Kilonova Emission from Compact Binary Mergers: Opacities of Lanthanide-rich and Lanthanide-free Ejecta

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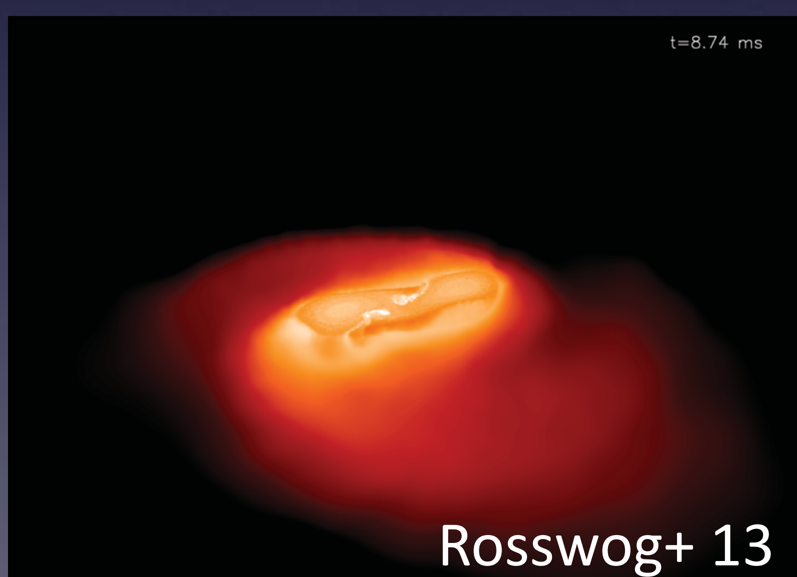
- Introduction
- New opacity calculations
- Applications to kilonova

Merger → **r-process nucleosynthesis** → **Radioactive decay => kilonova**

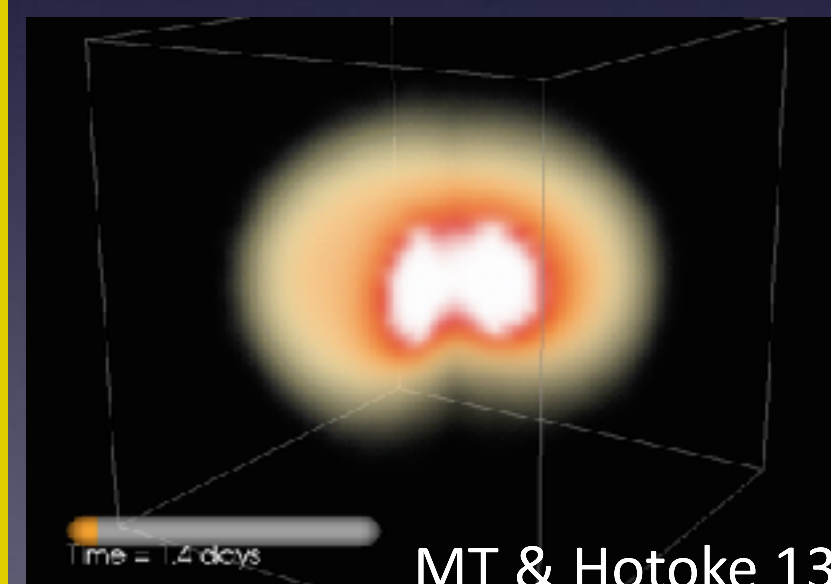
Dynamical ejection | **Post-merger ejection**

< 10 ms | **~< 100 ms** | **< 1 sec** | **~ days**



Rosswog+ 13

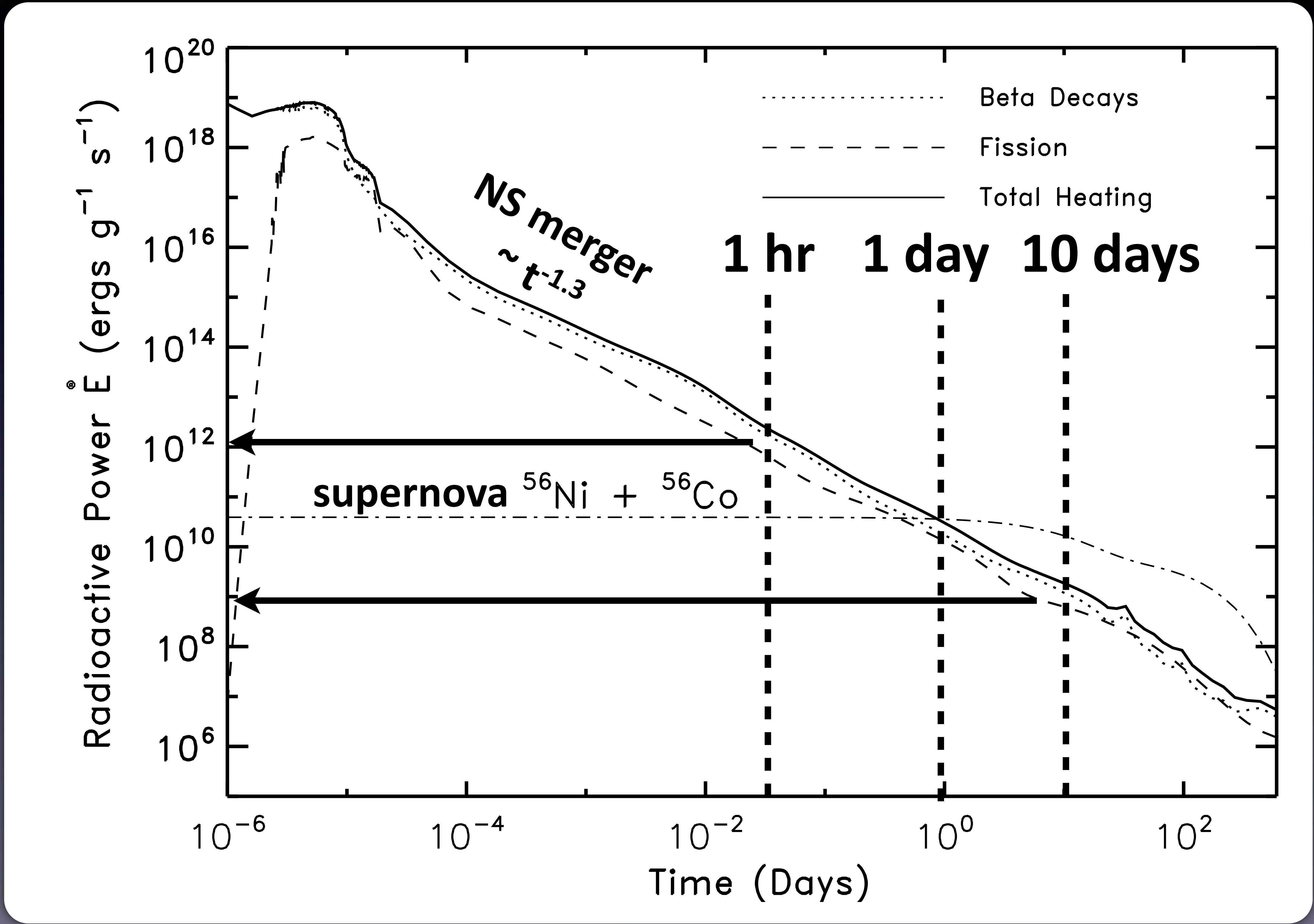
Shibata, Giacomazzo, Foucart, Just, Siegel, Tchekhovskoy, Perego, Wu, McLaughlin…


MT & Hotoke 13

This talk

Korobkin and Baron

Radioactive heating (decay of many r-process nuclei)



10^{43} erg s^{-1}

10^{40} erg s^{-1}

(for M = 0.01 Msun)

Metzger+10

“Kilonova/Macronova"

Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, …
High opacity: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, …

Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$

$$\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

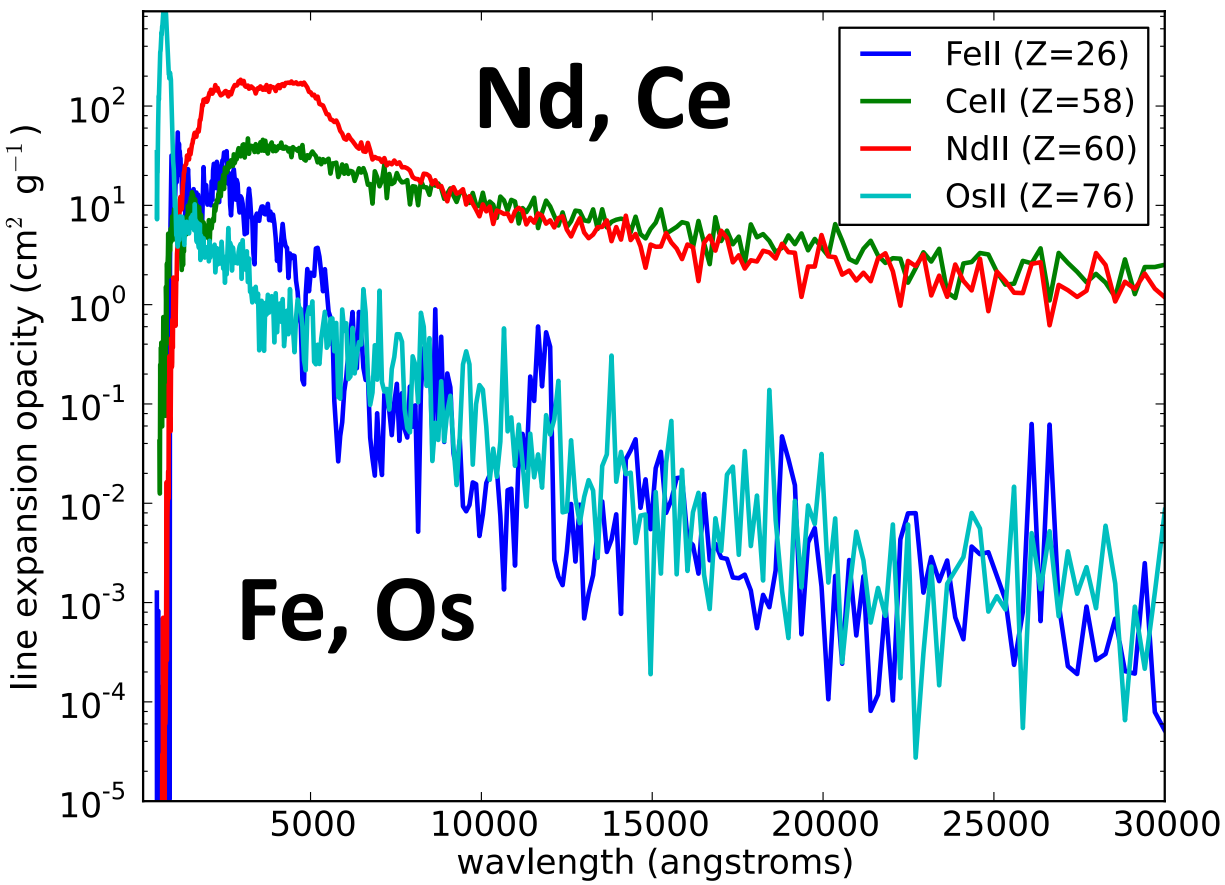
Luminosity

$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$

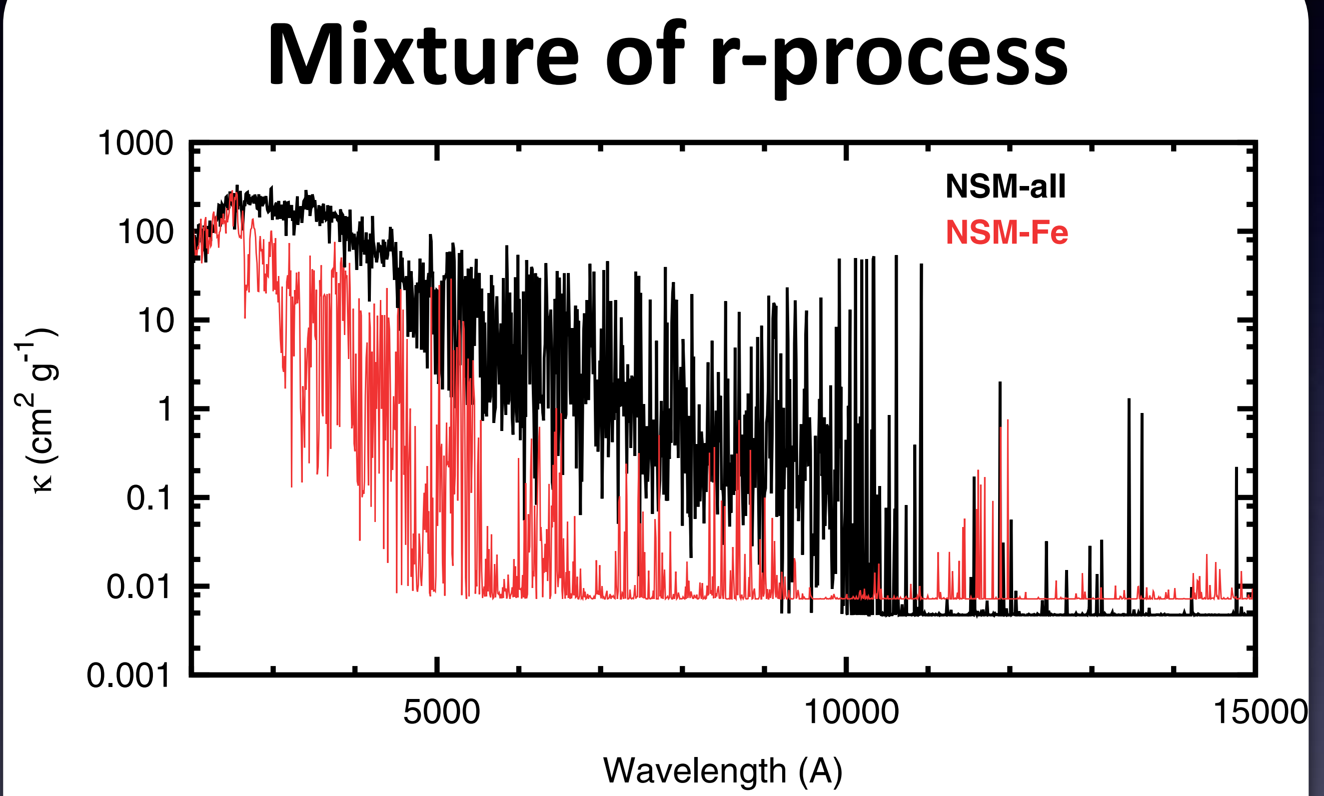
$$\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\rm ej}}{0.01M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{-0.65}$$

*assuming 50% thermalization

High opacity of NS merger ejecta

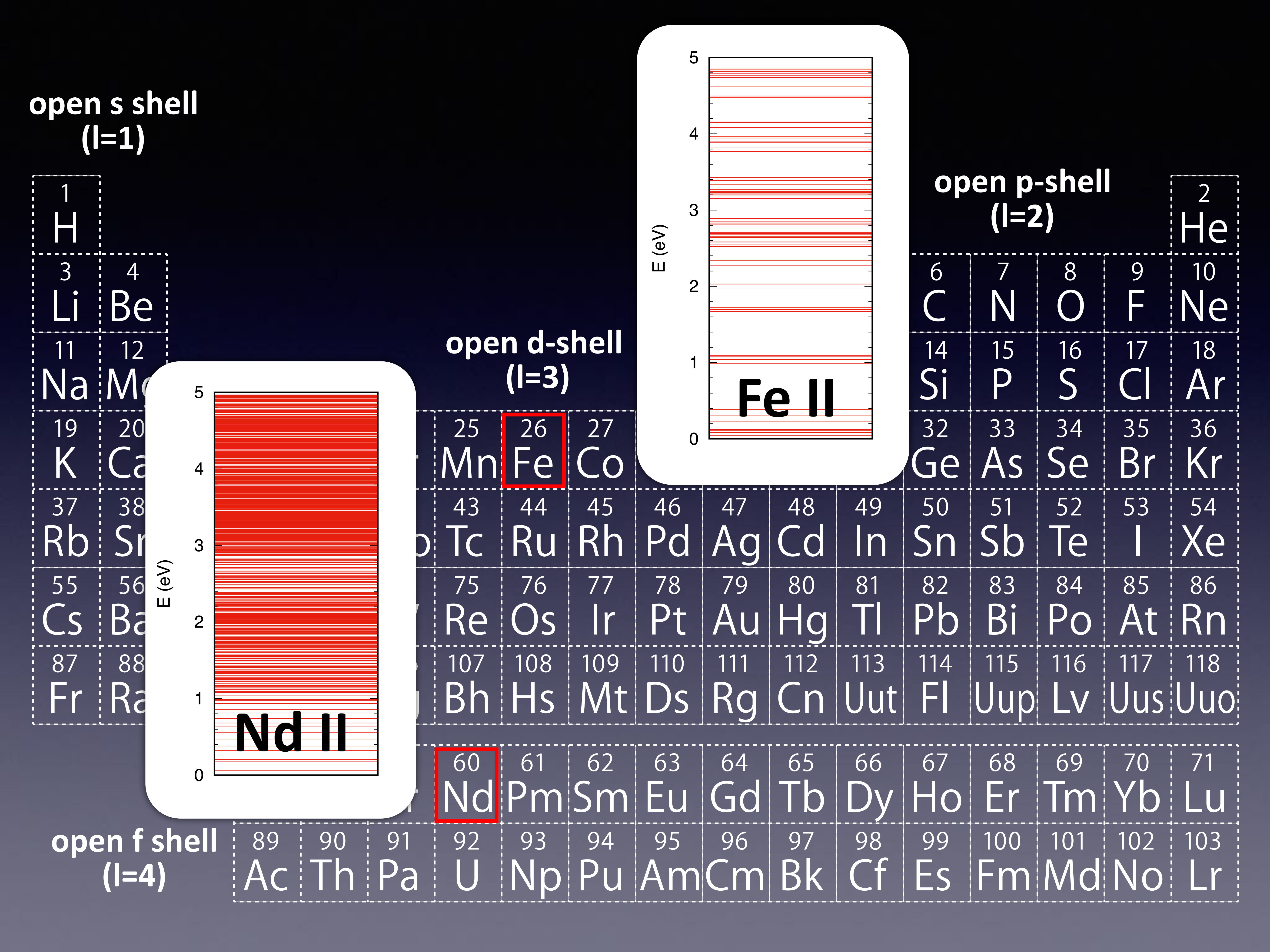


Kasen, Badnell, & Barnes 13



MT & Hotokezaka 13

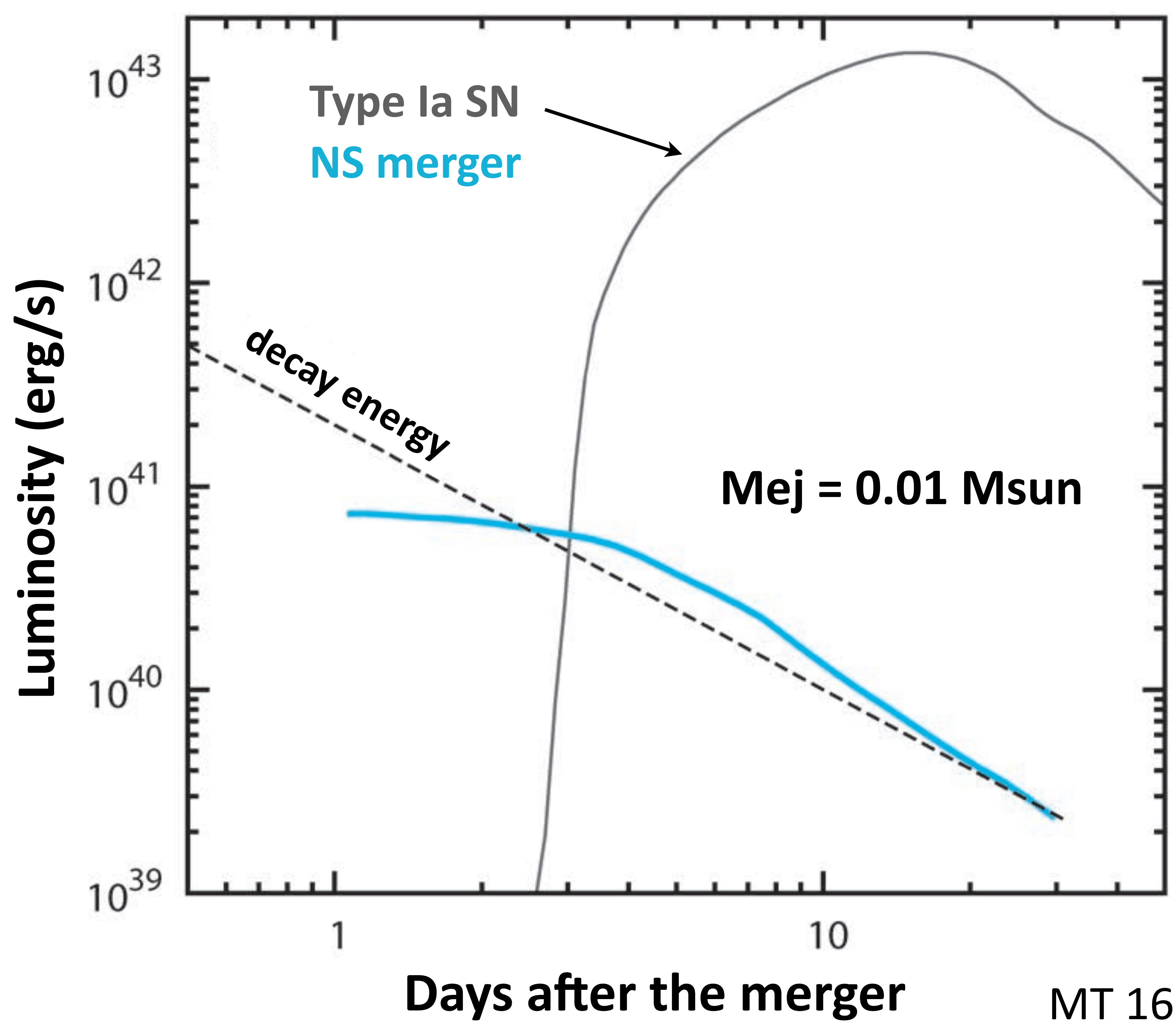
$\kappa \sim 10\ cm^2\ g^{-1}$


open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
1 H
2 He
3 Li
4 Be
6 C
7 N
8 O
9 F
10 Ne
11 Na
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
25 Mn
26 Fe
27 Co
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
107 Bh
108 Hs
109 Mt
110 Ds
111 Rg
112 Cn
113 Uut
114 Fl
115 Uup
116 Lv
117 Uus
118 Uuo
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No
103 Lr
Fe II
E (eV)
0 1 2 3 4 5
Nd II
E (eV)
0 1 2 3 4 5

Light curve

see Barnes & Kasen 13, MT & Hotokezaka 13

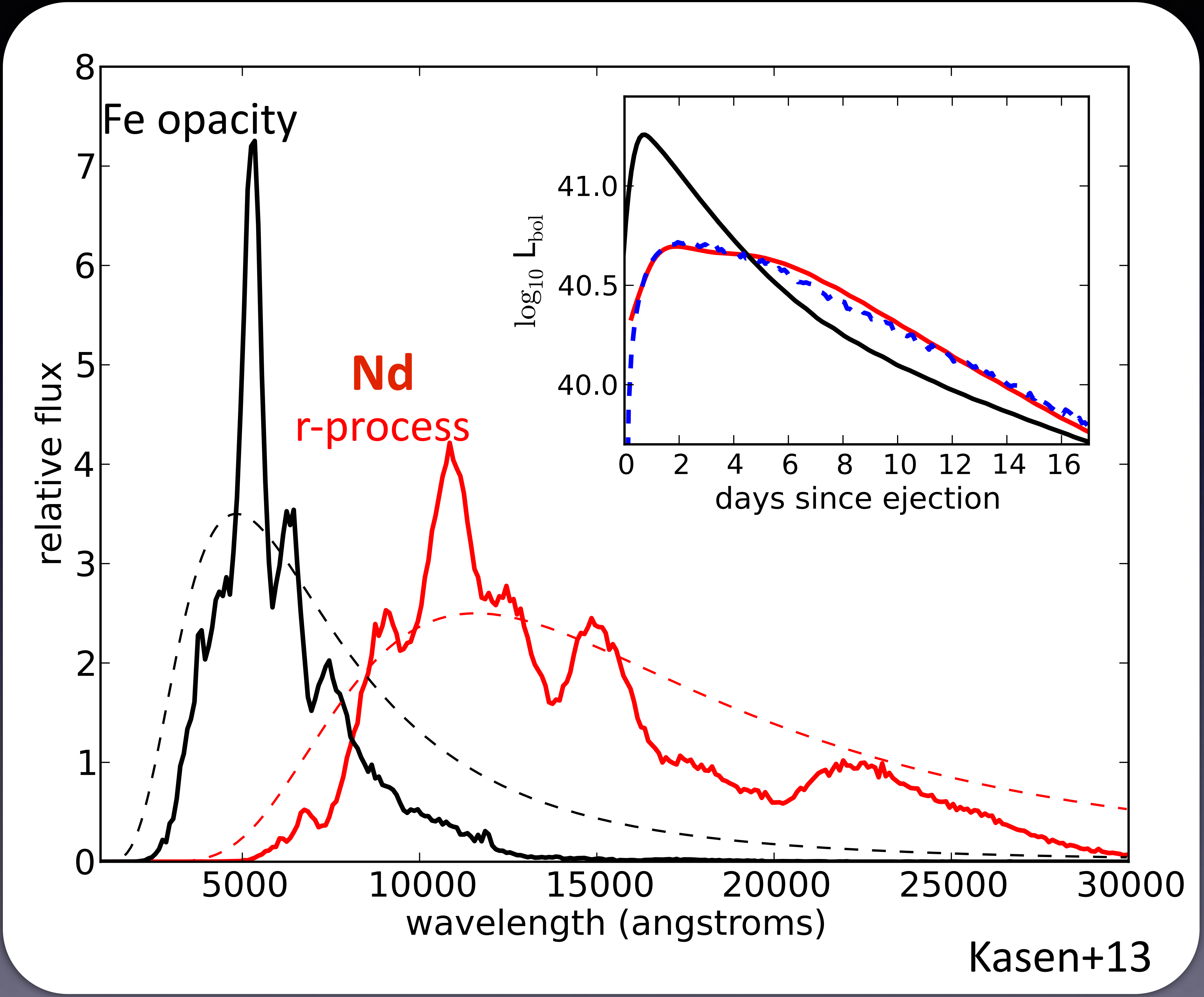
a few x 10^{40} erg/s
@ ~1 week



MT 16

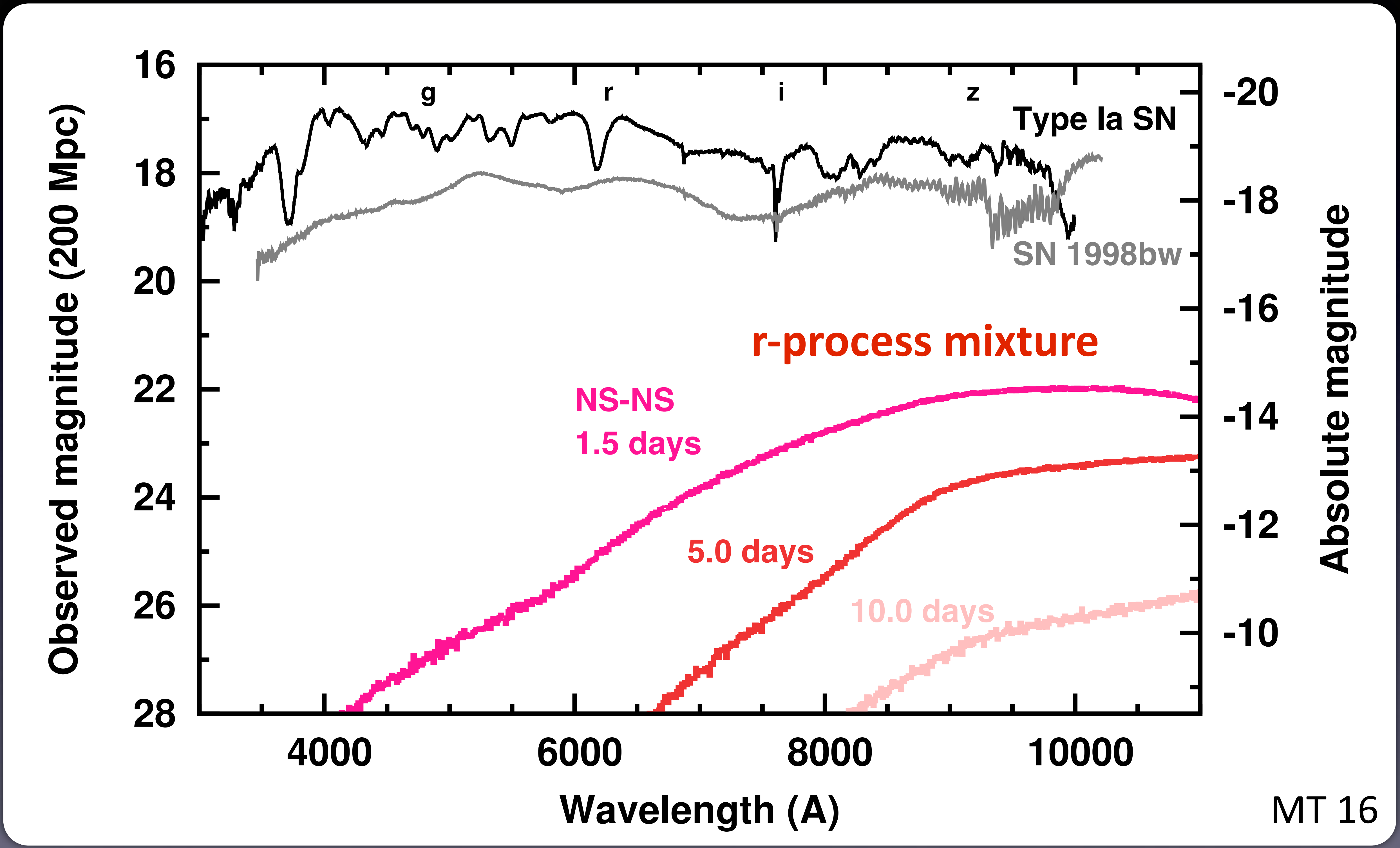
Spectra

See Eddie's talk



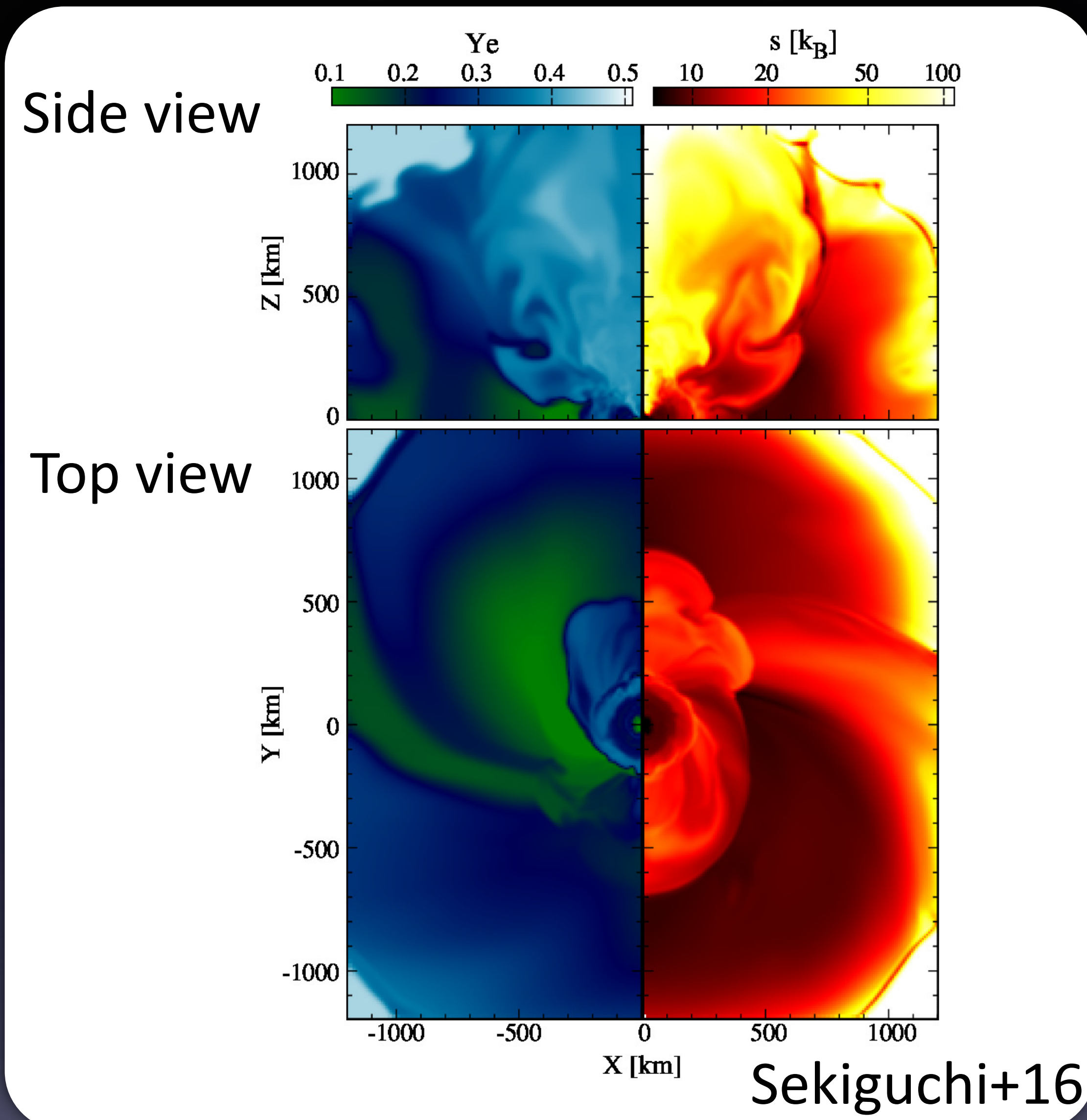
Extremely red spectra

Spectra



Much redder than supernovae

Dynamical ejecta (~< 10 ms)

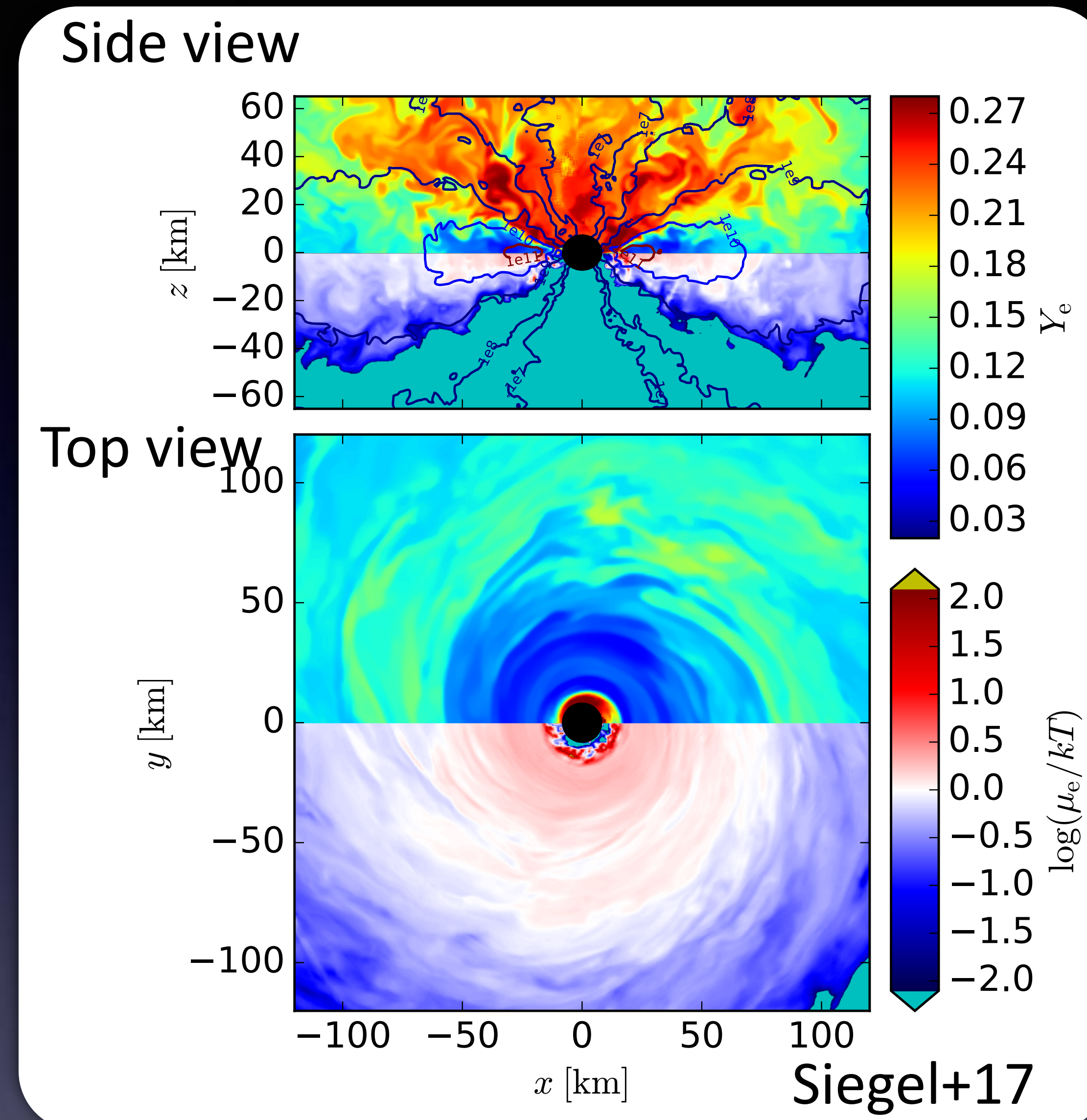


Sekiguchi+16

Rosswog+99, Lee+07, Goriely+11, Hotokezaka+13, Bauswein+13, Radice+16…

- Mej ~ 10^{-3} - 10^{-2} Msun
- v ~ 0.1-0.2 c
- wide Ye

Post-dynamical ejecta (~< 100 ms)



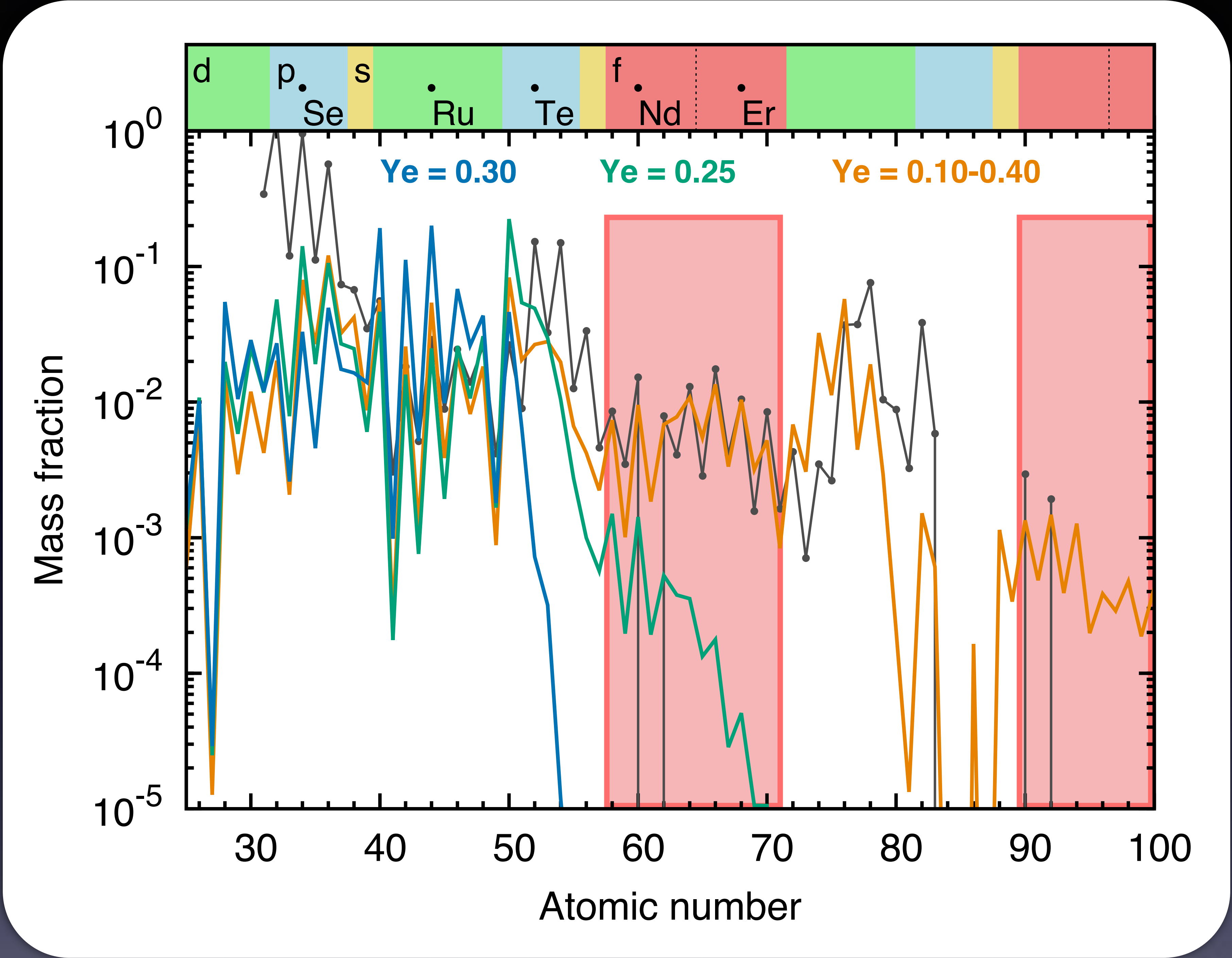
Siegel+17

Fernandez+13,15, Perego+14, Kiuchi+14,15, Martin+15, Just+15, Wu+16, Siegel & Metzger 17…

- Mej >~ 10^{-3} Msun
- v ~ 0.05 c
- relatively high Ye

$n + \nu_e \rightarrow p + e^-$

$n + e^+ \rightarrow \bar{\nu}_e + p$



@ 1 day
(Wanajo+14)

"Blue" kilonova?

Simulations with Fe opacity or gray opacity
Metzger+14, Kasen+15, Fernandez & Metzger 16, Metzger 16

New opacity calculations for
Se (Z=34), Ru (Z=44), Te (Z=52), Nd (Z=60), Er (Z=68)

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Atomic structure calculations

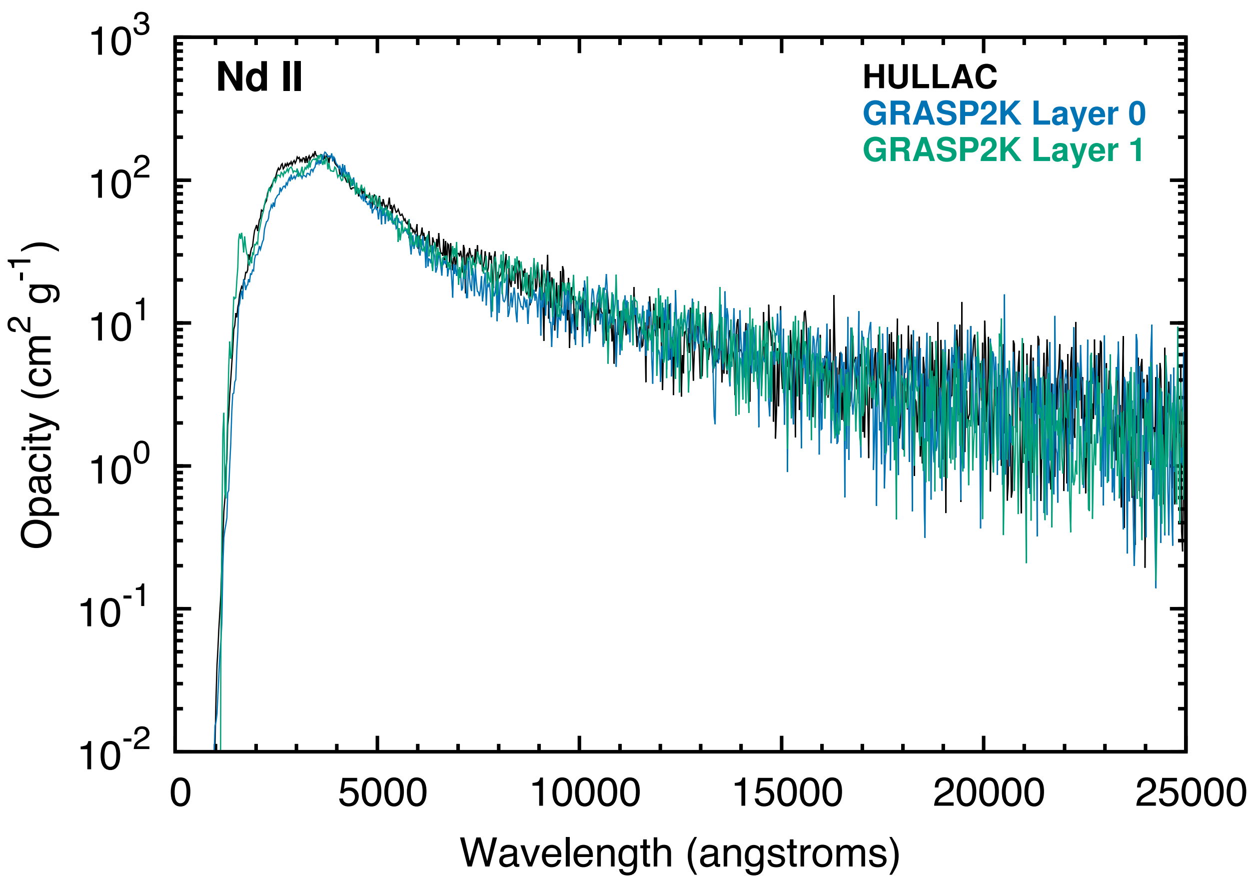
HULLAC code (relativistic, local radial potential, Bar-Shalom+99)

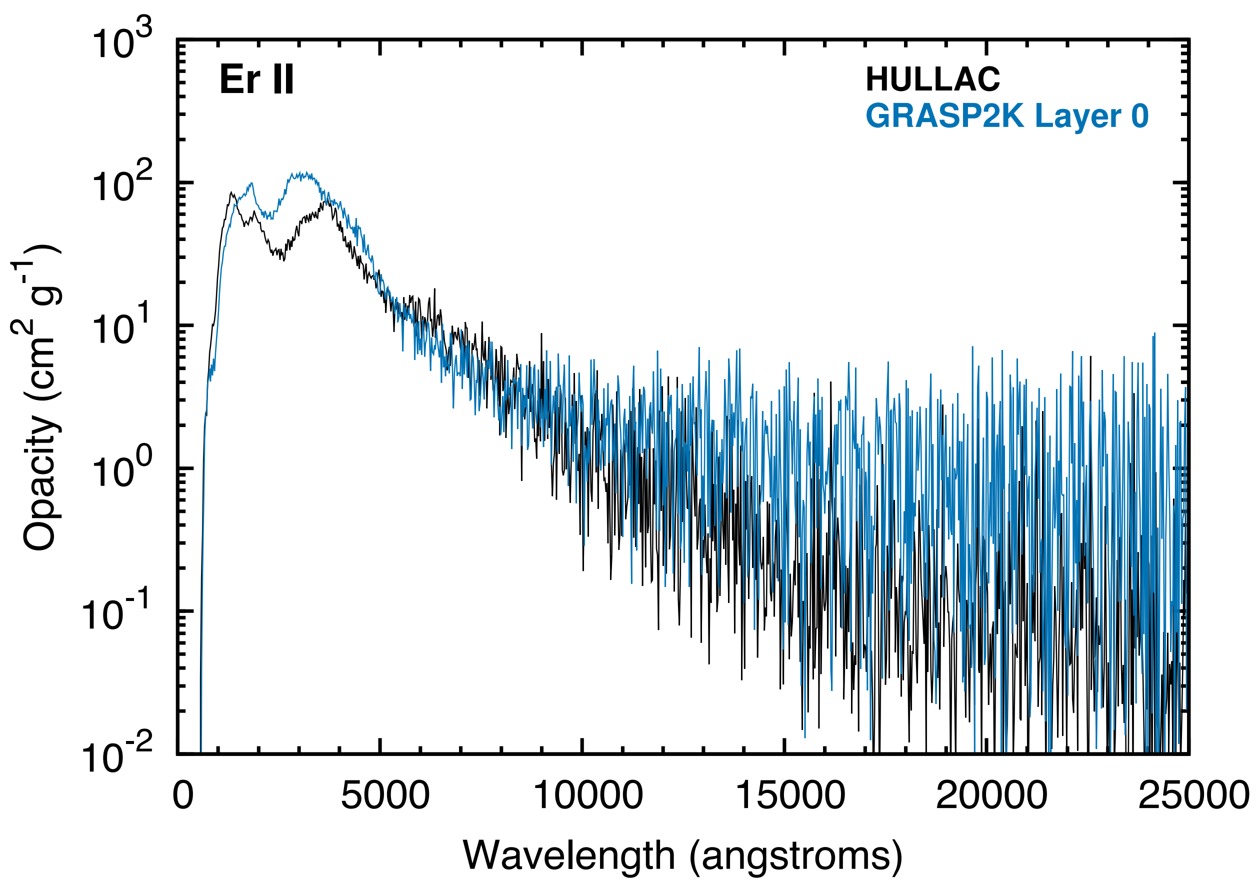
Se I-III (Z=34, p), Ru I-III (Z=44, d), Te I-III (Z=52, p),
Nd I-III (Z=60, f), and Er I-III (Z=68, f)

GRASP code (relativistic, e-e interaction, Jonsson+07)

Nd II-III (Z=60, f) and Er II-III (Z=68, f)

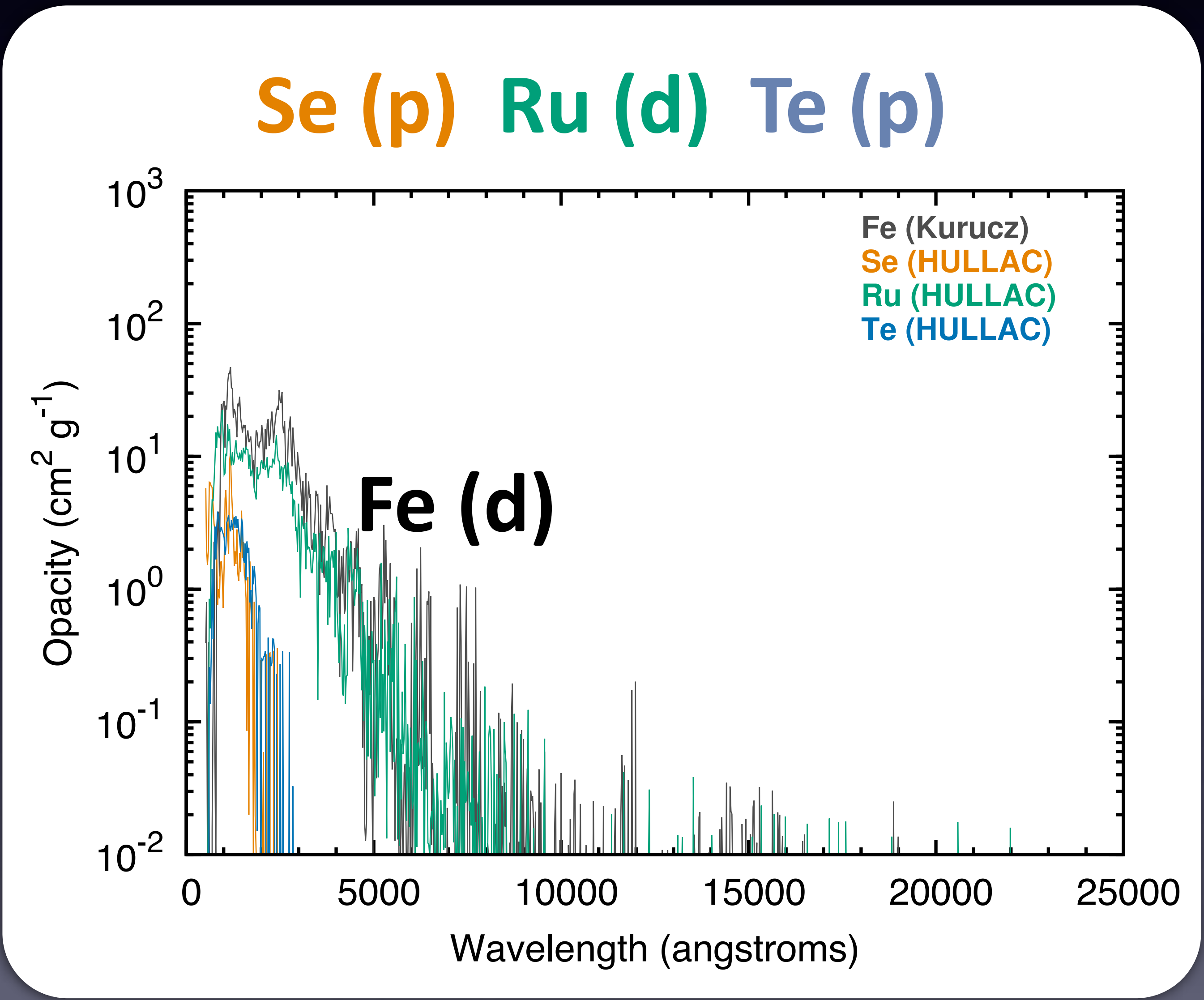
Line expansion opacity (from two codes)

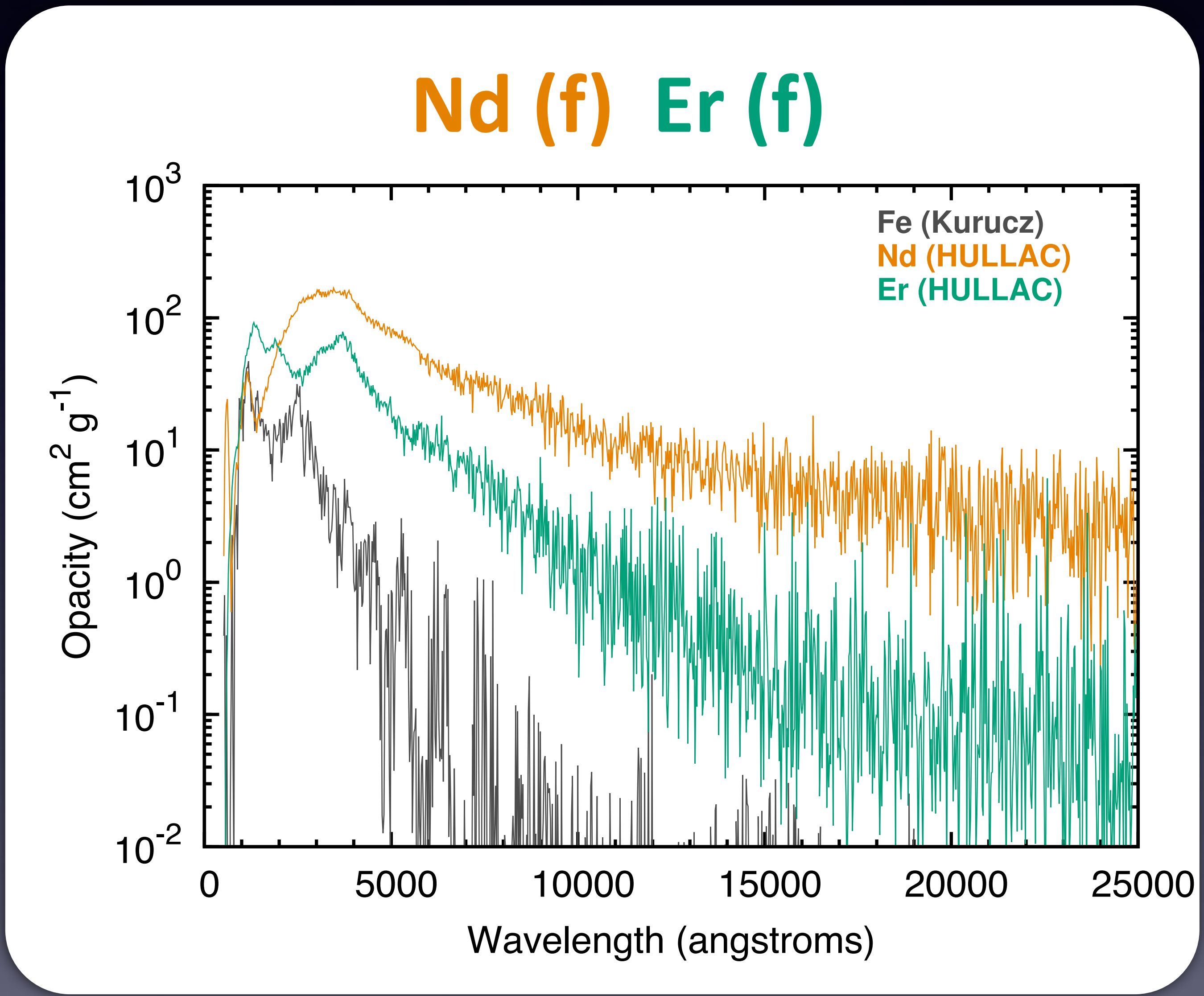




Consistent within a factor of 2 even for the worst case (Er II)
Consistent with results by Kasen+13 (Autostruture code)

Line expansion opacity (for each element)





MT+ in prep.

κ (p shell) << κ (d shell) << κ (f shell)

see Kasen+13, Fontes+17

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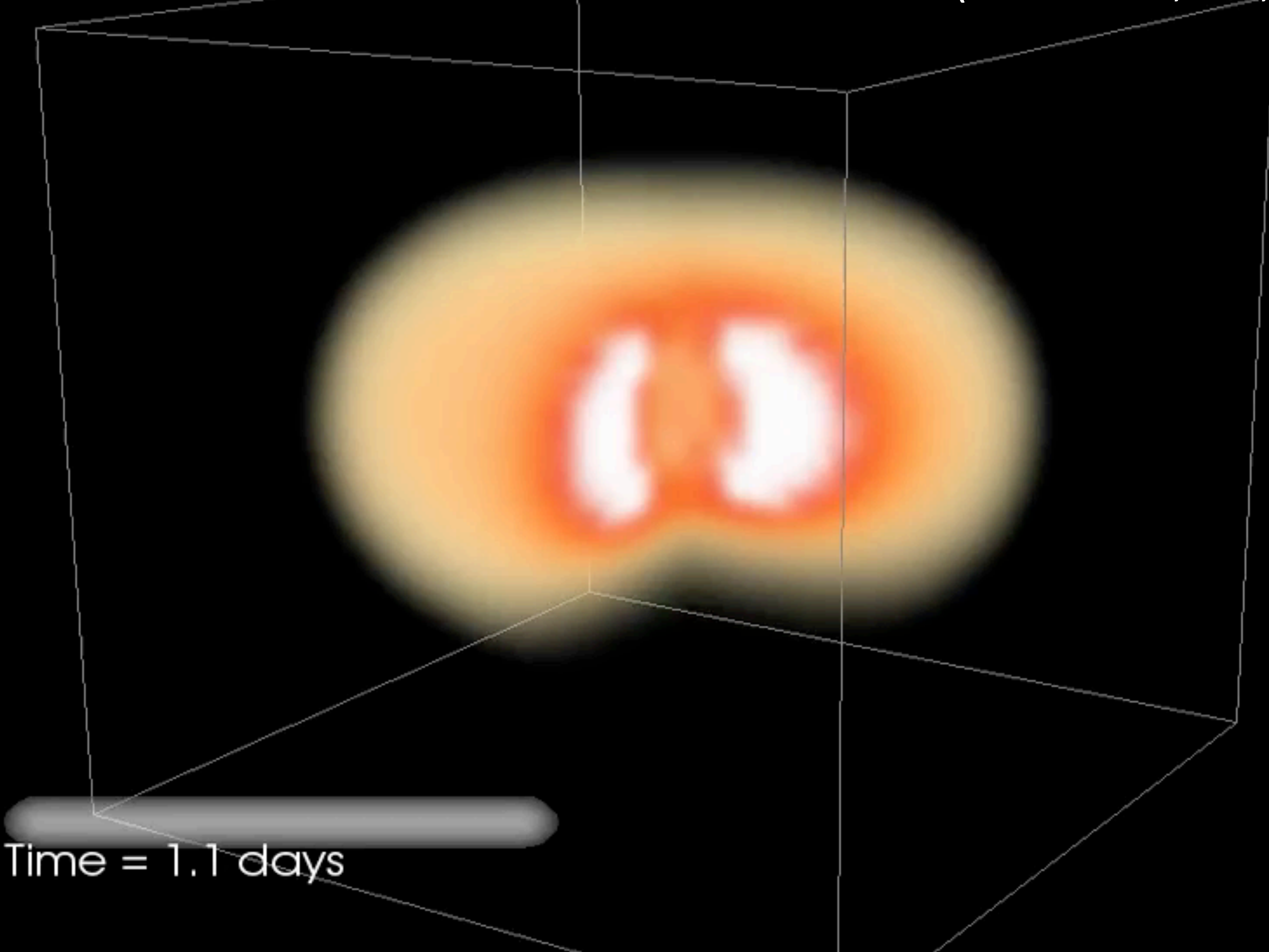
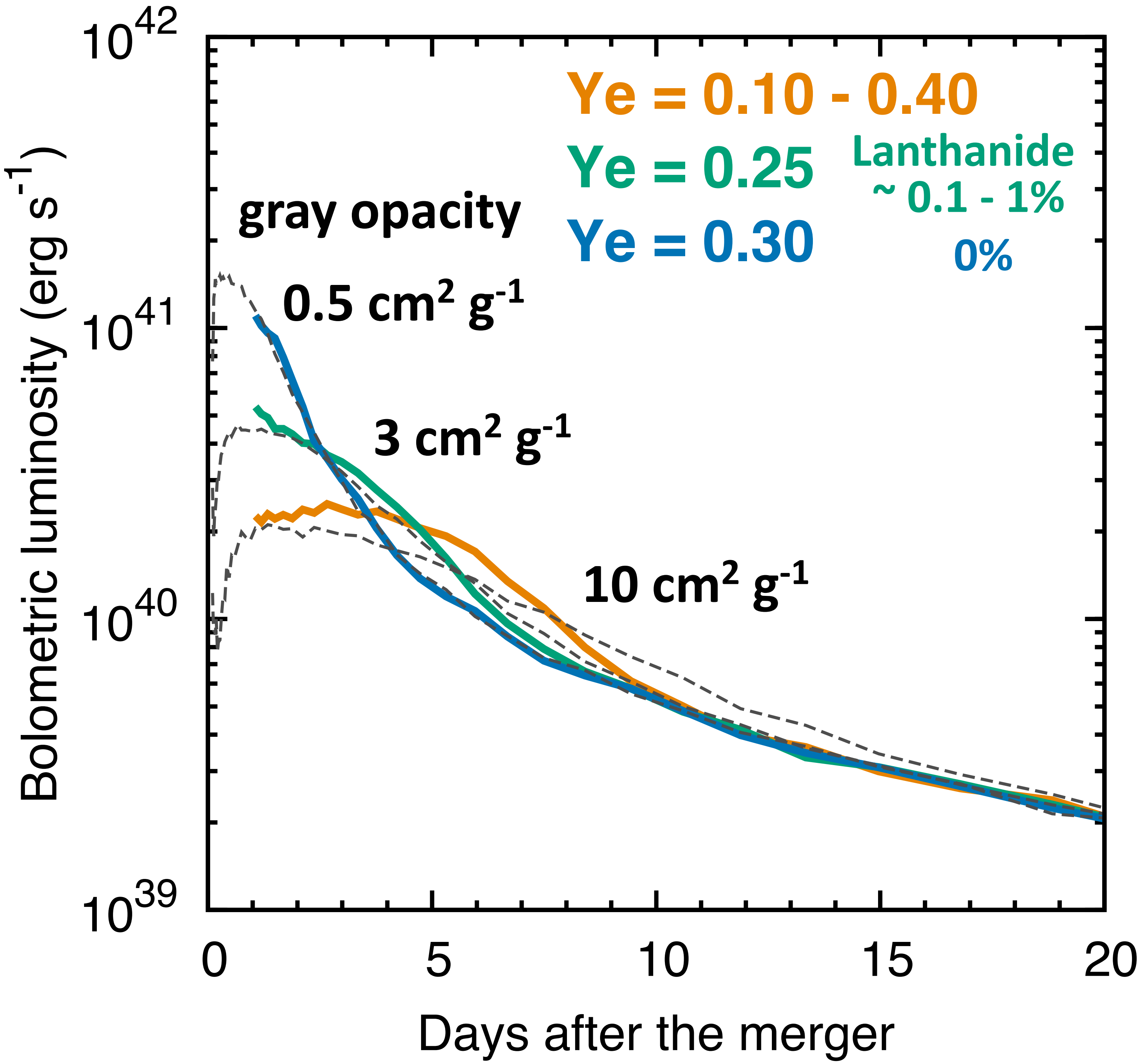
3D Monte-Carlo time/frequency-dependent radiation transfer

(MT & Hotokezaka 13, MT+14, MT 16)

~6,000,000 b-b transitions

(out of ~70,000,000)



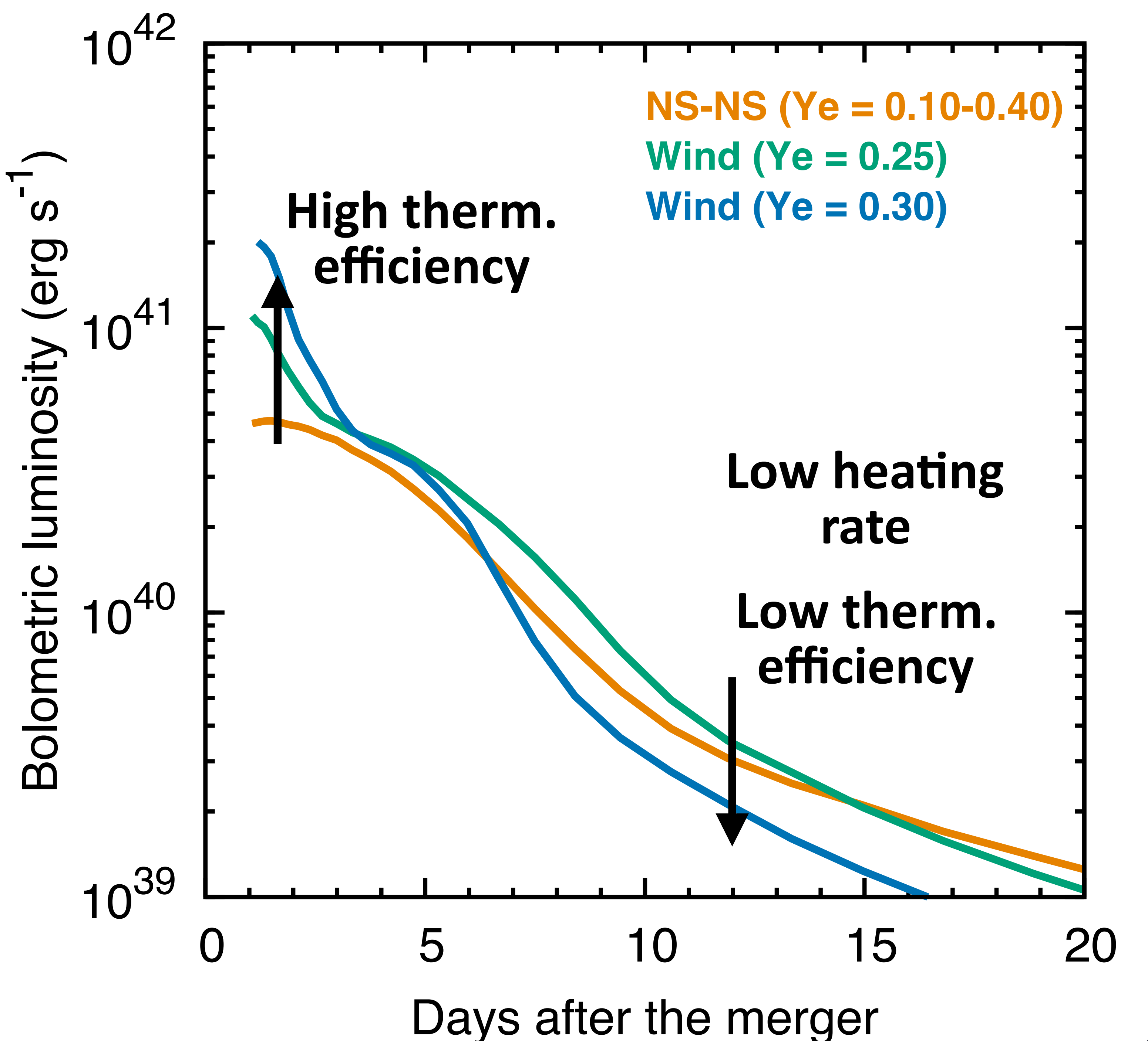


Simple model

- Mej = 0.01 Msun
- v = 0.1c
- Heating rate ~ $t^{-1.3}$
- Constant thermalization (0.25)

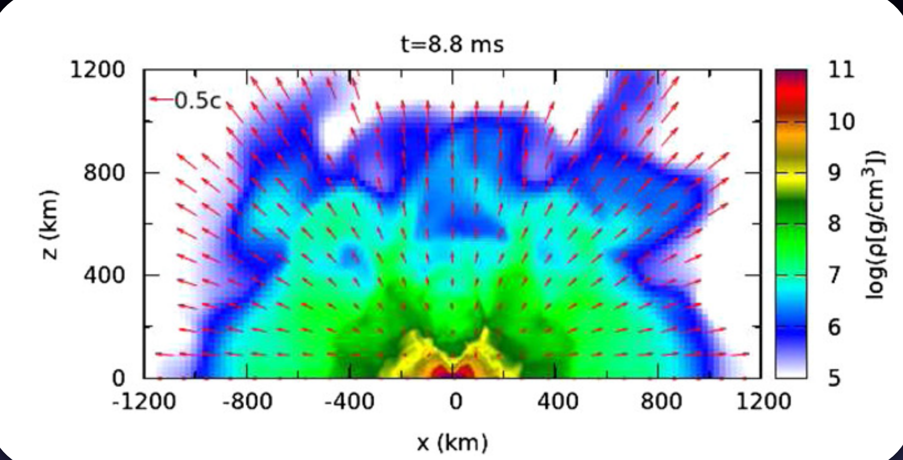
Depends sensitively on Ye

κ ~ 0.5 cm^2 g^{-1} for Lanthanide-free ejecta (Ye ~ 0.3)



NS-NS

- Mej = 0.01 Msun
- v = 0.2c



Hotokezaka+13, Sekiguchi+15,16

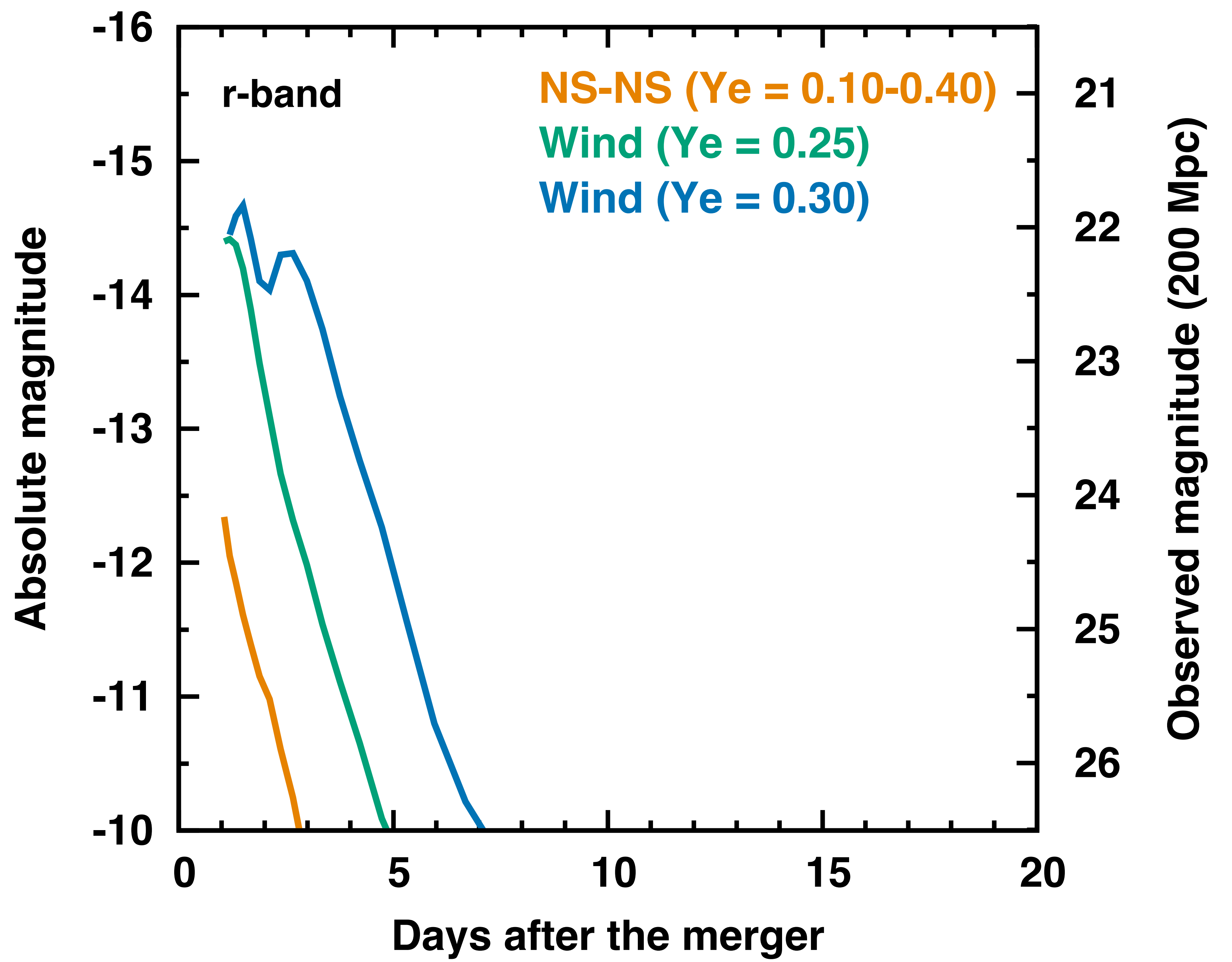
Wind

- Mej = 0.01 Msun
- v = 0.05c

- Heating rate from nucleosynthesis calc.
- Thermalization (Barnes+16)

Optical (r-band)

Mej = 0.01 Msun



MT+ in prep.

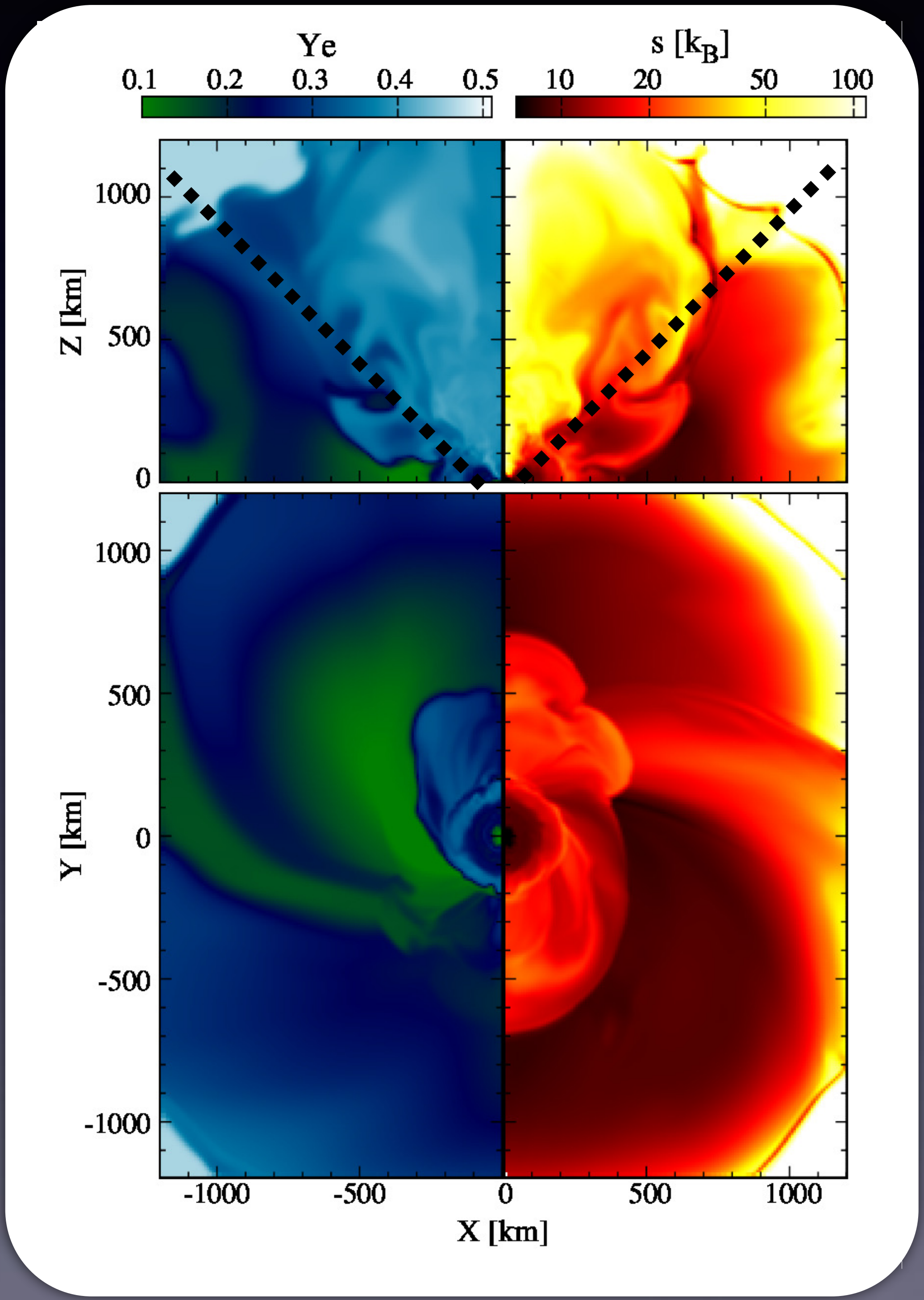
Wide variety even for the same ejecta mass

=> Accurate estimate of Ye is crucial

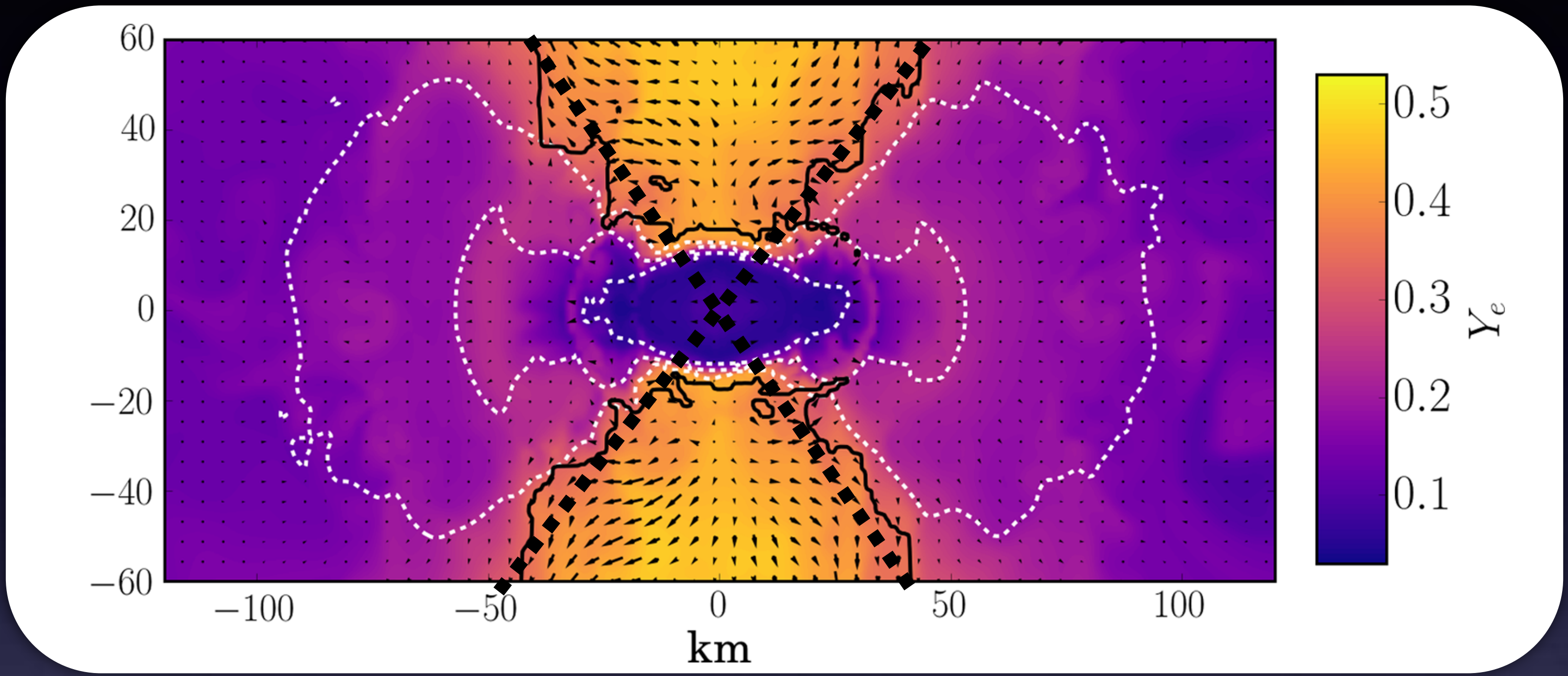
See Francois's, Oliver's, Sasha's, Albino's talks

Blue component may be absorbed by dynamical ejecta?

e.g., Kasen+15, Metzger 17



Sekiguchi+16



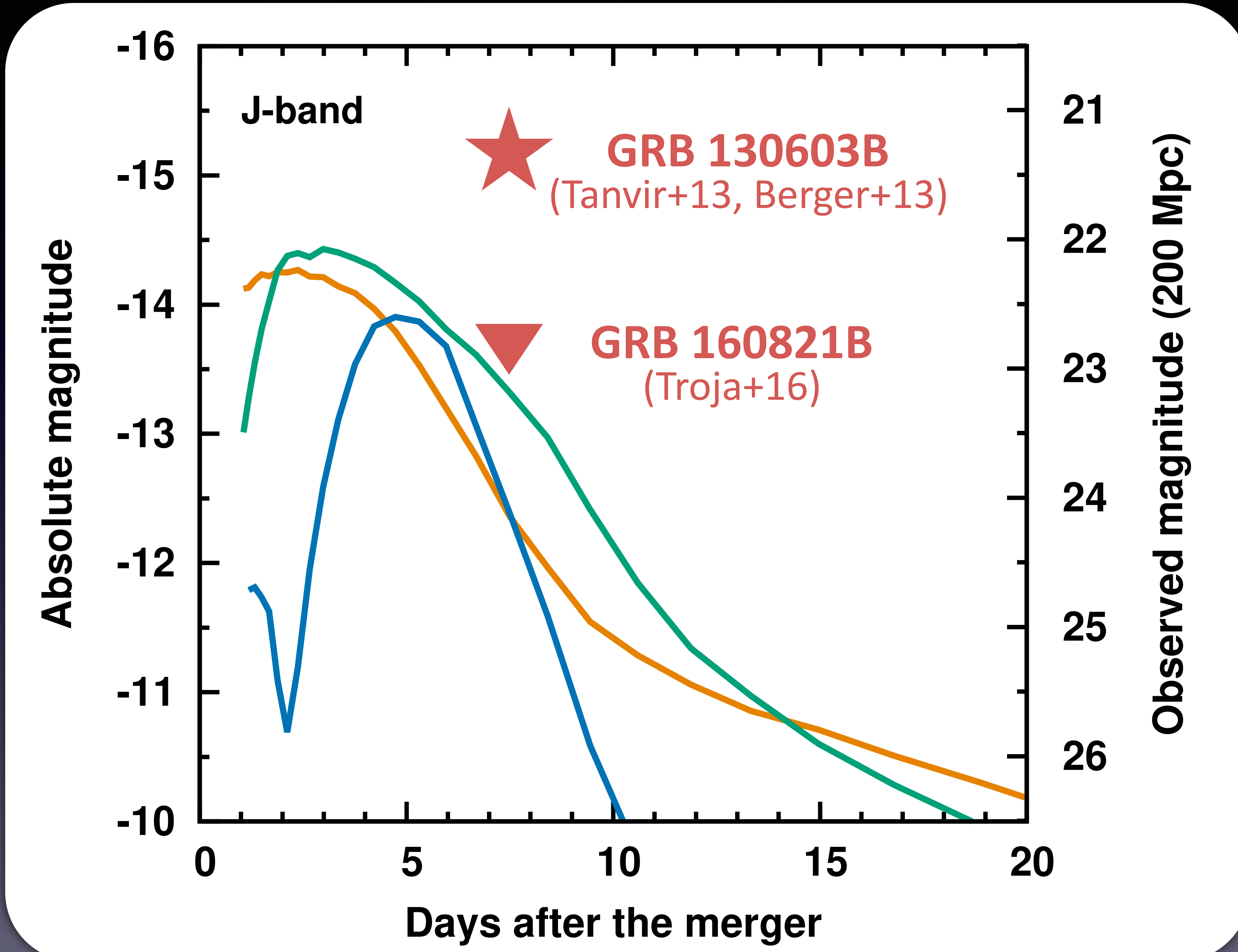
Foucart+16

See Francois's talk

High Ye in the polar region (< 30-45 deg)
=> Blue emission may be able to escape

NIR (J-band)

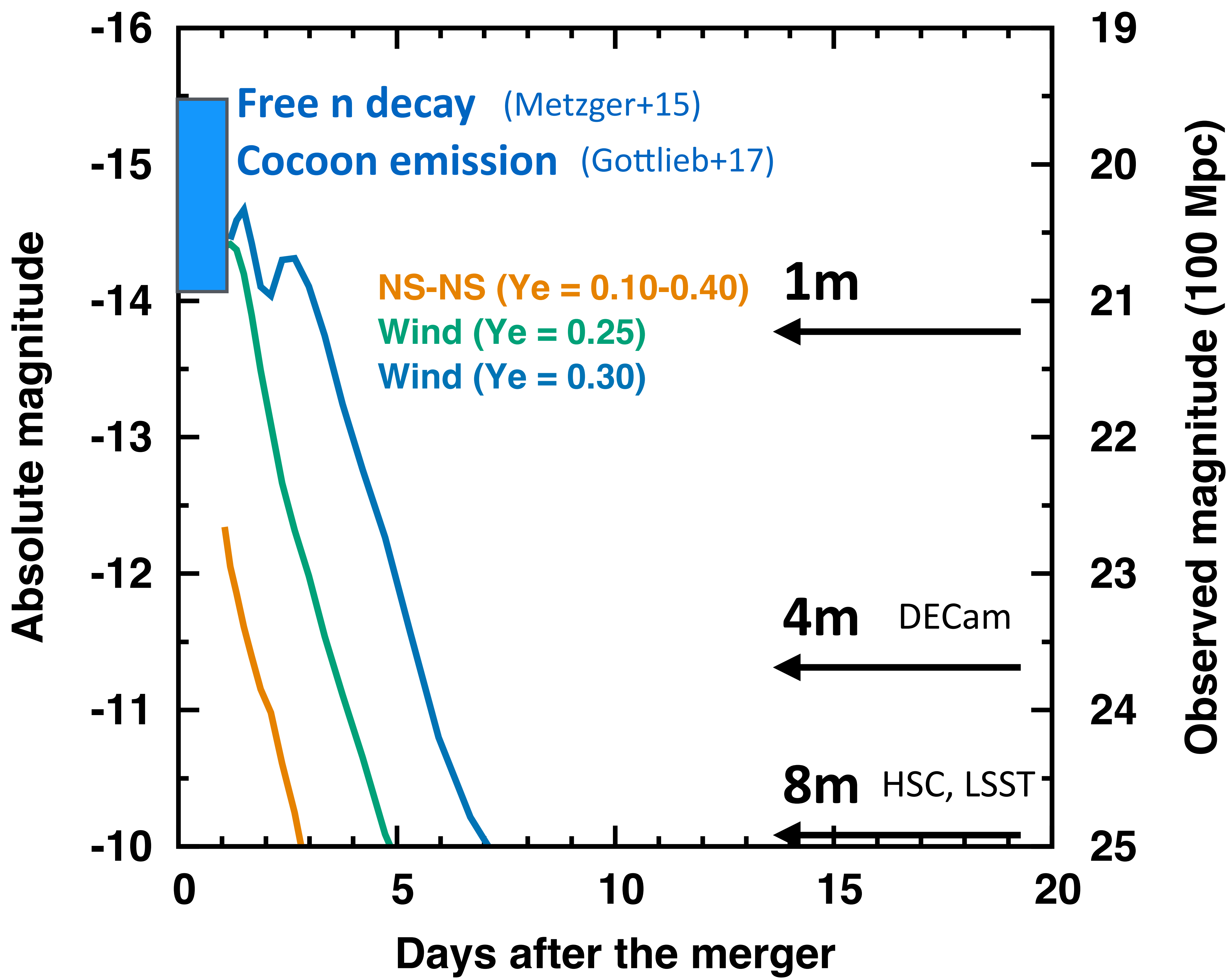
Mej = 0.01 Msun



see also Kasliwal+17

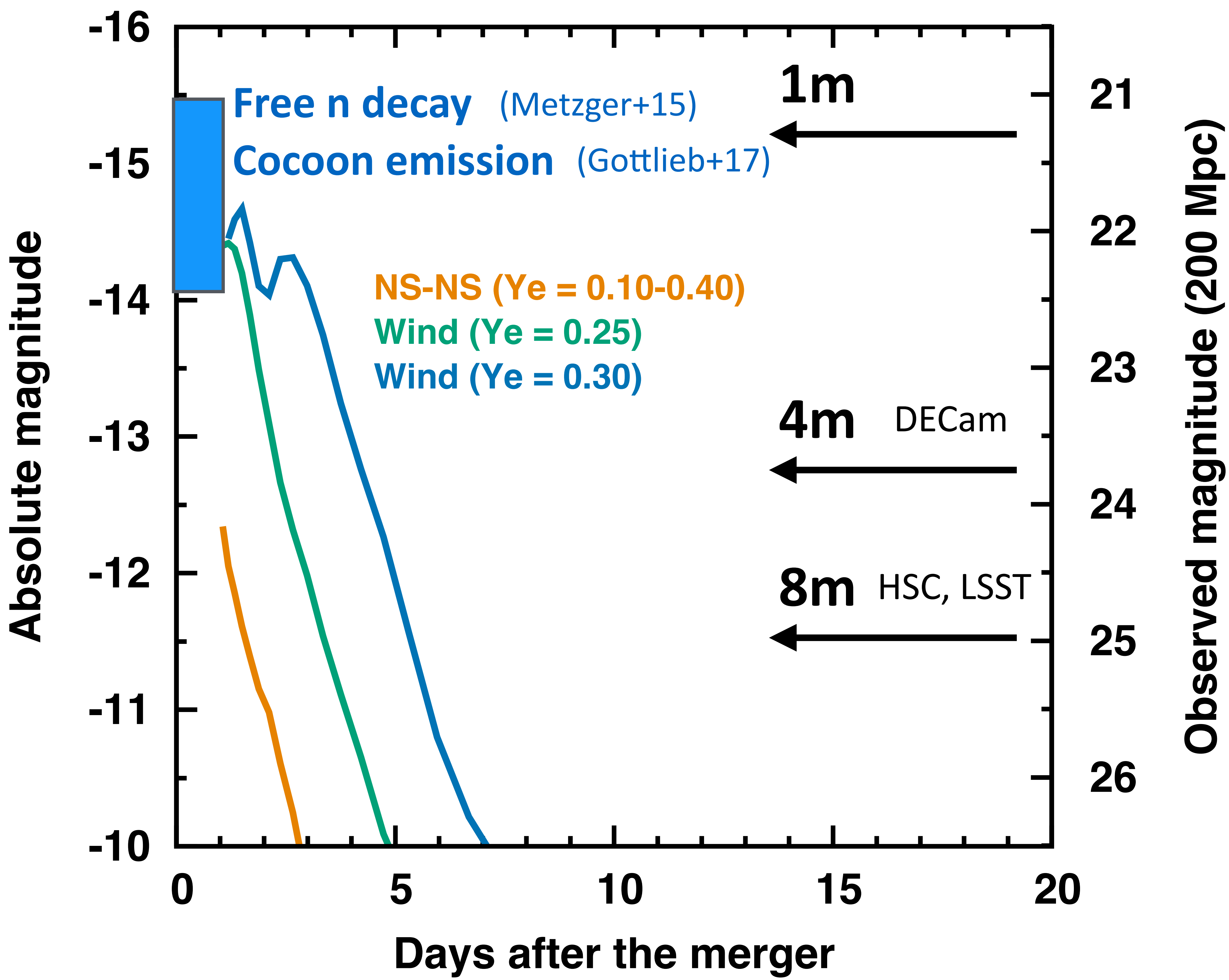
M ~ 0.06 Msun for GRB 130603B Barnes+16 r-band magnitude @ 100 Mpc

Mej = 0.01 Msun



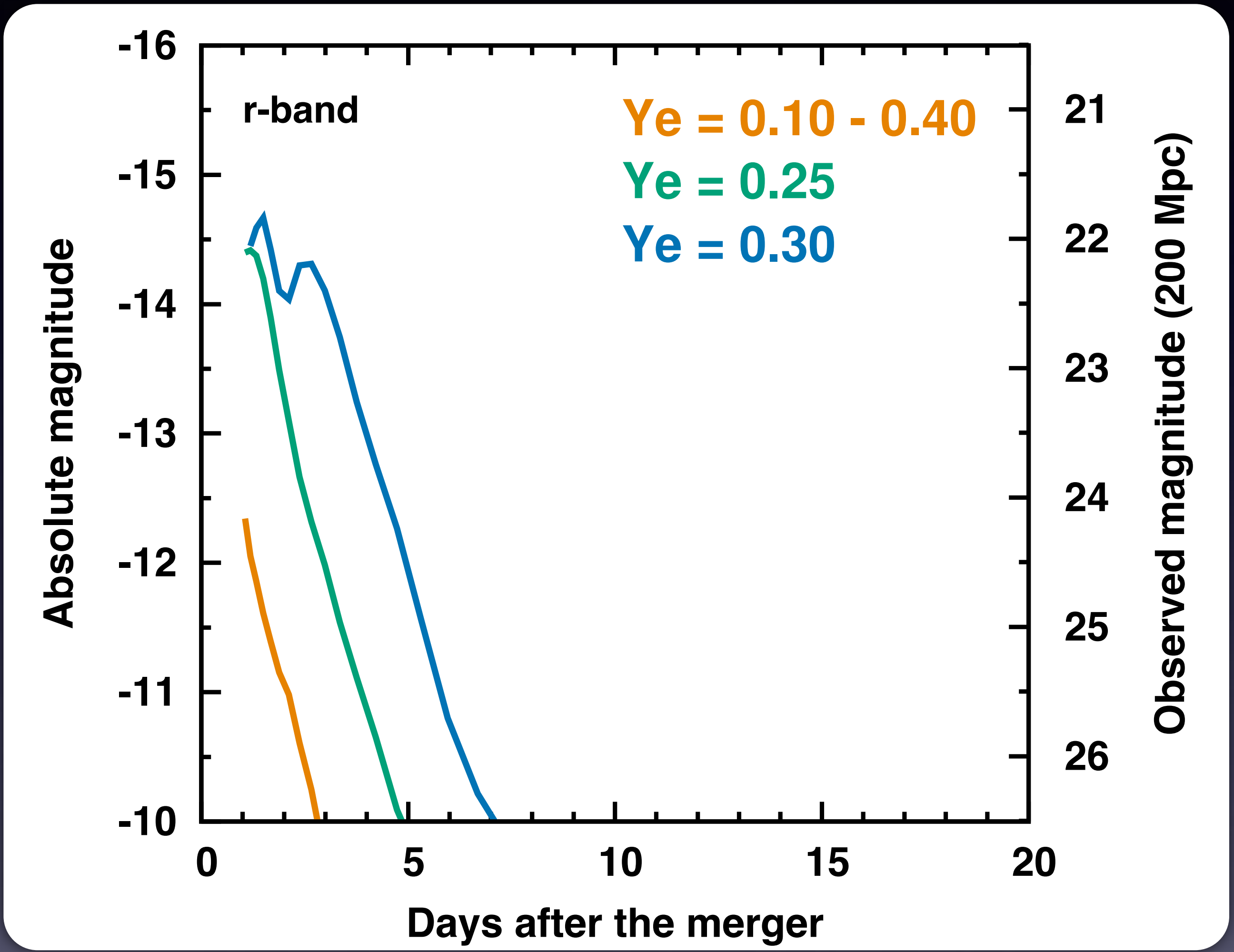
r-band magnitude @ 200 Mpc

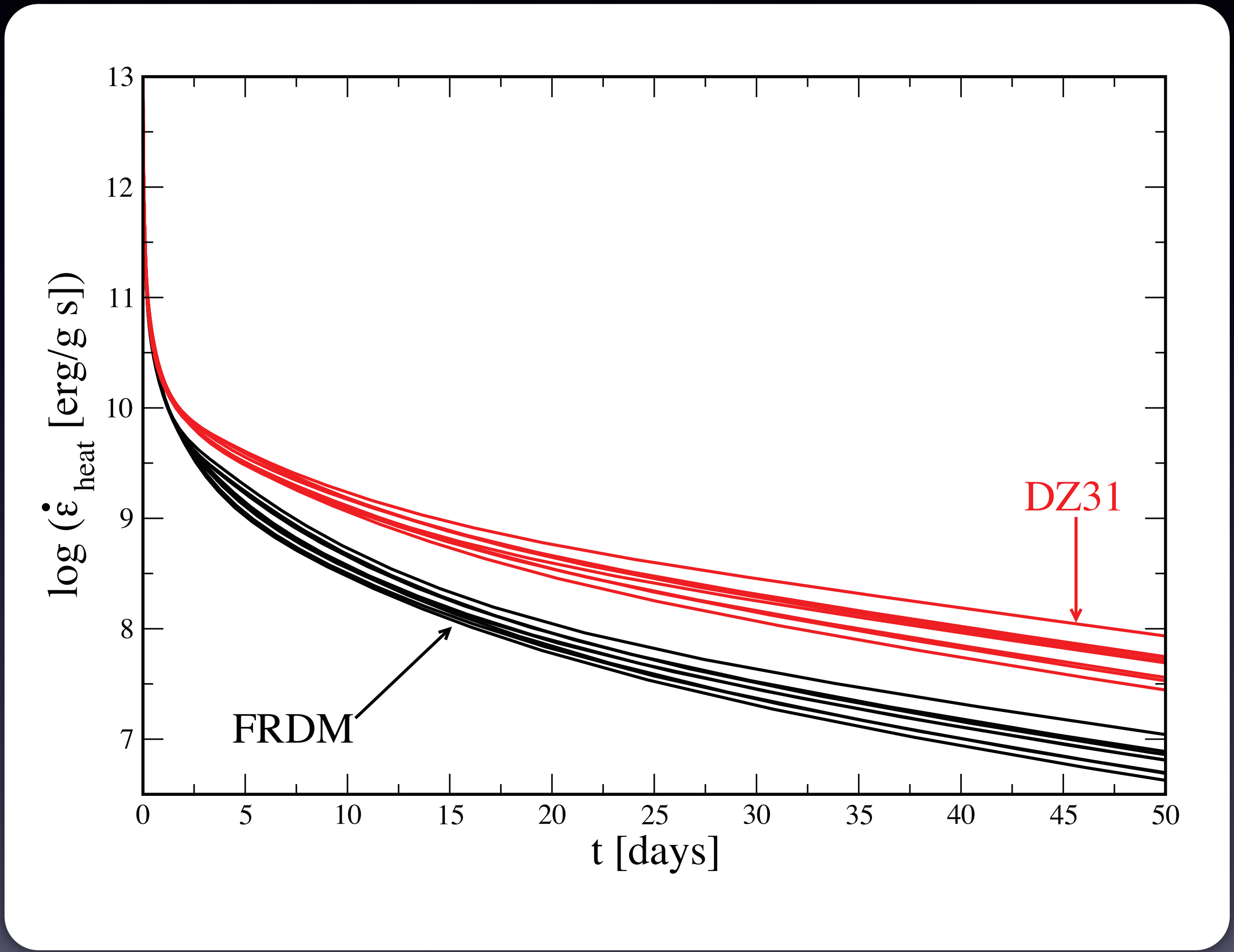
Mej = 0.01 Msun



Can we "measure" mass of r-process elements?

Mej = 0.01 Msun





Rosswog+17

We need (1) multi-color observations, and

(2) good theoretical models

- mergers and nucleosynthesis (long-term simulations)
- heating rate (nuclear physics)
- radiative transfer (atomic data, opacity)

Summary

- **New opacity calculations for Se, Ru, Te, Nd, and Er**
- **Opacity sensitively depends on compositions**
  => Accurate estimate of Ye is critical
  - $\kappa \sim 0.5$ cm^2 g^{-1} for Ye ~ 0.3 (Lanthanide free)
  - $\kappa \sim 10$ cm^2 g^{-1} for solar abundance
- **Wide variety depending on compositions**
  - Optical: 22-25 mag for ~3 days @ 200 Mpc (0.01 Msun)
  - NIR: 22-24 mag for ~7 days @ 200 Mpc (0.01 Msun)
- **Observational prospects**
  - How to select NS mergers?
    Association w/ nearby galaxies, faintness, and rapid evolution
    (possible diversity in color) ==> multi-visit observations
  - Mass of r-process elements? ==> multi-color observations