High energy neutrinos from blazars and supernovae

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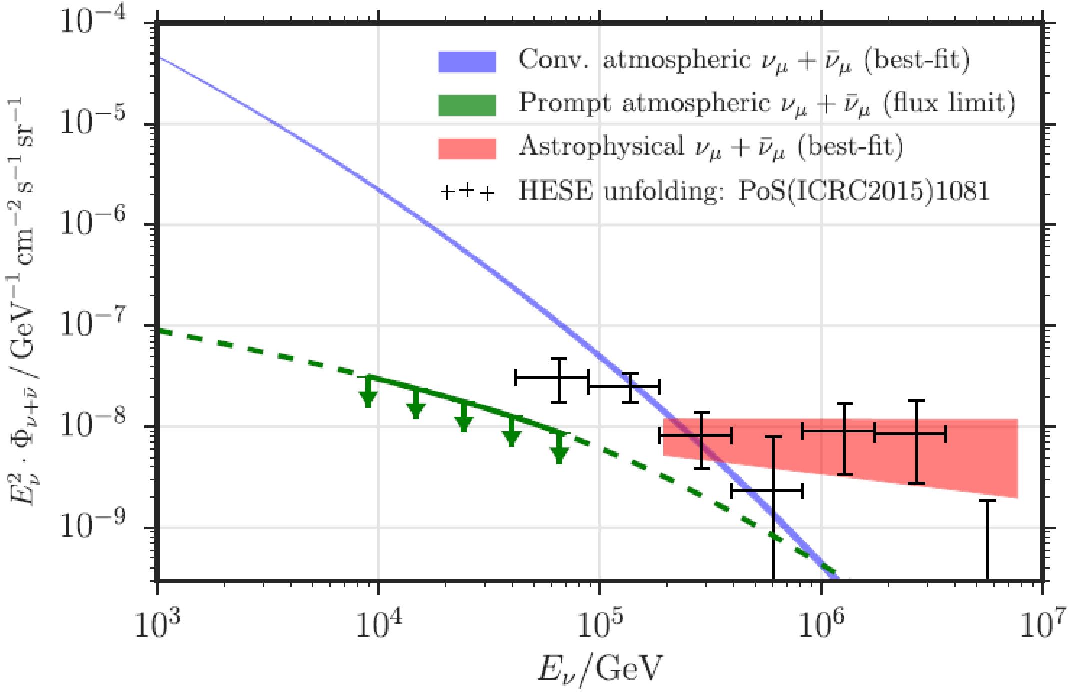
TeV-PeV neutrinos at IceCube

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

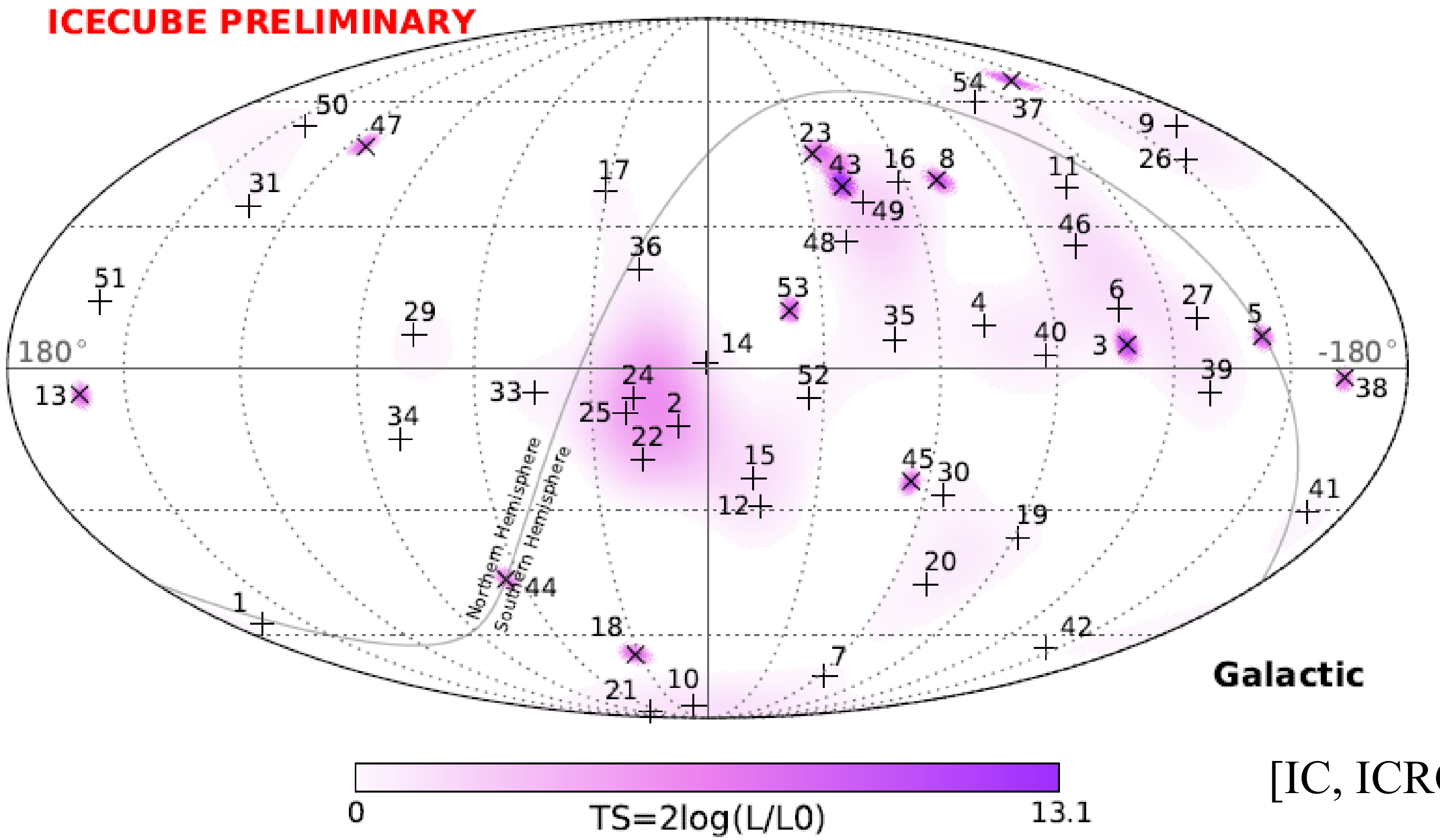
starting evts (southern) consistent w/ upgoing track evts (northern)



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

Blazars and GRBs as sources?

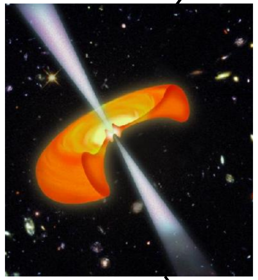
- Stacking limit of blazars/GRBs

  &

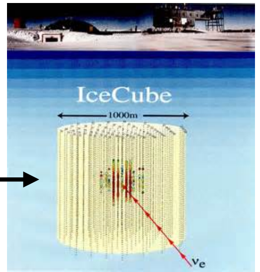
- Knowledge of blazar/GRB population

- ➔ blazars/GRBs cannot account for diffuse neutrino flux

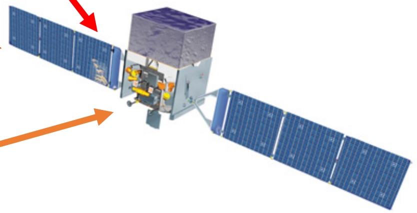
Photon – neutrino connection



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



I



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

II

Connections:

I. neutrino – secondary electron/gamma-ray

II. neutrino – primary electron/proton

Blazars

- 33 bright FSRQs selected based on gamma flux

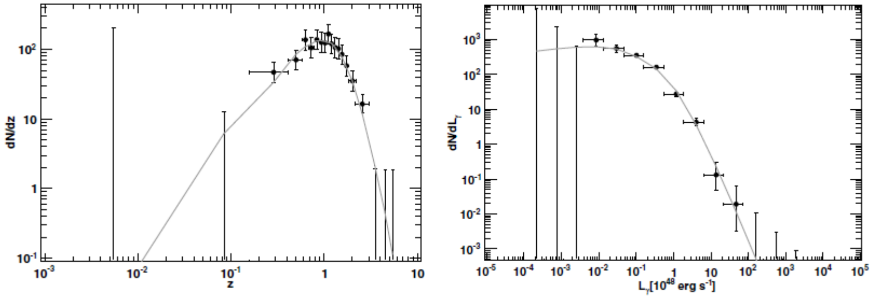
IC upper limits to the 33

IC detection

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

Fermi-LAT detections of the 33

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



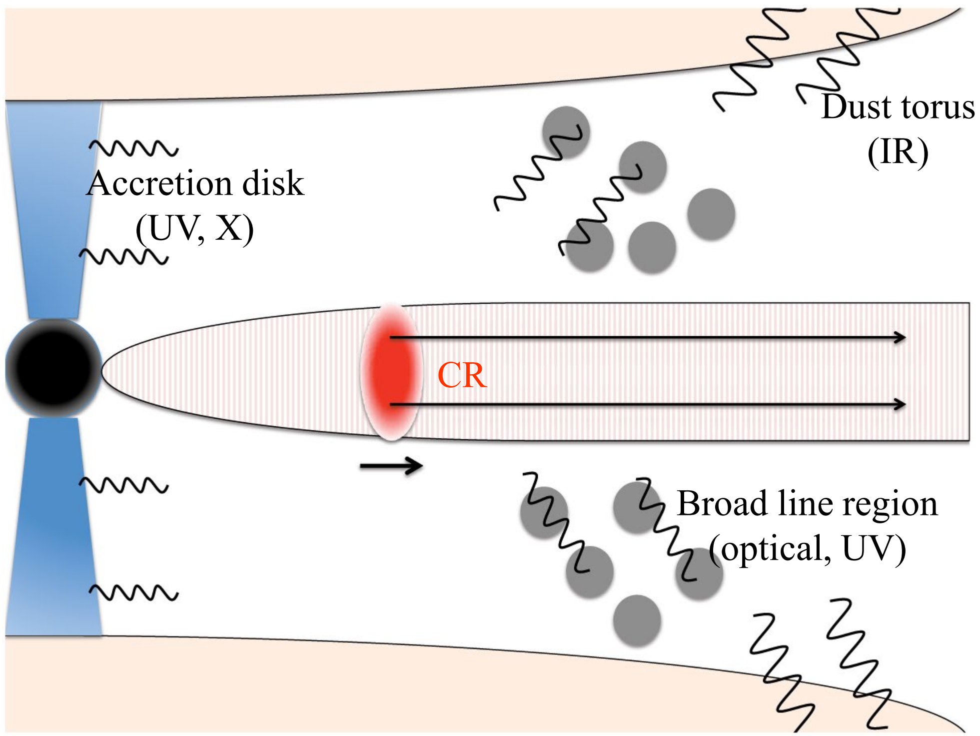
[Fermi-LAT, Ajello+ 2012]

FSRQs can only account for <10% neutrinos

[Wang & ZL, 2016]

Blazar model

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



Murase+14

Blazar model

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

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

- Stacking search constrains CR loading

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

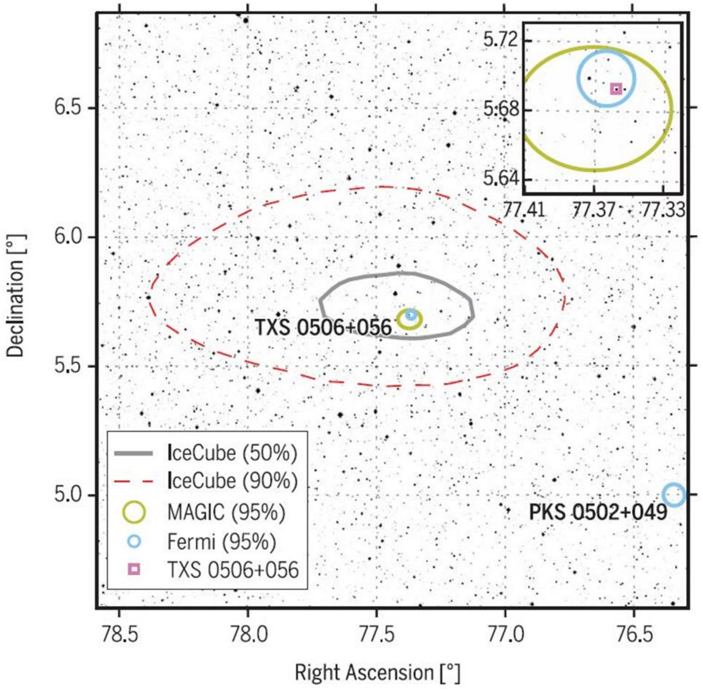
$$\sum_i E_\nu^2 \Phi_{\nu,i} < E_\nu^2 \Phi^{90\%}_{\nu_\mu + \bar{\nu}_\mu} \Rightarrow \hat{\xi}_{\rm cr} < 0.062 f^{-1}_{{\rm cov},-1} \zeta^{-1}$$

- Blazars account for <10% IC neutrinos

[Zhang, ZL 2017]

Comment on the neutrino/BL Lac association

IC-170922A/TXS 0506+056 association, 4sigma coincidence [IC18a]

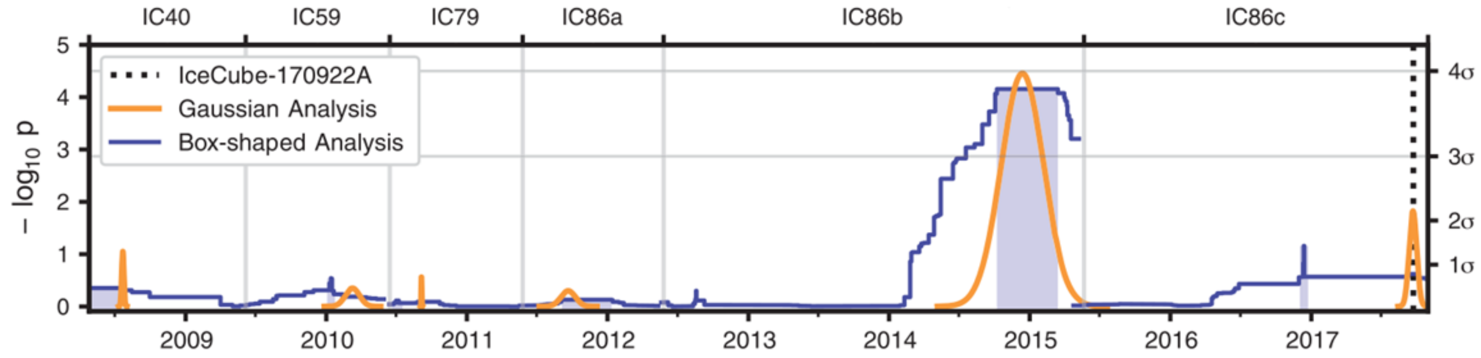


However,
IC limit of 27 LSP BL Lacs
→ $\hat{\xi}_{cr} < 0.92\zeta^{-1}$
→LSP BL Lacs contribute <17% neutrinos

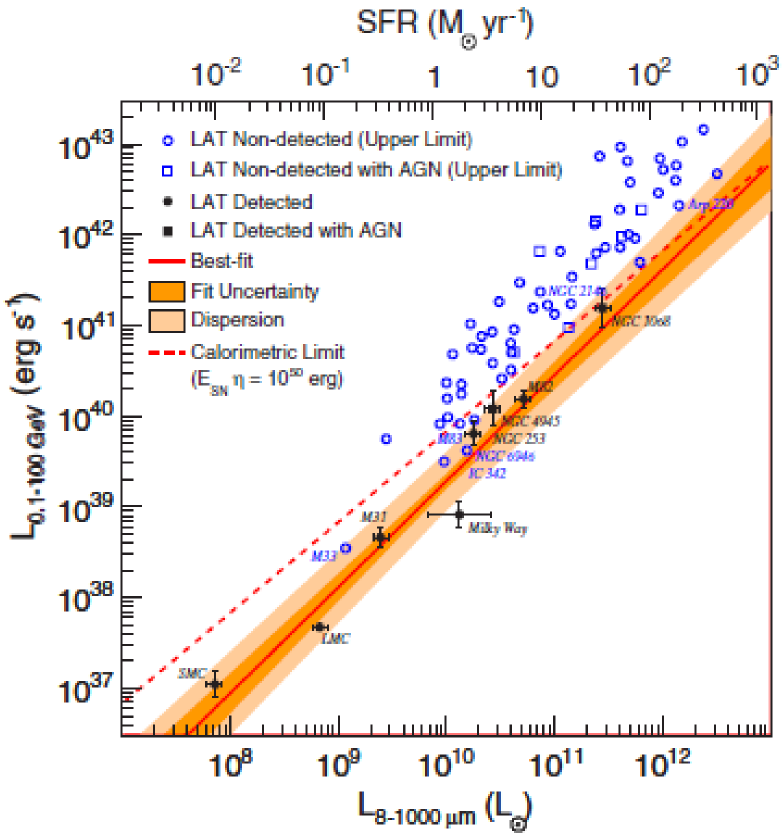
[Zhang, ZL 2017]

Neutrino burst/flare in archive data, 3.5sigma signal [IC18b]

So,
TXS 0506+056 like BL Lacs should contribute the bulk of the neutrino flux.



Starburst galaxies



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

[Fermi-LAT, Ackermann+12]

GeV neutrino ~ GeV gamma

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

extrapolated to PeV $\sim E_p^{-2.2}$

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

Consistent with >60TeV data

[Wang, Zhao, ZL 14]

IceCube neutrino sources?

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

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

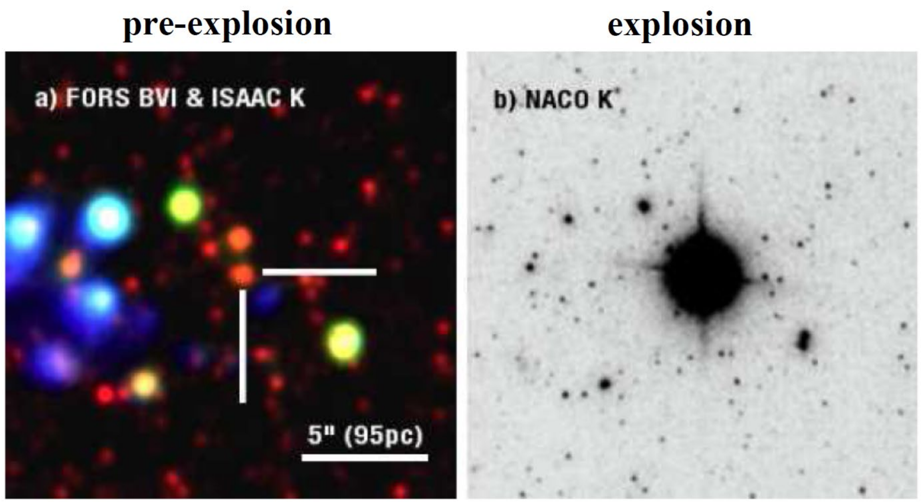
- *Wind breakout of type II SNe*

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

[ZL 2019 SCPMA]

Type II SNe

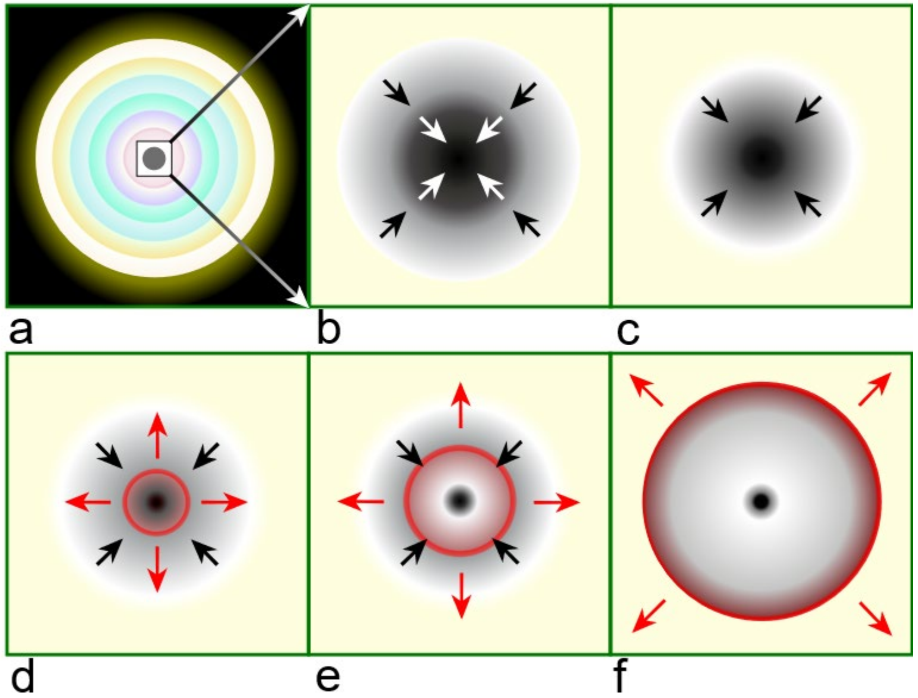
- Progenitors are red/blue super giants



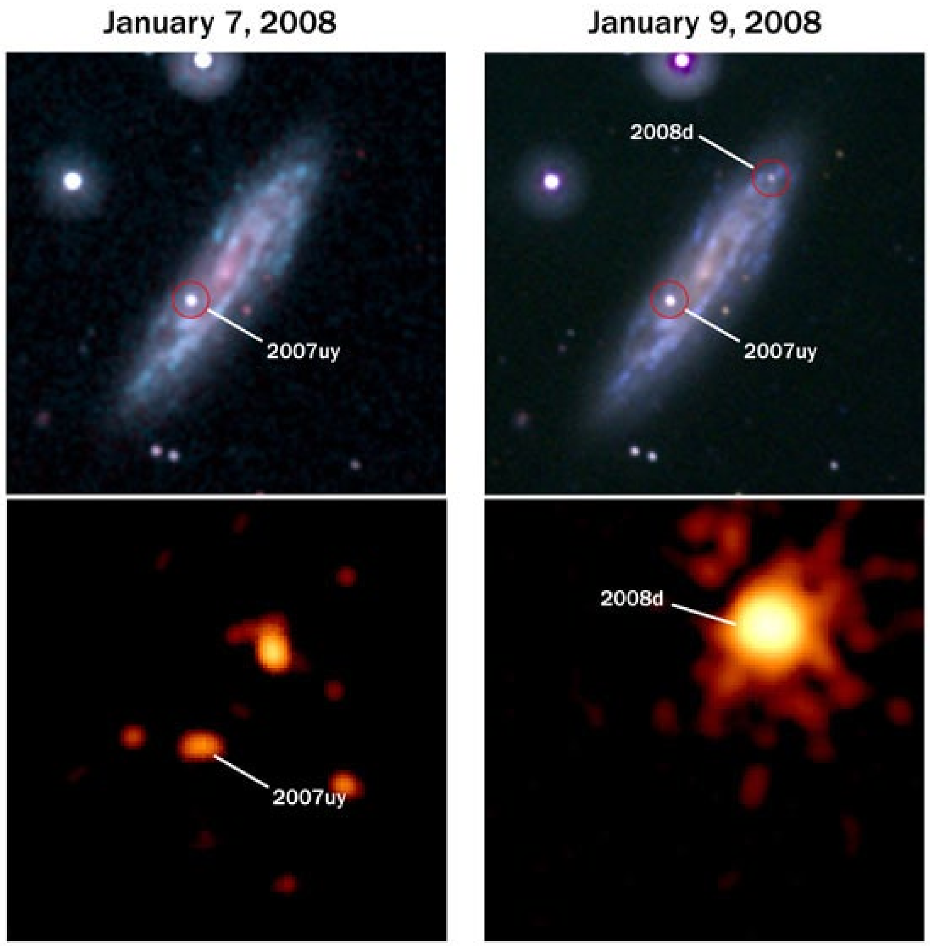
SN2008bk [Mattila+2008]

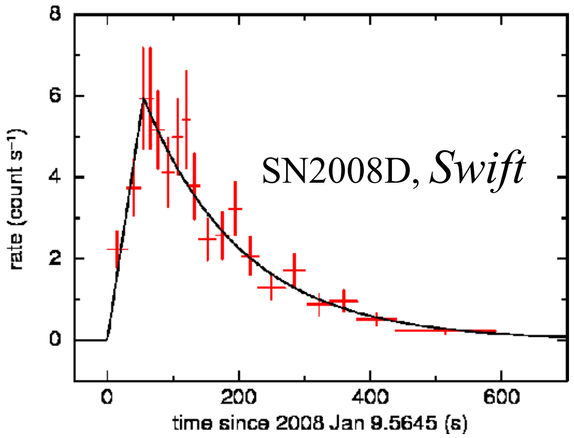
- Triggered by core collapse

- A shock wave disrupts the star

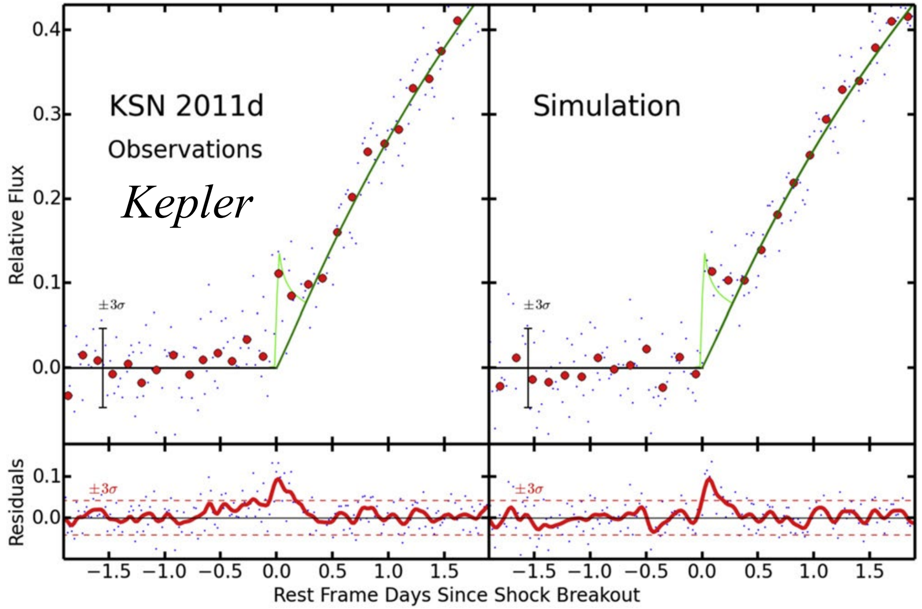


Shock breakout flash





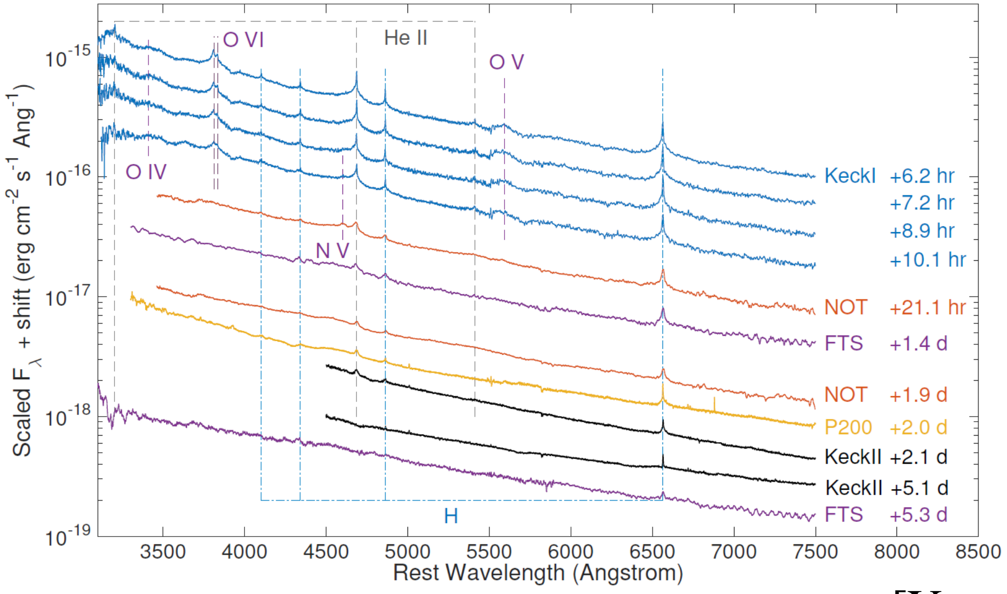
[Soderberg+08]



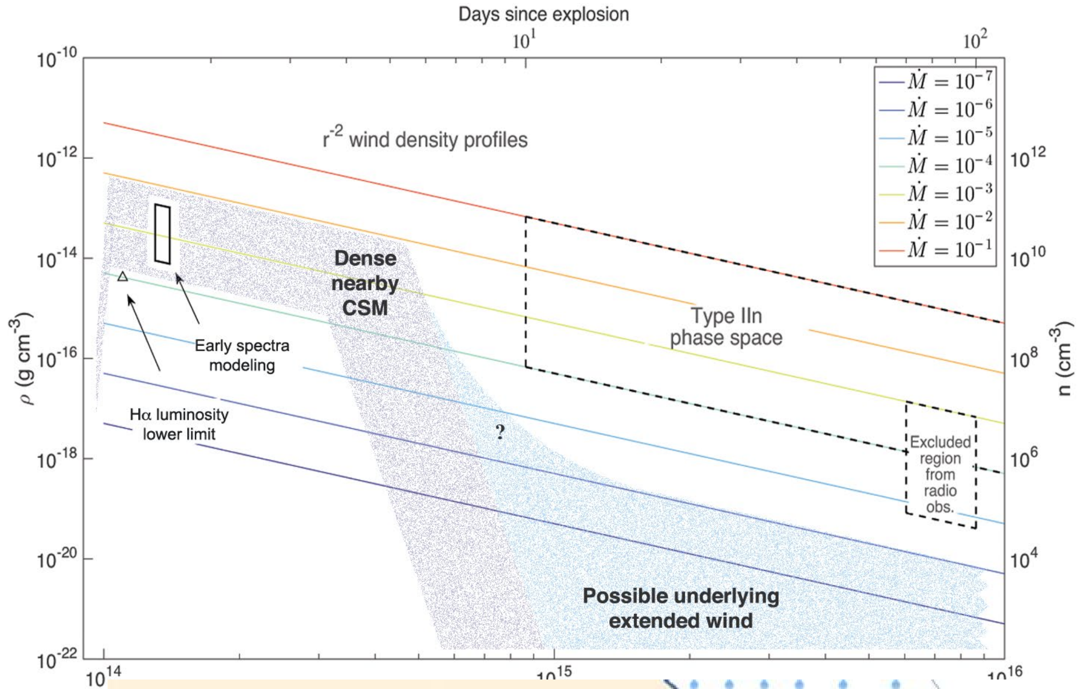
[Garnavich+16]

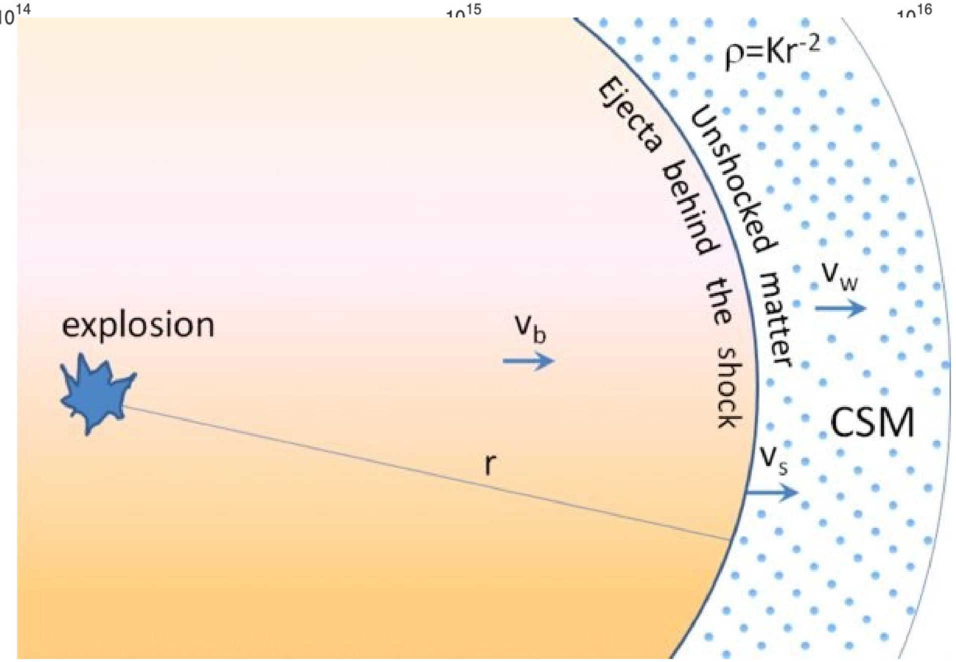
Dense stellar wind

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



[Yaron+2017]

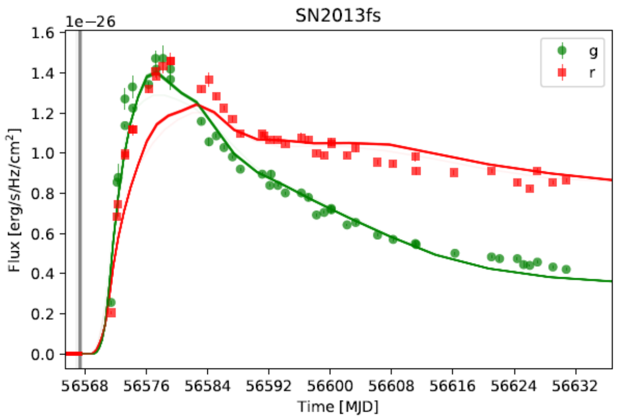




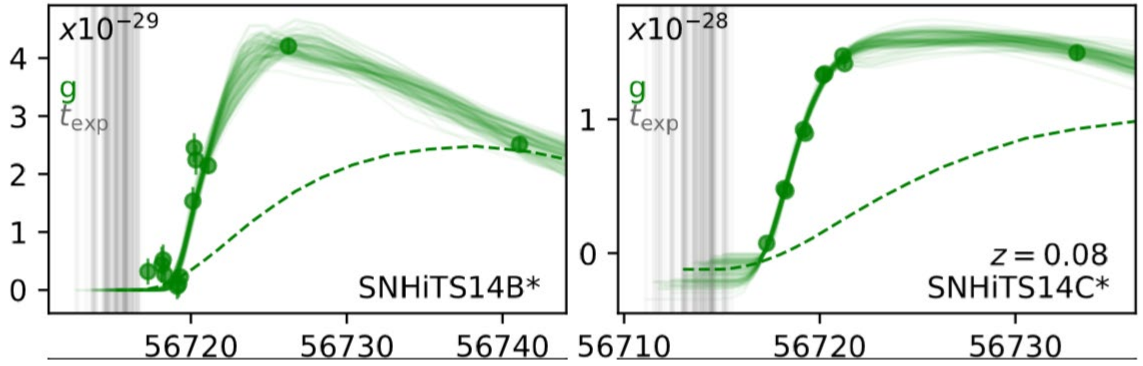
Dense stellar winds

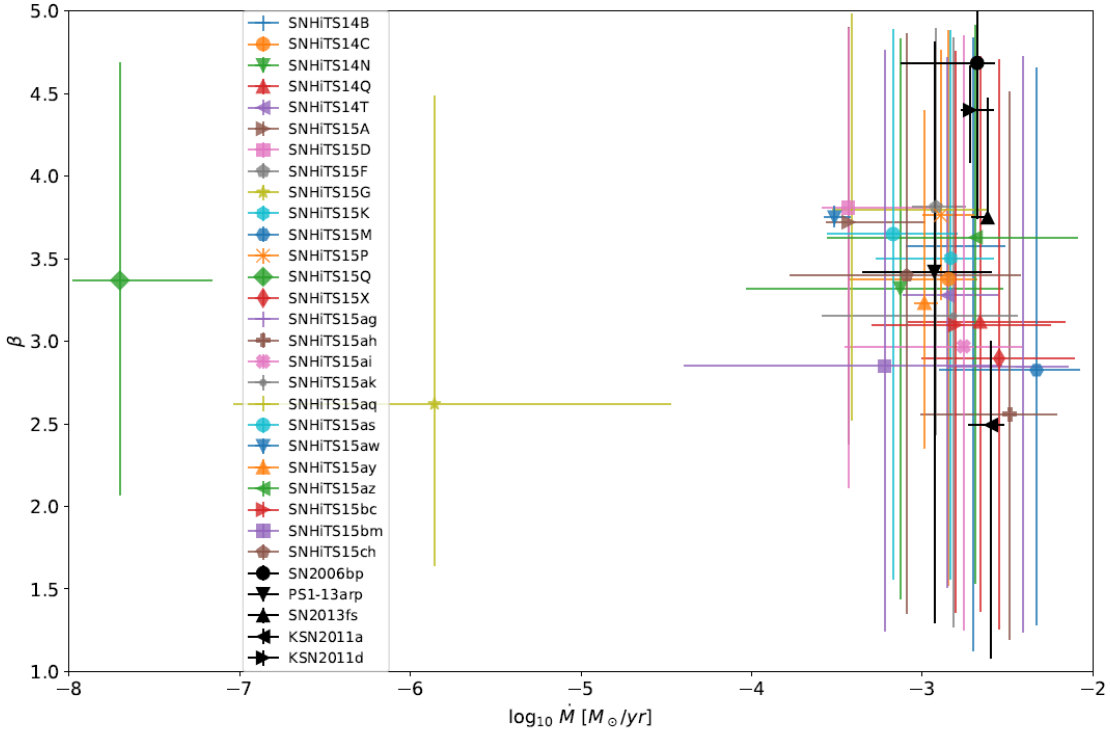
- Steep light-curve rise of a few days seen in 24 of 26 SNe II: shock breakout in dense circumstellar material
- 10^{-4}Msun/yr w/ v=10km/s

  → 3 times denser

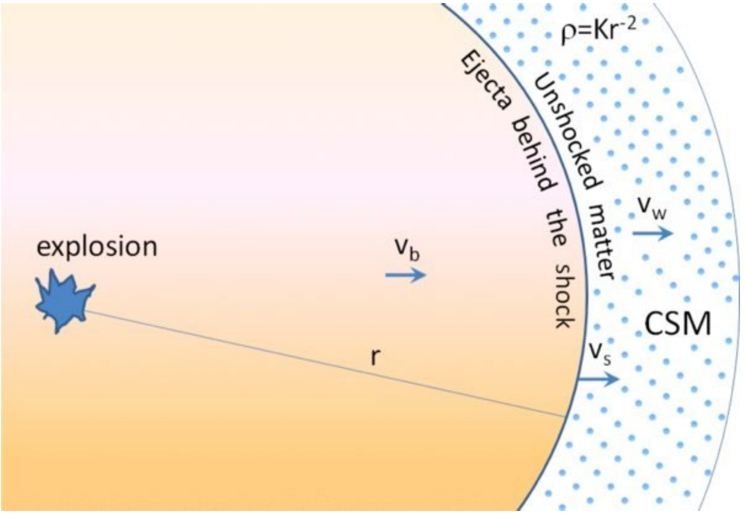


[Forster + 18]





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

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

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

$$E^{pp}_{p,\max}(R) = 35 \frac{\mathcal{E}^{3/2} \epsilon_{B,-2}^{1/2}}{A_\star^{7/8} \mathcal{M}^{9/8} \theta f_B} R_{15}^{5/8} \mathrm{PeV}$$

$$R_{pp}(E_p) = 3.1 \times 10^{15} \frac{A_\star^{9/7} \mathcal{M}^{3/7} \theta^{8/7}}{\mathcal{E}^{4/7}} \mathrm{cm}$$

Neutrinos from SN2013fs

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

$$\eta^{\rm CW} = 0.91 \times 10^{-2} \frac{A_\star^{3/4} R_{w,15}^{3/4}}{\mathcal{M}^{3/4}}$$

$$E_{ej}(> v) = E_k (v/v_b)^{-\chi} \quad (v \geq v_b)$$

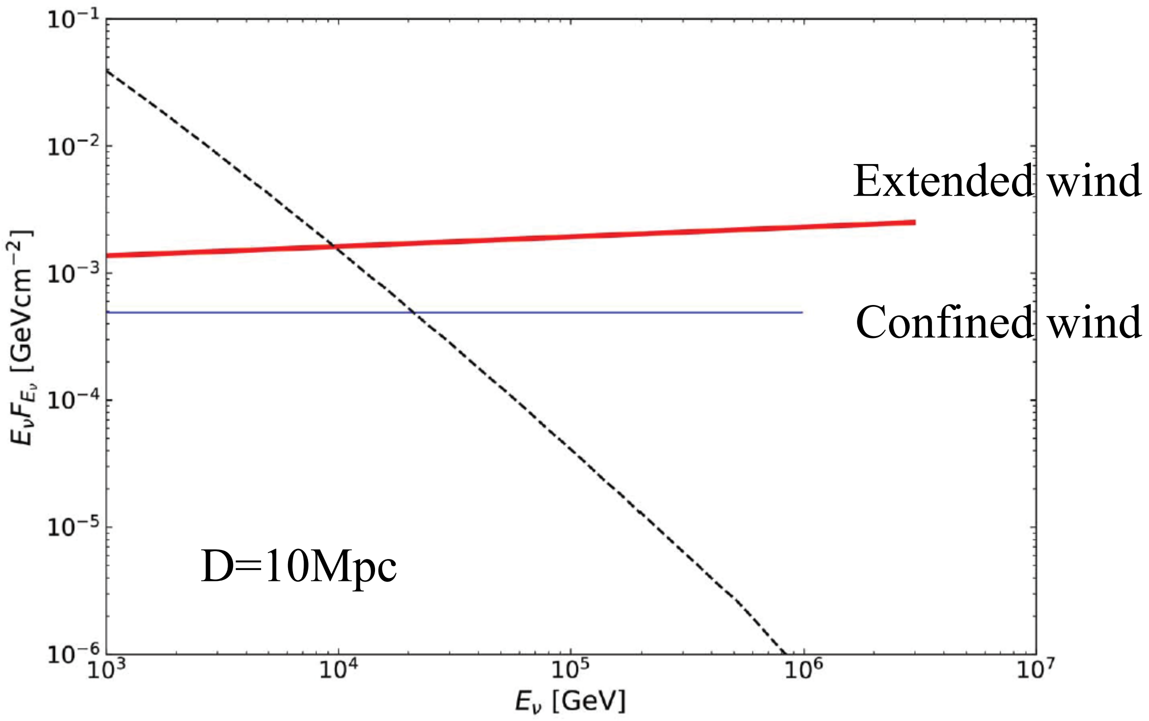
- A fraction goes to cosmic rays
  - ξ~0.1
- A fraction 2/3 goes to charged pions at R<Rpp
- A fraction ¾ goes to neutrinos

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

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = 9.4 \times 10^{45} \frac{\xi_{-1} A_\star^{3/4} \mathcal{E} R_{w,15}^{3/4}}{\mathcal{M}^{3/4}} \mathrm{erg}$$

$$E_{p,\max} \theta^{2/7}(E_{p,\max}) = 71 \frac{\mathcal{E}^{8/7} \epsilon_{B,-2}^{1/2}}{A_\star^{1/14} \mathcal{M}^{6/7} f_B} \mathrm{PeV}$$



- Duration ~50 days: $$T \simeq 46 \frac{A_\star^{79/56} \mathcal{M}^{45/56} R_{w,15}^{1/8} \theta^{8/7}}{\mathcal{E}^{15/14}} \mathrm{day}$$

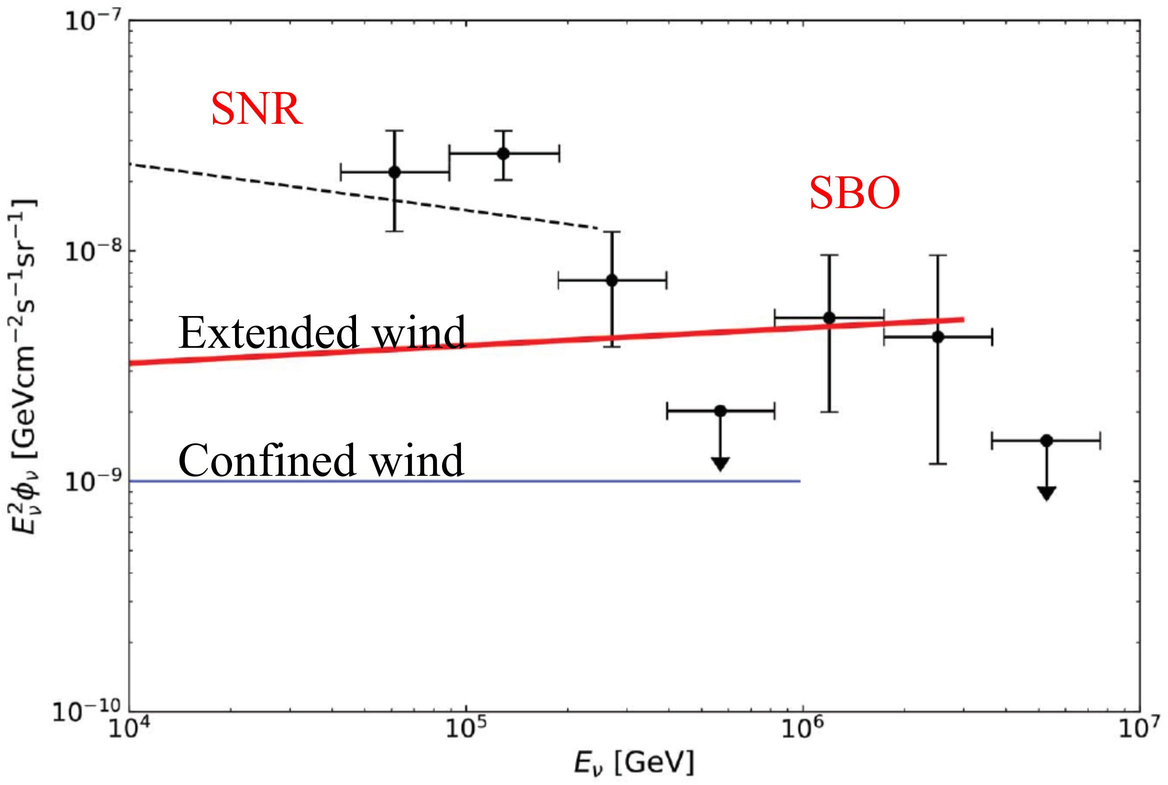
Diffuse neutrinos: If dense wind is common

- Diffuse neutrinos from integration of all SNe II in the universe

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

$$\dot{\rho} = 0.7 \times 10^{-4} \mathrm{Mpc}^{-3} \mathrm{yr}^{-1}$$

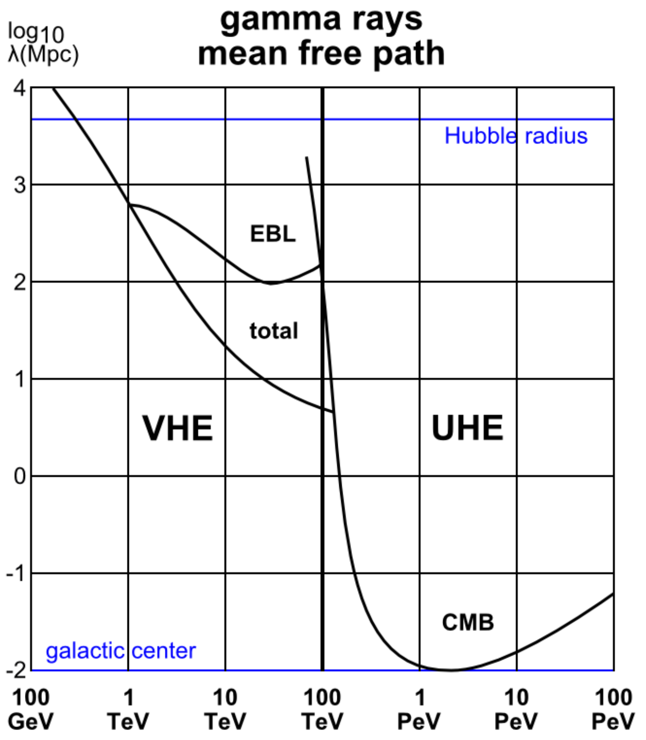
- SN II-P, with SN2013fs-like wind, produce a PeV flux comparable to IceCube
  - Within a factor 3 below (confined wind)
  - Maybe SN II-P+SN IIn combined account for the total
  - Maybe most SNe are w/ extended winds



Gamma absorption: no hope for LHAASO/CTA?

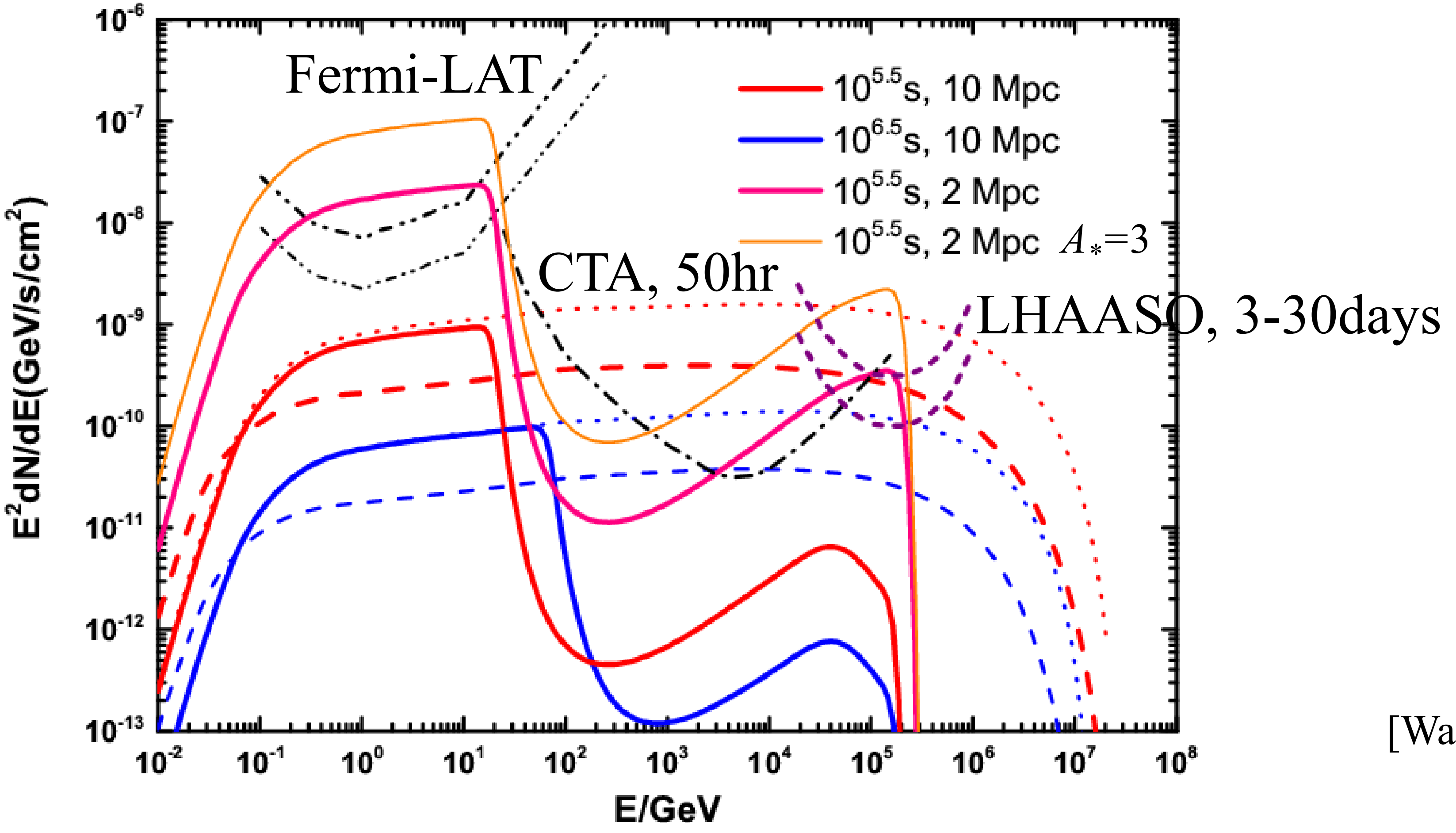
- For >10TeV photons,
  - gamma-gamma absorption with SN thermal radiation is not important
  - Propagation length in extragalactic background light is <20Mpc
- 10-100TeV photons from nearby SN II, <20Mpc, are expected for CTA and LHAASO

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



(wiki)

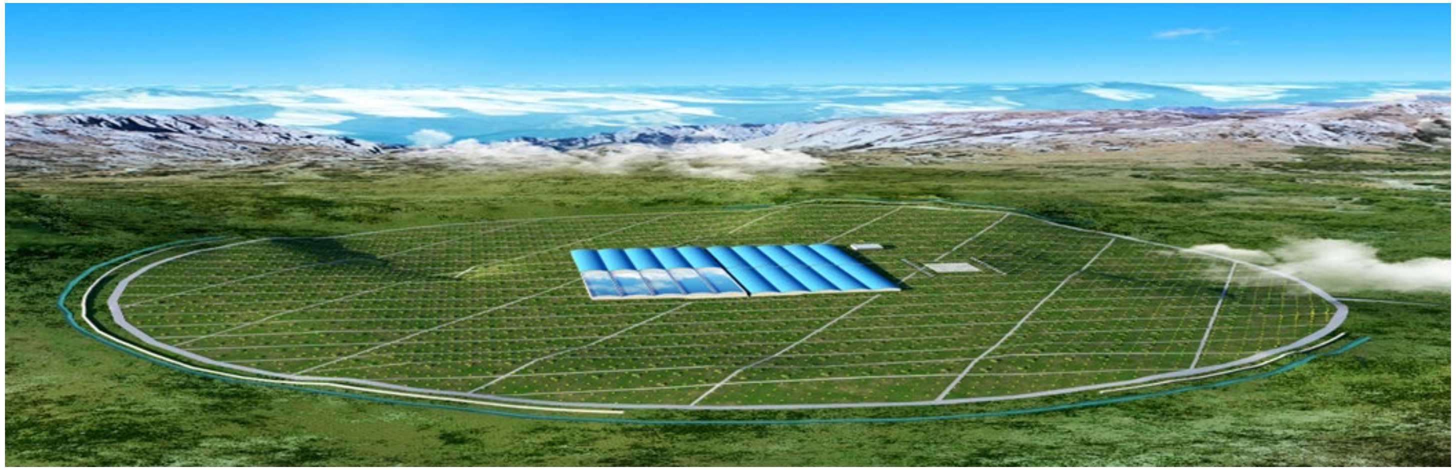
Nearby SNe II for Fermi-LAT, CTA & LHAASO



[Wang, Huang, & ZL 19]

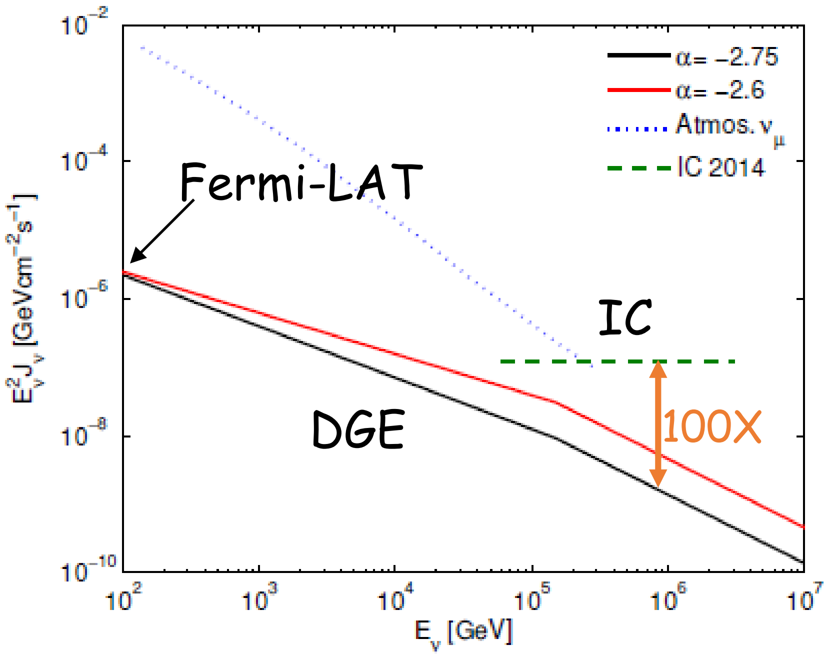
Pospect

- SNe II may contribute a significant fraction of PeV neutrino flux
- Nearby SNe II: 3 in10 yrs @<10Mpc
- Follow-up observations of LHAASO/CTA within ~50days of the SN discoveries
  - by LSST, PTF, ASSASN, EP, etc.
-



Diffuse Galactic emission

- Connection I
- $$\pi^+ : \pi^- : \pi^0 = 1:1:1$$
  $$E_\nu = \tfrac{1}{2} E_\gamma$$
  $$E_\nu{}^2 J_\nu(E_\nu) = \tfrac{1}{2} E_\gamma{}^2 J_\gamma(E_\gamma)$$
- Extrapolation, 100GeV to PeV
  - Neutrinos follow CR spectrum
- DGE accounts for <1% IC flux



[Wang, Zhao, ZL 14]

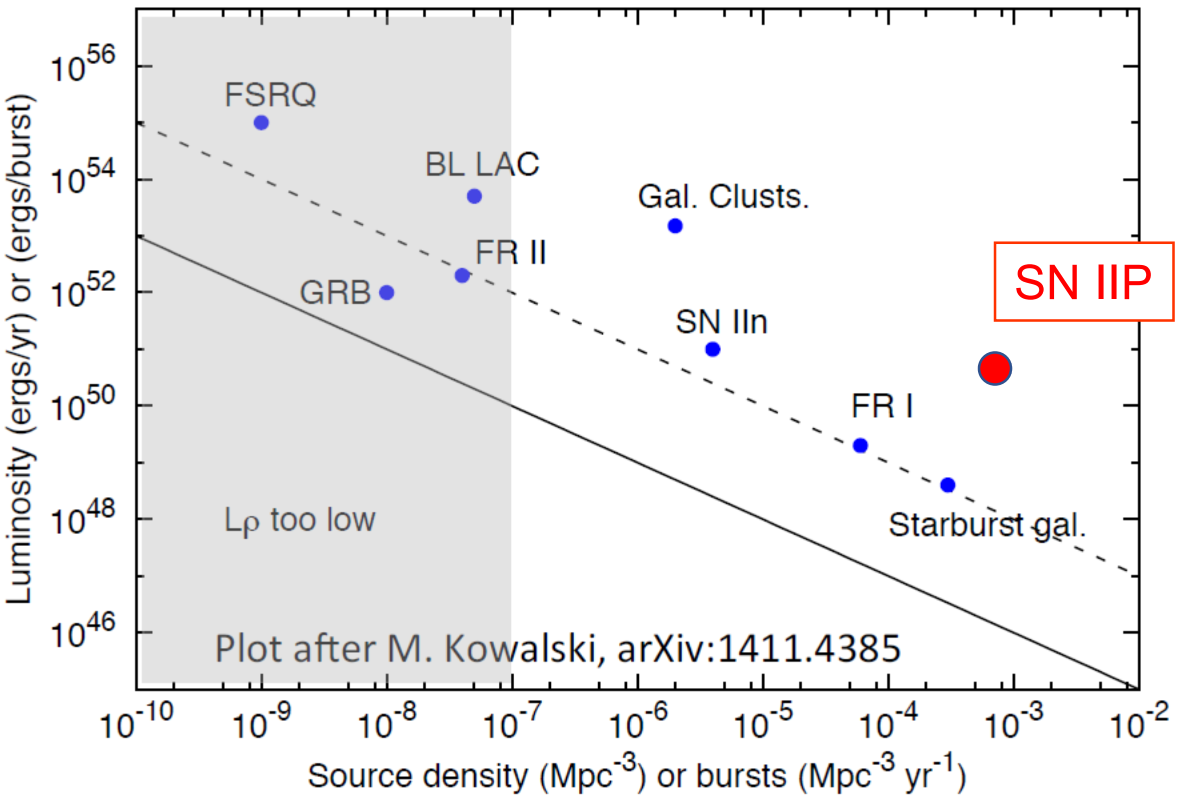
Implication from point source limits and presence of (strong) diffuse flux

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