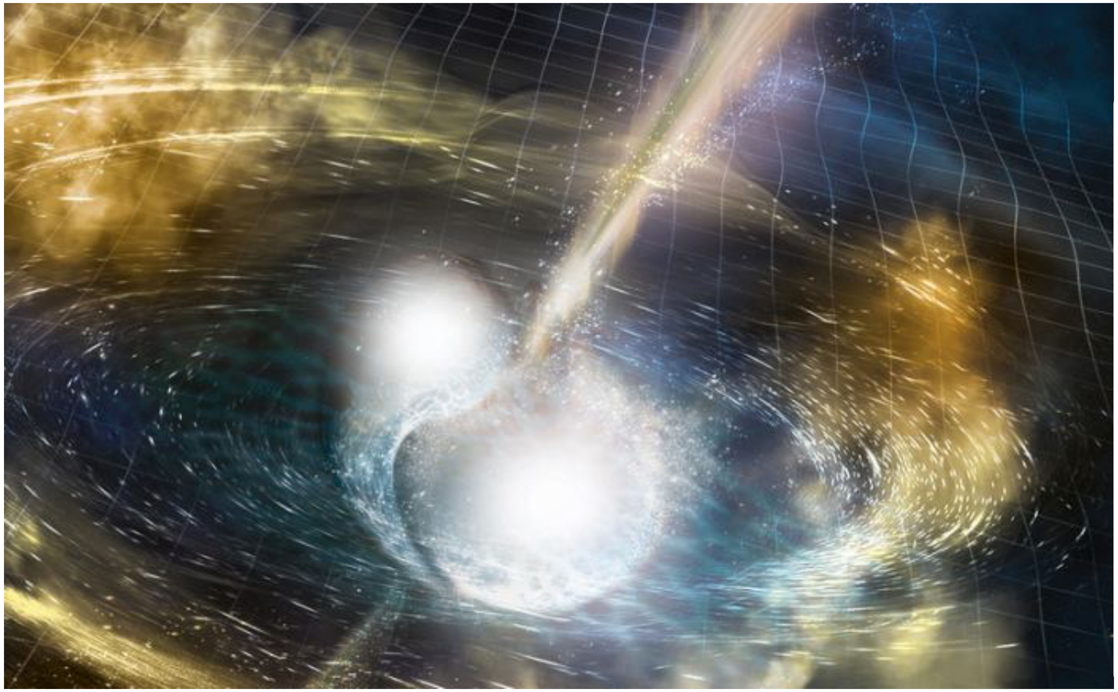
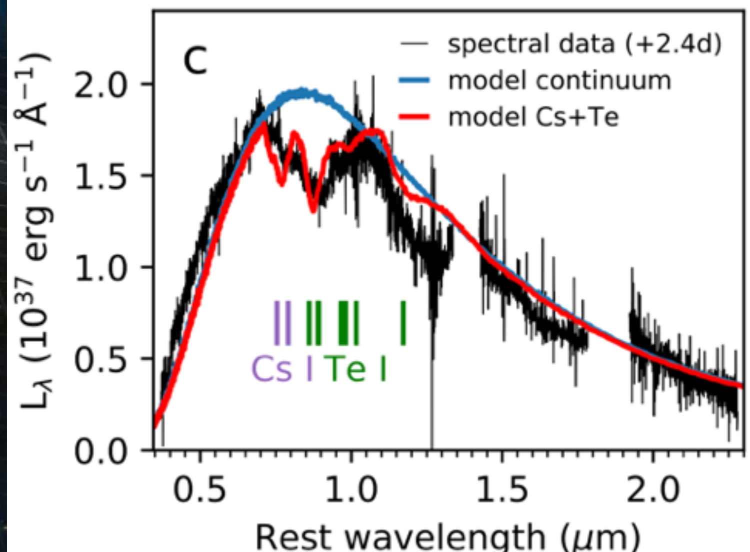
Modelling light curves and spectra of supernovae and kilonovae





Anders Jerkstrand, MPI for Astrophysics

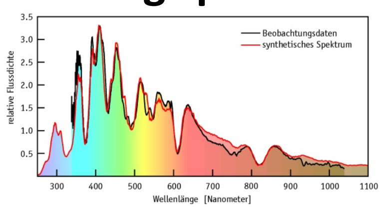
Max Planck Institute for Astrophysics

Photospheric vs nebular phase

Long escape time for radiation
→ $L_{out}(t) = \int_0^t K(t')L_{in}(t')t'$

Spectra probe surface layers only

Many lines excited and significant optical depth –>
Scattering spectra



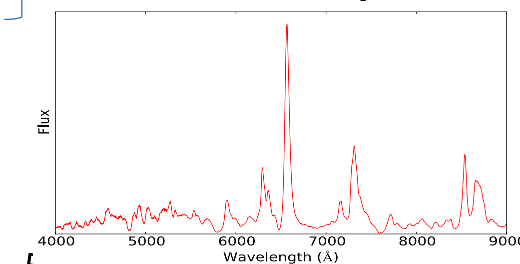
Simple microphysics (LTE)

Short escape time for radiation
→ $L_{out}(t) \sim L_{in}(t)$

Spectra probe <u>all</u> ejecta

Few lines excited and reduced optical depth -->
- More variation in line emissivity
- Fewer ”P-Cygni” line profiles

Emission-line spectra



Radioactivity → linear in mag scale

Complex microphysics (NLTE)

Luminosity

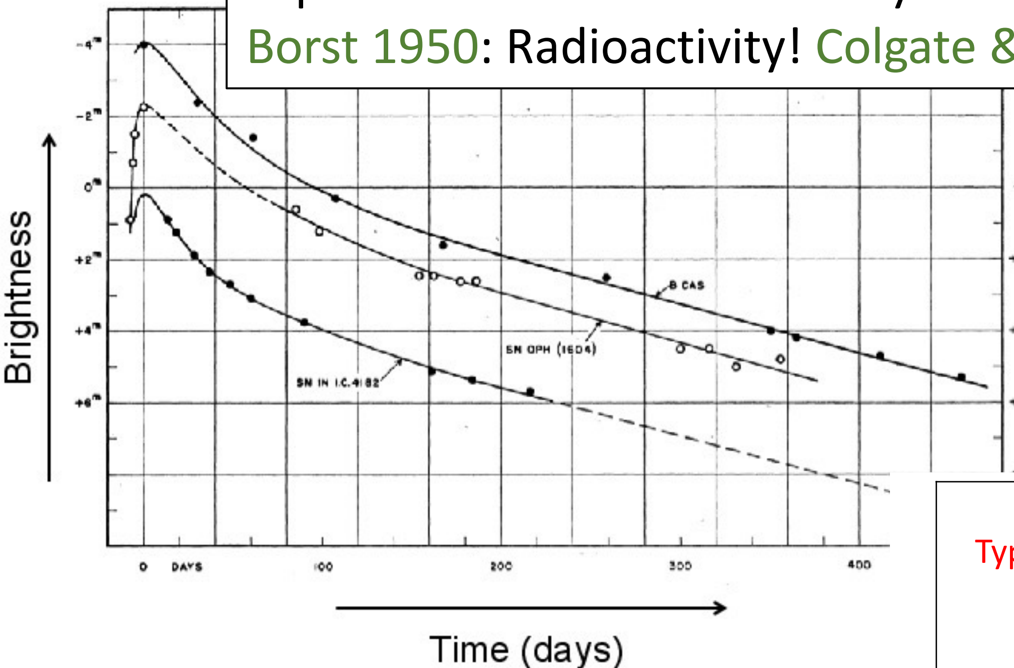
Time

Uniform ball: t_{thick} = 80d $kappa_{0.1}{}^{1/2} M_{Msun} E_{51}{}^{-1/2}$

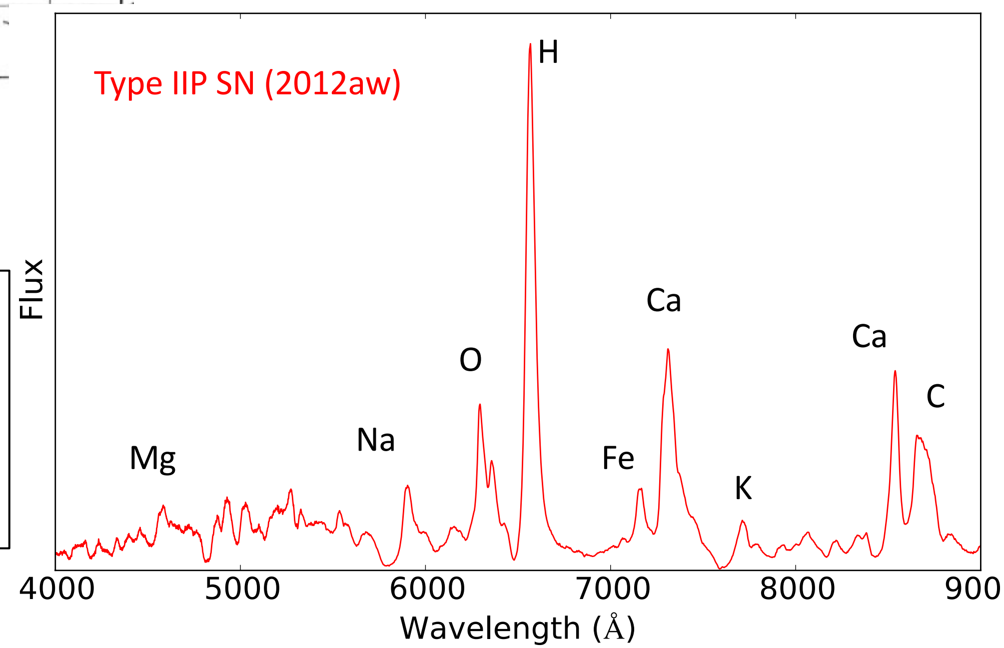
Transition epochs: IIP SNe: ~**140d**, Ibc SNe: ~**40d**, KN: ~**2d**

The nebular phase

Exponential tails discovered by Baade+1945.
Borst 1950: Radioactivity! Colgate & McKee 1969: $^{56}Ni/^{56}Co$!

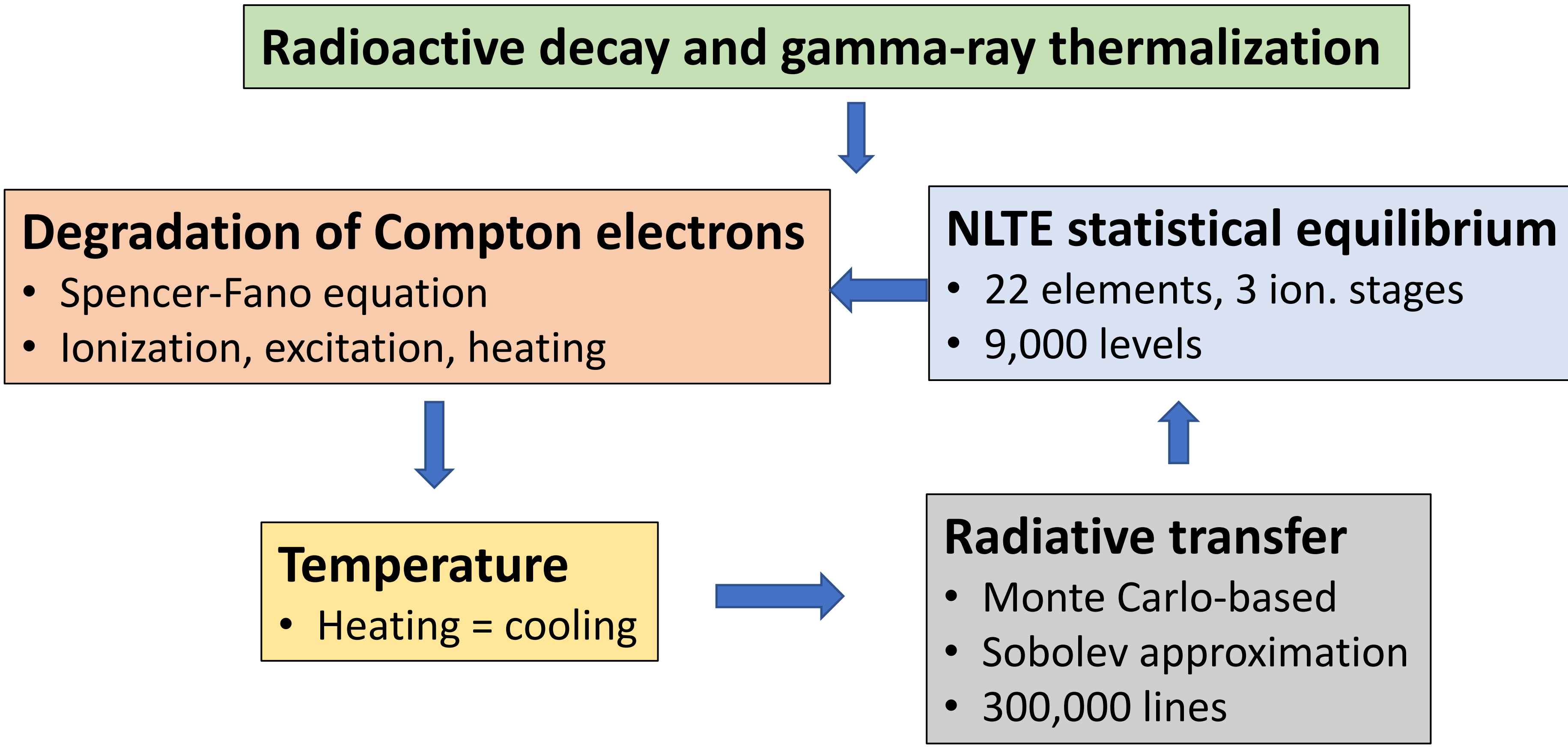


- ~100d – 1000d post explosion
- Emission lines from all nuclear burning regions → window on nucleosynthesis and ejecta morphology.



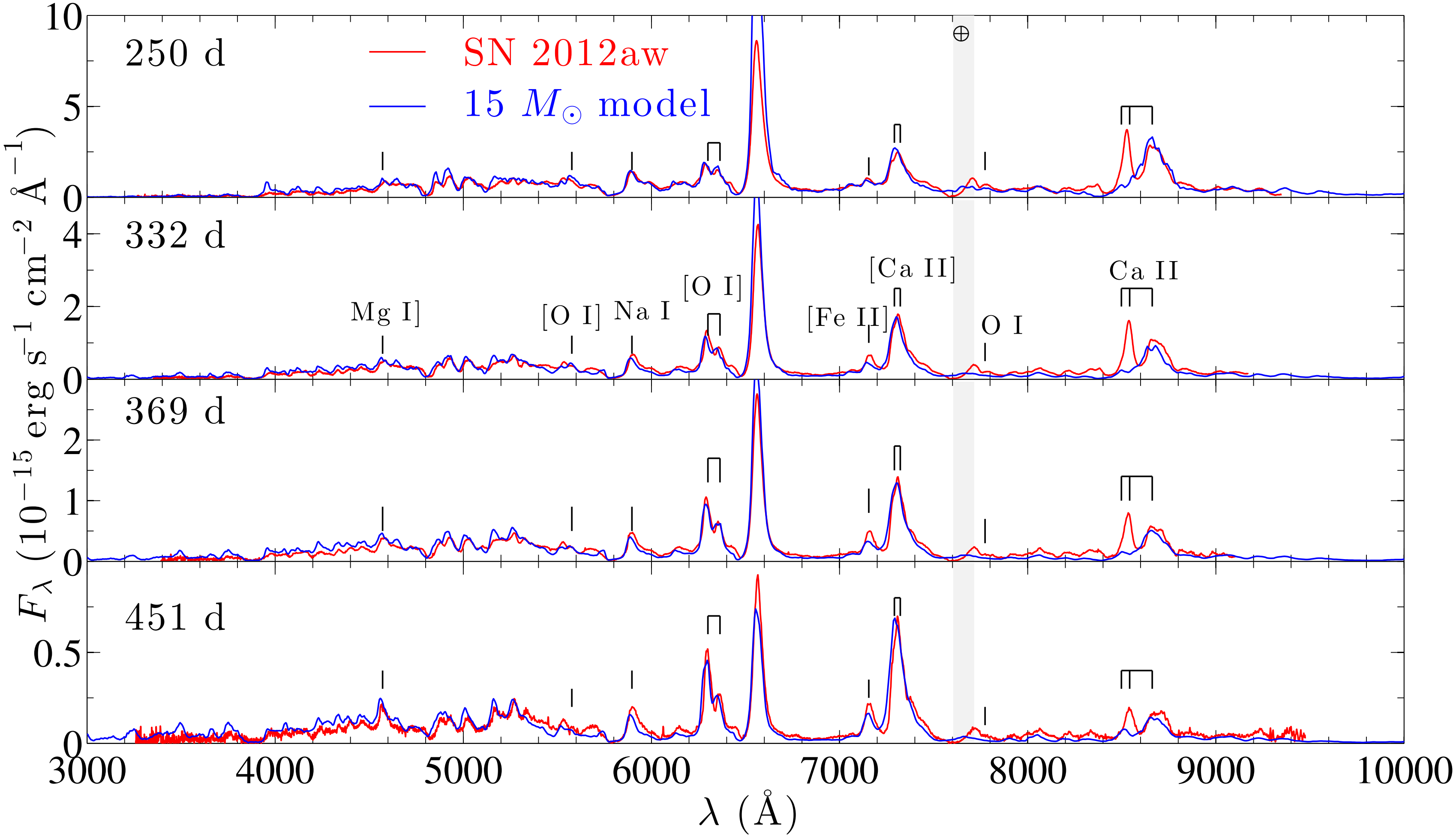
- Data collection rate: ~5-10 SNe per year (<1% of all discovered SNe).
- Current number of SNe with nebular spectra: ~50-100

The SUMO code (models nebular-phase spectra) AJ+2011, 2012



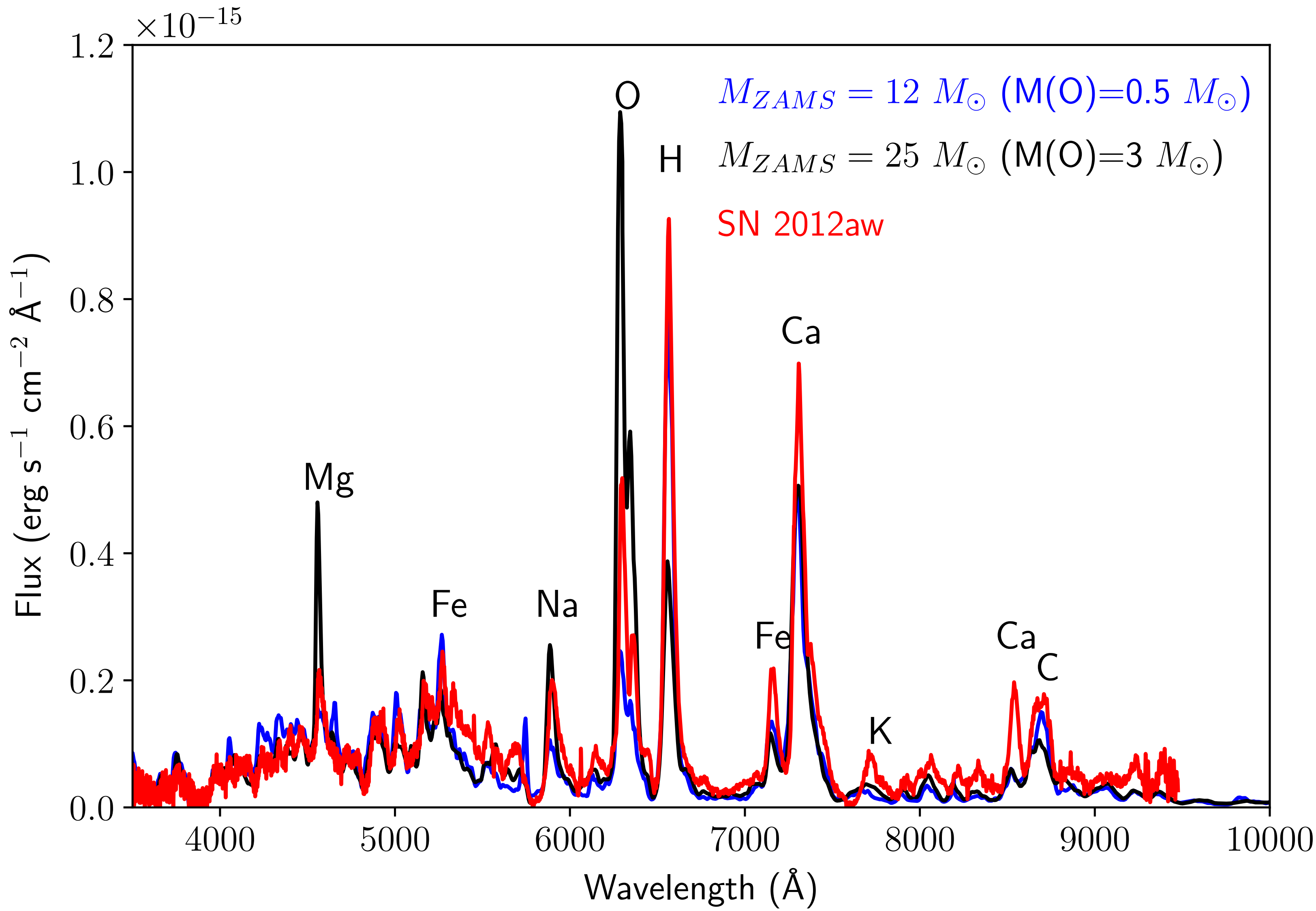
- Code is 1D but allows treatment of mixing by “virtual grid method”.

Type II supernovae. Breakthrough a few year ago: *Model spectra start to agree quite well with observed spectra*



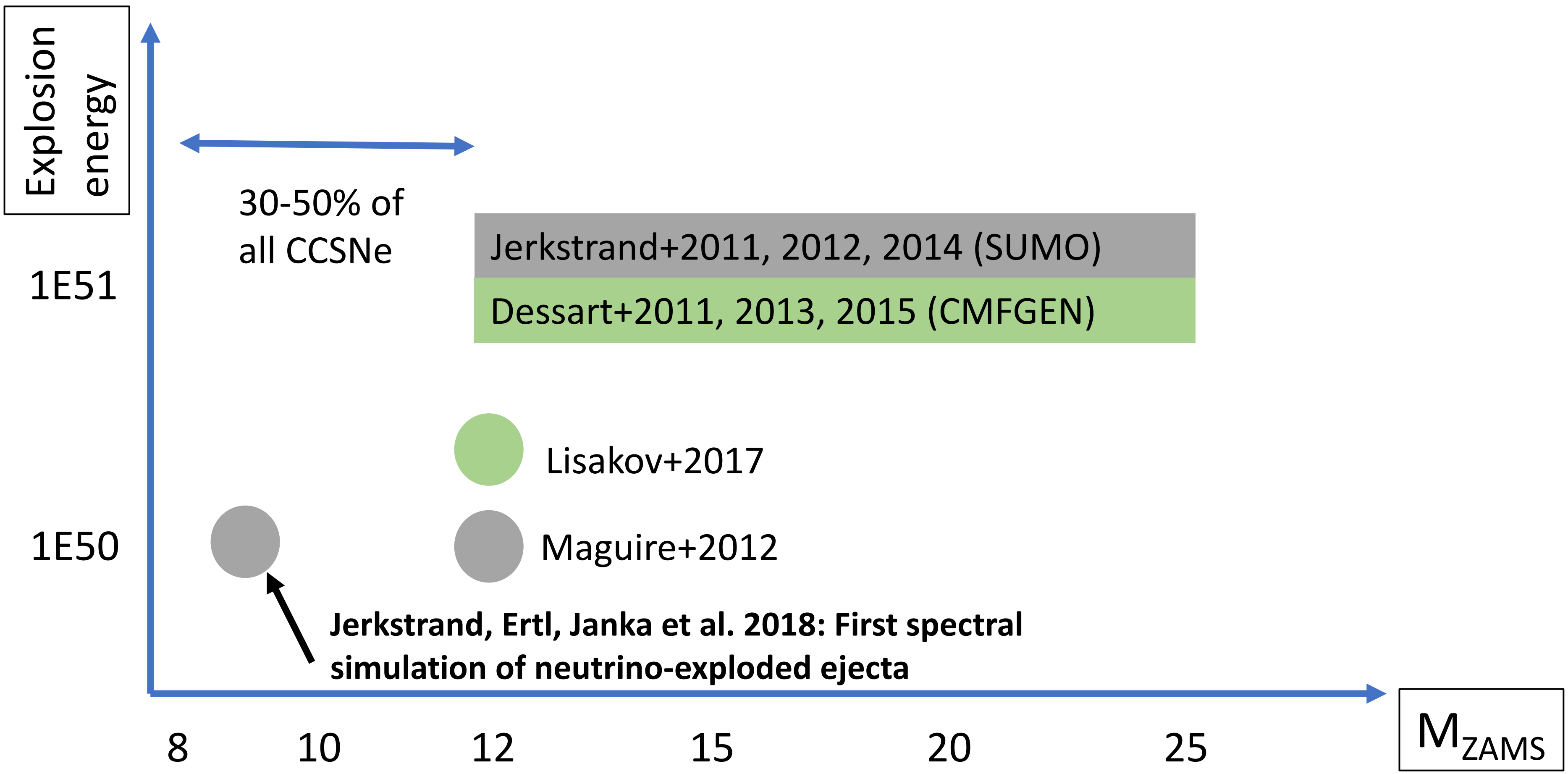
AJ+2014. See also Dessart+2013.

Can start to make detailed model comparisons, e.g. find best-fitting M_{ZAMS}



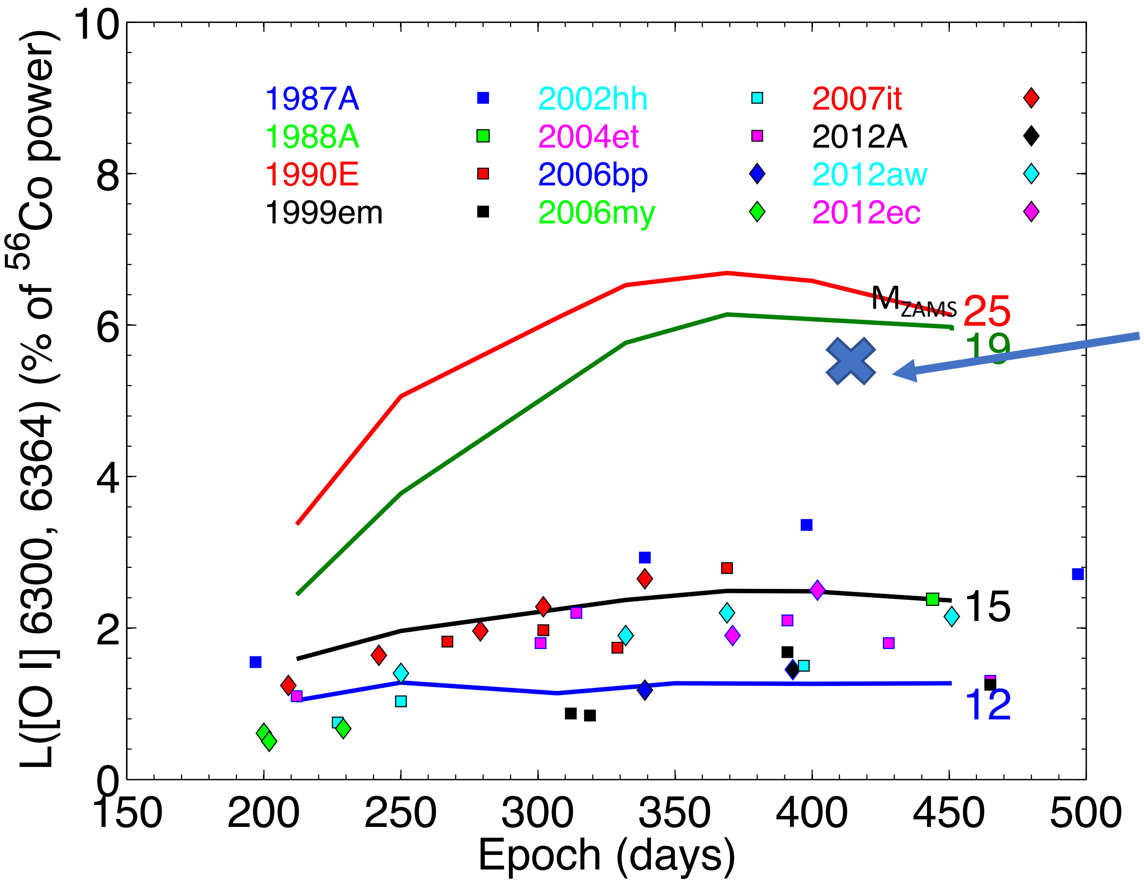
AJ+2014.

Available nebular-phase models for Type II SNe



Standard IIP supernovae: explosions of M_{ZAMS} ~ 10-17 $M_\odot$ stars

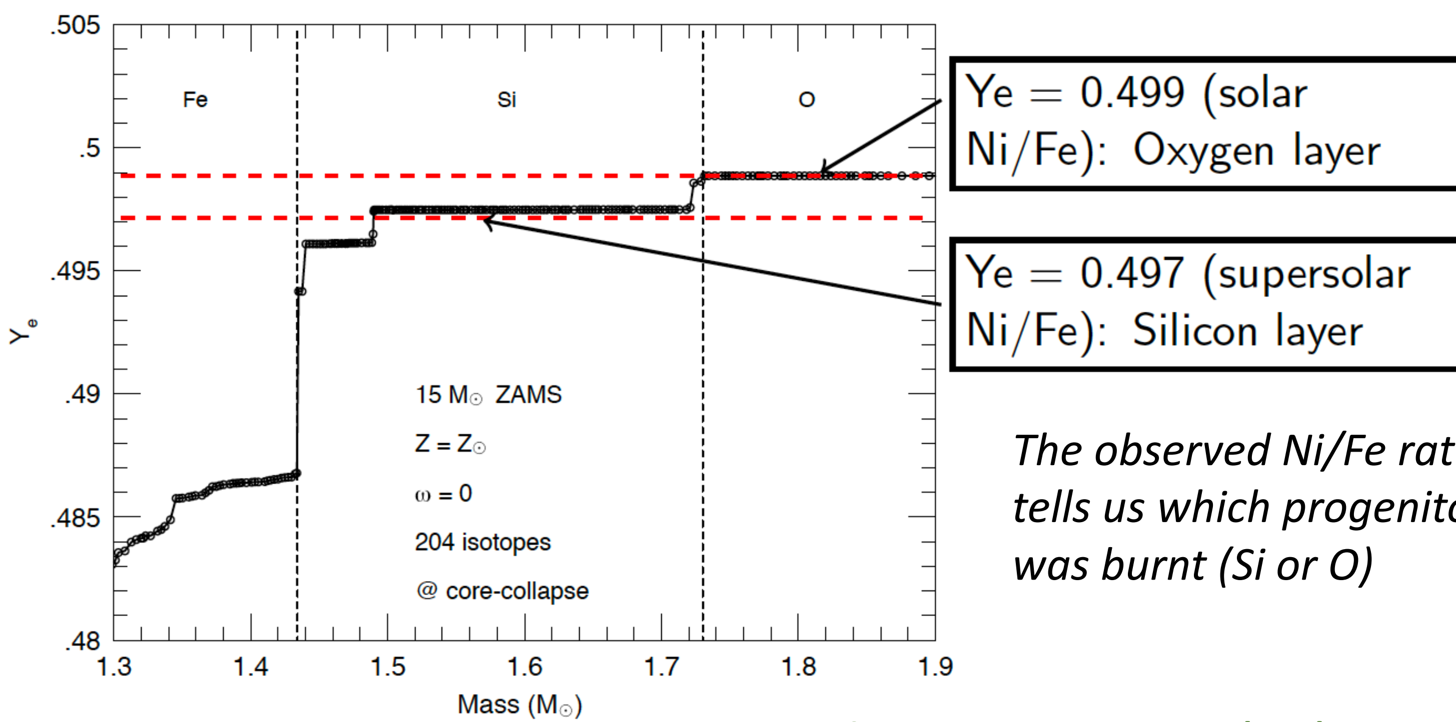
AJ+2015 (MNRAS), AJ in prep.



- "RSG problem" (Smartt 2009) is real: confirmed from two directions.
- However, first object with possibly M > 20 M_{sun} now discovered (Anderson+2018): low metallicity.
- Same trend for Type IIb SNe (AJ+2015 (A&A))

Diagnosing the explosive nucleosynthesis: Ni/Fe ratios

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine 1989, Macalpine 2007
SN 1987A	0.5 – 1.5	Rank1988, Wooden1993, AJ+2015
SN 2004et	~1	AJ+2012
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012A	~ 0.5	AJ+2015
SN 2012aw	~ 1.5	AJ+2015
SN 2012ec	2.2 – 4.6	AJ+2015



The observed Ni/Fe ratio tells us which progenitor layer was burnt (Si or O)

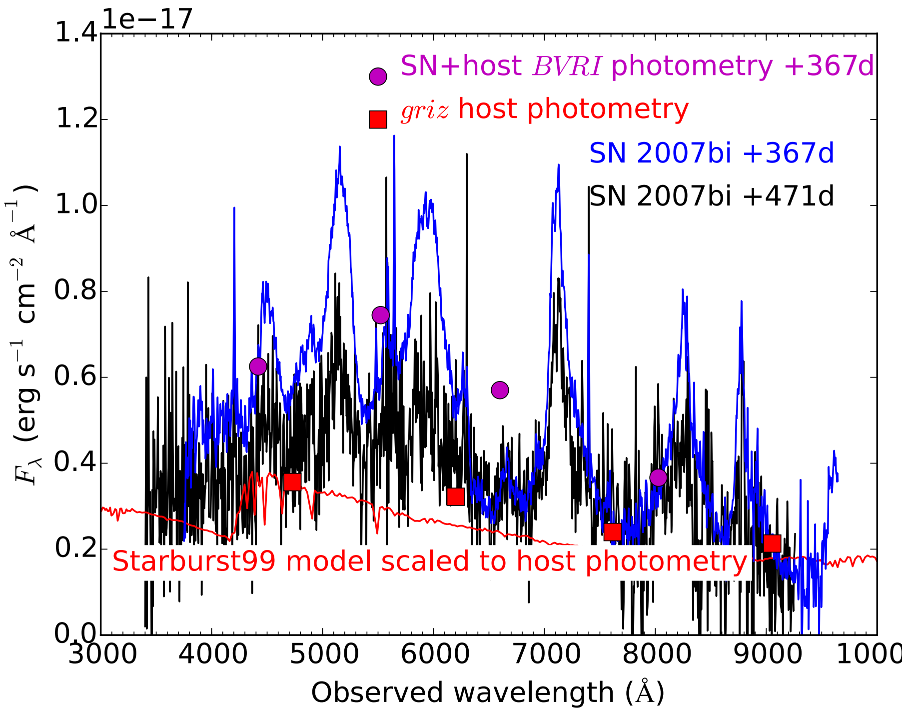
AJ,Magkotsios,Timmes+2015 (ApJ)

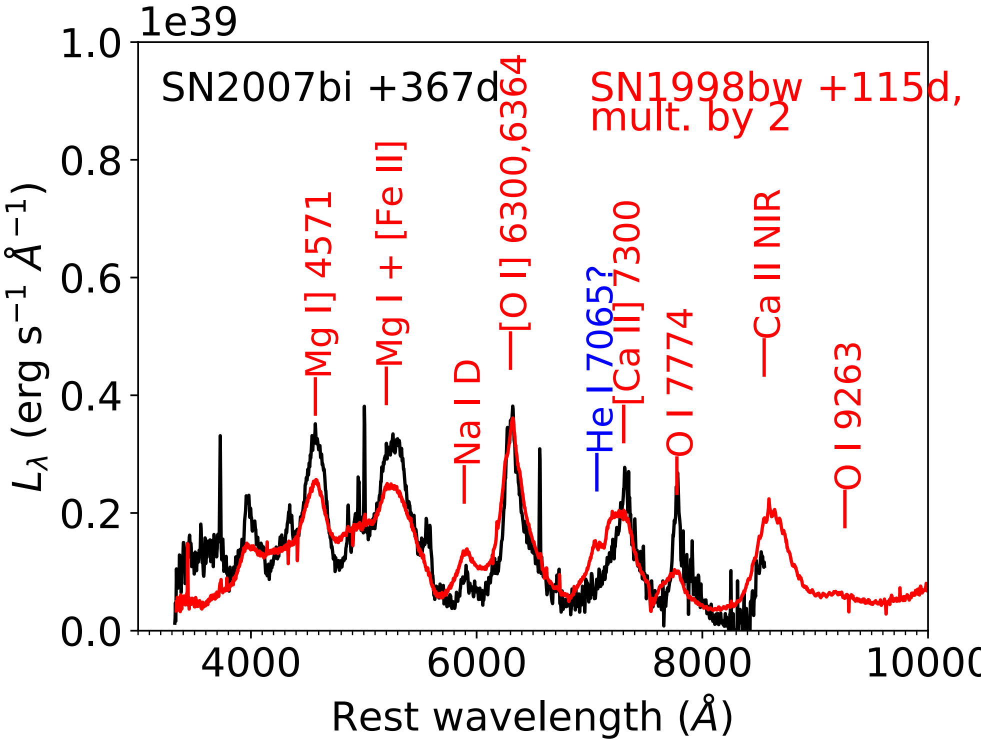
The monsters

Superluminous
Type I supernovae

Nebular spectra of SLSN Ic: *with galaxy subtraction, prototype SN 2007bi (Gal-Yam+2009) is similar to SN 1998bw*

AJ+2017



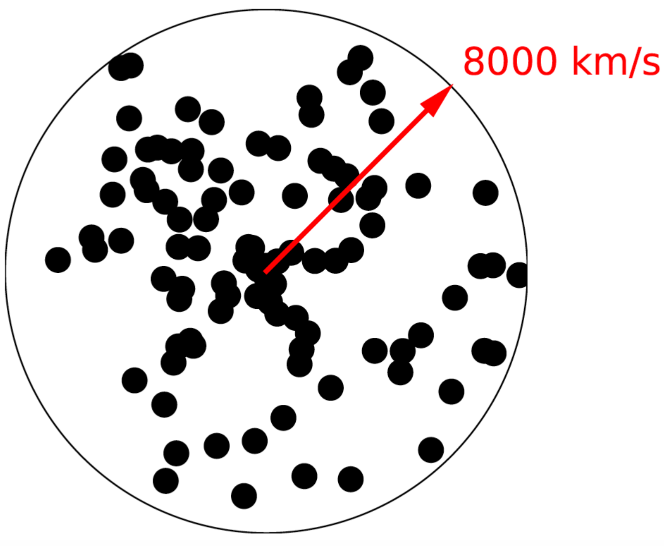


[O I] lines : Very large O masses required ($\gtrsim 10\ M_\odot$)
→ These SNe come from very massive stars ($M_{ZAMS} \gtrsim 40\ M_\odot$)

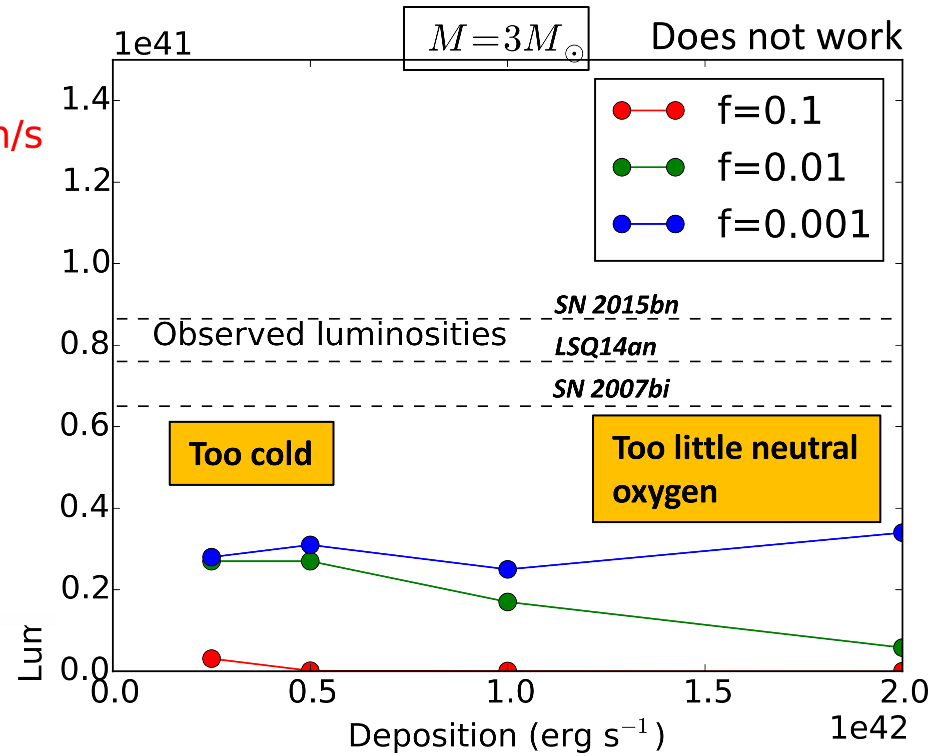
AJ+2017

Three parameters:

- O mass
- Powering level
- Filling factor



O-rich clumps



[O I] lines : Very large O masses required ($\gtrsim 10\ M_\odot$)
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AJ+2017

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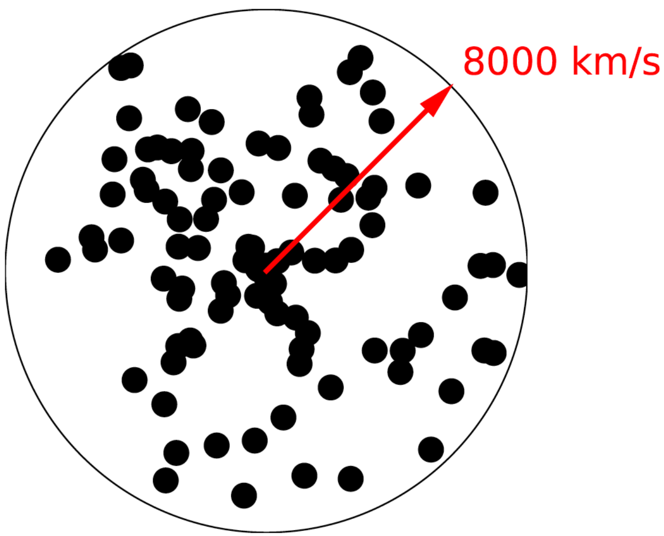
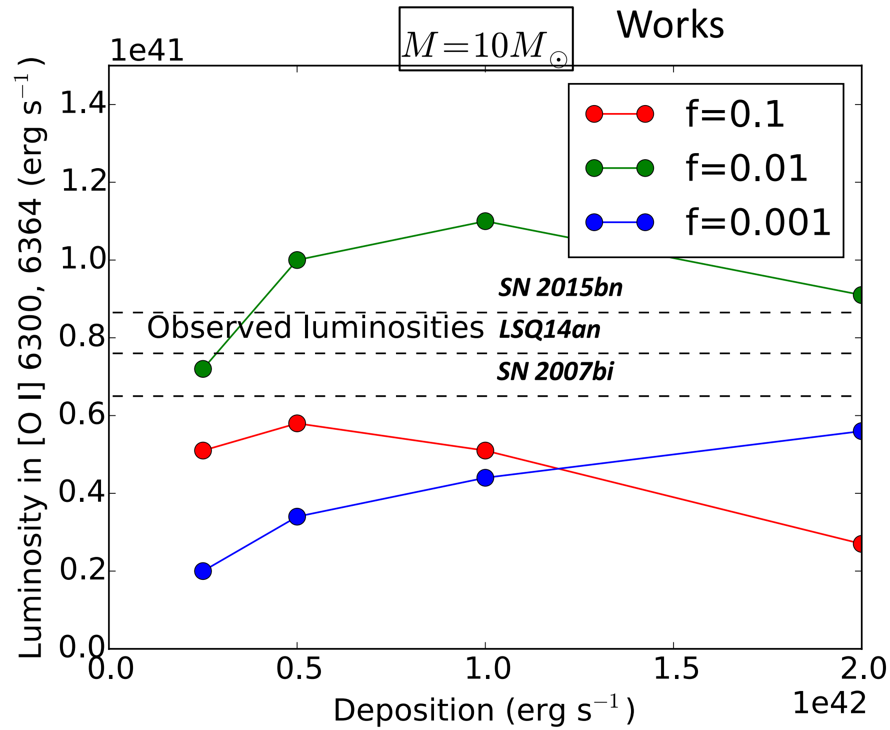


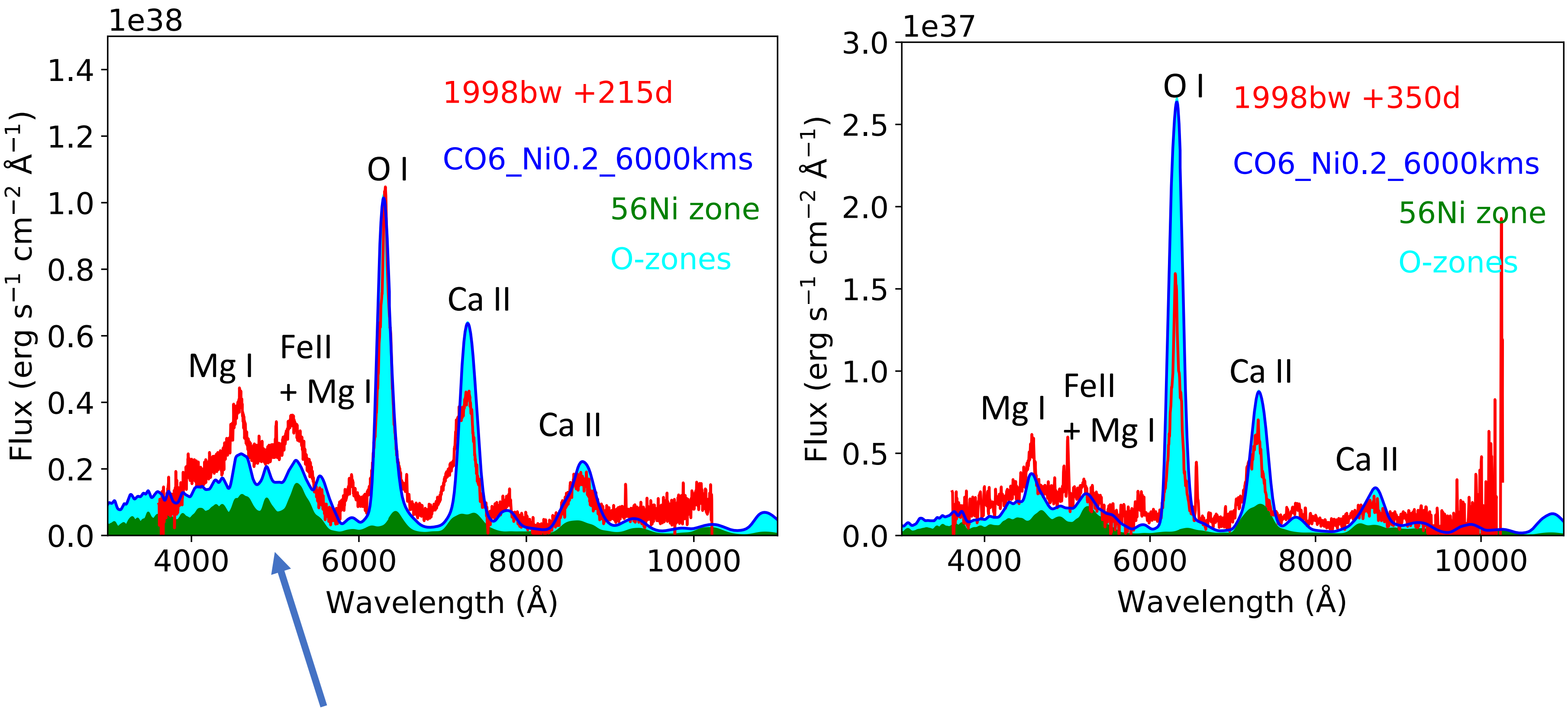
O-rich clumps



- Independent support from large inferred Mg masses (1.5-15 M_{sun})
- Recombination lines suggest material is <u>clumped or compressed</u> in shells (f $\lesssim$ 0.01).

SN 1998bw: Standard ^{56}Ni-powered models, powering 6-10 M_{sun} CO cores fit well.

AJ+2018, in prep.
See also Mazzali+2001, Maeda+2006, Dessart+2018.



<5500 Å region dominated by complex radiative transfer effects

Summary of Ic supernovae : view from late-time spectra

Broad-lined Ic
(e.g. 1998bw)

M(CO) ~ 6 M_{sun}
M_{ZAMS} ~ 25 M_{sun}

Superluminous SN Ic fast

??
No nebular data

Superluminous SN Ic slow

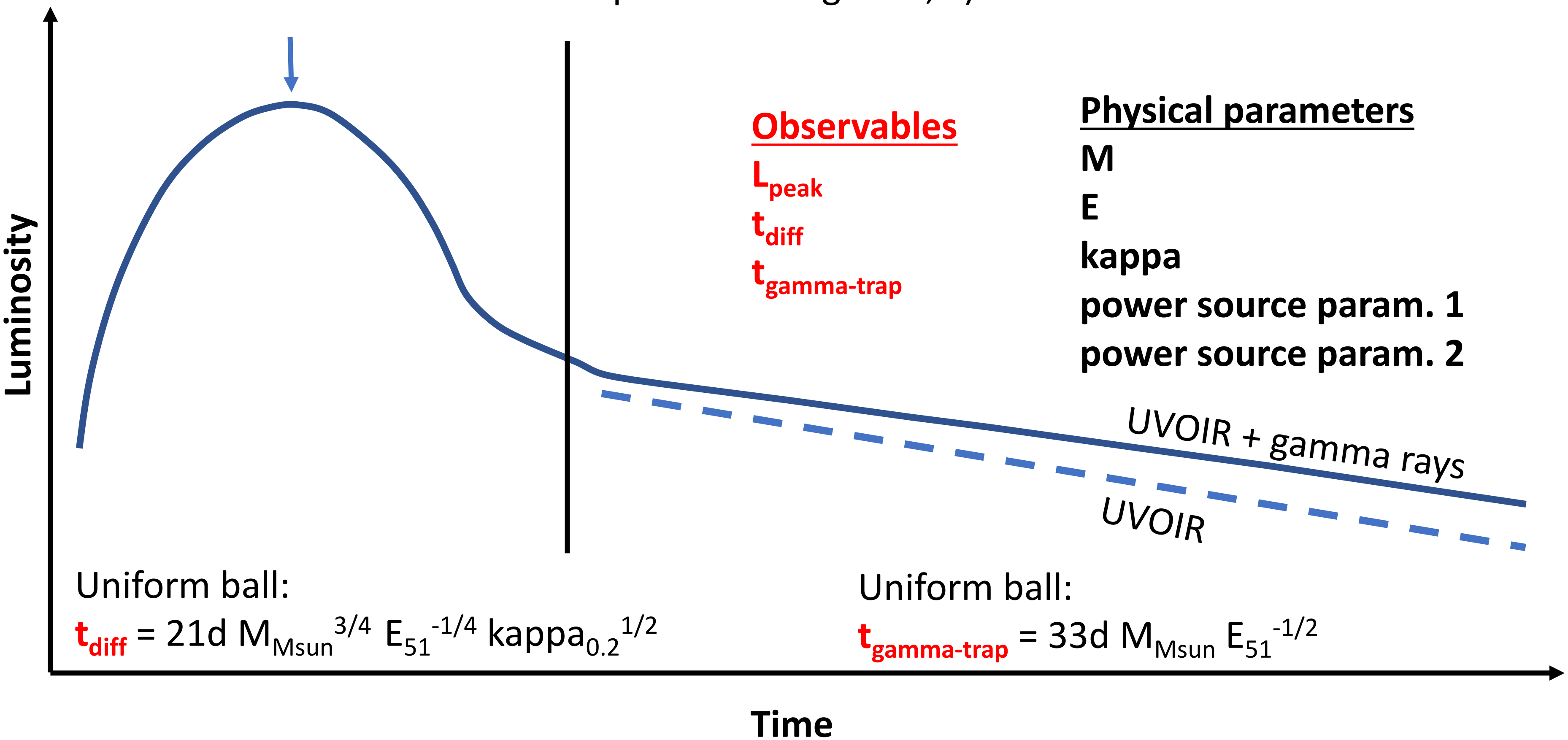
M(CO) >~ 15 M_{sun}
M_{ZAMS} ~ 40-100* M_{sun}

* Upper limit set by PPISN limit.
Association with pair-instability SNe (>130 M_{sun}) not likely (**AJ+2016**).

Light curve modelling : searching for the power source of SLSNe

L_{peak} ~ $L_{in}(t_{peak})$ ("Arnetts law")

More generally, "brightness" depends on strength of power sourcec(amount of radioactivity, spin-down power of magnetar,...)



Observables

- L_{peak}
- t_{diff}
- $t_{gamma\text{-}trap}$

Physical parameters

- **M**
- **E**
- **kappa**
- **power source param. 1**
- **power source param. 2**

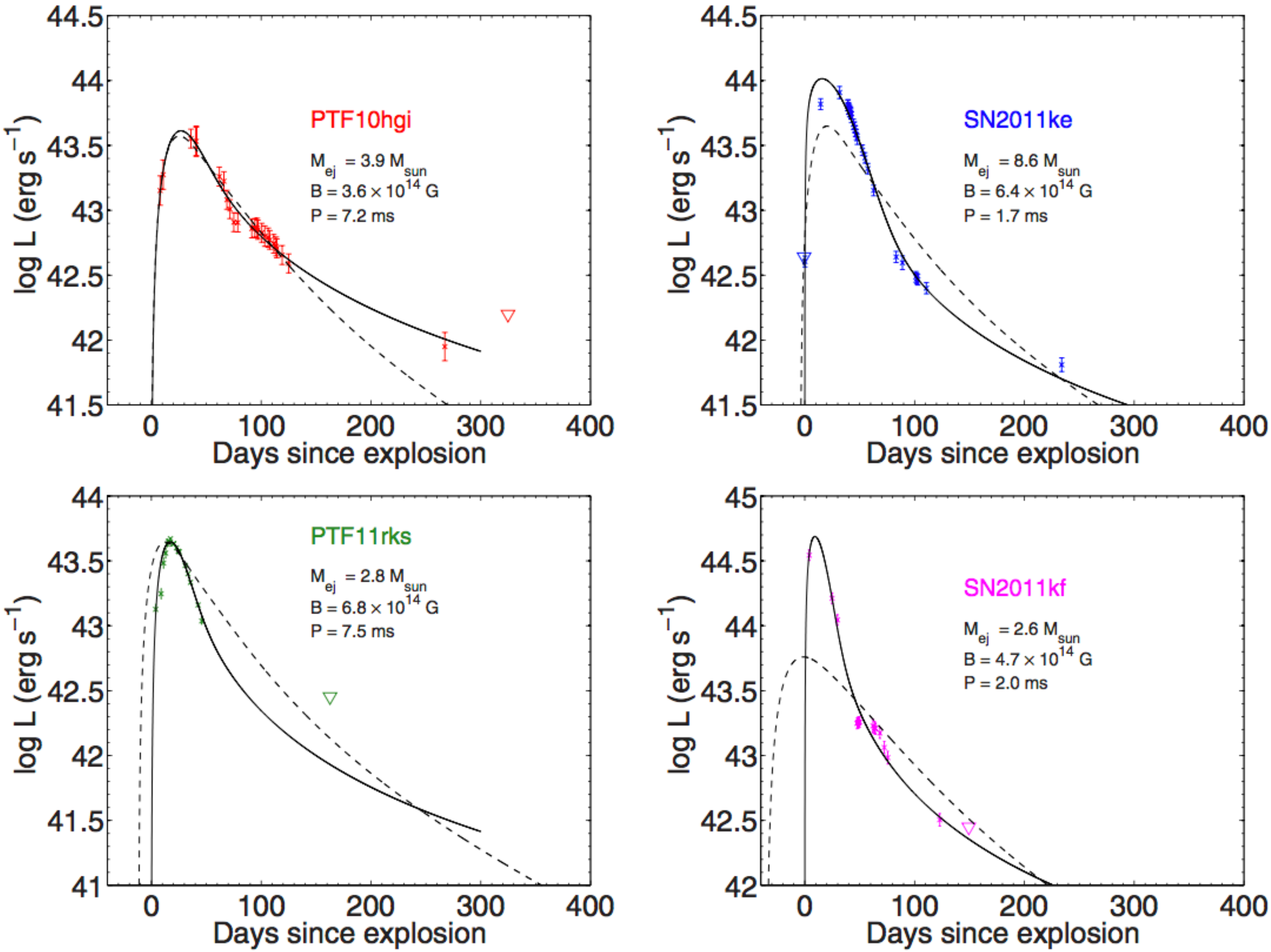
Uniform ball:

$t_{diff} = 21\text{d}\, M_{Msun}^{3/4}\, E_{51}^{-1/4}\, \text{kappa}_{0.2}^{1/2}$

Uniform ball:

$t_{gamma\text{-}trap} = 33\text{d}\, M_{Msun}\, E_{51}^{-1/2}$

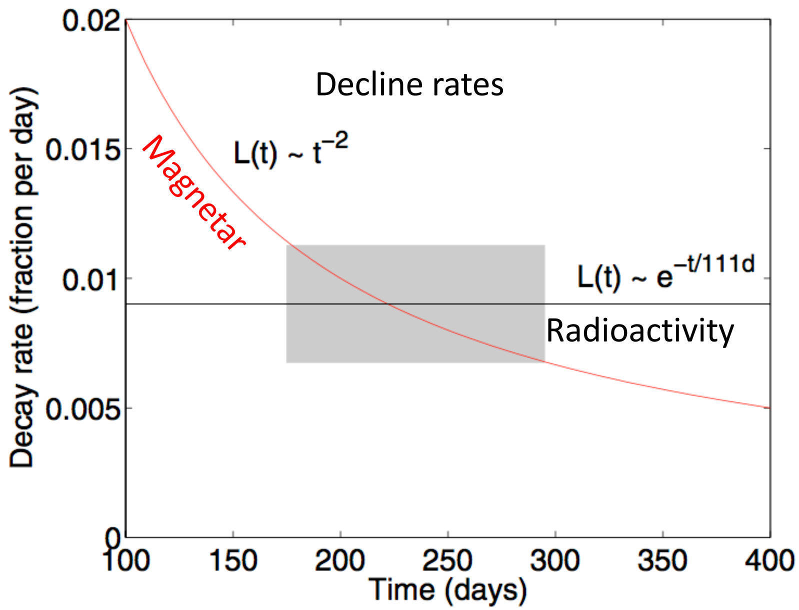
Light curve modelling of SLSNe : evidence for magnetars?

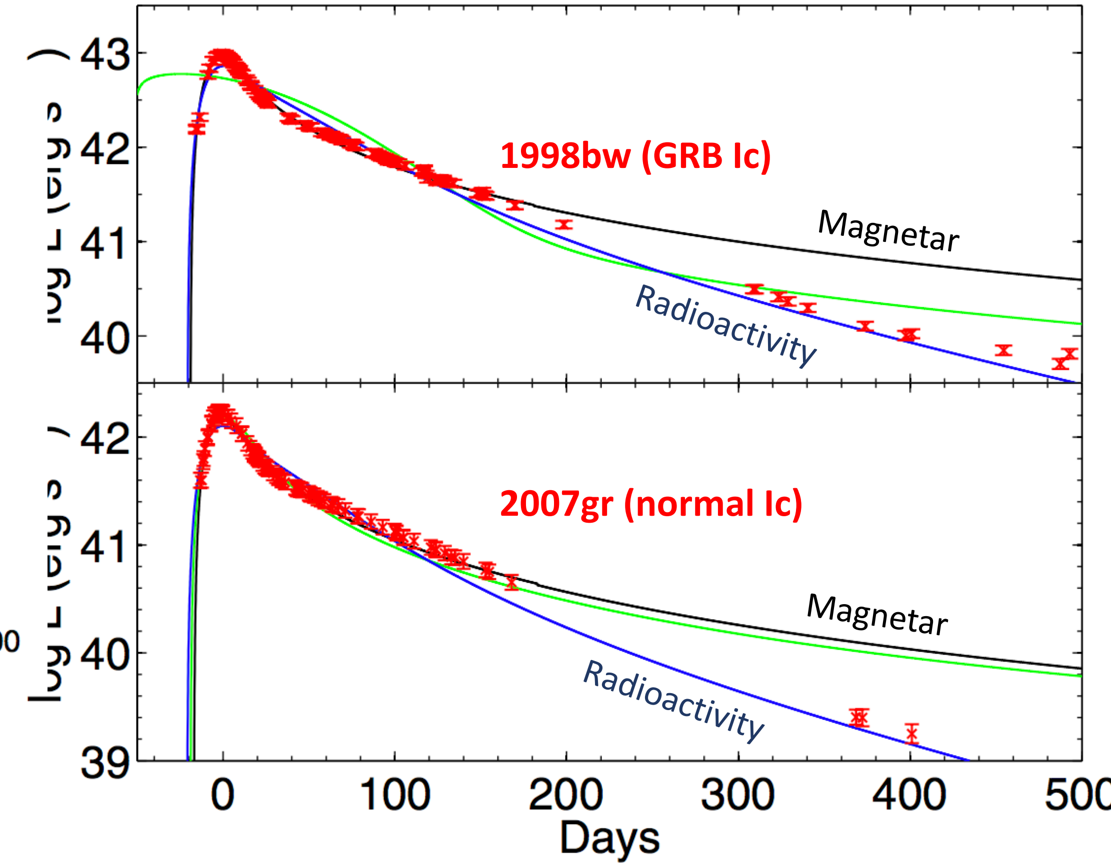


Inserra, Smartt, Jerkstrand et al 2013

LC fitting code publicly available at https://star.pst.qub.ac.uk/webdav/public/ajerkstrand/Codes/Genericarnett/

Distinguishing magnetar powering from radioactivity

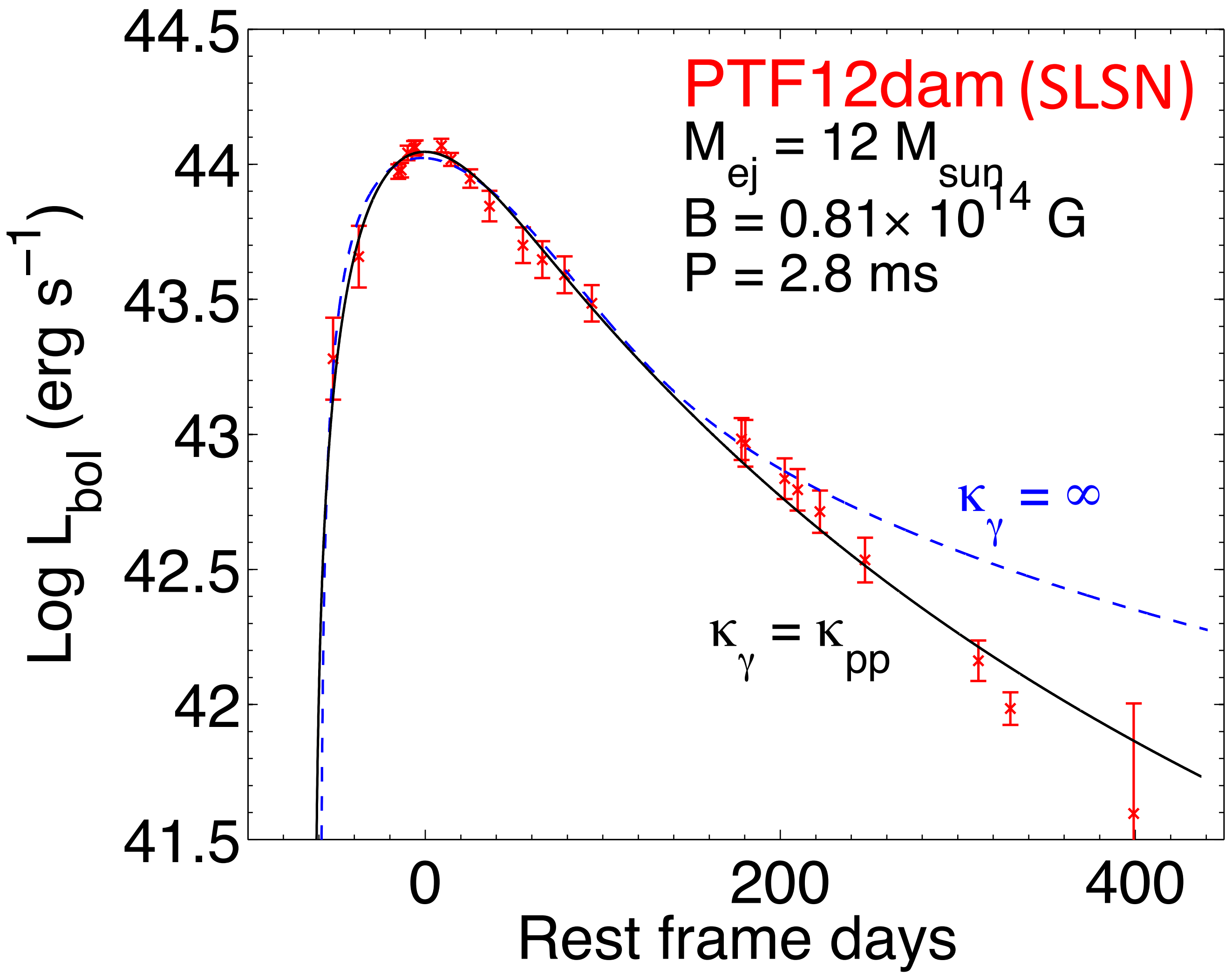




Inserra, Smartt, Jerkstrand et al 2013

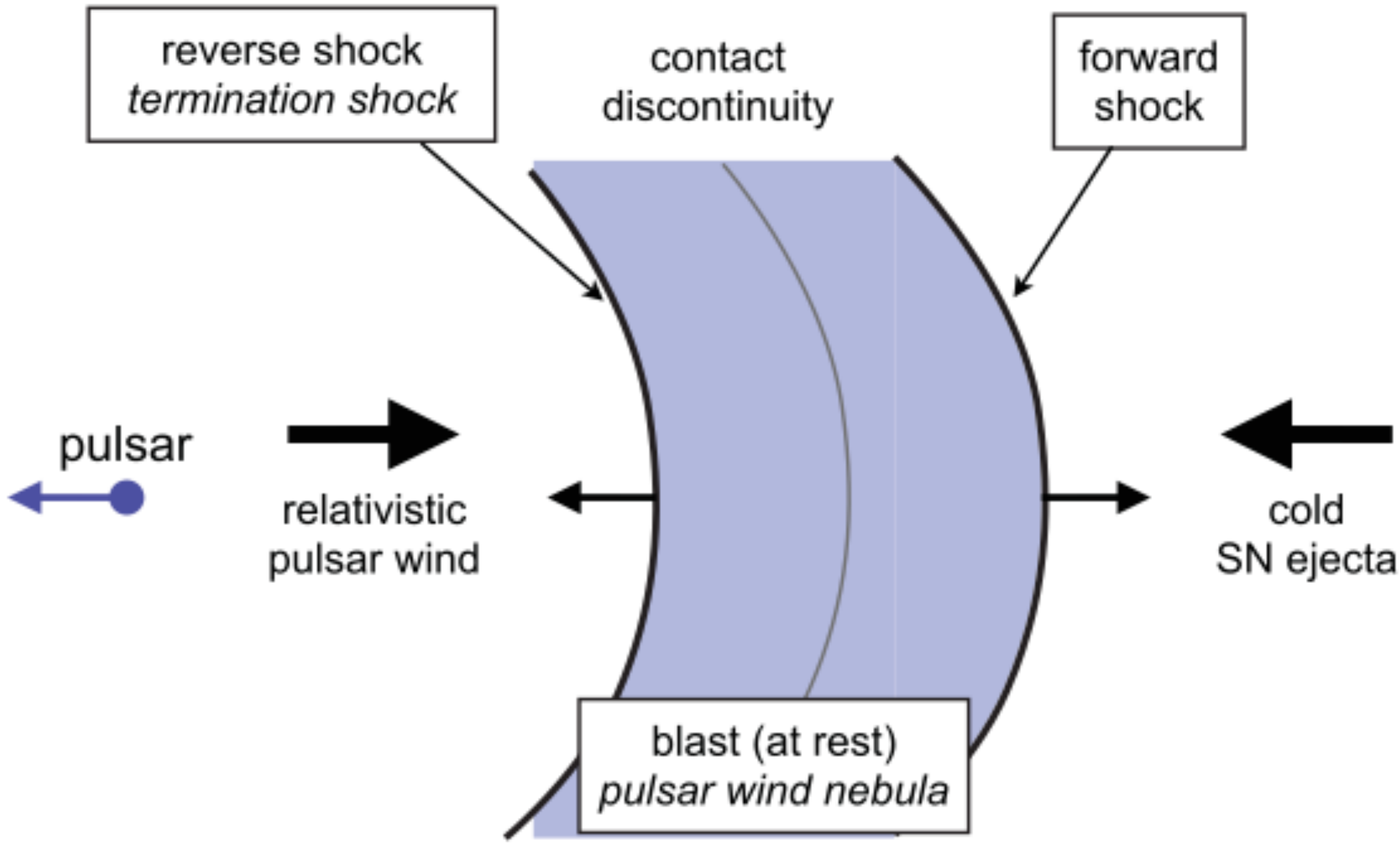
For non-superluminous Type Ibc SNe radioactivity fits better than magnetar powering

However : allowing for escape of high-energy radiation from pulsar-wind region is an issue



Chen+2015

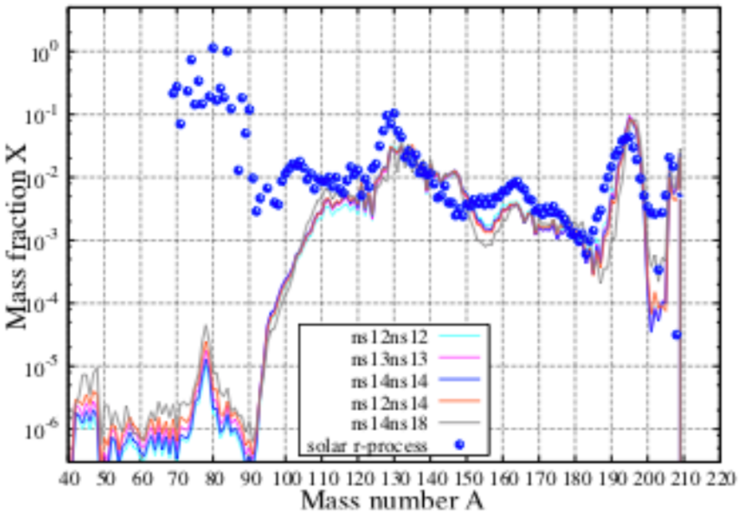
Modelling what's going on in the pulsar wind nebula is a formidable problem that noone has solved yet



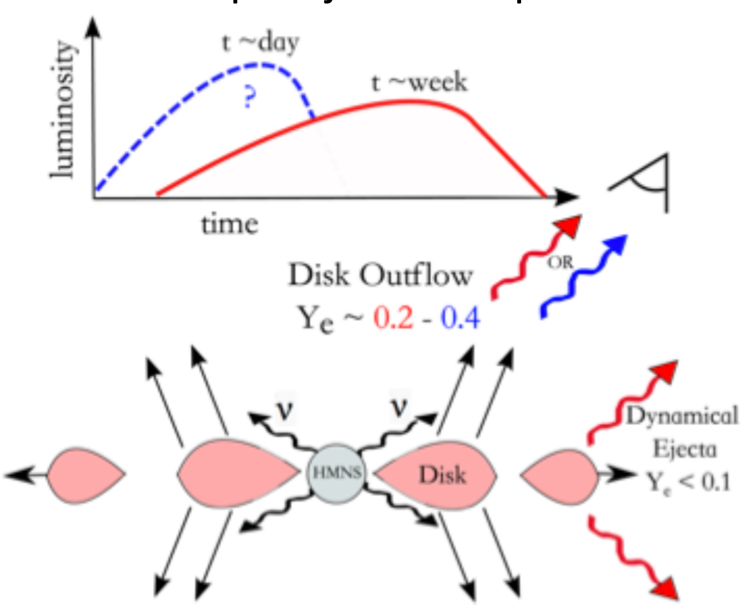
Kotera+2013

Kilonovae

Pure –process ejecta

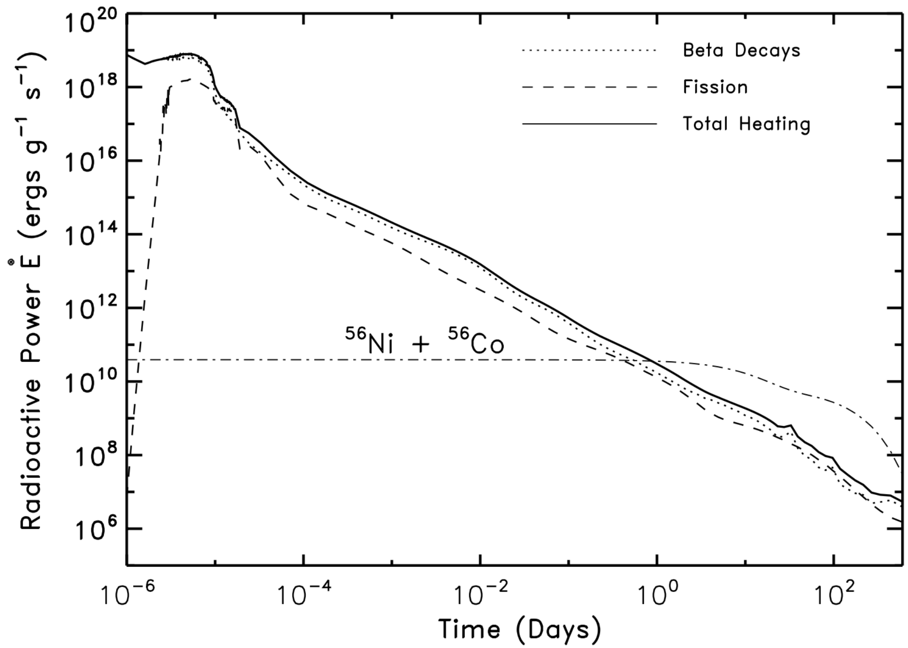


Multiple ejecta components



Metzger+ 2014

Radioactivity now well understood

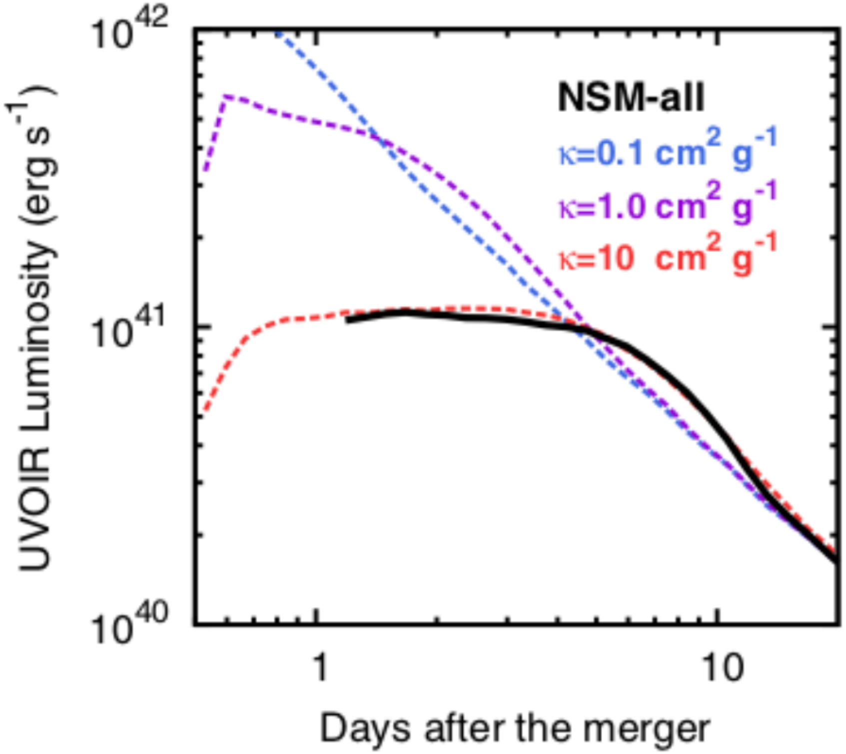


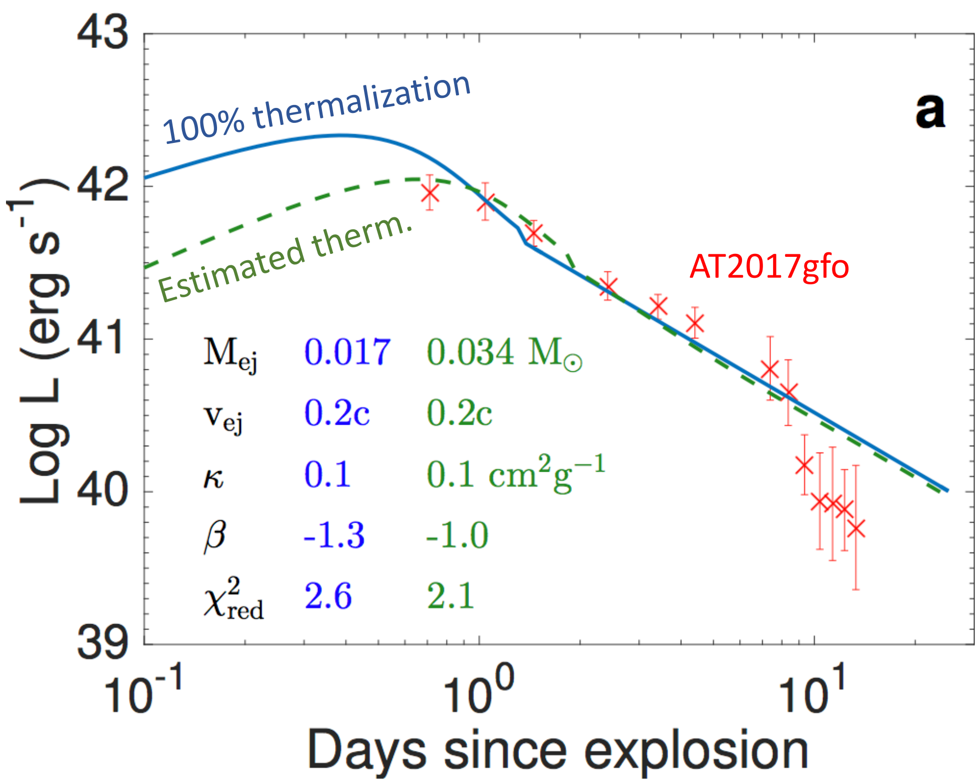
Metzger+ 2010

One parameter less than supernovae (<u>all</u> ejecta are radioactive, not some fraction X of it)

On the other hand more complex morphology and composition.

Kilonovae : modelling the light curve





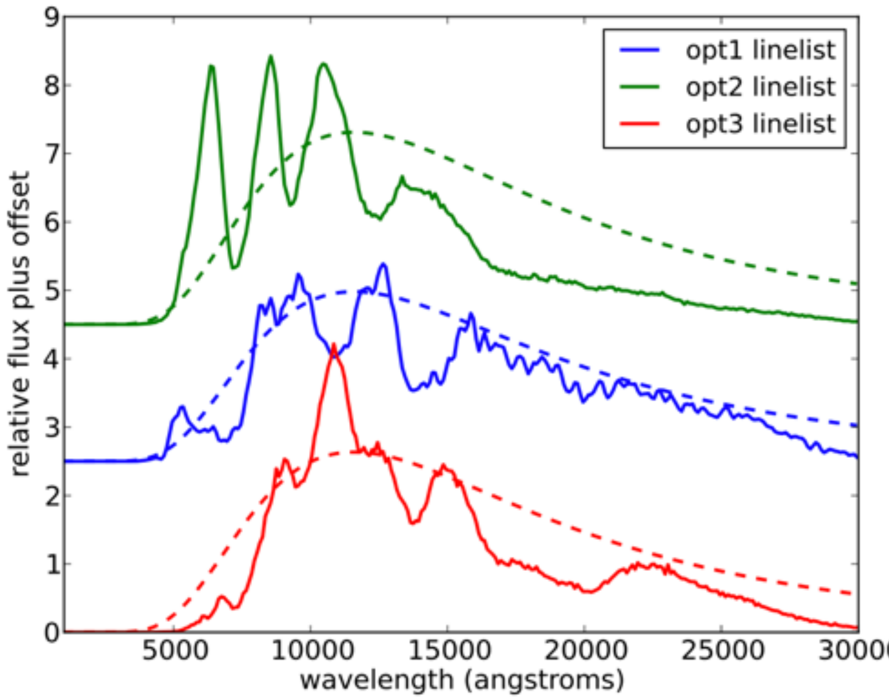
Tanaka+2013: Fixed opacity models do quite well

Smartt, Chen, Jerkstrand+2017, Nature

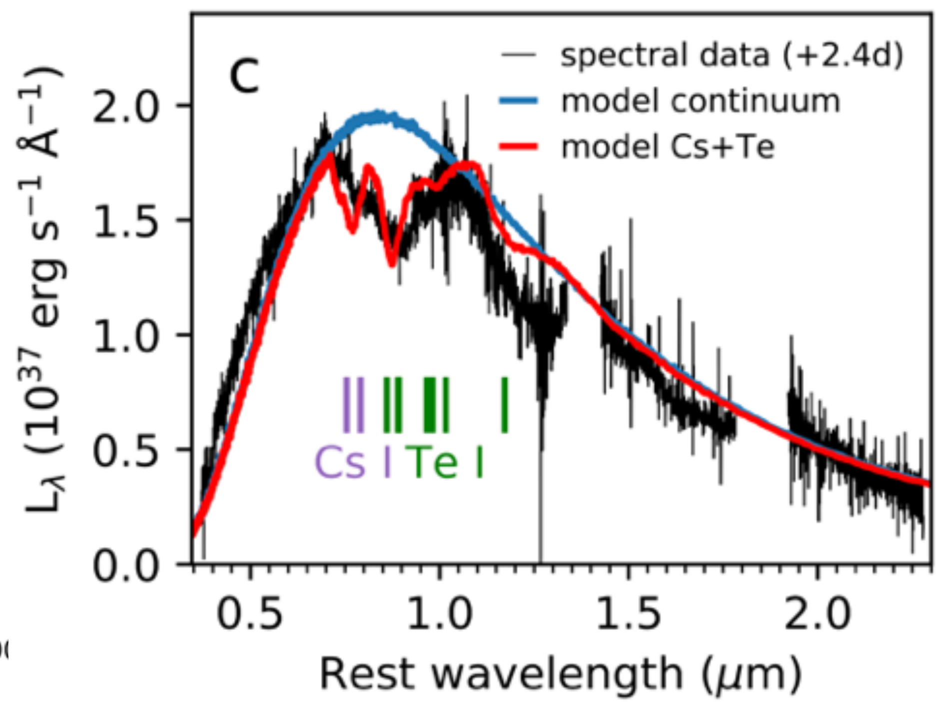
AT2017gfo ejected ~0.03 M_{sun} of ejecta at 20% speed of light. Powering consistent with predicted r-process radioactivity.

Kilonovae : modelling the spectra

Kasen+2013: Issues with r-process atomic data: much work still to be done



Smartt+2017: A toy fit including only Cs and Te.



Kilonovae reach NLTE regime already after few days → NLTE codes like SUMO or CMFGEN are needed.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