The IceCube Puzzle

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Neutrino astronomy:

- **natural extension**
- **closely related** to cosmic rays (CRs) and γ-rays via pion-production:
  \[ \pi^0 \rightarrow \gamma \gamma \]
  \[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \]
- **smoking-gun** of CR sources
- **weak interaction** during propagation
- **low** statistics
- **large** backgrounds
High-energy neutrino detection

- High energy neutrino collisions with nuclei are **rare** → huge detectors needed!
- Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media, *e.g.* ice or water

**back-of-the-envelope** \( (E_\nu \sim 10^{15} \text{ eV}) : \)

- **flux of neutrinos**:
  \[
  \frac{d^2 N_\nu}{dt \; dA} \sim \frac{1}{\text{cm}^2 \times 10^5 \text{yr}}
  \]

- **cross section**:
  \[
  \sigma_{\nu N} \sim 10^{-33} \text{ cm}^2
  \]

- **targets**:
  \[
  N_N \sim N_A \times V/\text{cm}^3
  \]

- **rate of events**:
  \[
  \dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{d^2 N_\nu}{dt \; dA} \sim \frac{1}{\text{year}} \times \frac{V}{1 \text{km}^3}
  \]
High-energy neutrino detection

- High energy neutrino collisions with nuclei are **rare** → huge detectors needed!
- Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media, e.g. ice or water
Cherenkov radiation in transparent media (glaciers, lakes, oceans,...).
Coherent radio Cherenkov emission (Askaryan effect).
Observation in-situ, balloons or satellites.
Coherent radio Cherenkov emission (Askaryan effect).
Observation from lunar regolith.
Neutrino observation at very high energies

Acoustic detection?
Neutrino observation at very high energies

Deeply penetrating quasi-horizontal showers.
Observation by CR surface arrays.
Neutrino observation at very high energies

Observation by CR surface arrays and/or fluorescence detectors/satellites.
Earth-skimming tau neutrinos.
Neutrino Cherenkov Telescopes

Astrophysical neutrinos are an important addition to **multi-messenger** astronomy (no deflection & absorption in space; “smoking-gun” of cosmic rays)

**detector requirements:**

\[
N_N \times \sigma_{\nu N} \times \frac{d^2 N_\nu}{dt \, dA} \sim \frac{1}{\text{year}} \times \frac{V}{1\text{km}^3}
\]

\[M_{\text{det}} \simeq V \times m_p \sim 1\text{ Gton}\]

**realization:**

Observation of **Cherenkov light** in km\(^3\)-volumes of deep ocean water (Mediterranean), fresh water (Lake Baikal) or ice (Antarctic).
The IceCube Observatory

- Giga-ton telescope at the South Pole
- Collaboration of about 250 people at 43 intl. institutions
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase
  (2004-2011)
- **price tag: 30 Cents per ton**
The IceCube Observatory

IC-1 (IT-4)  IC-9 (IT-16)  IC-22 (IT-26)  IC-40 (IT-40)
04-05 Season 05-06 Season 06-07 Season 07-08 Season
IC-59 (IT-59)  IC-79 (IT-73)  IC-86 (IT-81)
08-09 Season 09-10 Season 10-11 Season
The IceCube Observatory

incorporate the disciplines of manufacturing and systems engineering into a group that had little experience with large-scale high-reliability production of anything, let alone highly complex digital sensors that had to survive deep-ice deployments—that in itself is a story to tell many pages.

Somehow in this time we worked through the design issues, spun out three further revisions of the mainboard, assembled and tested DOMs, and wrote software to read out the sensors. We also built three production sites including the enormous deep freezer laboratories to cold-test each and every module at -55 °C while being subjected to a battery of functional tests and optical calibrations, bought a bunch of cables, and adapted a standard ship-sending container already at the South Pole and equipped it with electronics to make a temporary IceCube counting house. Vivid memories remain of the numerous meetings and telephone calls, travels, tense moments and outright arguments, diagrams drawn, nails bitten, and plan Bs.

And so in 2005 there was one string—string 21—that made it into the ice and when we turned it on, voila! all modules were working just fine. One module started to spark several weeks after deployment, but this case was happily resolved by turning down the high voltage applied to the phototube. It was a great relief to us all that all the DOMs were talking with the surface. Despite previous experience with AMANDA modules and all the engineering that went into making the IceCube DOMs even more robust, no one really knew that everything would work until the modules were in the ice.

Each DOM's pressure housing had been tested to 10,000 psi but the refreezing ice could have easily crushed the cabling or snapped the penetration point where the cable enters the glass sphere. Building a laboratory to simulate refreeze seemed a project as big as IceCube so we had to cross our fingers at this point.

The design, having been proved in ice, did not change significantly from that first year. The one major design flaw with the DOM, an improperly spec'd signal transformer, was fixed along with some other minor changes. A later “high quantum efficiency” DOM was produced beginning in 2008 for IceCube's DeepCore extension;
The IceCube Observatory

IceCube Lab
The IceCube Observatory

Drilling with new IceTop tanks
Inside an IceTop Tank
The IceCube Observatory

Firn & Ice Drilling
String & Optical Module
The IceCube Observatory

- “cascades”: **good** energy, but **poor** angular resolution ($\Delta \theta > 10^\circ$)
- “tracks”: **poor** energy, but **good** angular resolution ($\Delta \theta \lesssim 1^\circ$)
- **time-dependent** signal: early to late light detection

**track event** (IC-79)

**cascade event** (IC-86)

[two examples from the high-energy starting event (HESE) analysis; IceCube Science 342 (2013)]
The individual and combined results of IceCube, DeepCore and IceTop and the unique geographical location allows for a wide scientific program:

- atmospheric neutrino fluxes and oscillations
- diffuse high-energy neutrino fluxes
- point source fluxes
- cosmic ray flux in the knee region
- CR anisotropies in the Southern hemisphere
- CR composition measurements
- indirect dark matter detection
- galactic supernova
- exotic signals
- ...
IceCube HESE Sample (3yrs)

- **High-Energy Starting Event (HESE) sample:**
  - bright events \( E_{\text{th}} \gtrsim 30 \text{TeV} \) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 37 events in about three years:  
  [IceCube PRL 113 (2014)]
  - 28 *cascades* events
  - 8 *track* events
  - 1 *composite* event (removed)

- expected background events:
  - \( 6.6^{+5.9}_{-1.6} \) atmospheric neutrinos
  - \( 8.4^{+4.2}_{-4.2} \) atmospheric muons

- significance of \( 5.7\sigma \) above backgrounds
• 28 “cascade events” (circles) and 7 “tracks events” (diamonds); size of symbols proportional to deposited energy (30 TeV to 2 PeV) [IceCube PRL 113 (2014)]

× no significant spatial or temporal correlation of events
Spectrum

- $E^{-2}$-spectrum of the HESE 3yr sample within $(0.1 - 1)\text{PeV}$: \cite{IceCube PRL 113 (2014)}

$$E_{\nu}^2 \Phi_{\nu\alpha} \simeq (0.95 \pm 0.3) \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

- "classical" muon-neutrino analysis (dominated by Northern Hemisphere) sees flux excess consistent with HESE sample \cite{IceCube APS meeting'14}

- extended HESE sample with lower energy threshold indicates softer spectrum: \cite{IceCube 1410.1749}

$$E^2 \Phi_{\nu\alpha}(E) \simeq \left(2.06^{+0.4}_{-0.3}\right) \times 10^{-8} \left(\frac{E_{\nu}}{100\text{TeV}}\right)^{-0.46\pm0.12} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

![Graph showing differential spectrum and best-fit power law](image-url)
Neutrino Flavors

- Neutron decay (1:0:0)
- Oscillation-averaged pion & muon decay (1:2:0)
- Muon-suppressed pion decay (0:1:0)

- 25%
- 50%
- 75%

- $\nu_\tau$
- $\nu_\mu$
- $\nu_e$

- “NuFit 1.3”: $\sin^2 \theta_{12} = 0.304 / \sin^2 \theta_{23} = 0.577 / \sin^2 \theta_{13} = 0.0219 / \delta = 251^\circ$

- Observed events consistent with equal contributions of all neutrino flavors
Multi-messenger paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and $\gamma$-rays.

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV $\gamma$-rays

→ very interesting energy range:
  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?
  - chemical composition?
  - $pp$ or $p\gamma$ origin?
Proposed Source Candidates

- **Galactic:** (full or partial contribution)
  - heavy dark matter decay [Feldstein et al. 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic $\gamma$-ray emission [e.g. Ingelman & Thunman'96; MA & Murase 1309.4077]
  - unidentified Galactic TeV $\gamma$-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic $\gamma$-ray emission [Neronov, Semikoz & Tchernin 1307.2158]
  - “Fermi bubbles” [Su, Slatjer & Finkbeiner’11; Crocker & Aharonian’11; Lunardini & Razzaque’12]
    [MA & Murase’13; Razzaque’13; Lunardini et al.’13]

- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
    [Katz, Waxman, Thompson & Loeb 1311.0287; Fang, Fujii, Linden & Olinto 1404.6237]
  - GZK from low $E_{\text{max}}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [e.g. Stecker et al.’91; Stecker 1305.7404]
  - AGN jets [e.g. Murase, Inoue & Dermer 1403.4089; 1406.2633]
  - low-power $\gamma$-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [e.g. Loeb & Waxman’06; He et al. 1303.1253]
    [Murase, MA & Lacki 1306.3417; Anchordoqui et al. 1405.7648; Chang & Wang 1406.1099]
  - hypernovae in star-forming galaxies [Liu, Wang, Inoue, Crocker & Aharonian 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin’97; Murase, MA & Lacki 1306.3417]
Fermi Bubbles

- two extended GeV $\gamma$-ray emission regions close to the Galactic Center  
  [Su, Slatyer & Finkbeiner’10]
- hard spectra and relatively uniform emission
- some correlation with WMAP haze and X-ray observation
- model 1: hadronuclear interactions of CRs accelerated by star-burst driven winds and convected over few $10^9$ years  
  [Crocker & Aharonian’11]
- model 2: leptonic emission from 2nd order Fermi acceleration of electrons  
  [Mertsch & Sarkar’11]
- probed by associated neutrino production  
  [Lunardini & Razzaque’12]
Fermi Bubbles

Northern Hemisphere
Southern Hemisphere
Galactic Plane
"Bubble"
Fermi Bubbles

- small zenith “excess” in IceCube HESE 2yr sample (but not significant)
- Galactic Center source(s) of extended source, e.g. “Fermi Bubbles”?

⚠ $\Gamma = 2.4$ extrapolation of hadronic $\gamma$-ray/neutrino flux unlikely to produce an “excess” at 100 TeV to PeV in FB region
Active Galactic Nuclei

- neutrino interactions from $p\gamma$ interactions in AGN cores
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate

IceCube excess

[Stecker et al.'91]
[Stecker'05;'13]
[Stecker et al.'91]
Active Galactic Nuclei

- neutrino from $p\gamma$ interactions in AGN jets
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos

[Murase, Inoue & Dermer 1403.4089] [Mannheim’96; Halzen & Zas’97]

FIG. 1: Schematic picture of a blazar, showing external radiation fields relevant for neutrino production.
Gamma-ray Bursts

- strong limits on neutrino emission associated with the fireball model [Abbasi et al.’12]
- IceCube excess exceeds IC40+59 limit by factor $\sim 5$
- loophole: undetected low-power $\gamma$-ray bursts (GRB) [Murase & Ioka 1306.2274]

[modified from Abbasi et al.’12]
Starburst galaxies

- intense CR interactions (and acceleration) in dense starburst galaxies
- cutoff/break feature \((0.1 - 1)\) PeV at the CR knee (of these galaxies), but very uncertain
- plot shows muon neutrinos on production \((3/2 \text{ of total})\)

[Loeb & Waxman'06]
Neutrino Point-Source Limits

- upper flux limits and sensitivities of Galactic neutrino sources with “classical” muon neutrino search ($\theta_{\text{res}} \approx 0.3^\circ - 0.6^\circ$)

- sensitivity for extended sources weaker by
  $\sqrt{\Omega_{\text{ES}}/\Omega_{\text{PSF}}} \approx \theta_{\text{ES}}/\theta_{\text{res}}$

- strongest limits for sources in the Northern Hemisphere (IceCube FoV for upgoing $\nu$’s)

- time-dependent sensitivity:
  \[ E^2 \Phi_{\nu\mu} \approx (0.1 - 1) \text{GeVcm}^{-2} \]

Fig. 11.— Muon neutrino upper limits with 90% C.L. evaluated for the 44 sources (dots), for the combined four years of data (40, 59, 79, and 86 string detector configurations). The solid black line is the flux required for 5\sigma discovery of a point source emitting an $E^2 \Phi_{\nu\mu}$ flux at different declinations while the dashed line is the median upper limit or sensitivity also for a 90% C.L. The ANTARES sensitivities and upper limits are also shown (Adrián-Martínez et al. 2014). For sources in the southern hemisphere, ANTARES constrains neutrino fluxes at lower energies than this work.
• **relative strength** of neutrino limits assuming hadronic TeV $\gamma$-ray emission (only shown for selected strong sources):

$$F_\gamma(E_\gamma > E_{th})/F_{\nu}^{90CL}(E_\nu > E_{th}/2)$$

✗ **caveats**: soft spectra, low energy cutoffs and extended emission
Diffuse vs. Point-Source flux

- point-source flux:
  \[ F_{\text{PS}} = \frac{L}{4\pi d_L^2(z)} \simeq \frac{L}{4\pi r^2} \]

- (quasi-)diffuse flux:
  \[ F_{\text{diff}} = \frac{1}{4\pi} \int dz \frac{d\nu_C}{dz} \mathcal{H}(z) \frac{L}{4\pi d_L(z)^2} \simeq \frac{L}{4\pi} \int_0^{1/H_0} dr \mathcal{H}(r) \]

- typically, the density \( \mathcal{H} \) of extra-galactic sources is:
  - \( 10^{-3} - 10^{-2} \text{ Mpc}^{-3} \) for **normal galaxies**
  - \( 10^{-5} - 10^{-4} \text{ Mpc}^{-3} \) for **active galaxies**
  - \( 10^{-7} \text{ Mpc}^{-3} \) for **massive galaxy clusters**
  - \( > 10^{-5} \text{ Mpc}^{-3} \) for **UHE CR sources**

- PS flux based on HESE measurement:
  \[ F_{\text{PS}}(E_\nu) \simeq 9 \times 10^{-13} \text{ TeV cm}^{-2} \text{s}^{-1} \left( \frac{\mathcal{H}_0}{10^{-5} \text{ Mpc}^{-3}} \right)^{-1} \left( \frac{r}{10 \text{ Mpc}} \right)^{-2} \left( \frac{\xi_z}{2.4} \right)^{-1} \]
Identification of Extragalactic Point-Sources?

- total number of sources
  \[ n_s \simeq 10^6 - 10^7 \]

- total number of “slices”
  \[ n_{\text{slice}} \simeq (n_s)^{\frac{1}{3}} \]

- total number of events
  \[ \bar{N} \simeq m \times n_{\text{slice}} = m \times (n_s)^{\frac{1}{3}} \]

✓ required number of events to see a doublet \((m = 2)\)
  \[ \bar{N} \simeq 200 - 500 \]

✗ random clusters are very likely with bad angular resolution!
Identification of Extragalactic Point-Sources?

- IceCube flux normalizes the contribution of individual sources
- Dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution $\xi_z$
- PS observation requires rare sources
- Non-observation of individual neutrino sources exclude source classes, e.g.
  - FSRQs
    \[ \mathcal{H} \approx 10^{-9}\text{Mpc}^{-3} / \xi_z \approx 7 \]
  - “Normal” GRBs
    \[ \dot{\mathcal{H}} \approx 10^{-9}\text{Mpc}^{-3}\text{yr}^{-1} / \xi_z \approx 2.4 \]

[MA&Halzen’14]
Association with Known Sources?

- total number of **known** closeby \((r < r_{th})\) sources, \(e.g.\)
  \[ n_{\text{cat}} \simeq 100 \]

- total number of events
  \[ \bar{N} \simeq m^* \times n_{\text{slice}} = m \times \left( \frac{n_s}{n_{\text{cat}}} \right)^{\frac{1}{3}} \]

- required number of events to see an association \((m = 1)\)
  \[ \bar{N} \simeq 20 - 50 \]
Multimessenger Signal

TeVCat $\gamma$-ray sources

LBL, IBL, LBL, FRI, FSRQ
Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN
Shell, SNR/Molec.Cloud, Composite SNR
Starburst
Others [TeVCat'14]
Multimessenger Signal

Auger 2010 $E > 55$ EeV / TA 2014 $E > 57$ EeV

$\langle \theta \rangle \simeq 1^\circ \left( \frac{D}{\lambda_{coh}} \right)^{\frac{1}{2}} \left( \frac{E}{55 \text{ EeV}} \right)^{-1} \left( \frac{\lambda_{coh}}{1 \text{ Mpc}} \right) \left( \frac{B}{1 \text{ nG}} \right)$

[Waxman & Miralda-Escude’96]
Isotropic Diffuse Gamma-Ray Background (IGRB)

- neutrino and $\gamma$-ray fluxes in $pp$ scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

  → low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

  × constraint by IGRB
  
  [Murase, MA & Lacki’13; Chang & Wang’14]

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$

- Galactic emission: $\Gamma \lesssim 2.0$

  → $\gtrsim 10\%$ contribution to IGRB at $E_\gamma \gtrsim 100\text{GeV}$

[Murase, MA & Lacki’13; updated with Fermi 1410.3696]
DM decay

- heavy (>PeV) DM decay?
  [Feldstein et al. 1303.7320; Esmaili & Serpico 1308.1105; Bai, Lu & Salvado 1311.5864]

- initially motivated by PeV “line-feature”, but continuum spectrum with/without line spectrum equally possible

→ observable PeV $\gamma$-rays from the Milky Way halo?

![Plot showing events per 662 days vs. $E_\nu$ [TeV]]

[Bai, Lu & Salvado’13]
Proposed detector configuration for IceCube-Gen2/HEX:
120 additional strings with average spacing of 240m (left) and 300m (right).
• IceCube 4th year HESE data to be unblinded soon.

• Refined analysis strategies with reduced atmospheric backgrounds and lower energy threshold under development.

• Do we see individual sources or just a diffuse background?

→ Input from $\gamma$-ray astronomy will be essential to identify extragalactic source populations.

• How well can we determine the spectrum and flavor composition?

• Is the corresponding CR population responsible for UHE CRs (WB saturation)?

• Local PeV $\gamma$-ray astronomy?

• Extragalactic contributions of EeV neutrinos (GZK)?

• Studies of possible future extensions of IceCube underway.
Appendix
Cosmogenic neutrinos

- **cos-mo-gen-ic** (adj.): “produced by cosmic rays”

>> but this is true for all high-energy neutrinos...

→ **more specifically**: not in the source or atmosphere, but during **CR propagation**

- most plausibly via pion production in $p\gamma$ interactions, *e.g.*

\[ p + \gamma_{\text{bgr}} \rightarrow \Delta \rightarrow n + \pi^+ \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad \& \quad \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \]

(e.g. Centaurus A)
Cosmogenic neutrinos

- Neutrino flux depends on source evolution model (strongest for “FR-II”) and EBL model (highest for “Stecker” model)

- “Stecker” model disfavored by Fermi observations of GRBs
- Strong evolution disfavored by Fermi diffuse background
UHE CR associations

- neutrino and CR nucleon relation:
  \[
  \frac{1}{3} \sum_{\alpha} E^{2}_{\nu} Q_{\nu\alpha}(E_{\nu}) \approx \frac{1}{4} \frac{f_{\pi} K_{\pi}}{1 + K_{\pi}} E^{2}_{N} Q_{N}(E_{N})
  \]

- UHE CR proton emission rate density:
  \[
  E^{2}_{p} Q_{p}(E_{p}) \simeq (1 - 2) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}
  \]

- cosmic evolution, e.g. \(H_{0}(z) = \Theta(2 - z)\) or
  \[
  H_{SFR}(z) = \begin{cases} 
  (1 + z)^{3.4} & z < 1, \\
  N_{1} (1 + z)^{-0.3} & 1 < z < 4, \\
  N_{1} N_{4} (1 + z)^{-3.5} & z > 4
  \end{cases}
  \]

[Hopkins&Beacom’98]  
[MA&Halzen’12]
UHE CR associations

- diffuse extragalactic neutrino emission:

\[
J_\nu(E_\nu) = \frac{1}{4\pi} \int_0^\infty \frac{dz}{H(z)} \mathcal{H}(z) Q_\nu((1 + z)E_\nu)
\]

- per flavor flux ($\xi_z \simeq 0.5 - 2.4$ and $K_\pi \simeq 1 - 2$):

\[
E_\nu^2 J_\nu(E_\nu) \simeq f_\pi \frac{\xi_z K_\pi}{1 + K_\pi} (2 - 4) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}
\]

- **WB bound:** $f_\pi \leq 1$ 

  [Waxman&Bahcall’98]

- $f_\pi \simeq 1$ requires efficient pion production

- **how to reach** $E_{\text{max}} \simeq 10^{20}$ eV in environments of high energy loss?

- **two-zone models:** acceleration + CR “calorimeter”?
  - starburst galaxies
  - galaxy clusters

  [Loeb&Waxman’06]

  [Berezinsky,Blasi&Ptuskin’96;Beacom&Murase’13]

- “holistic” CR models: universal time-dependent CR sources?

  [Parizot’05;Aublin&Parizot’06;Katz,Waxman,Thompson&Loeb’13]
Contrast of GC excess

- Galactic Center (GC) flux:
  \[ F_{\text{GC}} \simeq \frac{L_{\text{GC}}}{4\pi d_{\text{GC}}^2} \]

- (quasi-)diffuse flux from similar galaxies:
  \[ F_{\text{diff}} = \frac{1}{4\pi} \int dz \frac{dV_C}{dz} \mathcal{H}(z) \frac{L_{\text{GC}}}{4\pi d_L(z)^2} \simeq \frac{L}{4\pi} \frac{\xi_z \mathcal{H}_0}{H_0} \]

\( \rightarrow \) flux ratio depend on local source density \( \mathcal{H}_0 \) and evolution parameter \( \xi_z \):

\[ \frac{F_{\text{GC}}}{4\pi F_{\text{diff}}} \simeq \frac{H_0}{4\pi \xi_z \mathcal{H}_0 d_{\text{GC}}^2} \simeq 100 \left( \frac{\xi_z}{2.4} \right)^{-1} \left( \frac{\mathcal{H}_0}{10^{-3}} \right)^{-1} \]

- “benchmark” local density \( \mathcal{H}_0 \simeq 10^{-3} - 10^{-2} \, \text{Mpc}^{-3} \) (normal galaxies)
- “benchmark” evolution \( \xi_z \simeq 2.4 \) (star-formation rate)

\( \rightarrow \) Additional component needed for full observation.
Contrast of DM decay

- Galactic neutrino flux from DM decay:

\[
F_{\text{gal}} = \frac{Q_\nu}{m_X\tau_X} \frac{1}{2} \int_{-1}^{1} dc \alpha \int \frac{ds}{\rho_{\text{gal}}(r(s, c_\alpha))} \simeq \frac{Q_\nu}{m_X\tau_X} \langle \rho_{\text{gal}} \rangle d_{\text{halo}}
\]

- Extragalactic diffuse signal:

\[
F_{\text{diff}} = \frac{\Omega_{\text{DM}} \rho_{\text{cr}}}{4\pi m_X \tau_X} \int_0^\infty \frac{dz}{H(z)} Q_\nu ((1 + z)E_\nu) \simeq \frac{1}{4\pi} \frac{Q_\nu}{m_X \tau_X} \frac{\xi_z \Omega_{\text{DM}} \rho_{\text{cr}}}{H_0}
\]

→ flux ratio:

\[
\frac{F_{\text{gal}}}{4\pi F_{\text{diff}}} \simeq \frac{\langle \rho_{\text{gal}} \rangle}{\Omega_{\text{DM}} \rho_{\text{cr}}} \frac{d_{\text{halo}}}{\xi_z / H_0} \simeq 1 \left( \frac{d_{\text{halo}}}{20\text{kpc}} \right) \left( \frac{\xi_z}{0.5} \right)^{-1}
\]

→ Similar contributions from Galactic and extragalactic DM decay.
Diffuse emission in GP

- **diffuse $\gamma$-ray & $\nu$ emission** from CR propagation ($|b| < 2^\circ$)

- **unresolved supernova remnants:**
  \[
  R_{SN} \simeq 0.03 \text{yr}^{-1} \\
  \mathcal{E}_{ej} \simeq 10^{51} \text{ erg} \\
  N_{SNR} \simeq 1200
  \]

- **unresolved hypernova remnants:**
  \[
  R_{HN} \simeq 0.01 R_{SN} \\
  \mathcal{E}_{ej} \simeq 10^{52} \text{ erg} \\
  N_{HNR} \simeq 20
  \]

- **flux concentrated in Galactic Plane:**
  \[
  J \propto 50\% \text{ for } |b| < 5^\circ \\
  J \propto 30\% \text{ for } |b| < 10^\circ
  \]

- however, this does not account for **local fluctuation**

[MA & Murase 1309.4077]
Diffuse emission in GP

- diffuse $\gamma$-ray & $\nu$ emission from CR propagation ($|b| < 2^\circ$)

- unresolved supernova remnants:
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- unresolved hypernova remnants:
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- flux concentrated in Galactic Plane:
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[MA & Murase 1309.4077]