DIM JETS AS VERY HIGH ENERGY NEUTRINO SOURCES

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TeVPA
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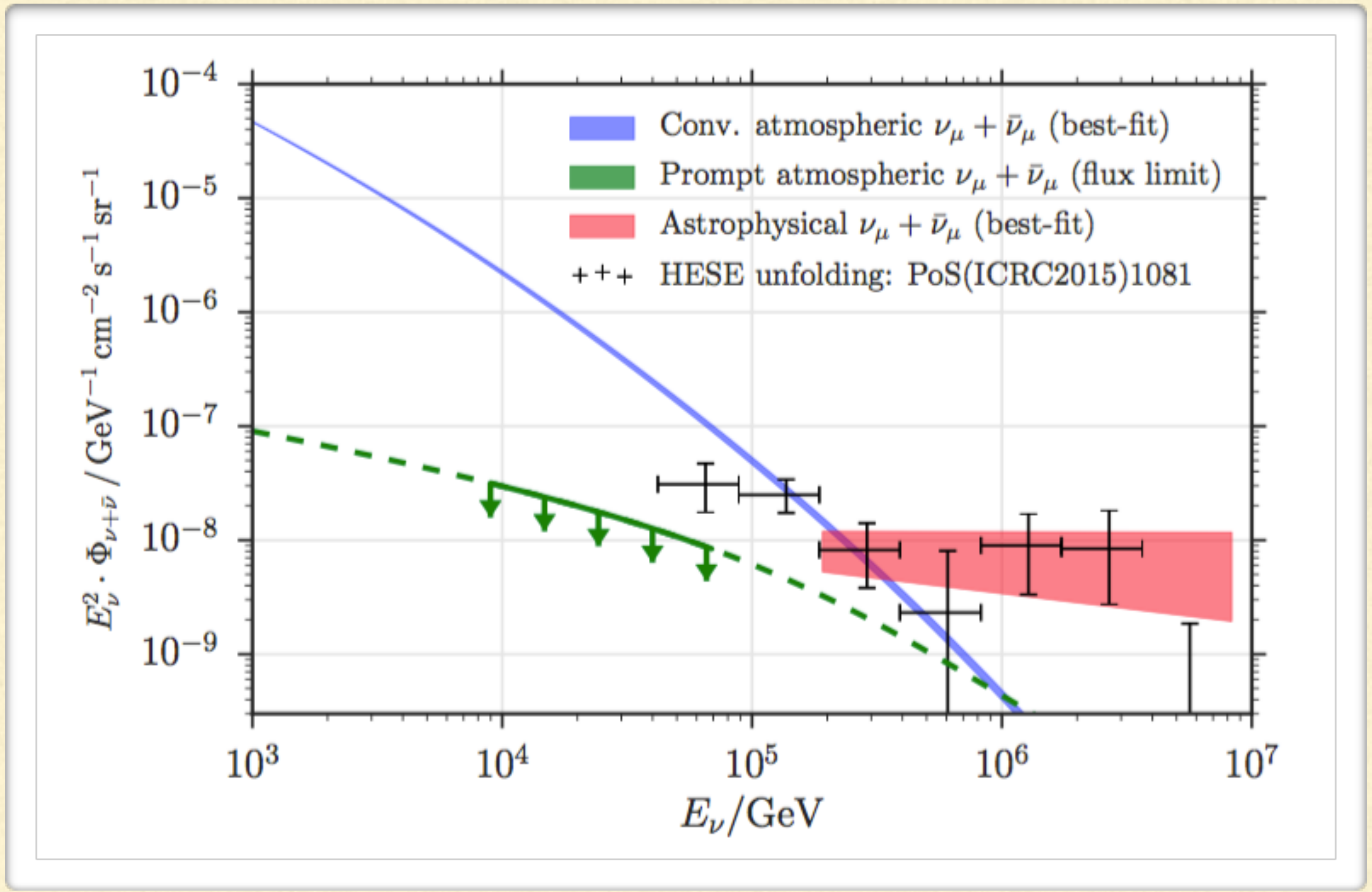
CERN

ICECUBE (IC) NEUTRINO FLUX



Potential sources:

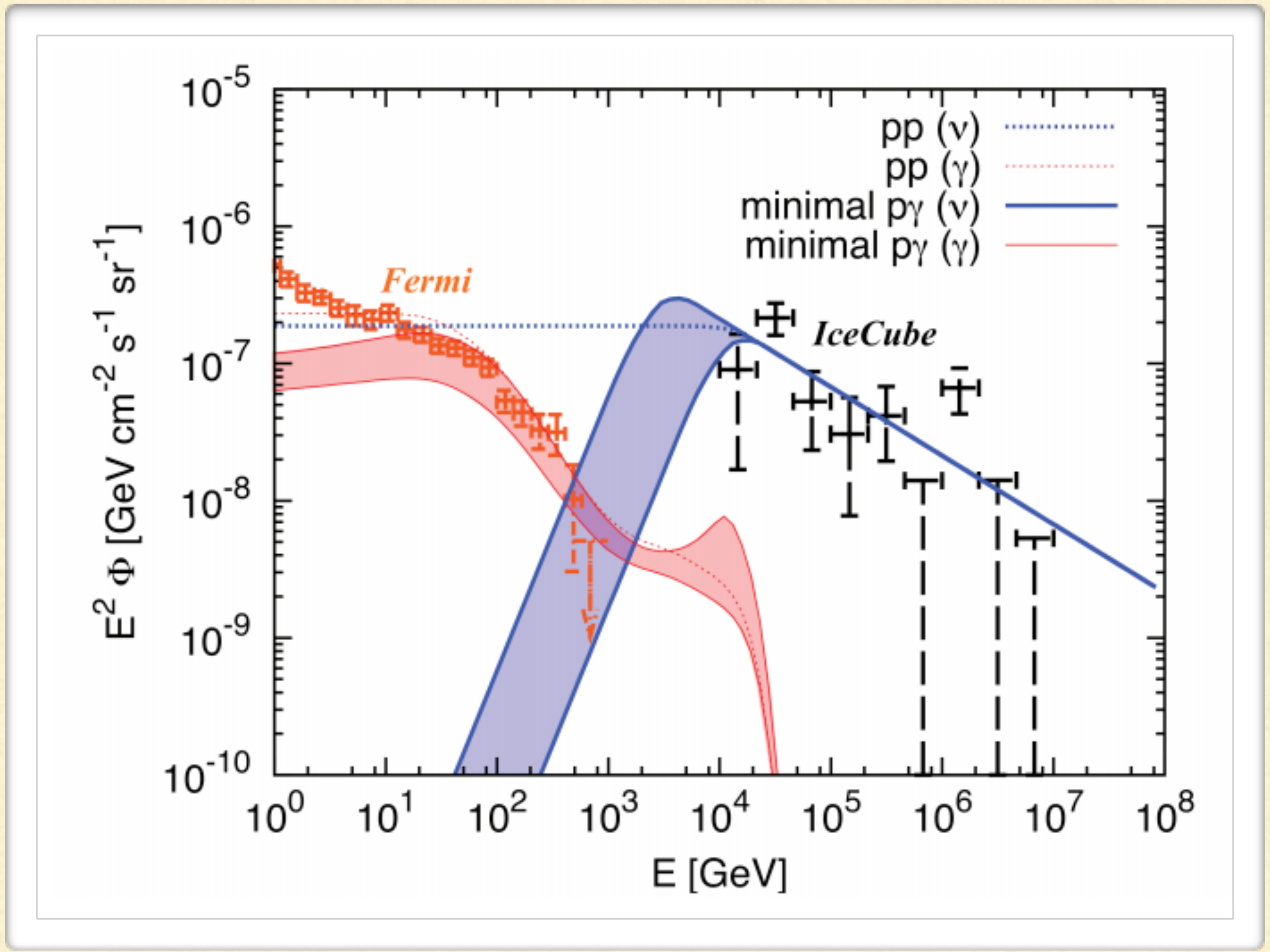
1. Starburst Galaxies
2. Blazars
3. GRBs
4. ???

Minimal pp and pγ models

$$\epsilon_\gamma^2 \Phi_\epsilon \simeq 2^{s-1} \varepsilon_\nu \Phi_\varepsilon \big|_{\varepsilon_\nu = 0.5\epsilon_\gamma}$$

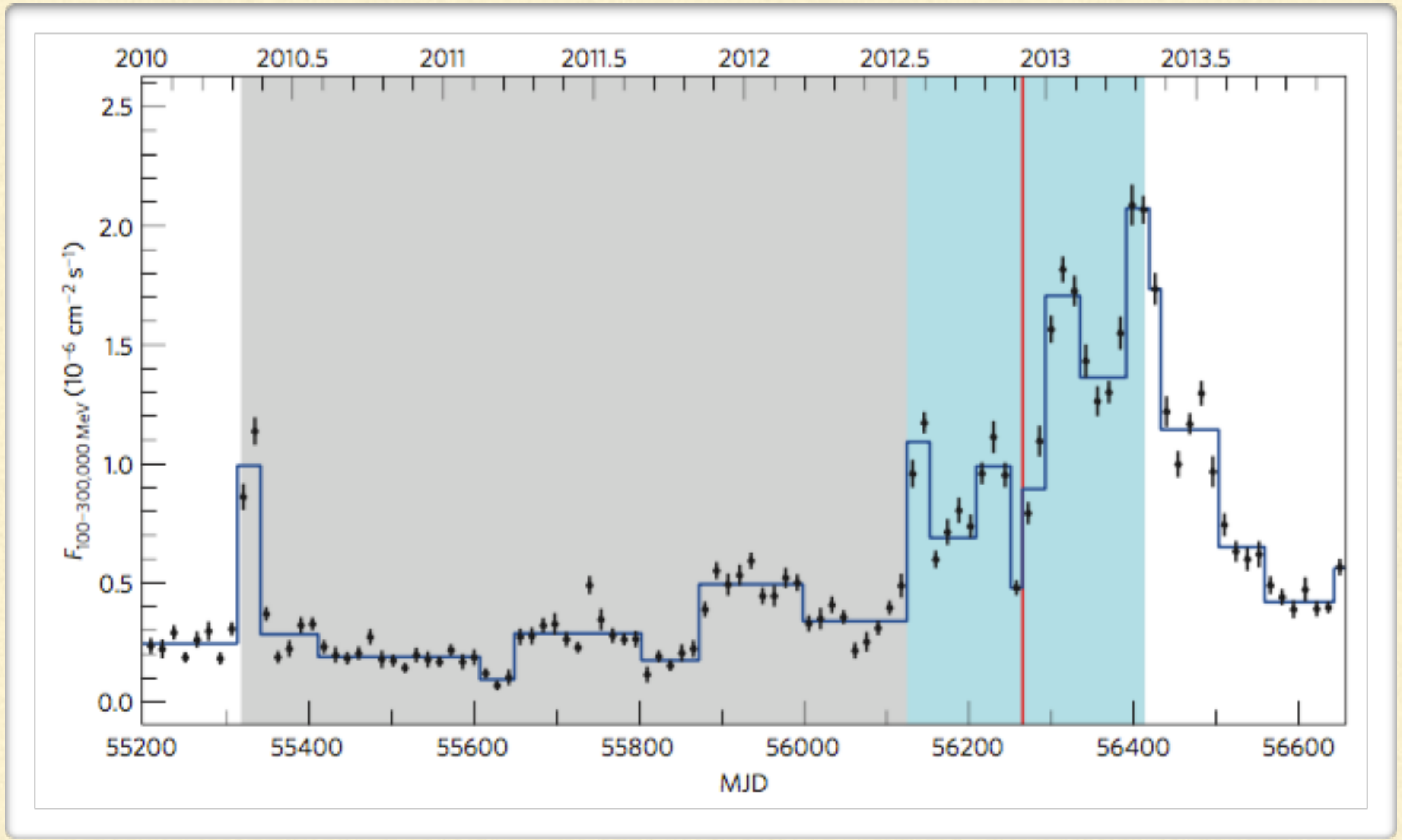
- In 2015 the *Fermi*-LAT Collaboration released a new studying claiming that "point sources account for at least 86+16-14% of the total extragalactic γ-ray background" (EGRB) (Ackermann et al. PRL 116, 151105 (2016))

- Minimal model that is fit only to IC data points is inconsistent with the EGRB if source is γ-ray transparent



Murase et al. PRL 116, 071101 (2016)

Why not Blazars?



- Coincidence of "Big Bird" 2PeV Cascade event with PKS B1424-418
- "Probability of ~5% for a chance coincidence"

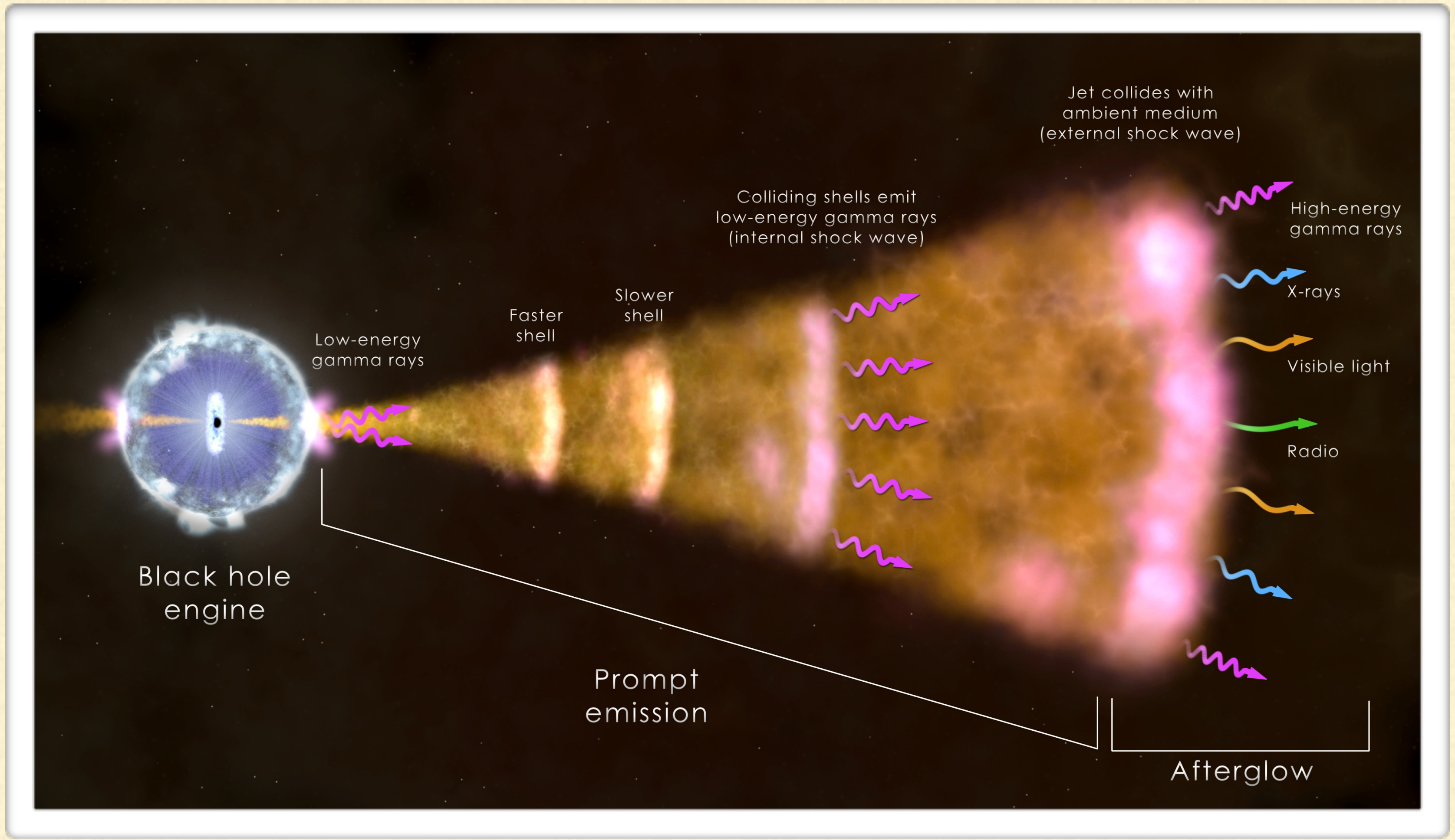
Kadler et al. Nat. Phys. 12, 807 (2016)

However:

- Model independent search finds ~10-20% of the HESE neutrinos are found to be coincident with Blazars (Padovani et al. MNRAS 457, 3582 (2016))
- GRB prompt emission accounts for < 1% of the IC neutrino flux (Aartsen et al. ApJ 805:L5 (2015))
- No neutrino point sources found to date (2015 ICRC Conference Proceedings arXiv:1510.05222)

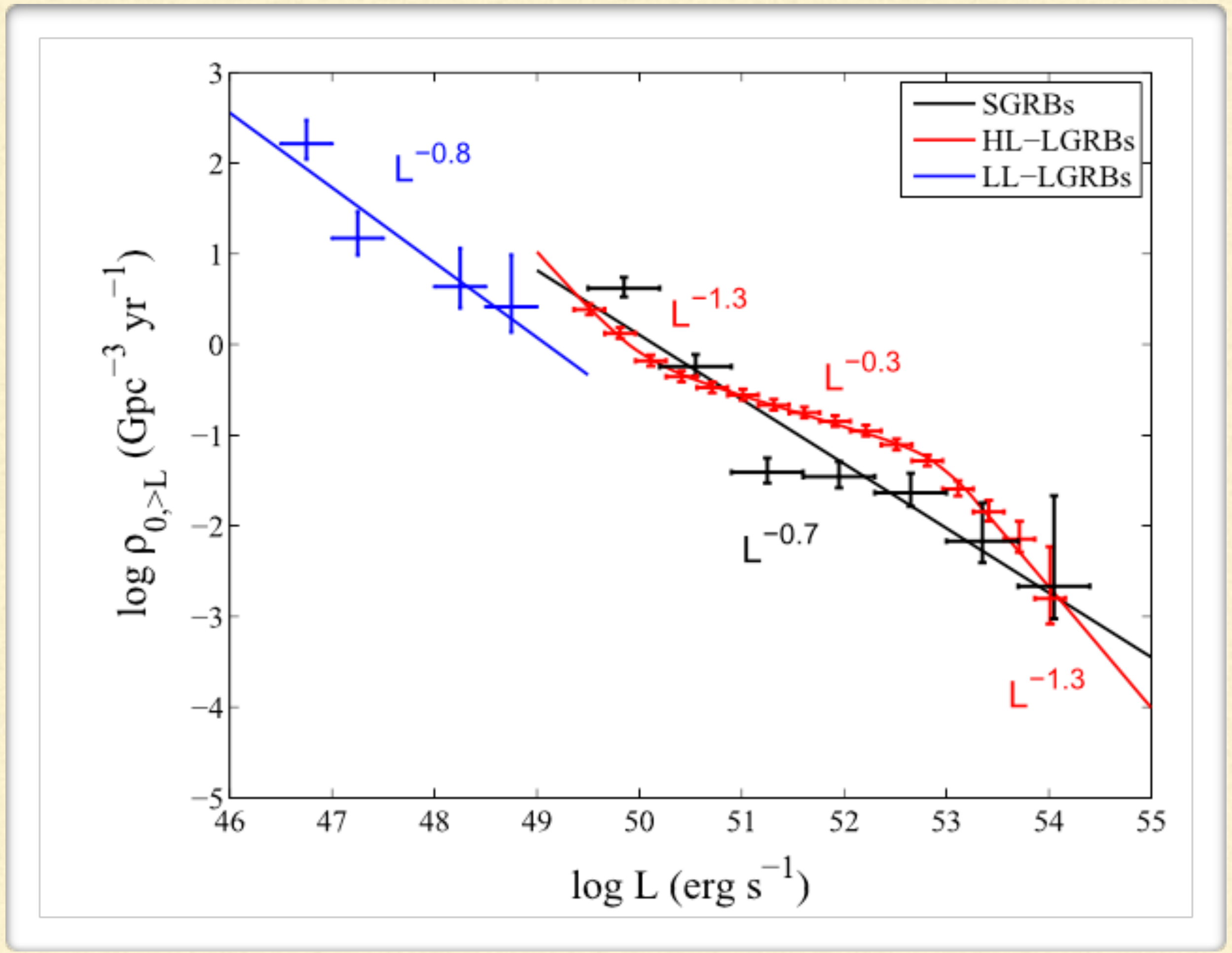
CHOKED JETS AND LL GRBs AS HIDDEN NEUTRINO FACTOIRES

Gamma-Ray Bursts (GRBs) are the most luminous explosions in the Universe. While their origin remains somewhat mysterious, it is generally believed that their emission stems from an ultra-relativistic fireball launched by **the collapse of a massive star** (i.e. the collapsar scenario) or from the merger of two compact binary objects. We consider the former case.

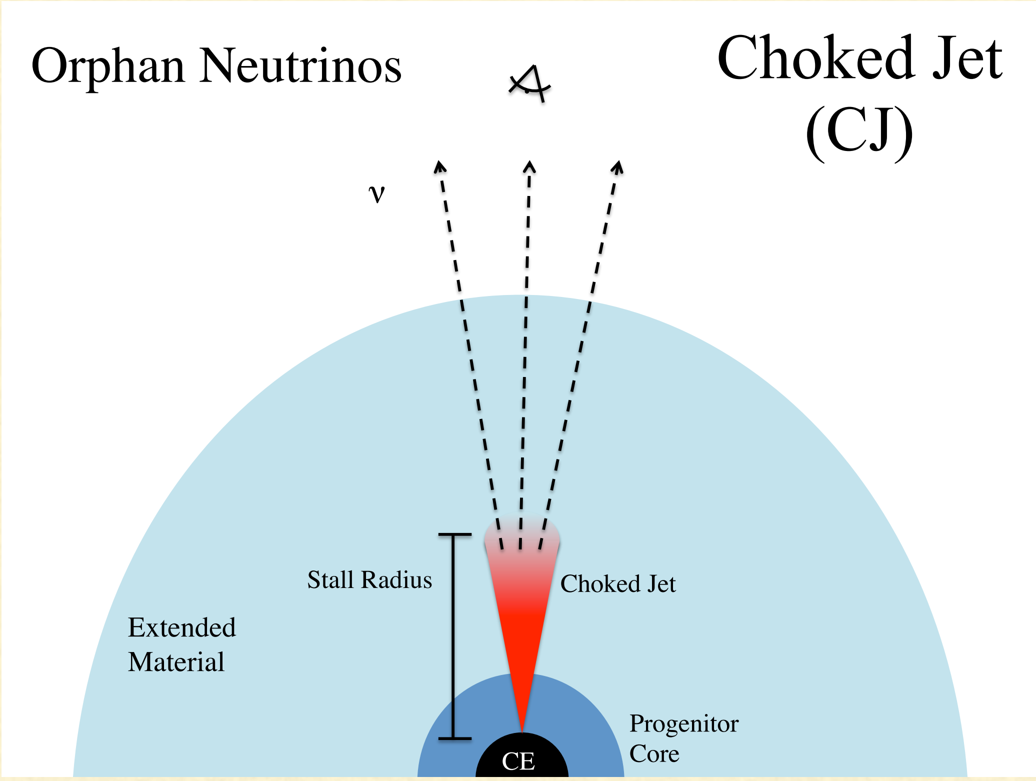


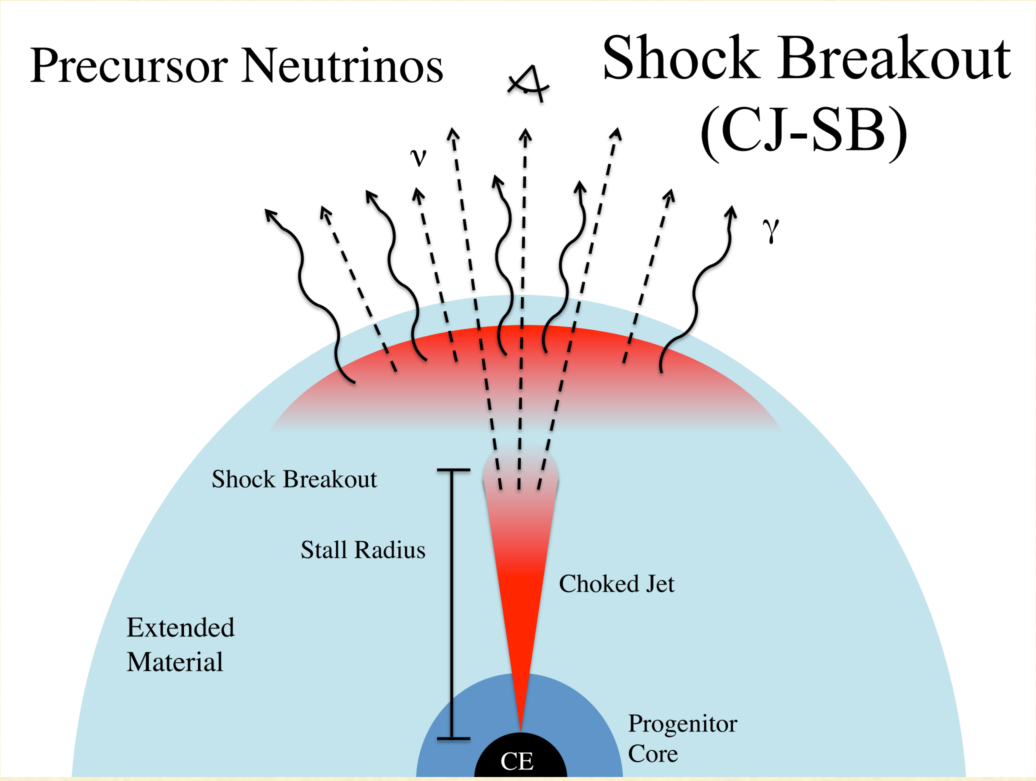
The high velocity of their jets and significant non-thermal emission make GRBs natural candidates for producing ultra high-energy cosmic-rays (UHECR) with energies $> 10^{18}$ eV

- LL GRBs are markedly different than conventional long GRBs:
  - their prompt emission lasts ~10^3 s vs. ~10s of seconds
  - they exhibit smooth prompt emission light curves versus the millisecond variability time scales for HL GRBs
  - they occur 100 × more frequently in the local Universe

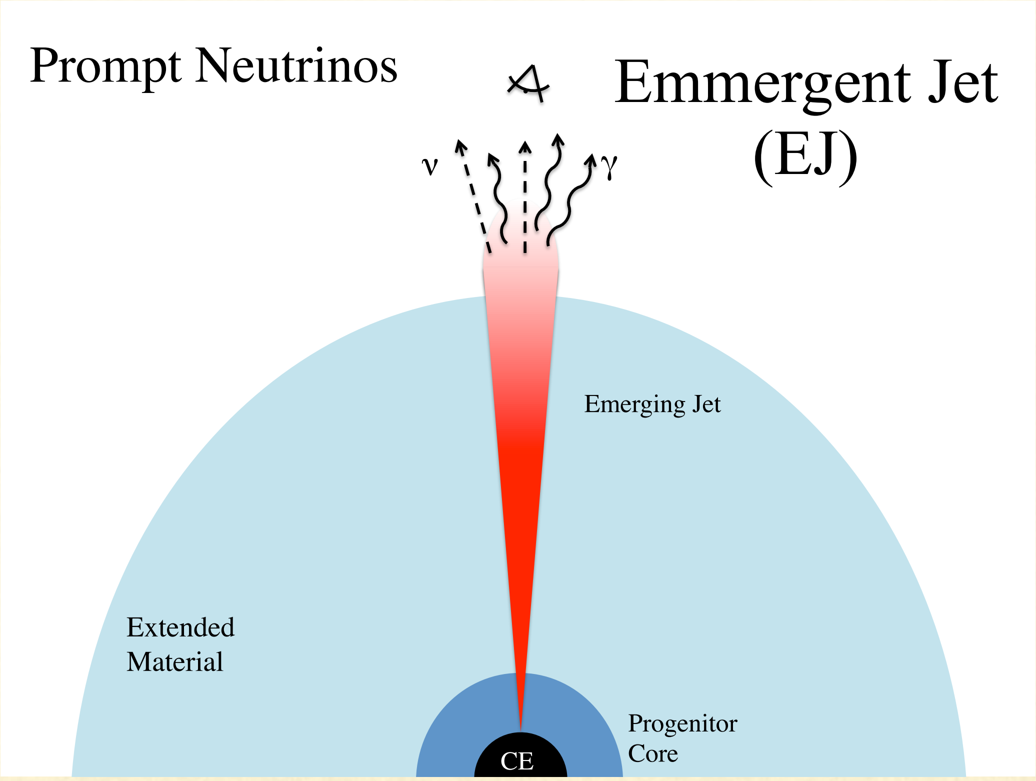


- It has been shown that LL GRBs may also have more favorable environments for CR acceleration based on radiation constraints





- We attempt to explain the observed neutrino flux using low luminosity (LL) and choked GRBs
- The intrinsic jet properties of all bursts are similar but some are smothered by a dense, circumstellar envelope.



- Limits on jet luminosity for LL GRBs
  - The jet stalling condition gives:

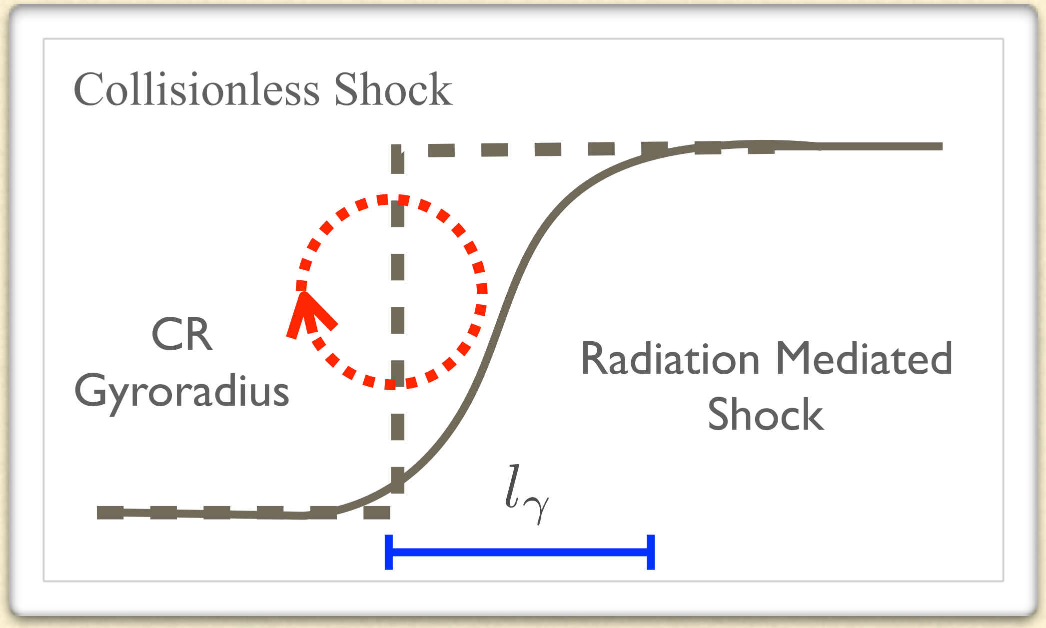
$$L_\gamma \lesssim L_\gamma^{\rm JS} \approx 0.95 \times 10^{48}\ {\rm erg\ s^{-1}}\ \left(\frac{\bar{\epsilon}_\gamma}{0.25}\right)\left(\frac{\theta_j}{0.2}\right)^2 t_{{\rm eng},1.5}^{-1} T_{3.5}^{-1} \rho_{\rm env} r_{{\rm env},13.5}^4,$$

  in agreement with the maximum observed luminosity for a LL GRB

  - Radiation Constraint:

$$L_\gamma \lesssim L_\gamma^{\rm RC} \approx 8.6 \times 10^{49}\ {\rm erg\ s^{-1}}\ \left(\frac{\bar{\epsilon}_\gamma}{0.25}\right)\left(\frac{\theta_j}{0.2}\right)^2 \Gamma_2^6 t_{{\rm eng},1.5}^3 T_{3.5}^{-1} \rho_{\rm ext}^{-1} r_{{\rm ext},13.5}^{-2}$$

  - Only collisionless shocks (shocks that are mediated by magneto-hydrodynamic instabilities) are capable of efficiently accelerating CRs.



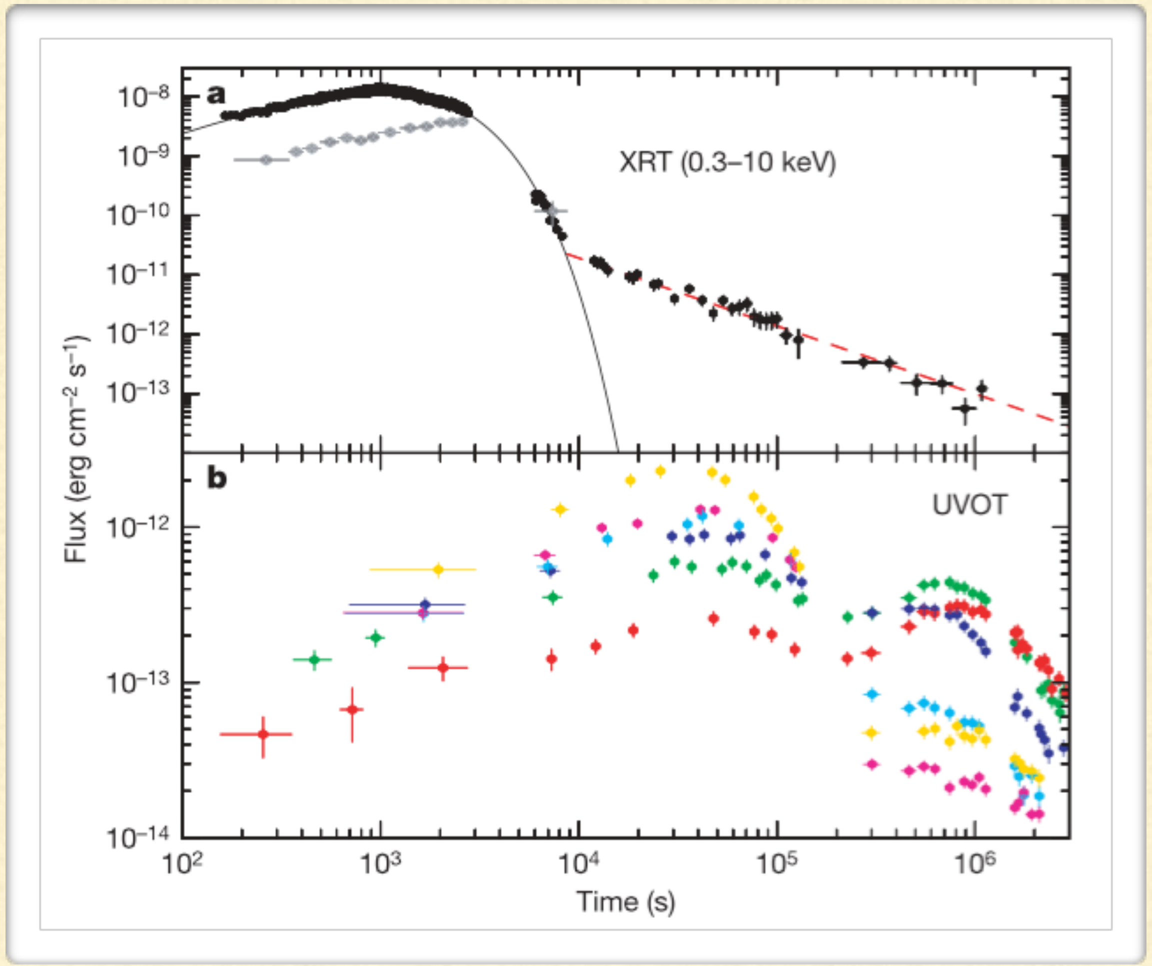
- We assume that the quasi-spherical shock breaks out when it reaches the edge of the circumstellar envelope, producing a LL GRB.

- The prompt emission lasts for

$$T \sim r_{env}/v_{sh} \to 1000 \text{ s} \left(\frac{v_{sh}}{c}\right)^{-1} r_{env,13.5}$$

in agreement with observations

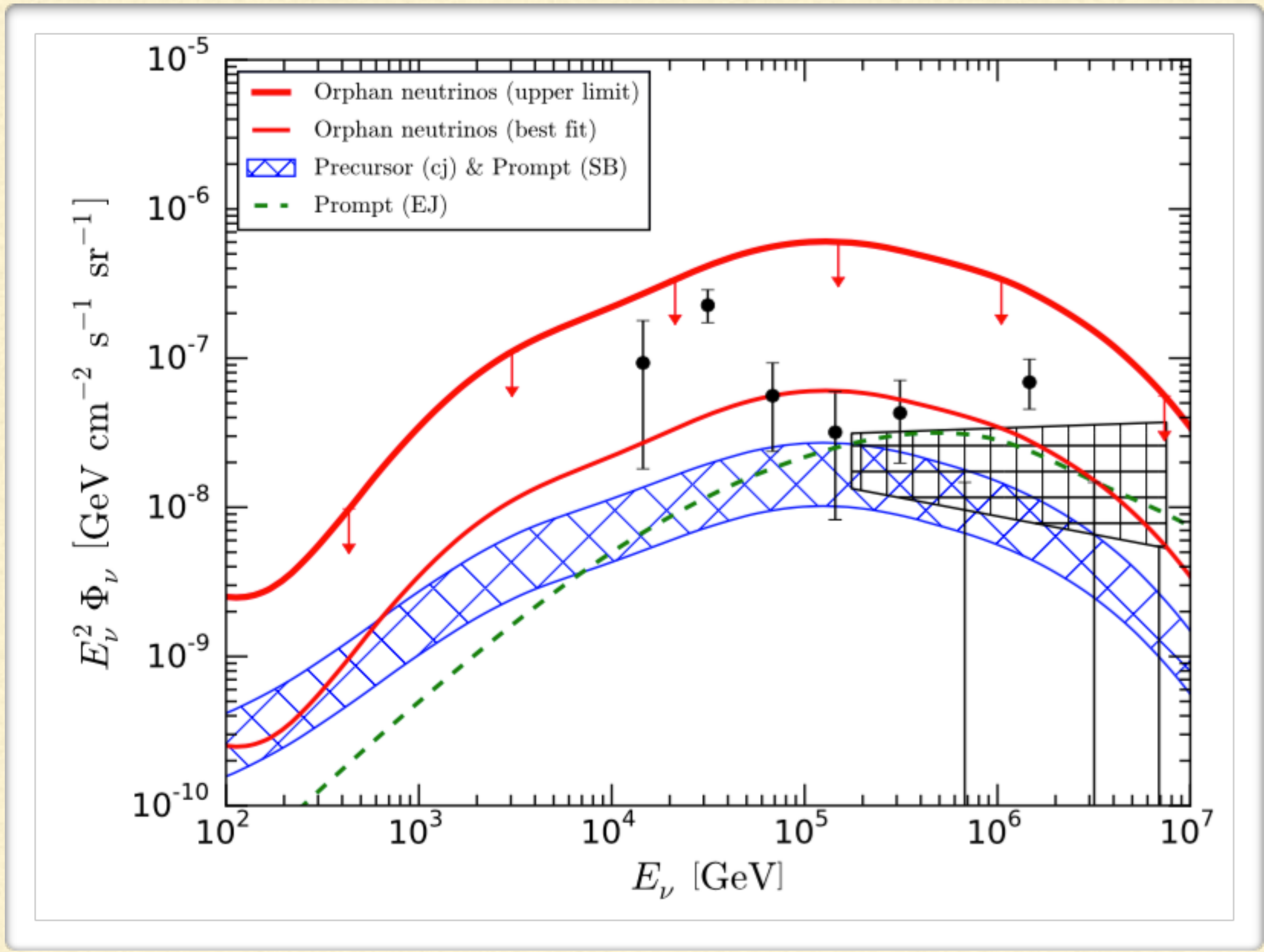
- Note that the shock breakout emission is delayed with respect to the neutrino signal from the choked jet by $(r_{sb} - r_{stall})/c \sim 100 - 1000$ s



- For LL GRB 060218 a PL afterglow was observed in agreement with theory

CJ-SB Model for LL GRBs

- A precursor neutrino signal is expected ~100-1000s before the electromagnetic detection of the LL GRB
- Note that we have not tuned any parameters except to match the observations of individual LL GRBs and the overall distribution of bursts in luminosity and redshift.
- The CJ-SB model could explain the diffuse neutrino flux between $50\ \mathrm{TeV} \lesssim \varepsilon_\nu \lesssim 300\ \mathrm{TeV}$



NS et al. PRD 93 083003 (2016)

Connection between neutrino production and γ-ray attenuation

- The same photons that produce neutrinos via pγ interactions can also attenuate accompanying γ-rays produced by π^0 decay.

$$\gamma + \gamma \rightarrow e^- + e^+$$

- Because the sources of the IC neutrinos must be efficient CR converters, this means the γγ optical depth is also high

$$\tau_{\gamma\gamma}(\varepsilon_\gamma^c) \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_{p\gamma}(\varepsilon_p) \sim 10 \left(\frac{f_{p\gamma}(\varepsilon_p)}{0.01} \right)$$

$$\varepsilon_\gamma^c \approx \frac{2 m_e^2 c^2}{m_p \bar{\varepsilon}_\Delta} \varepsilon_p \sim \mathrm{GeV} \left(\frac{\varepsilon_\nu}{25\ \mathrm{TeV}} \right)$$

Murase et al. PRL 116, 071101 (2016)

CONCLUSIONS AND OUTLOOK

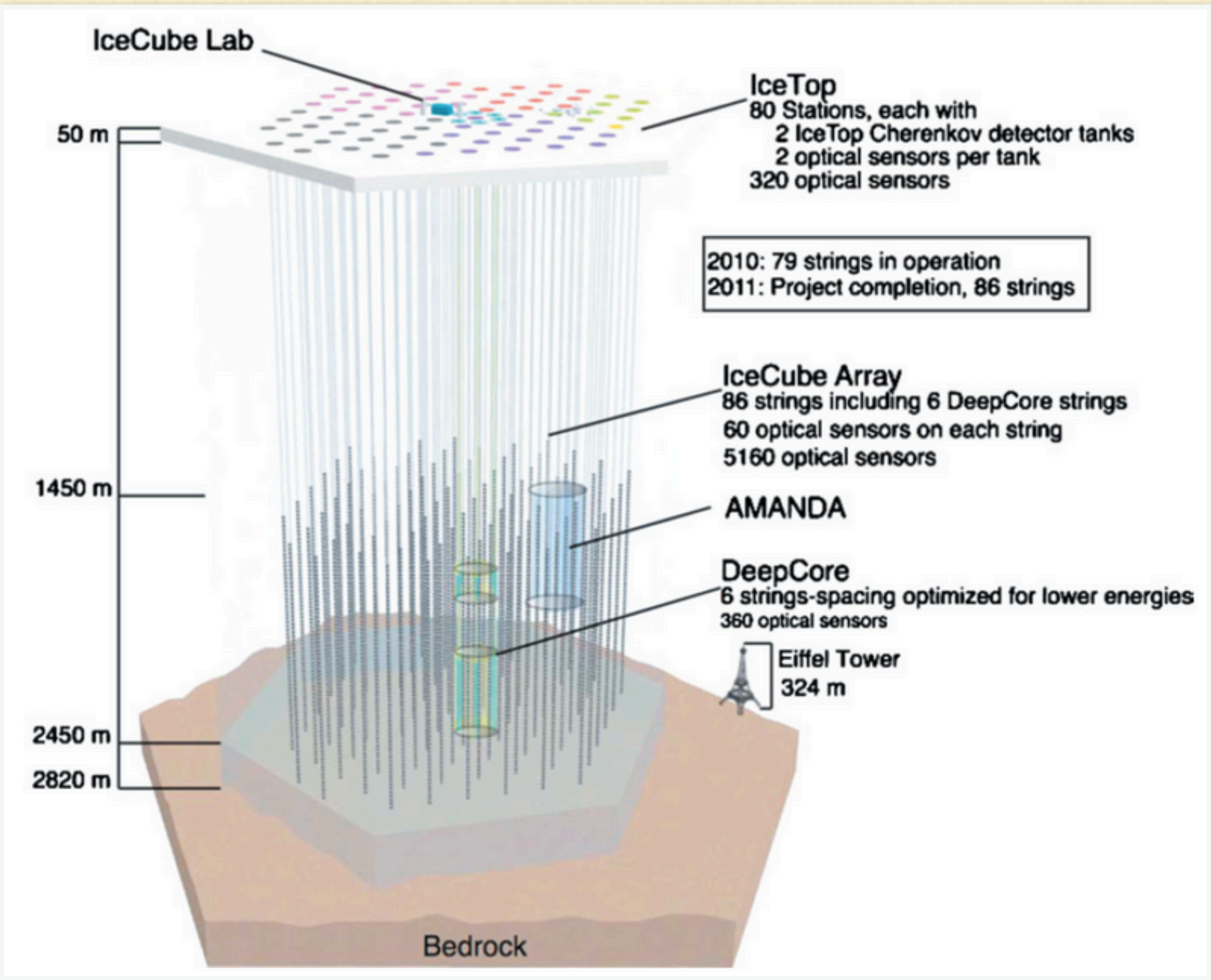
- Electromagnetic (and now gravitational) observations have yielded no significant coincident neutrino events to date. Fermi-LAT observations of the extra-galactic γ-ray background are beginning to exclude unresolved sources such as SBGs.
- Non-detections are beginning to rule out classes of source models for GRBs and blazars.
- Electromagnetically dim, relativistic, and jetted objects such as CJs and CJ-SBs are increasingly attractive as dark sources of neutrinos.

CONCLUSIONS AND OUTLOOK

- Tantalizingly, if an event such as GRB 060218 or GRB 100316D had occurred after the completion of the IC 86 string array, our model predicts that they would have had a ≳50% chance of being detected.
- Four such events have occurred since 1998, and we should expect the next LL GRB in the coming years.
- A precursor VHE neutrino signal ~100-1000s *before* the detection of a long duration LL GRB with slowly varying prompt emission would be a smoking gun signature of the CJ-SB scenario.
- Because the target photons for pγ interactions attenuate high energy γ-rays (0.1-100 GeV), all sky surveys for high-energy events bright in x-rays and TeV γ-rays will be needed to perform multi-messenger searches for the sources of the IC neutrinos.

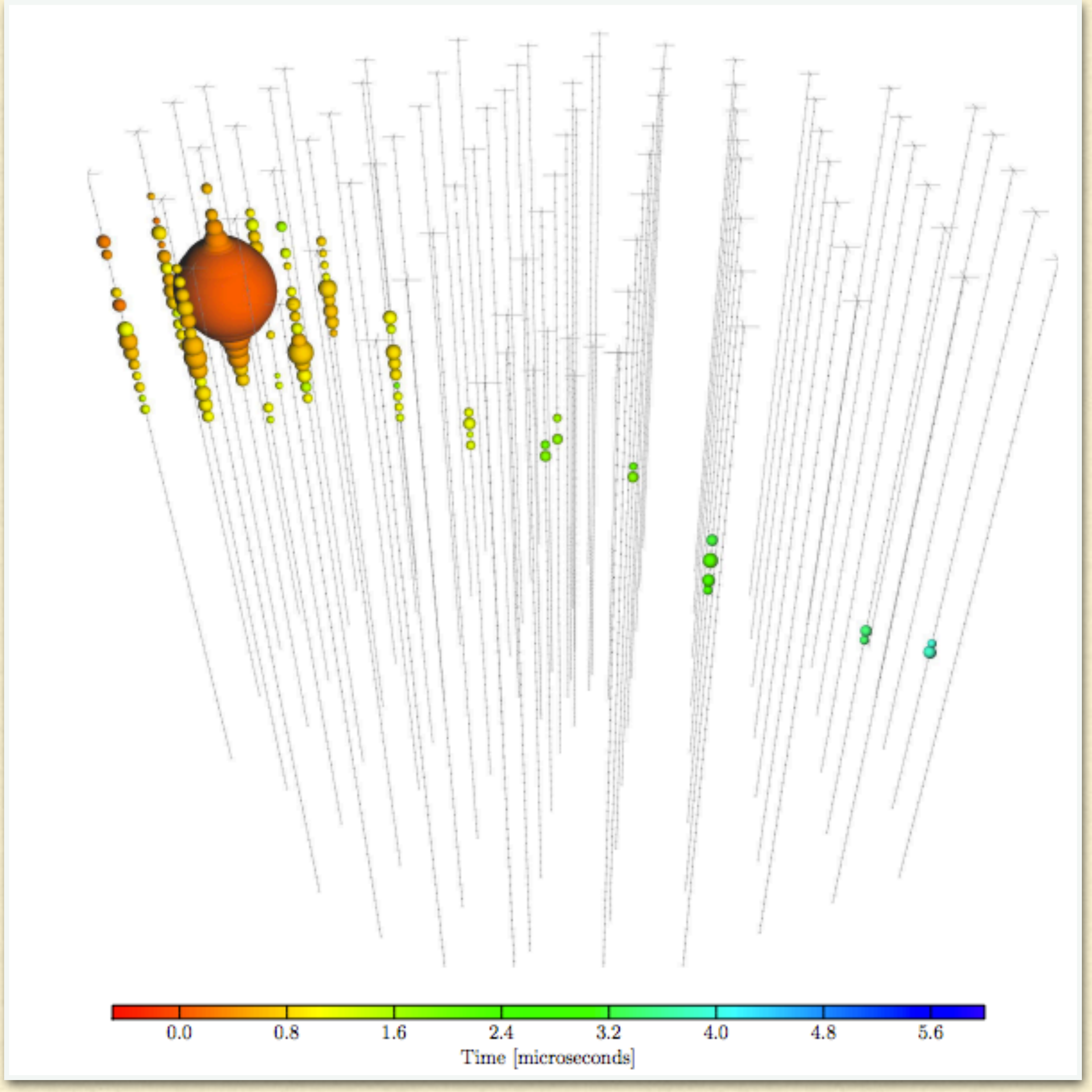
EXTRA

THE ICECUBE OBSERVATORY AND ASTROPHYSICAL NEUTRINOS

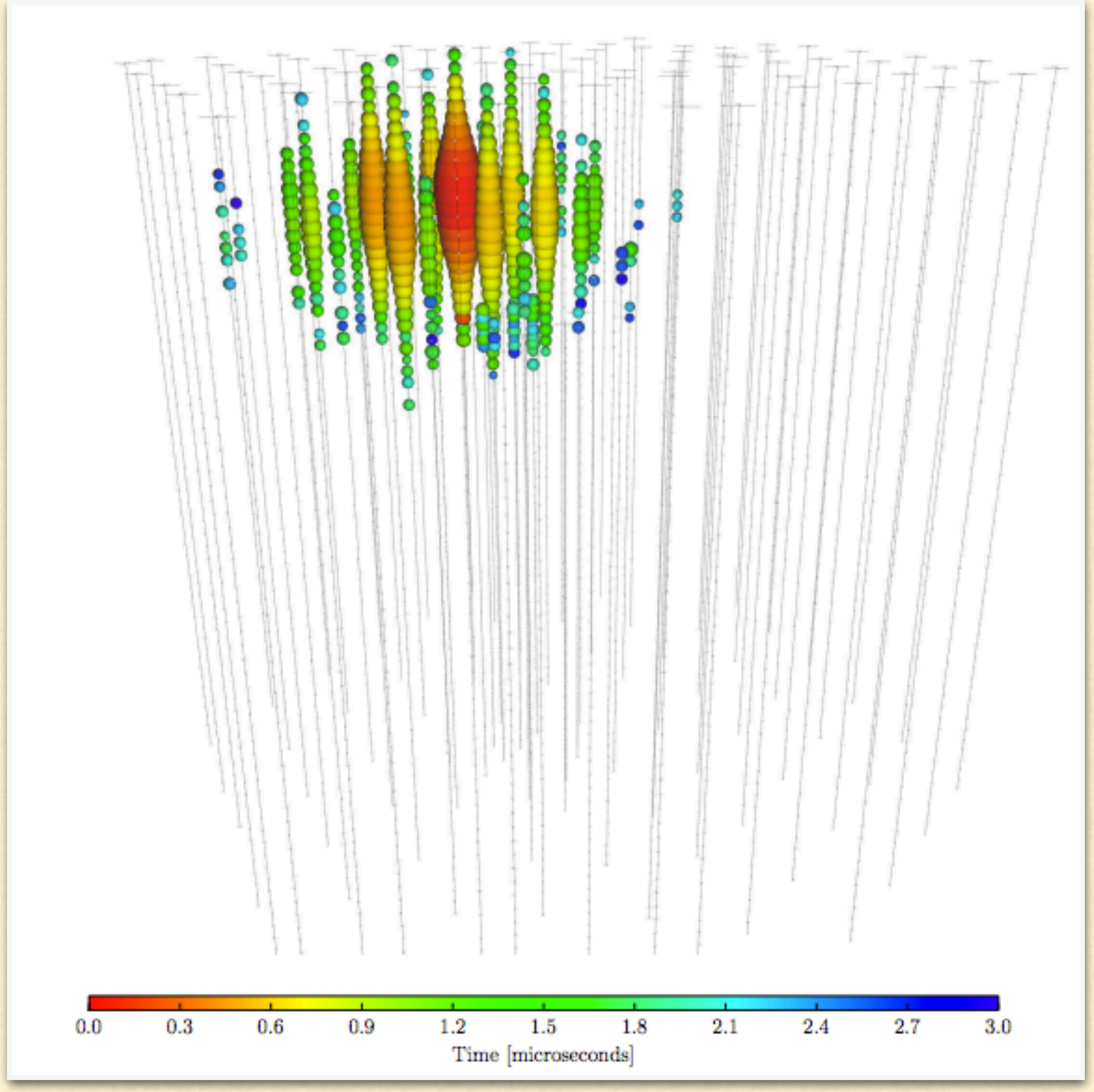


- The IceCube (IC) neutrino observatory is located at the Antarctic pole and has been at full operating capacity since 2011.
- Neutrinos produce charged particles when they interact with ice molecules. The Cherenkov radiation from these particles are observed by the DOMs.
- They are sensitive to two types of signal:
    - Charged current (CC) muon interactions are seen as track-like events
    - CC electron and tau interactions and all neutral current (NC) interactions are seen as cascades

Event 18:
Track event with 31 TeV of energy deposited in the detector



Event 35: "Big Bird"
Cascade event with 2 PeV of energy deposited in the detector

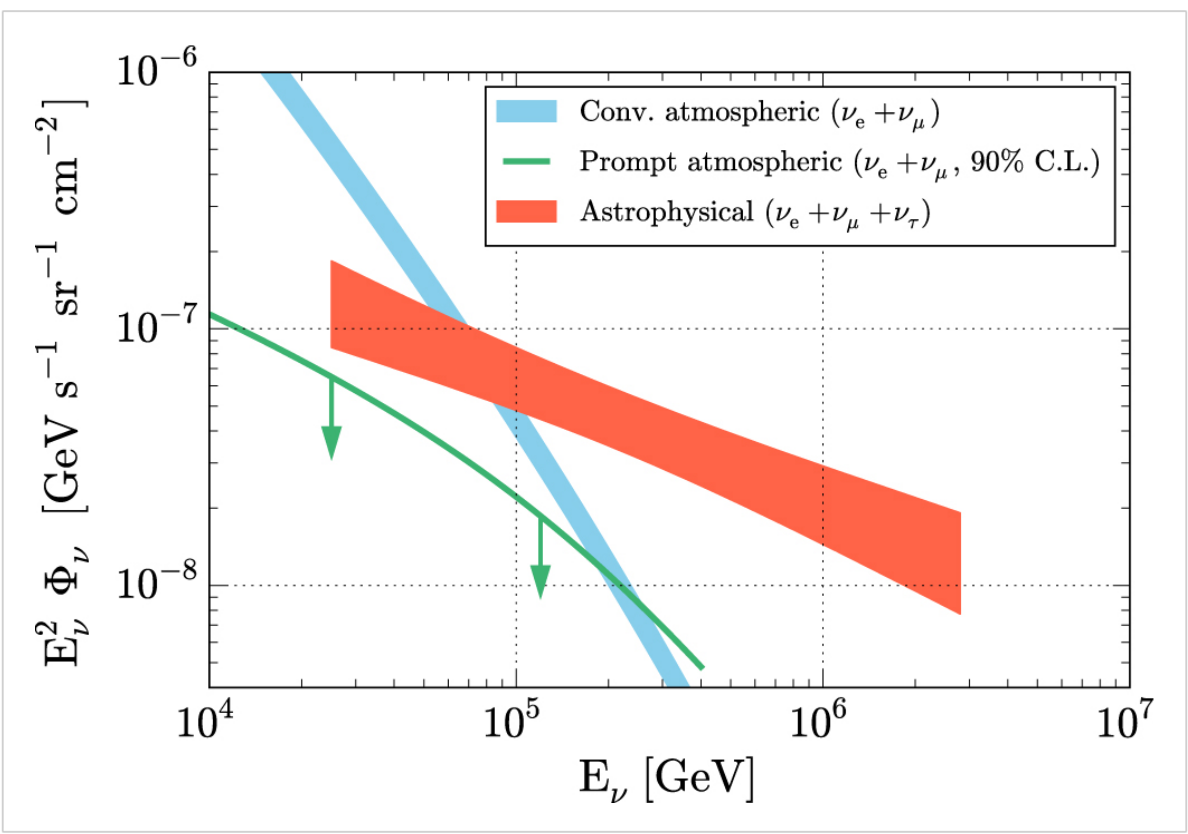


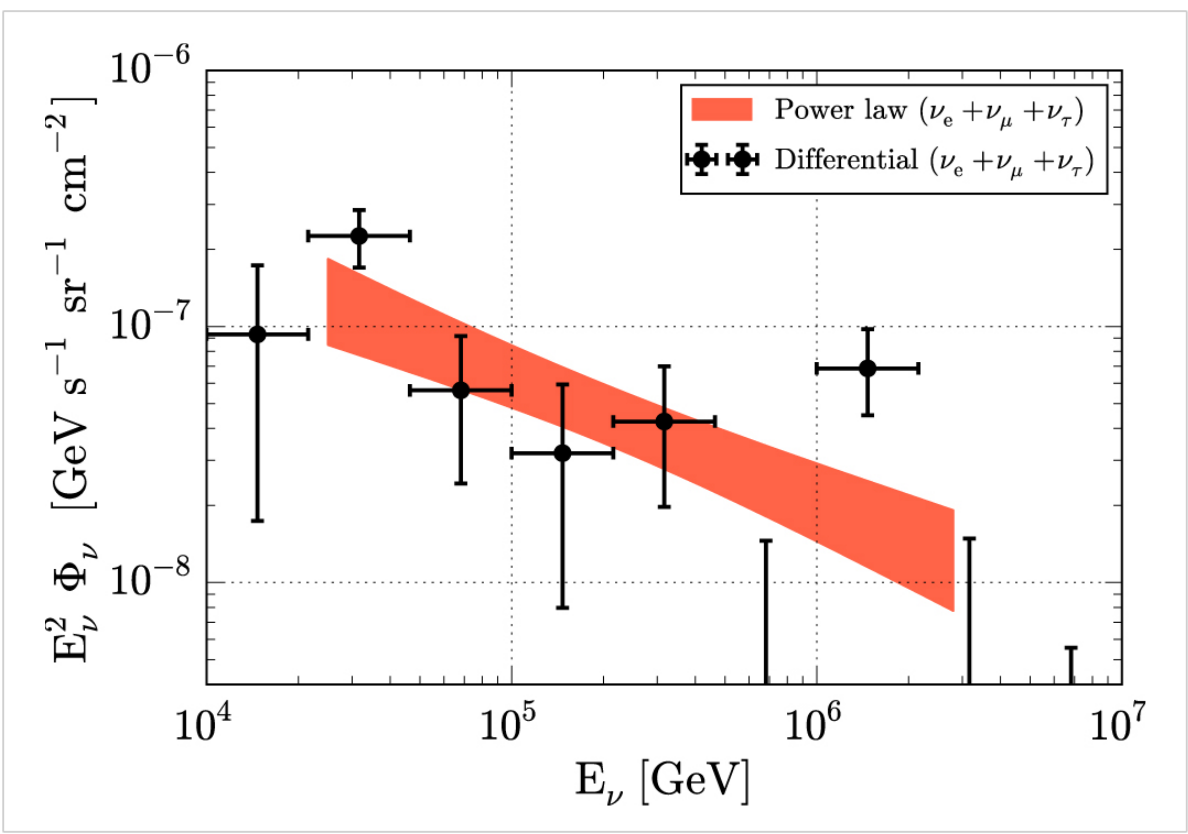
IceCube Collaboration. "Evidence for high-energy extraterrestrial neutrinos at the IceCube detector." Science 342.6161 (2013): 1242856.

Aartsen, M. G., et al. "Observation of high-energy astrophysical neutrinos in three years of IceCube data." Physical review letters 113.10 (2014): 101101.

- Since the first PeV cascade event was discovered in 2012, there is now strong evidence for a diffuse, astrophysical flux of neutrinos with energies between 25 TeV and 2.8 PeV.

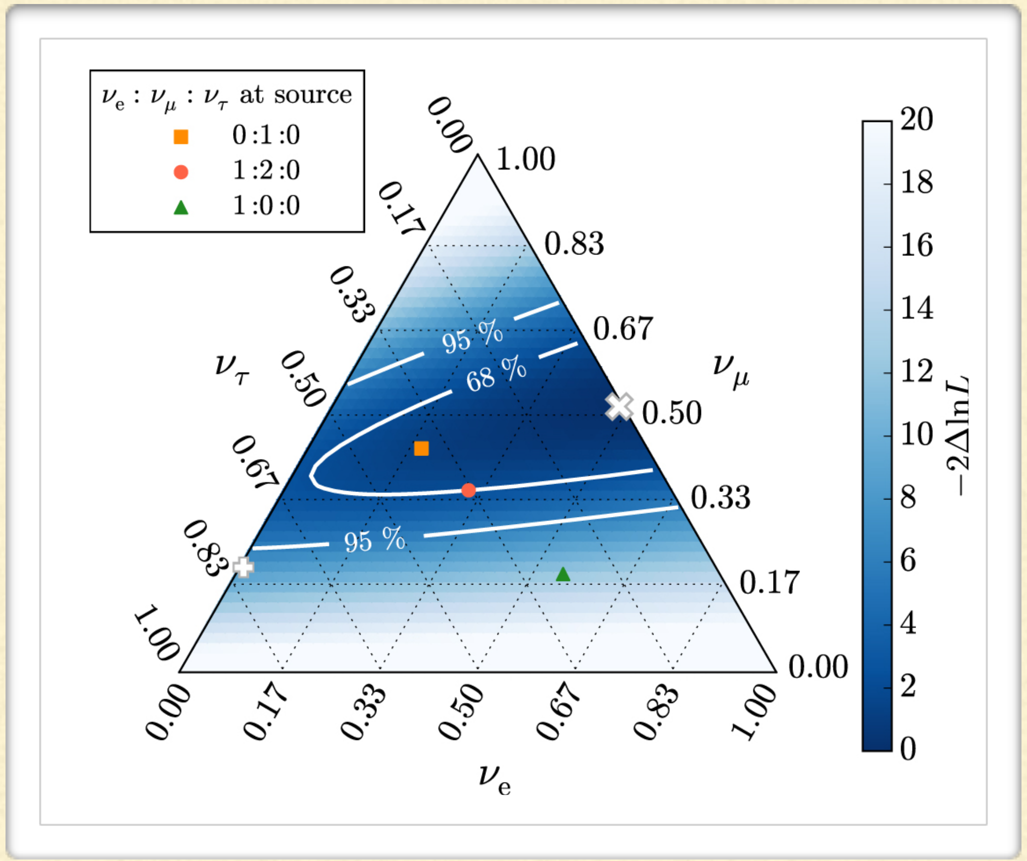
- The measured flux is well fit (at the 3.8σ level) by an soft, unbroken power-law with index -2.50 ± 0.09 and an all-flavor flux of ~ 7 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV is consistent with the prediction of Waxman and Bahcall

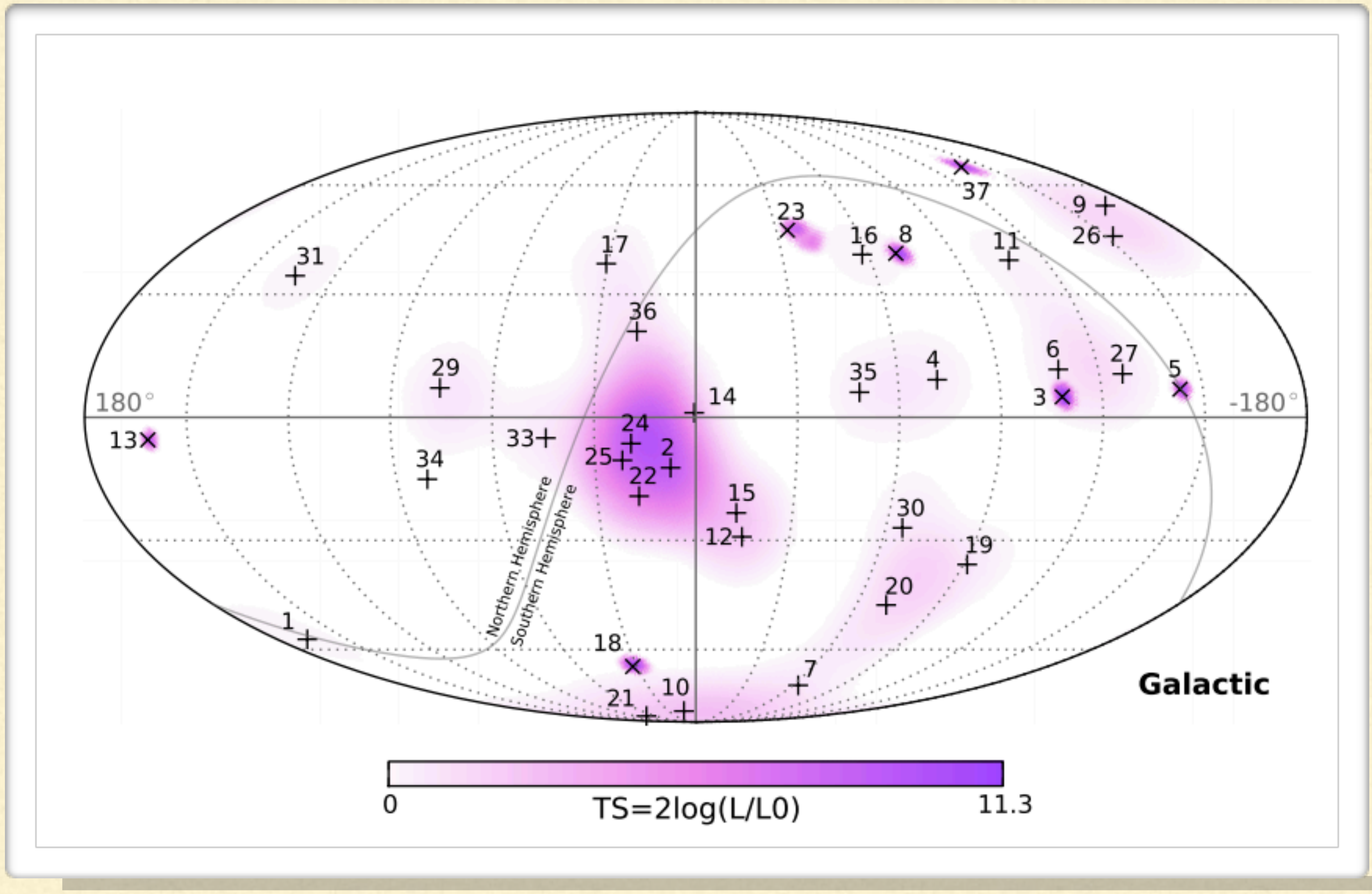




- There is increasing evidence for an extra-galactic origin for the observed neutrinos

- The measured flavor ratio (ν_e:ν_μ:ν_τ) is consistent with oscillation over cosmological distances (>100 Mpc)





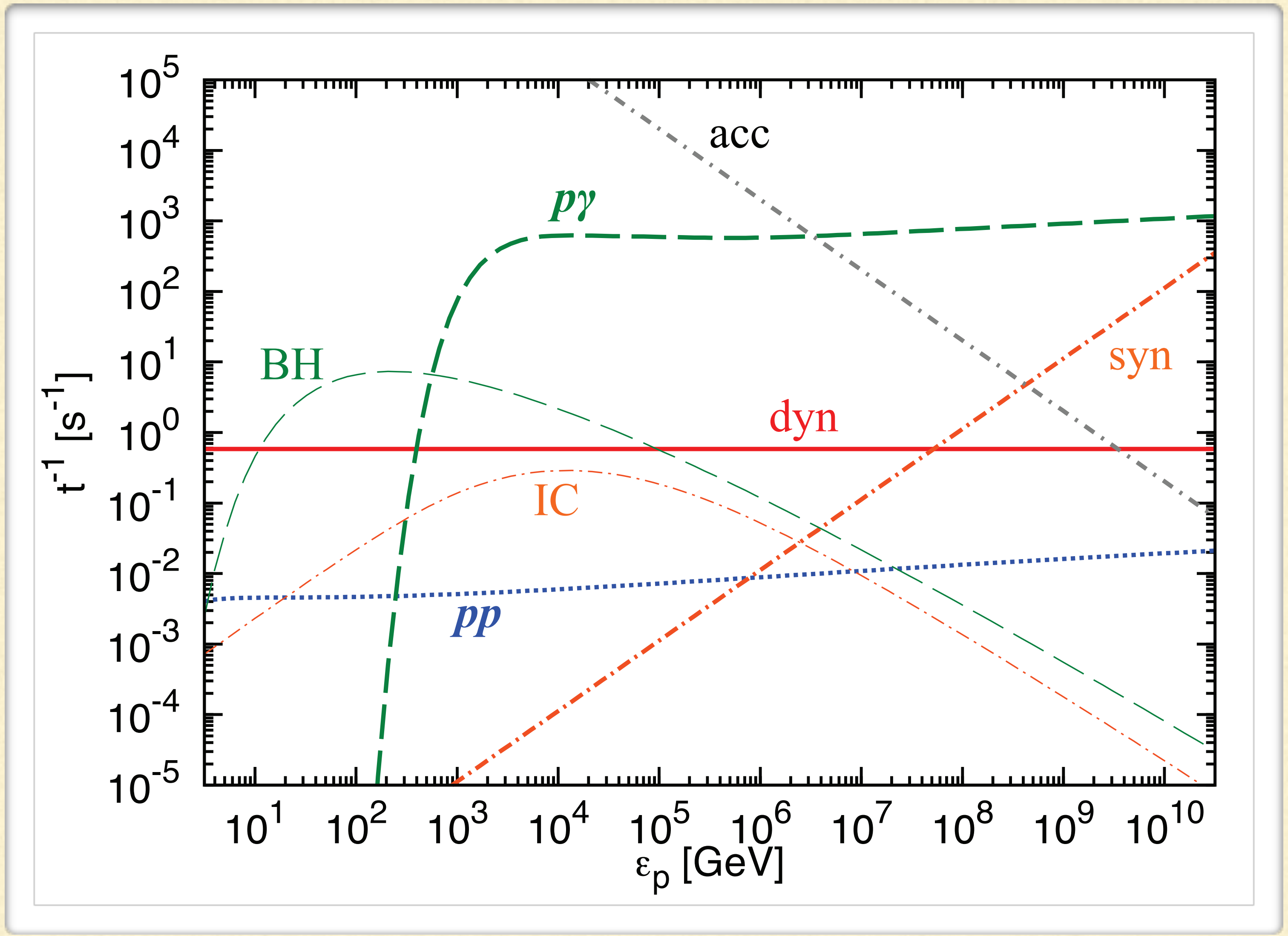
- The neutrino arrival directions are consistent with isotropically distributed sources

COSMIC-RAY ACCELERATION AND NEUTRINO PRODUCTION

- It is expected that the majority of astrophysical neutrinos are produced by CR interactions with ambient light or matter (pγ or pp interactions respectively)
- These processes produce VHE neutrinos and γ-rays with ~0.05% and ~0.1% of the initial CR energy respectfully. Note that CRs with energy ~50-100 PeV are needed to produce neutrinos of energy 25 TeV - 5 PeV
- To find the maximum CR energy achievable in our source models we compare the acceleration time with the various cooling timescales

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + \ldots$$

- The relevant cooling mechanisms are calculated numerically solving the CR kinetic equations.
- The plasma properties (e.g. the turbulent magnetic field strength and ambient photon density) are relevant for this calculation



For simplicity we assume:

$$t_{acc} \sim \frac{\varepsilon'_p}{eB'c}$$

$$\dot{n}_\pi(\varepsilon_\pi) = \int d\varepsilon_{cr}\; n_{cr}(\varepsilon_{cr}) t^{-1}_{pp/p\gamma}(\varepsilon_{cr}) \frac{dN^{p\gamma}_{p\to\pi}}{d\varepsilon_\pi}(\varepsilon_{cr}, \varepsilon_\pi)$$

$$t^{-1}_{p\gamma}(\varepsilon_{cr}) = \frac{1}{2}\frac{m_p^2}{\varepsilon_{cr}^2}\int_{\frac{\epsilon_{th} m_p}{2\varepsilon_{cr}}}^{\infty} dE\; \frac{n_\gamma(E)}{E^2}\int_{\epsilon_{th}}^{2E\varepsilon_{cr}/m_p} d\epsilon_r \epsilon_r \sigma^{p\gamma}(\epsilon_r)$$

$$t^{-1}_{pp} \simeq n_p \sigma_{pp}(\varepsilon_{cr}) c$$

- Note that neutrinos produced by pp interactions have the same spectral shape as the parent CRs if other cooling mechanisms are not important
- The spectral shape of neutrinos produced by pγ interactions is a convolution of the seed photon and parent CRs spectrum
- This difference is significant for multimessenger studies, especially for energies $\lesssim$ 10TeV

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$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + ...$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \ , \\ & \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\begin{aligned} \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \ , \\ & \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{aligned}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

- Both ν_e and ν_μ are produced by charged pion decay, assuming the resulting muons do not cool significantly before decaying

- Additionally, γ-ray photons are produced by neutral pion decay. Secondary leptonic pairs produced by muon decay may also up scatter ambient photons to GeV-TeV energies as well

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$$K^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$n \rightarrow p + e^{-} + \bar{\nu}_{e}$$

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HYPERNOVAE AND STARBURSTS AS SOURCES OF VHE NEUTRINOS

- Hypernovae (HNe) are a class of Type Ibc core collapse supernovae (ccSNe) which release up to 10x more energy in their ejecta $\sim 10^{52}$ ergs
- An unusually high fraction of the HNe energy is typically found in trans-relativistic ejecta, in conflict with the current understanding of the hydrodynamics of SN explosions. Stalled jets have been suggested as a mechanism to accelerate the ejecta.
- SNe are presumed to be CR accelerators up to ~ PeV energies. HNe should have similar acceleration mechanisms, but with higher velocity ejecta capable of produceing 100 PeV protons.
- Observations suggest that up to 10% of the ejecta energy may go to CR acceleration

$$D \sim D_* \left[(\varepsilon_{cr}/\varepsilon_*)^\alpha + (\varepsilon_{cr}/\varepsilon_*)^2 \right]$$

$$D_{*,sbg} \sim 1.4 \times 10^{29} \;\; l_{g,20} \text{ cm}^2 \text{ s}^{-1}$$

$$\alpha \sim 1/2$$

The Antennae Galaxies
Credit: NASA/ESA

- Starburst galaxies (SBGs) are defined as having unusually high star formation activity and a significant amount of free gas.
- Some typical values:

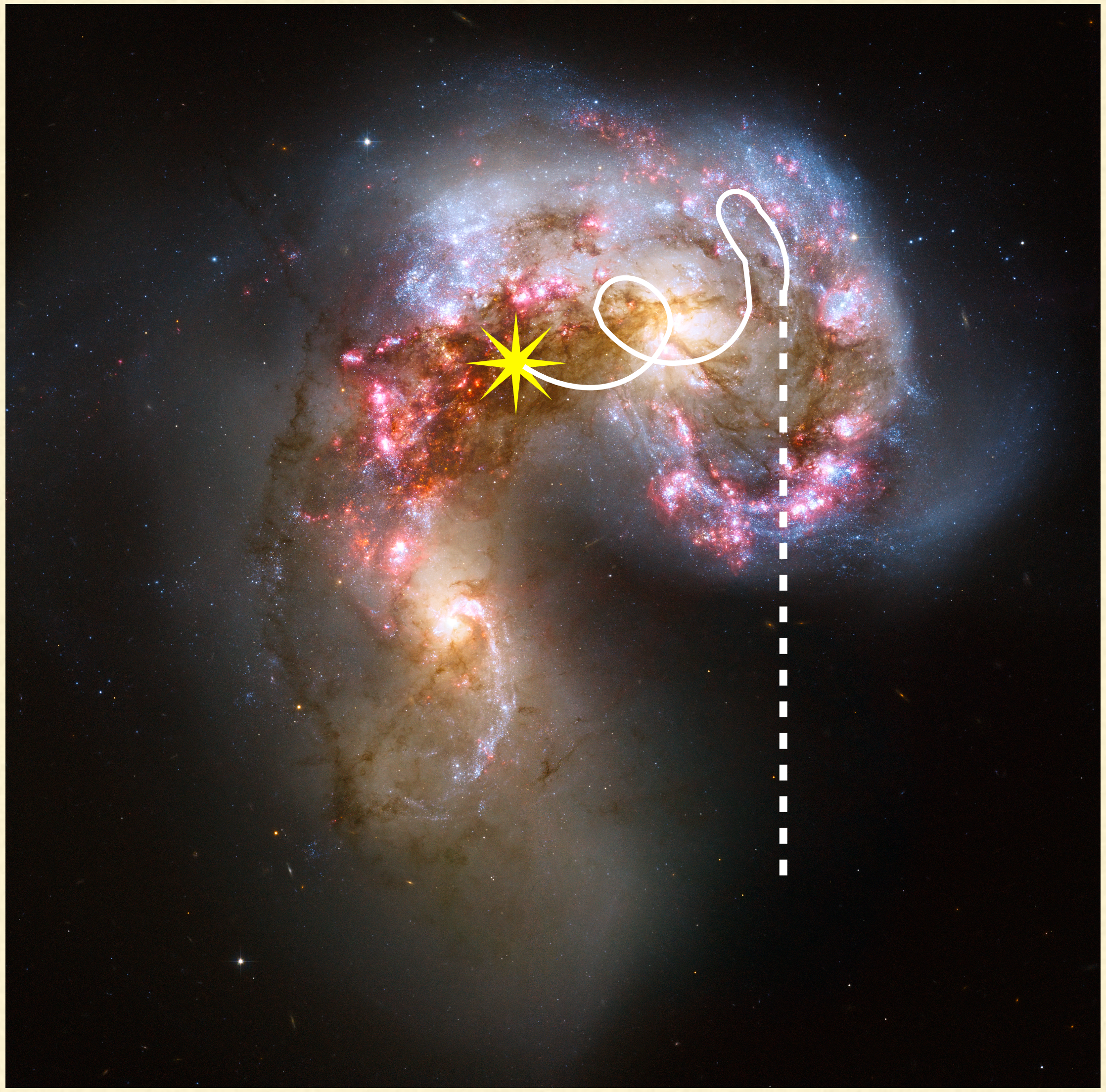
$$n_p \sim 10 - 100 \text{ cm}^{-3} \qquad B_g \sim 200 \ \mu\text{G}$$

$$H_{sbg} \sim 30 - 300 \text{ pc} \qquad l_{c,g} \sim 10 \text{ pc}$$

- Can be triggered by the collision or interaction of two galaxies
- Compare with typical star forming galaxy

$$n_p \sim 1 \text{ cm}^{-3} \qquad B_g \sim 6 \ \mu\text{G}$$

$$H_{sbg} \sim 1000 \text{ pc}$$



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$$D_{*,sbg} \sim 1.4 \times 10^{29}\ l_{g,20} \text{ cm}^2 \text{ s}^{-1}$$

$$\alpha \sim 1/2$$

Comparing the pp timescale $t_{pp} \sim (n_p \sigma_{pp} c)^{-1}$ with the escape time due to magnetic diffusion $t_{esc,diff} \sim H_g/6D_g$ gives an estimate as to the fraction of CRs which produce neutrinos and γ-rays before escaping the SBGs.

Then pp optical depth is given by:

$$\tau_{pp,g} \sim 4.9 \times 10^{-3}\, n_{g,2.3} H_{g,21}^2 \ell_{g,20} B_{g,-3.7}^2 \varepsilon_{cr,19}^{-2} \quad : \quad \varepsilon_{cr} > \varepsilon_{cr,*}$$

$$\tau_{pp,g} \sim 0.55 \quad n_{g,2.3} H_{g,21}^2 \ell_{g,20} B_{g,-3.7}^2 \varepsilon_{cr,17.2}^{-1/3} \quad : \quad \varepsilon_{cr} < \varepsilon_{cr,*}$$

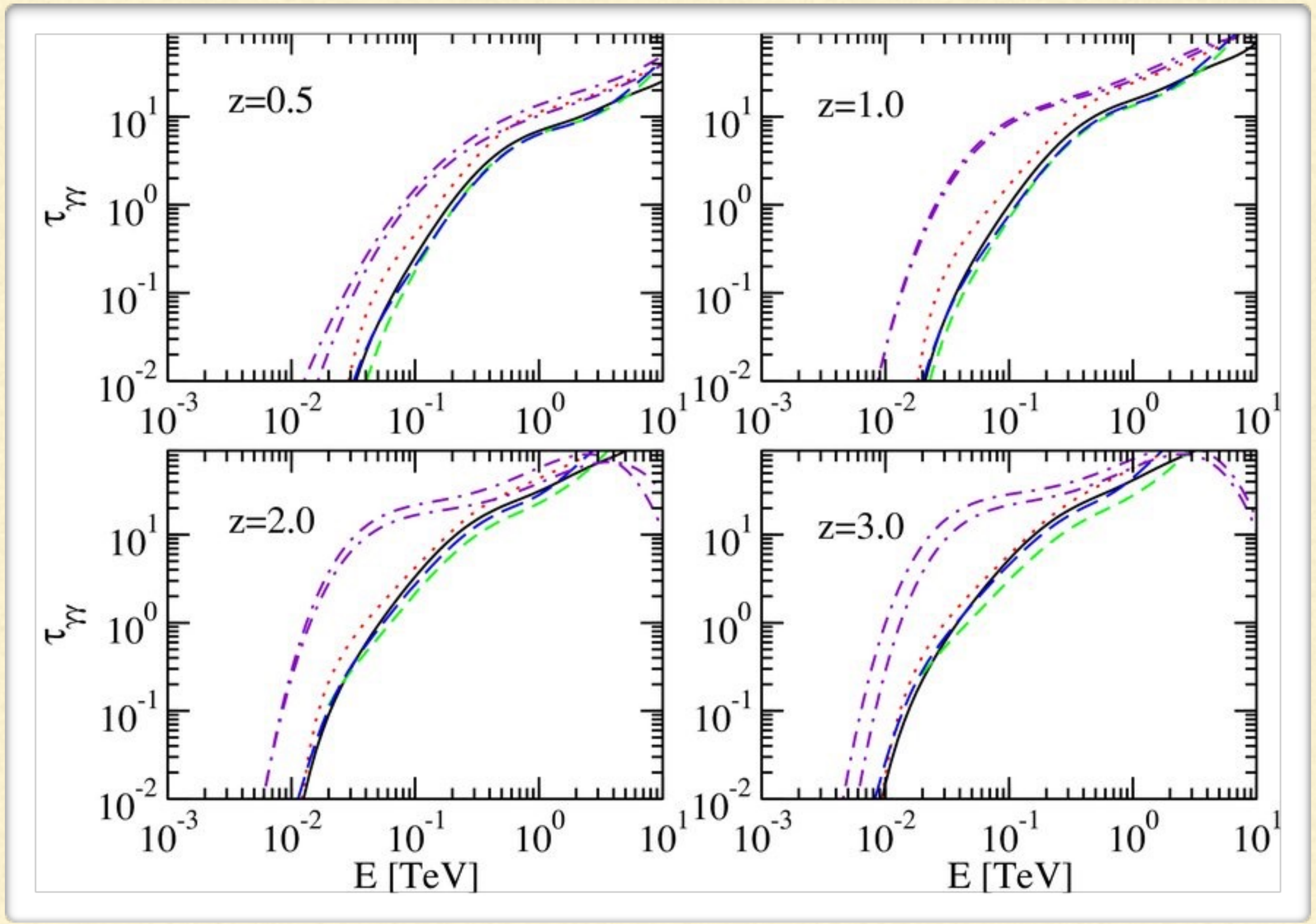
Analytic calculations confirm that SBGs can be efficient neutrino producers

NS et al. 2015

VHE γ-rays are expected to accompany neutrinos. Using the ratio of charged to neutral pions the fluxes are related via:

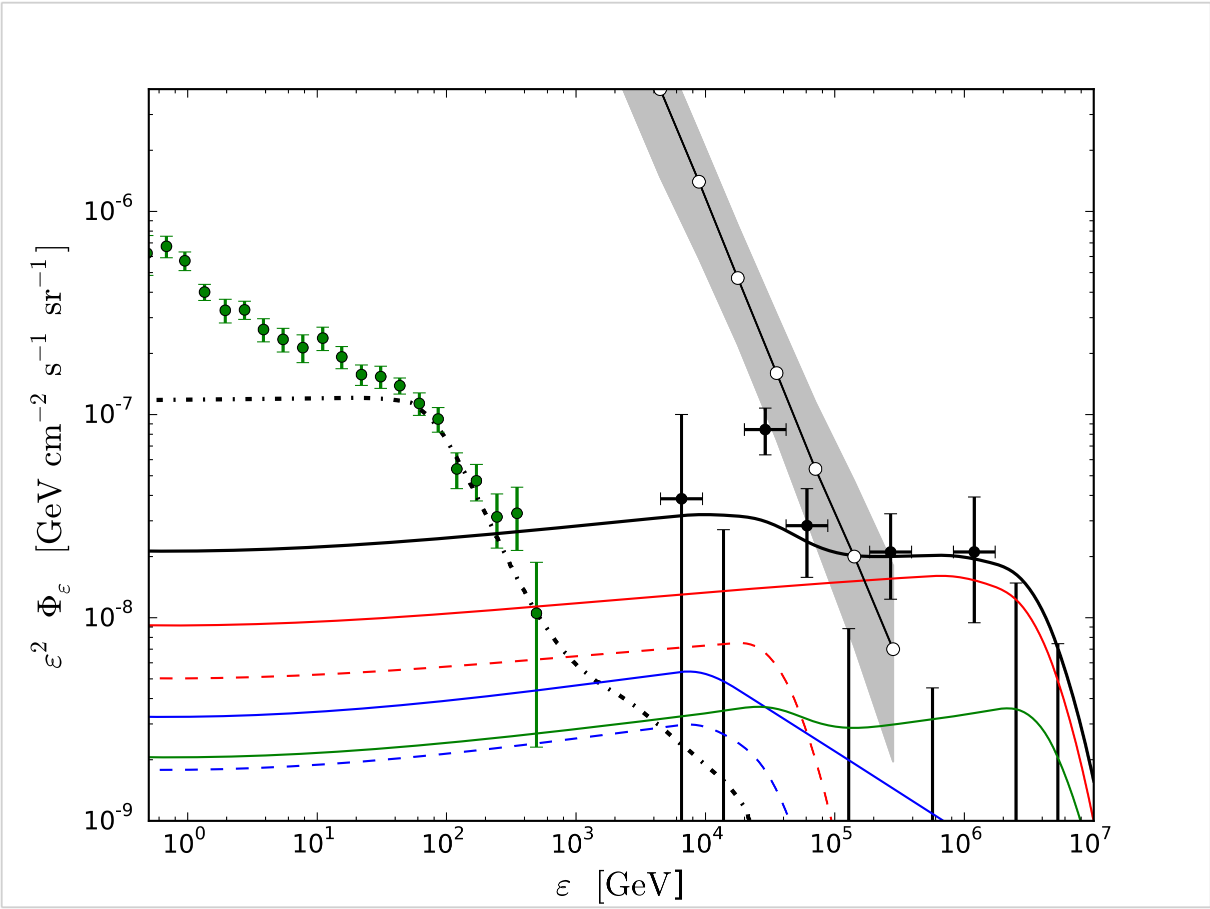
$$\epsilon_\gamma^2 \Phi_\epsilon \simeq 2^{s-1} \varepsilon_\nu \Phi_\varepsilon \Big|_{\varepsilon_\nu = 0.5\epsilon_\gamma}$$

- γ-rays are attenuated by extra-galactic background light (EBL) inducing a cascade.
- The resulting spectrum is universal for large distances.



Finke et al. 2010

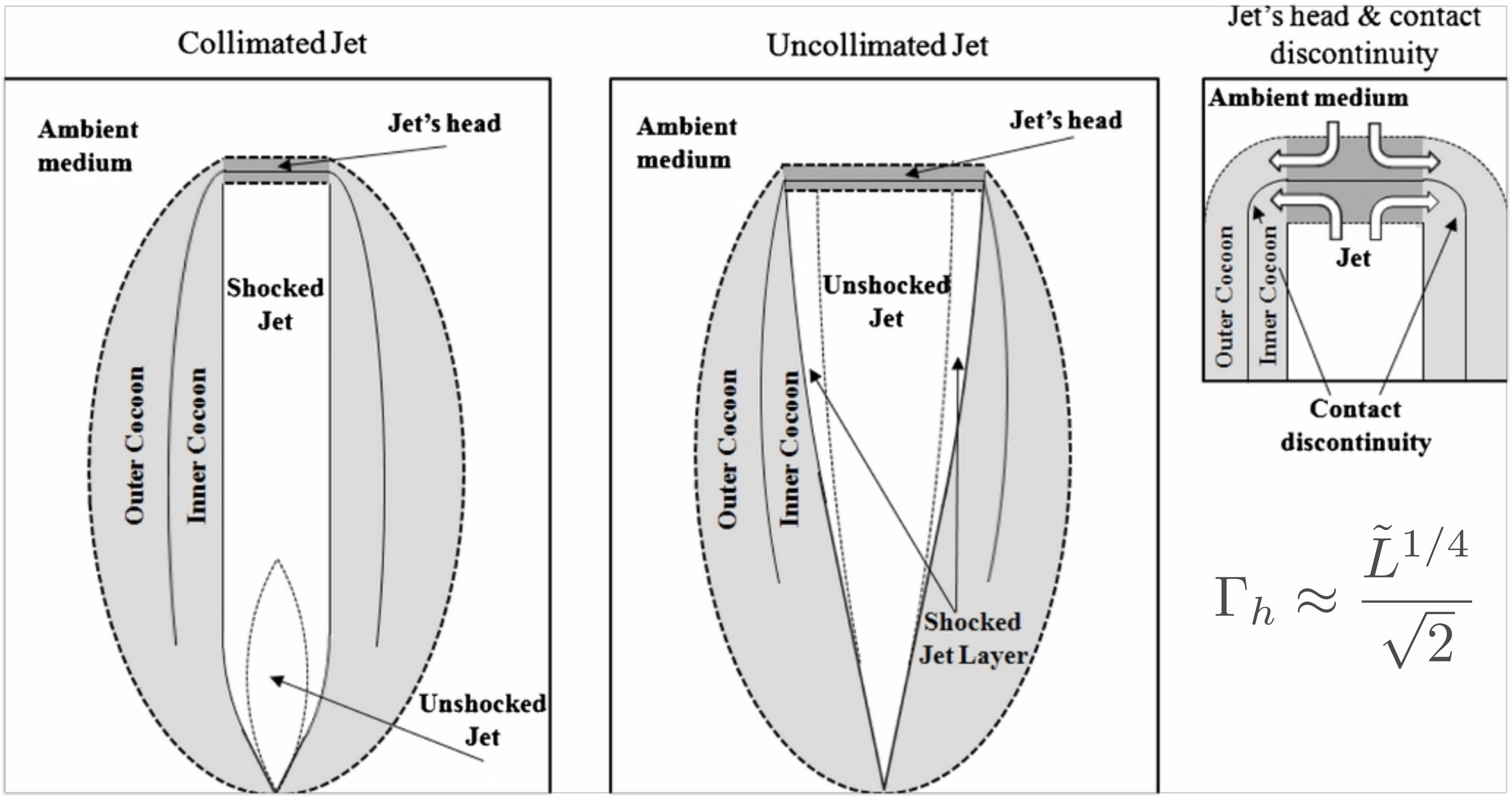
- The associated γ-ray spectrum can also be compared with observations of the extra-galactic diffuse γ-ray background (EGB)
- Multi-messenger studies of potential neutrino sources are incredibly valuable for their additional constraints



- Comparison of the neutrino and γ-ray flux using measurements of the EGB from 2014. At the time ~50% of the measured flux was unattributed to any sources

- It is important to understand the dynamics of the jet in the circumstellar envelope.

$$\tilde{L} \simeq \frac{L}{\pi(\theta_j r_j)^2 \rho_a c^3}$$



$$\Gamma_h \approx \frac{\tilde{L}^{1/4}}{\sqrt{2}}$$

$$\tilde{L} \ll \theta_j^{-4/3} \qquad \tilde{L} \gg \theta_j^{-4/3}$$

Bromberg et al. 2011

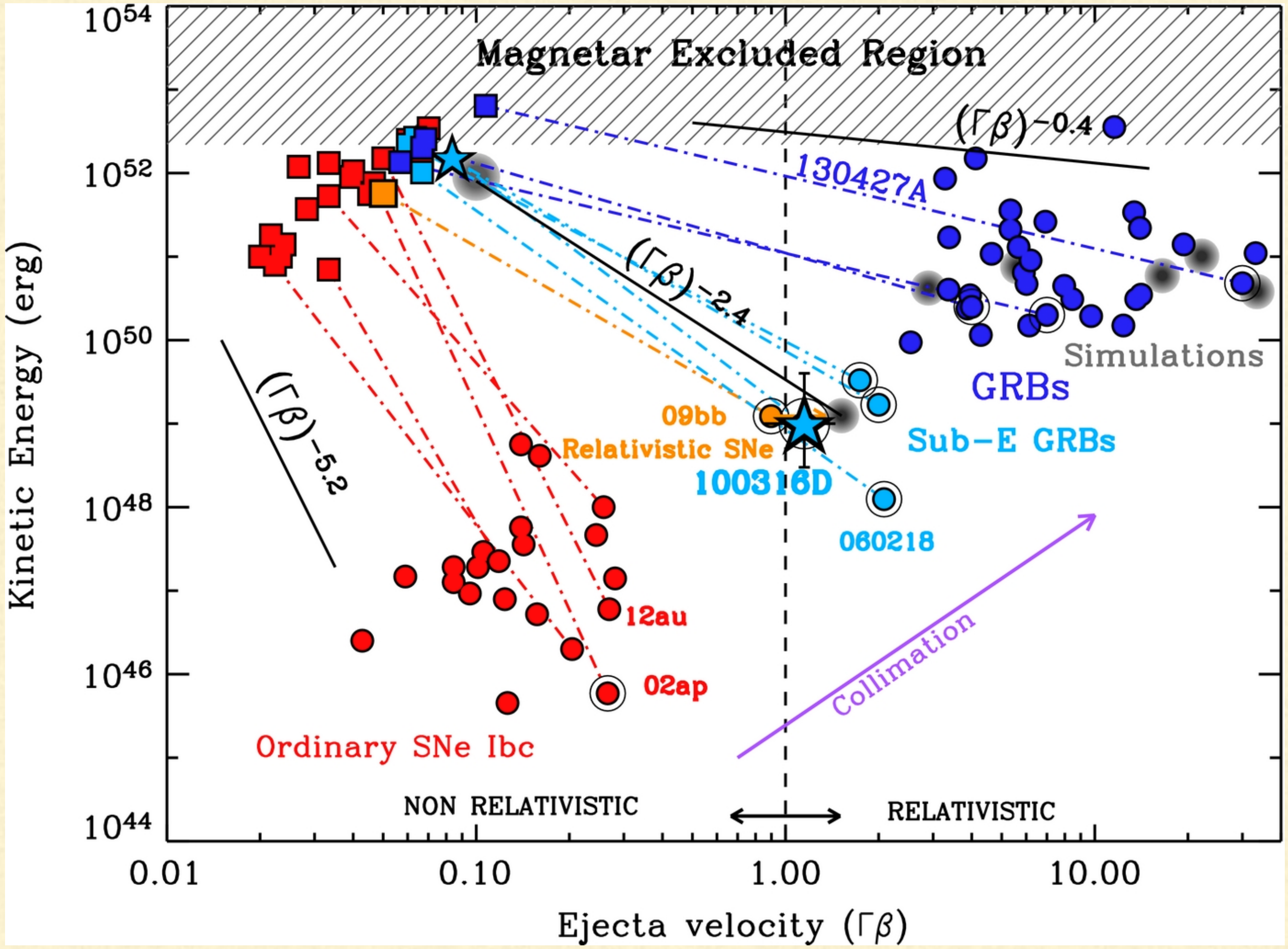
- While the environment around a collapsar is very uncertain, Nakar used a circumstellar envelope of a WR star to explain LL GRB 060218
  - $M_{env} \sim 0.01\ M_\odot$
  - $R_{env} \sim 3 \times 10^{13}$ cm
  - Assume a wind profile of $\rho \propto r^{-2}$ ⟶ $\rho_{env}\ 5\times10^{-11}$ g cm^{-3}
- If we assume that the central engine is active for t_{eng} = 30 s the radius at which the jet stalls in the envelope is

$$r_h \approx 2\Gamma_h^2 ct \simeq 2.3 \times 10^{13}\ \mathrm{cm}\ L_{0,52}^{1/2} \rho_{env,-10.3} r_{env,13.5}^{-1} t_{eng,1.5}$$

- Long GRBs (with prompt emission lasting ≳2s) are also associated with Type Ibc SNe.

- The latter are known to be formed from the collapse of massive stars, specifically Wolf-Rayet (WR) or other CNO stars.

- We attempt to explain the GRB/SNe connection by postulating that both arise from the same progenitor, with the observed characteristics determined by the circumstellar environment.



Margutti et al. ApJ 778, 18 (2013)

- Using the observed properties of LL GRBs, we can require the jet to stall in the envelope giving an upper limit on the observed luminosity
- Assume the observed luminosity is: $L_\gamma \approx \bar{\epsilon}_\gamma \frac{\theta_j^2}{2} \frac{L\, t_{eng}}{T_{dur}}$
- The jet stalling condition gives:

$$L_\gamma \lesssim L_\gamma^{\rm JS} \approx 0.95 \times 10^{48}\ {\rm erg\ s^{-1}} \left(\frac{\bar{\epsilon}_\gamma}{0.25}\right) \left(\frac{\theta_j}{0.2}\right)^2 t_{\rm eng,1.5}^{-1} T_{3.5}^{-1} \rho_{\rm env} r_{\rm env,13.5}^4,$$

in agreement with the maximum

observed luminosity for a LL GRB

- Only collisionless shocks (shocks that are mediated by magneto-hydrodynamic instabilities) are capable of efficiently accelerating CRs.

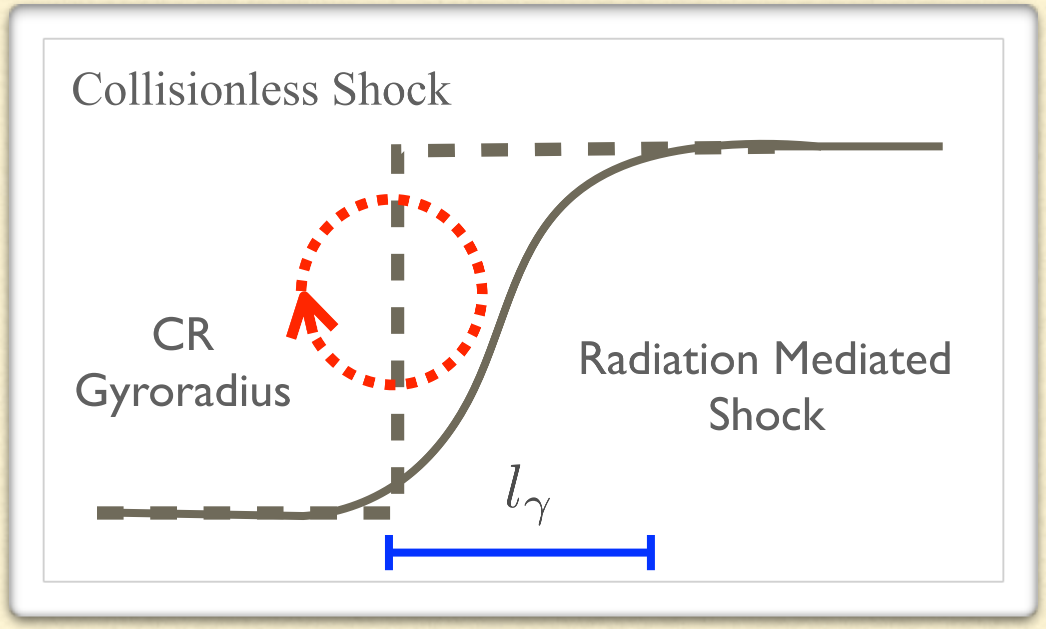
- Because of the high photon density in the jet, the internal and termination shocks may be **mediated by Thomson scattering.**

- In this case the photon deceleration length is longer than the Larmor radii of VHE CRs, and they do not experience the strong compression of the shock.

- For efficient CR acceleration we require

$$\tau_T \simeq n'_\gamma \sigma_T (r_{sh}/\Gamma) \lesssim \min[\Gamma_{rel}^2, 0.1\mathcal{C}^{-1}\Gamma_{rel}^2]$$

$$\mathcal{C} = 1 + 2\ln\Gamma_{\rm rel}^2$$



- The limit set by radiation constraints are very sensitive to both the position at which the shock occurs and the bulk Lorentz factor the of the jet.

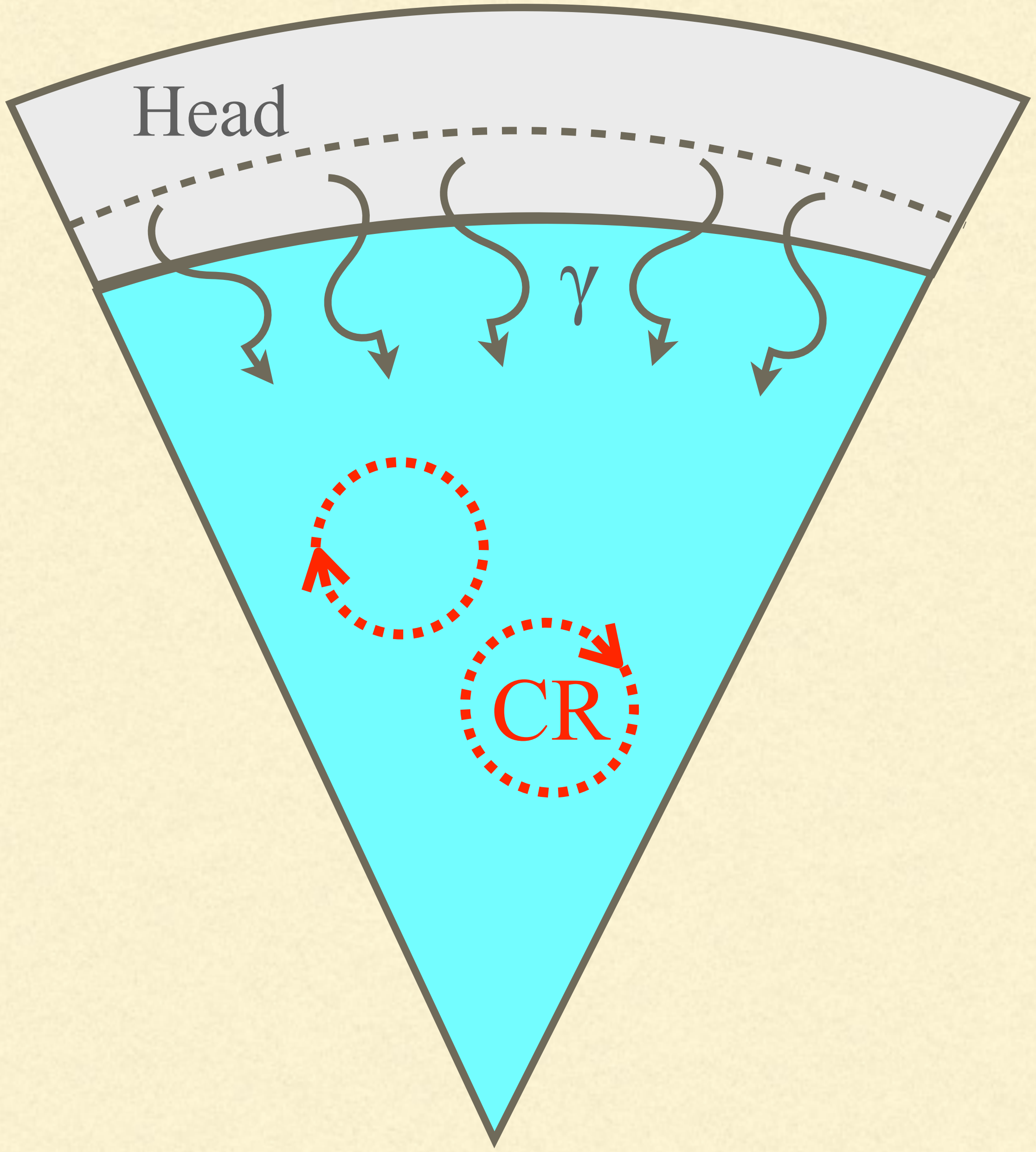
$$L_\gamma \lesssim L_\gamma^{\rm RC} \approx 8.6 \times 10^{49}\ {\rm erg\ s^{-1}}\ \left(\frac{\bar{\epsilon}_\gamma}{0.25}\right)\left(\frac{\theta_j}{0.2}\right)^2 \Gamma_2^6 t_{{\rm eng},1.5}^3 T_{3.5}^{-1} \rho_{\rm ext}^{-1} r_{{\rm ext},13.5}^{-2}$$

- This feature has often been **neglected** in the literature regarding neutrinos from GRBs.

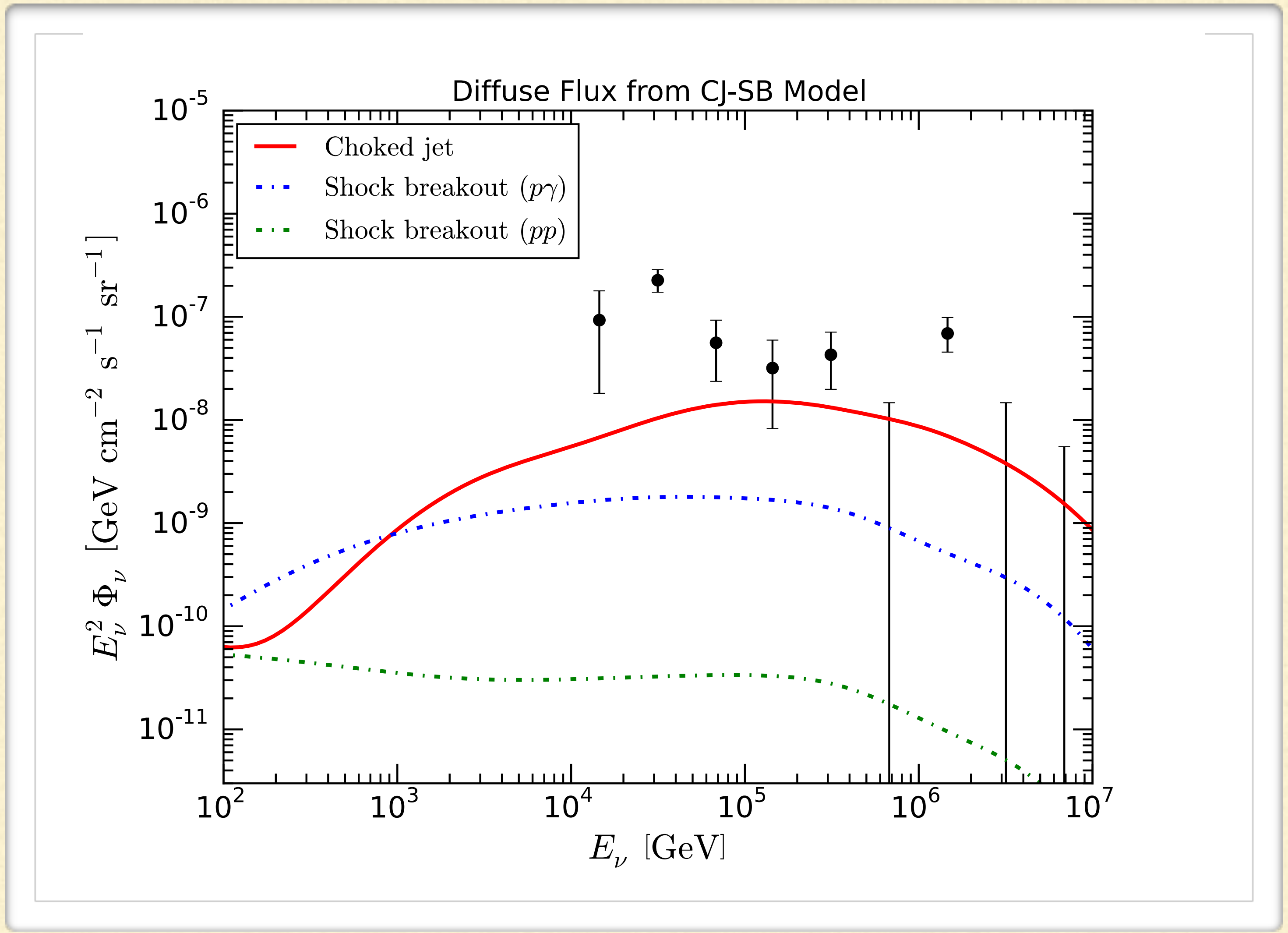
- Note that shocks which occur at smaller radii (i.e. in the CJ scenario) are more favorable as high-luminosity CR accelerators.

- Neutrino observations may open a window into to the potentially rich structure of buried jets.

Neutrinos from pγ interactions



- By assumption, the gas surrounding the jet body is optically thick
- Therefore, the seed photons must come from the jet itself, or from the layer of last scattering surrounding it
- The black-body radiation from the jet head forms the dominate photon field, if non-thermal emission is neglected
- Both the temperature in the head and the photon density are Lorentz boosted in the co-moving frame of the jet



- To calculate the diffuse flux, we determine the contribution from CJ-SBs with 10^{45} erg s^{-1} $\lesssim L_\gamma \lesssim 10^{48}$ erg s^{-1}
- The luminosity function is the PL derived by Sun et al. 2015
- The redshift evolution follows the star formation rate

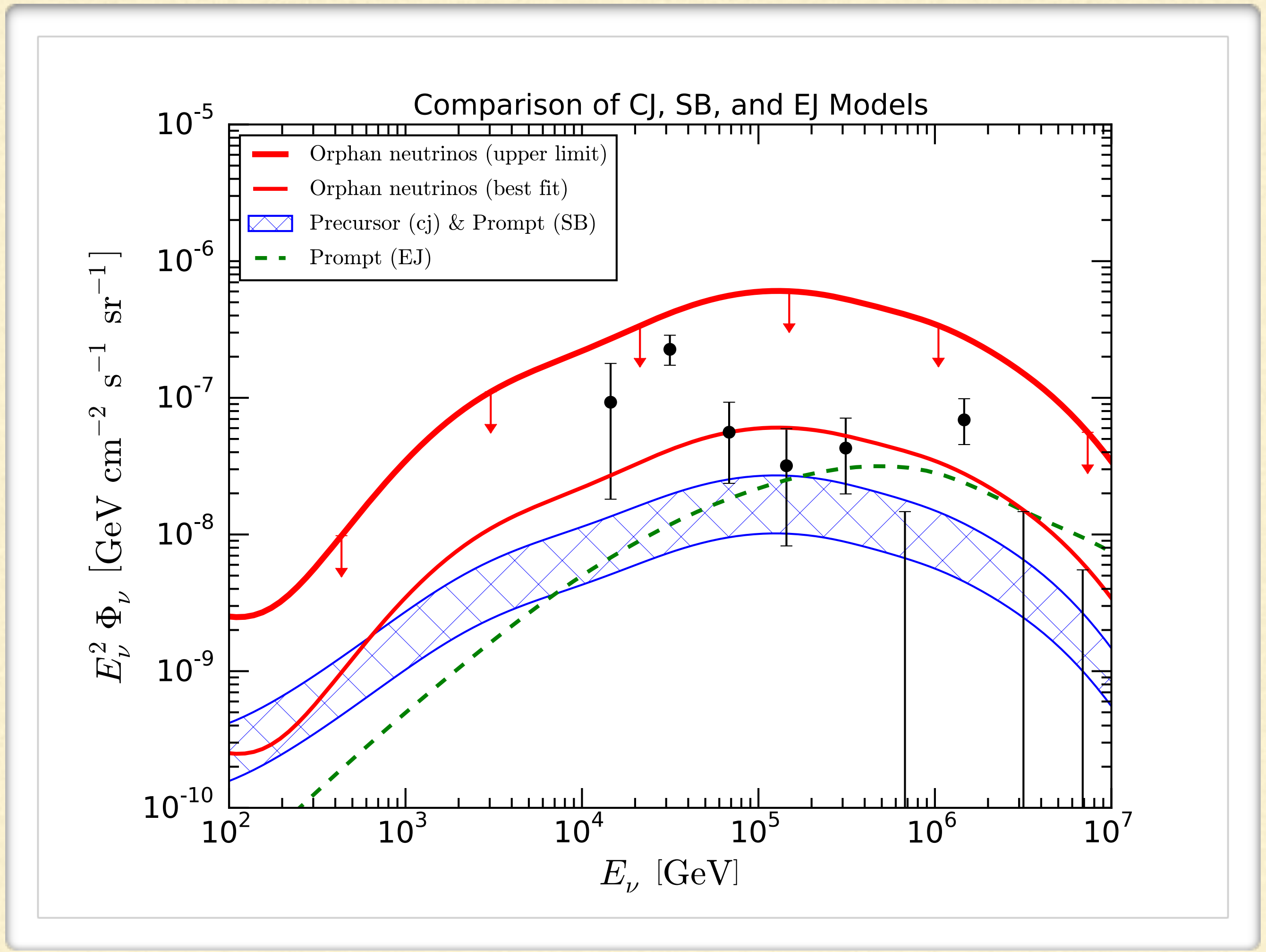
$$\Phi_\nu = \frac{c}{4\pi H_0} \int_{z_{\rm min}}^{z_{\rm max}} dz \int_{L_{\rm min}}^{L_{\rm max}} dL_\gamma \frac{dR_{\rm CJ-SB}(z)/dL_\gamma}{\sqrt{\Omega_M\,(1+z)^3+\Omega_\Lambda}} \left(\frac{dN_\nu((1+z)E_\nu, L_\gamma)}{dE'_\nu}\right)$$

CJ Model

$$E_\nu^2\Phi_\nu \simeq 0.76\times10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}\ \min[1, f_{p\gamma}]\times\left(\frac{\xi_z}{3}\right)\left(\frac{f_{\rm cho}\mathcal{E}_{\rm CR}R_{\rm LL}}{10^{45}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}}\right)\mathcal{R}_{p,1}^{-1}$$

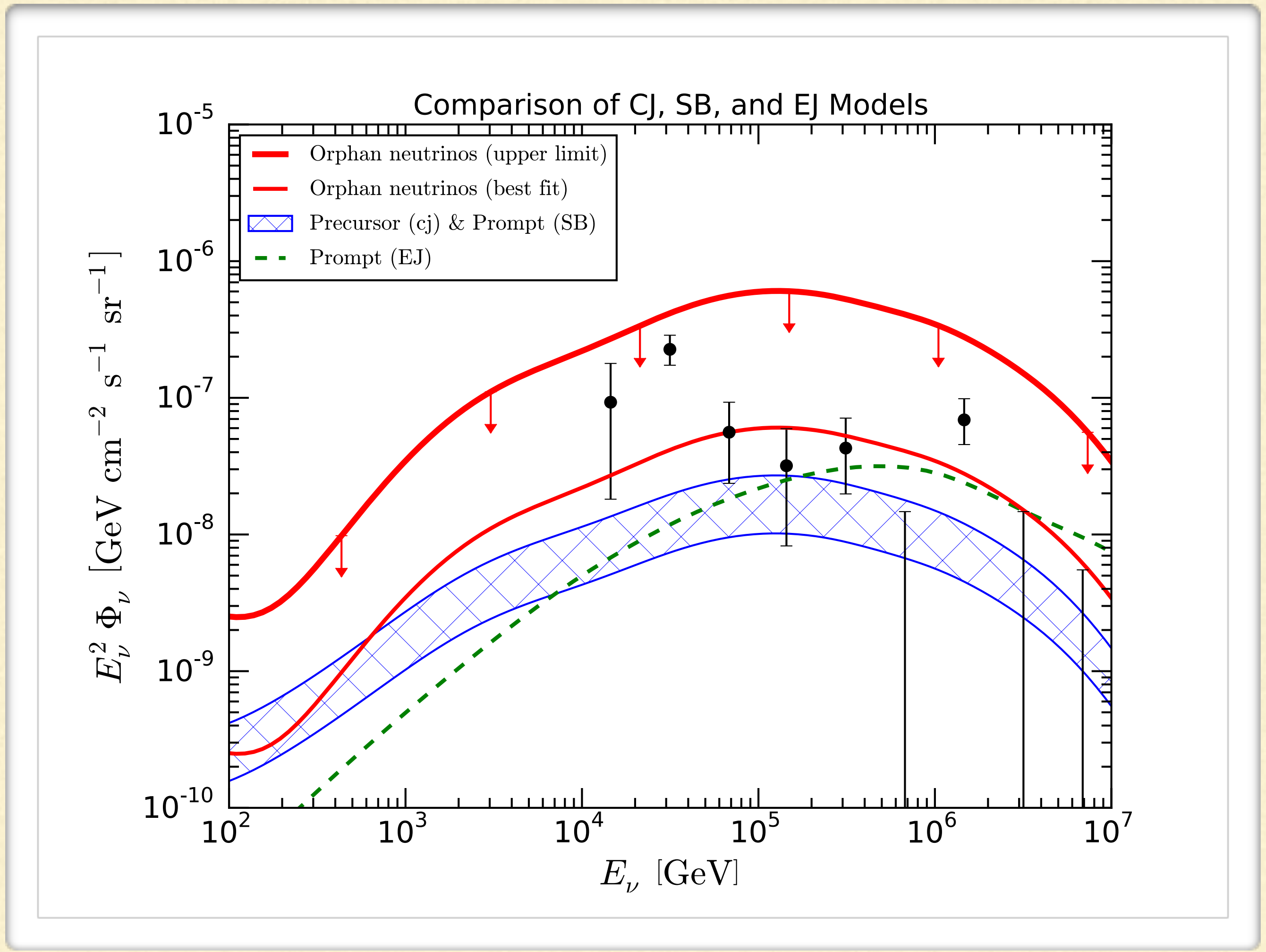
- Orphan neutrinos are expected with no corresponding VHE γ-ray signal
- Because they are not observable, the rate of CJ events is impossible to determine. The rate of HNe could give a reasonable estimate.
- We assume that the CR energy injection rate of CJs does not exceed the observed Galactic rate of

$\dot{\mathcal{E}}_{cr} \sim 10^{45}$ (best fit) – 10^{46} (optimistic) $\mathrm{erg\ Mpc^{-3}\ yr^{-1}}$



EJ Model

- Both neutrinos and γ-rays are expected together as prompt emission
- Only the highest energy neutrinos can be explained
- Because of their higher luminosity, emission radii, and bulk Lorentz factors, EJs are expected to be poor CR accelerators



CONCLUSIONS AND OUTLOOK

- Because the sources are dark, it is imperative that we correctly extrapolate the properties of of HL GRBs to CJs and LL GRBs.
- If CJs/-SBs are in fact the sources of VHE neutrinos, they can probe the hidden jet structure of collapsar jets. Such observations could elucidate the mechanisms of prompt emission from GRBs and the environment surrounding a massive star in the months before its death.
- Detailed modeling of both hydrodynamical and Poynting (magnetically dominated) jets *and their associated emission mechanisms* will be critical towards this end.

CONCLUSIONS AND OUTLOOK

- All sky surveys sensitive to photons with energy $\gtrsim$ 1 keV will help to identify coincidences between VHE neutrinos and Type Ic-bl SNe and LL GRBs.
- Collaborations between electromagnetic, neutrino, and gravitational wave observatories such as the Astrophysical Multimessenger Observatory Network (AMON) at Penn State will improve the usefulness of previously sub-threshold observations.