High-Energy Neutrinos from Supernovae:
New Prospects for the Next Galactic Supernova

arXiv:1705.04750

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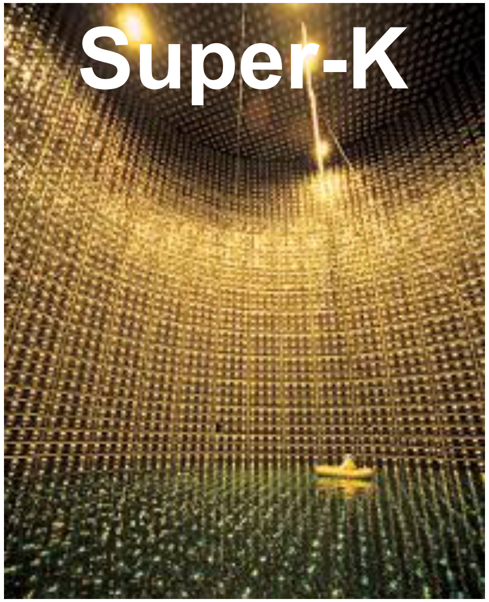
TeVPA 2017 @ Columbus, Ohio

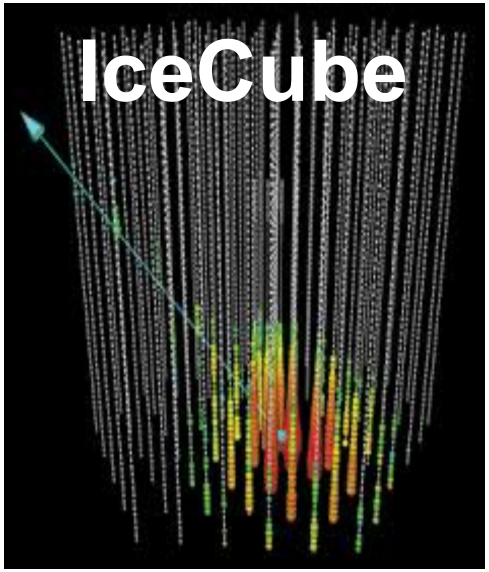
Neutrinos: Unique Probe of Cosmic Explosions



~10 MeV neutrinos from supernova
thermal: core's grav. binding energy

- supernova explosion mechanism
- progenitor
- neutrino properties, new physics

Super-K can detect ~8,000 ν at MeV (at 8.5 kpc)

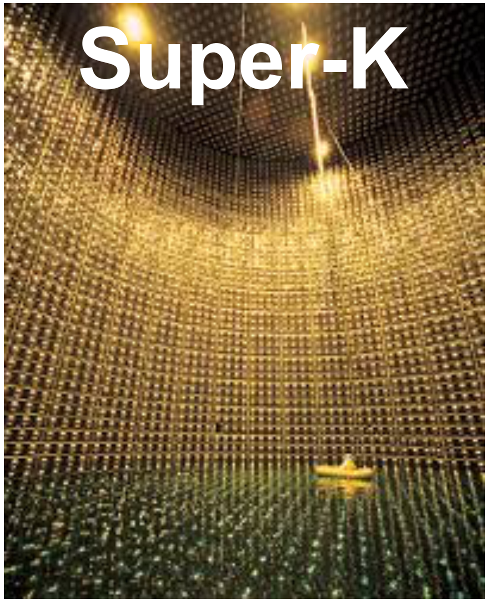


GeV-PeV neutrinos from supernova?
non-thermal: shock dissipation

- physics of cosmic-ray acceleration
- progenitor & mass-loss mechanism
- neutrino properties, new physics

IceCube/KM3Net can detect ??? ν at TeV

Neutrinos: Unique Probe of Cosmic Explosions



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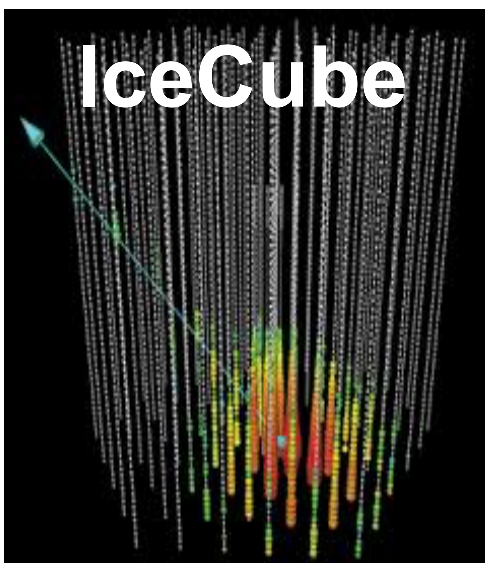

GeV-PeV neutrinos from supernova?
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IceCube/KM3Net can detect ~1000 ν at TeV

Early Diffusive Shock Acceleration in Supernovae?

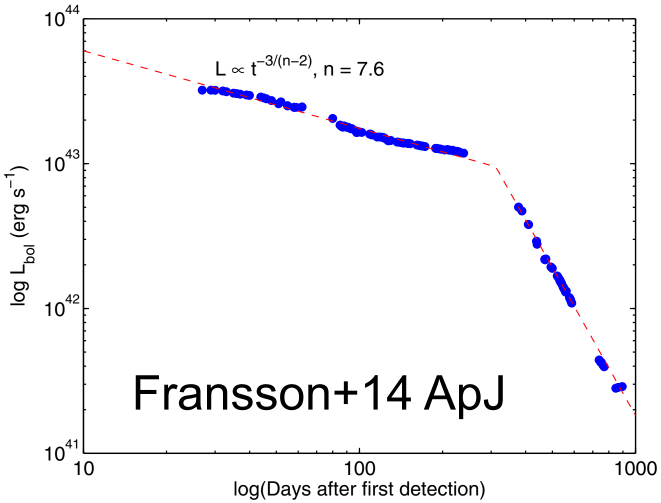
- CR and high-energy neutrino production is initially negligible
  most of energy is in a kinetic form until the Sedov time
  uniform ISM: CR energy $\propto$ dissipation energy $\propto t^3$

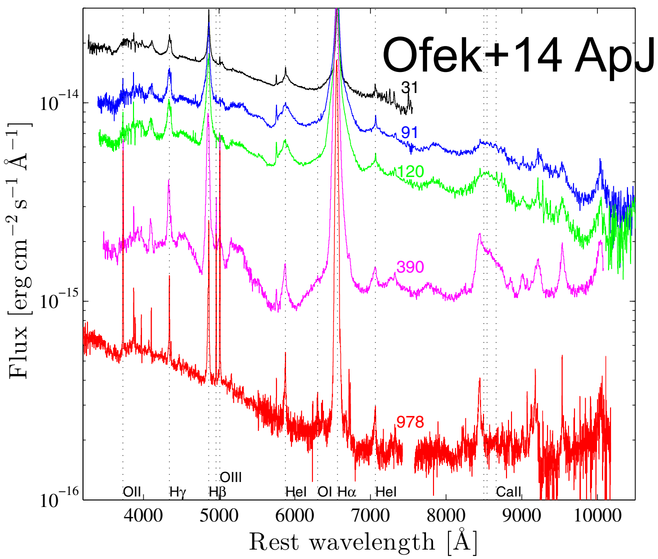
- But situations are different
  when circumstellar material (CSM) exists
  many observational evidences in the recent several years

(Raffaella Margutti's talk)

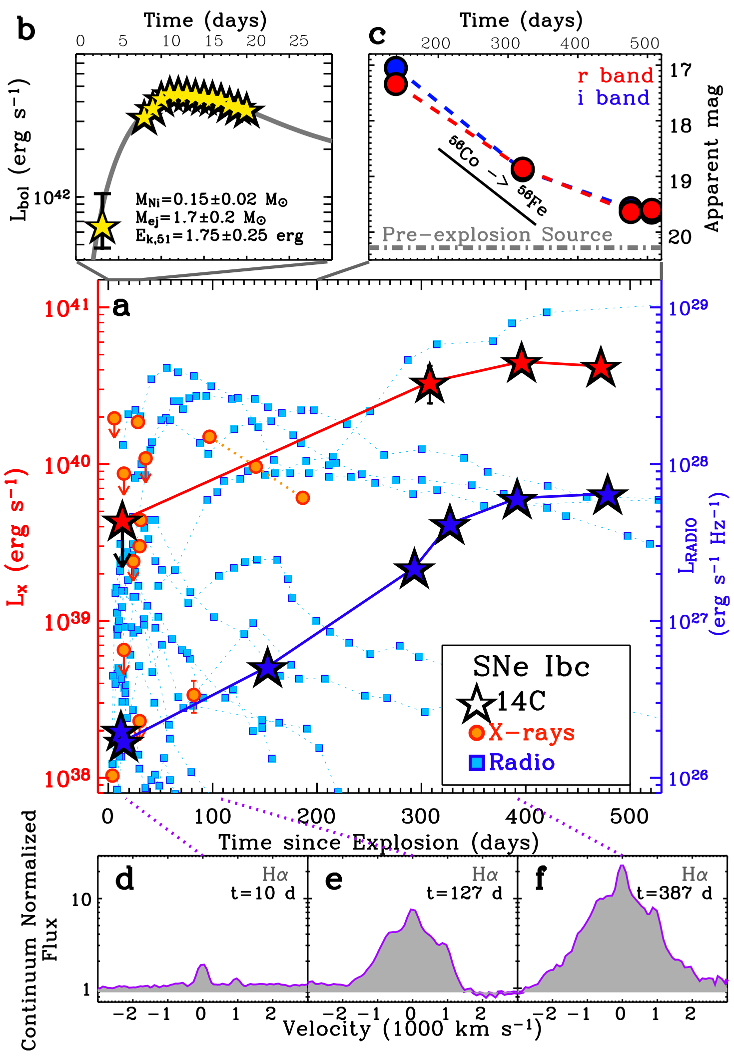
Evidence of Strong Interactions w. Dense CSM

SN 2010jl (IIn)



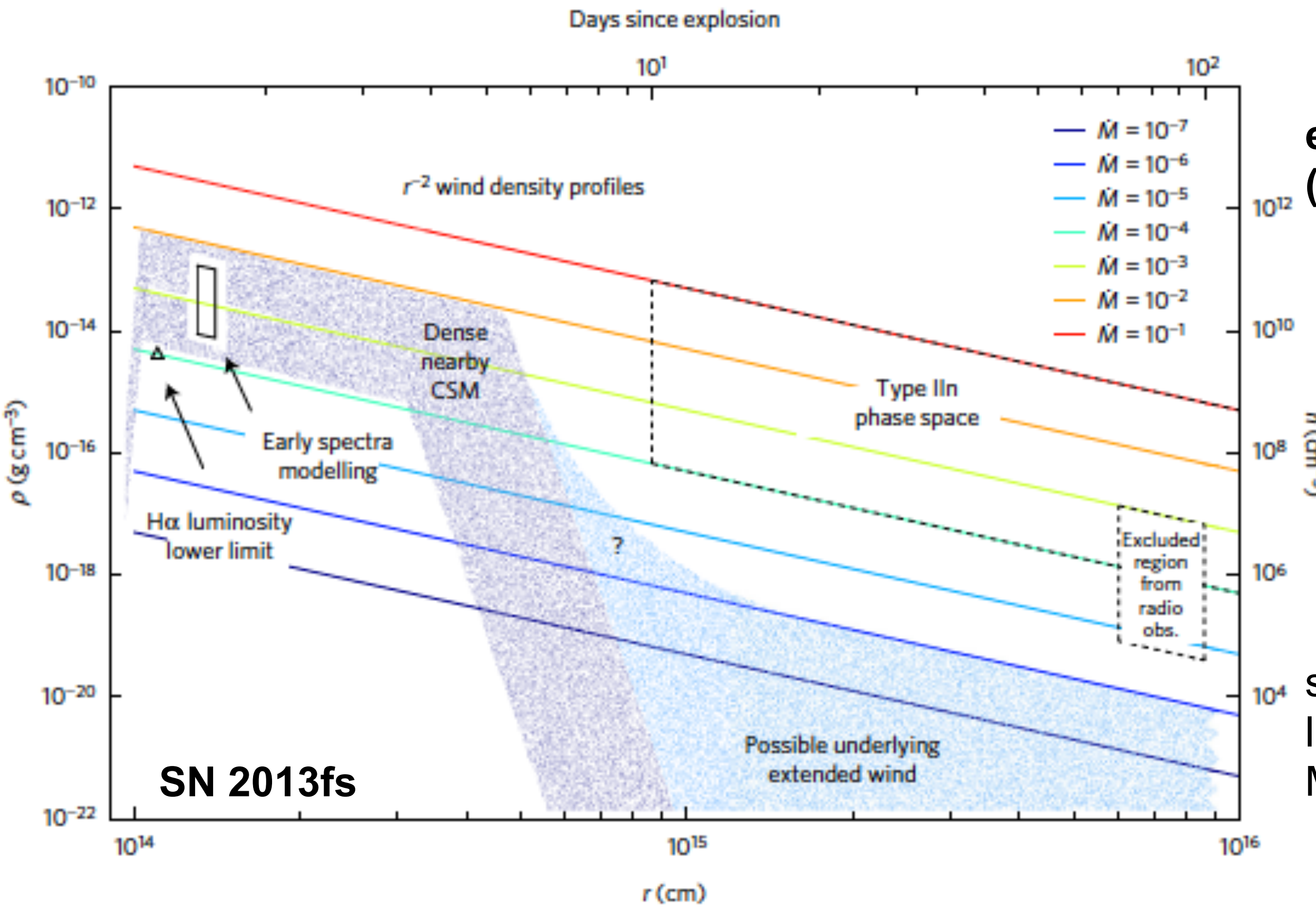


SN 2014C (Ib->IIn) Margutti et al. 16



examples of strong interactions w. dense wind or CSM (IIn, SLSN-II)

Evidence for Dense Material in Ordinary SNe II



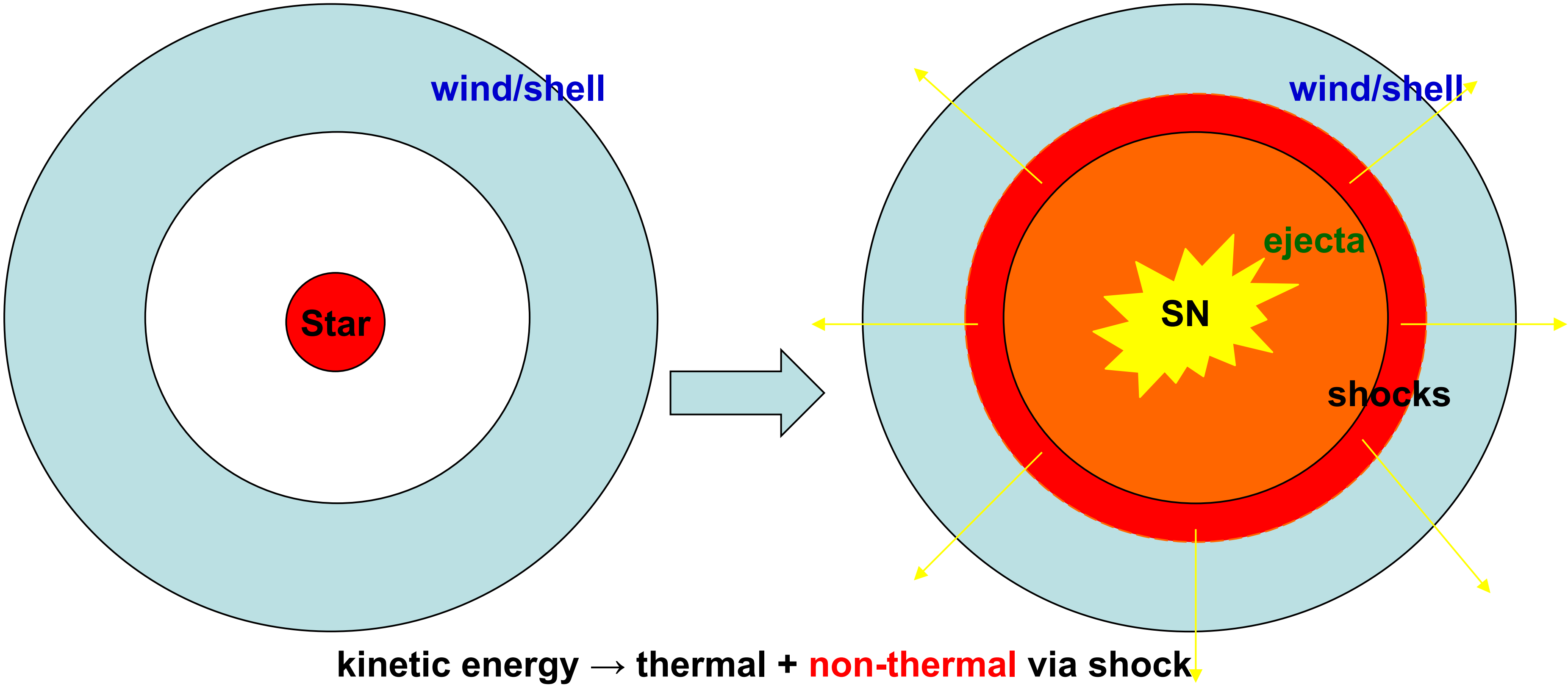
early spectroscopy (Yaron+ 16 Nat. Phys.)

see also
light curve modeling
Morozova+ 17 ApJ

Extended material is common even for Type II-P SNe

→ Mdot~10^{-3}-10^{-1} M_{sun} yr^{-1} (>> $3x10^{-6}$ M_{sun} yr^{-1} for RSG)

Supernovae with Interactions with CSM



kinetic energy → thermal + non-thermal via shock

$$p + p \longrightarrow N\pi + X$$

$$\pi^{\pm} \longrightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$
$$\pi^{0} \longrightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

Shock Dynamics -> Time-Dependent Model

equation of motion of the shocked ejecta

$$M_{\rm sh}\frac{dV_{\rm s}}{dt} = 4\pi R_s^2[\varrho_{\rm ej}(V_{\rm ej}-V_s)^2 - \varrho_{\rm cs}(V_s - V_w)^2]$$

self-similar solution (Chevalier 82)

shock radius
$$R_s = X(w,\delta) D^{-\frac{1}{\delta-w}} \mathcal{E}_{\rm ej}^{\frac{\delta-3}{2(\delta-w)}} M_{\rm ej}^{-\frac{\delta-5}{2(\delta-w)}} t^{\frac{\delta-3}{\delta-w}}$$

CSM parameter
$$D = \frac{\dot{M}_w}{4\pi V_w}$$

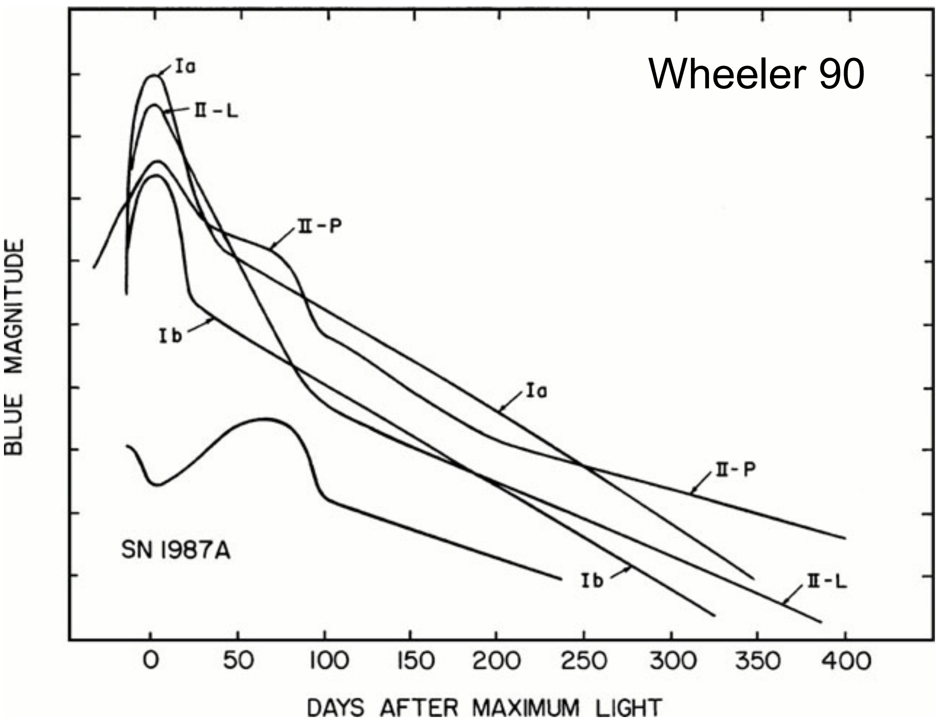
E_{ej} ~ 10^{51} erg, M_{ej} ~ 10 M_{sun}

w=2 for a wind CSM **δ~10-12 for typical progenitors**

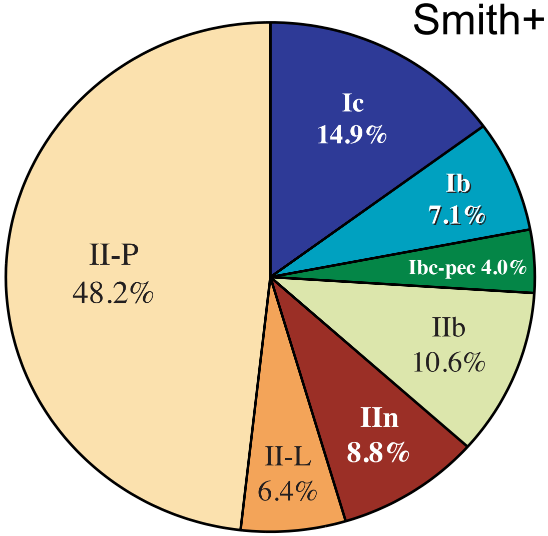
dissipation luminosity
$$L_d = 2\pi \varrho_{\rm cs} V_s^3 R_s^2 \propto t^{\frac{6w-15+2\delta-\delta w}{\delta-w}}$$

parameters can be determined by photon (opt, X, radio) observations!
E_d ~ $E_{ej}(>V_s)$ in the detailed model, different from E_d ~$(M_{cs}/M_{ej})E_{ej}$ by KM+11

Diversity of Core-Collapse Supernovae



Smith+ 11 MNRAS

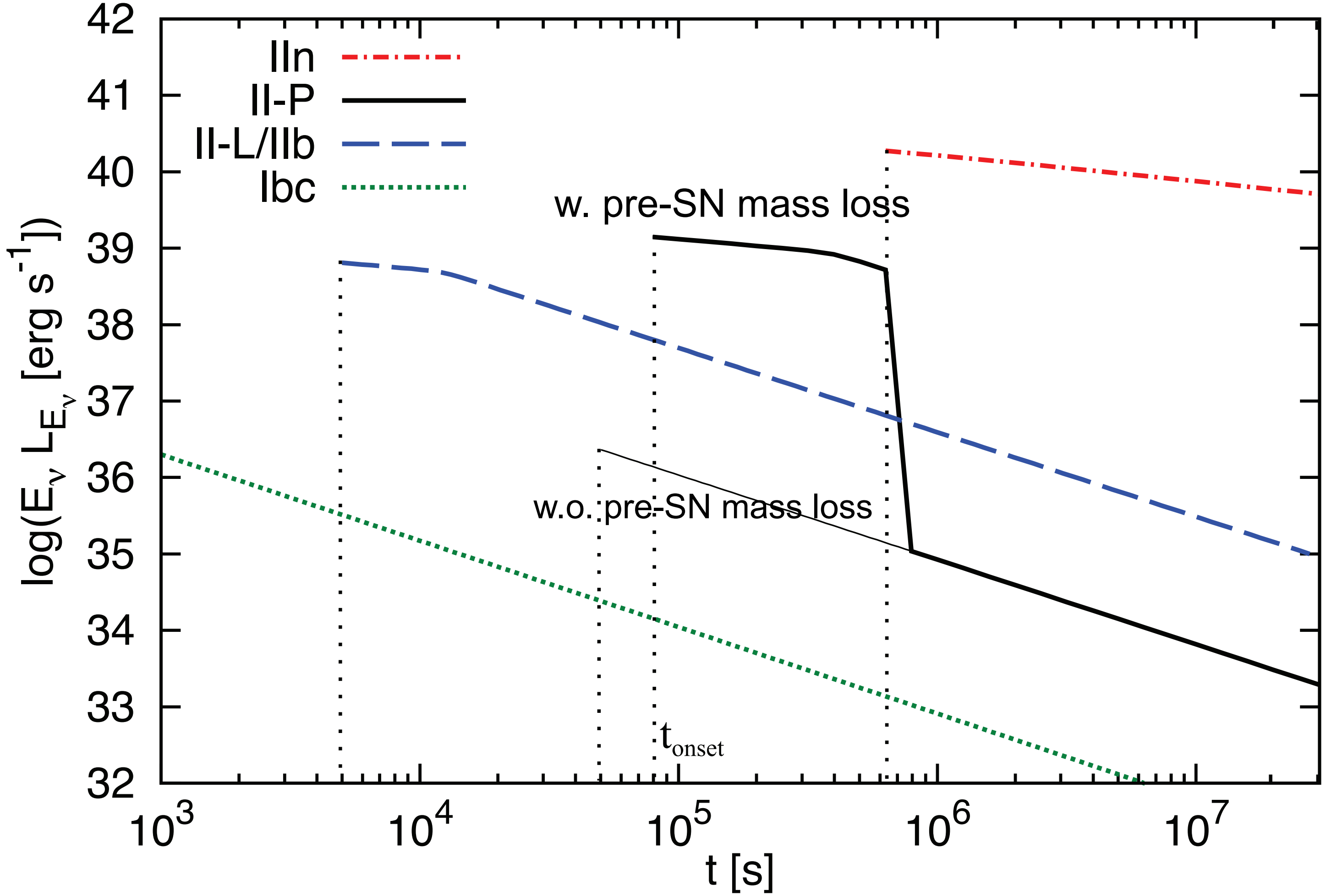


Core-Collapse SN Fractions

Type II SN frac. ~ 2/3

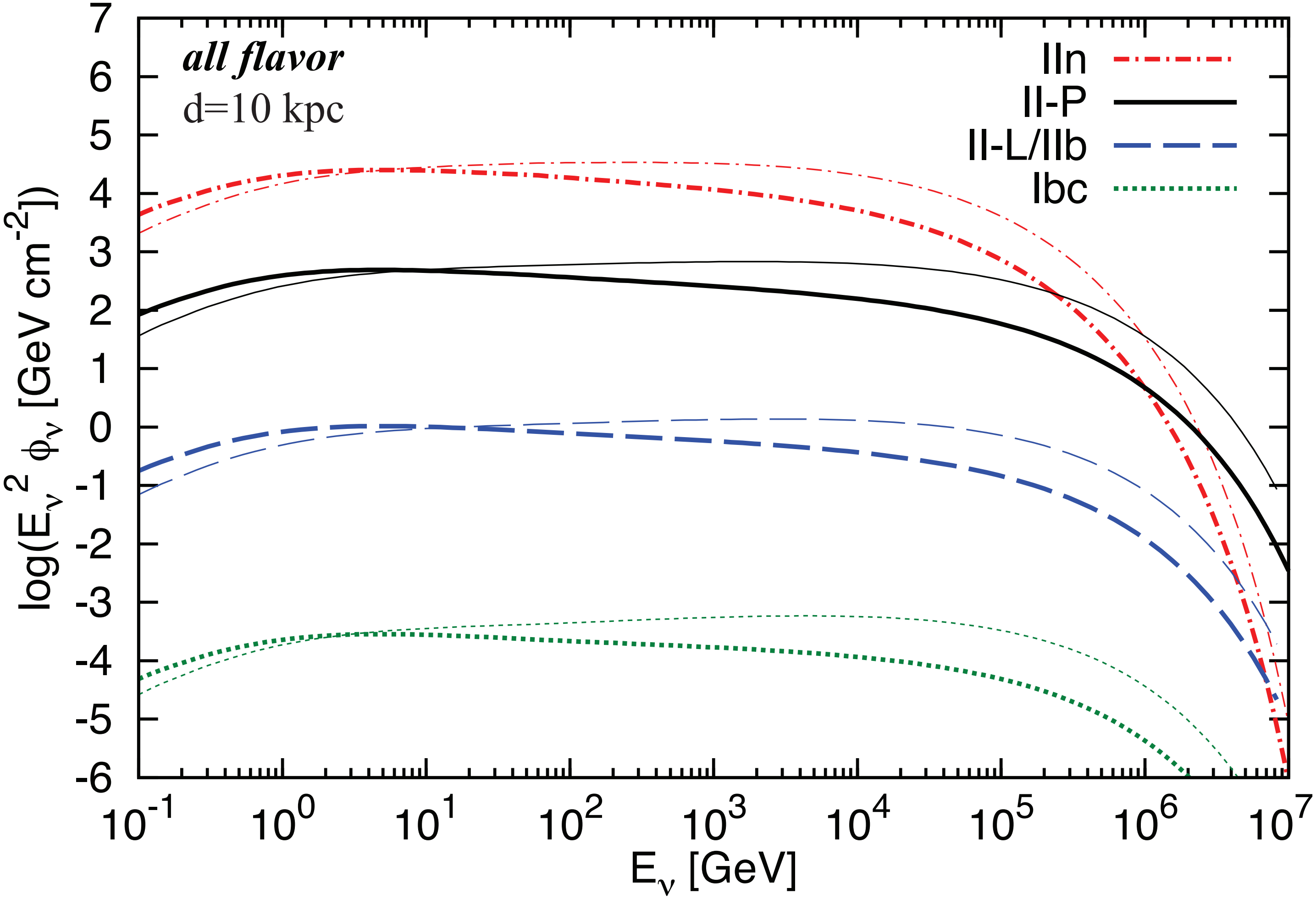
Class	D_*	$\dot{M}_w$ $[M_\odot\ \mathrm{yr}^{-1}]$	V_w $[\mathrm{km\ s}^{-1}]$	R_* [cm]	
IIn	1	10^{-1}	100	10^{13}	
II-P^a	10^{-2}	10^{-3}	100	6×10^{13}	w. pre-SN mass loss
II-P^b	1.34×10^{-4}	2×10^{-6}	15	6×10^{13}	stellar wind only
II-L/IIb	10^{-3}	3×10^{-5}	30	6×10^{12}	
Ibc	10^{-5}	10^{-5}	1000	3×10^{11}	

Neutrino Light Curve



t_{onset} ~ time leaving the star (typical) or breakout time (IIn)
slowly declining light curve while pion production efficiency ~ 1

Neutrino Fluence



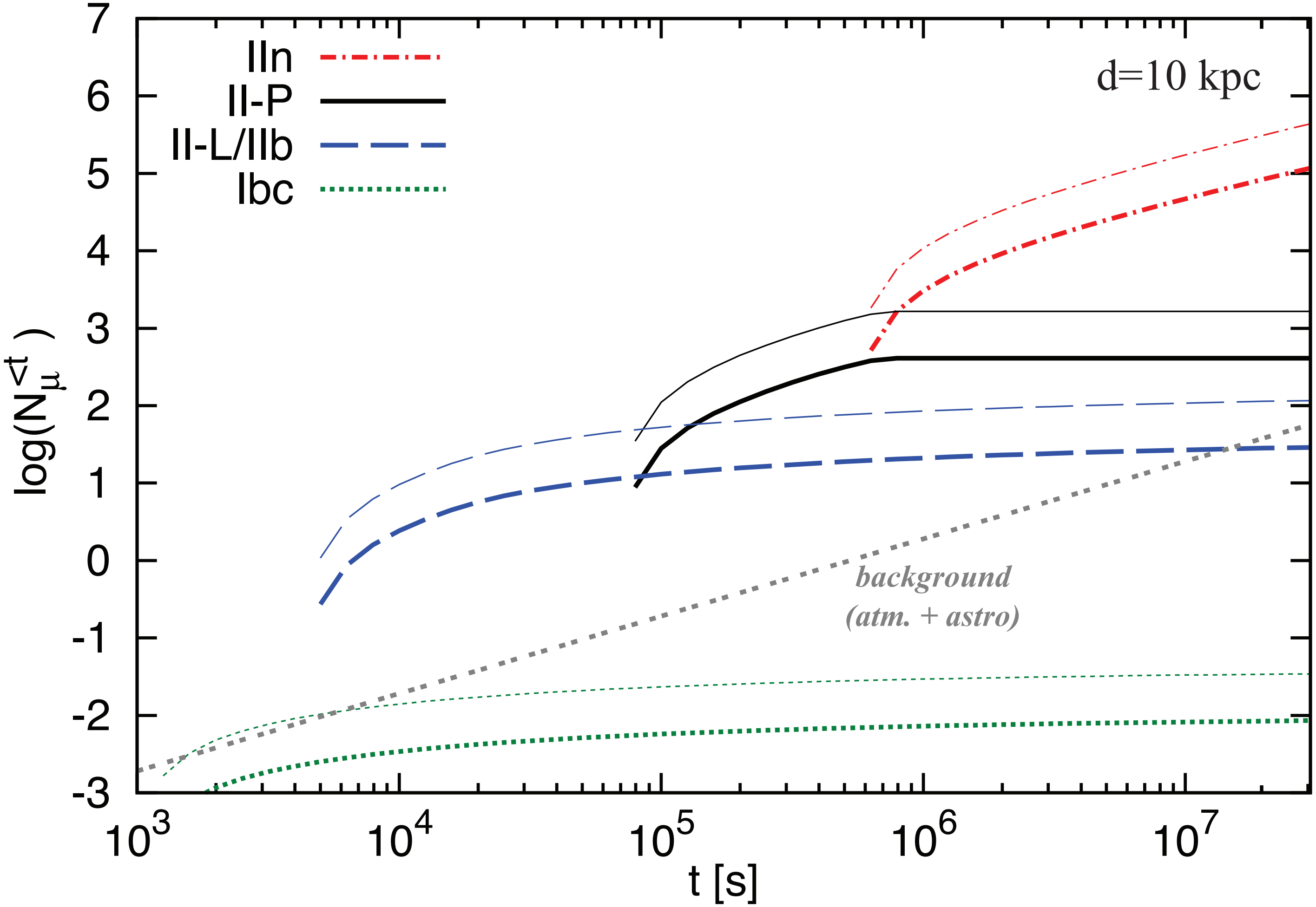
thick: s=2.2

thin: s=2.0

Fluence for an integration time at which $S/B^{1/2}$ is maximal (determined by the detailed time-dependent model)

Prospects for Neutrino Detection

through-going muon events



~ 10-1000 events for Type II supernovae at 10 kpc

~ 0.01-0.1 events for Ibc (but see Kashiyama, KM+ 13 ApJL)

Some Remarks

- Testable & clear predictions (no need for jets, winds, shocks in a star)
  free parameters: ε_{CR} & s $\Leftrightarrow$ shock acceleration theory (ε_{CR}~0.1 & s~2.0-2.3)

- Time window
  depends on SN types; guidelines are provided by the theory (f_{pp}~t_{dyn}/t_{pp}~1)
  e.g., characteristic time window: ~1-10 day for SNe II

- Energy range
  IceCube/KM3Net: TeV-PeV (detectable Glashow res. anti-ν_e & ν_τ events)
  Hyper-K/PINGU/ORCA: GeV

∗ Type II cases are different from the Type IIn case
  II-P/II-L/IIb/Ibc: shock in the CSM is collisionless & $M_{csm} << M_{ej}$
  IIn: shock can be radiation-mediated & M_{csm} could be larger than M_{ej}
    t_{onset} determined by photon breakout, ejecta deceleration,
    radiative shock, other relevant CR cooling processes…
    (for work on SNe IIn, see KM, Thompson, Lacki & Beacom 11 and Petropoulou's talk)

Implications

- Astrophysical implications

  a. pre-explosion mass-loss mechanisms
     how does a dense wind/shell form around the star ?

  b. PeVatrons
     can CRs be accelerated up to the knee energy at $10^{15.5}$ eV?

  c. real-time observation of ion acceleration for the first time
     is it consistent with the diffusive shock acceleration?

  d. promising targets of multi-messenger astrophysics
     MeV νs & possibly gravitational waves
     optical, X-rays, radio waves, and gamma rays (up to ~Mpc by Fermi)

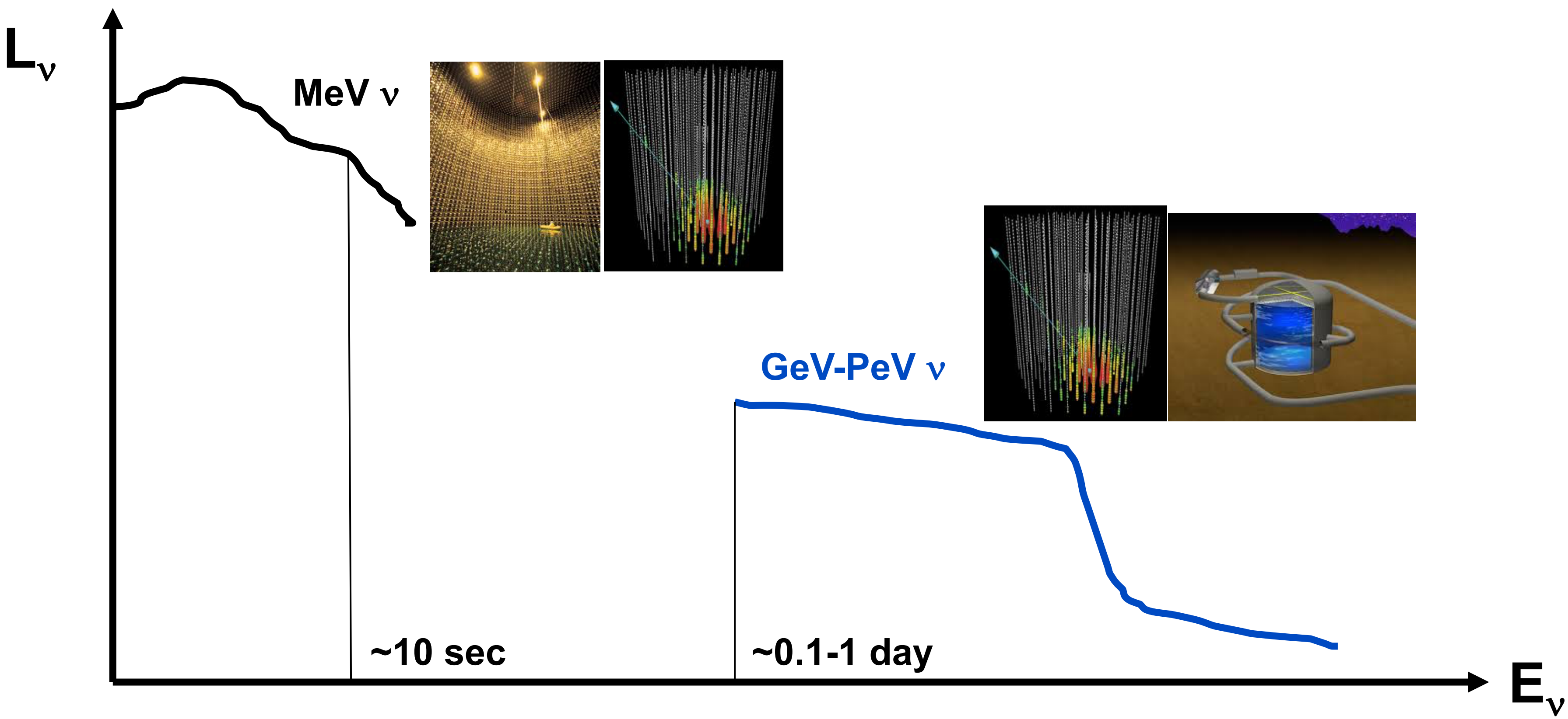
- Particle physics implications

  neutrino flavors (matter effect is not relevant), neutrino decay, neutrino self-interactions, oscillation into other sterile states etc.

cf. more lucky examples?
Betelgeuse: ~10^3-3×10^6 events
Eta Carinae: ~10^5-3×10^6 events

Take Away

- We provided the time-dependent model for high-energy neutrino/gamma-ray emission from different classes of SNe
- Type II: ~1000 events of TeV ν from the next Galactic SNe
- SNe as “multi-messenger” & “multi-energy” neutrino source



CRs Should Lead to Efficient Hadronic Interactions

particle collisions with CSM $p + p \rightarrow N\pi + X$

$t_{pp} = 1/(n\,\kappa_{pp}\sigma_{pp}c)$
$t_{dyn} = R/\beta c$ $\rightarrow$ $f_{pp} = (R/\beta)\, n\, \kappa_{pp}\sigma_{pp}$

($\sigma_{pp} \sim 3\times10^{-26}$ cm^2)

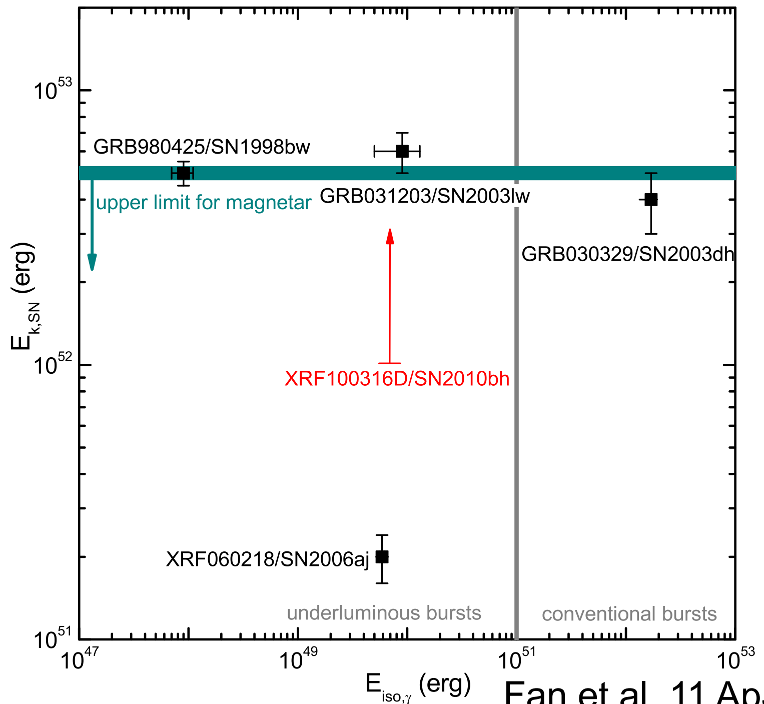
$f_{pp}(r_{bo}) \sim \beta^{-2}(\kappa_{pp}\sigma_{pp}/\sigma_T) \sim 0.03\,\beta^{-2}$ at breakout: $\tau_T = 1/\beta$

$\beta \sim 0.1$-1 $\Leftrightarrow$ transrelativistic SNe
$\beta \sim 0.01$-0.03 $\Leftrightarrow$ nonrelativistic SNe
most CR energy goes to pions

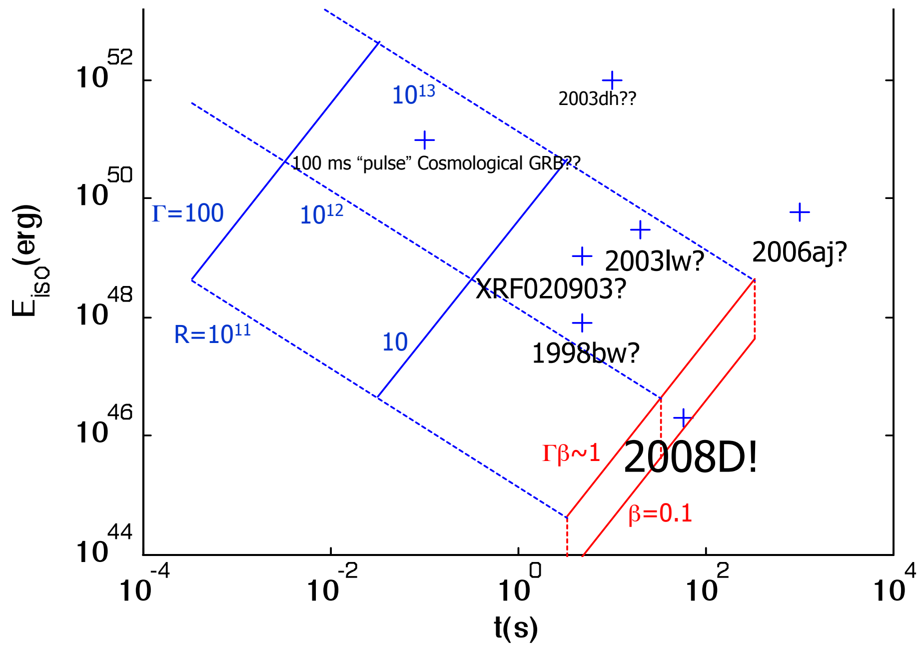
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + e^\pm$$

new probes!

Transrelativistic SNe (β~1)



Fan et al. 11 ApJL



from Katz 11

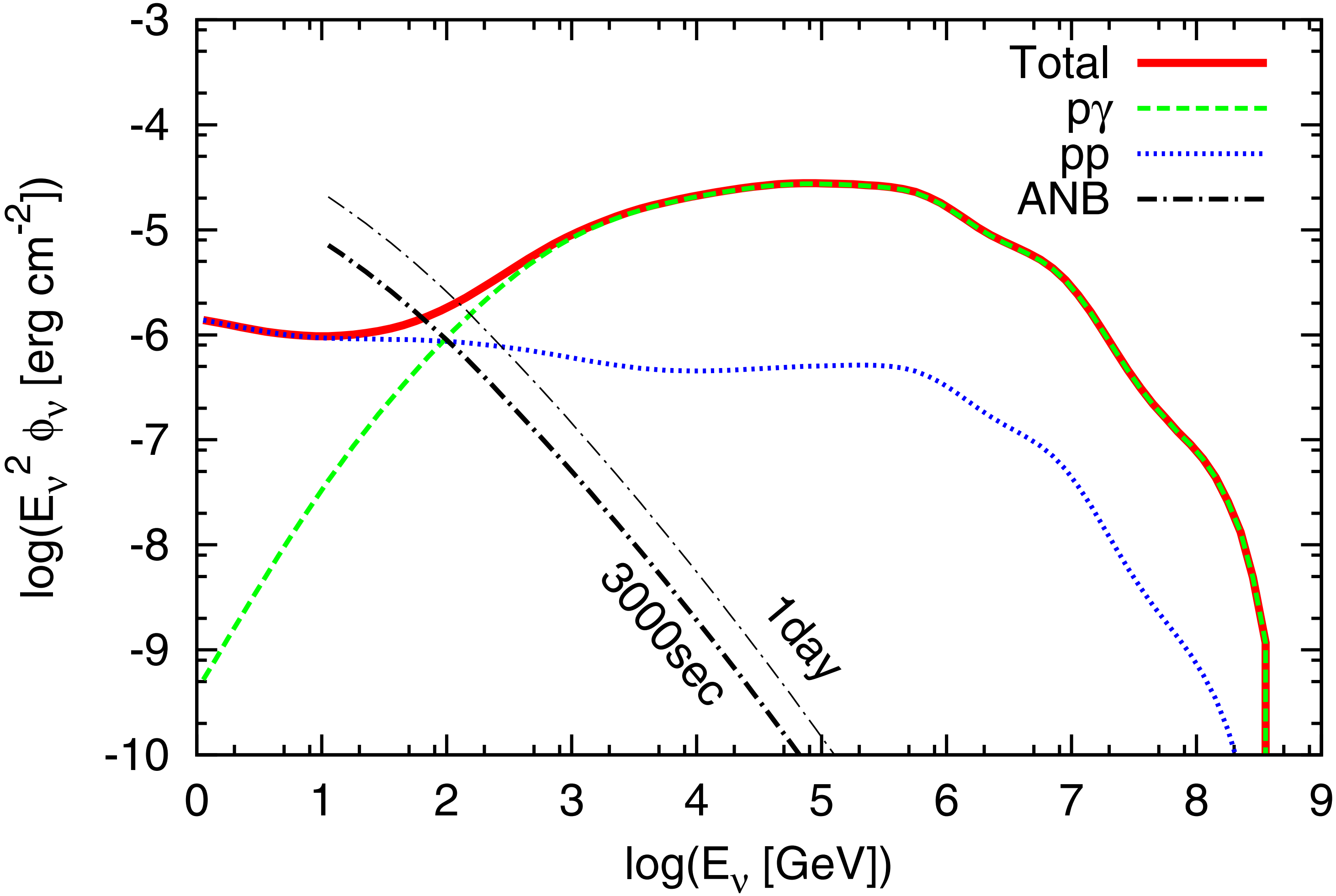
Nearby GRBs (ex. 060218@140Mpc, 980425@40Mpc) may form another class

- much dimmer ($E_{LL\gamma}^{iso}$ ~10^{50} erg ⇔ $E_{GRB\gamma}^{iso}$ ~10^{53} erg/s)
- more frequent (ρ_{LL} ~$10^{2\text{-}3}$ Gpc^{-3} yr^{-1} ⇔ ρ_{GRB} ~0.05-1 Gpc^{-3} yr^{-1})
- relativistic ejecta (the other GRB-SNe + 2009bb) (Soderberg+ 10 Nature)

\- maybe more baryon-rich? (e.g., Zhang & Yan 11 ApJ)

Neutrinos from Transrelativistic SNe

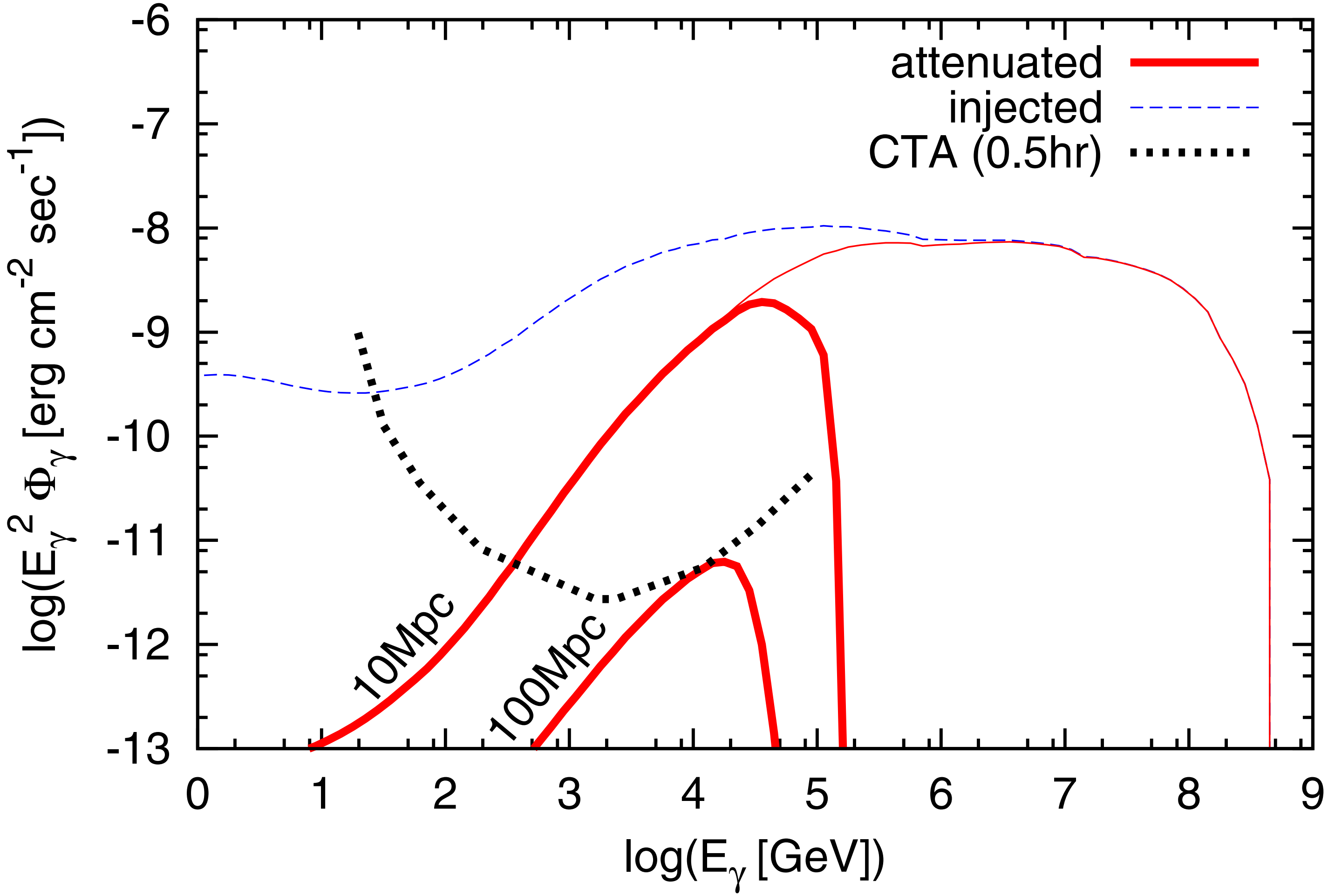
Kashiyama, KM+ 13 ApJL



- Detectable by IceCube up to ~10 Mpc
- Stacking analyses may be possible

Gamma Rays from Transrelativistic SNe

Kashiyama, KM+ 13 ApJL



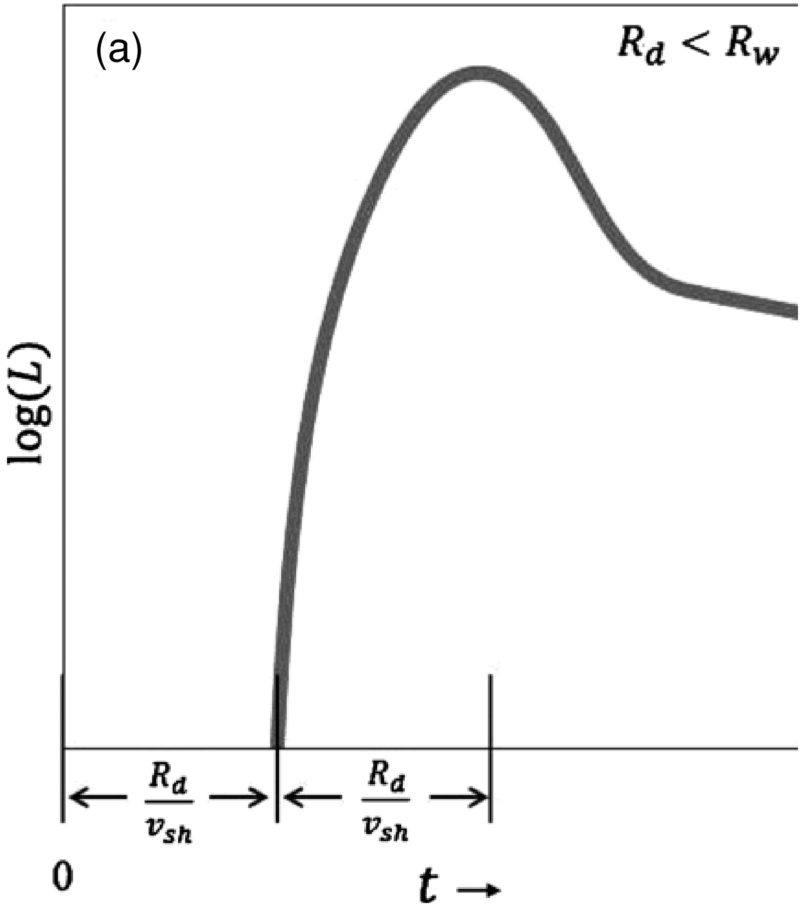
- Detectable by CTA up to ~100 Mpc
- Detection → SN-GRB connection, physics of breakout and CRs

Shock Breakout Emission from Dense CSM

photon diffusion time
$t_{diff} \sim R^2/\kappa_{rad} \sim n\sigma_T R^2/c$

⇔

dynamical time:
$t_{dyn} \sim R/\beta c$, $\beta=V/c$



Chevalier & Irwin 11 ApJL

shock breakout:
$t_{rise}=t_{diff}=t_{dyn} \Leftrightarrow \tau_T=1/\beta=c/V$

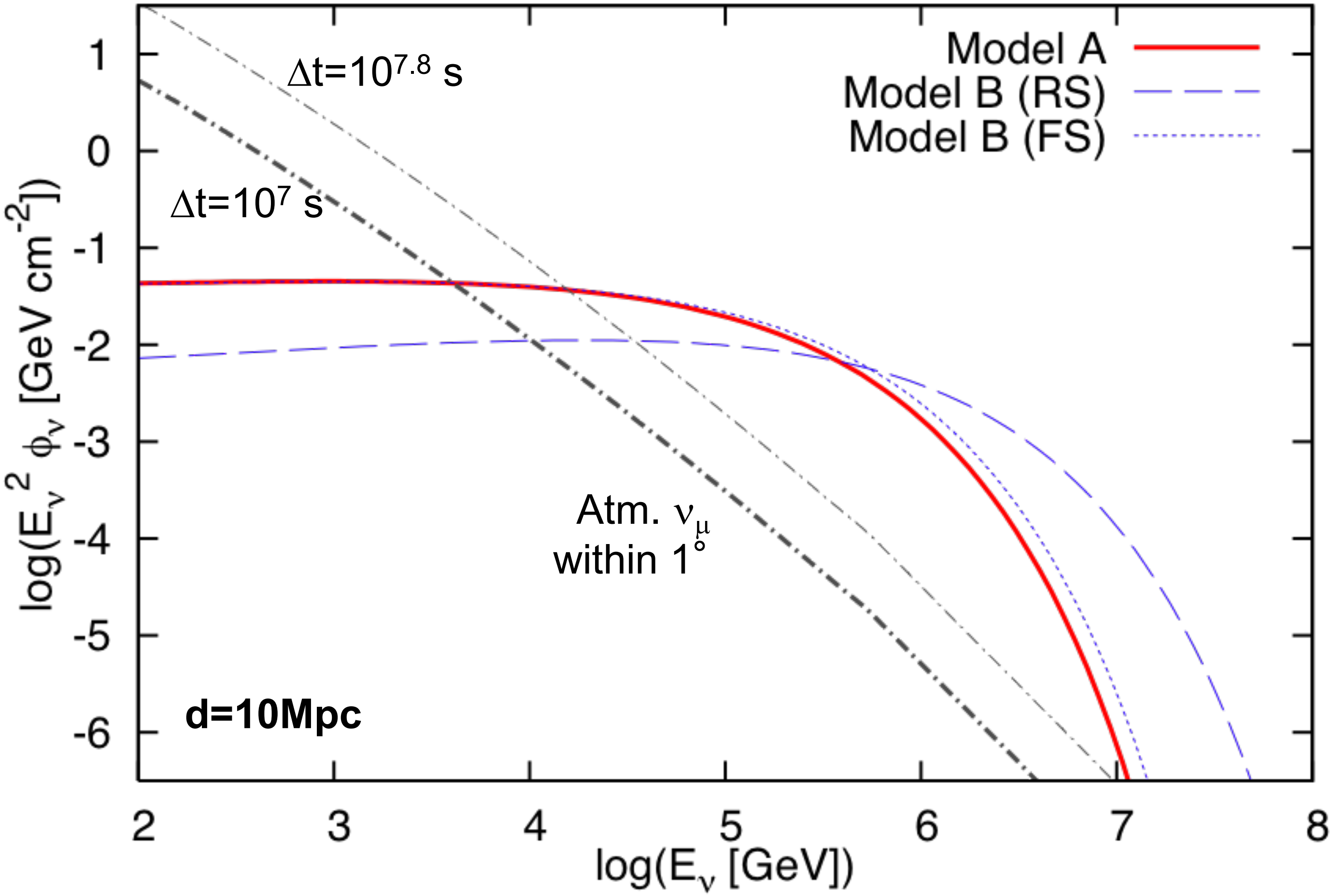
CSM mass:
$M_{cs} \sim (4\pi R^2/3\sigma_T)m_P\tau_T$
Dissipation energy:
$E_{rad} \sim (1/2)M_{cs}V^2$

ex. SN 2009ip
$t_{rise}=10$ d, $R=0.5\times10^{15}$ cm
$\rightarrow M_{cs} \sim 0.05\ M_{sun}$
$\rightarrow E_{rad} \sim 2\times10^{49}$ erg

consistent w. obs.!

Neutrinos from Type IIn SNe

KM, Thompson, Lacki & Beacom 11 PRD



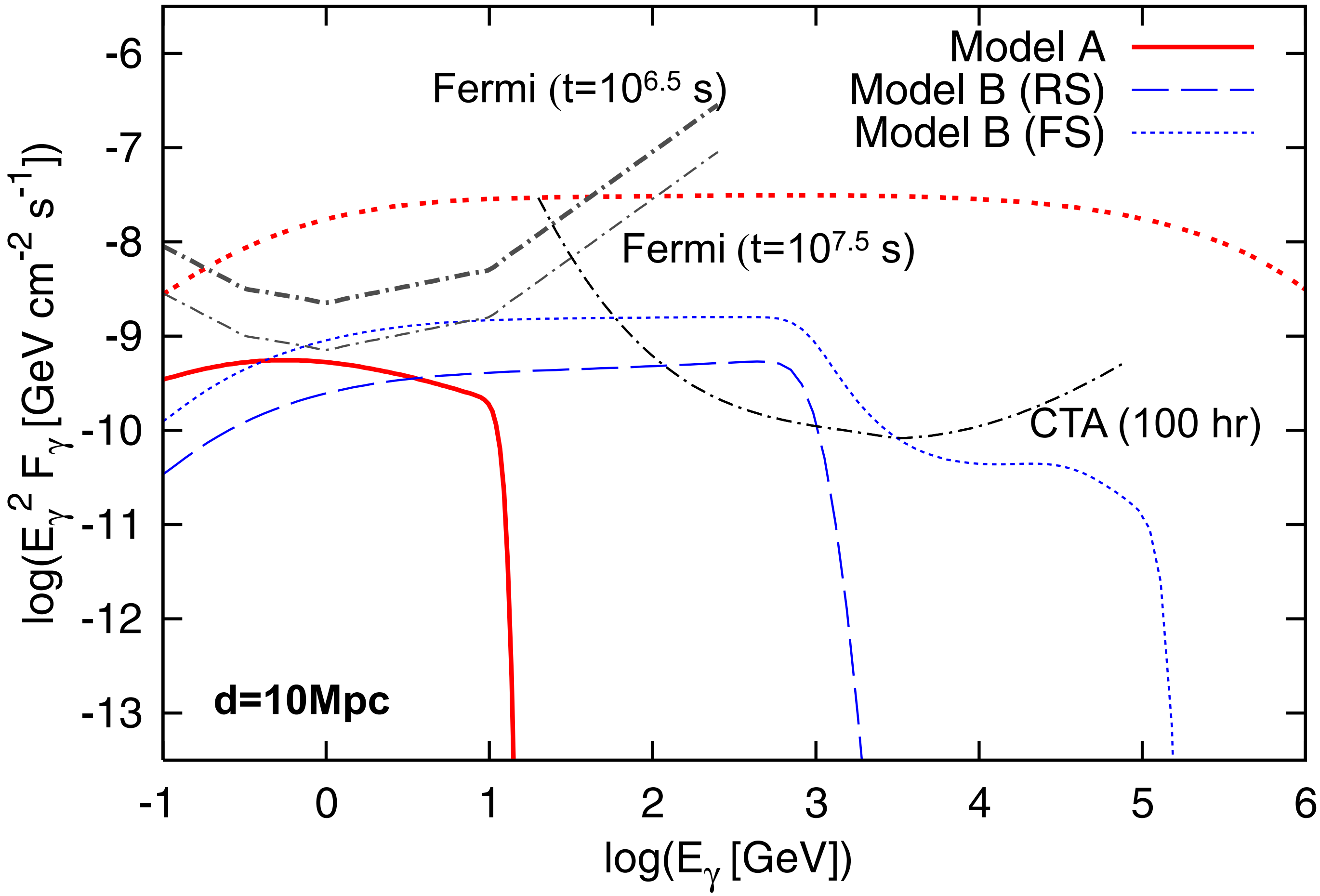
Model A
- optically thick collision

Model B
- optically thin collision

- If CRs carry ~10% of E_{ej} → # of μs ~a few for SN@10Mpc
- Stacking analyses for nearby SNe (~O(100) needed)

Gamma Rays from Type IIn SNe

KM, Thompson, Lacki & Beacom 11 PRD



Model A
- optically thick collision

Model B
- optically thin collision

- GeV γ rays can be seen by Fermi up to ~30 Mpc
- TeV γ rays are detectable by CTA up to ~30-100 Mpc