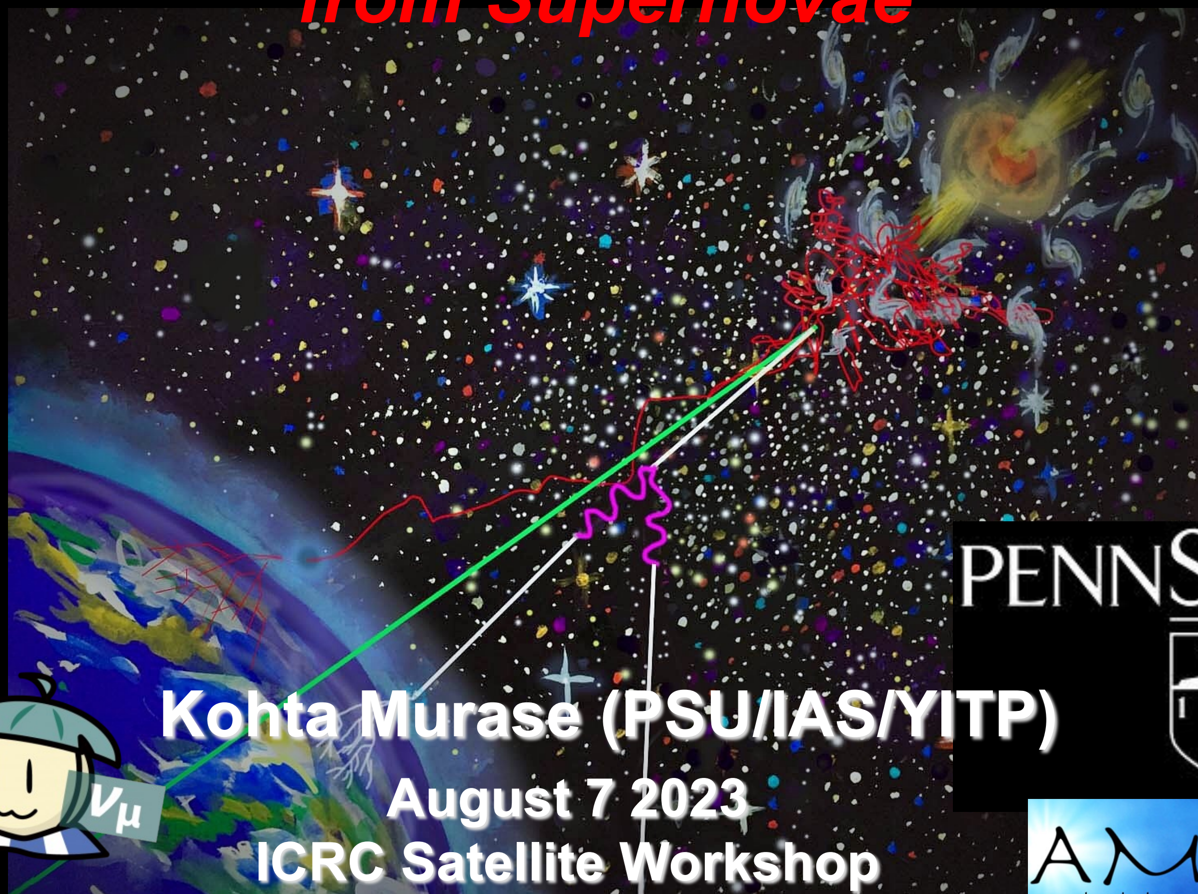
High-Energy Multimessenger Emission from Supernovae



Kohta Murase (PSU/IAS/YITP)

August 7 2023

ICRC Satellite Workshop

PENNSTATE

1855

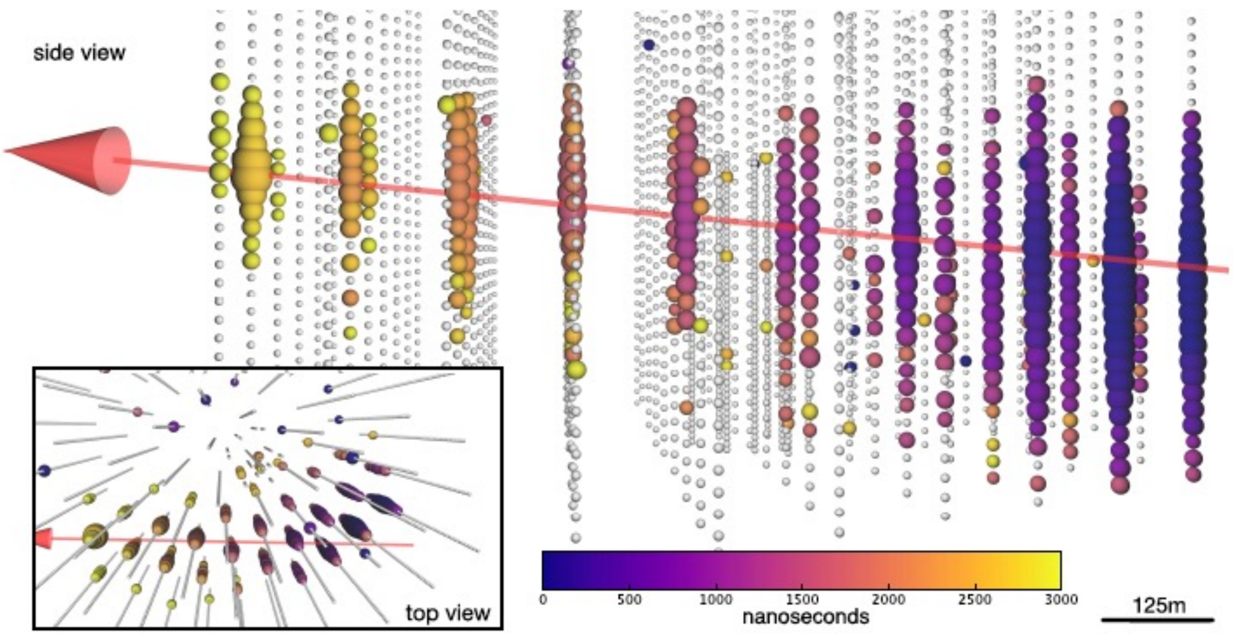
AMON

Astrophysical Multimessenger Observatory Network

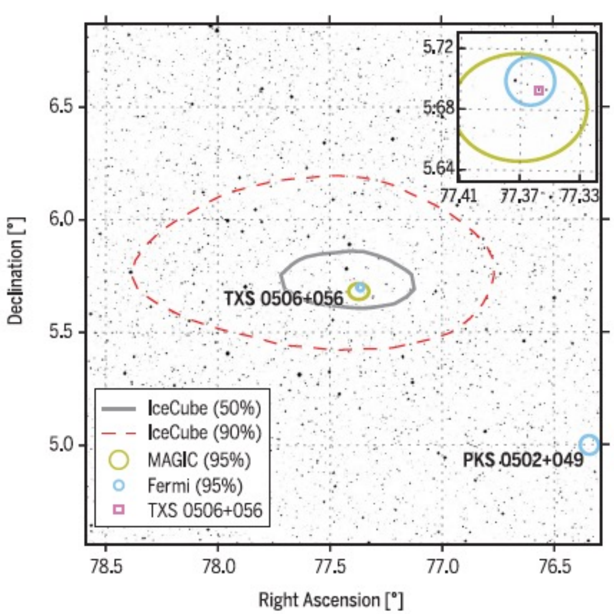
Why Transients?

1. Pointing & timing → reducing atmospheric backgrounds
2. Dominant sources ≠ brightest sources
3. Still viable as the dominant origin
4. Flares/bursts → more target γs → enhanced ν production

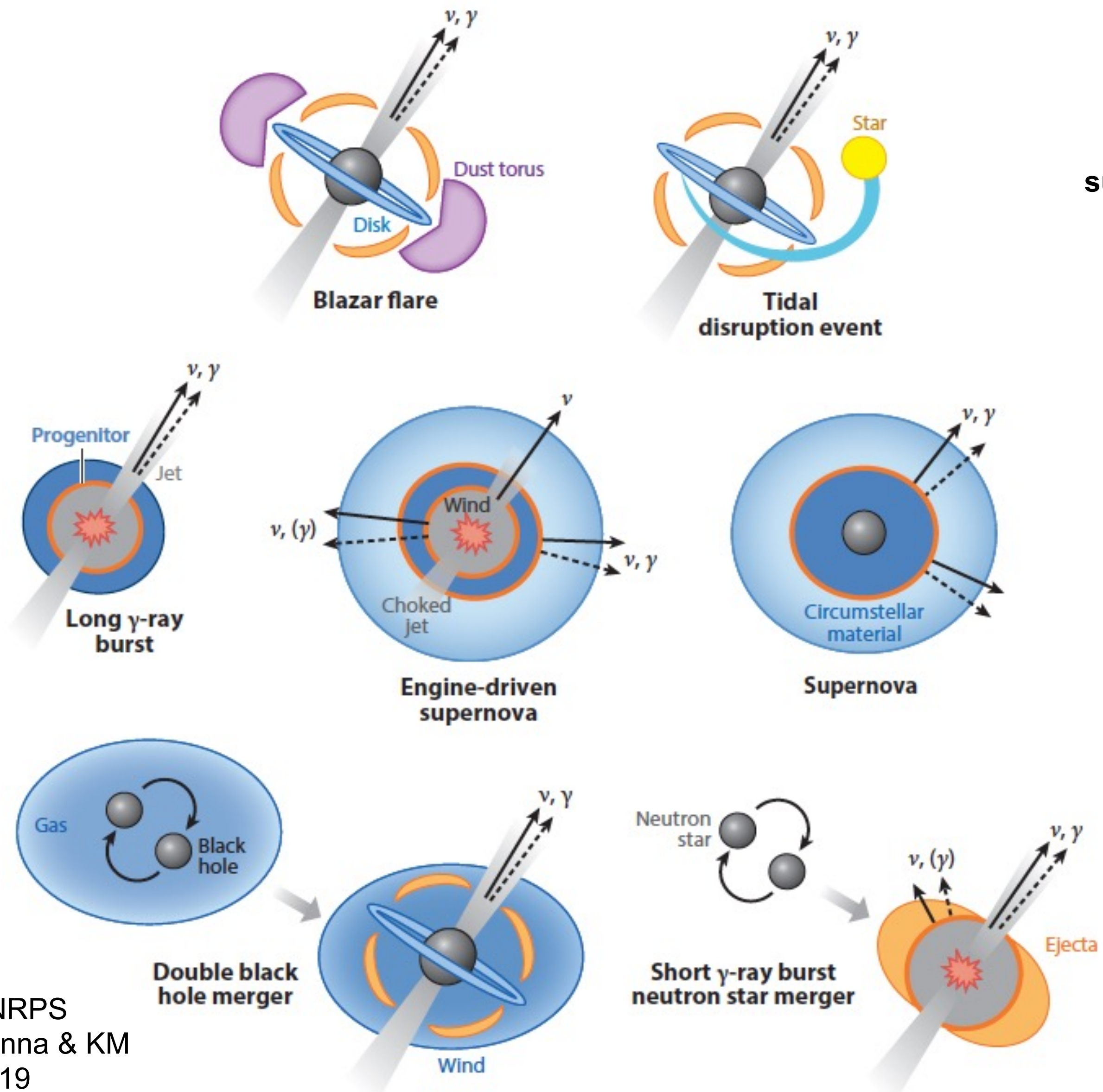
→ Good opportunities to find rare bright transients even now



IceCube 2018 Science



Diversity of High-Energy Transients



supermassive black holes

massive stellar deaths

compact mergers
(promising GW sources)

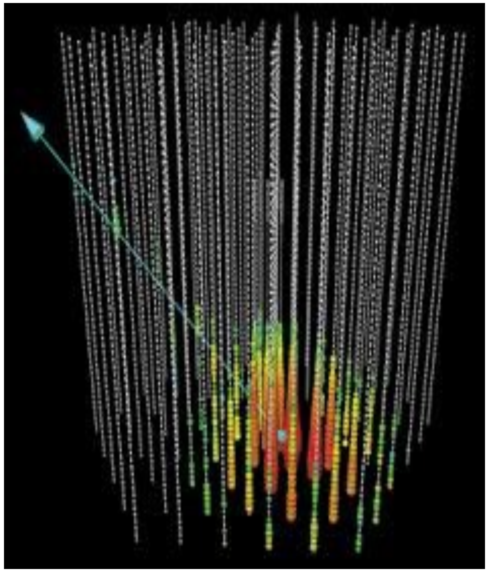
KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

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

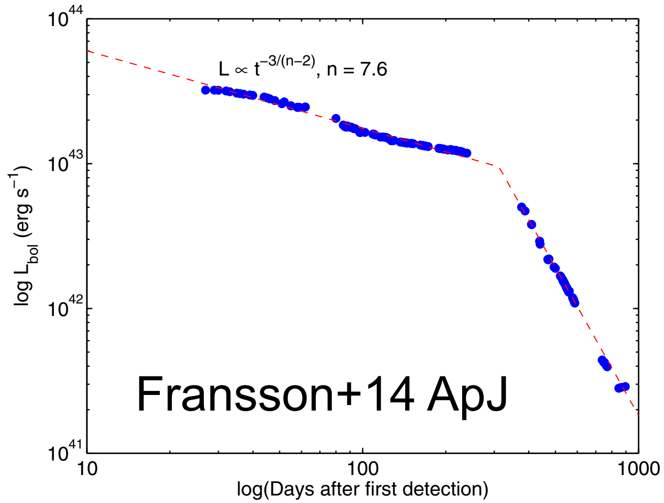
Diffusive Shock Acceleration in Supernovae?

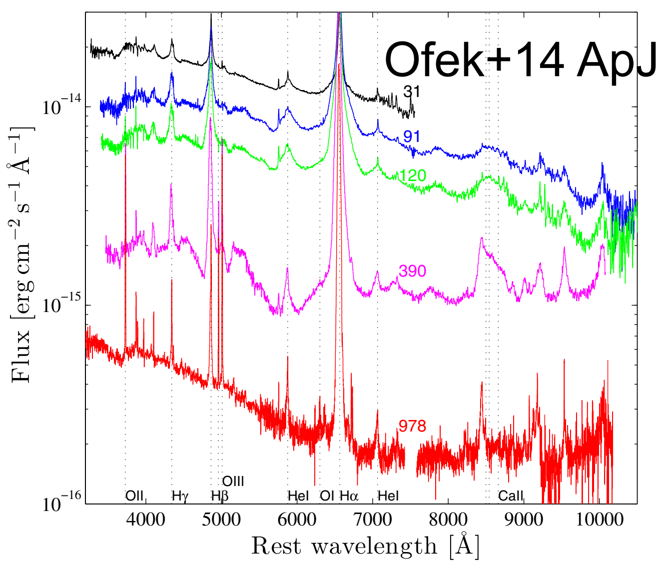
- Young supernova "remnants":
  believed to be responsible for CRs up to the knee region
  diffusive shock (Fermi) acceleration
- Naively, early CR and HE neutrino production are negligible
  most of energy is in a kinetic form until the Sedov time
  ex. uniform ISM: CR energy ∝ dissipation energy ∝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

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

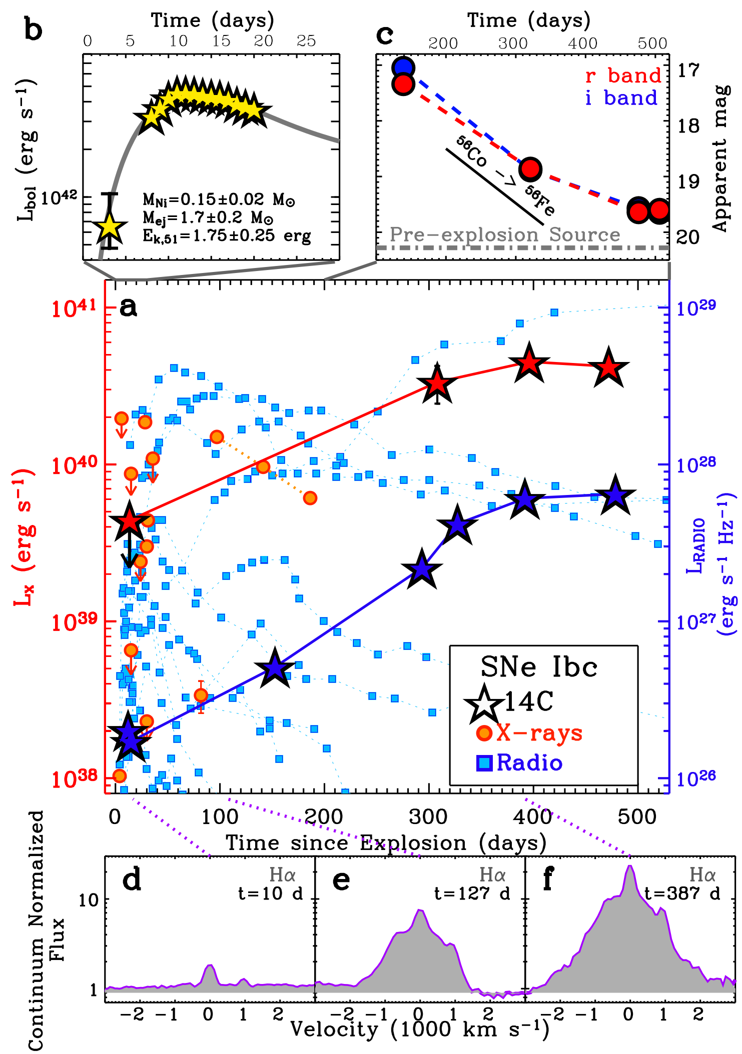
Evidence of Strong Interactions w. Dense CSM

SN 2010jl (IIn)



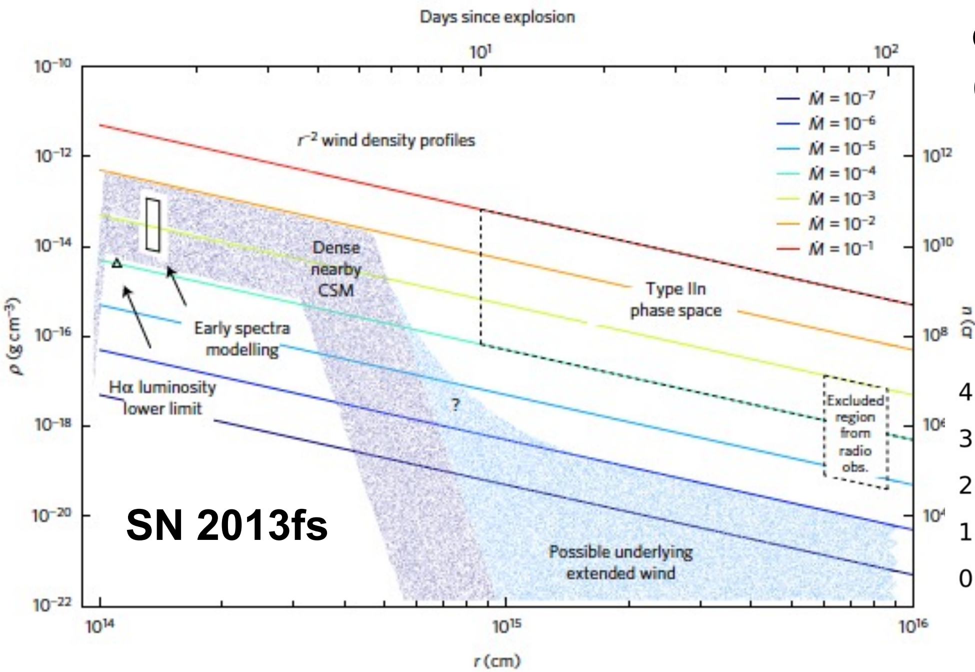


SN 2014C (Ib->IIn) Margutti et al. 16

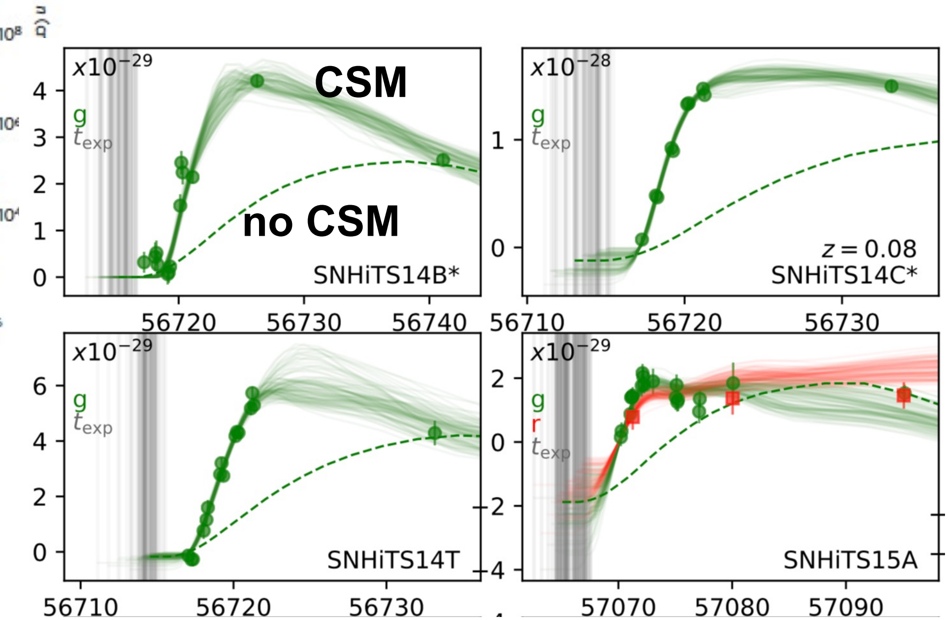


IIn, SLSN-II: strong interactions w. dense wind or CSM (M_{cs}~0.1-10 M_{sun})

Evidence for "Confined" CSM around Progenitors



early spectroscopy
(Yaron+ 16 Nature Phys.)

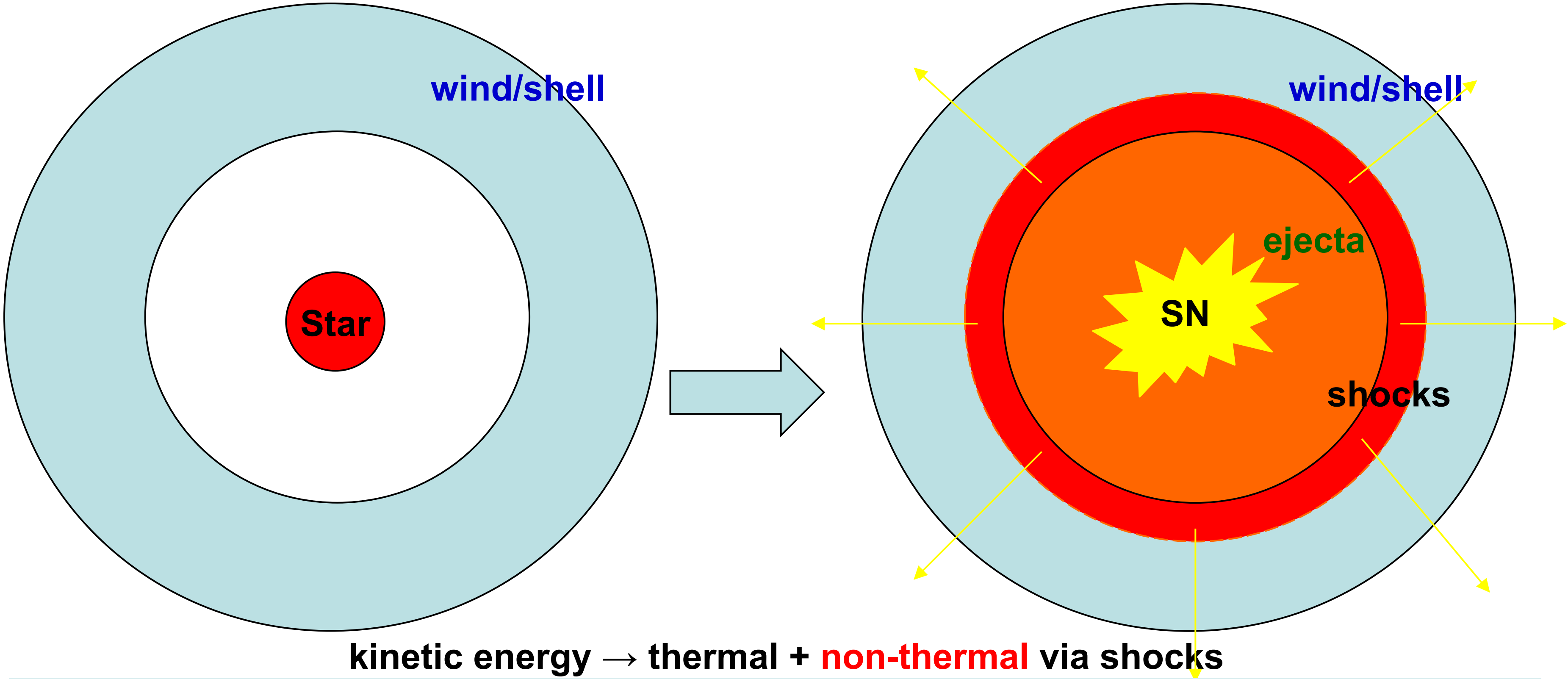


light curve modeling
(Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ)

- **May be common even for Type II-P SNe**
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- **Confined CSM** (R_{cs} <~ 10^{15} cm): mass ejection or inflation

Multimessenger Emission from Interacting SNe

KM, Thompson, Lacki & Beacom 11, KM & Thompson & Ofek 14



kinetic energy → thermal + non-thermal via shocks

$$p + p \rightarrow N\pi + X$$

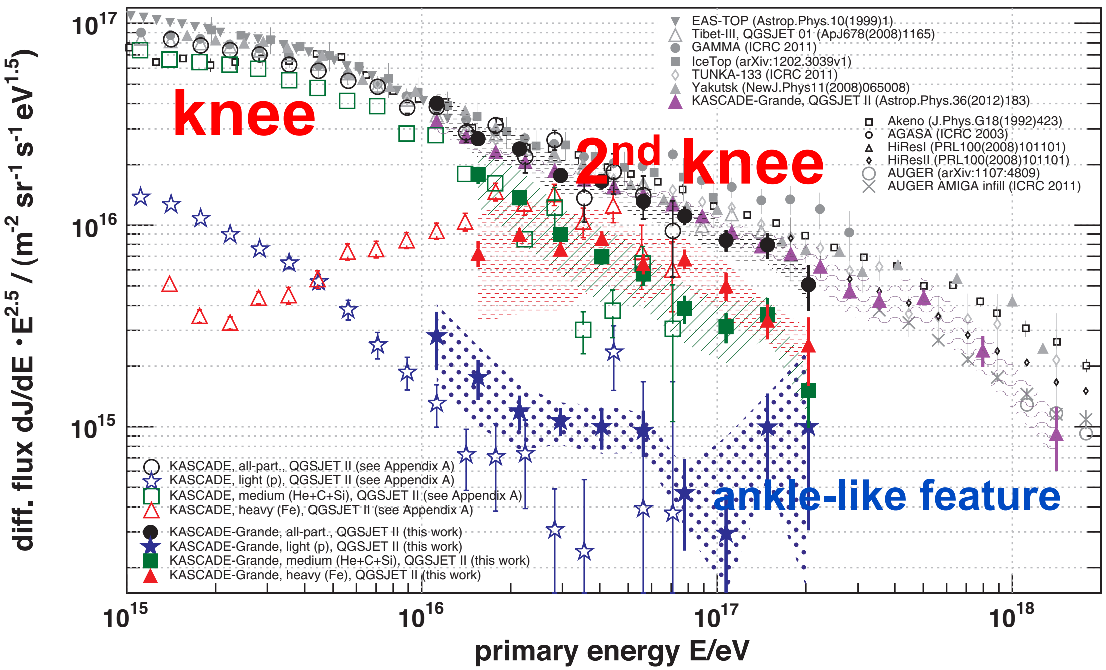
$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

Cosmic-Ray Origins?

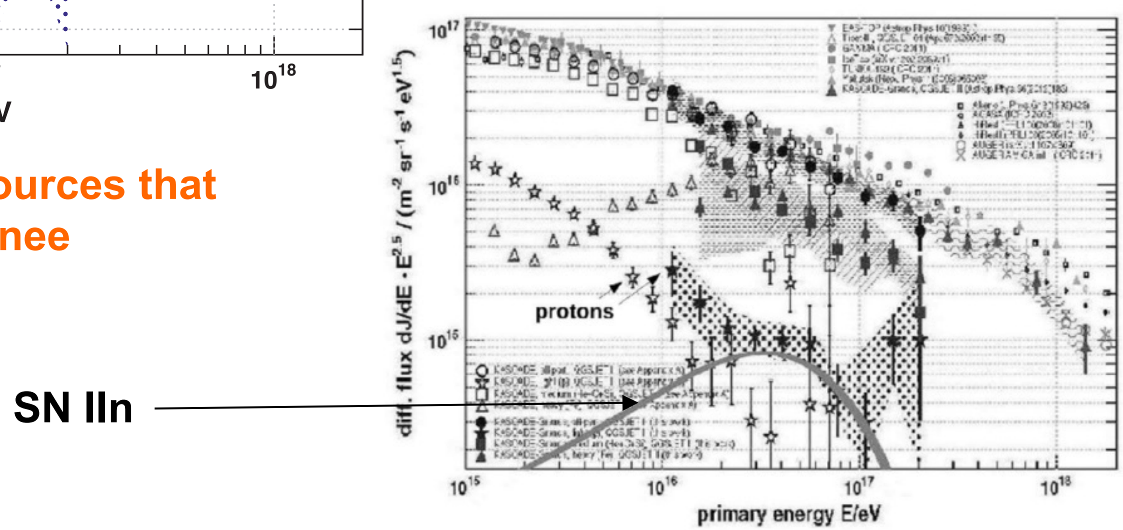
SNe IIn as the origin of CRs above the knee?



Apel et al. 13 APh

It seems that we need Galactic sources that can accelerate CRs beyond the knee

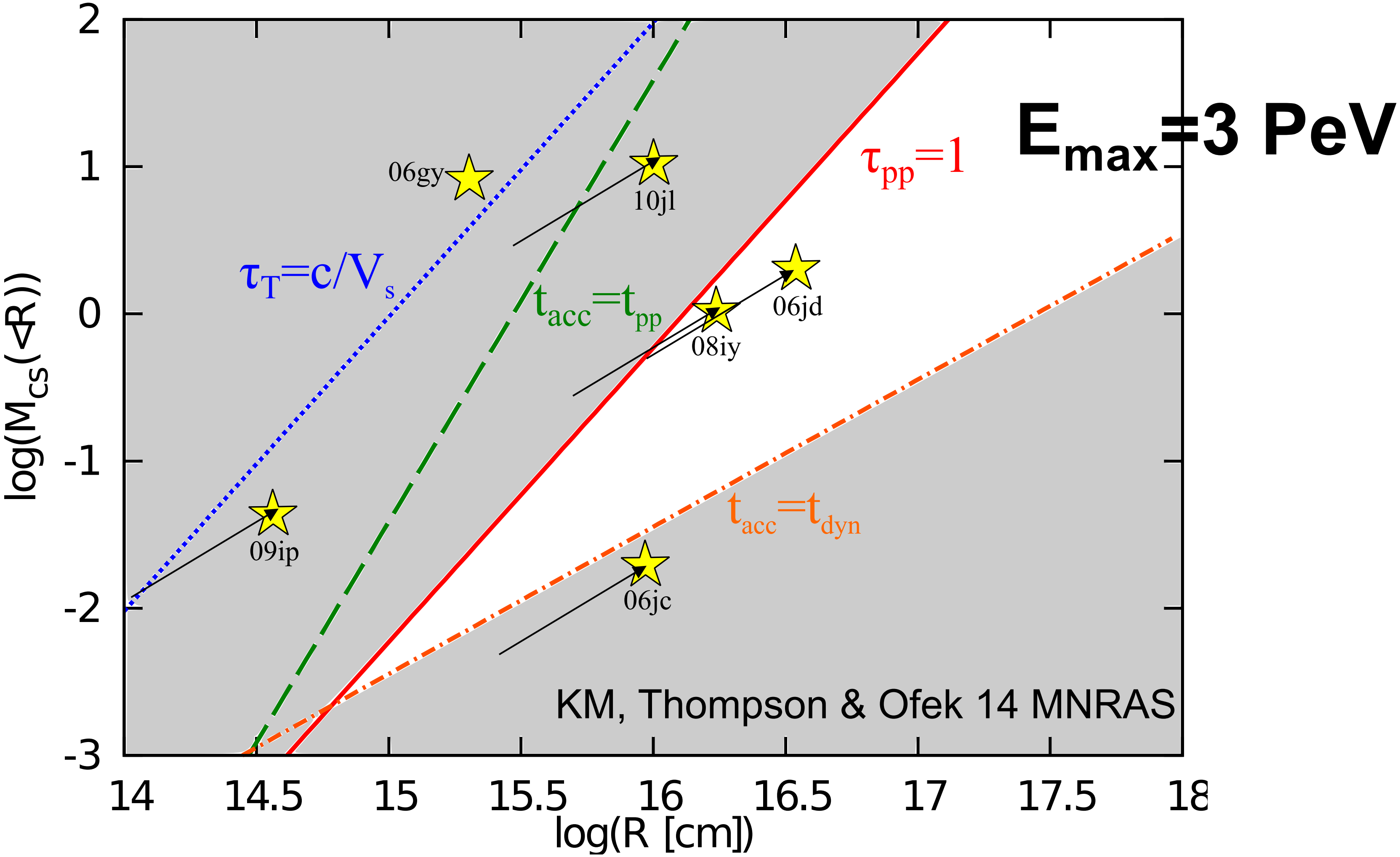
Zirakashvili & Ptuskin 16 APh



CR Acceleration in Interacting SNe?

- Quasi-parallel, Bohm limit

$$E_{\rm p}^{M} \approx 3.0 \times 10^{7}\,{\rm GeV}\,\varepsilon_{B,-2}^{1/2} D_{*}^{1/2} (V_{\rm s}/5000\,{\rm km\,s^{-1}})^{2}.\ D_{*} = D/(3\times10^{15}\ {\rm g\ cm^{-1}})$$



Shock Dynamics& Time-Dependent Model

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

velocity distribution
$E_{ej}(>V_{ej}) \propto V_{ej}^{-7}$-$V_{ej}^{-5}$

faster-velocity components in SN ejecta are decelerated earlier

CSM parameter $$D = \frac{\dot{M}_w}{4\pi V_w}$$ **where** $$\varrho_{\rm cs} = D R_{\rm cs}^{-2} \left(\frac{r}{R_{\rm cs}} \right)^{-w}$$

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 before the Sedov-Taylor-like deceleration (Chevalier 82)

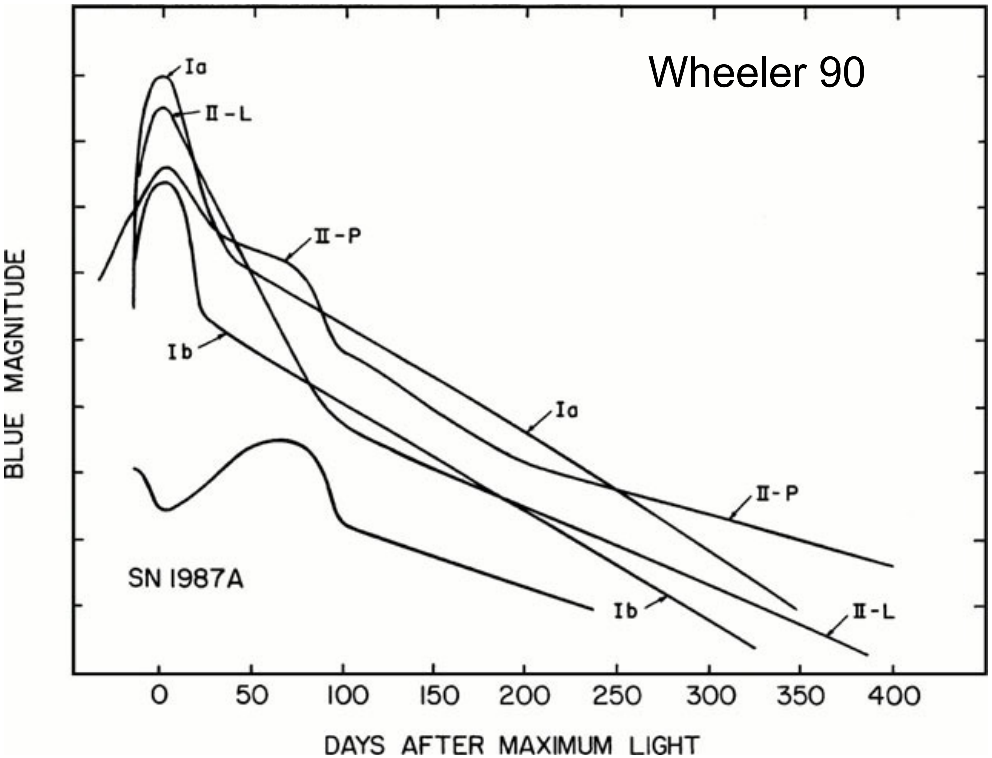
shock radius $$R_s = X(w,\delta) D^{-\frac{1}{\delta - w}} \mathcal{E}_{\rm ej}^{\frac{\delta-3}{2(\delta-w)}} M_{\rm ej}^{-\frac{\delta-5}{2(\delta-w)}} t^{\frac{\delta-3}{\delta-w}}$$

w=2 for a wind CSM
δ~10-12 for stars

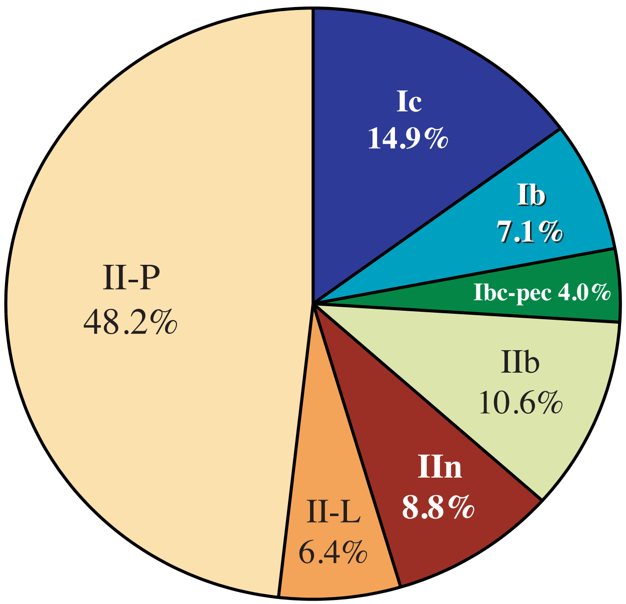
Kinetic luminosity $$L_d = 2\pi \varrho_{\rm cs} V_s^3 R_s^2 \propto t^{\frac{6w-15+2\delta-\delta w}{\delta-w}}$$

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

Diversity of Core-Collapse Supernovae



Smith+ 11 MNRAS



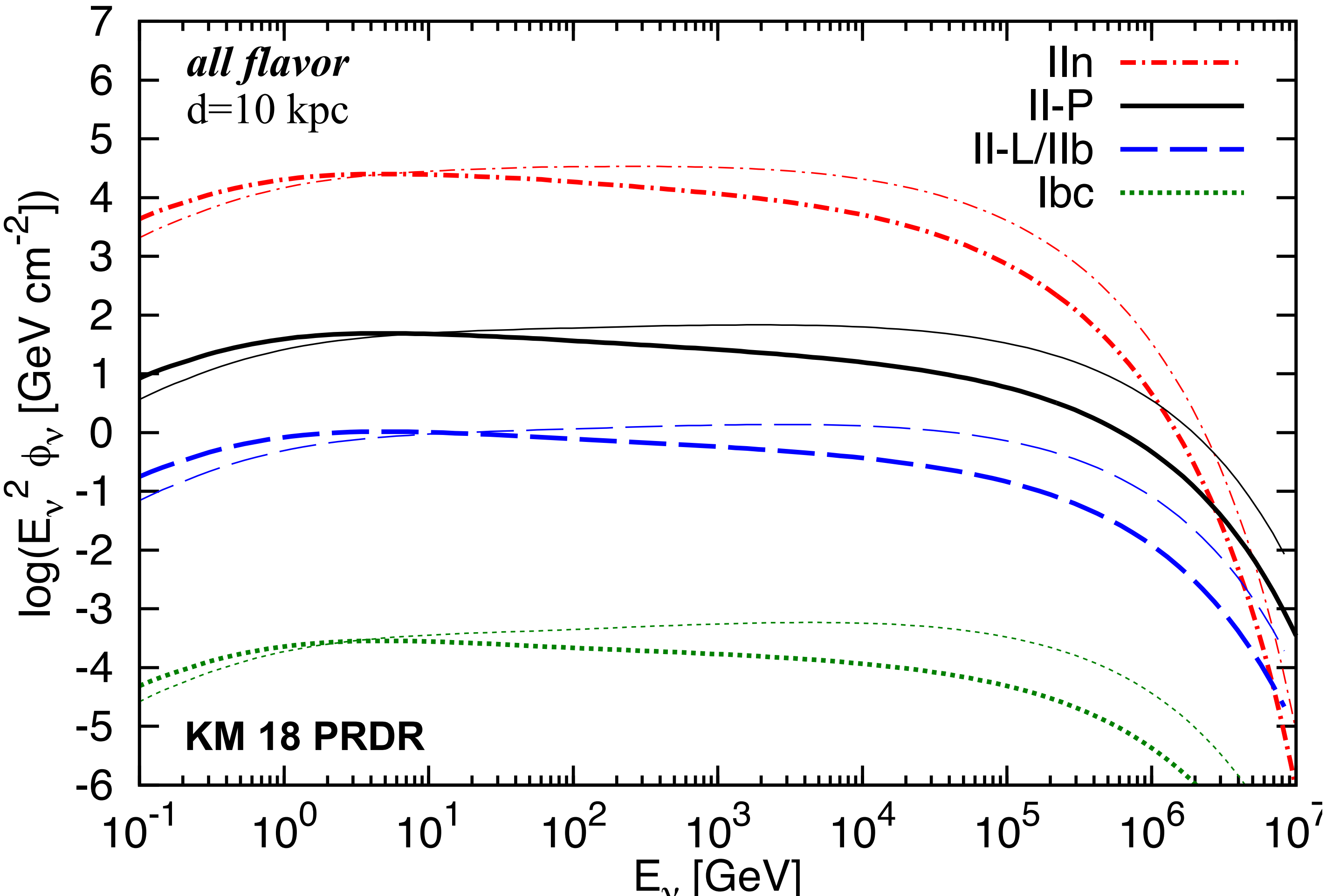
Core-Collapse SN Fractions

Class	D_*	$\dot{M}_w$ $[M_\odot\ \mathrm{yr}^{-1}]$	V_w $[\mathrm{km\ s}^{-1}]$	R_* [cm]
II (CCSM)	$10^{-2} - 1$	$10^{-3} - 10^{-1}$	100	6×10^{13}
IIn	1	10^{-1}	100	10^{13}
II-P[a]	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 (II-P row)

Neutrino Fluence

First prediction of HE neutrinos from SN w. confined CSM (KM 18 PRDR)

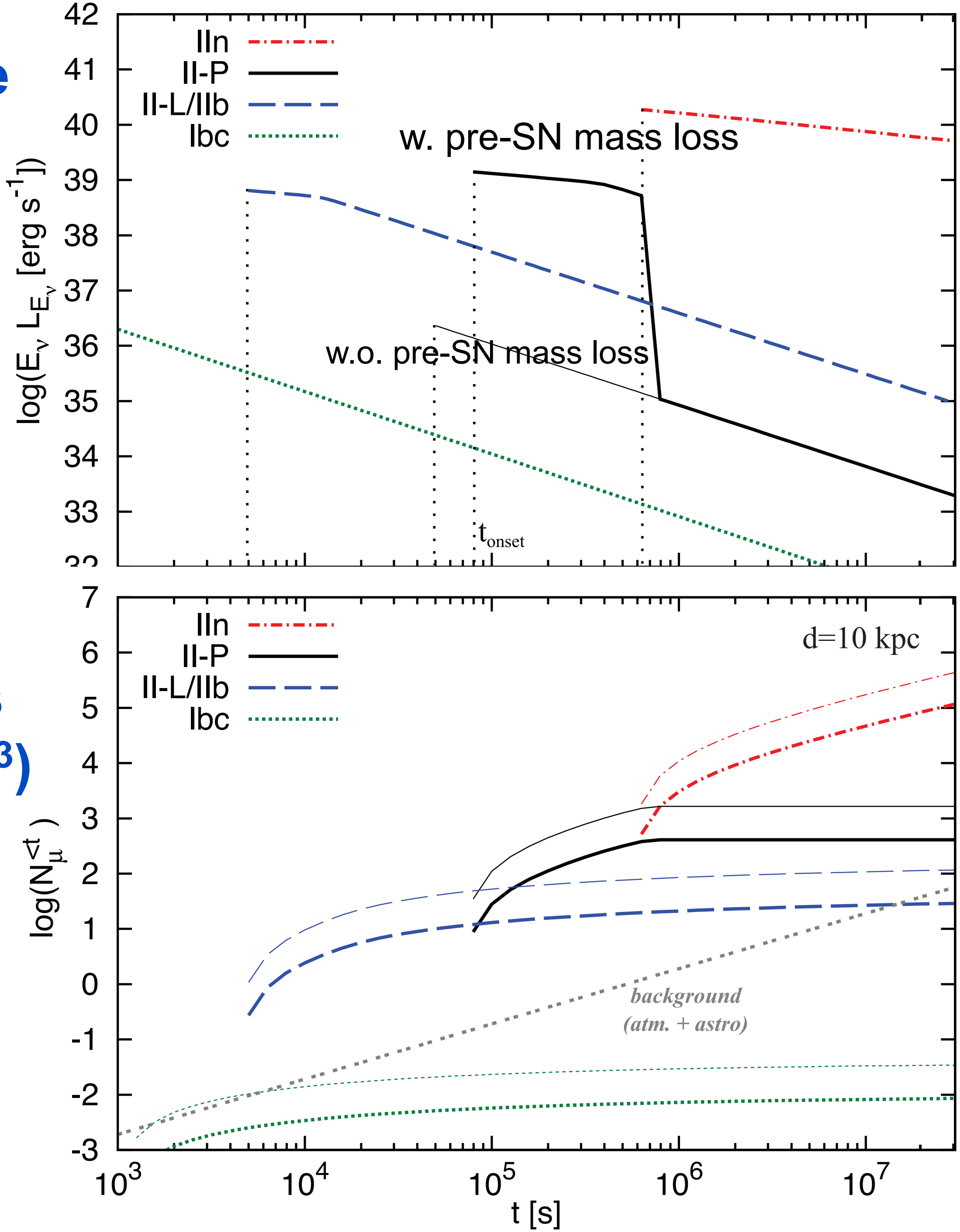


thick: s=2.2
thin: s=2.0

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

light curve

expected # of ν_μ tracks (w. V=1 km^3)



KM 18 PRDR

~100-1000 events for typical CCSNe

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:
  duration ~ calorimetry (f_{pp}~t_{dyn}/t_{pp}>1)
  e.g., ~days to weeks 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/IceCube-Upgrade/KM3Net-ORCA: GeV-TeV

∗ 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)

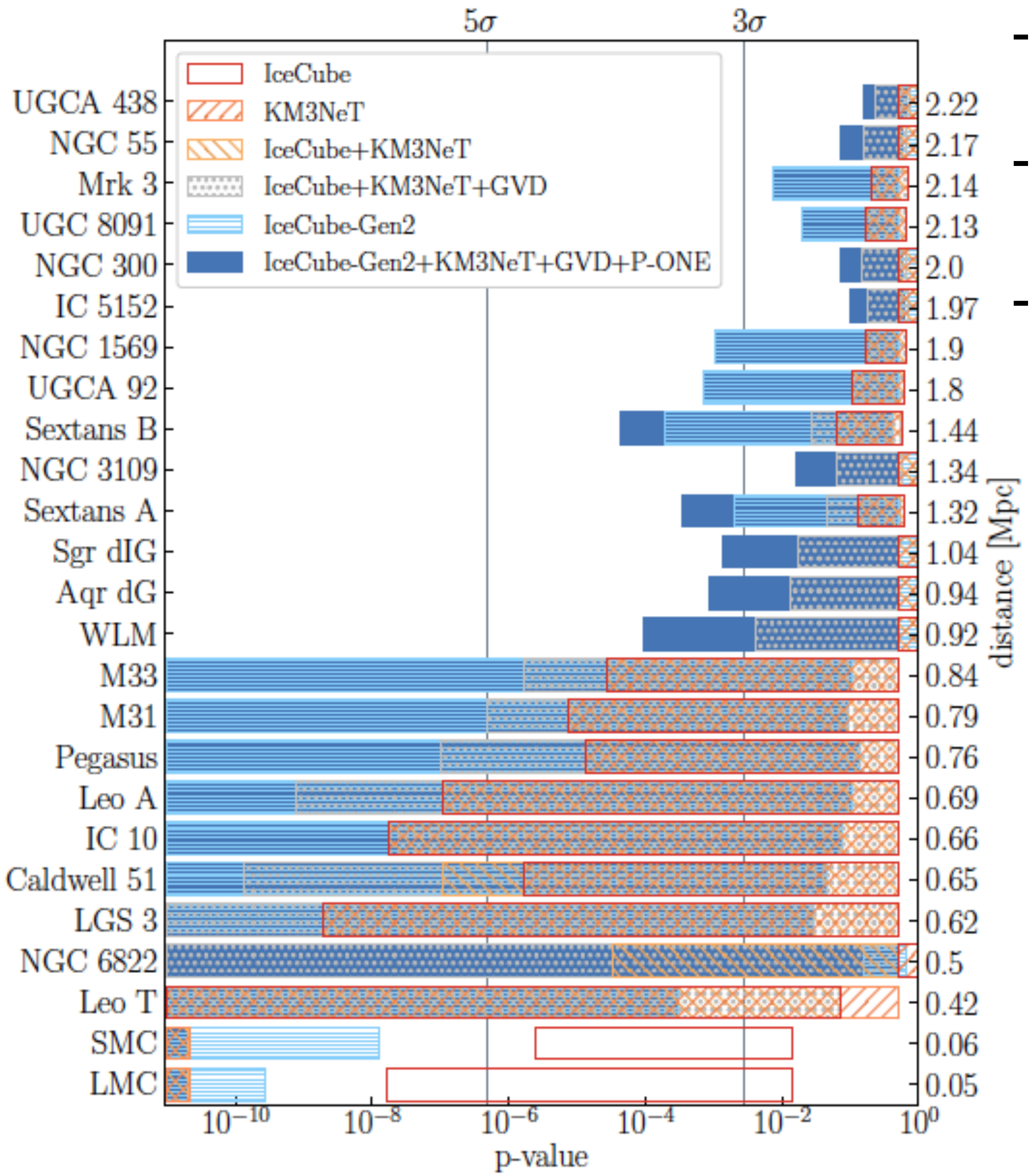
Implications

- 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)

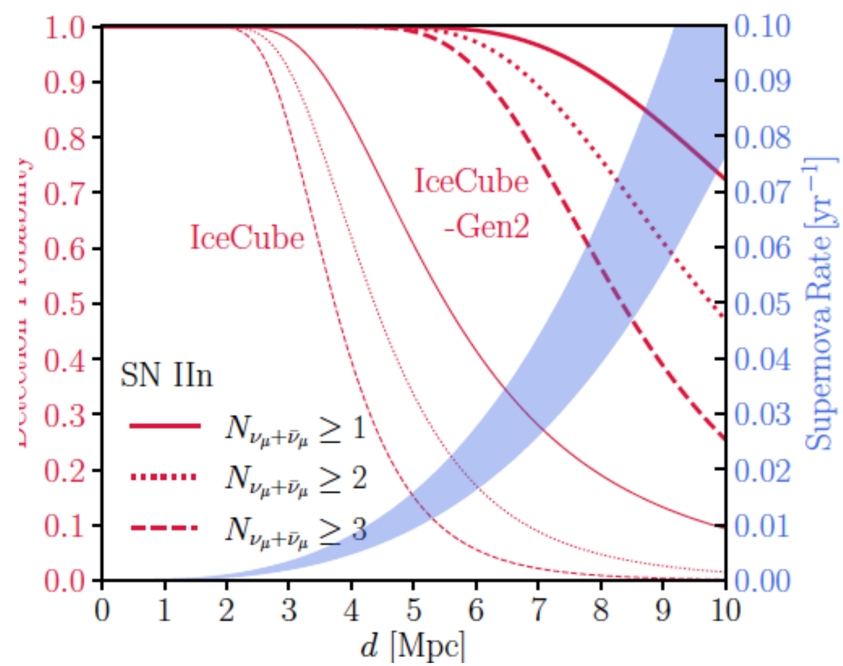
- Particle physics implications – large statistics
  flavor studies, BSM searches (neutrino self-interactions, neutrino decay, oscillation into other sterile states etc.

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

Detectability of "Miniburts"



- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II (CCSM): detectable to ~3-4 Mpc
  IIn: detectable to ~10 Mpc



Kheirandish & KM 22

AMES ***(***Astrophysical Multimessenger Emission Simulator***)***

Purpose:

Tool for "observers" to generate ν and broadband EM light curves and spectra

- "Source dependent" python module (GRB, SNe, TDE, AGN)
- Physics processes based on C++
- Standard model parameters determined by EM data

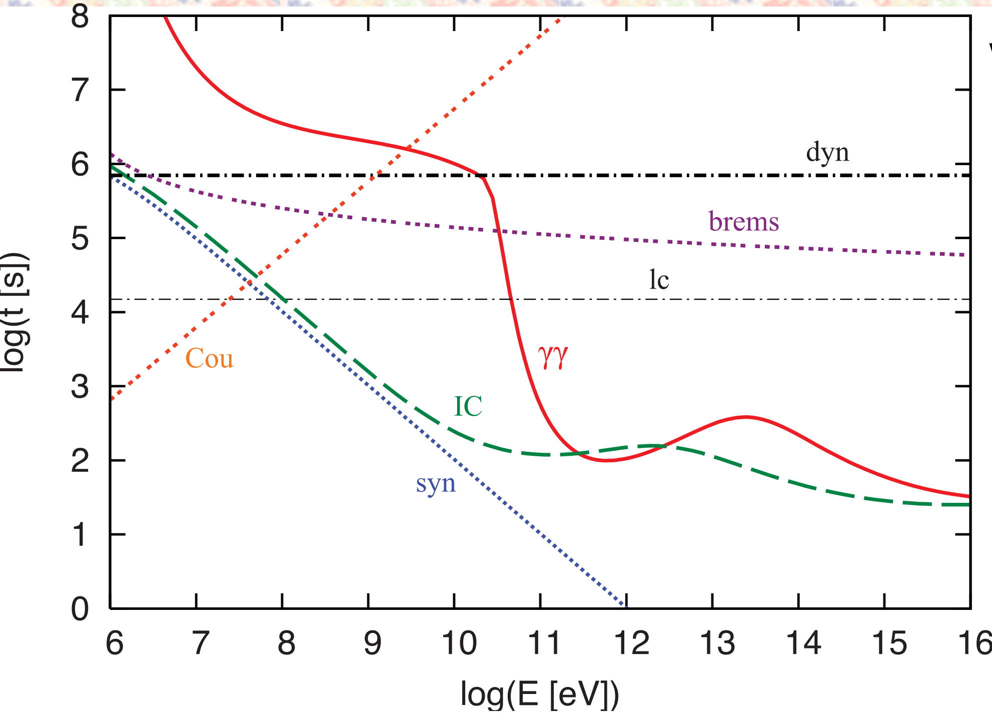
Current status:

GRB (GRB leptonic afterglow): already public
https://github.com/pegasuskmurase/AMES-GRBAfterglow
SN (interacting SNe/pulsar-powered SNe): ready

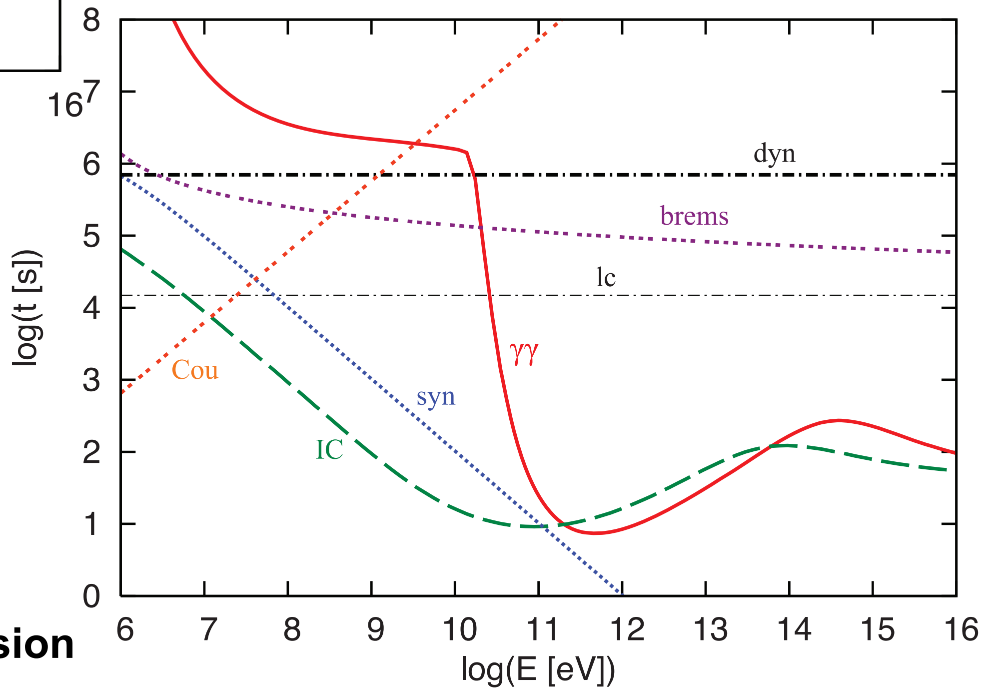
SN model templates:

https://github.com/pegasuskmurase/ModelTemplates/tree/main/SNHEMM

Fate of γ & $e^{\pm}$: Electromagnetic Cascade

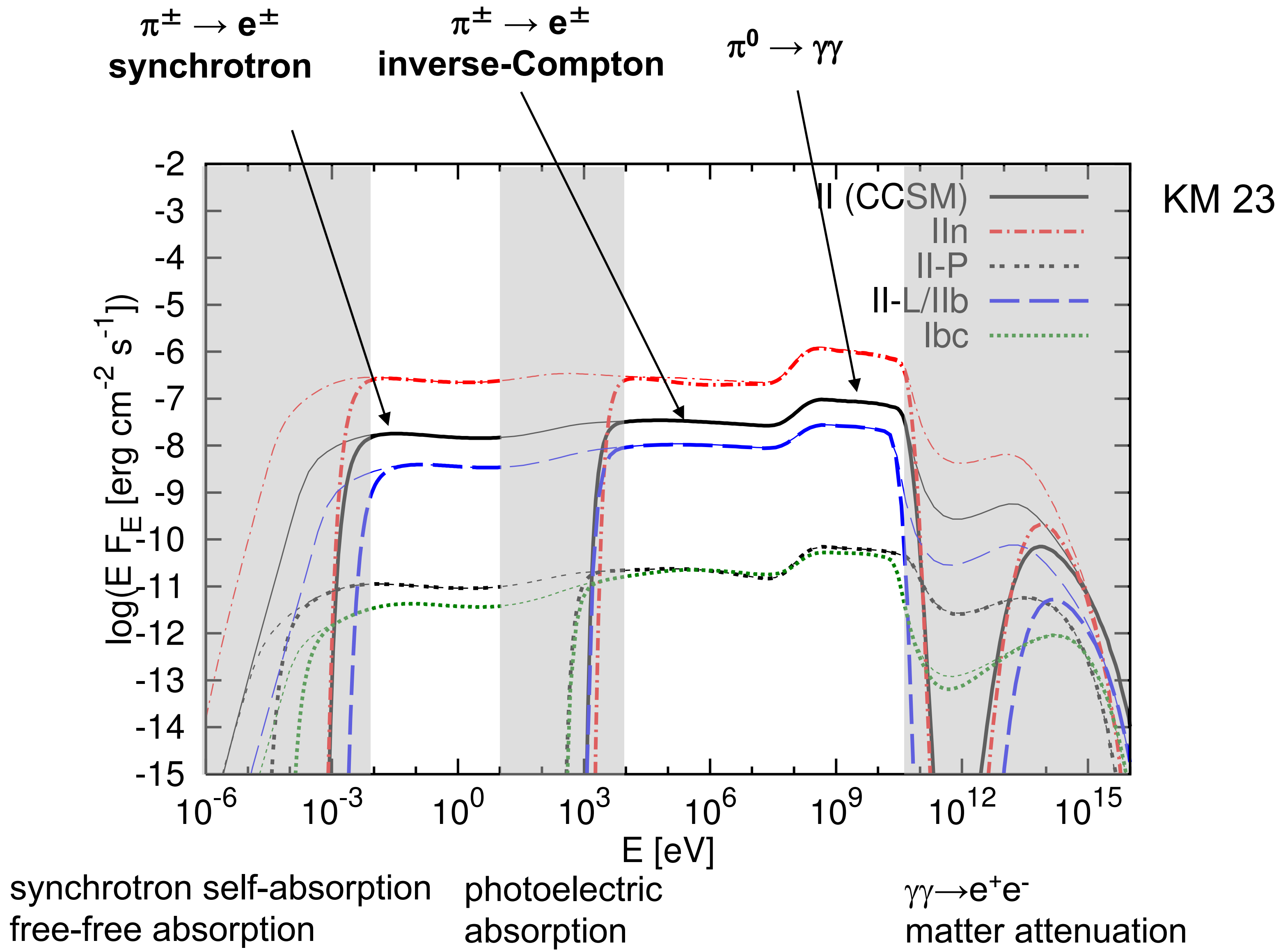


w.o. SN plateau emission



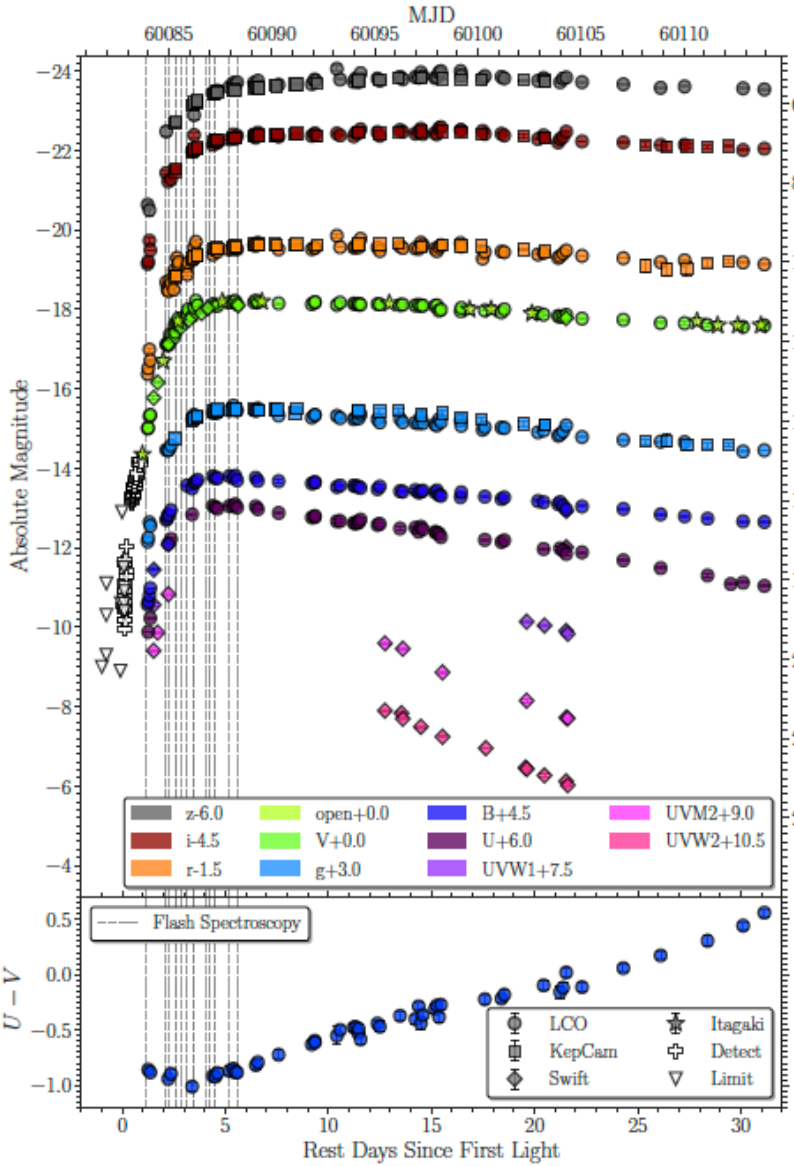
w. SN plateau emission

Multi-Wavelength Non-Thermal Spectra

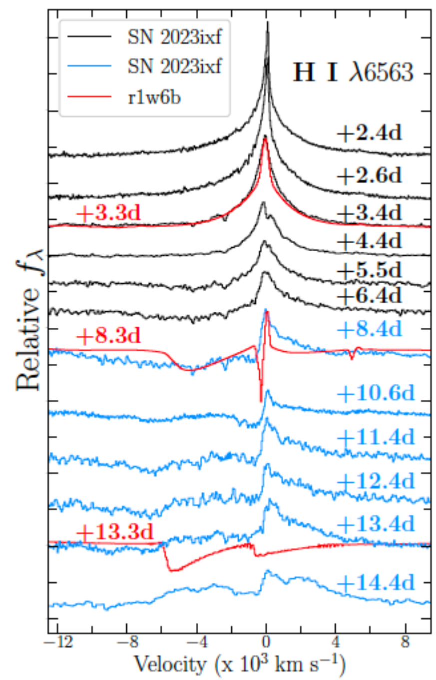


Example: SN 2023ixf

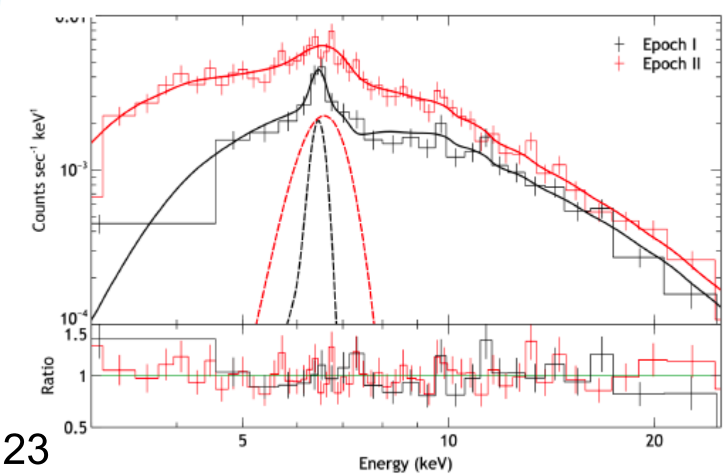
Hiramatsu+ 23



Jacobson-Galan+ 23



- M101 @ 6.9 Mpc
- Optical
  $dM_{cs}/dt \sim 10^{-2}$-10^{-1} M_{sun} yr^{-1}
  R_{cs} ~ a few x 10^{14} cm
- X-ray
  $dM_{cs}/dt \sim (0.3\text{-}1) \times 10^{-3}$ M_{sun} yr^{-1}
  $R_{cs} \sim 10^{15}$ cm
- Radio
  VLA detection at ~30 d

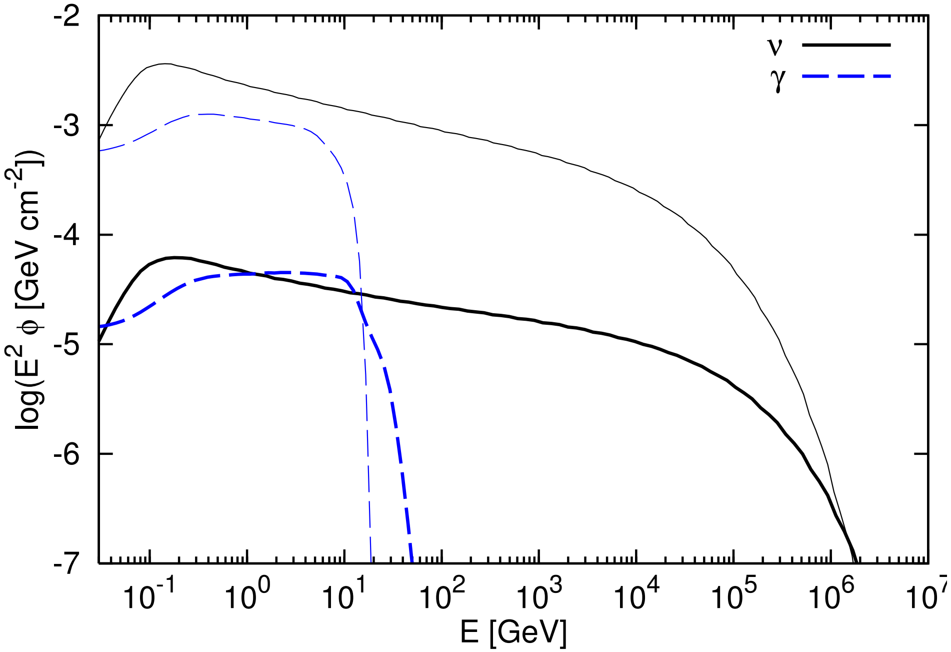


Grefenstette+ 23

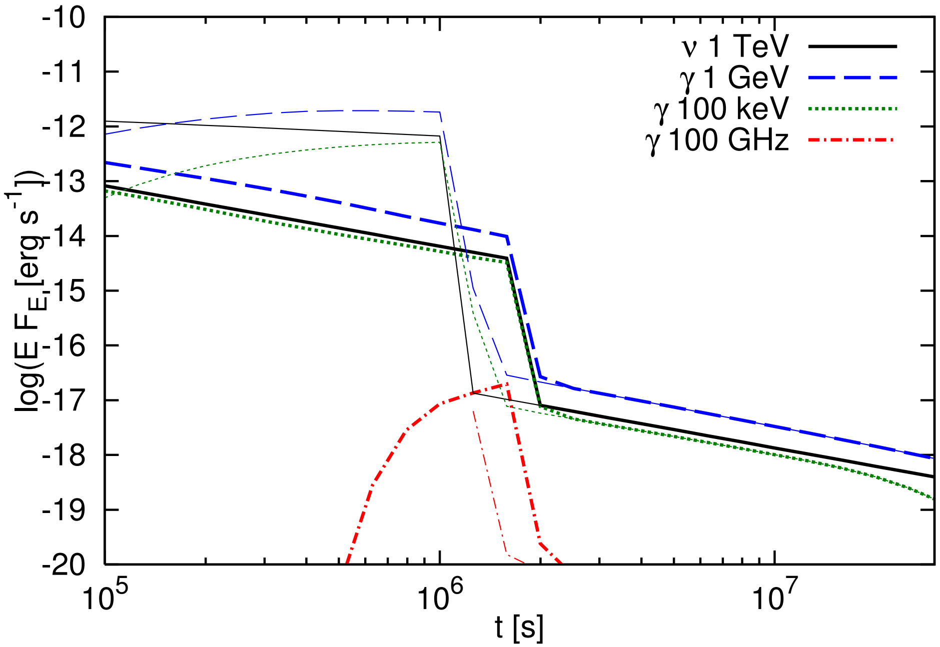
Multi-Messenger Spectra & Light Curves

KM 23

neutrino & gamma-ray fluences

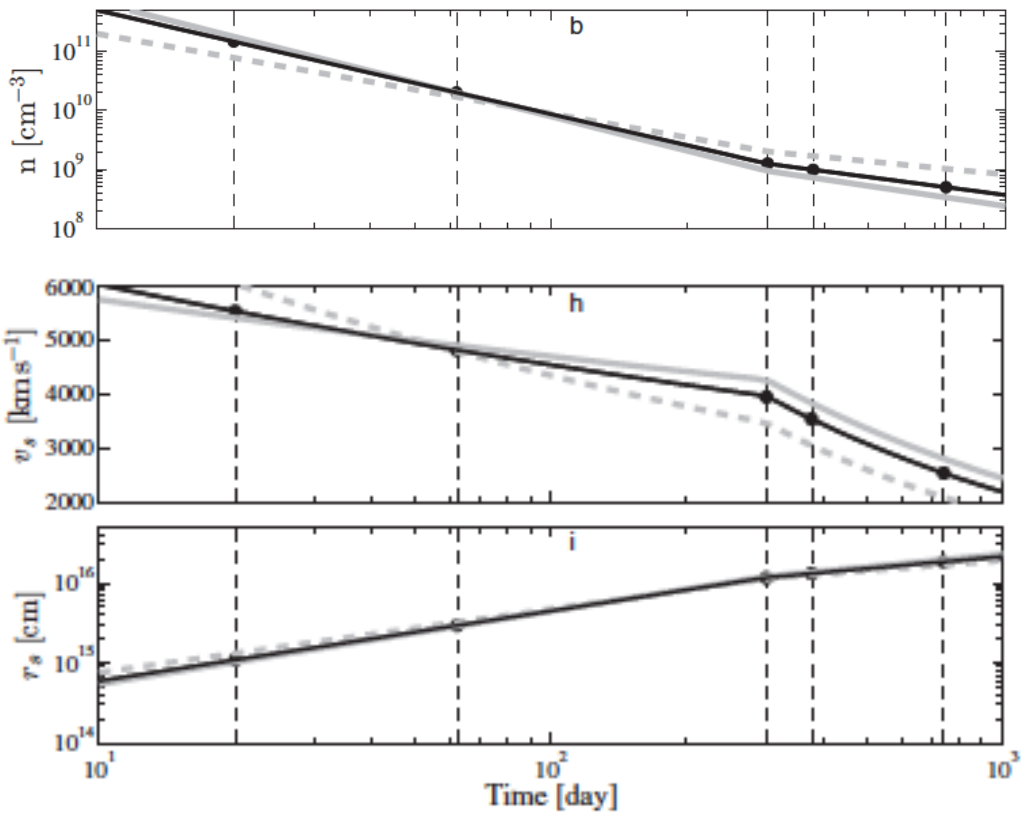


multi-messenger light curves

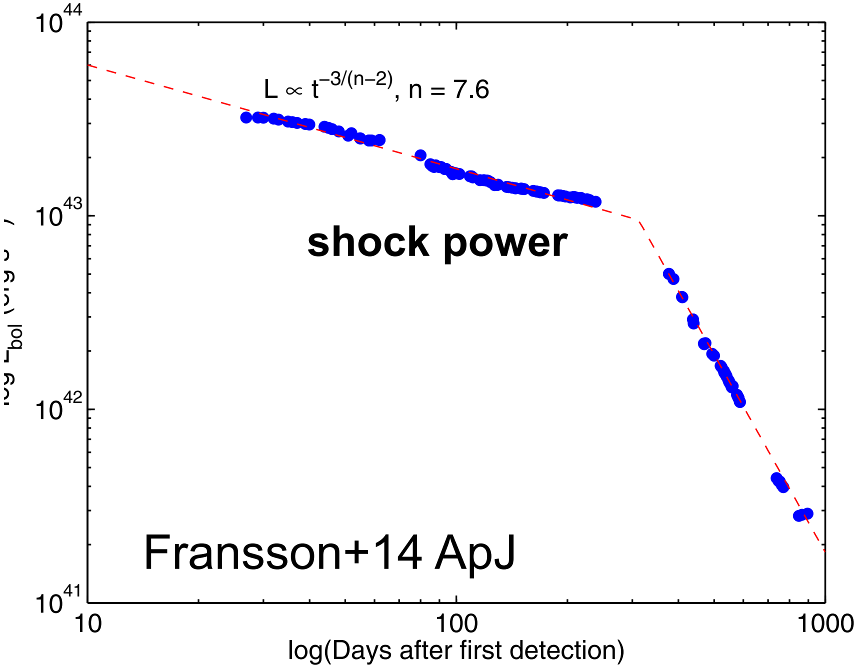


- Neutrino: consistent w. IceCube nondetection
- Gamma: consistent w. Fermi LAT nondetection
- X: consistent w. bremsstrahlung emission
- Radio: perhaps explaining VLA detection?

Example: SN 2010jl



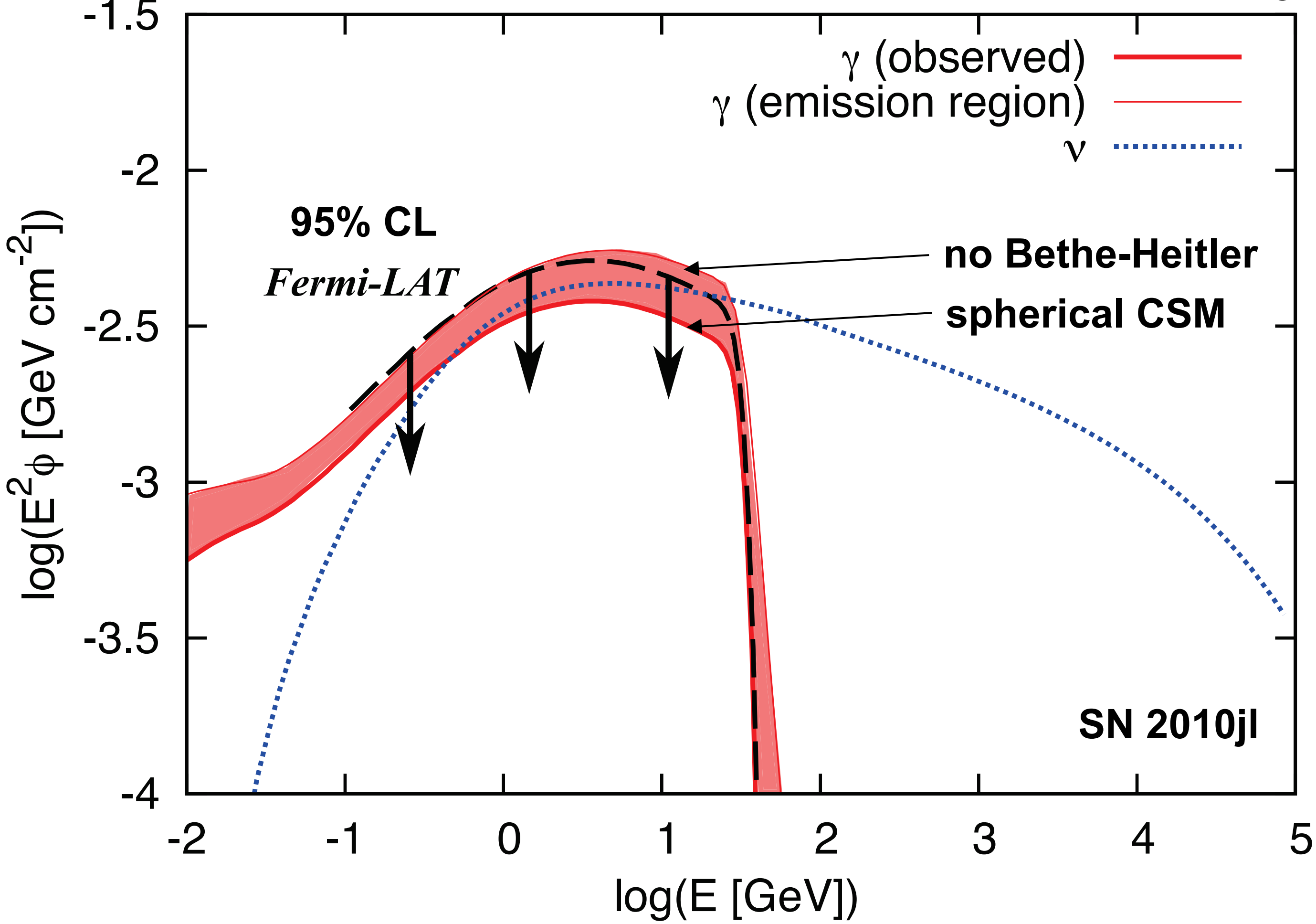
Ofek et al. 14 ApJ (see also Moriya et al. 13 MNRAS)



- $L = L_0\, t^{-\alpha}$ (α~0.54-0.56)
- "Data-driven" evolution of ρ_{cs}, R_s, V_s
- Time-dependent modeling from t=20 d (breakout) to t=250 d

Gamma-Ray Limits on SNe IIn

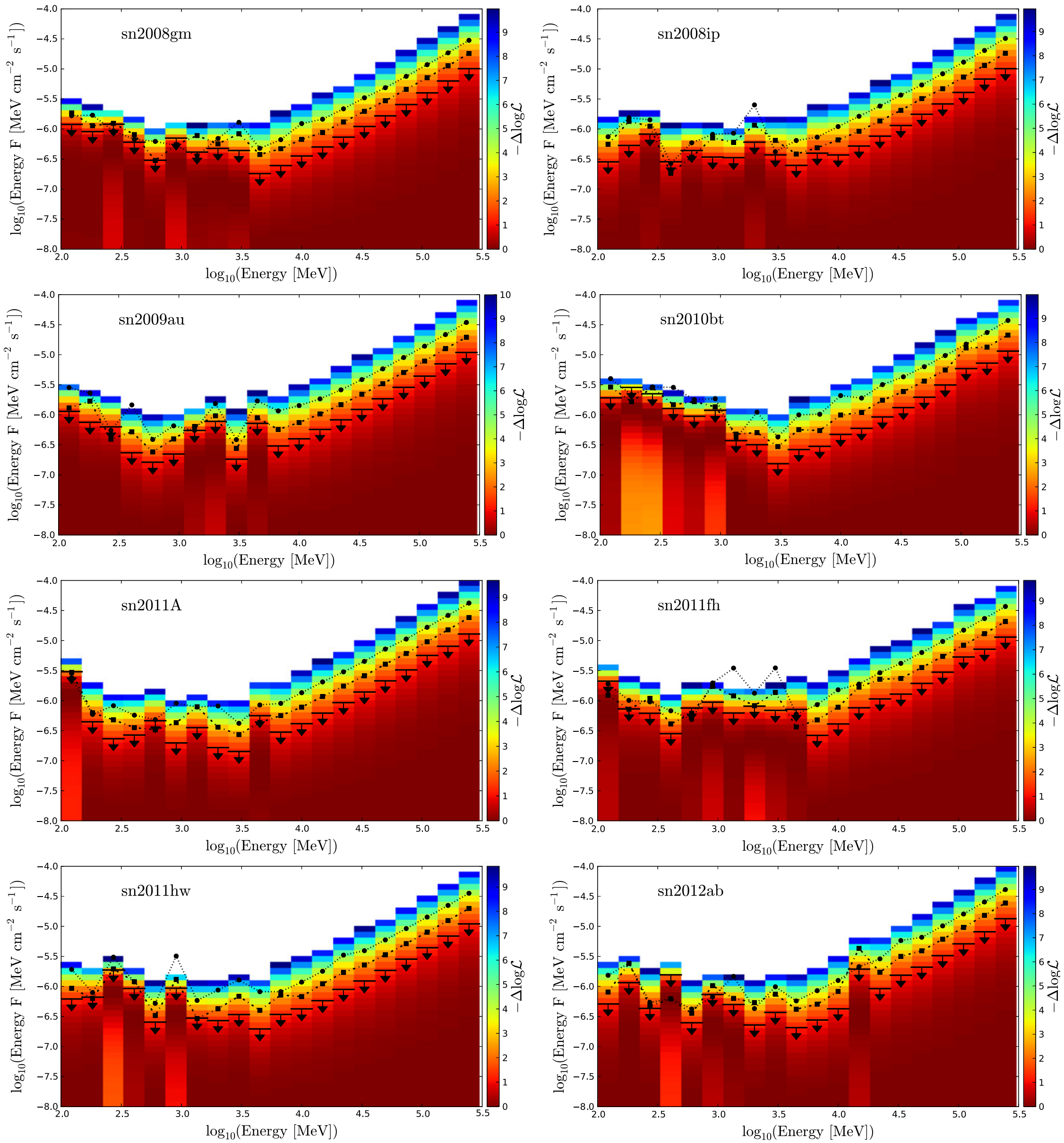
KM, Franckowiak, Maeda, Margutti & Beacom 19 ApJ



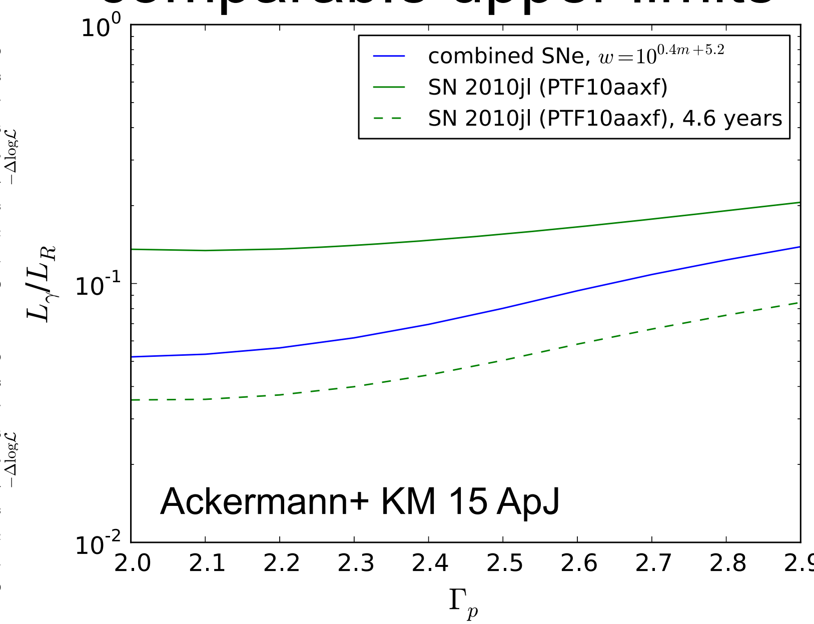
Interesting limits: **ε_p<0.05-0.1** (w. weak dependence on CR index)

brighter SNe or more SN samples or improved sensitivity

Gamma Rays: Fermi-LAT Stacking Search

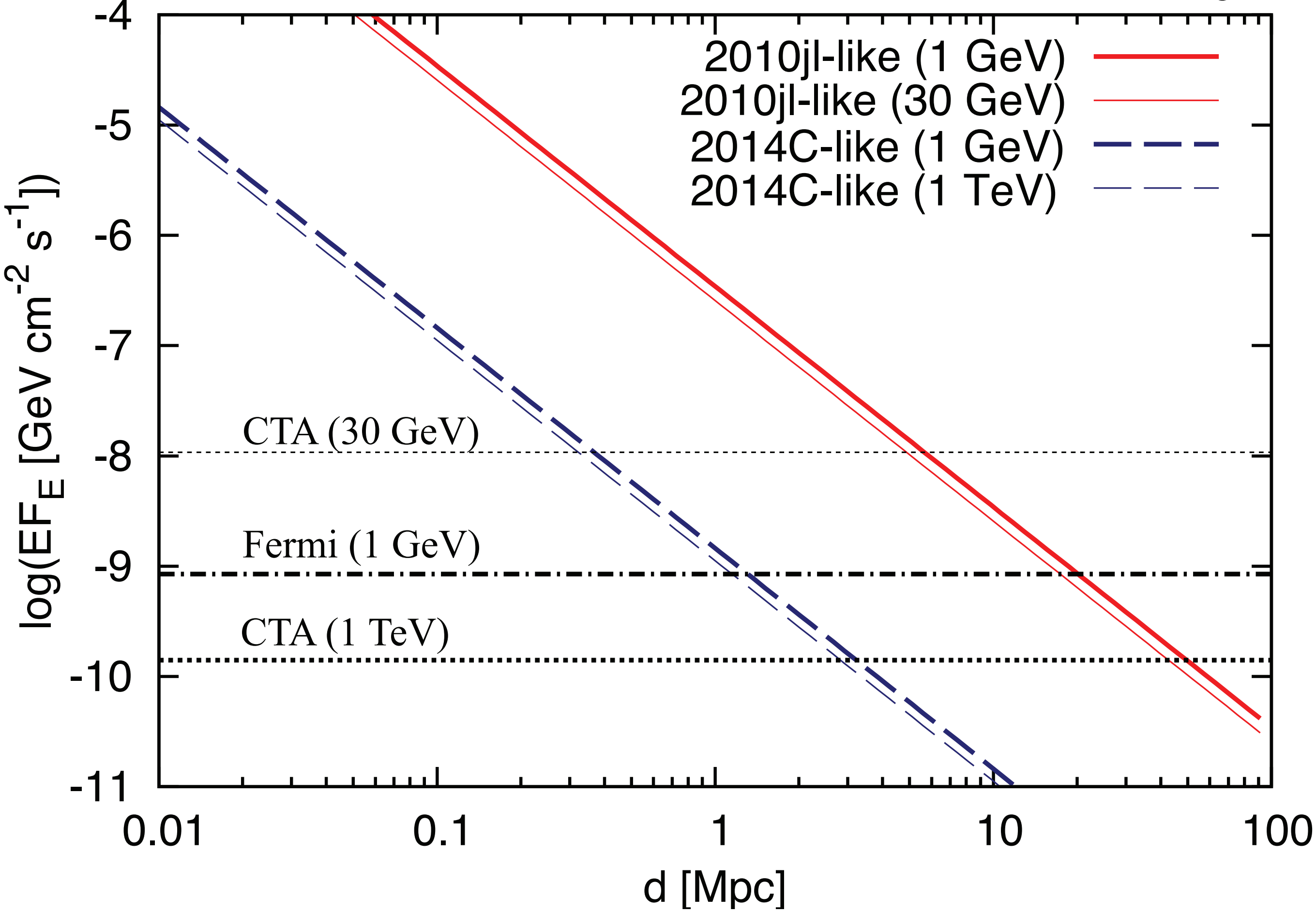


- 0.1-300 GeV
- 147 IIn samples (PTF in 2008-2012)
- Time windows
  1 month, 3 month, 1 yr
- Highest TS=14.4 (10bt)
- comparable upper limits



Gamma-Ray Detection Prospects

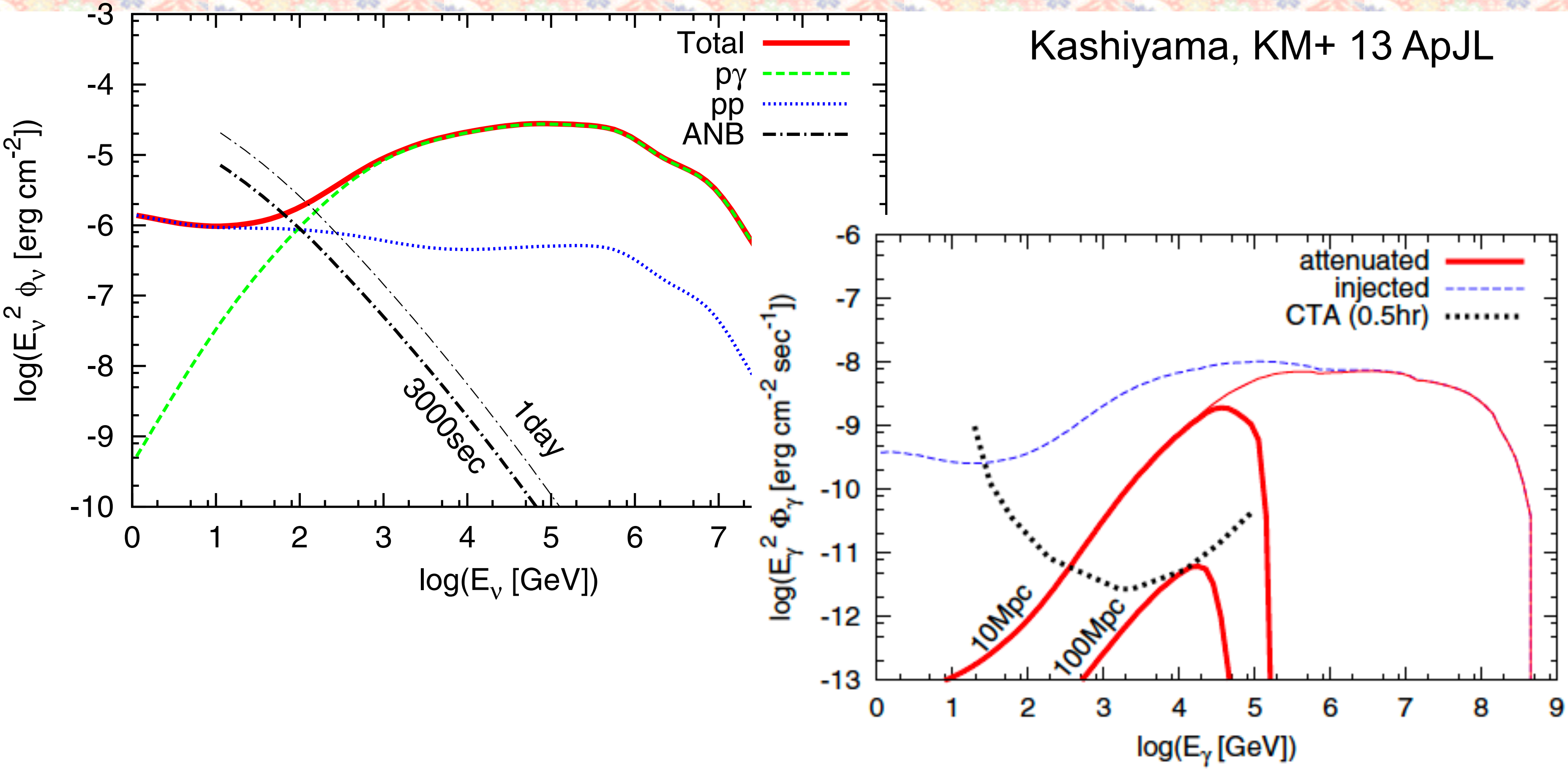
KM, Franckowiak, Maeda, Margutti & Beacom 19 ApJ



- Single SN: detectable up to ~10-50 Mpc
- Statistical approaches should also be powerful

SN Ibc with Confined CSM?

Kashiyama, KM+ 13 ApJL

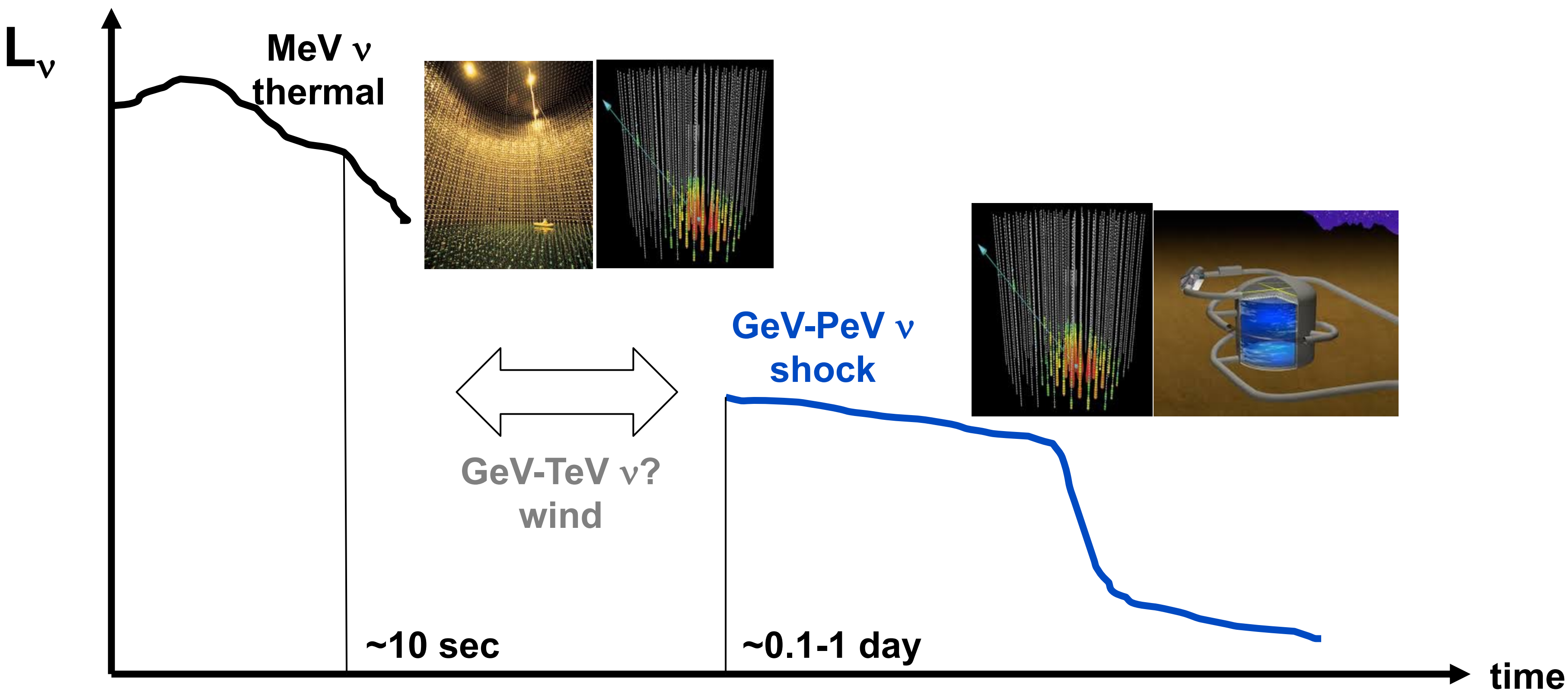


- SN 2010bh (LL GRB 100316D) : D_*~0.01 & R_{cs}~10^{14} cm
- Detectable by IceCube up to ~10 Mpc
- Detectable by CTA up to ~100 Mpc

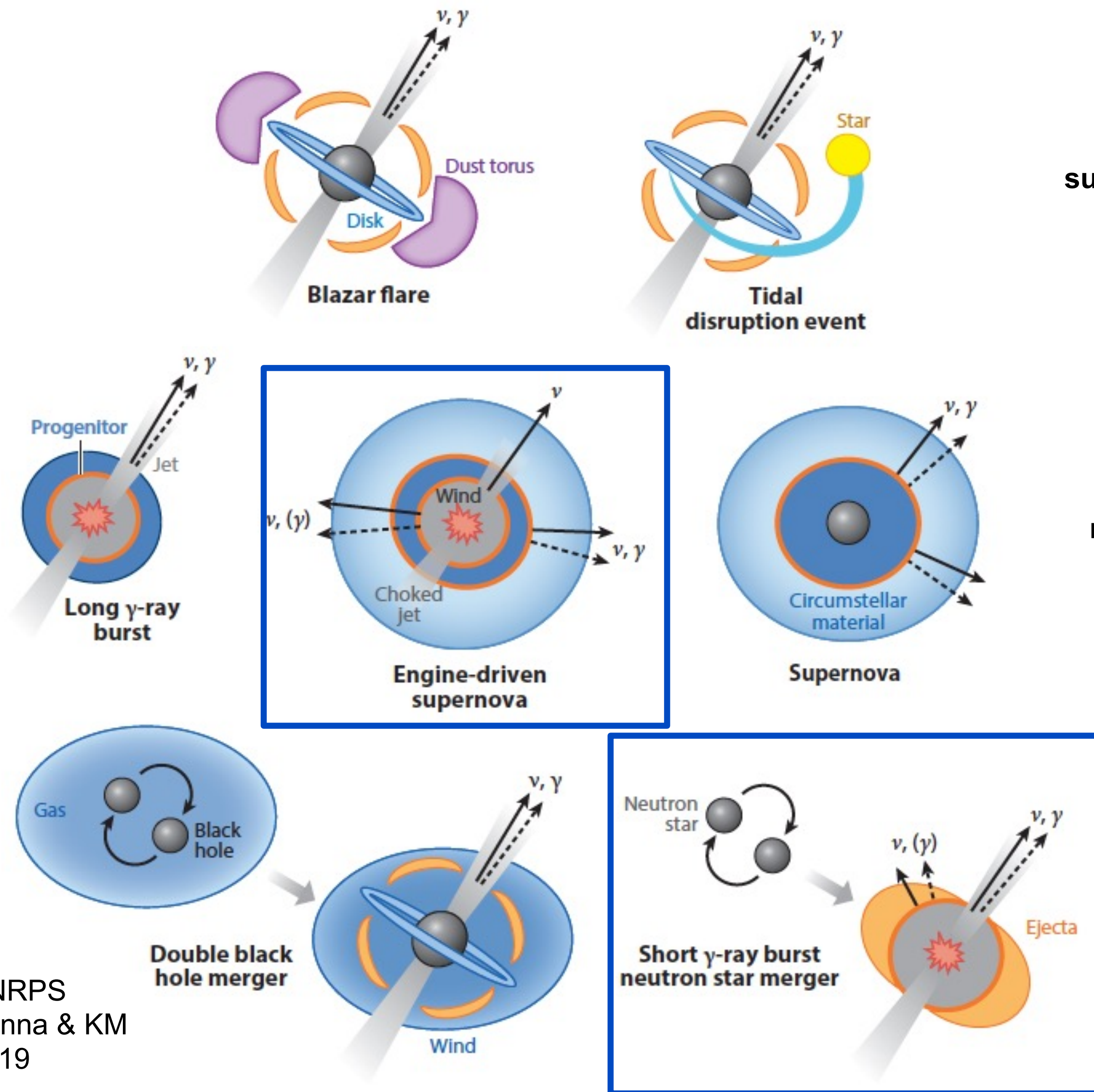
∗ duration depends on V_{ej} & R_{cs}

Take Away

- Development of 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



Diversity of High-Energy Transients



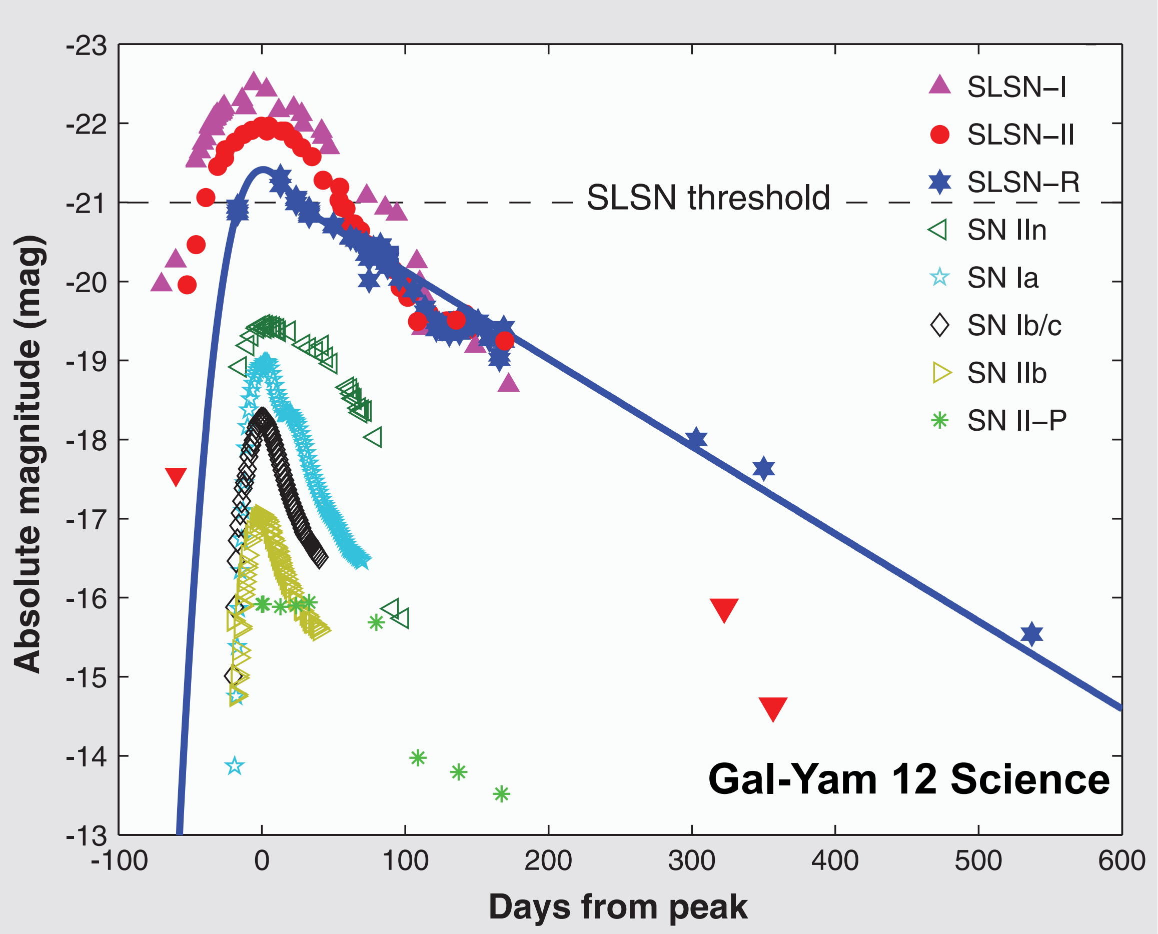
supermassive black holes

massive stellar deaths

compact mergers
(promising GW sources)

KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

Luminous Supernovae as Long-Duration Transients

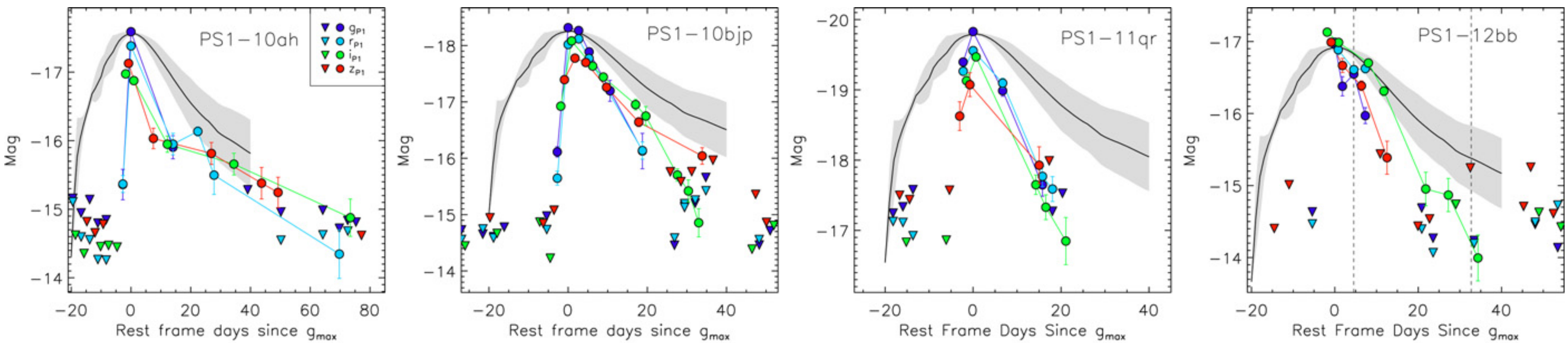


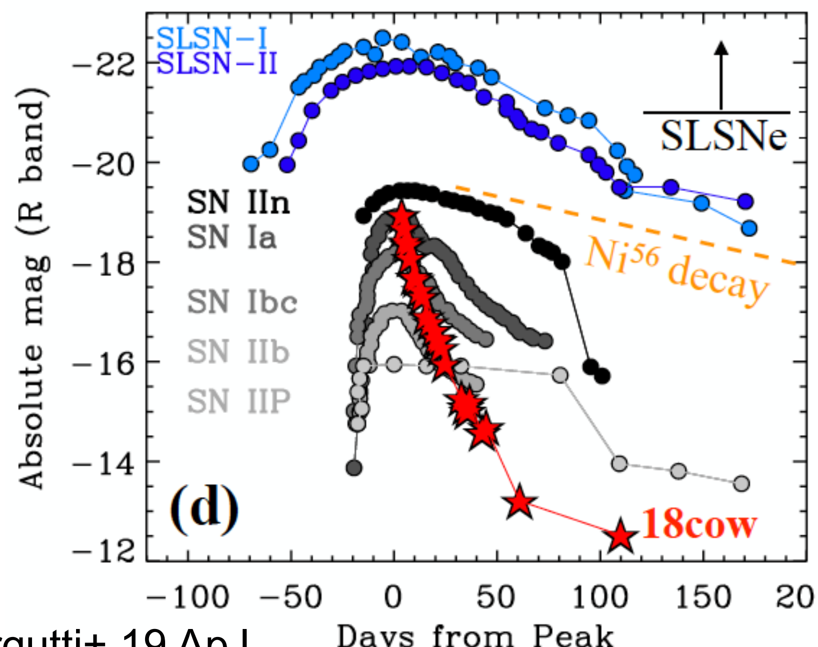
Luminous SNe explanations w. radioactivity for I and II often have difficulty

- SLSN-I (hydrogen poor) – energy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

Fast Blue Optical Transients

Drout+ 14 (see also Arcavi+ 13 etc)





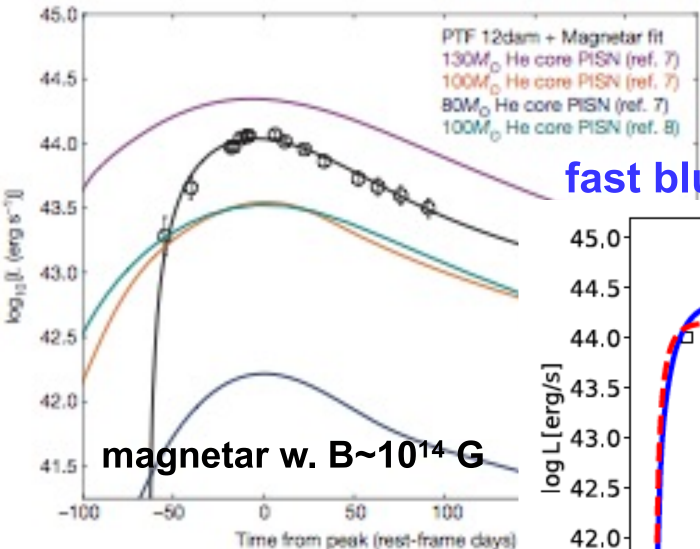
Margutti+ 19 ApJ

- Rapidly evolving (<10 day)
- Luminous & bright
- T ~ a fewx10^4 K (blue)
- Unlikely to be Ni-powered
- Star-forming region
- ~4-7% of core-collapse SNe (not so rare)

Pulsar/Magnetar-Driven Supernovae

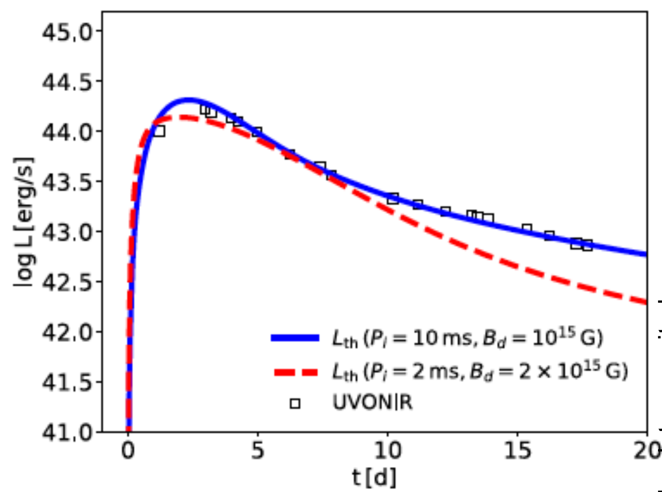
"Rapidly rotating pulsars" are popularly invoked to explain some SNe Ibc

super-luminous supernova (SLSN)



Nicholl et al. 13 Nature

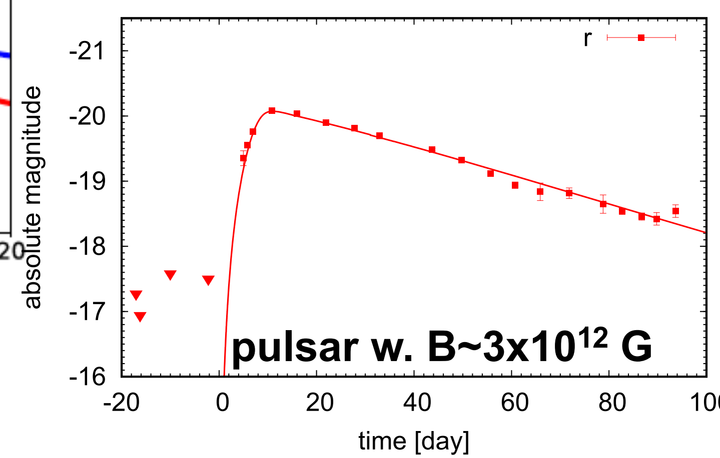
fast blue optical transient (FBOT)



Fang, Metzger, KM+ 19 ApJ

ultra-stripped supernova (USSN)

PTF10iam

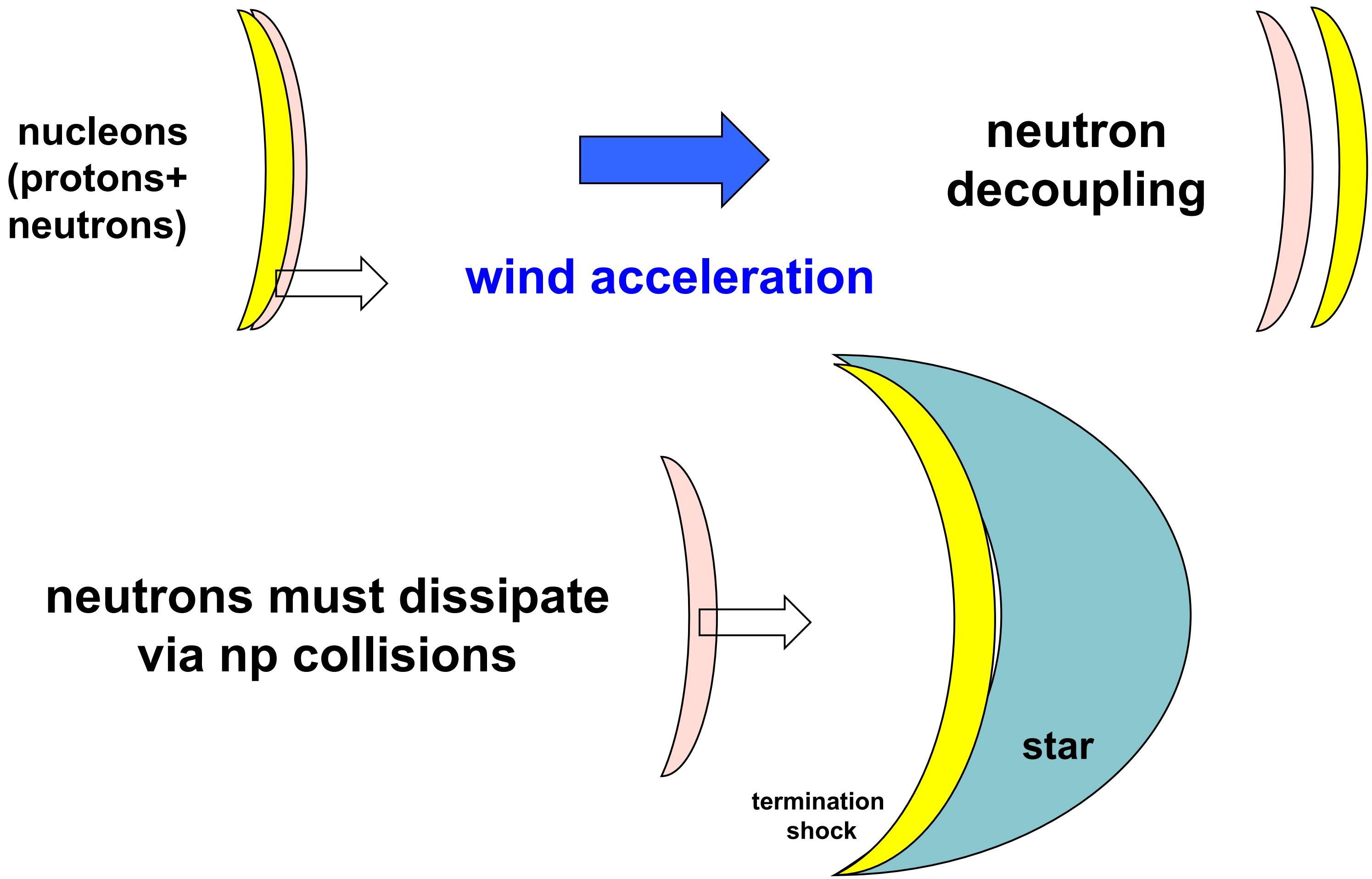


Hotokezaka, Kashiyama & KM 17 ApJ

requirement: rotation energy is converted into thermal energy

GeV-TeV Neutrinos from Pulsar/Magnetar-Driven SNe

- Neutron-loaded outflows from highly magnetized protoneutron stars
- Bulk wind acceleration → neutron decoupling → neutrino production
- No cosmic-ray acceleration is necessary (KM, Dasgupta & Thompson 14 PRD)



GeV-TeV Neutrinos from Pulsar/Magnetar-Driven SNe

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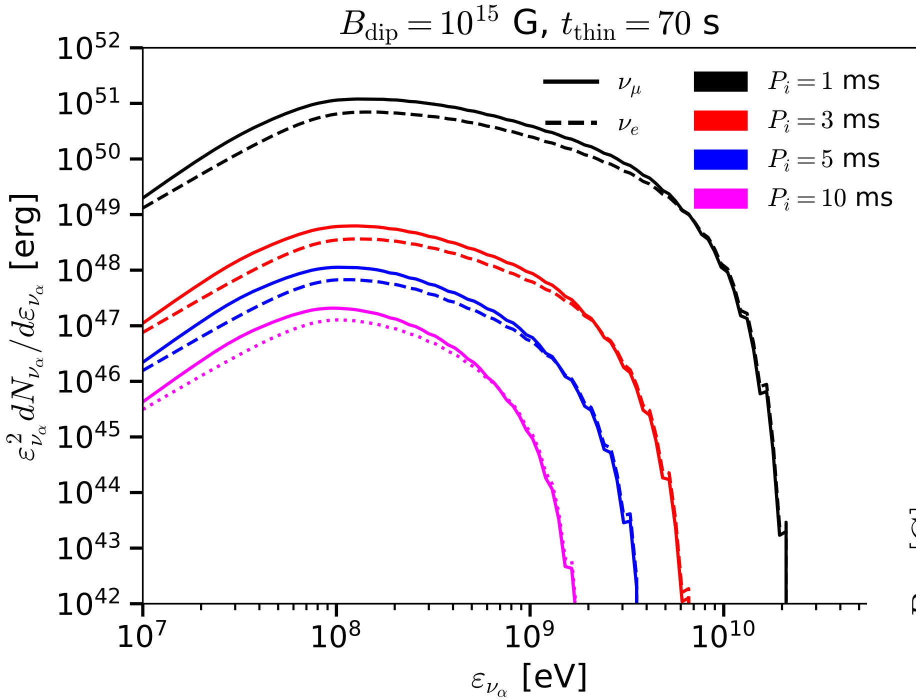
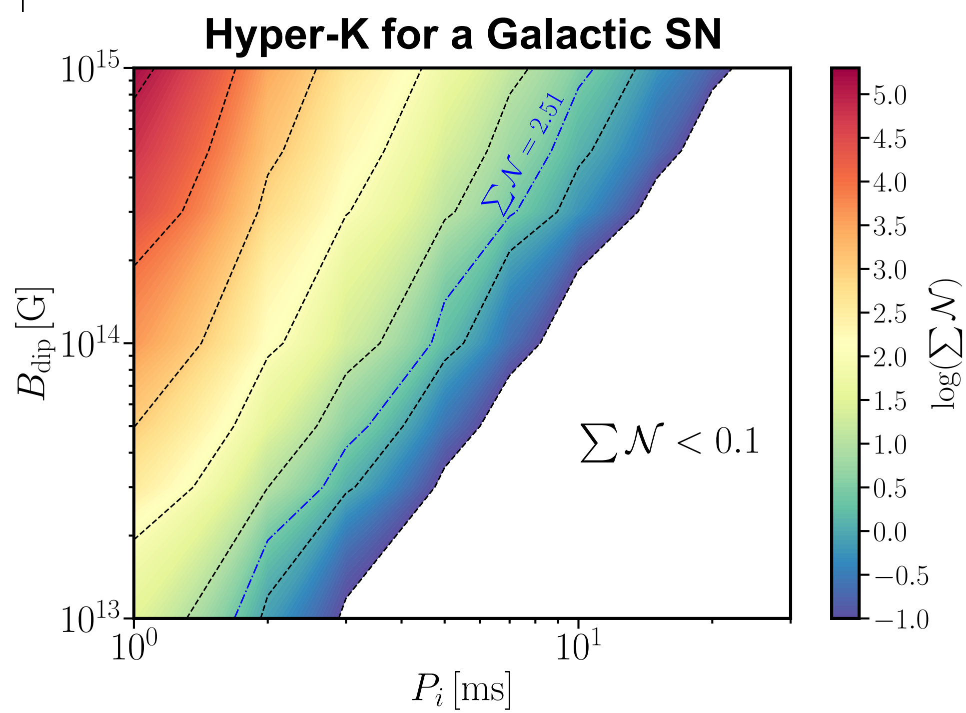
- Power-law spectrum as a result of time integration (w.o. cosmic rays)



Carpio, Bhattacharya, Ekanger, KM & Horiuchi 23
KM, Dasgupta & Thompson 14 PRD



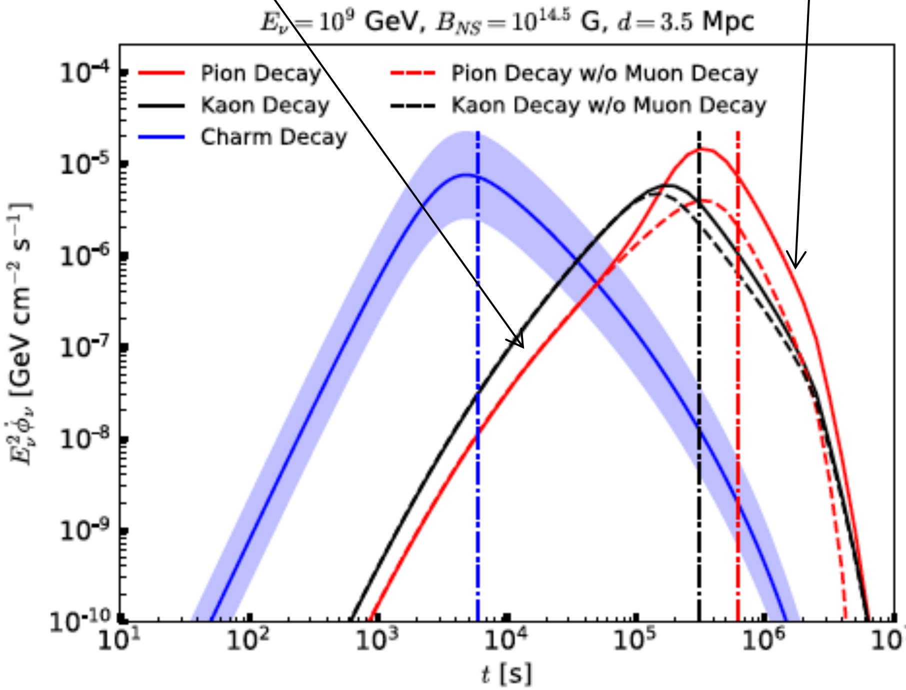
preliminary

PeV-EeV Neutrinos from Pulsar/Magnetar-Driven SNe

- (UHE) CRs could be accelerated via magnetic dissipation in the wind zone
- Efficient ν production should occur in hour-day-week time scales
– ν signals arrive earlier (ν alerts): followed by supernova optical emission

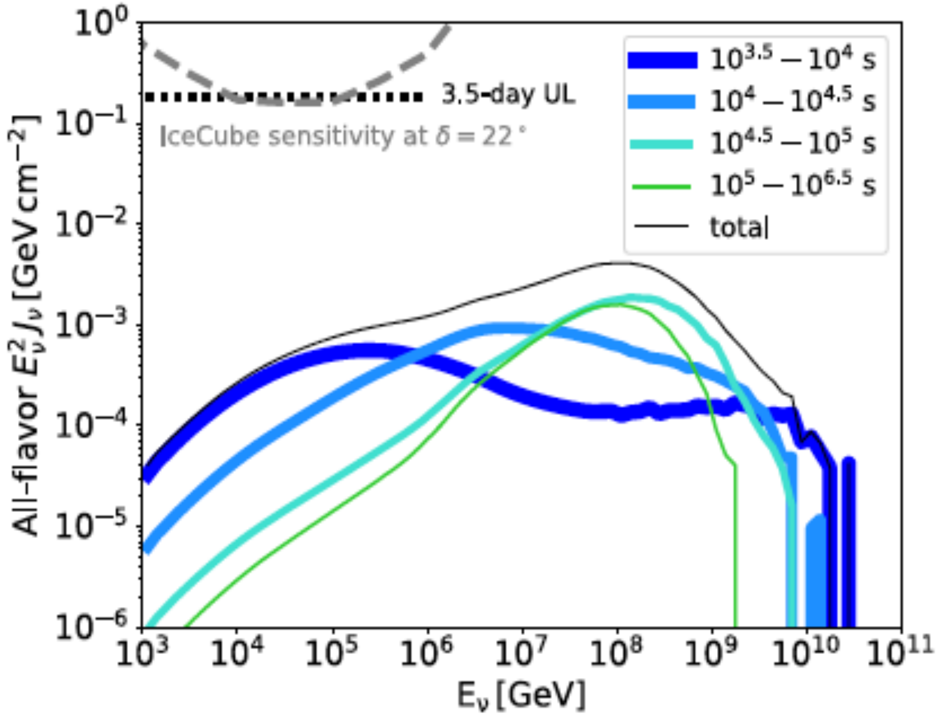
flux suppression due to hadronic cooling of mesons

spin-down



Carpio, KM, Reno, Sarcevic & Stasto 20 PRD
KM, Meszaros & Zhang 09 PRD

AT 2018cow @ 60 Mpc



Fang, Metzger, KM+ 19 ApJ

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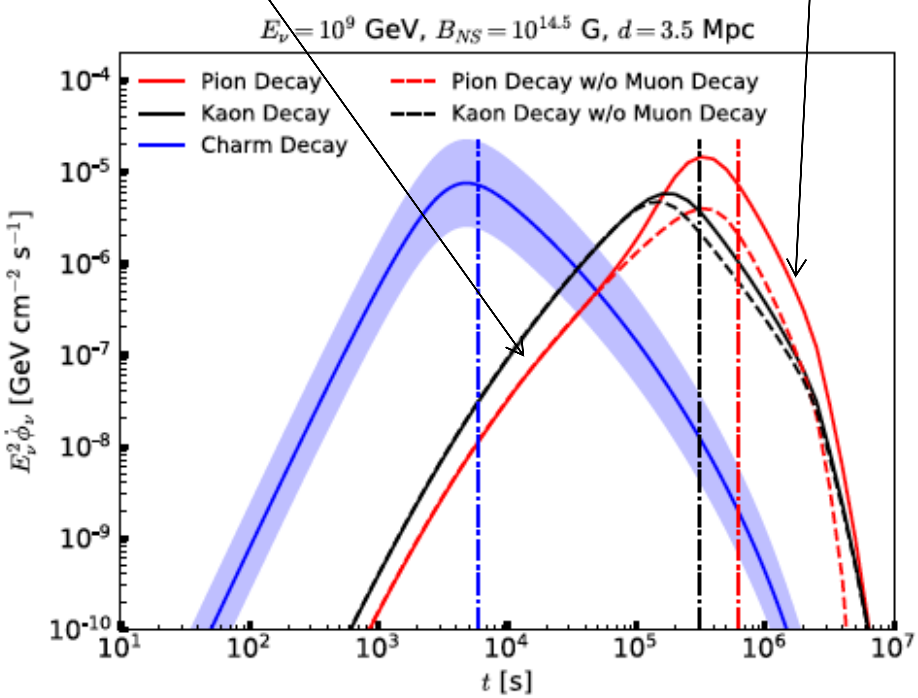
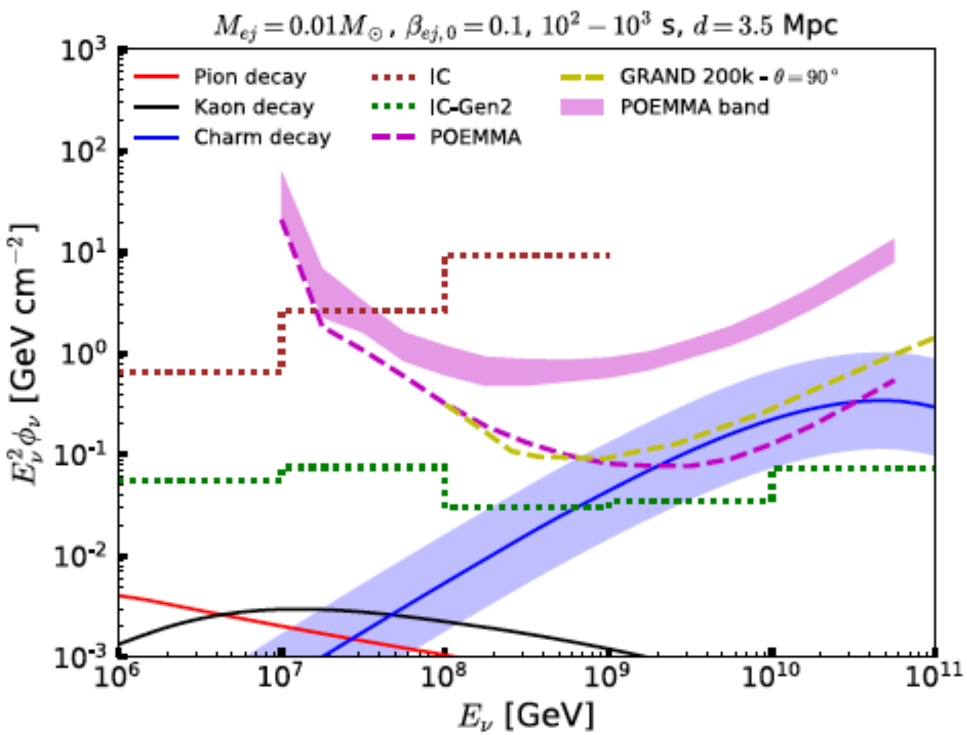
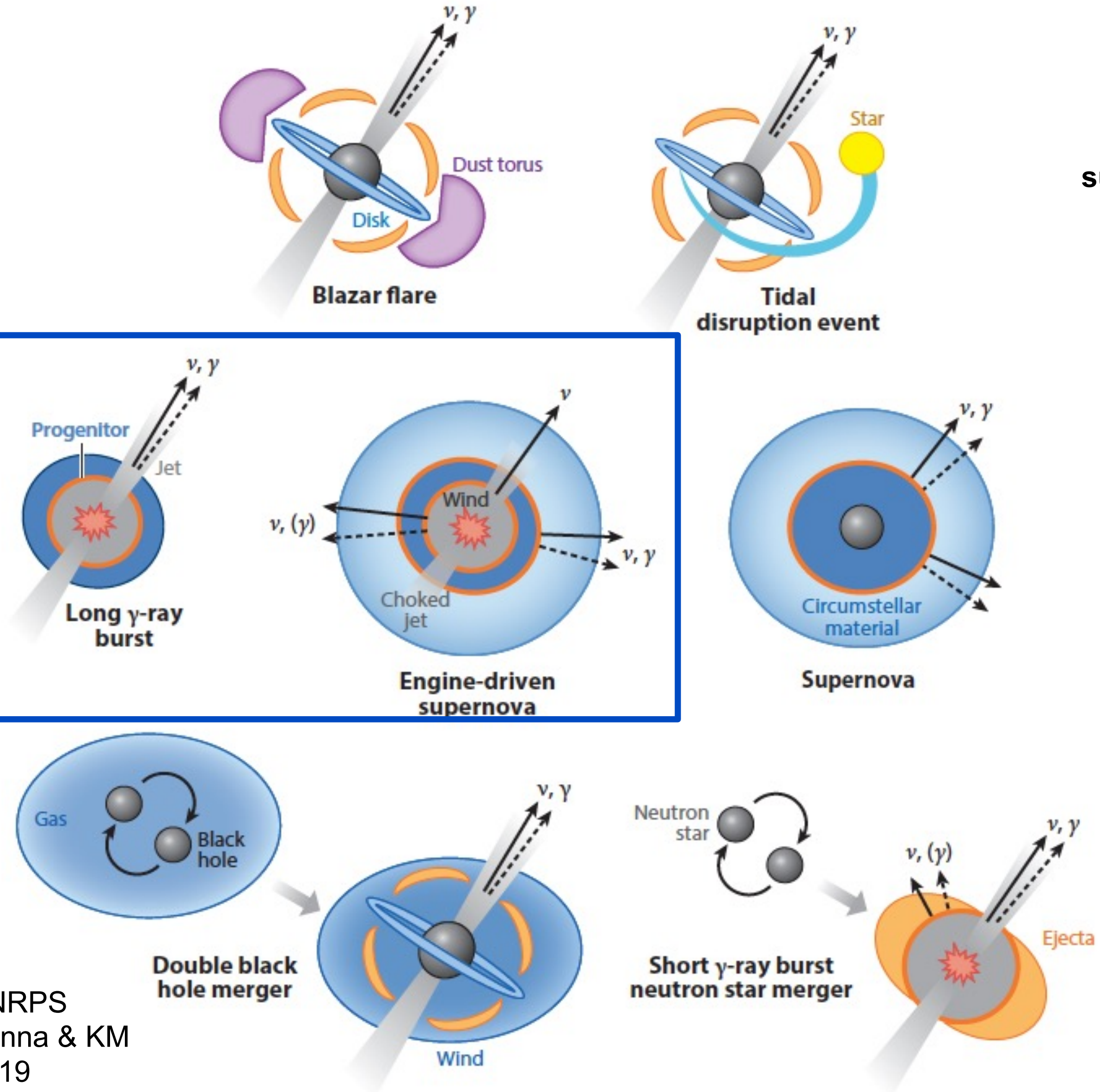


low-mass NS-NS merger



Carpio, KM, Reno, Sarcevic & Stasto 20 PRD
KM, Meszaros & Zhang 09 PRD

Diversity of High-Energy Transients



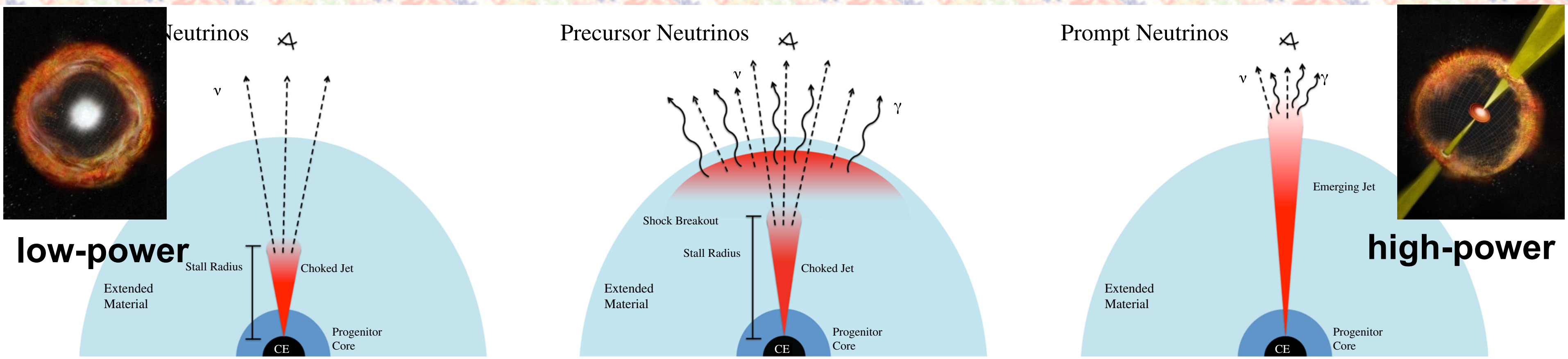
supermassive black holes

massive stellar deaths

compact mergers
(promising GW sources)

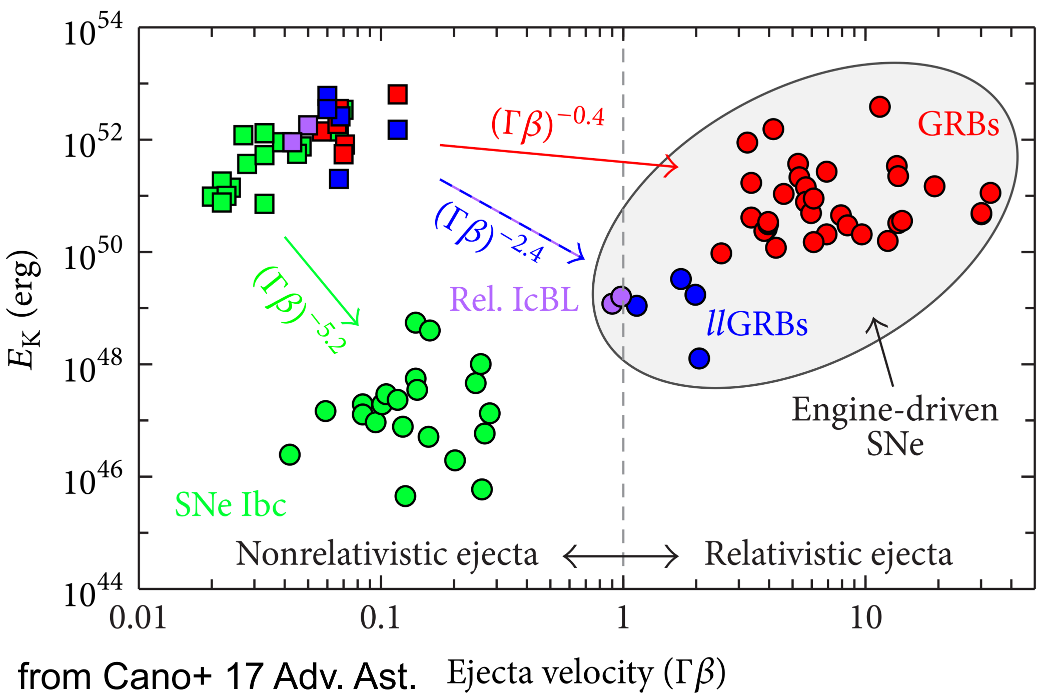
KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

HE Neutrinos from Choked Jets in Type Ibc SNe



low-power **high-power**

from Senno, KM & Meszaros 16 PRD



from Cano+ 17 Adv. Ast.

- Marginally choked jets: trans-relativistic SNe & low-luminosity (LL) GRBs
  (Toma+07, Nakar 15, Irwin & Chevalier 16)

- Low-power choked jets may contribute to the IceCube flux without violating GRB limits

  (KM+ 06 ApJL, Gupta & Zhang 07 APh, KM & Ioka 13 PRL, Denton & Tamborra 18 ApJ Carpio & KM 20 PRD)

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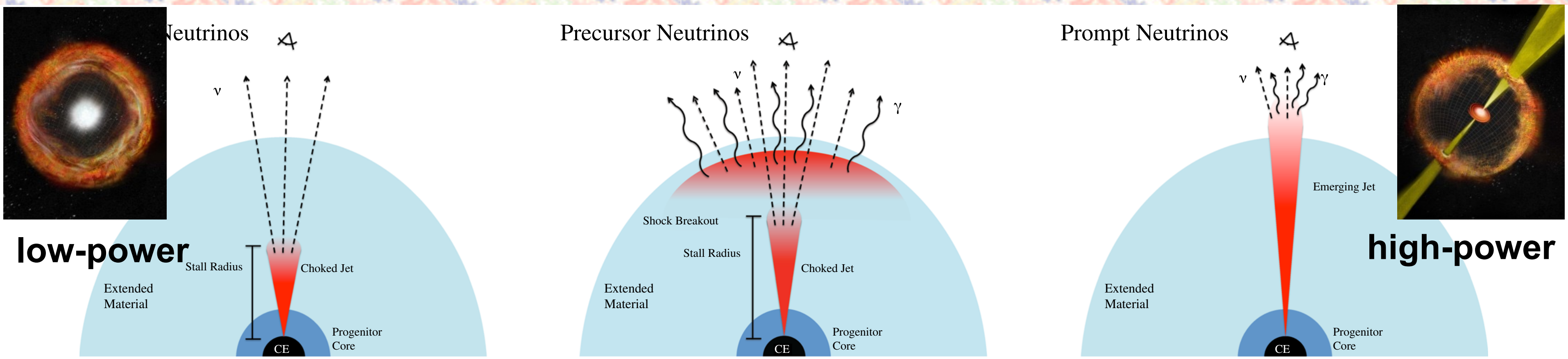
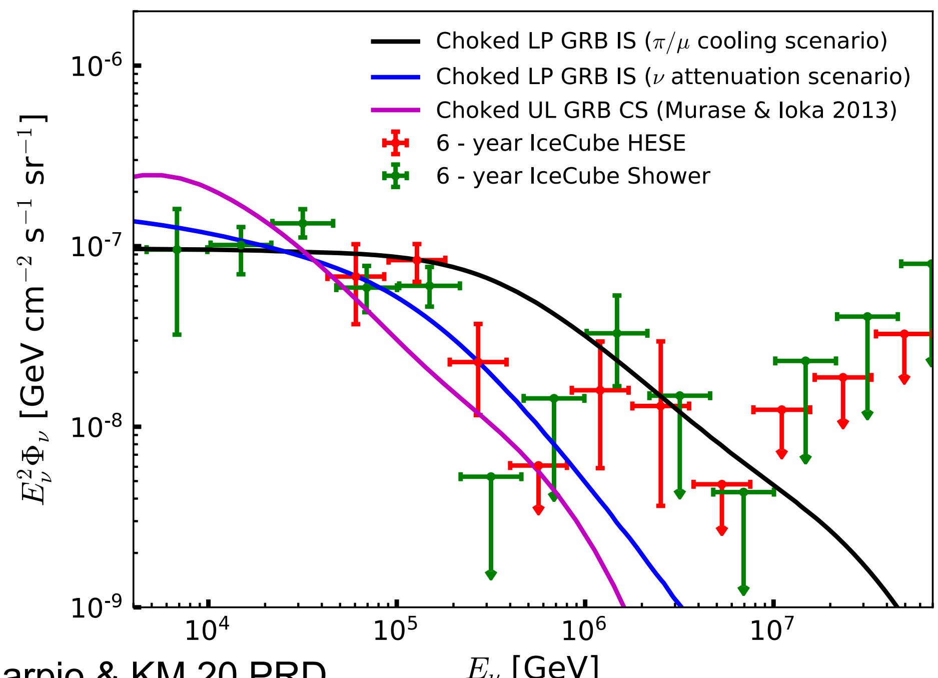


from Senno, KM & Meszaros 16 PRD



Carpio & KM 20 PRD

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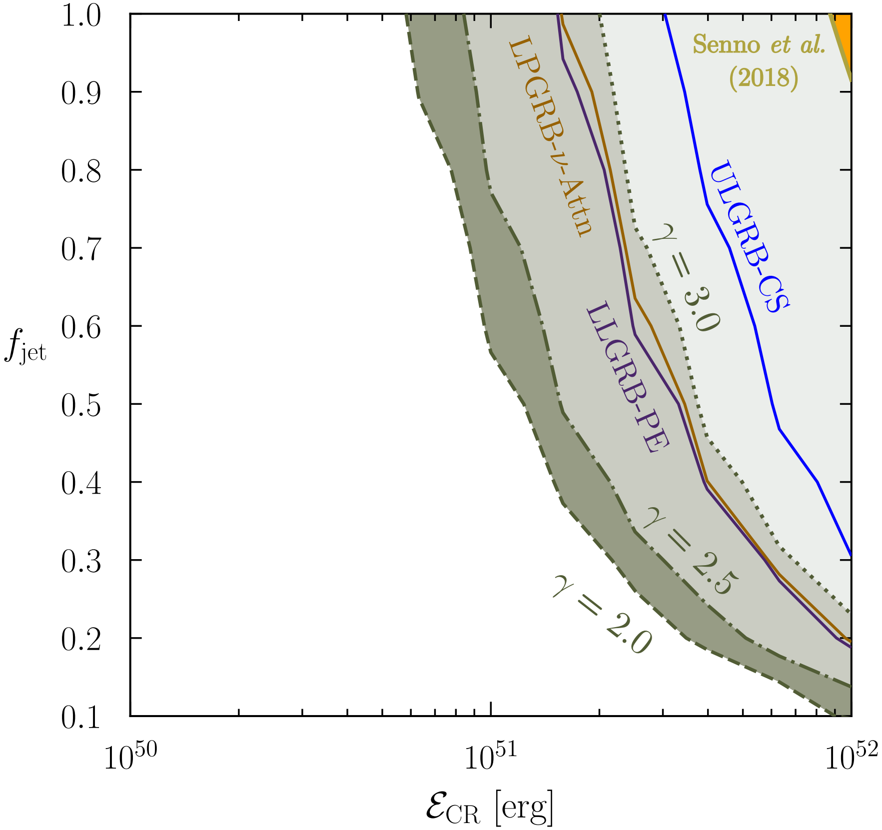
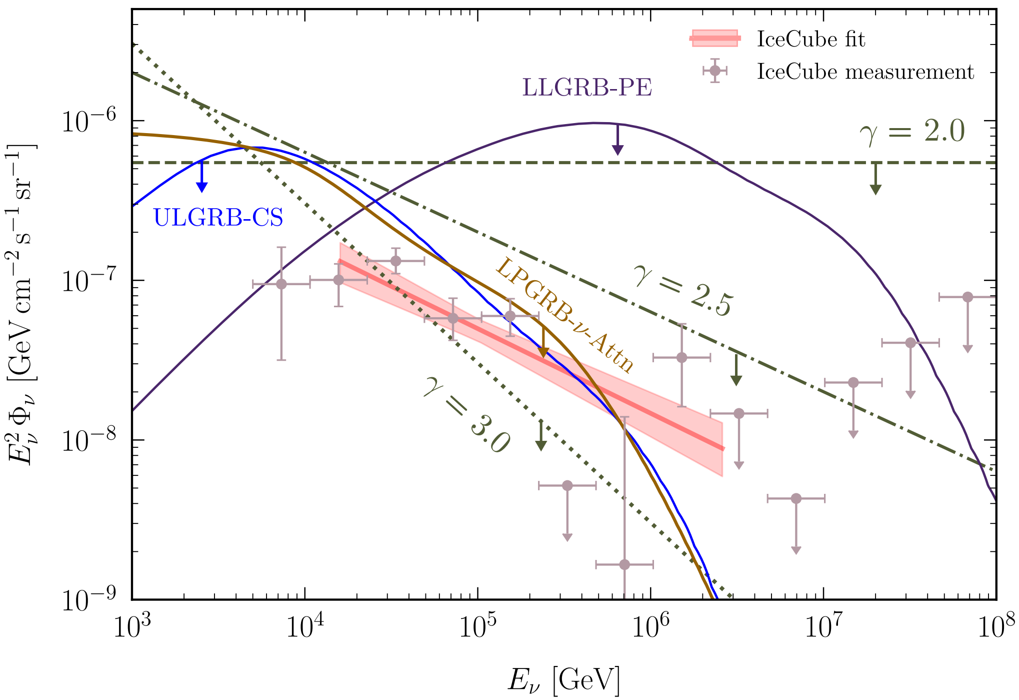
Powerful Stacking Searches

Stacking analyses on 386 SNe Ibc w. 10 yr IceCube data

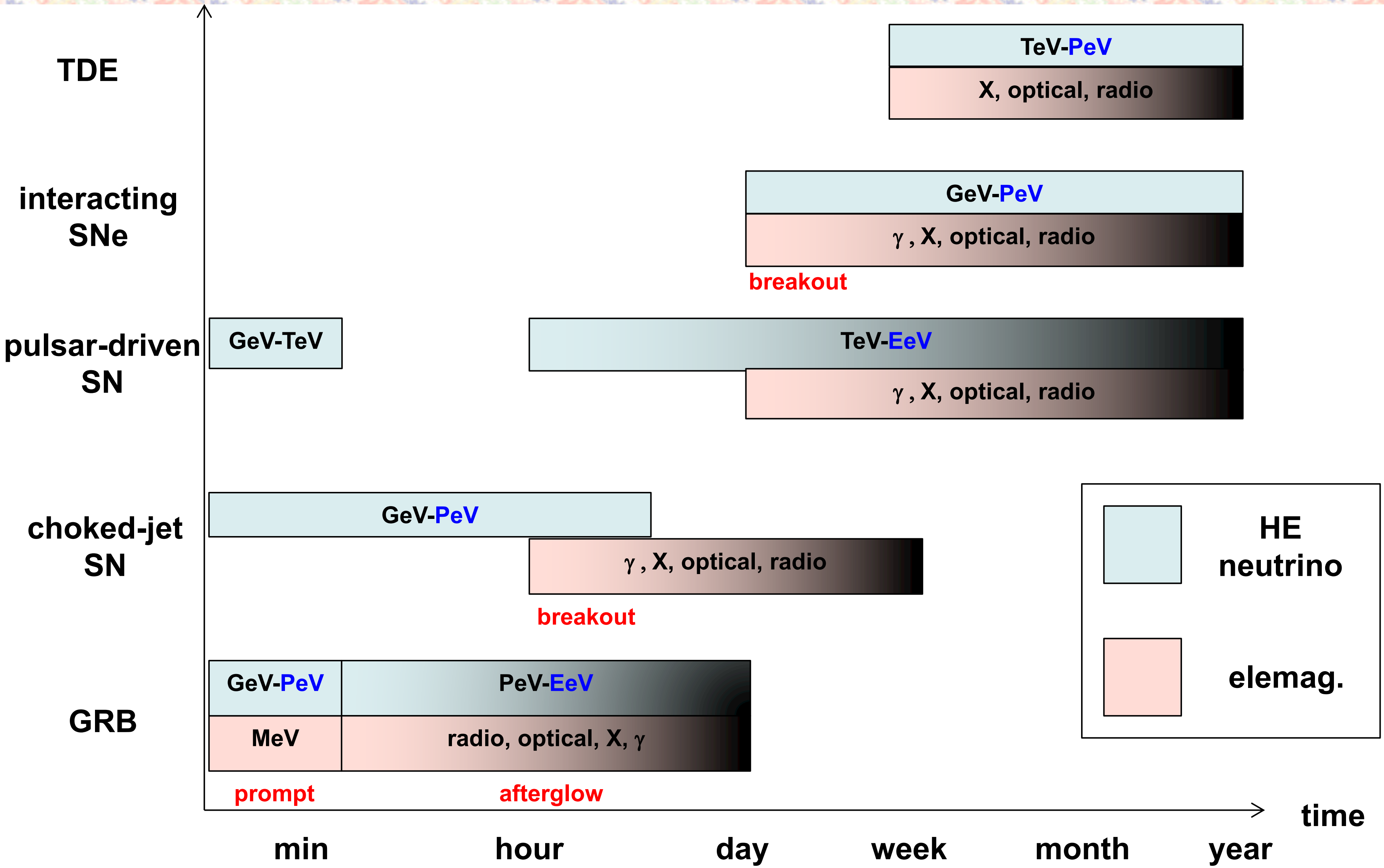


Chang, Zhou, KM & Kamionkowski 22
see early limits Senno, KM & Meszaros 18 JCAP
Esmaili & KM 18 JCAP



- Present constraints: $E_{cr}<10^{51}$-10^{52} erg (if all SNe emit νs)
- Future: readily improved w. more SNe (especially w. Rubin)
- Spectral templates are important (NOT power laws!!)

Summary of Energy & Time Window



What Do We Need?

Targets: long-duration HE ν/short-duration GeV-TeV ν transients

- Multimessenger coincident searches (e.g., AMON events) would be powerful for subthreshold events
- Neutrino multiplet followups would also be useful

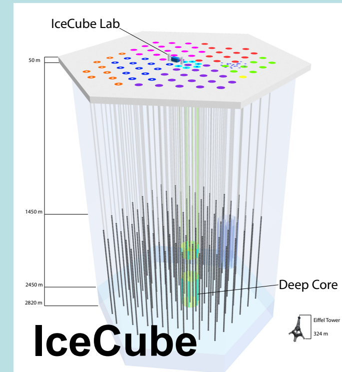
- Optical: spectroscopic information is relevant (SN brokers would be useful)
- Better hard X/γ-ray sky monitors needed (ex. >~10 times better than Swift for LL GRBs)
- Coincidences w. UV transients may also help (ex. ULTRASAT)
- Radio facilities may also help (ex. DSA-2000, ngVLA)

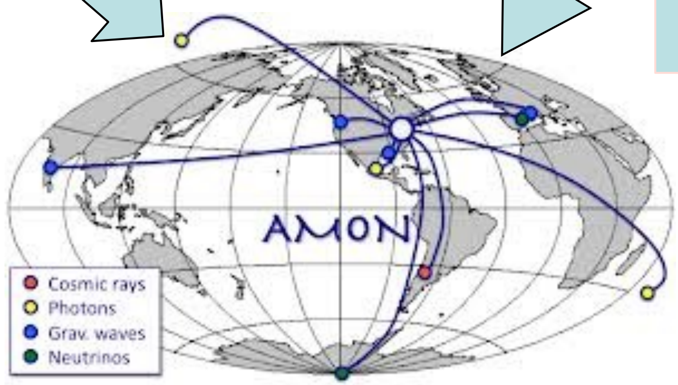
Ongoing "Multi-Messenger" Attempts

Light
(electromagnetic)

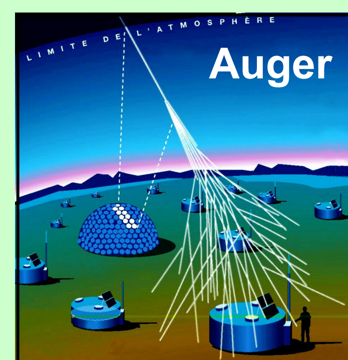
- **AMON**
- **SciMMA**
- **Astro-Colibri**

Neutrino (weak force)





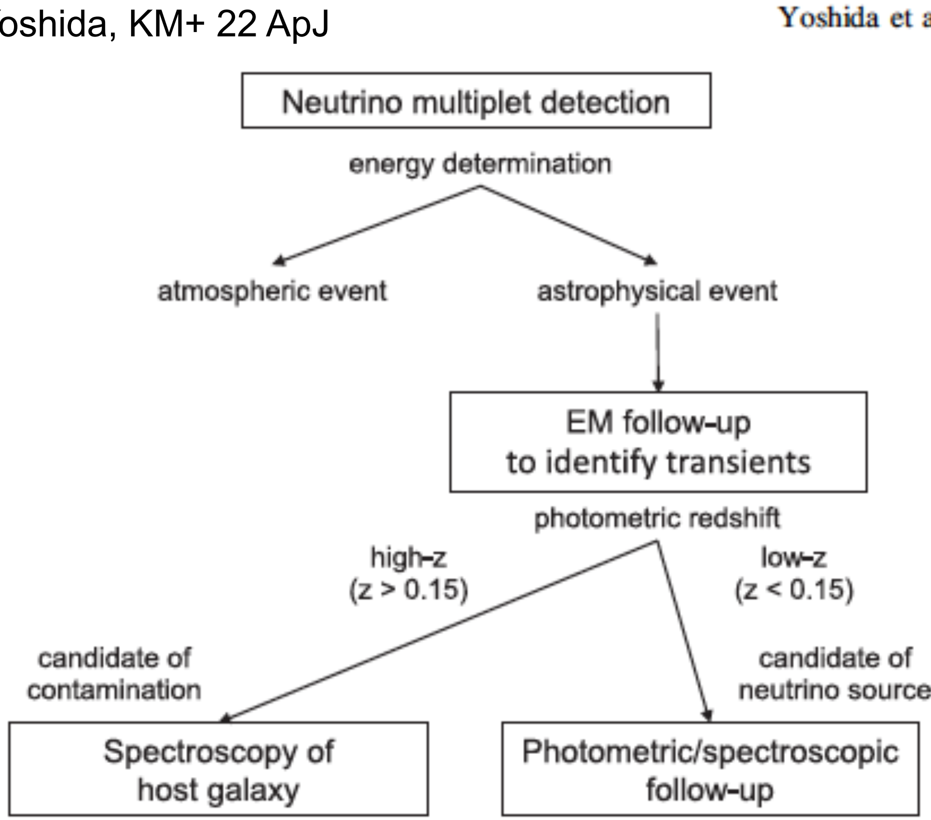
Cosmic-ray
(strong force)

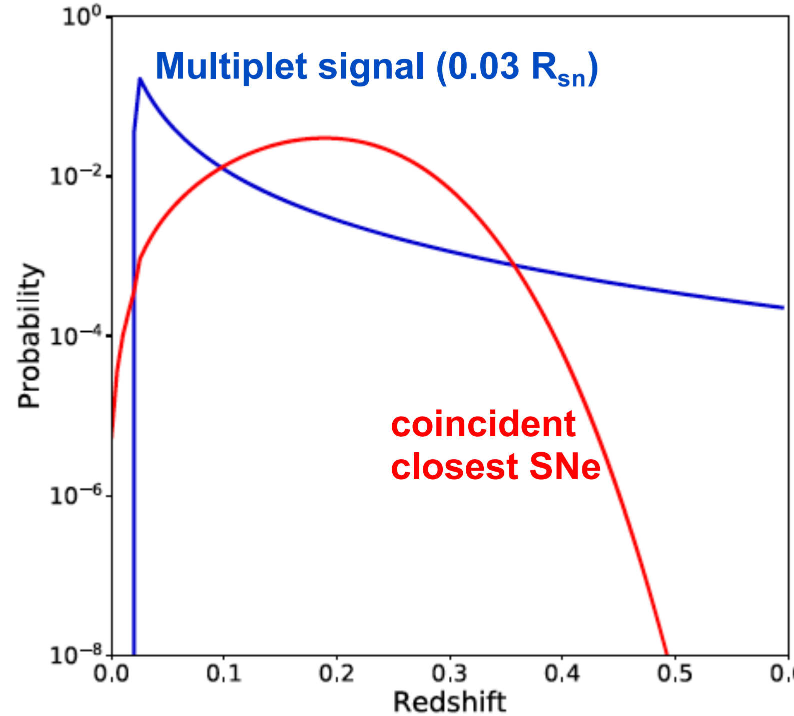


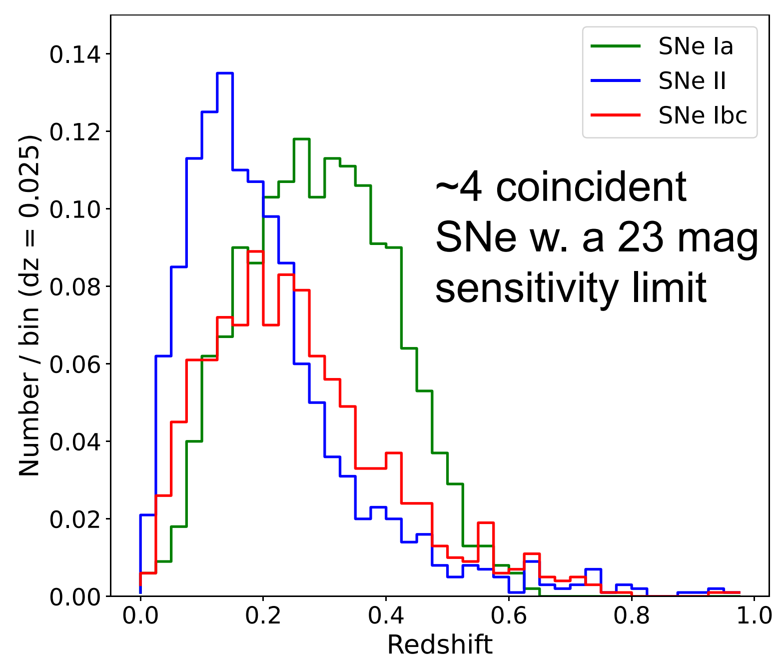
Gravitational wave
(gravity)

Don't miss interesting ν & GW events
- **Realtime coincident searches**
- **Prompt data-sharing for follow-ups**

Yoshida, KM+ 22 ApJ







- Need for long-duration multiplet alerts
  lower FAR (< 1/yr)
  likely to be low redshifts if SN-like

- Discriminating optical transients is a key

- Sensitivity: ~(30-3000) Gpc^{-3} yr^{-1}
  more improved w. KM3Net/IceCube-Gen2

Summary

Transients
Diversity, SNe are among the most promising targets!

Interacting-supernovae
Next Galactic SN: multi-energy ν source (>10-100 HE νs in IceCube)
SNe within a few Mpc: neutrino telescope networks + particle detectors

Wind-driven SNe
GeV-TeV νs from neutron-loaded outflows: detectable for Galactic SNe
PeV-EeV νs by accelerated ions: testing the UHECR origin

Jet-driven SNe
Still viable as the dominant origin of the all-sky neutrino flux
Stacking searches w. more samples especially with the Rubin era

Strategic multi-messenger searches
Multimessenger coincident searches (e.g., AMON)
Neutrino multiplet followups