On the Origin of IceCube High Energy Neutrinos
—High Energy Neutrinos from Supernovae

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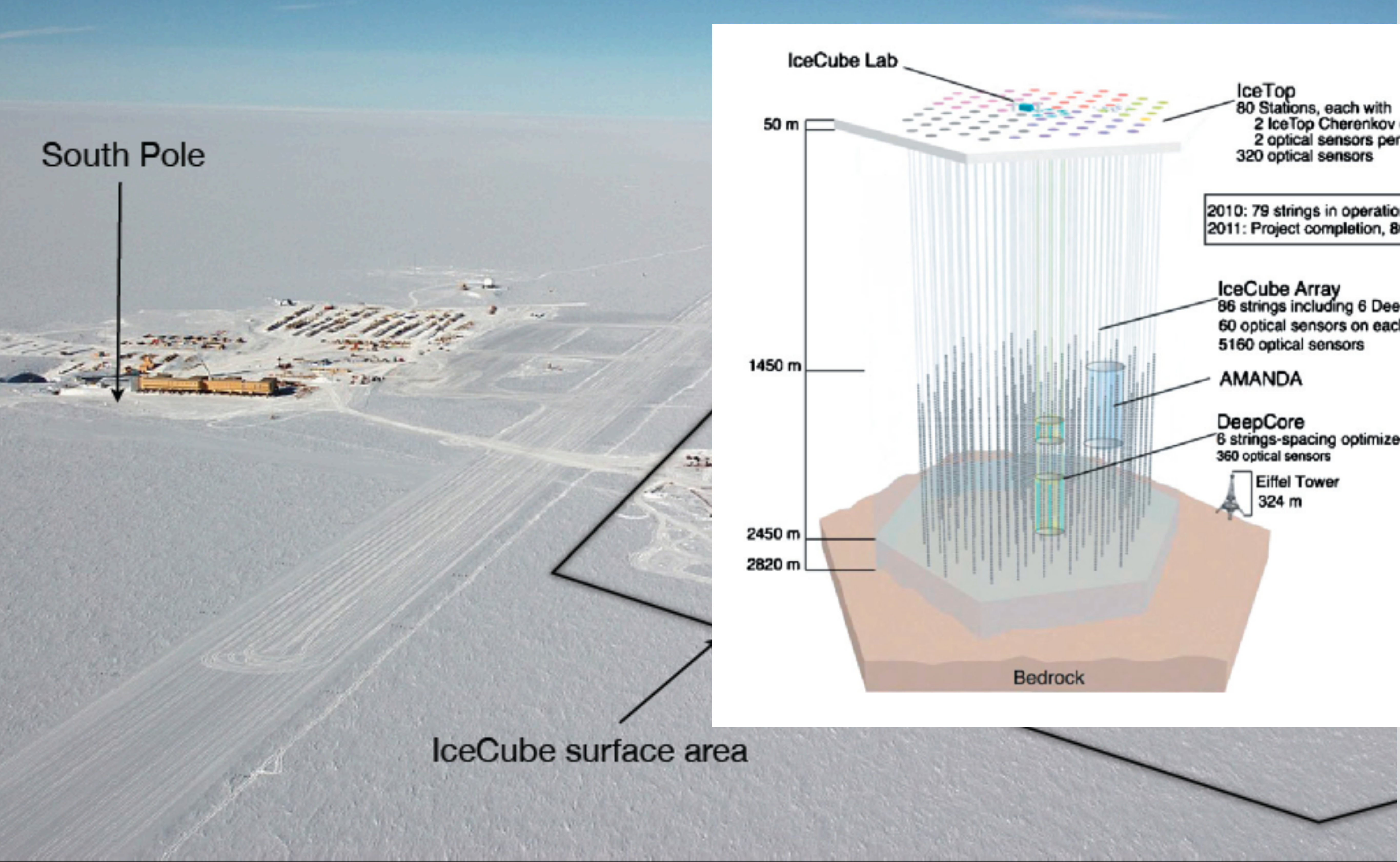
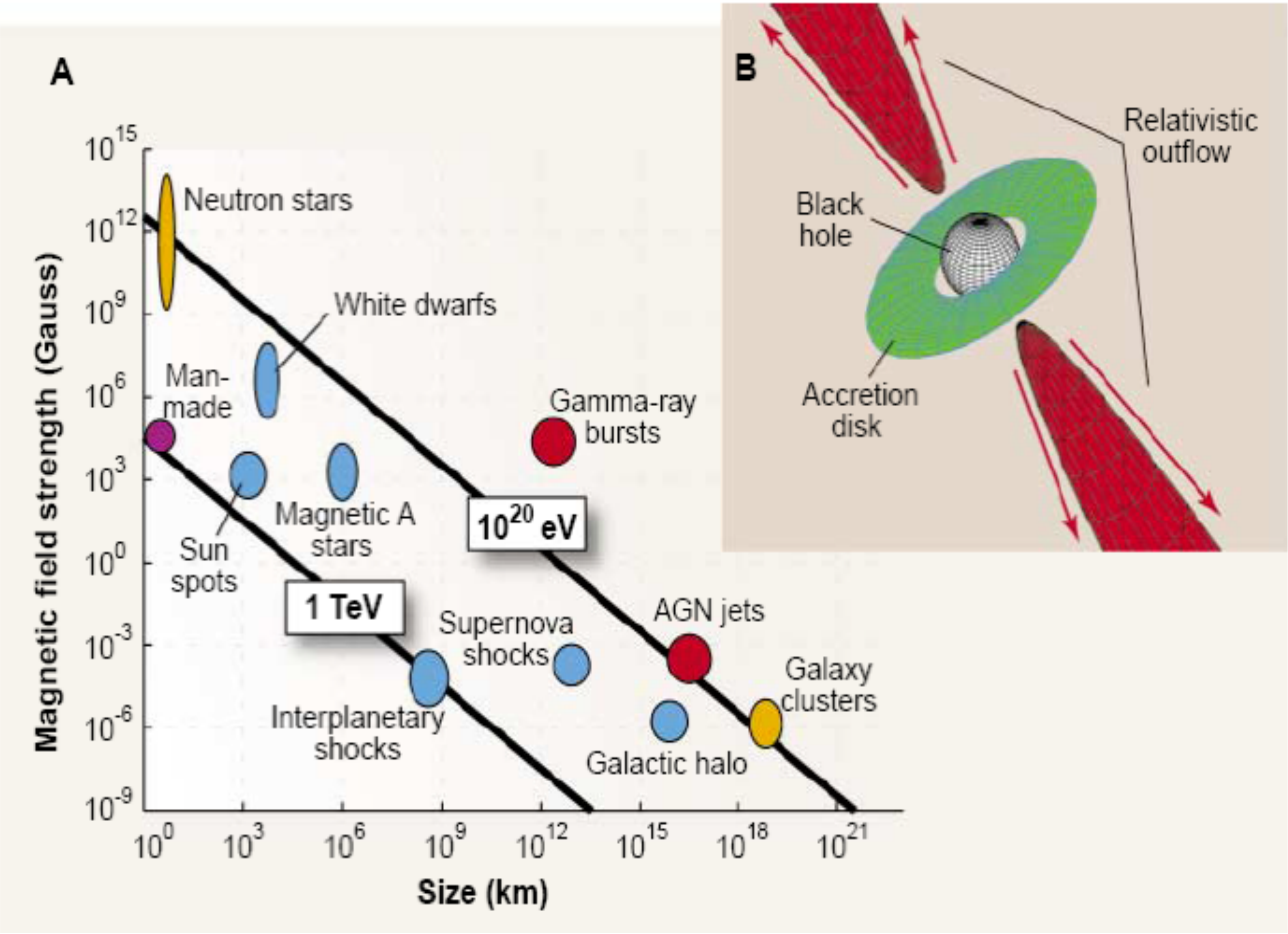
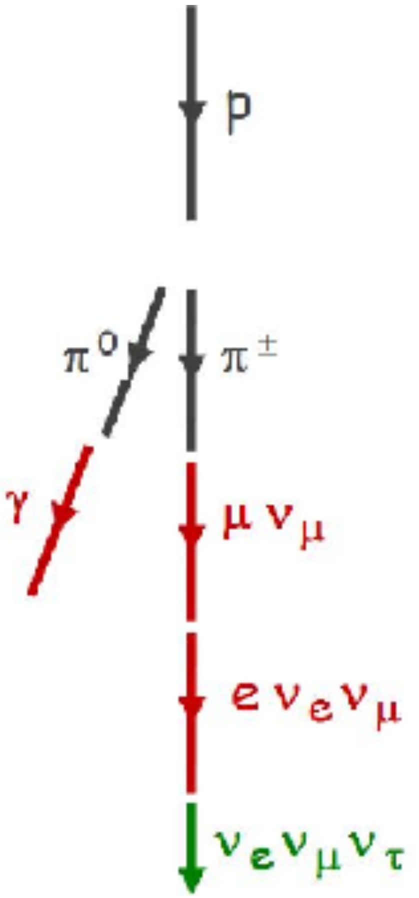
IceCube at the South Pole



Cosmic Ray Accelerators and Possible Neutrino Sources





Larmor Radius =
Typical scale of sources

Emax=ZBL

The SNe High Energy Neutrinos

- 1. SNe/HNe in the Starburst Galaxies/Star-Forming Galaxies
- 2. Choked Jet in the Star Envelope/CSM
- 3. SNe/HNe+Molecular Cloud Complex in the Galaxy

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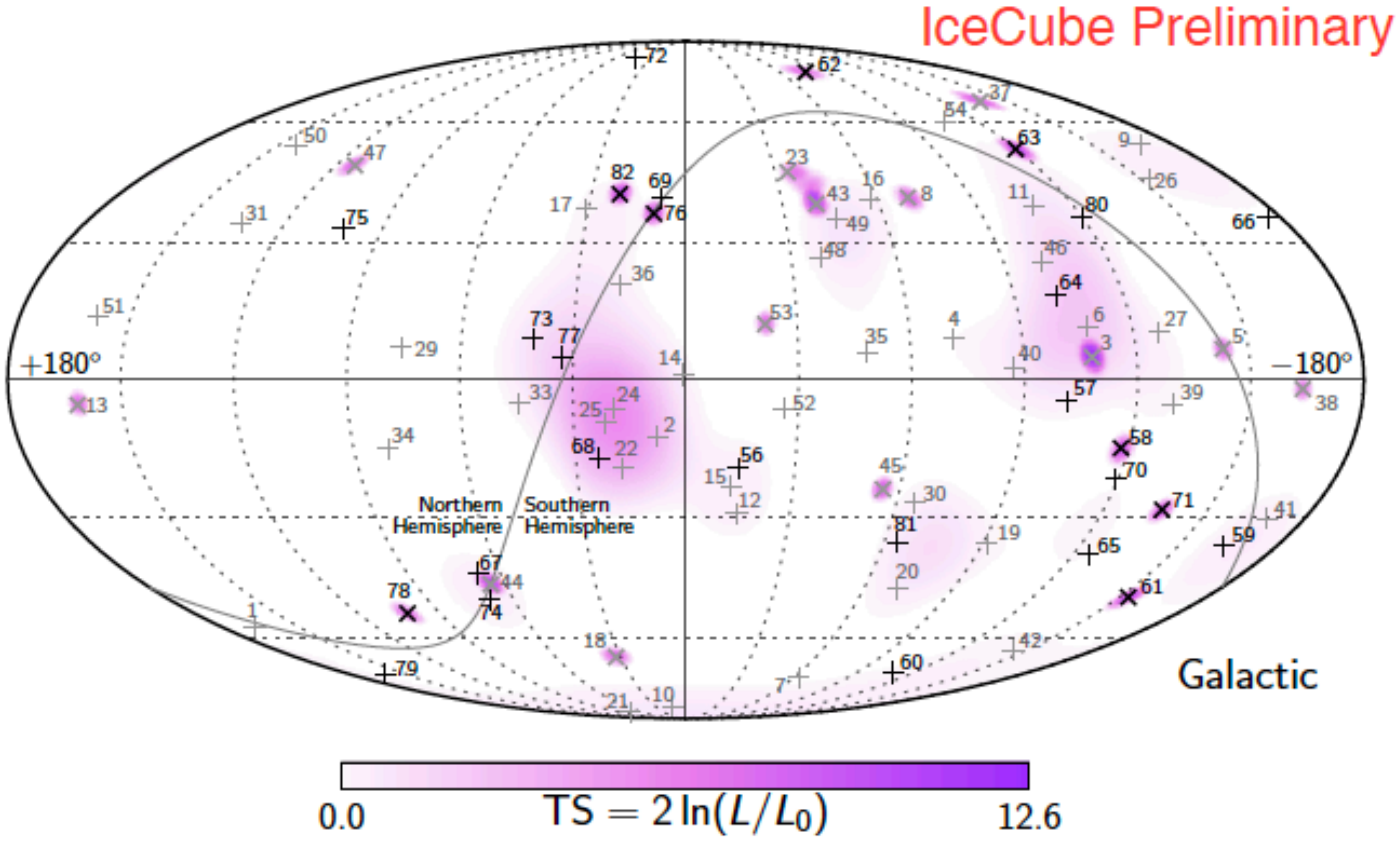
IceCube Neutrino Skymap



No significant clustering is found.
The energy of neutrinos is extended to >PeV.

Claudio Kopper (ICRC2017)

Hypernovae

SN 1997ef, SN 1997dq, SN 1998bw and SN 2002ap

Larger kinetic energy

+

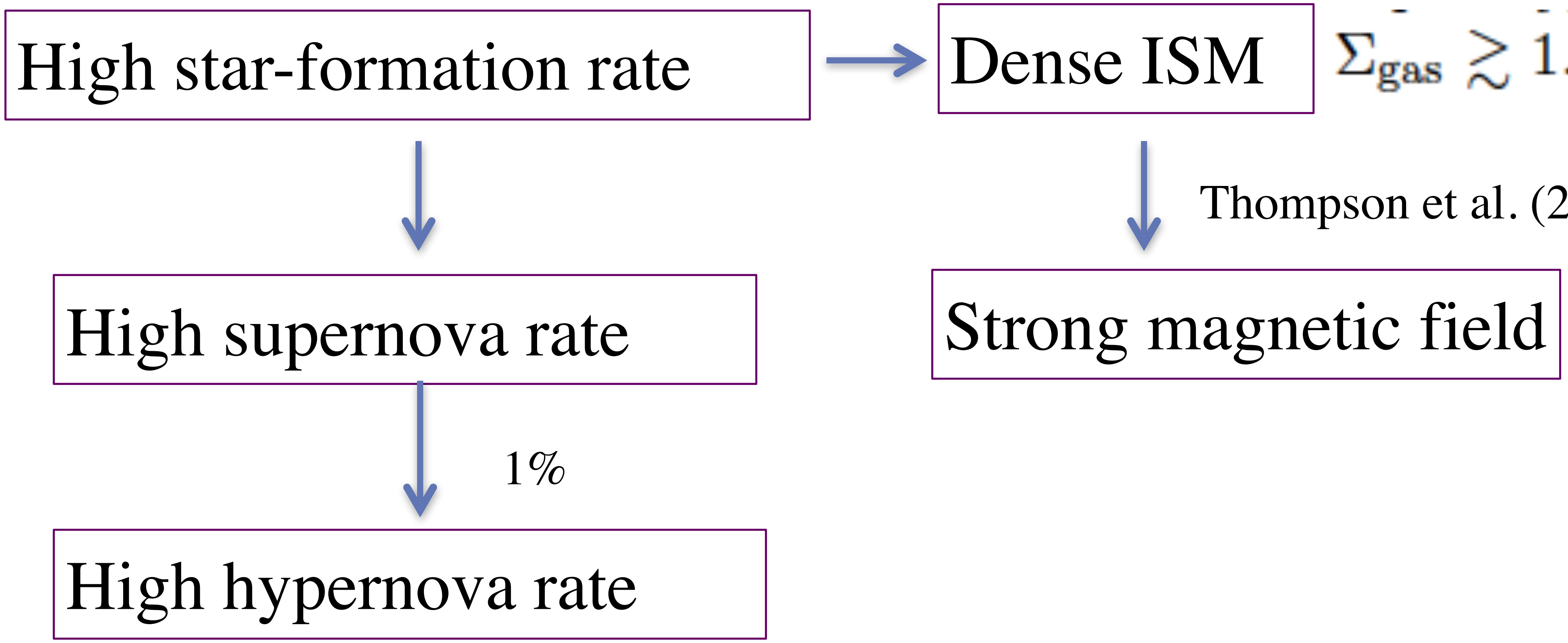
Larger velocity of the outflow

↓

Be able to accelerate particles to the energy as high as 100PeV

Properties of ULIRGs

Ultra-Luminous Infrared emission $L_{8-1000\mu\mathrm{m}} > 10^{12} L_{\odot}$



High star-formation rate

Dense ISM $\Sigma_{\mathrm{gas}} \gtrsim 1.0\ \mathrm{g\ cm^{-2}}$

Thompson et al. (2006)

Strong magnetic field

High supernova rate

1%

High hypernova rate

Cappelaro et al. 1999
Guetta& Della Valle, 2007

pp Collision in ULIRGs

Dense ISM+
Strong Magnetic
Field

$\tau_{\rm conf} \geqslant \tau_{\rm loss}$

pp collission
before escaping

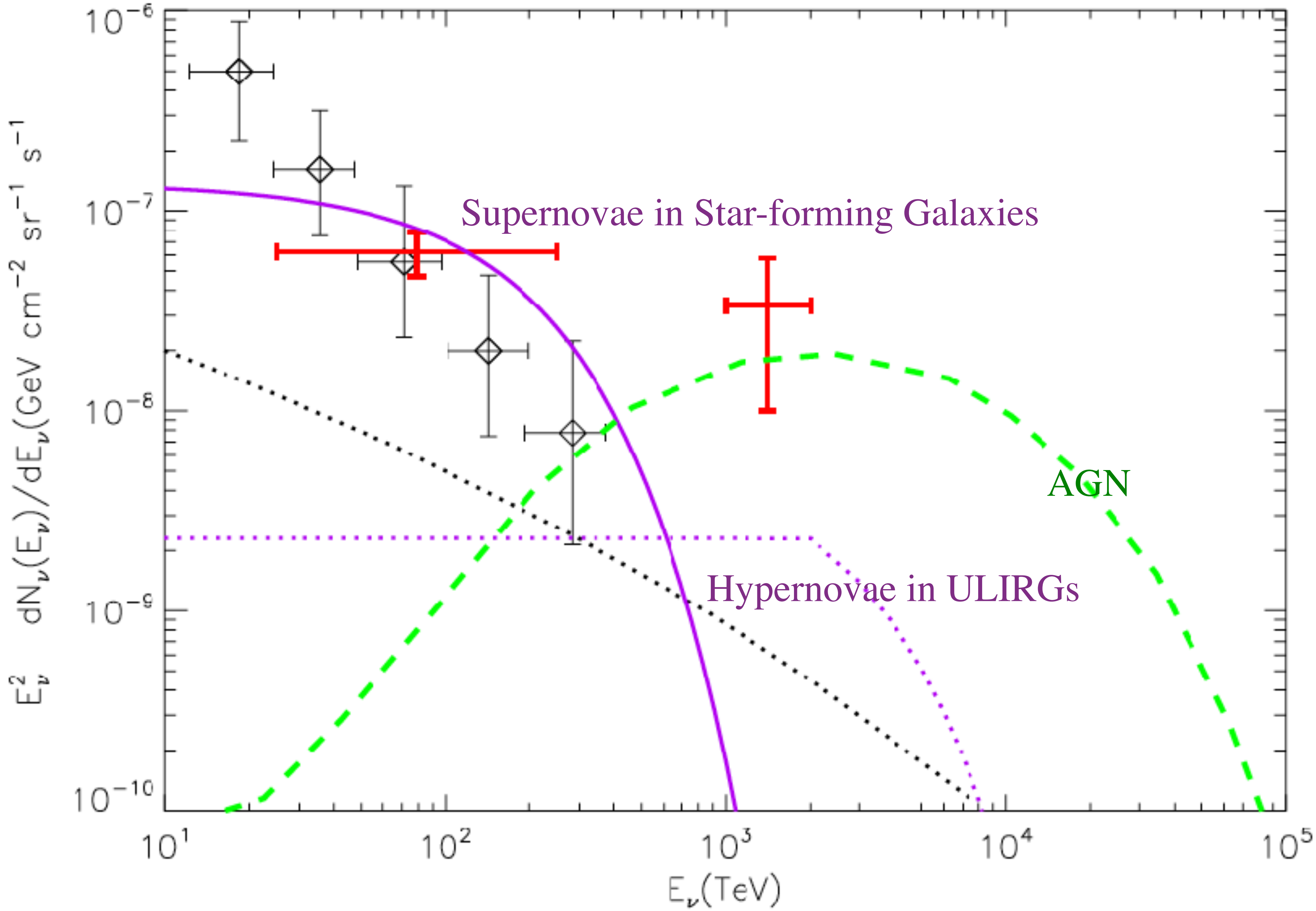
Protons with energy lower than 100PeV can be confined in the ULIRGs.
5% of the proton energy will be converted into neutrinos.

$$pp \longrightarrow \pi^0、\pi^{\pm}\ldots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

The Diffuse Neutrino Spectrum



We assume a flat proton spectrum with a cutoff.

He et al. 2013

The SNe High Energy Neutrinos

- 1. SNe/HNe in the Starburst Galaxies/Star-Forming Galaxies
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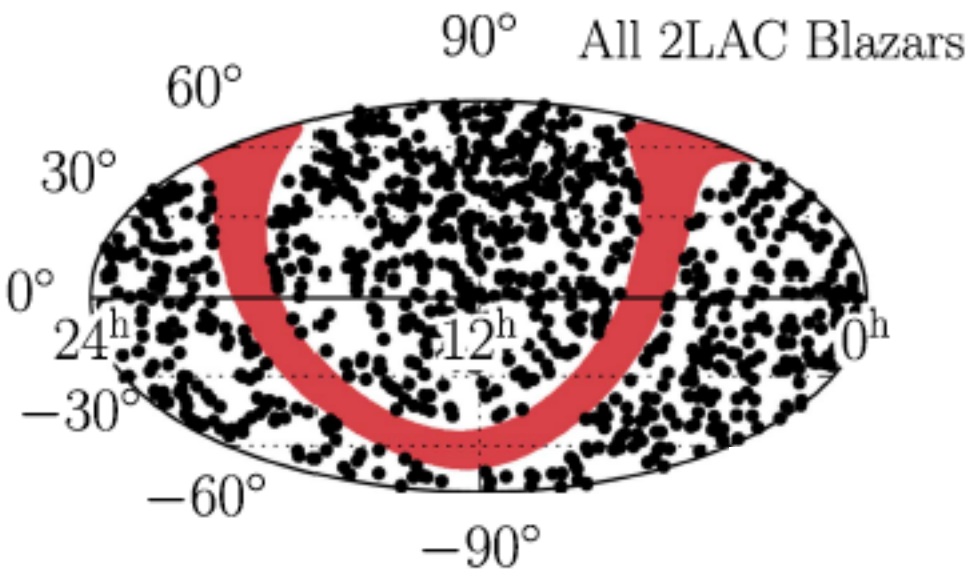
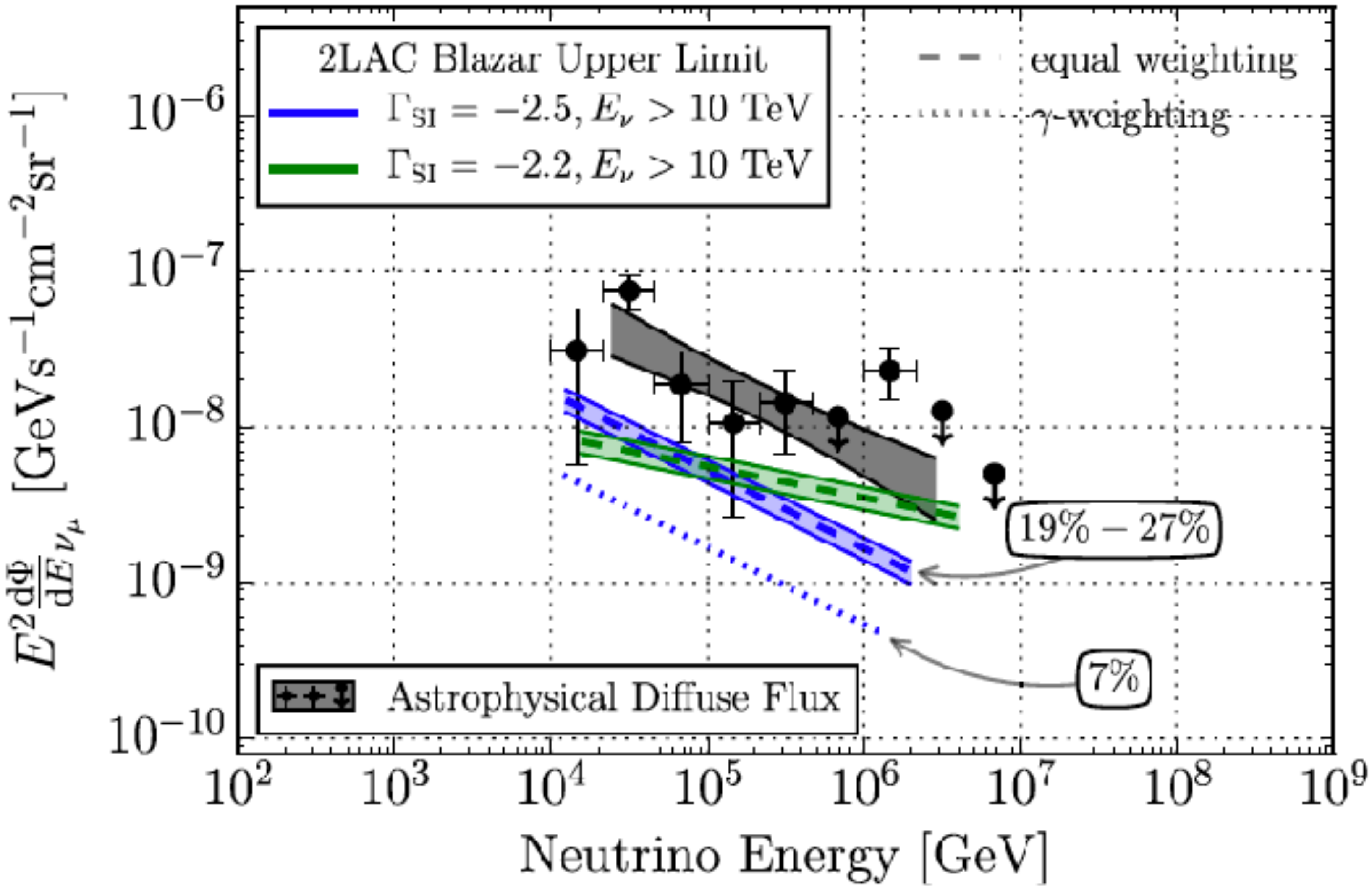
The Contribution of Fermi-2LAC Blazars

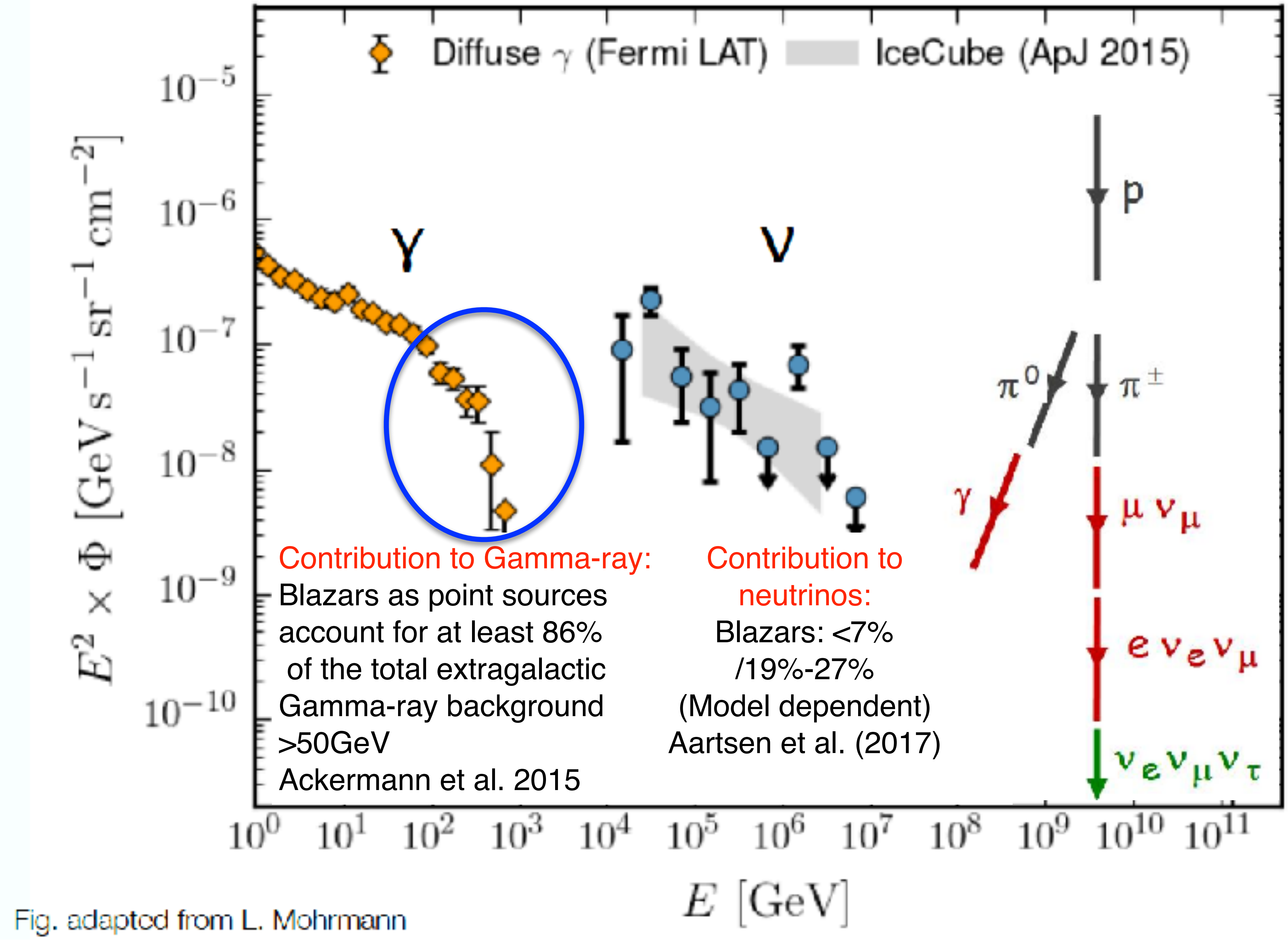


862 sources



The IceCube Collaboration, 2017,ApJ,835,45A

1. The neutrino sources themselves are opaque to gamma rays (choked jets, AGN cores).
2. Or the neutrino sources are distant(Chang et al. 2016).



Contribution to Gamma-ray:
Blazars as point sources account for at least 86% of the total extragalactic Gamma-ray background >50GeV
Ackermann et al. 2015

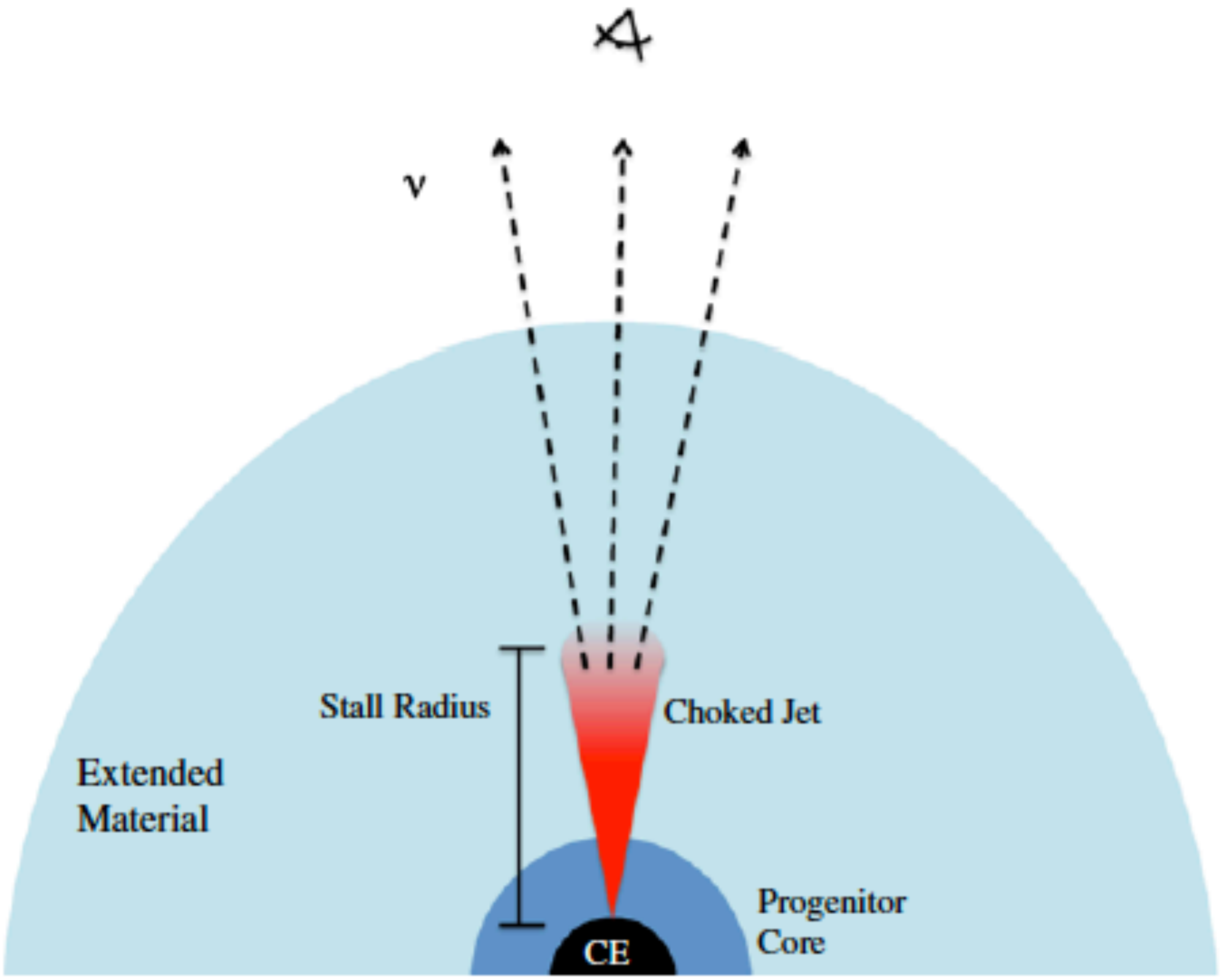
Contribution to neutrinos:
Blazars: <7% /19%-27%
(Model dependent)
Aartsen et al. (2017)

Fig. adapted from L. Mohrmann

The Choked Jet Model

1.The jet life time is shorter than the time of jet crossing the extended material/ a thick stellar envelope.

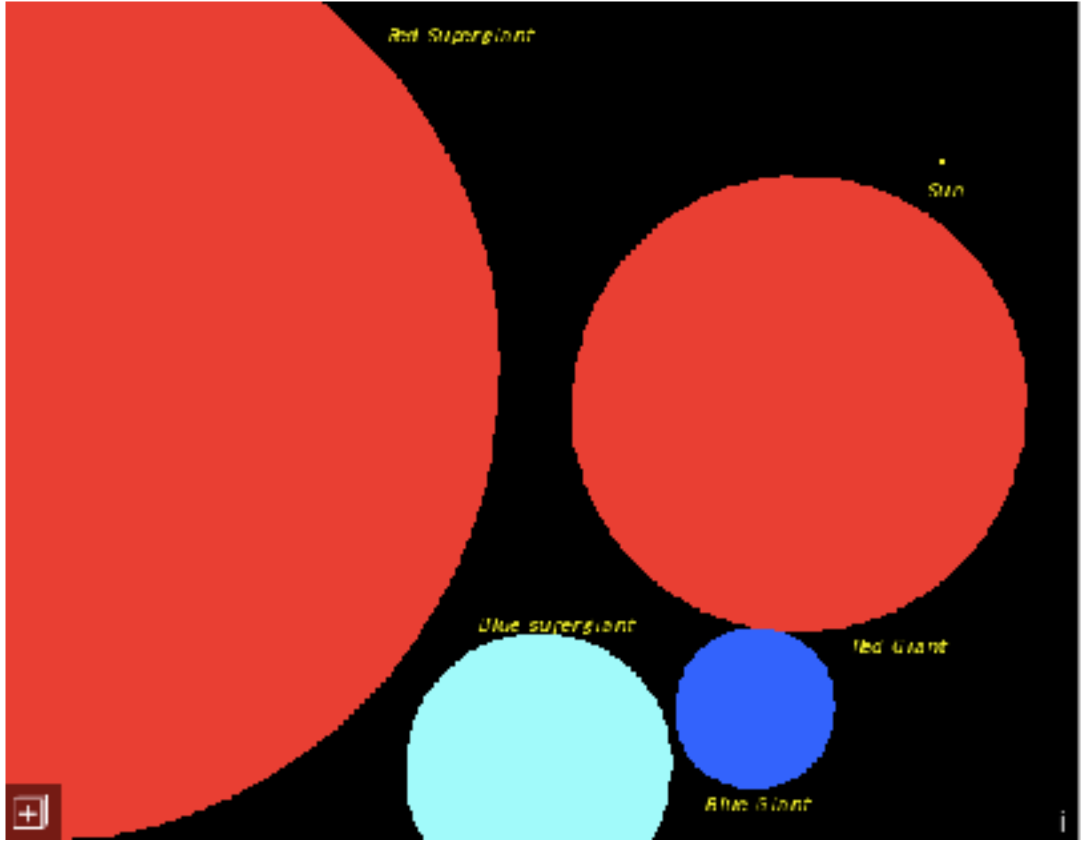
(Meszaros & Waxman 2001; Razzaque et al. 2004; Murase & Ioka 2013; Xiao & Dai 2014; Senno et al. 2016)



Senno et al. 2016

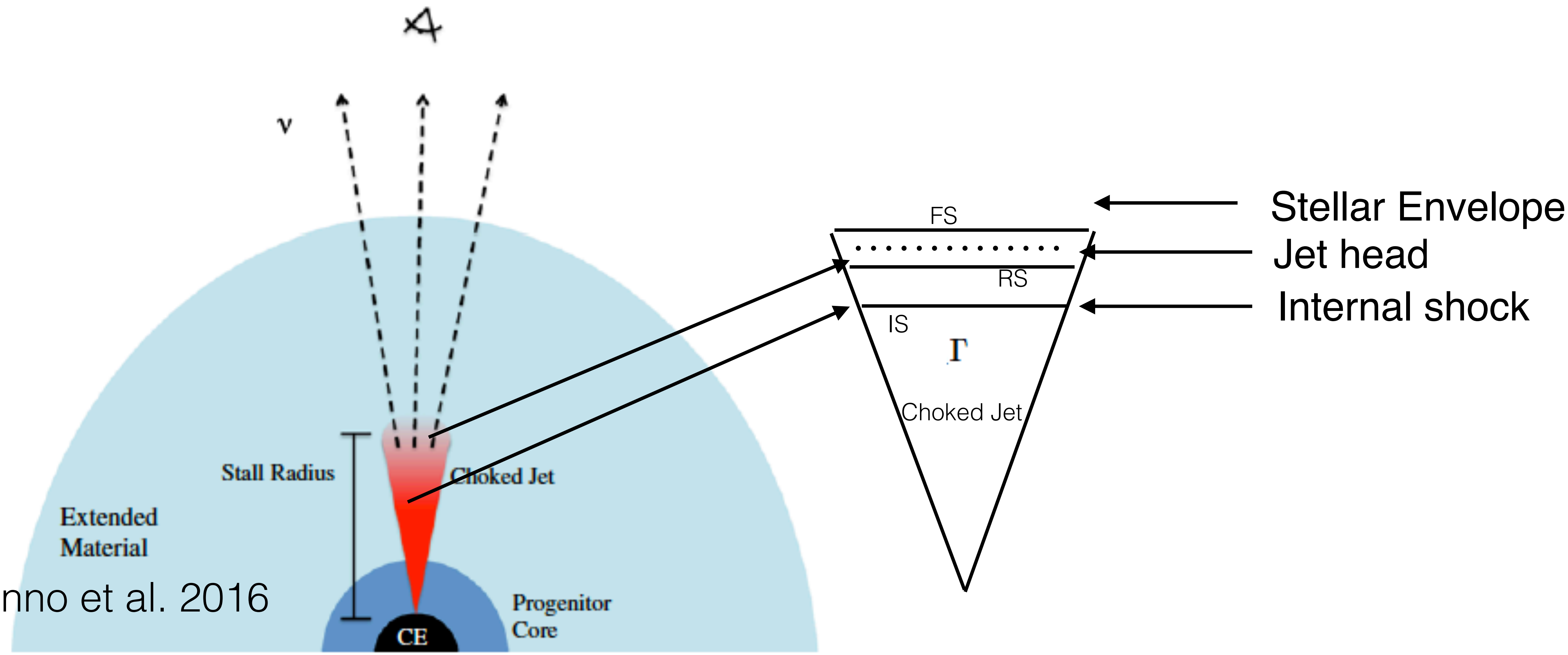
Red Supergiant Stars

Hydrogen envelope: R $\tilde{\sim} \ 3 \times 10^{13}$ cm



$t < t_{\rm cros}$ $\qquad t_{\rm cros} = 1.1 \times 10^5 \ {\rm s} \ R_{13.5}^2 L_{\rm iso,48}^{-1/2} \rho_{\rm H,-7}^{1/2}$

The Jet Head and Internal Shock in the Choked Jet



Stellar Envelope

Jet head

Internal shock

Senno et al. 2016

2.Cosmic rays are accelerated efficiently. The comoving size of the upstream flow is much smaller than the mean free path of the photons.

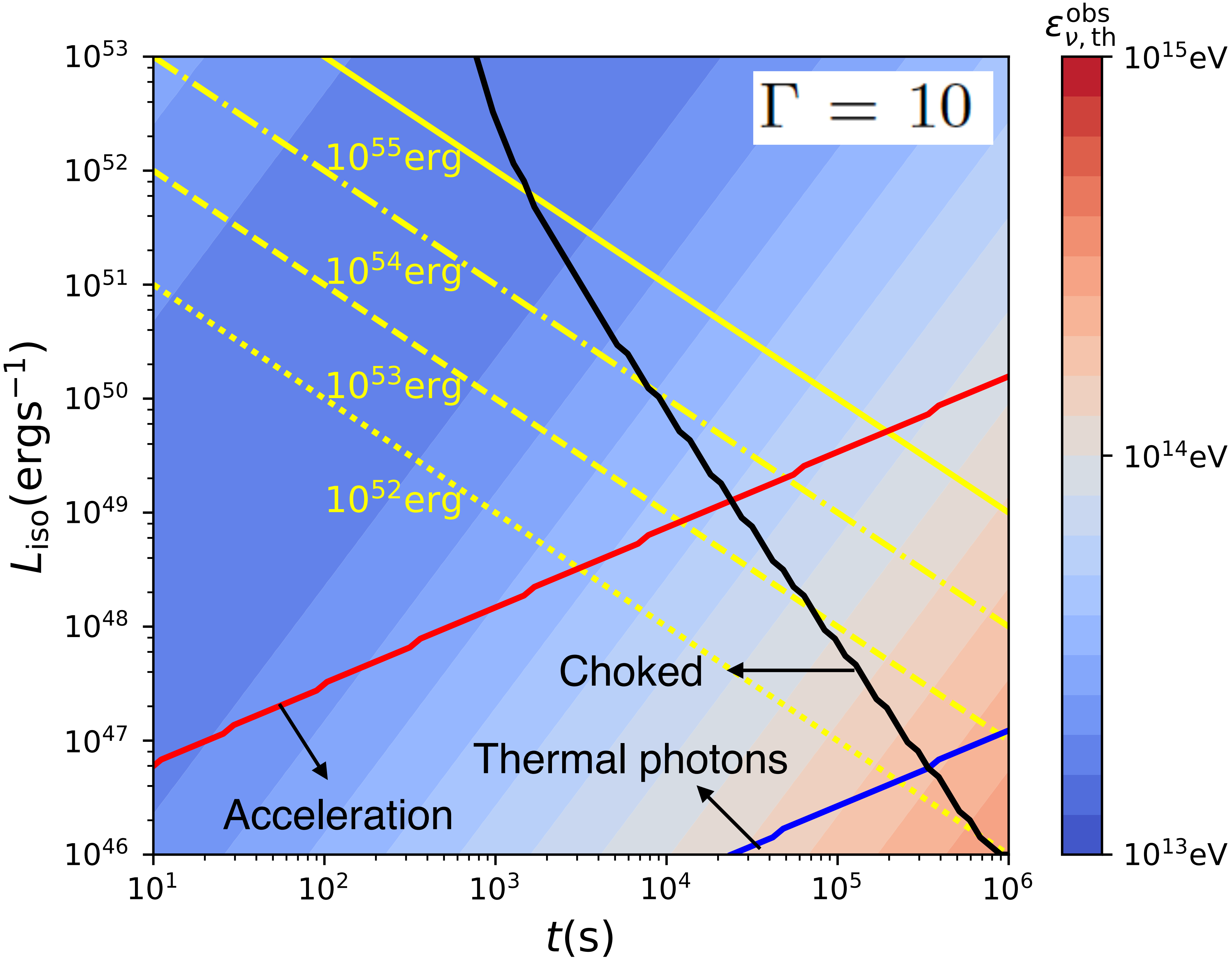
$$\tau = 0.13\,\Gamma_1^{-3} L_{\mathrm{iso},48}^{3/4} t_4^{-1/2} \rho_{\mathrm{H},-7}^{1/4} < \min[\Gamma_{\mathrm{rel}}^2, 0.1 C^{-1} \Gamma_{\mathrm{rel}}^3],$$

3. The jet head is optical thick, then thermal photons are produced and escaping to the internal shock with a fraction of $f_{\mathrm{esc}} = 1/\tau_{\mathrm{h}}$.

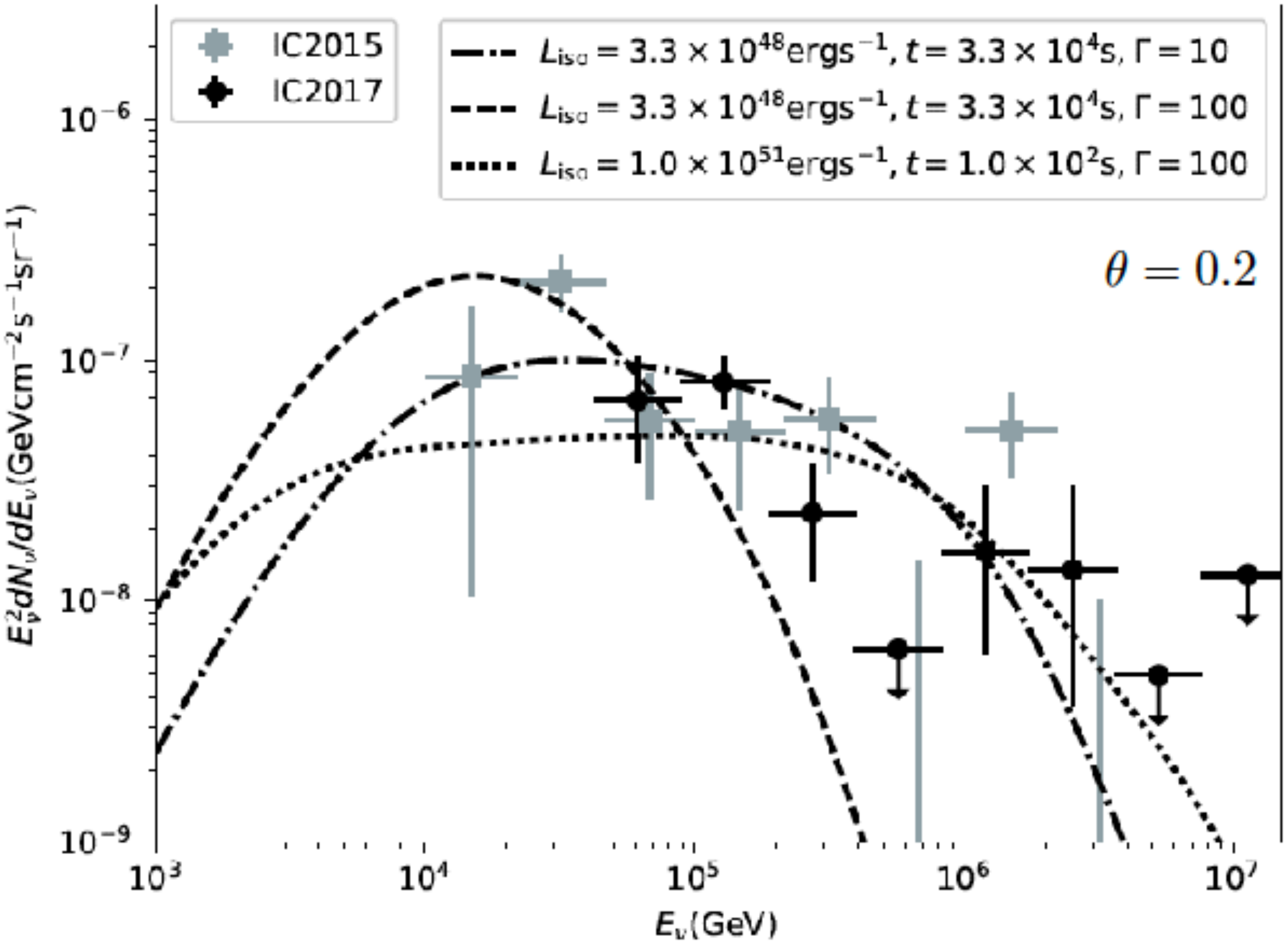
$$\tau_{\mathrm{h}} = n_{\mathrm{h}} \sigma_{\mathrm{T}} R_{\mathrm{h}} = 52\,\Gamma_1^{-1} L_{\mathrm{iso},48}^{3/4} t_4^{-1/2} \rho_{\mathrm{H},-7}^{1/4} f_{\mathrm{a}}$$

$$\epsilon_{\gamma,\mathrm{IS}} = \bar{\Gamma}(2.8 k_{\mathrm{B}} T_{\mathrm{h}}) = 2.8\times10^3\ \mathrm{eV}\ \epsilon_{\mathrm{e},-1}^{1/4} \Gamma_1 L_{\mathrm{iso},48}^{1/8} t_4^{-1/4} \rho_{\mathrm{H},-7}^{1/8} f_{\mathrm{c}}$$

Constraints on the Jet life time and the Luminosity



Diffuse Neutrino Spectra



We assume the choked jet rate is in proportion to the star formation rate

$$R_{\rm cj} = A_{\rm cj}\rho_{\rm sf}$$

$$\rho_{\rm sf} = 0.015\frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} M_\odot {\rm yr}^{-1}{\rm Mpc}^{-3}$$

Madau & Dickinson (2014)

The constrained local rate of the choked jet: 1%-20% of the typical SNII rate

$$1.5 \times 10^3 - 2.1 \times 10^4\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

The rate of observing a muon neutrino multiplet: ~0.4/year

He+, 2018,ApJ,856,119H

Follow-up Observations

Newborn jet-driven supernova: Type II supernova

1. IceCube Optical Follow-up (OFU) program and X-ray Follow-up (XFU) program (Kowalski & Mohr 2007; Abbasi et al. 2012; Aartsen et al. 2015c)

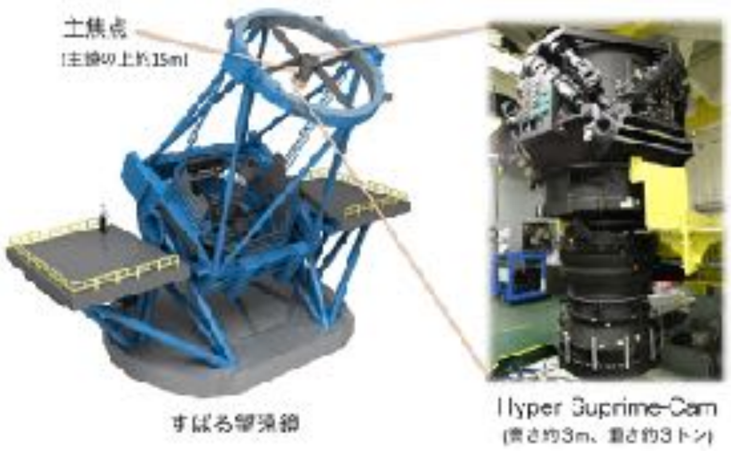
2. AMON ICECUBE_HESE EVENTS Alerts

Kiso Wide Field Camera (KWFC): 2.2 degree FOV

Large Synoptic Survey Telescope(LSST)

Pan-STARRS1(PS1) 3.3 degree FOV

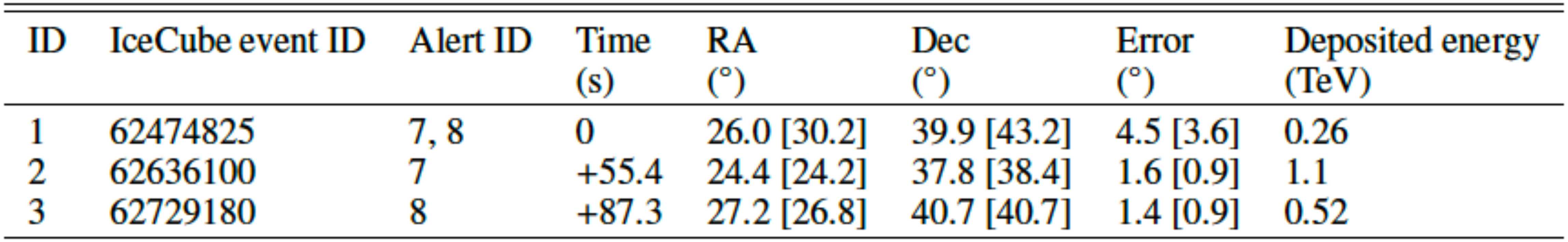
Subaru Hyper-Suprime-Cam (HSC):
1.5 degree FOV



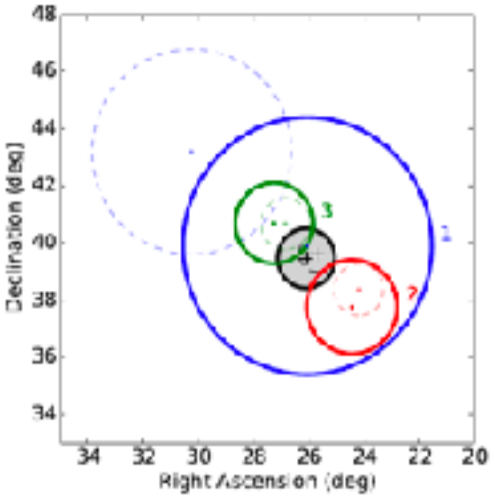
A Rare IceCube Neutrino Multiplet

On February 17, 2016, the IceCube real-time neutrino search identified, for the first time, three muon neutrino candidates arriving within 100 s of one another, consistent with coming from the same point in the sky.

Such a triplet is expected once every 13.7 years as a random coincidence of background events.

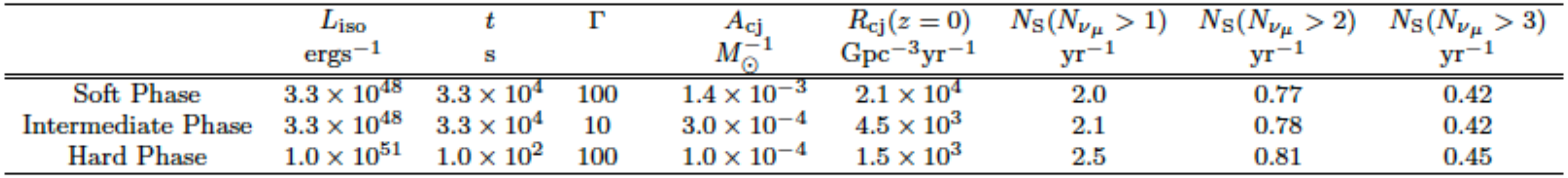


ID	IceCube event ID	Alert ID	Time (s)	RA (°)	Dec (°)	Error (°)	Deposited energy (TeV)
1	62474825	7, 8	0	26.0 [30.2]	39.9 [43.2]	4.5 [3.6]	0.26
2	62636100	7	+55.4	24.4 [24.2]	37.8 [38.4]	1.6 [0.9]	1.1
3	62729180	8	+87.3	27.2 [26.8]	40.7 [40.7]	1.4 [0.9]	0.52



The IceCube Collaboration, 2017

Multiplets Predicted by the Choked Jet Model



	$L_{\rm iso}$ ergs^{-1}	t s	Γ	$A_{\rm cj}$ $M_\odot^{-1}$	$R_{\rm cj}(z=0)$ Gpc^{-3}yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>1)$ yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>2)$ yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>3)$ yr^{-1}
Soft Phase	3.3×10^{48}	3.3×10^{4}	100	1.4×10^{-3}	2.1×10^{4}	2.0	0.77	0.42
Intermediate Phase	3.3×10^{48}	3.3×10^{4}	10	3.0×10^{-4}	4.5×10^{3}	2.1	0.78	0.42
Hard Phase	1.0×10^{51}	1.0×10^{2}	100	1.0×10^{-4}	1.5×10^{3}	2.5	0.81	0.45

- We predict that 4 multiplets within ~1000 s to ~10,000 s can be found in 10 years operation of IceCube.

- Wider time window might introduce more atmospheric neutrinos.

He+, 2018,ApJ,856,119H

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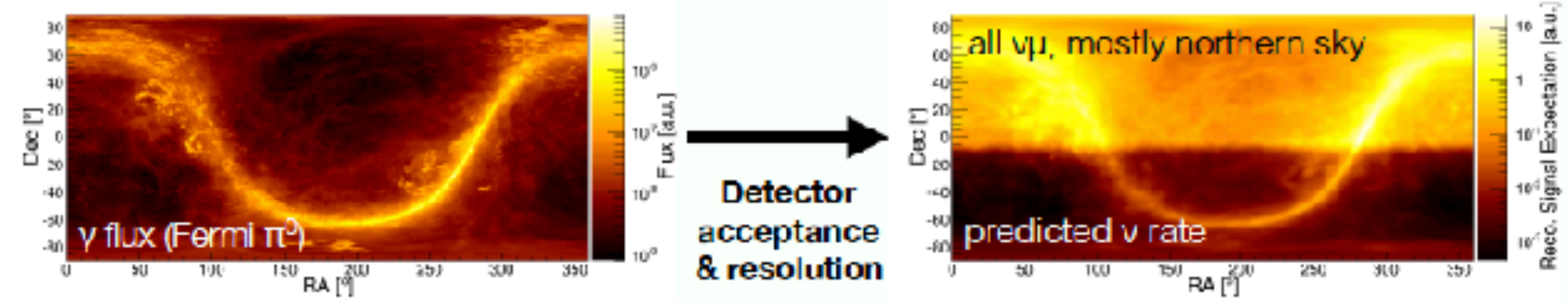
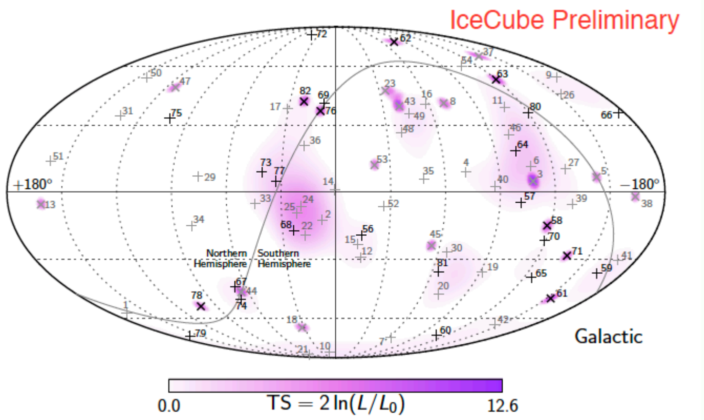
Neutrinos from the Galactic plane

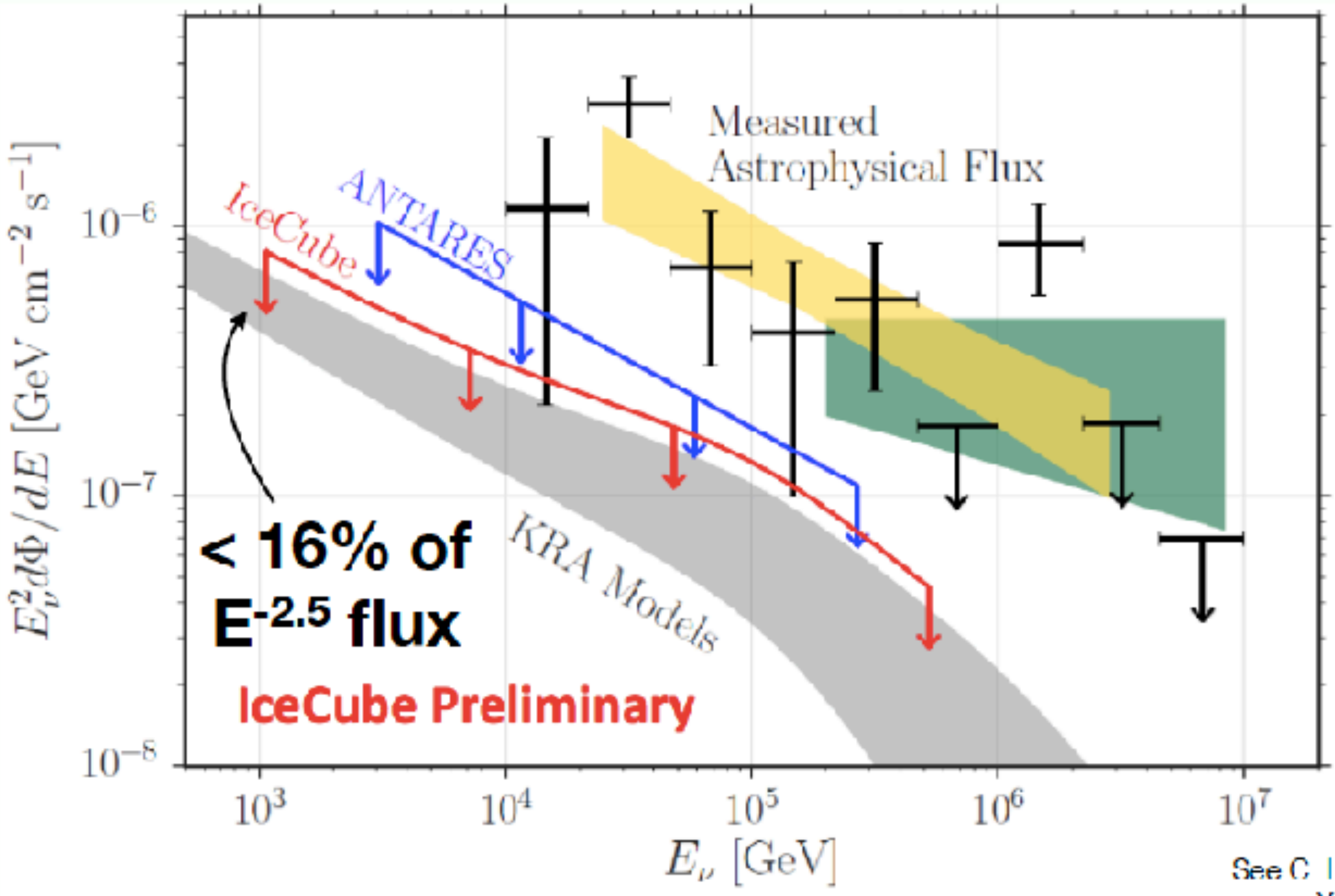
Two Assumptions:

1. Hadronic Origin
2. Cosmic rays are accelerated to >PeV.



Detector acceptance & resolution

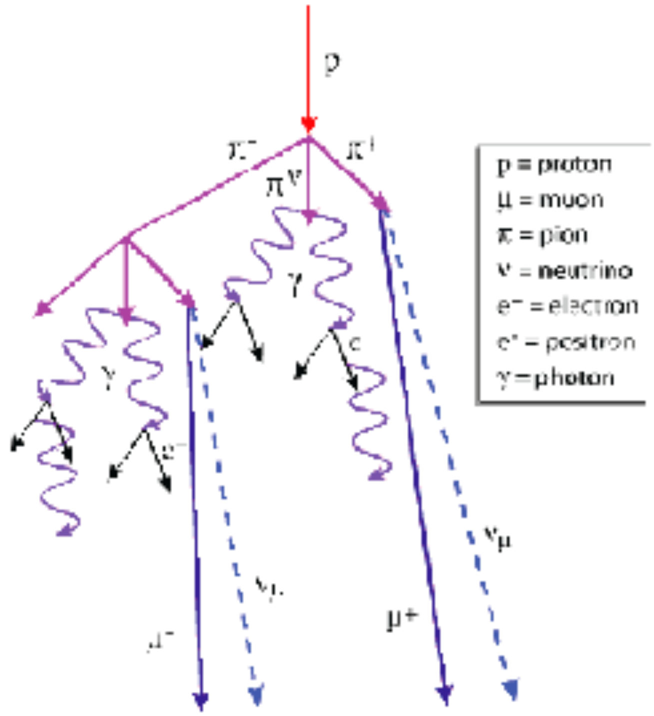




< 16% of $E^{-2.5}$ flux

IceCube Preliminary

See C. Haack, NU018
arXiv.1707.03416



Observations on >10 TeV Gamma-rays

Two Assumptions:

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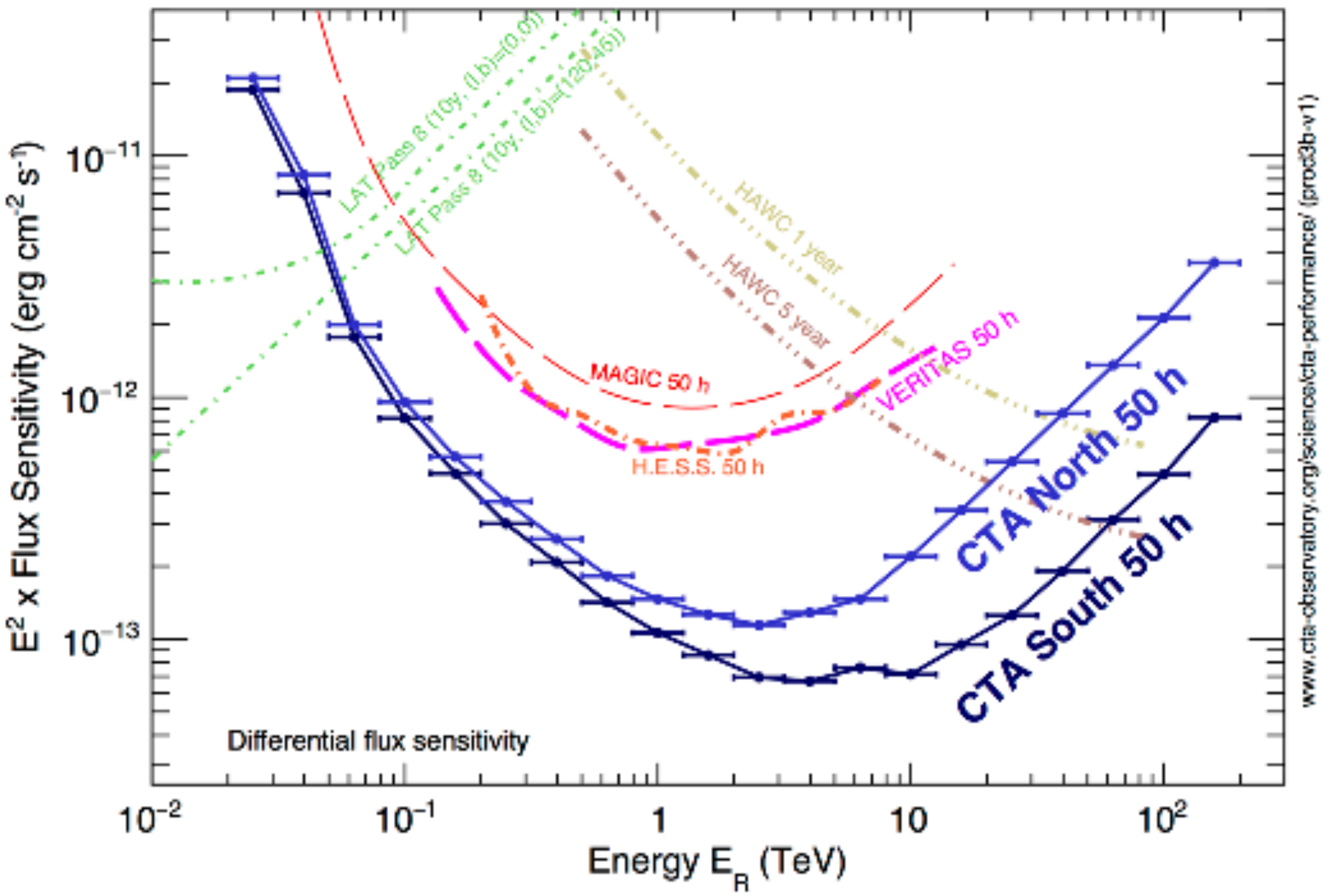
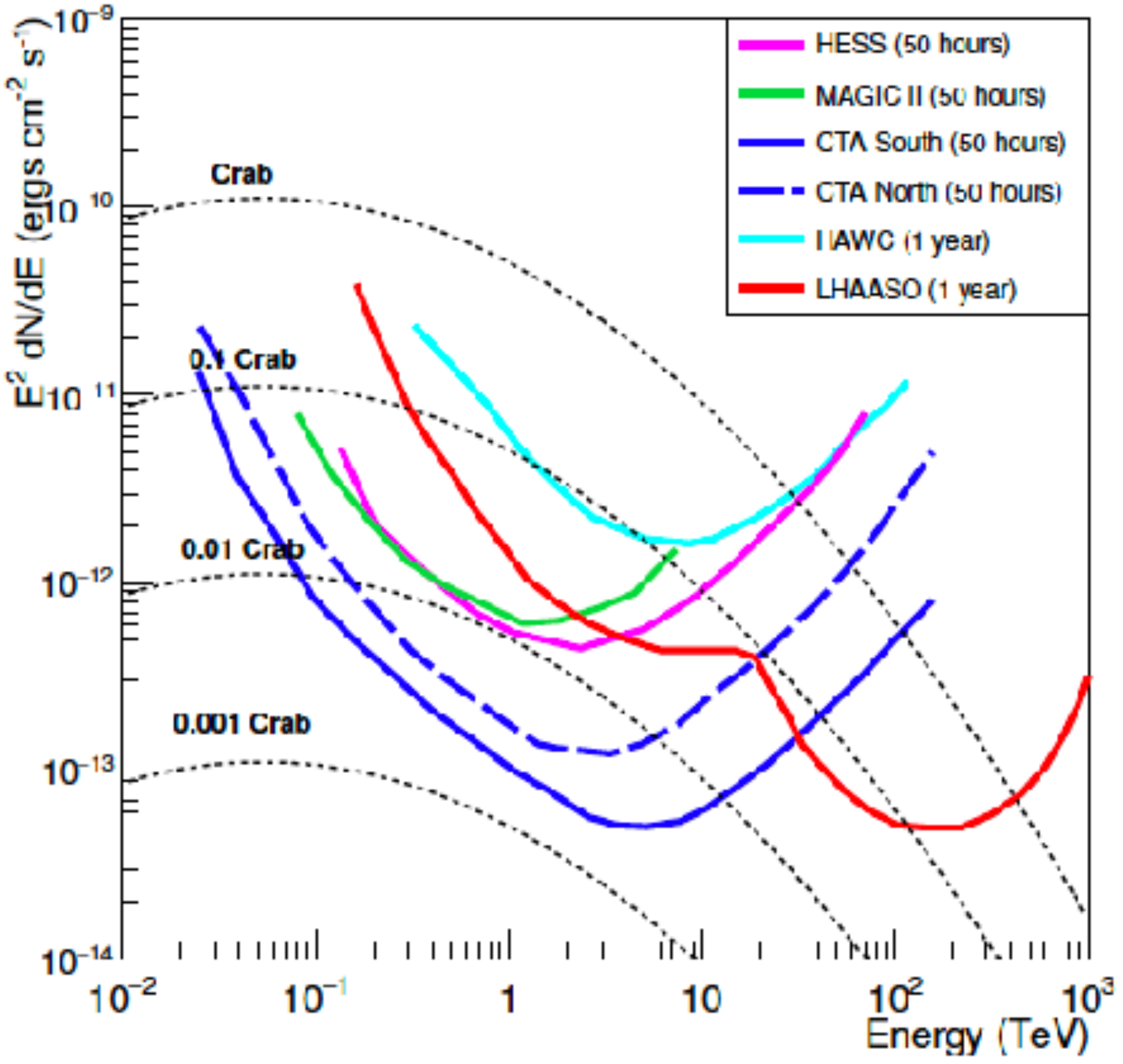
2. Cosmic rays are accelerated to >PeV.





Hypernova+Molecular Cloud Complex

In 10,000 years, there might be one HNe exploded in the Galaxy.

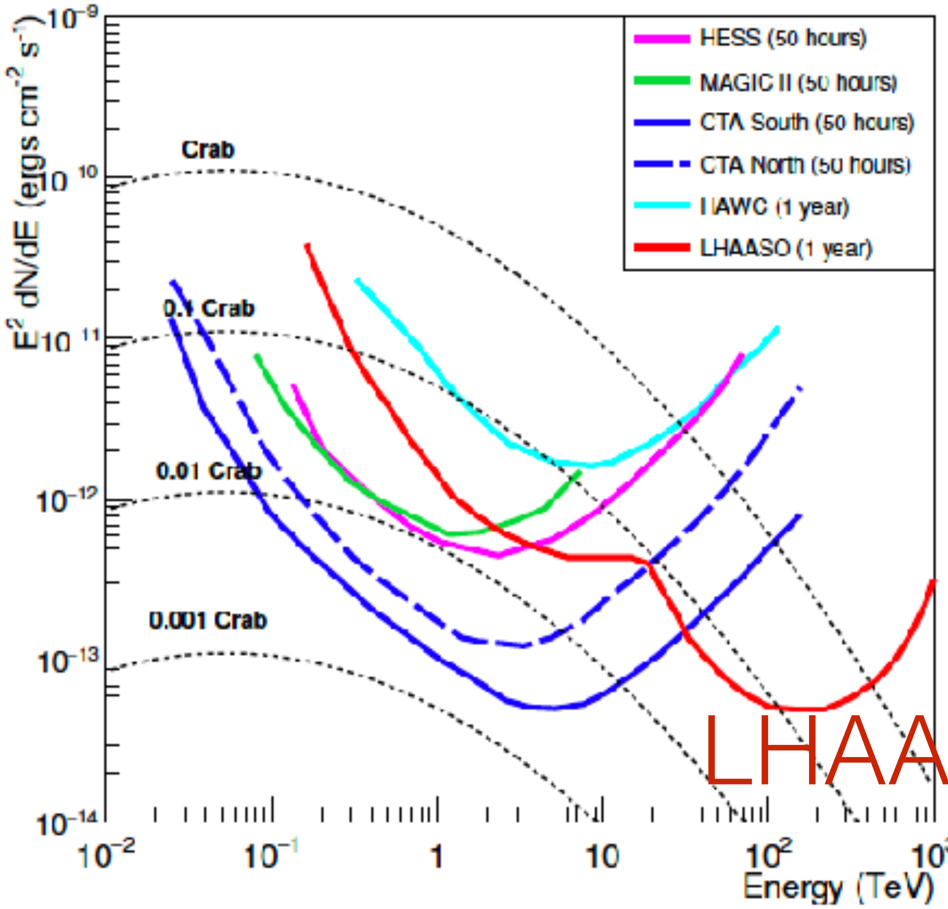
$$R_{\rm diff} = 2\sqrt{D(1{\rm PeV})T} = 0.2\ {\rm kpc} D_{100,29}^{0.5} T_4^{0.5}$$

The efficiency of the hadronuclear interaction for a single proton is approximated to be

$$f_{\rm pp,inj} = min(n_{\rm H}\sigma_{\rm pp}cT, 1) = min(1\times10^{-4}\ M_6 D_{100,29}^{-1.5} T_4^{-0.5}, 1)$$

$$n_{\nu_\mu} = \frac{L_\nu/3}{\epsilon_\nu 4\pi d_{\rm SFR}^2} A_{\rm eff}\Delta t = 1\ \underline{E_{\rm inj,50.7} M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm SFR,1}^{-2}} A_{\rm eff,0.5}\Delta t_1$$

$$F_\gamma = \frac{L_\gamma}{4\pi d_{\rm s}^2} = 5\times10^{-12}{\rm TeV cm^{-2} s^{-1}} E_{\rm inj,50.7} M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$$



LHAASO

$$t_{\rm LH} = 22\ {\rm day} E_{\rm inj,50.7} M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$$

10 TeV photons from the Galactic Center

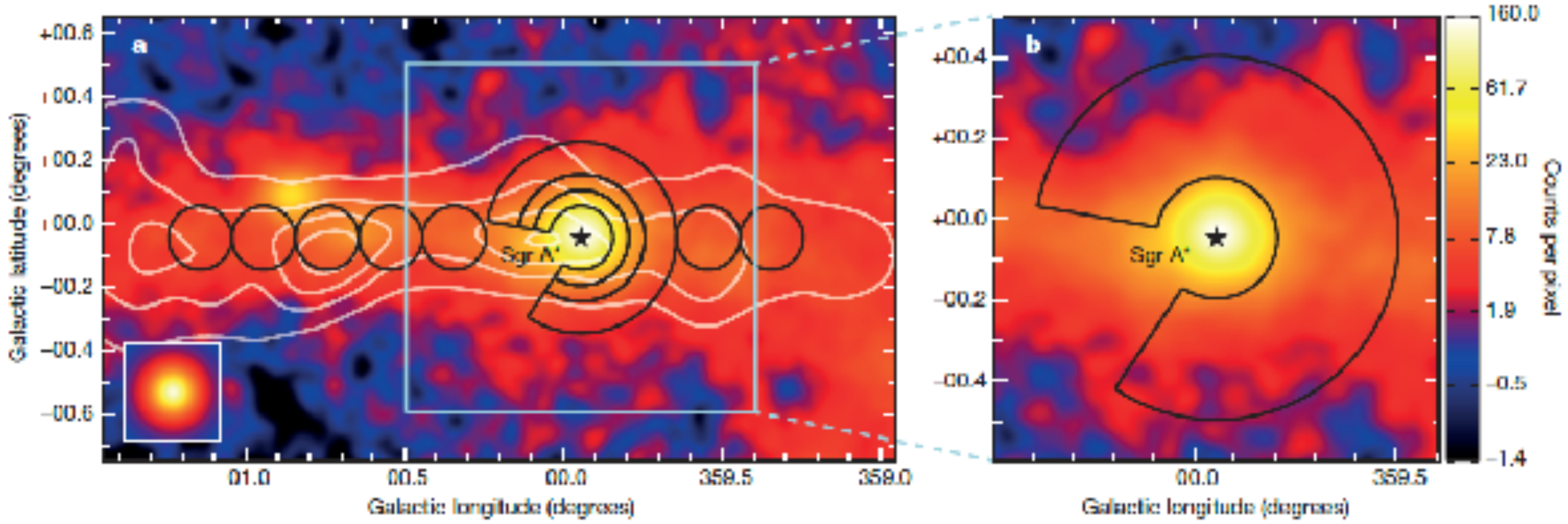


Figure 1 | VHE γ-ray image of the Galactic Centre region. The colour scale indicates counts per 0.02° × 0.02° pixel. a, The black lines outline the regions used to calculate the cosmic-ray energy density throughout the central molecular zone. A section of 66° is excluded from the annuli (see Methods). White contour lines indicate the density distribution of molecular gas, as traced by its CS line emission[30]. Black star, location of Sgr A*. Inset (bottom left), simulation of a point-like source. The part of the image shown boxed is magnified in b. b, Zoomed view of the inner ~70 pc and the contour of the region used to extract the spectrum of the diffuse emission.

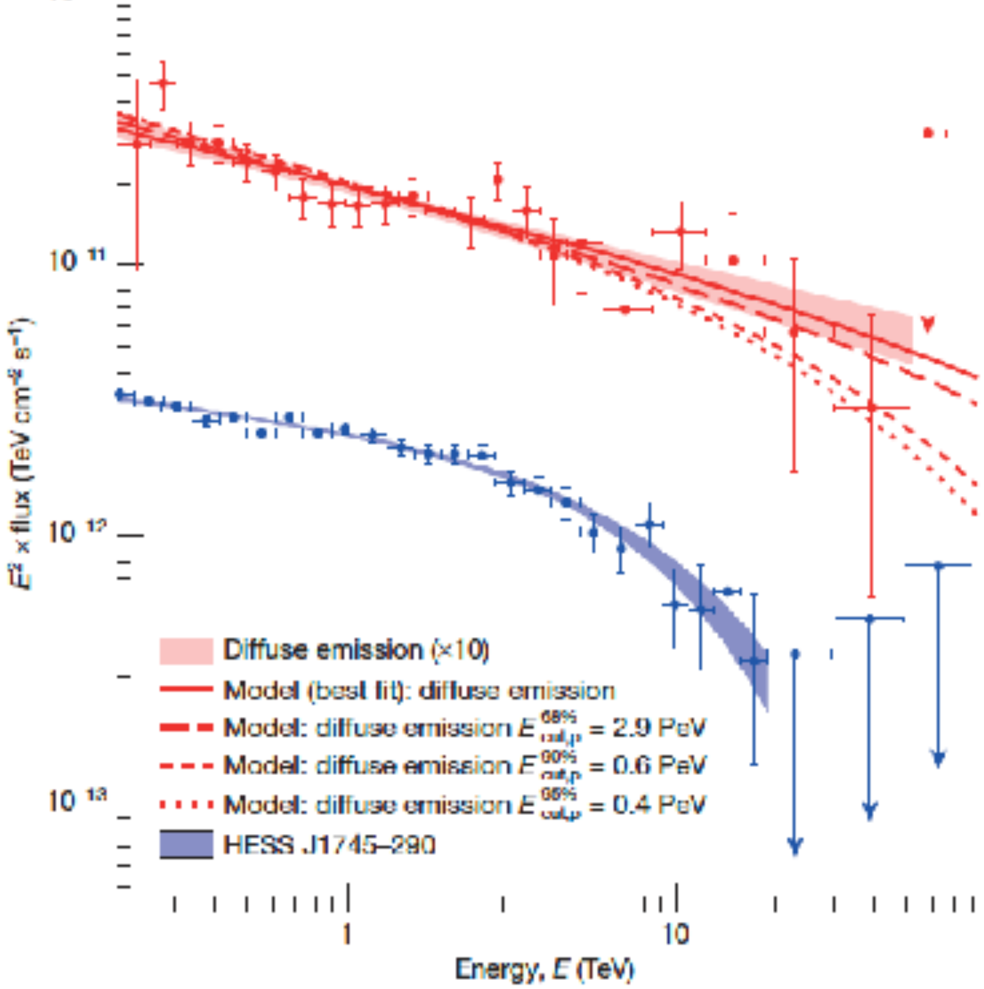
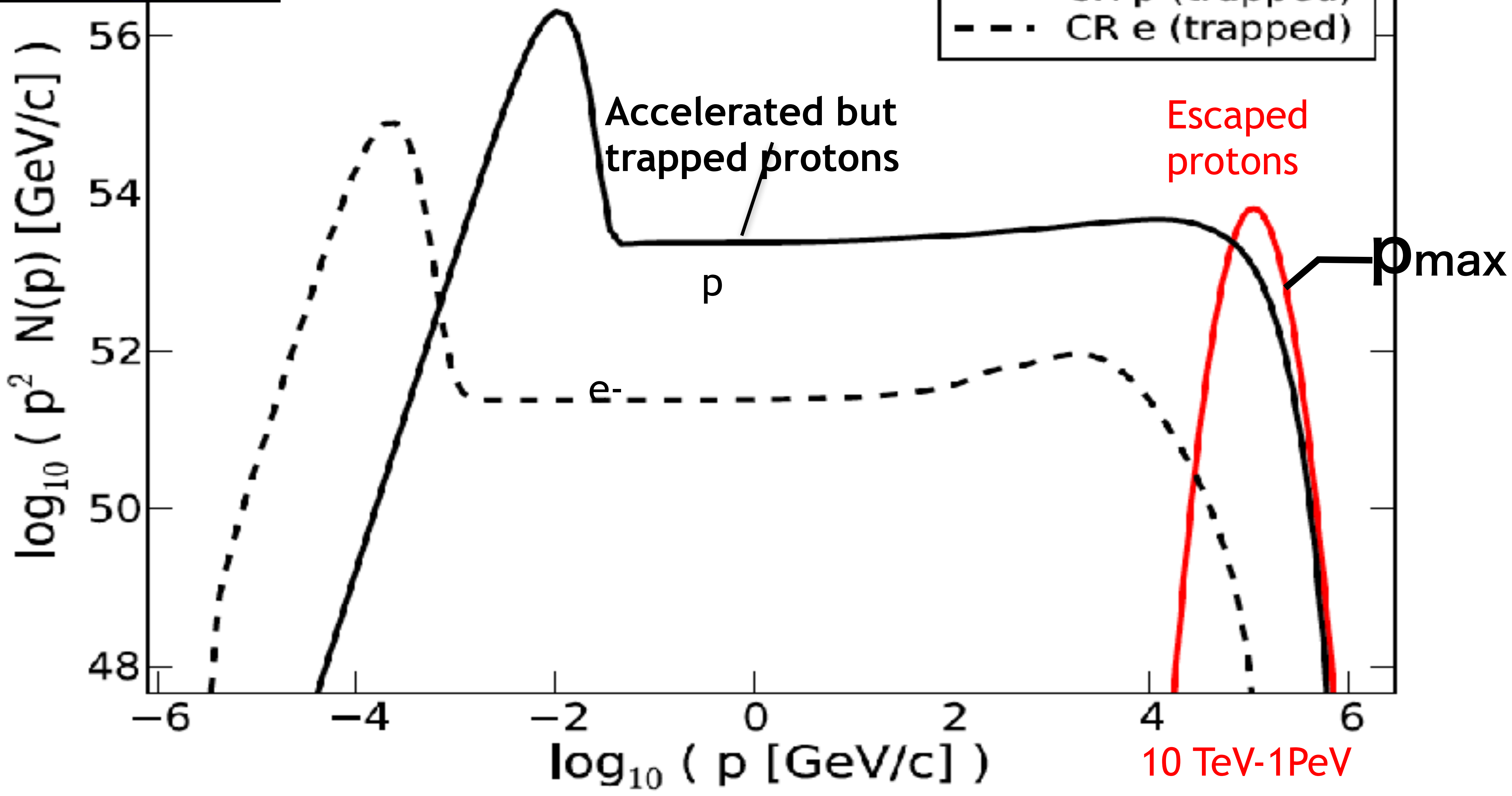


Figure 3 | VHE γ-ray spectra of the diffuse emission and HESS J1745–290. The y axis shows fluxes multiplied by a factor E^2, where E is the

Non-linear Diffusive Shock Acceleration in SNR/HNR

S.H. Lee
(Kyoto University)

Lee, Ellison & Nagataki (2012)



Evolving continuous escaping protons from a HNR

E_{SN} = 3e52 erg (c.f. SN1998bw)

M_{ejecta} = 14 M_{Sun}

dM/dt = 3e-5 M_{Sun}/yr

v_{wind} = 10 km/s

E_p=1e52erg

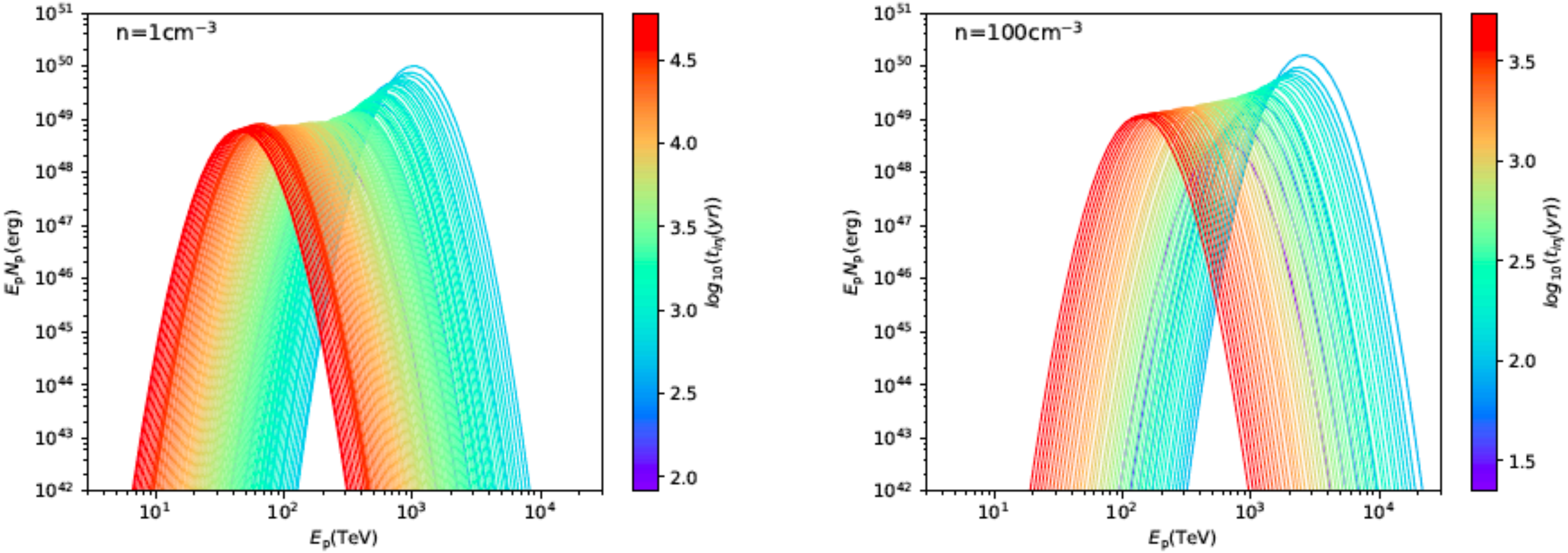
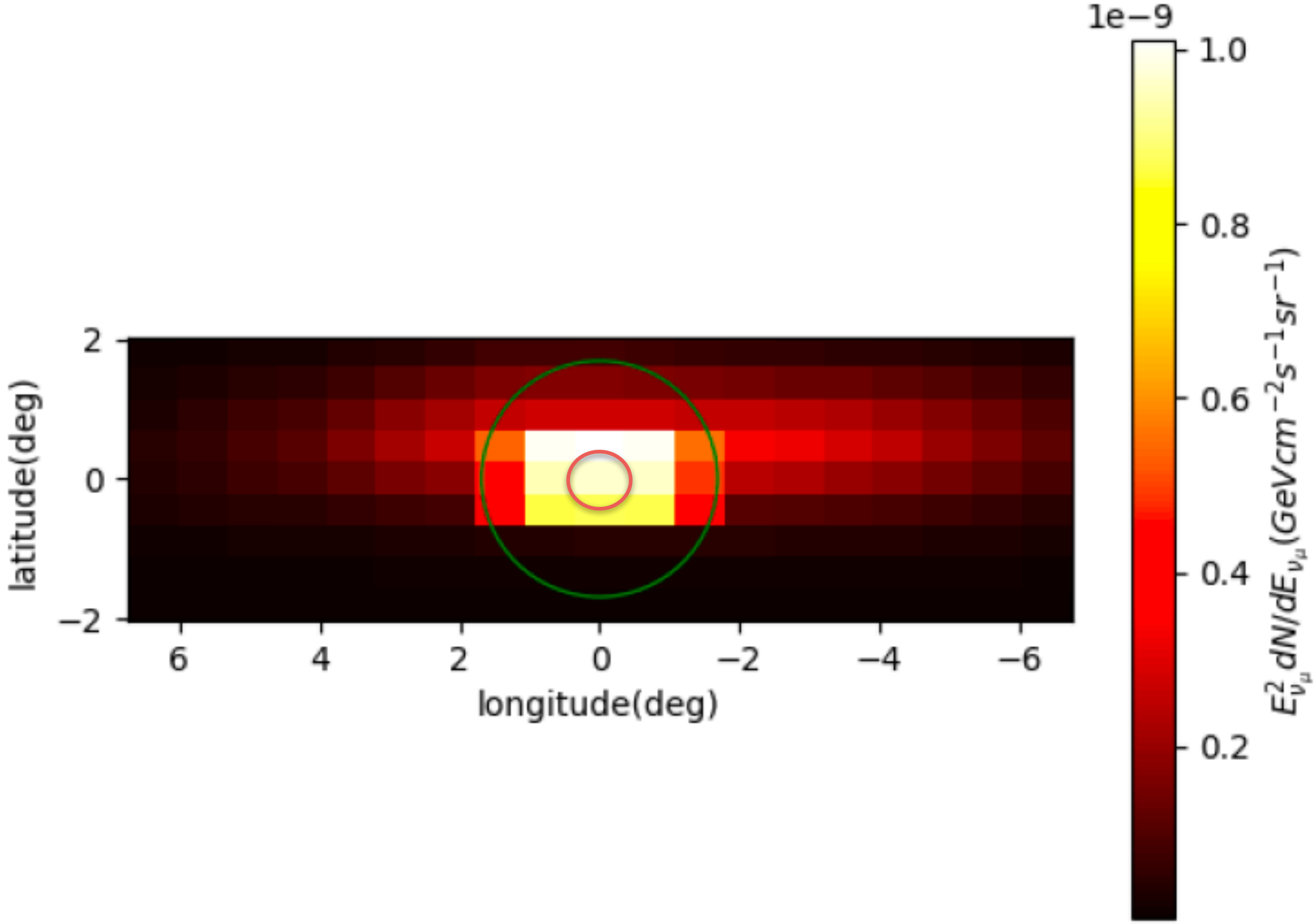


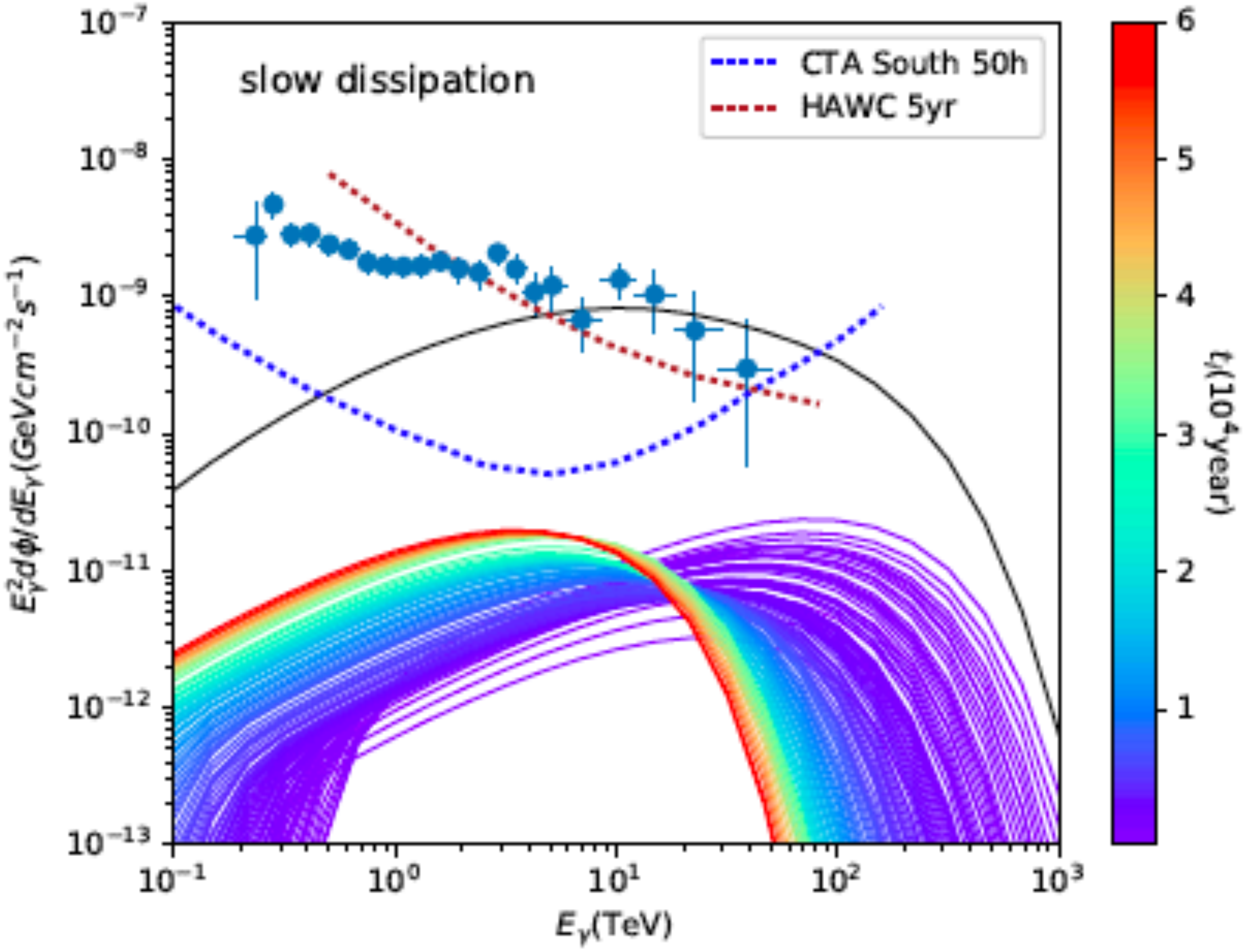
Figure 1. The energy spectrum of the escaping protons for the slow dissipation case (left panel) and the fast dissipation case (right panel), where $E_{\rm HN} = 3 \times 10^{52}$ erg and $M_{\rm ej} = 14\ M_{\odot}$.

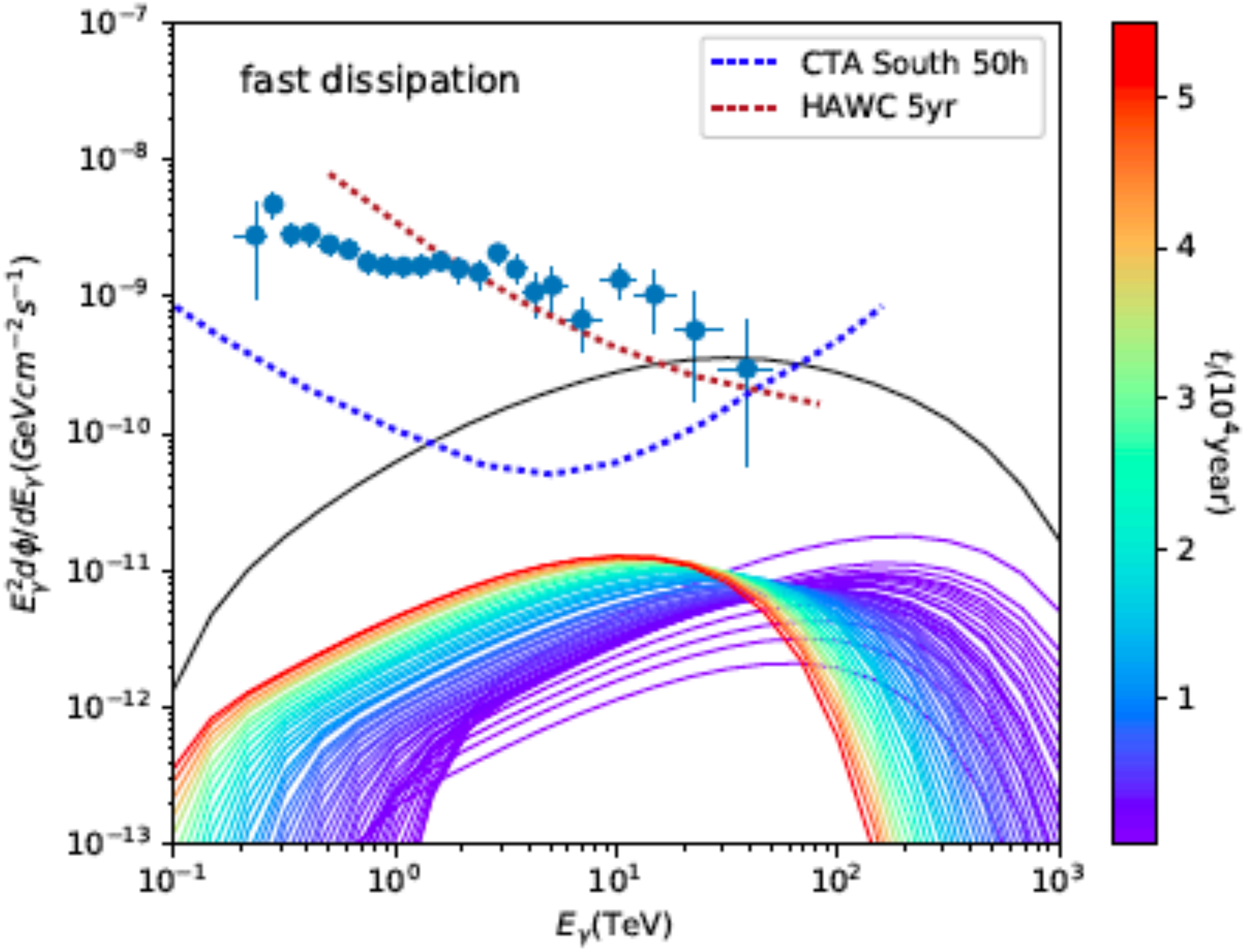
A Neutrino Template of the Galactic Center for IceCube



The neutrino distribution follows the Gas distribution around the Galactic Center presented in Nakanishi & Sofue (2006 , 2016).

Gamma-Ray Spectra

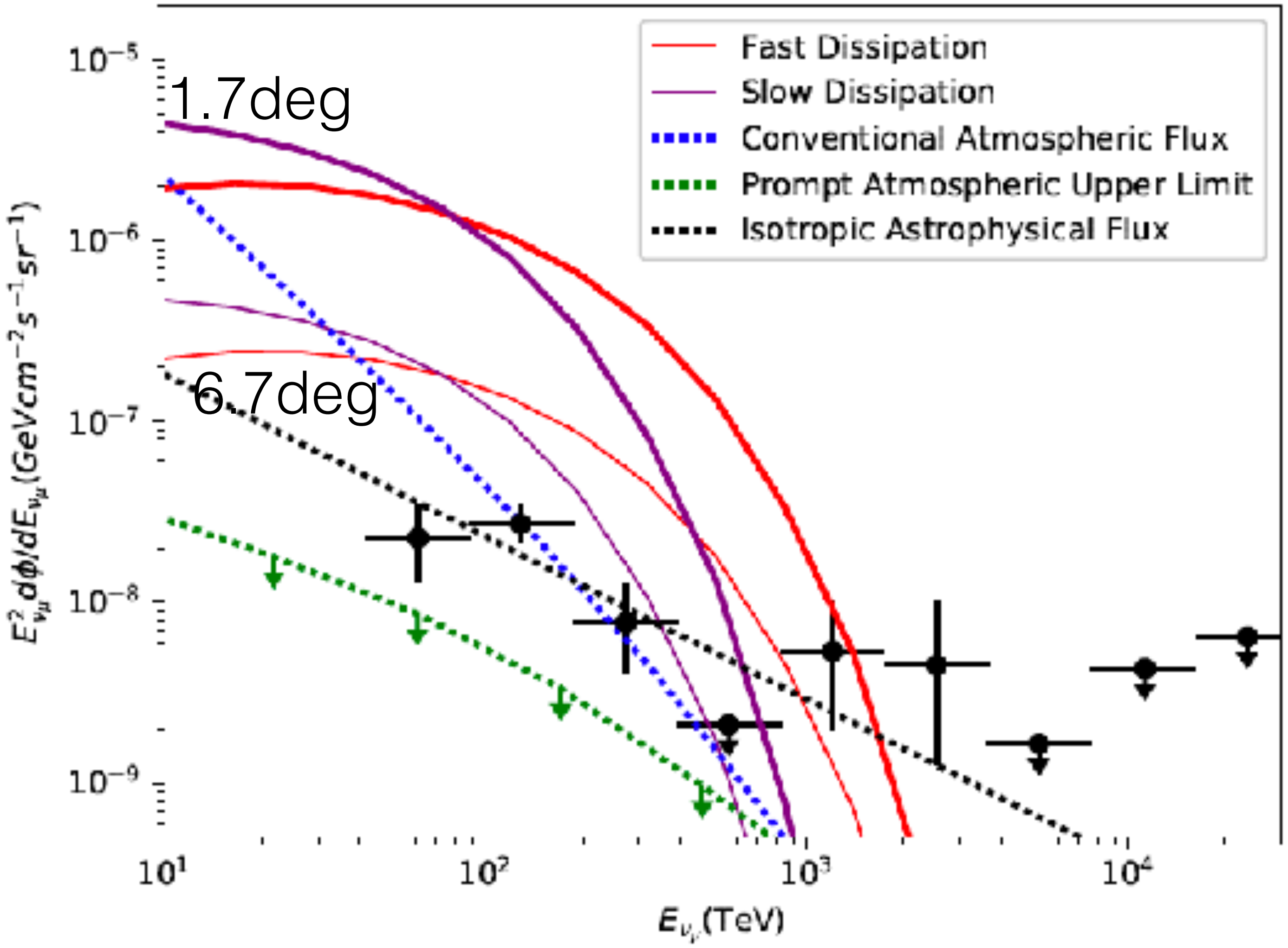




$D(\epsilon_\mathrm{p}) = D_{100}(\epsilon_\mathrm{p}/100 \text{ TeV})^\delta$ with δ assumed to be 0.6 here D100=1e29cm^2/s, T=3e5yr

He+ 2019, in preparation

Neutrino Spectra and Counts



IceCube Effective Area

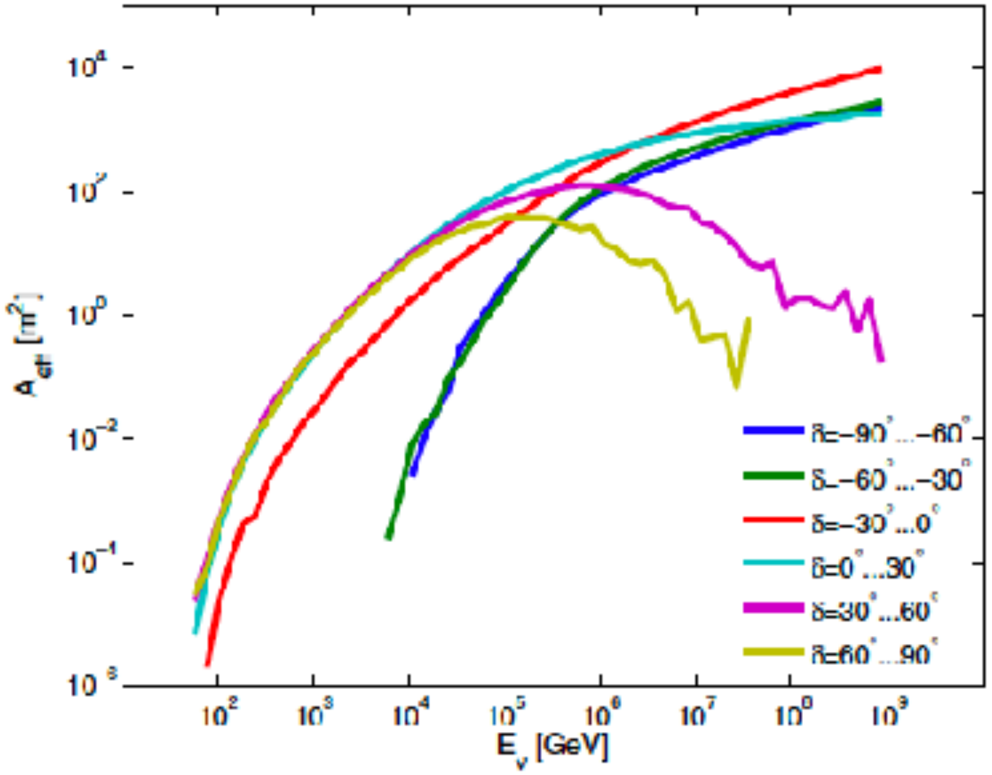


Figure 1. Effective area of the complete IC86 for ν_μ point sources vs. neutrino energy (A. Karle & J. Feintzeig 2014, private communication). Different declinations (δ) on the sky are plotted separately.

Neutrino Counts

$R_A = 6.7°$	N_{atm}	N_{iso}	N_{SD}	N_{FD}
$\epsilon_{\nu_\mu} > 10$ TeV	10	2.2	9.2	8.4
$\epsilon_{\nu_\mu} > 30$ TeV	2.4	1.1	4.7	5.7

$R_A = 1.7°$	N_{atm}	N_{iso}	N_{SD}	N_{FD}
$\epsilon_{\nu_\mu} > 10$ TeV	0.64	0.14	4.9	4.2
$\epsilon_{\nu_\mu} > 30$ TeV	0.15	0.068	2.4	2.8

N_{ν_μ}	1	2	3
C_{sd}	91.67%	99.31%	99.94%
C_{fd}	92.78%	99.48%	99.96%

The confidence level if detecting 1, 2, 3 muon neutrinos with energy larger than 30 TeV

Conclusions

- 1. The choked jet neutrinos can explain the neutrino flux observed by the IceCube under the constraint of the diffuse GeV gamma-ray background.

- 2. We make predictions on possible point sources/ multiplets/extended sources (choked jets, SN+MC complex, GC) for the IceCube's observation.

- 3. We make neutrino templets at the galactic center for the IceCube.

- 4. We make predictions for the future >10 TeV gamma-ray detections (CTA, LHASSO, HAWC).

Thank you!