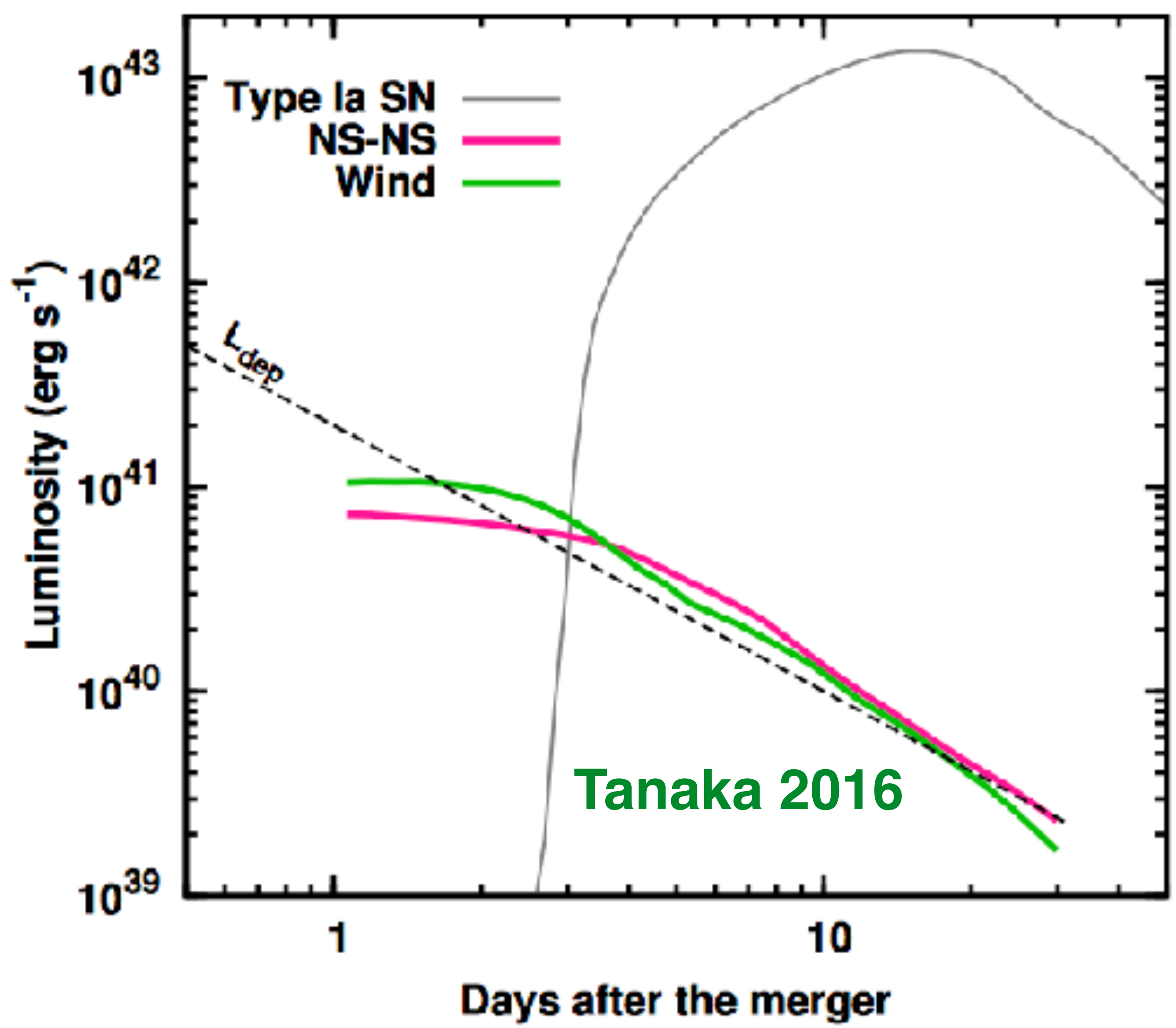
Light curves and spectra of kilonovae

Current expectations and possibilities

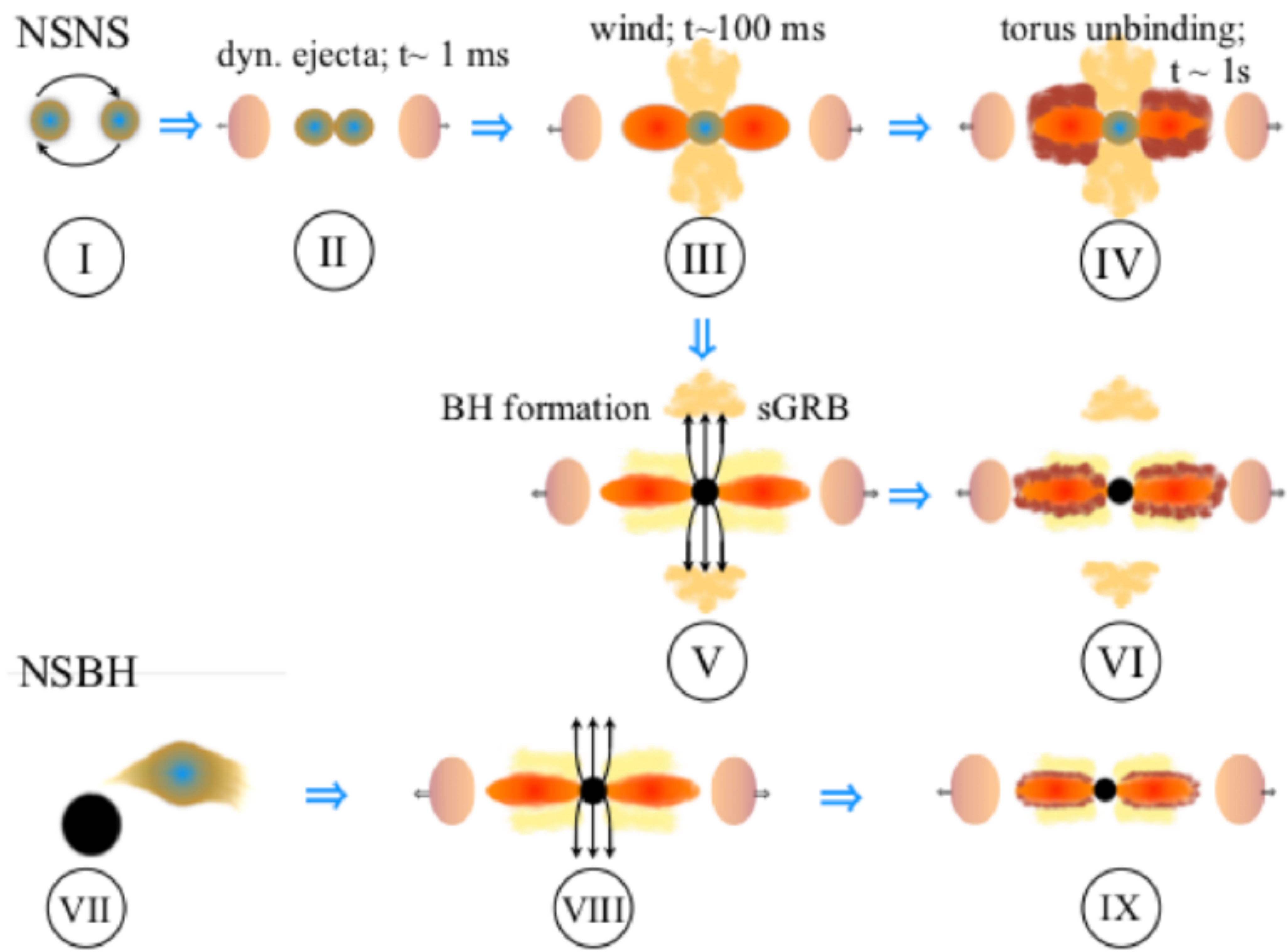


Anders Jerkstrand, MPA

Ingredients to predict observables

1. Mass, velocity and Ye of ejecta
2. Radioactivity and thermalization
3. Opacity and radiation transport

Overview of merging process

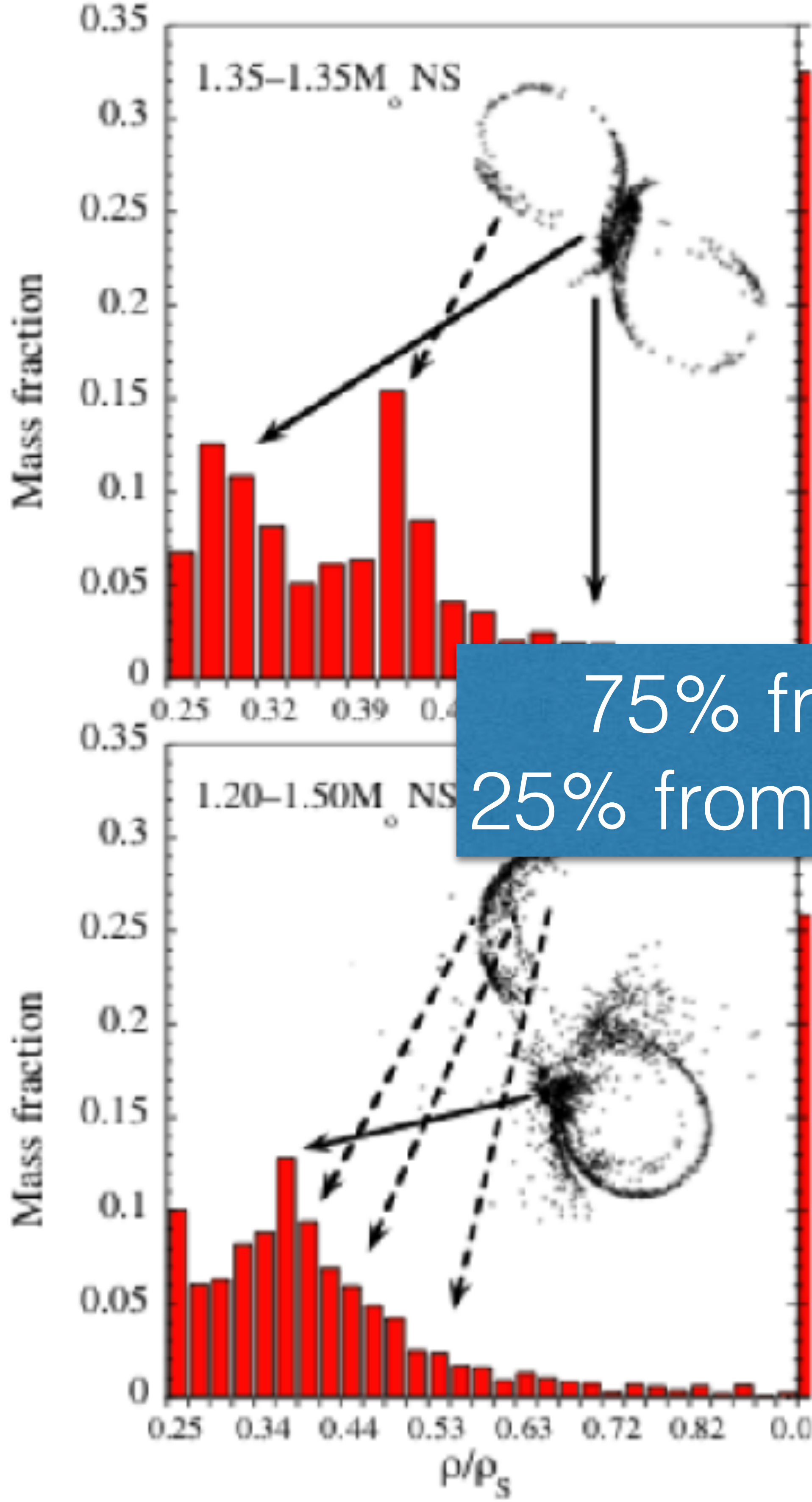


Rosswog 2017

Dynamic ejecta

- Significant differences in recent GR simulations to older Newtonian.
- Min 3 “parameters” (M_1, M_2, EOS). May also add eccentricity, spins,..
- Two components: tidal tails and interface squeezing.
- **Mass**: 0.001- 0.01 M_{sun} (Bauswein 2013, Hotokezaka 2013, Sekiguchi 2016). Higher for more asymmetry.
- **Velocity:** 0.1-0.4c.
- **Ye**:
    - Old simulations (no neutrinos) <~ 0.1.
    - Newer with neutrinos and e-e+: Broader distribution, up to 0.4 (Wanajo 2014, Sekiguchi 2016).

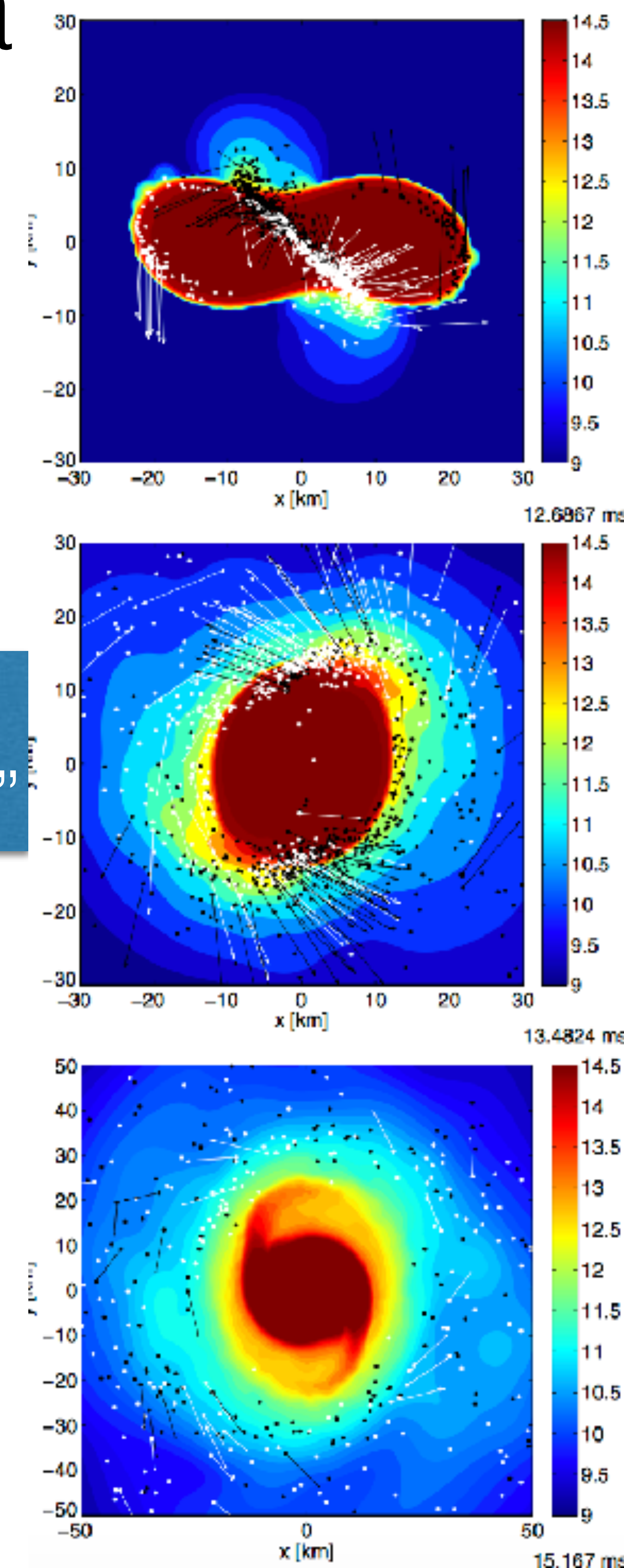
Dynamic ejecta



75% from contact interface
25% from other parts ("Tidal tail)"

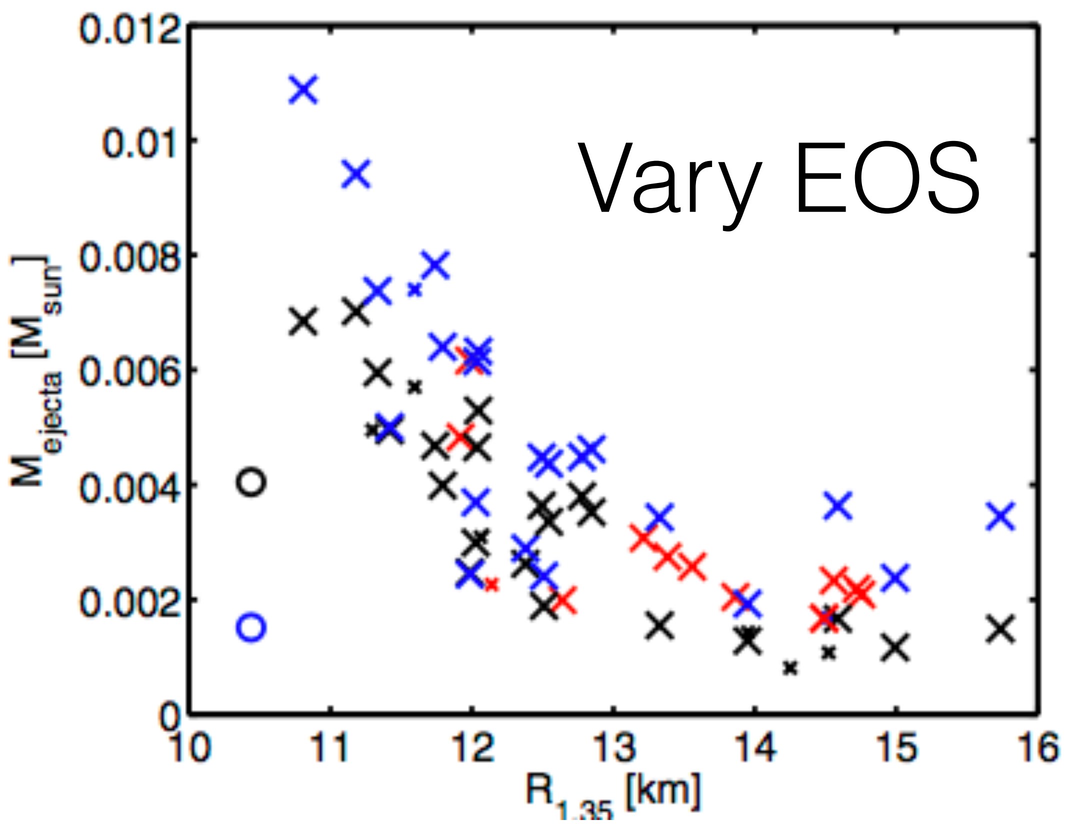
Goriely 2011

Bauswein 2013

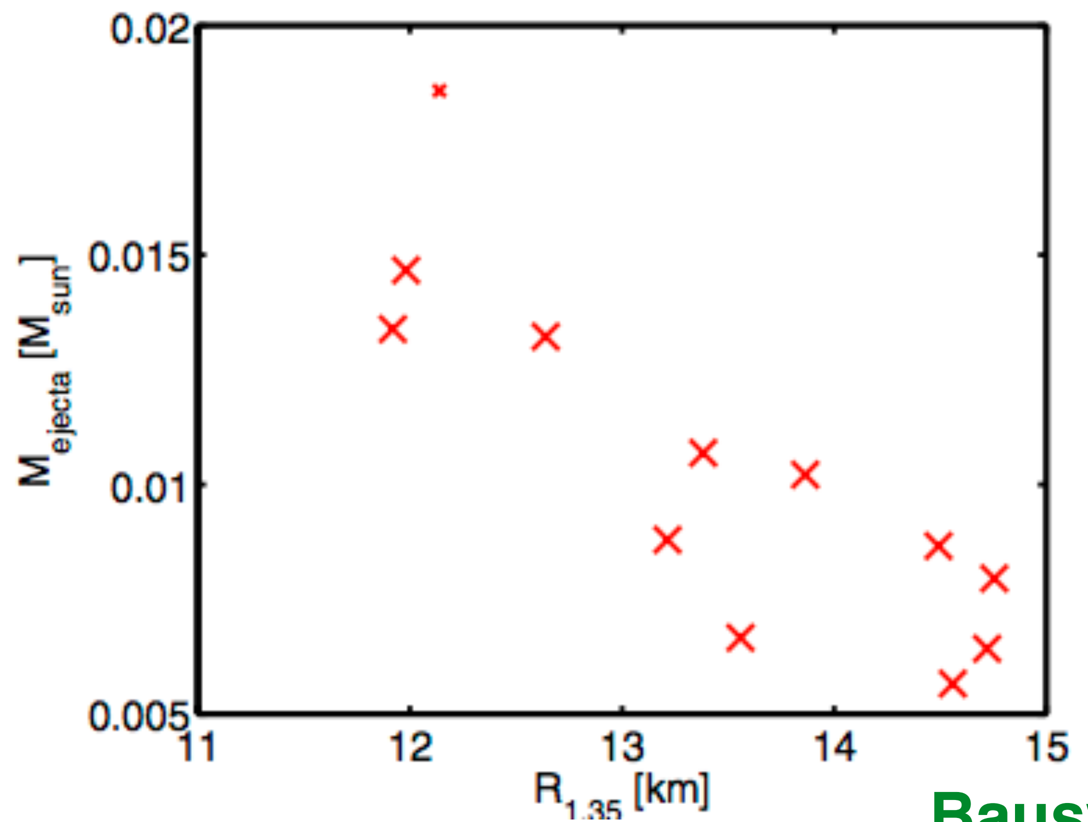


Dynamic ejecta : mass and velocity

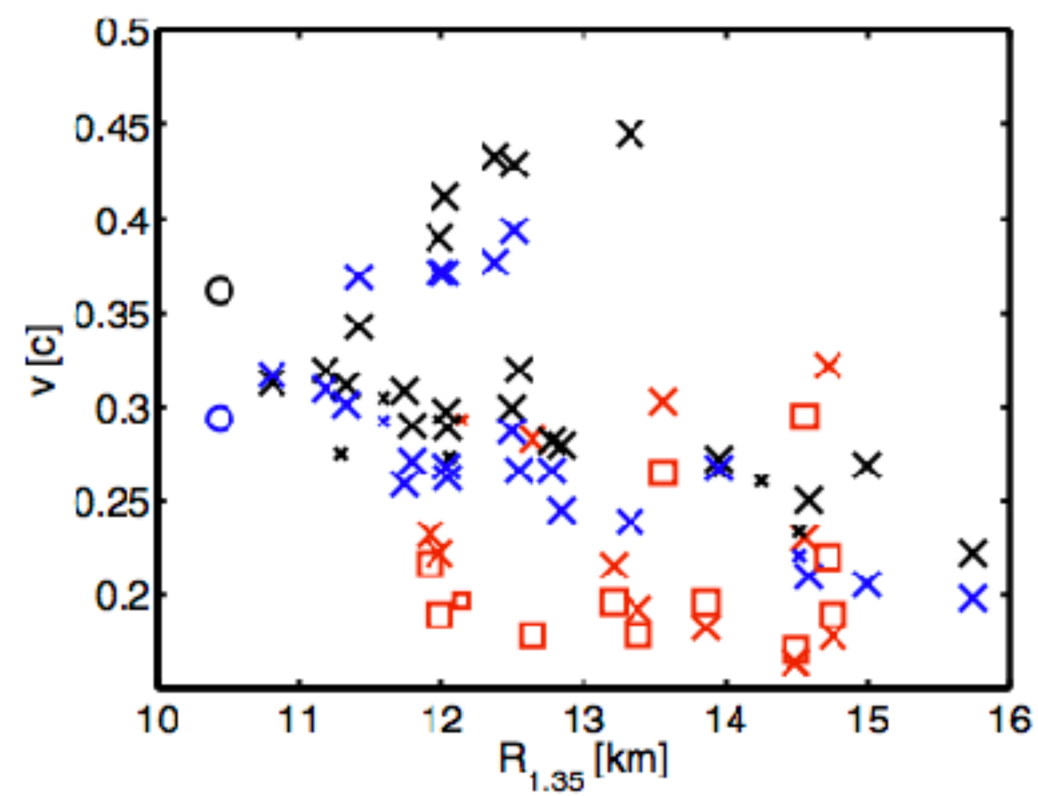
1.35 + 1.35 M_{sun}



1.2 + 1.5 M_{sun}



Bauswein 2013



- Mass typically less than 0.01 M_{sun}
- Asymmetric NSs eject more

NS-BH particulars

Kawaguchi 2015
(spin misalignment)

- Relative rate to NS-NS mergers largely unknown. No progenitor systems known.

- Larger dynamic ejecta masses, up to 0.1 M_{sun} (Kawaguchi 2016), but requires quite specific system parameters (low BH mass and/or large spin).

- More asymmetric ejecta : flattened and one-sided.

Disk wind

- Disk can be produced in both NS-NS and BH-NS mergers (Duez 2010). Mass 0.01-0.3 M_{sun}.

- Also two components (or more), neutrino-driven ejecta and MRI/viscous ejecta.

- **Mass**: Several % of disk mass typically ejected. Up to ~ 0.1 M_{sun}. Larger the longer the HMNS survives.

- **Velocity:** Similar to dynamic, but somewhat lower than dynamic ejecta.

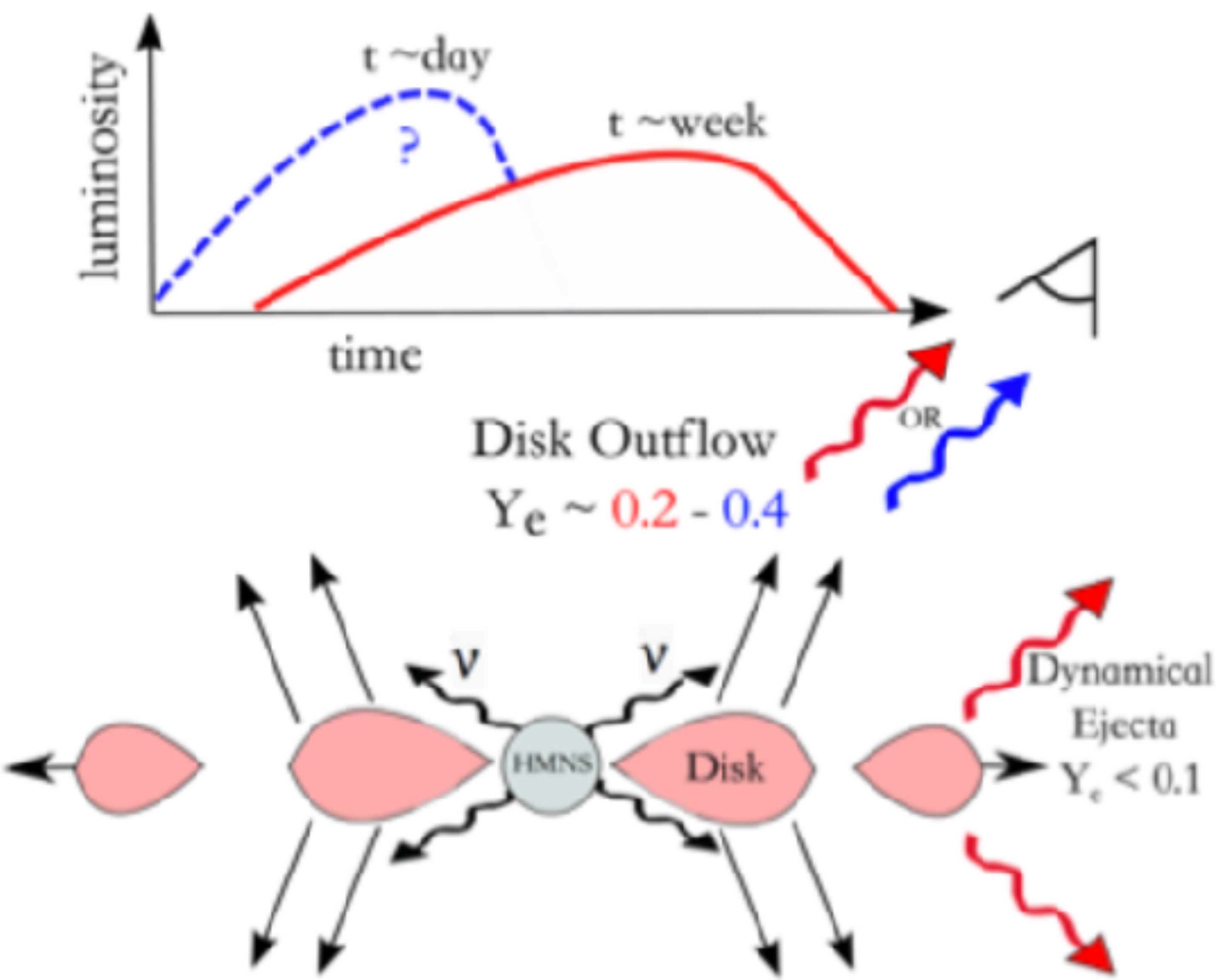
- **Ye**: 0.1-0.4, tends to be higher than dynamic.

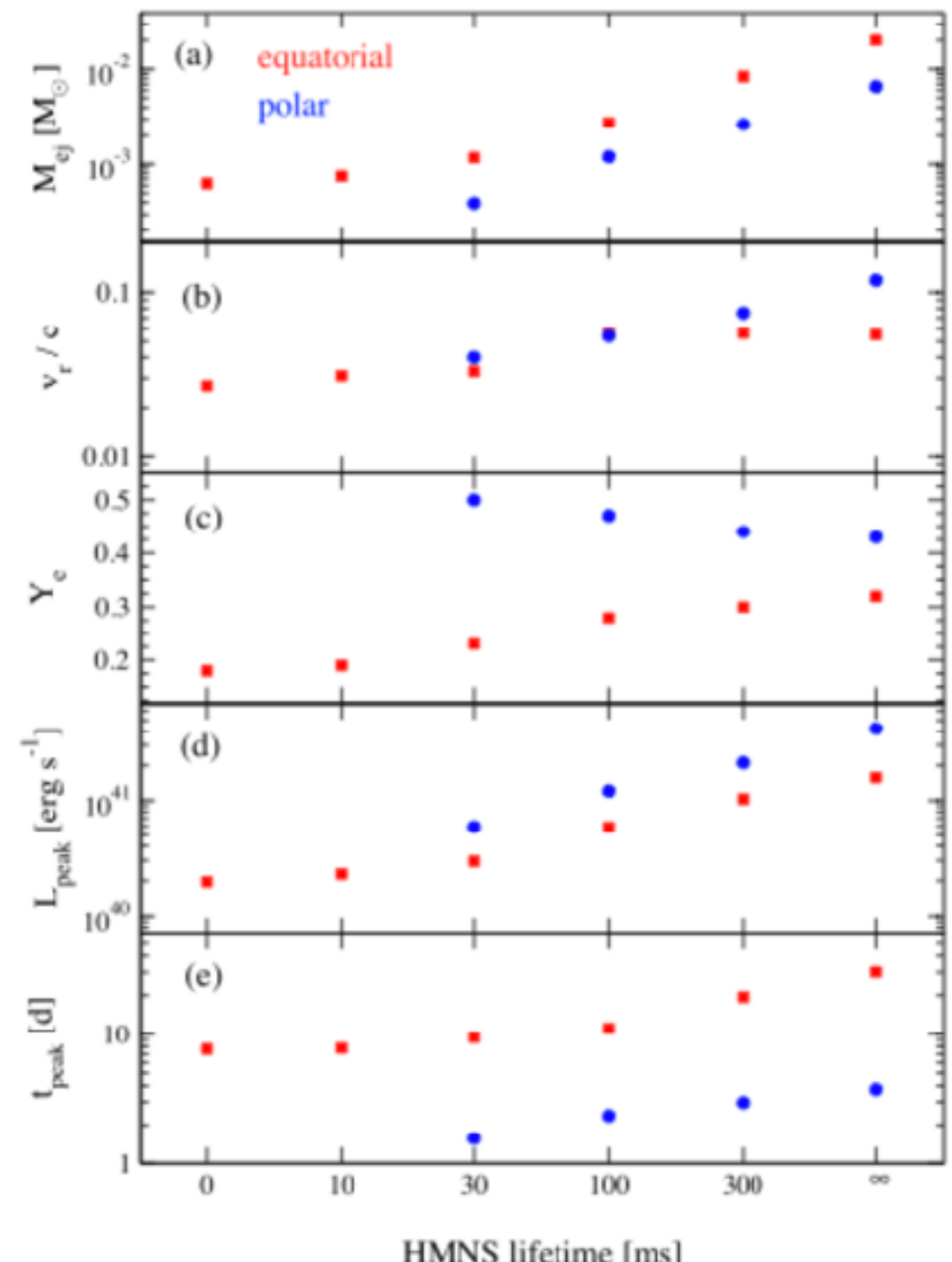
Wind : sensitivity to HMNS formation

Threshold at ~2.8 M_{sun} for direct collapse

HMNS can survive for ~0.1-1 s (Is this the 2s delay?)

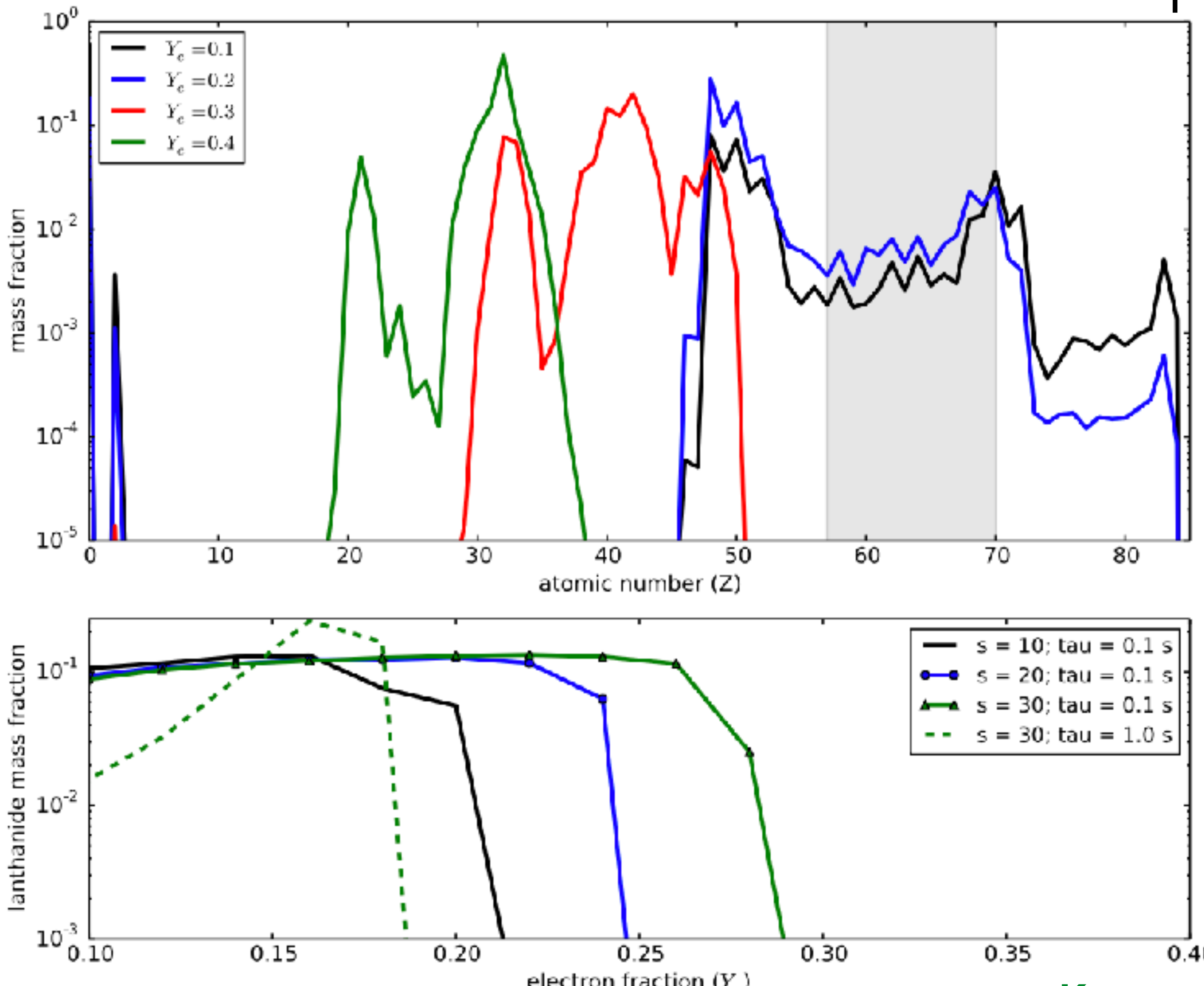
Neutrino irradiation in particular along polar directions.





Metzger 2014

The crucial role of Ye: higher Ye leads to lighter elements which have lower opacity



Kasen+2015

2) Powering

- Large number of radionuclides: $t^{-1.3}$ power law. Current uncertainties allow -1 to -1.5 exponent.

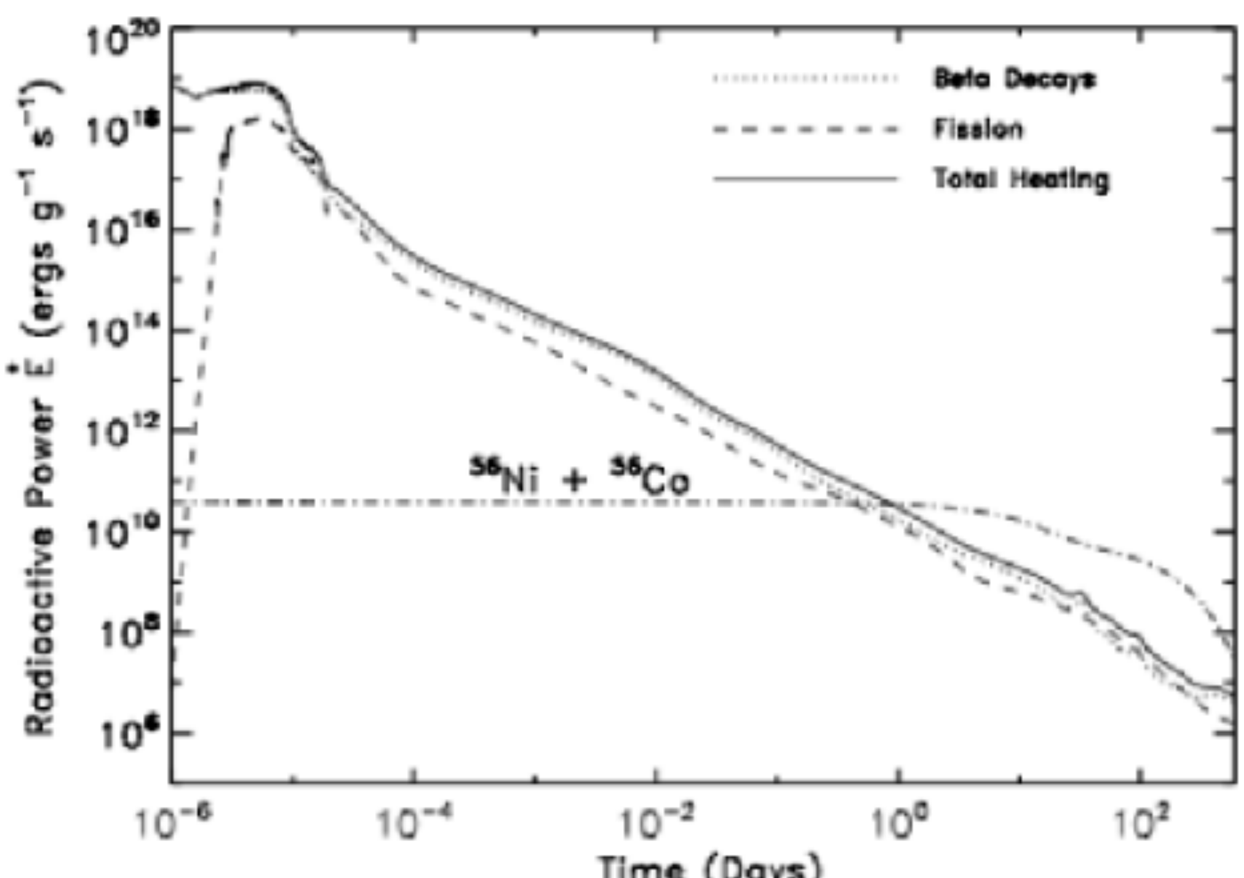
$$R=\int_0^\infty E\left(\frac{E^5}{t_0}\right)f(E)\exp(-E^5t/t_0)\,dE. \qquad (84)$$

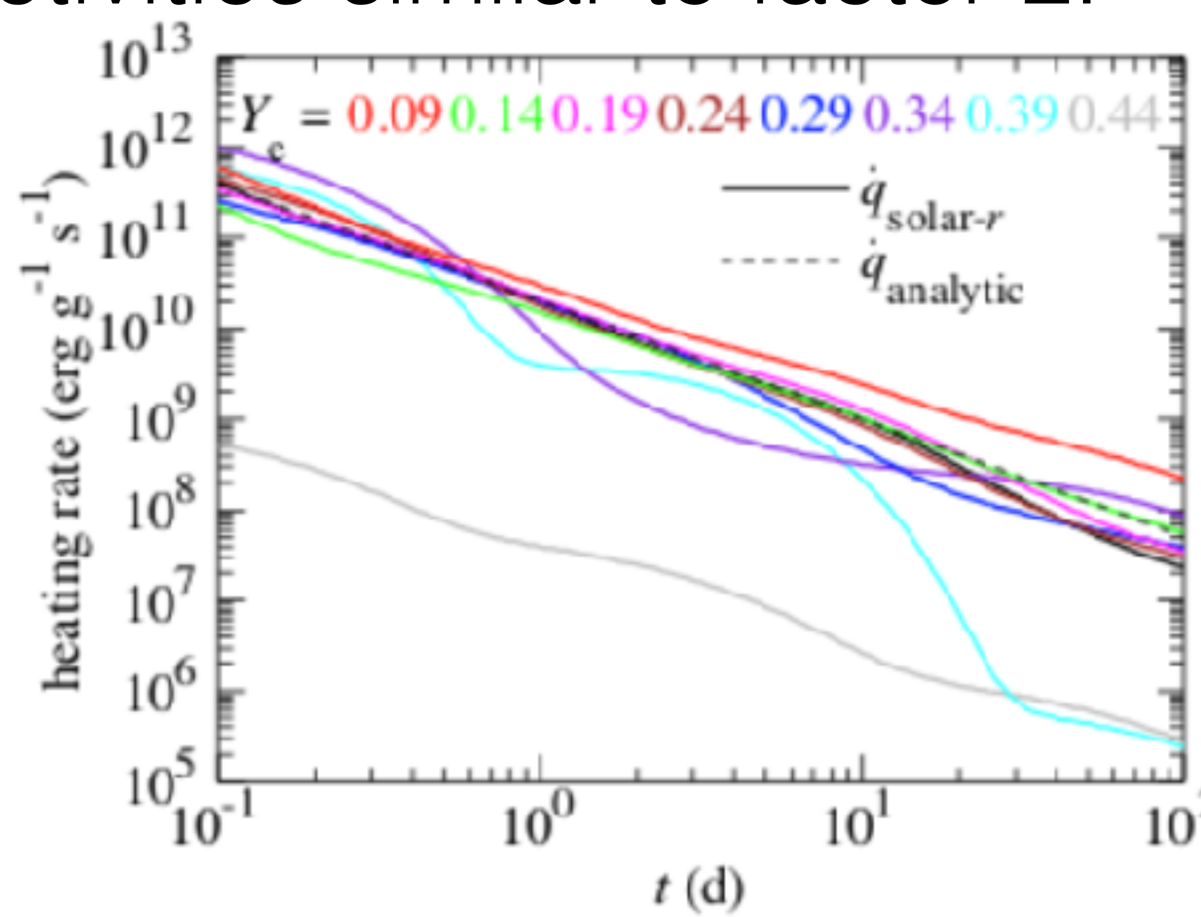
Since all decay energies $E \leq E_0$ are approximately equally probable where E_0 is the upper limit of the distribution $f(E)$, then $f(E)\simeq f_0$ for $E < E_0$, and a change of variables gives

$$R=\frac{\beta_0}{t_0}\left(\frac{t}{t_0}\right)^{-1.4}, \qquad (85)$$

Colgate and McKee 1966
Li & Paczynski 1998

- Dynamic and wind radioactivities similar to factor 2.





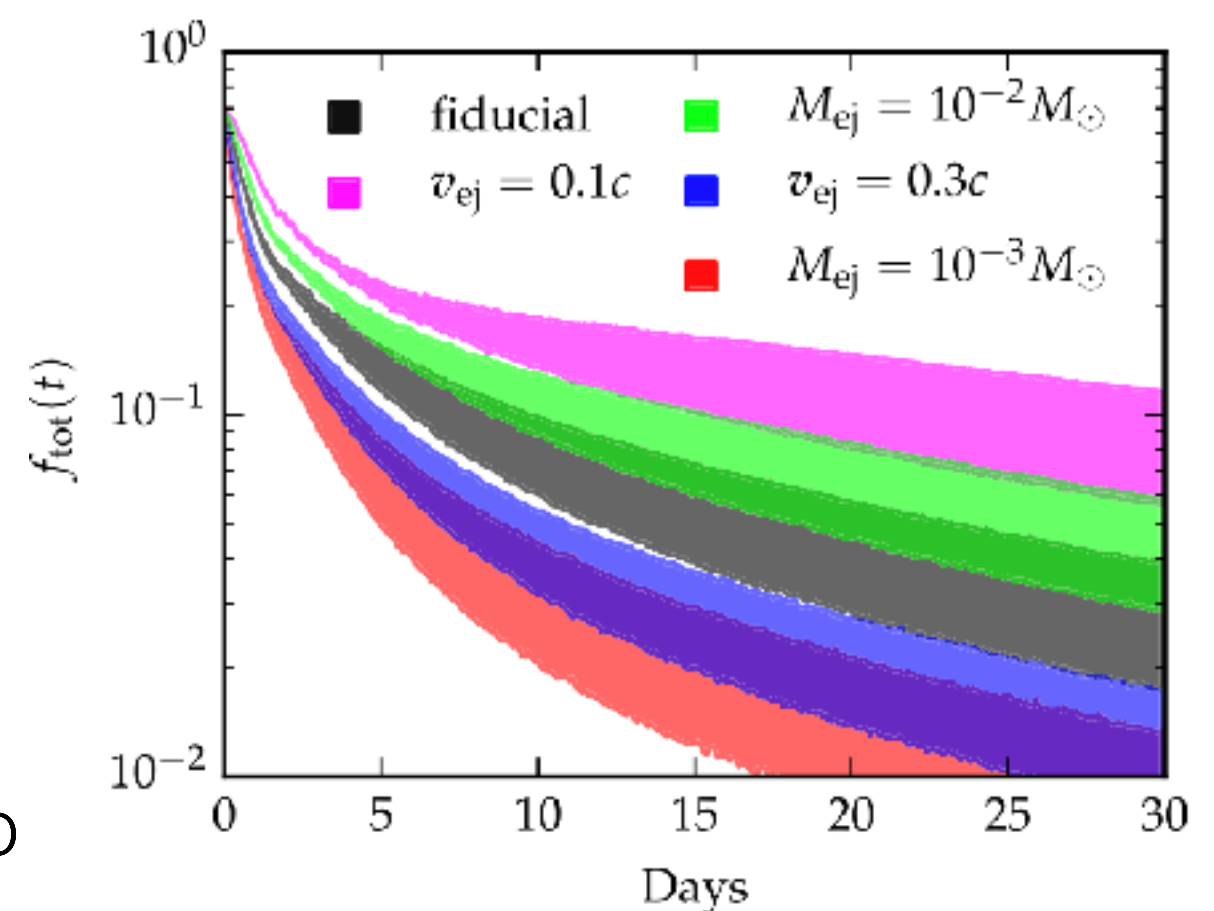
Metzger+2010
Processing of 11 year old simulation (Freiburghaus 1999)

Wanajo 2014

Trapping and thermalization

- **Neutrinos**: escape immediately.
- **Gammas**: escape early (hours).
- **Leptons** : escape within days/weeks (depend on B)
- **Alphas and fission products** : escapes within days/weeks (depend on B)
- Not only trapping matters, also the **time-scale** for thermalization: leads to drops also if B trapping.
- Current models: thermalization drops to 1-10% at 2 weeks.

Barnes 2016



3) Spectral modeling and opacity

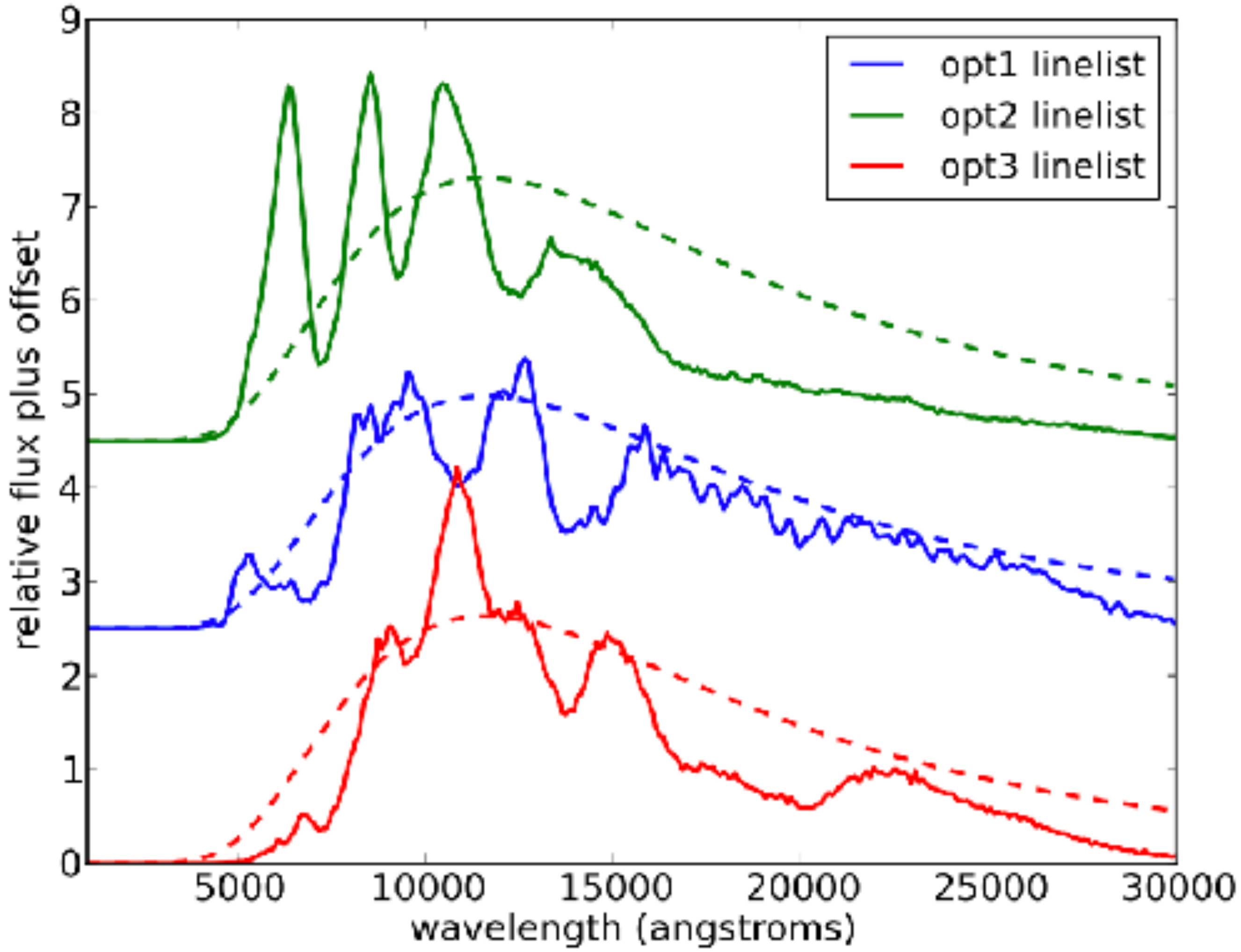
- **KASEN**
  - 3D Monte Carlo
  - LTE
  - Sobolev
  - Expansion opacity
  - Cs II-III, Nd I-IV, Os II, Sn II, ~30 million lines.

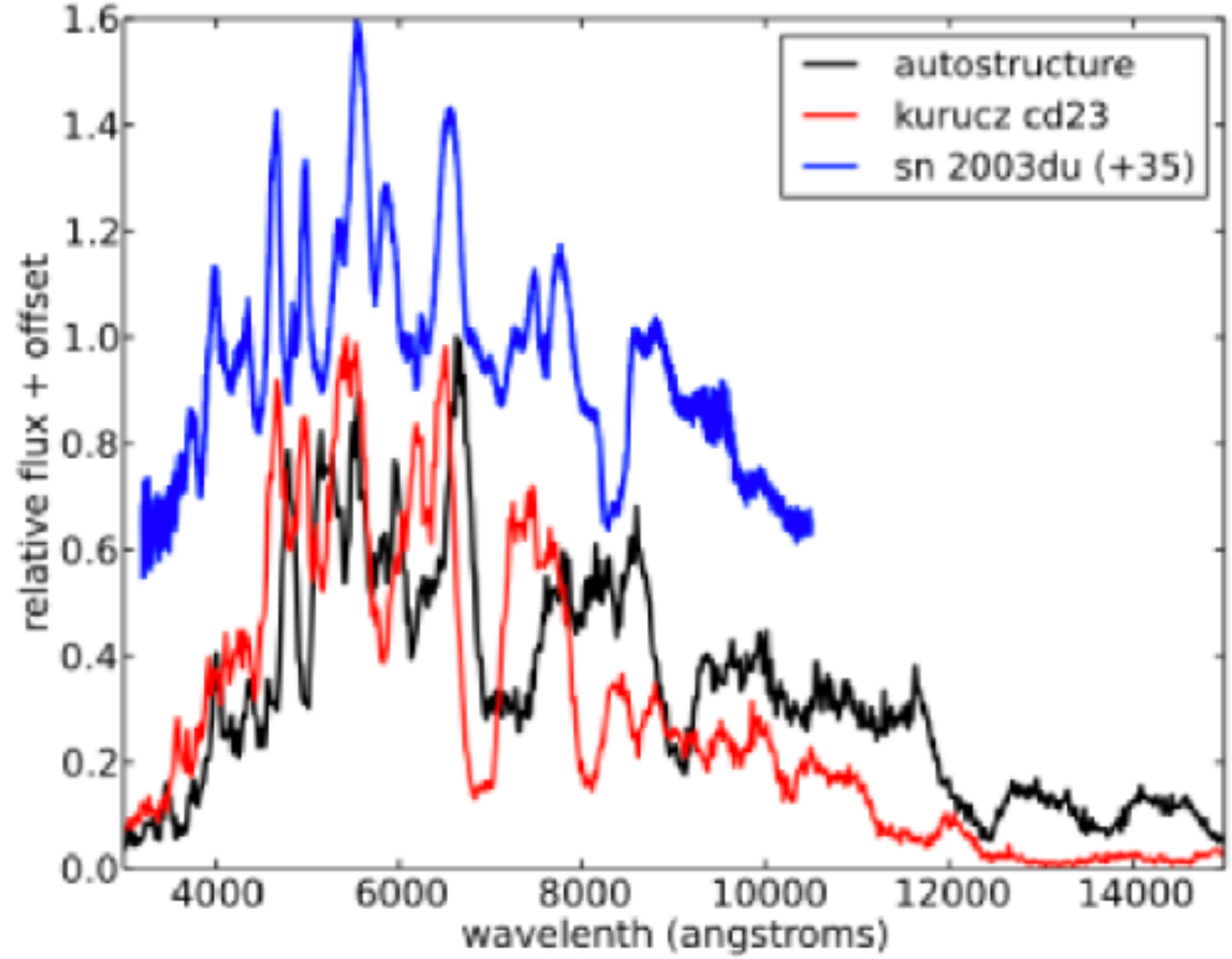
Kasen 2013, 2015, 2017

- **TANAKA**
  - 3D Monte Carlo
  - LTE
  - Sobolev
  - Expansion opacity
  - Se I-III, Ru I-III, Te i-III, Nd I-III, Er I-III, ~100 million lines.

Tanaka 2013, 2014, 2017

Big challenge ahead: Impact of varying atomic data method

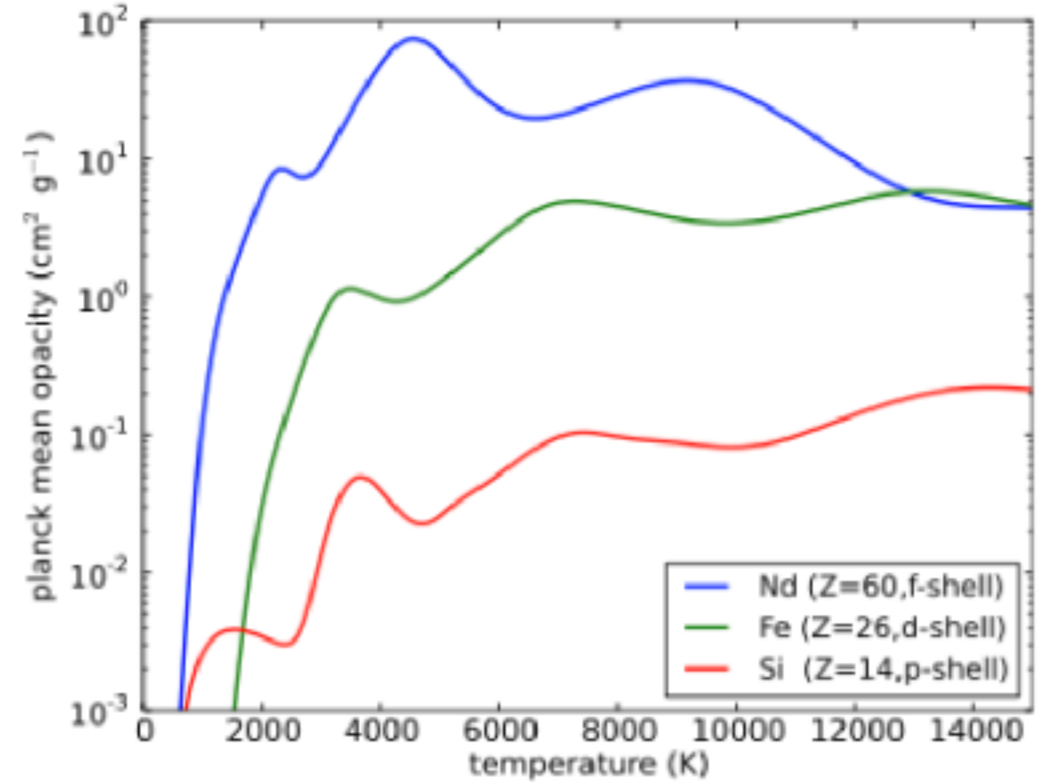


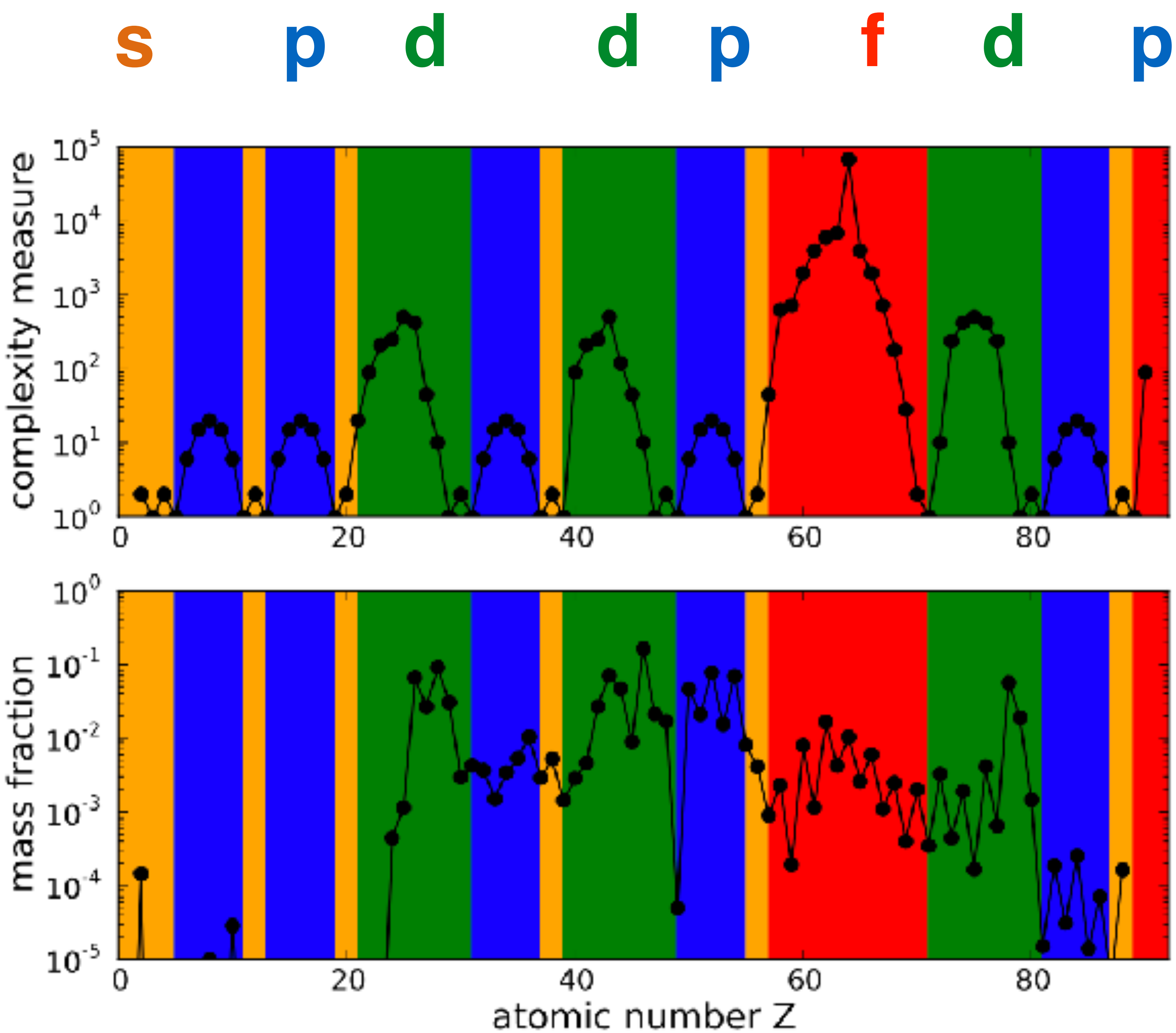


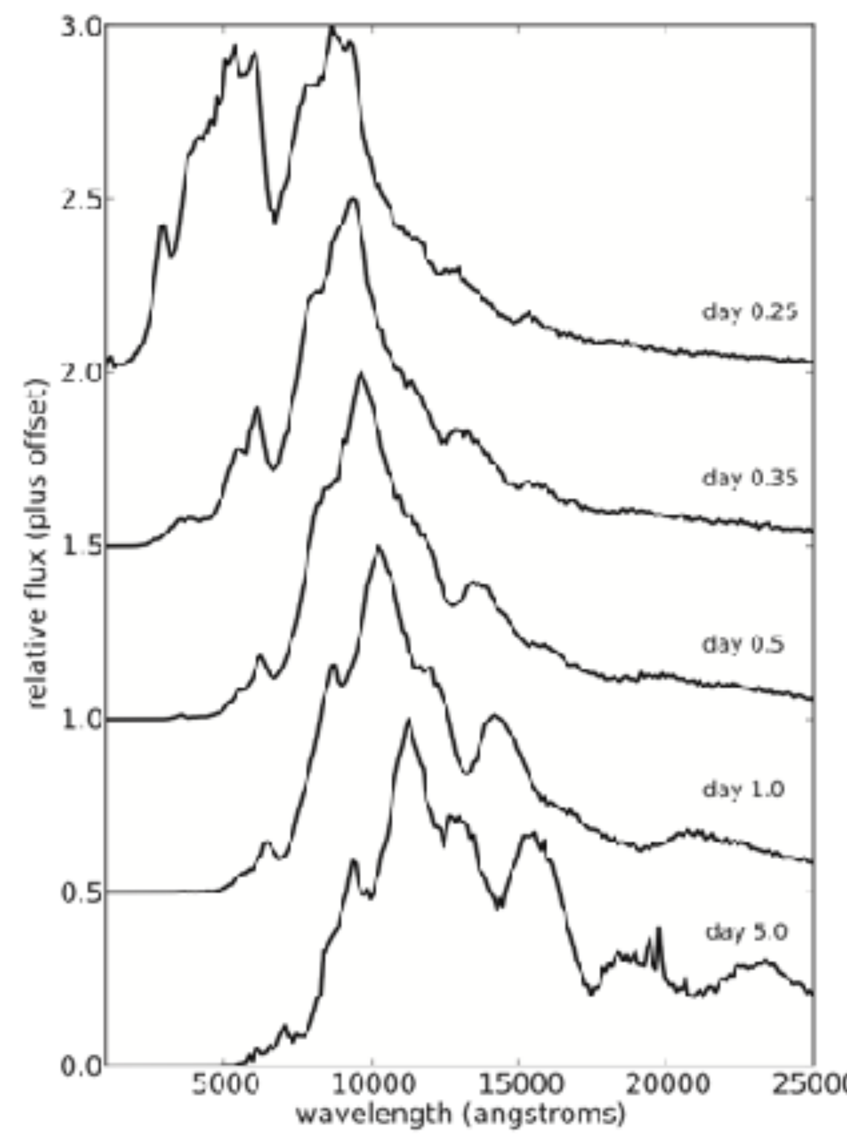
Kasen+2013 (0.01 Msun, 2.5d)

Opacity

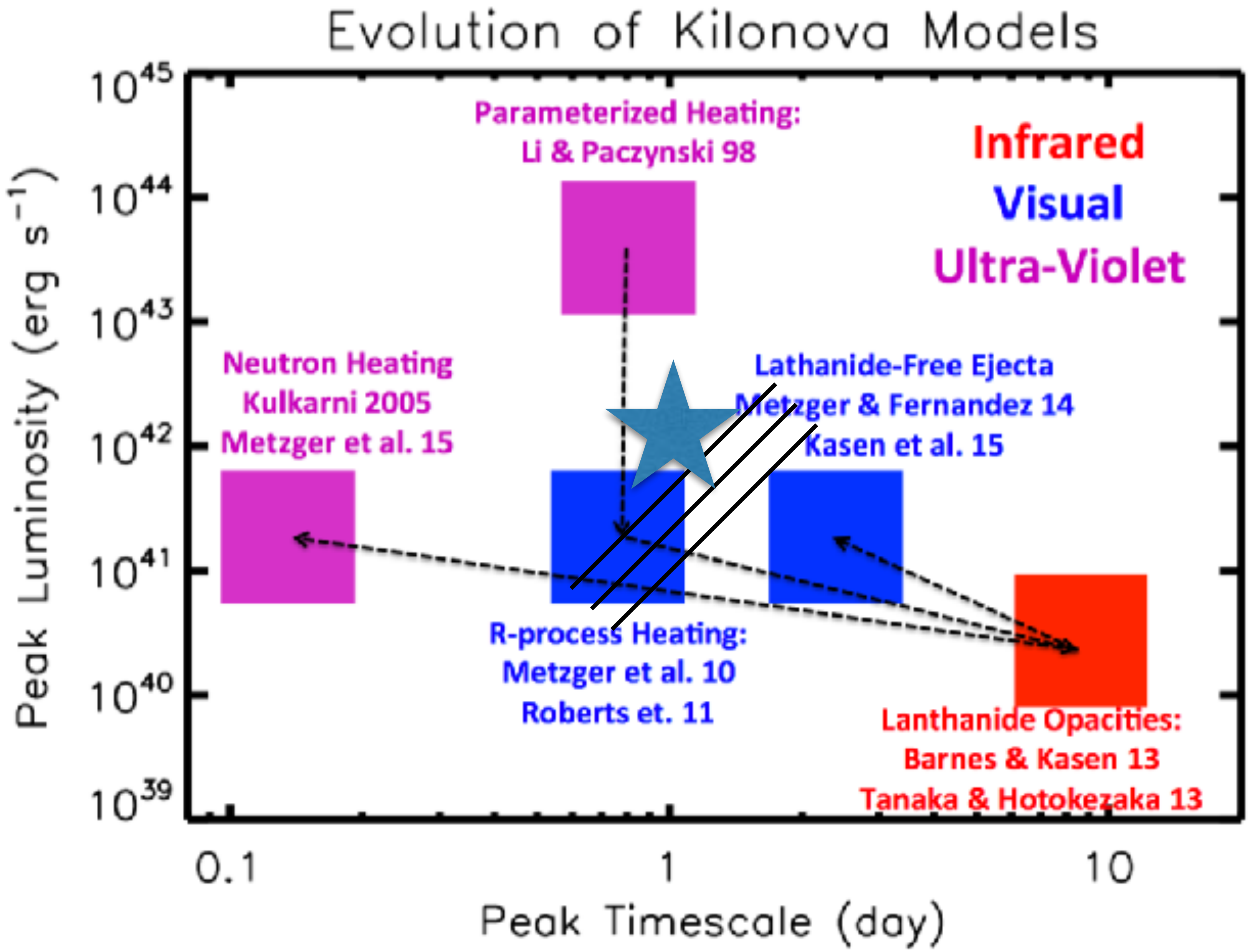
- Kasen 2013: **Lanthanides** (A=58-71) give high opacity.







The landscape with uncertainty in opacity



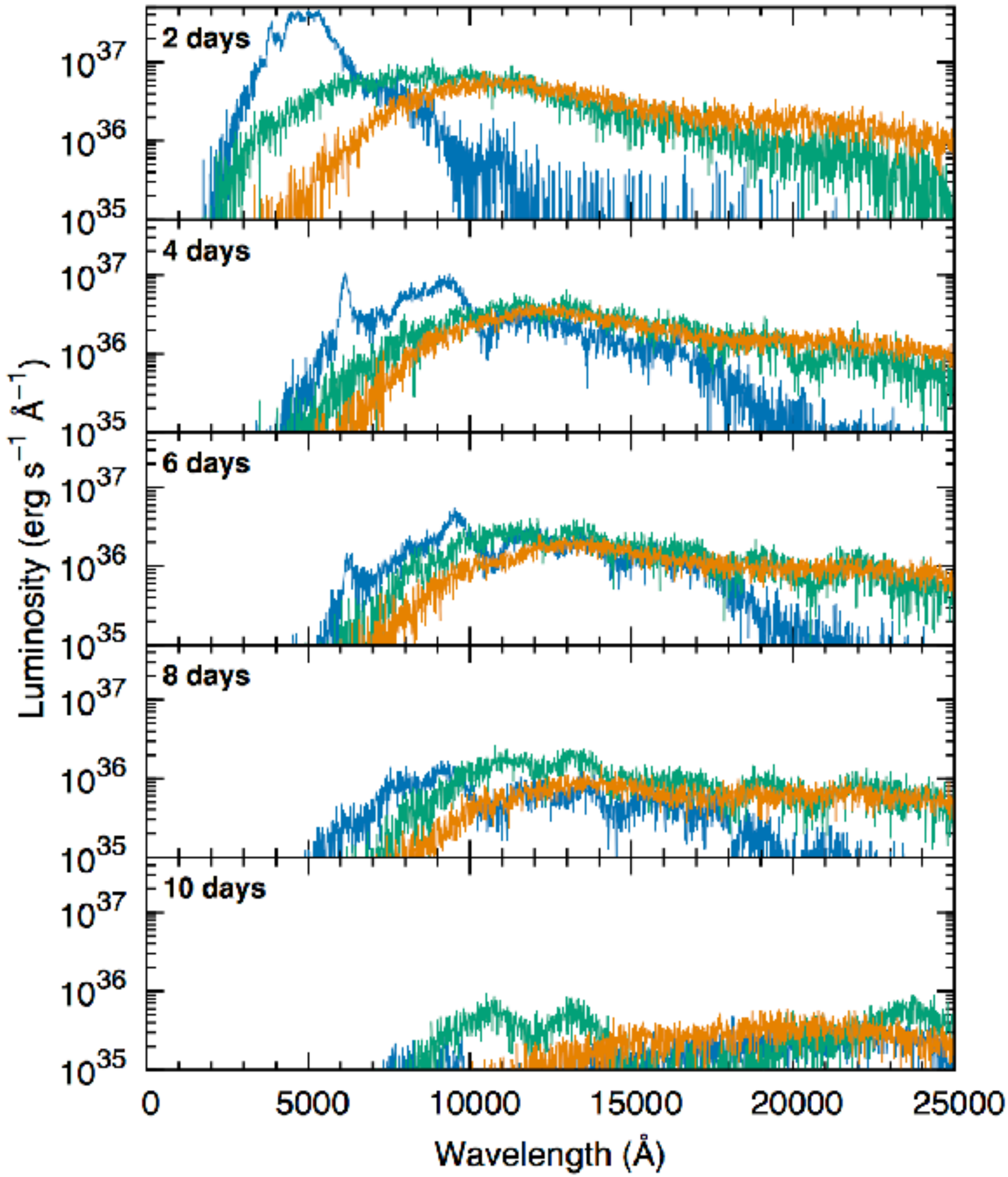
Metzger 2017

$t_{peak} \sim 1.6d\ M_{0.01}^{1/2}\ V_{0.1c}^{-1/2}\ \mathrm{kappa}^{1/2}$

Most recent models: Tanaka 2017

- If Ye is as broad as indicated by recent models (orange) with neutrino processing, quite featureless spectra.

- Even single Ye models (blue and green) relatively featureless due to many lines.



Current limitations for spectral models

- **NLTE**. Density too low for collisional LTE within days. Radiation field may maintain LTE for 1-2 weeks, but beyond 1-2 weeks almost certain strong NLTE effects.
- **Sobolev**. Too many lines to be valid.
- **Expansion opacities**. Only rough transfer method. Possible that KNe need completely new transfer methods.

$$\alpha_{\exp}^{\mathrm{bb}}(\lambda) = \frac{1}{ct} \sum_{l} \frac{\lambda_l}{\Delta\lambda} (1 - e^{-\tau_l}),$$

- **Atomic data.**
  - Still only a few elements of >100 necessary implemented.
  - Challenging to calculate accurately.

Adding it all up: The possible variety

- Mass anywhere from 0 to 0.1 Msun: Be prepared for both dimmer and brighter events compared to 2017gfo.
- Velocities anywhere from 0.05-0.4c.
- Opacity anywhere from 0.1 to 100 (and diverse composition).
- Significant viewing angle effects possible (in particular BH-NS mergers).
- Powering by central object could add further diversity.
- GRB may or may not associate (low mass NS don't make BH).

Necessary workflow

1. **Bolometric light curves**
    1. Unbiased approach ("I know no theory")
    2. Theory guided
2. **Photometry**
3. **Spectroscopy**
    1. Catch highly flattened systems to reduce blending?

Summary

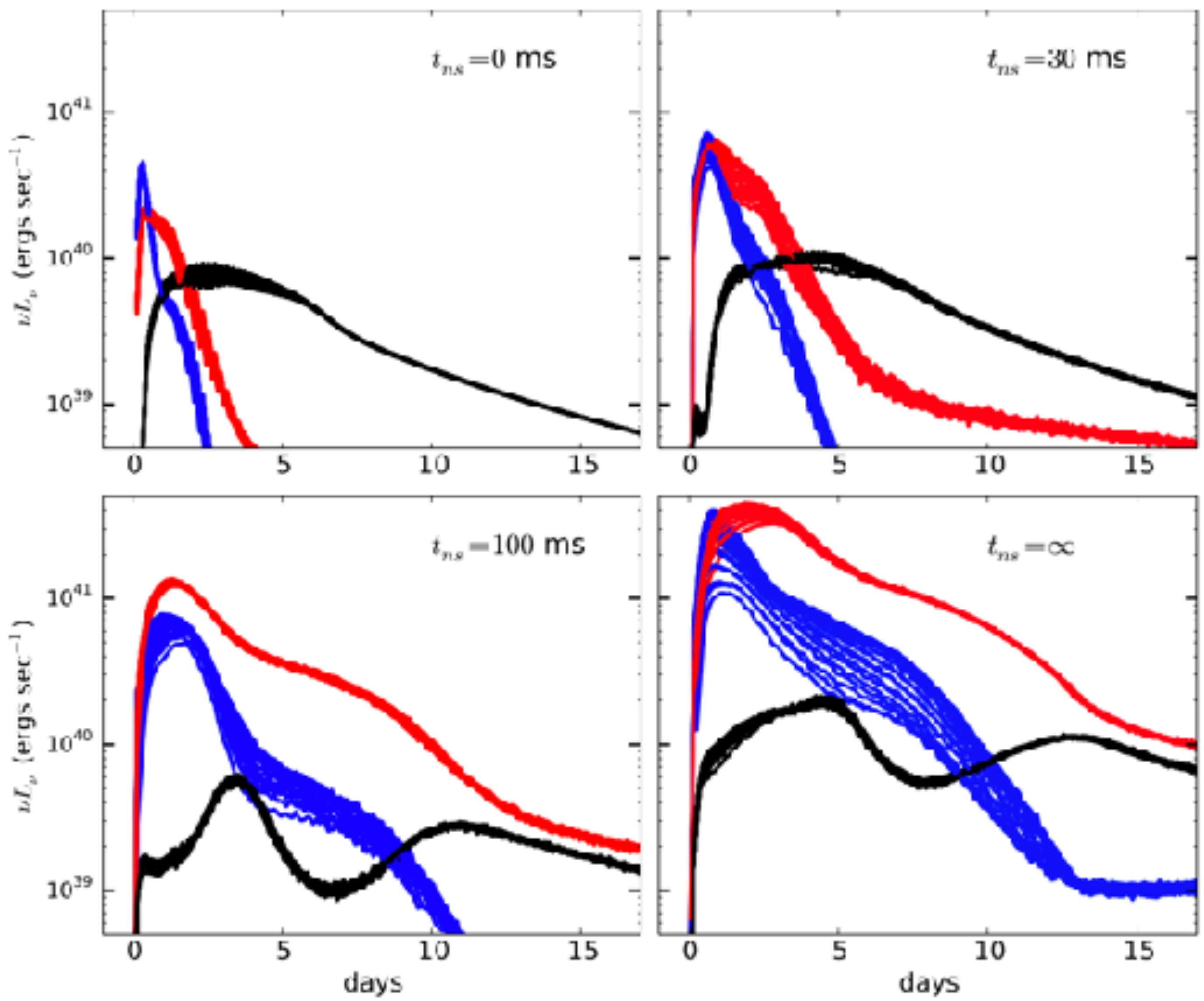
- Predictions of ejecta properties have rapidly changed over last years, considering 3D, GR, neutrino irradiation, magnetic fields,…

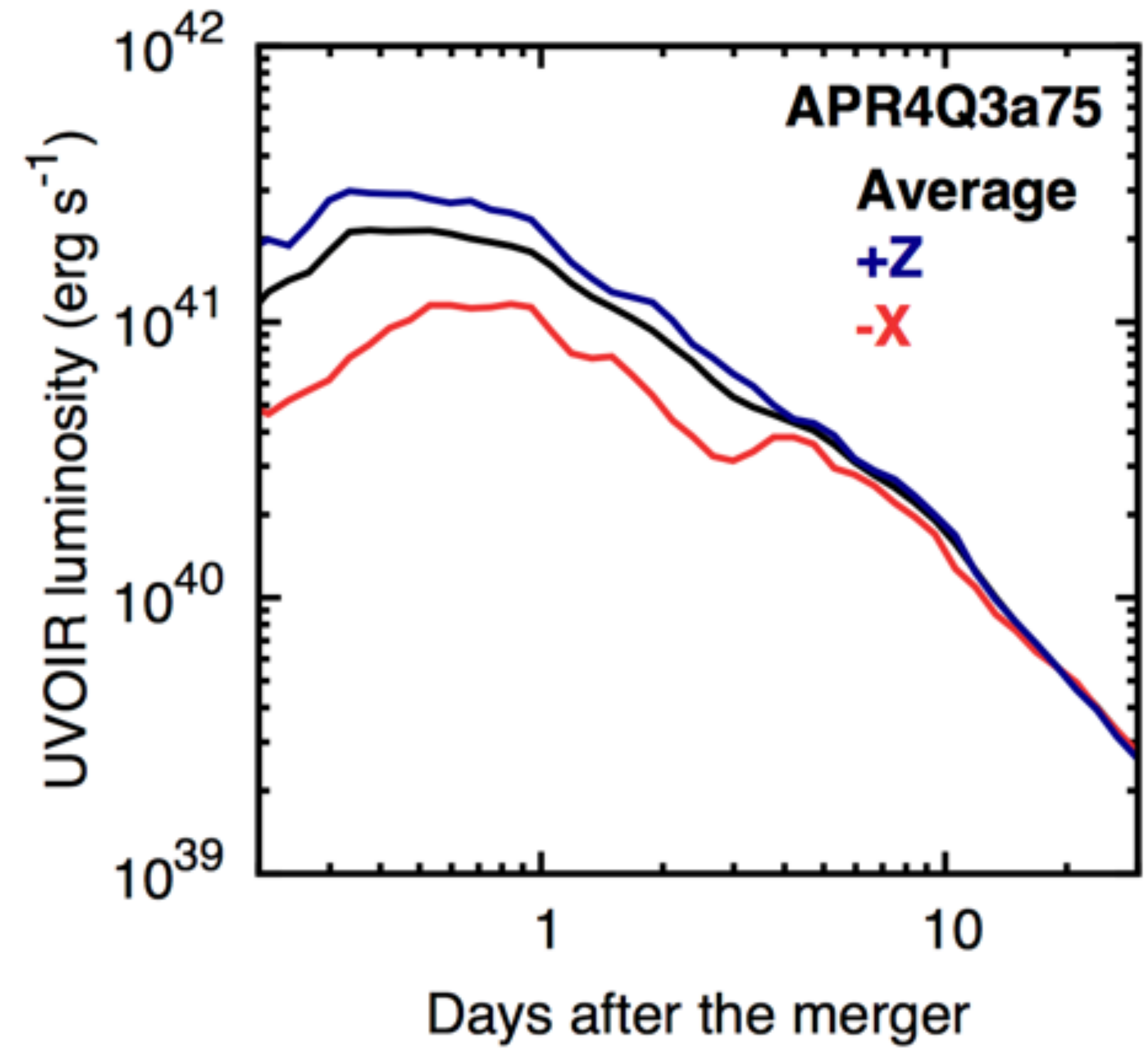
- Two main components are expected: dynamic and disk wind, but these each break up into subcomponents.

- Current picture has M_dyn <~ 0.01 Msun. Conflict with models for 2017gfo with M ~ 0.05 Msun and dynamic origin. Wind can more easily eject high mass.

- Spectral modelling so far hampered by both atomic data and RT method limitations..need mainly bolometric LCs in step 1.

Viewing angle effects





Kasen 2015 (wind)

Tanaka 2014 (dyn.)