Supernova Explosions and Neutron Stars

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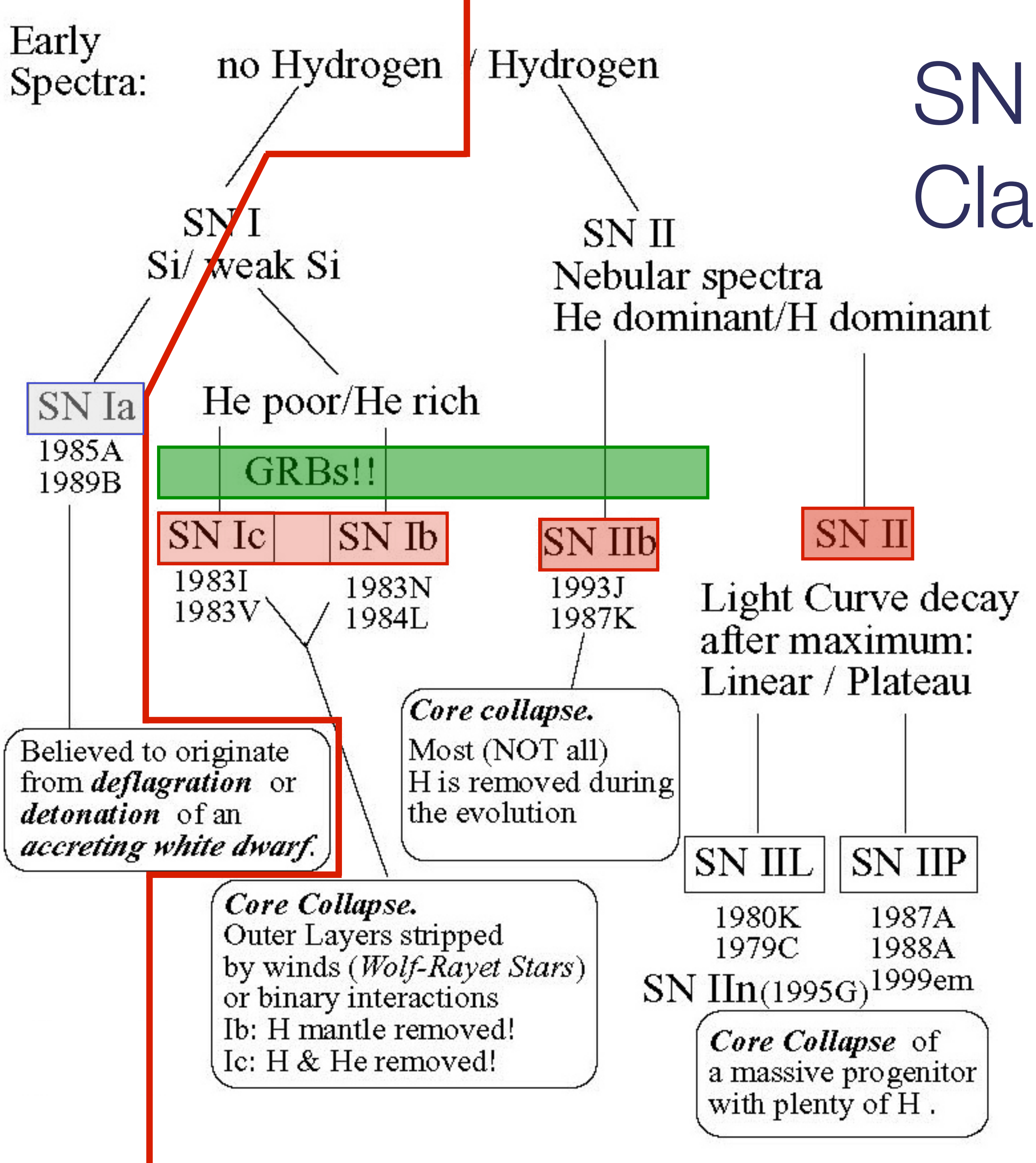
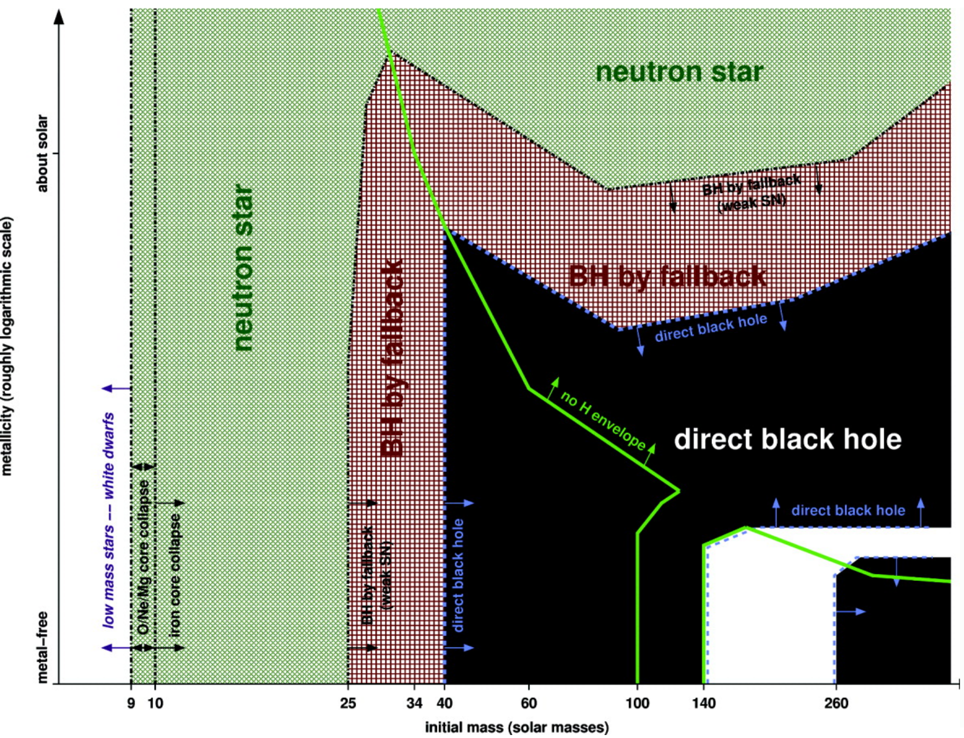
What do we want to learn about supernovae?

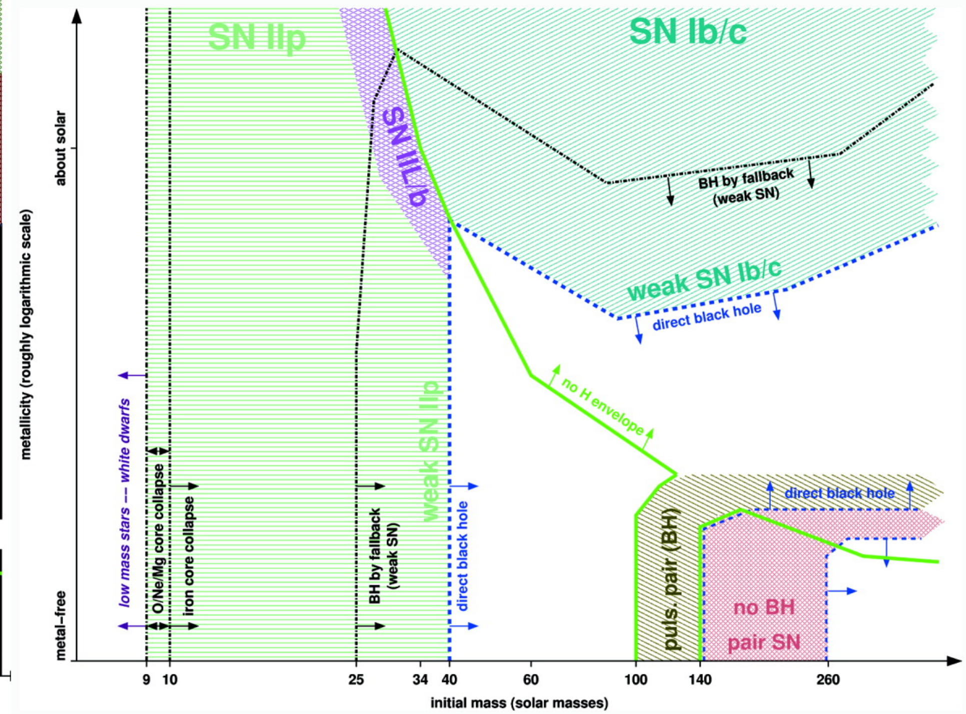
- What explodes?
  - progenitors, evolution towards explosion
- How does it explode?
  - explosion mechanisms
- Where does it explode?
  - environment
    - local and global
  - feedback
- What is left behind?
  - remnants
  - compact remnants
  - chemical enrichment
- Other uses of the explosions
  - light beacons
  - distance indicators
  - chemical factories

SN Classification



The expectations …

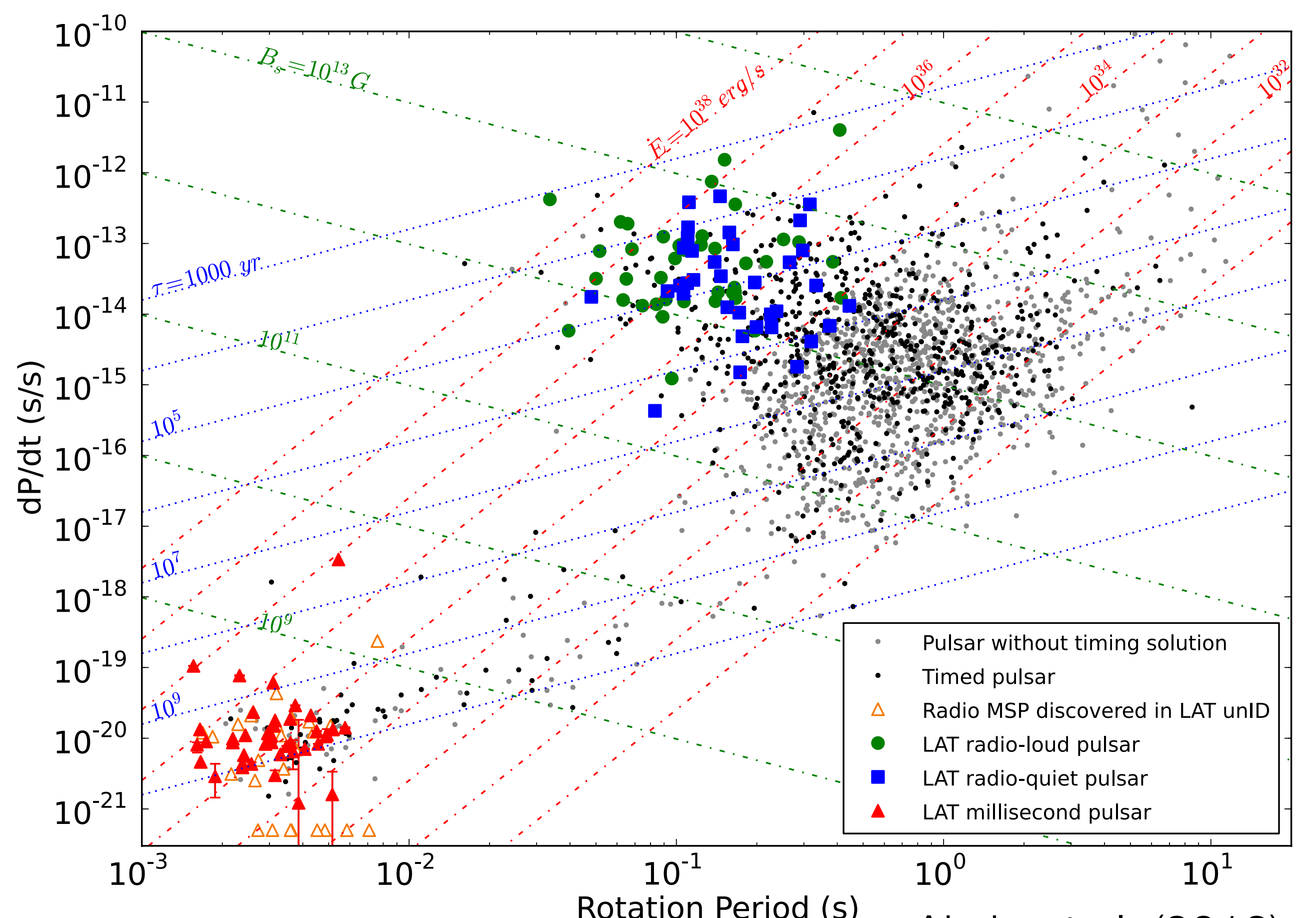




Heger et al. 2003

Difficulties

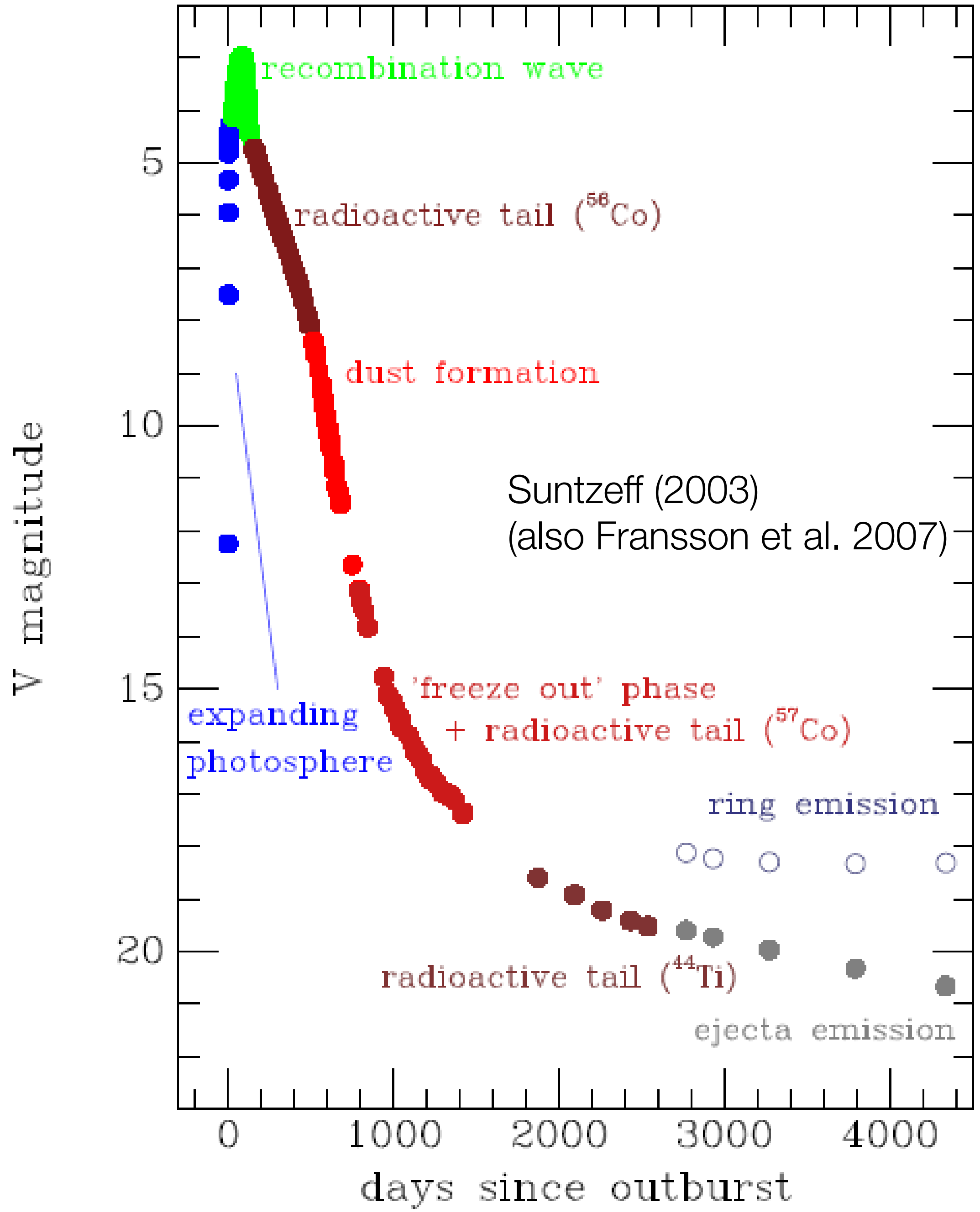
- Supernovae are bright (~10^{43} erg/s at peak)
- Neutron
  ~10^{35} erg
  the explo
  - need to
    transpa
- Superno
- Superno
  - complic
    - hydro
    - many
    - not e

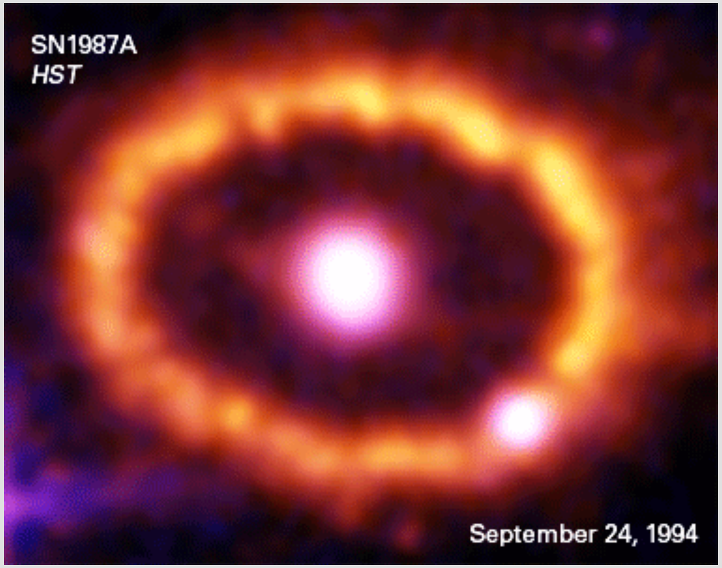


Abdo et al. (2013)

Energy escape from a (core-collapse) supernova

SN 1987A
the best observed supernova ever



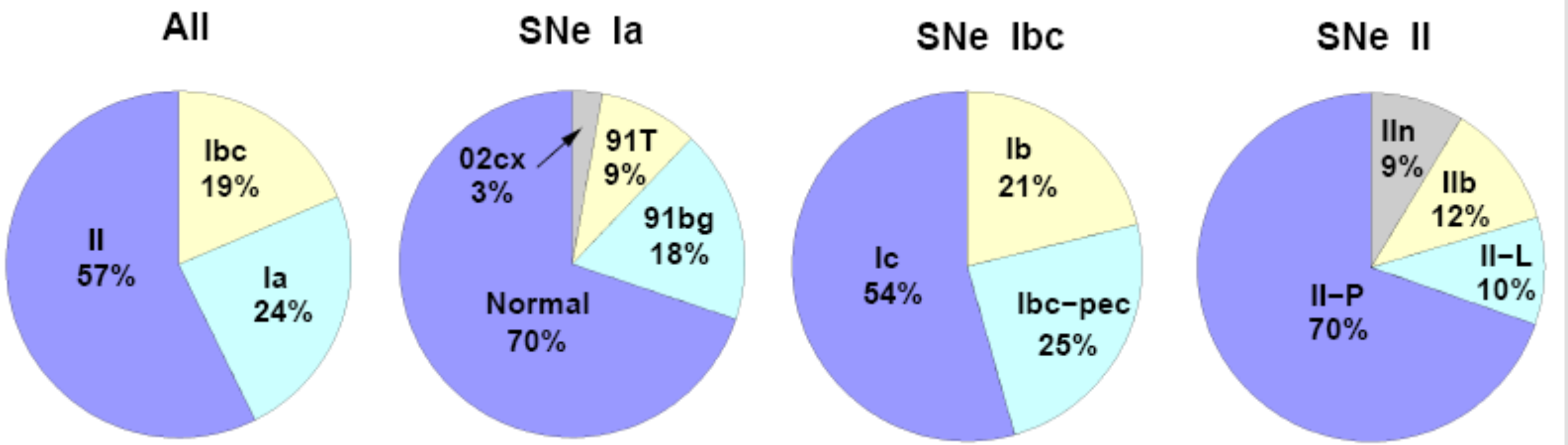


Detecting neutron stars in SNe

- Wait until remnant phase
  - patience → SN 1987A, Cas A, Crab
- Look for signatures in explosion
  - magnetar SNe?
- Trust explosion models
  - still many fundamental uncertainties
- Search for ensemble properties
  - neutron star kicks

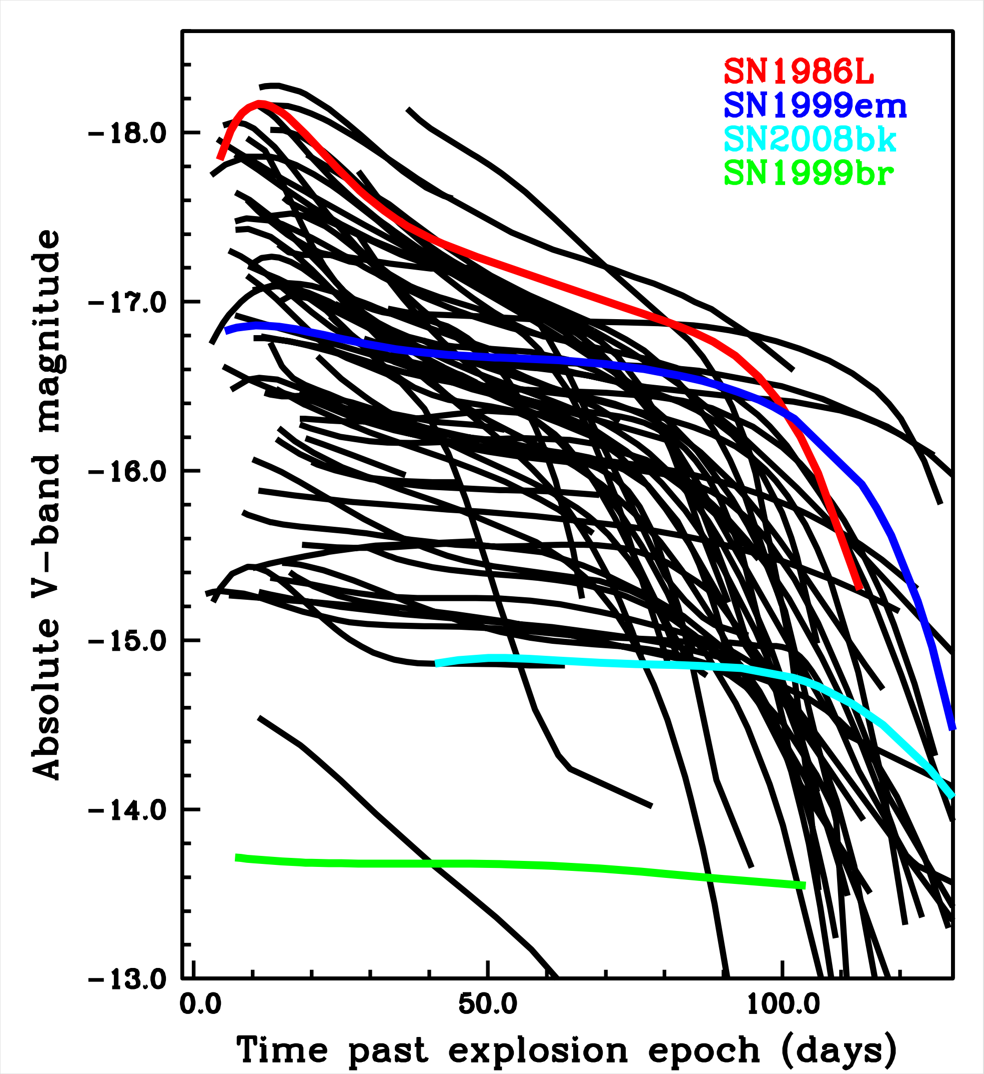
Lick Observatory Supernova Search

- Volume-limited sample in the local universe (out to 60 Mpc)



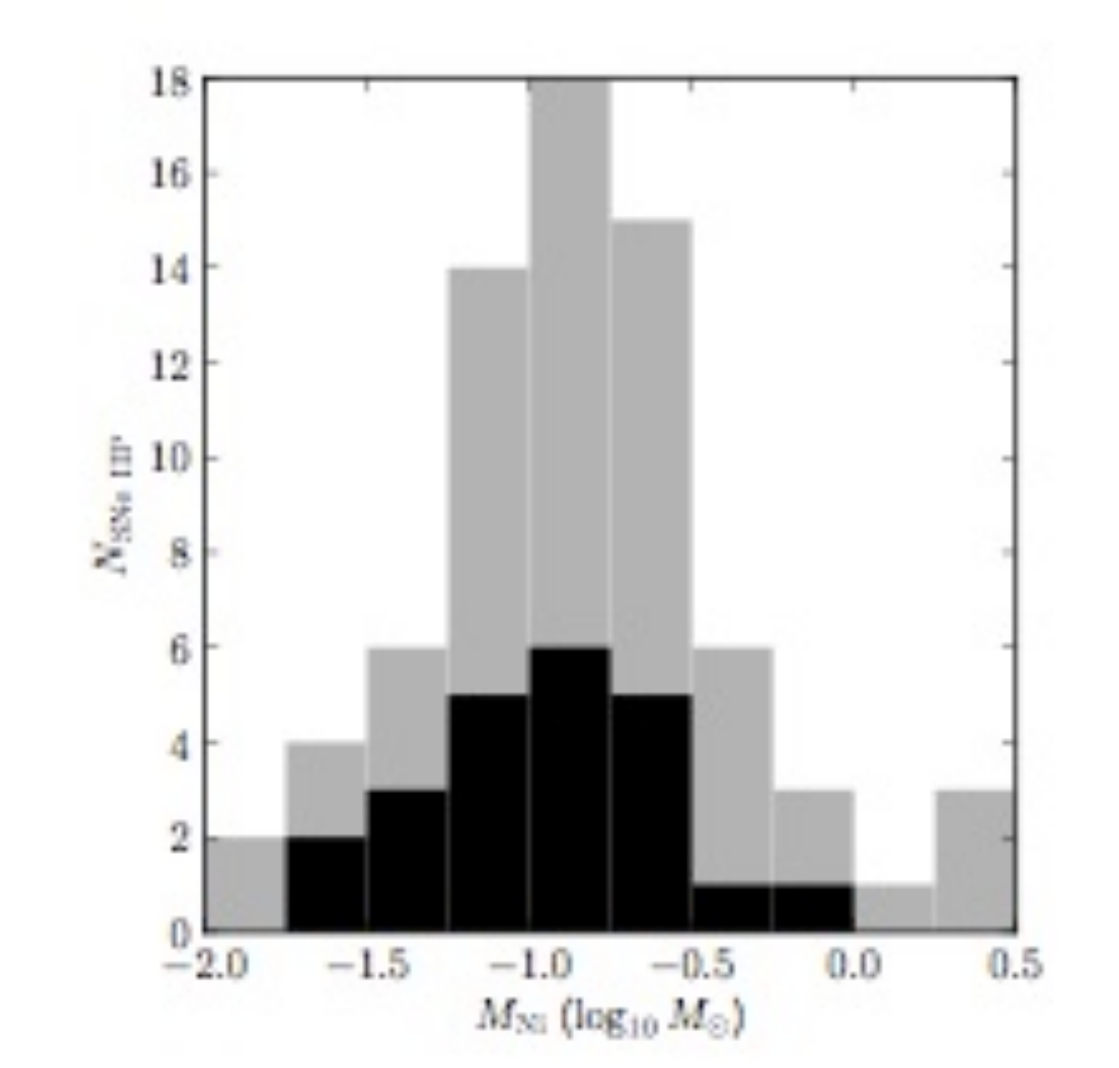
Leaman et al. 2010; Li et al. 2010

Type II SNe – Variable appearance



Anderson et al. (2014)

Very different explosions



Yet similar neutrons stars?

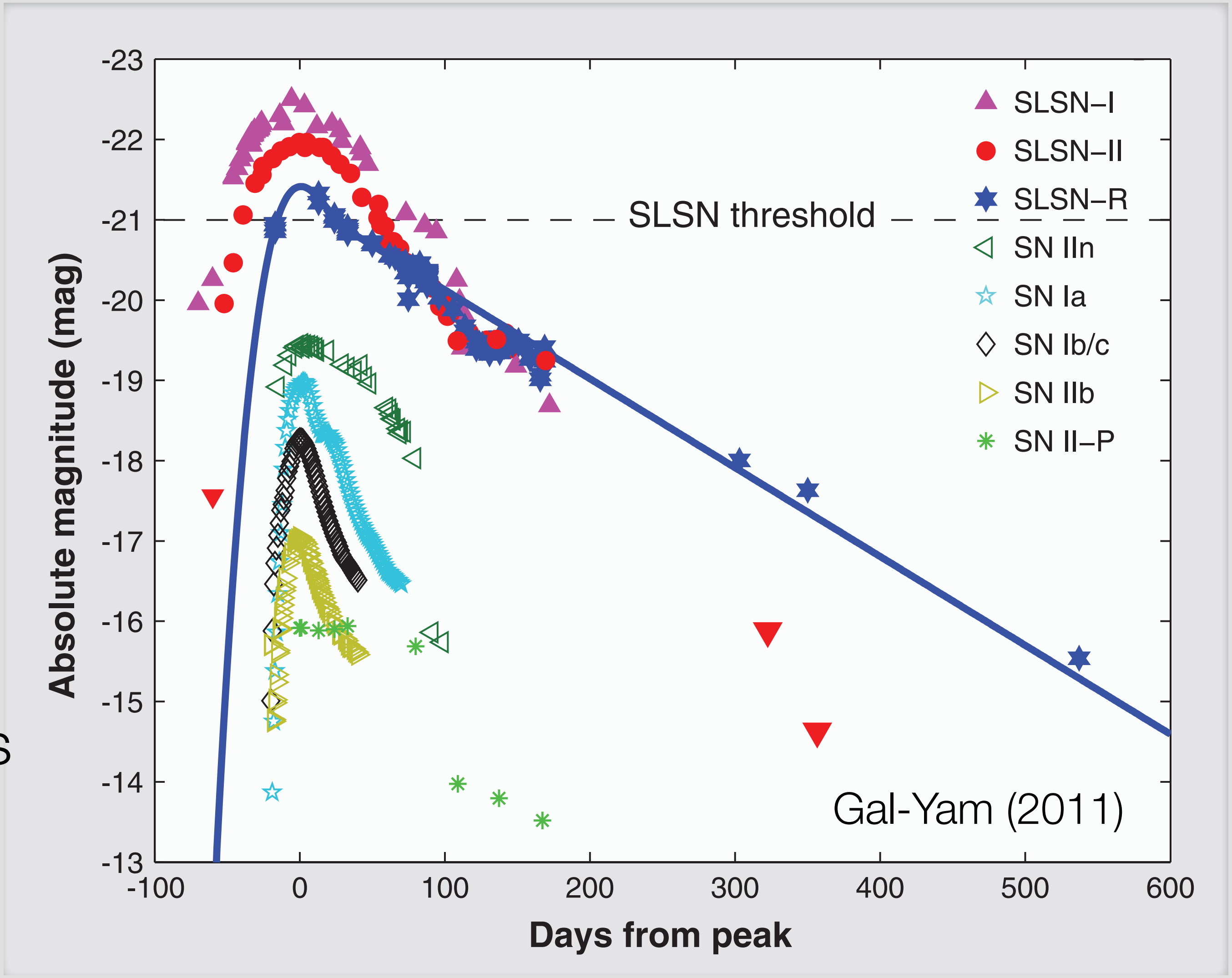
76 SNe II from PanSTARRS-1
Sanders et al. (2014)

Superluminous SNe

Very energetic explosions with $>10^{44}$ erg/s at peak

Ideas:

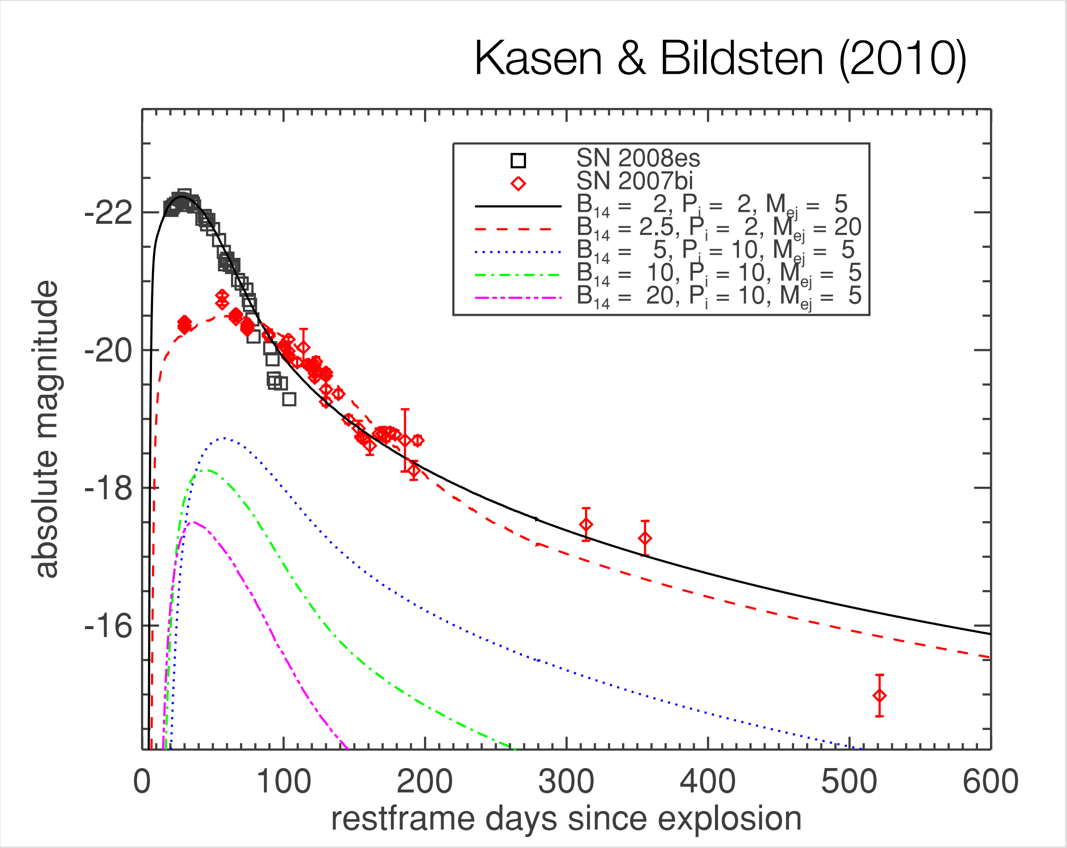
- pair-instability SNe
- circumstellar interaction
- massive winds 'bloated stars'
- 'internal engine'



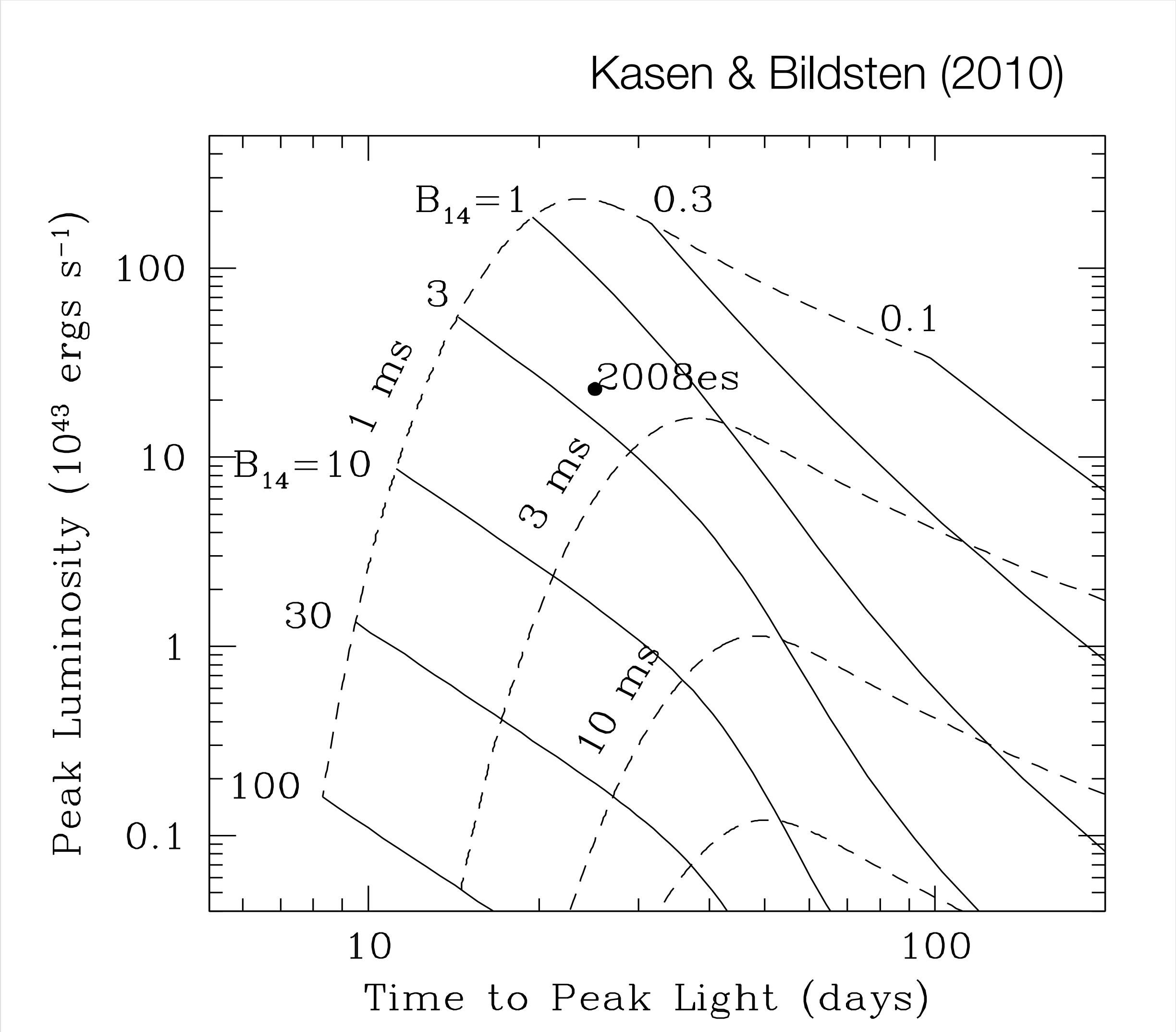
Magnetar-driven SNe

- Highly magnetic neutron star with high initial spin period
  - $B \geq 10^{14}$ G
  - P_i= 2-20 ms
  - energy release over days to weeks

Kasen & Bildsten (2010)
Woosley (2010)
Dessart et al. (2012)
Inserra et al. (2013)

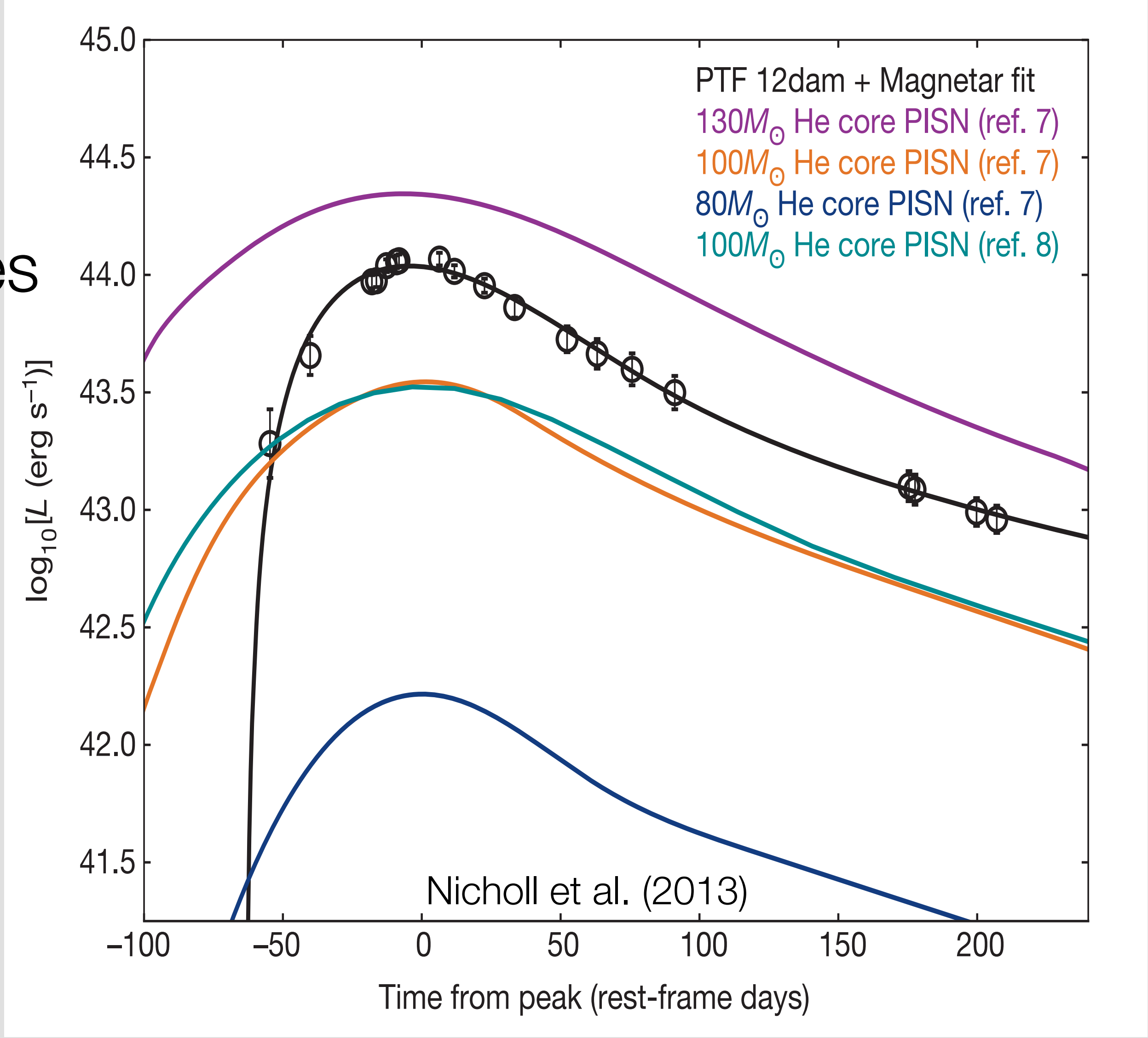


Determine the neutron star parameters



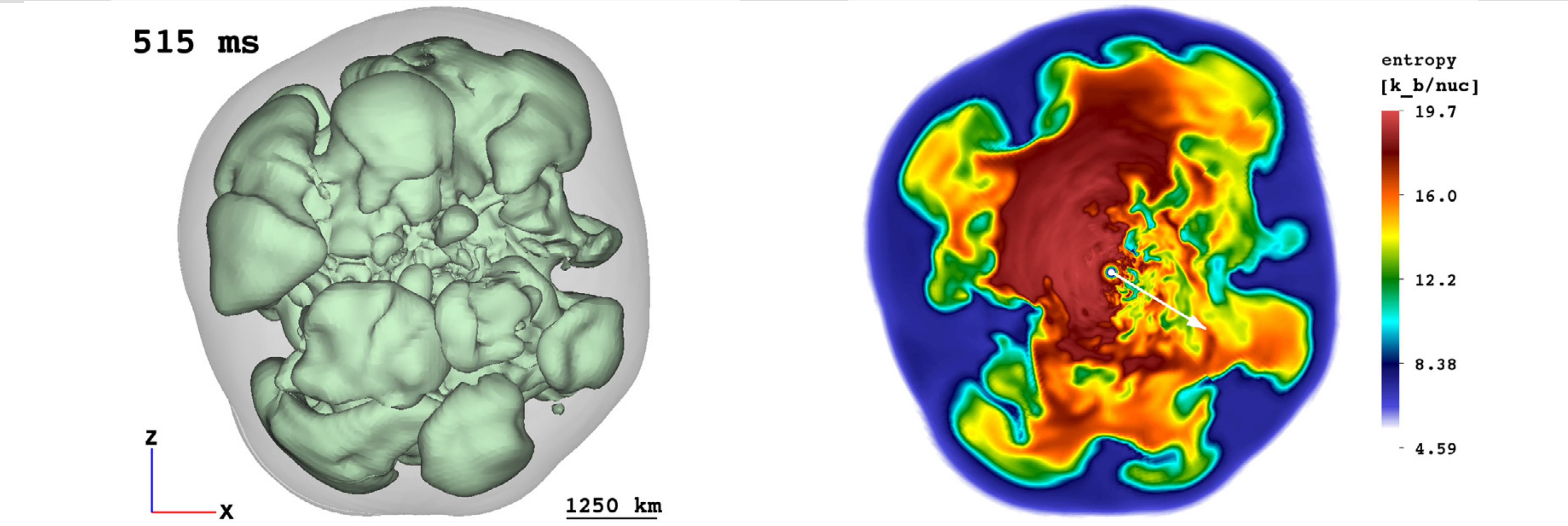
Further evidence

- Fast rise
- blue colours
- high temperatures



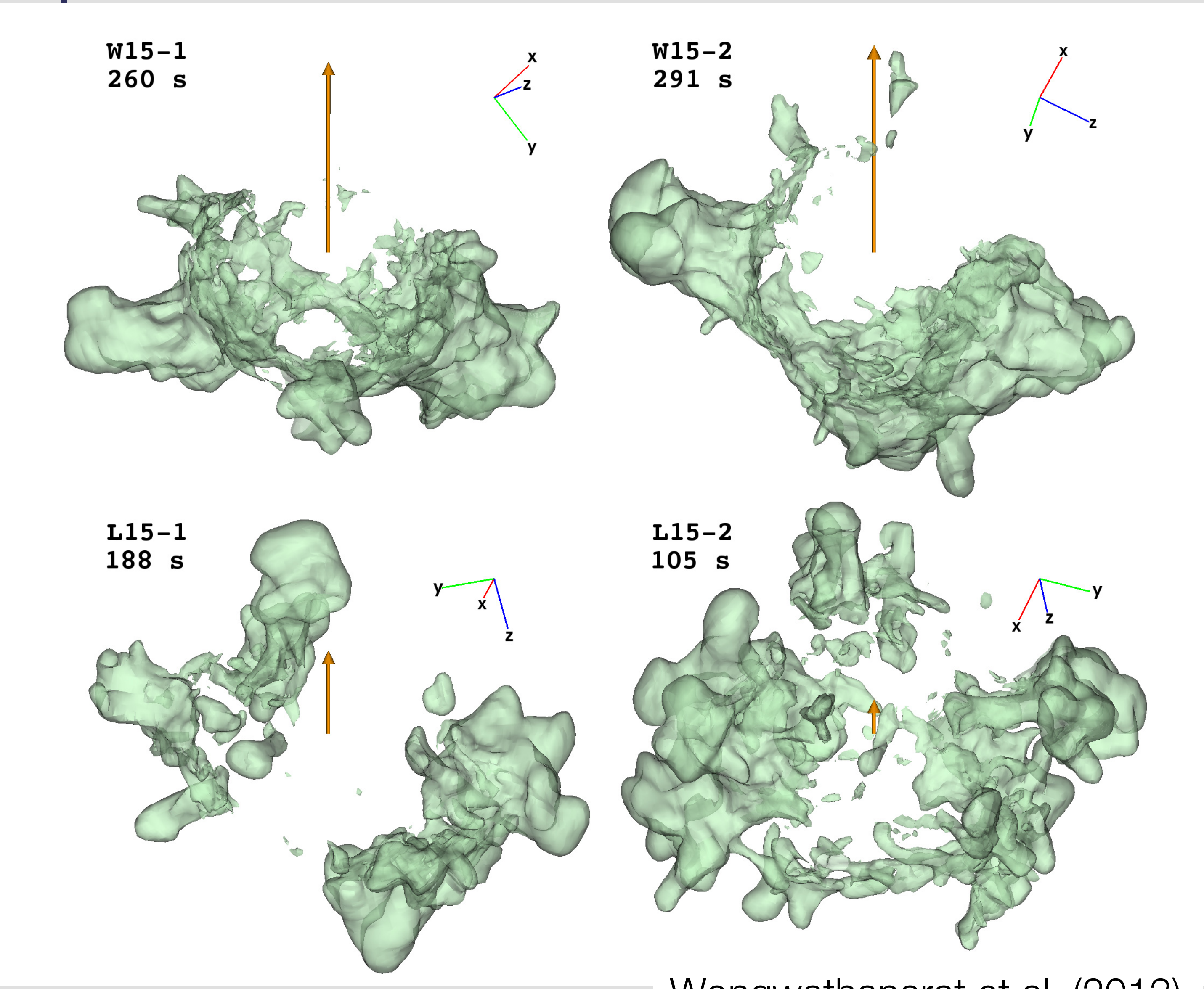
Neutron star “tug boat”

- Asymmetries in explosion models



Wongwathanarat et al. (2013)

Dependence on Ni distribution



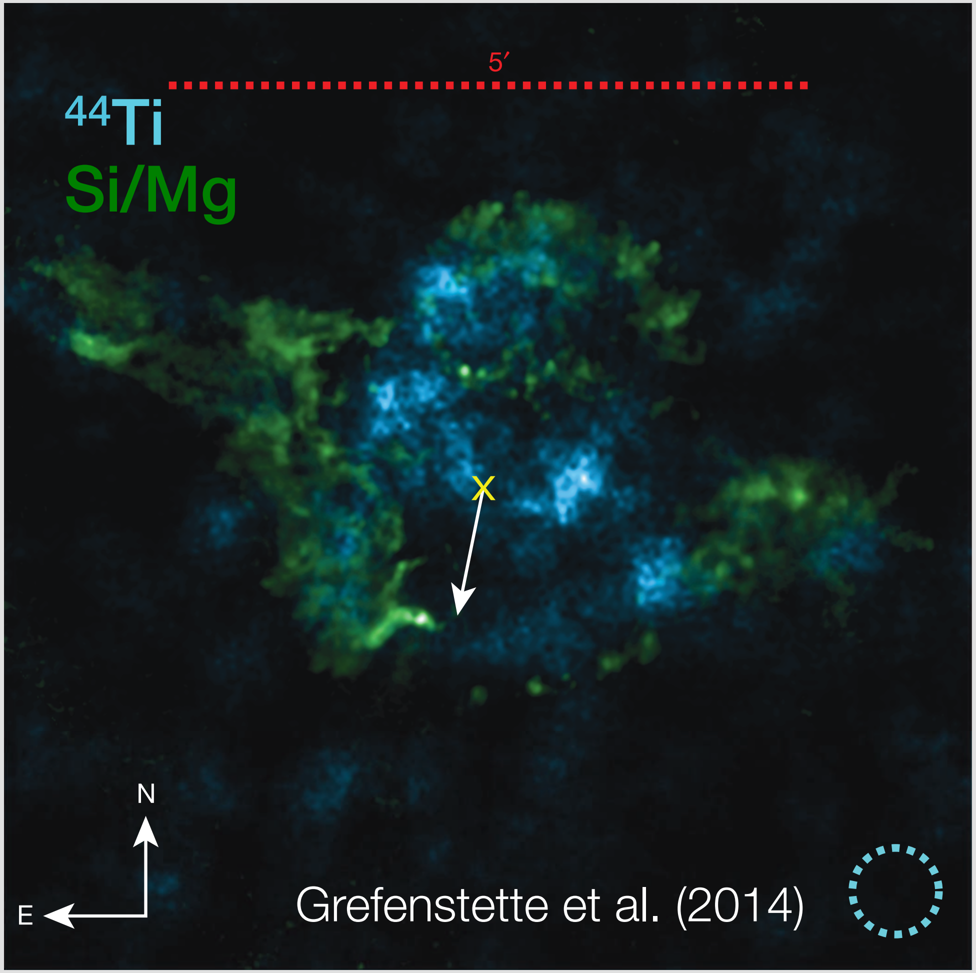
Wongwathanarat et al. (2013)

Is this observed?

- Resolved ejecta observations so far limited
  - SN 1987A
- Ni (Fe) distribution in SN remnants often difficult
  - stable Fe
  - pre-explosion Fe
- Other elements more easily accessible

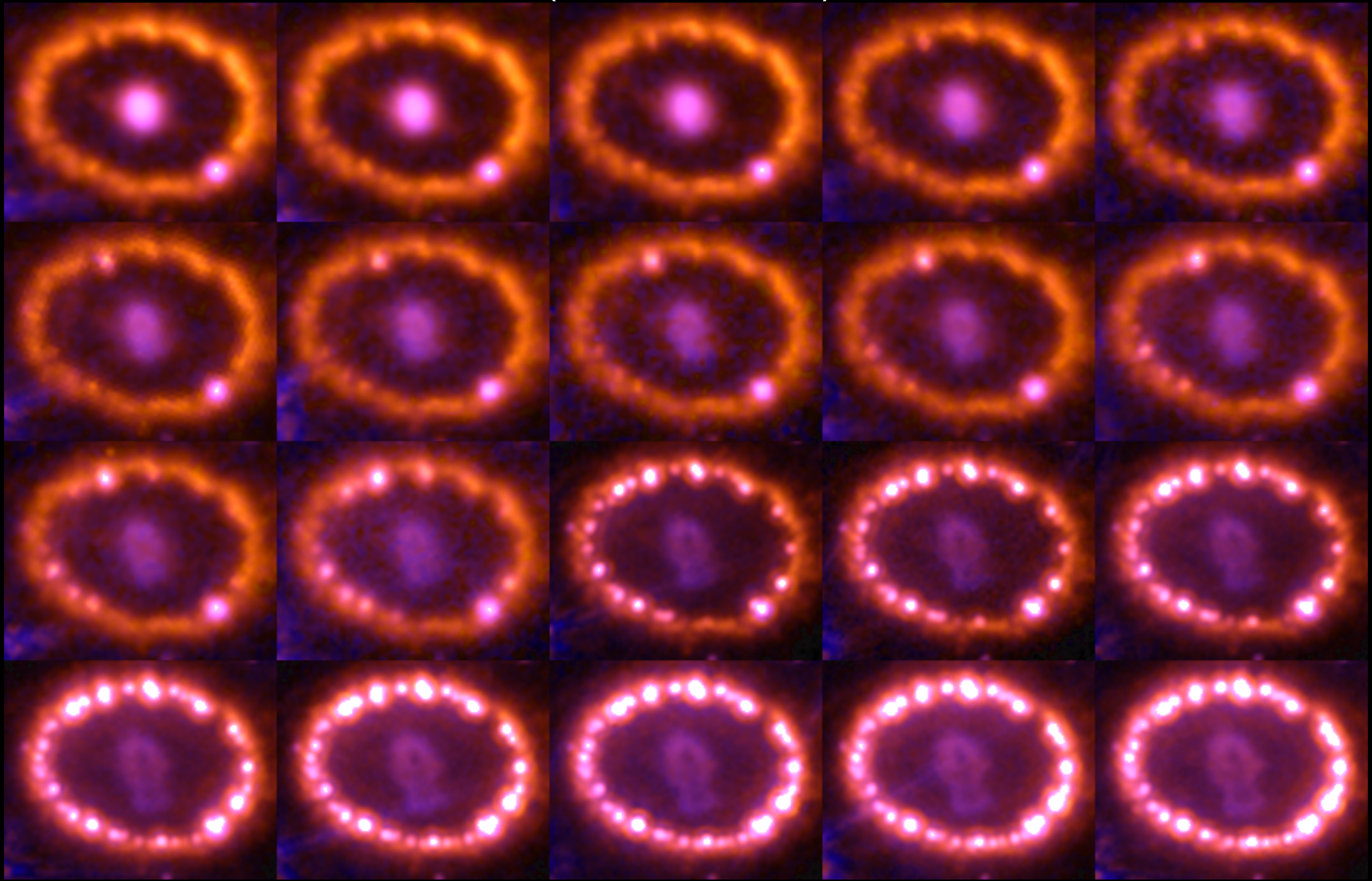
Cassiopeia A

- Asymmetry in ejecta
  - ^{44}Ti distributed differently from Si and Mg
  - ‘opposite’ to the motion of the compact object



SN 1987A evolution

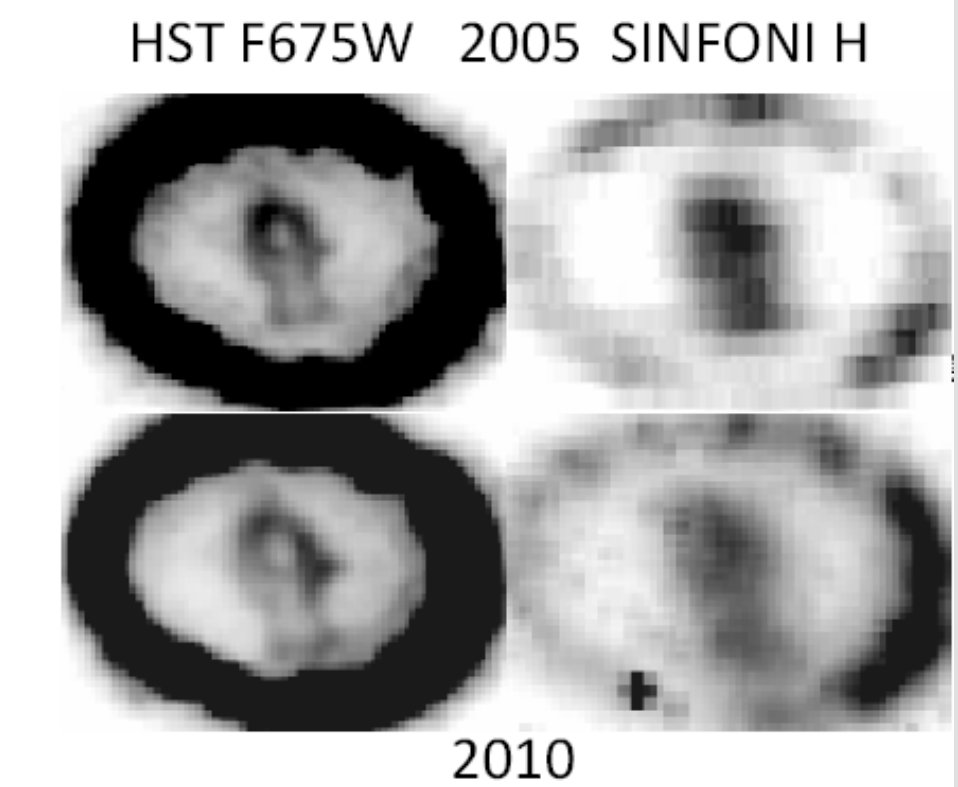
(1994-2010)



The inner ejecta

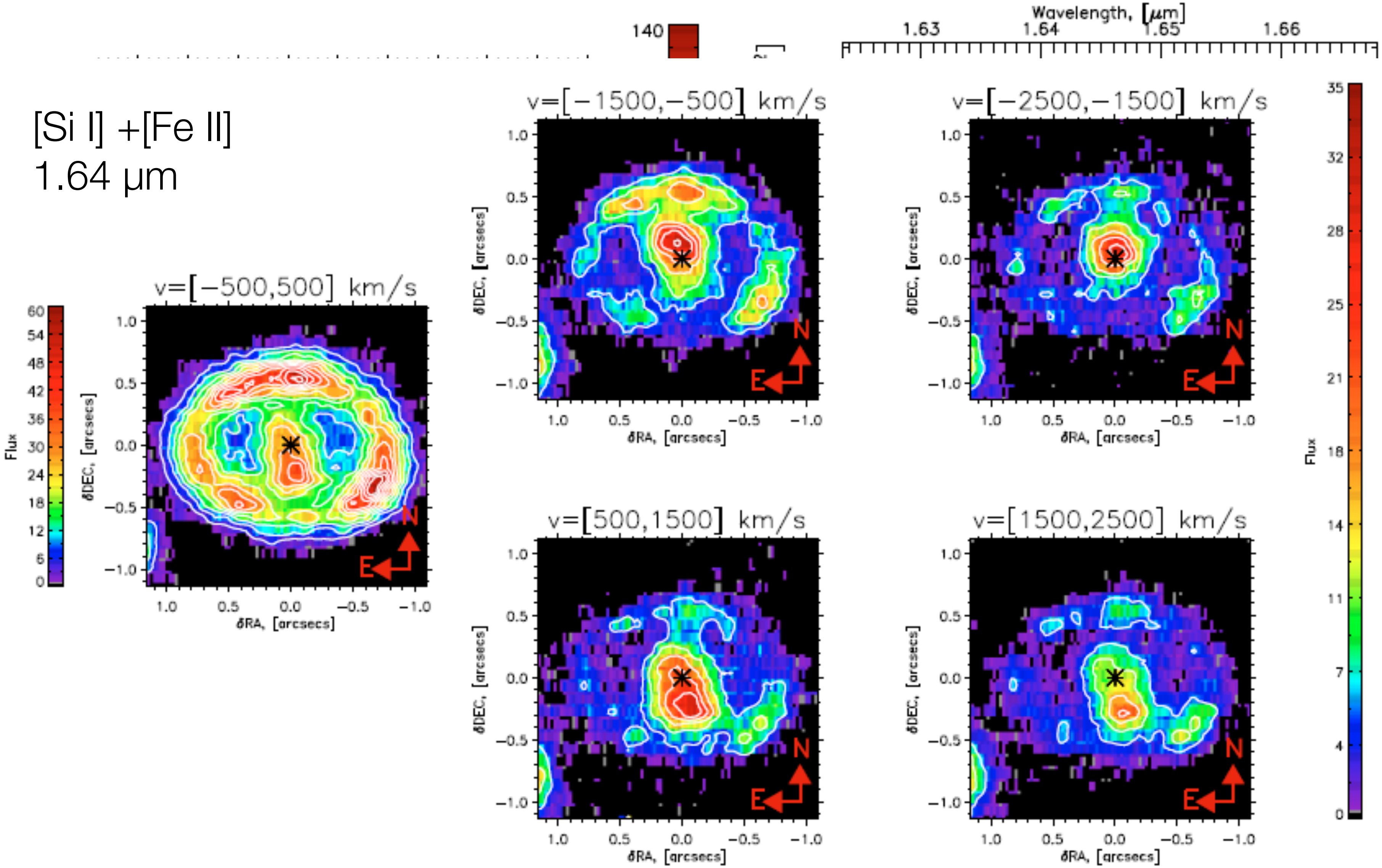
Comparison optical vs. IR

- optical
  - heated by X-rays
- IR
  - radioactive heating



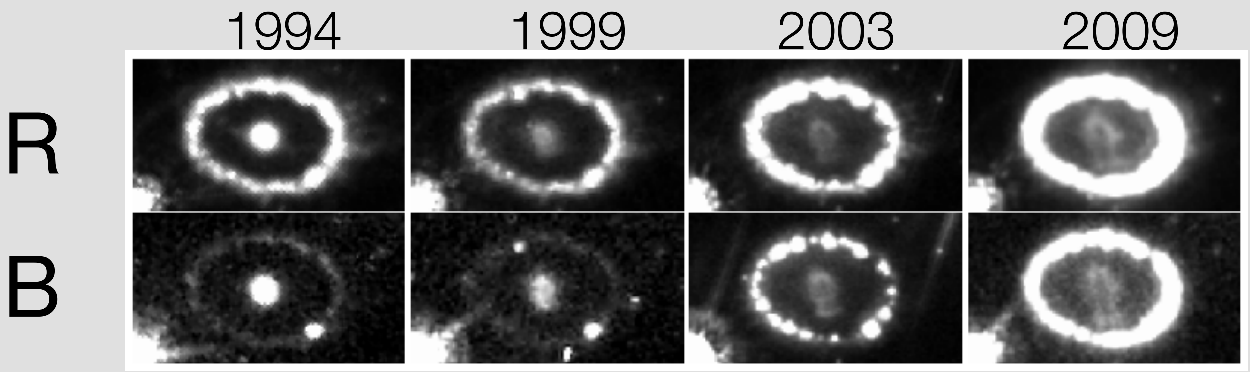
Asymmetry in the ejecta

[Si I] +[Fe II]
1.64 μm

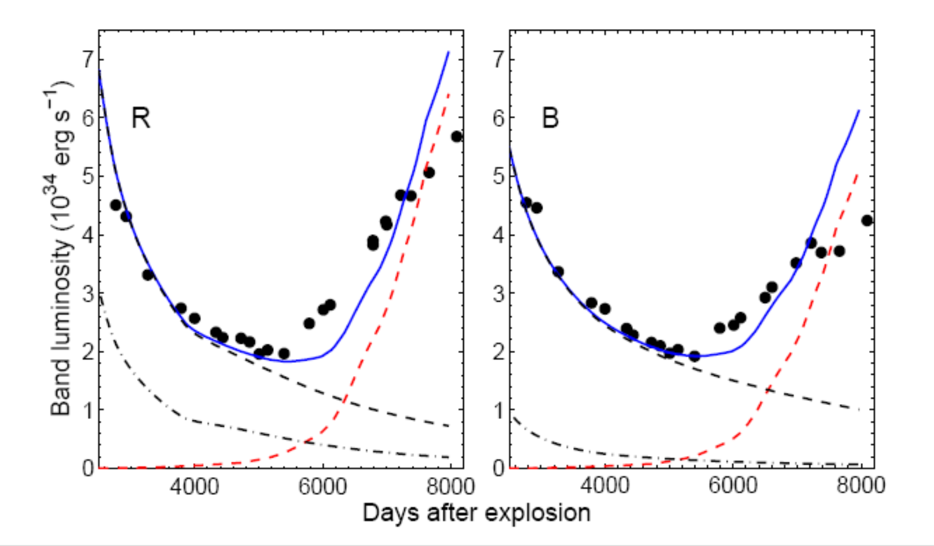


The next surprise

X-raying the ejecta of SN 1987A



Larsson et al. 2011



- flux of the inner ejecta has increased again (starting at about 13.5 years)
- sign of additional energy input

What's happening?

The outer ejecta has reached the equatorial ring and creates shocks in the dense material

X-rays are emitted in all directions

heat the inner ejecta

Other possibilities excluded

- reverse shock in HII region → no increase in (broad) Lyα or Hα observed
- pulsar → no trace so far (e.g. in radio or X-rays)
- transition from optically thick to optically thin dust → unlikely to occur at this point

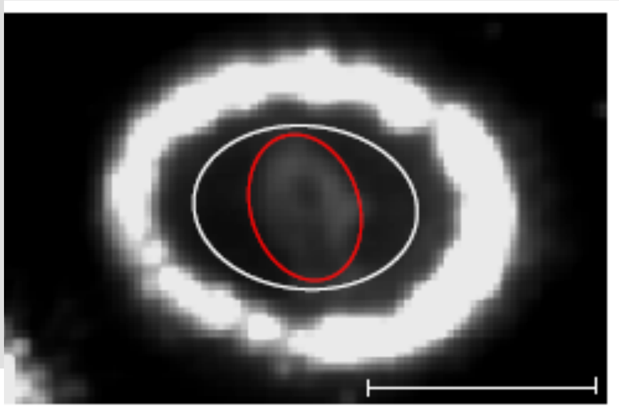
Transition to SN remnant

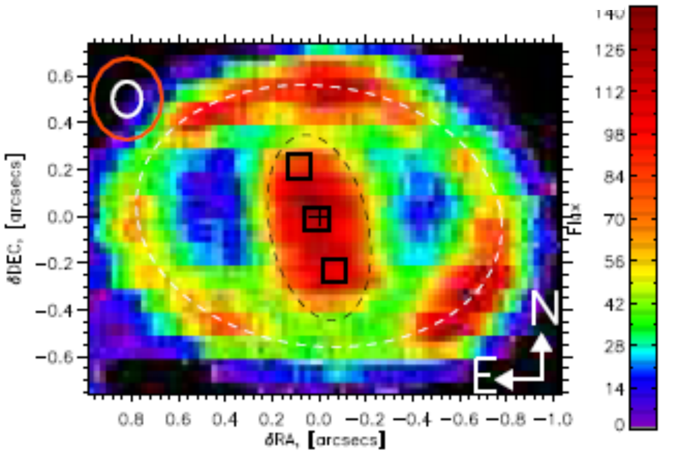
SN 1987A no longer powered by radioactive decays, but the kinetic energy from the shocks

Heating on the outskirts → shell-like structure

Different from the Fe-core still heated by ^{44}Ti

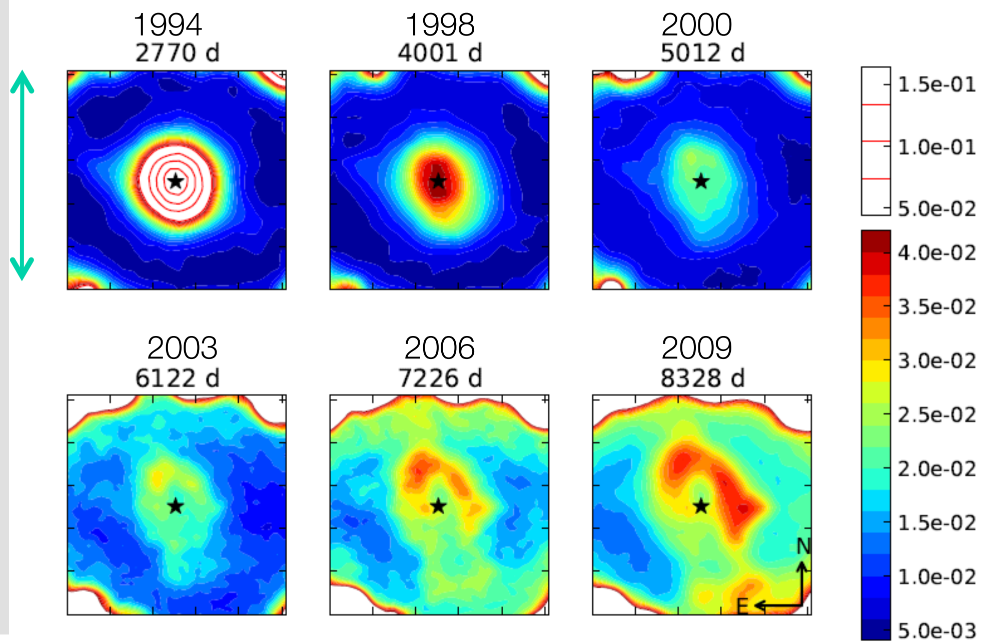
- Kjær et al. 2010;
- SINFONI observations



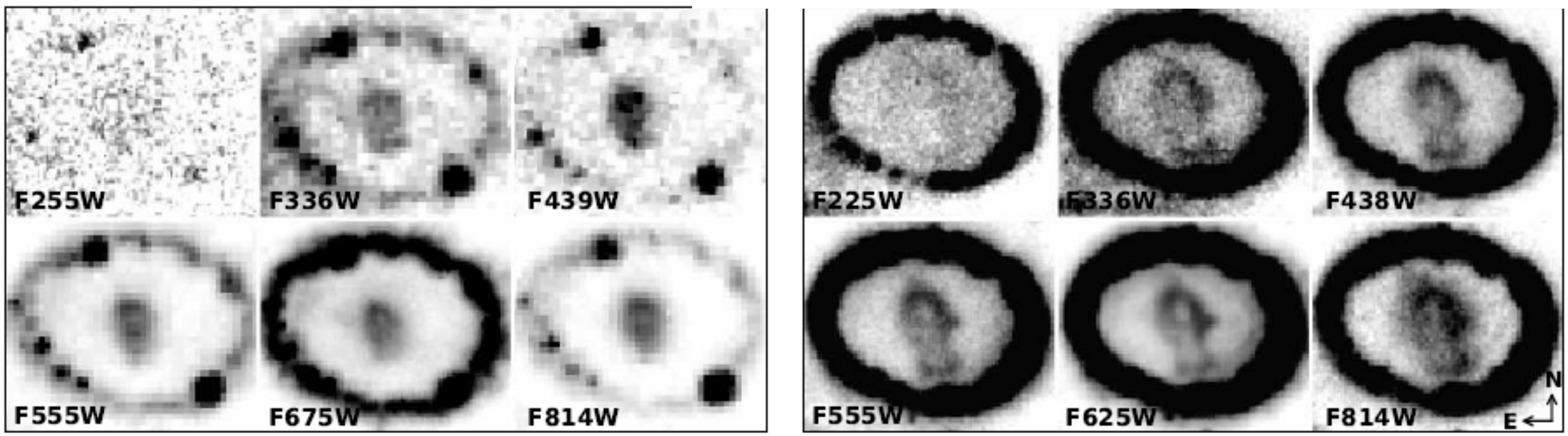


Evolution of the inner ejecta

Clear change in morphology at optical wavelengths



Larsson et al. 2013

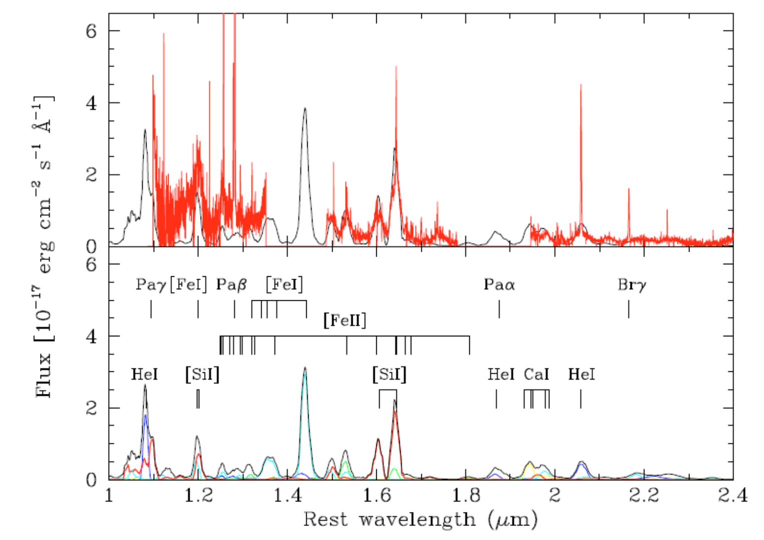


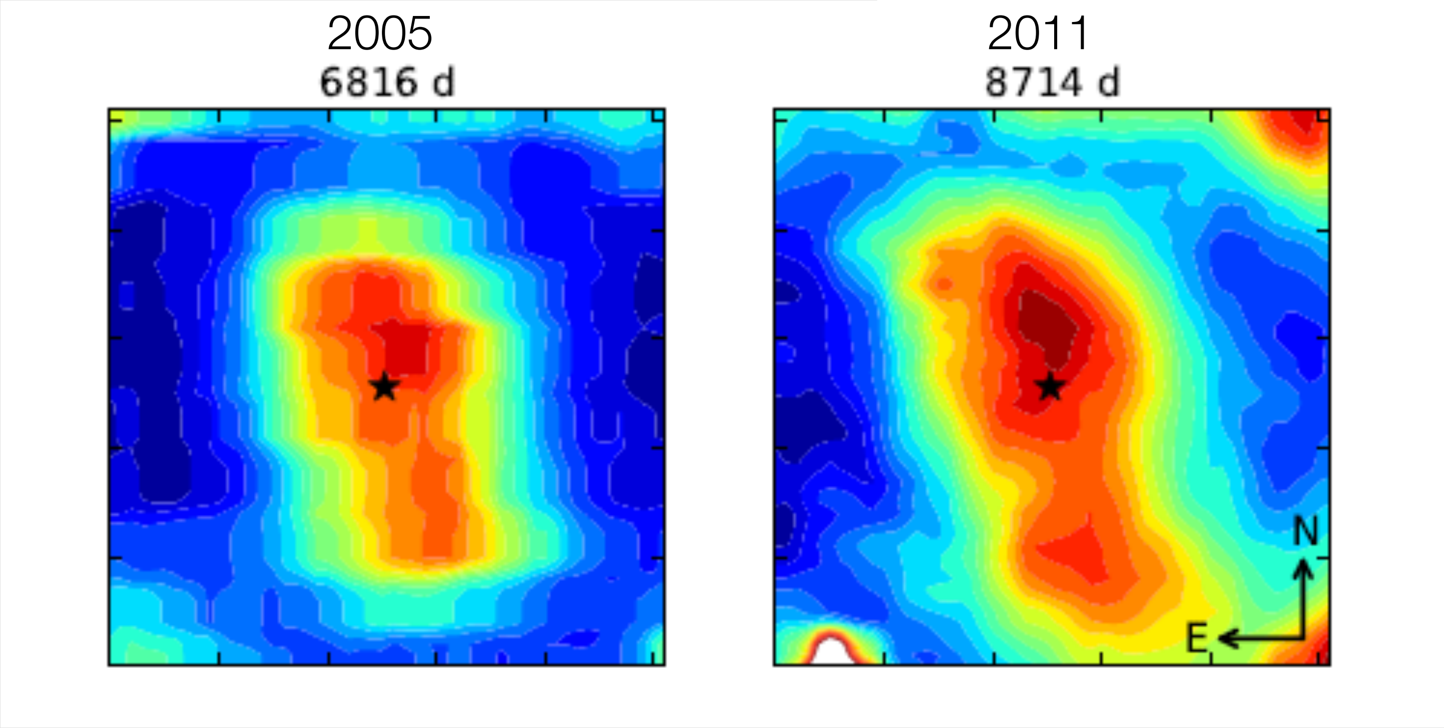
13 Nov 2000

12 Dec 2009

IR observations

[Si I]/[Fe II] 1.644μm emission



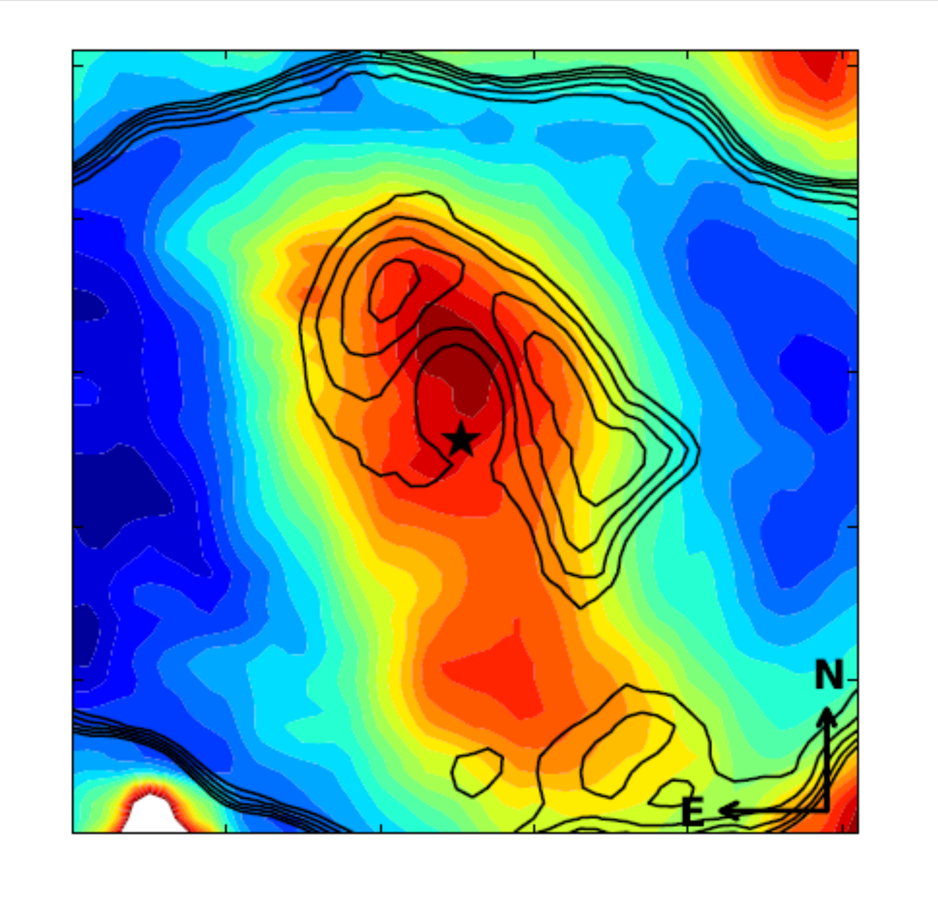


Complementary optical and IR observations

Optical emission clearly different from the IR

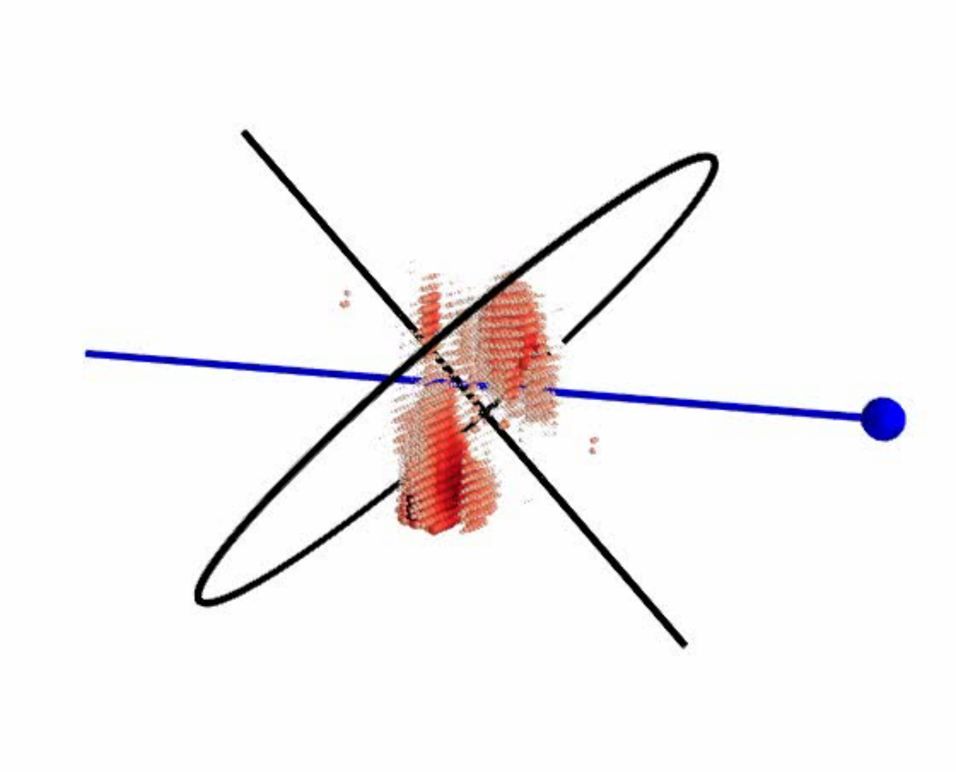
- [Si I]+[Fe II] concentrated towards the center
- Optical (Hα) in a 'shell'

➢ Different energy sources



3-dimensional picture

- Derived from [Si I]+[Fe II] 1.644μm emission
- Emission in the plane of the equatorial ring
- Clumpy distribution
- Extending out to ~4500 km s^{-1}

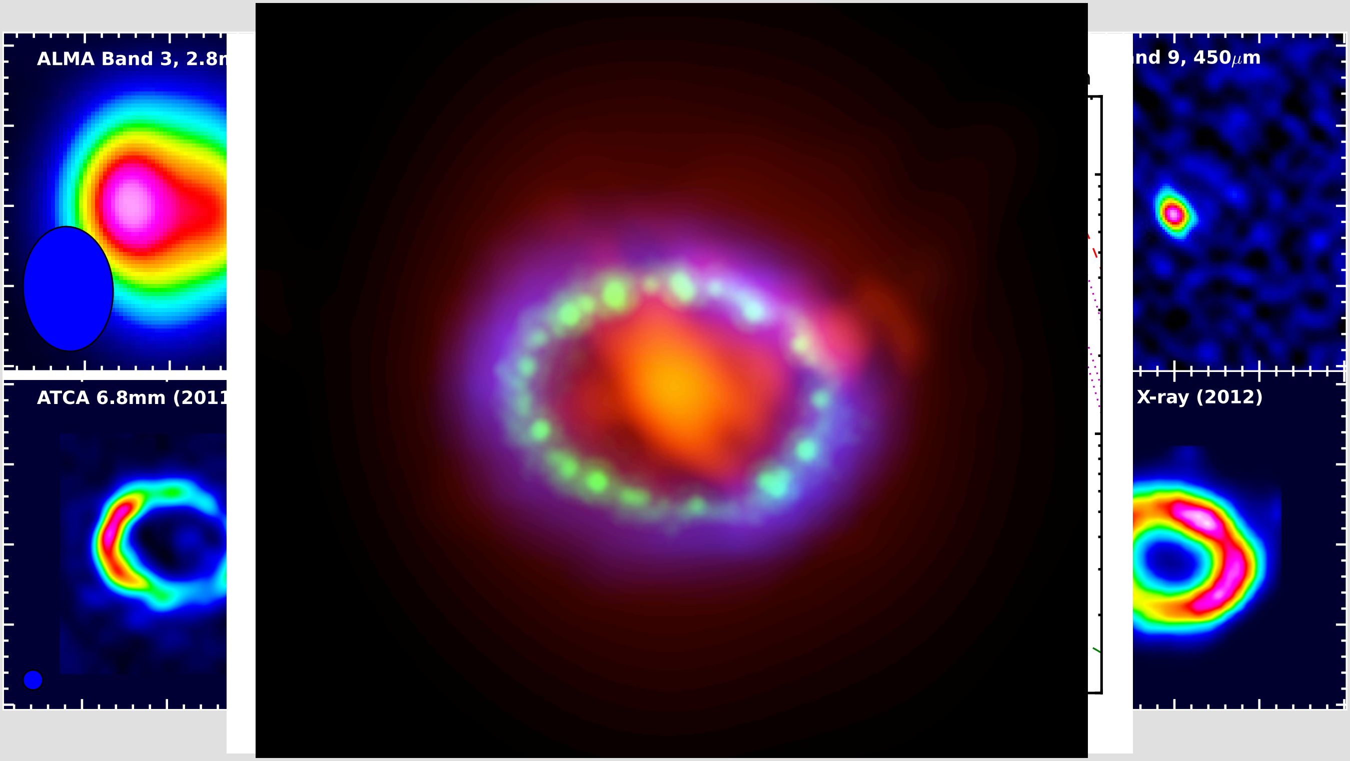


Larsson et al. 2013


No sign yet of a neutron star

Dust in SN 1987A

- Synchrotron emission from the ring
- Thermal dust in the inner ejecta



Indebetouw et al. 2014

Summary

- Connection between SN explosion and neutron star difficult
  - time scales
  - isolating explosion material from SN shocks in the interstellar
- Some SNe may be powered by the neutron star formed in the explosion
  - “fast” rise time + high luminosity
  - can be provided by the spin down energy of a magnetar

Summary

Cas A

- indications of asymmetric distribution of ^{44}Ti opposite compact remnant

SN 1987A

- first direct look at an explosion
  - resolved inner ejecta (iron core) are the immediate reflection of the explosion mechanism
  - confirmation asymmetries in the explosion
- possibly best chance to look for a neutron star in the coming years
  - illumination by external sources?
  - dust?