High energy neutrino & gamma from wind breakout of SN II

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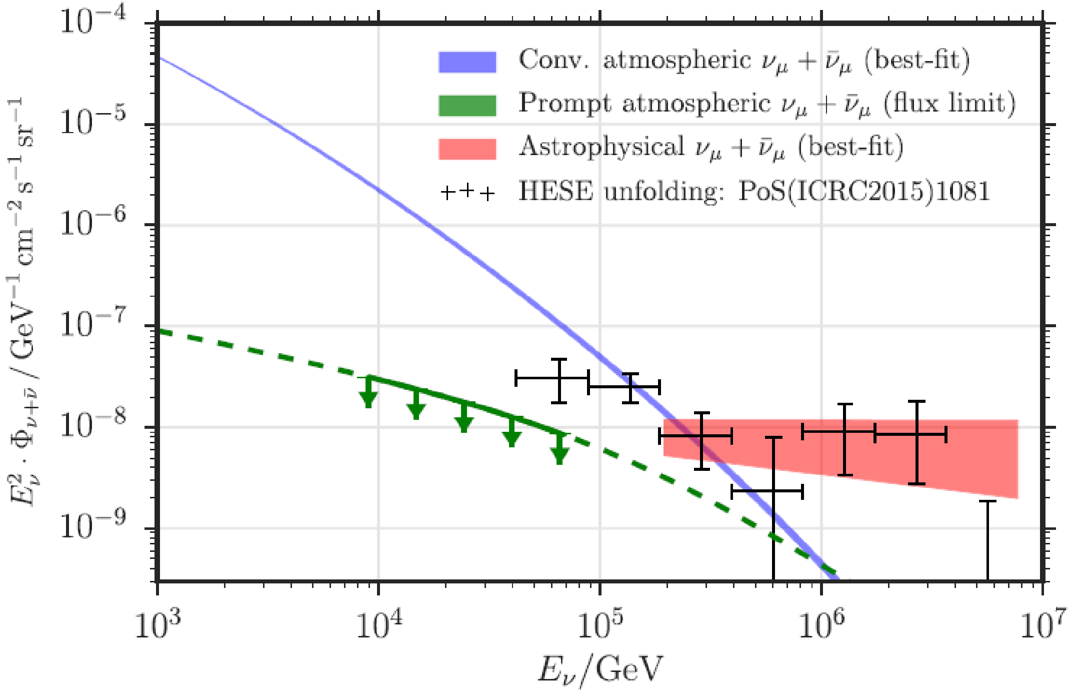
TeV-PeV neutrinos at IceCube

$E^2\Phi$~1e-8 GeV/cm2s sr @100TeV

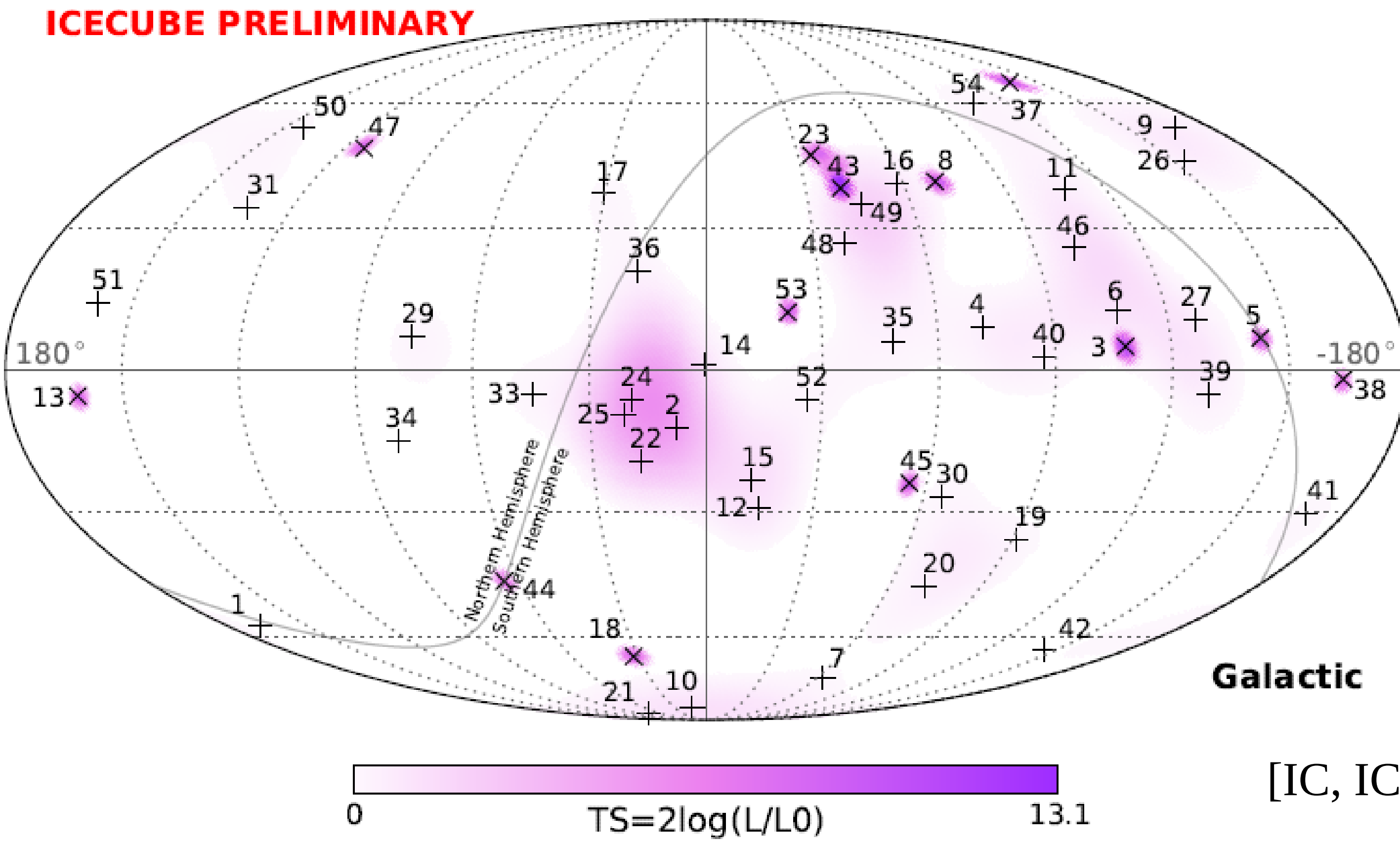
starting evts (southern) consistent w/ upgoing track evts (northern)



Hard spectrum at >200 TeV: s~-2
Cutoff at few PeV

Two spectral components at >50TeV?

Neutrino arrival directions



[IC, ICRC2015]

Starting events, 4yr

no significant spot, no clustering in time
no correlation with GRBs

Bright sources?

- Stacking limit of blazars/GRBs

  &

- Knowledge of blazar/GRB population

- ➔ blazars/GRBs cannot account for diffuse neutrino flux

Blazars

- 33 bright FSRQs, selected based on gamma flux
- FSRQs can only account for <10% IC neutrinos

IC upper limits to individuals

IC detection

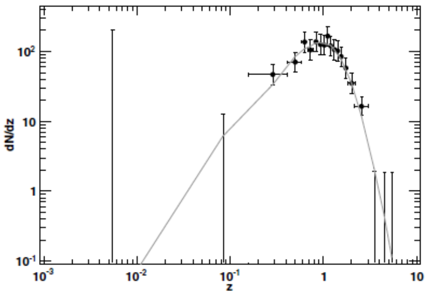
$$\frac{\nu \text{ flux (stacked)}}{\gamma \text{ flux (stacked)}} < \frac{\nu \text{ flux (all - sky)}}{\gamma \text{ flux (all - sky)}} \times 10\%$$

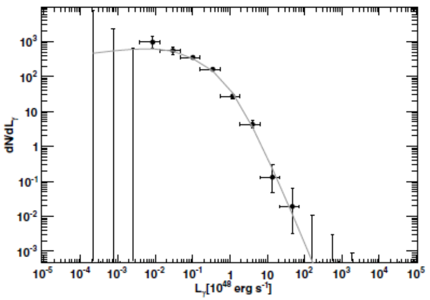
[Wang & ZL, 2016]

Fermi-LAT detections of individuals

Derived from Fermi-LAT measured LF and their z-distribution:

[Fermi-LAT, Ajello+ 2012]





IceCube neutrino sources?

- ☹diffuse Galactic emission, <1%
- ☹GRBs, <10%
- ☹AGN jets, <10%
- ☺starburst galaxies
  - SNR CRs w/ 100PeV?

[Wang, Zhao, ZL 2014 JCAP;
Wang, ZL 2016 SCPMA;
Zhang, ZL 2017 JCAP]

$$E_p \lesssim 5 \frac{\mathcal{E} \epsilon_{B,-2}^{1/2} n_{-1}^{1/6}}{\mathcal{M}^{2/3}} \mathrm{PeV}$$

[ZL 2017]

- *Wind breakout of type II SNe*

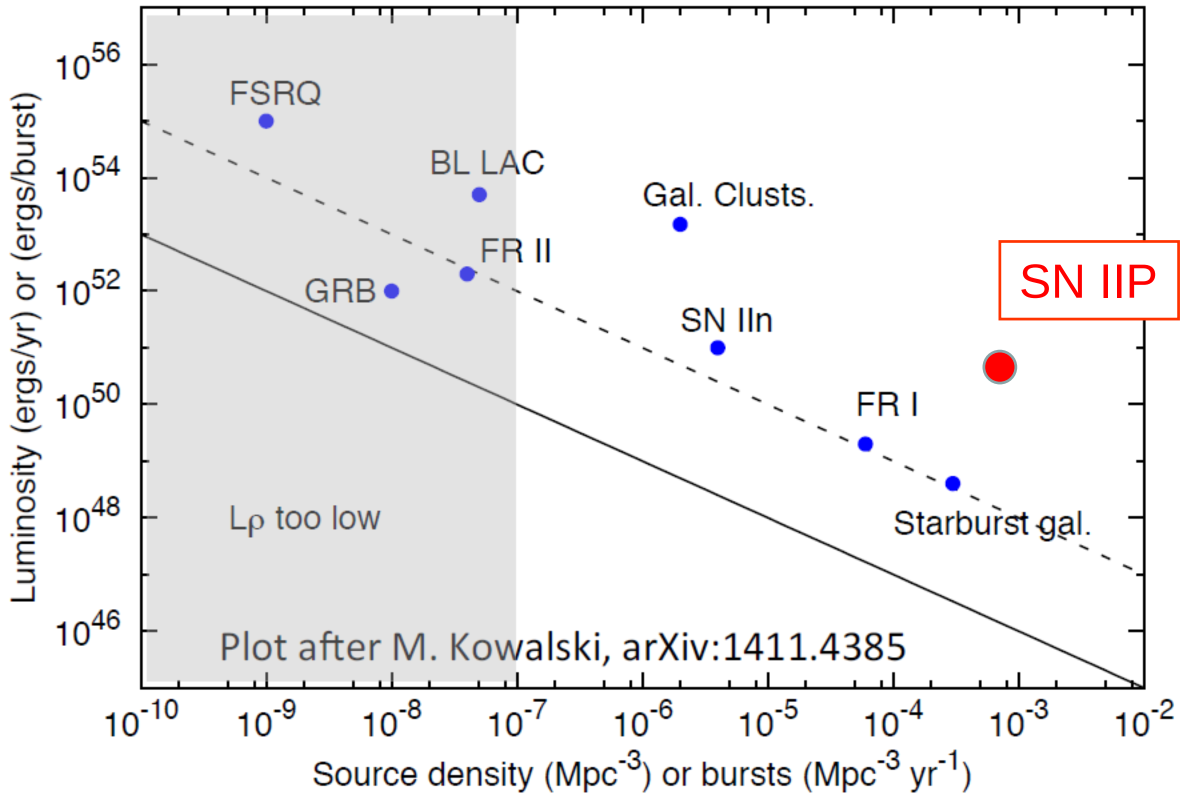
Implication from point source limits and presence of (strong) diffuse flux

Kowalski Plot

Source density and luminosity are related to produce the observed flux.

Absence of clustering sets a minimum on source density.

→Certain classes of sources disfavored.

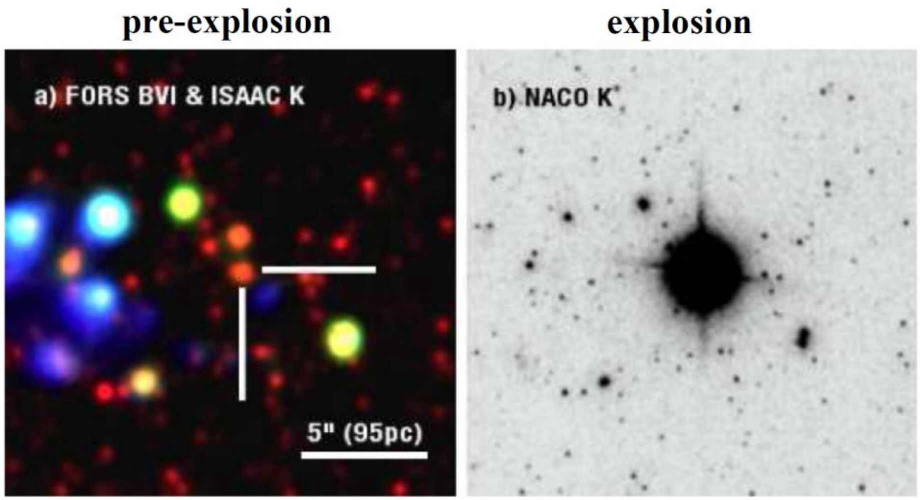


Dashed line assumes 1% efficiency for production of neutrinos

Slide adapted from Gaisser

Type II SNe

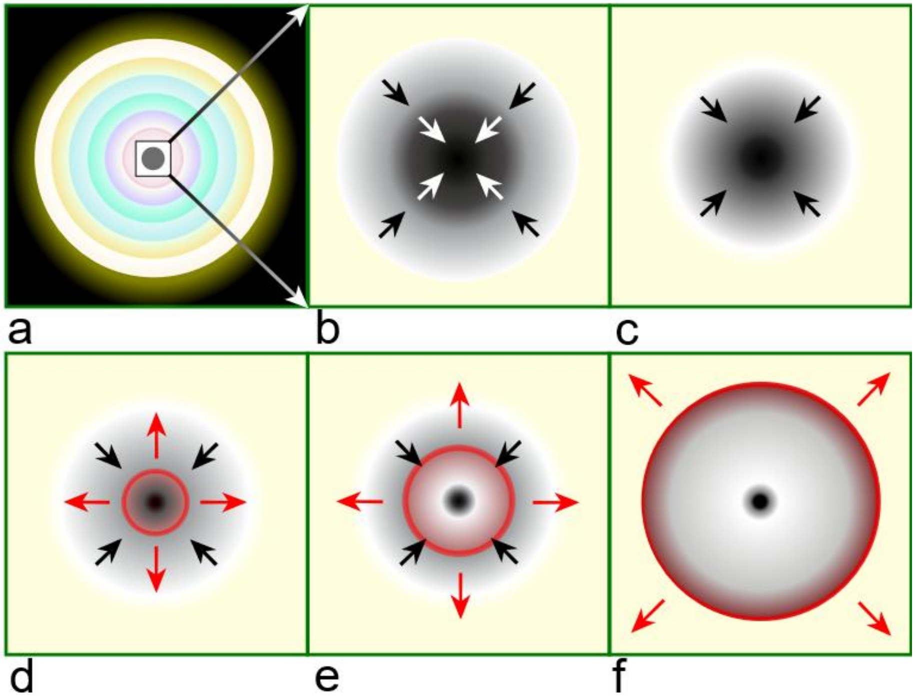
- Progenitors are red/blue super giants



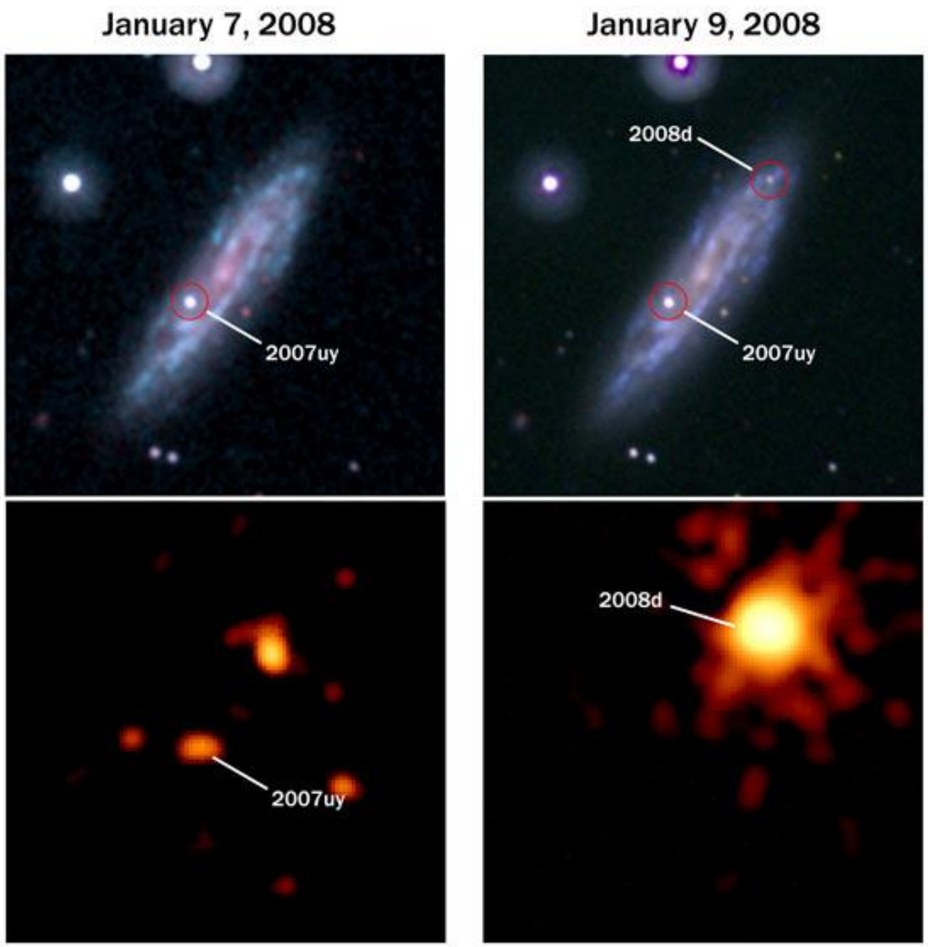
SN2008bk [Mattila+2008]

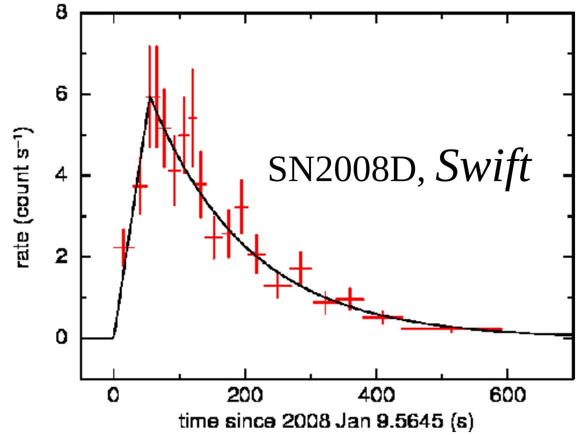
- Triggered by core collapse

- A shock wave disrupts the star

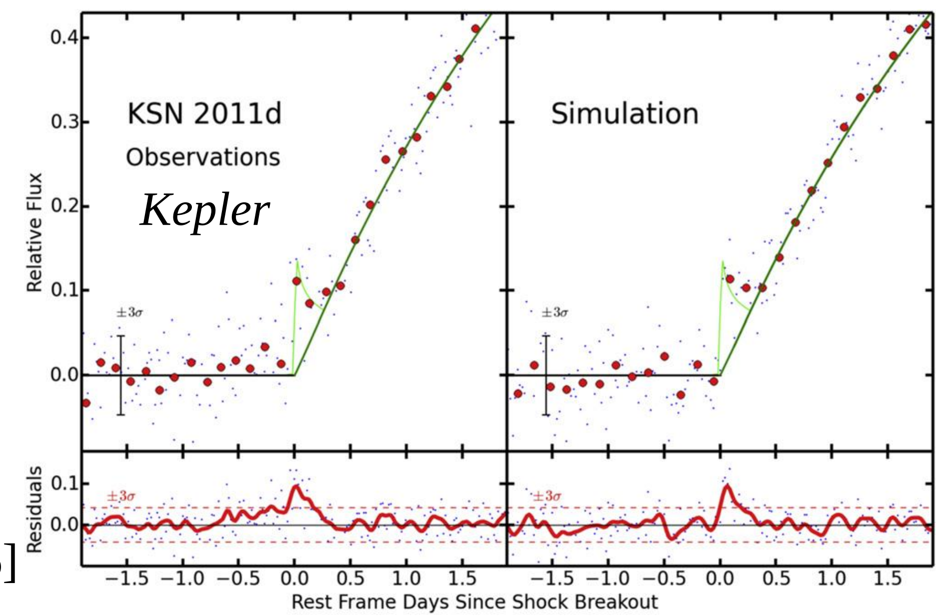


Shock breakout flash





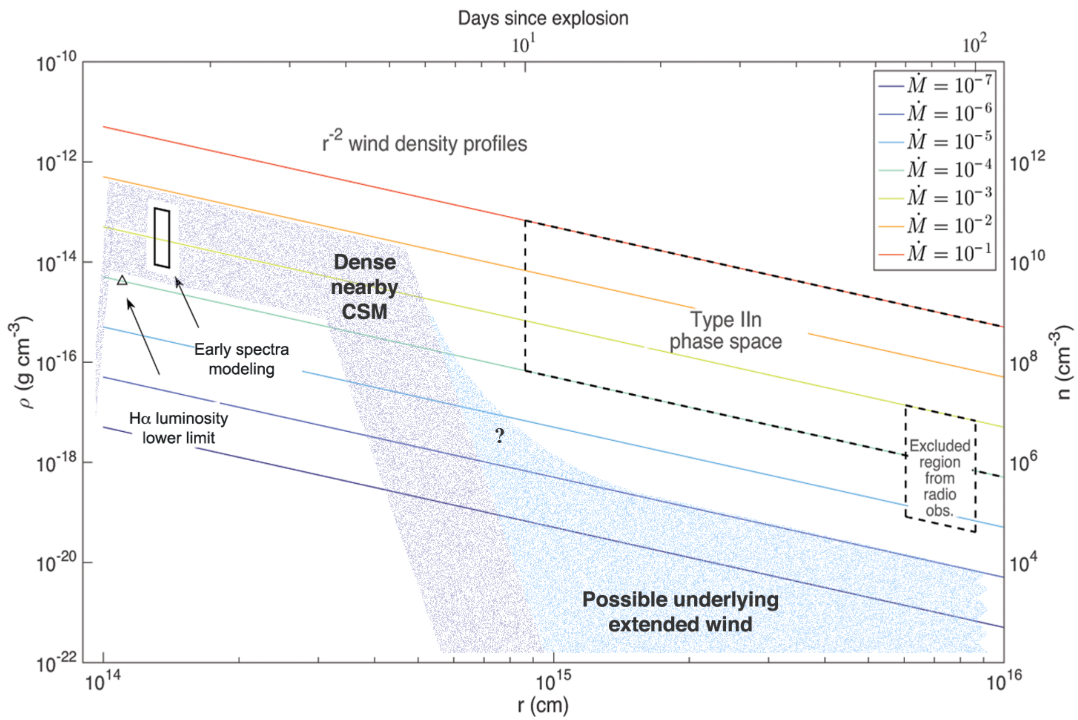
[Soderberg+08]

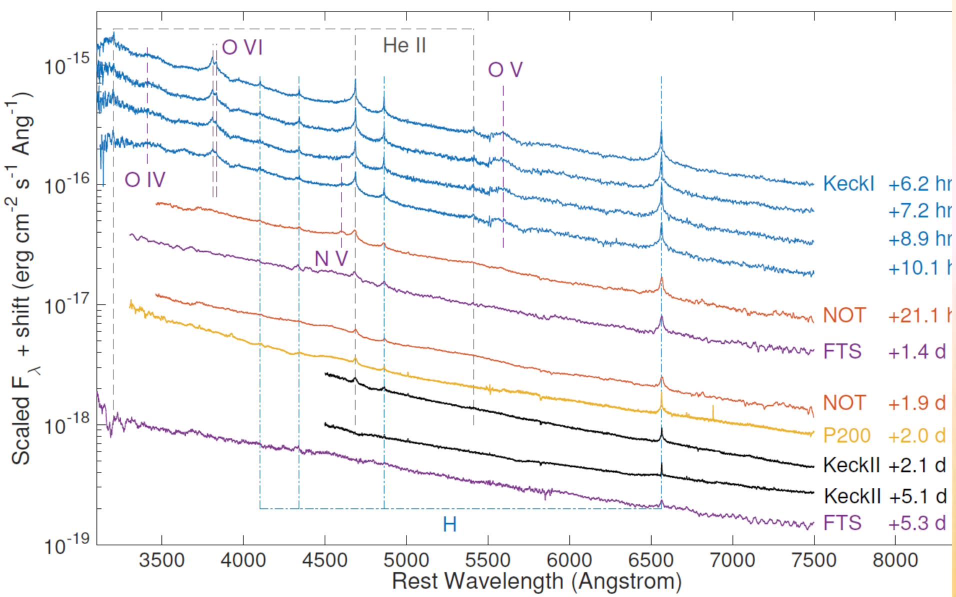


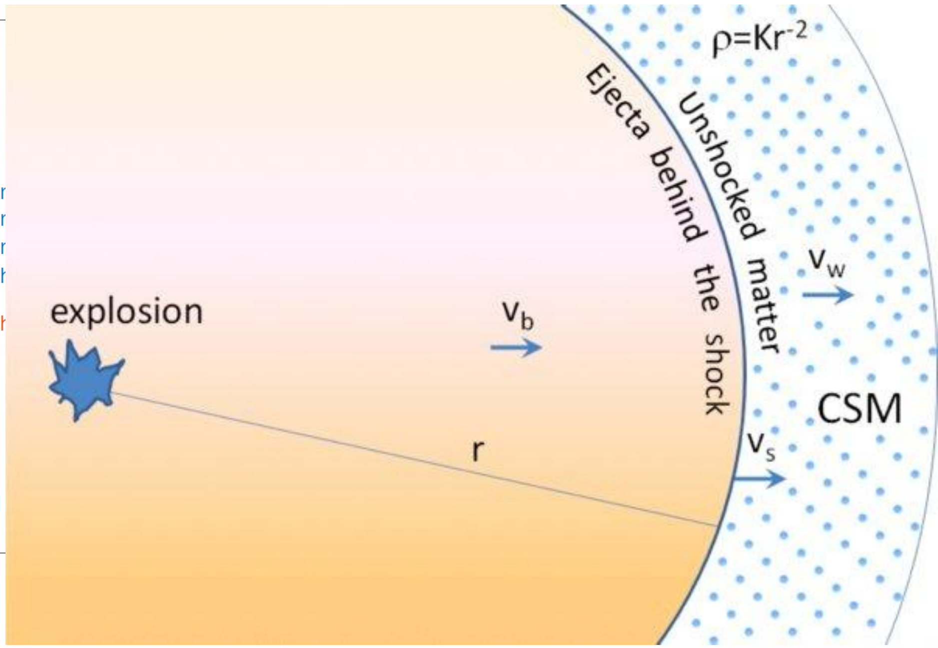
[Garnavich+16]

Dense wind

- iPTF13dqy/SN2013fs
  - A regular SN IIP
- flash spectroscopy: OIV, OV, OVII
- →3X10^{-3}M$_{sun}$/yr (w/100km/s)
- @ <10^{15}cm







pp in wind breakout of SN2013fs

- SN shock become collisionless after radiation escape
  - Diffusive shock acceleration
- Dense wind
  - may enhances particle acceleration
  - and pp energy loss

$$t_{acc} = f_B E_p c / v_s^2 e B \qquad B = \sqrt{8\pi\epsilon_B \rho v_s^2}$$

$$R_{acc}(E_p) = 7.7 \times 10^{14} \frac{A_\star \mathcal{E}^4 \epsilon_{B,-2}^2}{\mathcal{M}^3 f_B^4} (E_p/100\mathrm{PeV})^{-4} \mathrm{cm}.$$

$$R_{pp}(E_p) = 6.3 \times 10^{14} \frac{A_\star^{9/7} \mathcal{M}^{3/7} \theta(E_p)^{8/7}}{\mathcal{E}^{4/7}} \mathrm{cm}$$

Neutrinos from SN2013fs

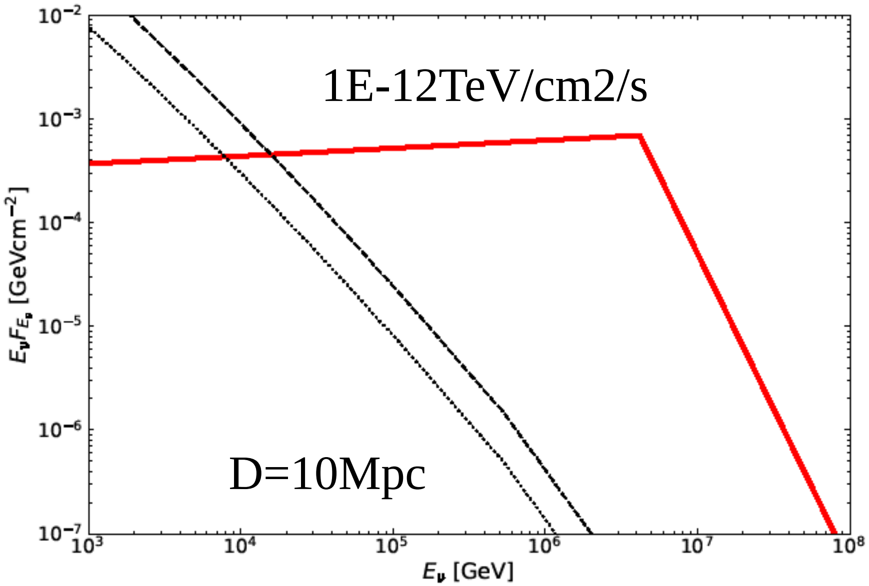
- Total ejecta energy Ek~1E51erg
- A fraction converted to SN shock at R,
  - η=Eej(>v(R))/Ek~0.6%

$$\eta = 6.4 \times 10^{-3} \frac{A_\star^{12/7} \theta^{6/7}}{\mathcal{E}^{3/7} \mathcal{M}^{3/7}} \qquad E_{ej}(> v) = E_k (v/v_b)^{-\chi} \quad (v \geq v_b)$$

- A fraction goes to cosmic rays
  - ξ~0.1
- A fraction 2/3 goes to charged pions at R<Rpp
- A fraction ¾ goes to neutrinos

Nu's from individual SN2013fs-like SNe II

- Assumptions
  - flat CR spectrum at SN shock, p=2
  - Fast particle acceleration at Bohm limit, f_B~1
- Spectrum:
  - Flat spectrum
  - Nu break at ~PeV



$$E_\nu^2 \frac{dN_\nu^{(1)}}{dE_\nu} = 6.7\times 10^{45} \frac{\xi_{-1} A_\star^{12/7} \mathcal{E}^{4/7} \theta(20E_\nu)^{6/7}}{\mathcal{M}^{3/7}} \mathrm{erg}$$

$$E_{p,\max} = 94 \frac{A_\star^{1/4} \mathcal{E} \epsilon_{B,-2}^{1/2}}{\mathcal{M}^{3/4} f_B} R_{15}^{-1/4} \mathrm{PeV}$$

$$E_{p,\mathrm{break}} \theta^{2/7}(E_{p,\mathrm{break}}) = 110 \frac{\mathcal{E}^{8/7} \epsilon_{B,-2}^{1/2}}{A_\star^{1/14} \mathcal{M}^{6/7} f_B} \mathrm{PeV}$$

- Duration 10 days:

$$T \simeq 9.9 \frac{A_\star^{11/7} \mathcal{M}^{6/7} \theta^{9/7}}{\mathcal{E}^{8/7}} \mathrm{day}.$$

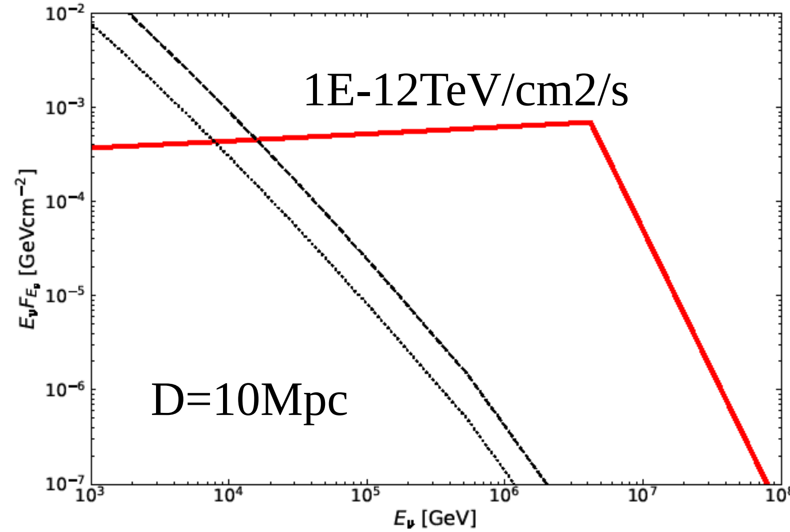
Diffuse neutrinos: If dense wind is common

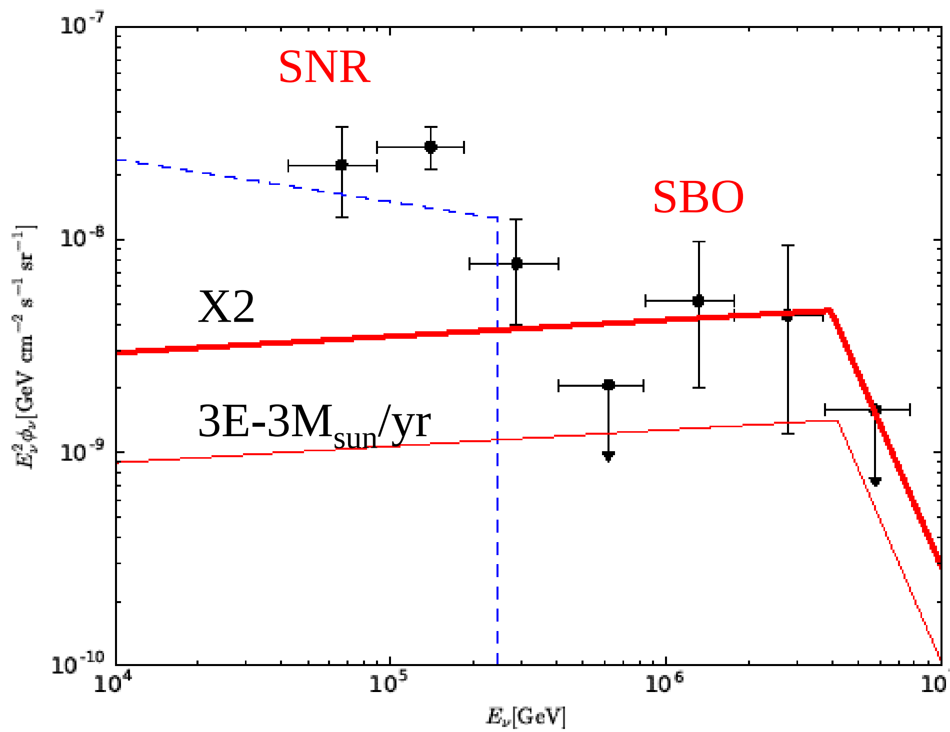
- Diffuse neutrinos from integration of all SNe II

$$E_\nu^2\phi_\nu = \frac{c}{4\pi}\zeta\dot{\rho}t_H E_\nu^2\frac{dN_\nu}{dE_\nu}$$

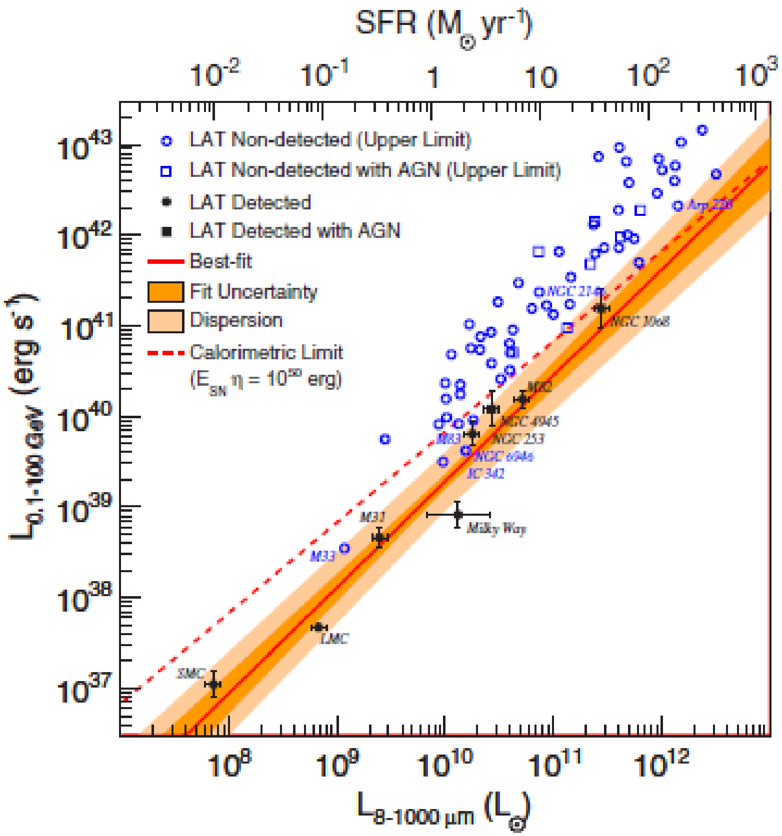
$$\dot{\rho} = 0.7\times10^{-4}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$$

- SN II-P, with SN2013fs-like wind, produce a PeV flux comparable to IceCube
  - Within a factor 3 below
- Maybe SN II-P+SN IIn combined account for the total





Starburst galaxies



$$\boxed{\nu L_\nu(\mathrm{GeV})/\mathrm{SFR} \approx 10^{46}\mathrm{erg}/M_\odot}$$

[Fermi-LAT, Ackermann+12]

GeV neutrino ~ GeV gamma

$$\sim \int \frac{\nu L_\nu}{SFR} \rho_{SFR}(z)\mathrm{d}z$$

extrapolated to PeV ~$E_p^{-2.2}$

$$\boxed{E_\nu^2 \Phi_\nu \approx 10^{-8} \frac{\xi_z}{3} \left(\frac{E_\nu}{1\mathrm{PeV}}\right)^{-0.2} \mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}}$$

Consistent with >60TeV data

[Wang, Zhao, ZL 14]

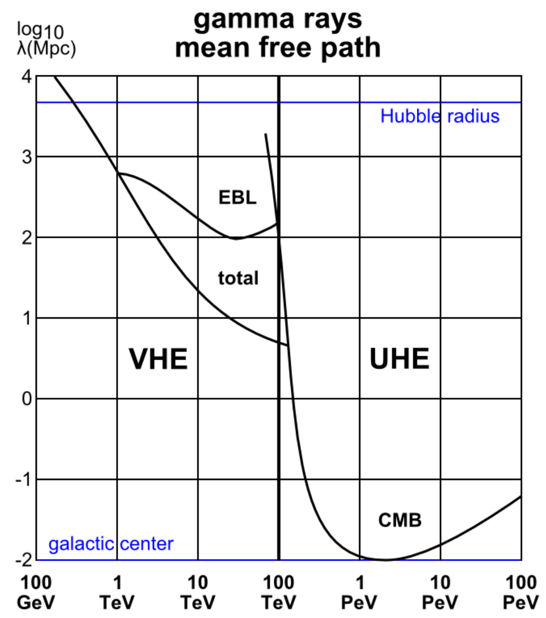
But a cutoff expected due to max p energy by SNR shock acc

$$E_p \lesssim 5 \frac{\mathcal{E}\epsilon_{B,-2}^{1/2} n_{-1}^{1/6}}{\mathcal{M}^{2/3}} \mathrm{PeV}$$

Gamma absorption: no hope for LHAASO/CTA?

- For >10TeV photons,
  - gamma-gamma absorption with SN thermal radiation is not important
  - Mean free path in extragalactic background light is <20Mpc
- 10-100TeV photons from nearby SN II, <20Mpc, are expected for CTA and LHAASO

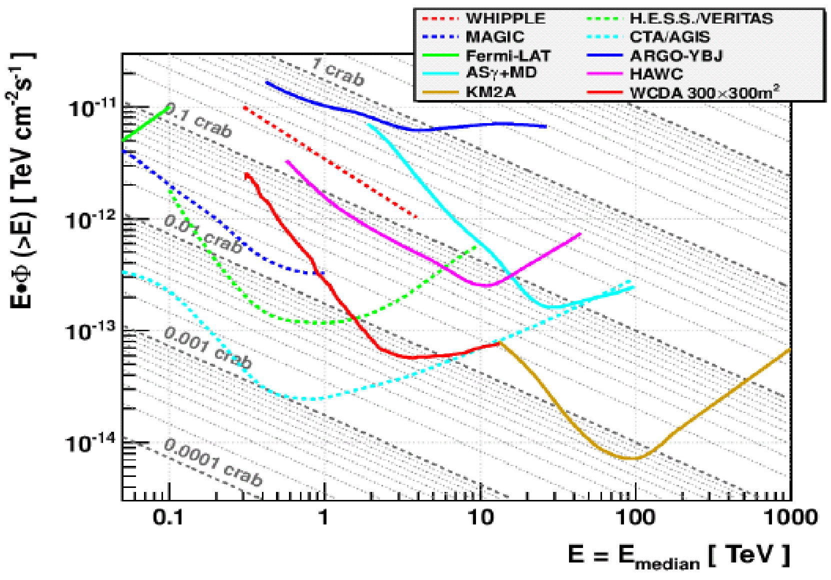
$$\tau_{\gamma\gamma} \sim n_{ph}(\sigma_T/5)R(E_{th}/3kT)$$
$$\sim 1.6R_{15}^{-1}(E_\gamma/10\mathrm{TeV})^{-1}$$

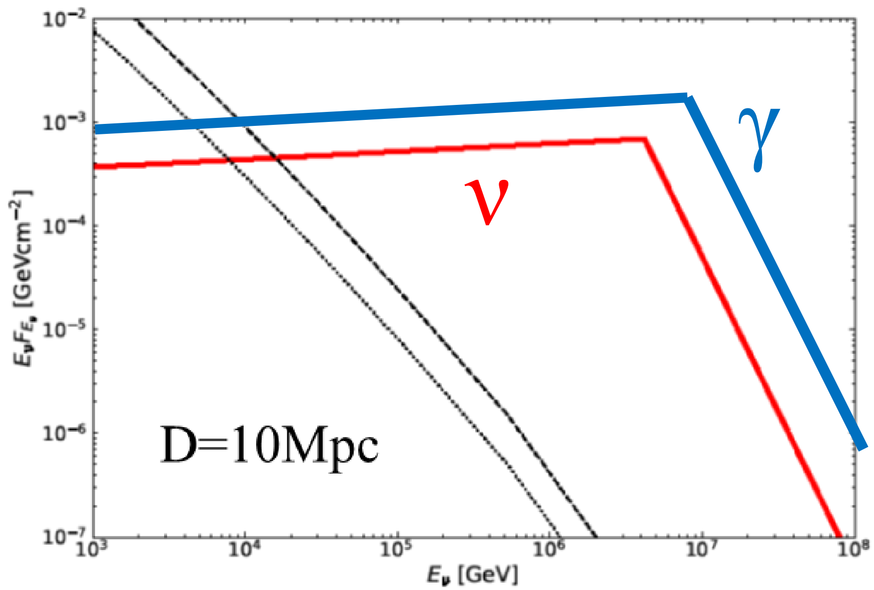


(wiki)

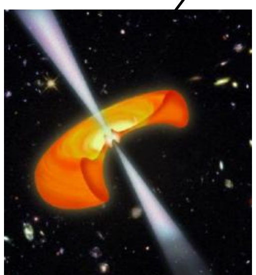
Nearby SNe II for LHAASO/CTA follow-up

- High event rate density
- $L_{gamma} \sim L_{nu}$
- T~10days
- 3/10yr @<10Mpc；
  20/10yr @<20Mpc

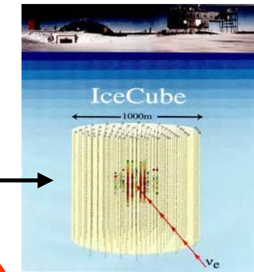




Photon – neutrino connection



$$p+\gamma(p) \rightarrow \begin{cases} N+\pi^{\pm} \\ \quad \pi^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \quad\quad e^{\pm} \rightarrow \text{syn/IC radiation} \\ N+\pi^{0} \\ \quad \pi^{0} \rightarrow \gamma+\gamma \end{cases}$$



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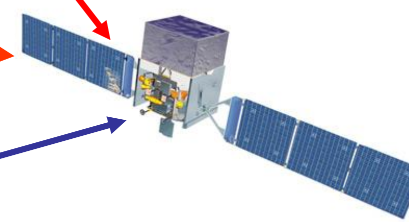


$$e^{-}(p) \rightarrow \text{synch/IC radiation}$$

II

Connections:

I. neutrino – secondary electron/gamma-ray

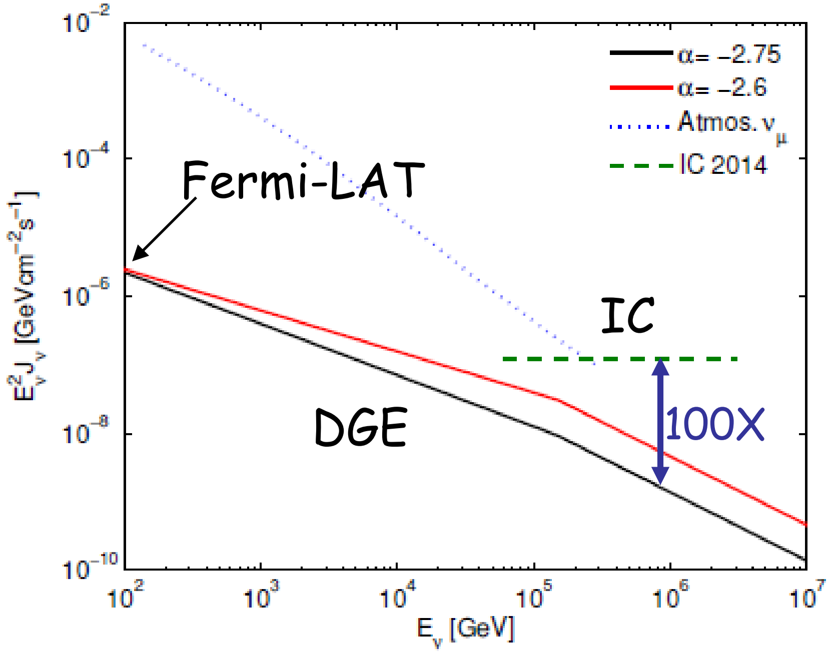
II. neutrino – primary electron/proton

Diffuse Galactic emission

- Connection I
- $\pi^+ : \pi^- : \pi^0 = 1:1:1$

  $E_\nu = \frac{1}{2} E_\gamma$

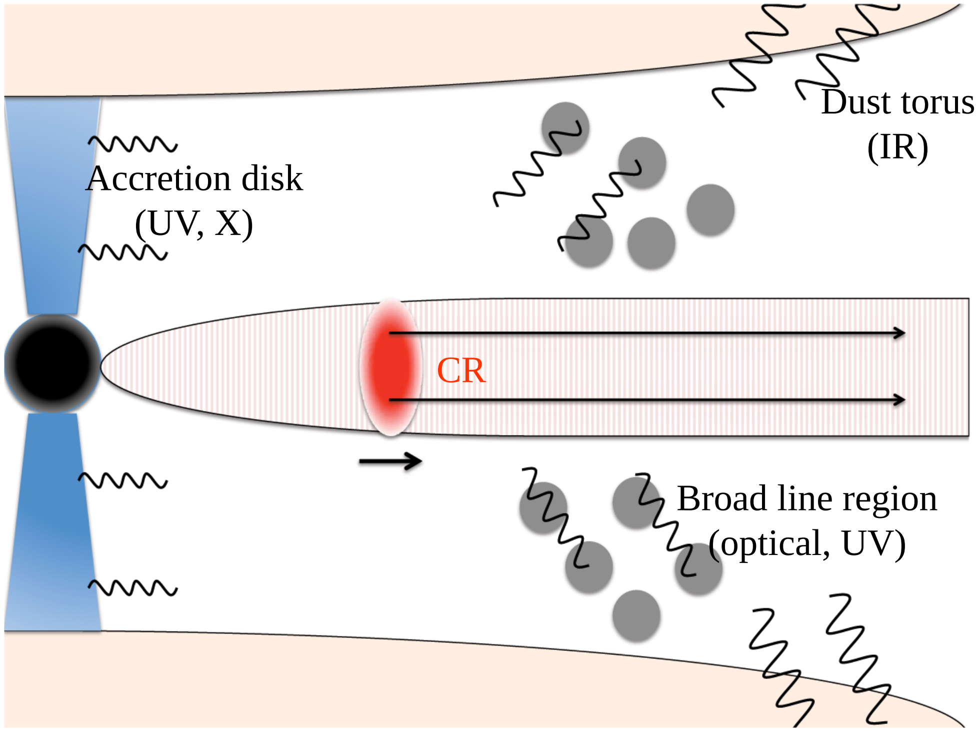
  $E_\nu{}^2 J_\nu(E_\nu) = \frac{1}{2} E_\gamma{}^2 J_\gamma(E_\gamma)$
- Extrapolation, 100GeV to PeV
  - Neutrinos follow CR spectrum
- DGE accounts for <1% IC flux



[Wang, Zhao, ZL 14]

Blazar model

- Jet model
  - CR accelerated at Jet
  - Target photon: jet+disk+BLR+torus
  - Relativistic beaming; bright



Murase+14

Blazar: specific model

- Total flux: $J_\nu \sim \iint L_\nu(L_\gamma)\rho(L_\gamma, z)\mathrm{d}L_\gamma \mathrm{d}z$
- Per source

$$E_\nu L_{E_\nu} \approx \frac{1}{8} f_{p\gamma} E_p L_{E_p} \approx \frac{1}{8} f_{p\gamma} \hat{\xi}_{\mathrm{cr}} L_{\mathrm{rad}}$$

- Stacking search constrains CR loading

$$E_\nu^2 \Phi_{\nu,i} = \frac{1}{8} f_{p\gamma}(L_{\gamma,i}) \frac{L_{\mathrm{rad}}(L_{\gamma,i})}{L_{\gamma,i}} \hat{\xi}_{\mathrm{cr}} S_{\gamma,i}$$

$$\sum_i E_\nu^2 \Phi_{\nu,i} < E_\nu^2 \Phi^{90\%}_{\nu_\mu + \bar{\nu}_\mu} \Rightarrow \hat{\xi}_{\mathrm{cr}} < 0.062 f^{-1}_{\mathrm{cov},-1} \zeta^{-1}$$

- Blazars account for <10% IC neutrinos

[Zhang, ZL 2017]