Possible Astrophysical Sources for IceCube High-Energy Neutrinos

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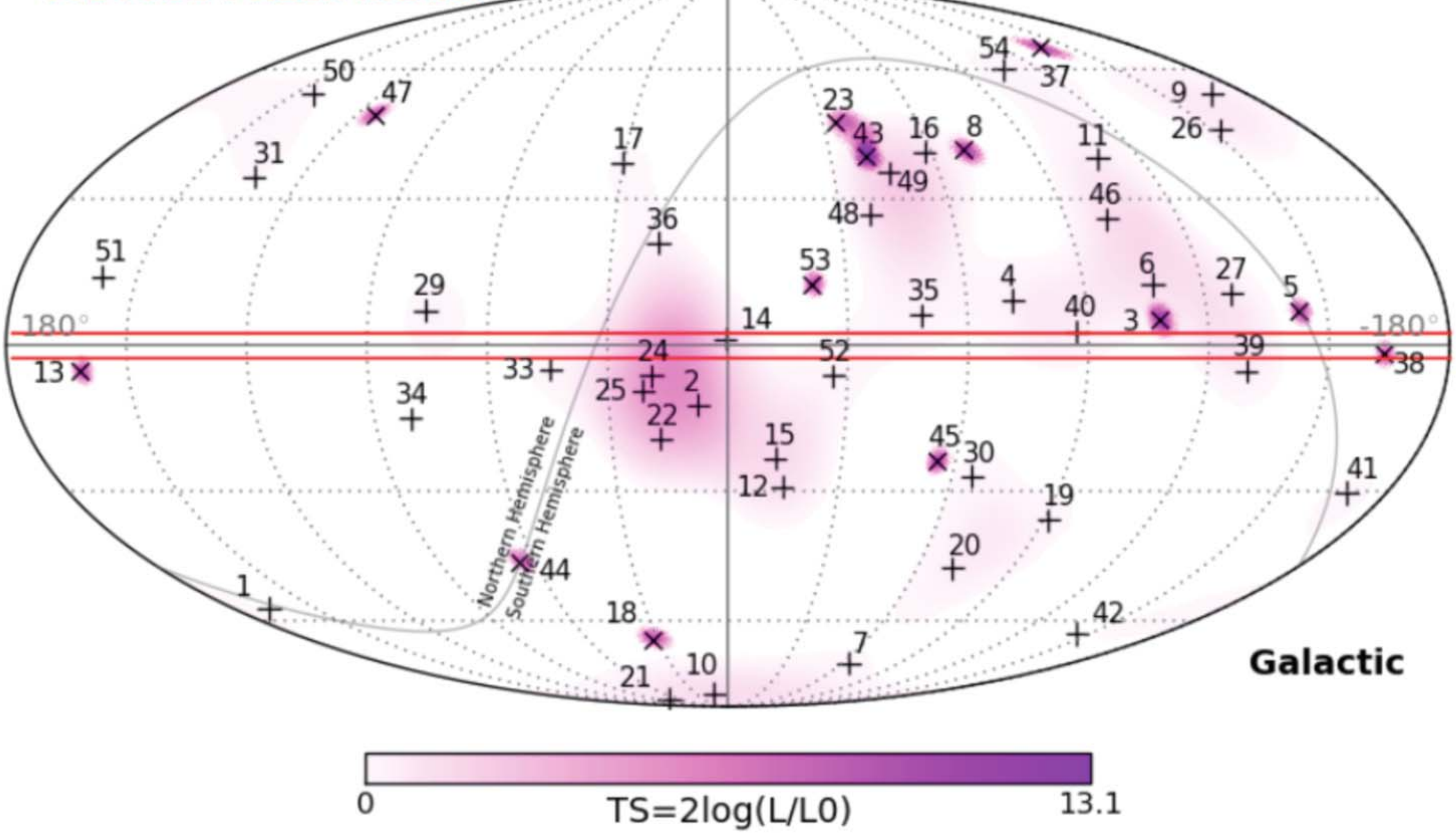
Outline

- Introduction
- Supernova remnants (SNRs) in Star-forming galaxies (SFGs) and Star-burst galaxies (SBGs) as High-energy neutrino (HENs) sources
- White Dwarf (WD) Mergers as HENs sources
- Summary

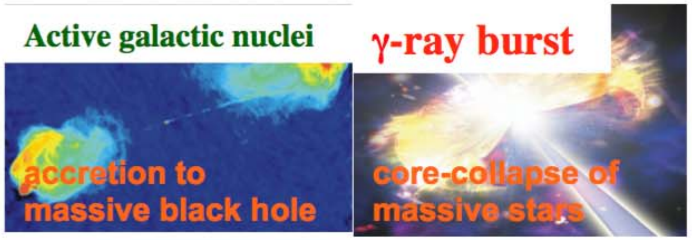
ICECUBE PRELIMINARY



Halzen (2016)

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



- γ-ray bursts
  ex. Waxman & Bahcall 97, KM et al. 06
  after Neutrino 2012:
  Cholis & Hooper 13, Liu & Wang 13
  KM & Ioka 13, Winter 13, Senno, KM & Meszaros 16

- Active galactic nuclei
  ex. Stecker et al. 91, Mannheim 95
  after Neutrino 2012:
  Kalashev, Kusenko & Essey 13, Stecker 13,
  KM, Inoue & Dermer 14, Dermer, KM & Inoue 14,
  Tavecchio et al. 14, Kimura, KM & Toma 15,
  Padvani et al. 15, Wang & Li 16

Cosmic-ray Reservoirs

- Starburst galaxies (not Milky-Way-like)
  ex. Loeb & Waxman 06, Thompson et al. 07
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Katz et al. 13,
  Liu et al. 14, Tamborra, Ando & KM 14,
  Anchordoqui et al. 14, Senno et al. 15

- Galaxy groups/clusters
  ex. Berezinsky et al. 97, KM et al. 08, Kotera et al. 09
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Fang & Olinto 16

Astrophysical Neutrinos

- **Hadronuclear and photohadronic scenarios**

$$p + p \longrightarrow p/n + N\pi$$

$$p + \gamma \longrightarrow p/n + N\pi$$

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

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

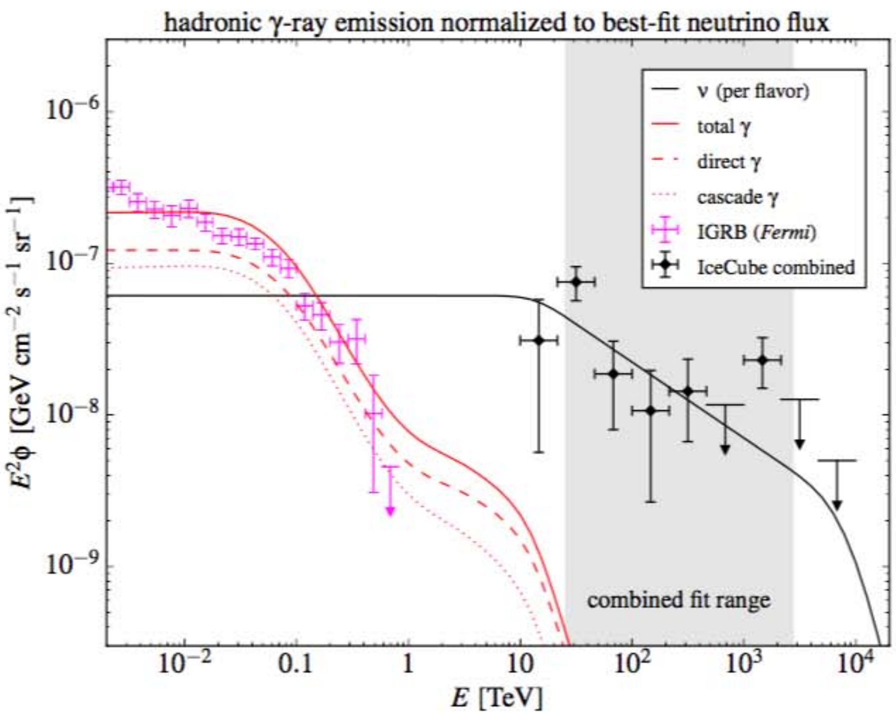
$$\pi^0 \longrightarrow \gamma + \gamma$$

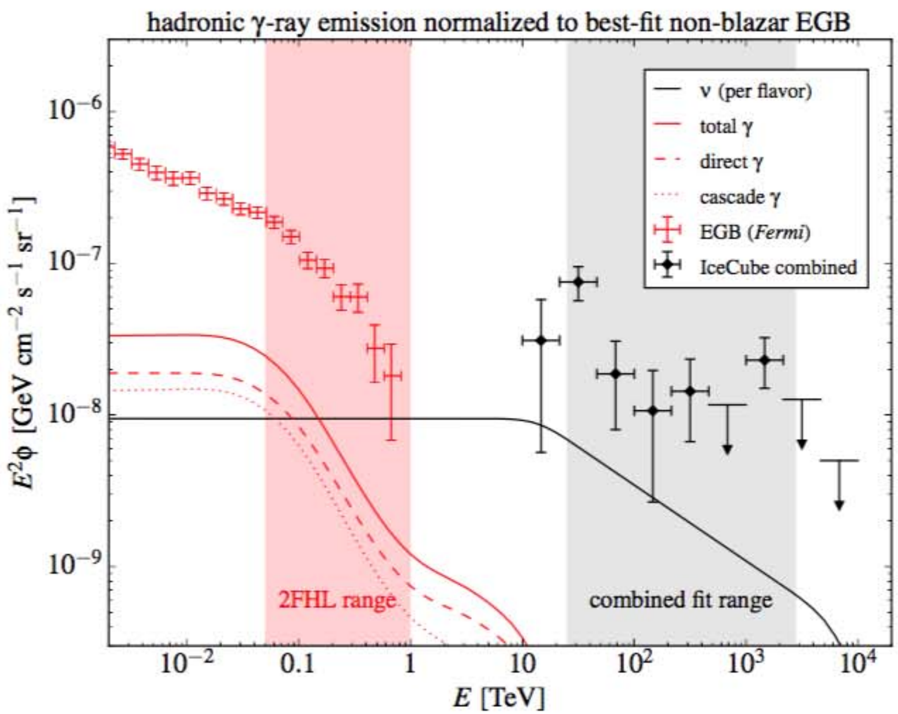
- **The neutrino and gamma-ray energy generation rates are conservatively related as**

$$\epsilon_\gamma^2 \Phi_\gamma = \frac{4}{K} \epsilon_\nu^2 \Phi_\nu |_{\epsilon_\nu = 0.5\epsilon_\gamma}$$

$$K \approx 1 \text{ for } p\gamma \text{ and } K \approx 2 \text{ for } pp$$

Problem in SFG scenario?





Bechtol et al. 2015, arxiv:1511.00688

SFG scenario revisited

(**DX**, Peter Meszaros, Kohta Murase & Zigao Dai 2016a, ApJ, 826, 133)

Two main differences:

- **Consider the time history of the SNR evolution, which affects the effective total CR spectral output.**
- **Add possible contributions of Pop-III HNRs up to z ~10 and show that they are not constrained by the gamma-ray data.**

Sedov-Taylor Phase of an SNR

$$t_0 = \frac{R_{\rm dec}}{v_{\rm ej}} = \frac{(3M_{\rm ej}/4\pi m_p n_0)^{1/3}}{(2\mathcal{E}_{\rm SN}/M_{\rm ej})^{1/2}}$$
$$\simeq 1.4\times 10^3 \mathcal{E}_{\rm SN,51}^{-1/2} n_{0,0}^{-1/3} M_{\rm ej,1}^{5/6}\ {\rm yr}$$

$$R = (25\mathcal{E}_{\rm SN}/4\pi m_p n_0)^{1/5} t^{2/5} \qquad v = (2/5)(25\mathcal{E}_{\rm SN}/4\pi m_p n_0)^{1/5} t^{-3/5}$$

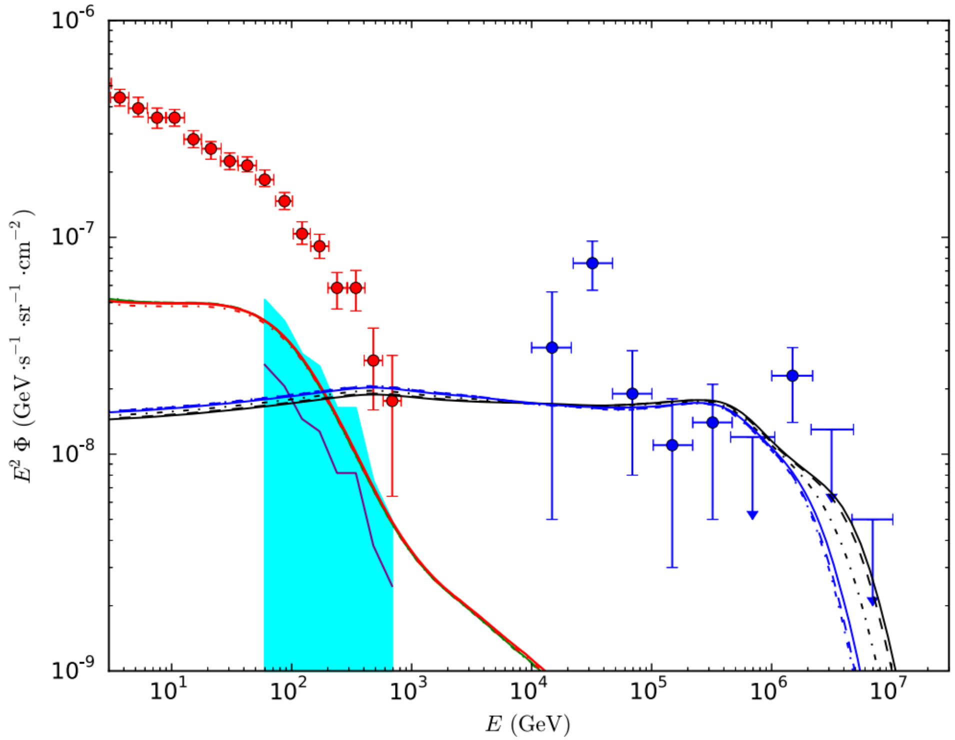
Maximum CR energy:

$$\epsilon_{p,\rm max} = 1.58\times 10^6 \mathcal{E}_{\rm SN,51} n_{0,0}^{1/6} M_{\rm ej,1}^{-2/3}\ \epsilon_{B,-2}^{1/2} (t/t_0)^{-4/5}\ {\rm GeV}$$

Energy Injection into CRs: $L_{\rm CR}(t) = \mathcal{A}(t/t_0)^{\alpha}$

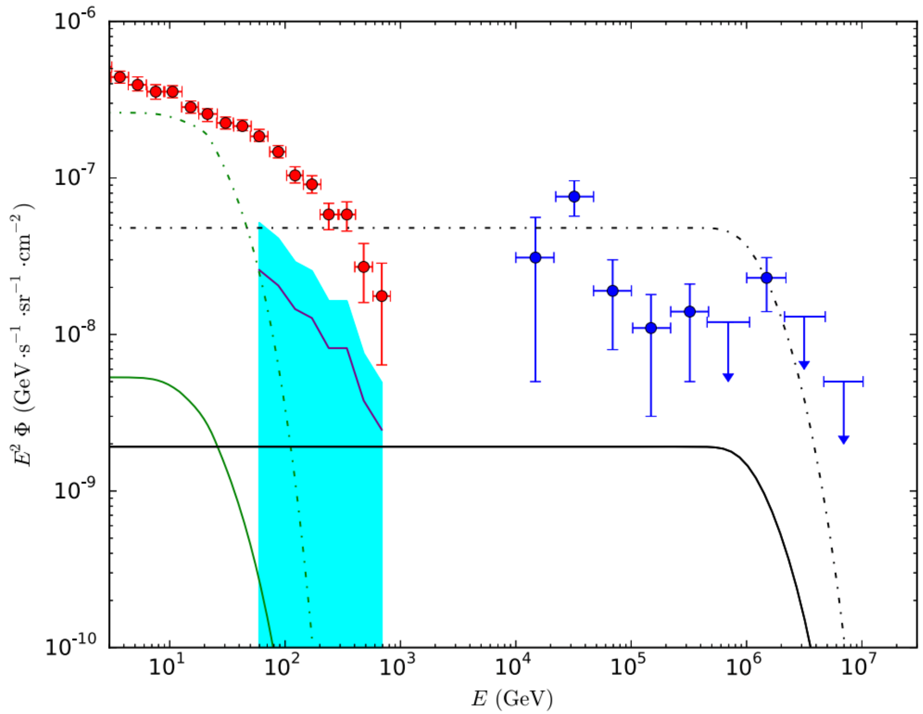
DX, Peter Meszaros, Kohta Murase & Zigao Dai 2016a, ApJ, 826, 133

Time history of SNRs evolution



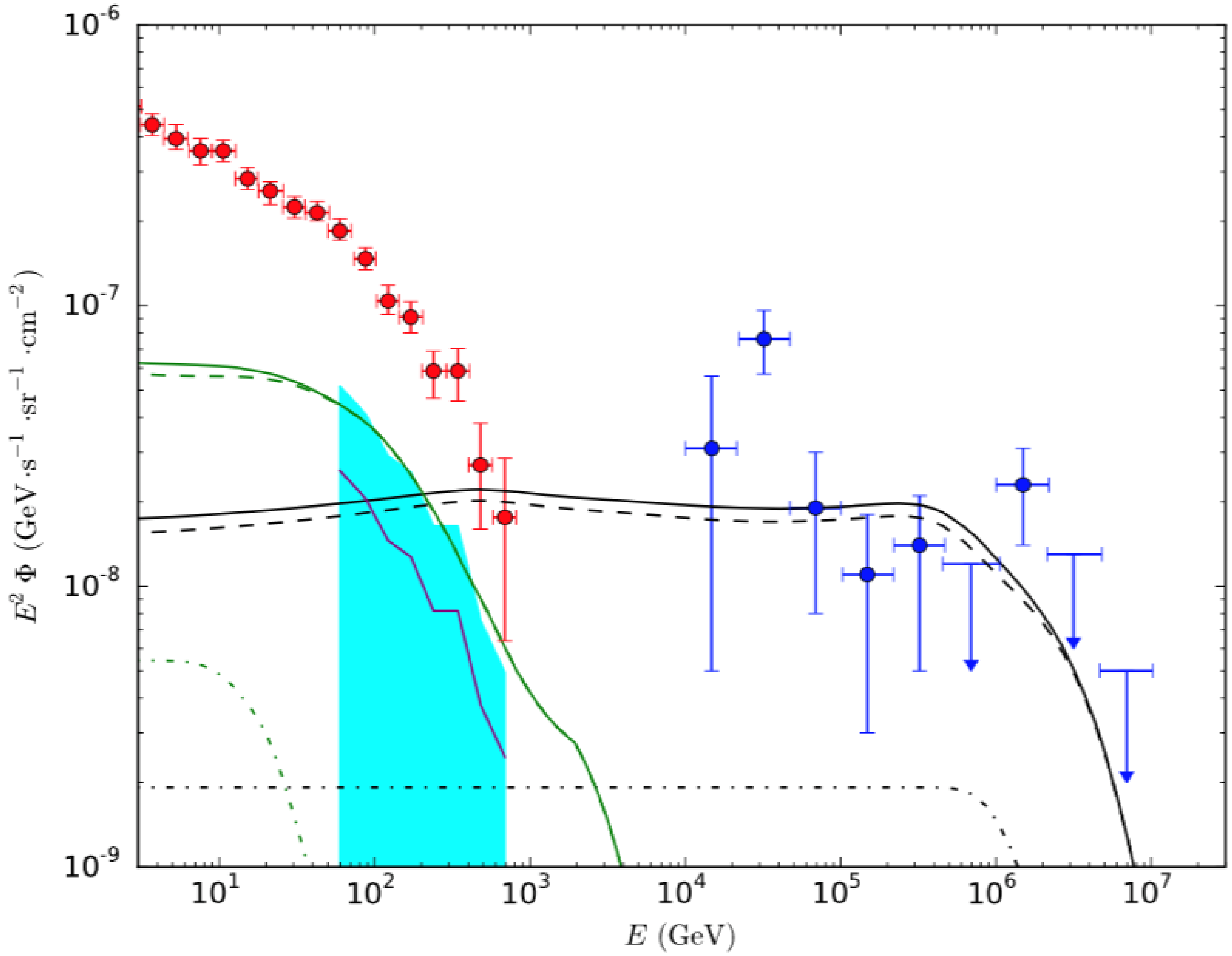
$z \lesssim 4$

$4 \lesssim z \lesssim 10$



The contribution of Pop III SNRs

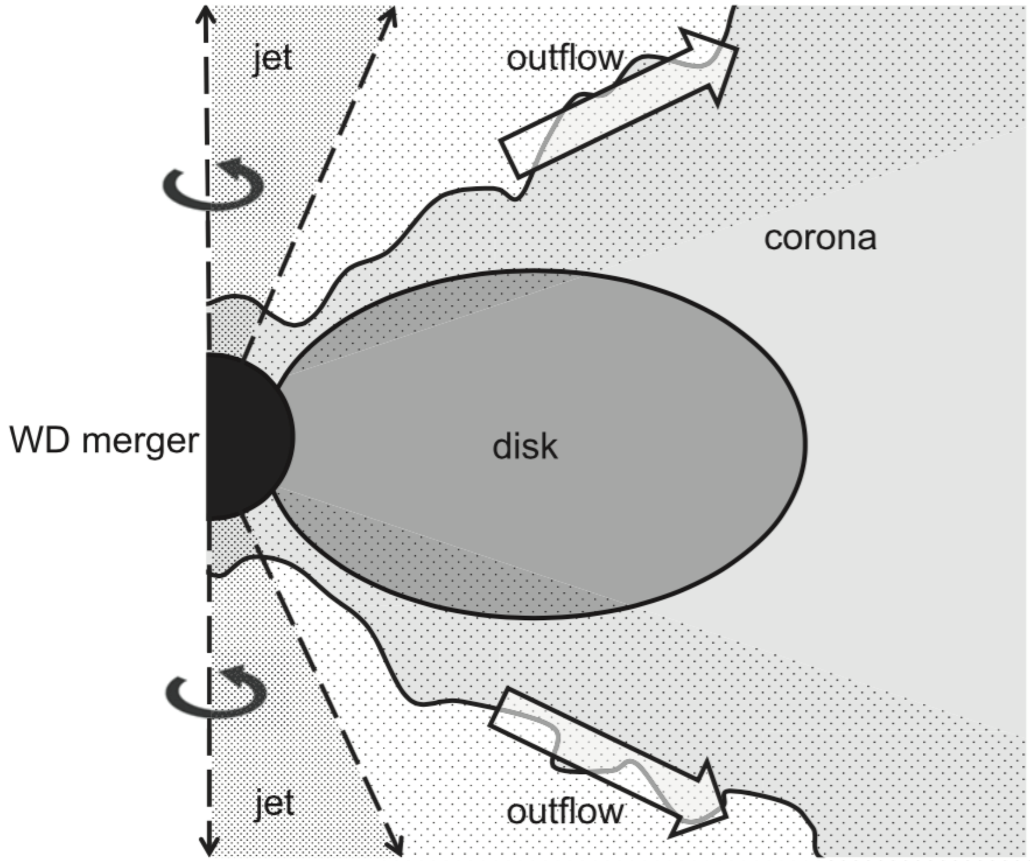
Two-component Contribution



DX, Peter Meszaros, Kohta Murase & Zigao Dai 2016a, ApJ, 826, 133

WD Mergers as HENs Sources

(**DX**, Peter Meszaros, Kohta Murase & Zigao Dai 2016b, ApJ, 832, 20)



S. Q. Ji et al. 2013, ApJ, 773, 136

Outflow from the merger region

- **Initially in the corona,**

$R_0 \sim 10^9$ cm , $T_0 \sim 10^8$ K, $B_0 \sim 10^{10}$ G, $rho_0 \sim 1$ g/cm^3

- **The radial dependences**

$$\rho(R) = \begin{cases} \rho_0 (R/R_0)^{-2} & \text{if } R_0 \leq R < R_{\rm cr}, \\ \rho_0 (R_{\rm cr}/R_0)^{-2} (R/R_{\rm cr})^{-3} & \text{if } \quad R \geq R_{\rm cr}. \end{cases}$$

$$T(R) = \begin{cases} T_0 (R/R_0)^{-2/3} & \text{if } R_0 \leq R < R_{\rm cr}, \\ T_0 (R_{\rm cr}/R_0)^{-2/3} (R/R_{\rm cr})^{-1} & \text{if } \quad R \geq R_{\rm cr}. \end{cases}$$

where $R_{\rm cr} \equiv v_0 t_{\rm visc}$

Magnetic energy dissipation

The total amount of magnetic energy ejected by the remnants is

$$\mathcal{E}_B \sim L_B t_{\rm visc} \sim 10^{48} - 10^{50}\ \mathrm{erg}$$

Assuming magnetic reconnection occurs at diffusion radius R_D.

Magnetic energy dissipation rate: $\dot{\mathcal{E}}_B \propto t^{-q}$

Neutrino spectra of single merger event

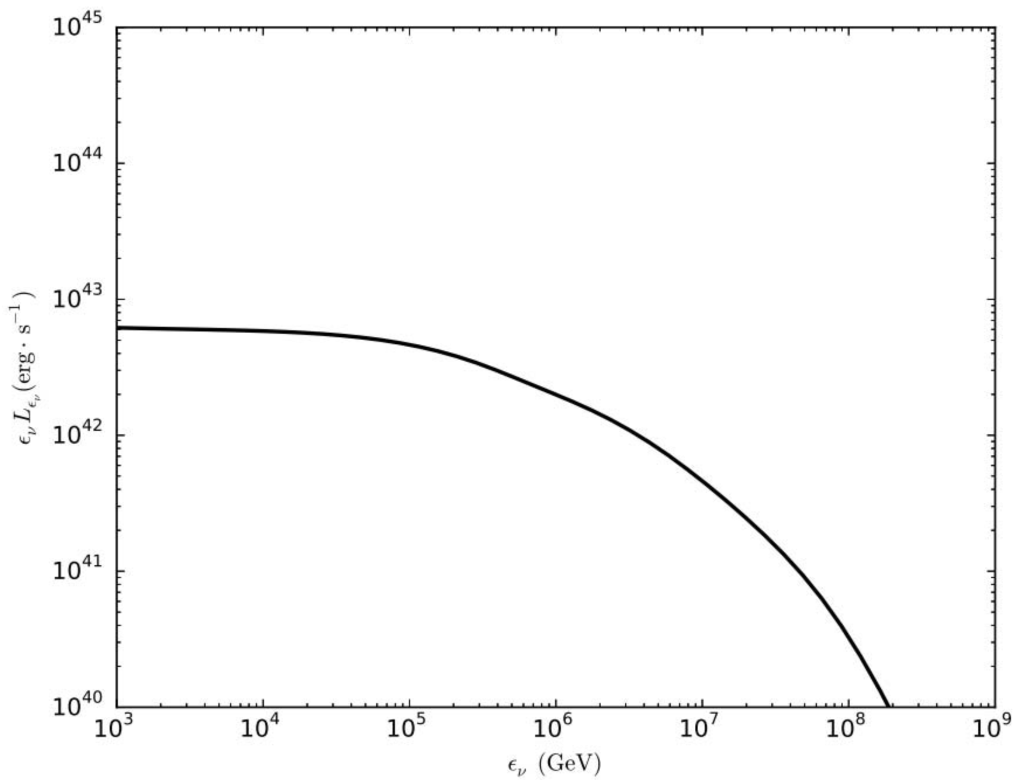
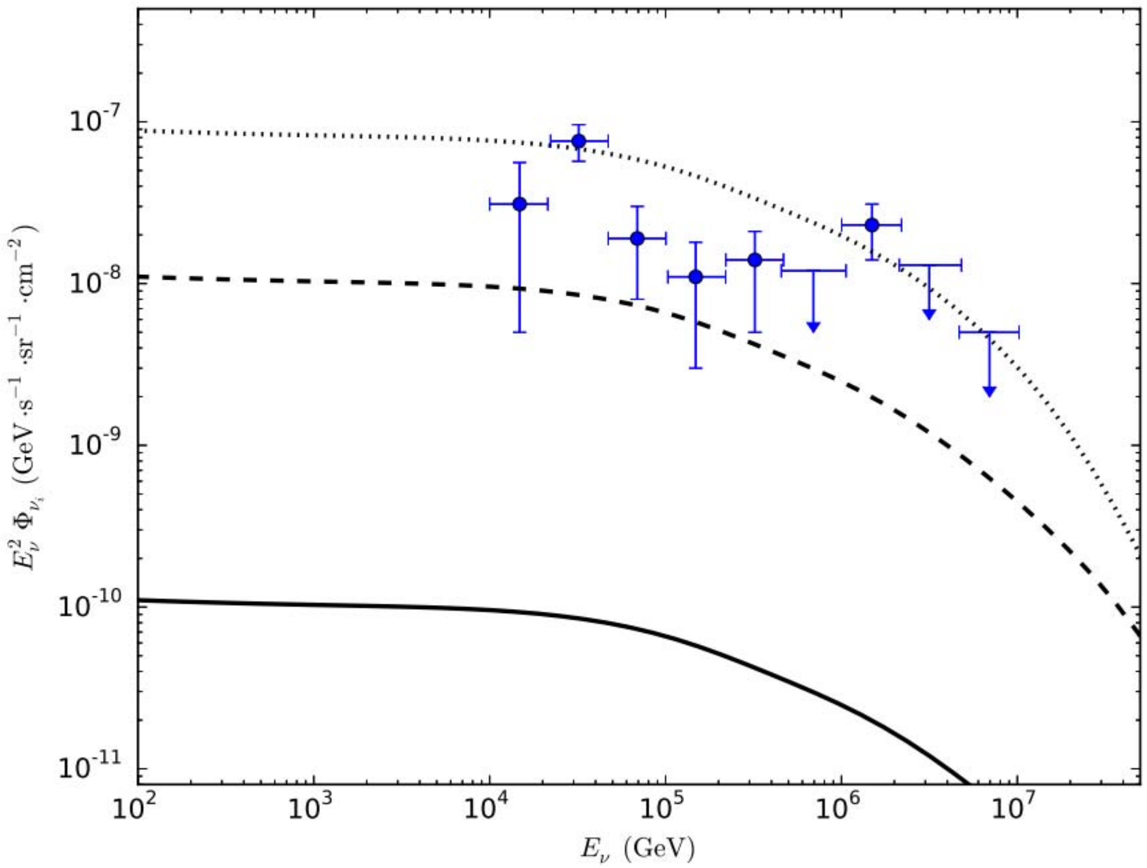


FIG. 2.— The neutrino spectra of a single merger event. The total dissipated magnetic energy is assumed to be $\mathcal{E}_B = 10^{50}$ erg.

Estimated event in IceCube: $N(> 1\text{TeV}) \sim 0.08$

(**DX**, Peter Meszaros, Kohta Murase & Zigao Dai 2016b, ApJ, 832, 20)

Contribution to the diffuse background



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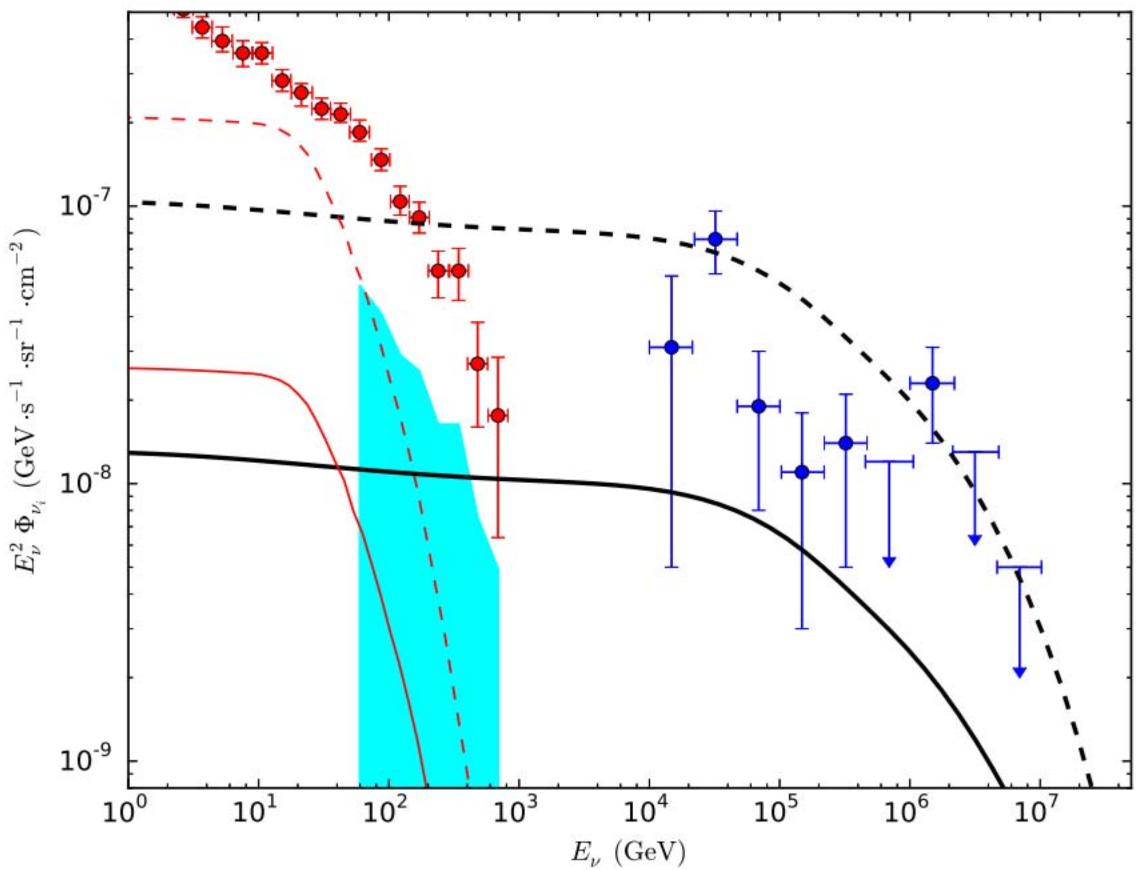
WD mergers belong to *hidden CR accelerators* (i.e. gamma-ray dark)



(**DX**, Peter Meszaros, Kohta Murase & Zigao Dai 2016b, ApJ, 832, 20)

Summary

- The origin of the diffuse high-energy (TeV to PeV) neutrino flux discovered by IceCube is currently under intense debate.
- The diffuse neutrino background above 100 TeV can be explained within SFG scenario without contradicting the gamma-ray data.
- WD mergers could contribute a substantial fraction of the IceCube observations.
- Gamma-ray dim neutrino sources are favored.

THANKS !