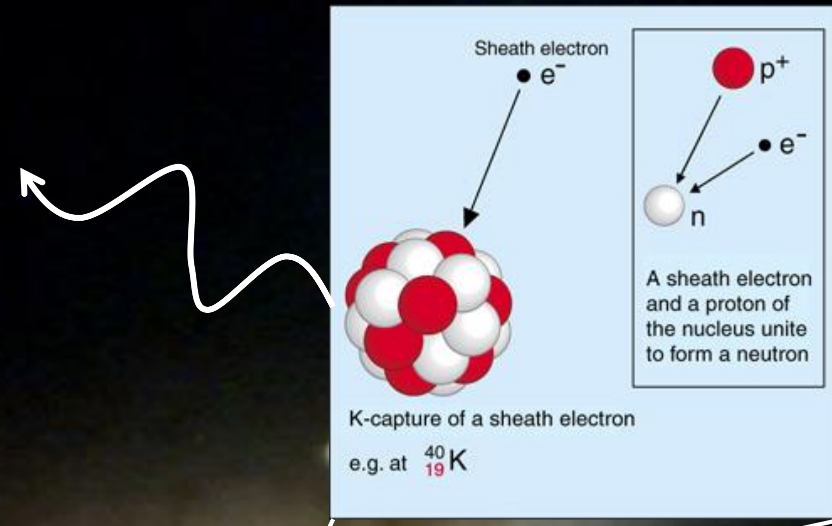


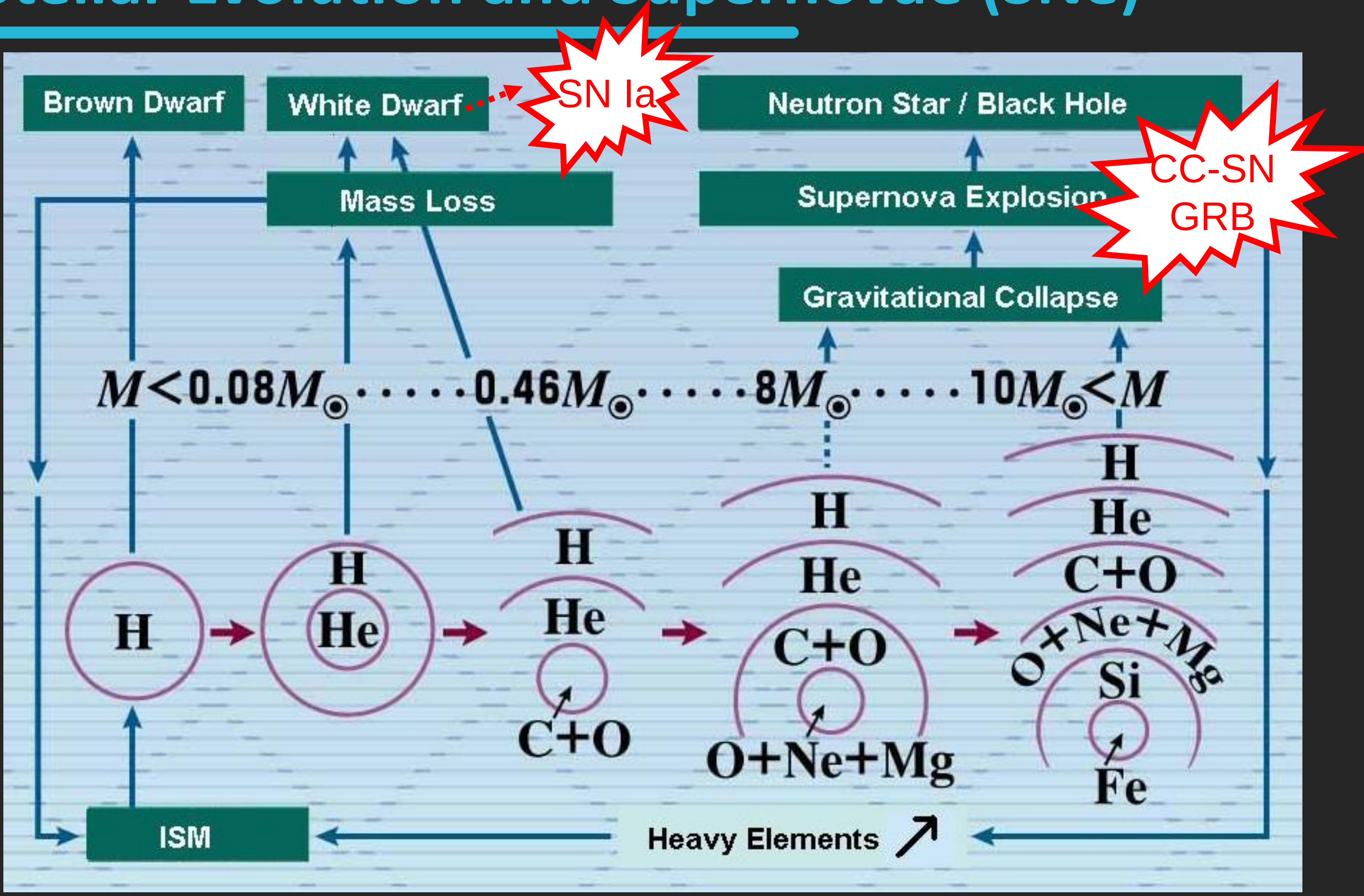
A MeV view on (extragalactic) Supernovae (diagnostics through nucleosynthesis)

前田　啓一（京大・宇物）

Announcement

- A plan for an intensive lecture series by Roland Diehl (MPE, SPI/ITEGARL):
  - At Kyoto, department of astronomy (?).
  - 3 days in the week of 4 – 8 Sep 2017 (?).

Stellar Evolution and Supernovae (SNe)



Contents

- A summary of explosive nucleosynthesis in SNe.
- Why MeV, current status in MeV, and future?
  – Core-collapse SNe.
  – Type Ia Supernovae.

Rough ideas about SNe

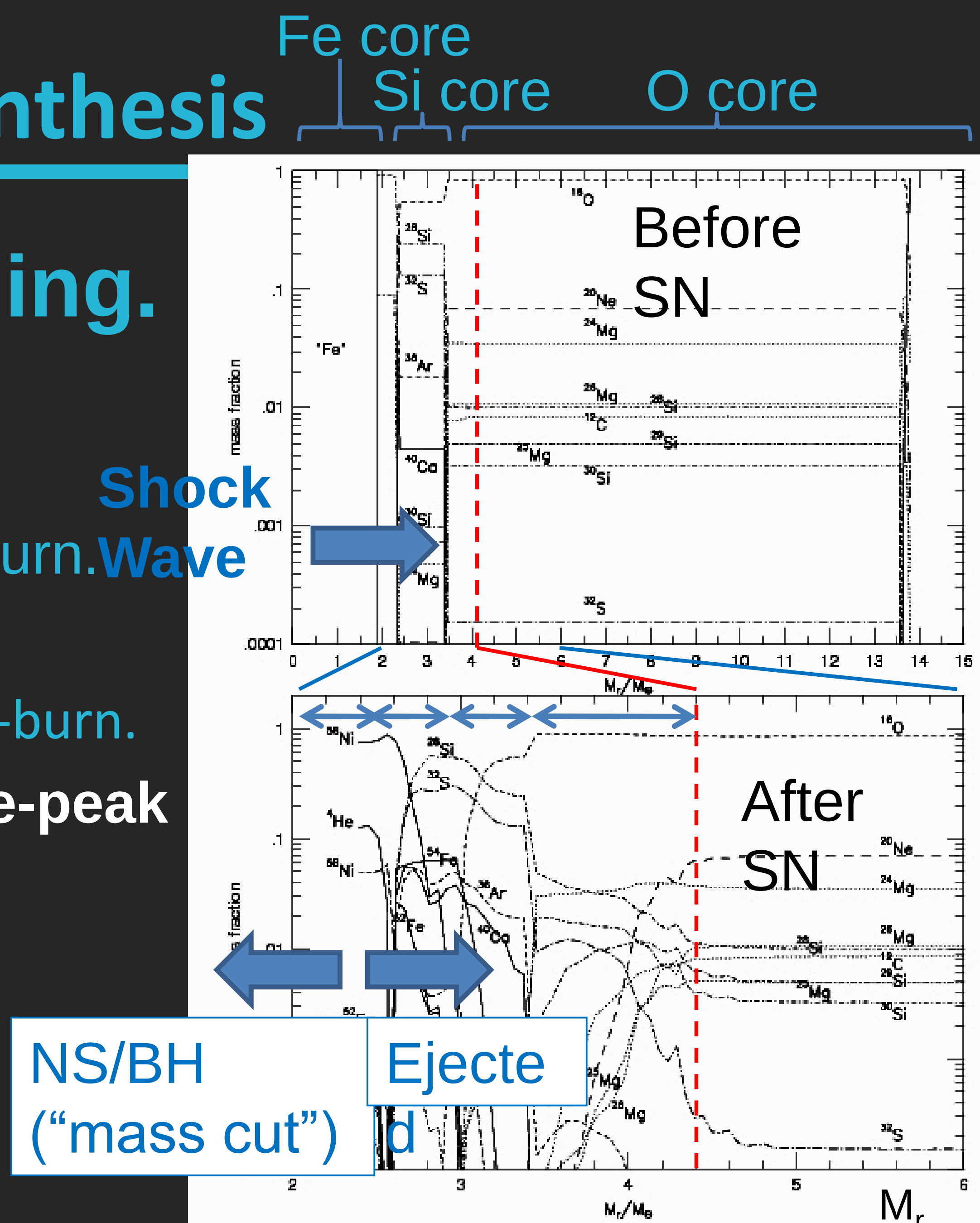
- Core-collapse SNe:
  - Progenitor: Massive stars ($M_{ms} > 8\ M_{\odot}$).
  - Explosion driver: Gravitation & Neutrinos.

- Type Ia Supernovae.
  - Progenitor: massive White Dwarf ($M_{wd} \sim 1.4\ M_{\odot}$).
  - Explosion driver: Thermonuclear runaway.

- In both cases, $E \sim 10^{51}$ erg.
  - $(4\pi/3)R^3aT^4 \sim E \Rightarrow$ **$R \sim (5 - 10) \times 10^8$cm w/ $T > 2 \times 10^9$ K.**

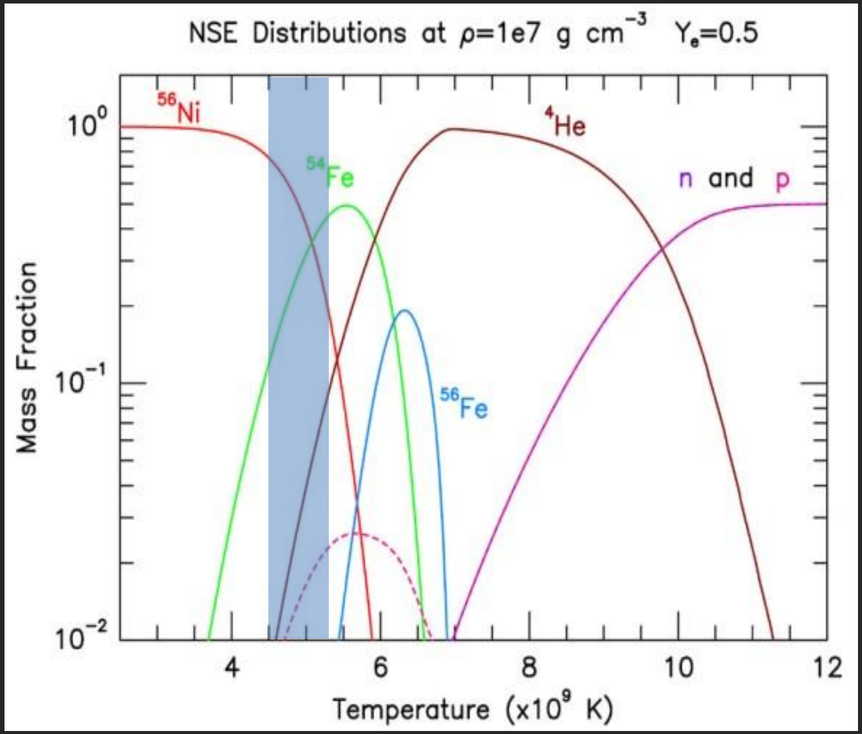
(CC-SN) Nucleosynthesis

- **Explosive burning.**
- **$T \propto (E_K/R^3)^{1/4}$**
  - $T_9 = T/10^9K > 5$: Si-burn.
    ^{56}Ni, He, Fe-peak
  - T_9 = 4-5: incomplete Si-burn.
    Si, S, Fe, Ar, Ca, Fe-peak
  - T_9 = 3-4: O-burn.
    O, Si, S, Ar, Ca
  - T_9 = 2-3: C,Ne-burn.
    O, Mg, Si, Ne



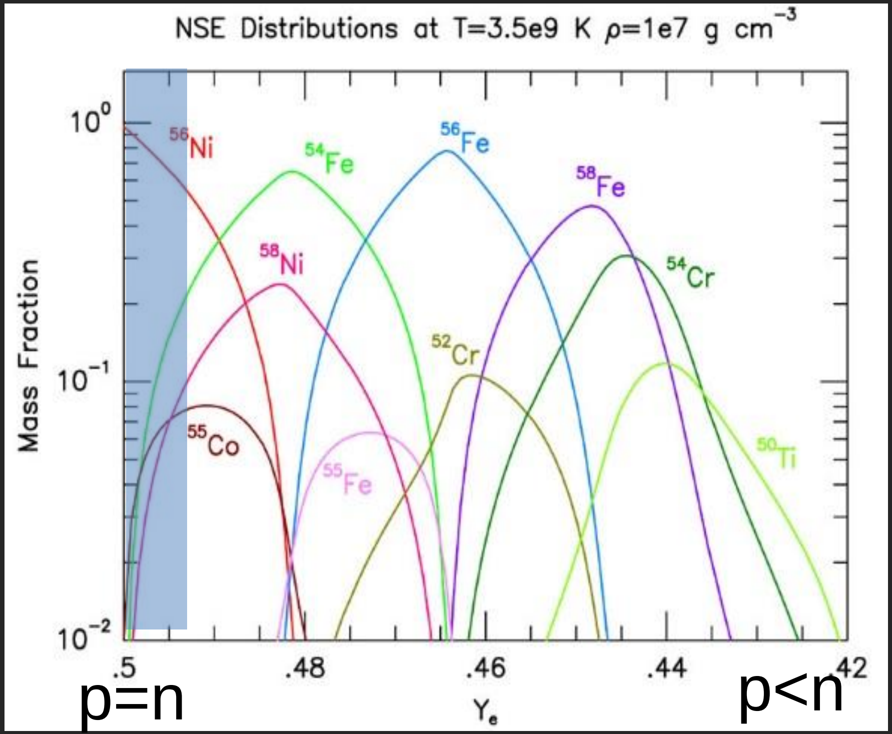
Nuclear Statistical Equilibrium (NSE)

Xi(T) for given ρ, Ye(=0.5)



Temperature given by explosion dynamics

Xi(Ye) for given ρ, T(=3.5 10^{9}K)



Ye given by
(1) Progenitor (before exp.)
(2) weak interaction (dur. exp.)

Important Radioactive Tracer: ^{56}Ni

α-rich freezeout (higher T)

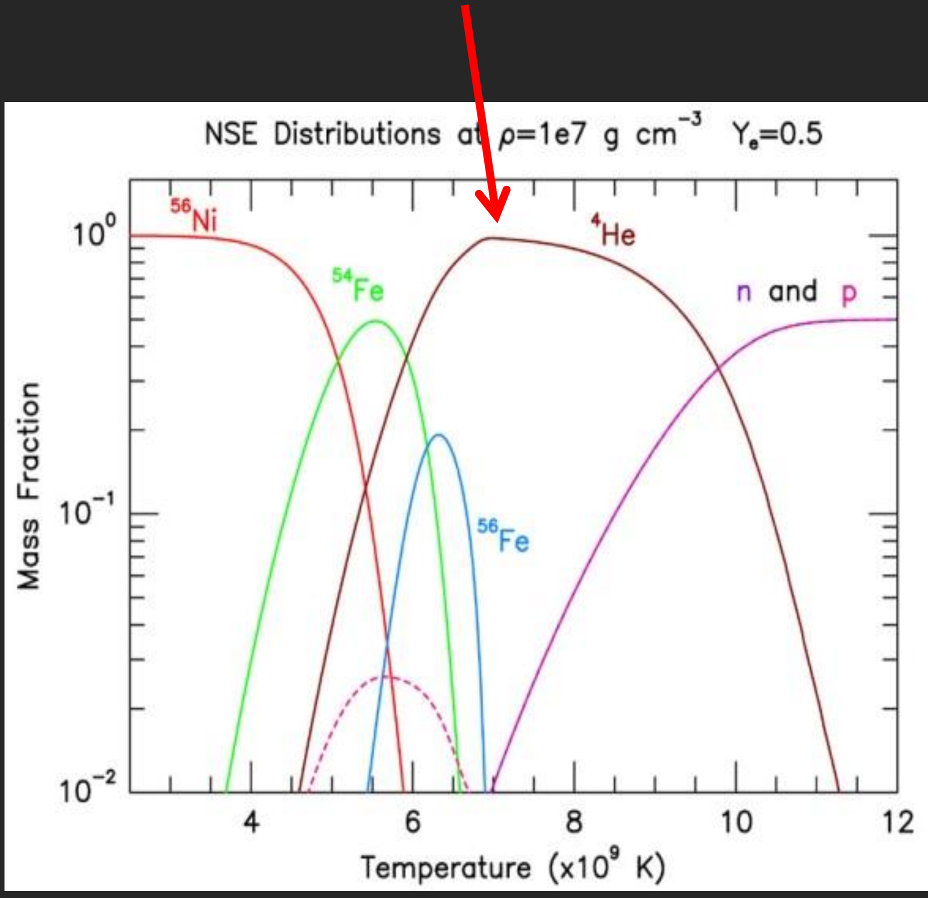
- For high entropy (or high T), triple-α decuples.
  - NSE (Fe-peaks) + α left after the “freezeout”.
- α eventually captured

by heavy (NSE) elements.

$^{40}\mathrm{Ca} \Rightarrow {}^{44}\mathrm{Ti} \Rightarrow {}^{48}\mathrm{Cr} (\rightarrow {}^{48}\mathrm{Ti})$

$\searrow {}^{44}\mathrm{Ca}$

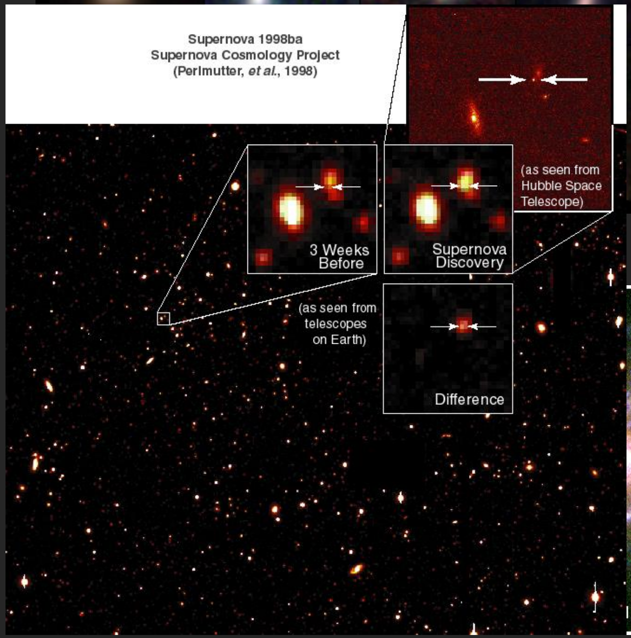
$^{56}\mathrm{Ni} \Rightarrow {}^{60}\mathrm{Zn} \Rightarrow {}^{64}\mathrm{Ge} (\rightarrow {}^{64}\mathrm{Zn})$

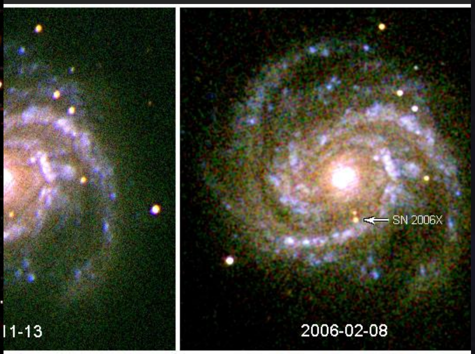


Sensitive to exp. Mech.

Important Radioactive Tracer: $^{44}\mathrm{Ti}$

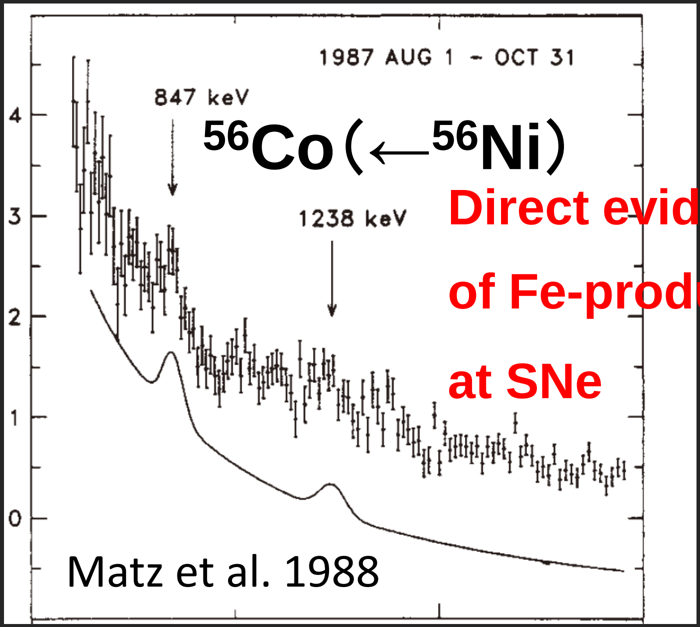
Extragalactic Supernovae
(> Mpc, days to yrs)



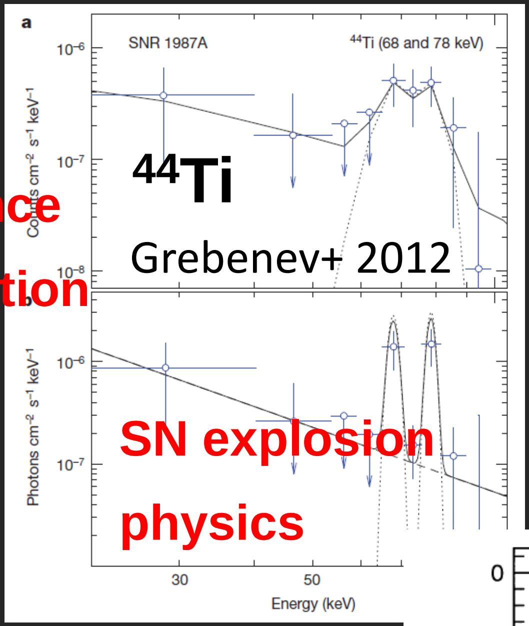


Supernova Radioactivity before 2014

One and only (as extragalactic) = SN 1987A.

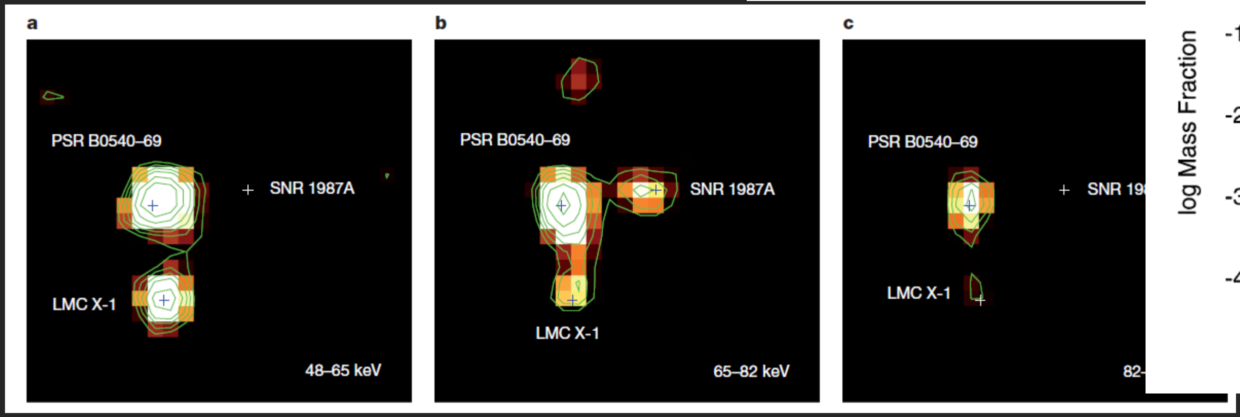


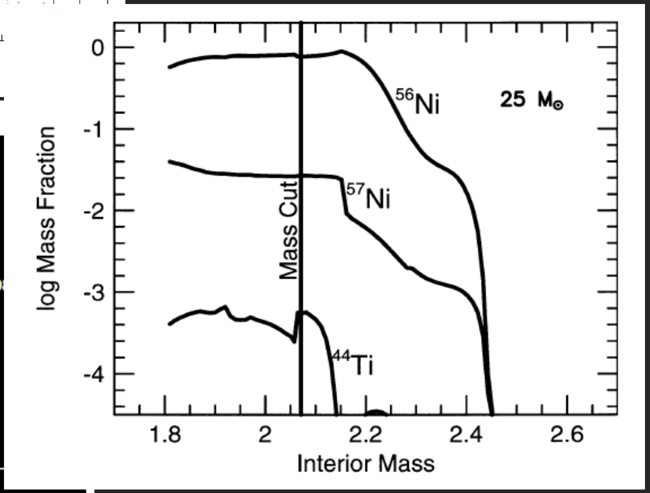
Direct evidence of Fe-production at SNe



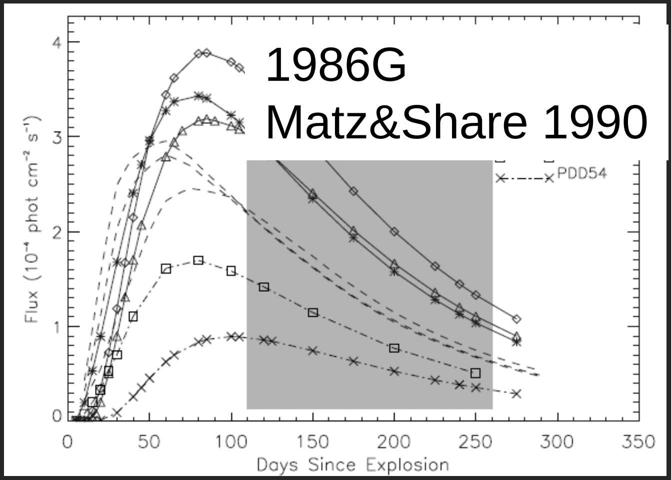
SN explosion physics

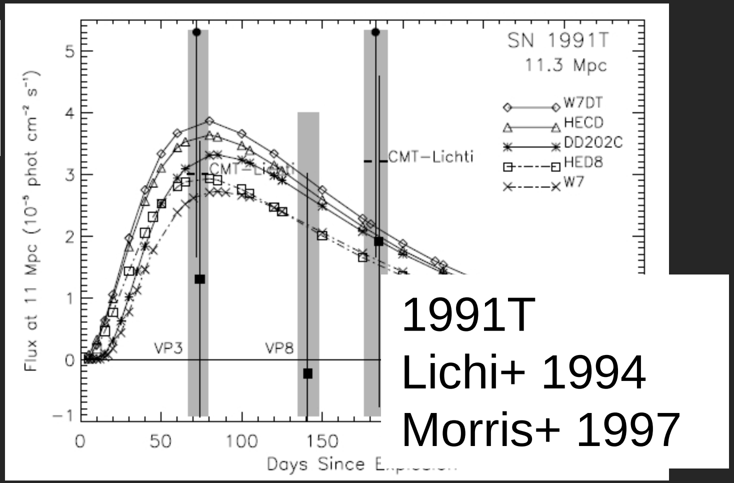
Massive star
→ gravitational collapse
→ NS/BH + core-collapse (CC) SNe

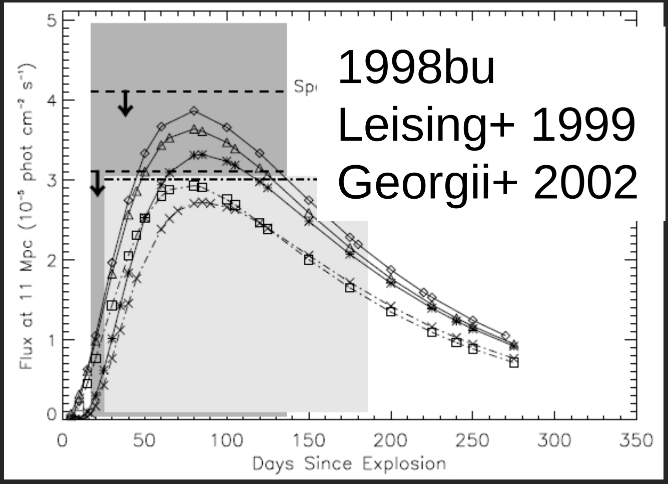




Supernova Radioactivity before 2014







(Chandrasekhar) WD
→ thermonuclear runaway→ SNe Ia

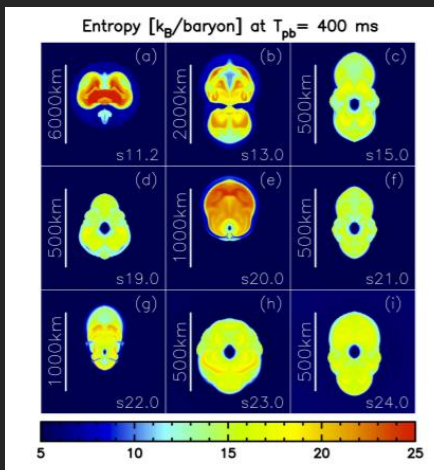
+ SN 2011fe @ 6.4 Mpc
(INTEGRAL, 4 Ms)
= 4 upper limits for SNe Ia

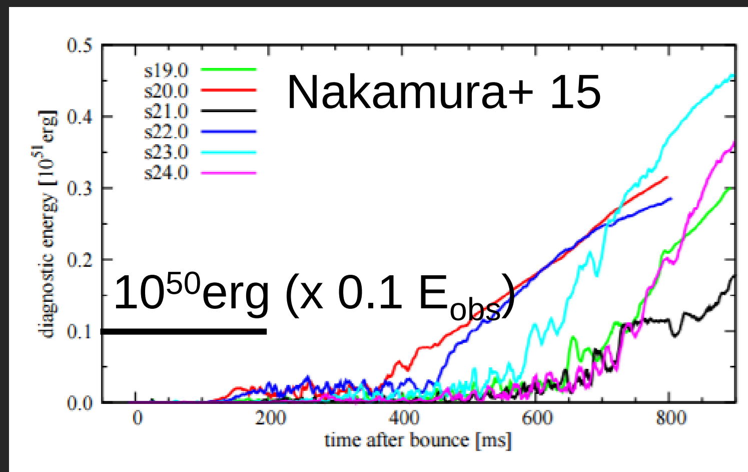
No solid case

 # SN Ia cosmology relies on
^{56}Ni production（γ→optical）

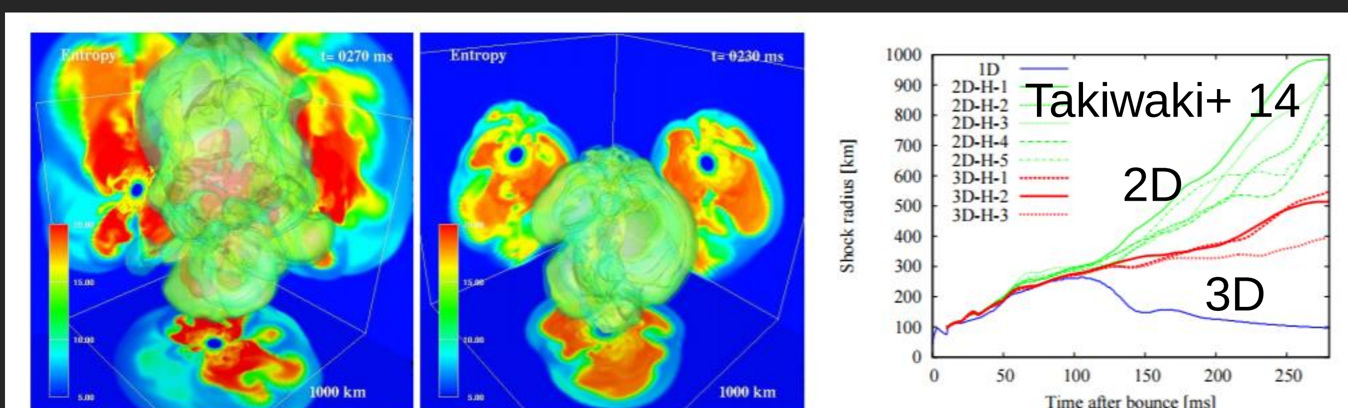
CC SN problem: Explosion Mechanism

Core-collapse induced explosions of massive stars (>8-10$M_{\odot}$)





Standard delayed-ν explosion seems to be working.

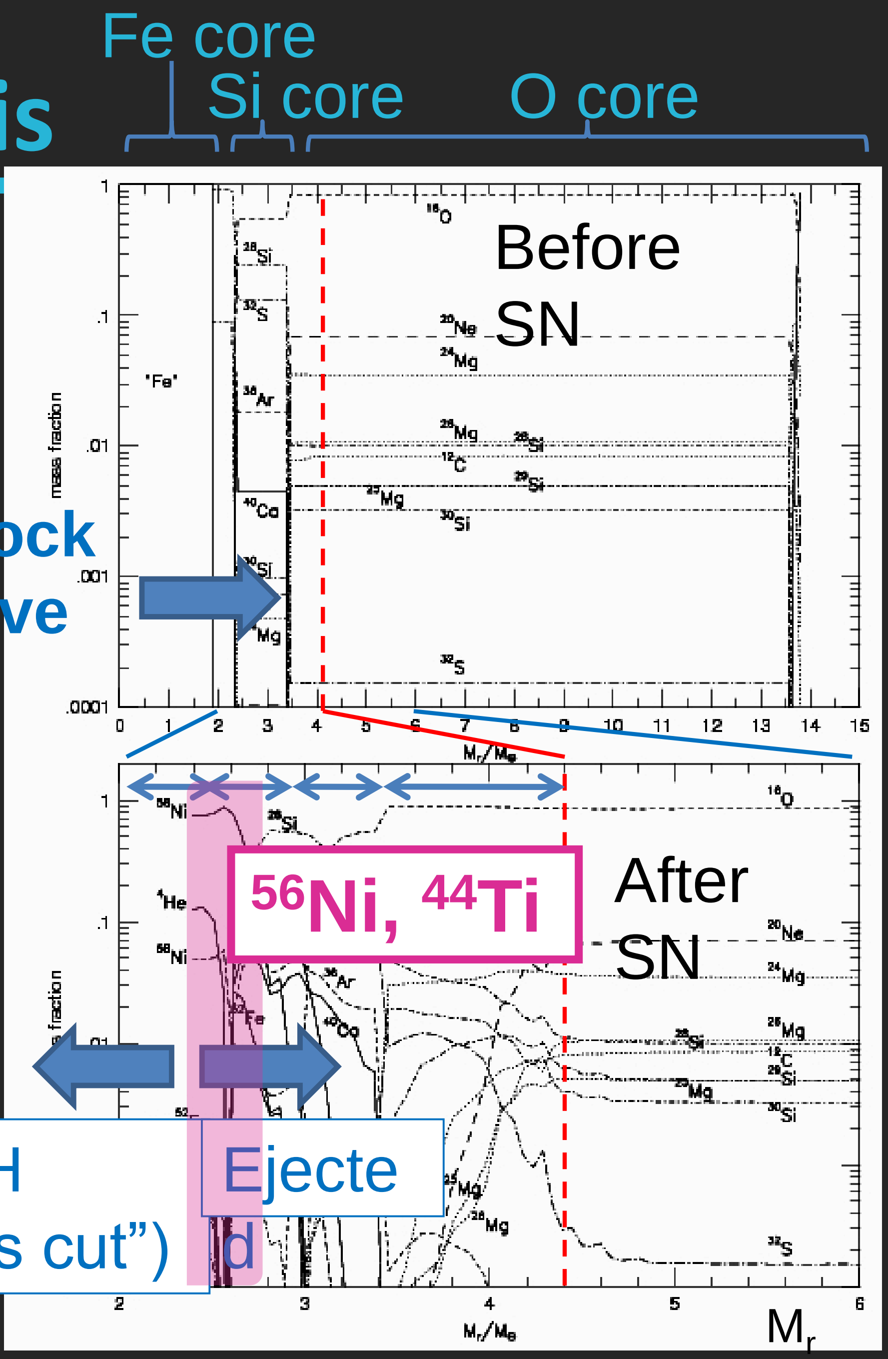


Not yet fully understood. Not at the level to represent real SNe.

The explosion mechanism is still an unresolved big issue.

CC-SN Nucleosynthesis

- **Explosive burning.**
  - **$T \propto (E_K/R^3)^{1/4}$**
    - $T_9 = T/10^9K > 5$: Si-burn.
      ^{56}Ni, He, Fe-peak
    - T_9 = 4-5: incomplete Si-burn.
      Si, S, Fe, Ar, Ca, Fe-peak
    - T_9 = 3-4: O-burn.
      O, Si, S, Ar, Ca
    - T_9 = 2-3: C,Ne-burn.
      O, Mg, Si, Ne



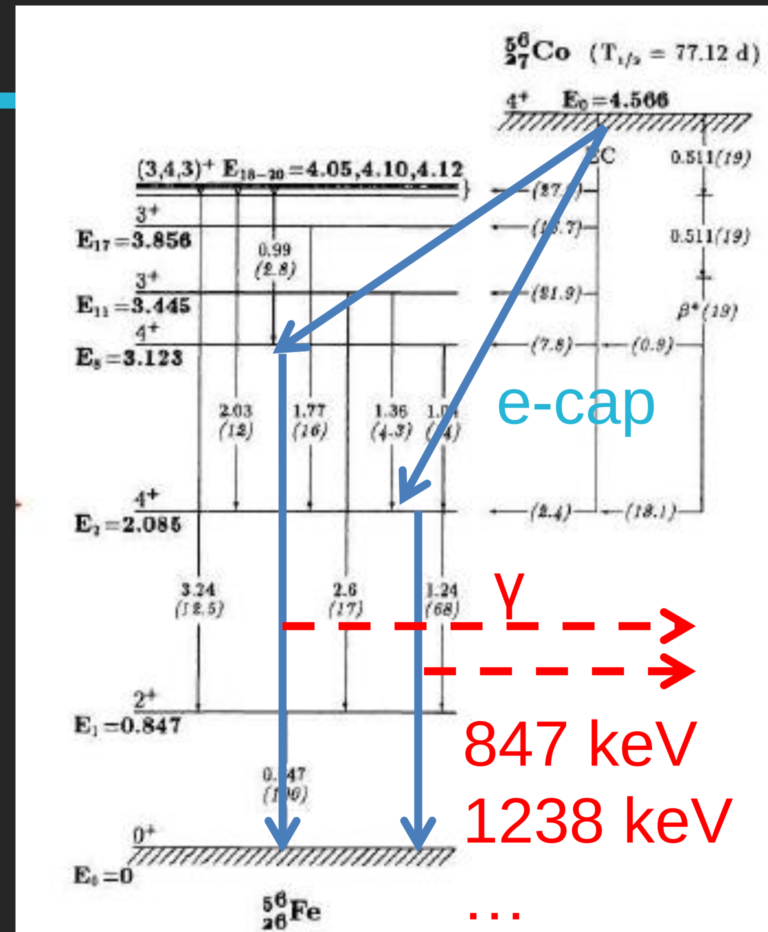
^{56}Ni→Co→Fe

- ~ 0.6 M$_\odot$ in each SN Ia.
- ~ 0.1 M$_\odot$ in each CC-SNe.
- ^{56}Ni→^{56}Co→^{56}Fe.
  ~1 week ~100 days

$$L_{\rm peak} \approx 7.8 \times 10^{43}\ M_{56{\rm Ni},\odot} \exp\left(\frac{-t_{\rm peak}}{8.8\ {\rm days}}\right)\ {\rm erg\ s^{-1}}$$

$$L_{\rm tail} \approx 1.3 \times 10^{43}\ {\rm erg\ s^{-1}}\, M_{56{\rm Ni},\odot} \times (\tau_\gamma + 0.035 f_{e+}) \exp\left(\frac{-t_{\rm tail}}{113.5\ {\rm days}}\right)$$

^{56}Fe ^{56}Co



Weeks — MeV → Optical

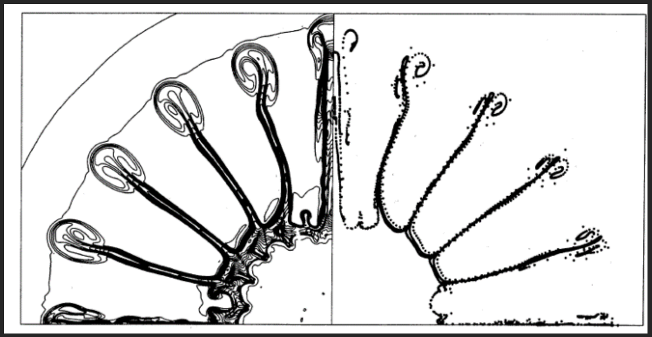
Expansion

Density↓

Months — MeV →

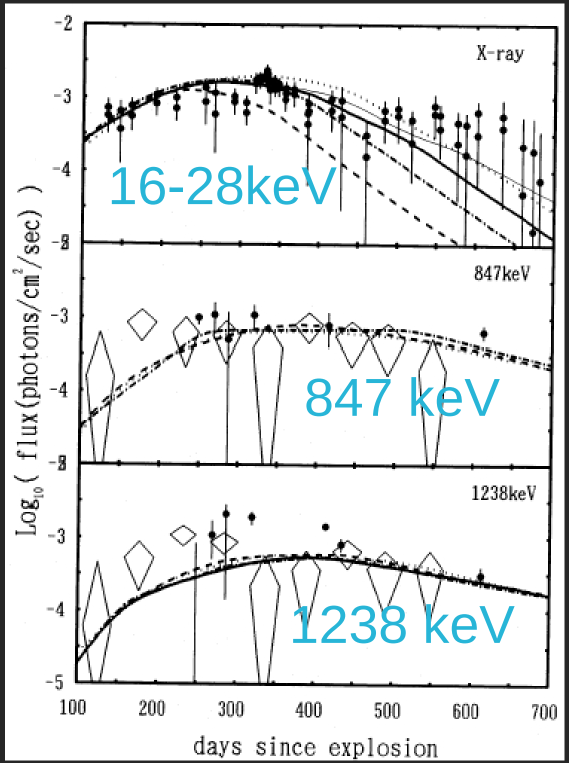
Radioactivity: SN 1987A

- $M(^{56}Ni) \sim 0.07 M_\odot$
- $M(^{57}Ni)/M(^{56}Ni) \sim 1.5\ [X(^{57}Fe)/X(^{56}Fe)]_\odot$
- $M(^{44}Ti)/M(^{56}Ni) < \sim 2.9\ [X(^{44}Ca)/X(^{56}Fe)]_\odot$



Hachisu+ 1992

Kumagai+ 93

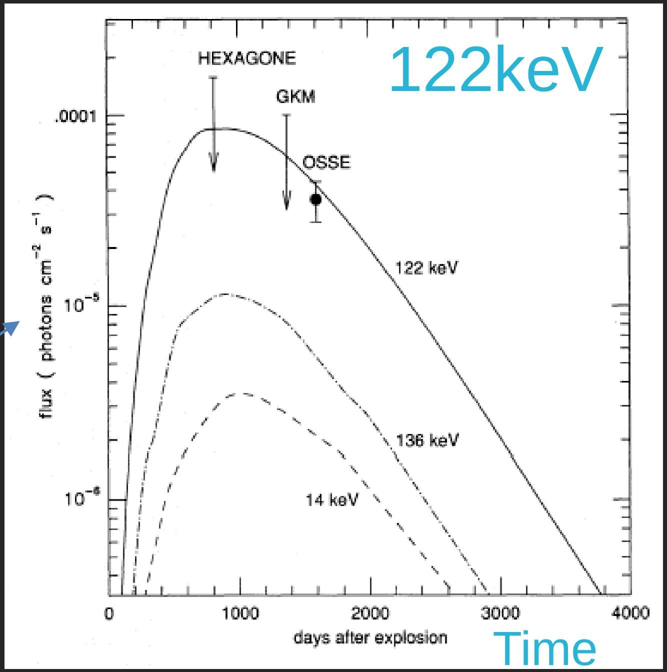


Kumagai+ 1989

^{56}Co/Fe

^{57}Co/Fe

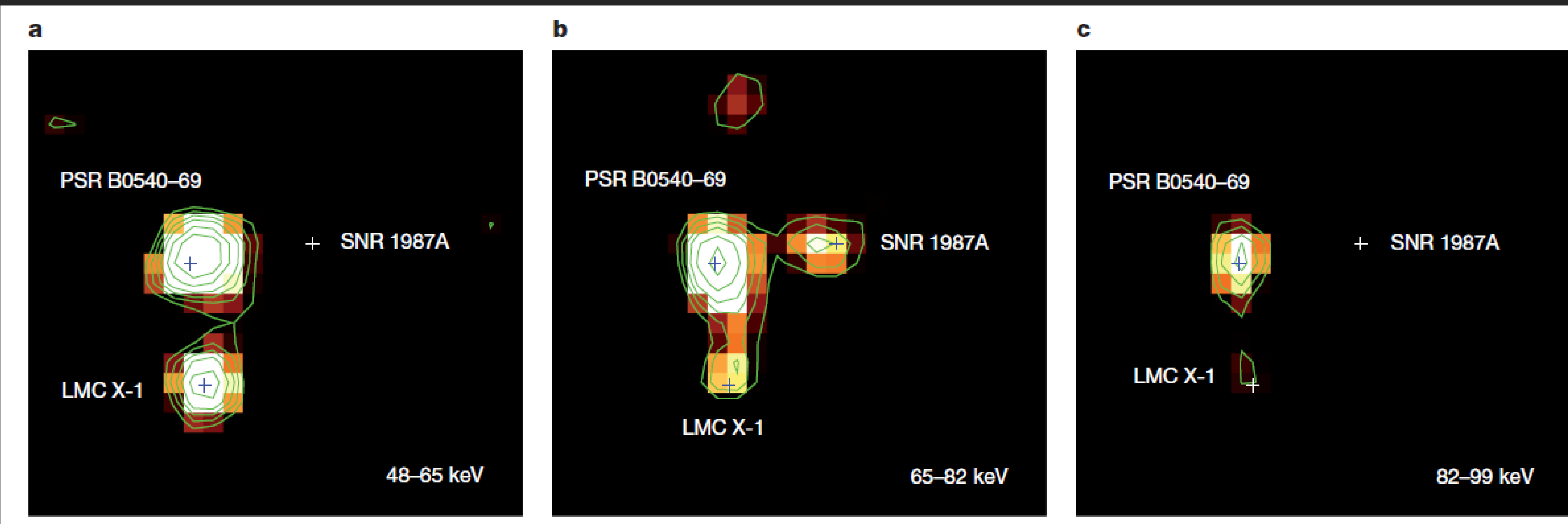
Time
(100 – 700 day)

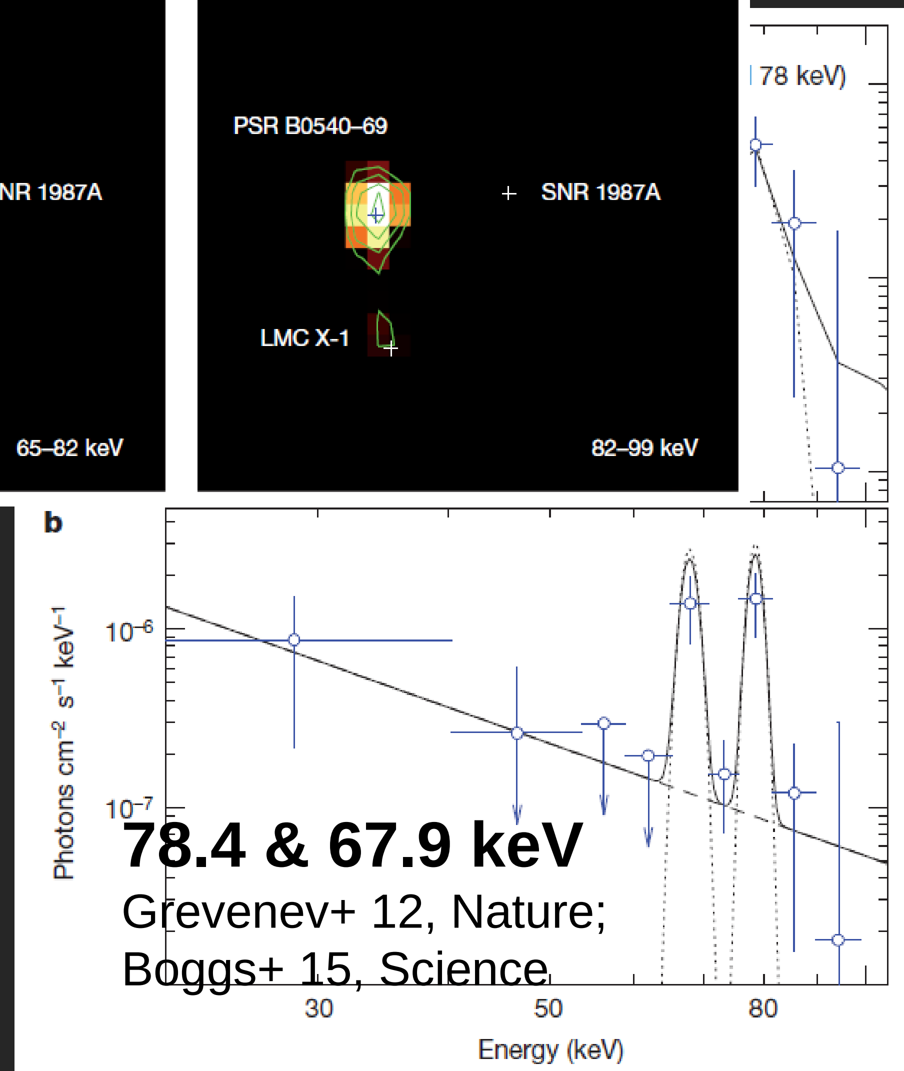


Time
(0 - 4000 day)

New insights: e.g., need for hydro mixing (pure 1D models too opaque).

Radioactive ^{44}Ti γ-rays from SN 1987A

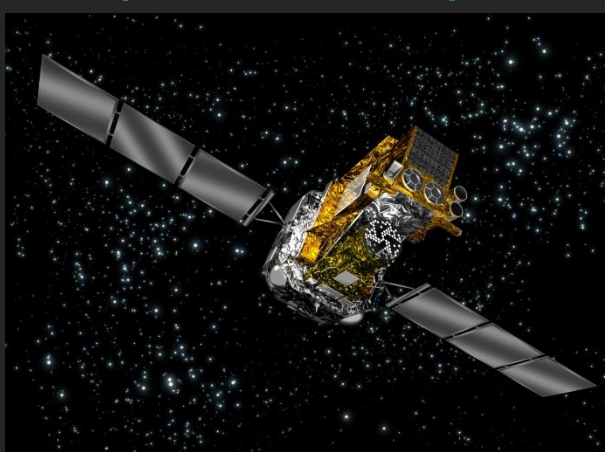




78.4 & 67.9 keV

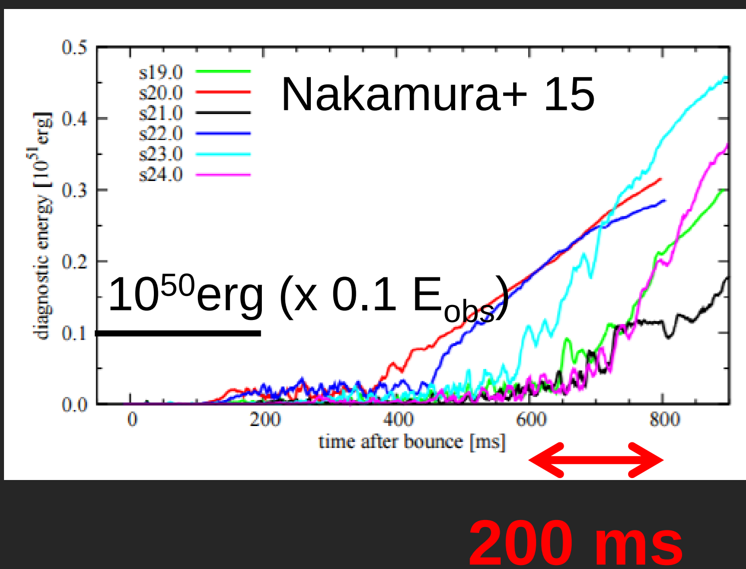
Grevenev+ 12, Nature;
Boggs+ 15, Science

^{44}Ti (INTEGARL)



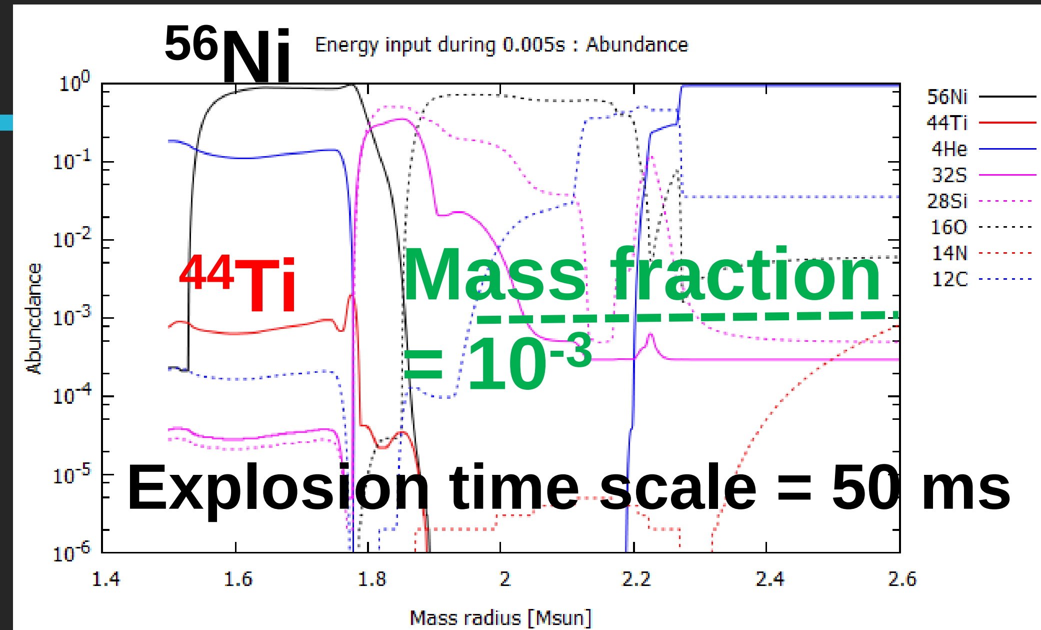
New Diagnostics to investigate

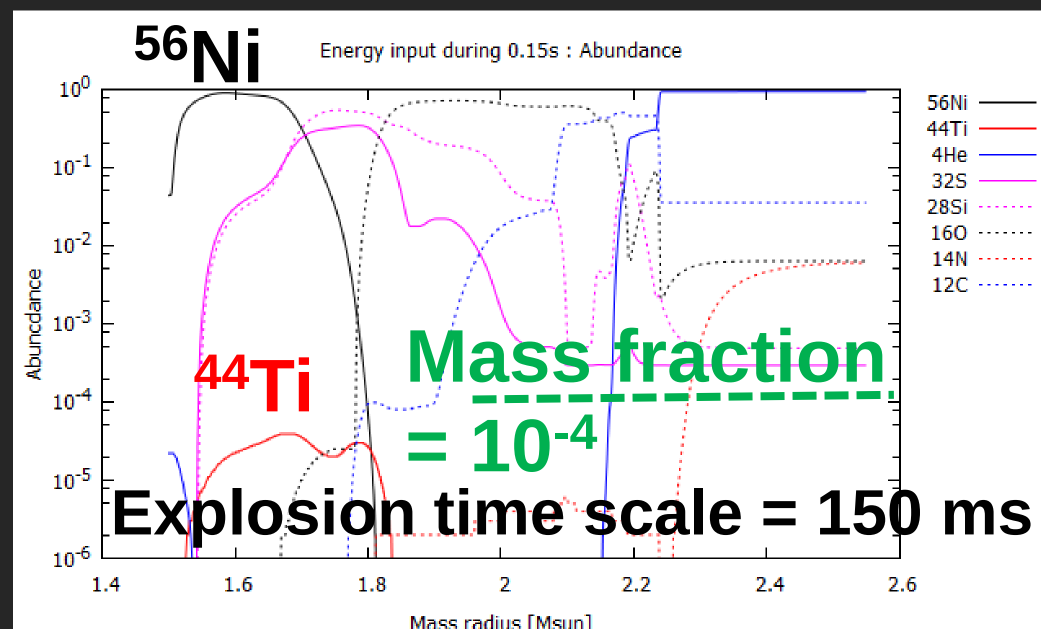
Explosion time scale may not be negligible.
⇒ **nucleosynthesis?**



Sensitively affects the radioactive isotopes.

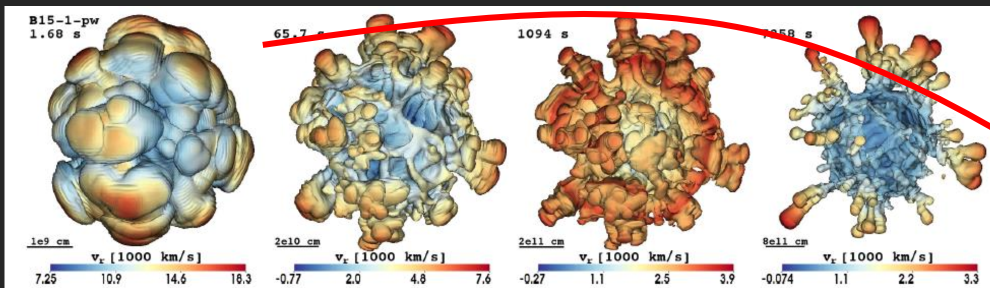
Sawada+ (master thesis)





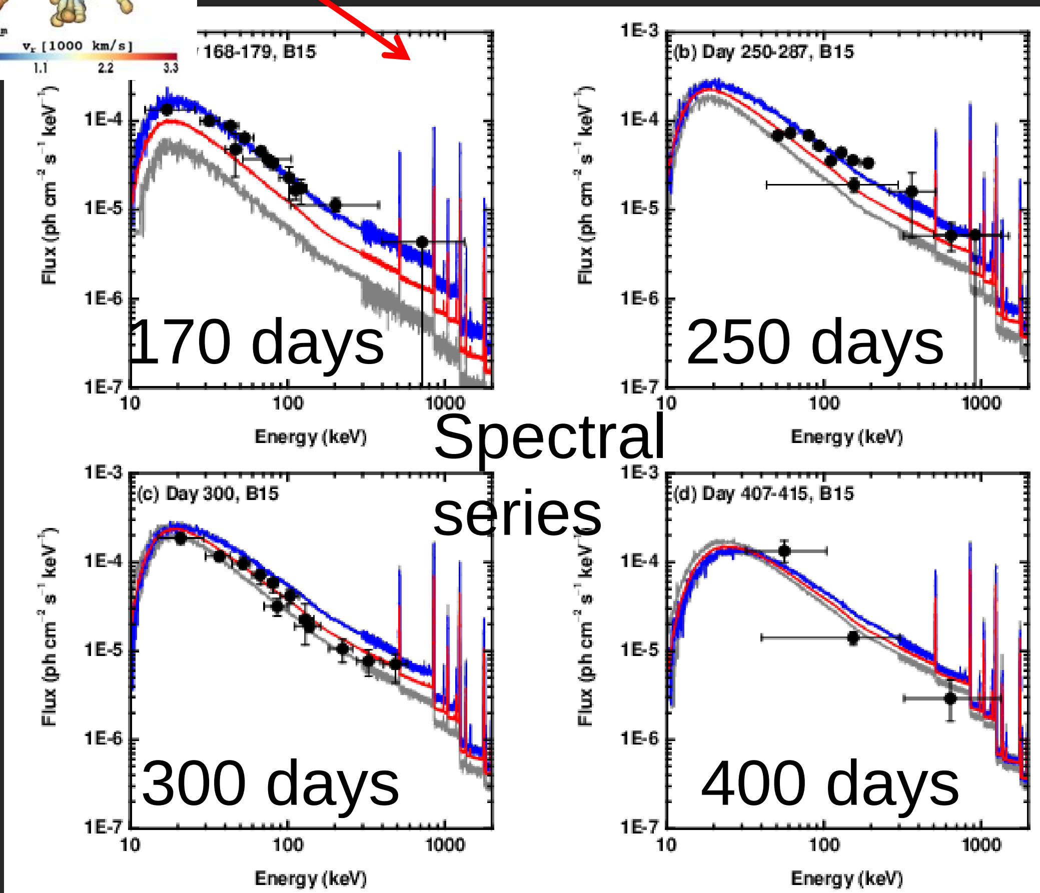
New Diagnostics to investigate

Radiation transfer for
v-driven 3D models
(KM, Wongwathanarat+,
in prep.)



1 sec

1000 sec



170 days

250 days

Spectral series

300 days

400 days

Gamma-ray signals well explained **w/o posteriori fine-tuning.**

Ready to provide theoretical signals for state-of-the-art models.

Future…?

Unfortunately, core-collapse SNe are not that bright in MeV.

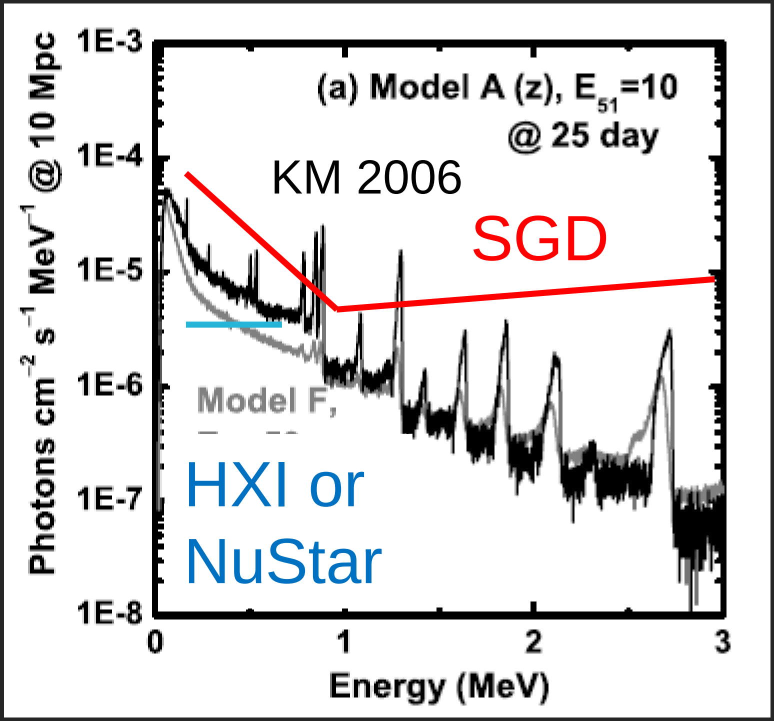
Astro-H/SGD-like or NuStar horizon

($^{56}Ni \Rightarrow ^{56}Co$ 128 keV+hard X cont.) : ~ weeks

Type IIb/Ib/Ic < ~5 Mpc… rare (once in a decade or two),

but…SN 2016adj @ Cen A (3.8 Mpc)

Hard X contaminated…



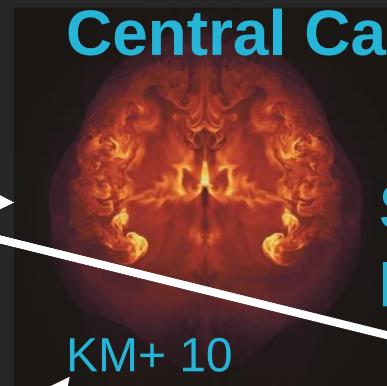
SNe Ia problem: Progenitor and explosion

- Explosion mechanism (multiple paths?).
- **Progenitor systems.**

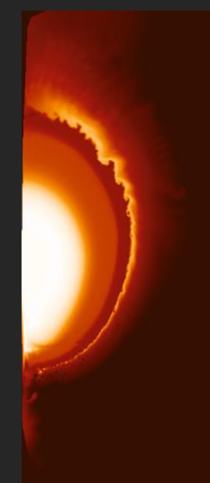
Single Degenerate (SD)

Double Degenerate (DD)

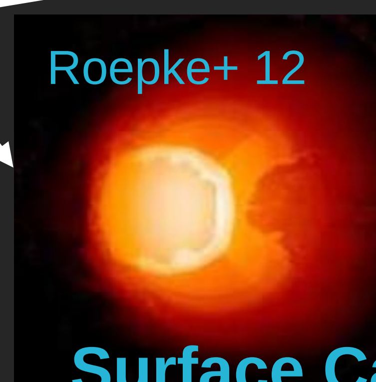
Central Carbon ignition



Surface Helium Ignition

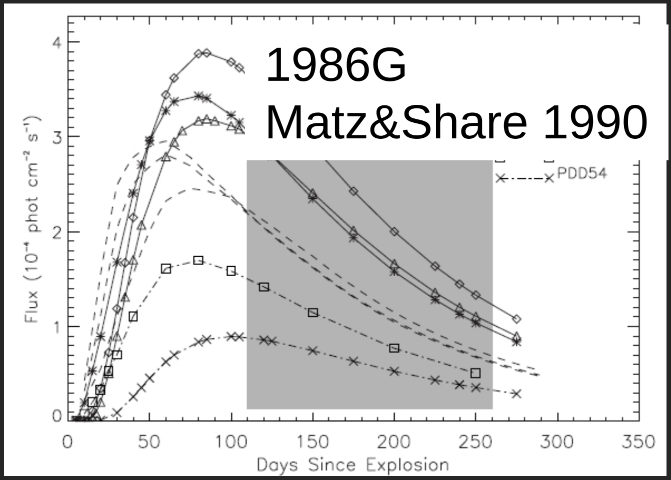


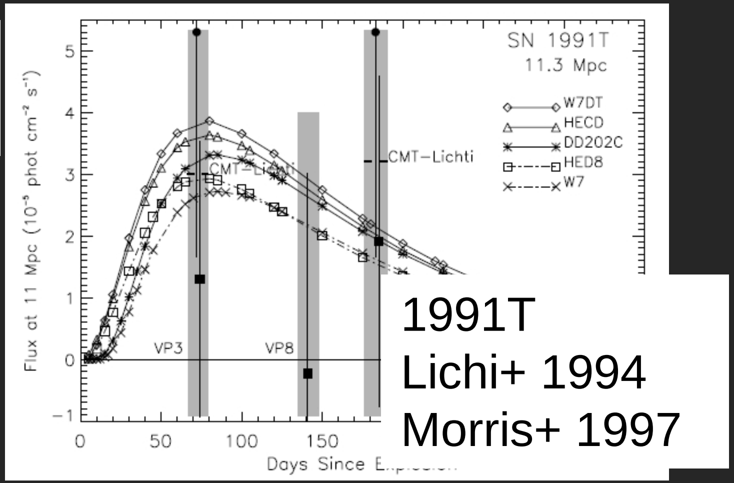
Fink+ 10

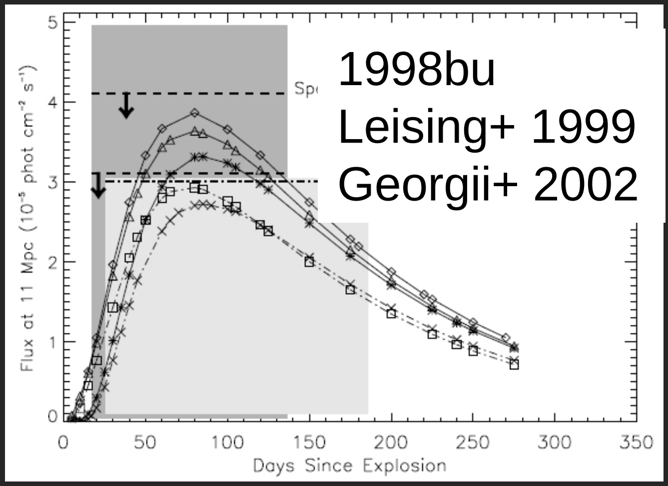


Surface Carbon Ignition

Supernova Radioactivity before 2014







(Chandrasekhar) WD
→ thermonuclear runaway→ SNe Ia

+ SN 2011fe @ 6.4 Mpc
(INTEGRAL, 4 Ms)
= 4 upper limits for SNe Ia

No solid case

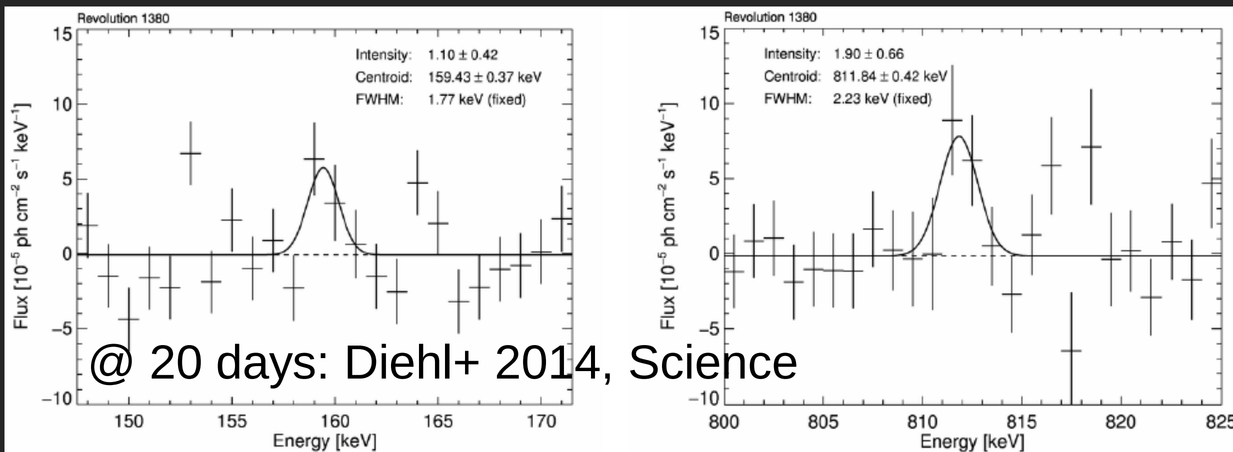
 # SN Ia cosmology relies on ^{56}Ni production（γ→optical）

INTEGRAL detection of MeV γ from SN Ia 2014J (~ 6 Ms in total)

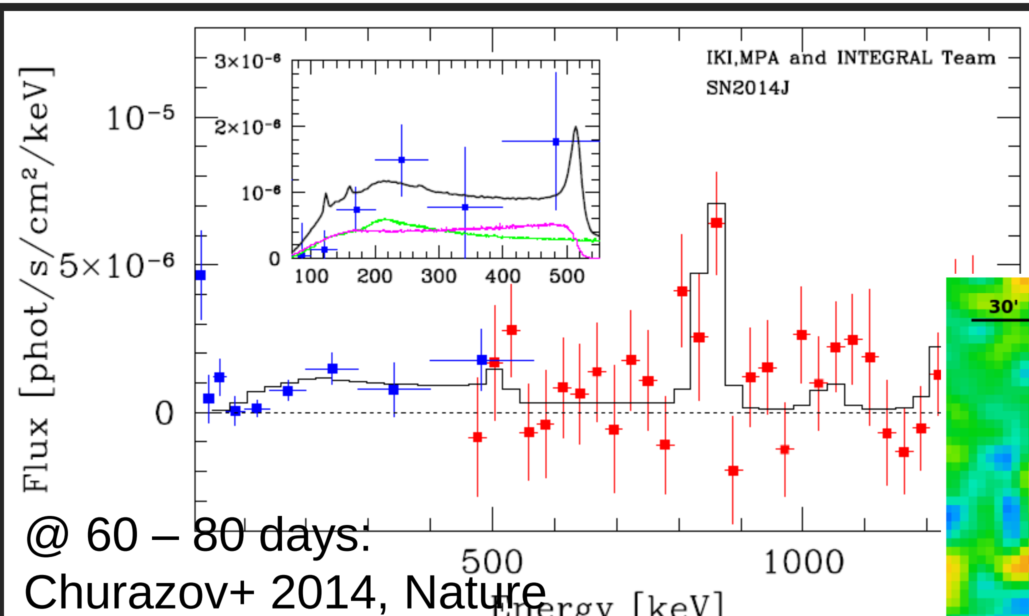
Supernova Radioactivity in 2014

日経（8/1）

SN Ia 2014J
@M82
Most nearby
SN Ia
since 1986

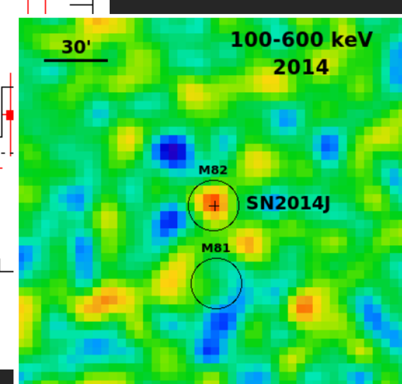


@ 20 days: Diehl+ 2014, Science



@ 60 – 80 days:
Churazov+ 2014, Nature

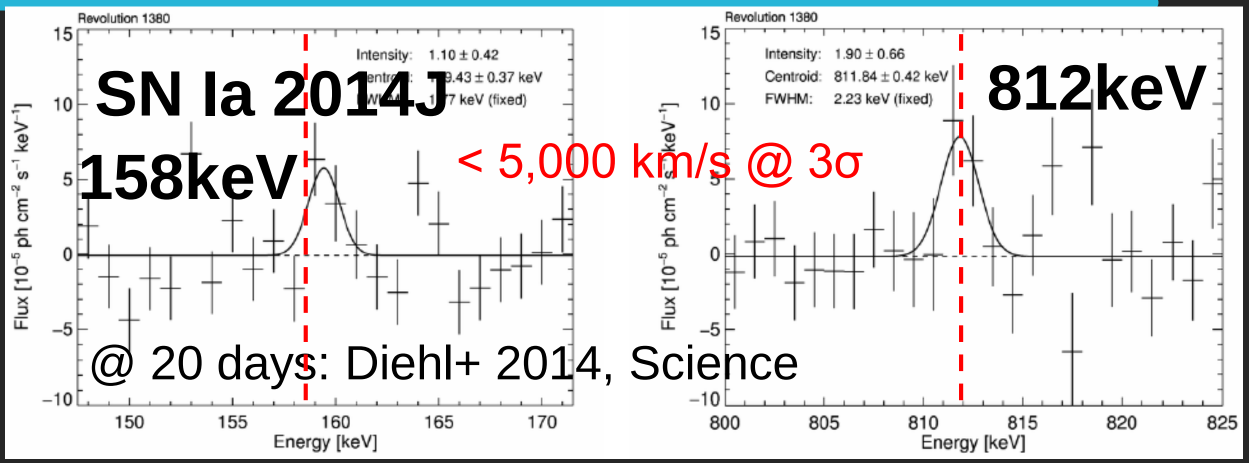
The first detection of ^{56}Ni/Co decays from SNe Ia.



Confirmation of basic concept of thermonuclear explosion, **but…**

Seen both in IBIS and SPI
SPI analyzed by two independent groups

Diagnostic Power: SN explosion physics



Challenge to theories

Early emergence

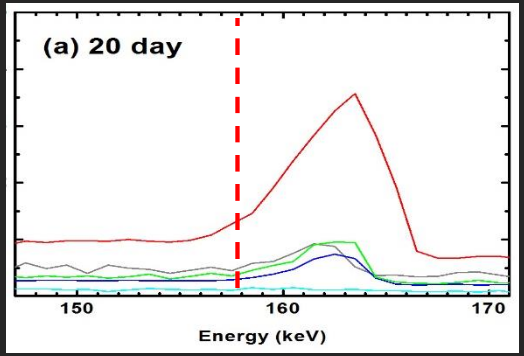
Small Doppler shift

⇒ Suggested scenario

WD + He donor

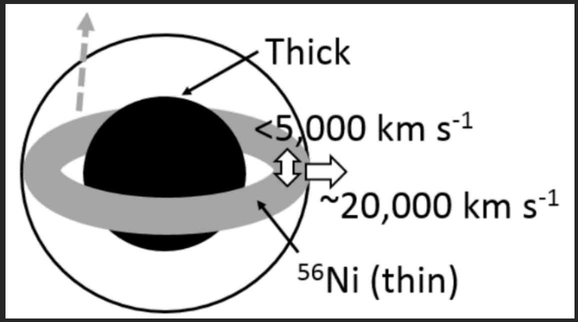
Surface He ignition

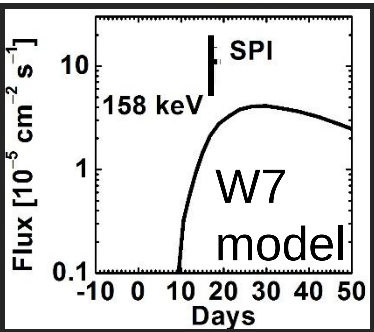
(**not** a leading model!)



Model Prediction

KM, Terada+ 2012





MeV, that unique

SN 2014J looks like quite normal in optical.

- The model applies to SNe Ia in general?
- Variations even if optical is identical?

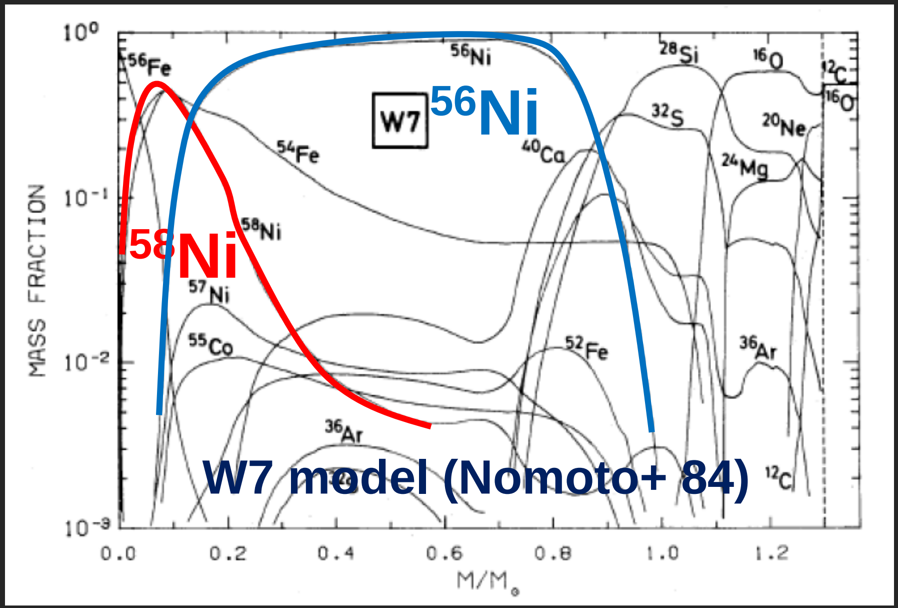
⇒ Need at least another few SNe detected.

SN 2014J: Suzaku ToO observation

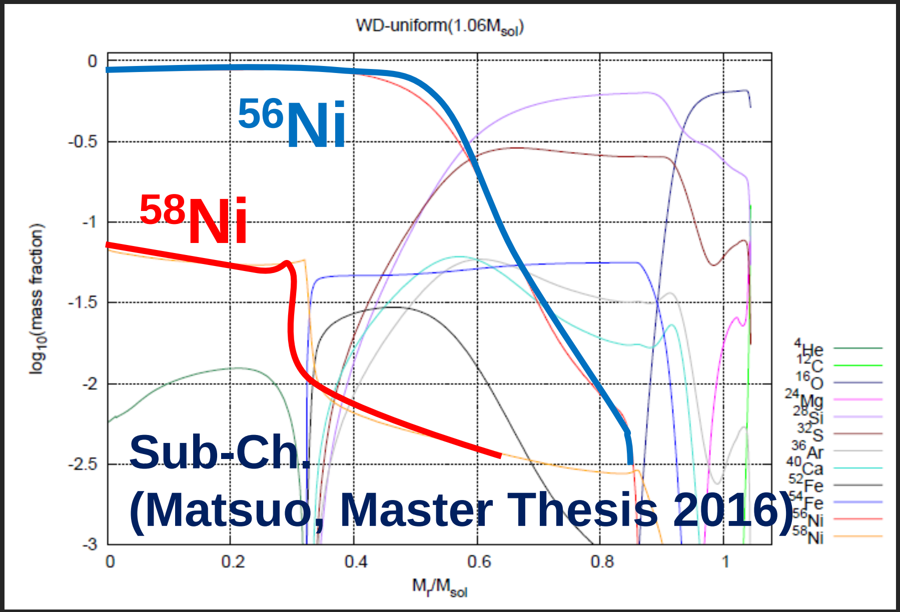
- See Terada-san's talk.

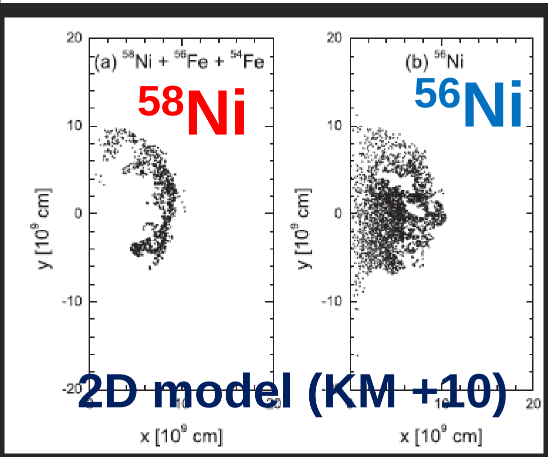
Diagnostics: Chandrasekhar or sub-Ch. WD?

Chandrasekhar WD



Sub-Chandrasekhar WD





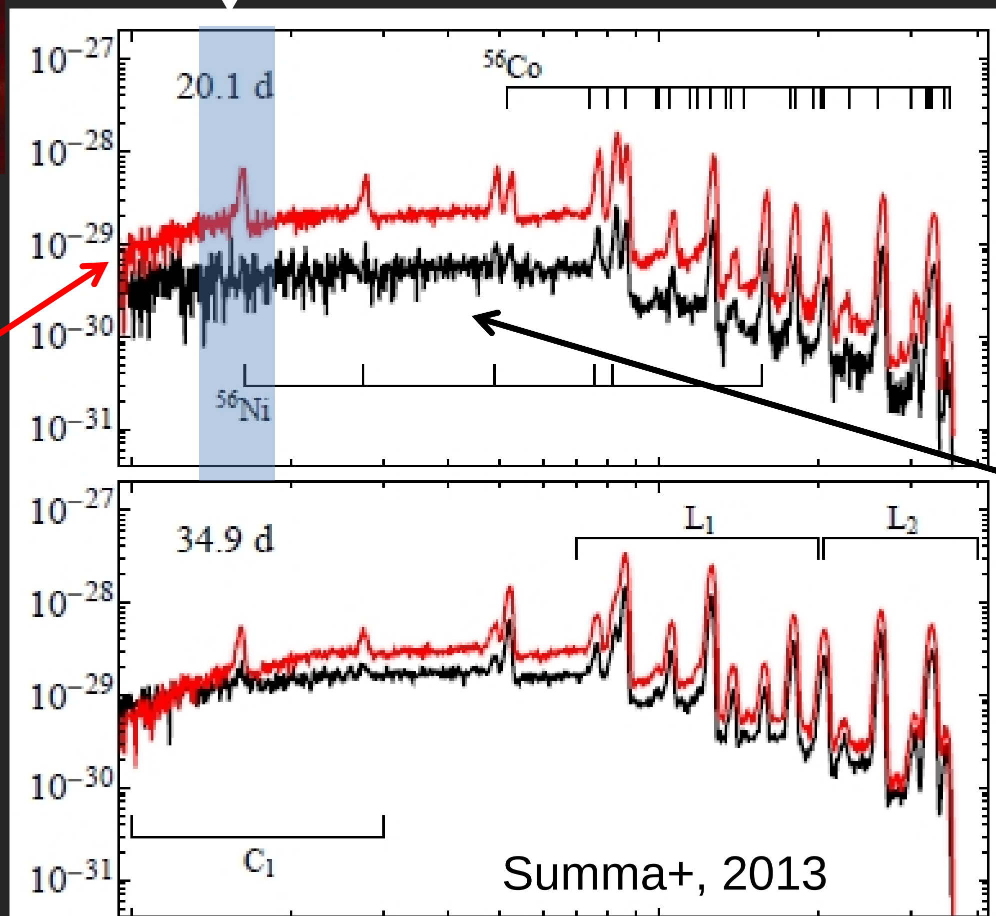
Cf. Shigeyama+92, Sim+ 10, Woosley+ 11

^{56}Ni mass and distribution

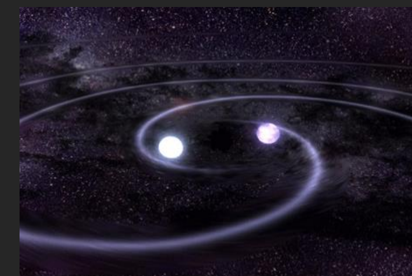
(also comparison to ^{58}Ni - optical)

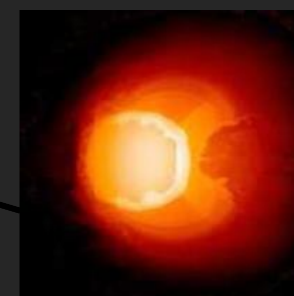
Diagnostic Power: SN progenitor

^{56}Ni decay, 158 keV



Popular model:
WD + MS/RG
Central ignition



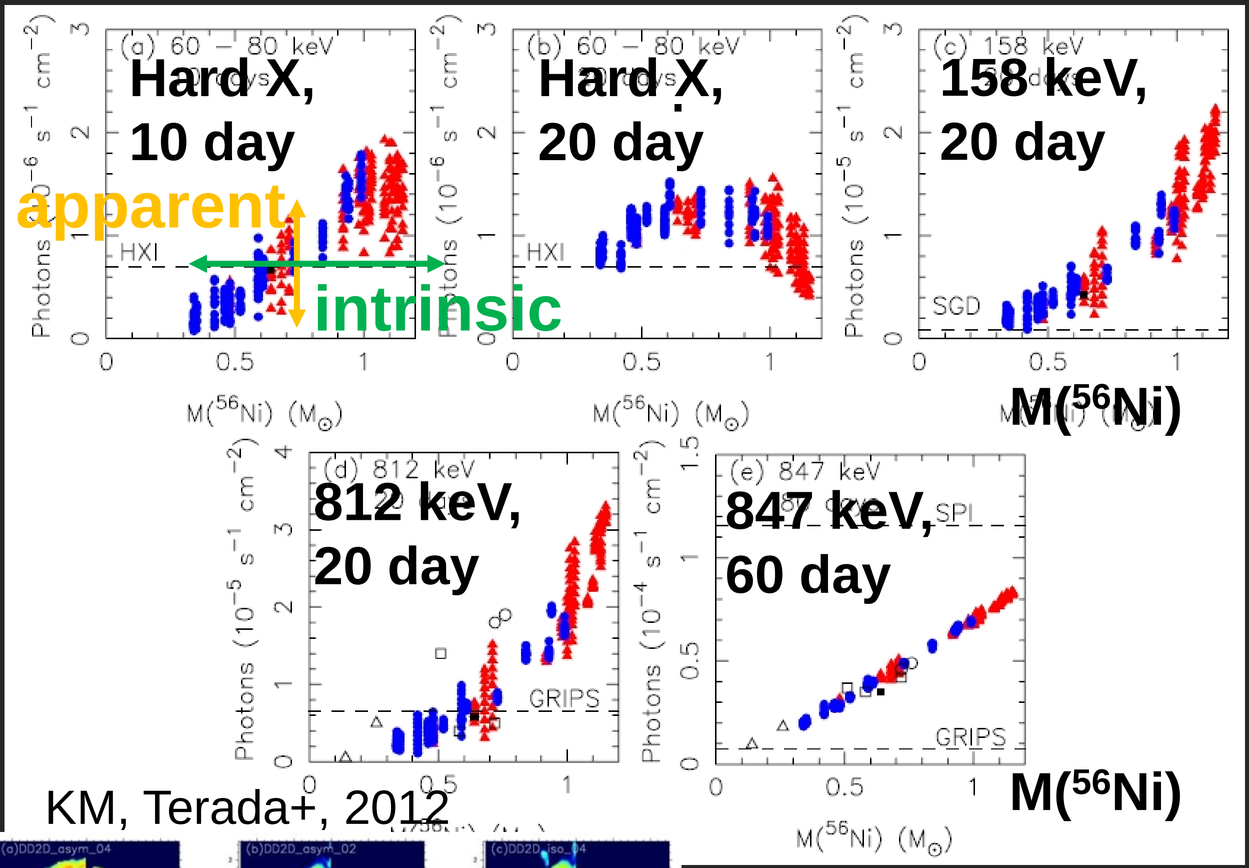


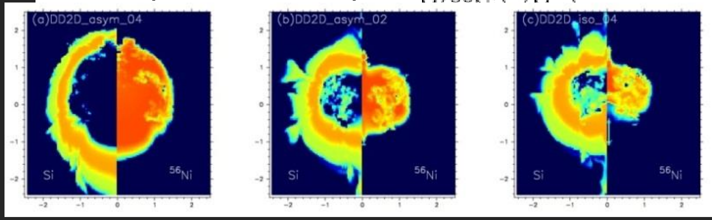
Popular model:
WD + WD
Surface ignition

A hope for ETC (Tanimori-san)

Diagnostics: SN Diversity and populations

Example: Ch.-WD central ignition w/ various explosion scale and asymmetry





1 M sec @ 10 Mpc

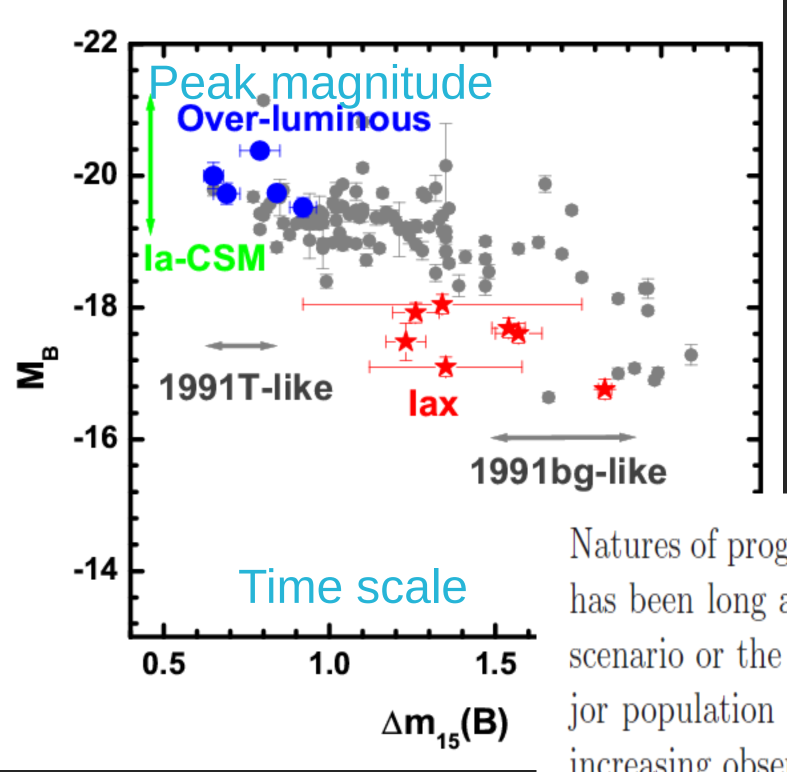
Different Models

⇒ Intrinsic variation (exp. strength) + Apparent variation (viewing direction)

⇒ Different distribution in flux and evolution.

⇒ 10 SNe to pick up the “dominant” scenario, more to identify relative contribution.

Understanding the origin of diversity



KM & Terada 2016

SNe Ia may likely come from multiple progenitor paths / explosion modes.

⇒ MeV follow-up (clear window for progenitors) not only for normal, but for outliers.

Natures of progenitors of type Ia Supernovae (SNe Ia) have not yet been clarified. There has been long and intensive discussion on whether the so-called single degenerate (SD) scenario or the double degenerate (DD) scenario, or anything else, could explain a major population of SNe Ia, but the conclusion has not yet been reached. With rapidly increasing observational data and new theoretical ideas, the field of studying the SN Ia progenitors has been quickly developing, and various new insights have been obtained in recent years. This article aims at providing a summary of the current situation regarding the SN Ia progenitors, both in theory and observations. It seems difficult to explain the emerging diversity seen in observations of SNe Ia by a single population, and we emphasize that it is important to clarify links between different progenitor scenarios and different sub-classes of SNe Ia.

Sensitivity curve from Takahashi SPIE 2010

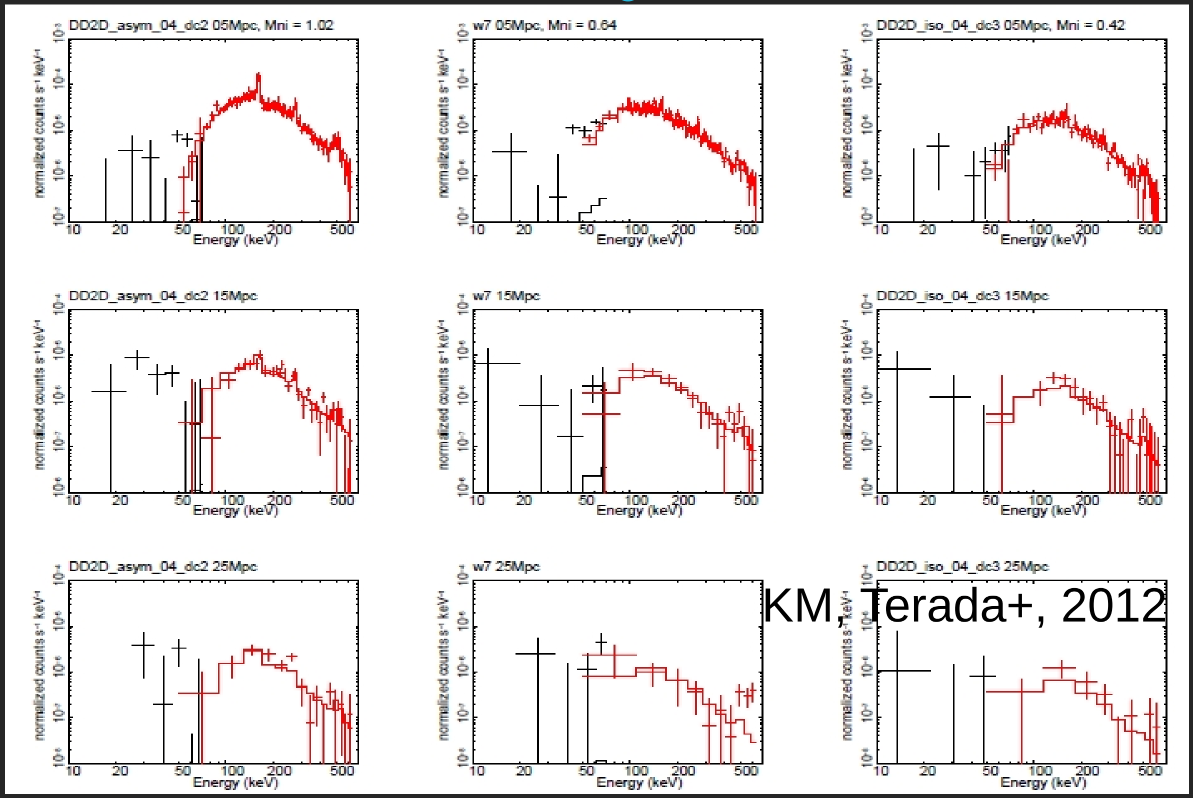
For HXI/SGD-like instrument

$M(^{56}Ni)=1M_{\odot}$(DDT) **$0.6M_{\odot}$ (W7)** **$0.4M_{\odot}$(DDT)**

5 Mpc

15 Mpc

25 Mpc

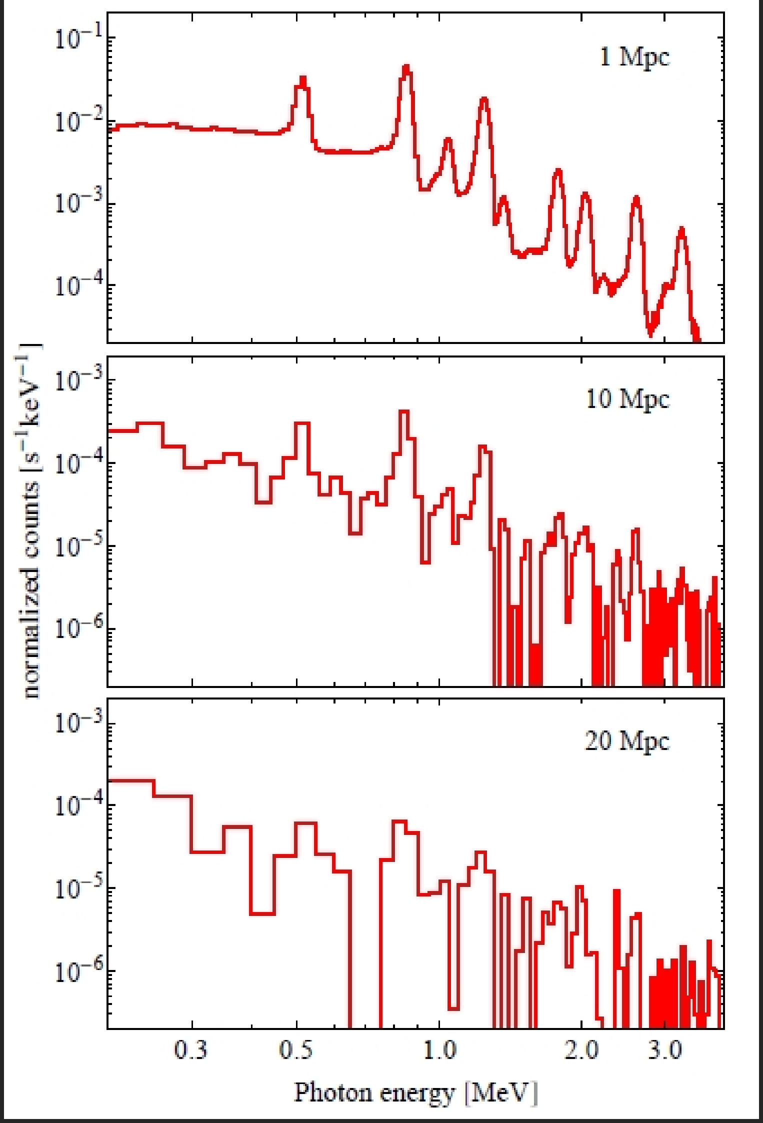


1 Ms exp., at ~ 20 days (~ 158 keV peak: ^{56}Ni→Co)

Detection up to ~ 20 Mpc at 158 keV

~ a few / yr; what about beyond 500 keV?

Further into future



Summa+, 2013, ApJ

- Proposed MeV instrument (here for GRIPS).
- Up to ~ 25 Mpc in MeV.

Detectability

~ a few SNe/yr ⇒ ~ 10 – 15 in 5 yrs
One/two very nearby for "intensive" samples.

	$M(^{56}Ni)/M_\odot$	DD2D_asym_04 1.02	W7 0.64	DD2D_iso_04 0.42
Band (keV)	Instrument	Mpc (SNe year^{-1})[b]		
60–80	HXI	13.9 (0.43)	17.7 (0.96)	10.5 (0.09)
	NuStar (cons.)[c]	13.0 (0.43)	16.5 (0.70)	9.7 (0.09)
	NuStar (opt.)[c]	18.4 (1.13)	23.3 (2.52)	13.8 (0.43)
158	SPI	4.6 (<0.09)	2.9 (<0.09)	2.3 (<0.09)
20 days	SGD (cons.)[d]	22.2 (2.09)	14.2 (0.43)	11.4 (0.09)
	SGD (opt.)[d]	38.5 (6.70)	24.6 (2.96)	19.7 (1.57)
200–460	SPI	3.7 (<0.09)	2.7 (<0.09)	2.3 (<0.09)
	SGD (cons.)	11.6 (0.09)	8.6 (0.09)	7.1 (0.09)
	SGD (opt.)	20.2 (1.74)	14.8 (0.43)	12.3 (0.26)
812	SPI	4.3 (<0.09)	2.6 (<0.09)	2.0 (<0.09)
	GRIPS	16.8 (0.87)	10.0 (0.09)	7.6 (0.09)
847	SPI	7.7 (0.09)	5.4 (<0.09)	4.6 (<0.09)
70 days	*GRIPS*	29.8 (4.52)	21.0 (2.00)	18.0 (1.04)

opt.… sensitivities: Takahashi SPIE 2010, Tajima SPIE 2010
cons… degraded by a factor of three than the 2010 response.

Summary

- Radioactive decay emission from nearby SNe.
  - Diagnostics for Nucleosynthesis, thus progenitor and explosion.
- CC-SNe:
  - ^{56}Ni, ^{44}Ti sensitive to details of explosions.
  - More theoretical models to come.
- SNe Ia:
  - ^{56}Ni mass and distribution. MeV provides a clear window to discriminate various models.
  - Likely multiple populations – need a sample.