高エネルギーニュートリノ放出天体の理論モデル

東北大学

学振研究員(PD)

木村成生

（Shigeo S. Kimura）

第12回光赤外天文学大学間連携ワークショップ 2021/11/24-2021/11/26

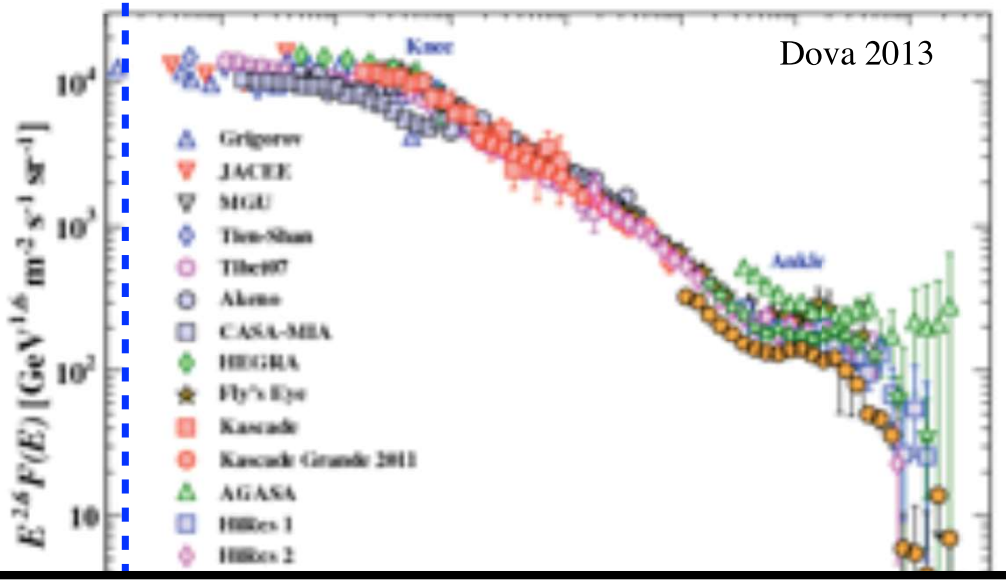
Contents

Contents

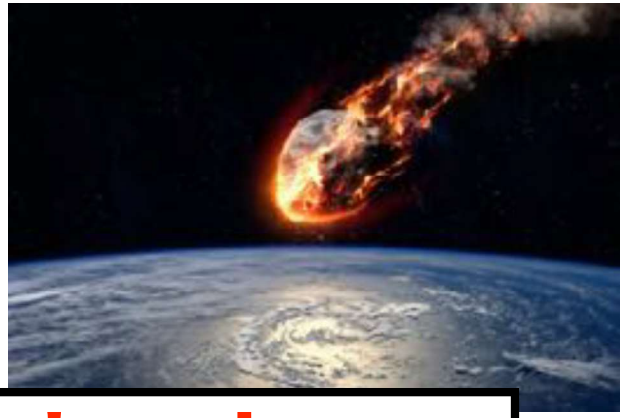
Cosmic-Rays (CRs)
: High-energy particles filling the Universe

1912
Discovery by HESS

Energy by
LHC@CERN



- UHE CRs 1 g
  → mass extinction!



Origins and **production mechanisms** are **unknown for a century**

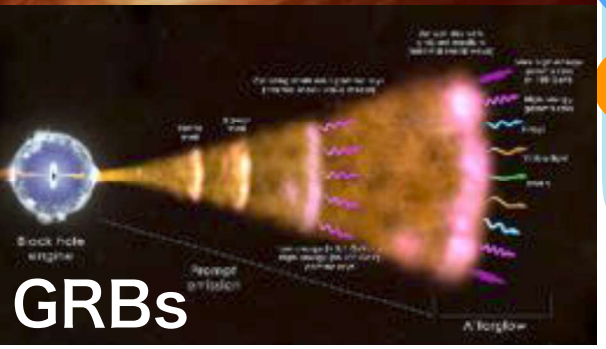
High-energy Neutrino Astrophysics

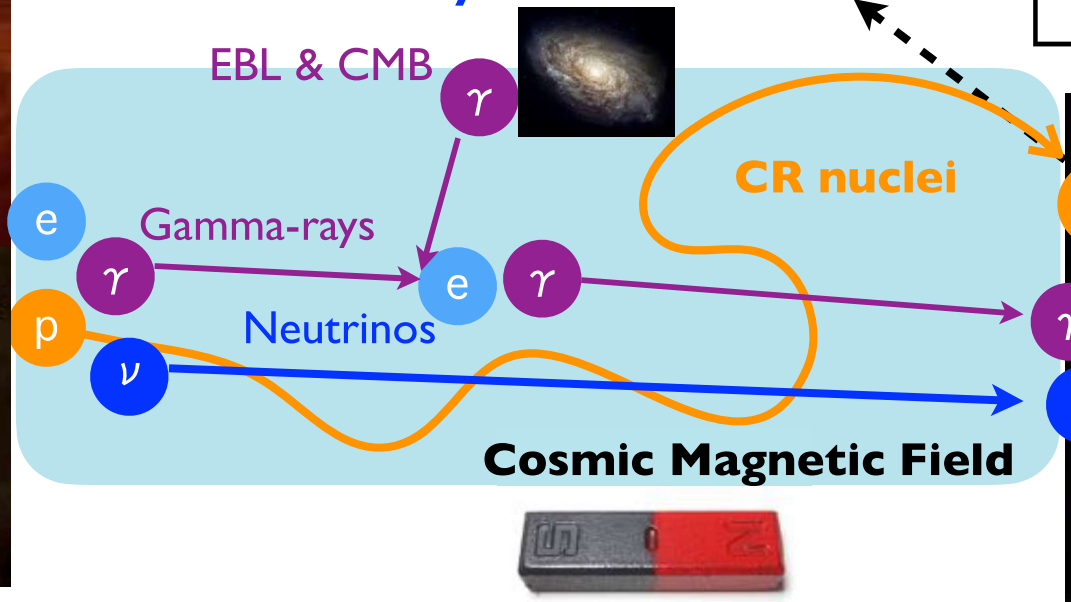
Cosmic-ray production at distant sources

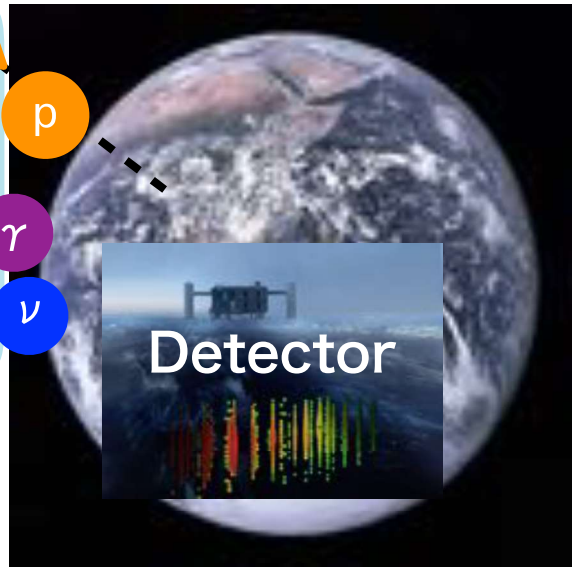
Propagation of intergalactic medium

CR nuclei : deflected by B-field
Gamma-rays : attenuated by soft photons
Neutrinos: directly arrive at Earth

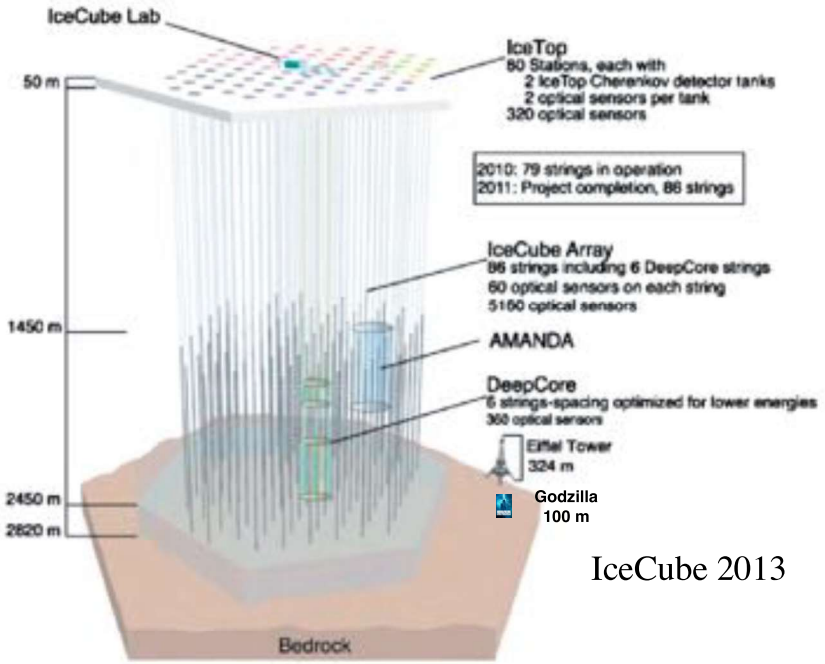
Detection at Earth



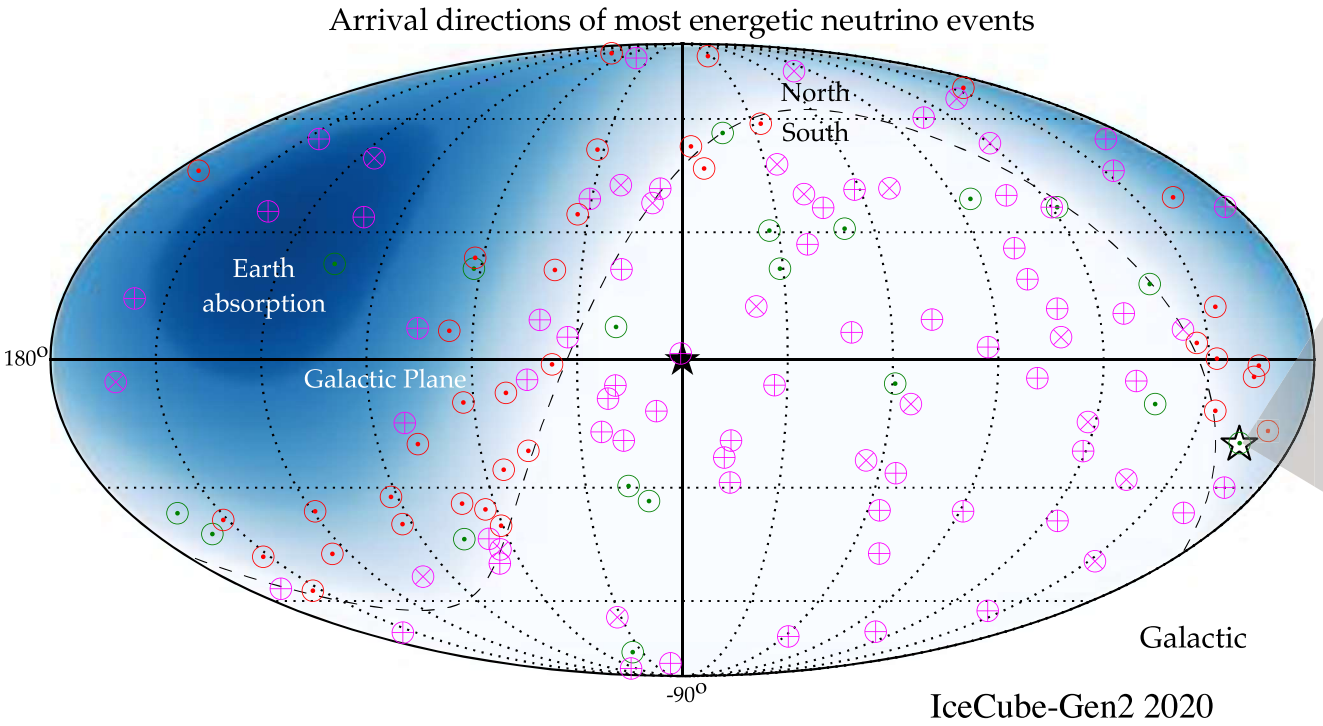




Detection of Astrophysical Neutrinos



IceCube 2013

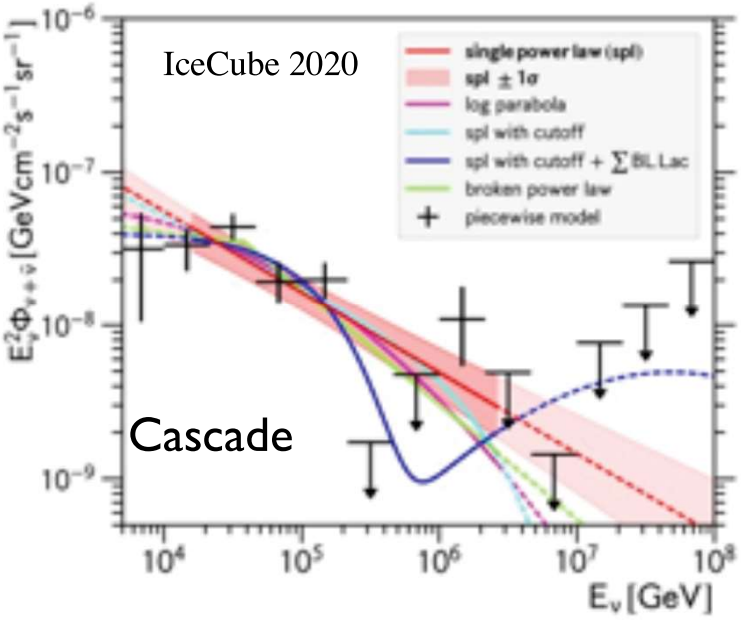


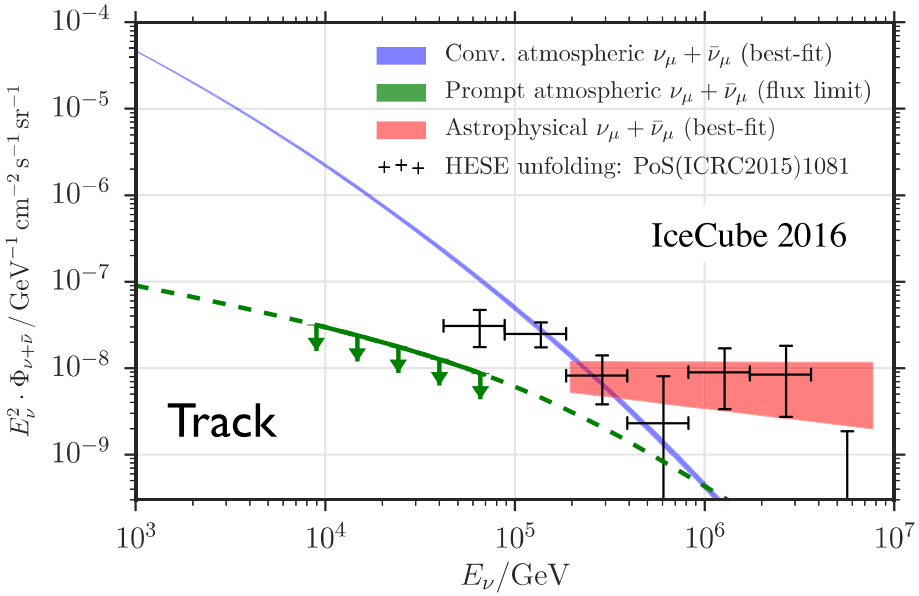
IceCube-Gen2 2020

- IceCube experiment reported detection of astro-ν (E ~ PeV) in 2013
- **Origin has yet to be determined**

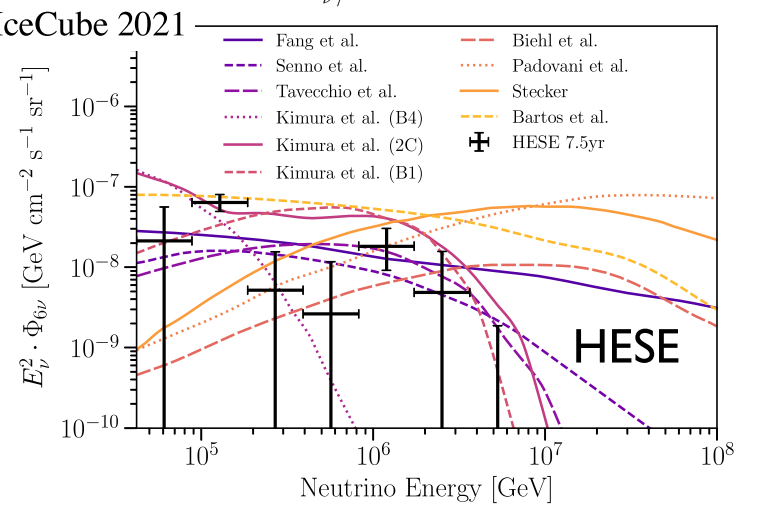
- Isotropic → Extragalactic origin
- No point-source/clustering detection → Galactic contribution: < 10%

Cosmic Neutrino Spectrum





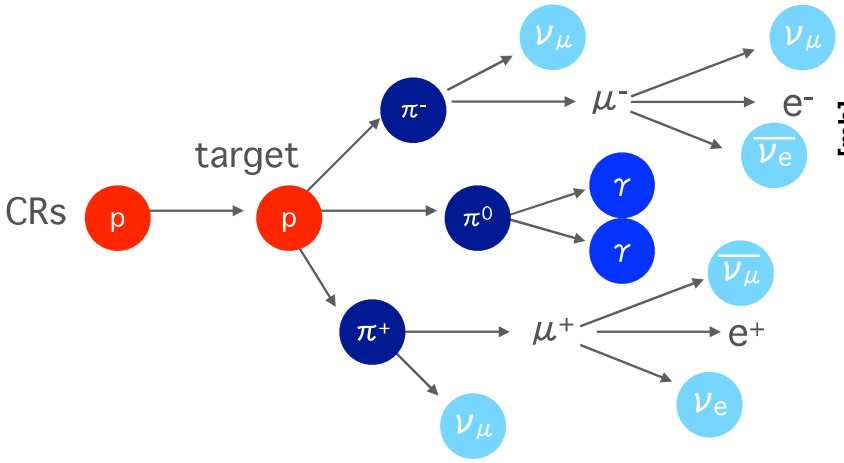
- Soft spectrum by the cascade analysis
  → **Medium energy excess**
  (High intensity @~10 TeV)
- Flat spectrum by the track analysis
- Each analysis provide different fitting value
  →**Hint of multiple component??**

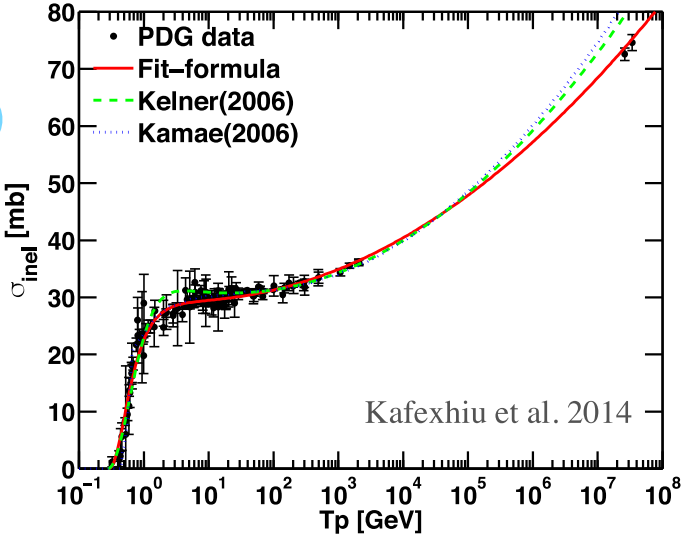


Contents

Neutrino Production Processes

- pp inelastic collision

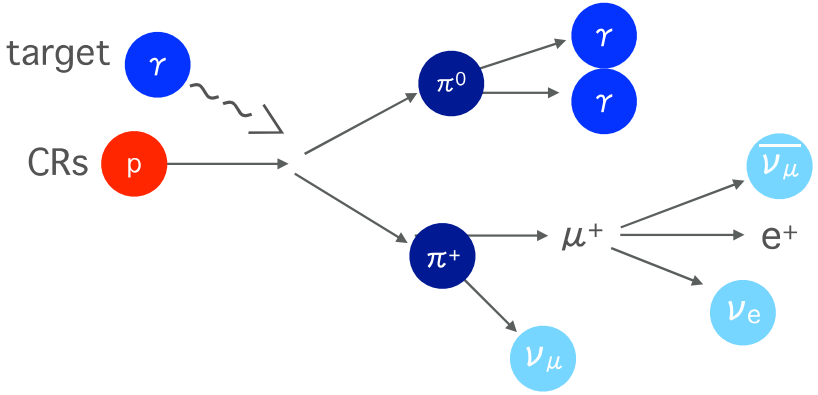


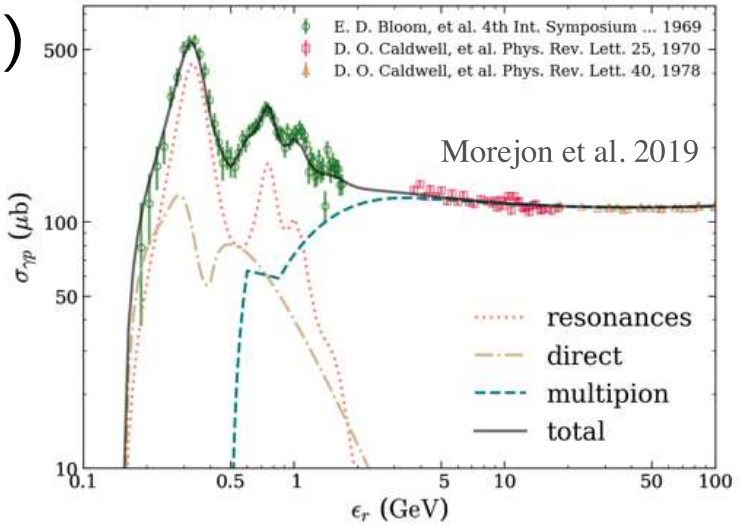


$p+p \rightarrow p+p+\pi$
$\pi^{\pm} \rightarrow 3\nu+e$
$\pi^0 \rightarrow 2\gamma$

σ_{pp} weakly depends on E_p
→ ν spectra ~ p spectra

- Photomeson production ($p\gamma$)





$p+\gamma \rightarrow p+\pi$
$\pi \rightarrow 3\nu+e$
$\pi^0 \rightarrow 2\gamma$

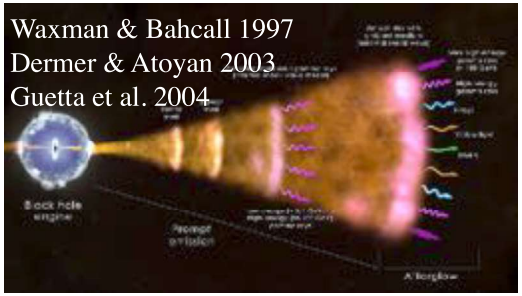
$\sigma_{p\gamma}$ is peaky function of E_p
→ target photon spectra affect ν spectra
e.g.
E_ν ~ 1 PeV ⇄ E_γ~10 eV

Pre-IceCube Astro-Neutrino Source Candidates

- **Cosmic-ray accelerators**

mainly pγ channel

- Gamma Ray Bursts (GRBs)



Especially Blazars

- Active Galactic Nuclei (AGN)

- Cosmic-rays are accelerated in the sources & produce neutrinos inside the sources

- **Cosmic-ray reservoirs**

mainly pp channel

- Galaxy Groups/Clusters

- Star Forming Galaxies (SFG)

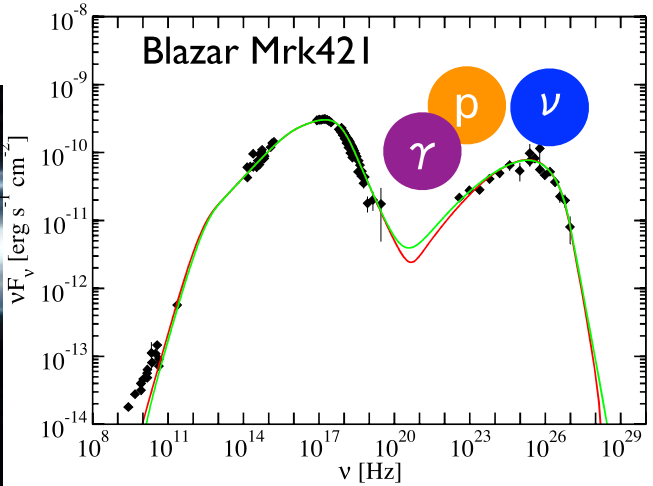
- Cosmic-rays are accelerated at accelerators in the reservoir
- Cosmic-rays are confined in the reservoir and produce neutrinos there

Pre-IceCube Model

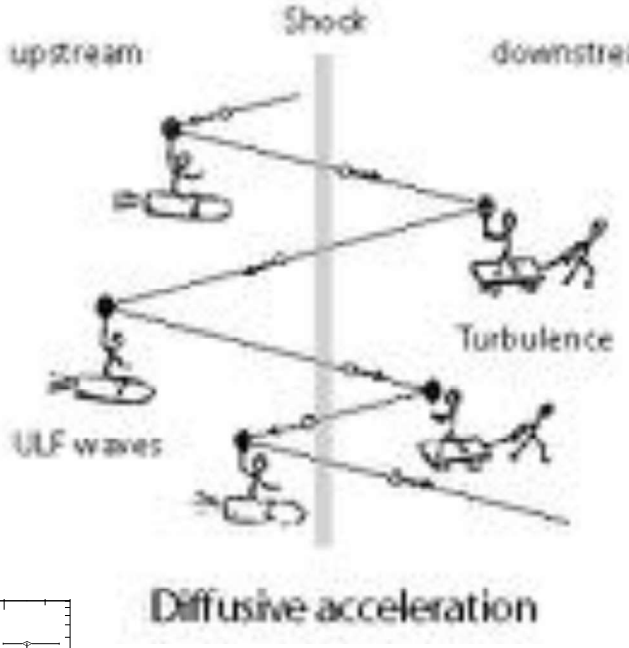
- **Cosmic-ray accelerators** mainly pγ channel

- Active Galactic Nuclei (AGN)
  Especially Blazars

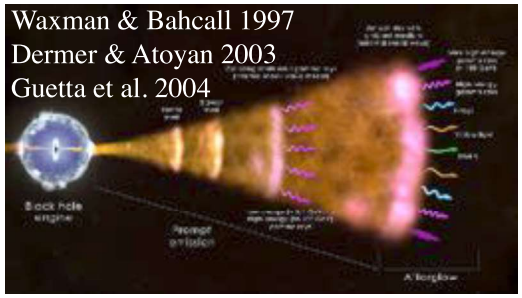
Fermi 2011

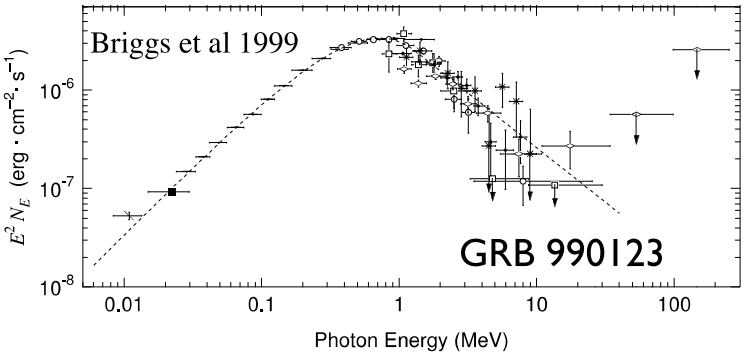


Treumann+ 08; Ohira-san's talk



- Gamma Ray Bursts (GRBs)





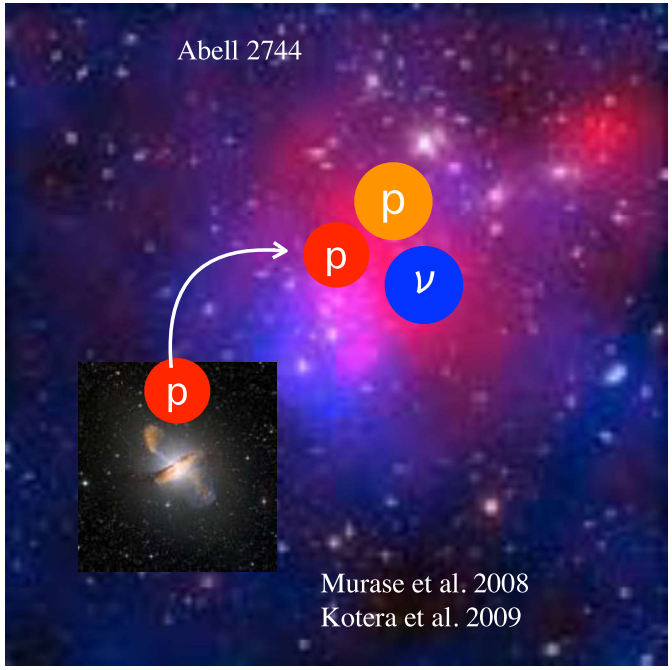
- Accelerated protons interact with photons produced by co-accelerated electrons

Pre-IceCube Model

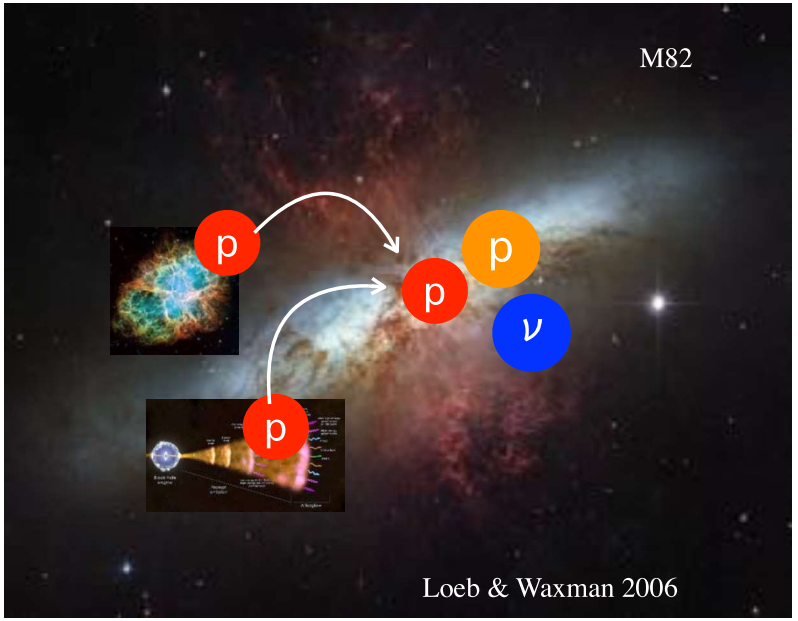
- **Cosmic-ray reservoirs**

mainly pp channel

- Galaxy Groups/Clusters

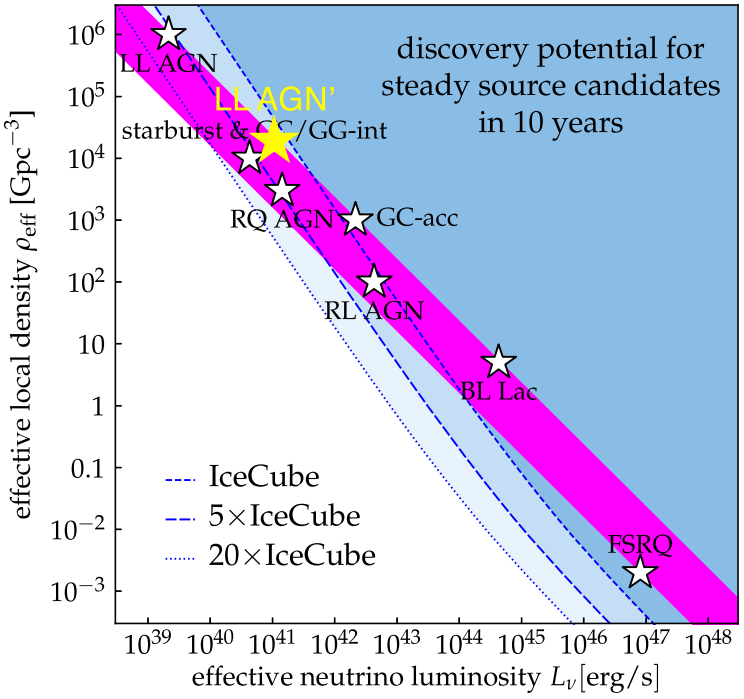


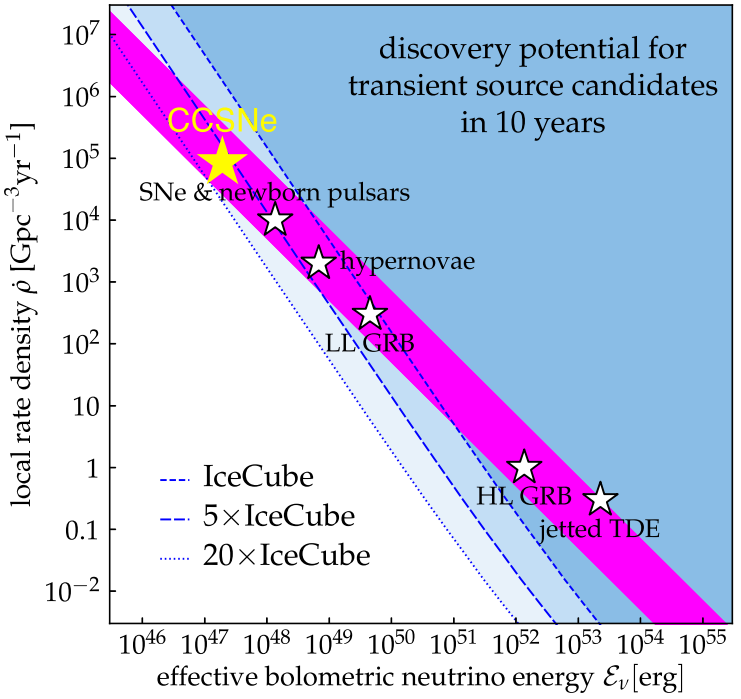
- Star Forming Galaxies (SFG)



- Cosmic-ray injection from accelerators
  → Cosmic-ray confinement in reservoirs
  → Neutrino production through pp collisions

Point-source constraint





IceCube-Gen2 2020; Murase & Waxman 2016

- Diffuse intensity

$$E_\nu^2 \Phi_\nu \sim \frac{c}{4\pi H_0} \rho_{\rm eff} L_{\nu,\rm eff}$$

$\rightarrow \rho_{\rm eff} \propto L_{\nu,\rm eff}^{-1}$ (pink band)

- ν flux from nearest source

$$E_\nu^2 \phi_\nu \sim \frac{L_{\nu,\rm eff}}{4\pi \rho_{\rm eff}^{-2/3}}$$

- No point source detection:

$E_\nu^2 \phi_\nu <$ (Sensitivity)

$\rightarrow \rho_{\rm eff} < \rho_{\rm crit} \propto L_{\nu,\rm eff}^{-3/2}$ (dotted lines)

- **No point-source detection disfavors luminous sources:** GRBs, Blazars (both BL Lac & FSRQ), Jetted TDEs
- **Detector with 5x bigger $A_{\rm eff}$, i.e., IceCube-Gen2, can detect a nearest source from almost all the models**
- Stacking analyses also disfavors GRBs and blazars

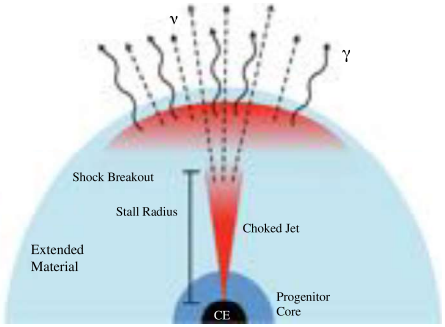
GRB: IceCube 2012, 2015, 2017
Blazars: IceCube 2017; Neronov+ 2017Yuan+ 2020;

PeV Neutrino Source Candidates

- **Cosmic-ray accelerators**

mainly pγ channel

- Gamma Ray Bursts (GRBs)
- Low-luminosity GRBs



Murase et al. 2013; Boncioli et al. 2018

Blazars→non-beamed AGN

- Active Galactic Nuclei (AGN)

- Cosmic-rays are accelerated in the sources & produce neutrinos inside the sources

- **Cosmic-ray reservoirs**

mainly pp channel

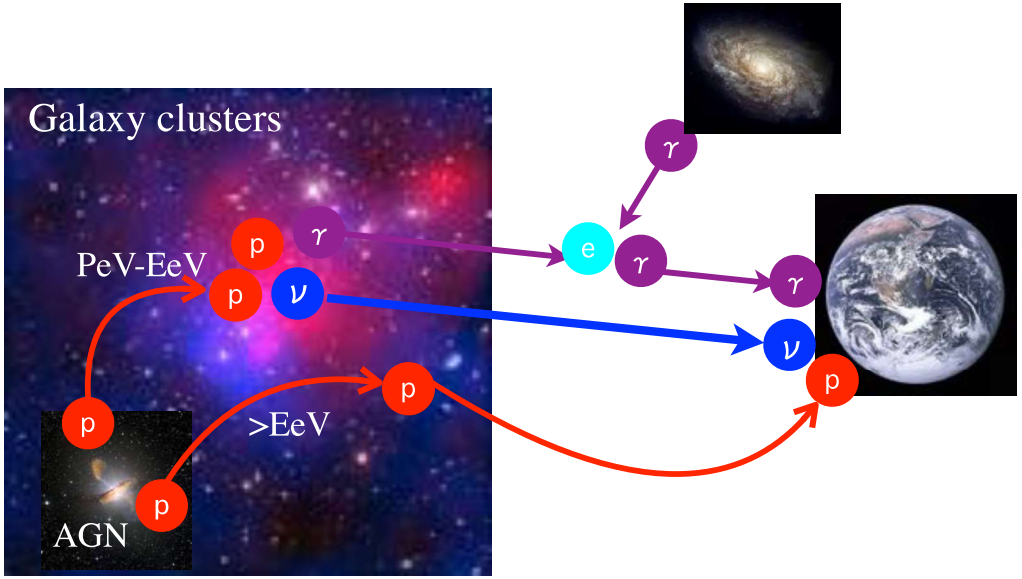
- Galaxy Groups/Clusters

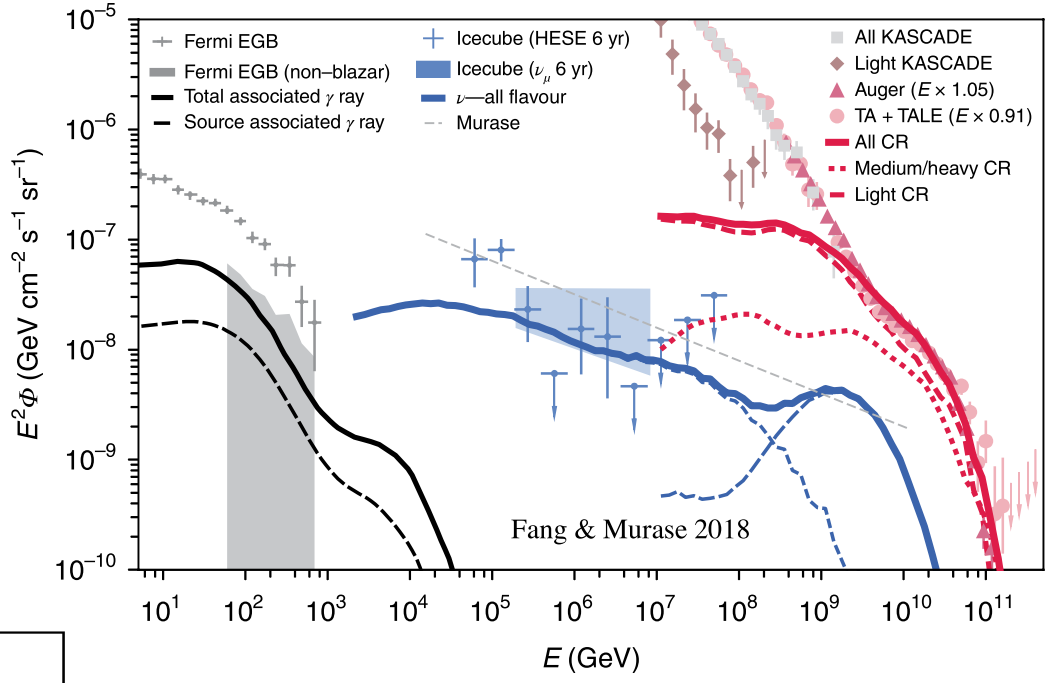
- Star Forming Galaxies (SFG)

- Cosmic-rays are accelerated at accelerators in the reservoir
- Cosmic-rays are confined in the reservoir and produce neutrinos there

Connecting High-energy Messengers

- 3 HE messengers (TeV γ, PeV ν, 10 EeV CR) have similar background intensities
  A common origin of sub-TeV γ, PeV ν, & UHECRs?





Cosmic-ray Reservoir scenario

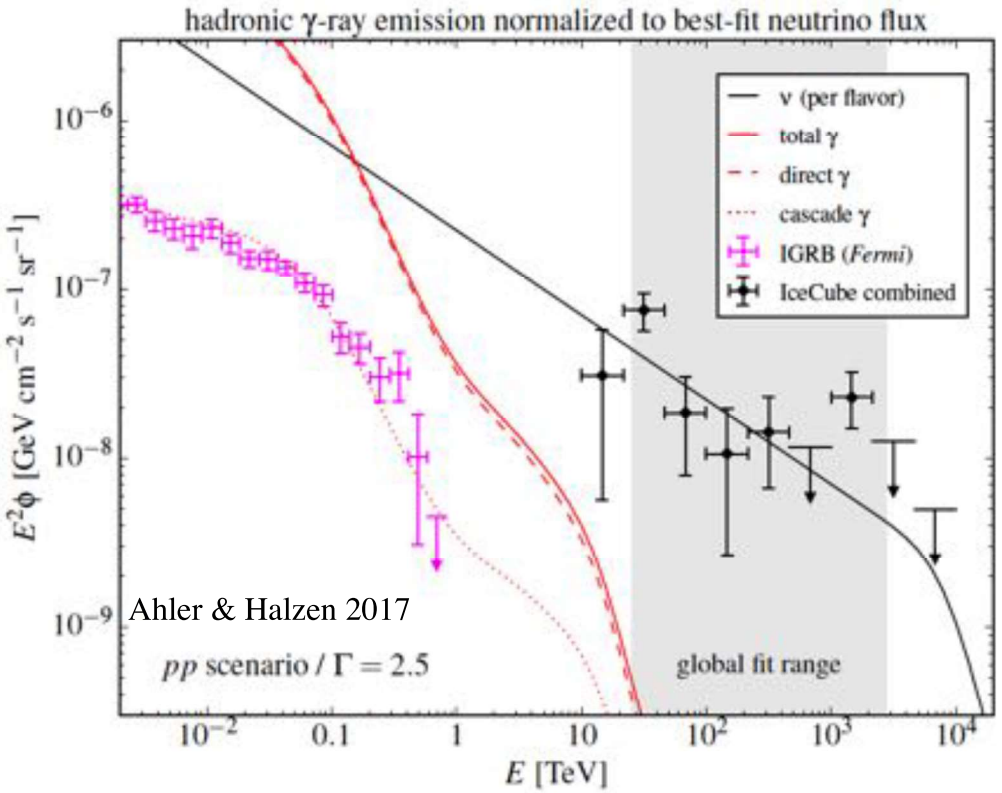
(Murase & Waxman 2016; Fang & Murase 2018)

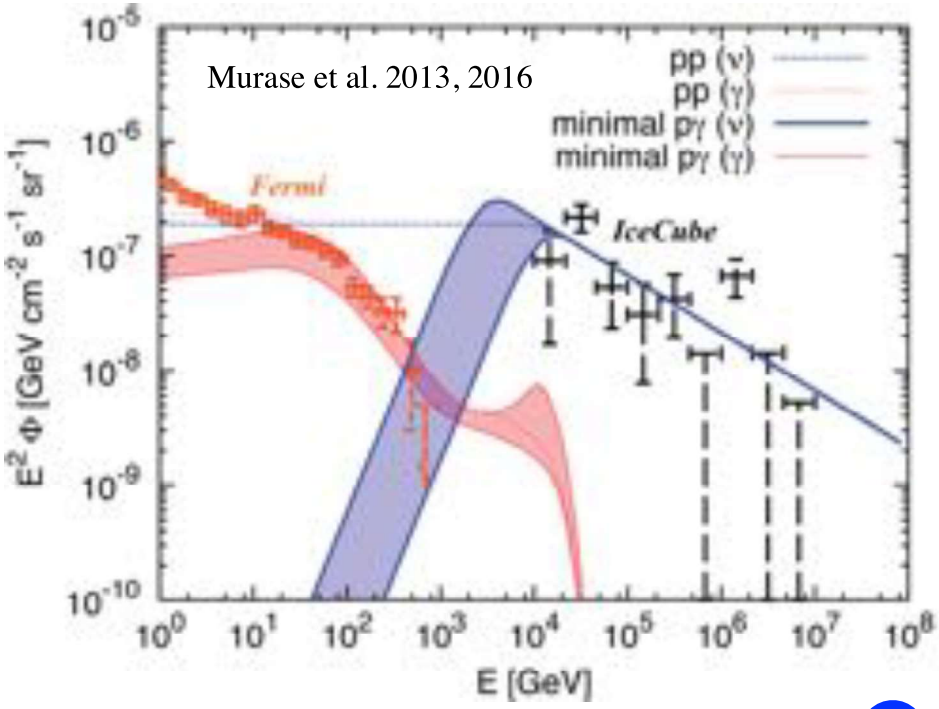
- CRs of > EeV can escape → observed as UHECRs
- CRs of < EeV are confined → PeV νs
- Intergalactic EM cascades → GeV-TeV γ-rays

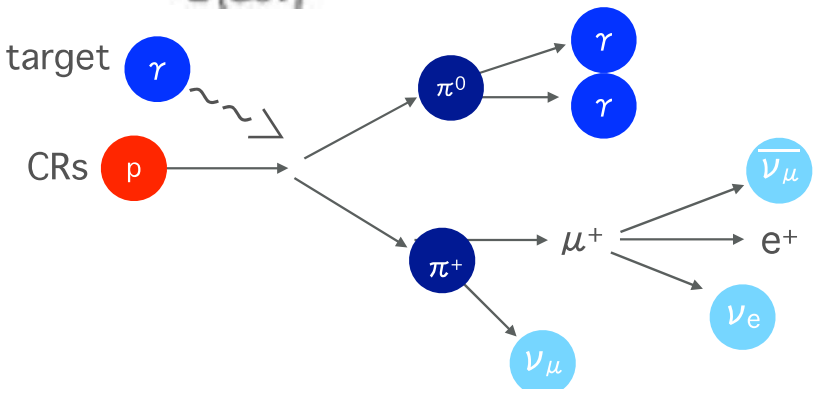
* Connecting PeV ν & UHECR by accelerators:
- LL GRBs

(Boncioli et al. 2018; Zhang, Murase, SSK+ 2018)
- TDEs (Biehl et al. 2018)
- p-γ sources (Yoshida & Murase 2020)

Gamma-ray Constraint







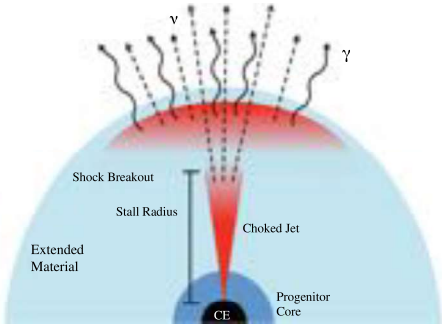
- Reservoirs produces both ν & γ
- ν flux@10 TeV > γ-ray flux@100 GeV
  → accompanying γ-rays overshoot Fermi data
  → **ν sources should be opaque to TeV γ rays**

10-100TeV Neutrino Source Candidates

- **Cosmic-ray accelerators**

mainly pγ channel

- Gamma Ray Bursts (GRBs)
- Low-luminosity GRBs



Murase et al. 2013; Boncioli et al. 2018

Blazars→non-beamed AGN

- Active Galactic Nuclei (AGN)

- Cosmic-rays are accelerated in the sources & produce neutrinos inside the sources

- **Cosmic-ray reservoirs**

mainly pp channel

- Galaxy Groups/Clusters

- Star Forming Galaxies (SFG)

- Cosmic-rays are accelerated at accelerators in the reservoir
- Cosmic-rays are confined in the reservoir and produce neutrinos there