中国科学院紫金山天文台
PURPLE MOUNTAIN OBSERVATORY , CAS

Neutrinos From A Past Hypernova In The Galactic Center

Haoning He (贺昊宁)
RIKEN / PMO

Collaborators: Alexander Kusenko, Shigehiro Nagataki, Herman Lee, Yizhong Fan, Daming Wei

Outlines

- 1. Neutrinos from a CR Accelerator+MC complex in the Galaxy
- 2. Neutrinos from A Past Hypernova the Galactic Center
- 3. Neutrinos from the Choked Jet Accompanied by SNII

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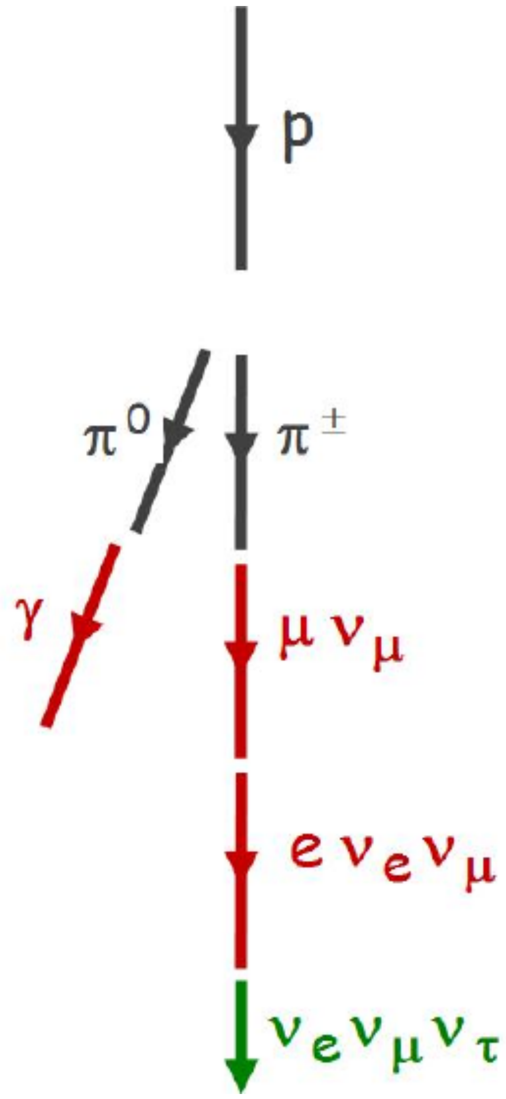
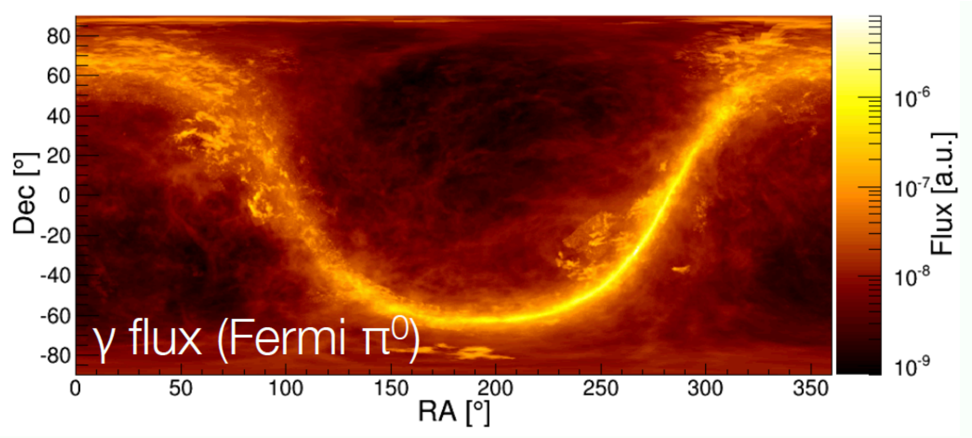
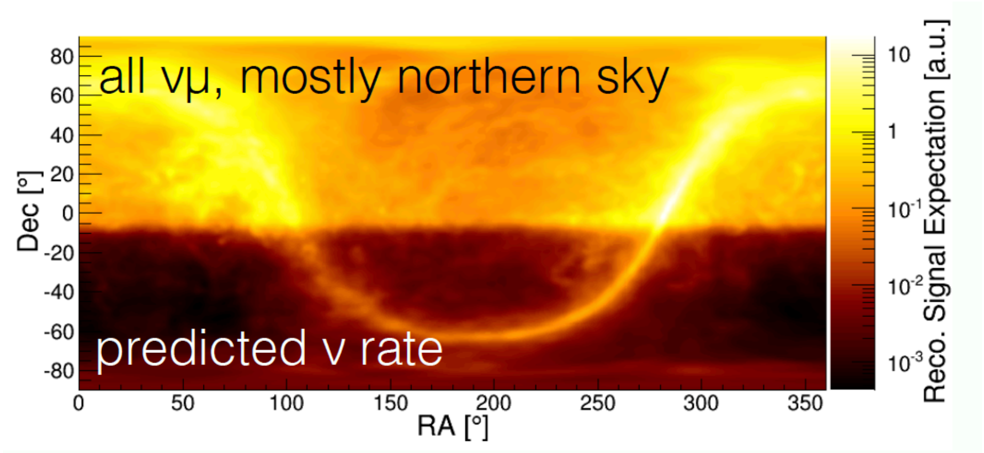
High Energy Neutrinos from the Galactic Plane



Two Assumptions:

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



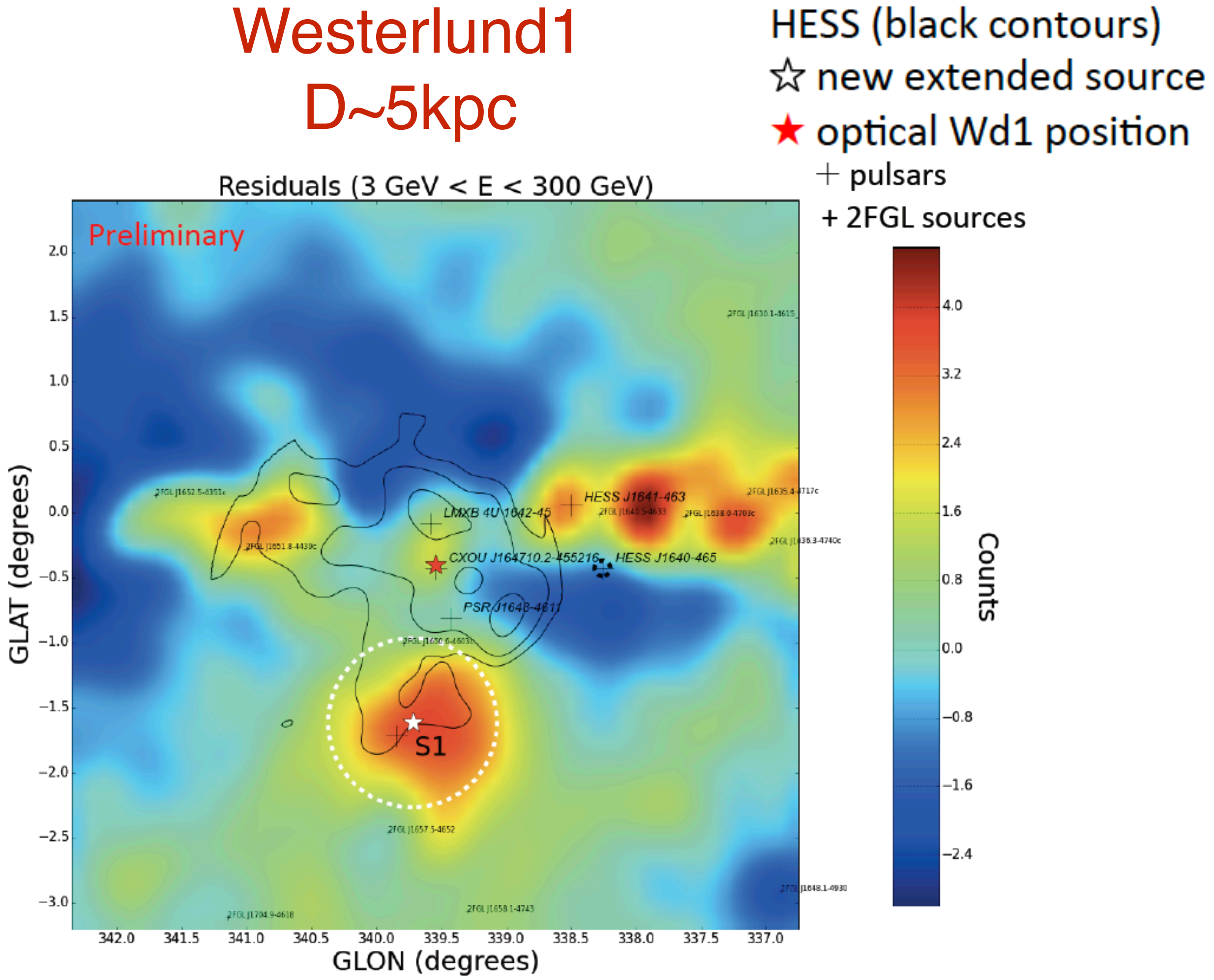


The IceCube Collaboration, ApJ, 849 (2017) 67

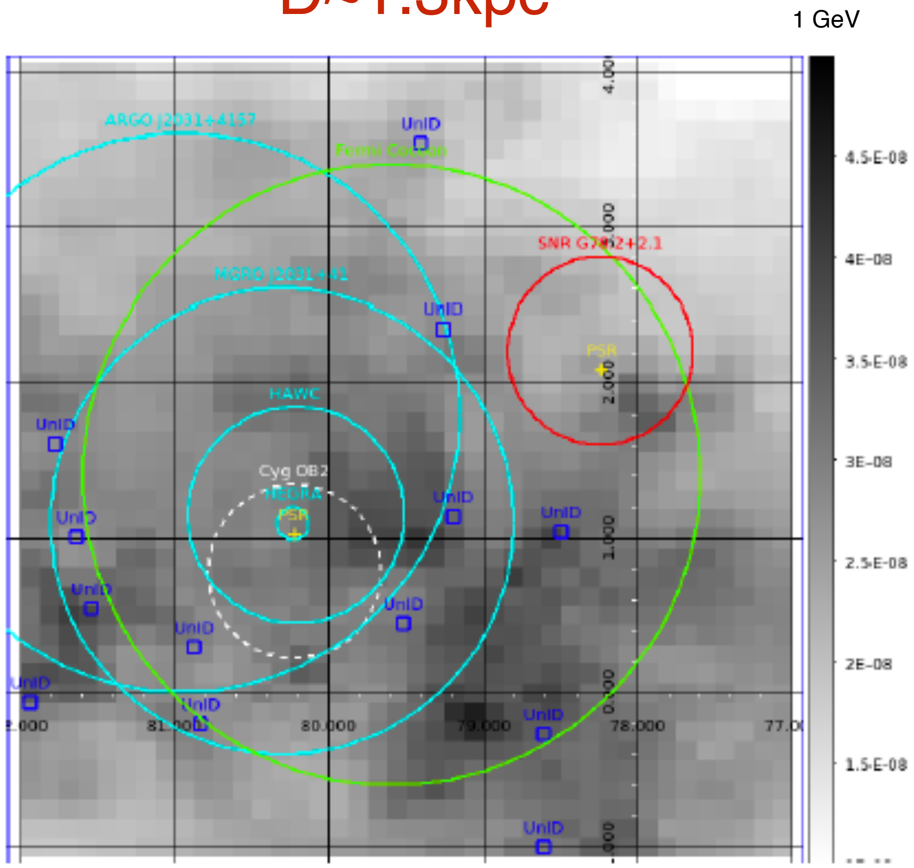
Possible CR Accelerator Sites in the Galaxy

Massive Stellar Cluster
Westerlund1
D~5kpc

Starforming Region
Cygnus X
D~1.3kpc



Adapted from Brandt's talk at ICRC2017



Yoast-Hull et al. 2017

Past Massive star explosions+Molecular Cloud Complex

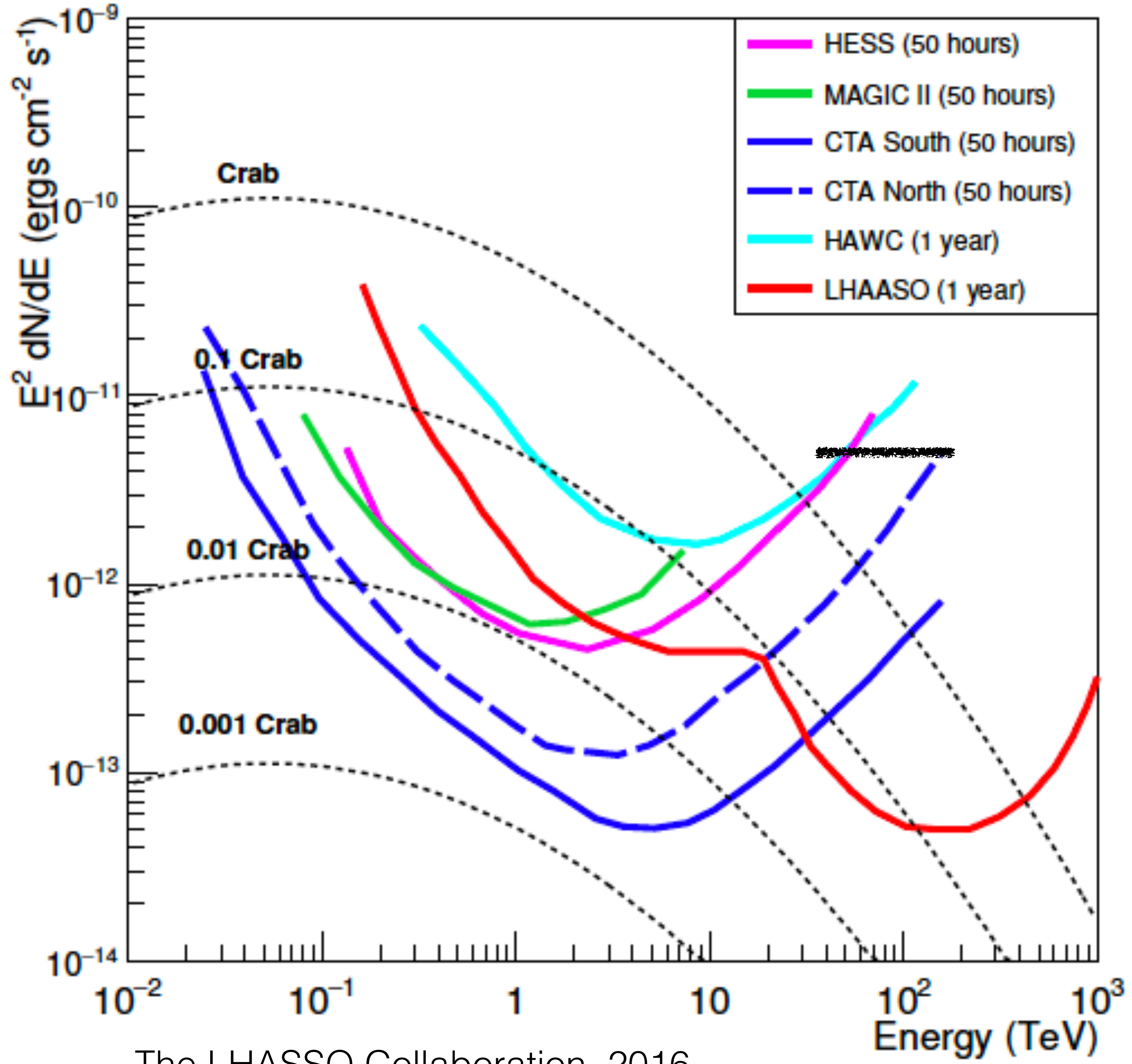
The efficiency of the hadronuclear interaction for a single proton is approximated to be

$$f_{\mathrm{pp,inj}} = \min\left(n_{\mathrm{H}}\sigma_{\mathrm{pp}}cT, 1\right) = \min(1 \times 10^{-4}\,\boxed{M_6}\,D_{100,29}^{-1.5}T_4^{-0.5}, 1)$$

A General Gamma-Ray Predictions

$$F_\gamma(100\ \mathrm{TeV}) \simeq \frac{L_\gamma}{4\pi d_{\rm s}^2} = 5\times10^{-12}\ \mathrm{TeV\ cm^{-2}\ s^{-1}}\,\frac{E_{\rm inj}(1\mathrm{PeV})}{5\times10^{50}\mathrm{erg}}\,M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}.$$

The exposure time needed for LHASSO: $t_{\rm LH} = 22\ \mathrm{day}\,\frac{E_{\rm inj}(1\mathrm{PeV})}{5\times10^{50}\mathrm{erg}}\,M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$



The LHASSO Collaboration, 2016

Uncertainties:

The injected energy of CRs

The injected time

The diffusion time

The total mass of MC

The distance of the source

A General Neutrino Predictions

$$n_{\nu_\mu} \simeq \frac{L_\nu/3}{\epsilon_{\nu_\mu} 4\pi d_{\rm s}^2} A_{\rm eff}\Delta t = 1 \times \frac{E_{\rm inj}(1{\rm PeV})}{5\times 10^{50}{\rm erg}} M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2} A_{\rm eff,0.5}\Delta t_1$$

$$F_\nu(50\ {\rm TeV}) \simeq \frac{L_\nu}{4\pi d_{\rm s}^2} = 5\times 10^{-12}\ {\rm TeV\ cm^{-2}\ s^{-1}} \frac{E_{\rm inj}(1{\rm PeV})}{5\times 10^{50}{\rm erg}} M_6 D_{100,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}.$$

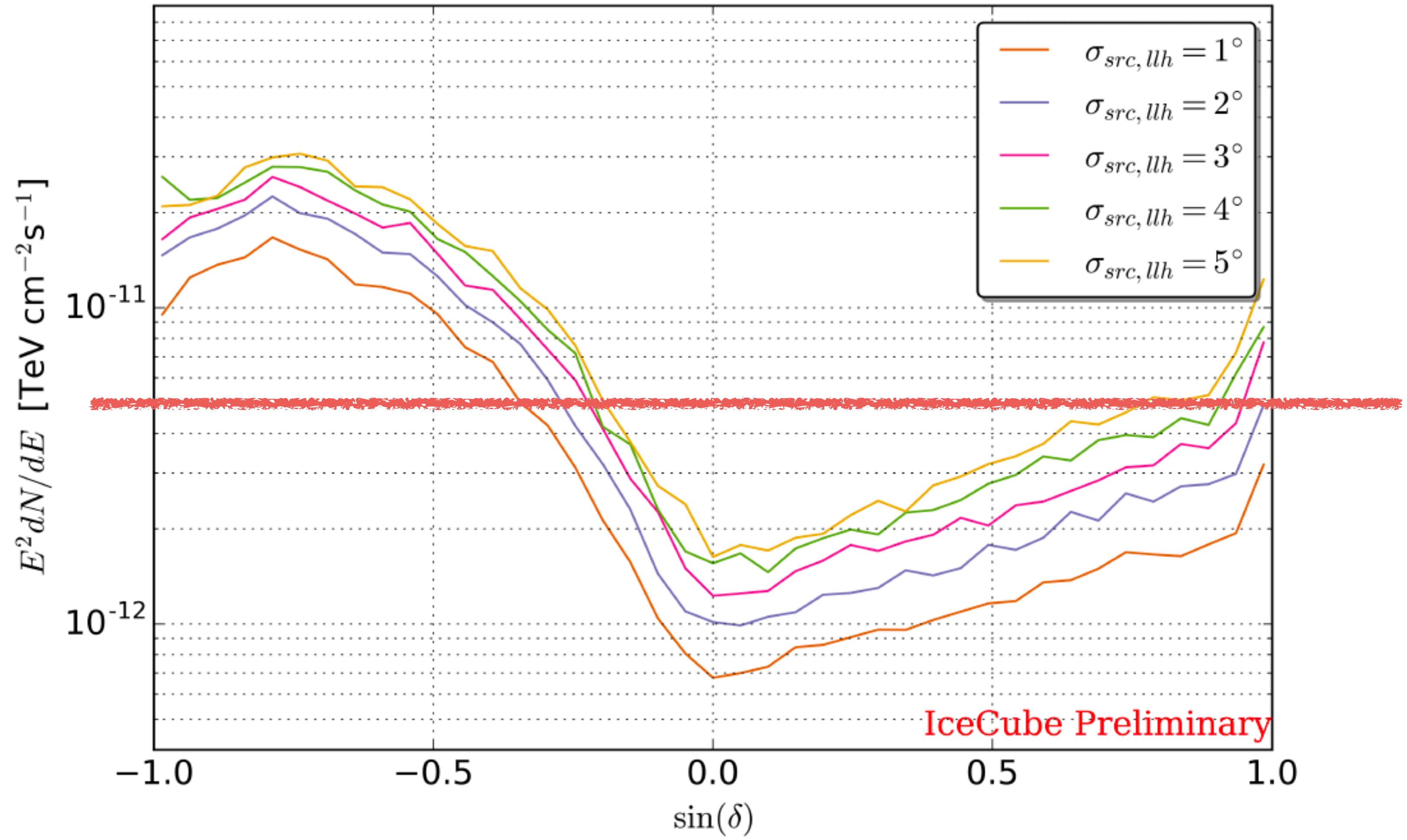


Figure 2: Sensitivity at 90% confidence level for the five extensions considered and an E^{-2} power law spectrum. The best case scenario is assumed, that is when the simulated source extension (σ_{src}) matches exactly the extension of the likelihood scan (σ_{llh}).

Pinat & Snchez (2018)

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>10 TeV photons from the Galactic Center

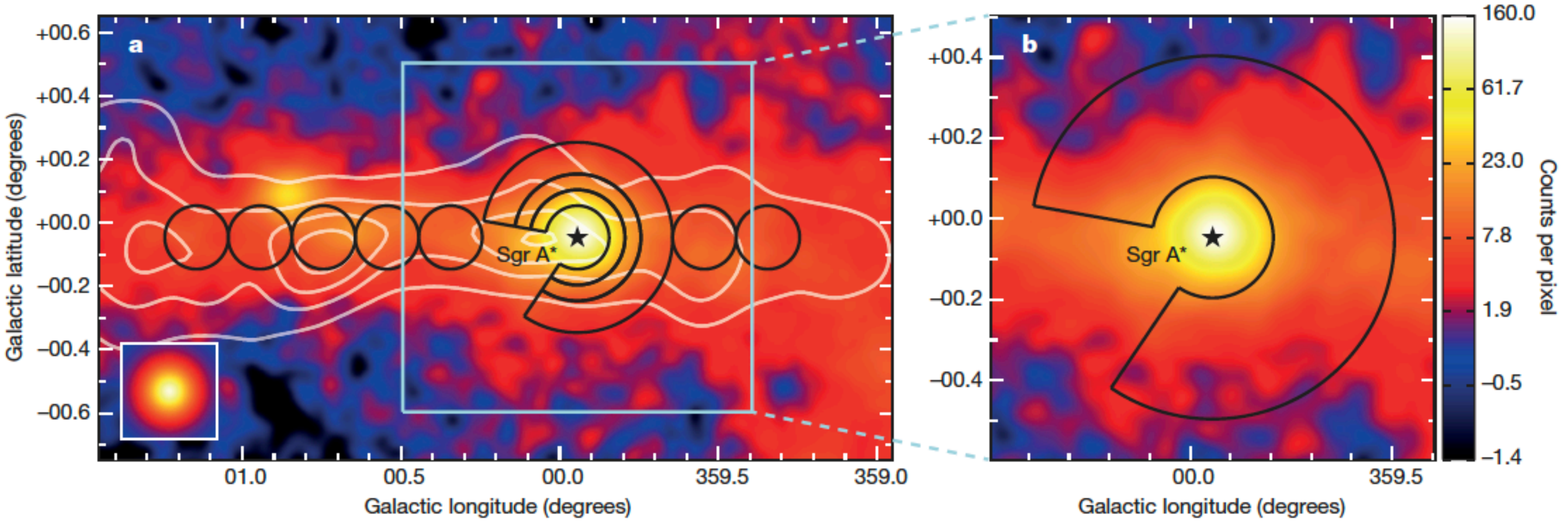


Figure 1 | VHE γ-ray image of the Galactic Centre region. The colour scale indicates counts per 0.02° × 0.02° pixel. **a**, The black lines outline the regions used to calculate the cosmic-ray energy density throughout the central molecular zone. A section of 66° is excluded from the annuli (see Methods). 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 $\sim$70 pc and the contour of the region used to extract the spectrum of the diffuse emission.

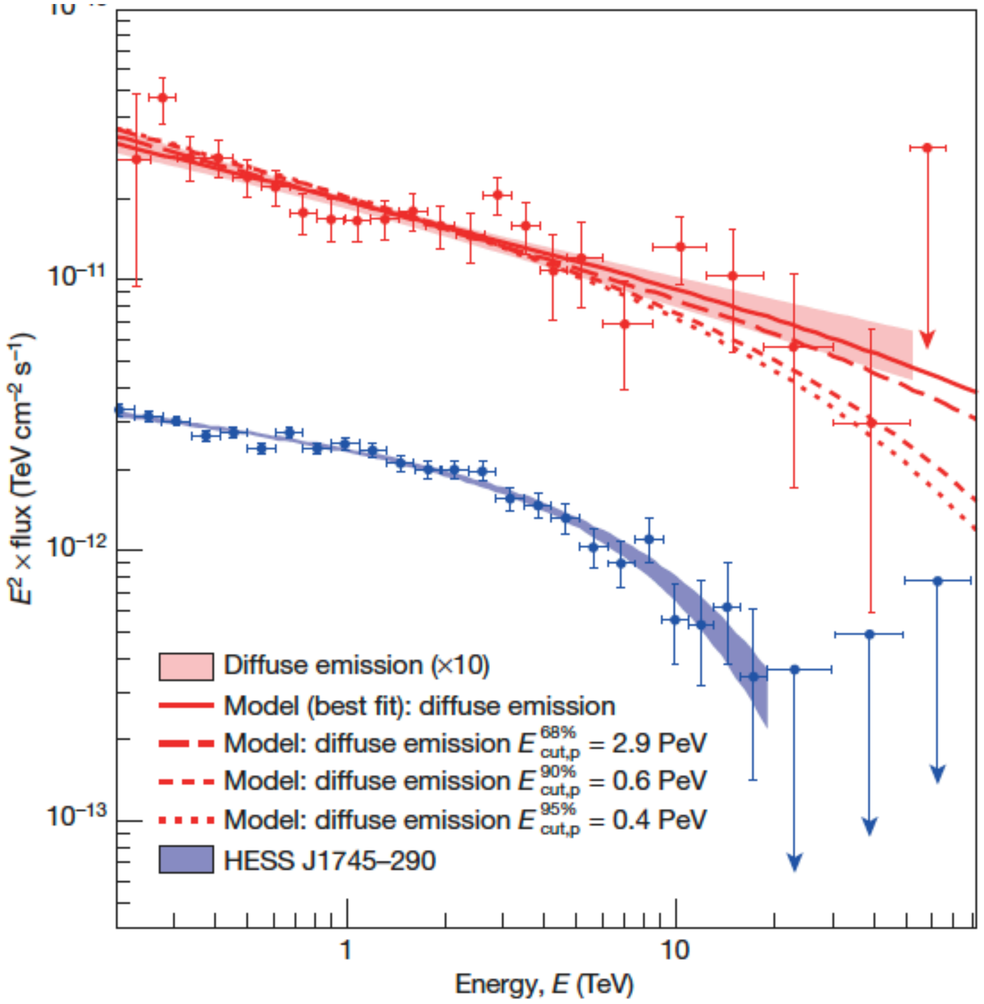


Figure 3 | VHE γ-ray spectra of the diffuse emission and HESS J1745−290. The y axis shows fluxes multiplied by a factor E^2, where E is the

Cosmic Ray Accelerators in the GC region

Fermi Bubble
(Su et al. 2010)

→

The past star formation activity or the central supermassive black hole activity

A group of massive supergiants and Wolf-Rayet stars
(Kauffmann 2017)

→

A high rate of SNe/HNe/GRBs

The star formation rate in the GC region peaks around 1e5 yr ago

$$\rho_{\rm SFR} = 0.14 \ M_{\odot} \ {\rm yr}^{-1}$$

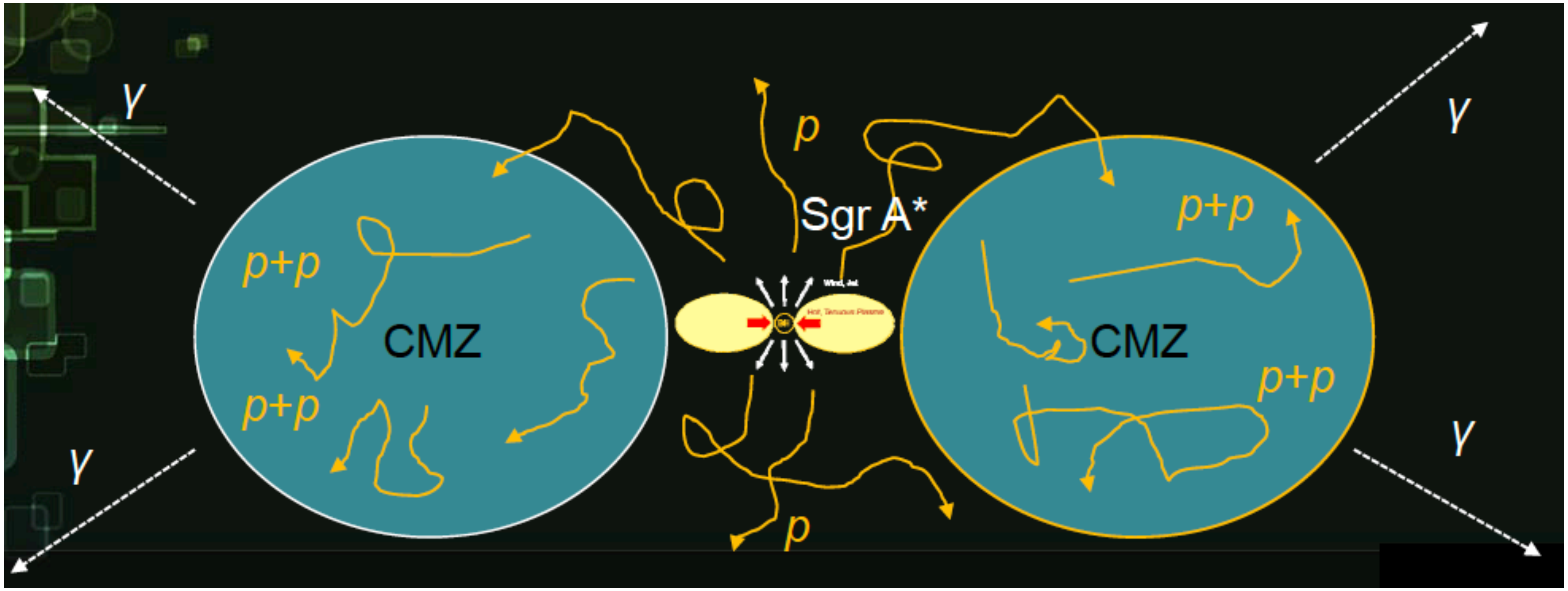
Yusef-Zadeh et al. (2009)

→

HNe Rate in the GC region: 1 per 1e5yr

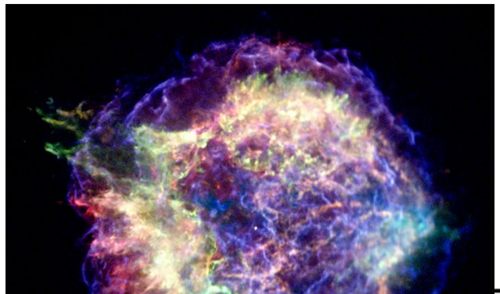
Past Activities of the Suppermassive Black Hole Sagittarius A*

1. Sgr A* is a LLAGN and has a Radiatively inefficient Accretion flows (RIAF) (Fujita, Murase, & Kimura, 2017)



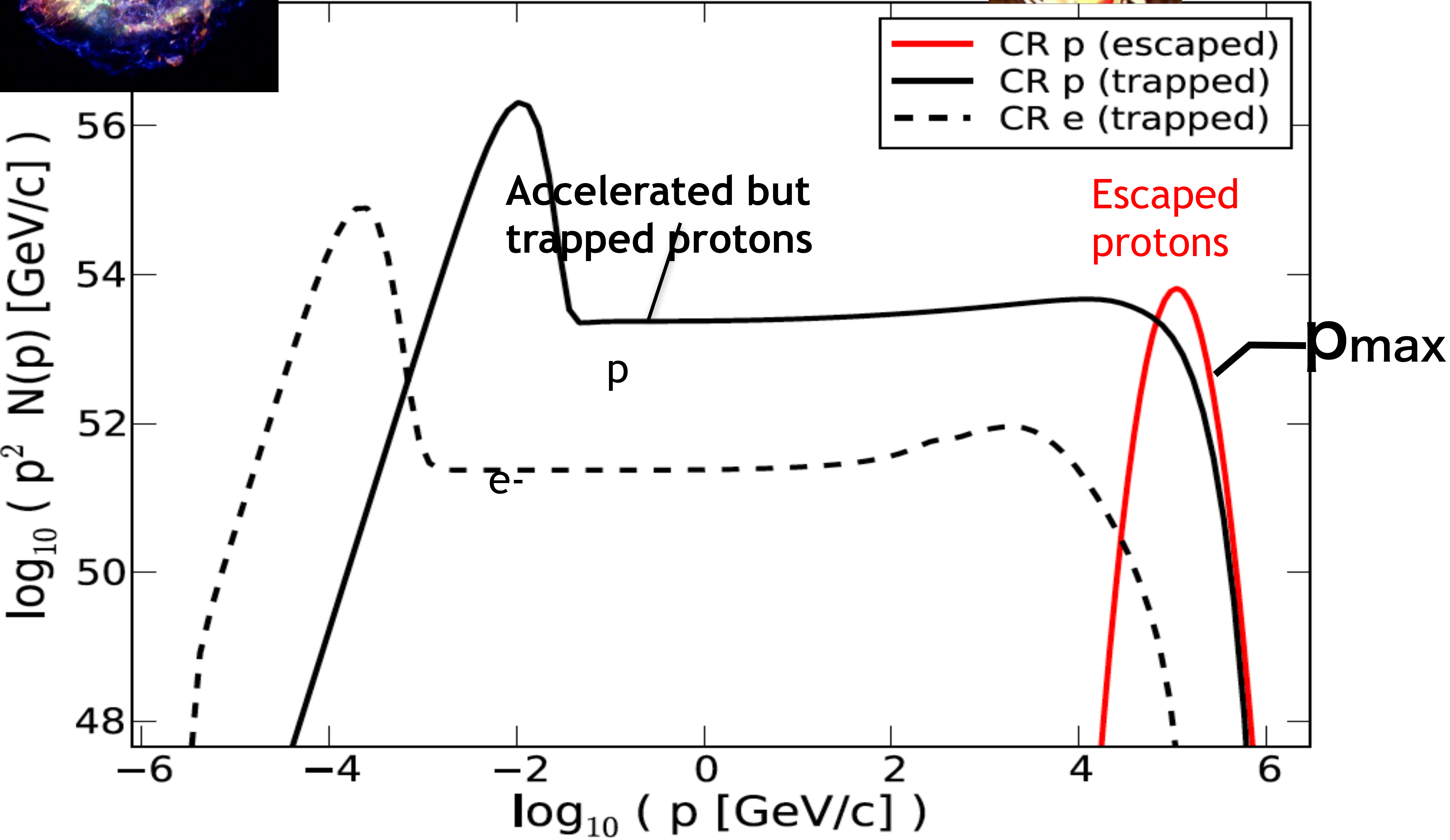
2. A tidal disruption event (TDE) caused by Sgr A* (Liu et al. 2016)

Non-linear Diffusive Shock Acceleration in SNR/HNR



Lee, Ellison & Nagataki (2012)

S.H. Lee
(Kyoto University)



Accelerated but trapped protons

Escaped protons

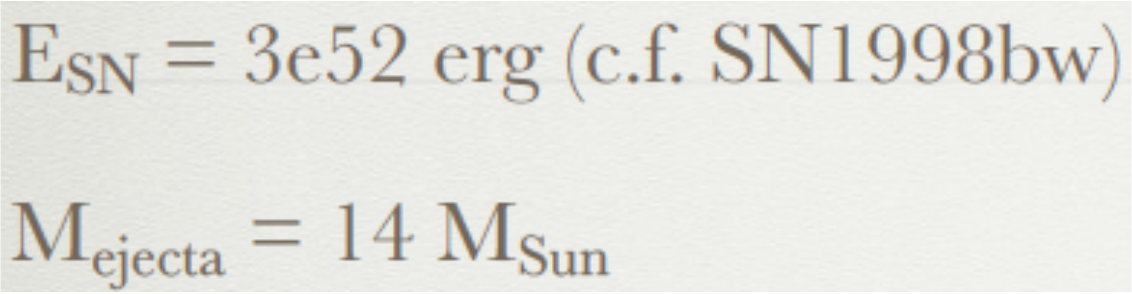
p

e-

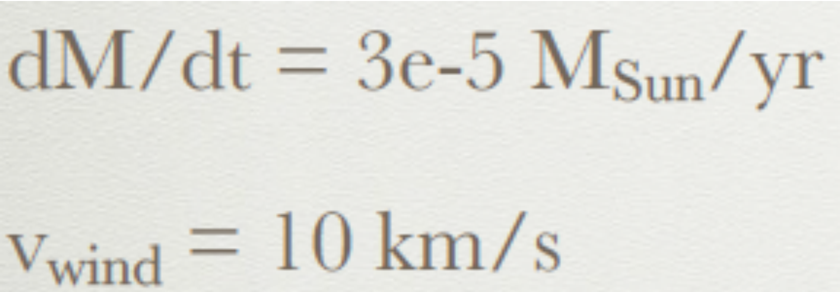
p_{max}

10 TeV-1PeV

Evolving continuous escaping protons from a HNR


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

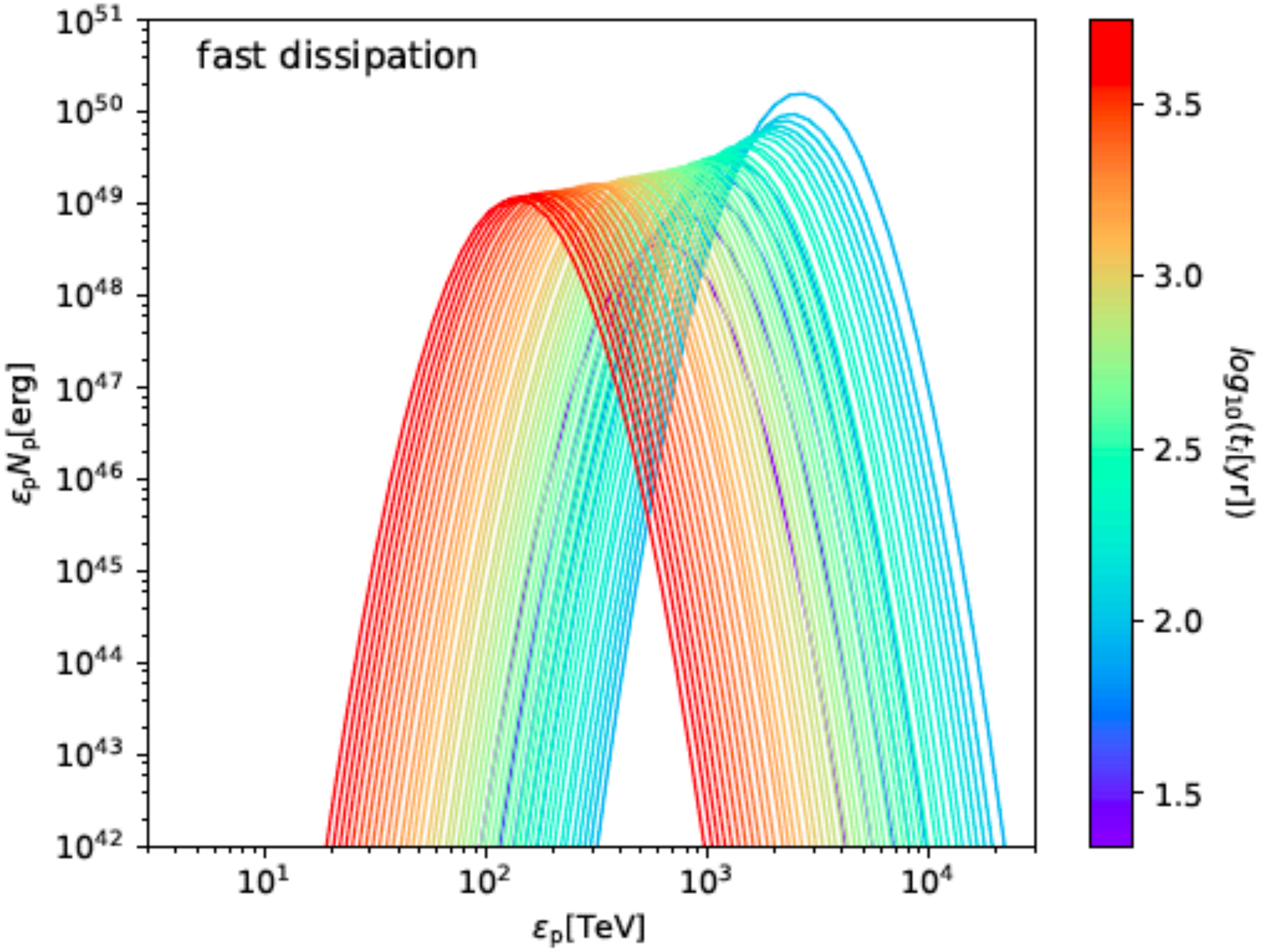
M_{ejecta} = 14 M_{Sun}


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

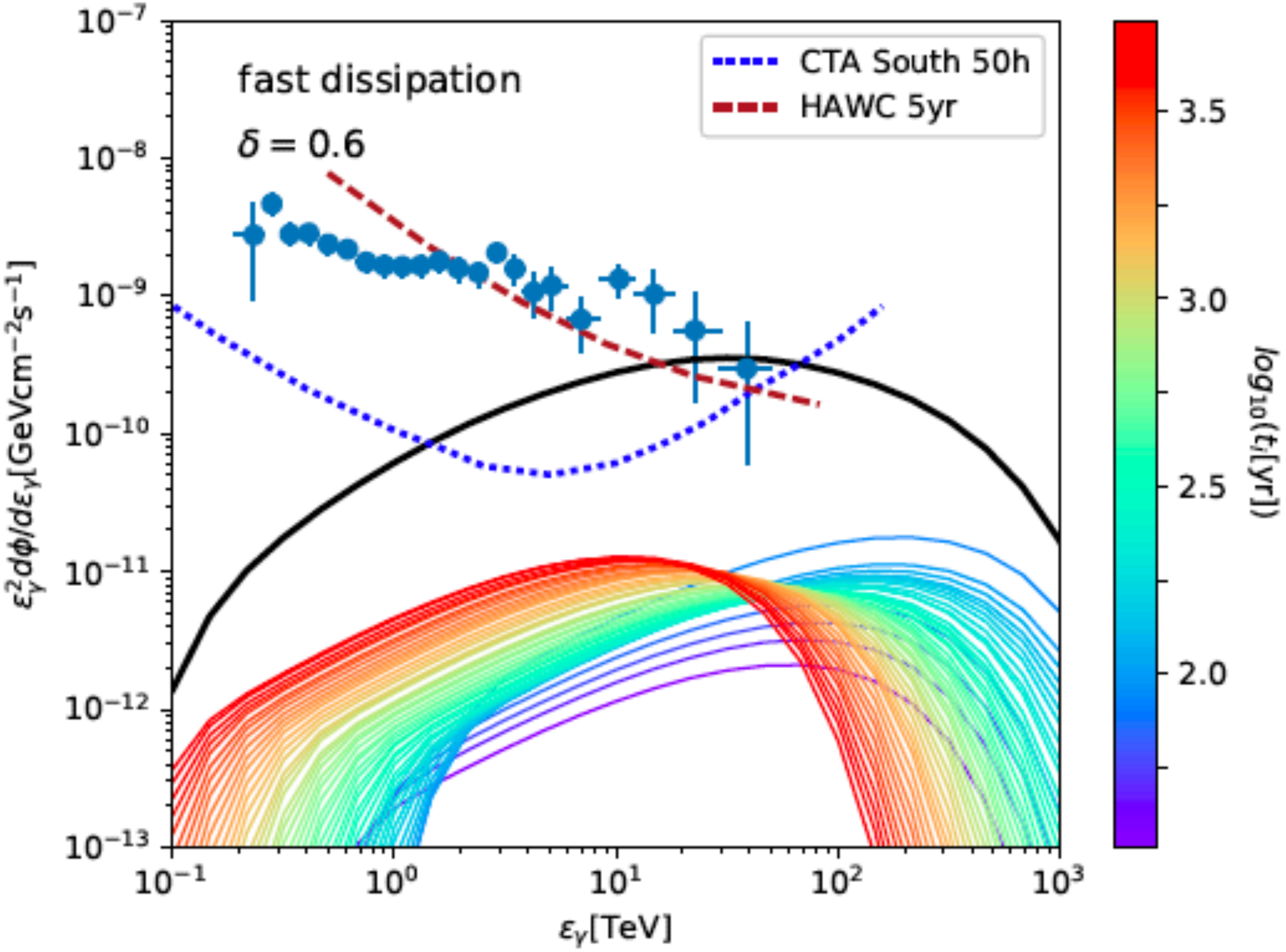
v_{wind} = 10 km/s

E_p=1e52erg

The account of escaping protons for each time bin and each energy bin

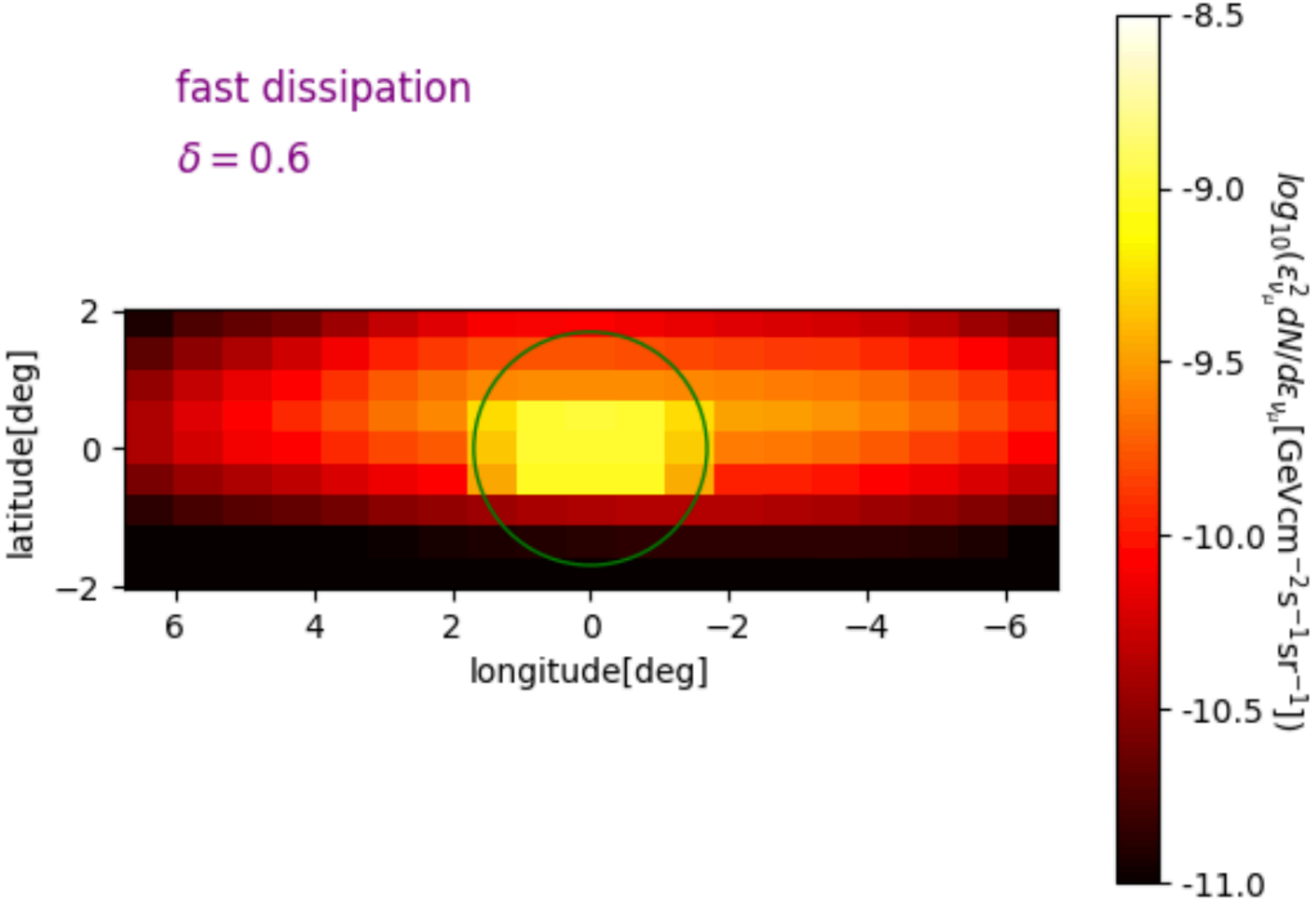


Gamma-Ray Spectra

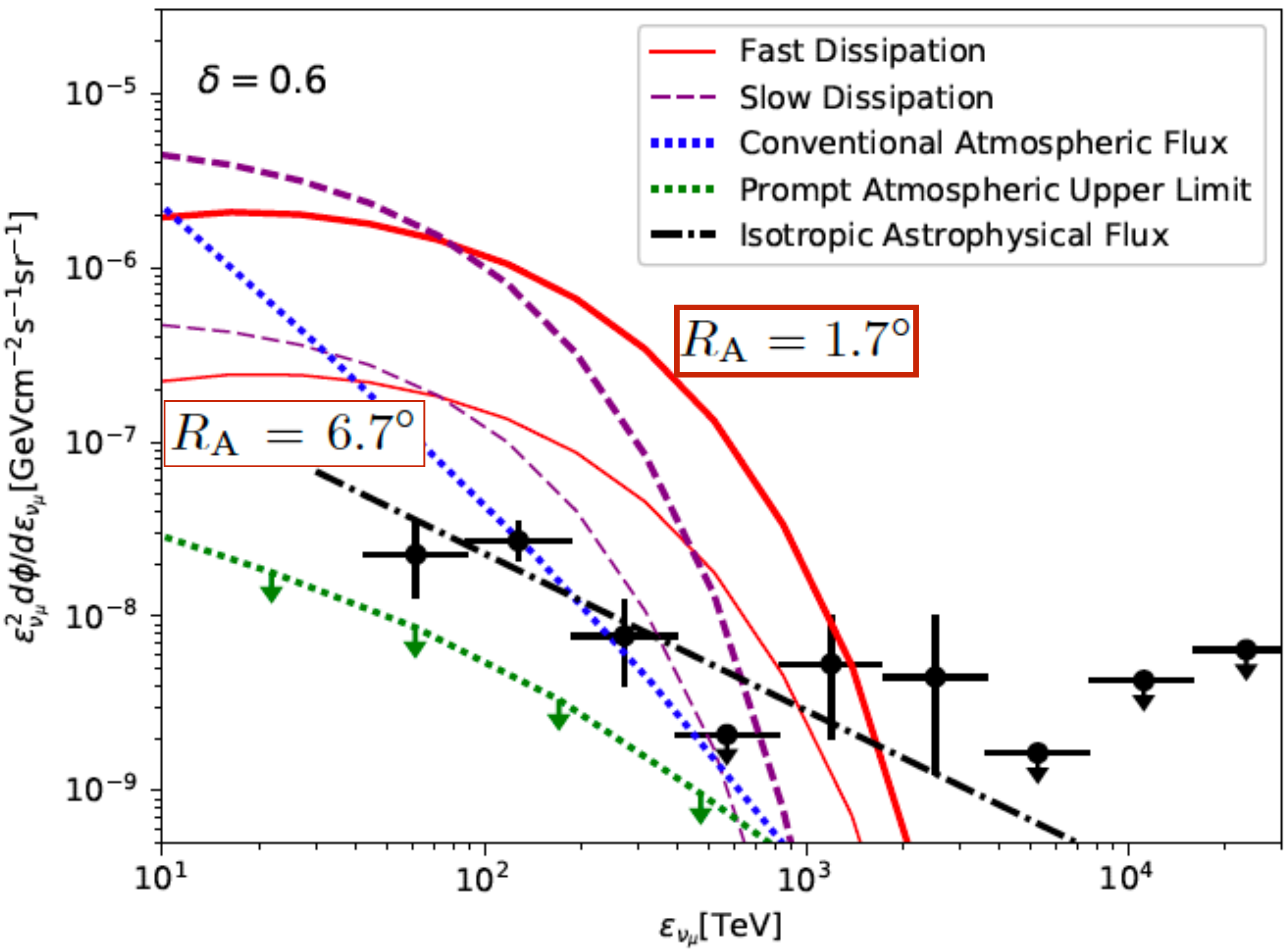


$D(\epsilon_\mathrm{p}) = D_{100}(\epsilon_\mathrm{p}/100\ \mathrm{TeV})^{\delta}$ D100=1e29cm^2/s, T=3e5yr He+ 2019, submitted

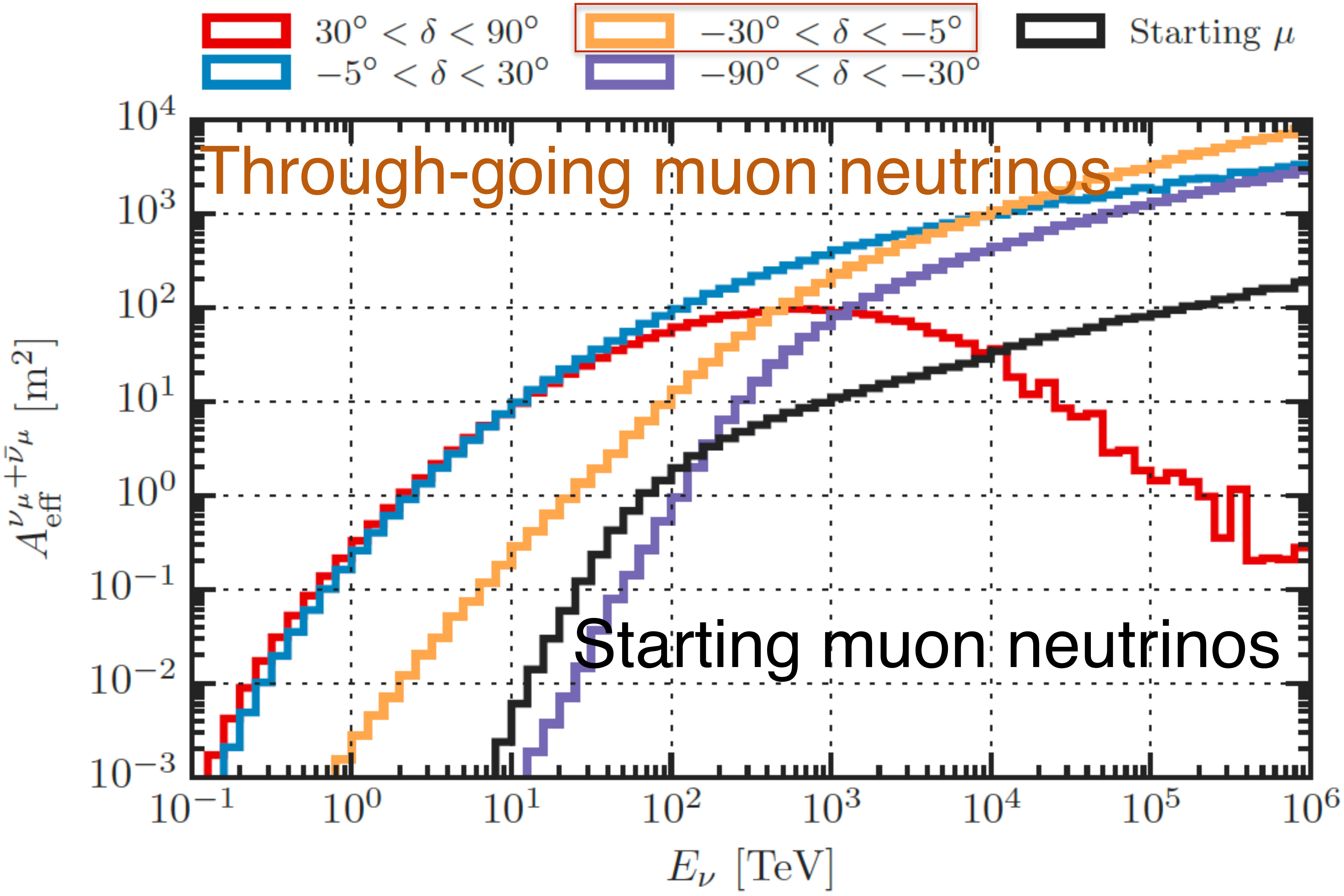
A muon-Neutrino Template of the Galactic Center for IceCube



Muon-Neutrino Spectra



IceCube Effective Area



Through-going muon neutrinos

Starting muon neutrinos

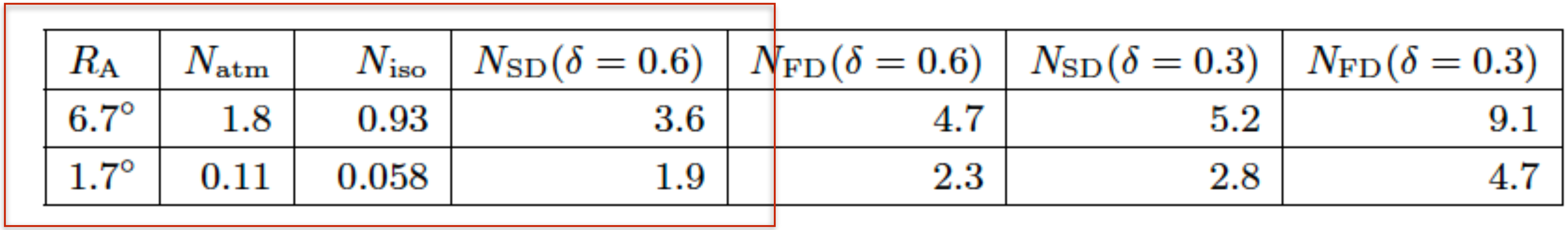
GC: $\mathrm{RA} = 17\mathrm{h}45\mathrm{m}40.04\mathrm{s}$ and $\mathrm{Dec} = -29°00'28.1''$

arXiv:1609.04981v2

Predicted muon-Neutrino Counts observed by the IceCube in 10-year Operation

- 1. Signal neutrinos V.S. Background neutrinos
- 2. Through-going muon neutrinos V.S. Starting muon neutrinos (More exposure is needed to observe starting muon neutrinos.)
- 3. R_A=1.7degree V.S. R_A= 6.7degree (The background is suppressed for central smaller region.)
- 4. E>30TeV V.S. E>100 TeV (Higher energy threshold will suppress the background.)

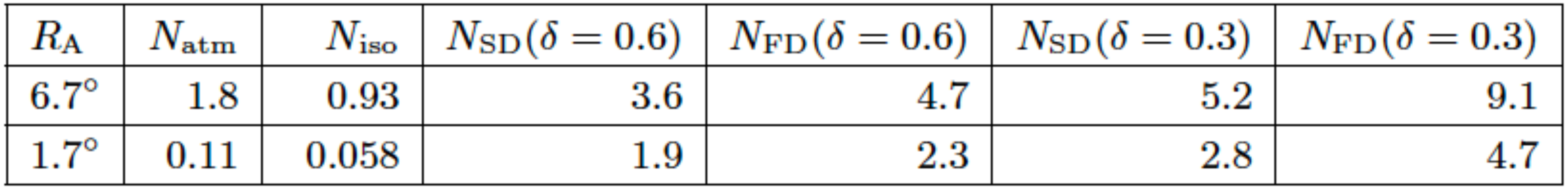
Through-going muon neutrinos with E>30 TeV



R_{A}	N_{atm}	N_{iso}	$N_{\mathrm{SD}}(\delta=0.6)$	$N_{\mathrm{FD}}(\delta=0.6)$	$N_{\mathrm{SD}}(\delta=0.3)$	$N_{\mathrm{FD}}(\delta=0.3)$
6.7°	1.8	0.93	3.6	4.7	5.2	9.1
1.7°	0.11	0.058	1.9	2.3	2.8	4.7

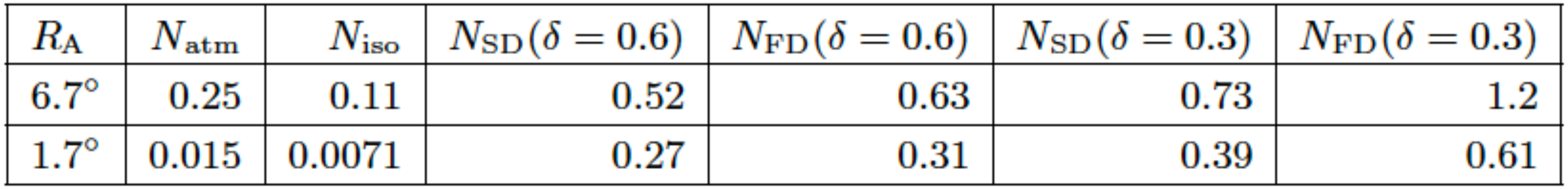
Neutrino Counts

Through-going muon neutrinos with E>30 TeV



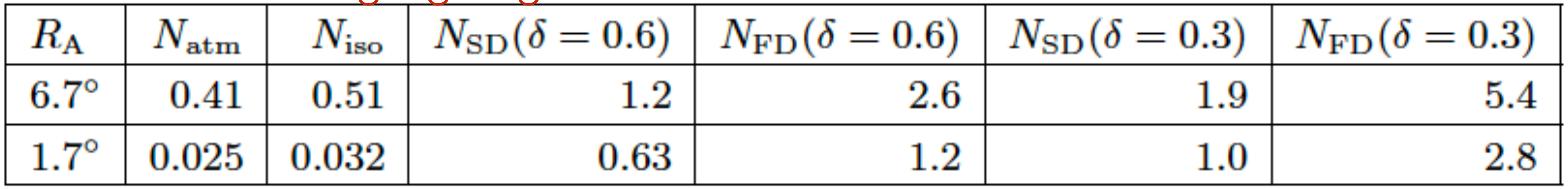
R_A	N_{atm}	N_{iso}	$N_{SD}(\delta = 0.6)$	$N_{FD}(\delta = 0.6)$	$N_{SD}(\delta = 0.3)$	$N_{FD}(\delta = 0.3)$
6.7°	1.8	0.93	3.6	4.7	5.2	9.1
1.7°	0.11	0.058	1.9	2.3	2.8	4.7

Starting muon neutrinos with E>30 TeV



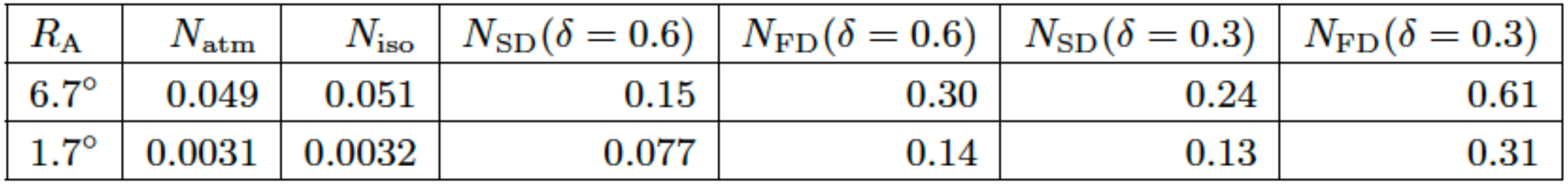
R_A	N_{atm}	N_{iso}	$N_{SD}(\delta = 0.6)$	$N_{FD}(\delta = 0.6)$	$N_{SD}(\delta = 0.3)$	$N_{FD}(\delta = 0.3)$
6.7°	0.25	0.11	0.52	0.63	0.73	1.2
1.7°	0.015	0.0071	0.27	0.31	0.39	0.61

Through-going muon neutrinos with E>100 TeV



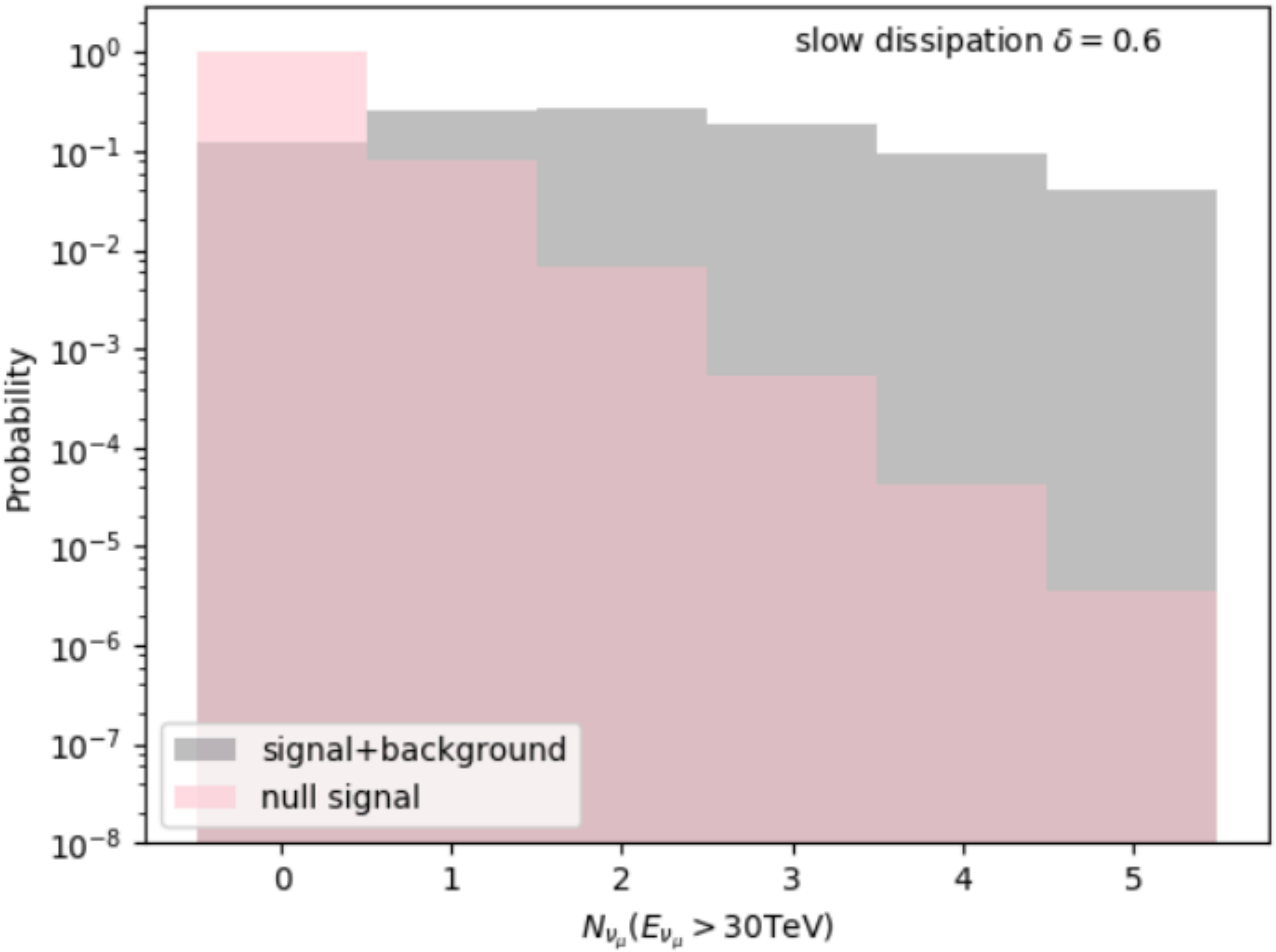
R_A	N_{atm}	N_{iso}	$N_{SD}(\delta = 0.6)$	$N_{FD}(\delta = 0.6)$	$N_{SD}(\delta = 0.3)$	$N_{FD}(\delta = 0.3)$
6.7°	0.41	0.51	1.2	2.6	1.9	5.4
1.7°	0.025	0.032	0.63	1.2	1.0	2.8

Starting muon neutrinos with E>100 TeV



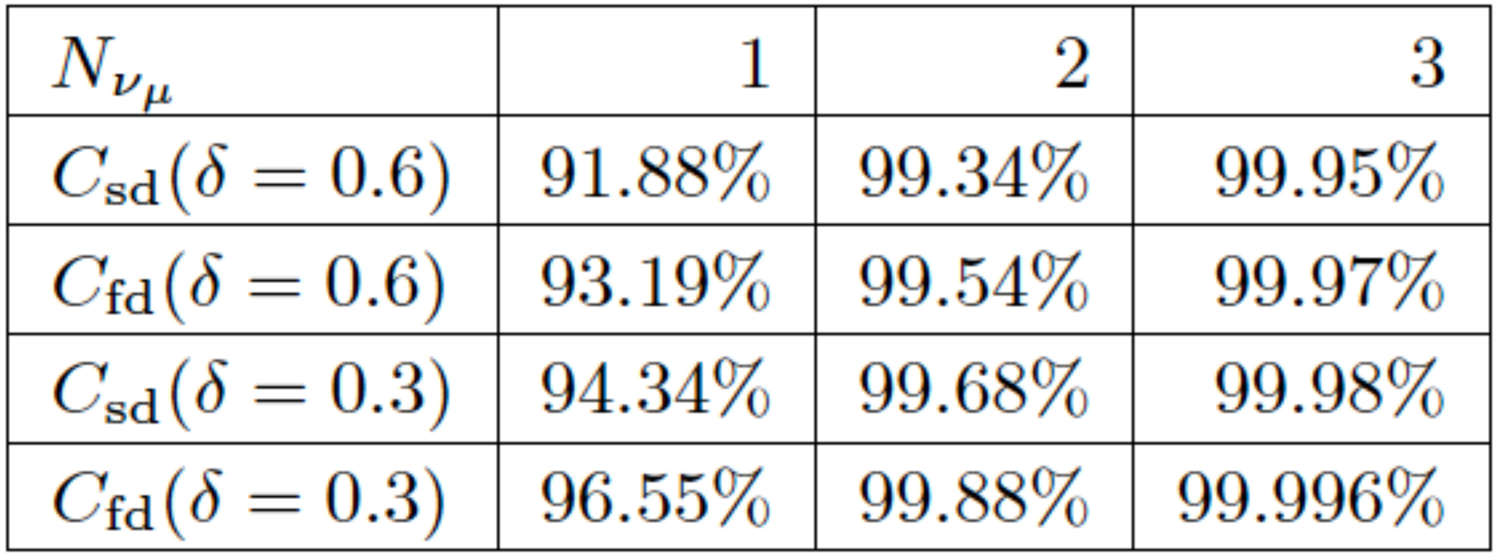
R_A	N_{atm}	N_{iso}	$N_{SD}(\delta = 0.6)$	$N_{FD}(\delta = 0.6)$	$N_{SD}(\delta = 0.3)$	$N_{FD}(\delta = 0.3)$
6.7°	0.049	0.051	0.15	0.30	0.24	0.61
1.7°	0.0031	0.0032	0.077	0.14	0.13	0.31

The probability of detecting 1-5 through-going muon neutrinos by IceCube in 10 years



The confidence level of discovery

If IceCube detect 1, 2, 3 through-going muon neutrinos with energy larger than 30 TeV in 10 years



N_{ν_μ}	1	2	3
$C_{\rm sd}(\delta = 0.6)$	91.88%	99.34%	99.95%
$C_{\rm fd}(\delta = 0.6)$	93.19%	99.54%	99.97%
$C_{\rm sd}(\delta = 0.3)$	94.34%	99.68%	99.98%
$C_{\rm fd}(\delta = 0.3)$	96.55%	99.88%	99.996%

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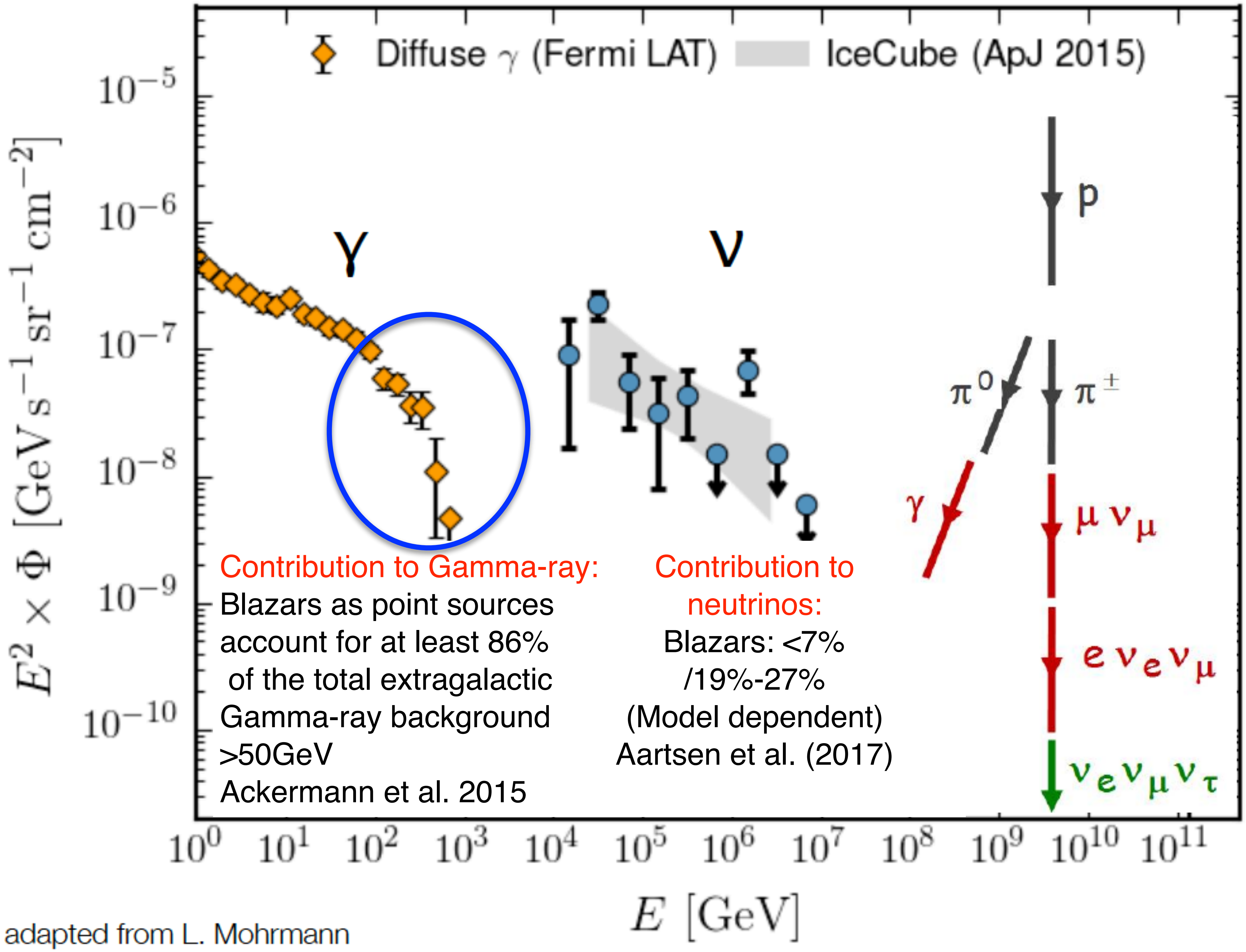
Constraints from diffuse gamma rays



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

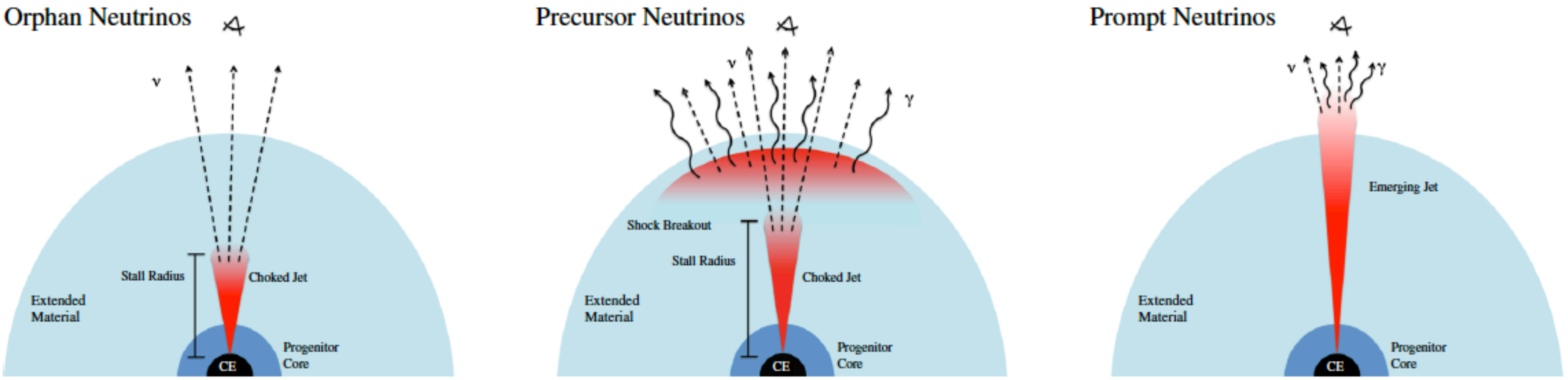
Possible solutions

1. The neutrino sources themselves are opaque to gamma rays (Hidden source) :

- choked jets in TDEs of supermassive black holes (Wang & Liu 2016; …)
- choked jets in core-collapse massive stars (Meszaros & Waxman 2001; Razzaque et al.2004; Murase & Ioka 2013; Xiao & Dai 2014; Senno et al. 2016; …)
- AGN cores (Stecker 2005; Murase et al. 2016; …)
- Starburst Galaxies (Chang et al. 2016; …)

2. The neutrino sources are distant (Chang et al. 2016;…)

Jets in Core-Collapse Massive Stars



Jet-driven SNe

Low luminosity GRBs
(Shock breakout)

High luminosity GRBs
& Low luminosity GRBs

Senno, Murase, & Meszaros 2016

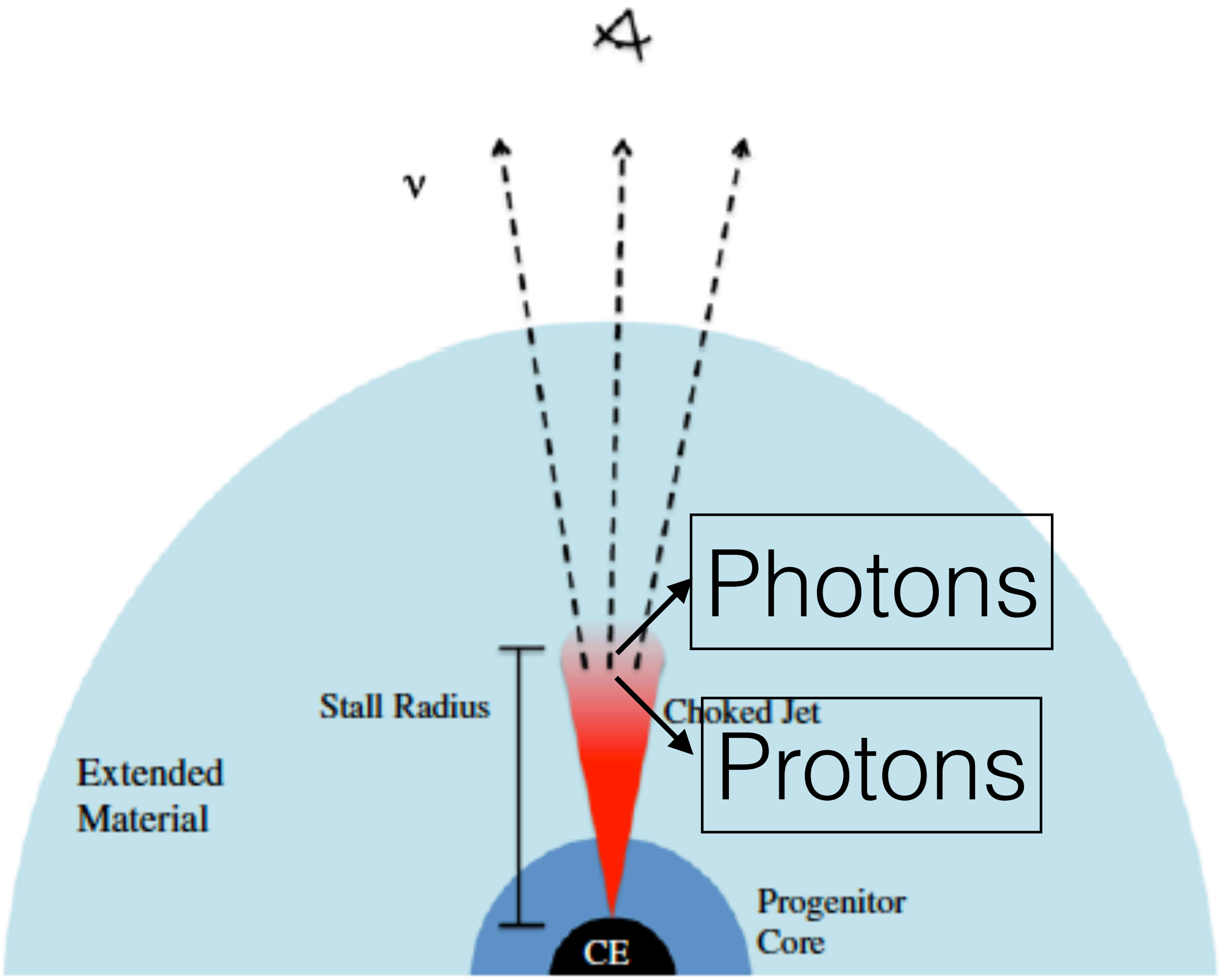
Local HL GRB rate: $0.8^{+0.1}_{-0.1}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Local LL GRB rate: $164^{+98}_{-65}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Local SNII rate: $10^{5}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Choked Jets in Red Supergiant Stars

The jet life time is shorter than the time of jet crossing the extended material/ a thick stellar envelope. $t < t_{\rm cros}$ $t_{\rm cros} = 1.1 \times 10^5\ {\rm s}\ R_{13.5}^2 L_{\rm iso,48}^{-1/2} \rho_{\rm H,-7}^{1/2}$
(Meszaros & Waxman 2001; Razzaque et al. 2004; Murase & Ioka 2013;
Xiao & Dai 2014; Senno et al. 2016)



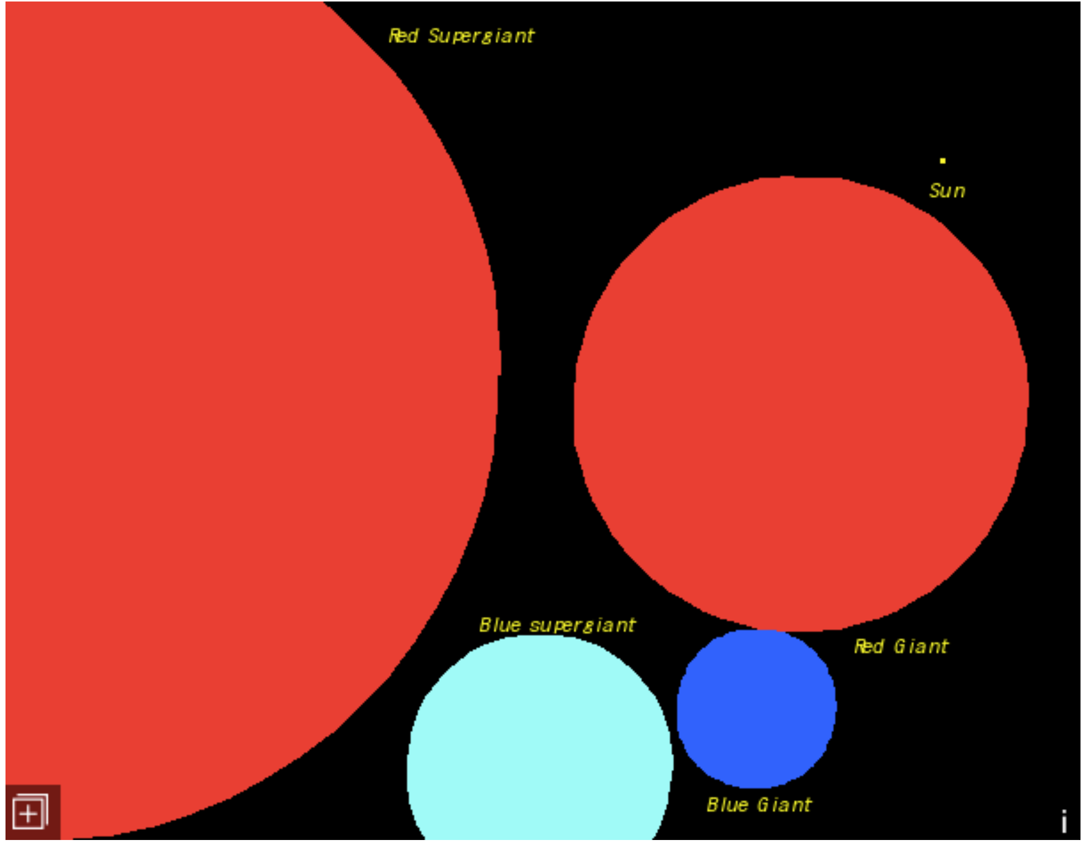
Photons

Protons

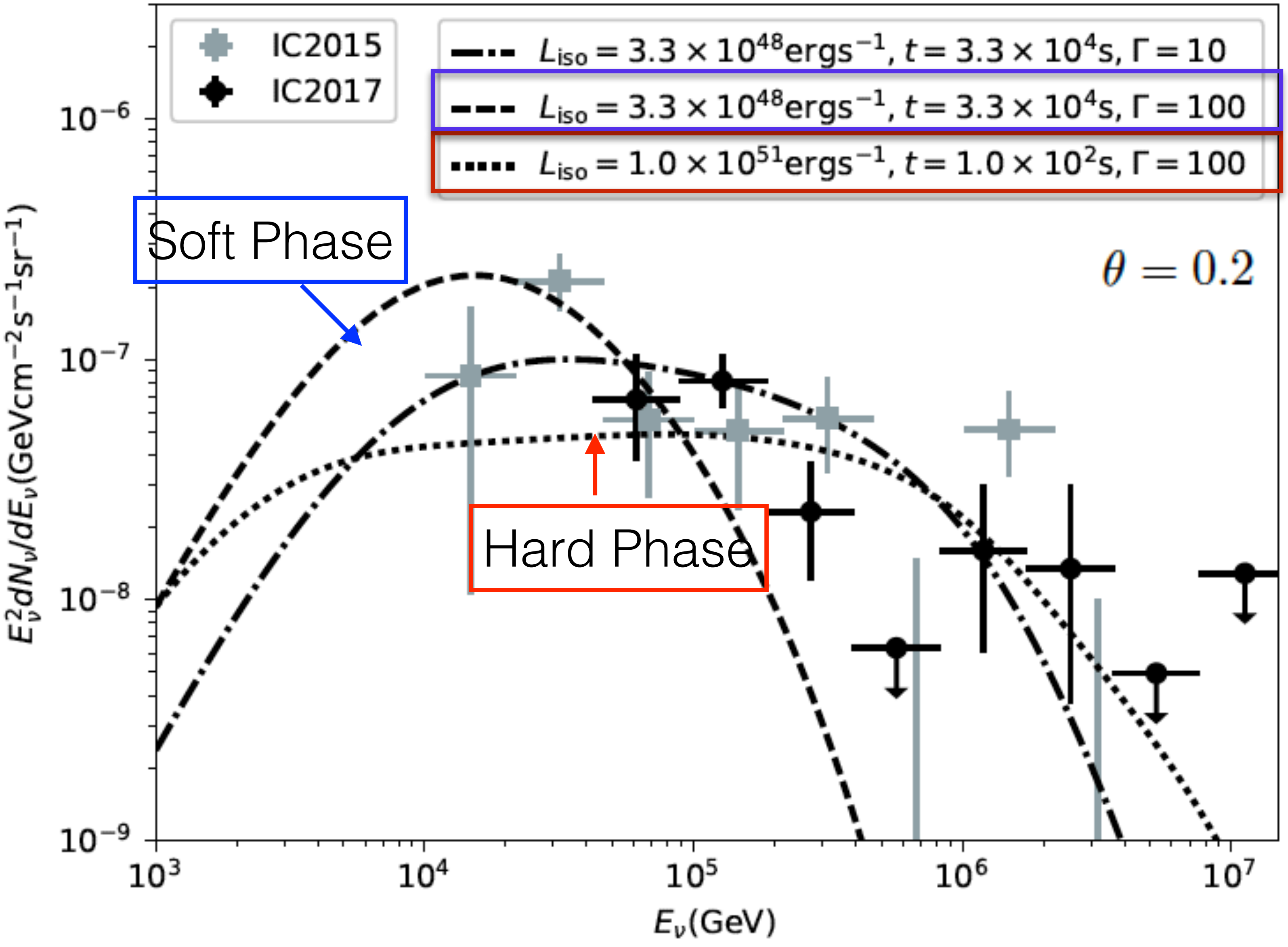
Senno, Murase, & Meszaros 2016

Red Supergiant Stars

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



Diffuse Neutrino Spectra: One-component Spectra



Soft Phase

Hard Phase

We assume the source rate is in proportion to the star formation rate

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

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

Madau & Dickinson (2014)

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

He+, 2018,ApJ,856,119H

Multiplets Predicted by the Choked Jet Model

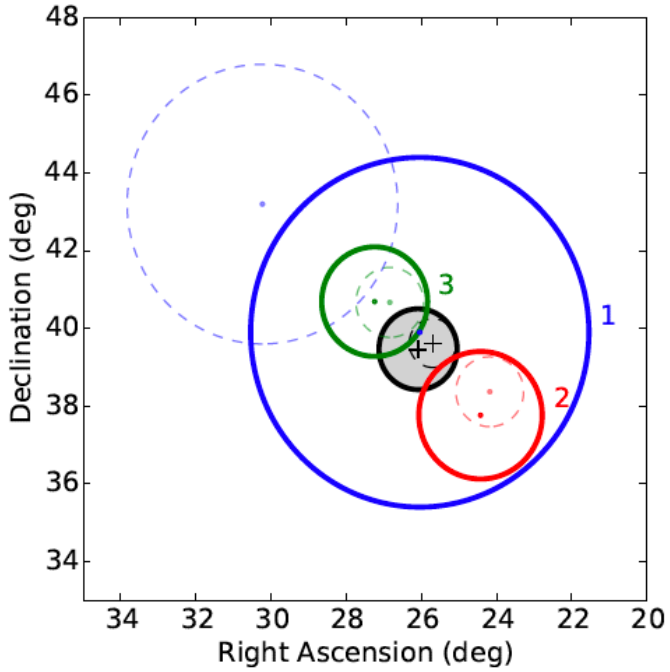
	$L_{\rm iso}$ ergs^{-1}	t s	Γ	$A_{\rm cj}$ $M_{\odot}^{-1}$	$R_{\rm cj}(z=0)$ Gpc^{-3}yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>1)$ yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>2)$ yr^{-1}	$N_{\rm S}(N_{\nu_\mu}>3)$ yr^{-1}
Soft Phase	3.3×10^{48}	3.3×10^{4}	100	1.4×10^{-3}	2.1×10^{4}	2.0	0.77	0.42
Intermediate Phase	3.3×10^{48}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

He+, 2018,ApJ,856,119H

- We predict that 4 multiplets within ~100 s to ~10,000 s can be found in 10 years operation of IceCube.

- On February 17, 2016, the IceCube real-time neutrino search identified, for the first time, a triplet arriving within 100 s of one another. No likely electromagnetic counterpart was detected. the probability to detect at least one triplet from atmospheric backgrounds is 32%.

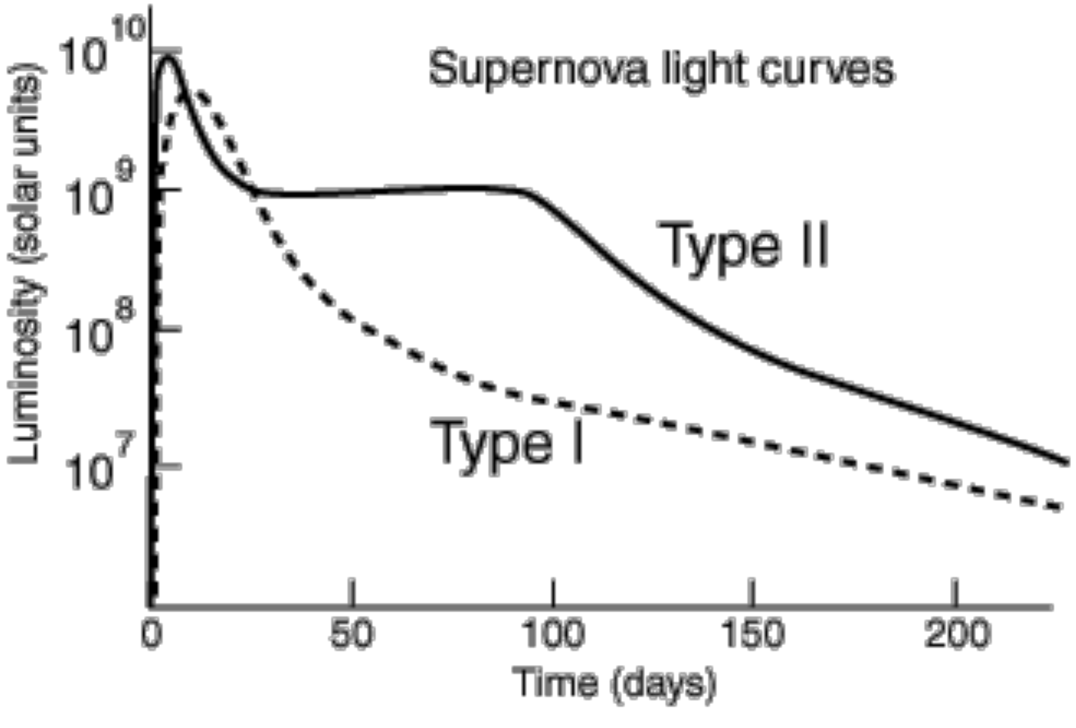
- Wider time window might introduce more atmospheric neutrinos.



The IceCube Collaboration, 2017

Follow-up Observations

- Newly Born Jet-driven SNII (asymmetry explosion)
- The time delay: A few hours.

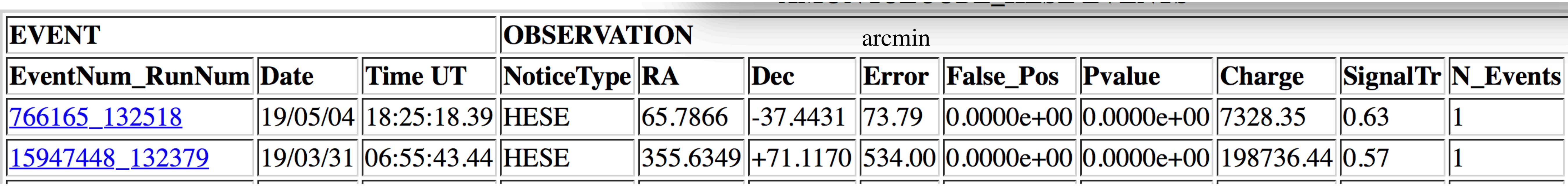


Adapted from Chaisson & McMillan

- For an extreme high isotropic energy, the associated SN might be a type II superluminous SN (SLSN). Multiplets can be observed by IceCube if the source is located within ~ 0.6 Gpc. This limitation on the source distance ($z<0.05$) is within the current detection radius of SLSNe.

Follow-up Observations

AMON ICECUBE_HESE/EHE EVENTS Alerts



EVENT			OBSERVATION			arcmin					
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15947448_132379	19/03/31	06:55:43.44	HESE	355.6349	+71.1170	534.00	0.0000e+00	0.0000e+00	198736.44	0.57	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)

X-ray： MAXI,Swift, insight-HXMT, SWOM

Optical：

\`Kanata' and \`HinOTORI' telescopes, Optical Wide-Field Surveys with Kiso/ Tomo-e Gozen, Okayama-3.8m, Wide Field Survey Telescope (WFST), Subaru Hyper-Suprime-Cam (HSC);

SWOM/GWAC-F60 A/B， SWOM/GWAC， Xinglong-2.16， GMG-2.4， ……

Large Synoptic Survey Telescope(LSST),Pan-STARRS1(PS1)

Summary

- 1. Neutrinos from a CR Accelerator+MC complex in the Galaxy (HAWC, CTA, LHASSO+Muon neutrinos)
- 2. Neutrinos from A Past Hypernova the Galactic Center (Through-going muon neutrinos with E>30 TeV from the central 1.7 degree region+HAWC&CTA)
- 3. Neutrinos from the Choked Jet Accompanied by SNII (A muon neutrino multiplet+The follow up optical and X-ray observations on SNII)

Thank you !