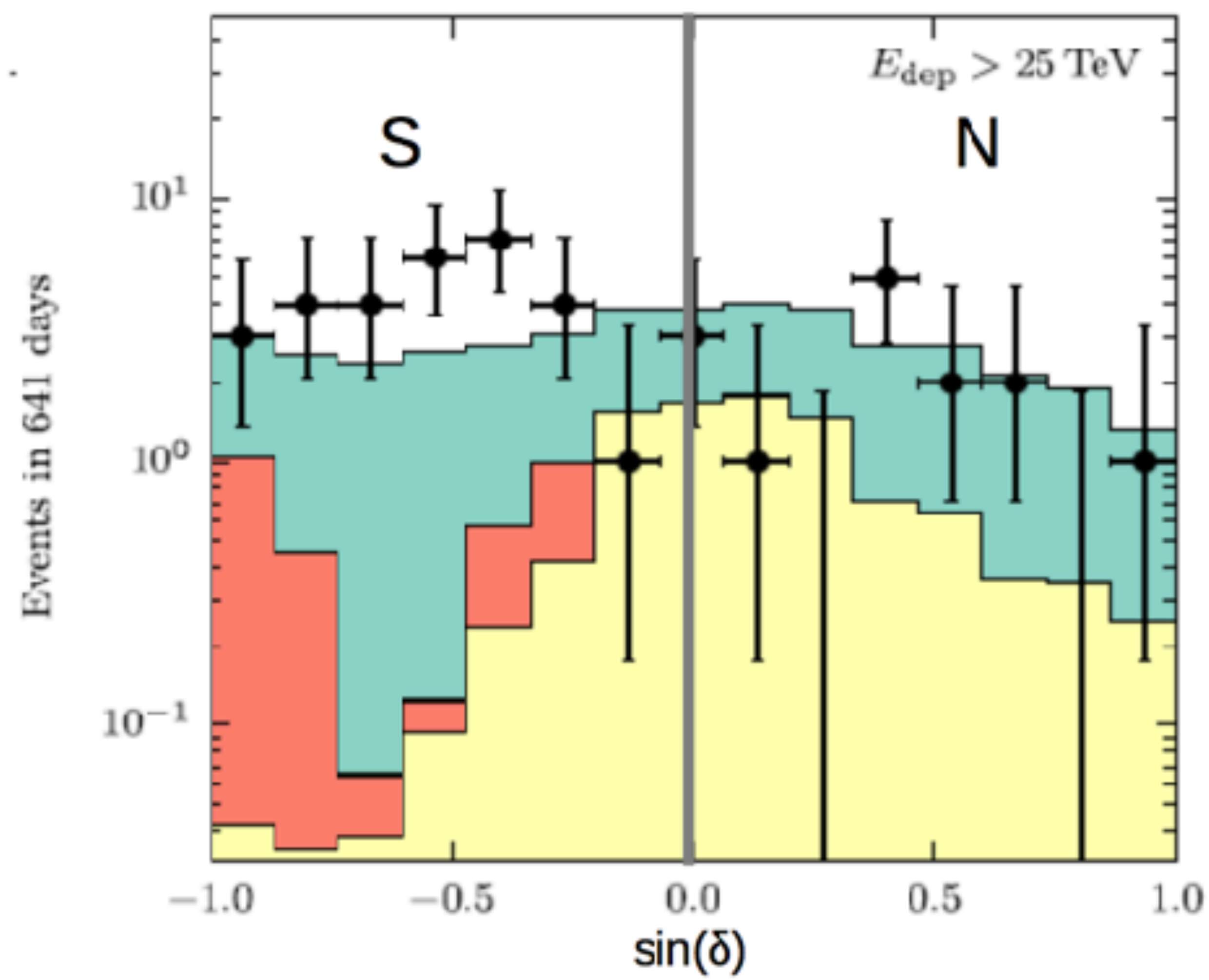
e

$$^{40}\text{K} + e^- \rightarrow {}^{40}\text{Ar} + \nu_e + \gamma.$$

Gli elettroni prodotti nel primo processo, spesso, hanno energia sufficientemente elevata da indurre l'effetto Cherenkov, mentre nel processo di cattura dell'elettrone, il fotone nello stato finale viene prodotto con un'energia ($E_\gamma = 1.46\,MeV$) che può facilmente portare alla produzione di elettroni con energie sopra la soglia di emissione di luce Cherenkov.

The IceCube signal



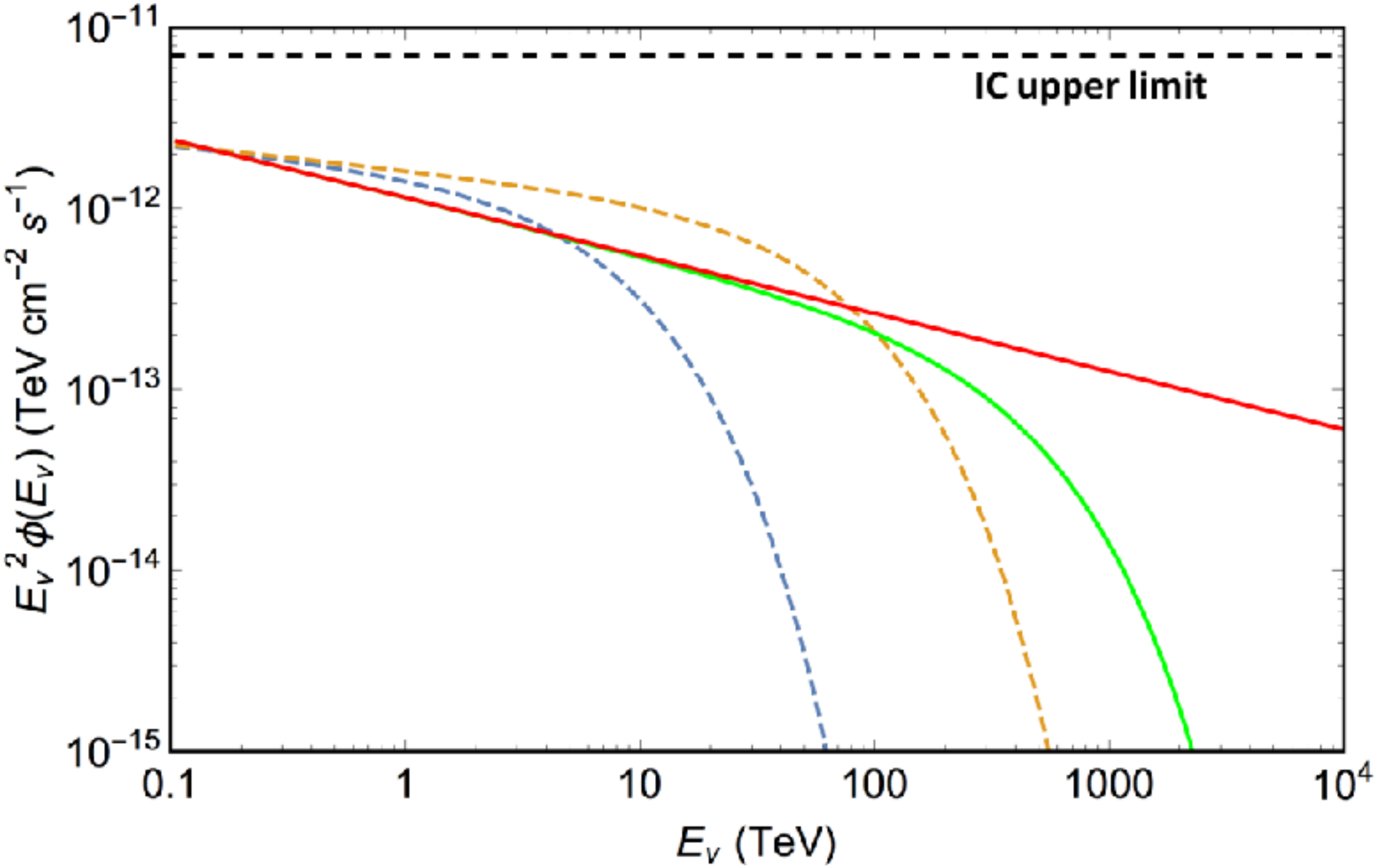


Slight tension among different analyses

γ_{astro}=[2:2.5]

Current IC upper limit

$$\phi(1\,\mathrm{TeV}) = 7.6 \times 10^{-12}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

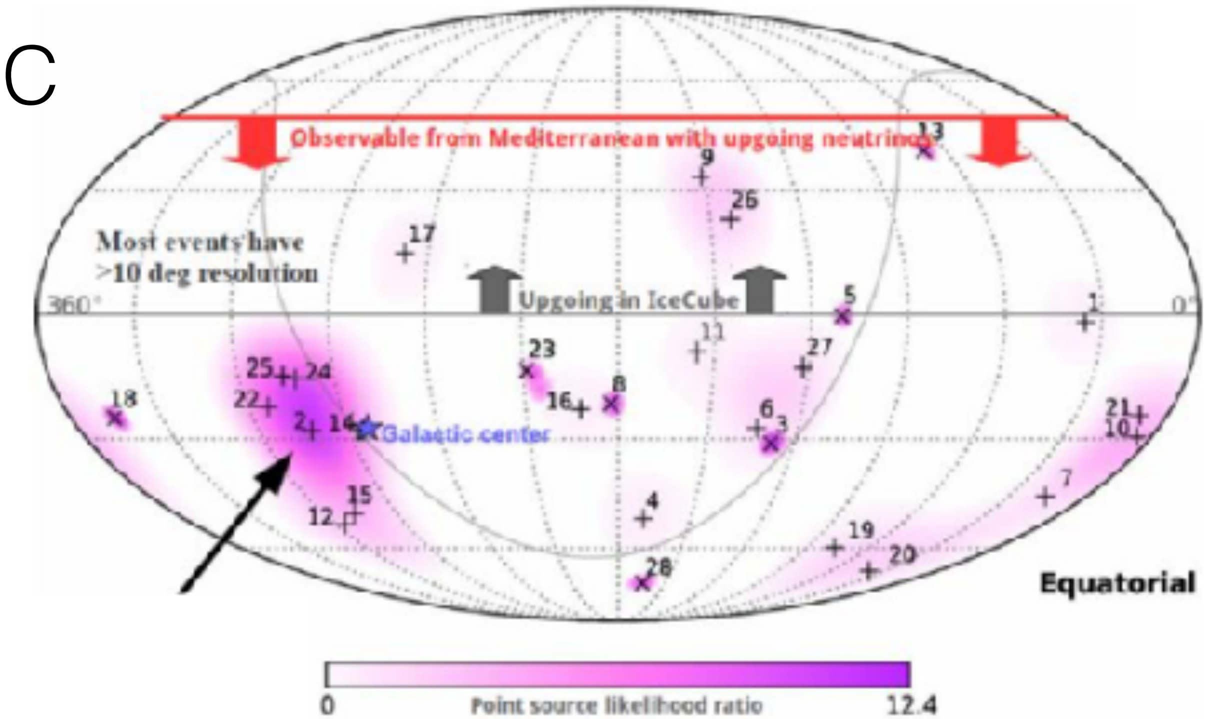


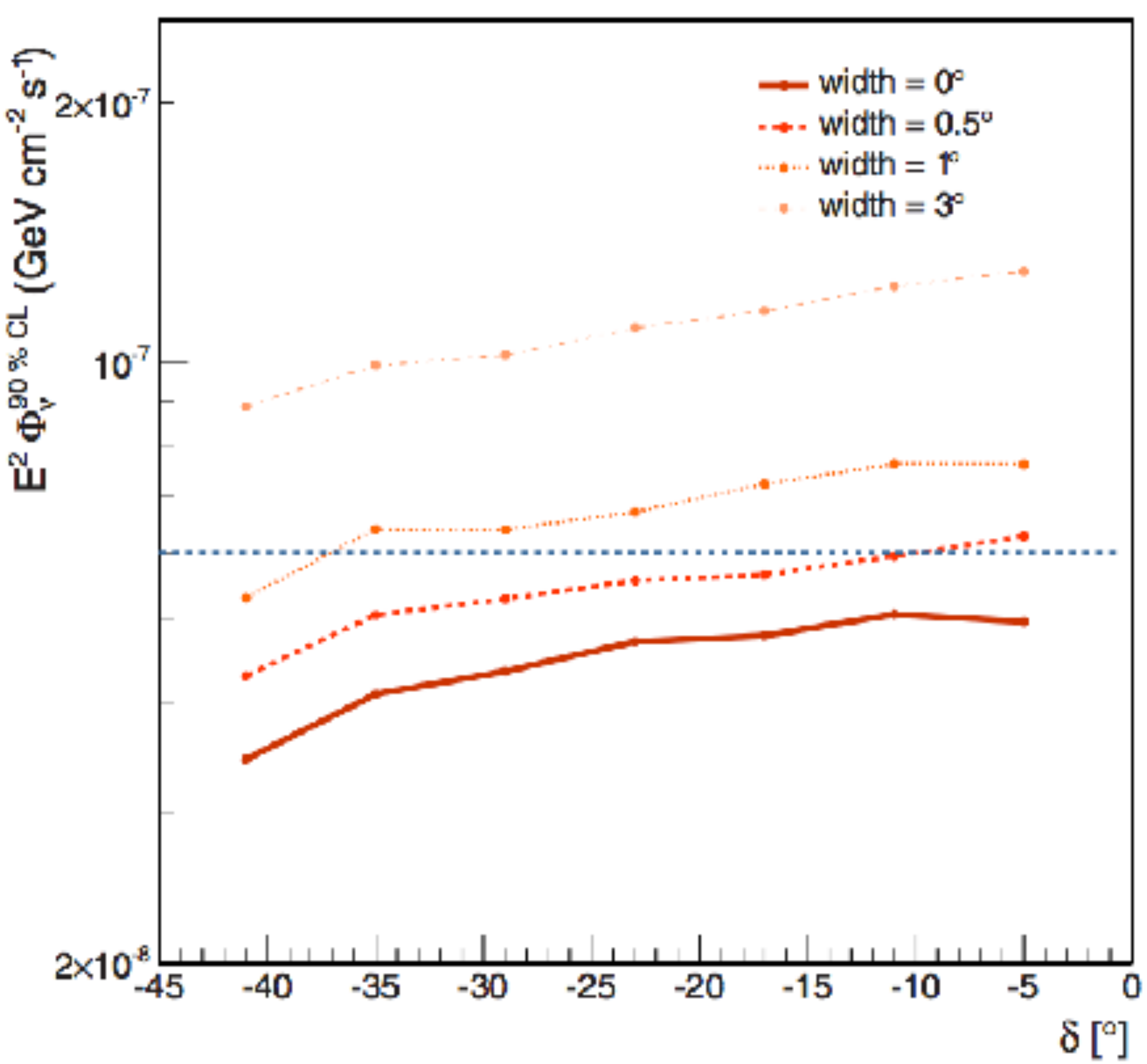
Aartsen *et al*. [IceCube Coll.],

APJ Letters, 824, 2, L28 (2016)

A point-source in the IC HS?

- Accumulation of IC events near the GC
- No PS claimed by IC
- If due to a PS, it would have a flux
  $\phi(E)=6\times10^{-8}$ GeV cm^{-2} s^{-1}
  and would be located in
  $(\alpha,\delta)=(-79°,-23°)$



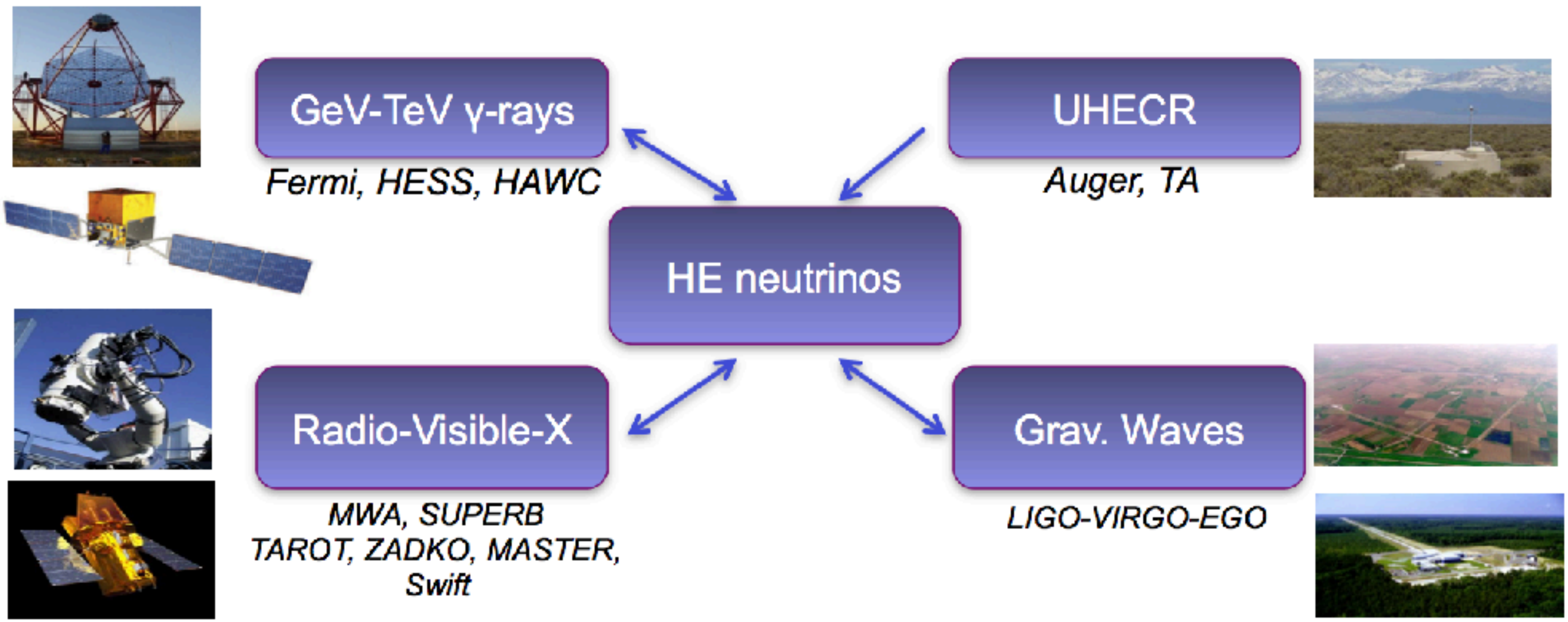


ANTARES full sky search algorithm in a region of 20° around the proposed location

NO SIGNIFICANT CLUSTERING BUT UPPER LIMITS EXCLUDE THE PRESENCE OF A PS

Adrian Martinez *et al.* [ANTARES Coll.],
The Astrophysical Journal Letters, 786:L5, 2014

ANTARES multi-messenger searches



- Better understanding of the source physics
- Improvement in the detector sensitivity (uncorrelated bkg)