High-Energy Multimessenger Emission from Supernovae

Kohta Murase

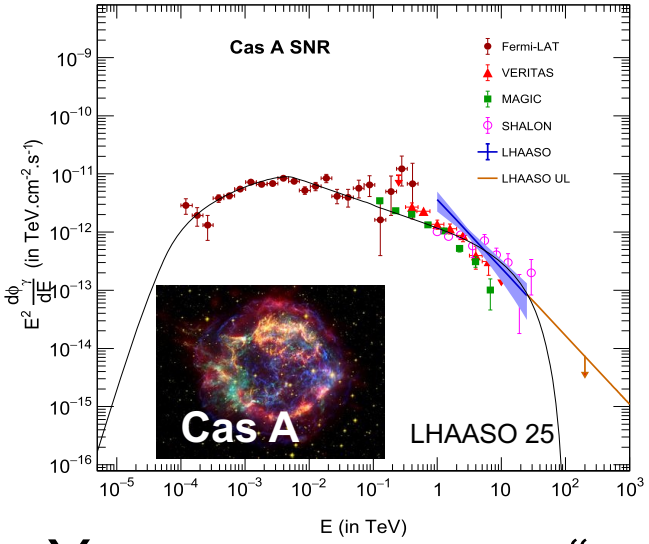
March 2026

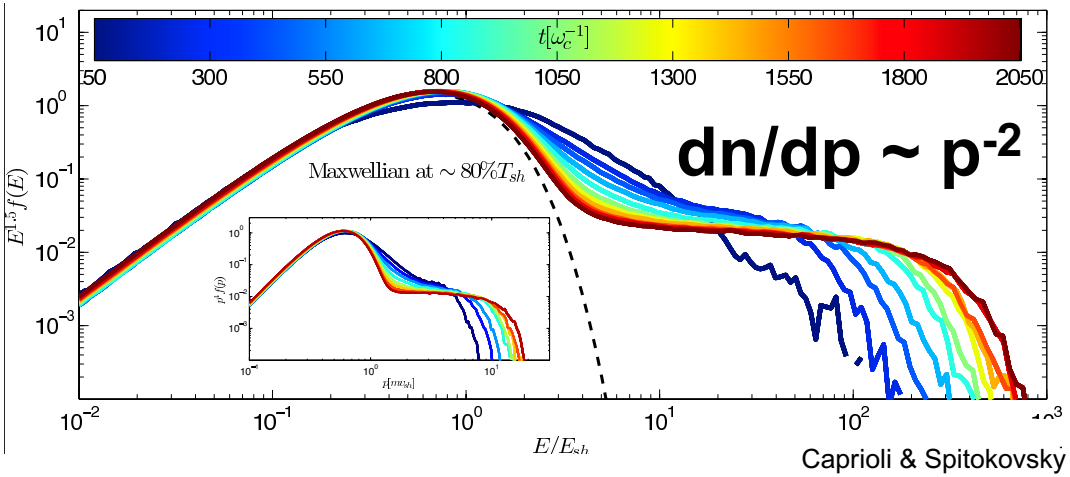
超新星ワークショップ

PENNSTATE

1855

Diffusive Shock Acceleration in Supernovae



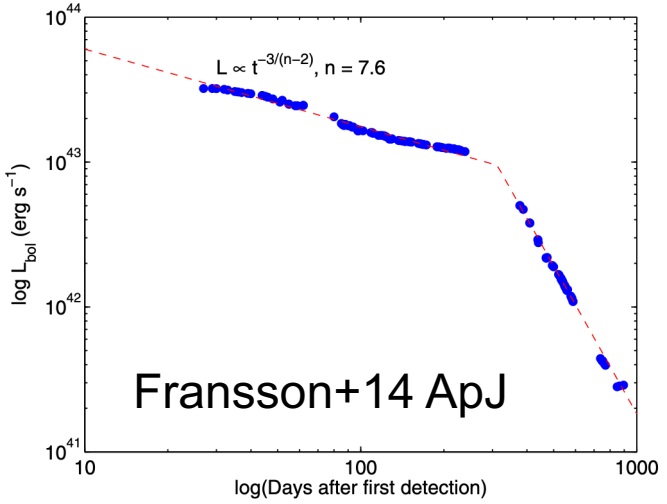


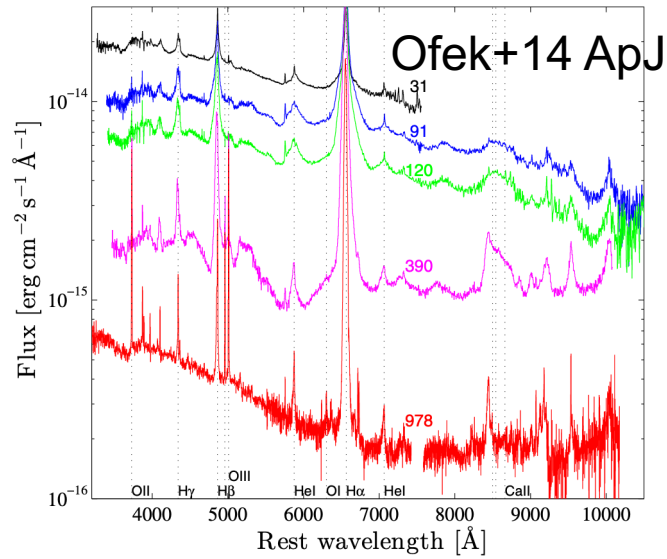
Caprioli & Spitokovsky 15

- Young supernova “remnants”:
  believed to be responsible for the origin of cosmic rays
  diffusive shock (Fermi) acceleration: detailed simulations
- Naively, early cosmic-ray production is negligible
  most of energy is in a kinetic form until the Sedov time
  ex. uniform ISM: cosmic-ray energy ∝ dissipation energy ∝ t^3
- But situations are different
  when circumstellar material (CSM) exists $\mathcal{E}_d = \frac{M_{\rm cs}}{M_{\rm ej}+M_{\rm cs}}\mathcal{E}_{\rm ej}$

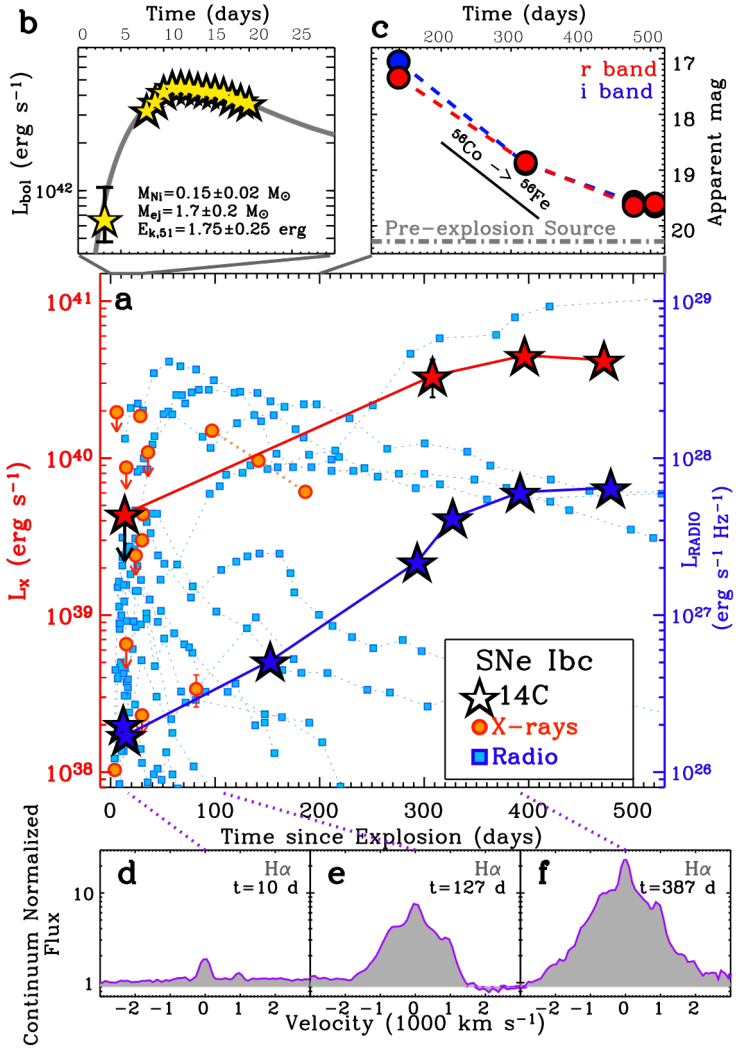
Evidence of Strong Interactions w. Dense CSM

SN 2010jl (IIn)



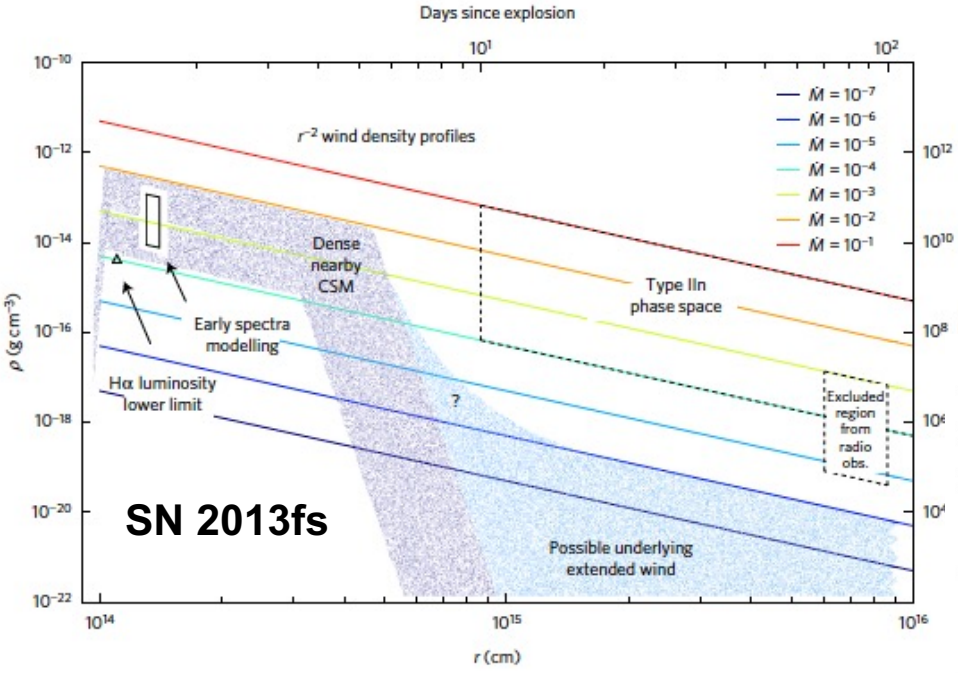


SN 2014C (Ib->IIn) Margutti+ 16 ApJ

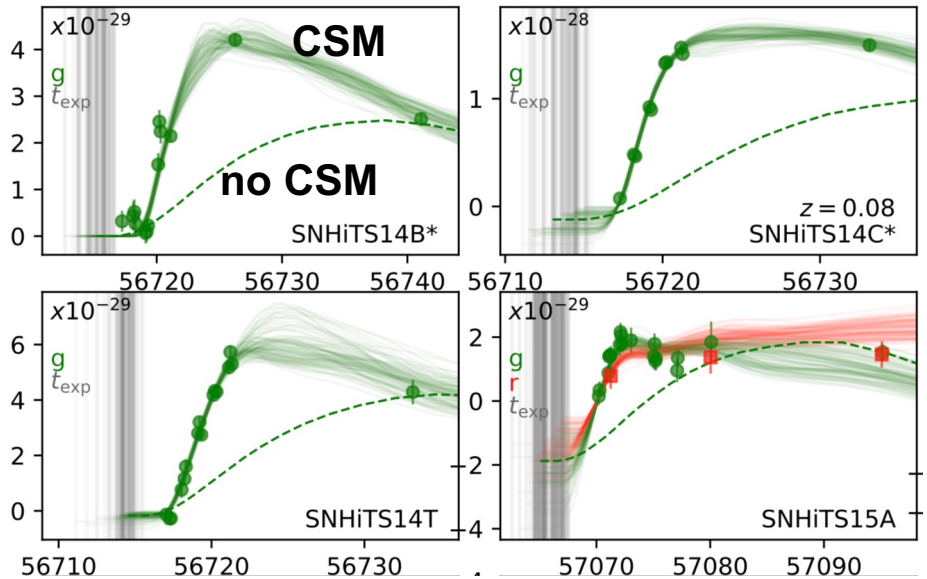


IIn, SLSN-II: strong interactions w. dense wind or CSM (M_{cs}~0.1-10 M_{sun})

Evidence for "Confined" CSM around Progenitors



early spectroscopy
(Yaron+ 16 Nature Phys.)

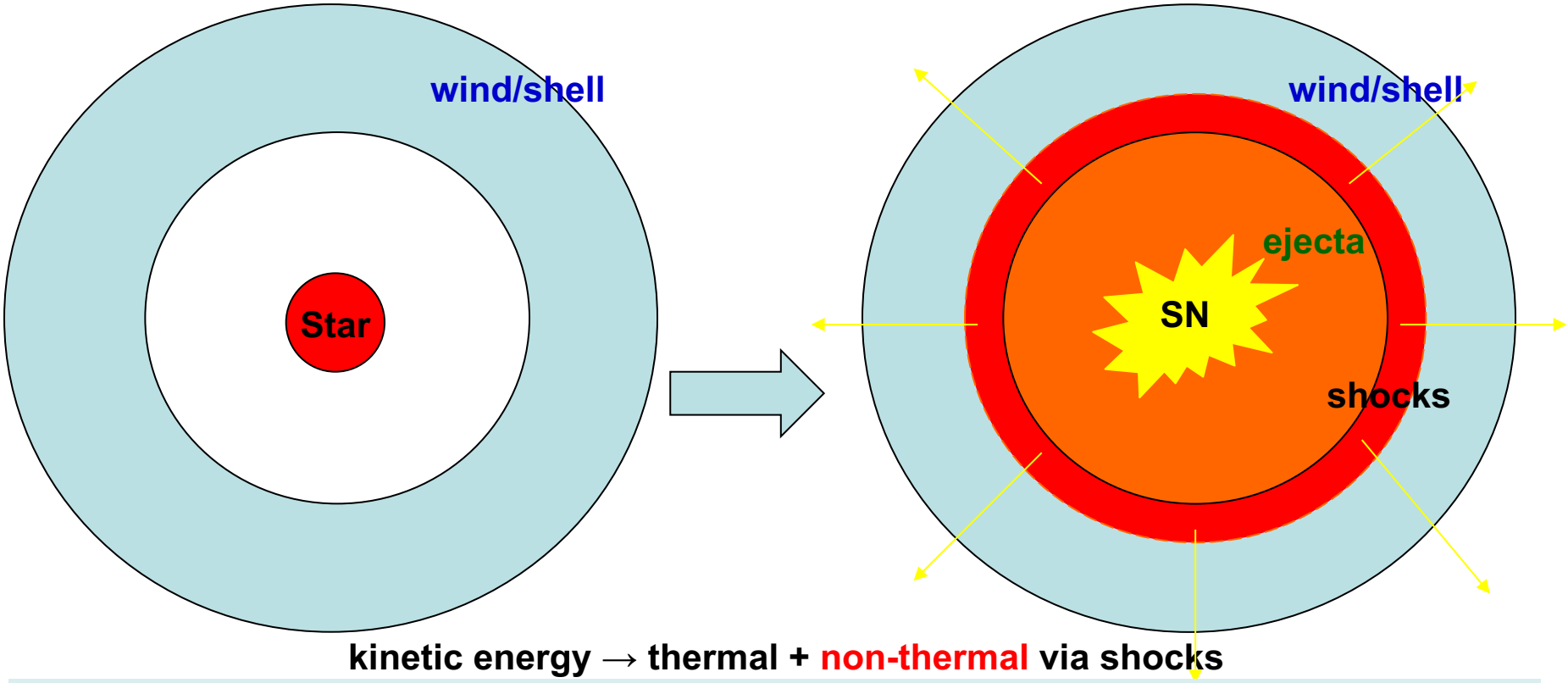


light curve modeling
(Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ)

- **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

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

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

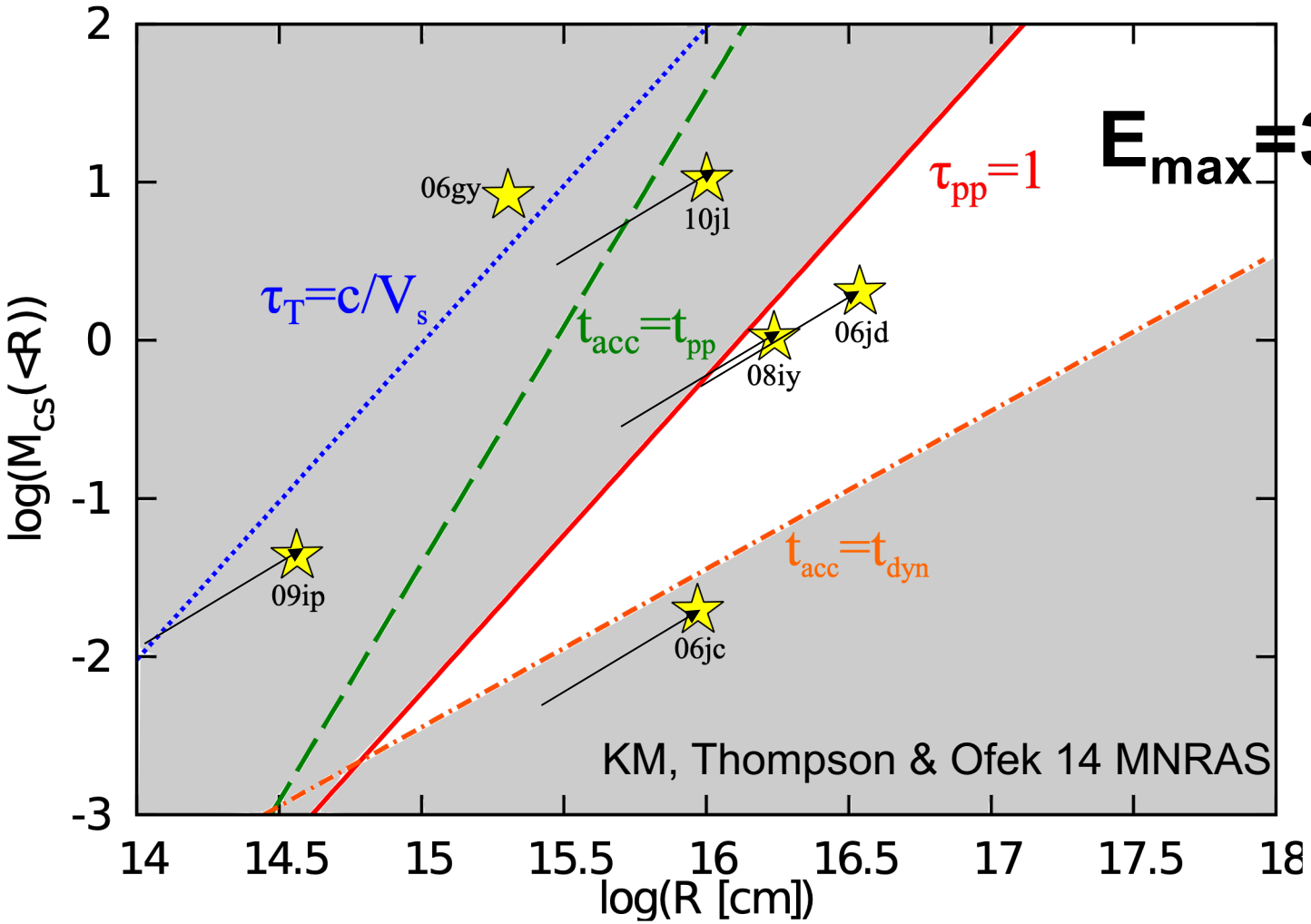
$$\pi^{0} \rightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

Interacting SNe as PeVatrons?

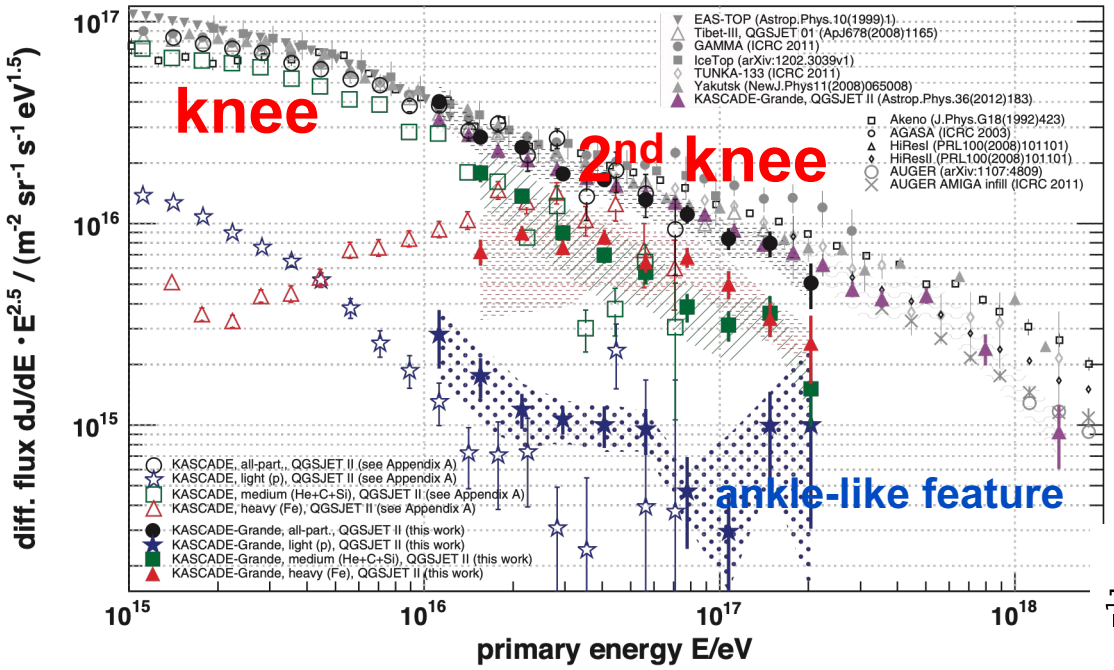
- Quasi-parallel, Bohm limit

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



Cosmic-Ray Origins?

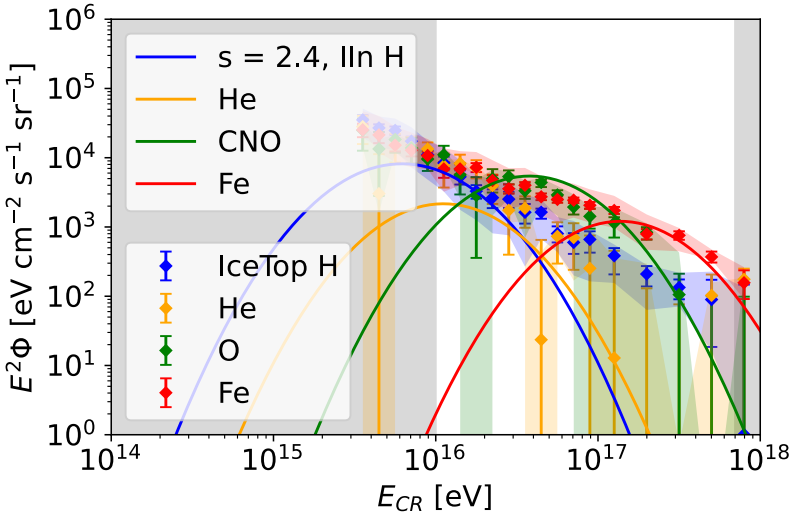
SNe IIn as the origin of CRs above the knee?



Apel et al. 13 APh

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

Ekanger, Kashiyama & Kimura 26



*AMES (*Astrophysical Multimessenger Emission Simulator*)*

Purpose:

Simulation tool for “observers” to generate ν and broadband EM spectra and light curves

- “Source dependent” python module (GRB, SN, TDE, AGN)
- Physics processes based on C++
- Input: standard model parameters

Current status:

ex. GRB (GRB leptonic afterglow): public
https://github.com/pegasuskmurase/AMES-GRBAfterglow

Interacting SN module with simply dynamics: ready
SN model templates:
https://github.com/pegasuskmurase/ModelTemplates/tree/main/SNHEMM
Interacting SN module with 1D hydrodynamical calculations

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 ejecta are decelerated earlier

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

Equation of motion $M_{sh} \frac{dV_s}{dt} = 4\pi R_s^2 [\varrho_{ej}(V_{ej} - V_s)^2 - \varrho_{cs}(V_s - V_w)^2]$

→ self-similar solution (Chevalier 82)

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

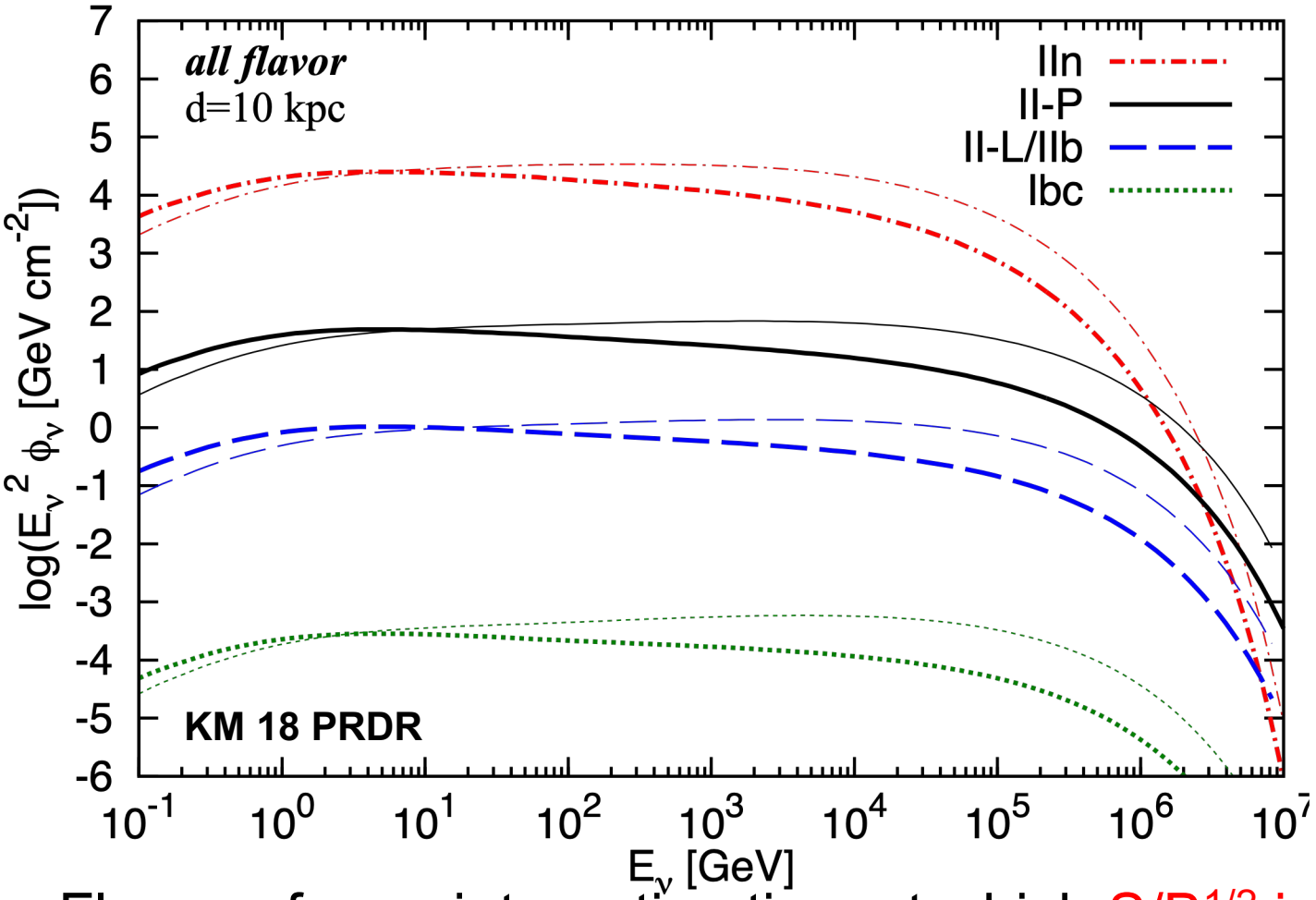
w=2 for a wind CSM
δ~10-12 for stars

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

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

Neutrino Fluence

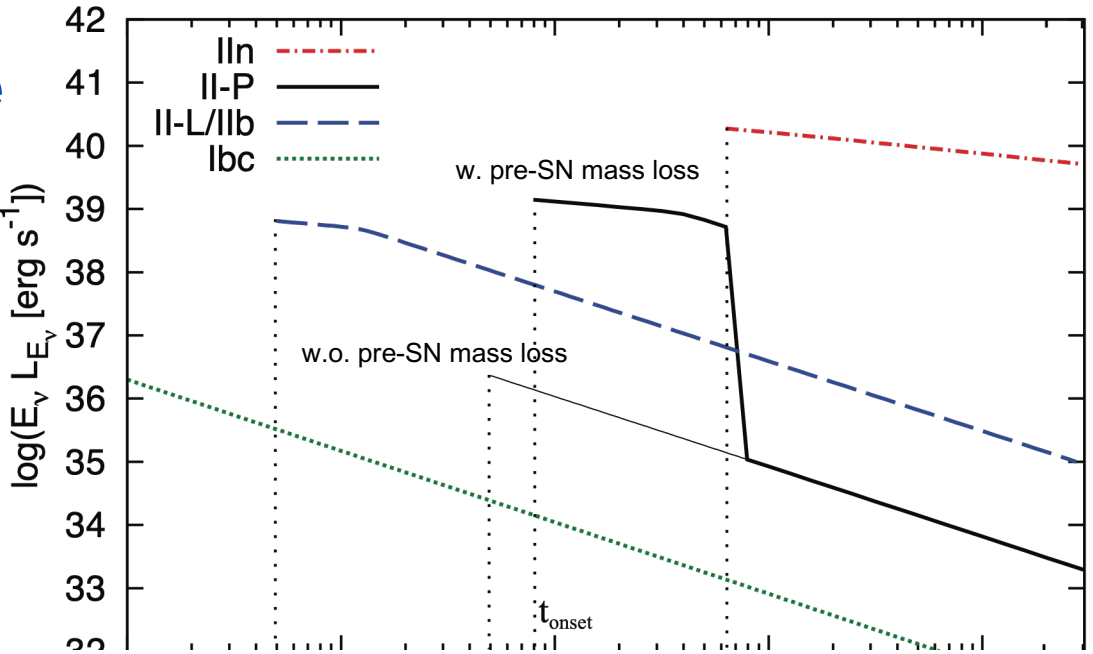
First prediction of HE neutrinos from SN w. confined CSM (KM 18 PRDR)



thick: s=2.2
thin: s=2.0

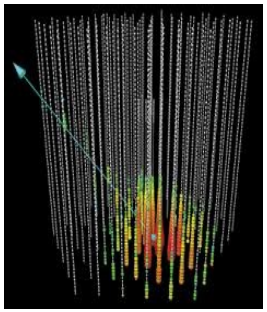
Fluence for an integration time at which $S/B^{1/2}$ is maximal (determined by the detailed time-dependent model)

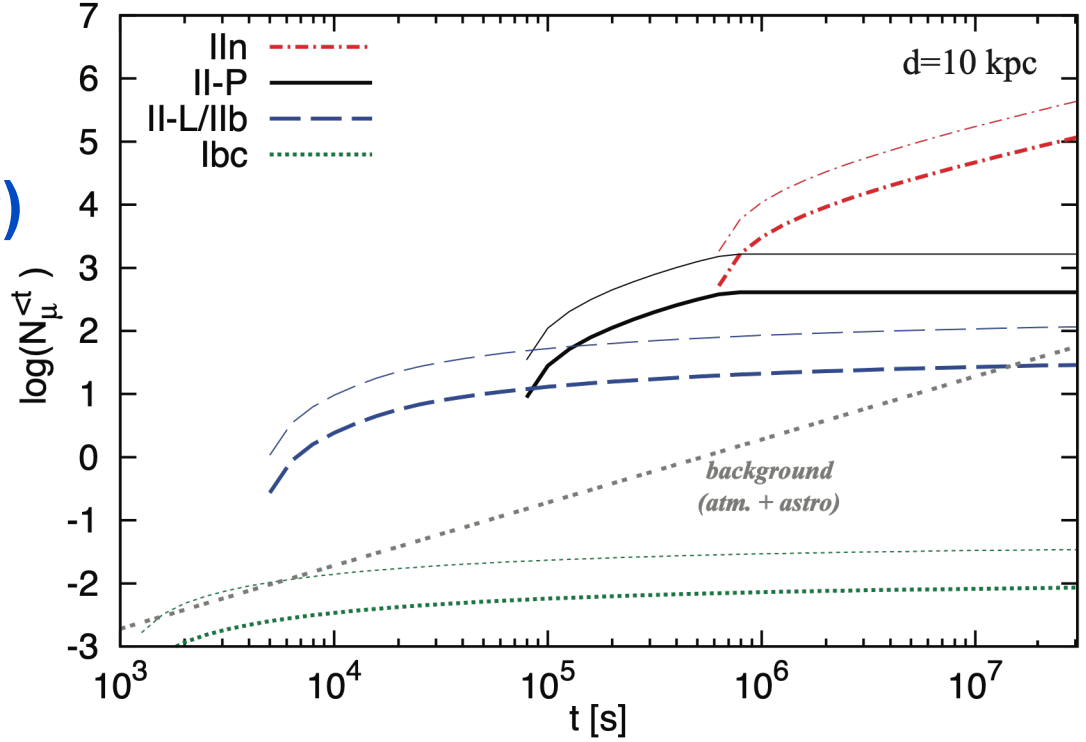
light curve



KM 18 PRDR

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





~100-1000 events for typical CCSNe

 # ~1000 events for Betelgeuse even w.o. confined CSM

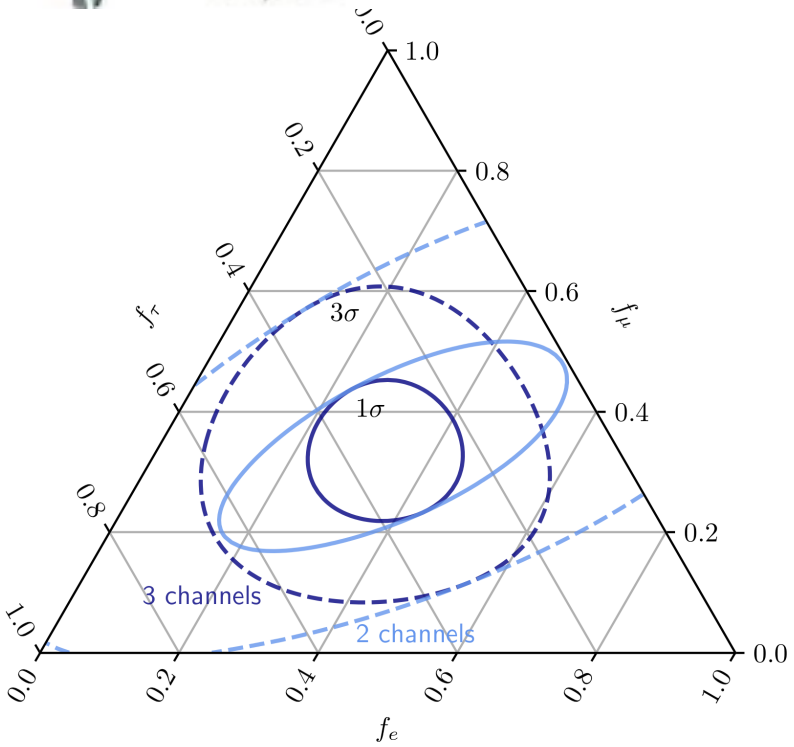
Key Points

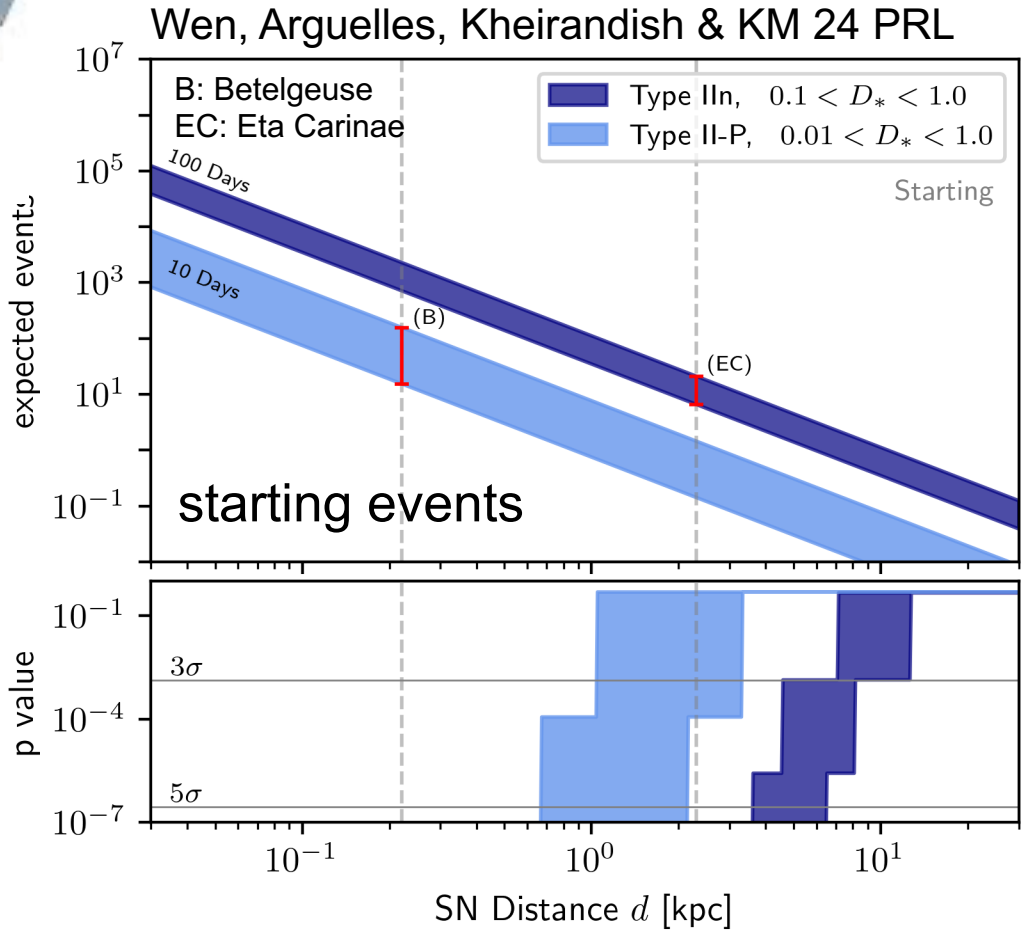
- Testable & clear predictions (no need for jets/winds)
  free parameters: ε_{CR} & s (typical values: ε_{CR}~0.1 & s~2.0-2.3)
- Time window:
  duration ~ calorimetry (f_{pp}~t_{dyn}/t_{pp}>1)
  e.g., ~days to weeks for SNe II (II-P/II-L/IIb), ~hours (Ibc), ~months (IIn)
- Energy range: multi-energy
  IceCube/KM3Net: TeV-PeV (even Glashow resonance anti-ν_e & ν_τ events)
  Hyper-K/IceCube-Upgrade/KM3Net-ORCA: GeV-TeV
- Astrophysical implications
  a. Pre-explosion mass-loss mechanisms
     How does a dense wind/shell form around the star ?
  b. PeVatron origin
     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
     Onset of CR ions acceleration & collisionless shock formation
  d. Particle physics implications – large statistics
     flavor studies, BSM searches

Detection w. Large Hadron Collider

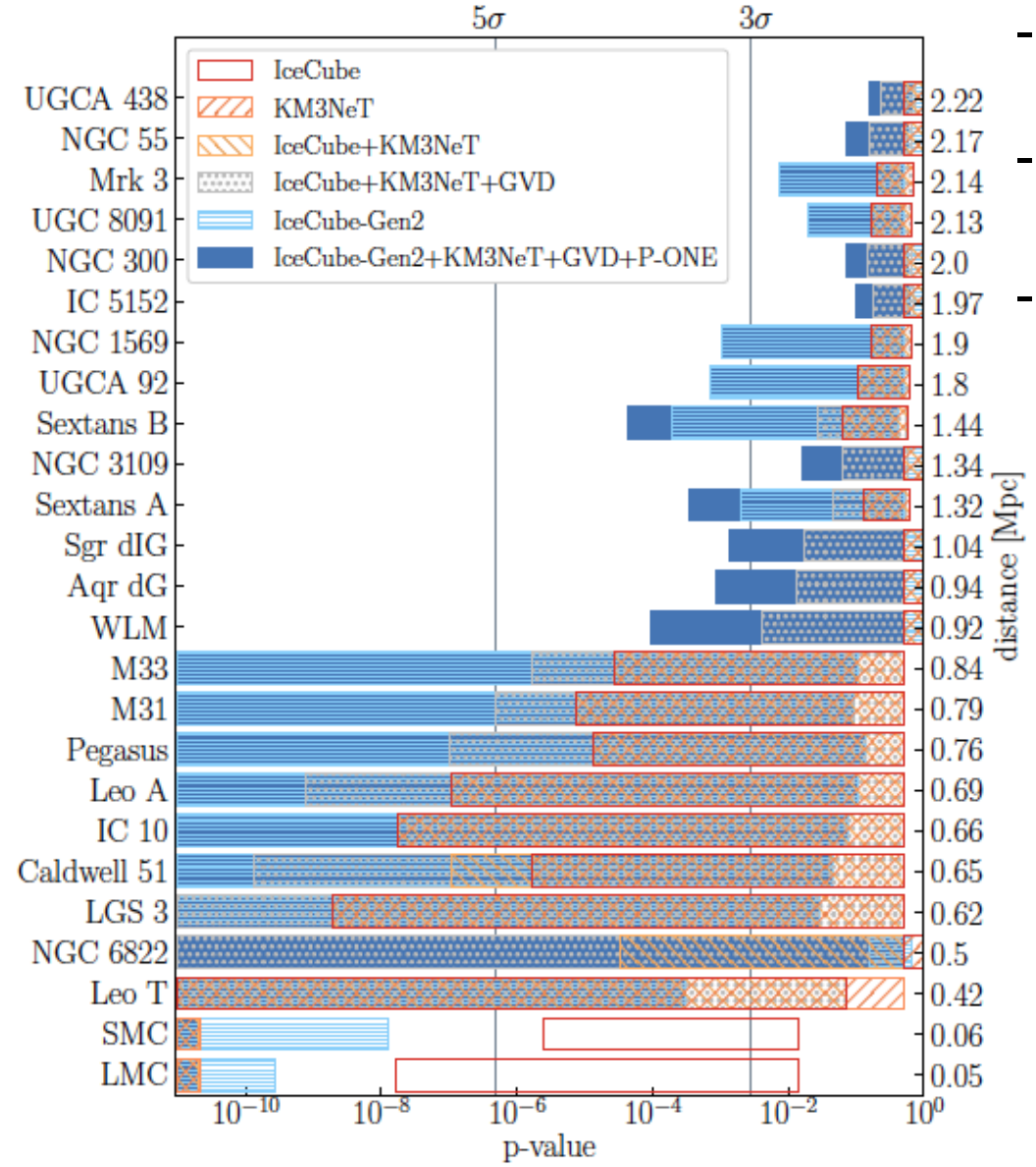
LHC ATLAS

calorimeter ρV=4 kt

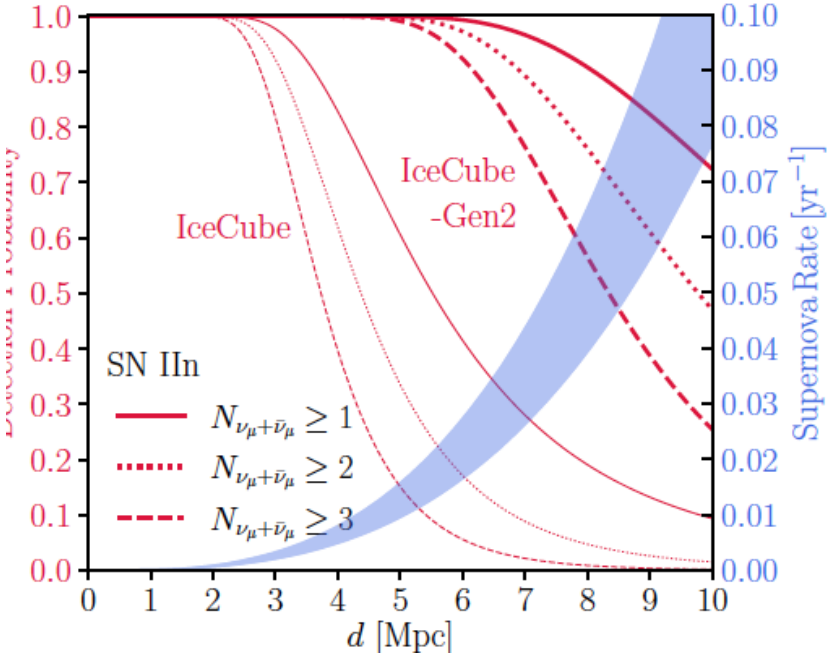




Detectability of "Minibursts"

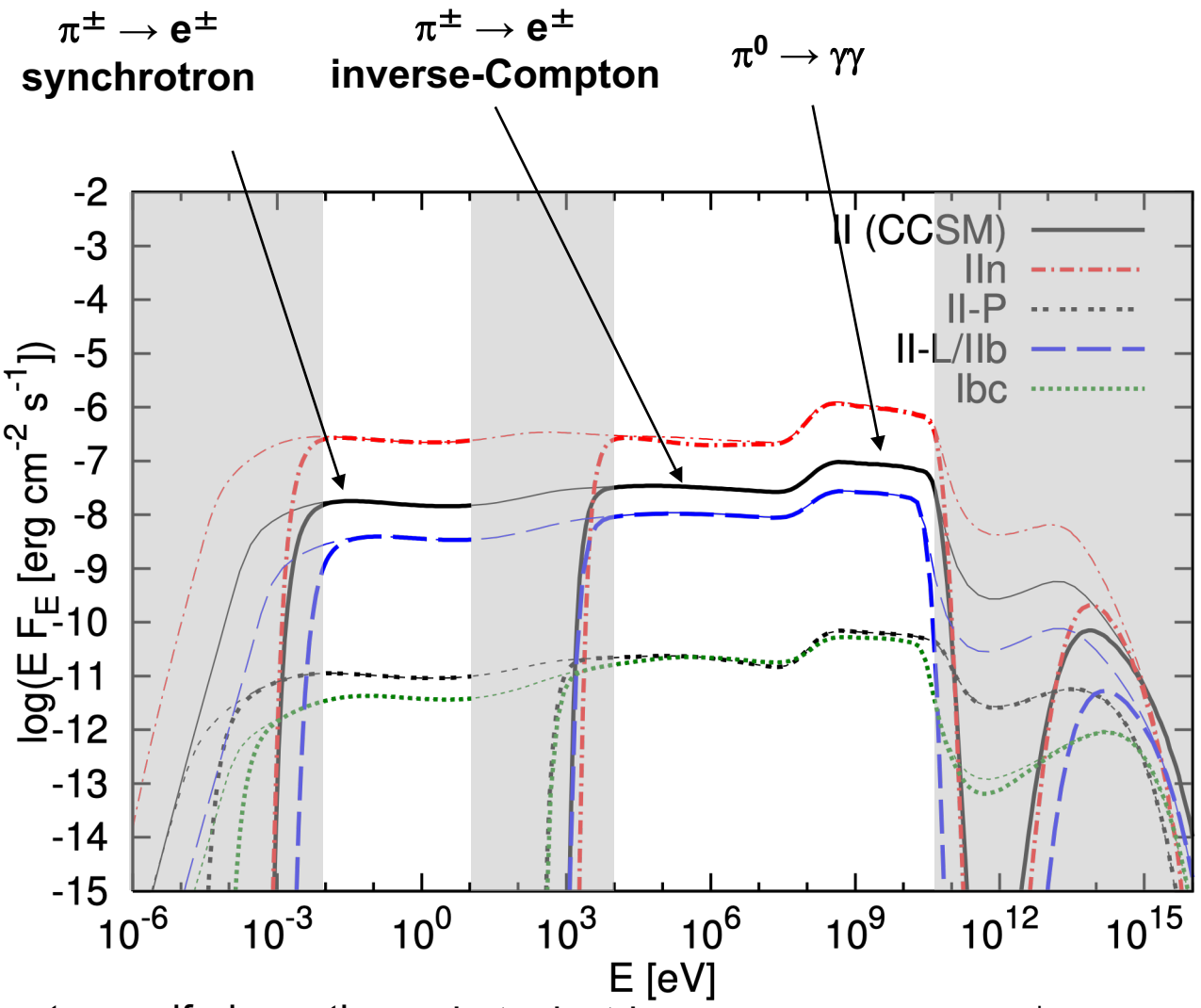


- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II (CCSM): detectable to ~3-4 Mpc
  IIn: detectable to ~10 Mpc



Kheirandish & KM 23 ApJL

Multiwavelength Photon Spectra



KM 24 PRD

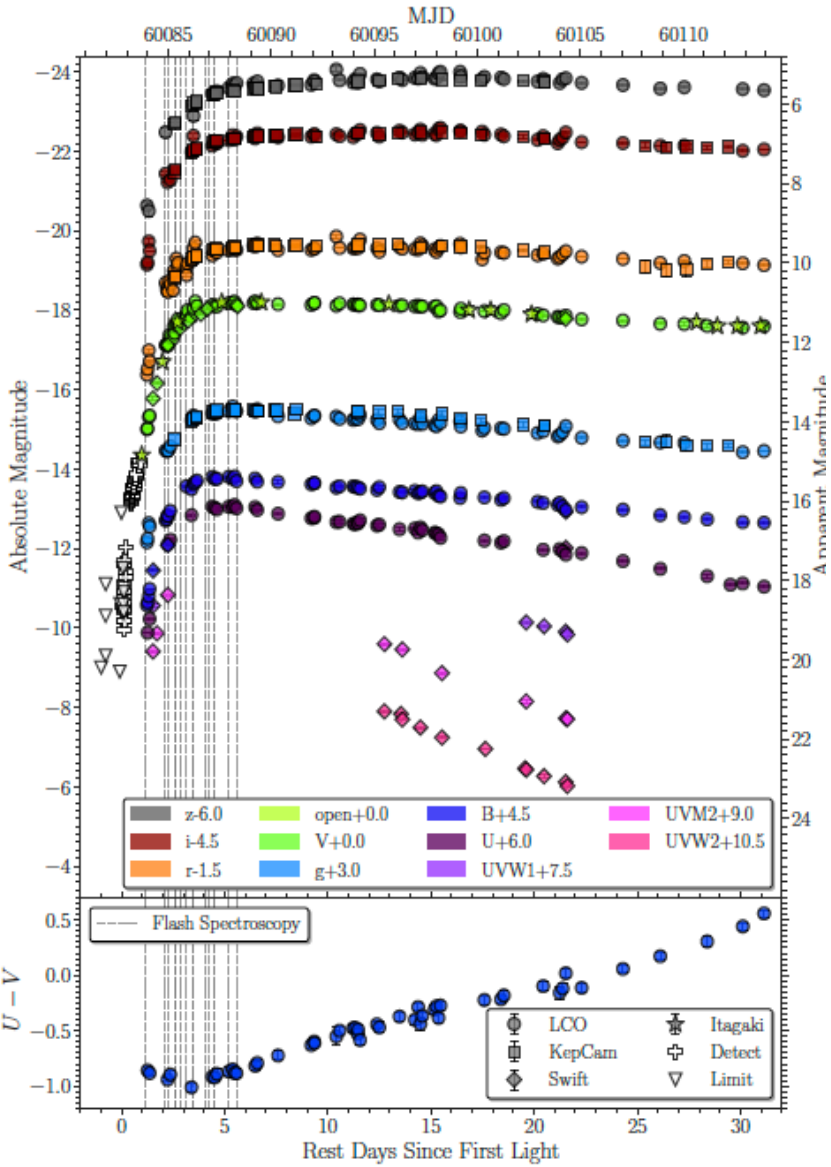
synchrotron self-absorption
free-free absorption

photoelectric absorption

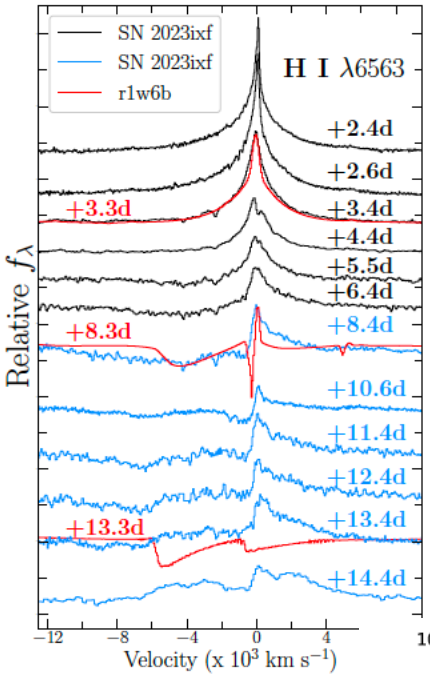
$\gamma\gamma \rightarrow e^{+}e^{-}$ matter attenuation

Example: SN 2023ixf

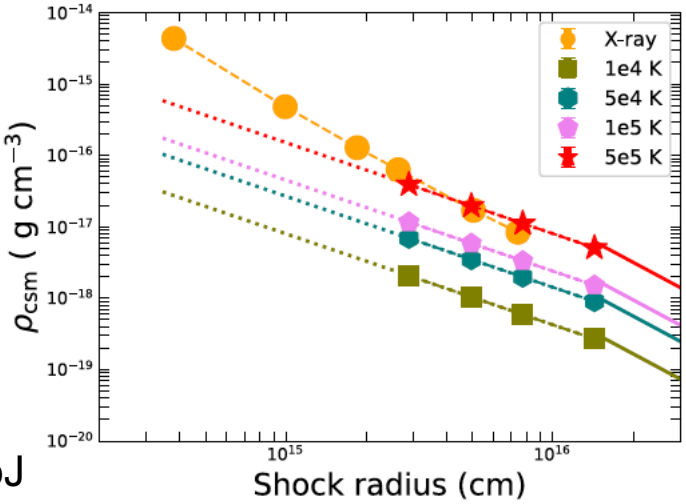
Hiramatsu+ 23



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
  $dM_{cs}/dt \sim (0.3\text{-}1)\times10^{-3}$ M_{sun} yr^{-1}
  R_{cs} ~ 10^{15} cm
- Radio
  VLA detection at ~30 d



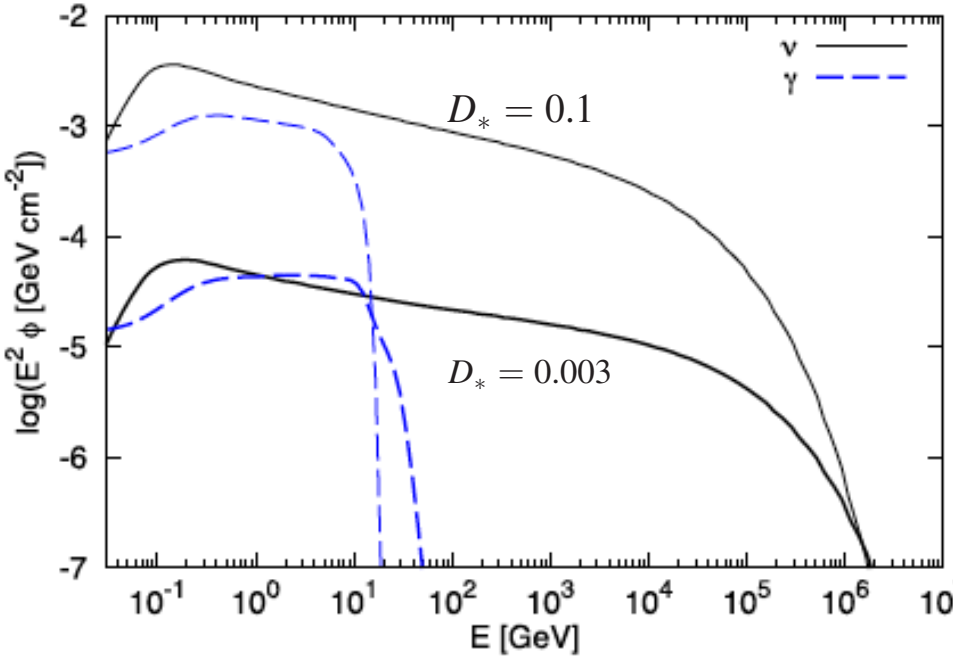
Nayana+ KM 25 ApJ

Multimessenger Spectra & Light Curves

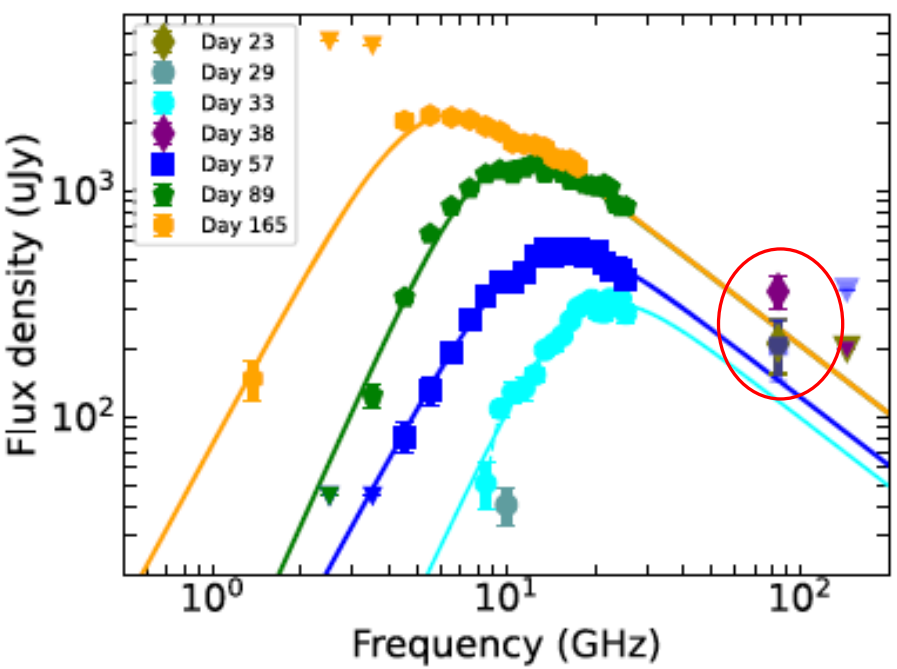
KM 24 PRD, Kheirandish & KM 23 ApJL

Nayana+ KM 25 ApJ

neutrino & gamma-ray fluences



radio flux

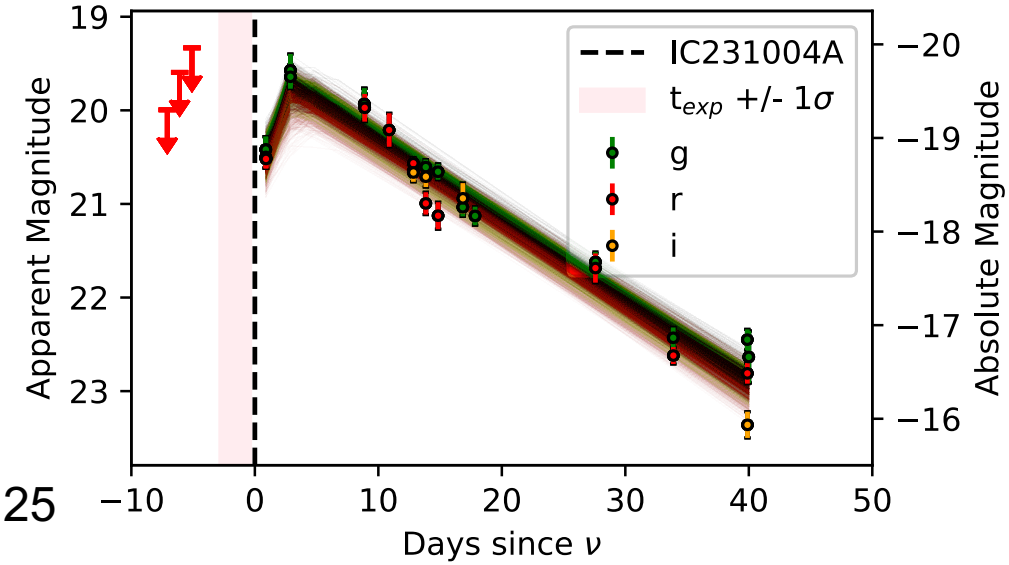


- Neutrino: consistent w. IceCube nondetection (N_ν~0.0007-0.02)
- Gamma: consistent w. Fermi LAT nondetection
- X: consistent w. bremsstrahlung emission
- Radio: NOEMA data could be consistent w. hadronic emission

Possible Neutrinos from SNe IIn/Ibn?

IceCube-231004A: ~400 TeV

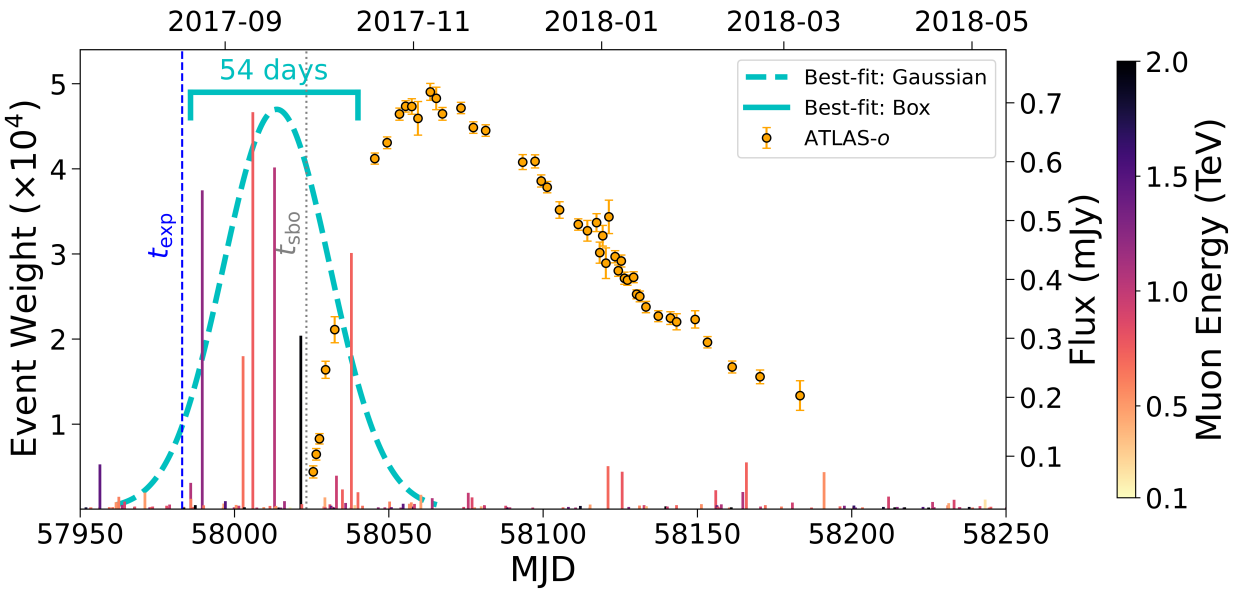
SN 2023uqf: bright Ibn



Stein + KM 25

archival analysis:
~11-13 signals

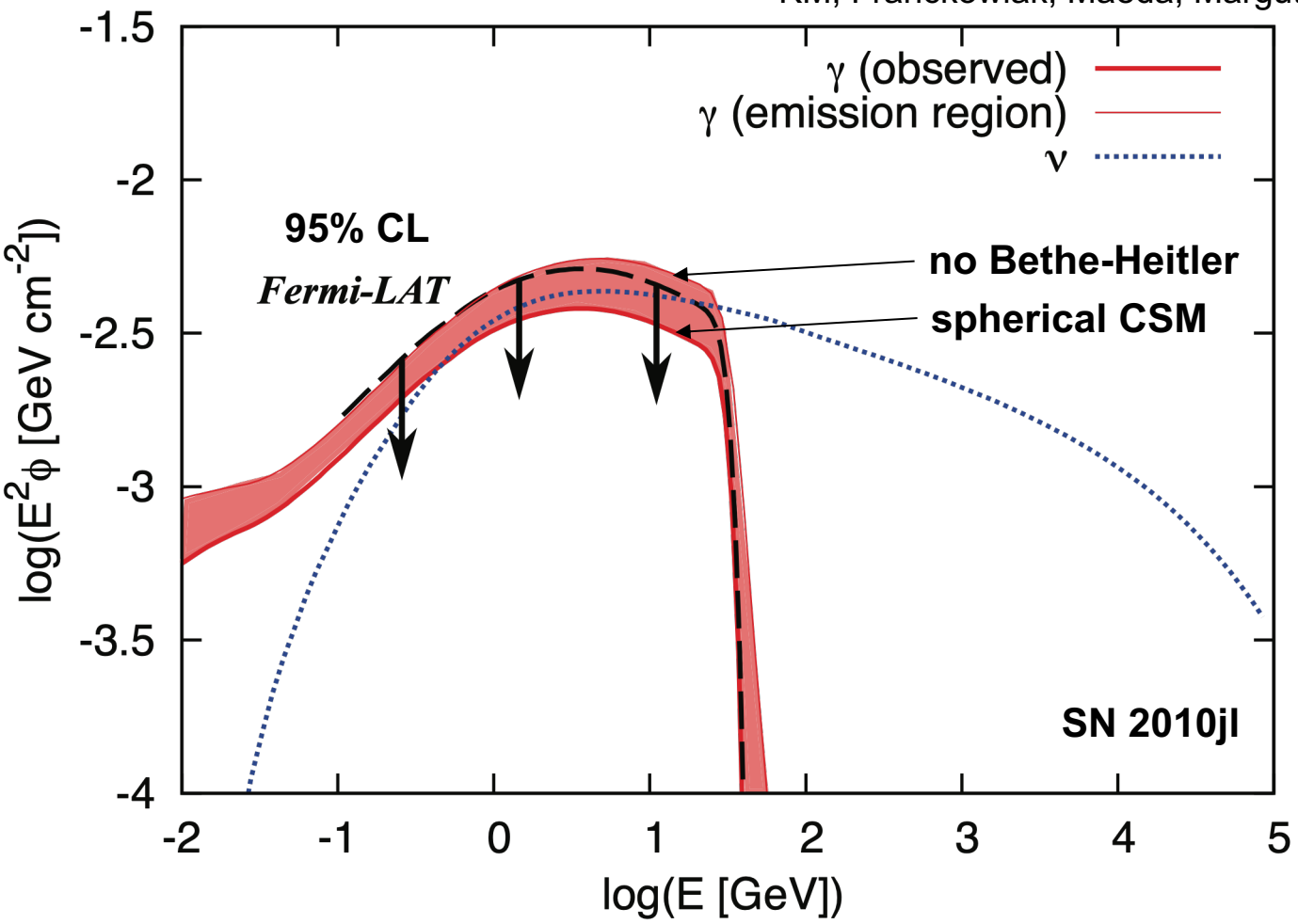
SN 2017hcd: IIn



Ji+ 26

Best Gamma-Ray Limits from SNe IIn

KM, Franckowiak, Maeda, Margutti & Beacom 19 ApJ

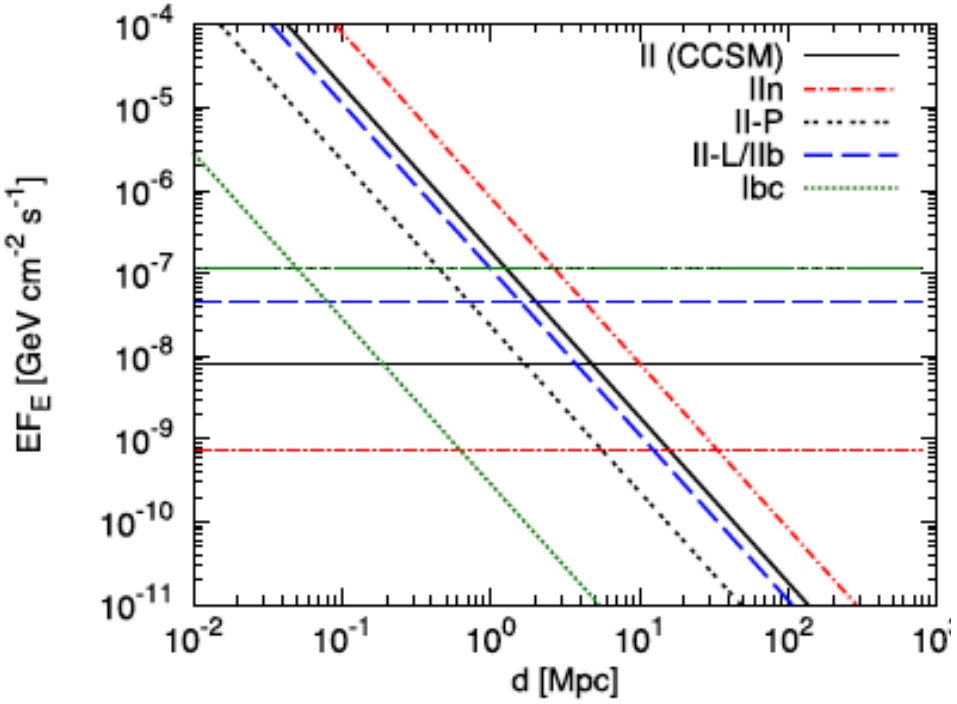


Interesting limits: ε_p<0.05-0.1 (w. weak dependence on CR index)
brighter SNe or more SN samples or improved sensitivity

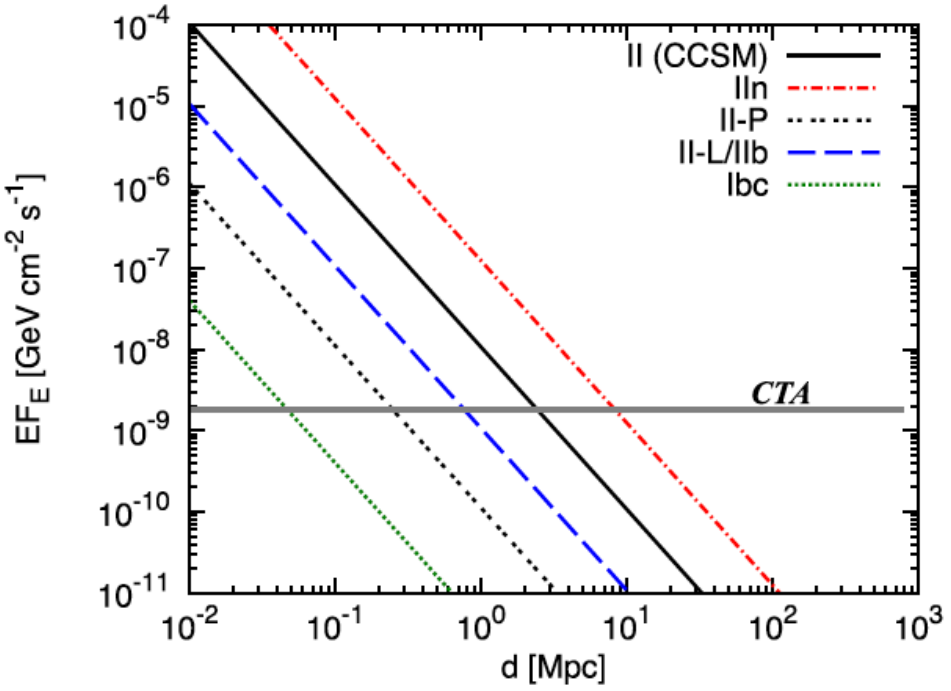
Gamma-Ray Detection Prospects

KM 24 PRD
KM, Franckowiak, Maeda, Margutti & Beacom 19 ApJ

Fermi LAT (1 GeV γ rays)



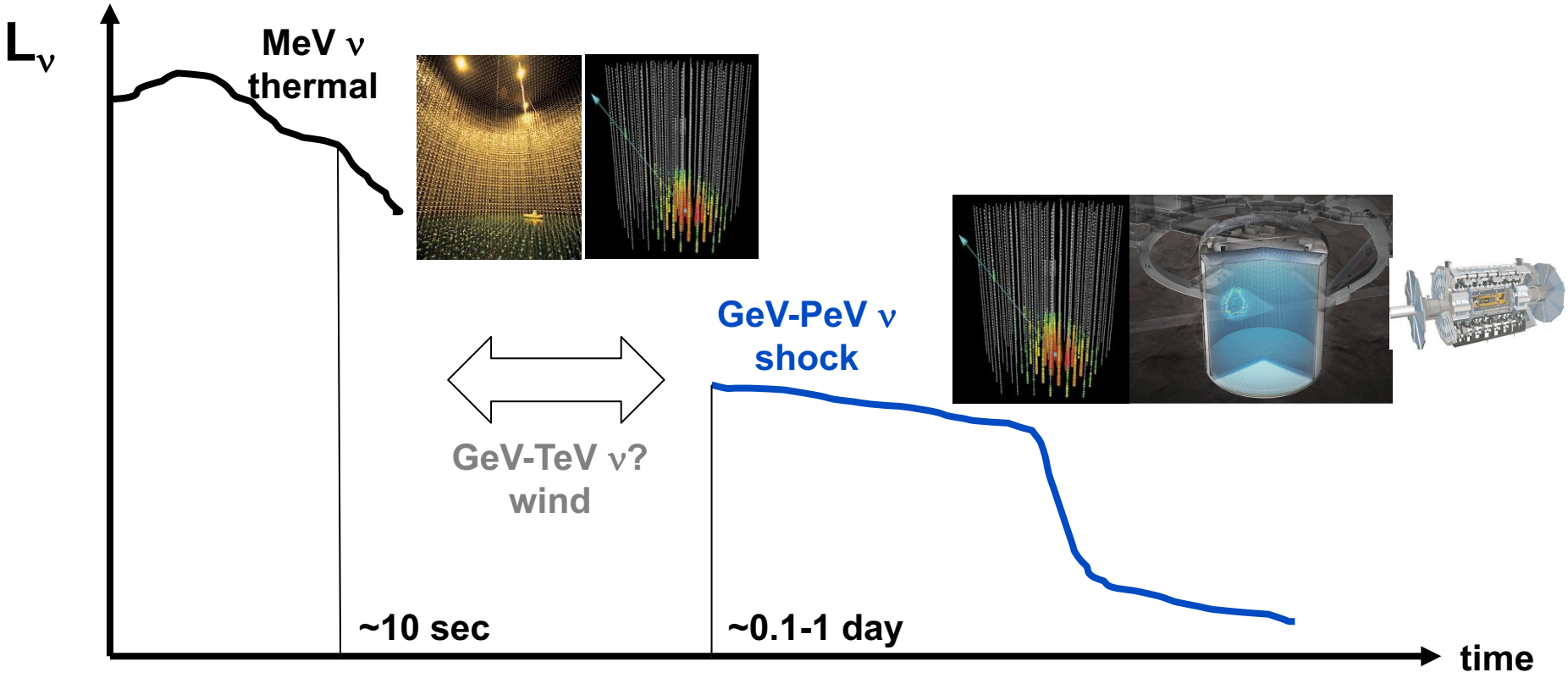
CTA (50 GeV γ rays)



- Single SN: detectable up to ~5-50 Mpc
- Statistical approaches should also be powerful

Take Away

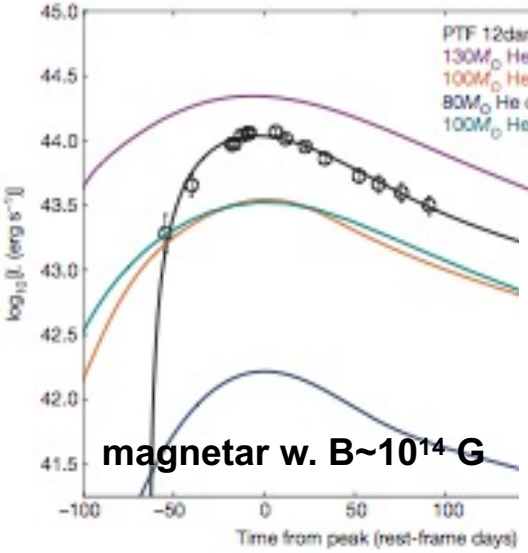
- Proposal and development of the time-dependent model for high-energy ν/γ-ray emission from different classes of SNe
- Type II: ~100-1000 events of TeV ν from the next Galactic SN
- Interacting SNe as "multimessenger" & "multi-energy" neutrino source
- Optical follow-up searches the Rubin/Subaru-PFS era



Pulsar/Magnetar-Driven Supernovae

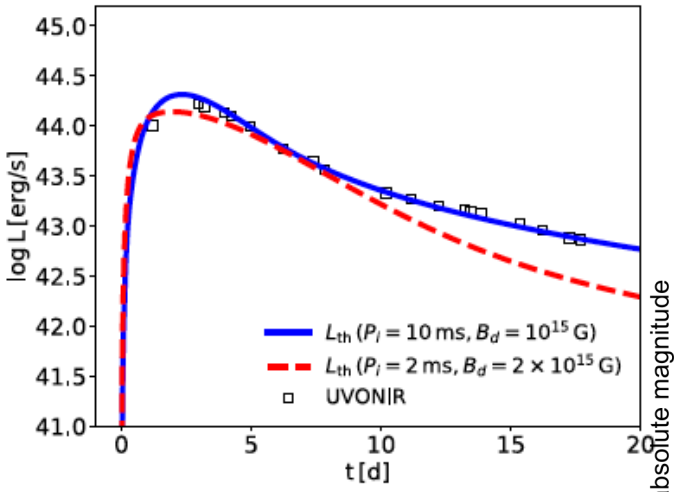
"Rapidly rotating pulsars" are popularly invoked to explain some SNe Ibc

super-luminous supernova (SLSN)



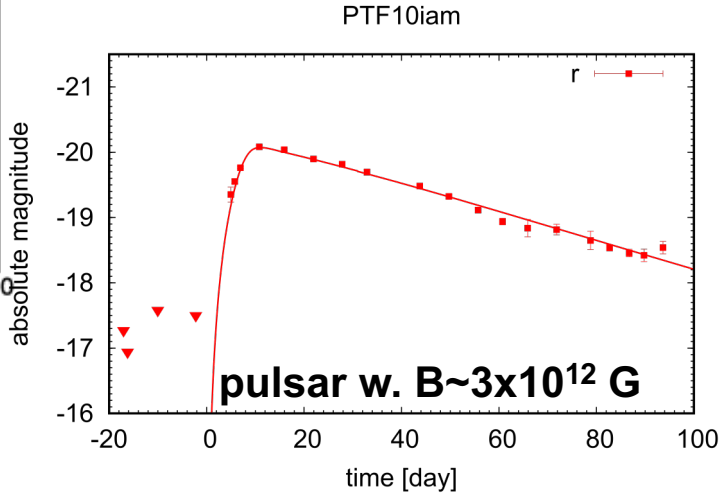
Nicholl et al. 13 Nature

fast blue optical transient (FBOT)



Fang, Metzger, KM+ 19 ApJ

ultra-stripped supernova (USSN)

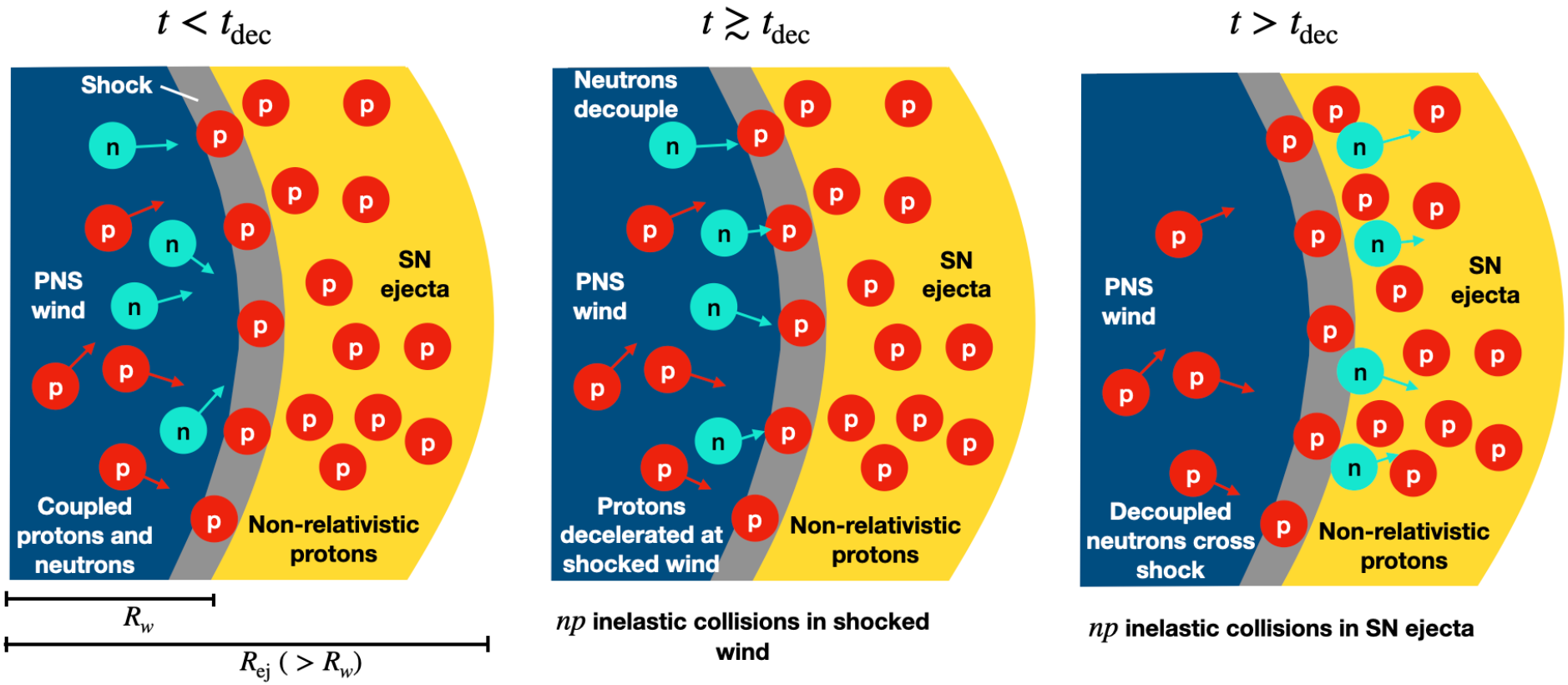


Hotokezaka, Kashiyama & KM 17 ApJ

requirement: rotation energy is converted into thermal energy

GeV-TeV Neutrinos from Pulsar/Magnetar-Driven SNe

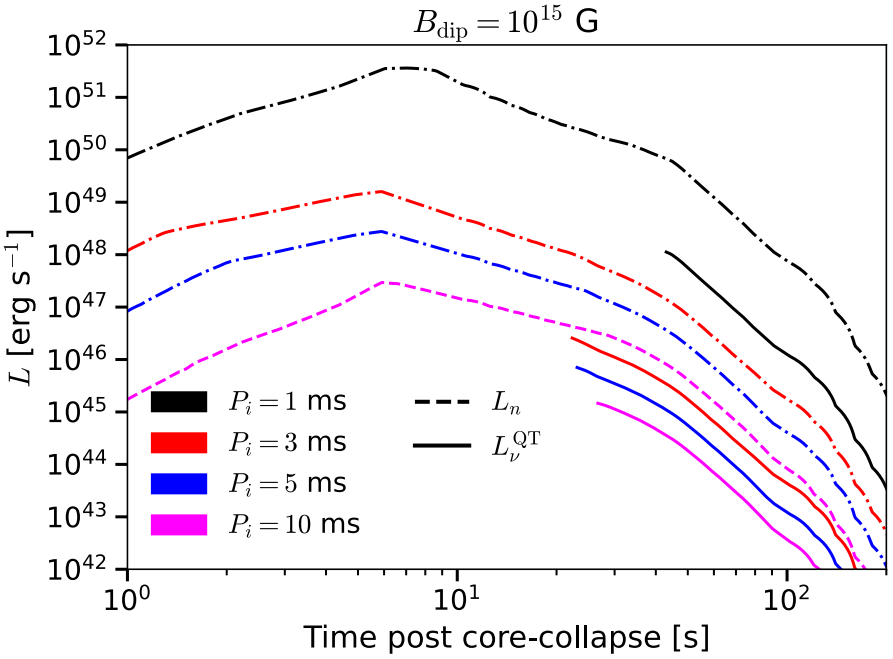
- Neutron-loaded outflows from highly magnetized protoneutron stars
- Bulk wind acceleration → neutron decoupling → neutrino production
- No cosmic-ray acceleration is necessary (KM, Dasgupta & Thompson 14 PRD)



taken from Carpio, Ekanger, Bhattacharya, KM & Horiuchi 24 PRD

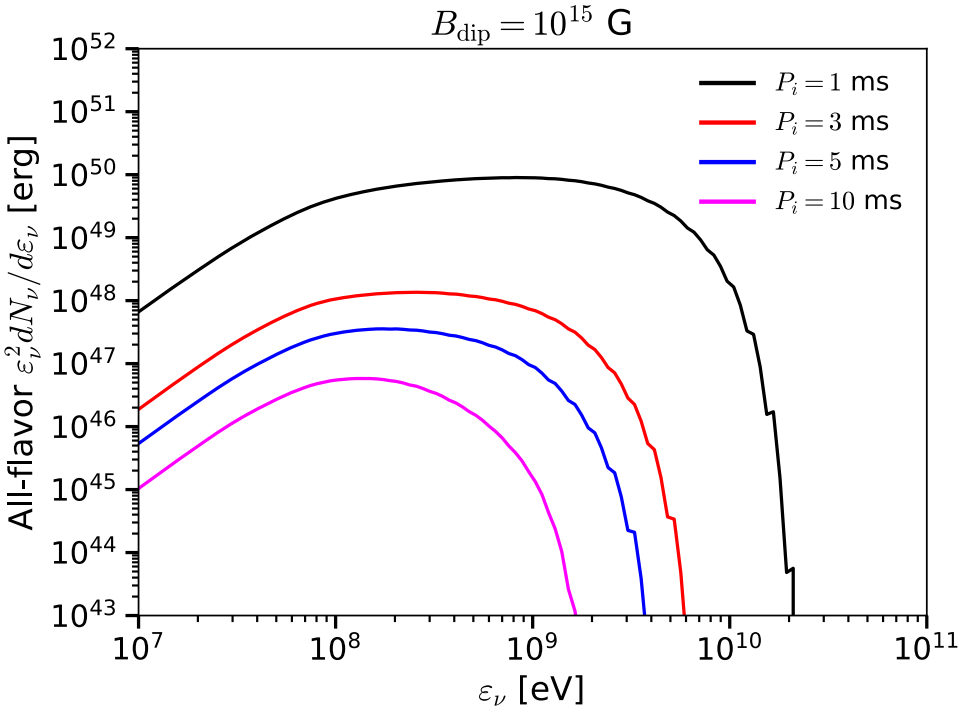
GeV-TeV Neutrinos from Pulsar/Magnetar-Driven SNe

- Neutron-loaded outflows from highly magnetized protoneutron stars
- Bulk wind acceleration → neutron decoupleng → neutrino production
- Faster-rotating/more strongly magnetized PNSs are better



Quasithermal neutrinos
(no cosmic-ray acceleration)

Carpio, Ekanger, Bhattacharya, KM & Horiuchi 24 PRD
KM, Dasgupta & Thompson 14 PRD



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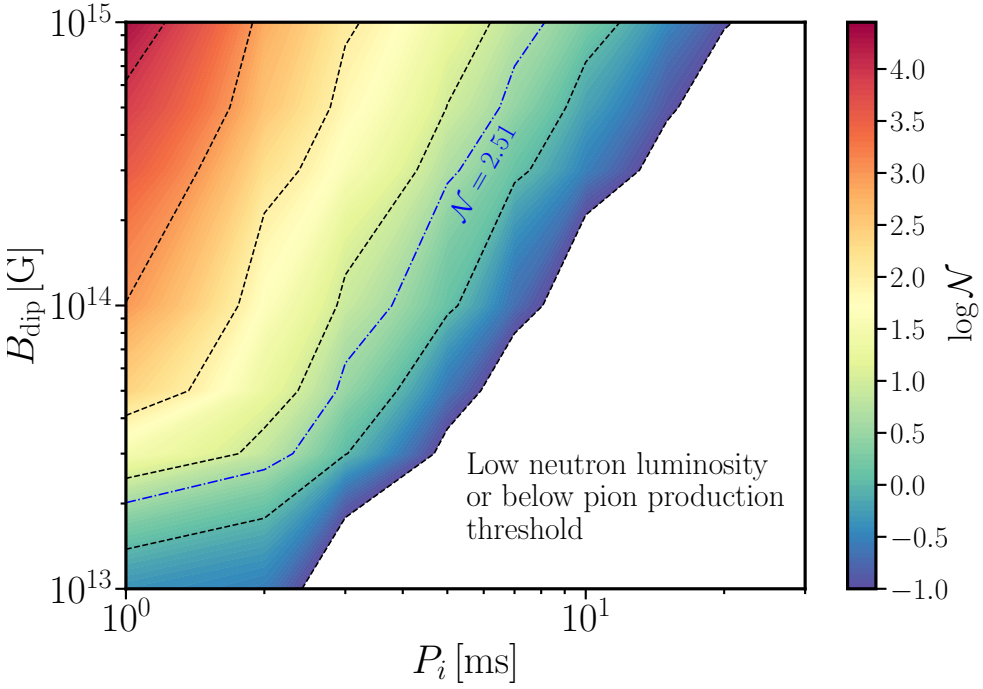
$(B_{\rm dip}/{\rm G}, P_i/{\rm ms})$	HK	KM3Net-ORCA	IceCube-Upgrade
$(10^{15}, 1)$	4.2×10^4	2.8×10^4	9.2×10^4
$(10^{15}, 3)$	2.4×10^2	25	1.8×10^2
$(10^{15}, 10)$	3.7	2.4×10^{-2}	1.0×10^{-1}
$(10^{15}, 30)$	4.2×10^{-2}	~ 0	~ 0
$(10^{14}, 1)$	1.2×10^3	3.9×10^2	2.3×10^3
$(10^{14}, 3)$	16	2.2×10^{-1}	1.5
$(10^{14}, 10)$	5.3×10^{-2}	~ 0	~ 0
$(10^{14}, 30)$	~ 0	~ 0	~ 0
$(10^{13}, 1)$	8.9×10^{-1}	~ 0	~ 0
$(10^{13}, 3)$	4.4×10^{-2}	~ 0	~ 0
$(10^{13}, 10)$	~ 0	~ 0	~ 0
$(10^{13}, 30)$	~ 0	~ 0	~ 0

Hyper-K for a Galactic SN @ 10 kpc



Carpio, Ekanger, Bhattacharya, KM & Horiuchi 24 PRD

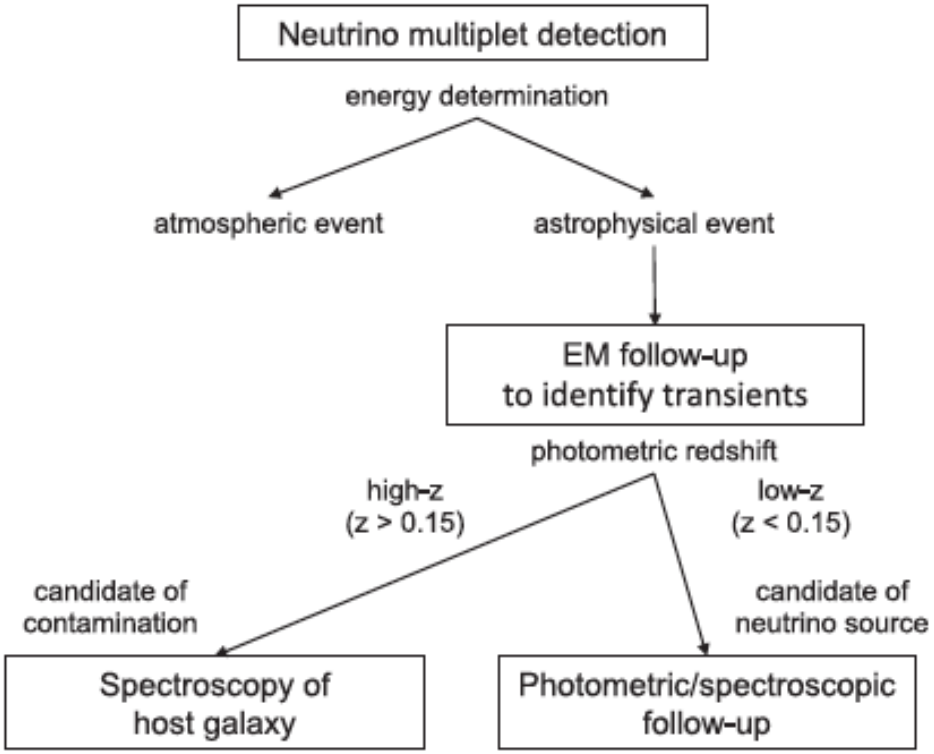
What Do We Need?

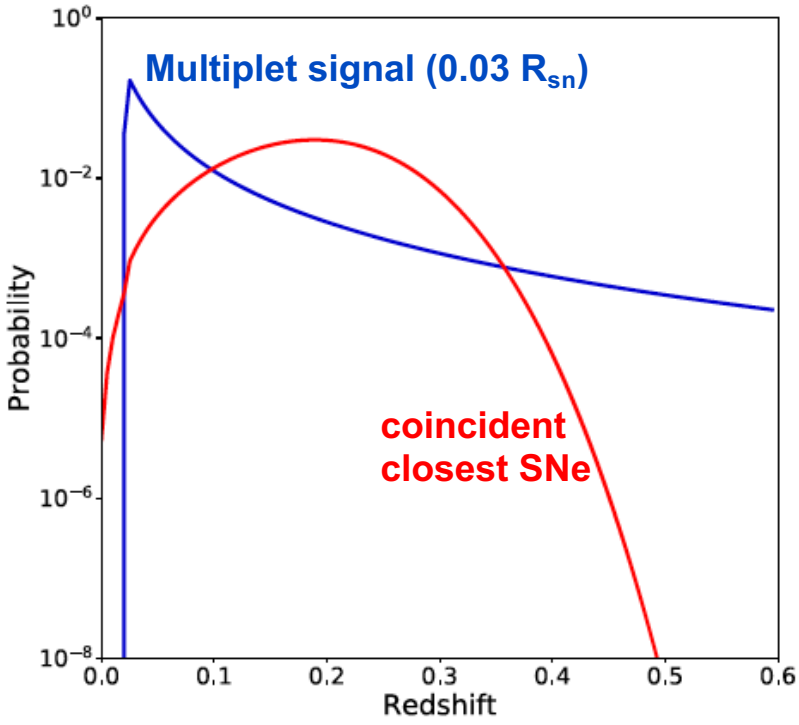
Targets: long-duration HE ν/short-duration GeV-TeV ν transients

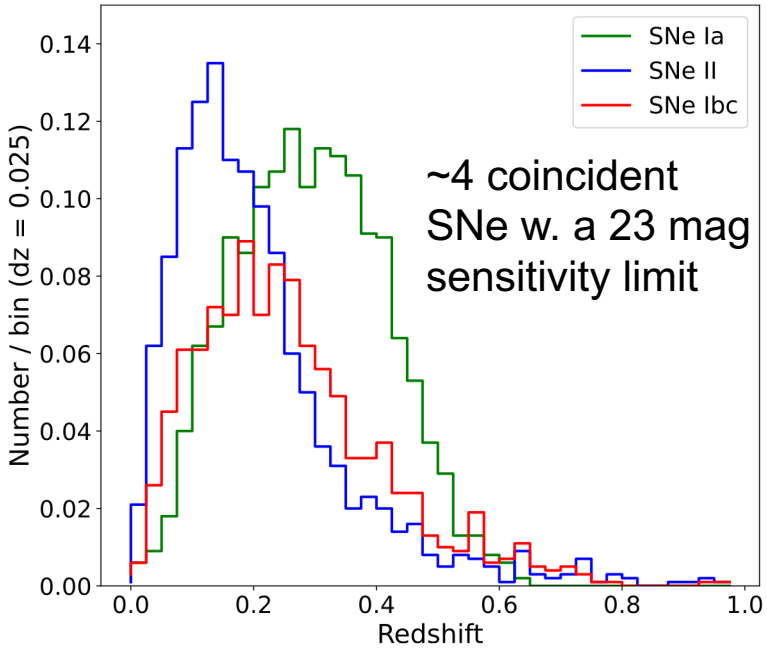
- Multimessenger coincident searches (e.g., AMON events) would be powerful for subthreshold events
- Neutrino multiplet followups would also be useful

- 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)

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