Theoretical Modeling of pp Collision-Induced Neutrino Emission from Astrophysical Sources

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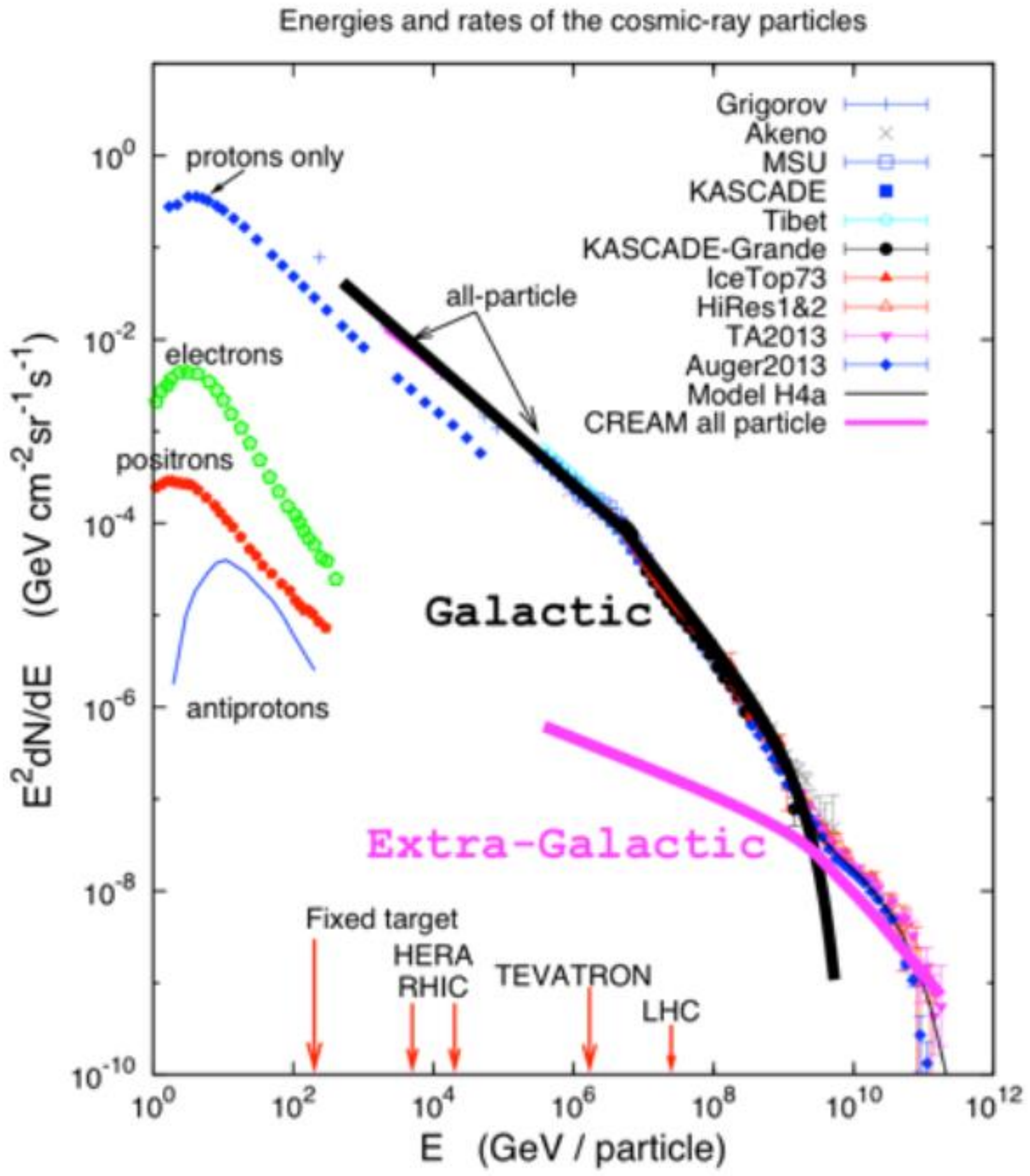
Cosmic Rays (CRs) from Astrophysical Objects



(1) Galactic Cosmic ray

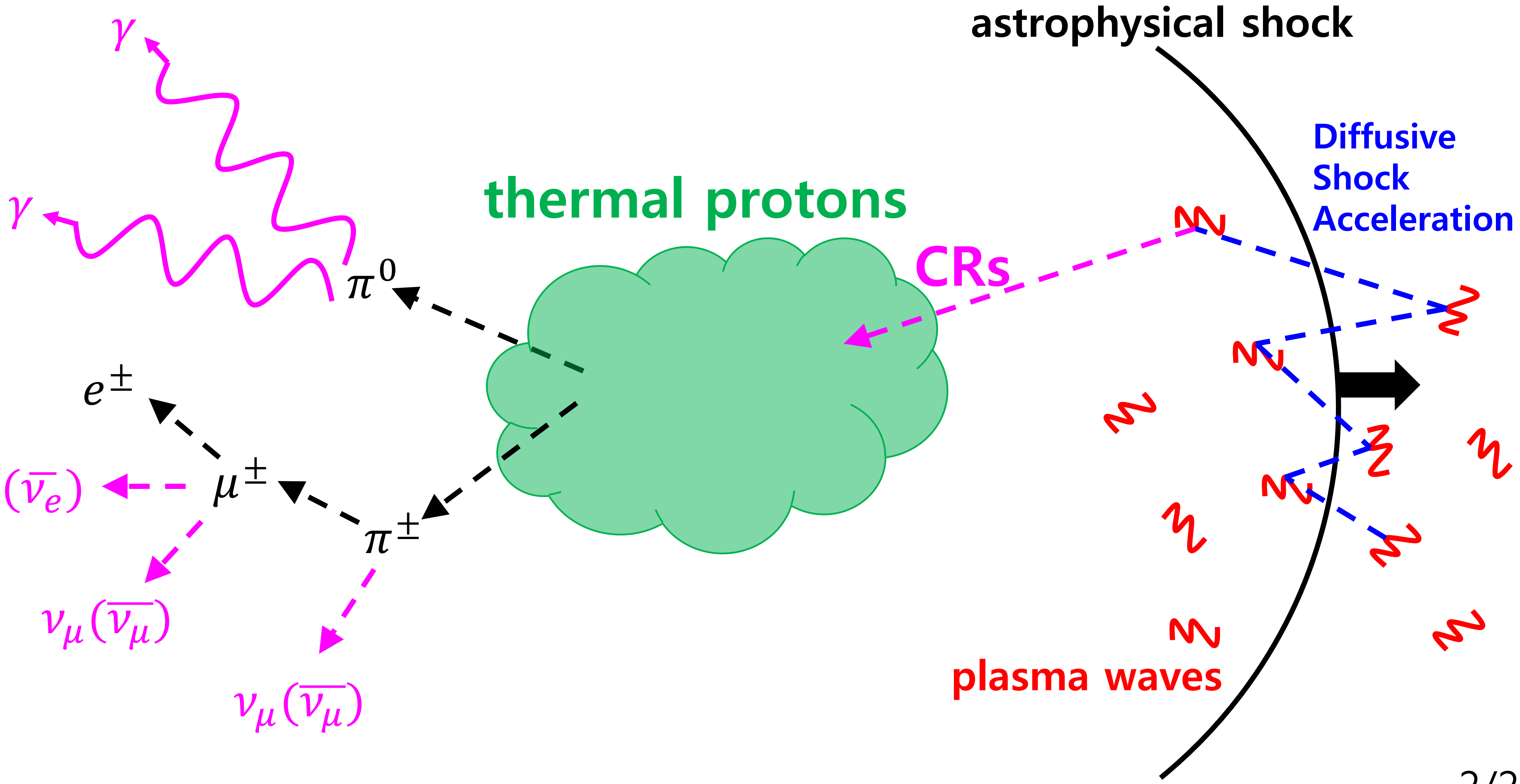
From supernova remnants…

(2) Extragalactic Cosmic ray

From clusters of galaxies, starburst galaxies, active galactic nuclei, gamma-ray bursts…

→ Neutrino emissions from astrophysical objects (??)

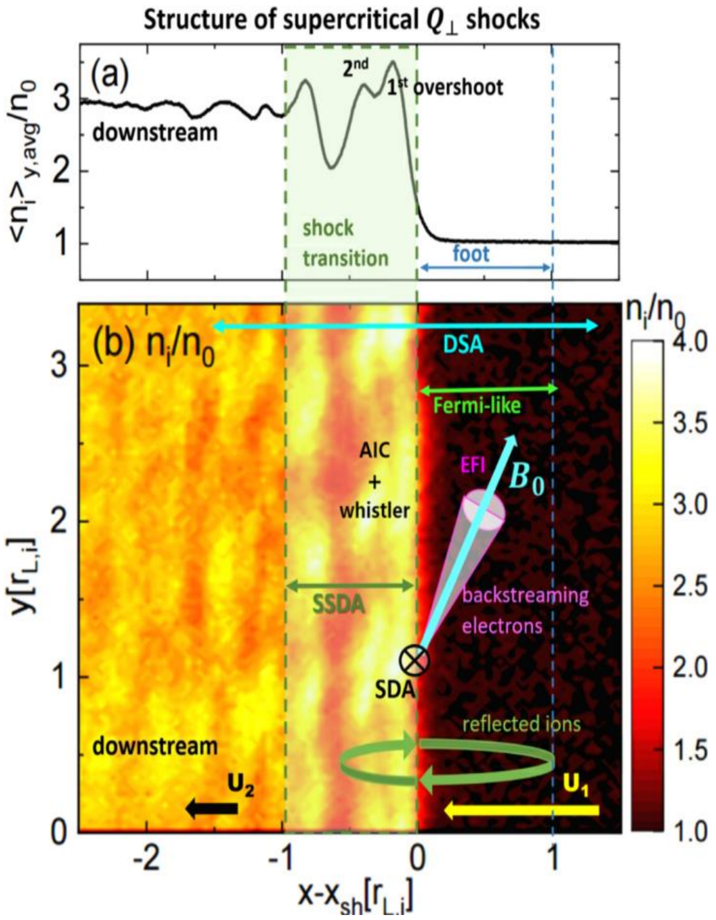
Astrophysical Shock and pp collision-induced Neutrino

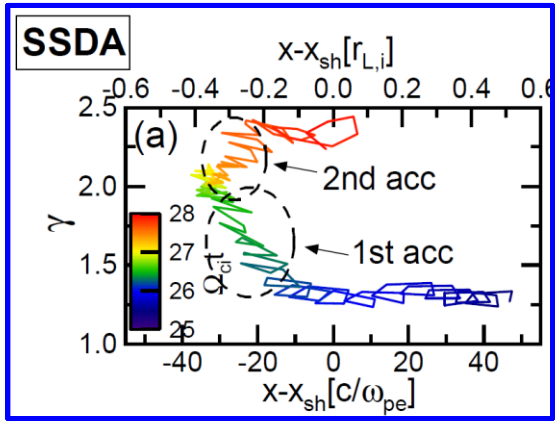


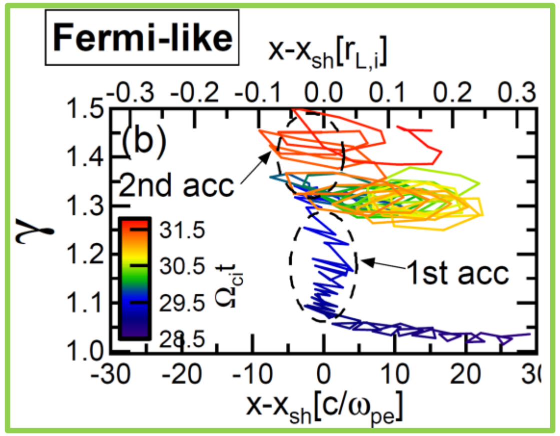
Acceleration Mechanism in Astrophysical Shocks

Generation of plasma waves and particle acceleration → plasma kinetic simulation

(e.g., Ha et al. 2018, 2021, 2022)



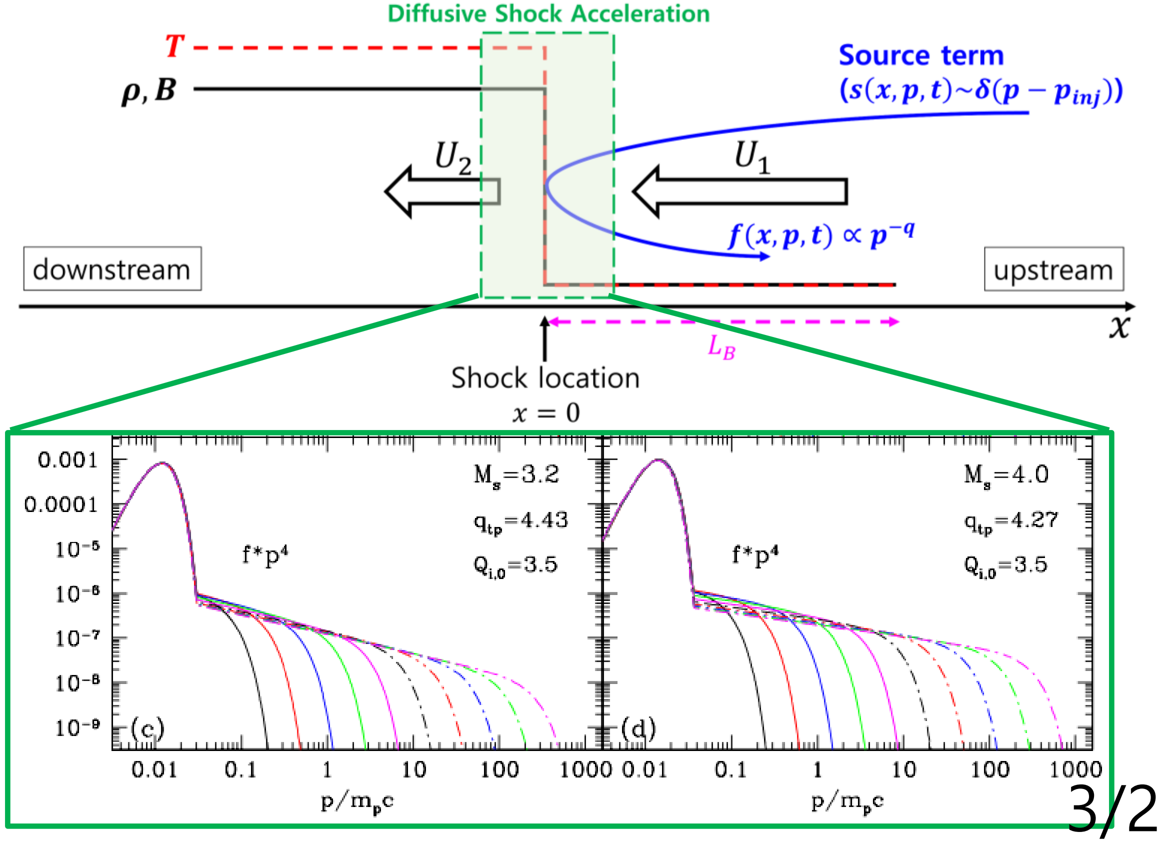




Particle acceleration modeling based on Diffusive Shock Acceleration (DSA) → Fokker-Planck equation

(e.g., Ryu et al. 2019, Ha 2024, 2025)

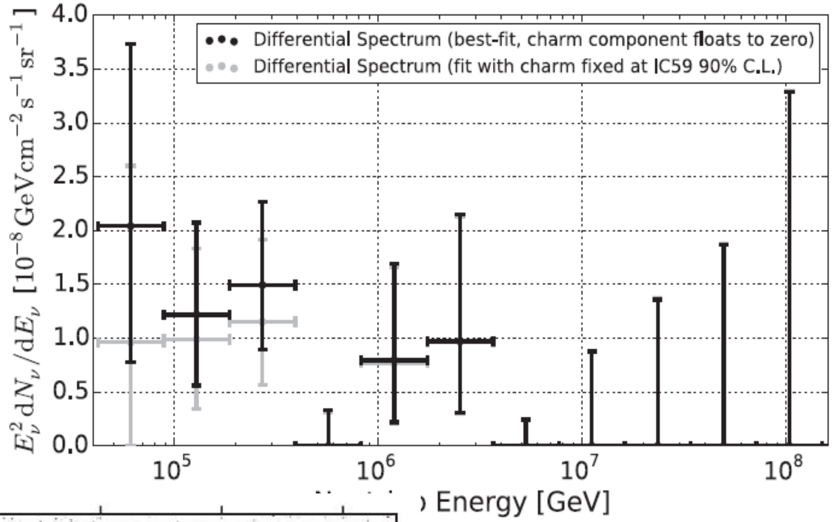
1D Fokker-Planck equation: $\frac{\partial f}{\partial t}+\frac{\partial}{\partial x}\left(U-\frac{D}{L_B}\right)f-\left(\frac{\partial U}{\partial x}-\frac{U}{L_B}\right)\frac{\partial}{\partial p}\frac{p}{3}f=\frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right)+s$



Observation of Astrophysical Neutrinos: (1) IceCube

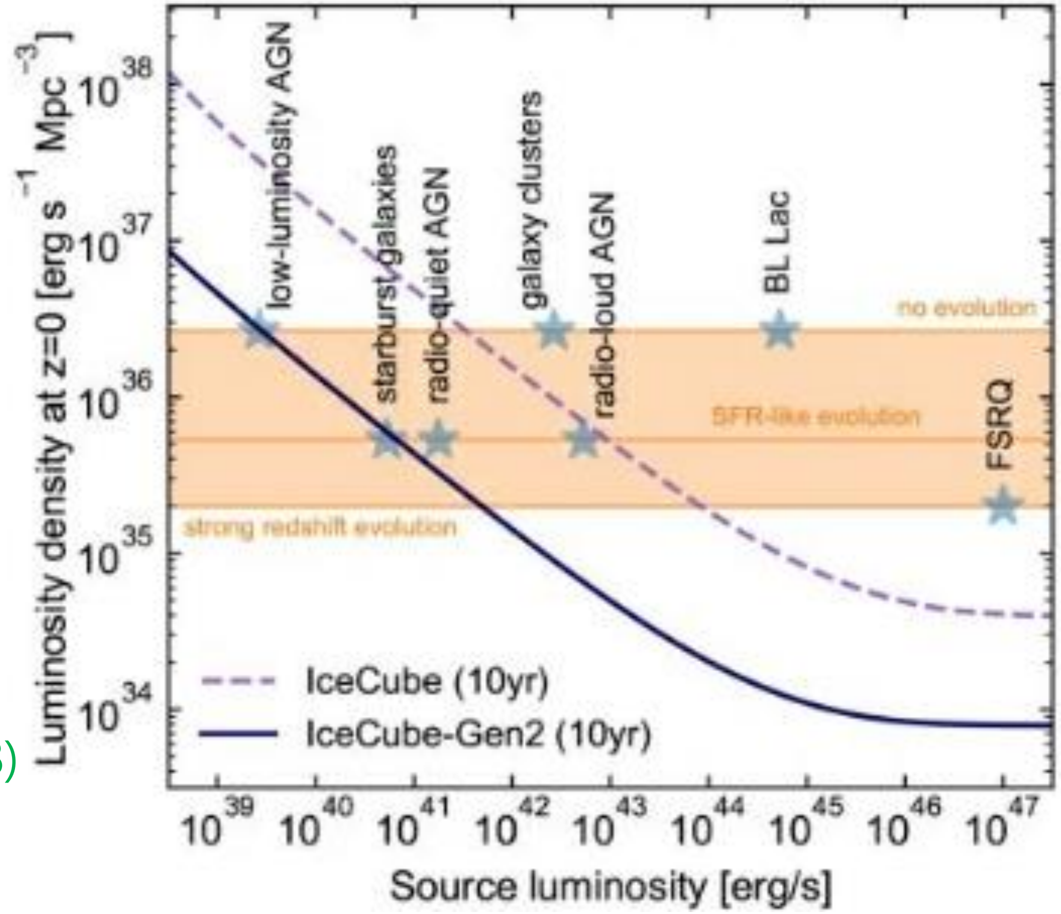
→ **Detecting astrophysical neutrinos in the energy range of TeV – PeV** (e.g., Aartsen et al. 2014a)

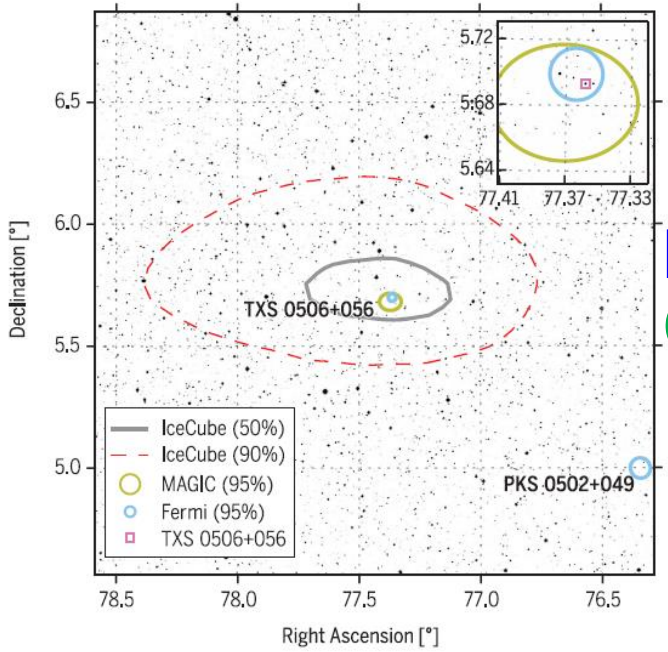
Neutrino flux as a function of energy



The source discovery potential of IceCube-Gen2

(Credit : IceCube Collaboration)





blazar TXS 0506+056

(The IceCube Collaboration 2018)

→ Detecting astrophysical neutrinos is challenging, but could it be possible?

Observation of Astrophysical Neutrinos: (2) KM3Net

→ **Detecting astrophysical neutrinos in the energy range of TeV – PeV**

(e.g., The KM3Net Collaboration 2025)

Locations of KM3Net

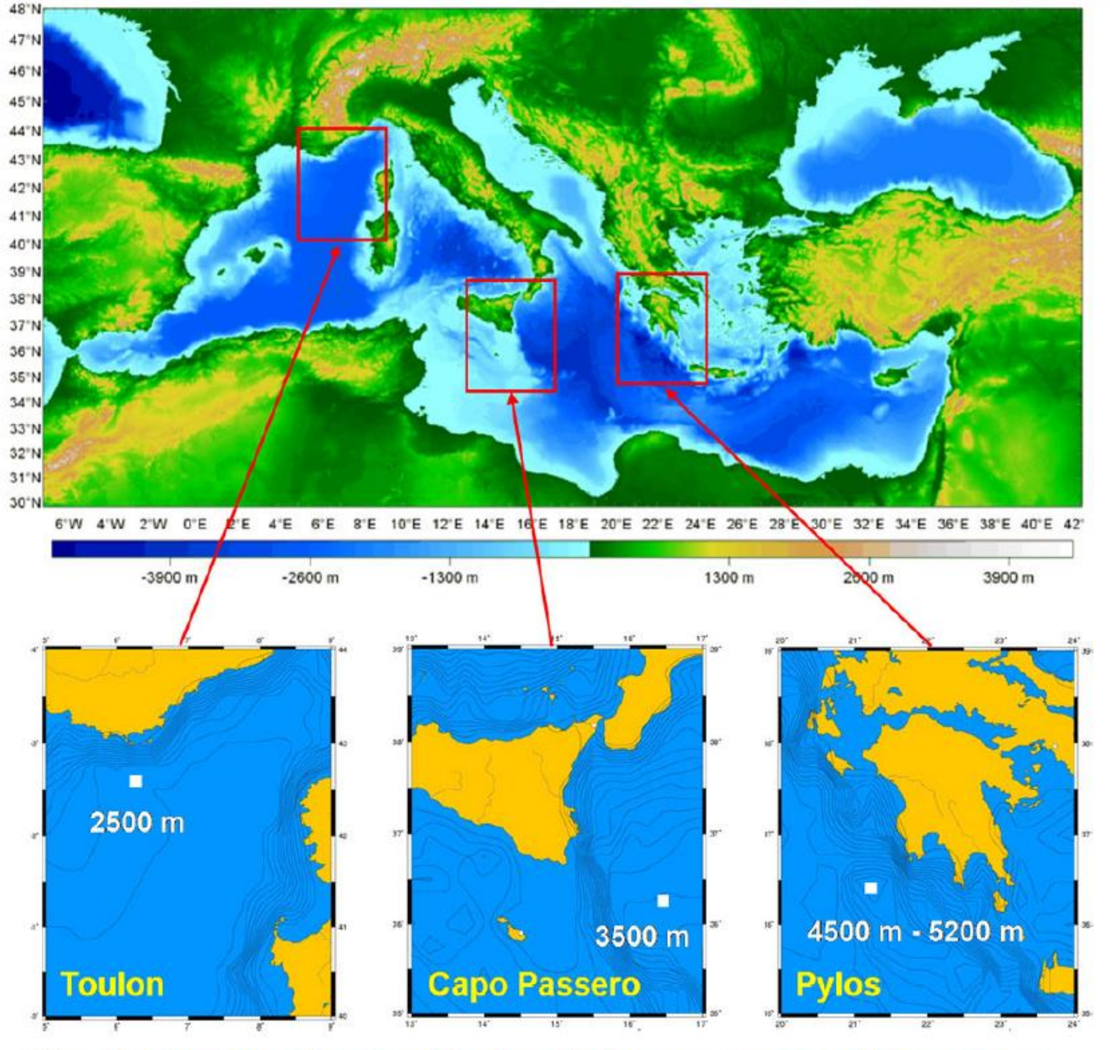
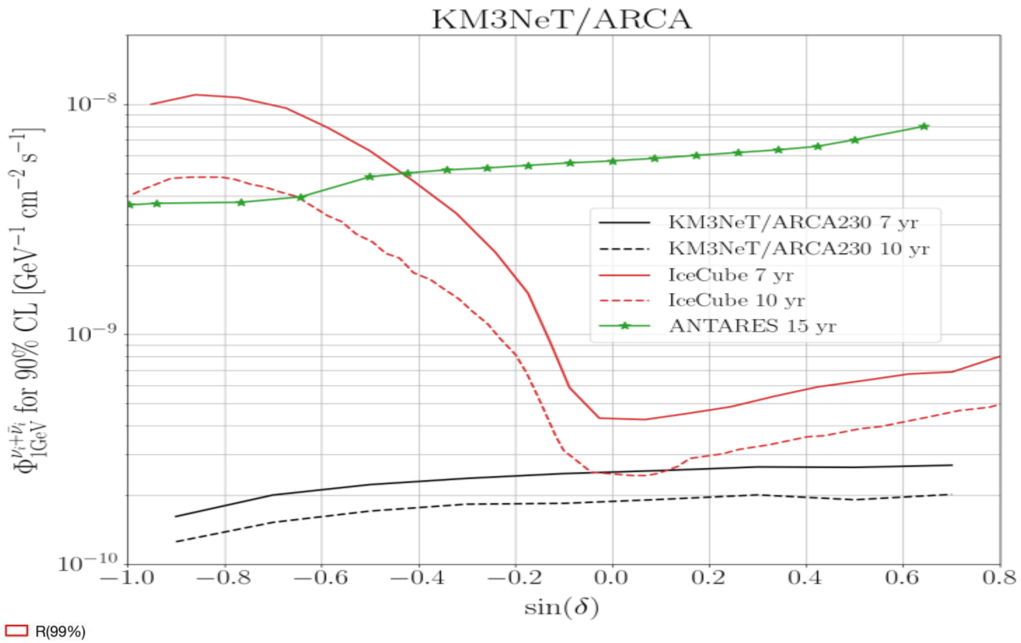
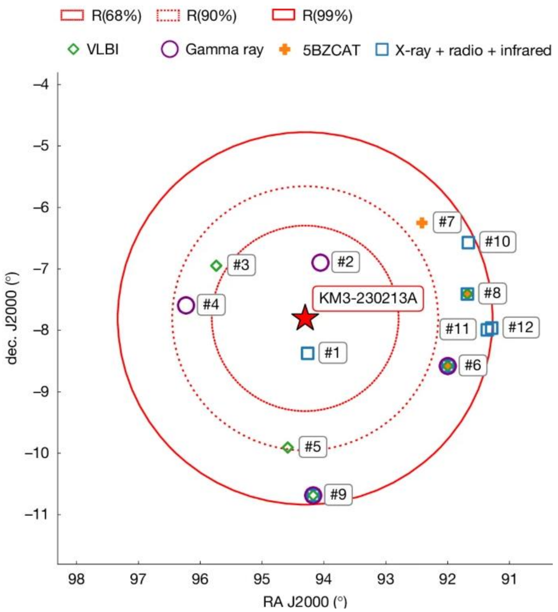


Figure 1-6: Locations of the sites of the three Mediterranean neutrino telescope projects.

sensitivity

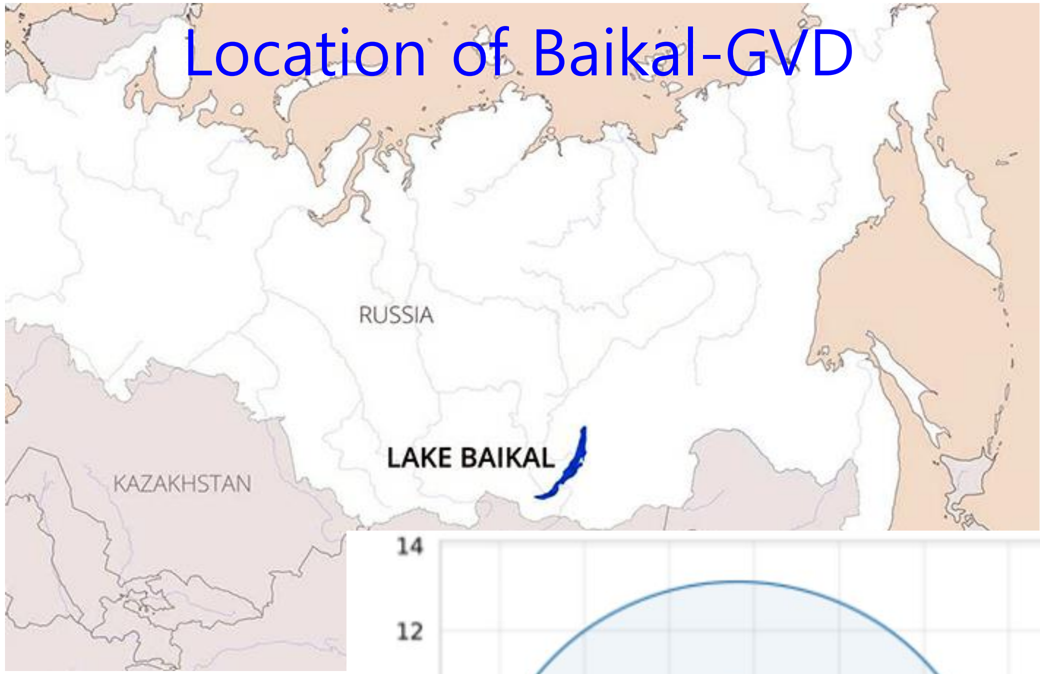


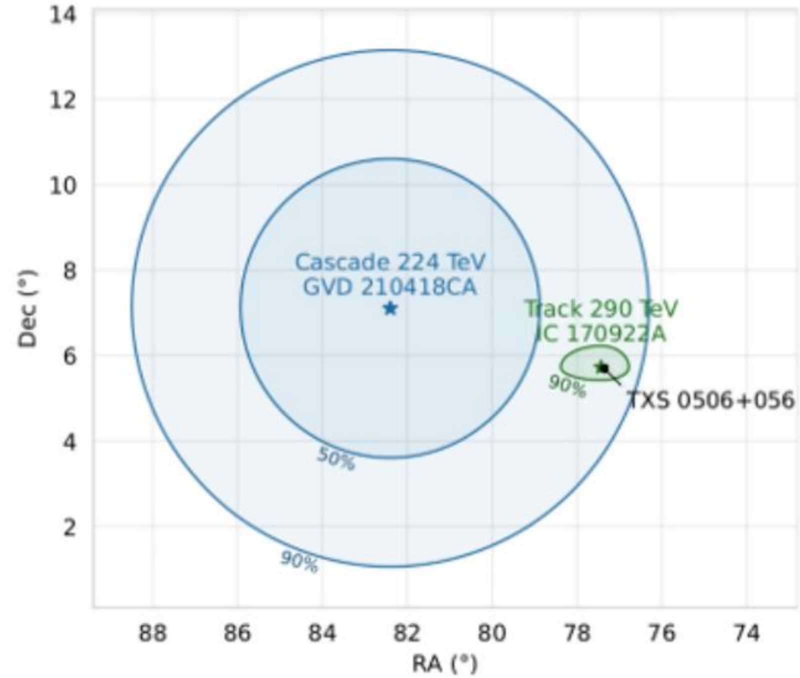


→ Detecting astrophysical neutrinos is challenging, but could it be possible?

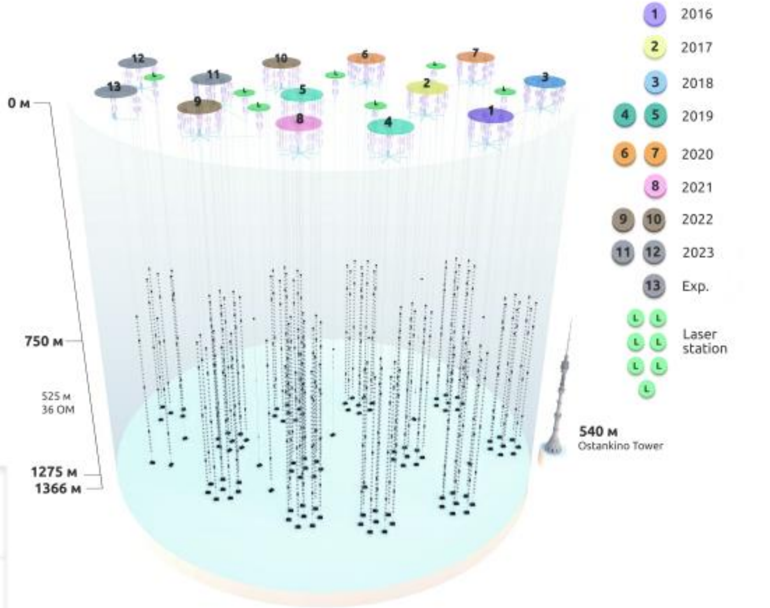
Observation of Astrophysical Neutrinos: (3) Baikal-GVD

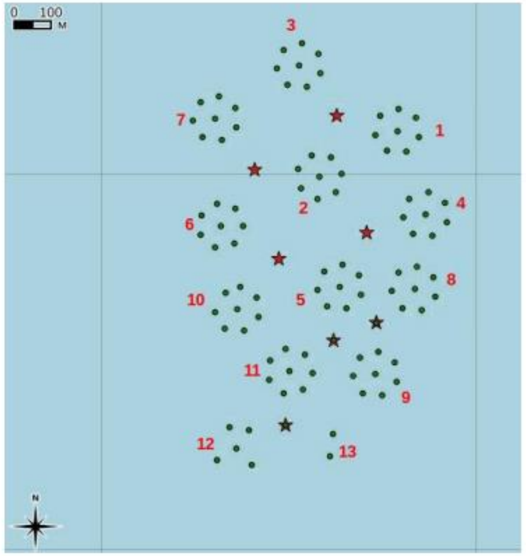
→ **Detecting astrophysical neutrinos in the energy range of TeV – PeV** (e.g., Aynutdinov et al. 2023)





Structure of Baikal-GVD





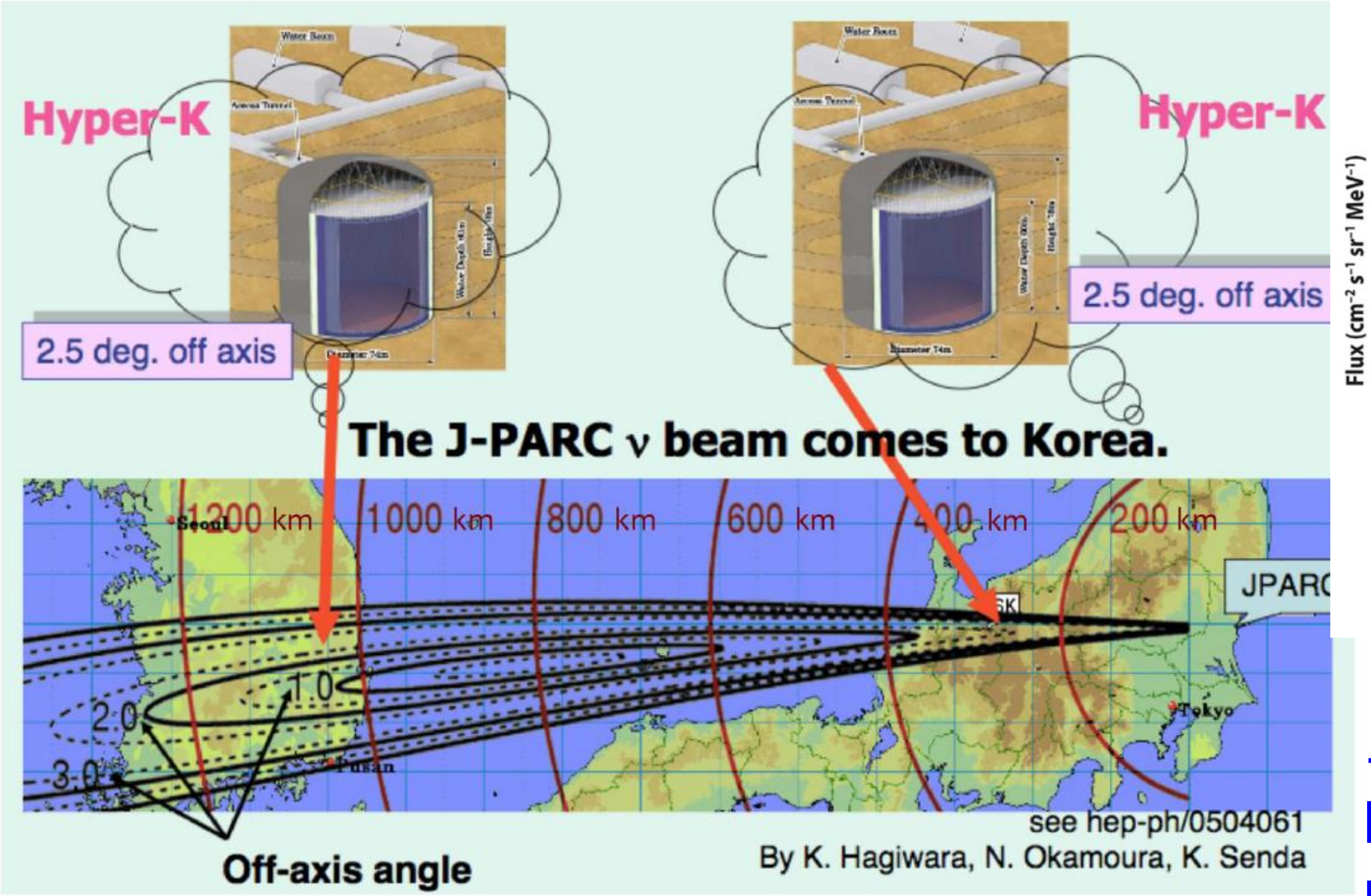
blazar TXS 0506+056

(e.g., Baikal-GVD collaboration 2023, ICRC)

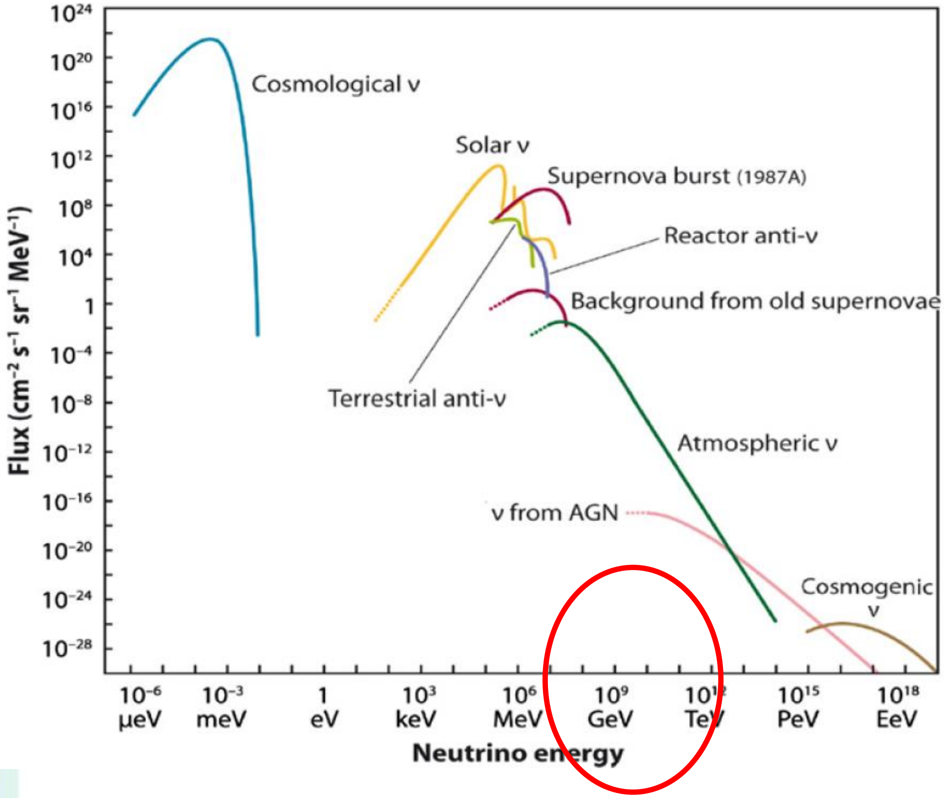
→ Detecting astrophysical neutrinos is challenging, but could it be possible?

Observation via Korean Neutrino Observatory (KNO)

2^{nd} Hyper-K Detector in Korea (KNO)



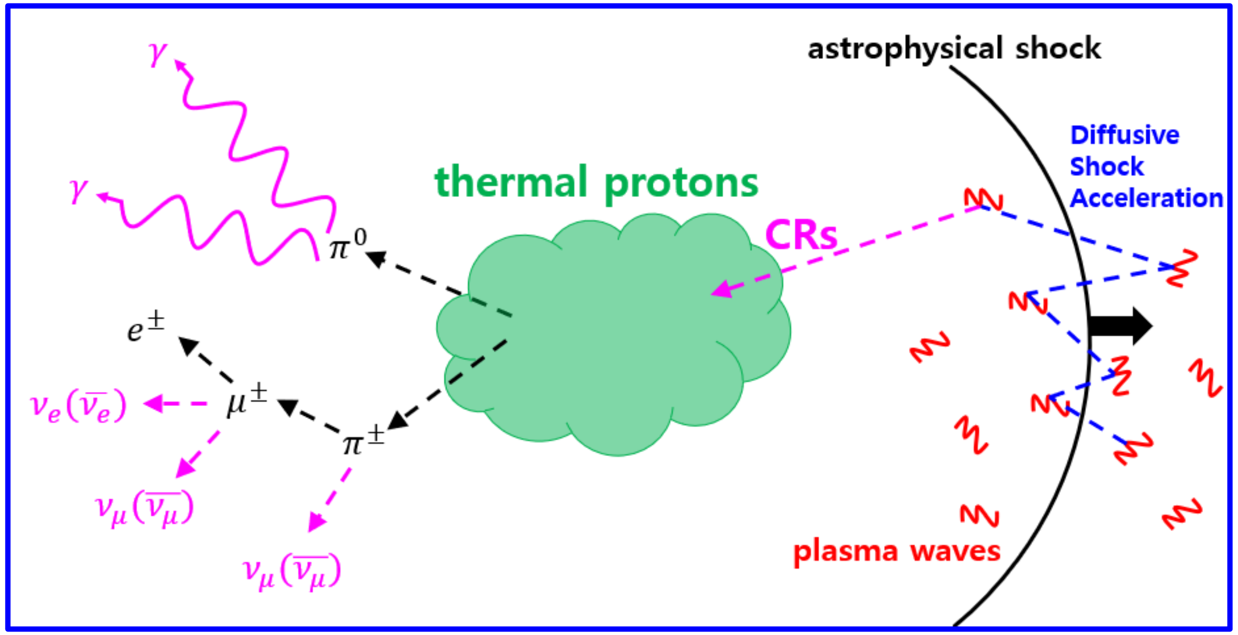
Measured and expected fluxes of natural and reactor neutrinos



KNO (10 MeV ~1 TeV ??)

→ Can astrophysical objects be identified as point-like neutrino sources via KNO?

Neutrino emission related to non-relativistic shocks is the main focus of this talk.



→ **Clusters of galaxies**

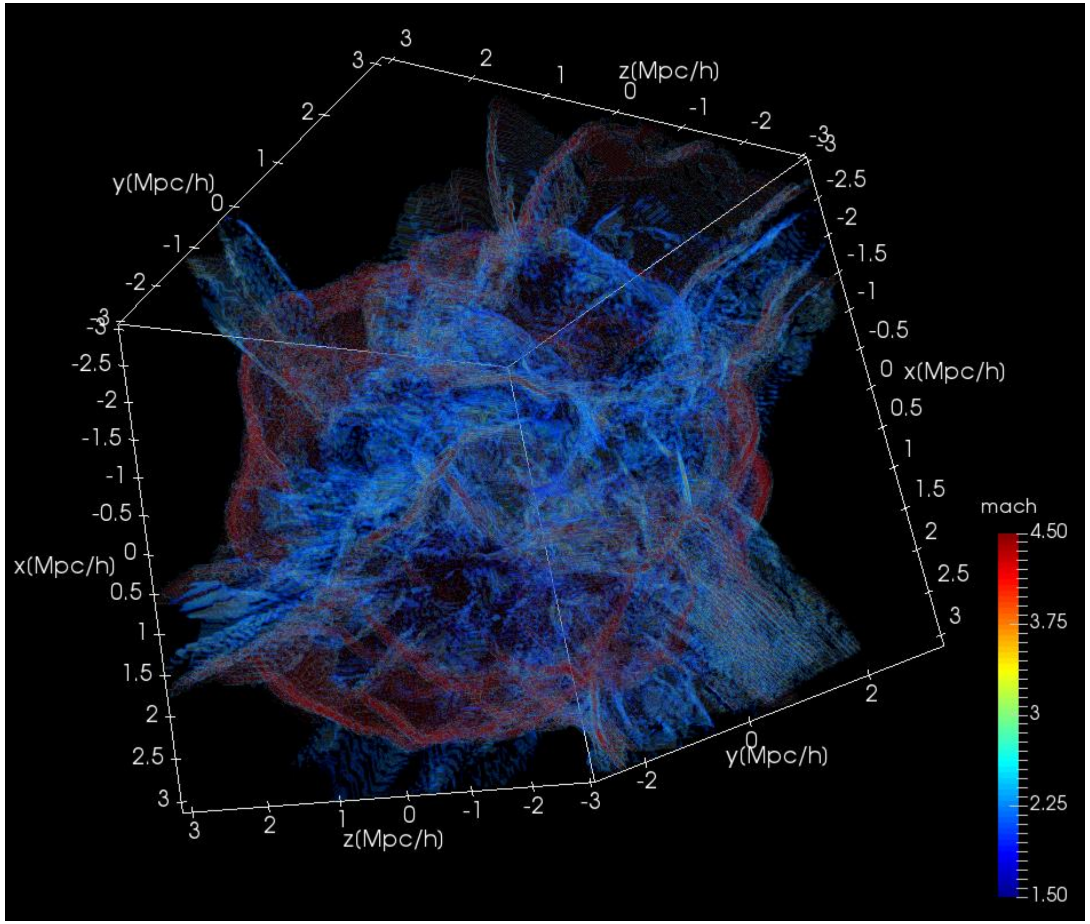
→ **Starburst galaxies (SBGs)**

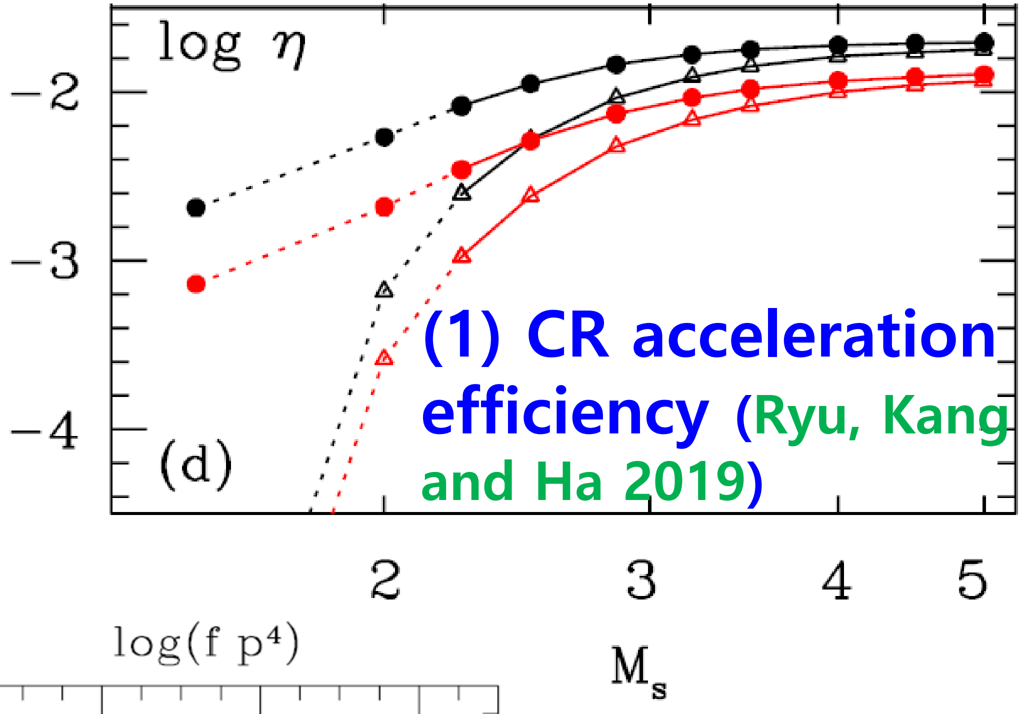
→ **Supernova remnants (SNRs)**

Clusters of Galaxies: CR Acceleration in Intracluster Shocks

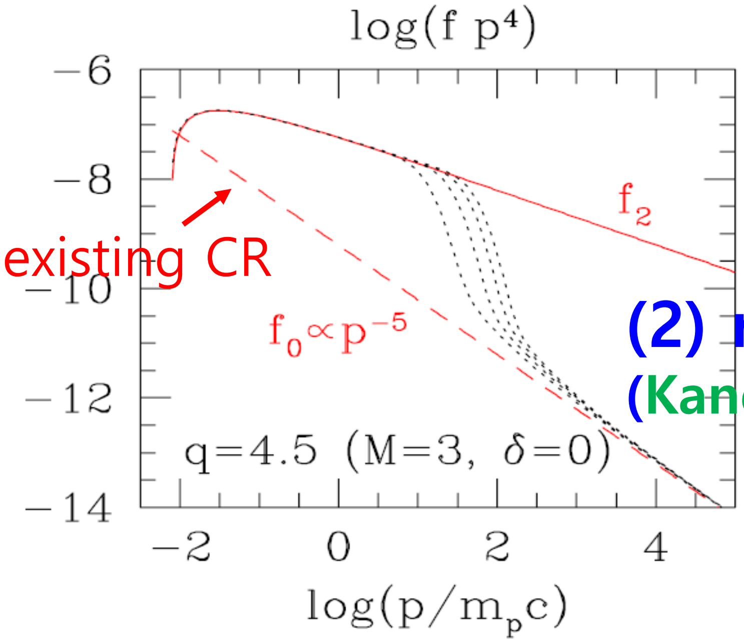
Ha, Ryu and Kang 2020

Cosmological hydrodynamic simulations
[L = 57 Mpc/h box (1650 cells)]





(1) CR acceleration efficiency (Ryu, Kang and Ha 2019)



(2) re-acceleration (Kang and Ryu 2011)

CR Production by Intracluster Shock

- **CR Spectrum: Diffusive Shock Acceleration (DSA)**

$$f_{\mathrm{CR}}(p) \approx n_2 \frac{\exp(-Q_{\mathrm{i}}^2)}{\pi^{1.5}\, p_{\mathrm{th,p}}^3} \left(\frac{p}{p_{\mathrm{inj}}}\right)^{-q} \quad \text{for } p \geqslant p_{\mathrm{inj}}$$

- **Integrated CR Spectrum in a Cluster of Galaxies**

$$\dot{\mathcal{N}}_{\mathrm{CR}}(p)\, dp = \sum_{Q_{\|}, M_s \geqslant 2.25} 4\pi s_{\mathrm{sh}} u_2 f_{\mathrm{CR}}(p)\, p^2 dp$$

- **CR Density in a Cluster of Galaxies**

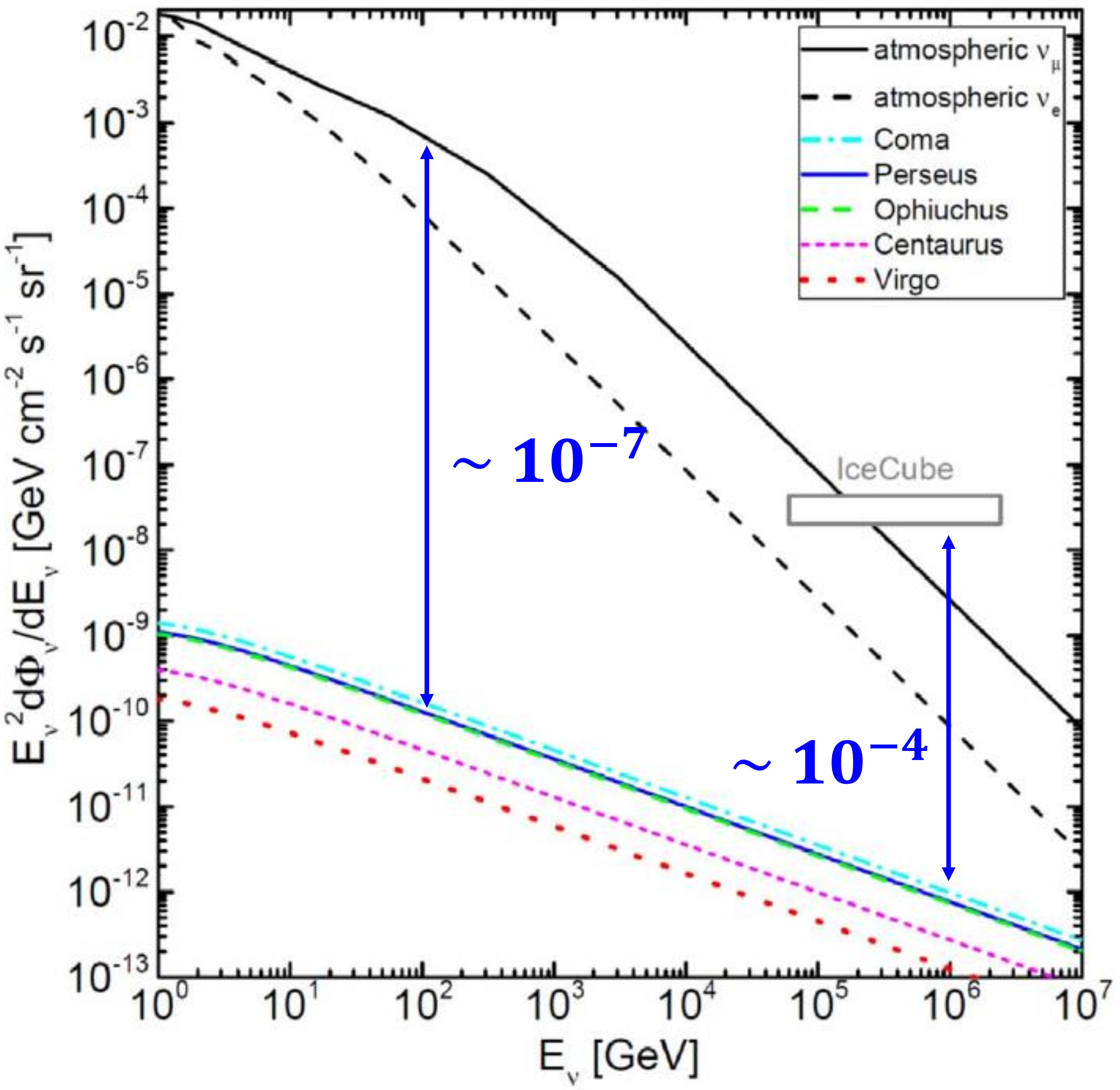
$$n_{\mathrm{CR}}(r, p)\, dp \approx n_{\mathrm{CR0}} \left[\frac{\bar{n}_{\mathrm{gas}}(r)}{n_{\mathrm{gas}}(0)}\right]^{\delta} \left(\frac{p}{\mathrm{GeV}/c}\right)^{-\alpha_p^r} \frac{dp}{\mathrm{GeV}/c}$$

- **Normalization Condition**

$$\int_{<r_{200}} \int n_{\mathrm{CR}}(r, p)\, dp\, dV = \int \mathcal{N}_{\mathrm{CR}}(p)\, dp$$

Predicted Neutrino Fluxes from Nearby Galaxy Clusters

Ha, Ryu and Kang 2020



(1) q_ν: neutrino source function

(2) The energy spectrum of neutrinos

$$\frac{dL_\nu}{dE_\nu} = \int_{<r_{200}} q_\nu(r, E_\nu)\, dV$$

(3) The neutrino flux

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi^2 R_{\rm vir}^2}\frac{dL_\nu}{dE_\nu}$$

→ The probability of detecting nearby galaxy clusters as an isolated neutrino source with KNO (or IceCube) is very small.

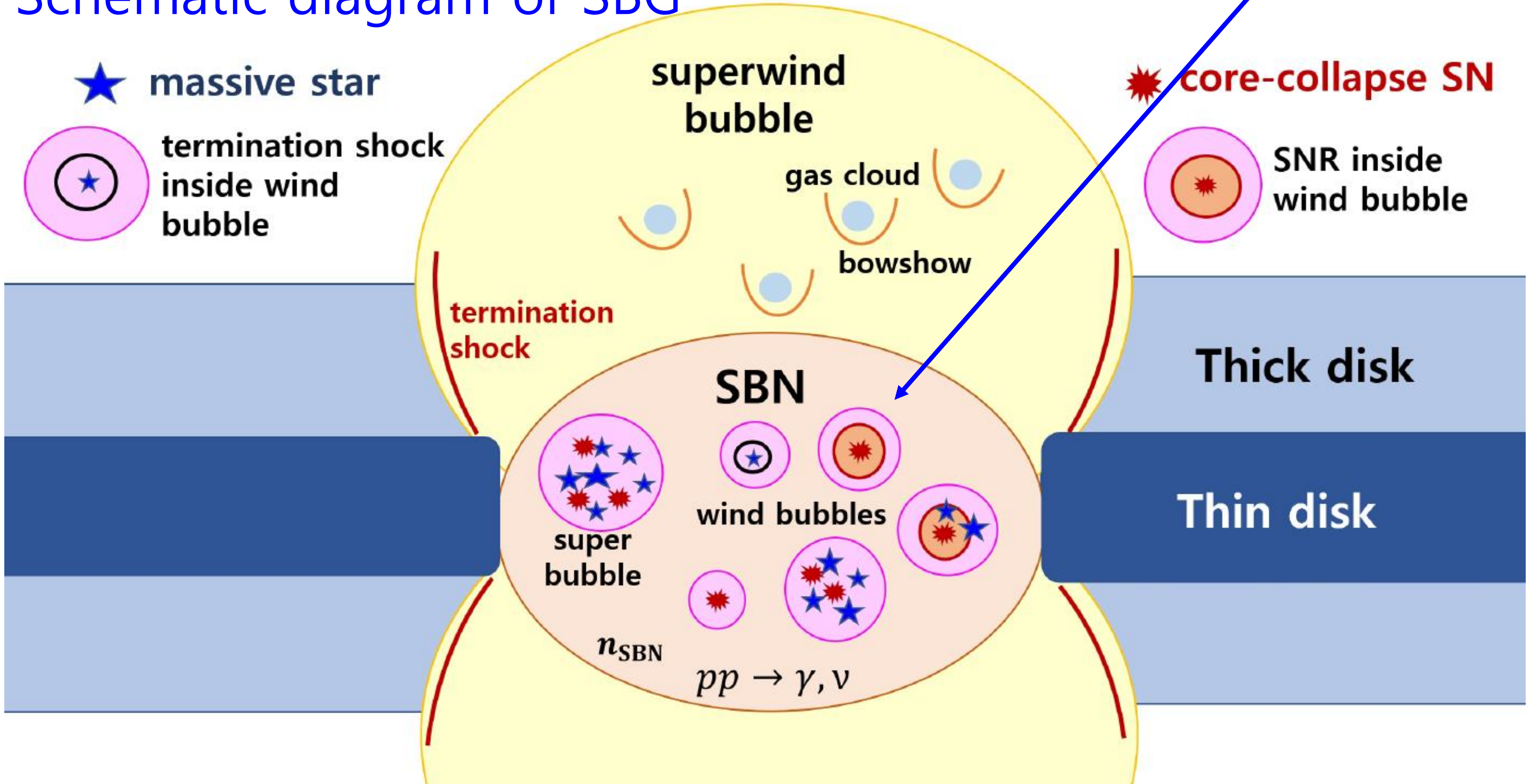
Starburst galaxies (SBGs)

→ high star formation rate (SFR ~ $\underline{2 - 200\, M_{sun}/yr}$)
+ high supernova rate $\underline{(\sim 0.02 - 2\, yr^{-1})}$:
→ **powerful CR factories!**

Ha, Ryu and Kang 2021

*Starburst nucleus (SBN)

Schematic diagram of SBG



→ CR production
(1) pre-SN stellar winds (SWs)
(2) supernova remnants (SNRs) from core-collapse supernova

→ CR transport
(1) SBN wind
(2) diffusion mediated by turbulence

CR production model in SBN

CR produced by a collection of shocks induced by supernova remnants

(1) single PL model

$$\mathcal{N}_{\rm SN,p}(p) \propto \left(\frac{p}{m_p c}\right)^{-\alpha_{\rm SN}} \exp\left(-\frac{p}{p_{\rm max}}\right)$$

$p_{\rm max} \simeq 1 - 100\ {\rm PeV}/c$

$\alpha_{\rm SN} \simeq 4.2 - 4.5$

$\alpha_{\rm SN,1} \simeq 4.2 - 4.5$

$\alpha_{\rm SN,2} \simeq 3.95 - 4.1$

(2) double PL model:

$$\mathcal{N}_{\rm SN,p}(p) \propto \begin{cases} \left(\frac{p}{m_p c}\right)^{-\alpha_{\rm SN,1}} & (p < p_{\rm brk}) \\ \left(\frac{p}{m_p c}\right)^{-\alpha_{\rm SN,2}} \exp\left(-\frac{p}{p_{\rm max}}\right) & (p \geq p_{\rm brk}), \end{cases}$$

CR produced by a collection of shocks induced by stellar winds

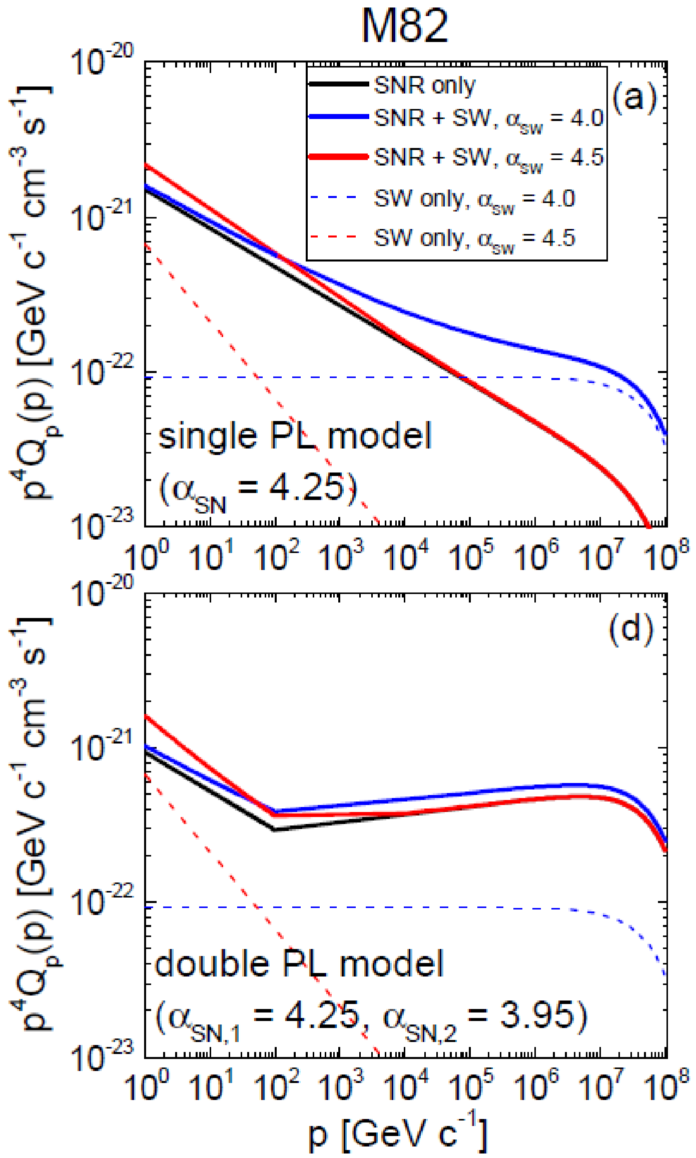
$$\mathcal{N}_{\rm SW,p}(p) \propto \left(\frac{p}{m_p c}\right)^{-\alpha_{\rm SW}} \exp\left(-\frac{p}{p_{\rm max}}\right)$$

$\alpha_{\rm SW} \simeq 4.0 - 4.5$

$p_{\rm max} \simeq 1 - 100\ {\rm PeV}/c$

Total CR injection rate in SBN:

$$Q_p(p) = \frac{\mathcal{N}_{\rm SN,p}(p) + \mathcal{N}_{\rm SW,p}(p)}{V}$$

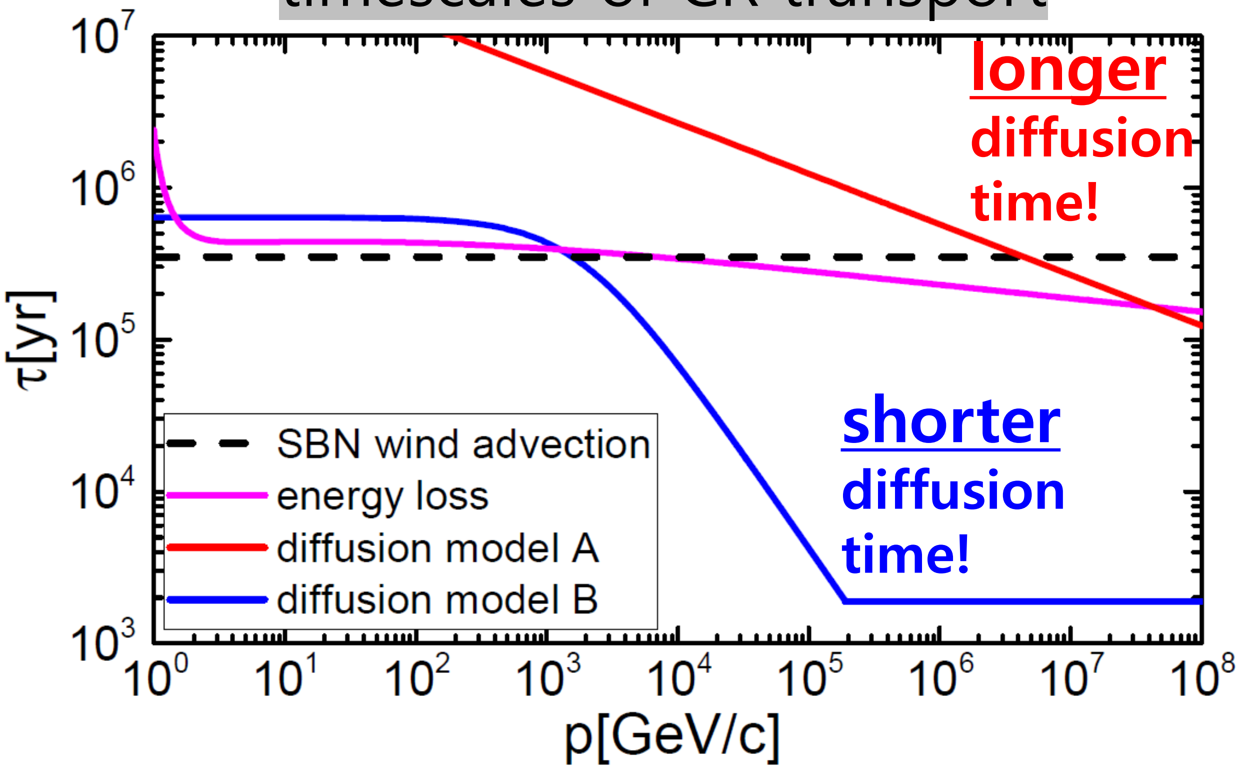


CR transport model in SBN

(1) SBN wind: advection of CRs, a phenomenon that typically acts in the same way for CRs of any energy.

(2) Diffusion mediated by turbulence: ??

timescales of CR transport



Model A (Sudoh et al. 2018, Peretti et al. 2019):

- CR diffusion through resonant scattering off the large-scale turbulence in SBN.

⇒ CRs are efficiently confined in SBN!

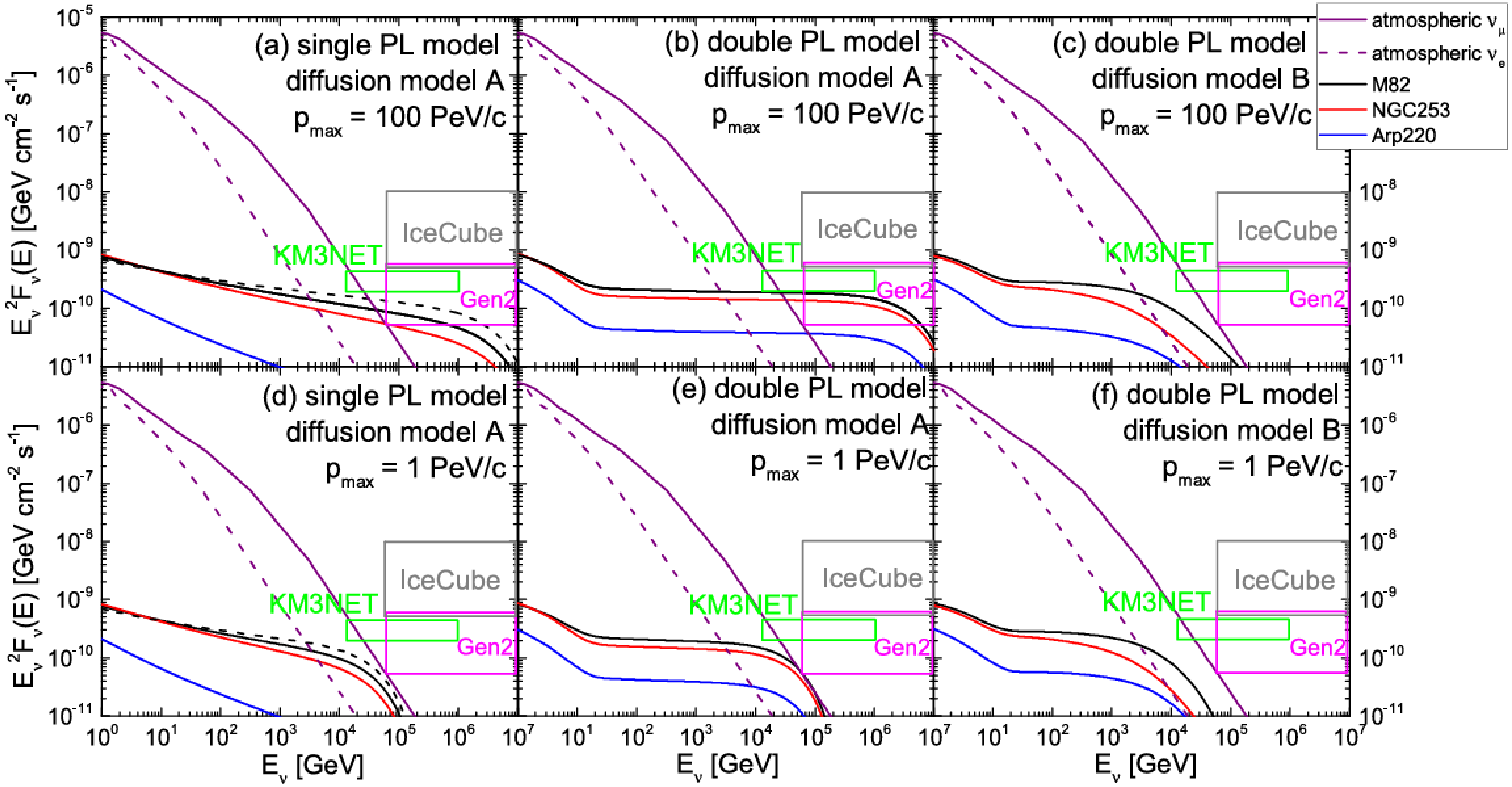
Model B (Krumholz et al. 2020):

- CRs interact with self-excited plasma waves via CR streaming instability.

⇒ CRs easily escape from SBN!

Predicted Neutrino Fluxes from Nearby SBGs

Ha, Ryu and Kang 2021



→ Except in the most optimistic scenario, the neutrino fluxes from nearby SBGs are too low to be detected as point sources.

To Understand the Scientific Potential of Neutrino Observatories to Detect Neutrinos from Supernova Remnants

→ **Source neutrino fluxes** in the energy range of GeV - PeV

→ Searching **galactic gamma-ray sources**

→ **Number of events??**

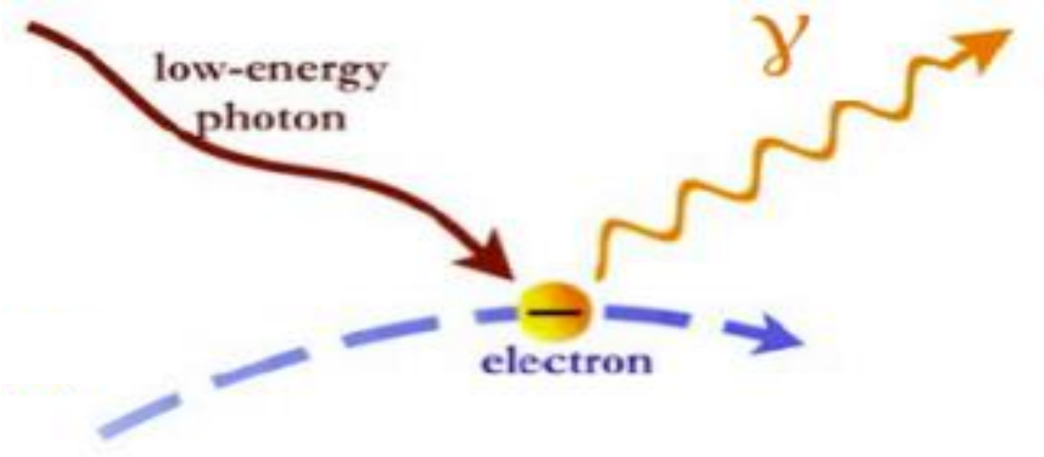
→ **Observation time??**

→ **etc...??**

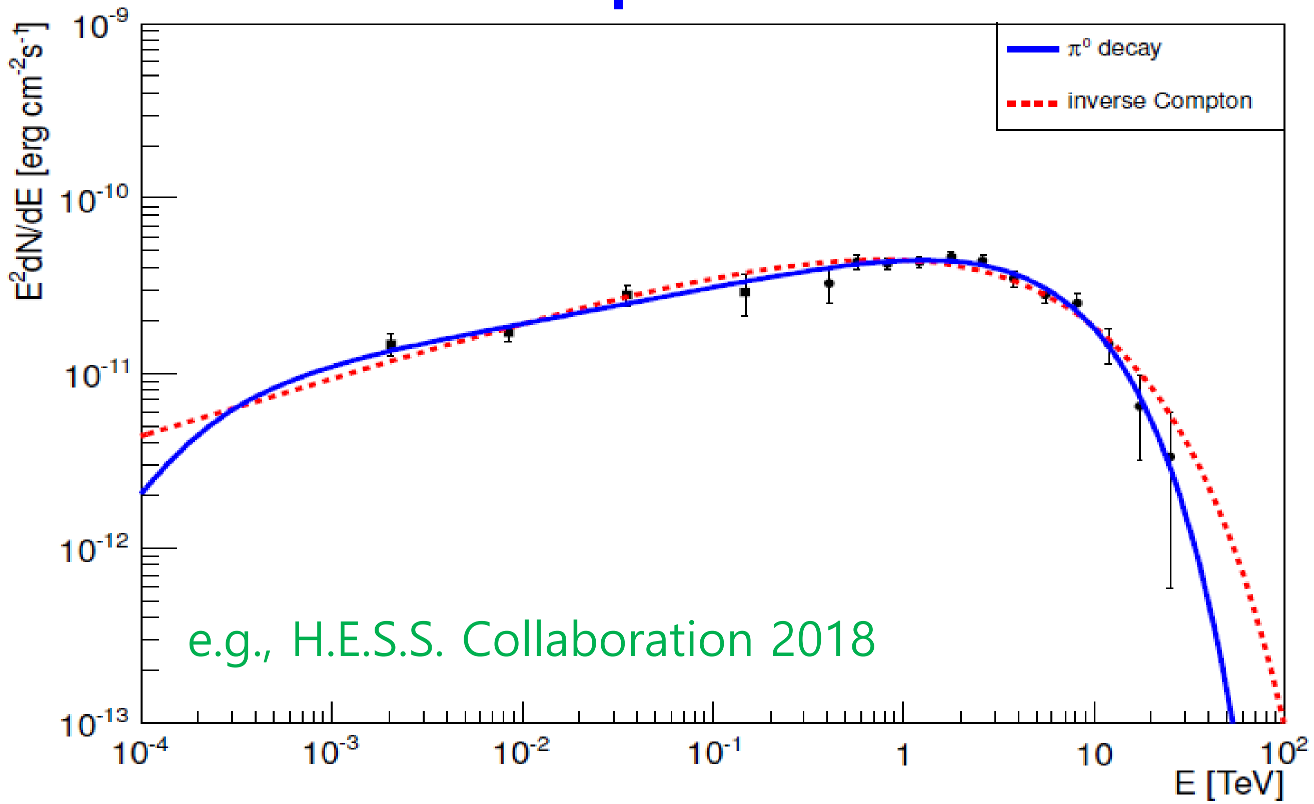
All of these issues require detailed investigation.

Scenario of Gamma-ray Production: Leptonic vs Hadronic

Inverse-Compton Scattering (leptonic)

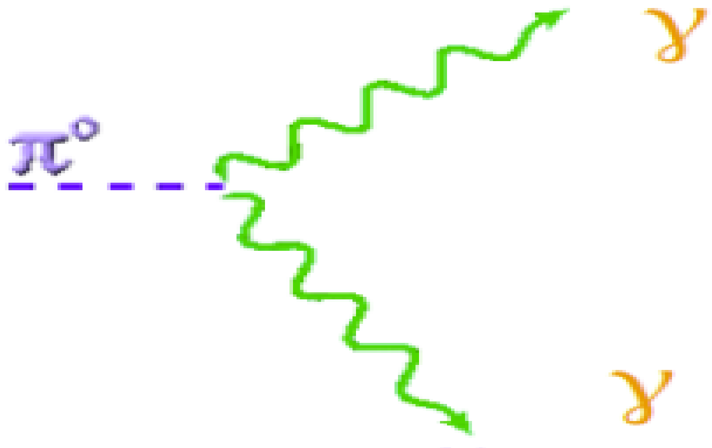


Example: Vela Jr



e.g., H.E.S.S. Collaboration 2018

Pion decay (hadronic)



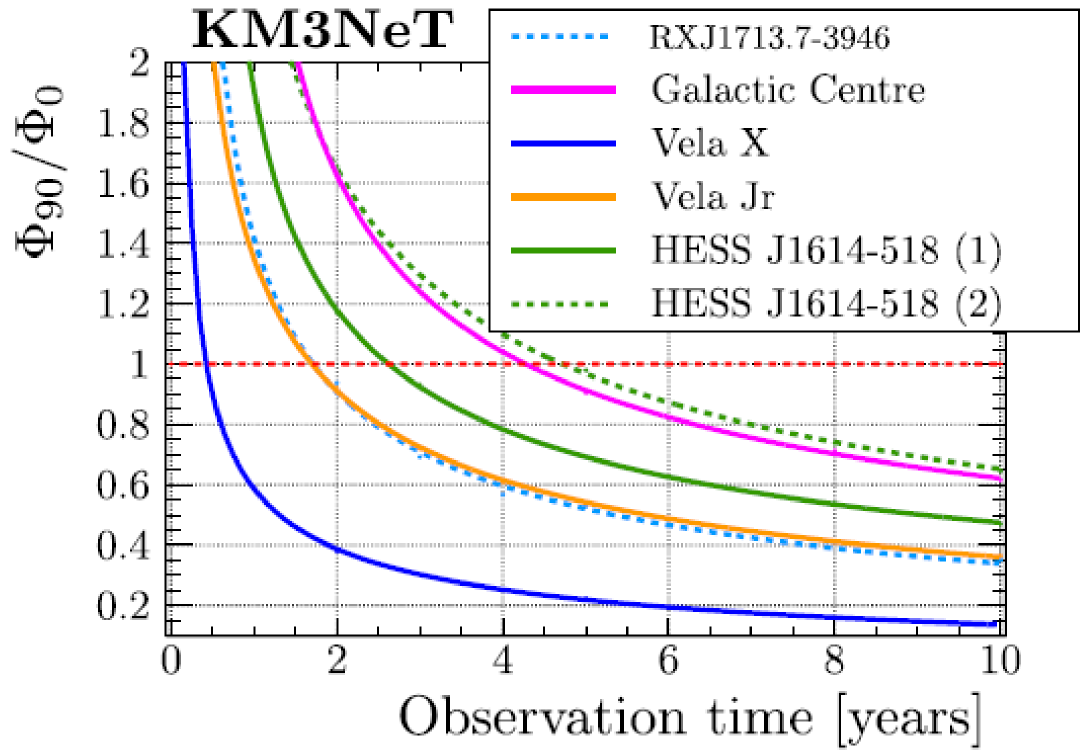
(Figure: H. Costantini 2017)

(1) Fully hadronic emissions (?)

(2) Hadronic + leptonic emissions (?)

Can galactic neutrino sources be detected as point sources of neutrinos?

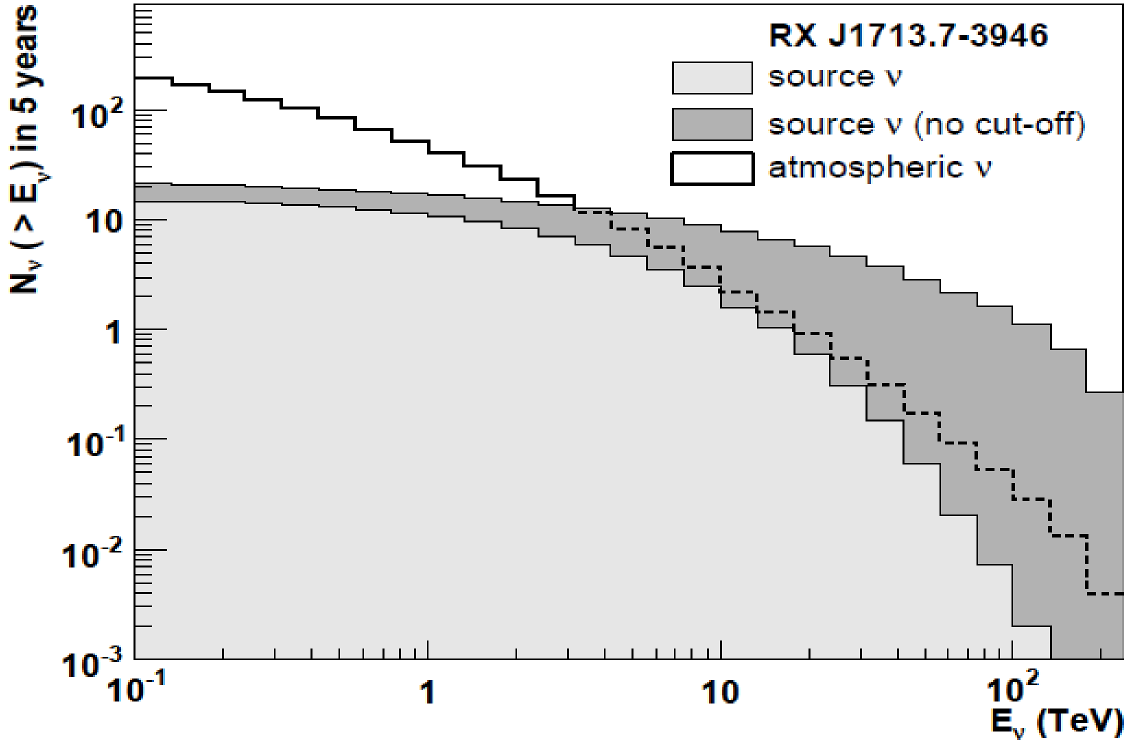
Ratio of the sensitivity and the expected flux
(Aiello et al. 2019)



Φ_{90}: minimum detectable flux (sensitivity)

Φ_0: expected flux inferred from gamma-ray flux by H.E.S.S.

Number of expected events in 5 yr
(kappes et al. 2006)

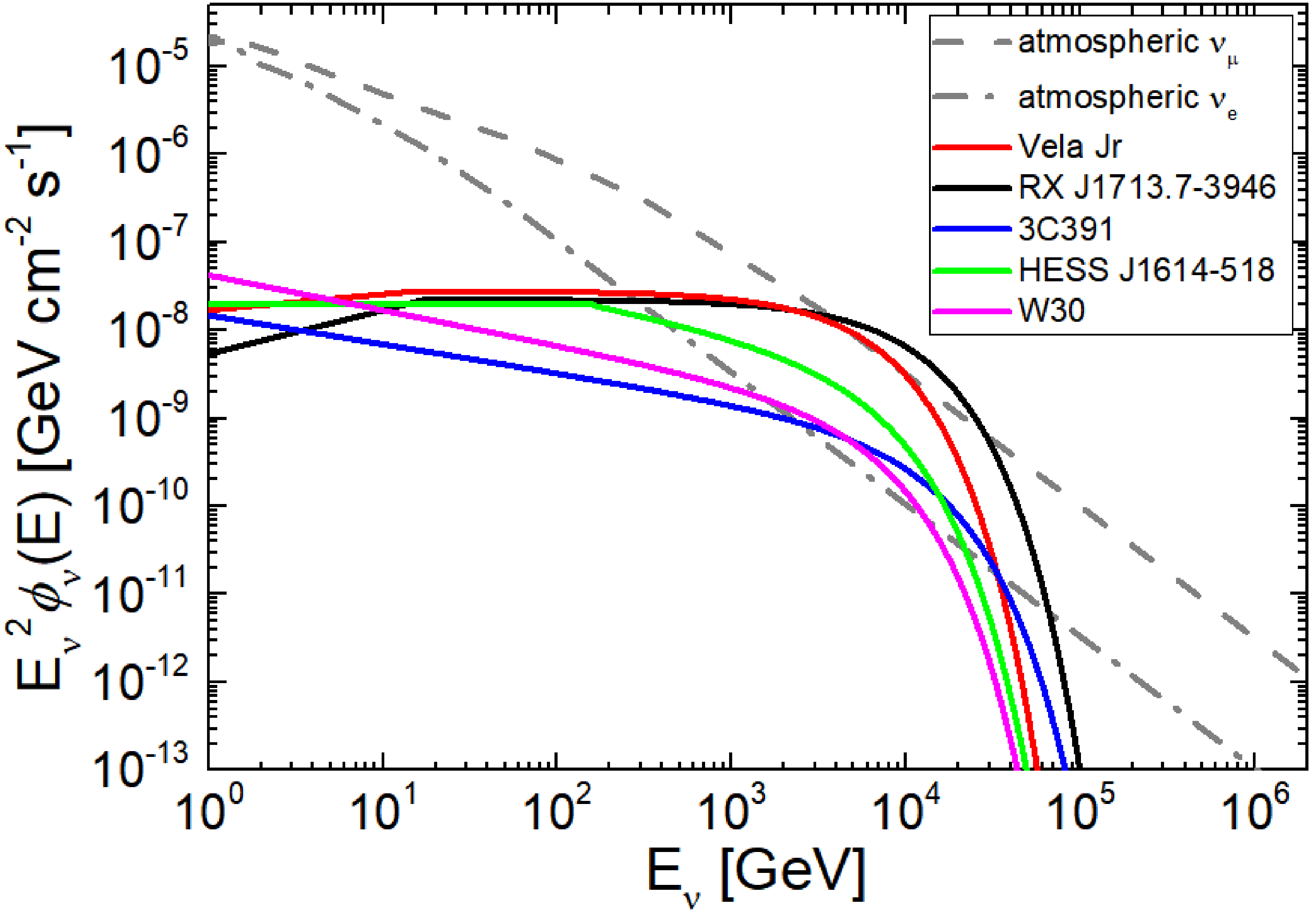


→ KM3NET: TeV – PeV
→ galactic sources are possibly detected within ~ 5 years with KM3NET

Predicted Neutrino Fluxes from Galactic Sources Derived from Measured Gamma-ray Fluxes

Ha et al. in prep.

Estimated neutrino fluxes inferred from fully hydronic scenario



$$\frac{1}{3}\sum_\alpha E_\nu^2 \phi_{\nu_\alpha}(z, E_\nu) \sim \frac{K_\pi}{4}\, E_\gamma^2 \phi_\gamma^{(obs)}(z, E_\gamma)$$

* $\alpha = \mu, e, \tau$

* $E_\gamma \approx 2E_\nu$

* K_π: the relative charged-to-neutral pion rate

2° search cone

(diameter of galactic sources <~ 2°)

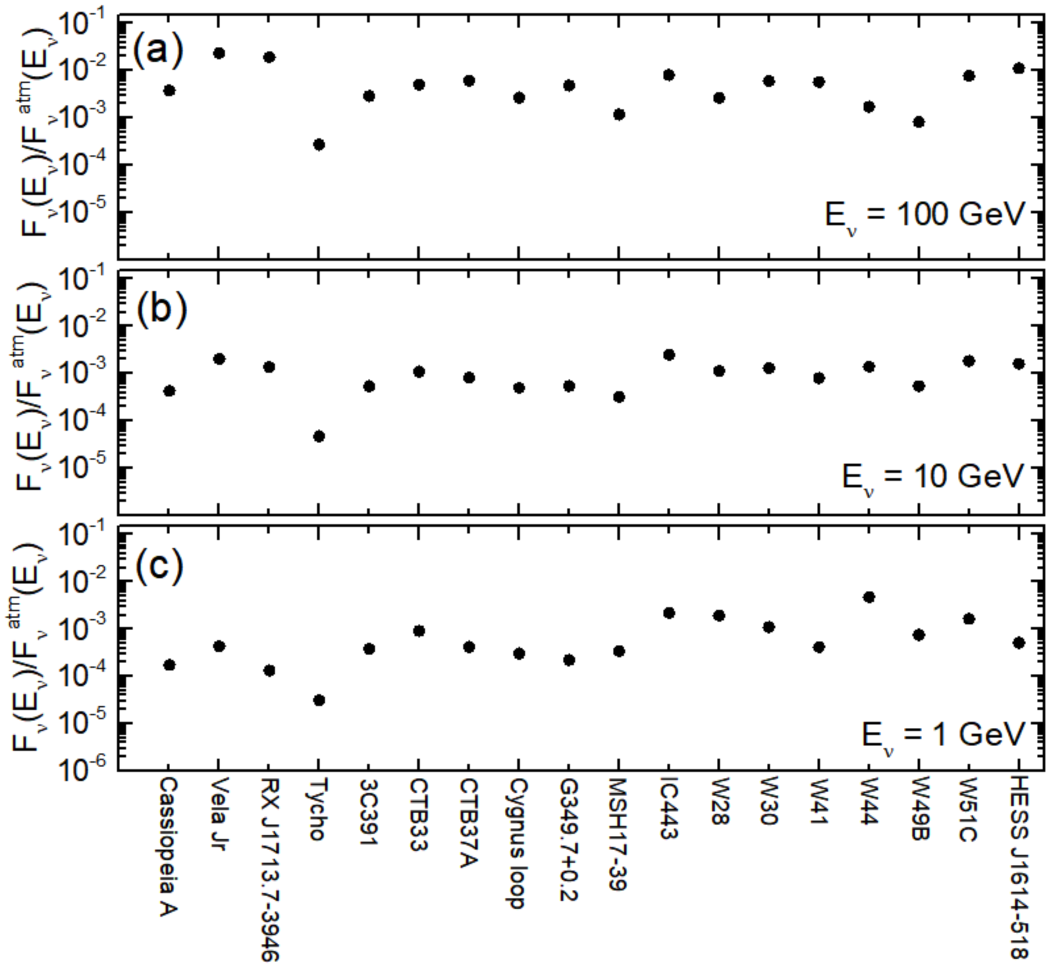
- KNO: ~ GeV – TeV
- IceCube, KM3NET, Baikal-GVD: ~ TeV - PeV

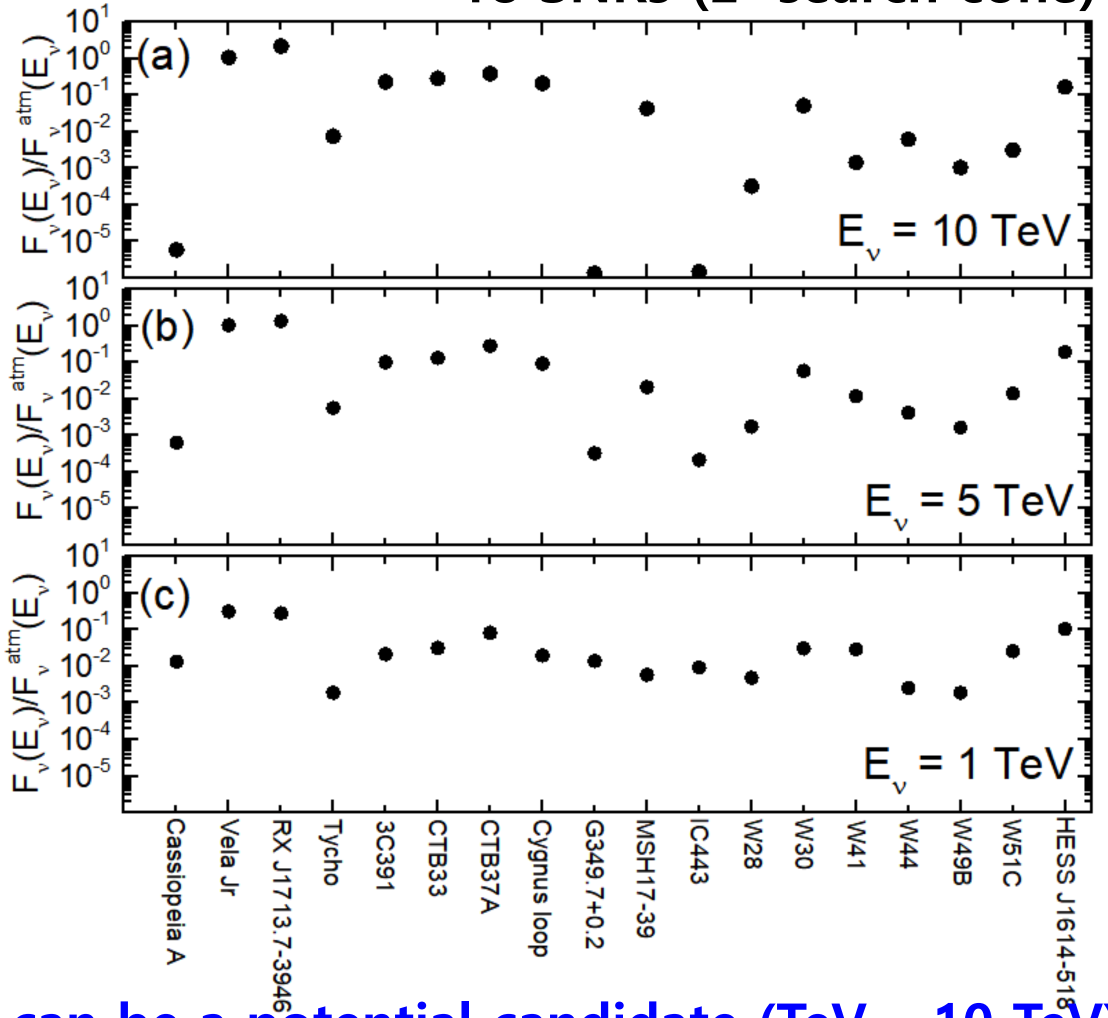
→ Neutrinos from galactic sources may be detected via KNO (??)

Searching for Galactic Gamma-ray Sources Listed in the Fermi-LAT Catalog: Detectability from GeV to 10 TeV

Ha et al. in prep.

* 18 SNRs (2° search cone)





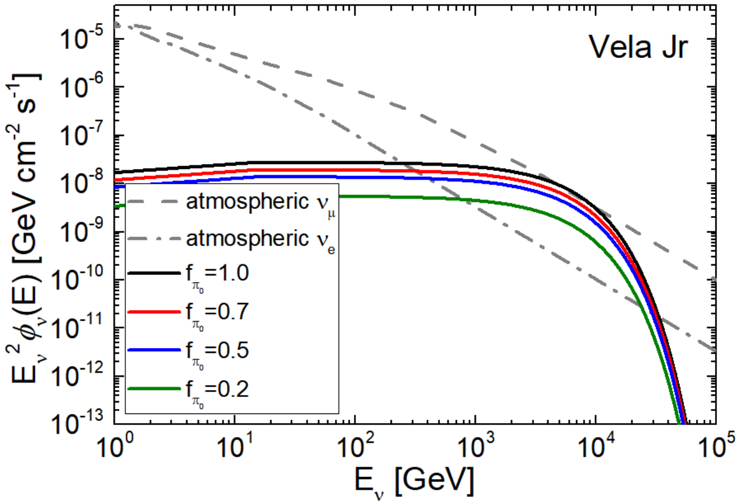
Signal to noise ratio: total neutrino flux: SNR can be a potential candidate (TeV – 10 TeV)

(1) $\dfrac{F_\nu(E_\nu = 100\ GeV)}{F_\nu^{atm}(E_\nu = 100\ GeV)} < \sim 10^{-1}$ (2) $\dfrac{F_\nu(E_\nu = 1\ TeV)}{F_\nu^{atm}(E_\nu = 1\ TeV)} < 1$ (3) $\dfrac{F_\nu(E_\nu = 10\ TeV)}{F_\nu^{atm}(E_\nu = 10\ TeV)} < \sim$ a few

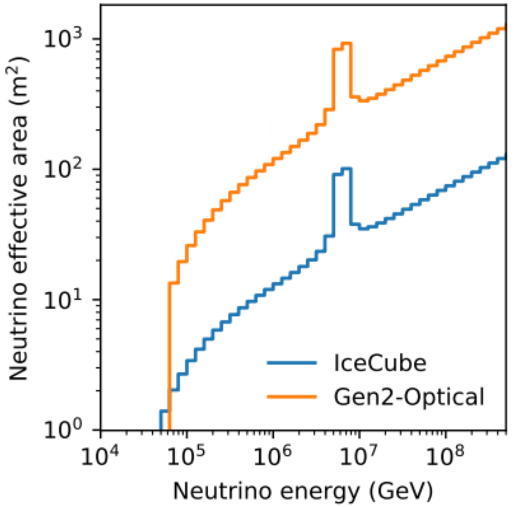
Dependence on the Fraction of Hadronic Gamma-rays

Ha et al. in prep.

Estimated neutrino fluxes



The IceCube-Gen2 Collaboration 2020

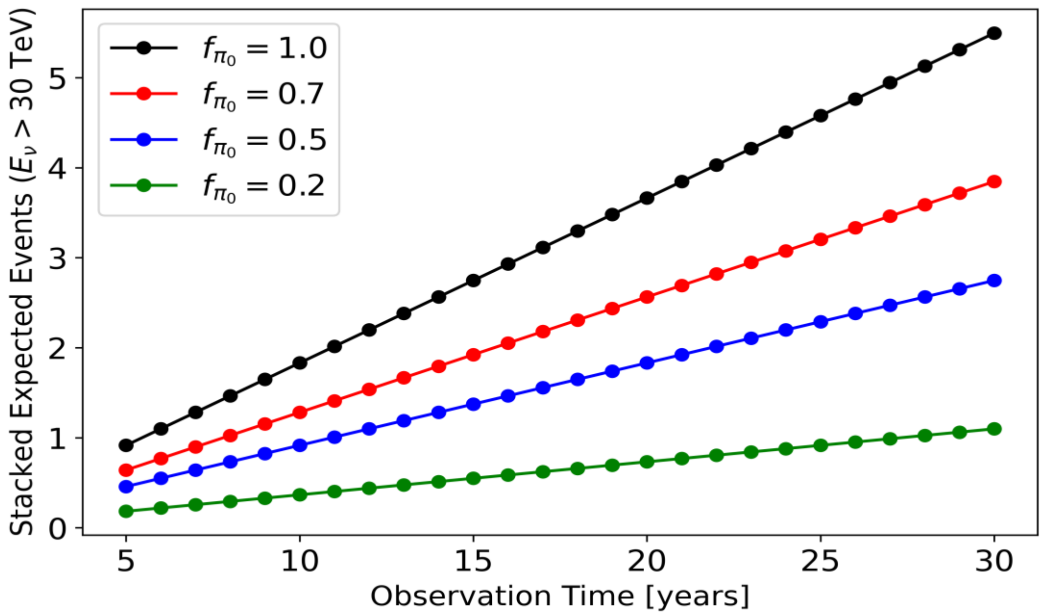


$$N_{evt} = T\int_{E_{\nu,min}}^{E_{\nu,max}} \phi_\nu(E_\nu)\cdot A_{eff}(E_\nu,\delta)dE_\nu$$

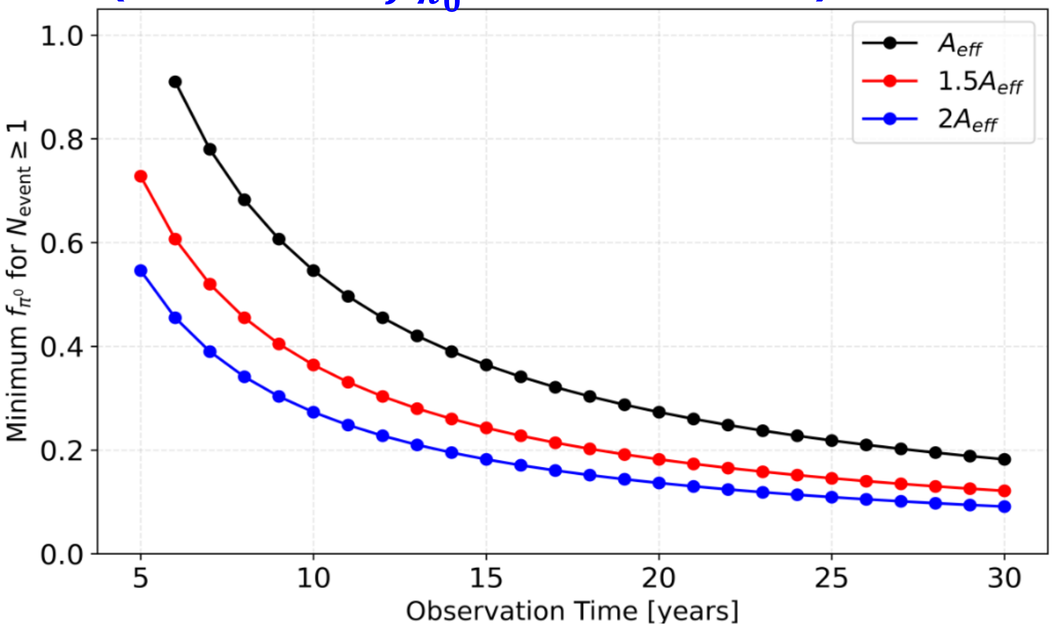
* $A_{eff}(E_\nu,\delta)$: Effective area of IceCube

* f_{π_0}: Fraction of hadronically originated gamma-rays

Stacked Expected Events (8 SNRs)



Dependence on the effective area (minimum f_{π_0} for detection)



Summary

- **Modeling**

→ Particle acceleration at astrophysical shocks

→ Constraints from gamma-ray observations and neutrino flux predictions

- **Clusters of galaxies**

→ Detection of neutrino emission is generally unlikely.

- **Starburst galaxies (SBGs)**

→ There is a minor possibility of detection by increasing the sensitivity of detectors (e.g., IceCube-Gen2).

- **Supernova remnants (SNRs)**

→ Detecting neutrino emission appears likely by stacking data from multiple supernova remnants (SNRs) over 10 to 20 years.

Спасибо большое!

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