High-energy neutrinos from Type IIn supernovae

Maria Petropoulou
Purdue University

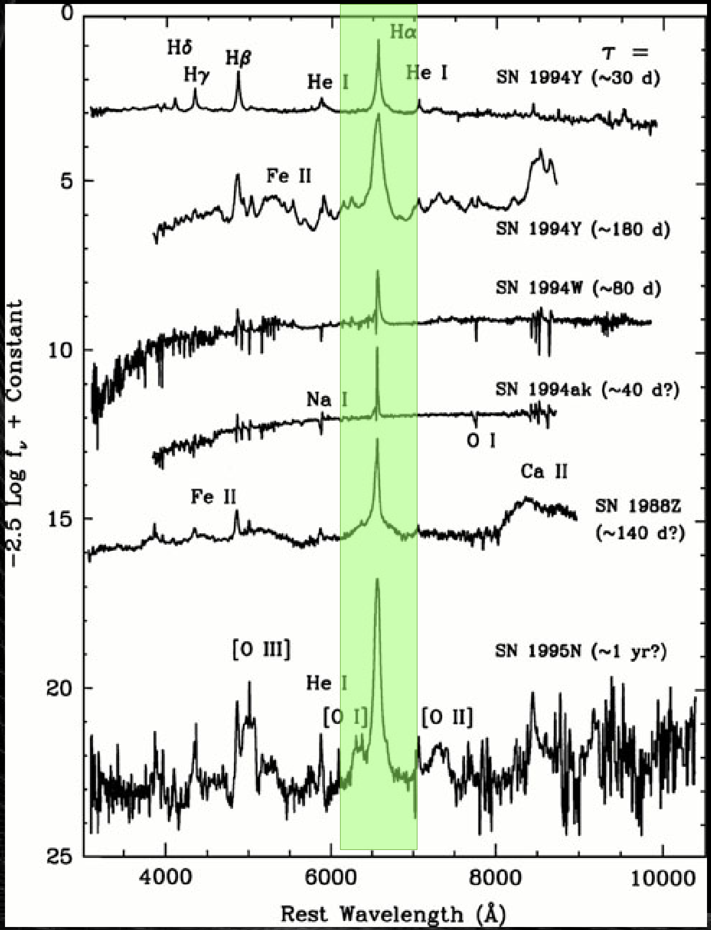
Columbus, Ohio , 08/10/2017

In collaboration with:

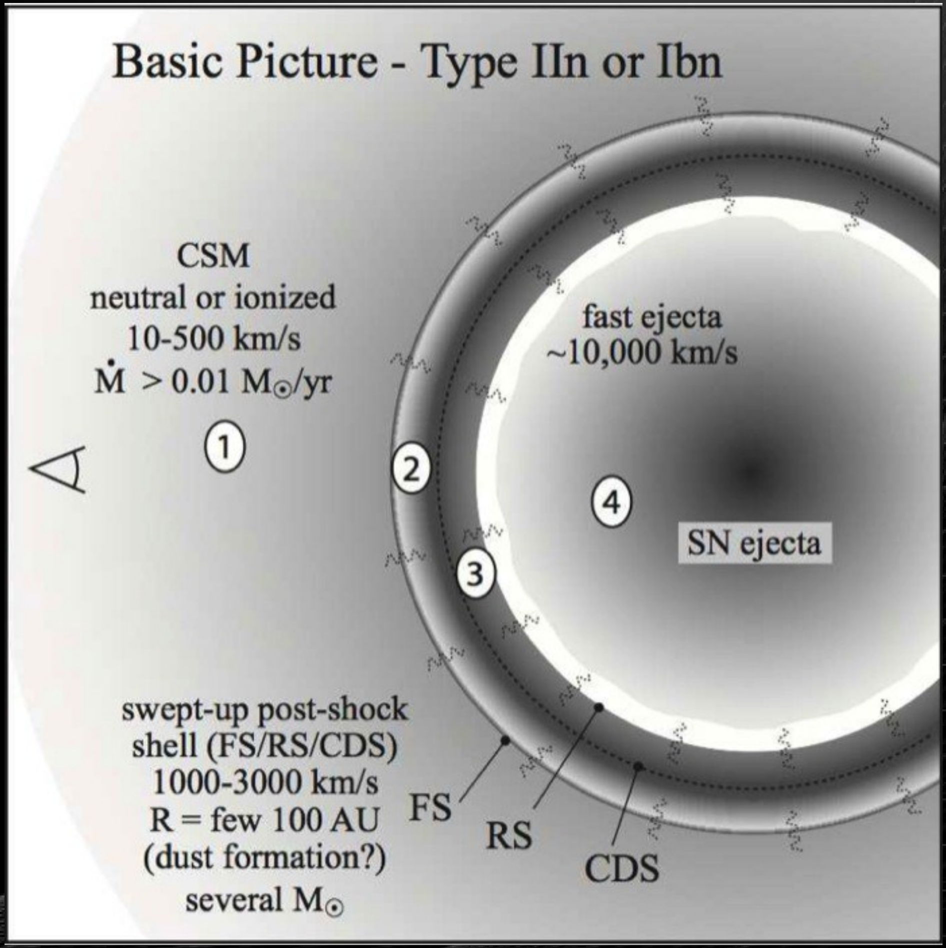
Stefan Coenders (TUM), Georgios Vasilopoulos (MPE), Atish Kamble (CfA-ITC), Lorenzo Sironi (Columbia University)

Type IIn SNe

- Narrow Ha lines, high bolometric and Ha luminosity → *Indication of circumstellar interaction (Chevalier 1982; Chevalier 1998; Weiler 2001; Chevalier & Fransson 2003 +++)*



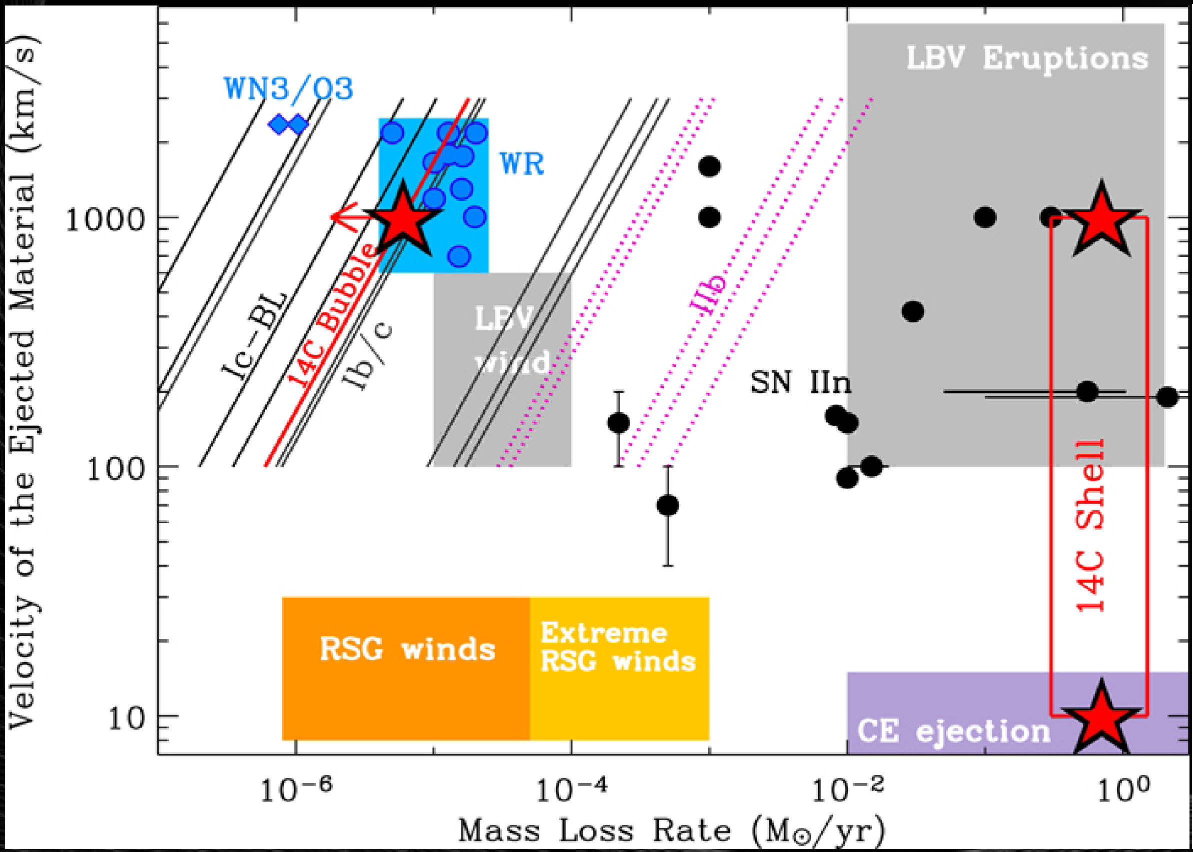
Fillipenko 1997

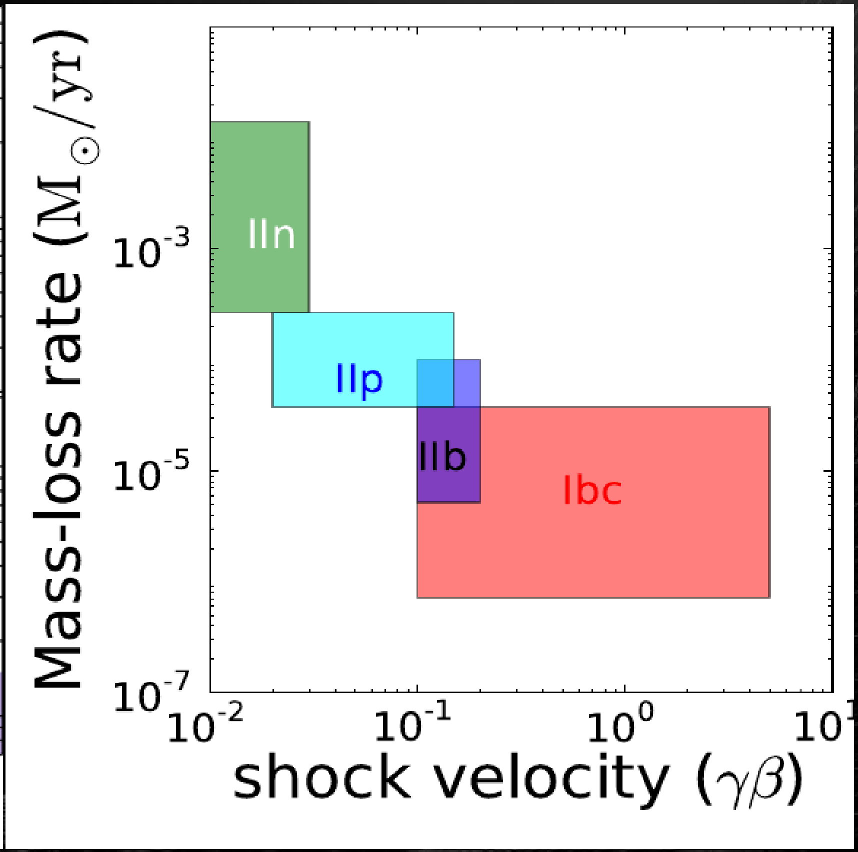


Smith 2016

Type IIn SNe

- High mass-loss rates (1e-4 –1e-1 $M_{\odot}$/yr) → *high luminosity of emission due to interaction* (Salamanca et al. 1998, Chugai et al. 2004, Chandra et al. 2015, Moirya et al 2014 +++)
- Diverse properties → *no typical SN*





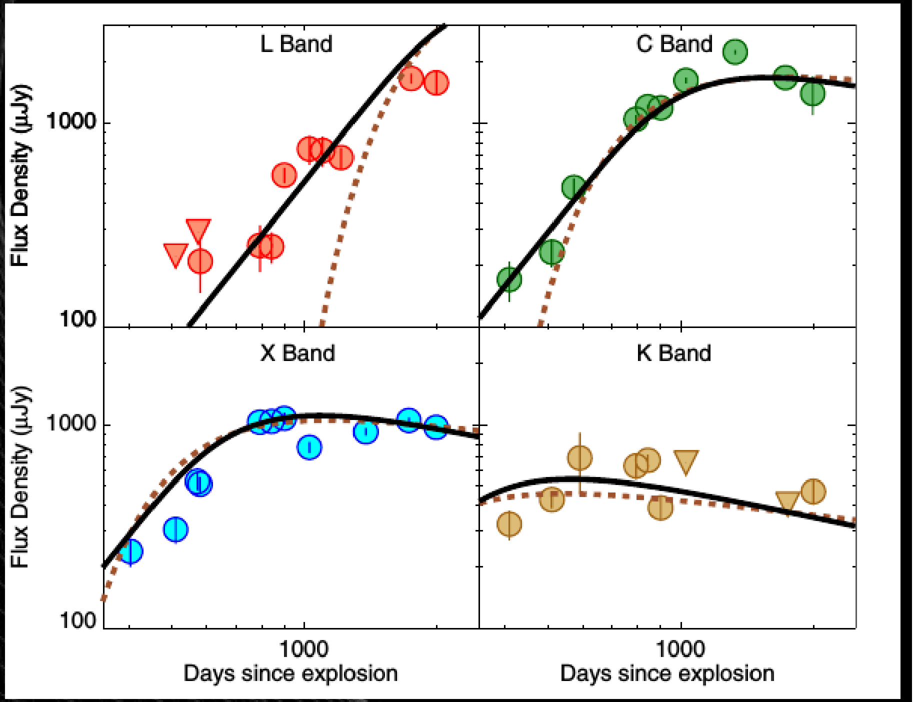
Margutti et al 2017

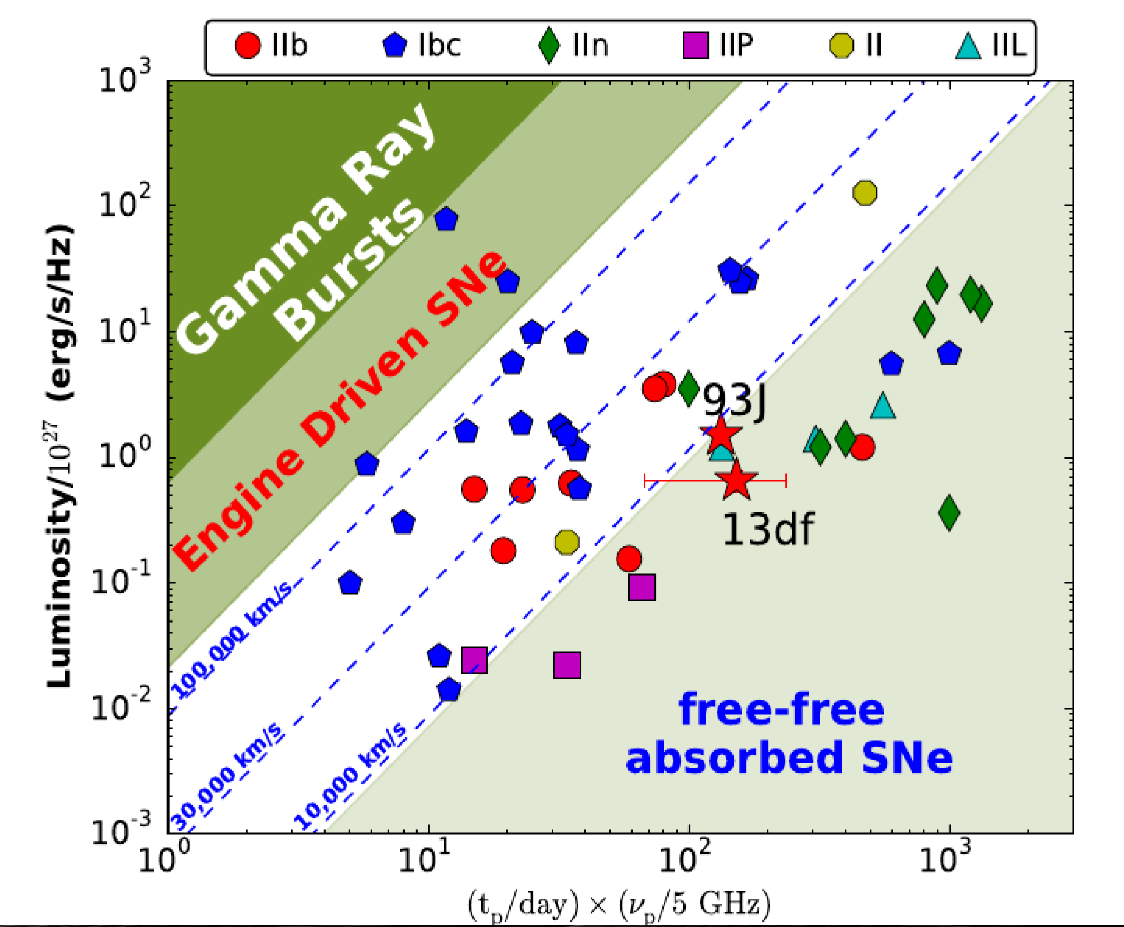
Credit: A. Kamble

Type IIn SNe

- Detection of radio emission → *Indication of electron acceleration at shocks*
- FFA absorbed radio emission → *Indication of very dense CSM*

Radio Flux



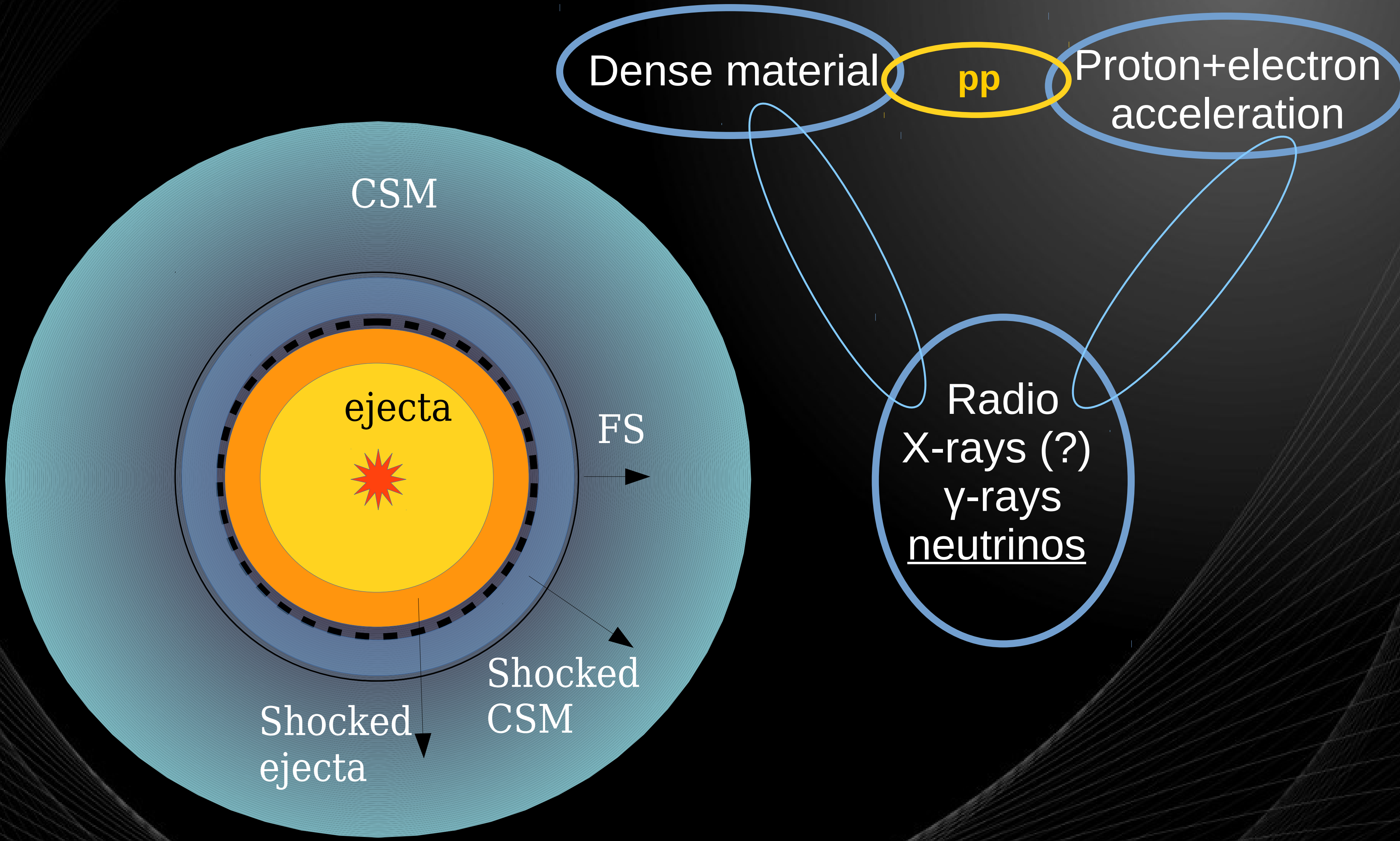


Time (days)

Chandra et al 2012

Kamble et al 2016

Type IIn SNe



(Murase et al. 2011, Margutti et al. 2014; Murase et al 2014; Petropoulou et al. 2016, Petropoulou et al. 2017)

Model ingredients

CSM: power-law density profile (n~ 1/ r^2)

Shock dynamics:
free expansion

Proton spectrum:
power law with evolving max, energy

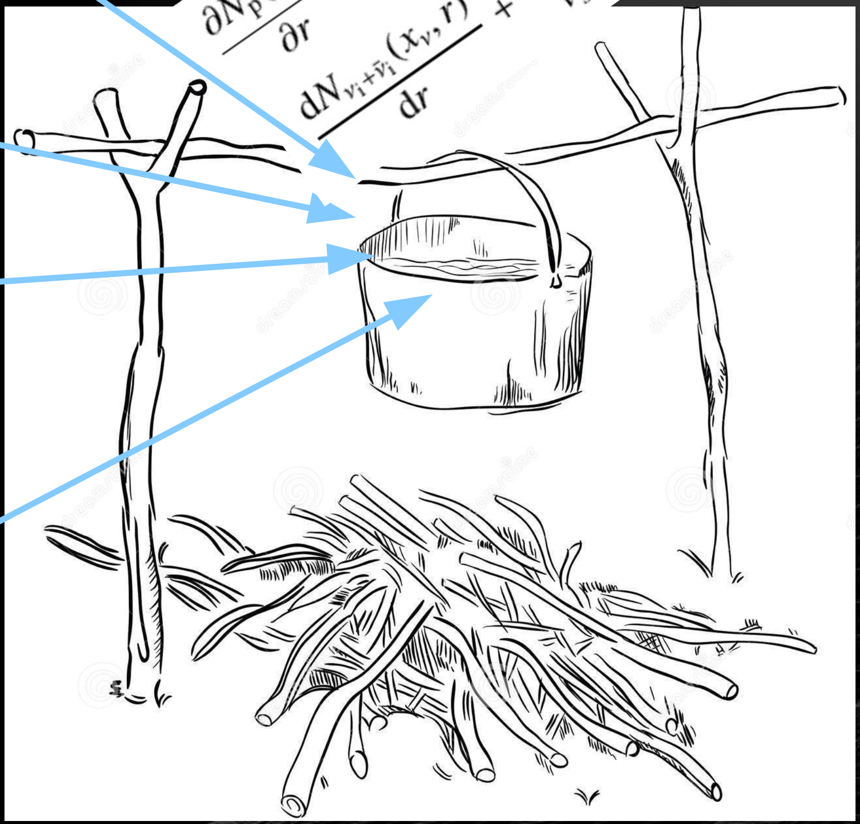
Physical processes:
adiabatic expansion & pp collisions

PROTONS

$$\frac{\partial N_{\rm p}(\gamma,r)}{\partial r} + \frac{N_{\rm p}(\gamma,r)}{v_{\rm sh} t_{\rm pp}(r)} - \frac{\partial}{\partial \gamma}\left[\frac{\gamma}{r} N_{\rm p}(\gamma,r)\right] = Q_{\rm p}(\gamma,r)$$

NEUTRINOS

$$\frac{dN_{\nu_i+\bar{\nu}_i}(x_\nu,r)}{dr} + \frac{N_{\nu_i+\bar{\nu}_i}(x_\nu,r)}{v_{\rm sh} t_{\rm esc}(r)} = Q_{\nu_i+\bar{\nu}_i}(x_\nu,r)$$



(Petropoulou et al. 2017)

Model parameters

Single source

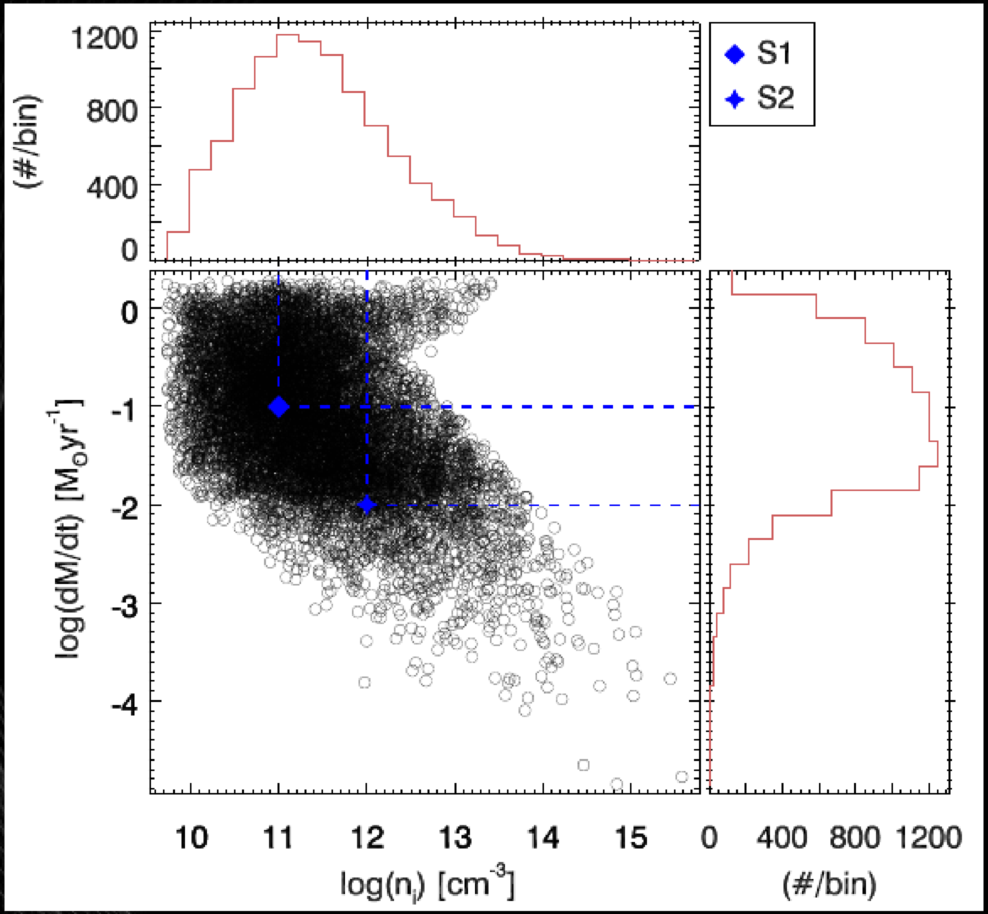
- Shock + wind velocity
- Ejecta + CSM mass
- Fraction of magnetic energy density (ε_B)
- Fraction of proton energy density (ε_p)

- Fraction of Type IIn SNe
- Redshift evolution of CC rate

Source population

Properties of simulated sources

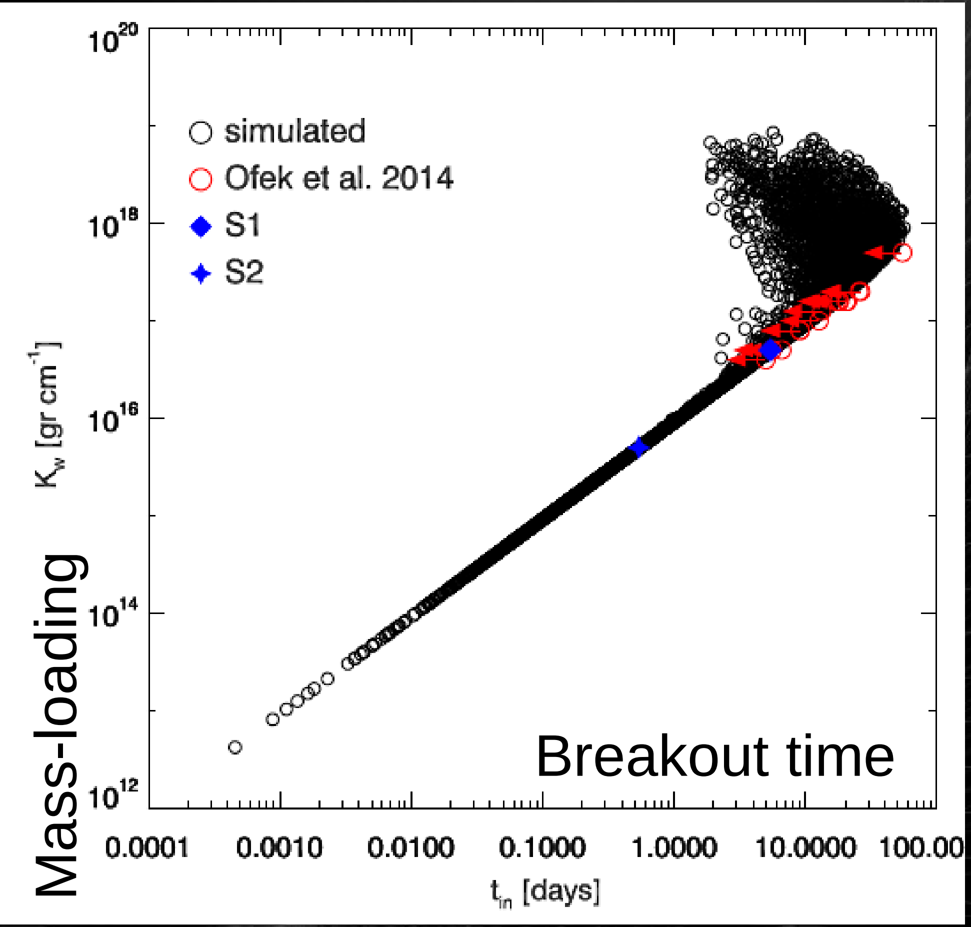
Mass-loss rate



Density at breakout (cm^{-3})

Novelty

- Monte Carlo calculations for diffuse neutrino emission
- 10,000 simulated sources



Mass-loading

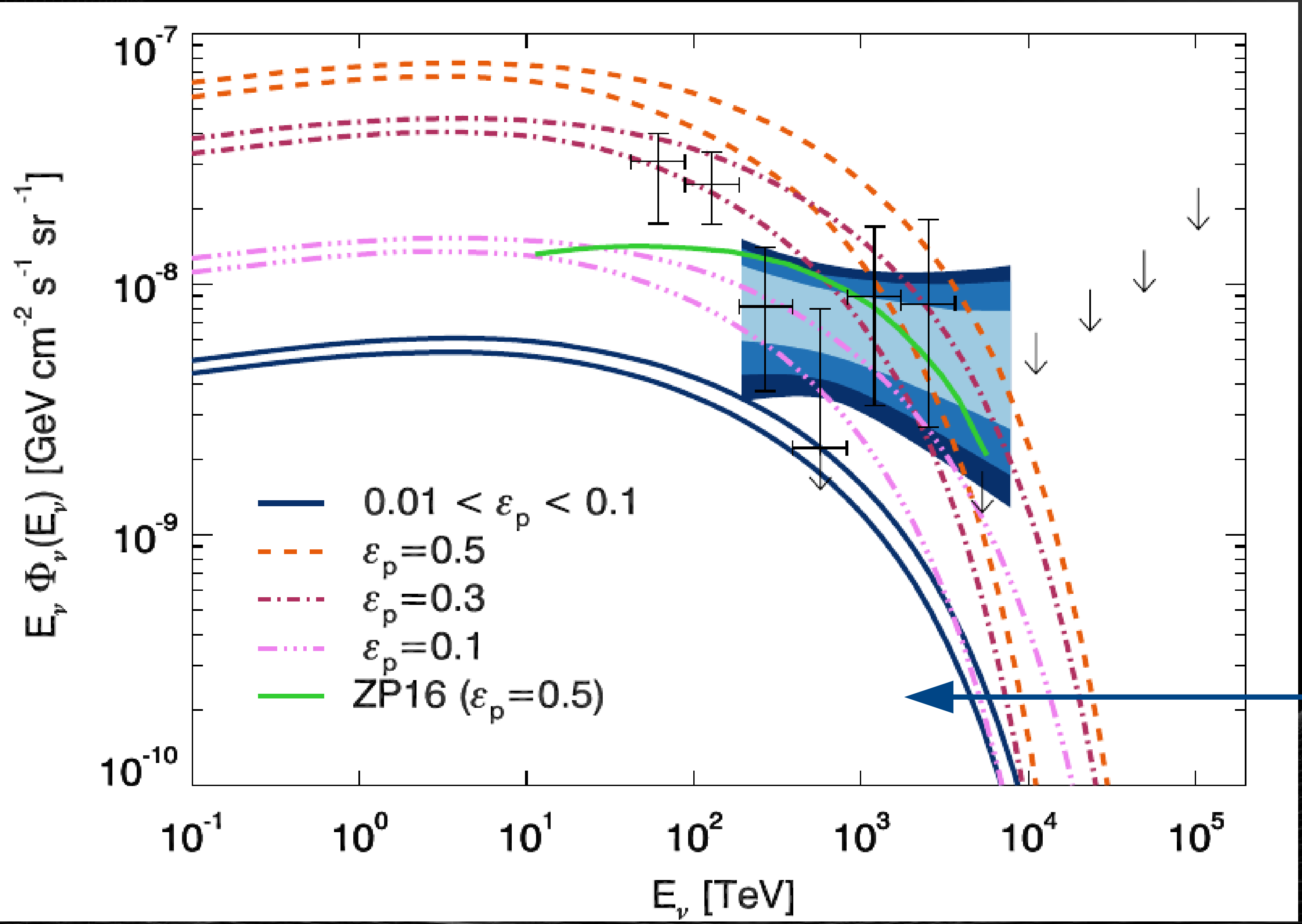
Breakout time

Mass-loading ~ dM/dt / v_w

Diffuse neutrino emission

- 10,000 simulated sources
- 100,000 redshifts
- 100 sets of 100,000 redshifts

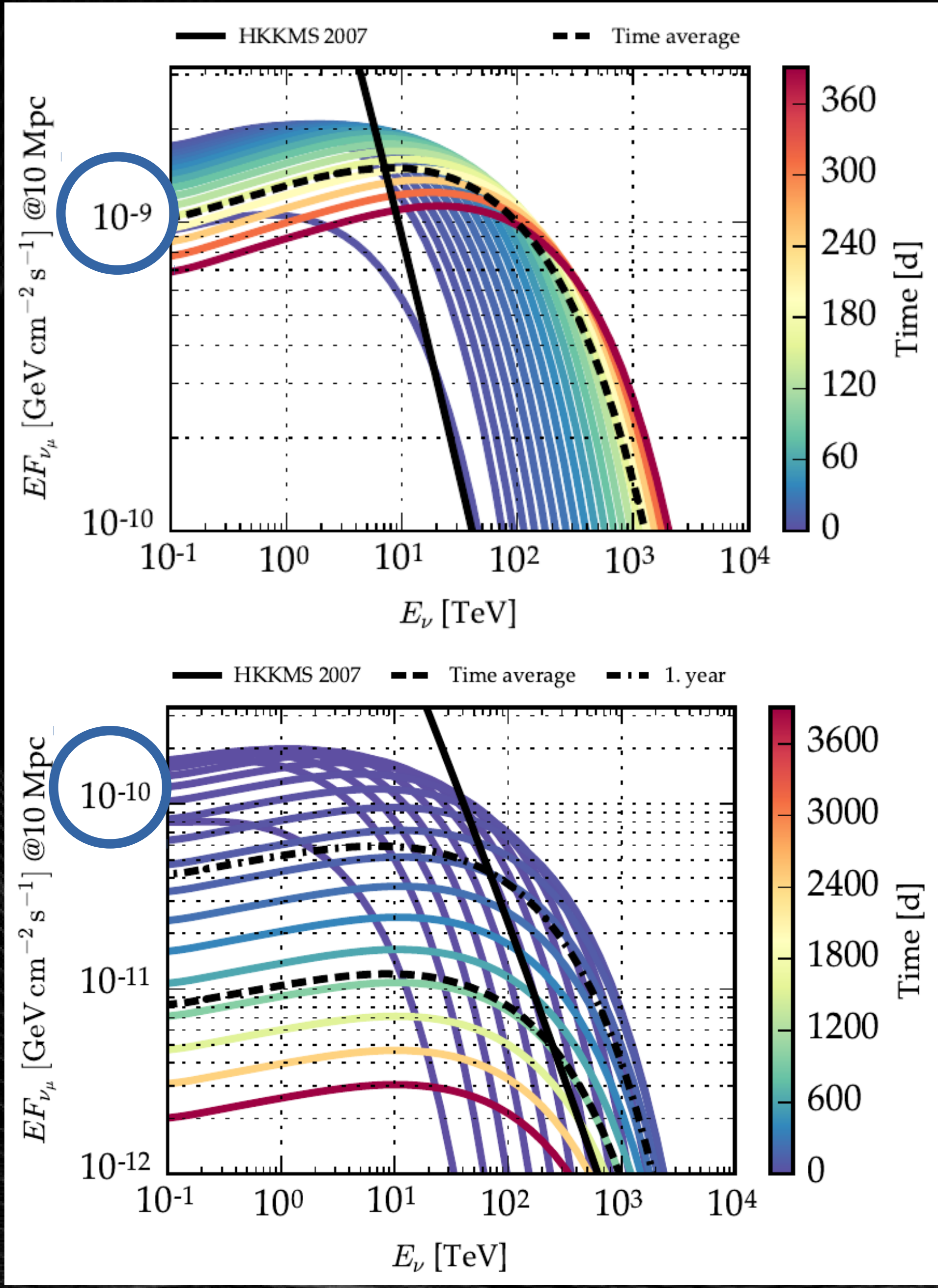
- CC rate *(Hopkins & Beacom 2006)*
- 4% of CC are SNe IIn



- Constraint on (fixed) proton energy fraction: $\varepsilon_p < 0.2$

- ~10% to IceCube flux, if ε_p differs among sources

Point-source neutrino emission



Source S1

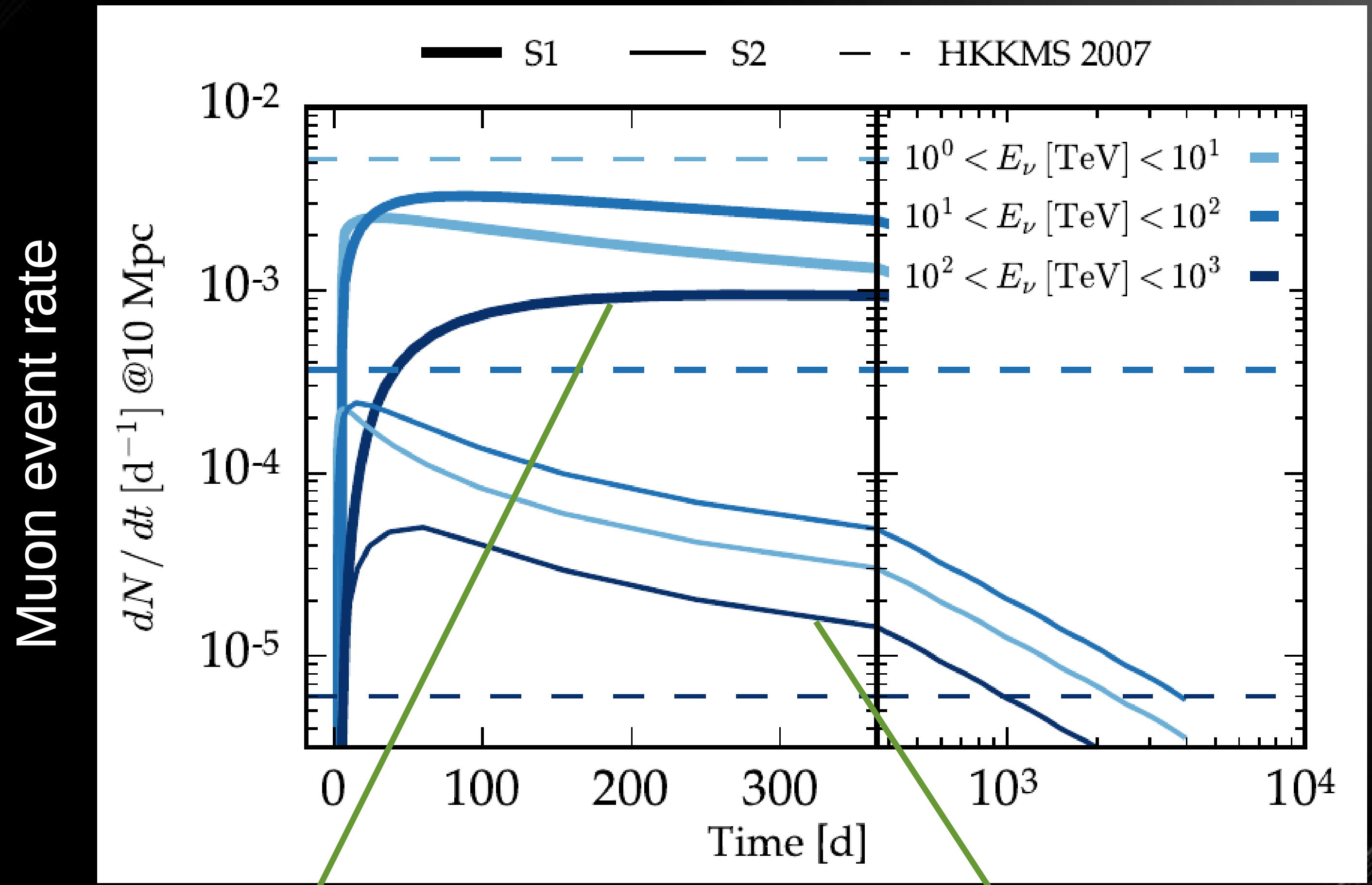
Parameter	S1	S2
r_w [cm]	3.2×10^{16}	3.2×10^{17}
M_{ej} [$M_\odot$]	10	
M_{csm} [$M_\odot$]	10	
v_{sh} [km s^{-1}]	9.5×10^3	
ϵ_B	3×10^{-4}	
ϵ_p	3×10^{-2}	
r_i [cm]	4.4×10^{14}	4.5×10^{13}
r_o [cm]	3.2×10^{16}	3.2×10^{17}
n_i [cm^{-3}]	10^{11}	10^{12}
K_w [g cm^{-1}]	4.5×10^{16}	4.5×10^{15}
$\dot{M}_w$ [$M_\odot$ yr^{-1}]†	0.1	0.01
t_i [d]	5.4	0.54
Duration [yr]	1	10.7

Source S2

Muon neutrino flux

Neutrino energy (TeV)

Expected IceCube neutrino rate



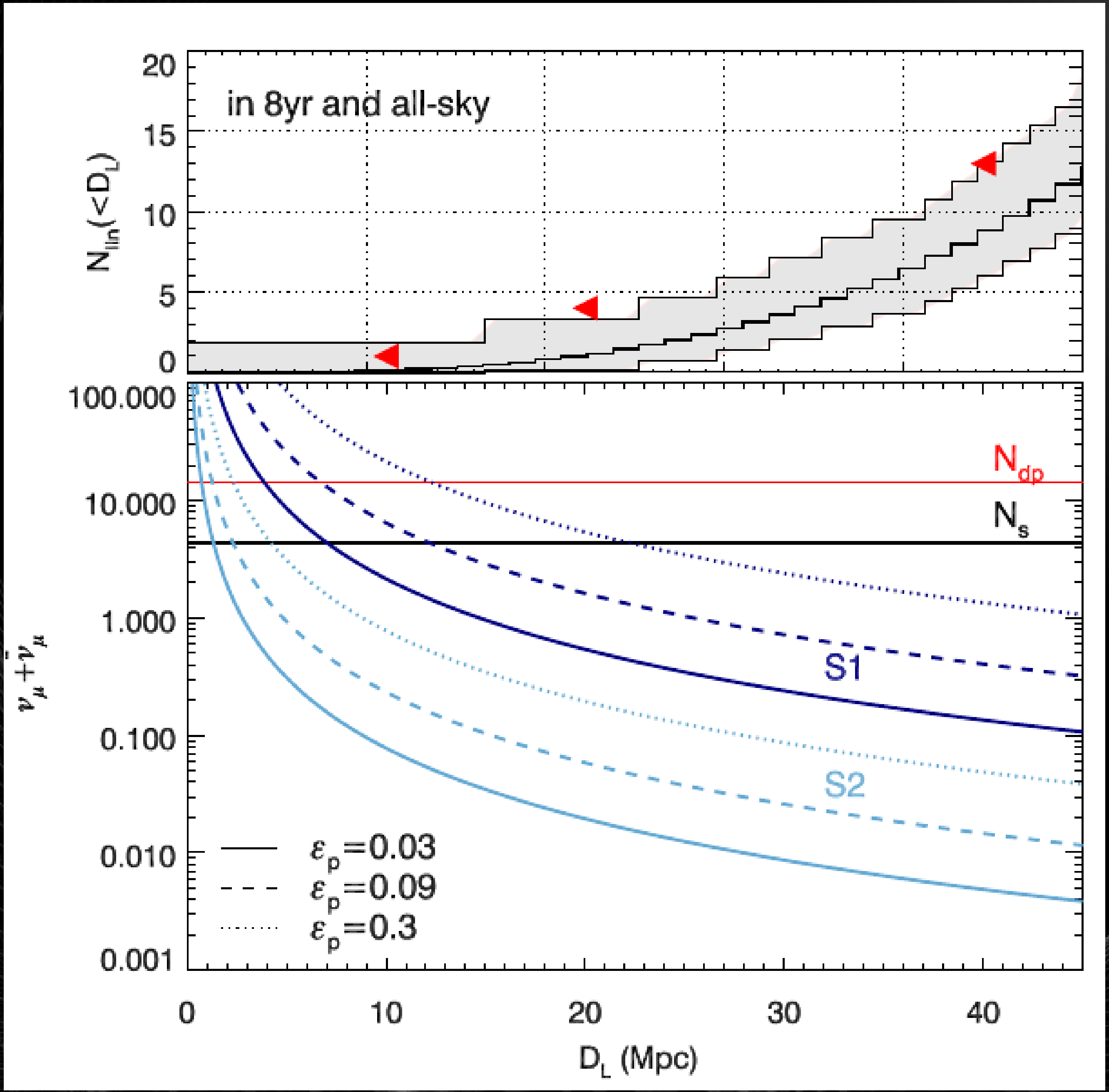
pp losses

$$F_\nu(E_\nu) \propto \epsilon_p v_{sh}^3 K_w t^0$$

Adiabatic losses

$$F_\nu(E_\nu) \propto \epsilon_p v_{sh} K_w^2 t^{-1}$$

Constraints on ε_p



Cumulative # of IIn

# of muon ν

Distance (Mpc)

# of events for IceCube discovery

# of events for IceCube sensitivity

Summary

SNe IIn may account for ~10% of IceCube flux above 100 TeV, if the wide spread in their properties is taken into account.

Diffuse neutrino measurements can constrain ε_p <0.2, if 4 % of CC SNe were of type IIn and ε_p is same in all sources.

Identification of a SN IIn as a neutrino point-source is possible with IceCube (up-going sample) 1 yr after breakout, if D<18 Mpc for ε_p <0.2 or D<7 Mpc for ε_p <0.03.

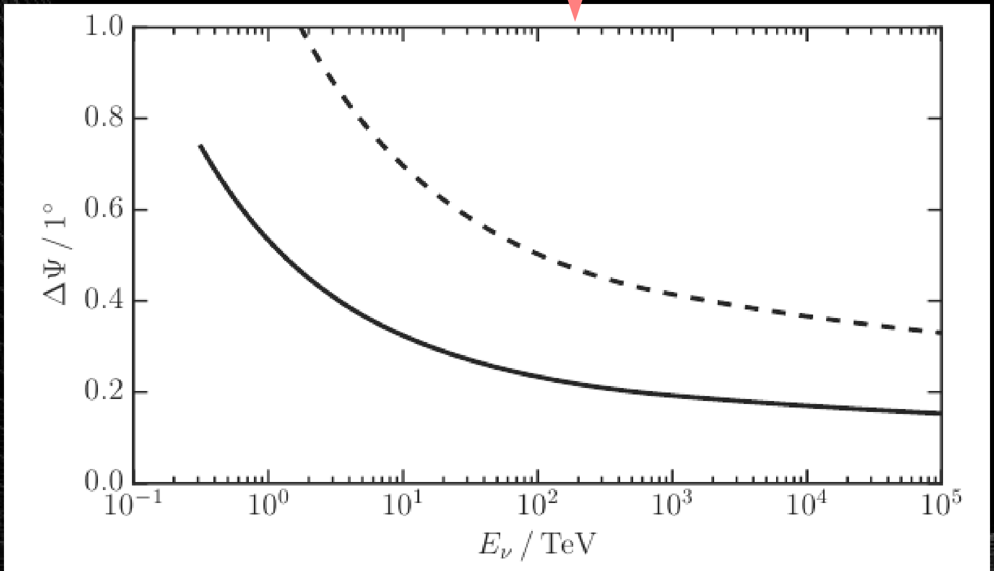
Thank you!

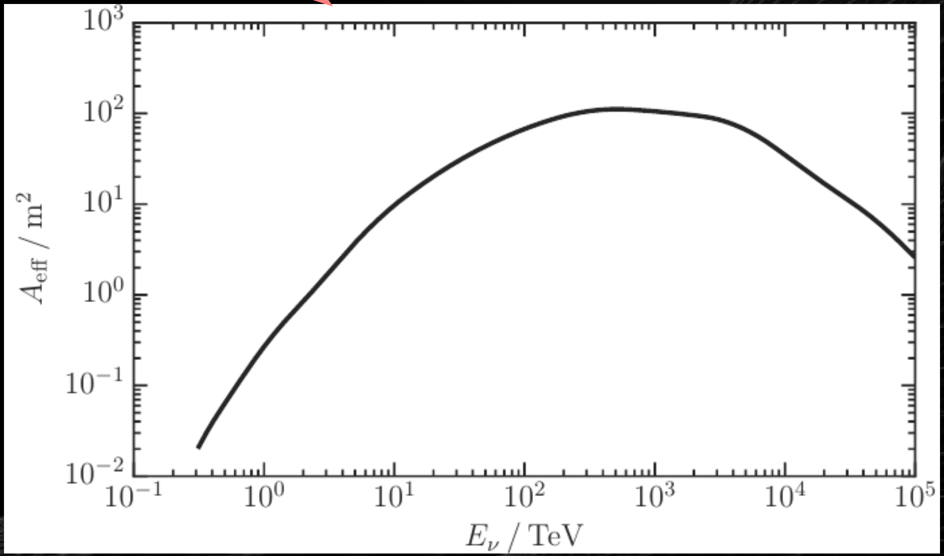
Backup Slides

Calculation of muon neutrino number

$$N_\nu = T \int_{E_{\nu,\min}}^{E_{\nu,\max}} dE_\nu \int_{\Delta\Omega(E_\nu)} \mathrm{d}\Omega\, A_{\mathrm{eff}}(E_\nu, \vec{x}) \sum_i \frac{\partial^2 F_{\nu,i}}{\partial\Omega \partial E_\nu}$$

1) Atmospheric background
2) Diffuse Astrophysical Flux
3) Point source flux





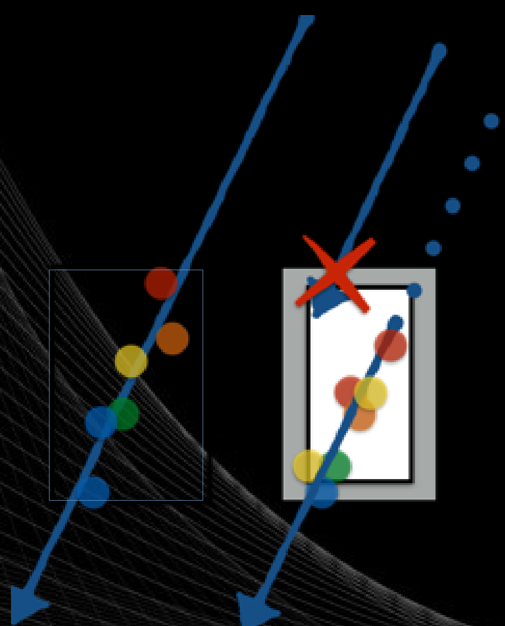
Point-source searches with IceCube

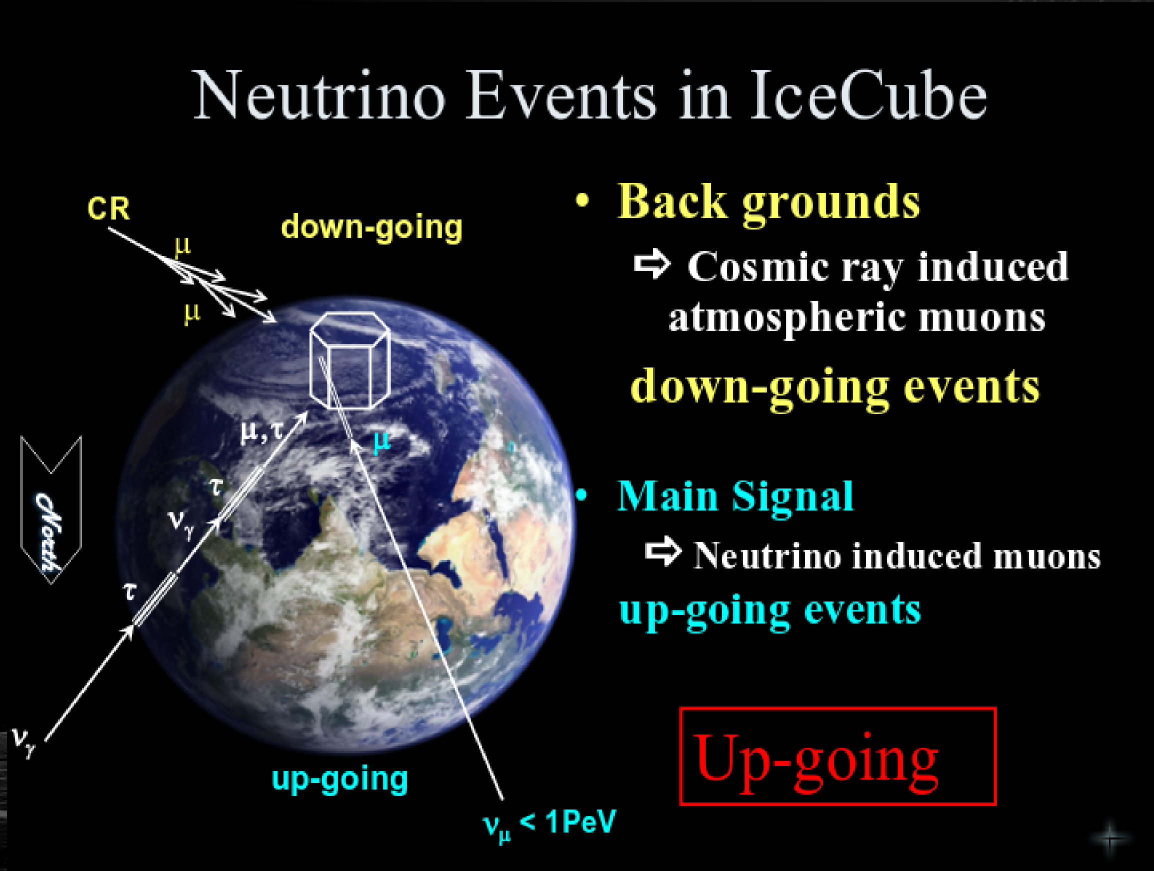
Up-going events

- Larger statistical sample
- Larger effective volume
- Atm. background not removed
- Poorer energy determination

High-energy starting events (HESE)

- Smaller statistical sample
- Smaller effective volume
- Atm. Background removed
- Accurate energy determination





SN IIn -neutrino coincidence?

Name	T_{max} (MJD)†	Host Galaxy	R.A. (J2000)	Dec. (J2000)	z	D_L (Mpc)
SN2008S	54508.5	NGC 6946	20:34:45.4	+60:05:57.8	0.0002	0.7
SN2008X	54502.5	NGC 4141	12:09:48.33	+58:51:01.6	0.006	28.0
SN2009ip‡	56206.5	NGC 7259	22:23:08.3	-28:56:52.4	0.006	26.4
SN2009kr	55148.5	NGC 1832	05:12:03.3	-15:41:52.2	0.007	16.0
SN2011A	55562.5	NGC 4902	13:01:01.2	-14:31:34.8	0.009	39.7
SN2011fh	55797.5	NGC 4806	12:56:14.0	-29:29:54.8	0.008	36.0
SN2011ht	55879.5	UGC 5460	10:08:10.58	+51:50:57.1	0.004	16.0
SN2013gc	56603.5	ESO 430-G20	08:07:11.9	-28:03:26.3	0.003	15.1
PSN J14041297-0938168	56645.5	IC 4363	14:04:13.0	-09:38:16.8	0.003	12.5
CSS140111:060437-123740	56734.5	MCG-02-16-02	06:04:36.71	-12:37:40.6	0.007	32.9
SN2014G	56674.5	NGC 3448	10:54:34.13	+54:17:56.9	0.005	20.0
SN2015bh	57163.5	NGC 2770	09:09:34.96	+33:07:20.4	0.006	28.5
SN2015J	57201.5	A073505-6907	07:35:05.2	-69:07:53.1	0.005	24.0
PSN J13522411+3941286	57071.5	NGC5337	13:52:24.1	+39:41:28.6	0.007	32.1
ASASSN-15lf	57194.5	NGC 4108	12:06:45.56	+67:09:24.00	0.008	37.3
SNhunt248	56828.5	NGC 5806	14:59:59.5	+01:54:26.2	0.005	20.1

ID 16 from 4yr HESE sample:

- Cascade-like event
- 1.13 days after T_max
- Angular offset ~7 degrees

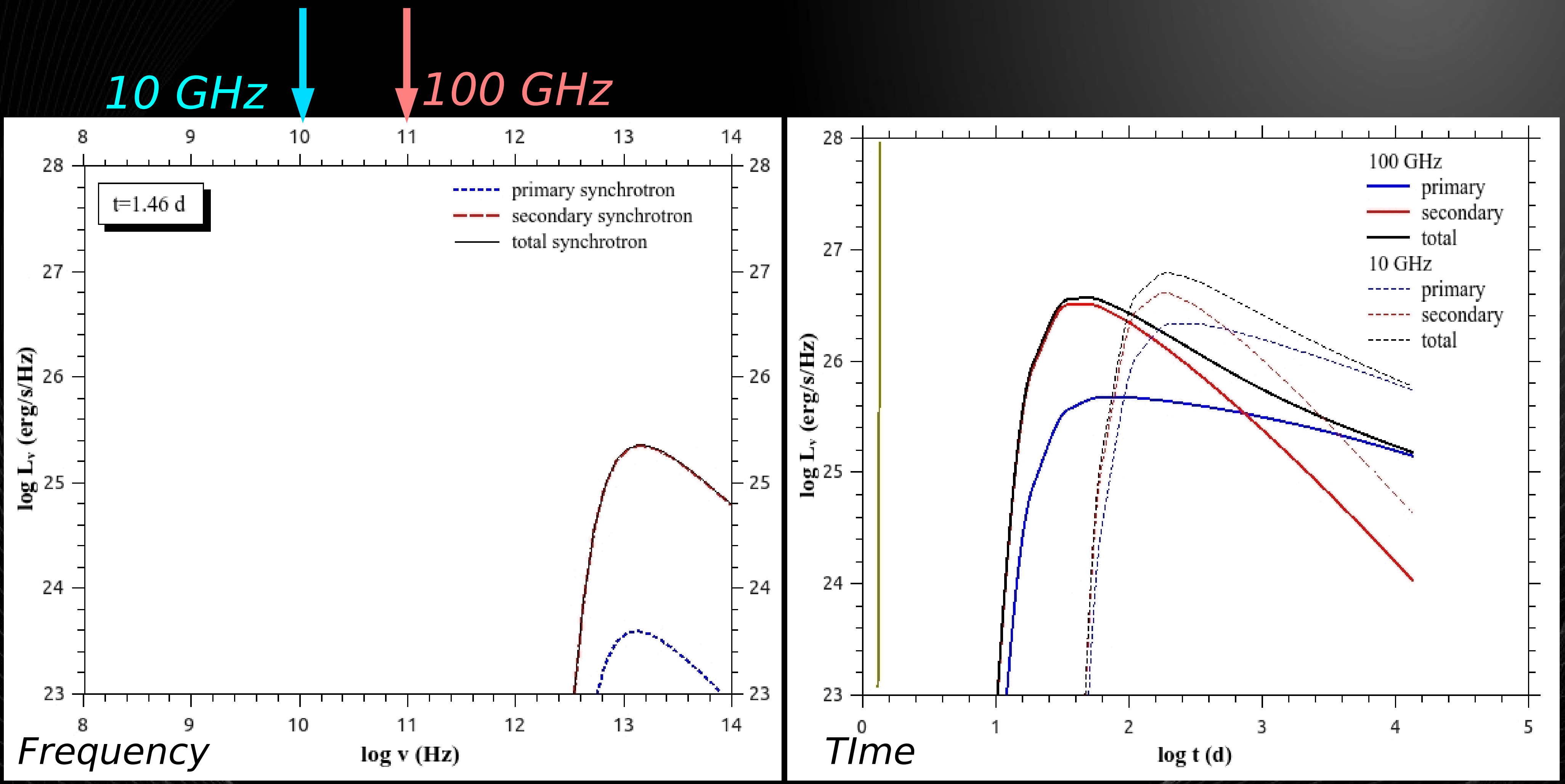
Detection of ID16 deviates from background expectation at ~2.8σ

SN IIn -neutrino coincidence?

$$\frac{K_w \times \epsilon_{\rm p}\big|_{\rm 2011fh}}{K_w \times \epsilon_{\rm p}\big|_{\rm S1}} = 200\left(\frac{v_{\rm sh}^{\rm S1}}{v_{\rm sh}^{\rm 2011fh}}\right)^3 \left(\frac{D_L^{\rm 2011fh}}{D_L^{\rm S1}}\right)^2 \frac{N_{\rm 2011fh}}{N_{\rm S1}} \approx 579\ldots 2.3\times 10^4.$$

Assuming that in SN2011fh $\epsilon_{\rm p} = 0.2$ (i.e., the largest allowed value from the diffuse neutrino flux measurements), its mass-loading parameter has to be at least $K_{\rm w}^{\rm 2011fh} \sim 87\, K_w^{\rm S1} \sim 4\times10^{18}$ g cm^{-1}. Radio observations of SN2011fh could place strong constraints on $K_{\rm w}^{\rm 2011fh}$ and, ultimately, exclude (or not) a physical connection to neutrino ID 16.

Radio spectra & light curves

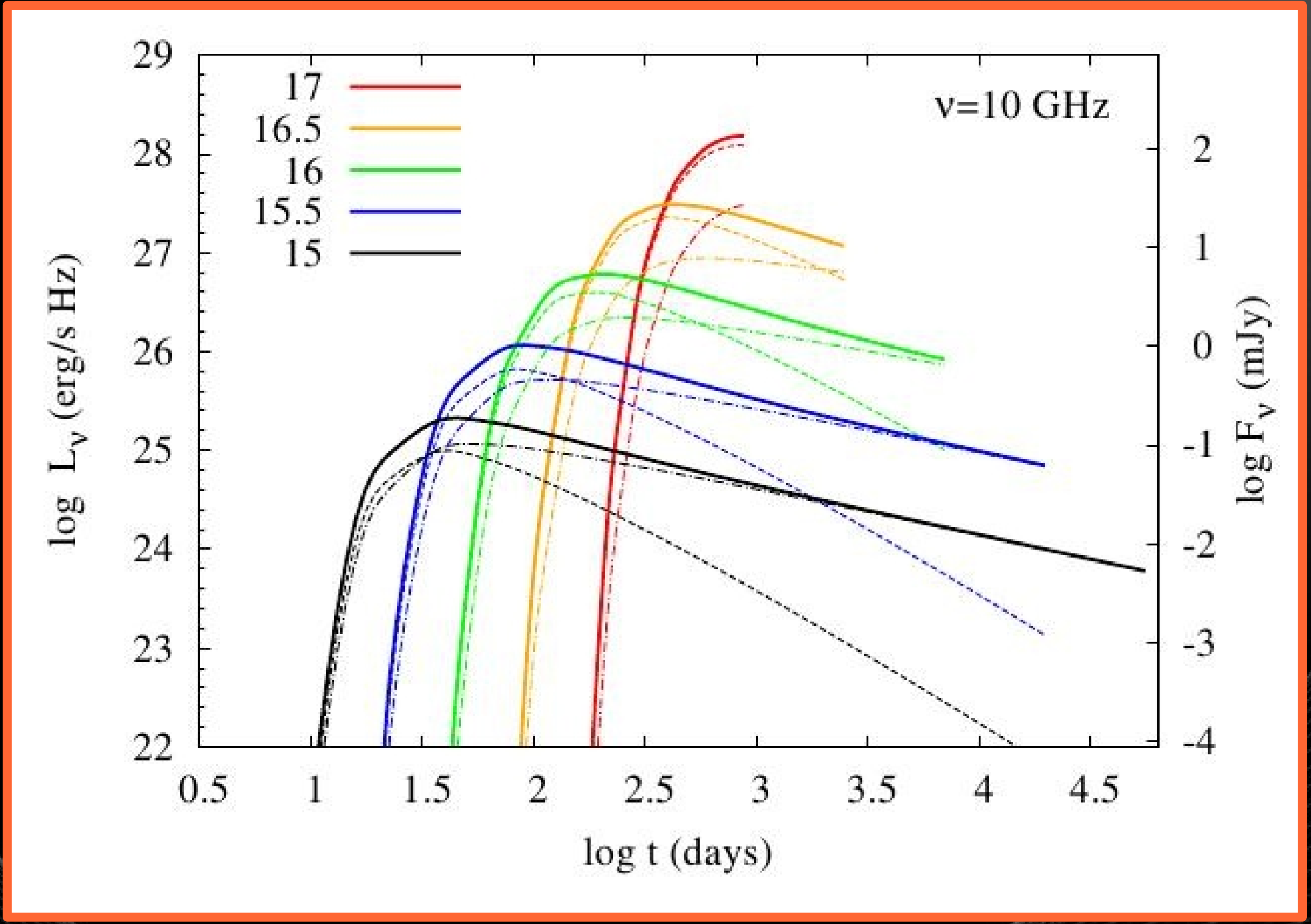


Parameters: v_{sh}=9000 km/s, A_w=10^{16} gr/s (0.05 M_{sun} /yr), Mej=10M_{sun}, εB=0.01, εp=0.1, K_{ep}=0.001, T_e=10^5 K

(Petropoulou et al. 2016, MNRAS 460)

Radio light curves

Role of CSM density



Denser CSM → Higher Peak luminosity → Later peak time → Larger % of peak luminosity dominated by secondary synchrotron

(Petropoulou et al. 2016, MNRAS 460)