Different views on nucleosynthesis and excellence

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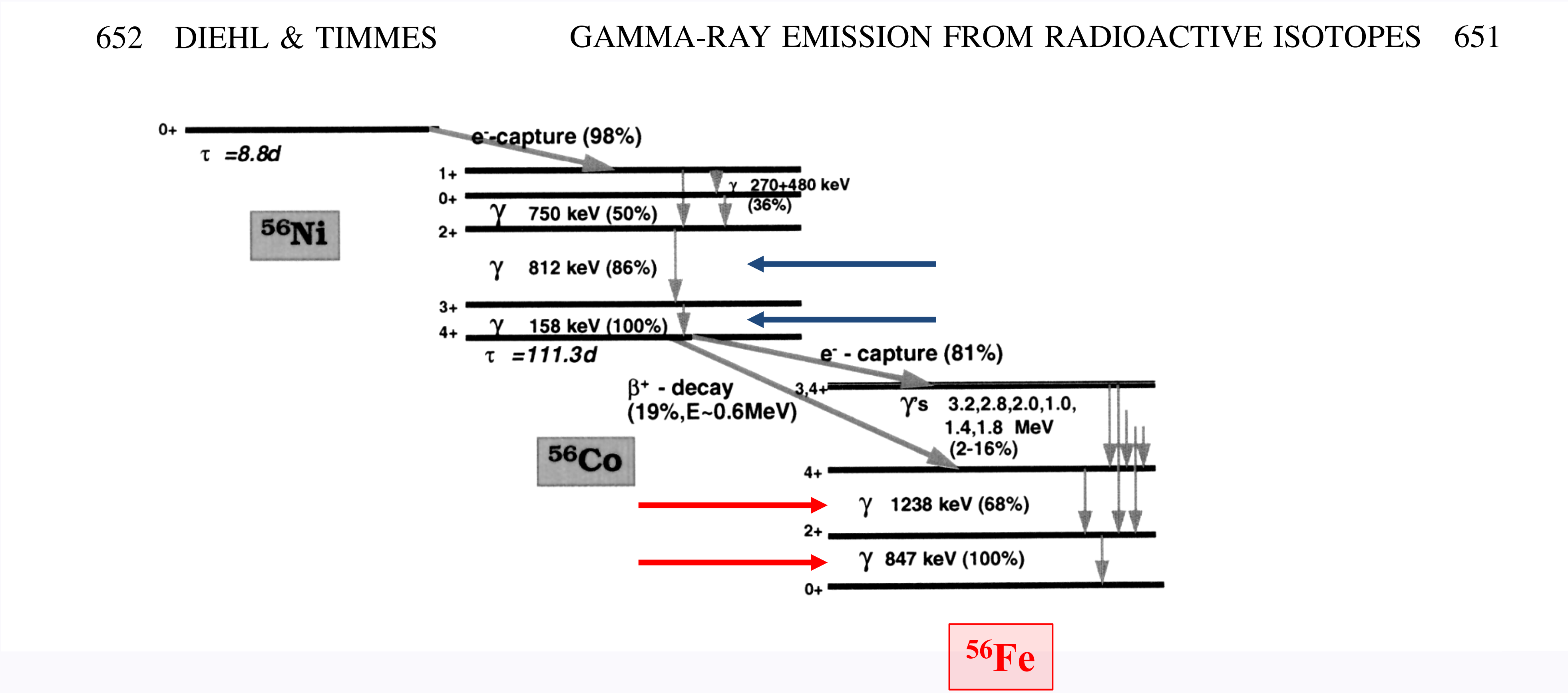
Inside vs. Outside

- γ-rays
  - direct detection of nuclear decays
  - direct measurement of Ni mass
  - distribution of radioactive material
- Optical ("bolometric")
  - energy balance
    - Arnett's rule → Ni mass
  - indirect inference of energy source
    - complication: radiation transport
  - direct detection of atomic transitions

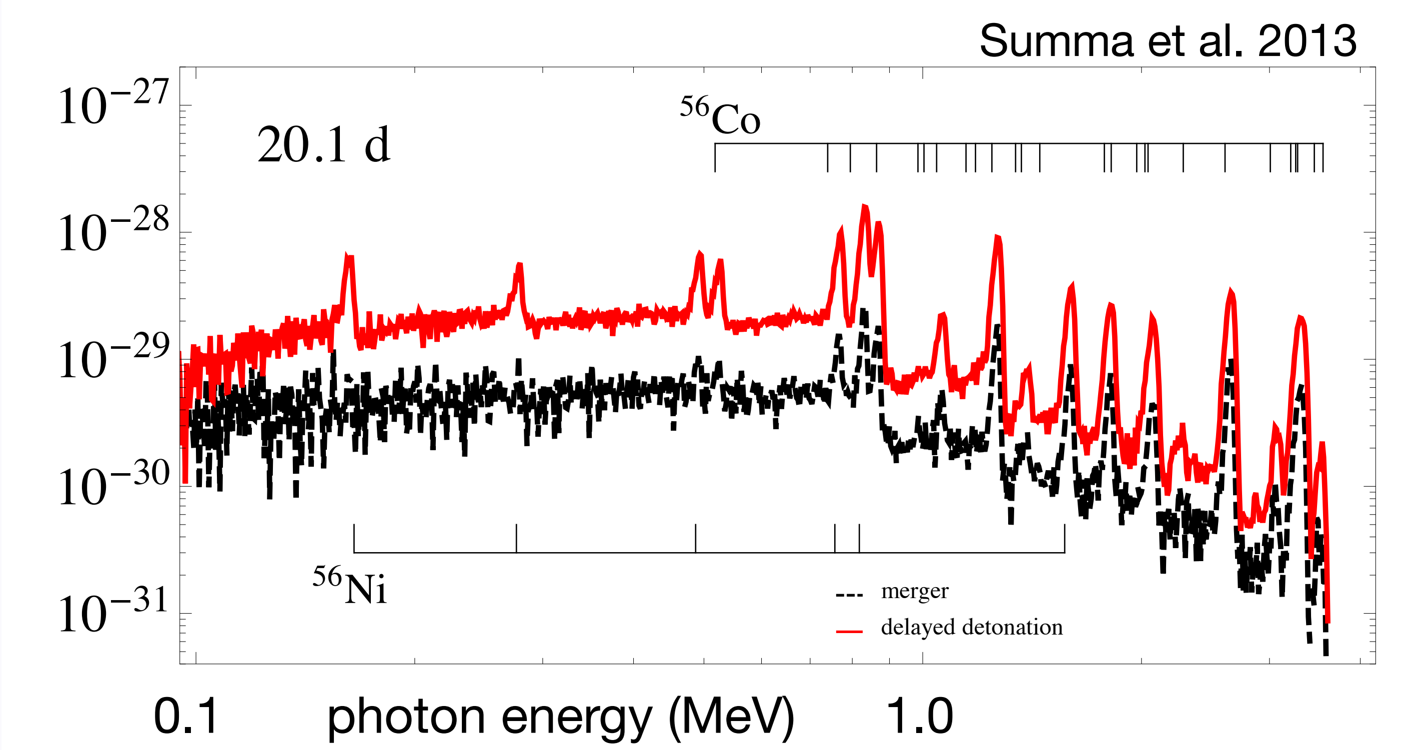
The Gospel



652 DIEHL & TIMMES
GAMMA-RAY EMISSION FROM RADIOACTIVE ISOTOPES 651
0+
τ =8.8d
e⁻-capture (98%)
1+
0+
2+
γ 270+480 keV (36%)
γ 750 keV (50%)
56Ni
γ 812 keV (86%)
3+
4+
γ 158 keV (100%)
τ =111.3d
e⁻ - capture (81%)
β⁺ - decay (19%,E~0.6MeV)
3,4+
γ's 3.2,2.8,2.0,1.0, 1.4,1.8 MeV (2-16%)
56Co
4+
γ 1238 keV (68%)
2+
γ 847 keV (100%)
0+
56Fe

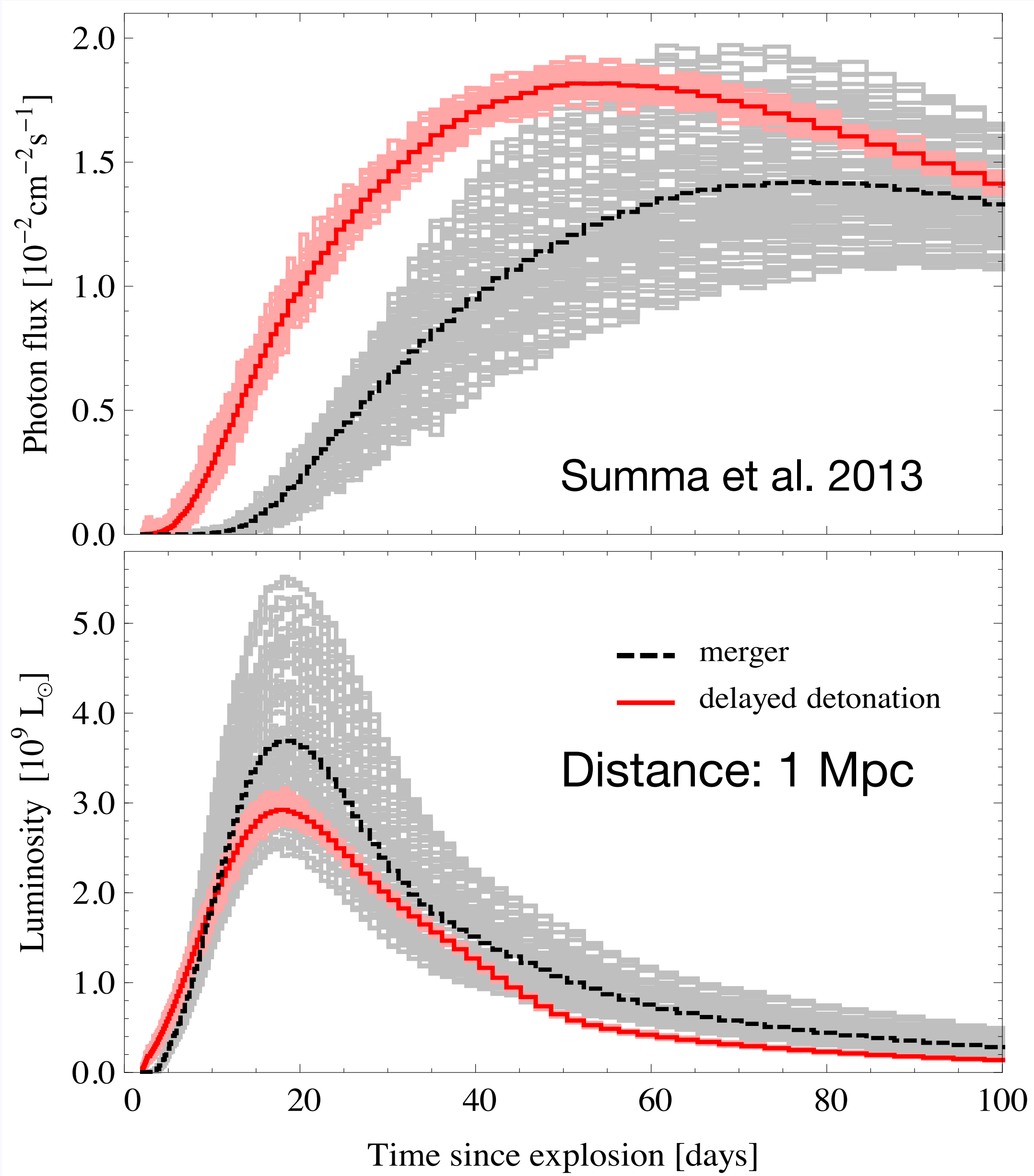
Expectations

- Calculations from different explosion models



Expectations

- Light curves



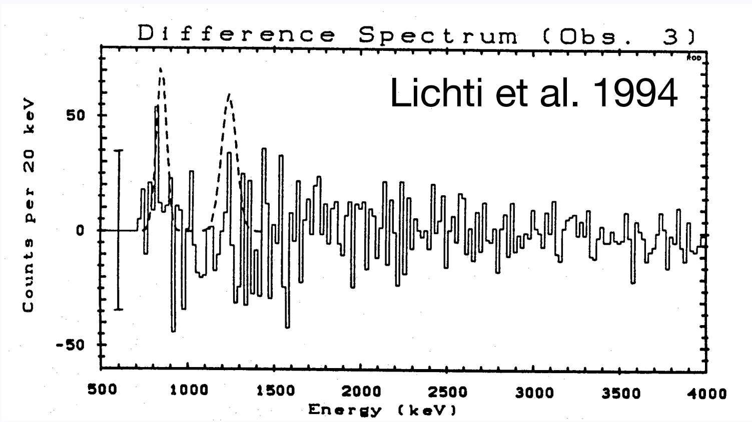
Searching – SN 1991T

- 2nd brightest SN Ia since SN 1972E

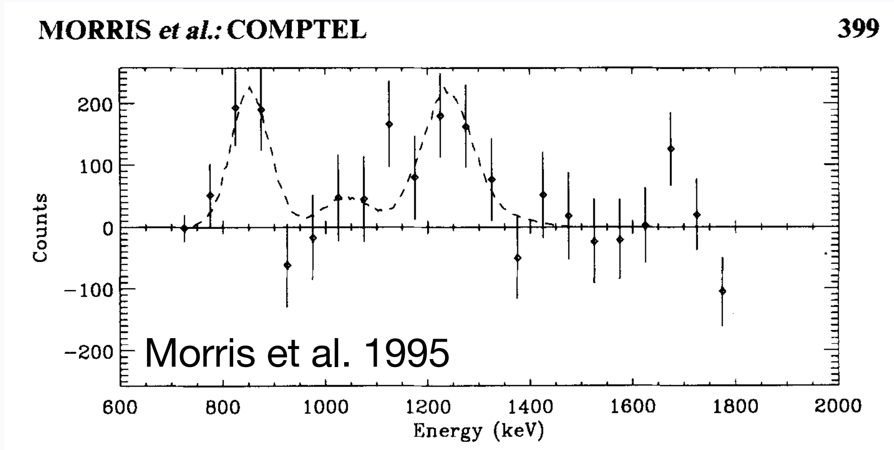
  (SN 1986G was slightly brighter, but heavily extinct)

  – first COMPTEL SN

    - discovered one week after launch of the Compton Gamma-Ray Observatory



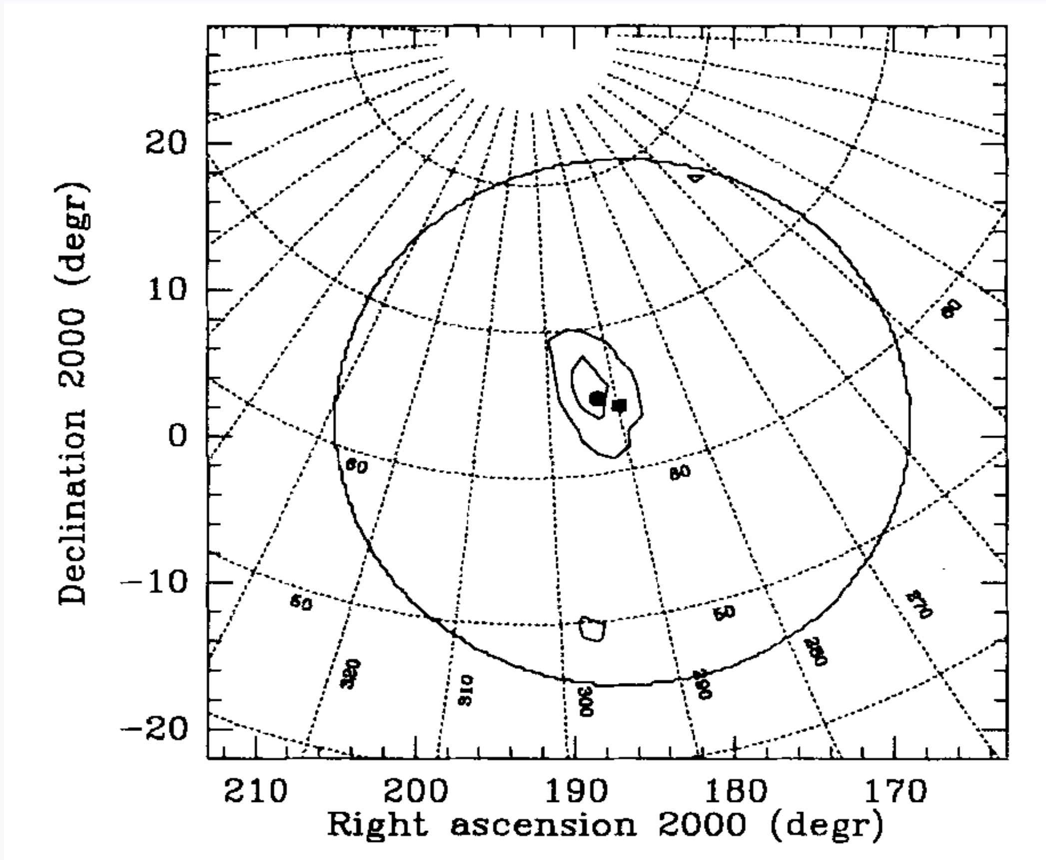
?



Searching – SN 1991T

- Complication
  - 3C273 at only 1.4 degrees
  - PSF ~2 degrees

Morris et al. 1995

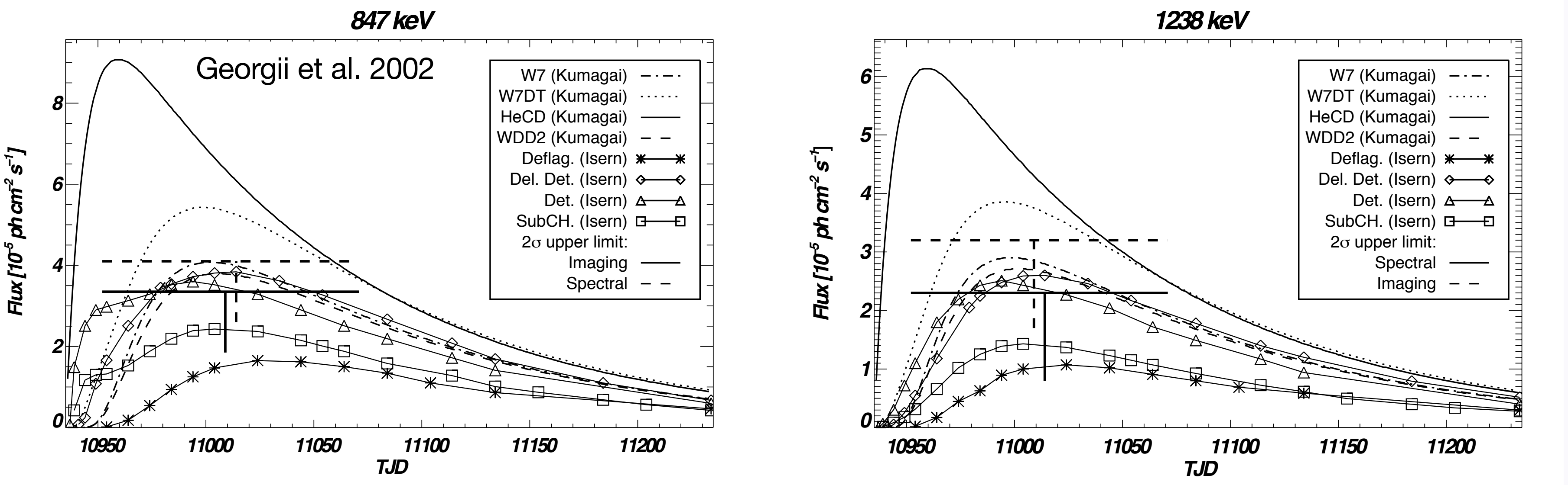


Searching – SN 1991T

- Detection limits
  - 847 kev: $(5.3 \pm 2.0 \pm 1.6) \cdot 10^{-5}\ cnts\ s^{-1} cm^{-2}$
  - 1238 kev: $(3.6 \pm 1.4 \pm 1.1) \cdot 10^{-5}\ cnts\ s^{-1} cm^{-2}$
- Unusually high Ni mass
  - $M_{Ni} > (1.3 \pm 0.5)\ M_{\odot}$ for a distance of 13 Mpc
    - (actual distance 14Mpc – Saha et al. 2006)
  - 'Unacceptable' in 1995?
    - Chandrasekhar-mass explosions
    - Super-Chandra's not part of 'main stream' yet

Searching – SN 1998bu

- Heavily obscured SN Ia
  - light echoes observed
- Upper limits on Co $\boldsymbol{\gamma}$-rays
  - 847 keV: $3.1 \cdot 10^{-5}\ cnts\ s^{-1} cm^{-2}\ (2\sigma)$
  - 1238 keV: $2.3 \cdot 10^{-5}\ cnts\ s^{1}\ cm^{-2}\ (2\sigma)$



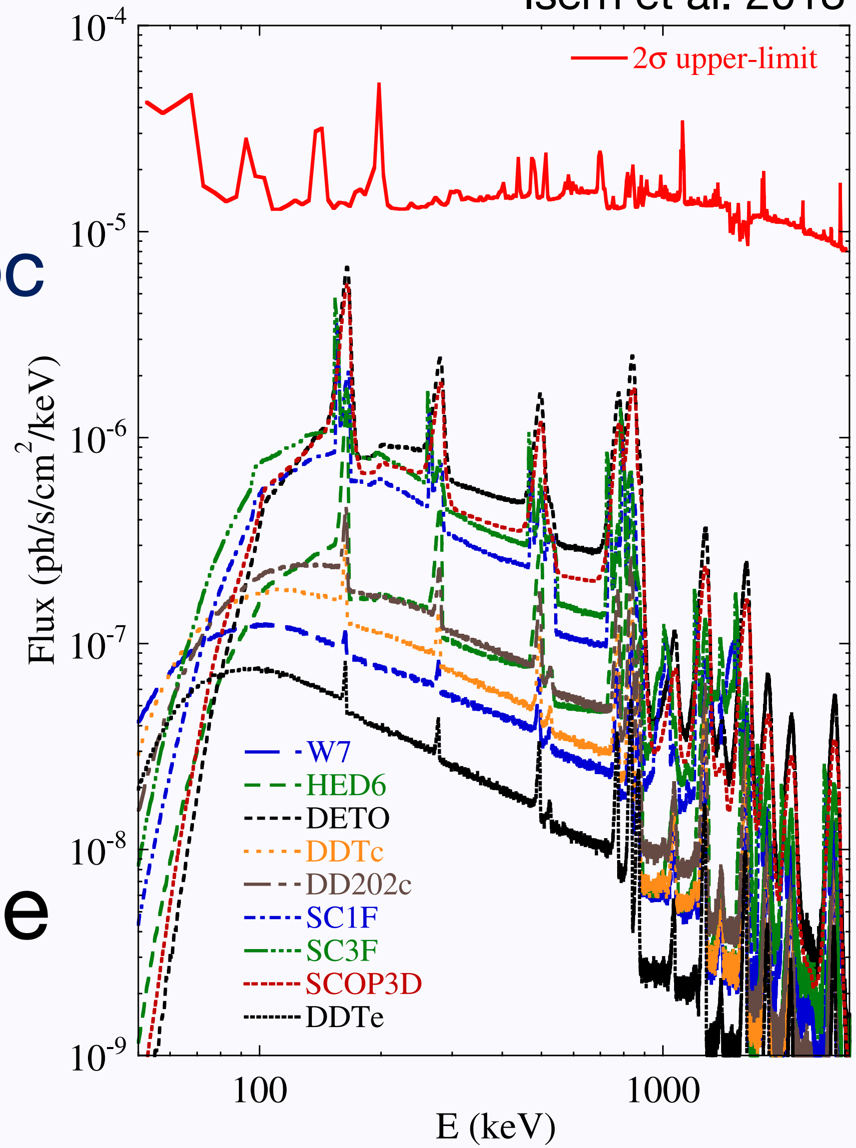
Searching – SN 1998bu

- Exclusion of some popular explosion models
- Inferred $M_{Ni} \leq 0.35\ M_{\odot}$ (11.9 Mpc)
  - Optical/NIR $M_{Ni} = (0.58 \pm 0.12) M_{\odot}$ (Dhawan et al. 2016)
    - derived 'reddening-independent'
  - Discrepancy due to $\boldsymbol{\gamma}$-ray escape model?
    - explosion model, Ni distribution, photon transport
- Clear indication of importance of details in the explosions

Searching – SN 2011fe

- Nearest SN Ia since SN 1972E
  - Distance (M101): 6.4 Mpc
- Search for early Ni
  - INTEGRAL observations pre optical maximum
- Exclude any surface nickel
- What about the late-time data? Published?

Isern et al. 2013

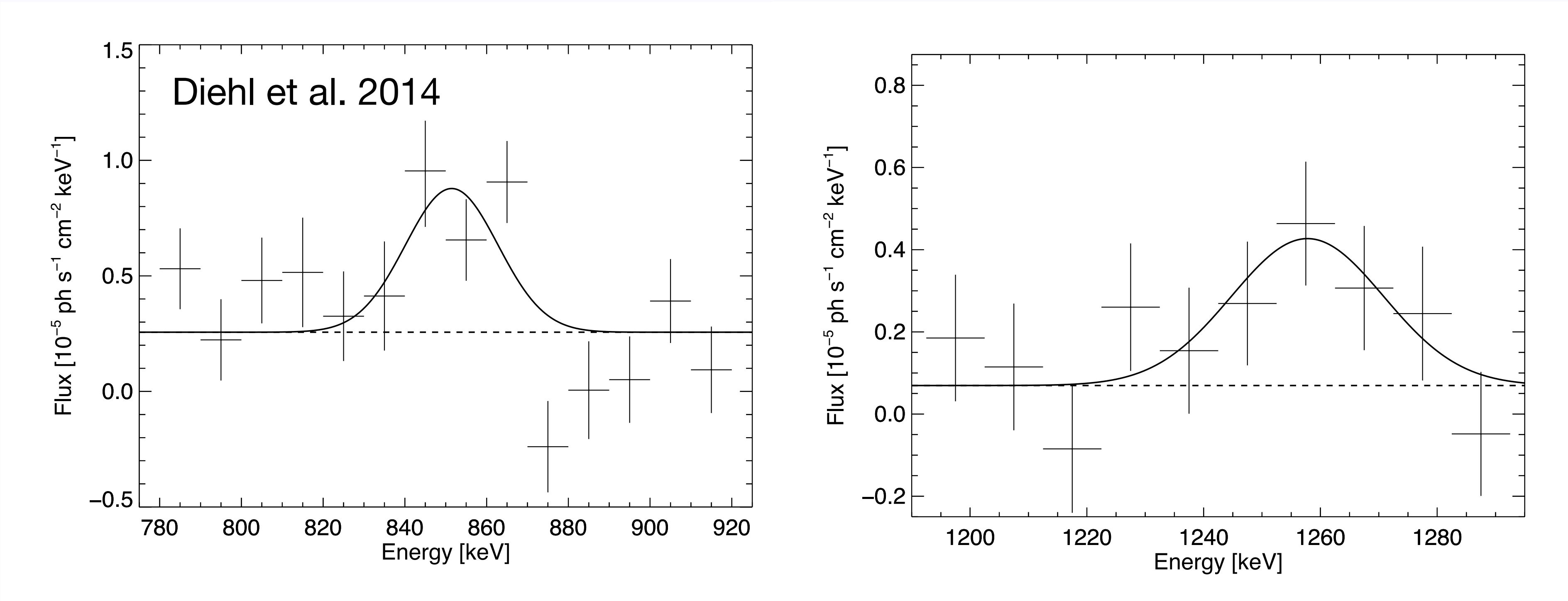


Finding SN 2014J

- Closest SN Ia in over 70 years
  - M82: Distance 3.3 Mpc
- Heavily reddened

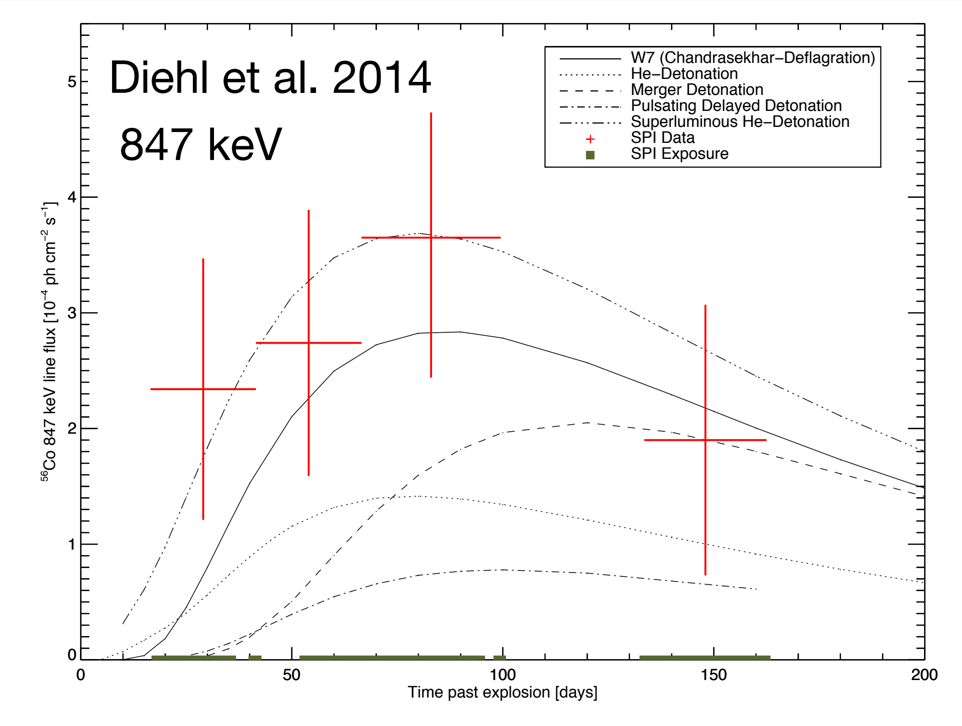
Finding SN 2014J

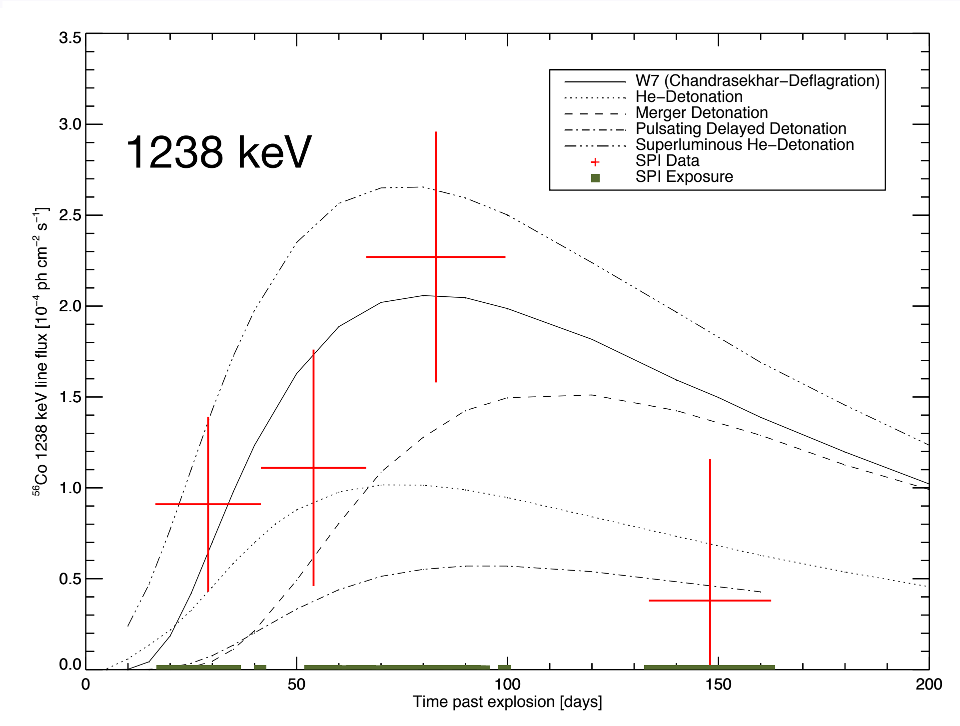
- First clear detection of cobalt decay lines
  - Integration from 17 to 164 days after explosion



Finding SN 2014J

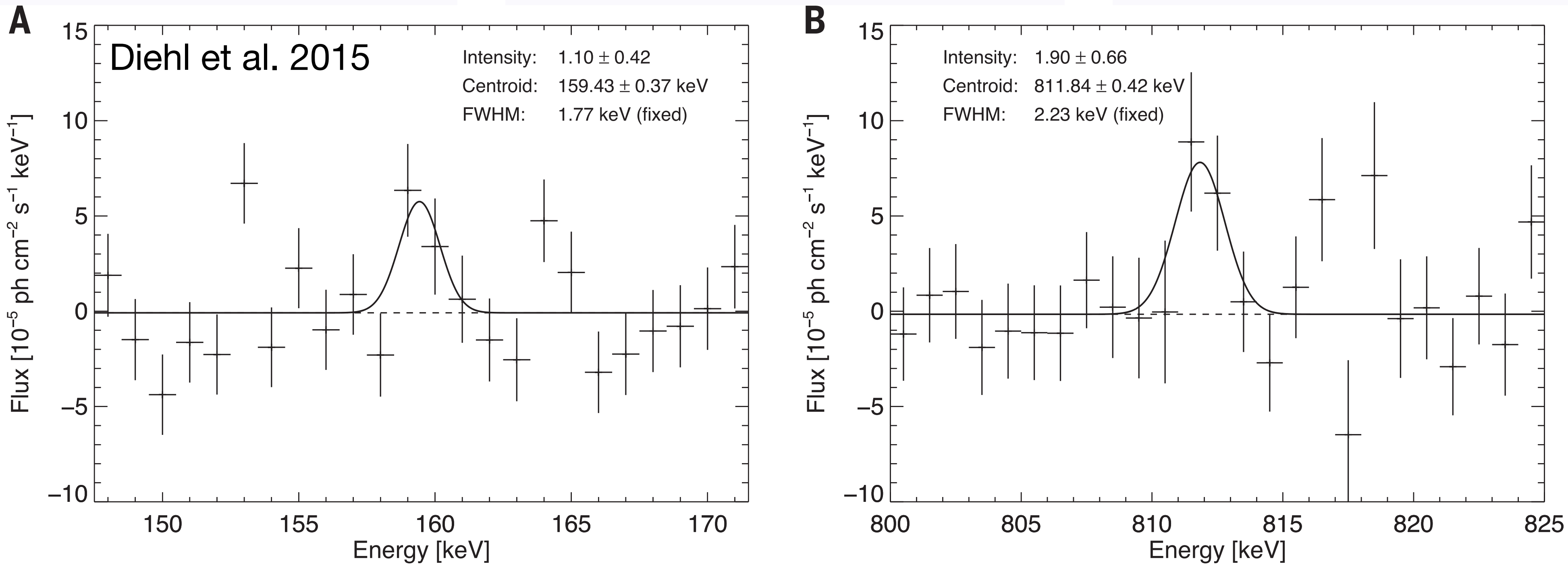
- Temporal evolution





Finding SN 2014J

- Surprise – detection of Ni → Co decay lines 17 days after explosion
  - requires about $0.06\ M_{\odot}$ nickel on the outside



Finding SN 2014J

- If Ni distributed uniformly, i.e. a shell
  - line broading expected → not observed
- Radial symmetry needs to be broken
  - indications on asymmetry in the explosion

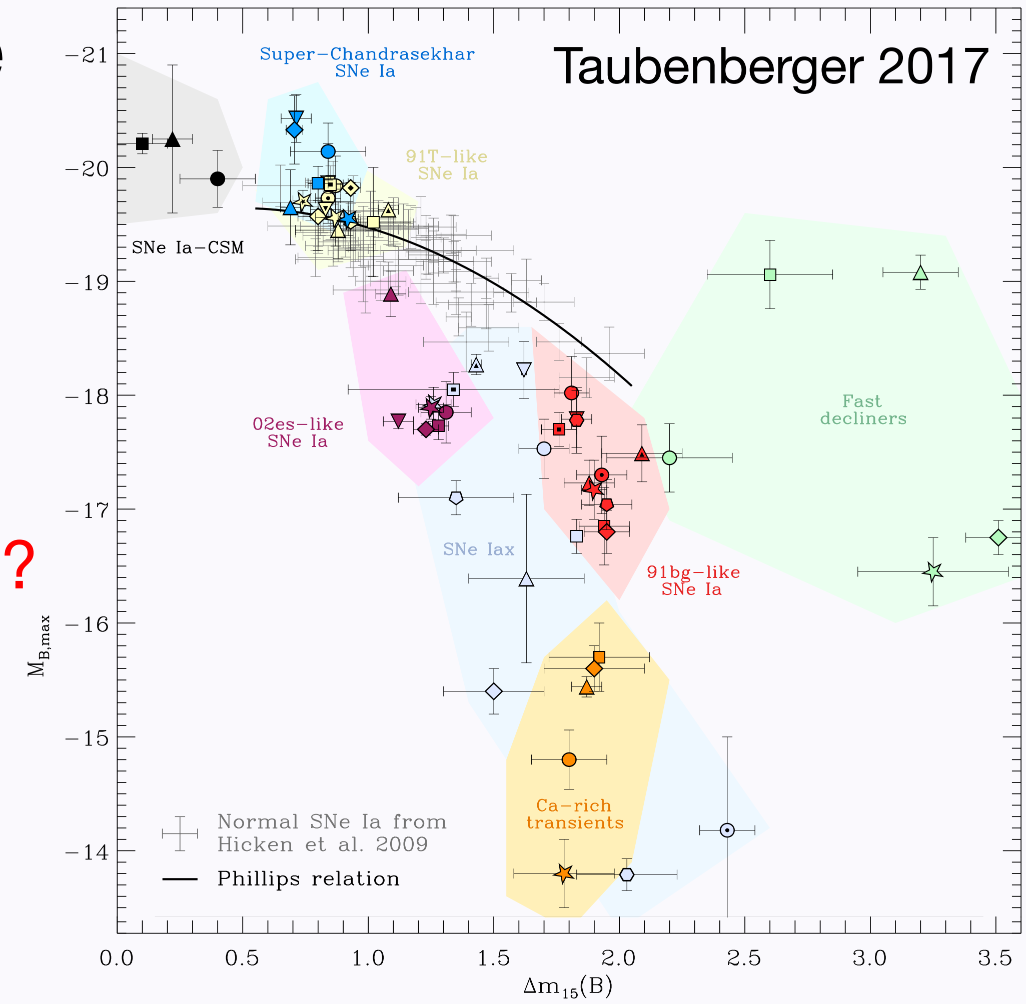
So what about the outside?

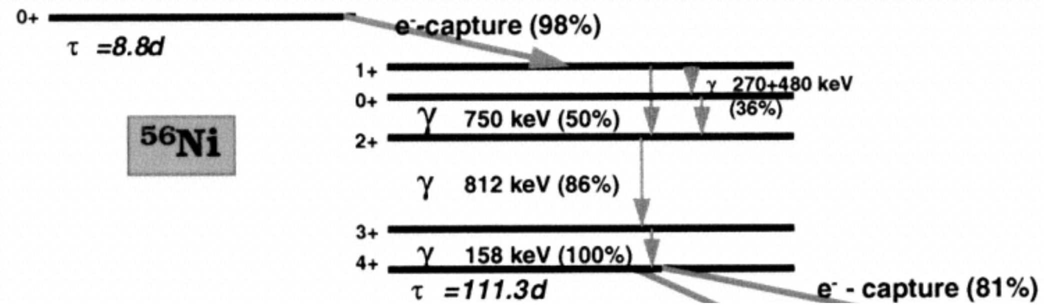
- Very indirect
- Many more supernovae
- Much larger data samples
- Statistical anaylses

Type Ia Supernovae

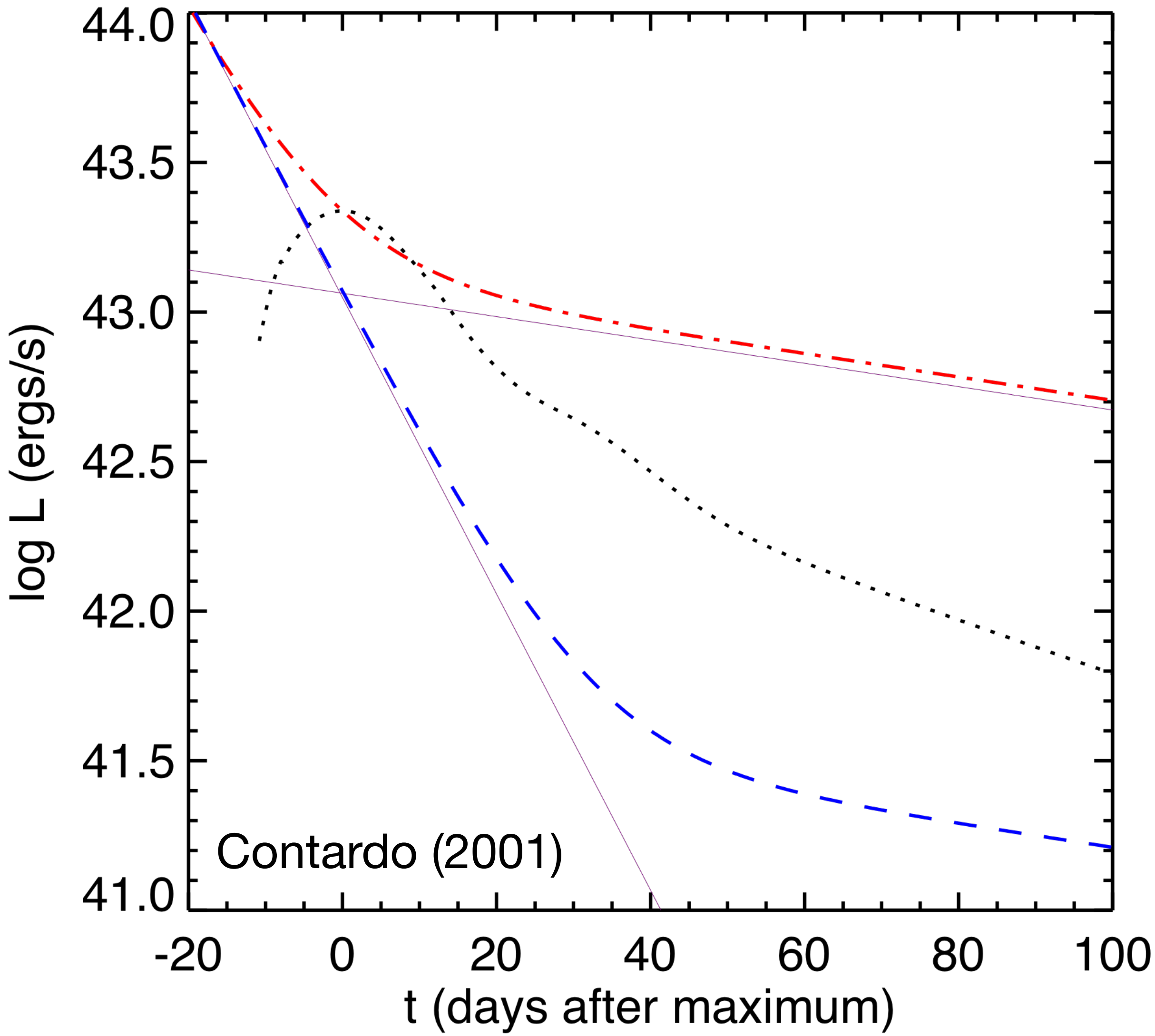
Variations on a theme

- critical parameters?
  - nickel mass
  - ejecta mass
  - explosion energy(?)
  - explosion mechanism?
  - progenitor evolution?





Radioactivity



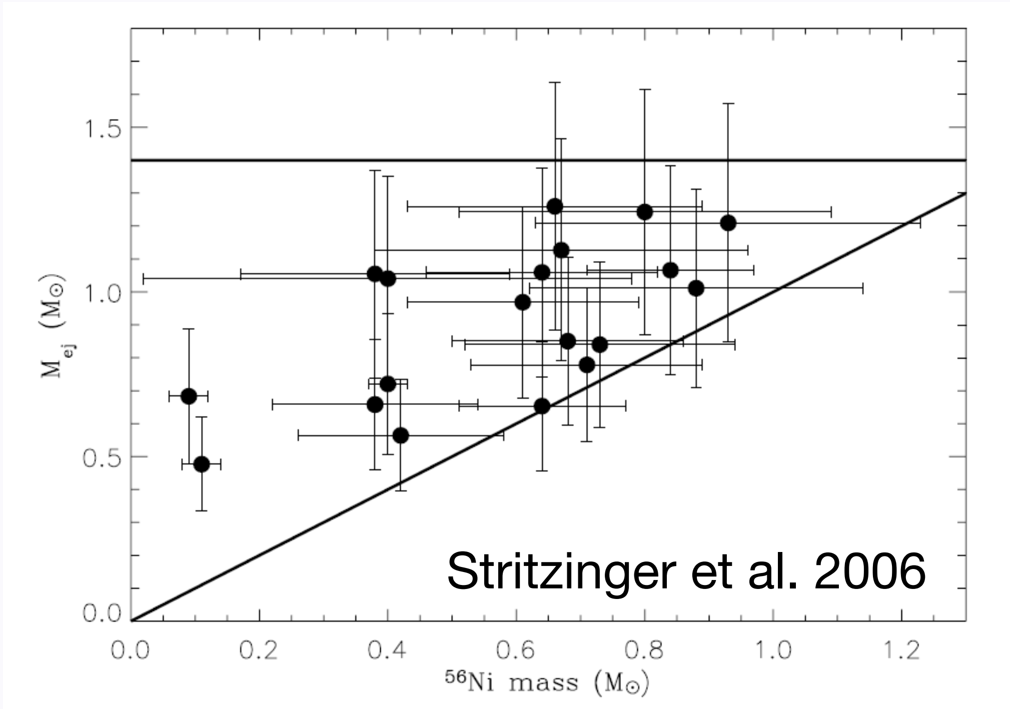
Isotopes of Ni and other elements

- conversion of γ-rays and positrons into heat and optical photons

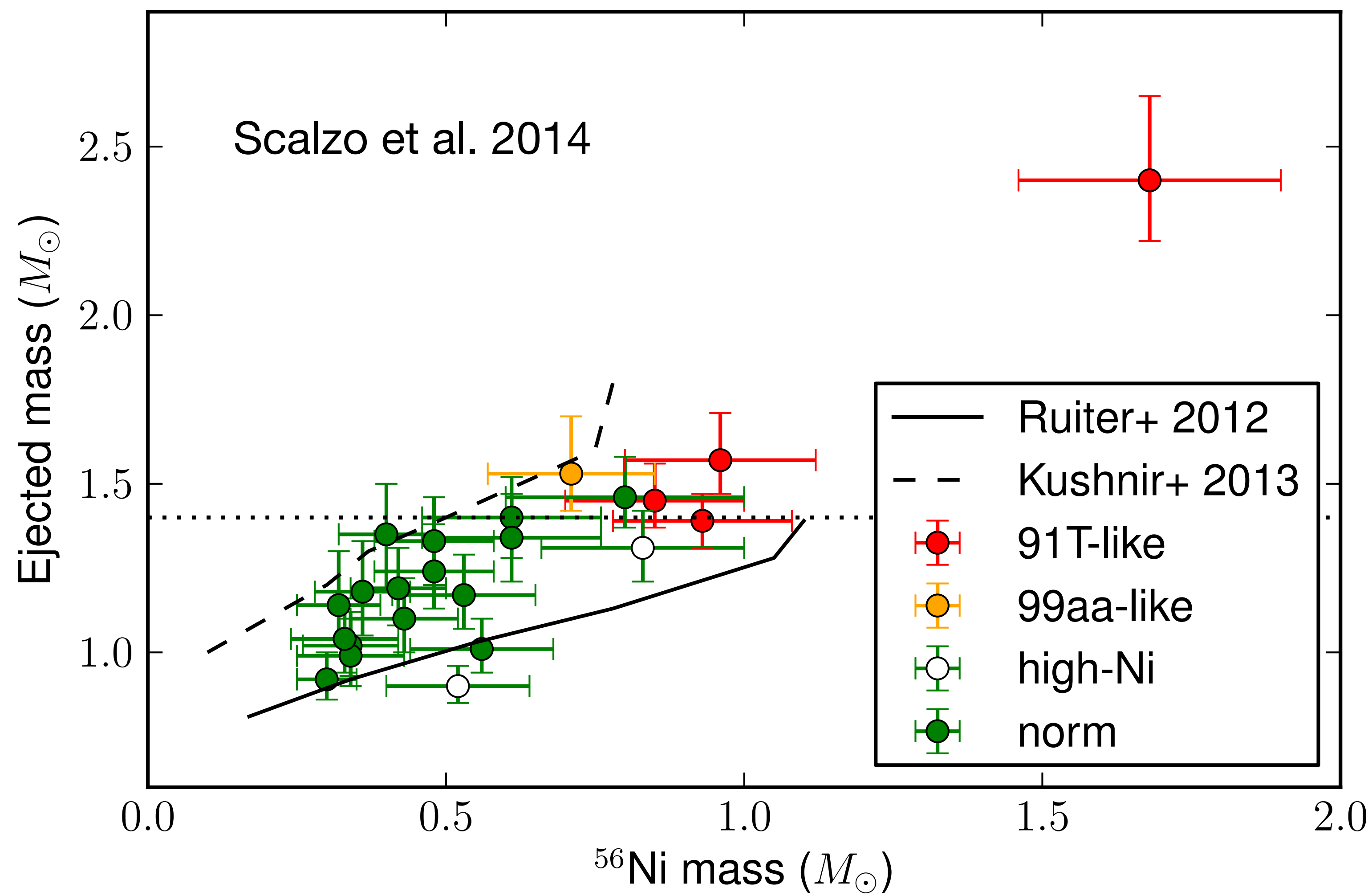
Ejecta masses

Large range in nickel and ejecta masses

- no ejecta mass at $1.4M_{\odot}$
- factor of 2 in ejecta masses
- some rather small differences between nickel and ejecta mass

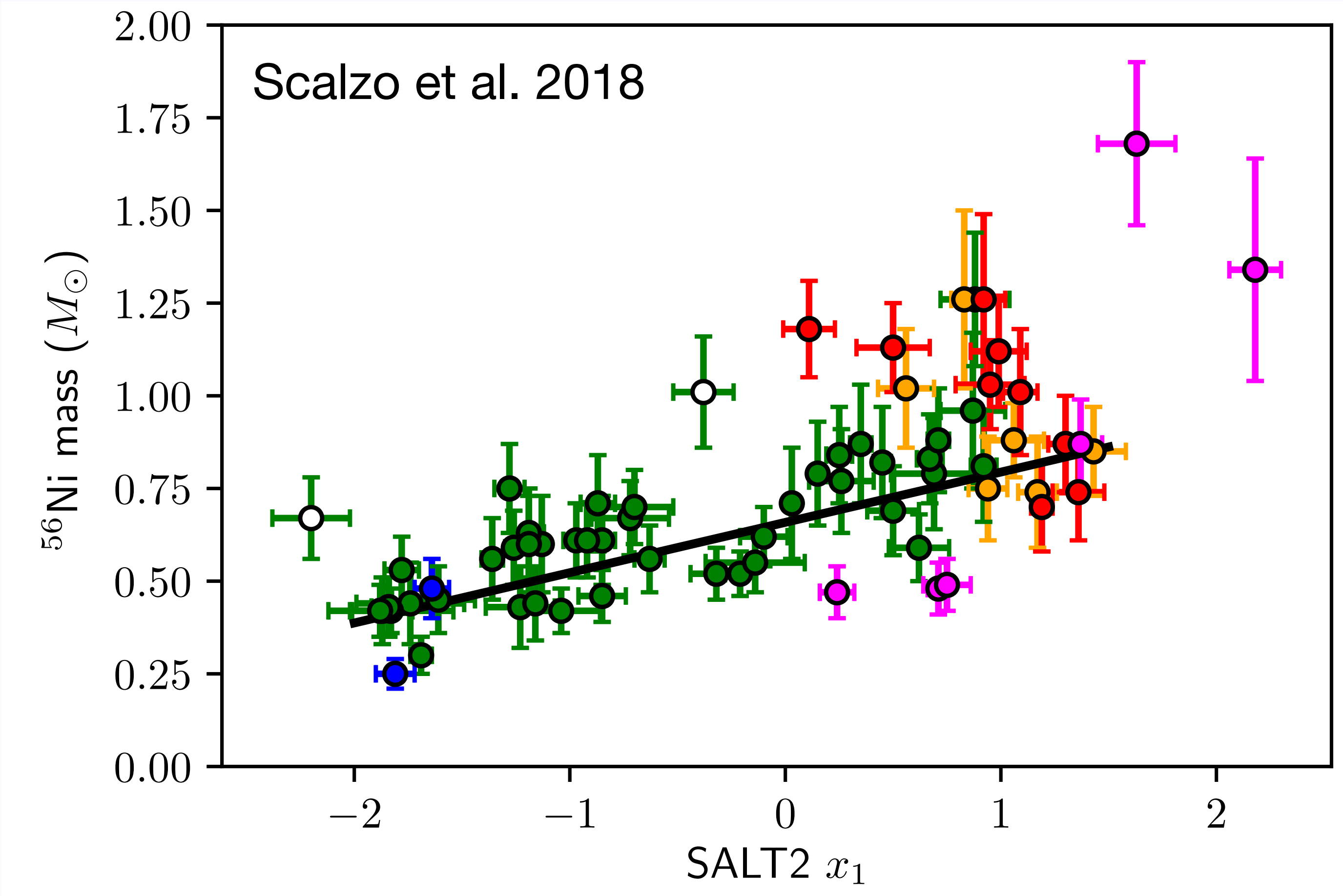


Ejecta masses



Nickel masses

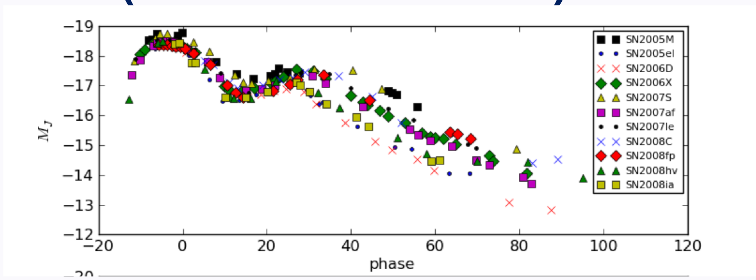
- Bolometric light curve analysis with 39 SNe Ia



SNe Ia in the NIR

Consistent picture emerging

– Second peak in the near-IR is the result of the recombination of Fe^{++} to Fe^{+} (Kasen 2006)



– Uniform ejecta structure
  - late declines very similar

– higher luminosity indicates higher ^{56}Ni mass

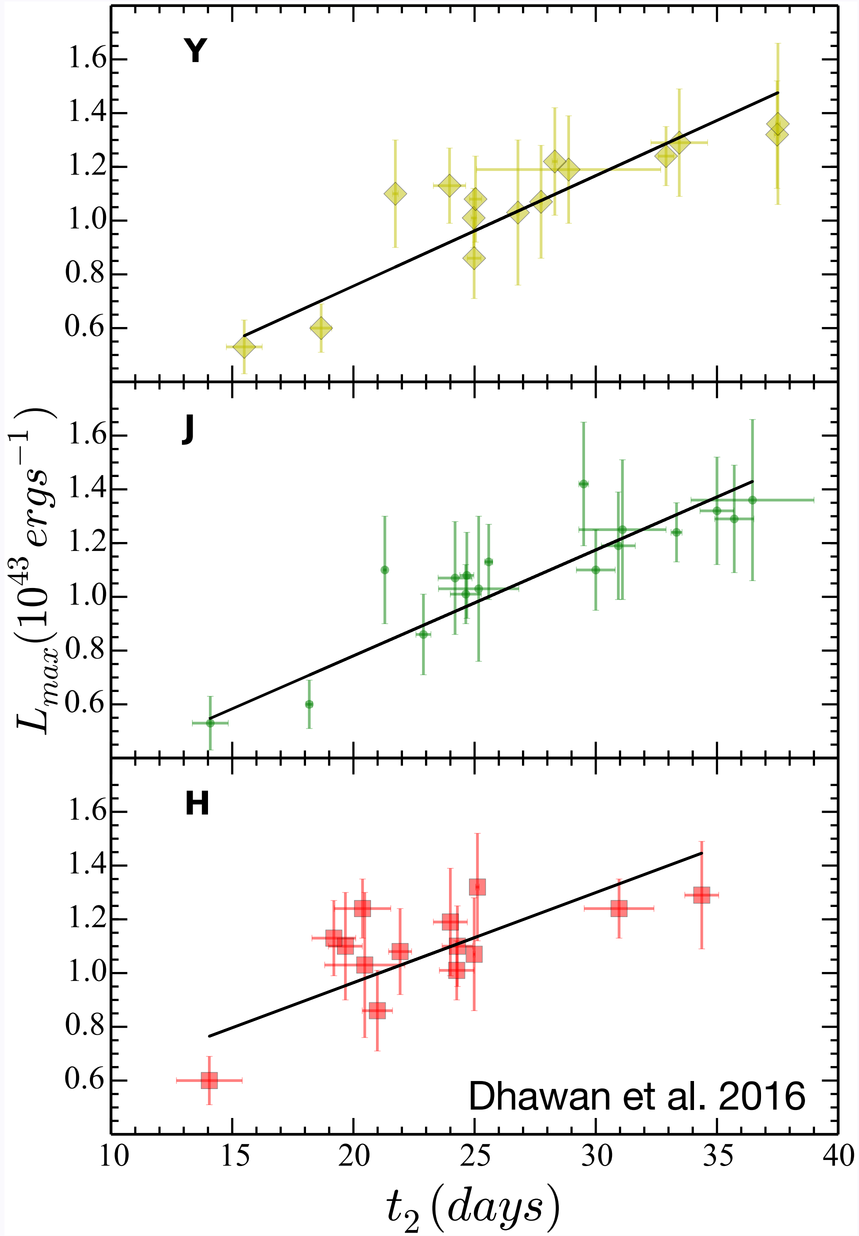
– later secondary peak also indicates higher Fe/Ni mass

– Ni mass and (optical) light curve parameters correlate (Scalzo et al. 2014)

Luminosity function of SNe Ia

Use the phase of the second maximum to derive the bolometric peak luminosity

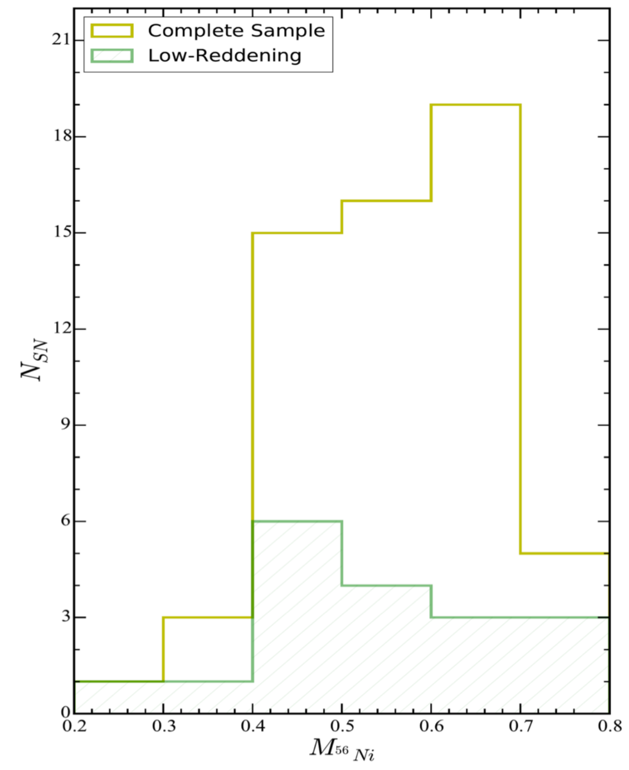
- calibrated on a sample of reddening-free SNe Ia
  - SNe with E(B-V)<0.1
  - pseudo-bolometric light curves (UBVRIYJH)
- apply to reddened objects



Luminosity function of SNe Ia

M_{Ni} (inferred)	σ	Method	Reference
0.62	0.13	γ ray lines	Churazov et al. (2014)
0.56	0.10	γ ray lines	Diehl et al. (2015)
0.37	...	Bolometric light curve $A_V = 1.7$ mag	Churazov et al. (2014), Margutti et al. (2014)
0.77	...	Bolometric light curve $A_V = 2.5$ mag	Churazov et al. (2014), Goobar et al. (2014)
0.64	0.13	NIR second maximum	this work (combined fit)
0.60	0.10	NIR second maximum + measured rise	this work

- SN 2014J test passed
- Potential to determine the luminosity function and Ni distribution

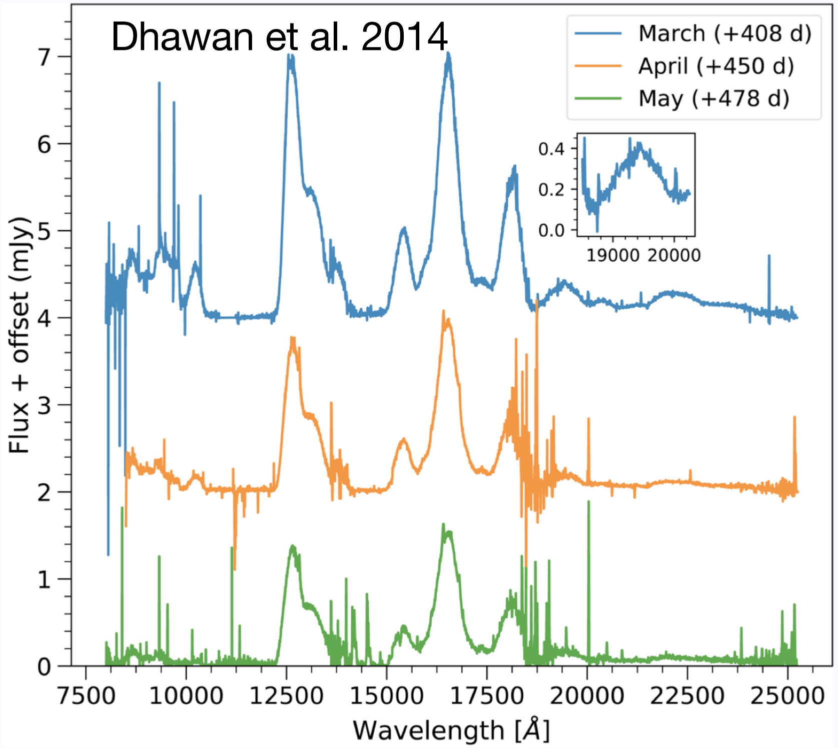


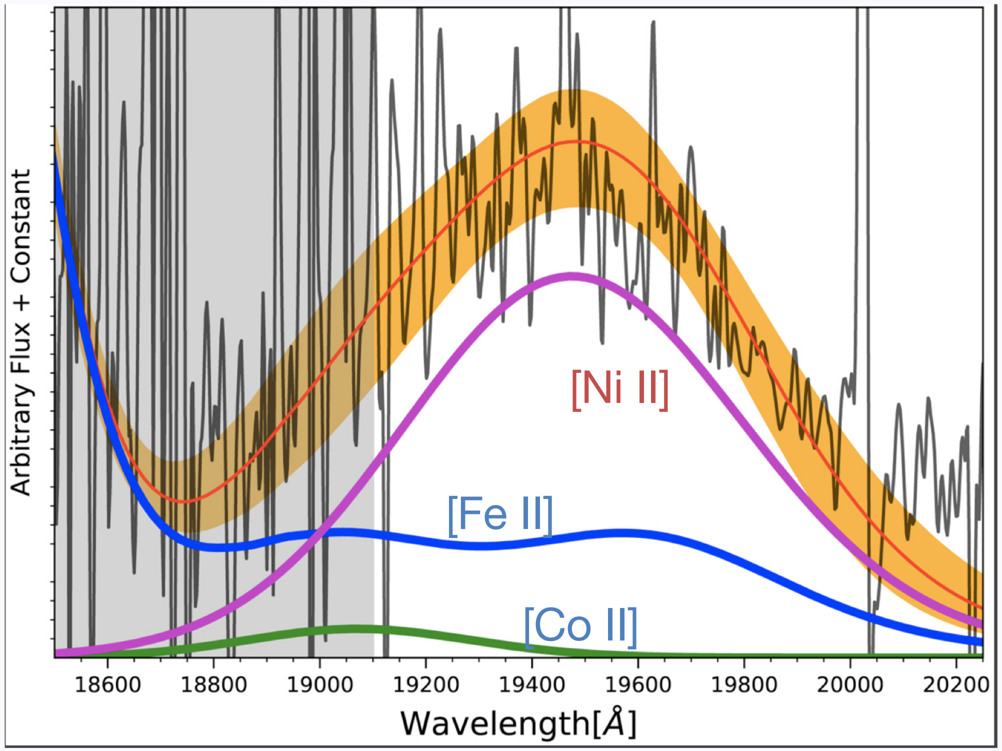
Dhawan et al. 2016

Coda: SN 2014J

- Stable nickel detected
  - NIR nickel line at 1.939μm 450 days after maximum
  - Estimated $M_{Ni}(stable) \approx (0.53 \pm 0.018) M_{\odot}$

roughly 10% of all nickel





Excellence in 2016

Perspectives of nuclear astrophysics

- Influence of new and exotic phenomena on chemical evolution
  - ☞ neutron star mergers
    - theoretically attractive
    - not observed/identified so far
  - ☞ massive explosions
    - superluminous supernovae
      - – observed but not understood
    - pair-instability supernovae
      - – predicted but not observed/identified

➔Complex formation histories have to be considered

➔Identification of single enrichment source becomes difficult/impossible

Roland's foresight (2016)

Perspectives of nuclear astrophysics

- Test of general relativity in strong gravitational field
  - ☞ passage of S2 near the supermassive black hole at the MW center in 2018
    - detailed observations in preparation → GRAVITY
- Gravitational waves from neutron star mergers
  - ☞ beyond the reach of aLIGO/VIRGO → requires LISA
- Chemical evolution studies of stellar subgroups in the Milky Way
  - ☞ Gaia streams, stellar groups
  - ☞ In- and outflows into the Milky Way
    - pristine material vs. local enrichment
    - galactic fountains
  - ☞ evolution histories of spiral arms vs. bulge

…and another one

Perspectives of nuclear astrophysics

- Multi-messenger astrophysics
  - ☞ neutrinos, gravitational waves, ultra-high energy radiation, cosmic rays
    - all related to high-energy events and processes
    - new facilities
      - IceCube, aLIGO/VIRGO, CTA, Auger
    - new connections
      - SFB 1258 "Neutrinos and Dark Matter"
- New views into planetary systems and their evolution
  - ☞ young disks, transition disks, debris disks, proto-planets
    - ALMA, infrared adaptive optics (VLT/SPHERE)
  - ☞ white dwarf chemistry
    - planetary material/higher elements on the surface of white dwarfs

‘Universe’ to ‘Origins’

- Decided to leave a gap in the evolution from energy (early universe) to life
  - no nuclear astrophysics
- Exciting science topics need to be accommodated in other topics
  - multi-messenger astrophysics
    - gravitational waves, neutrinos
    - neutron star mergers, supernovae

Cosmic Nucleosynthesis Universe vs. Origins

☞ Across the Entire Cycle of Matter: Nuclear Astro-Physics