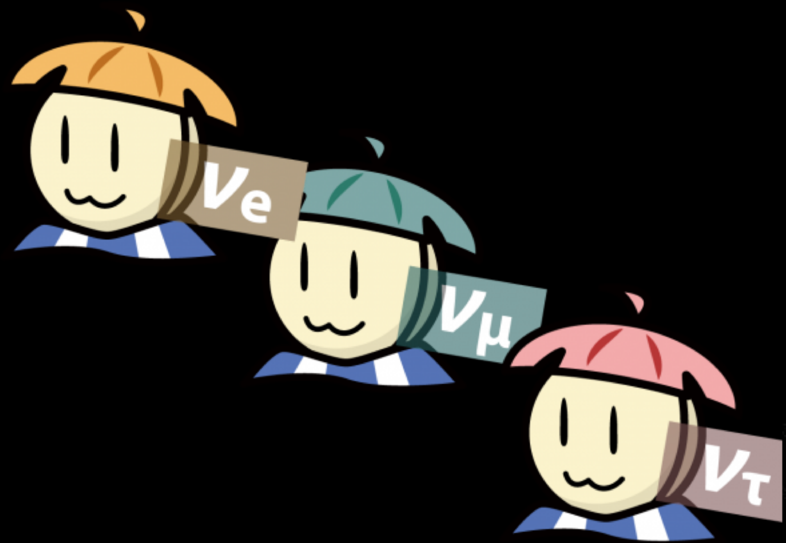
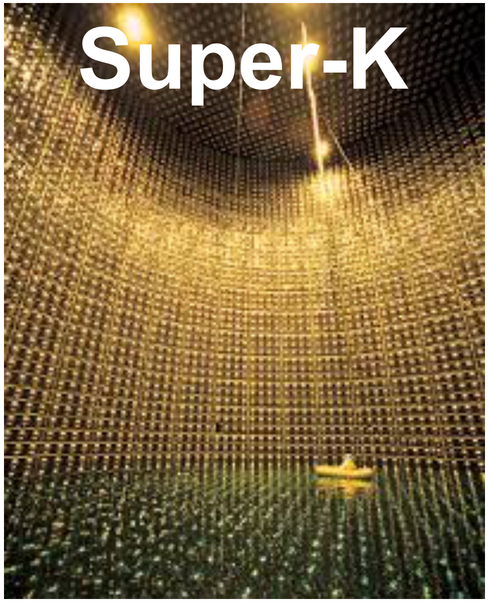
High-Energy Neutrinos from Supernovae



Kohta Murase (Penn State)

SNEWS20 workshop @ Sudbury

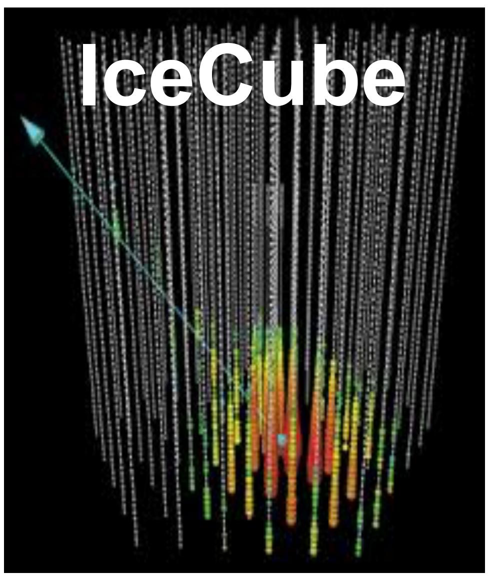
Neutrinos: Unique Probe of Cosmic Explosions



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

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

Super-K detect ~8,000 ν at ~10 MeV (at 8.5 kpc)

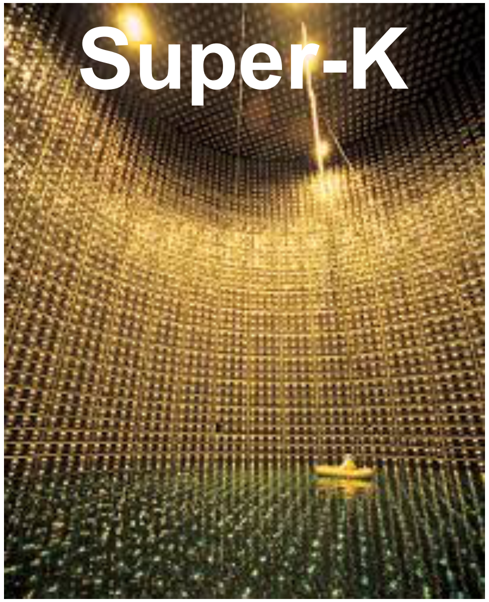


GeV-PeV neutrinos from supernova?
non-thermal: shock dissipation

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

IceCube/KM3Net detect ??? ν at TeV

Neutrinos: Unique Probe of Cosmic Explosions



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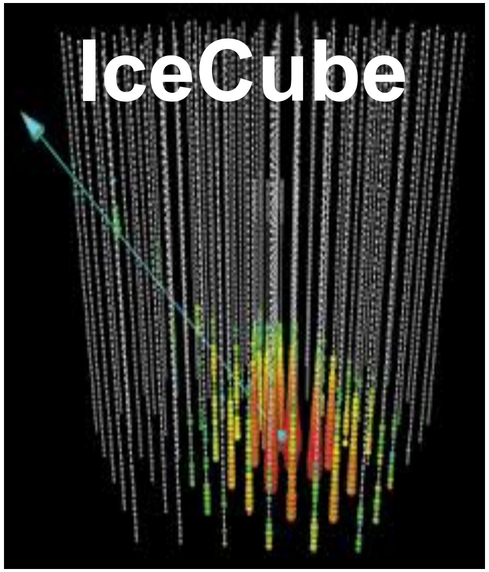

GeV-PeV neutrinos from supernova?
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IceCube/KM3Net detect ~100-1000 ν at TeV

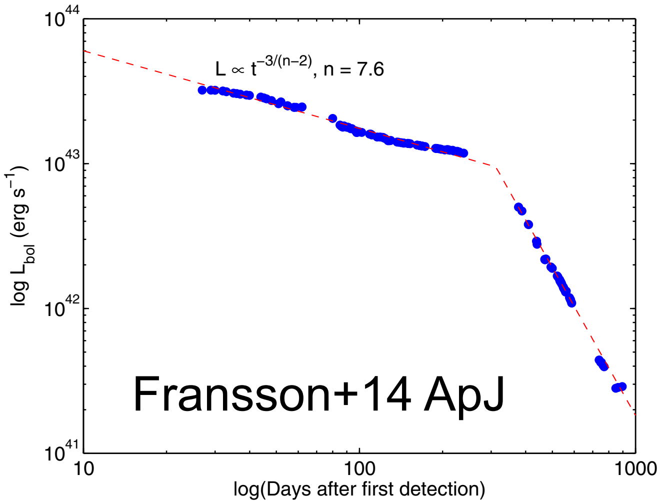
Diffusive Shock Acceleration in Supernovae?

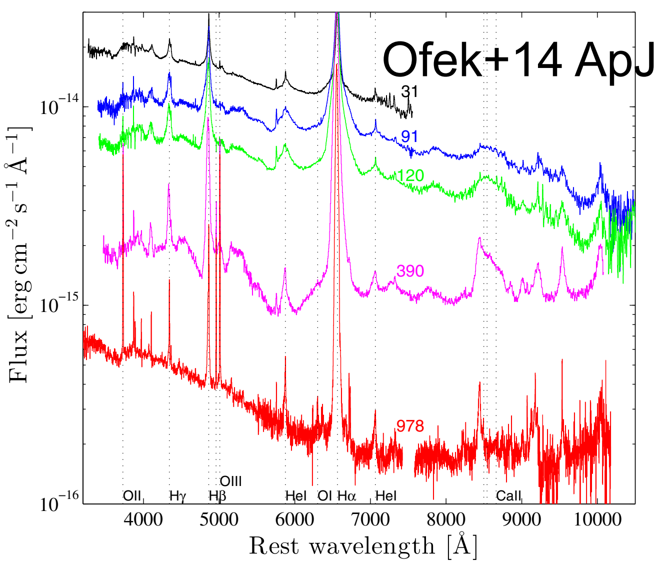
- Young supernova "remnants":
  responsible for CRs up to the knee and second (iron) knee
  diffusive shock (Fermi) acceleration: supported by simulations
- Naively, early CR and HE neutrino production is negligible
  most of energy is in a kinetic form until the Sedov time
  ex. uniform ISM: CR energy ∝ dissipation energy ∝ t^3
- But situations are different
  when circumstellar material (CSM) exists

$$\mathcal{E}_d = \frac{M_{\rm cs}}{M_{\rm ej} + M_{\rm cs}} \mathcal{E}_{\rm ej}$$

Evidence of Strong Interactions w. Dense CSM

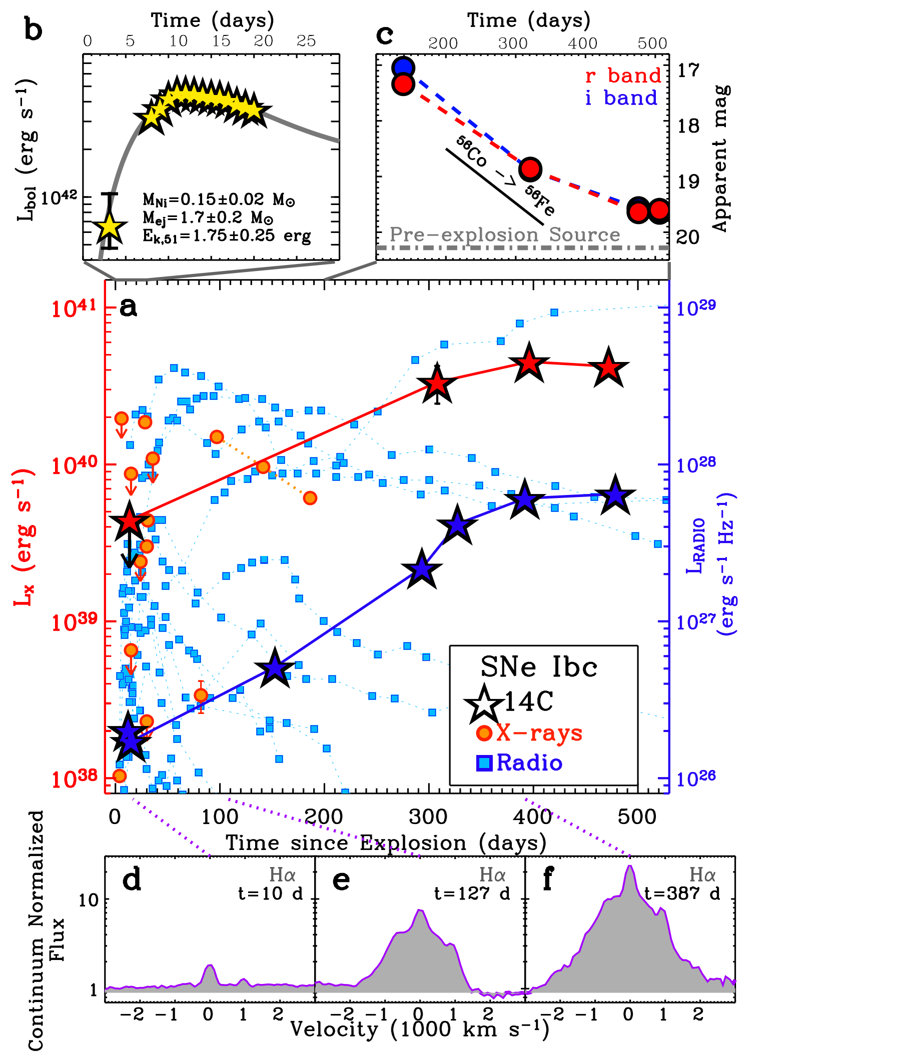
SN 2010jl (IIn)





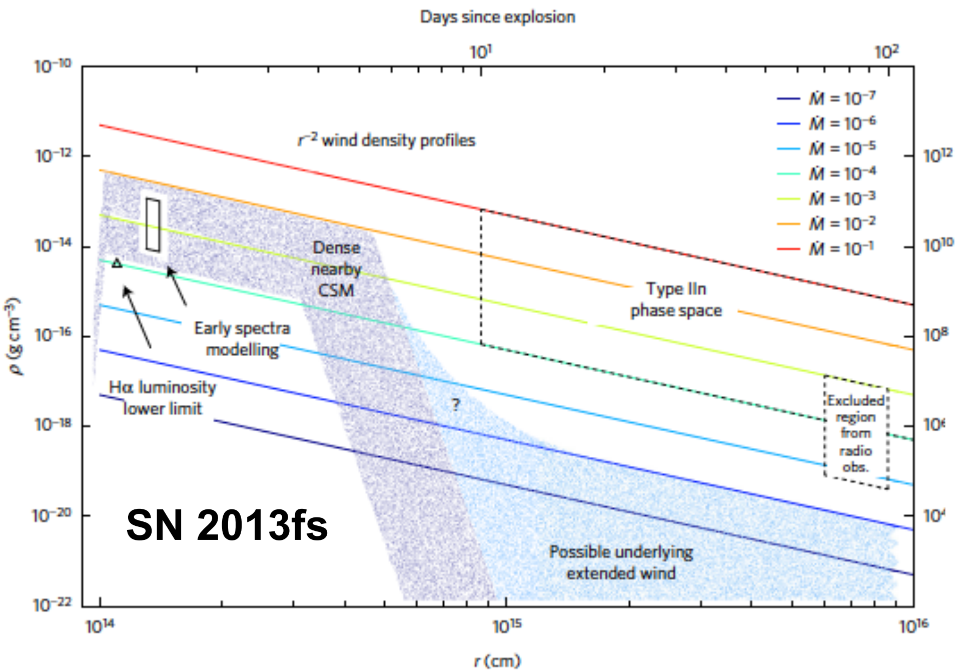
SN 2014C (Ib->IIn)

Margutti et al. 16

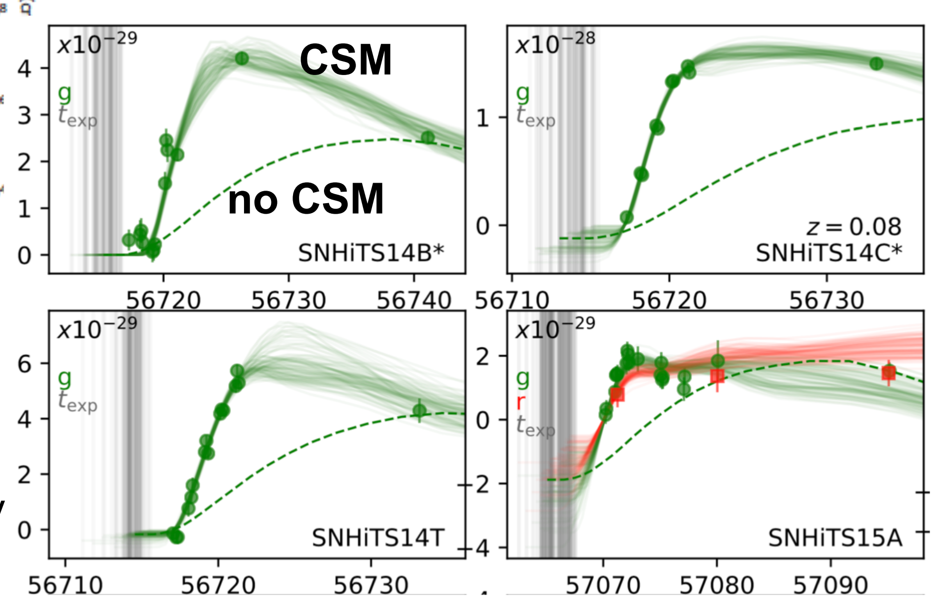


examples of strong interactions w. dense wind or CSM (IIn, SLSN-II)

Evidence for Dense Material around Progenitor



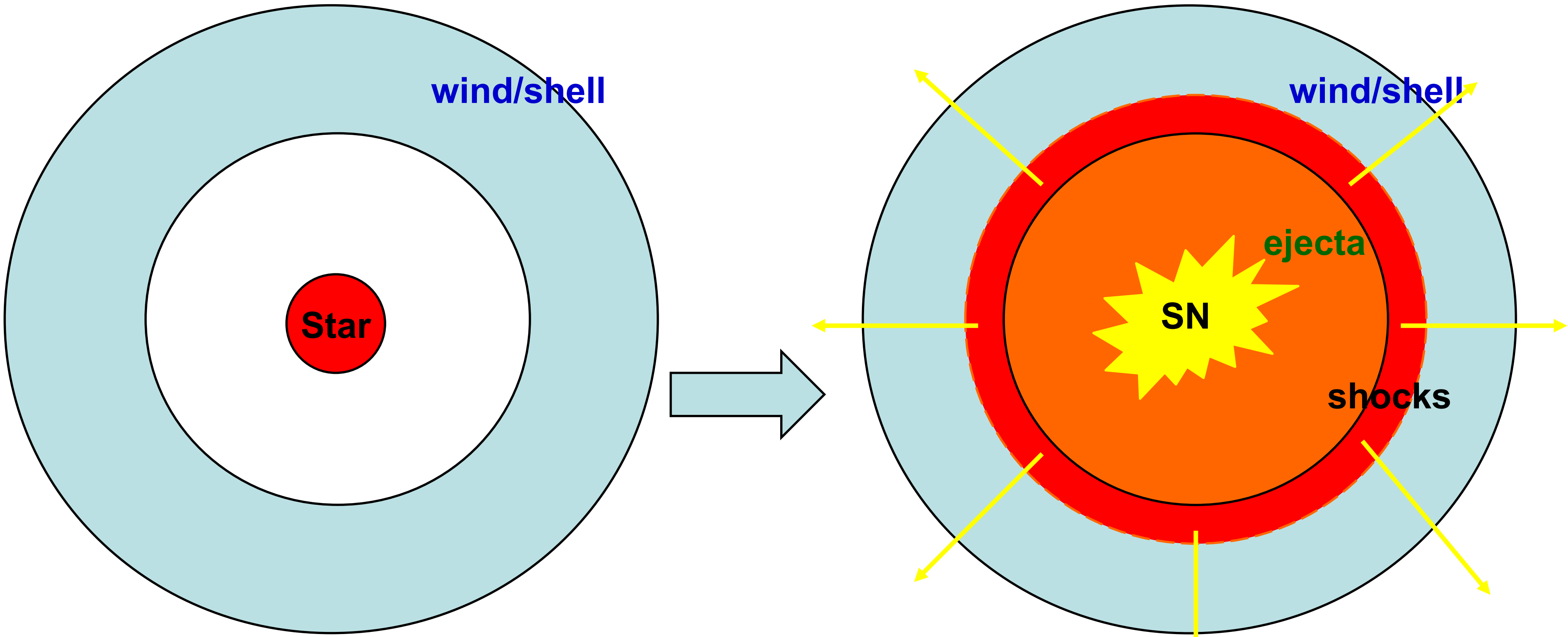
early spectroscopy
(Yaron+ 16 Nature Phys.)



light curve modeling
Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ

- **Known to exist for Type IIn SNe** (M_{cs}~0.1-10 M_{sun})
- **May be common even for Type II-P SNe**
  dM_{cs}/dt~10^{-3}-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-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

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

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**

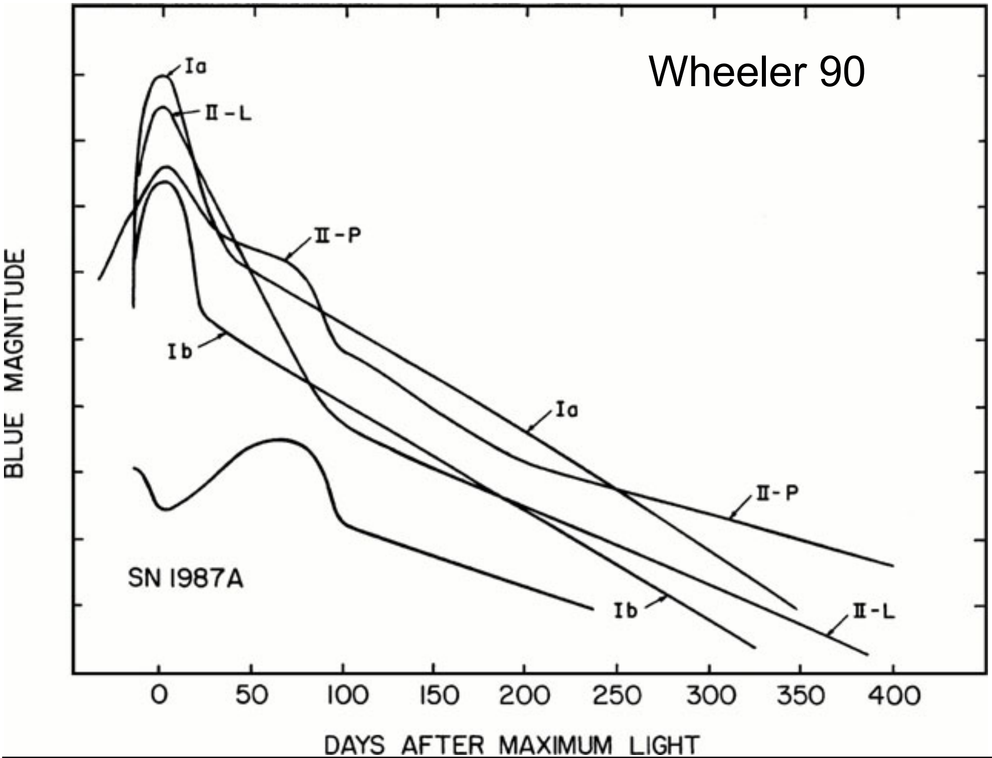
Kinetic luminosity

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

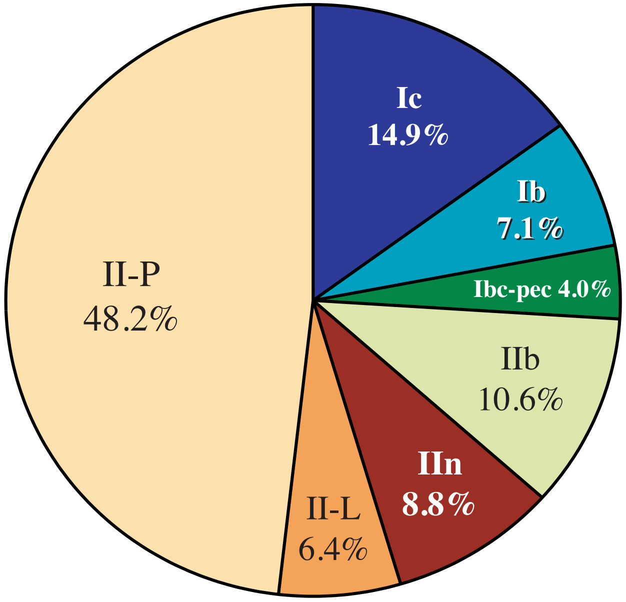
parameters for dynamics: determined by photon (opt, X, radio) observations

※ Detailed model gives L_d t ~ E_{ej}(>V_s), larger than L_d t ~(M_{cs}/ M_{ej} +M_{cs})E_{ej}

Diversity of Core-Collapse Supernovae



Smith+ 11 MNRAS



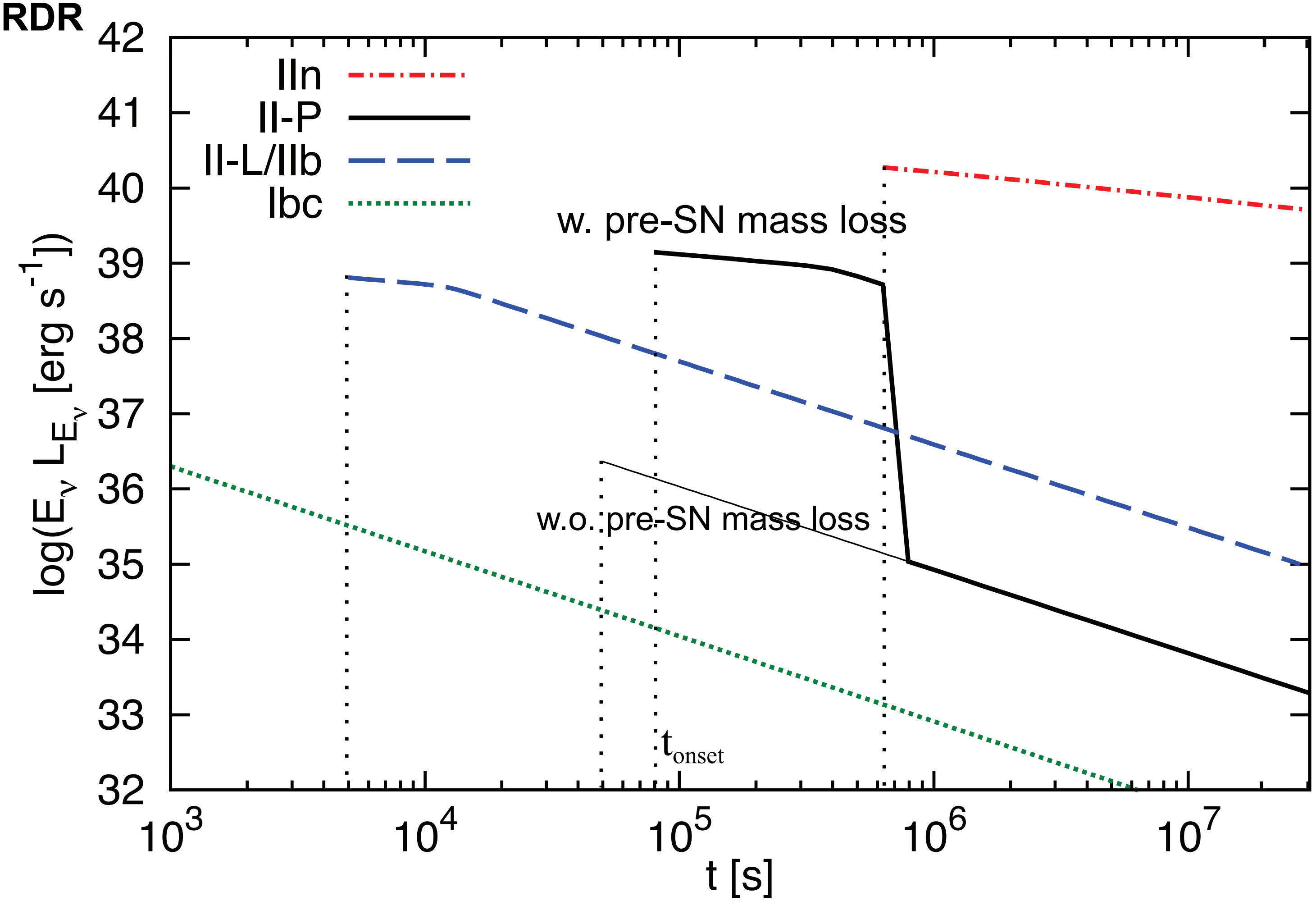
Core-Collapse SN Fractions

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

← Betelgeuse

Neutrino Light Curve

KM 18 PRDR

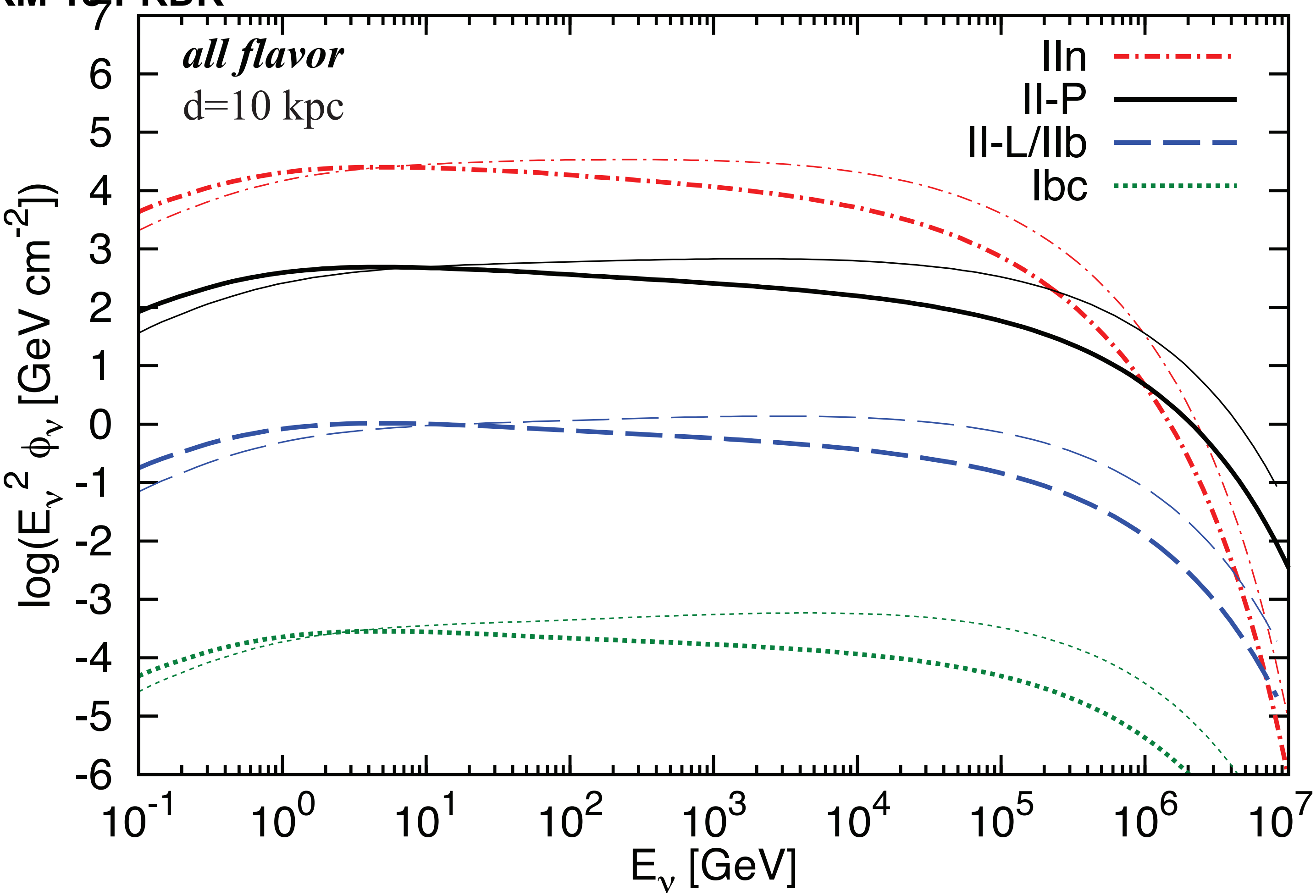


t_{onset} ~ time leaving the star (typical) or breakout time (IIn)

slowly declining light curve while pion production efficiency ~ 1

Neutrino Fluence

KM 18 PRDR



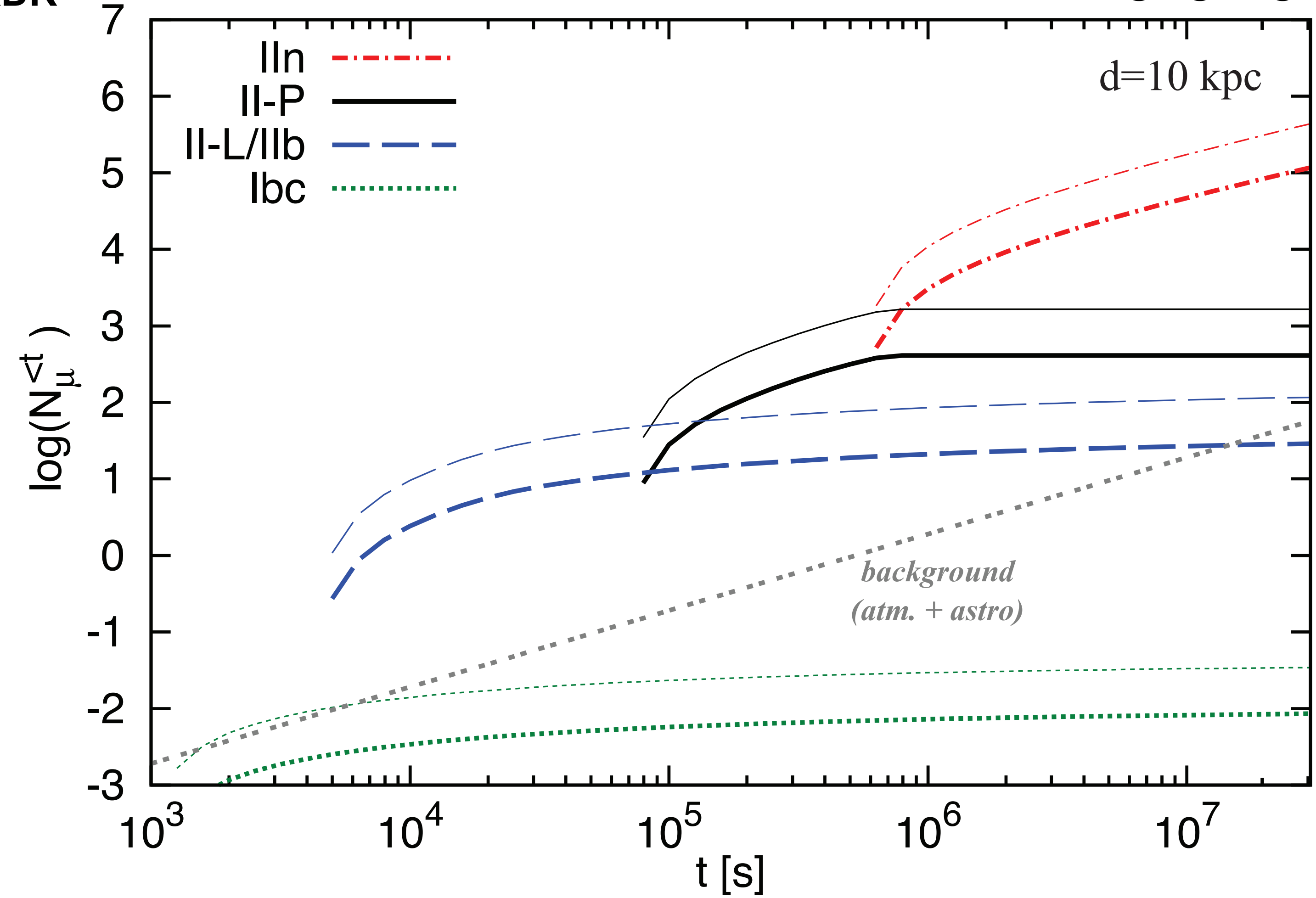
thick: s=2.2
thin: s=2.0

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

Prospects for Neutrino Detection

KM 18 PRDR

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)

Key Points

- Testable & clear predictions (no need for jets, winds, shocks in a star)
  free parameters: ε_{CR} & s (typical values: ε_{CR}~0.1 & s~2.0-2.3)

- Time window:
  provided by the theory (f_{pp}~t_{dyn}/t_{pp}~1)
  e.g., ~hours to days for SNe II (II-P/II-L/IIb), ~hours (Ibc), ~months (IIn)

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

∗ Type II cases: rather different from the Type IIn case
II-P/II-L/IIb/Ibc: shock is collisionless & $M_{csm} << M_{ej}$
IIn: shock can be radiation-mediated & M_{csm} could be larger than M_{ej}
→ more complications (limitation of self-similar, ejecta deceleration, radiative shock, other relevant processes (Coulomb collisions etc.)…

※ νs from breakout from envelope (previously studied) : largely suppressed (see KM+19 ApJ)

Implications

- Astrophysical implications
  a. Pre-explosion mass-loss mechanisms
     How does a dense wind/shell form around the star ?
  b. PeVatrons
     Are supernovae the origin of CRs up to the knee energy at $10^{15.5}$ eV?
  c. Real-time observation of ion acceleration for the first time
     How are CR ions accelerated?
  d. Best targets for multi-energy neutrino & multi-messenger astrophysics
     MeV νs & possibly gravitational waves, followed by GeV-PeV νs
     optical, X-rays, radio waves, and gamma rays (up to ~Mpc by Fermi)

- Particle physics implications – large statistics
  flavor studies, BSM searches (neutrino self-interactions,
  neutrino decay, 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 new 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