Young supernovae populating our universe with high energy neutrinos and gamma-rays

Prantik Sarmah

Indian Institute of Technology Guwahati
North Guwahati-781039, Assam, India
Email: prantik@iitg.ac.in

In Collaboration with **Sovan Chakraborty** (IITG), **Irene Tamborra** (NBI) and **Katie Auchettl** (UM).

Based on JCAP 08 (2022) 08, 011

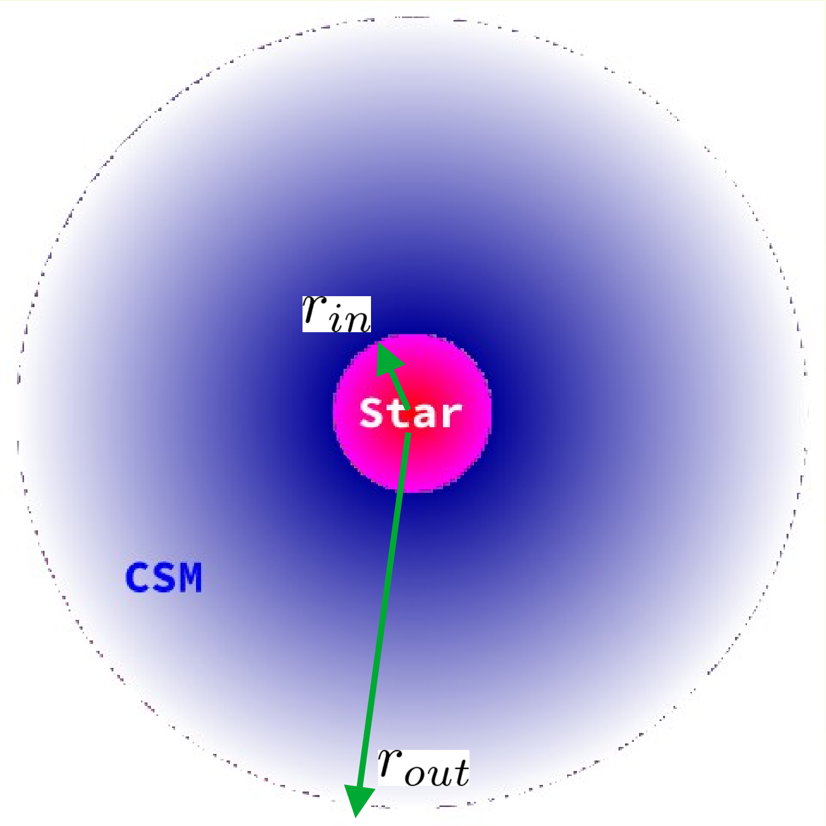
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS-43rd Course
Erice, Sicily, 20-09-2022

Outline

- Introduction
- Model of Neutrino and gamma-ray emission
- Diffuse backgrounds
- Results
- Summary and Conclusion

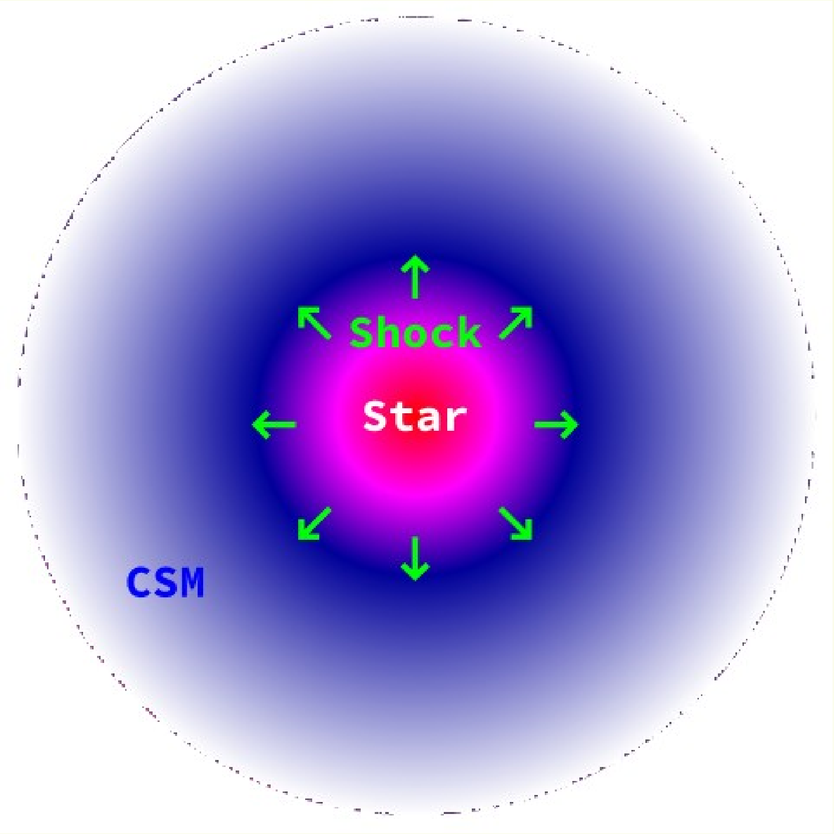
Introduction

- Supernova (SN) explosion is death of a star.
- Core Collapse Supernovae (CCSNe).
- Heavy mass loss prior to explosion $\sim 1 M_{\odot} yr^{-1}$
- Formation of a dense circumstellar medium (CSM), mostly protons. Density~r^{-2}.



Ref: astro-ph/0110060, 1012.2834, 1402.1237

- SN ejecta interacts with CSM.
- Formation of shockwaves.
- Particle acceleration via Fermi's diffusive shock acceleration.
- Proton-proton collisions.



$$pp \longrightarrow \pi^{\pm} + \pi^{0}$$

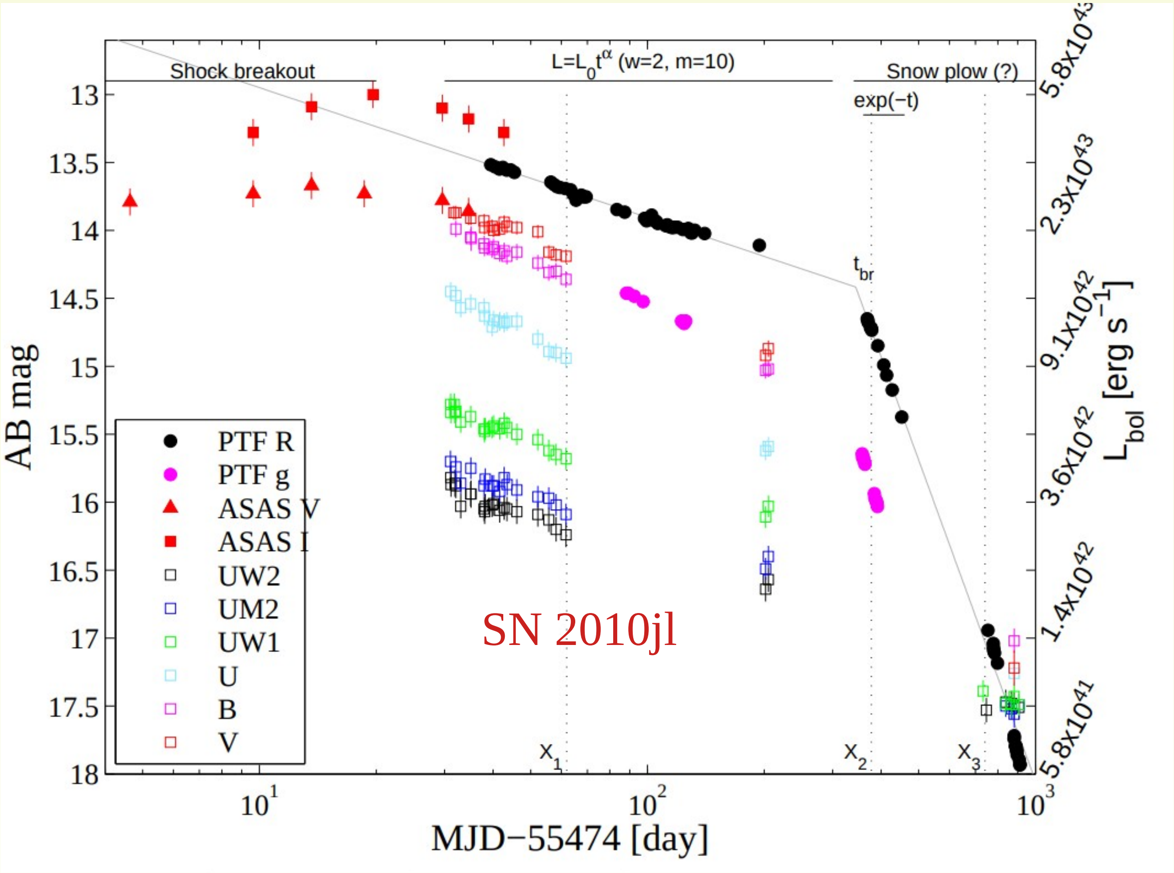
$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}$$

$$\pi^{0} \longrightarrow 2\gamma$$

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu_{\mu} + \nu_{e}$$

Ref: 1705.04750, 1705.06752, PRD 74, 034018

Duration of interaction~ a few months-years

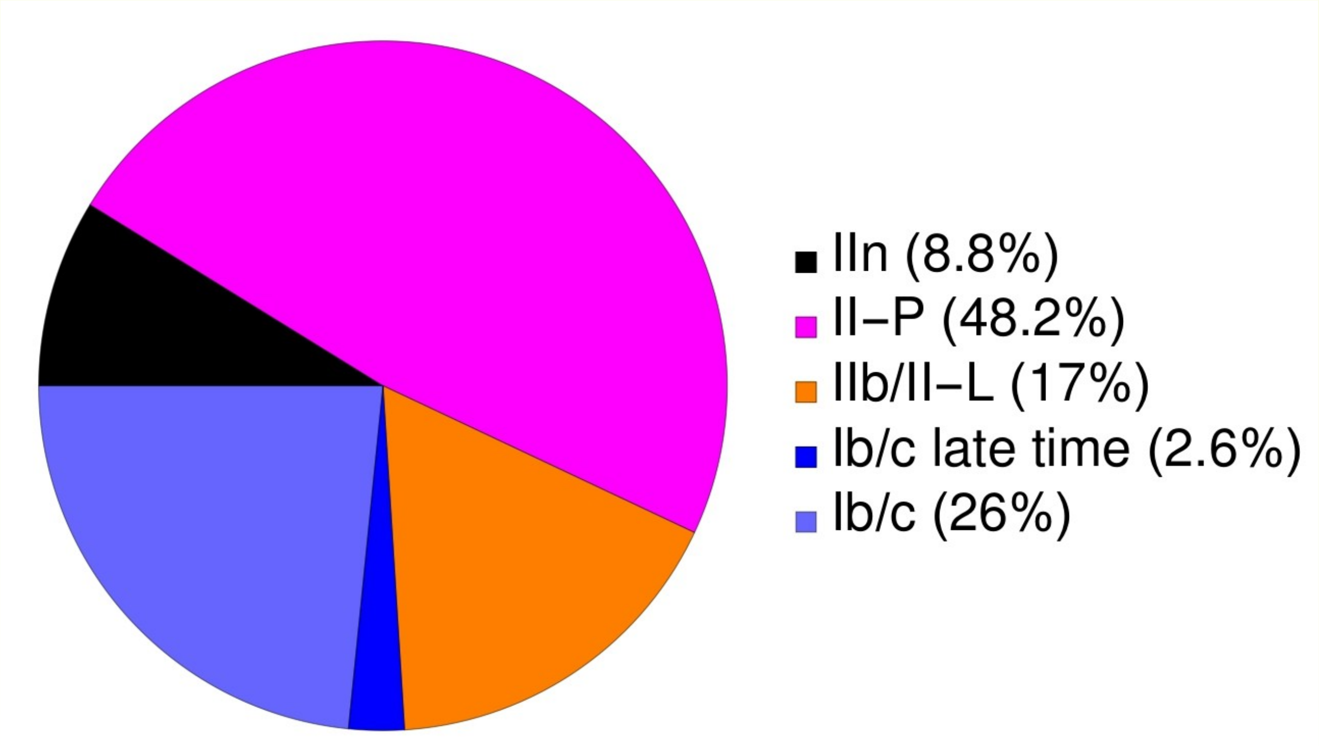


Young supernovae (YSNe) ~ 1 Year

Ref: 1307.2247

Goal: Calculate fluxes of these ν and γ from YSNe

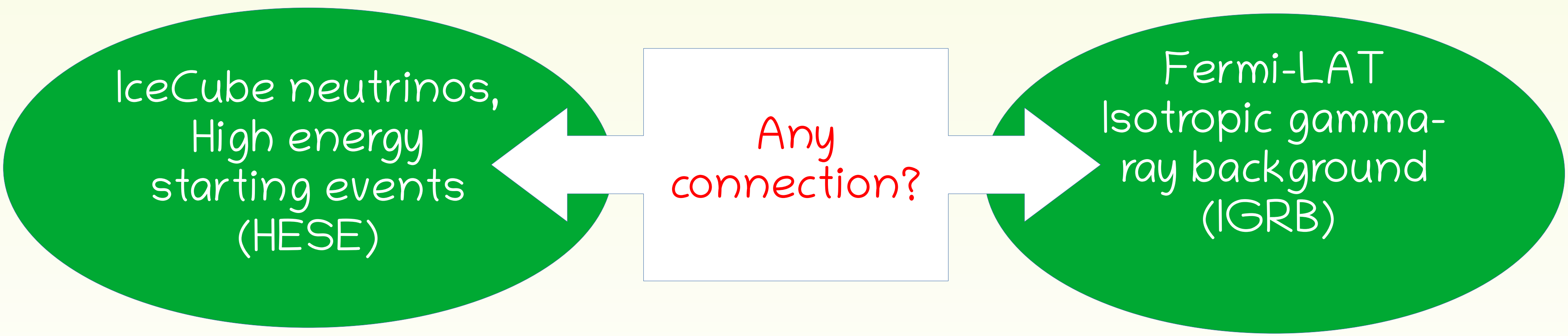
Types of CCSNe:



Ref: 1006.3899, 1601.06806

Goal: Calculate fluxes of these ν and γ from YSNe

Why?



Hadronic origin: pp interaction

Ref: 2011.03545, 1410.3696, PRD 74, 034018

Model of Neutrino and gamma-ray emission

Production rate
(Kelner et al. 2006)

$$\phi_{source}(E_{\nu/\gamma}, r) \propto n_{CSM}(r) \times N_p(E_p, r) \times F_{\nu/\gamma}$$

CSM density:

$$n_{CSM} = n_{in}\left(\frac{r_{in}}{r}\right)^2$$

Inner radius

Initial CSM density

Mass-loss rate, wind velocity

Ref: 1705.06752, 1603.00891

Accelerated protons:

Power law index, generally 2

$$N_p(E_p, r) \propto E_p^{-\alpha} \exp\left(-\frac{E_p}{E_{p,max}(r)}\right)$$

Maximum proton energy

$E_{p,max}(r)$ depends on:

- Acceleration, pp loss and adiabatic loss time scales.
- Shock velocity (v_{sh}), CSM density (n_{in}), magentic field (ϵ_B).

Normalisation:

- Total energy of the accelerated protons = $\epsilon_p \times$ Shock kinetic energy.

fraction

~10^4 km/s 10^{-4}-10^{-2}

Essential parameters: v_{sh}, n_{in}, ϵ_B, ϵ_p

~10^{11} cm^{-3} 0.01-0.1

Gamma-ray absorption:

$$\gamma + \gamma_{SN} \longrightarrow e^- + e^+$$ (Dominant)

$$\gamma + N \longrightarrow N + e^- + e^+$$

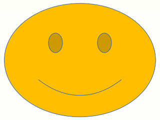
Attenuation factor:

$$f_a = e^{-\tau_{\gamma\gamma}}$$ ← Optical depth

$\tau_{\gamma\gamma}$
- SN Photon density: SN peak luminosity.
- average energy ($\sim$ 1 eV)

Electromagnetic cascade:

- Electrons and positron lose energy.
- Might annihilate to create gamma-rays.

$\phi_{source}(E_{\nu/\gamma}, r)$ is ready! 

Ref: 1807.01460, 1603.00891, 1406.1099

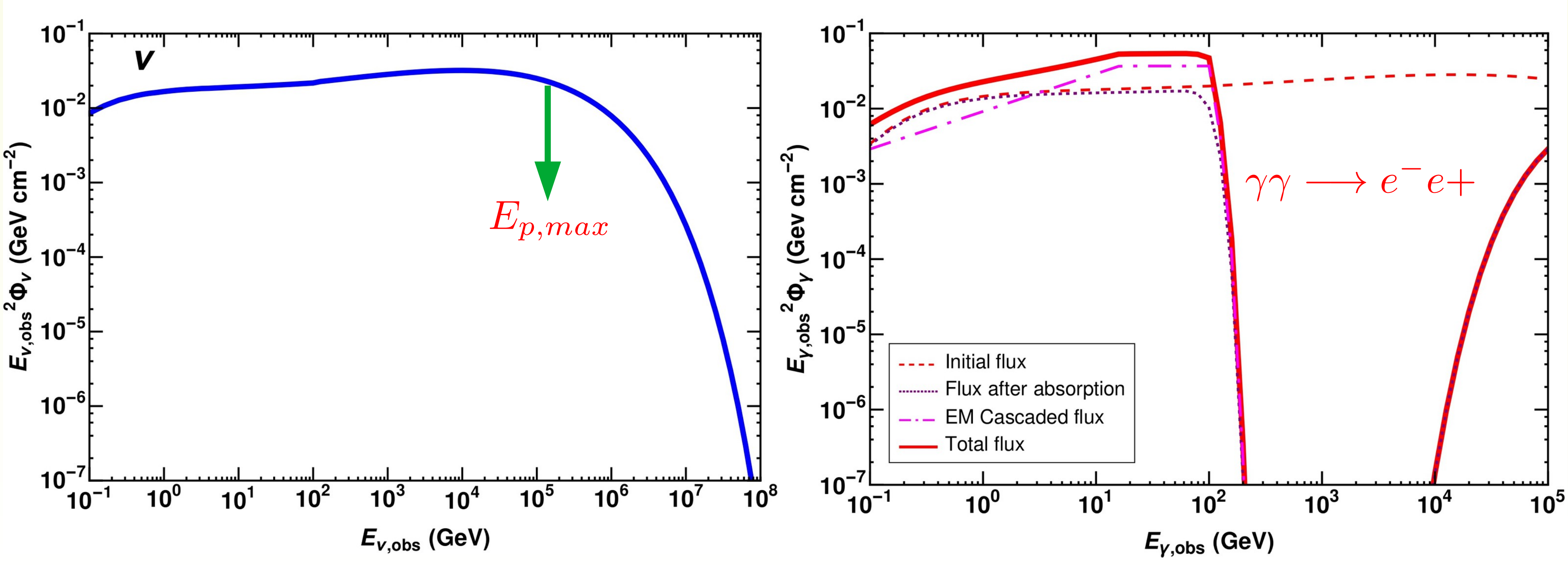
Flux at earth from distance d:

$$\phi_{\nu/\gamma}(E_{\nu/\gamma}, r) = \frac{\phi_{source}(E_{\nu/\gamma}, r) \times f_a}{4\pi d^2}$$

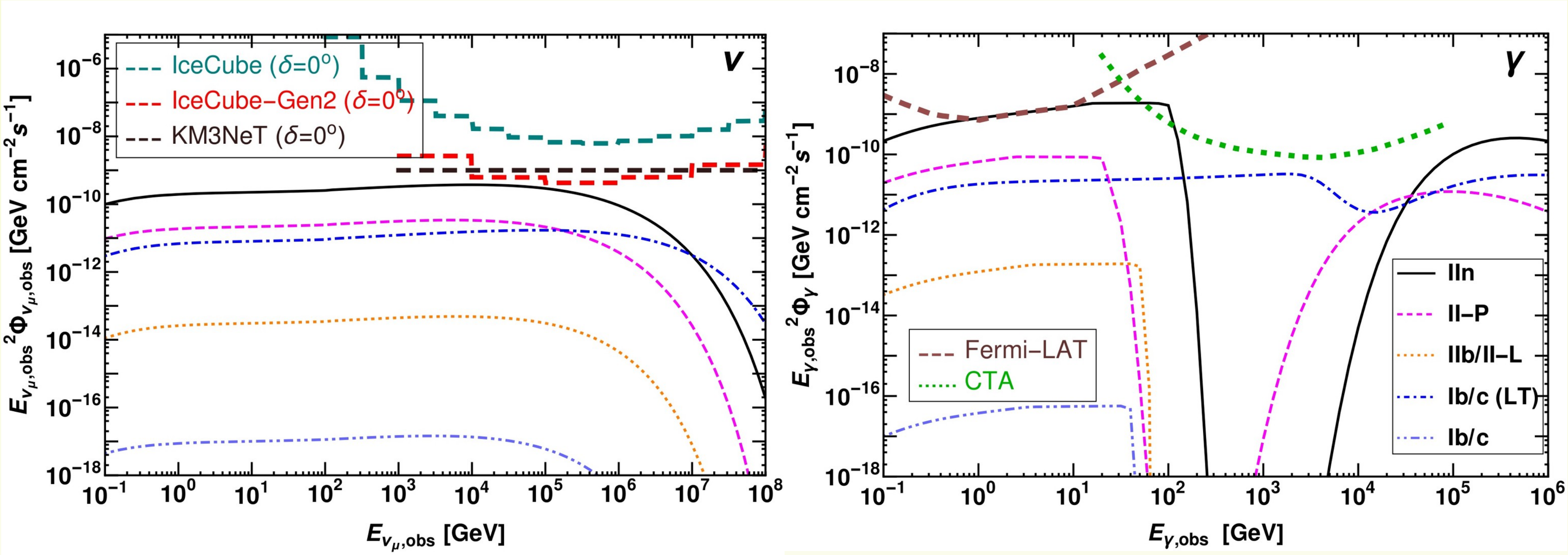
Time evolution: $r = v_{sh} t$

Example: Type IIn at 10 Mpc (Integrated for 1 yr)

$$n_{in} \sim 10^{11} cm^{-3},\ v_{sh} = 10^4\ km\ s^{-1}, \epsilon_B \sim 0.01,\ \epsilon \sim 0.01$$



Detection prospects at 10 Mpc:



- IIn produces largest flux.
- Neutrino detectors < 10 Mpc, but gamma-ray detectors ~ 10 Mpc for IIn.
- Other YSNe < 10 Mpc.

Diffuse backgrounds

Rate of CCSN → $R_{\rm CCSN}(z)$; Source flux → $\phi_{\rm j}^{\rm s}(E_{\rm j})$

$$E^2_{\rm j,obs}\phi_{\rm j,diff}(E_{\rm j,obs}) = \zeta \frac{c}{H_0}\int_0^{z_{\rm max}} {\rm d}z \frac{R_{\rm CCSN}(z) E_{\rm j}^2 \phi_{\rm j}^{\rm s}(E_{\rm j})}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} e^{-\tau_{\rm j,EBL}(E_{\rm j},z)}$$

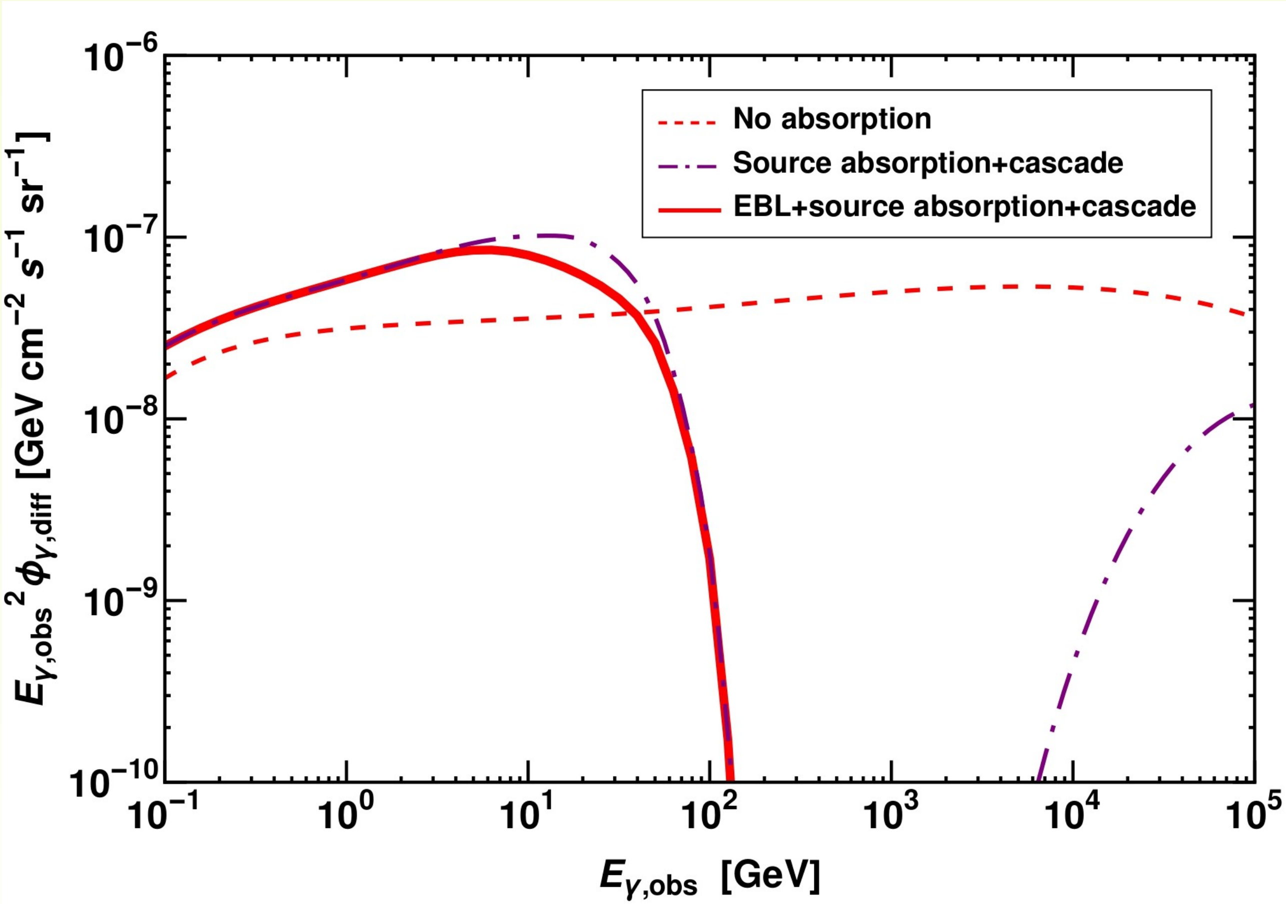
$j = \nu$ orγ $\quad\quad$ $\zeta:$ fraction YSN type

$\tau_{\rm j,EBL}(E_{\rm j}, z)$: Optical depth of extra-galatic background light (EBL).
Neutrinos: 0, Gamma-rays: Stecker et al.

$$H_0 = 68\ km\ s^{-1} Mpc^{-1}, \quad \Omega_m = 0.31, \quad \Omega_\Lambda = 0.69$$

Ref: 1509.06574, 1403.0007

Effect of EBL, example: IIn

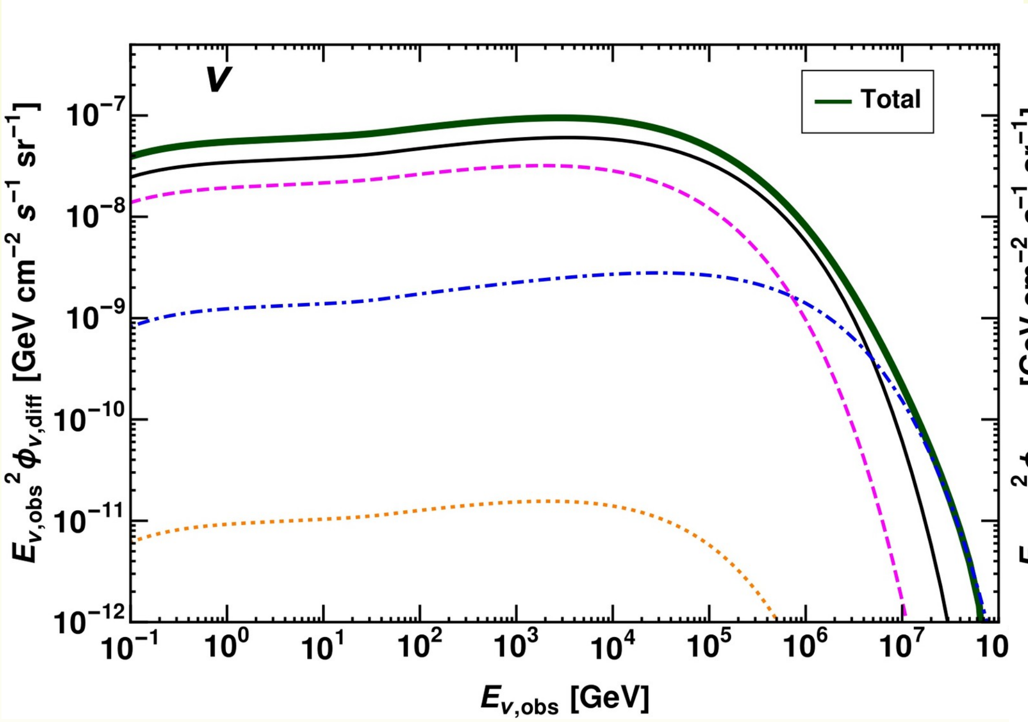


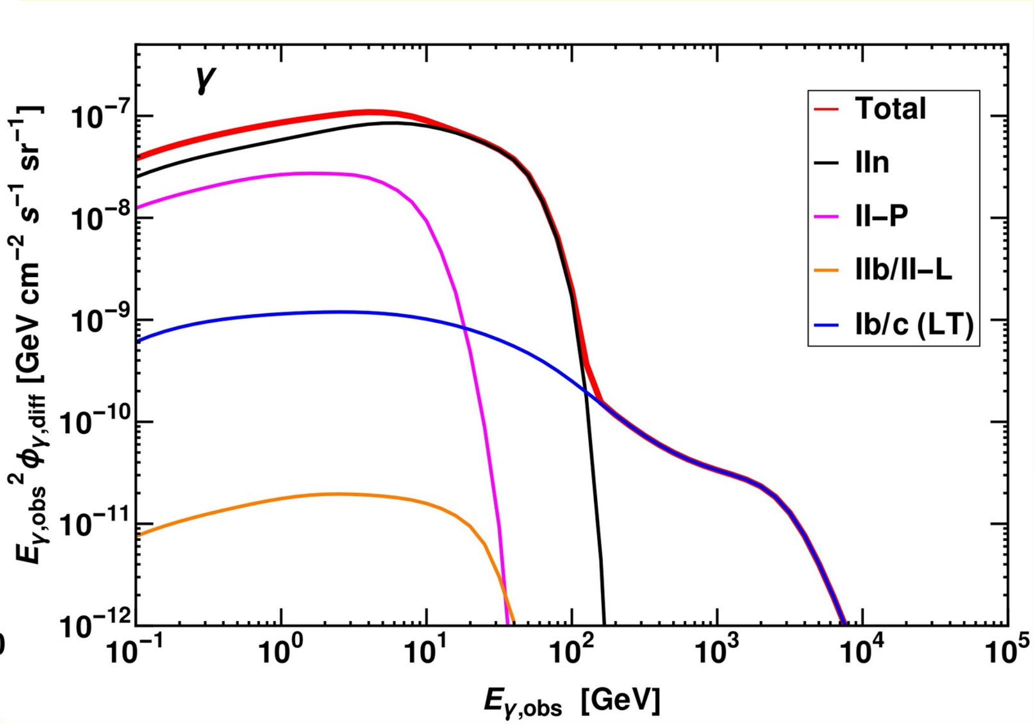
$\gamma\gamma_{SN} \longrightarrow e^- e^+$

$\gamma\gamma_{EBL} \longrightarrow e^- e^+$

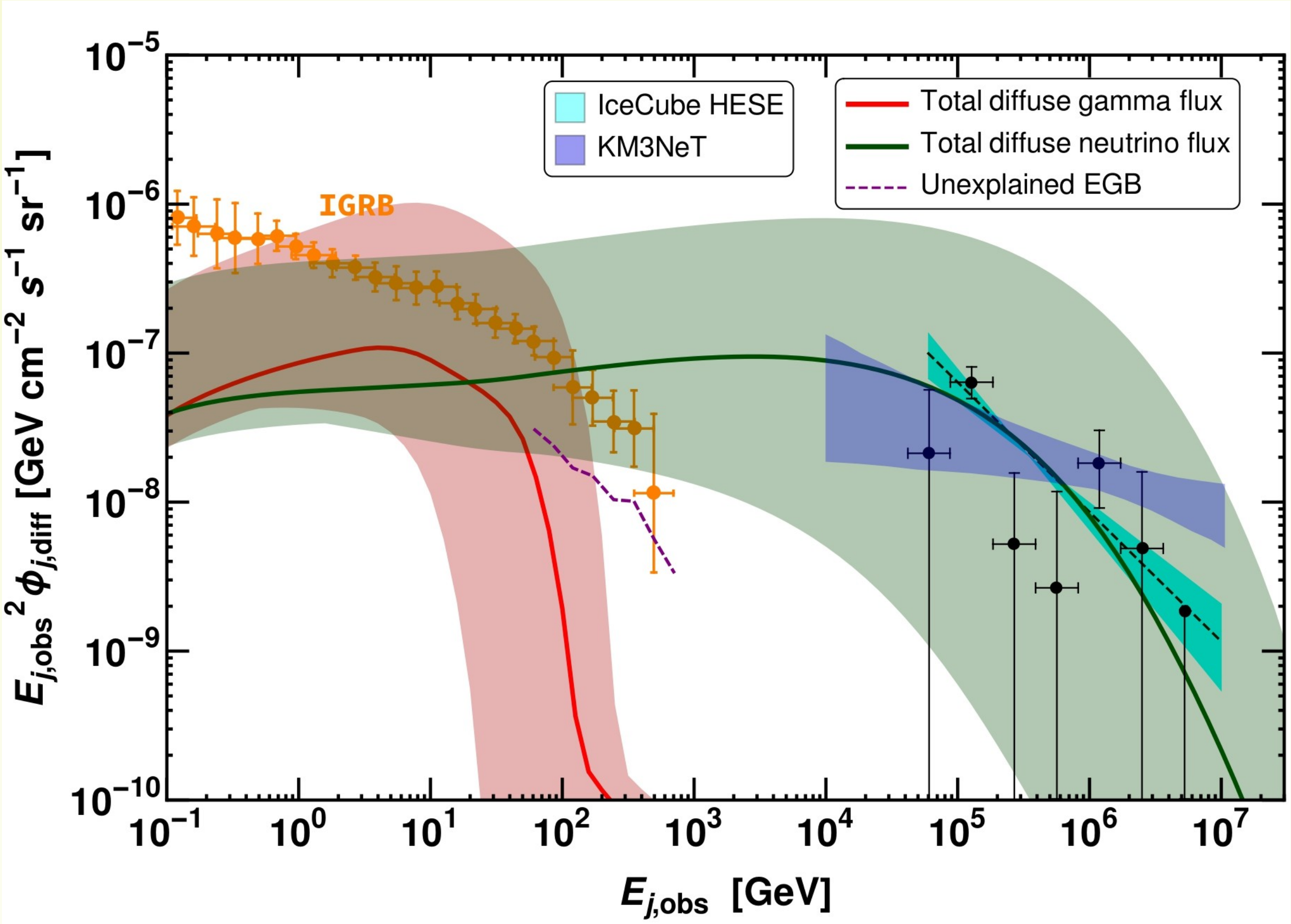
Results

Diffuse flux for YSN types:





- Type IIn is dominant.
- Important contributions from II-P and Ib/c late time.



$v_{sh} \sim (5-20)\times 10^3$ km s^{-1}

$\epsilon_p \sim 0.01 - 0.1$

$\epsilon_B \sim 10^{-4} - 10^{-2}$

- Explains the IceCube HESE data.
- Fermi-LAT IGRB is not disturbed.
- Multi-messenger constraint excludes some parameter space.

Ref: 2011.03545, 1410.3696, 1511.00693, 1501.02615, 2109.07598

Summary and Conclusion

- Neutrino & gamma-ray fluxes estmated for different YSN types.
- Type IIn produces largest flux in both neutrinos and gamma-rays. IceCube-Gen2 and Fermi-LAT ~ 10 Mpc.
- Type IIn dominates diffuse backgrounds, significant contribution from II-P and Ib/c (LT) as well.
- Total diffuse neutrino background explains the IceCube HESE data.
- Total diffuse gamma-ray background does not create tension to the Fermi-LAT IGRB.

Thank you!

Questions?

Backup slides

pp loss timescale

$$t_{\rm pp} = (\kappa_{\rm pp}\sigma_{\rm pp}(E_{\rm p})n_{\rm CSM}(r)c)^{-1}$$

Acceleration timescale

$$t_{\rm acc} = \frac{6E_{\rm p}c}{eBv_{\rm sh}^2}$$

Adiabatic/dynamic timescale

$$t_{\rm ad} \sim t_{\rm dyn} = \frac{r}{v_{\rm sh}}$$

E_{max} is obtained by

$$t_{\rm acc} = \min\left[t_{\rm pp}, t_{\rm ad}\right]$$

Backup slides

pp loss timescale

$$t_{\rm pp} = (\kappa_{\rm pp}\sigma_{\rm pp}(E_{\rm p})n_{\rm CSM}(r)c)^{-1}$$

Acceleration timescale

$$t_{\rm acc} = \frac{6E_{\rm p}c}{eBv_{\rm sh}^2}$$

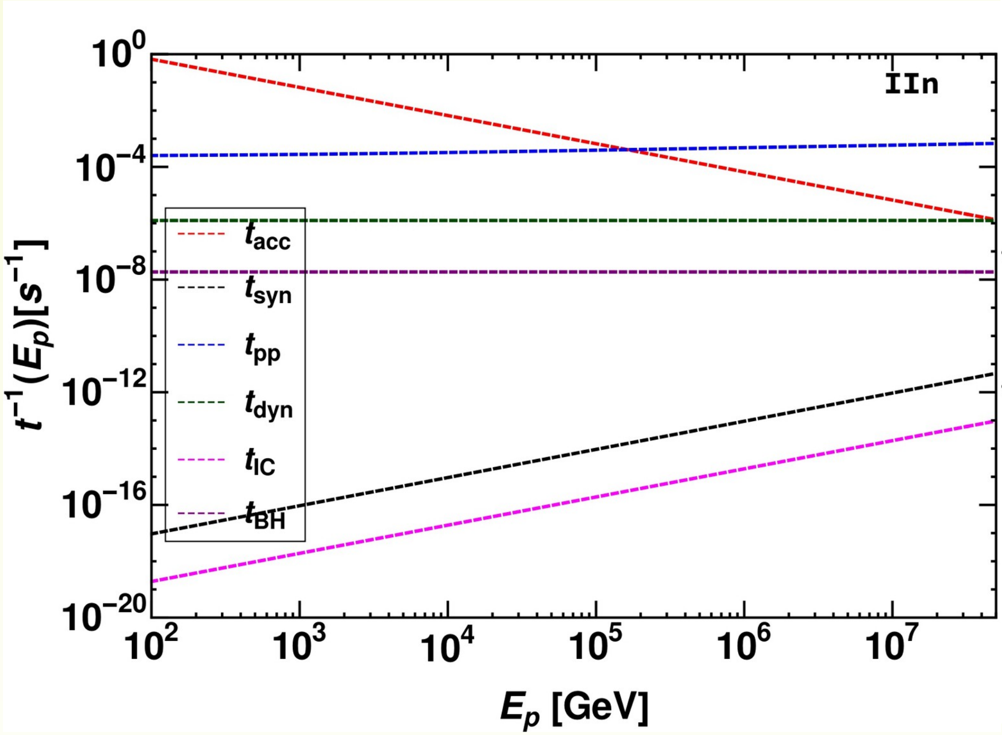
Adiabatic/dynamic timescale

$$t_{\rm ad} \sim t_{\rm dyn} = \frac{r}{v_{\rm sh}}$$

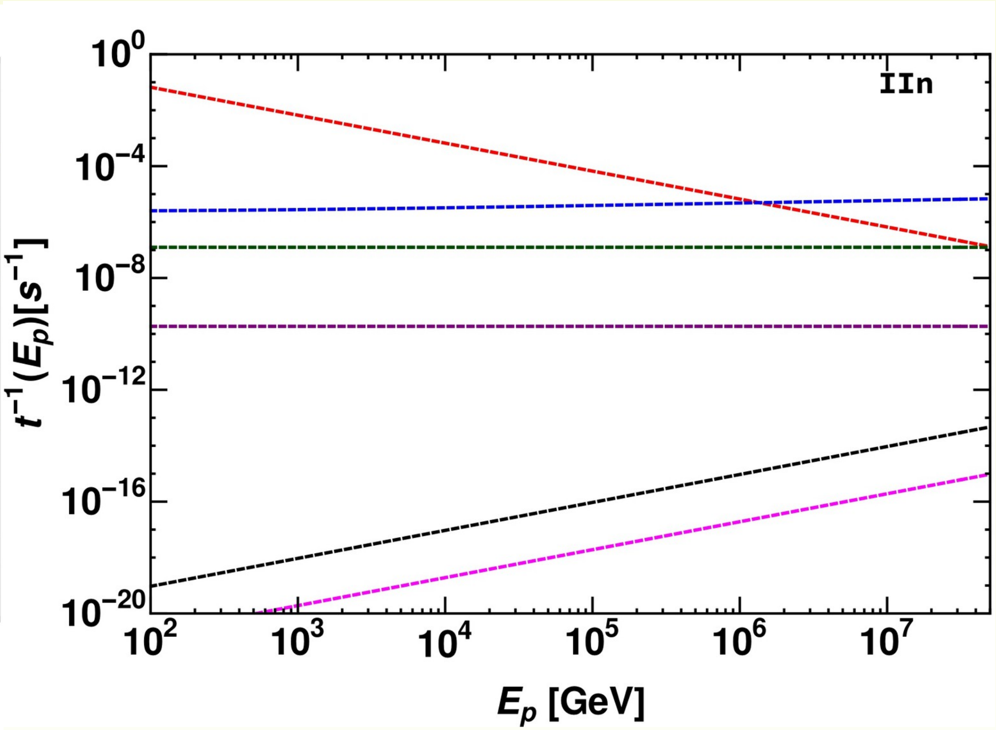
E_{max} is obtained by

$$t_{\rm acc} = \min\left[t_{\rm pp}, t_{\rm ad}\right]$$

Different loss timescales for IIn:



$r = r_{in}$

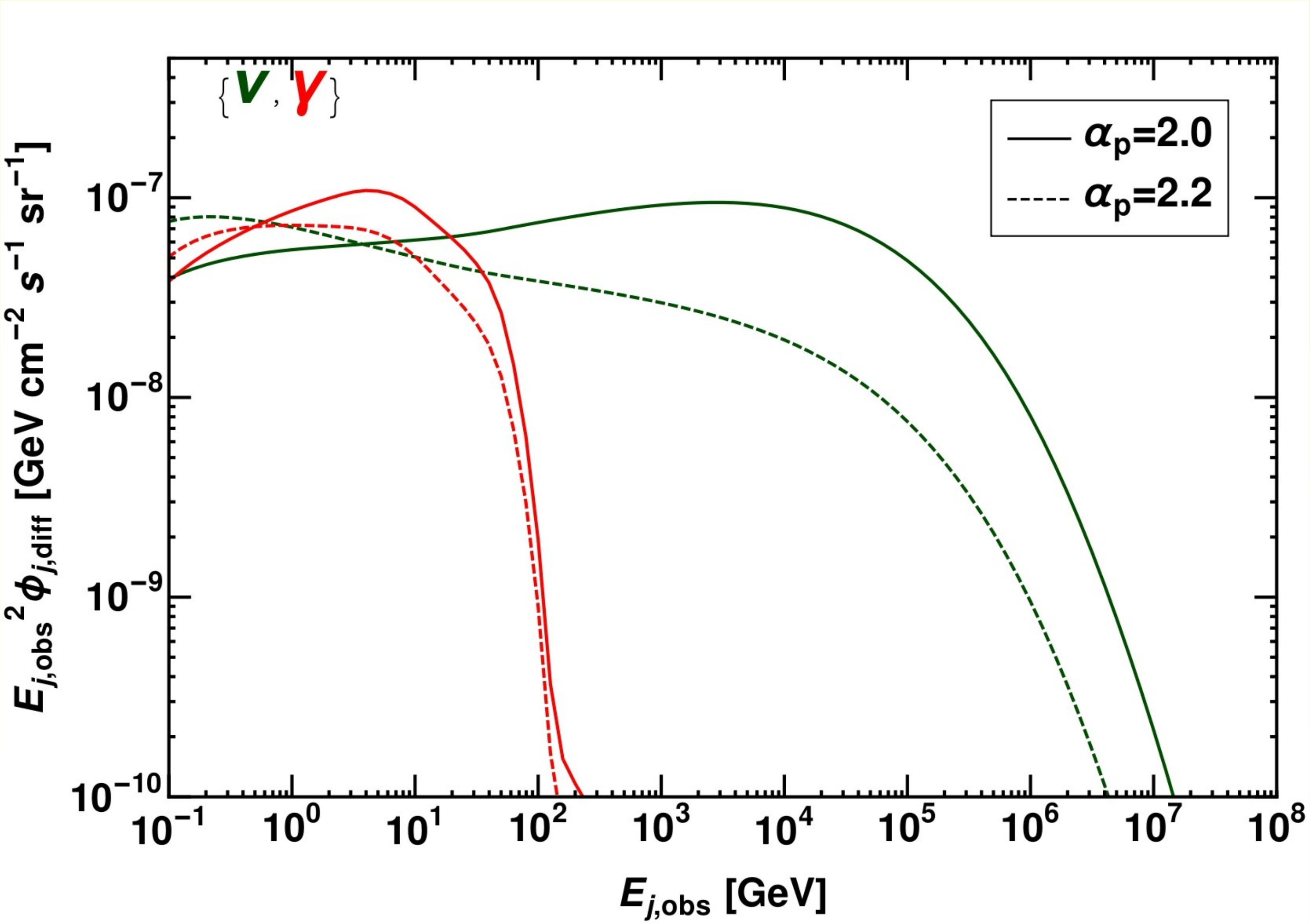


$r = 10r_{in}$

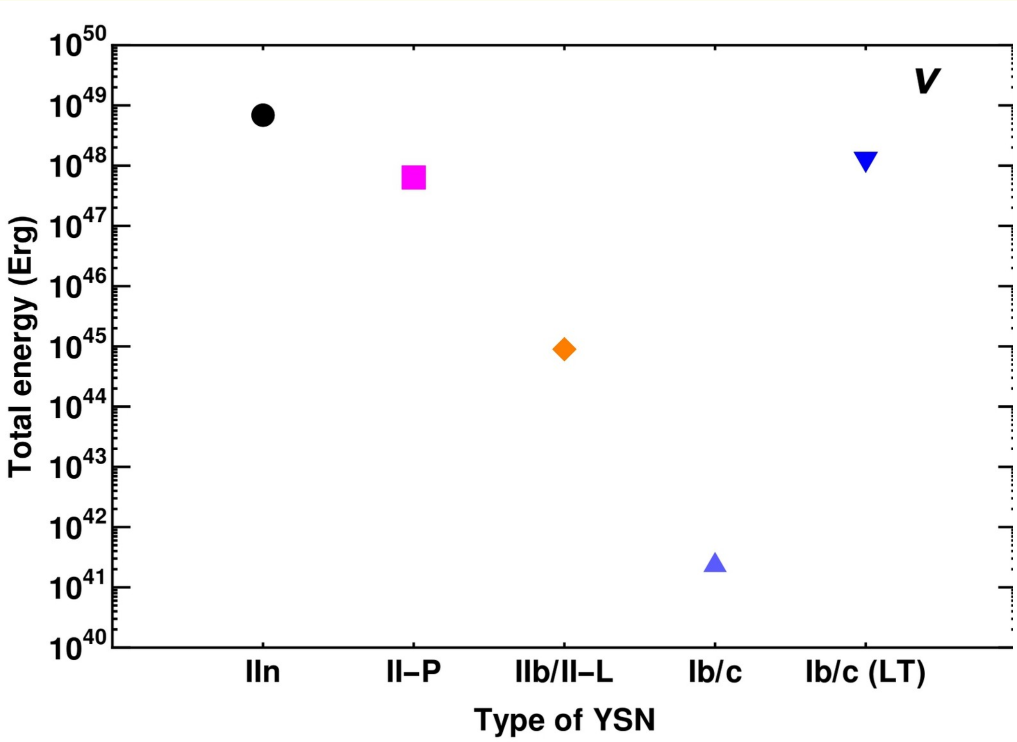
Table of parameters:

Parameters	**IIn** (1 yr)	**II-P**		**IIb/II-L** (1 yr)	**Ib/c** (1 yr)	**Ib/c (LT)** (1.5 yrs)
		Eruptive (≤ 12)	**Normal** (> 12 days)			
$n_{\rm in,CSM}$ ($\rm cm^{-3}$)	10^{11}	10^{12}	10^{9}	6×10^{11}	2.4×10^{12}	2×10^{6}
$\dot{\rm M}_W$($\rm M_\odot$ yr^{-1})	10^{-1}	10^{-2}	2×10^{-6}	3×10^{-5}	10^{-5}	2×10^{-2}
$v_{\rm w}$ ($\rm kms^{-1}$)	10^{2}	10^{2}	1.5×10^{1}	3×10^{1}	10^{3}	10^{2}
$r_{\rm out}$ (cm)	2×10^{16}	10^{15}	3×10^{16}	3×10^{16}	6×10^{16}	10^{17}
$v_{\rm sh}$ ($\rm kms^{-1}$)	7×10^{3}	10^{4}	10^{4}	10^{4}	2×10^{4}	10^{4}
$r_{\rm in}$ (cm)	4×10^{14}	6×10^{13}	6×10^{13}	6×10^{12}	3×10^{11}	5×10^{16}
$\epsilon_{\rm p}$	10^{-2}	10^{-1}	10^{-1}	10^{-1}	10^{-1}	5×10^{-2}
$\epsilon_{\rm B}$	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}	10^{-2}

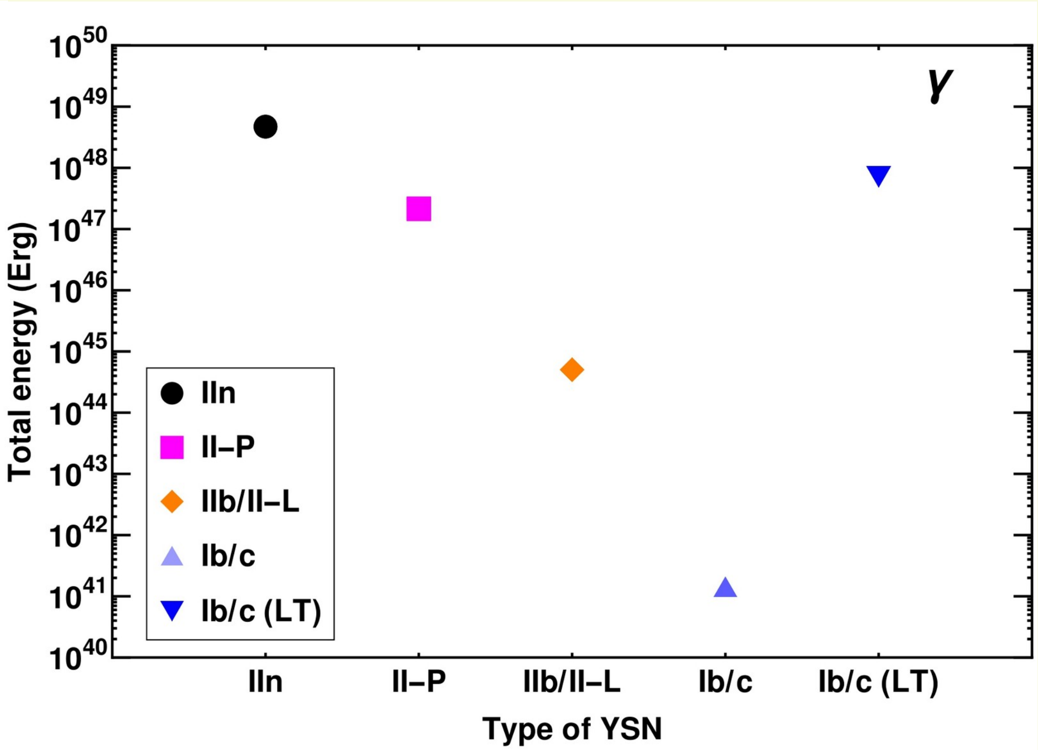
Dependence on power law:



Energetics:

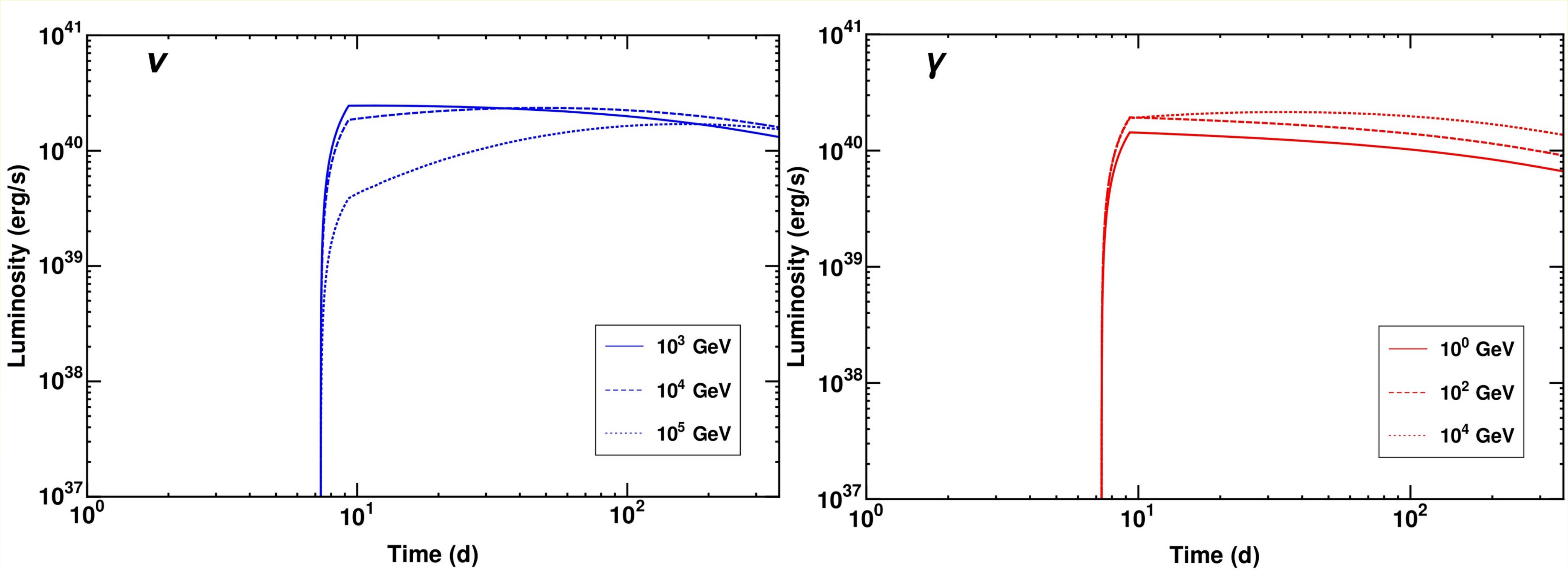


ν
Total energy (Erg)
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
10^{45}
10^{44}
10^{43}
10^{42}
10^{41}
10^{40}
IIn
II–P
IIb/II–L
Ib/c
Ib/c (LT)
Type of YSN

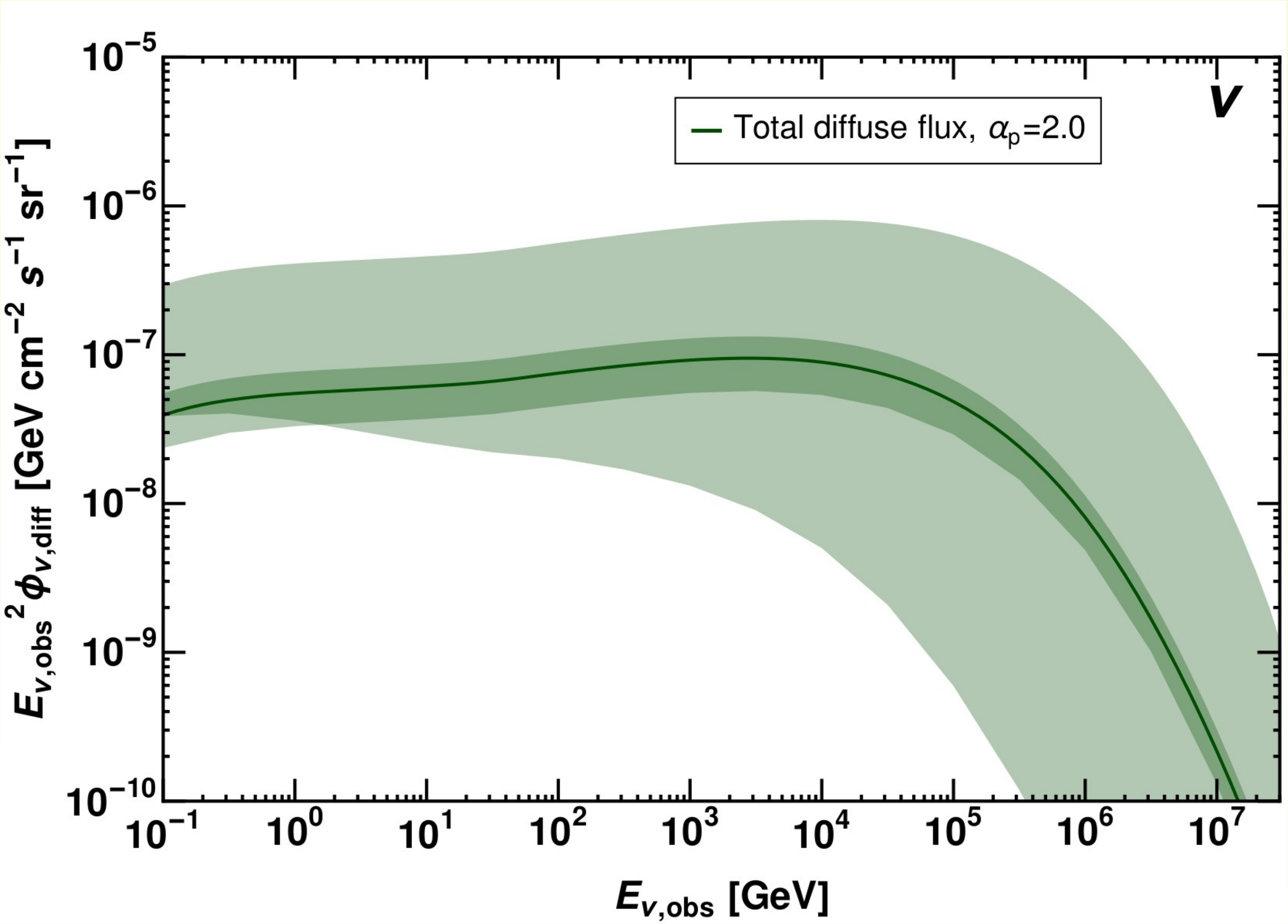


γ
Total energy (Erg)
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
10^{45}
10^{44}
10^{43}
10^{42}
10^{41}
10^{40}
IIn
II–P
IIb/II–L
Ib/c
Ib/c (LT)
IIn
II–P
IIb/II–L
Ib/c
Ib/c (LT)
Type of YSN

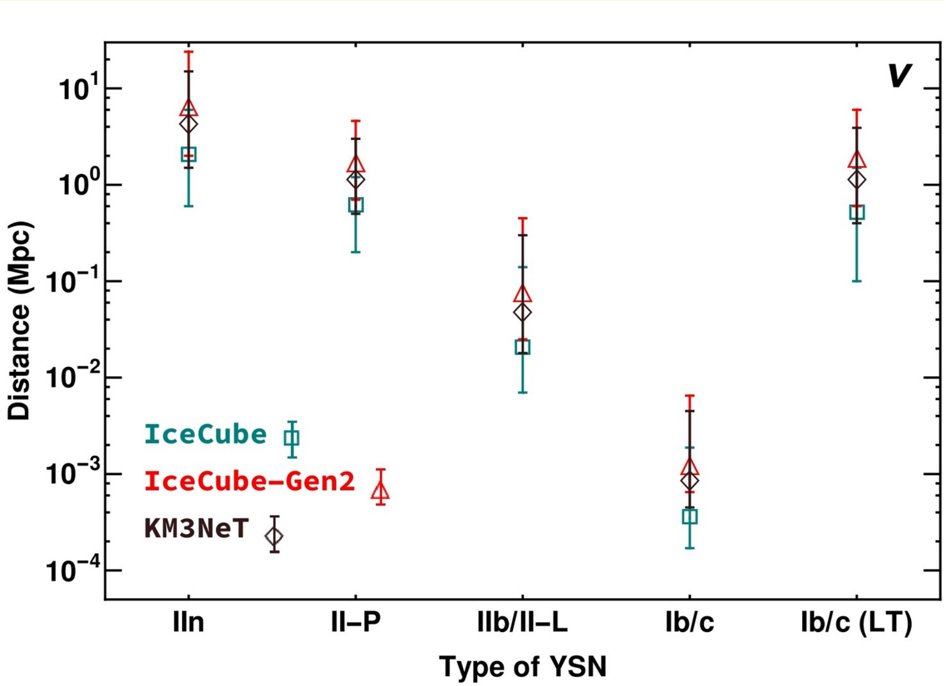
Light curves:

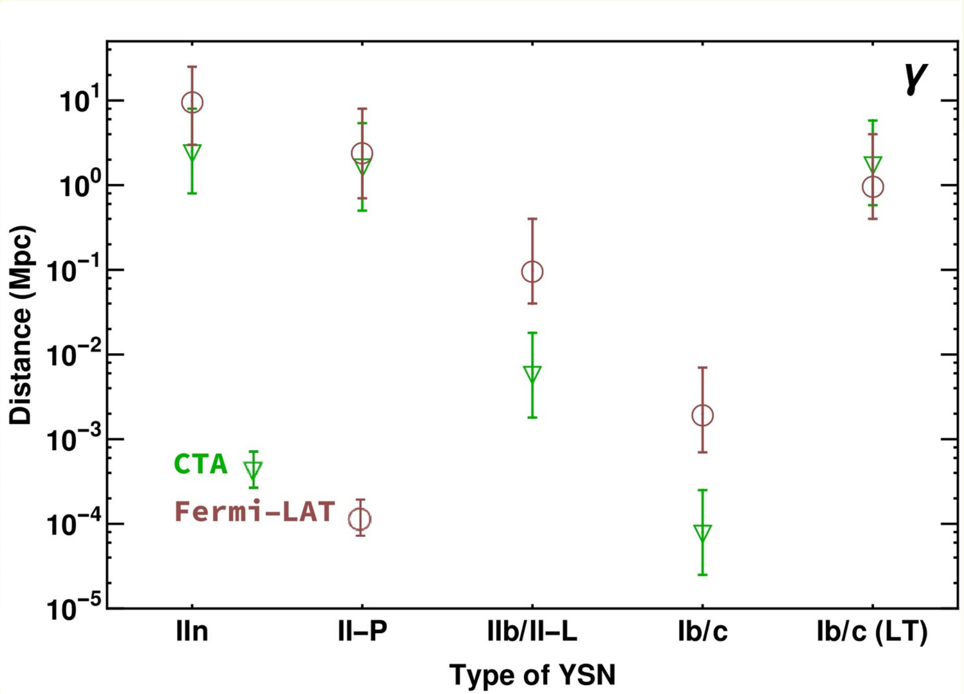


SN rate uncertainty:



Horizon of different detectors:





- IIn~6 Mpc for IceCube-Gen2, ~10 Mpc for Fermi-LAT.
- Other YSNe are detectable at smaller distances.