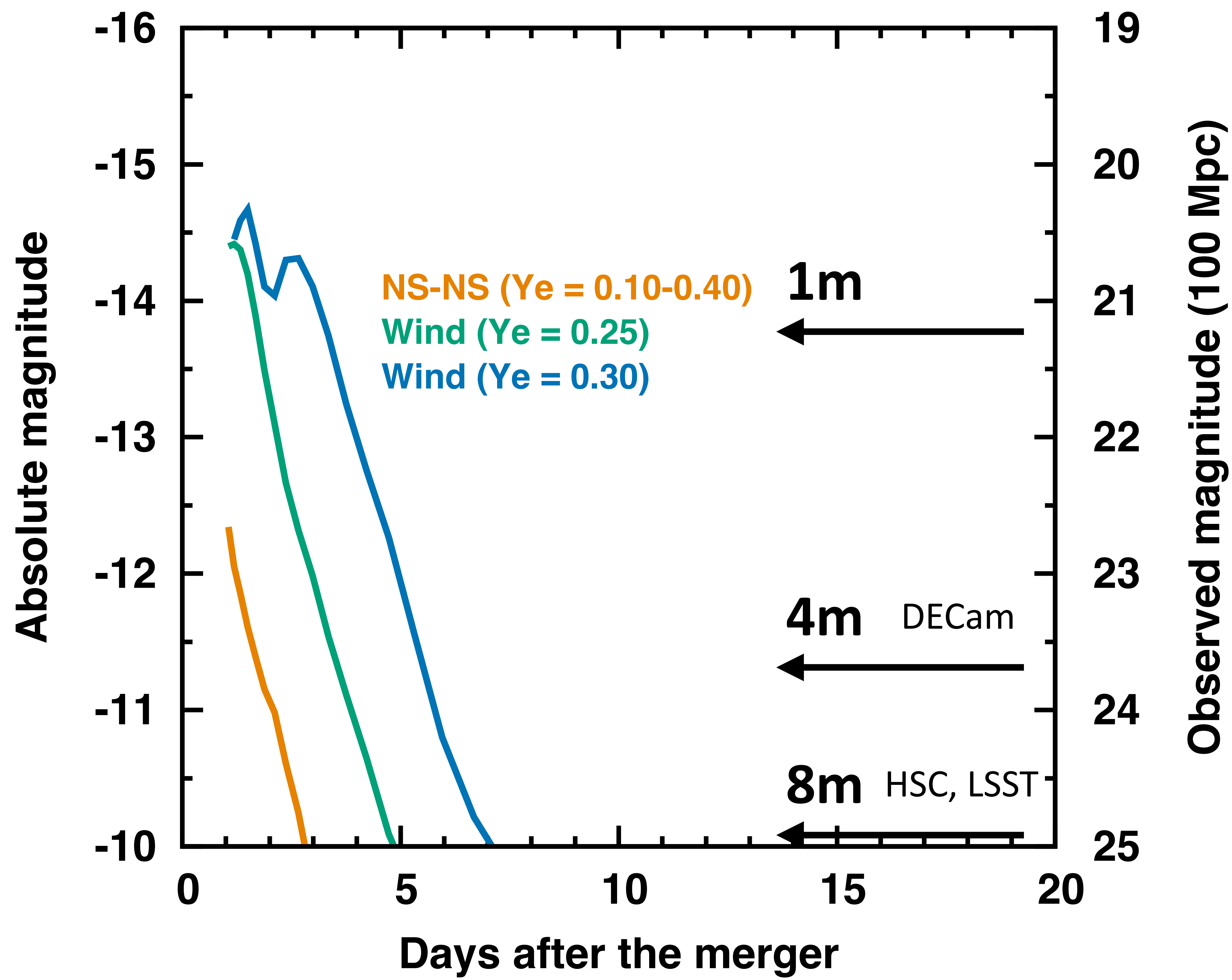
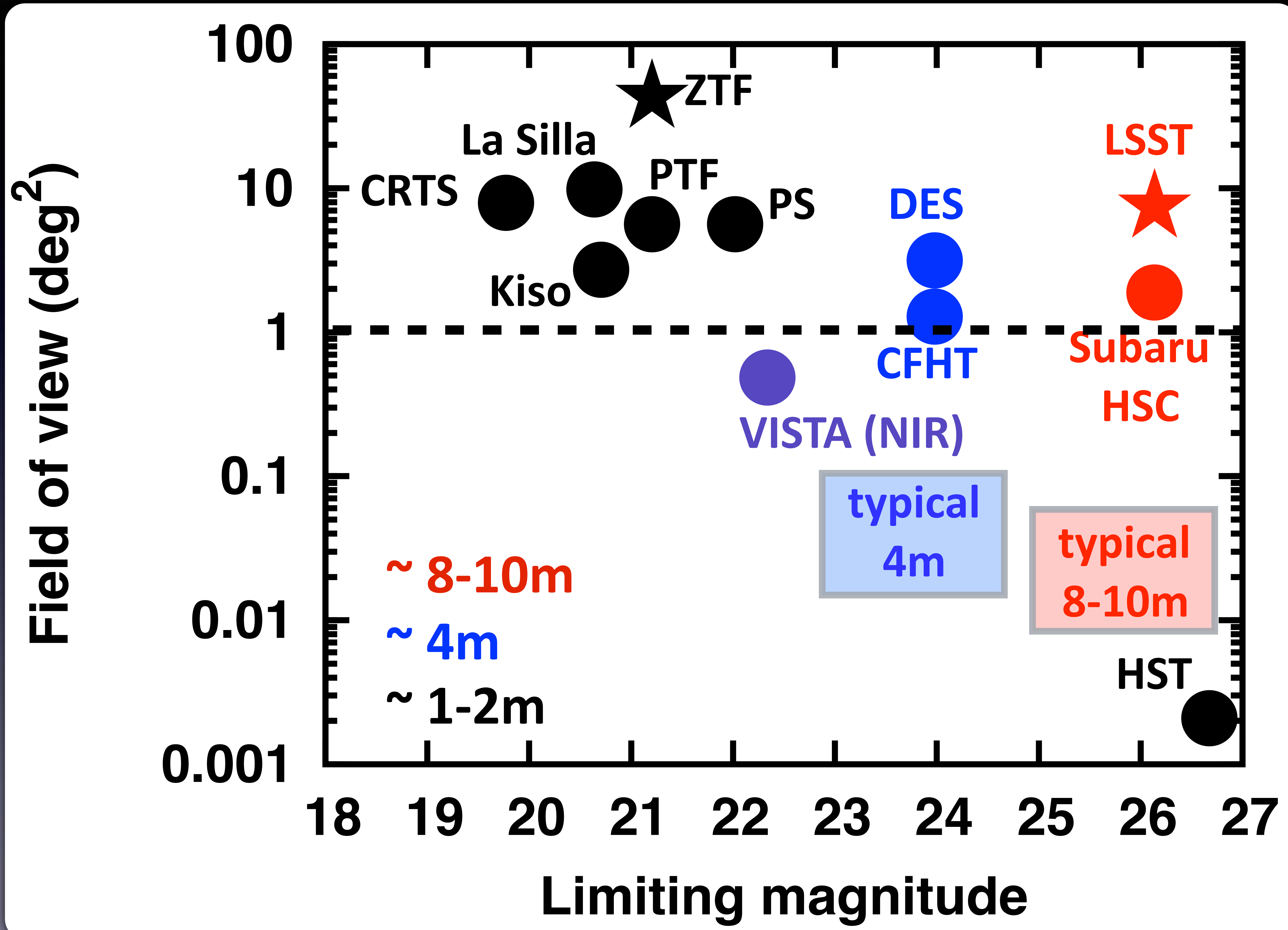
Opacities of and light curves of kilonovae

Masaomi Tanaka
(National Astronomical Observatory of Japan)

r-band magnitude @ 100 Mpc

Mej = 0.01 Msun




Field of view (deg2)
100
10
1
0.1
0.01
0.001
18
19
20
21
22
23
24
25
26
27
Limiting magnitude
ZTF
La Silla
CRTS
PTF
PS
Kiso
DES
CFHT
LSST
Subaru
HSC
VISTA (NIR)
typical
4m
typical
8-10m
HST
~ 8-10m
~ 4m
~ 1-2m

- Atomic and opacity calculations
- Kilonova light curves

Collaboration with

Daiji Kato (National Institute for Fusion Science, Japan),
Gediminas Gaigalas, Pavel Rynkun, Laima Radziute
(Vilnius University, Lithuania)

“Kilonova/Macronova"

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

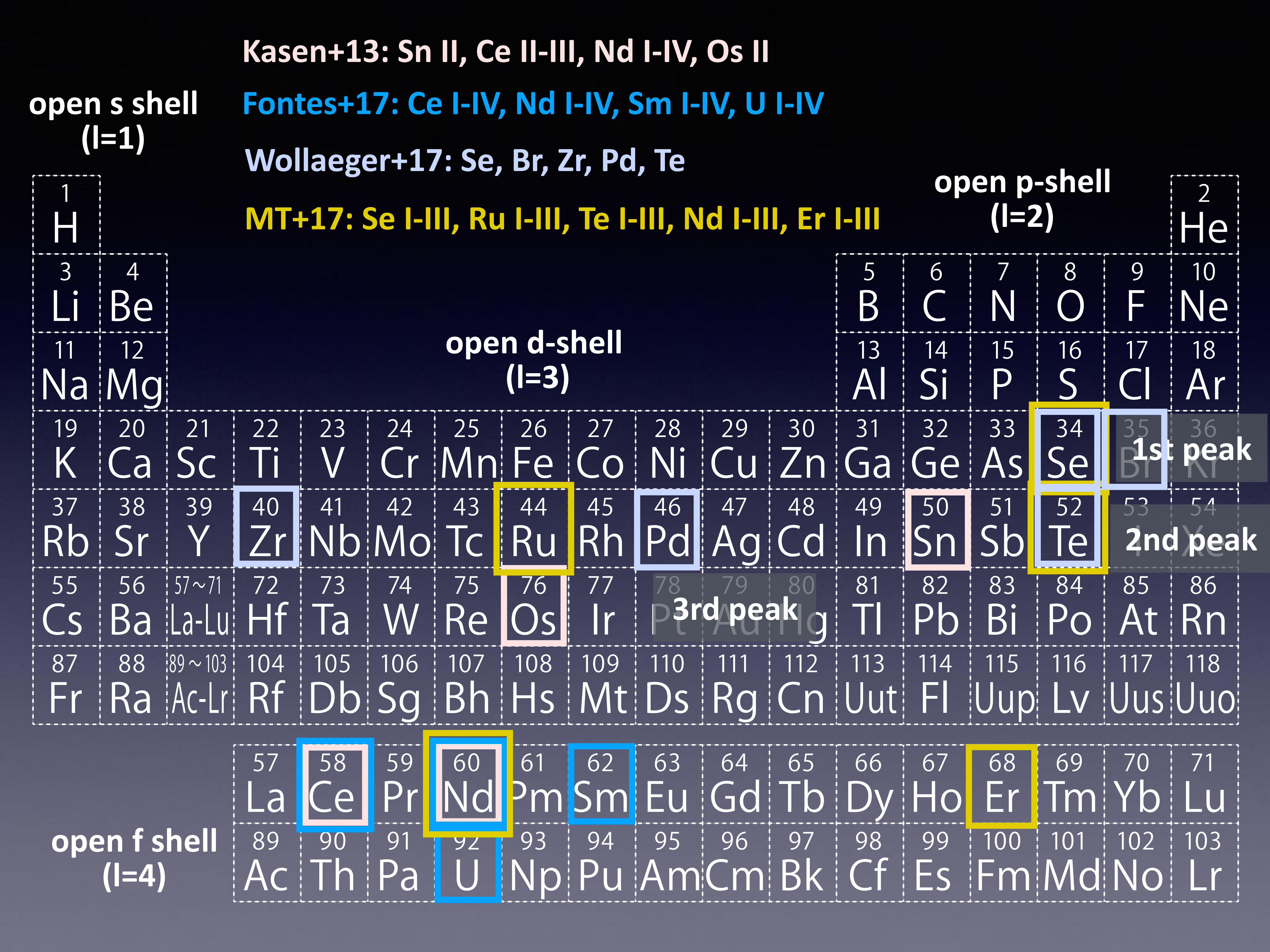
Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$
$$\simeq 8.4 \ {\rm days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \ {\rm cm^2 \ g^{-1}}}\right)^{1/2}$$

Luminosity

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

*assuming 50% thermalization



Kasen+13: Sn II, Ce II-III, Nd I-IV, Os II
Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV
Wollaeger+17: Se, Br, Zr, Pd, Te
MT+17: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III
open s shell (l=1)
open p-shell (l=2)
open d-shell (l=3)
open f shell (l=4)
1st peak
2nd peak
3rd peak
1 H
2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 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 56 Ba 57~71 La-Lu 72 Hf 73 Ta 74 W 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 88 Ra 89~103 Ac-Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Uut 114 Fl 115 Uup 116 Lv 117 Uus 118 Uuo
57 La 58 Ce 59 Pr 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

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)

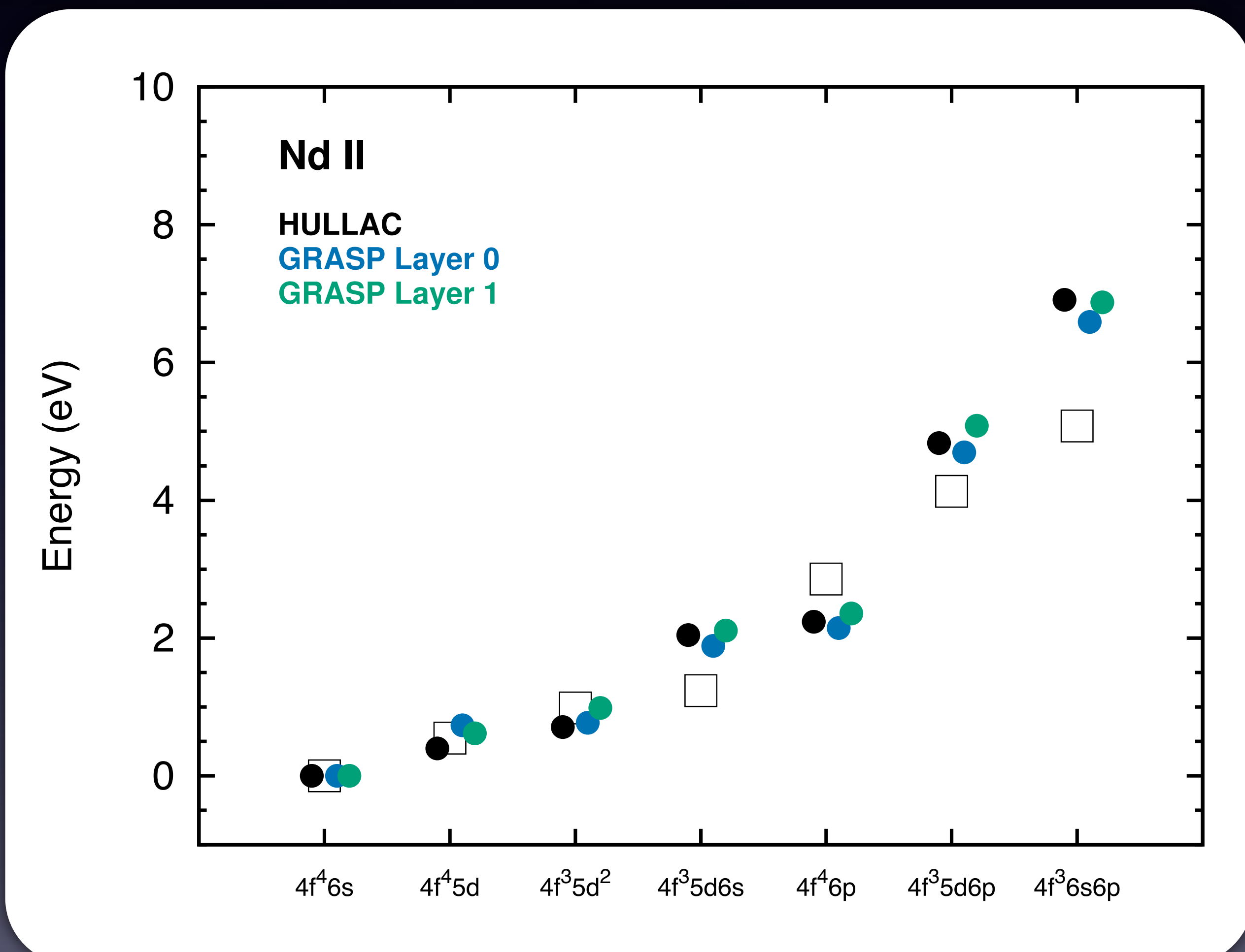
Er I-III
(Z=68, f)

Ion	Configurations	Number of levels	Number of lines
HULLAC			
Se I	$\mathbf{4s^24p^4}$, $4s^24p^3(4d,4f,5-8l)$, $4s4p^5$, $4s4p^4(4d,4f)$, $4s^24p^2(4d^2,4d4f,4f^2)$, $4s4p^3(4d^2,4d4f,4f^2)$	3076	973,168
Se II	$\mathbf{4s^24p^3}$, $4s^24p^2(4d,4f,5-8l)$, $4s4p^4$, $4s4p^3(4d,4f)$, $4s^24p(4d^2,4d4f,4f^2)$, $4s4p^2(4d^2,4d4f,4f^2)$	2181	511,911
Se III	$\mathbf{4s^24p^2}$, $4s^24p(4d,4f,5-8l)$, $4s4p^3$, $4s4p^2(4d,4f)$, $4s^2(4d^2,4d4f,4f^2)$, $4s4p(4d^2,4d4f,4f^2)$	922	92,132
Ru I	$\mathbf{4d^75s}$, $\mathbf{4d^65s^6}$, $\mathbf{4d^8}$, $4d^7(5p,5d,6s,6p)$, $4d^65s(5p,5d,6s)$	1,545	250,476
Ru II	$\mathbf{4d^7}$, $4d^6(5s-5d,6s,6p)$	818	76,592
Ru III	$\mathbf{4d^6}$, $4d^5(5s-5d,6s)$	728	49,066
Te I	$\mathbf{5s^25p^4}$, $\mathbf{5s^25p^3(4f,5d,5f,6s-6f,7s-7d,8s)}$, $5s5p^5$	329	14,482
Te II	$\mathbf{5s^25p^3}$, $\mathbf{5s^25p^2(4f,5d,5f,6s-6f,7s-7d,8s)}$, $5s5p^4$	253	9,167
Te III	$\mathbf{5s^25p^2}$, $\mathbf{5s^25p(5d,6s-6d,7s)}$, $5s5p^3$	57	419
Nd I	$\mathbf{4f^46s^2}$, $\mathbf{4f^46s(5d,6p,7s)}$, $\mathbf{4f^45d^2}$, $\mathbf{4f^45d6p}$, $4f^35d6s^2$, $4f^35d^2(6s,6p)$, $4f^35d6s6p$	31,358	70,366,259
Nd II	$\mathbf{4f^46s}$, $\mathbf{4f^45d}$, $4f^46p$, $4f^36s(5d,6p)$, $4f^35d^2$, $4f^35d6p$	6,888	3,951,882
Nd III	$\mathbf{4f^4}$, $4f^3(5d,6s,6p)$, $4f^25d^2$, $4f^25d(6s,6p)$, $4f^26s6p$	2252	458,161
Er I	$\mathbf{4f^{12}6s^2}$, $\mathbf{4f^{12}6s(5d,6p,6d,7s,8s)}$, $4f^{11}6s^2(5d,6p)$, $4f^{11}5d^26s$, $4f^{11}5d6s(6p,7s)$	10,535	9,247,777
Er II	$\mathbf{4f^{12}6s}$, $4f^{12}(5d,6p)$, $4f^{11}6s^2$, $4f^{11}6s(5d,6p)$, $4f^{11}5d^2$, $4f^{11}5d6p$	5,333	2,432,665
Er III	$\mathbf{4f^{12}}$, $4f^{11}(5d,6s,6p)$	723	42,671

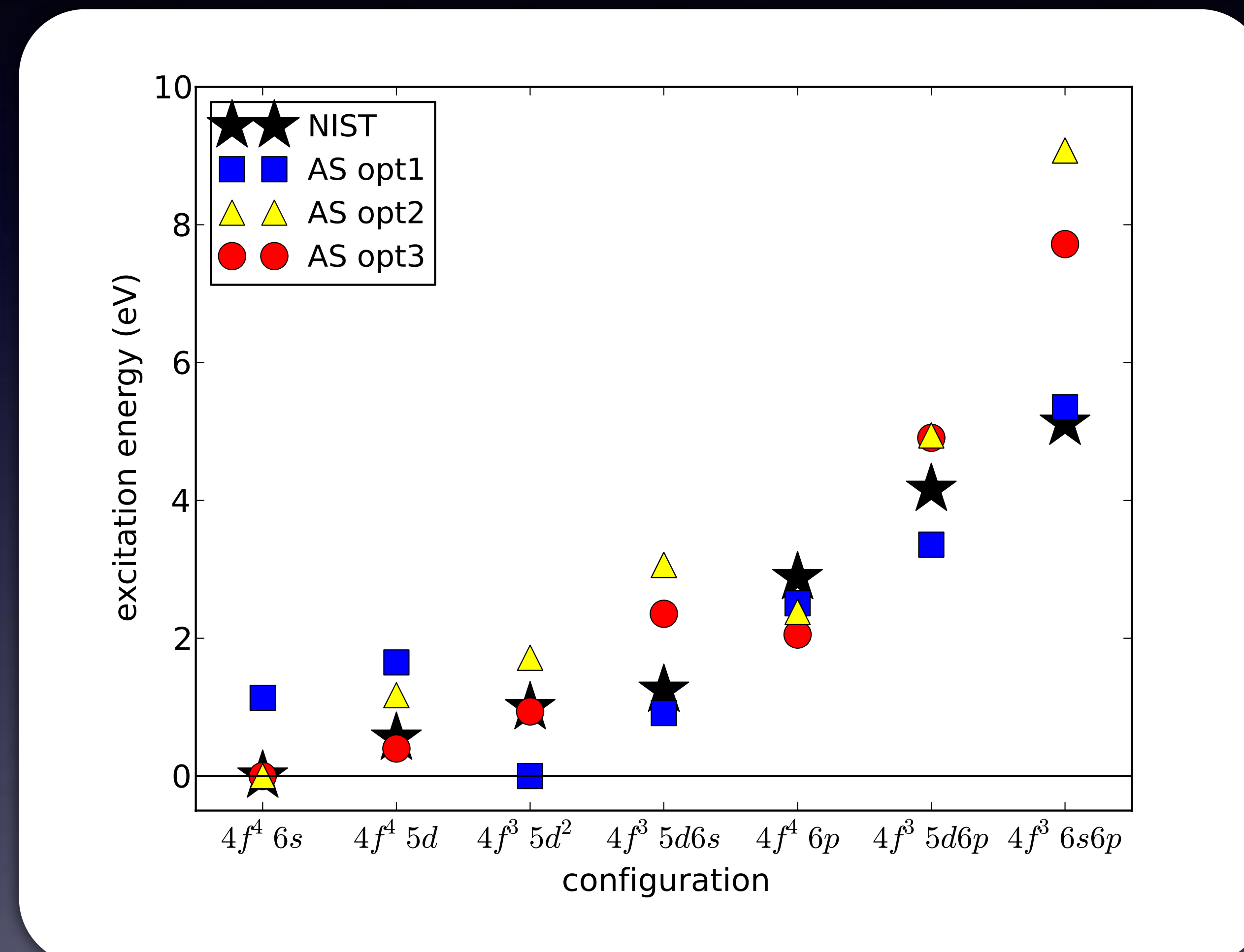
GRASP2K code (relativistic, e-e correlation, Jonsson+07)

Nd II-III, Er II-III

Energy levels of Nd II



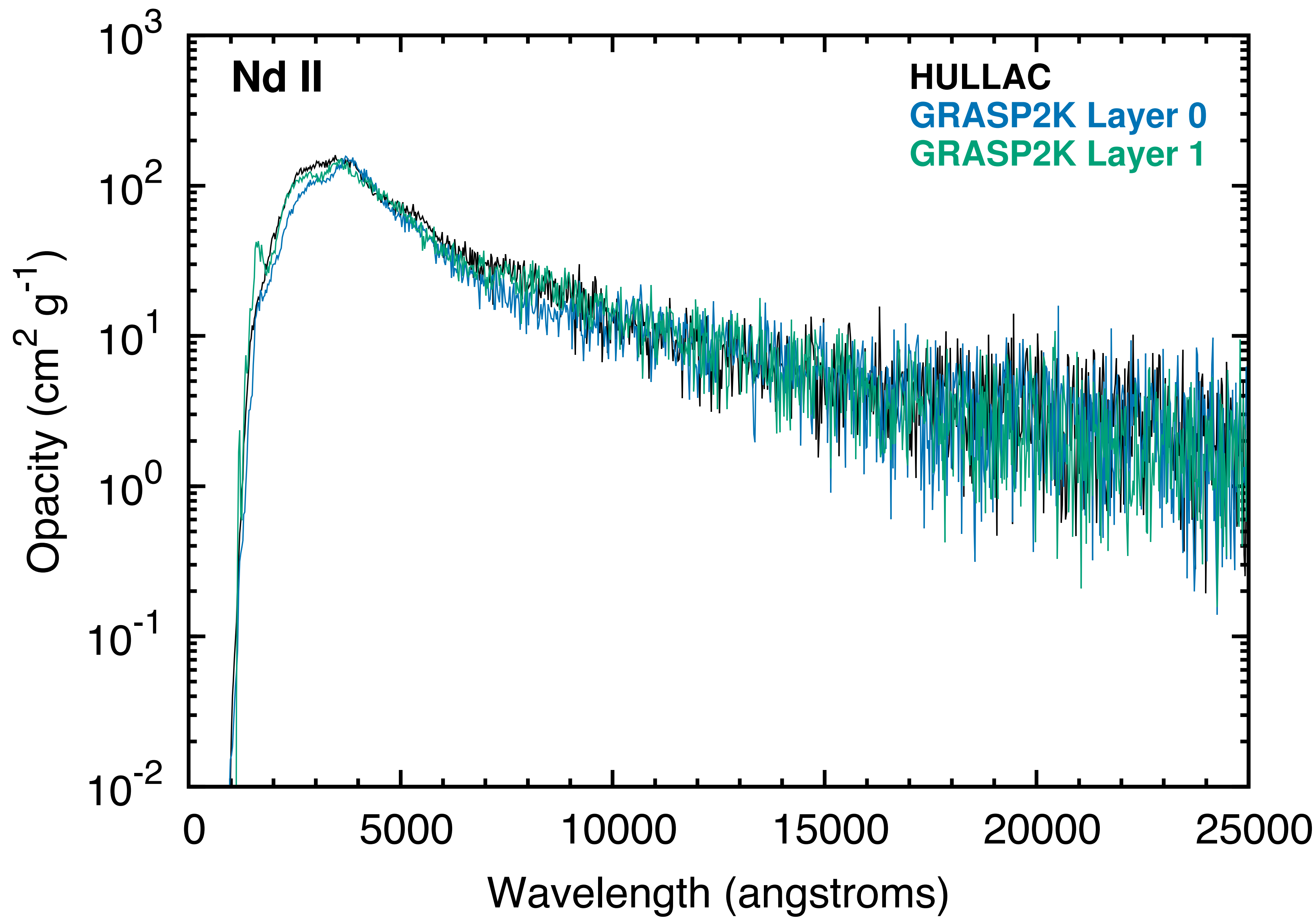
MT+ in prep



Kasen+13 (Autostructure code)

Line expansion opacity of Nd II

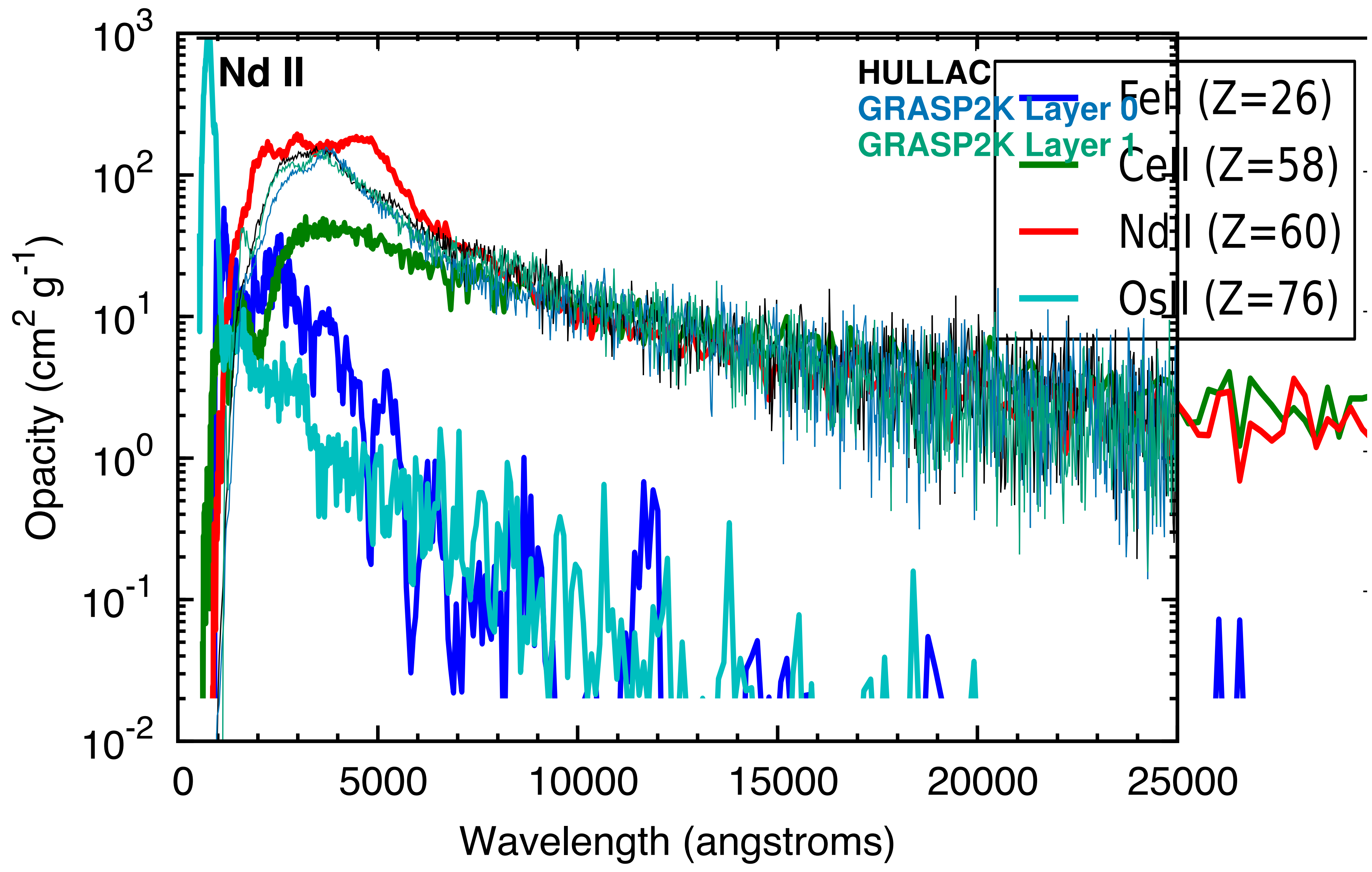
T = 5,000 K, $\rho = 10^{-13}$ g cm^{-3}, t = 1 day



Opacities from two codes agree very well

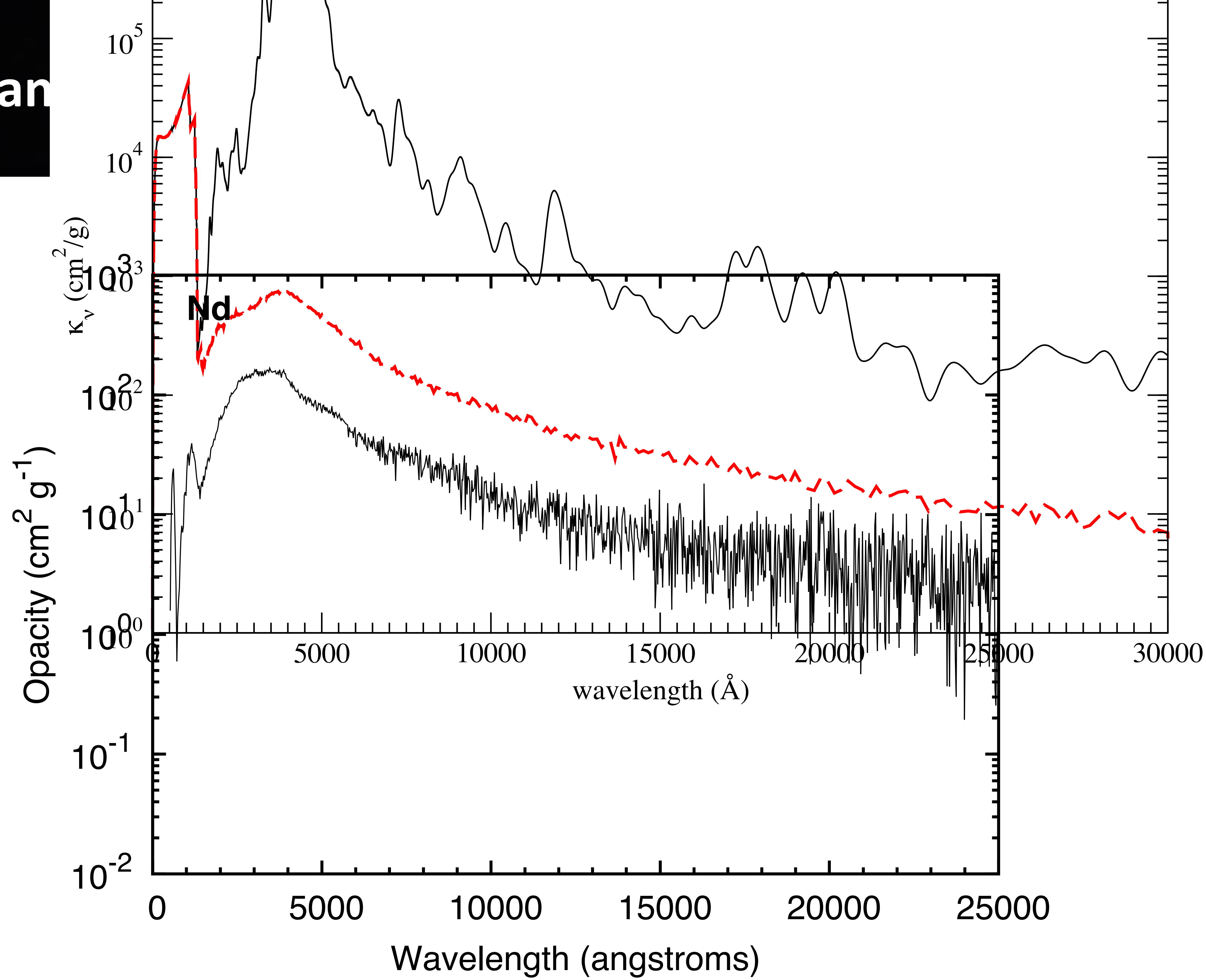
Line expansion opacity of Nd II

T = 5,000 K, $\rho = 10^{-13}$ g cm^{-3}, t = 1 day



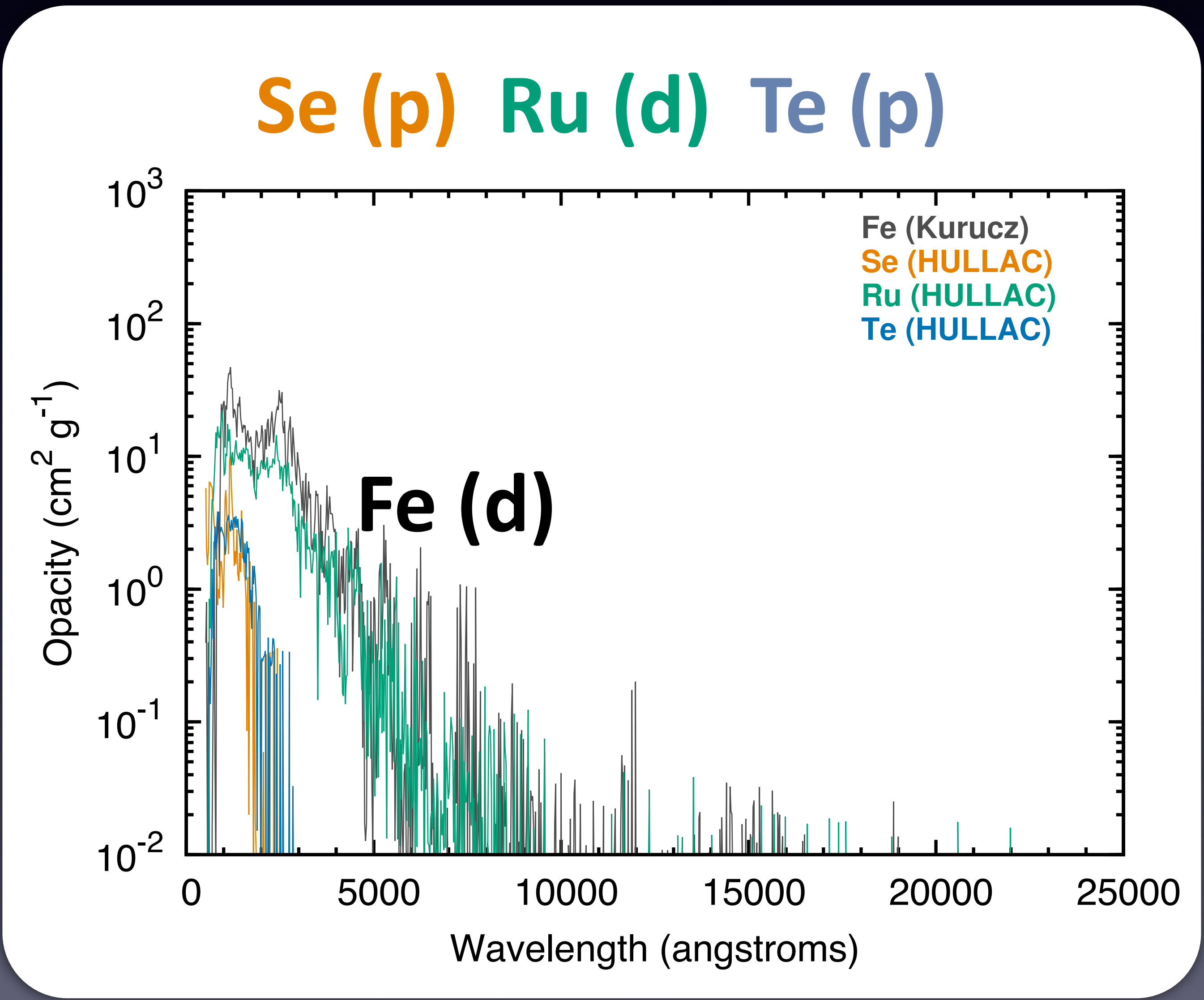
Consistent with results by Kasen+13 (Autostruture code)

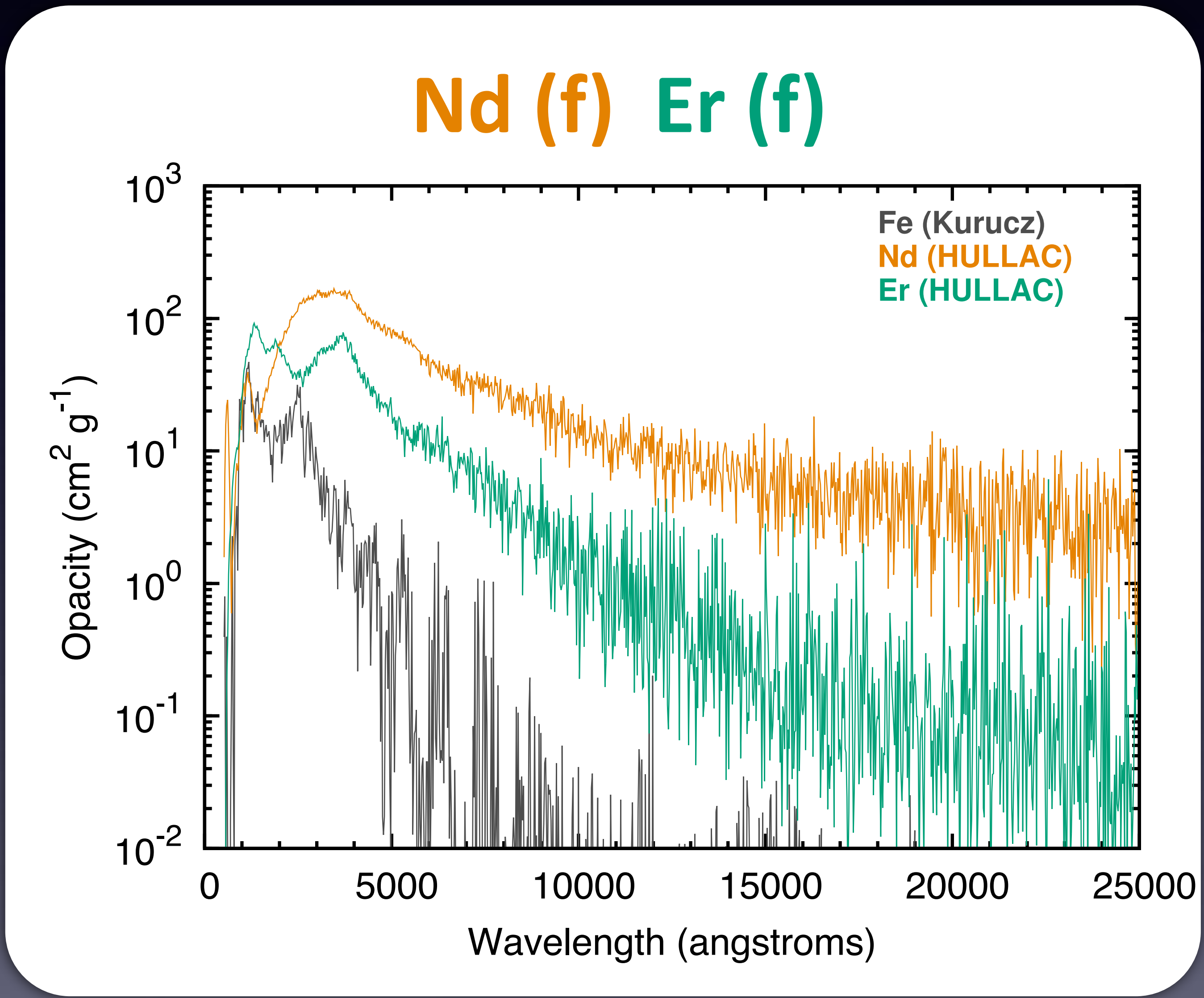
Line expan



Expansion opacity of Fontes+17 is higher by a factor of 3-5

Line expansion opacity (for each element)



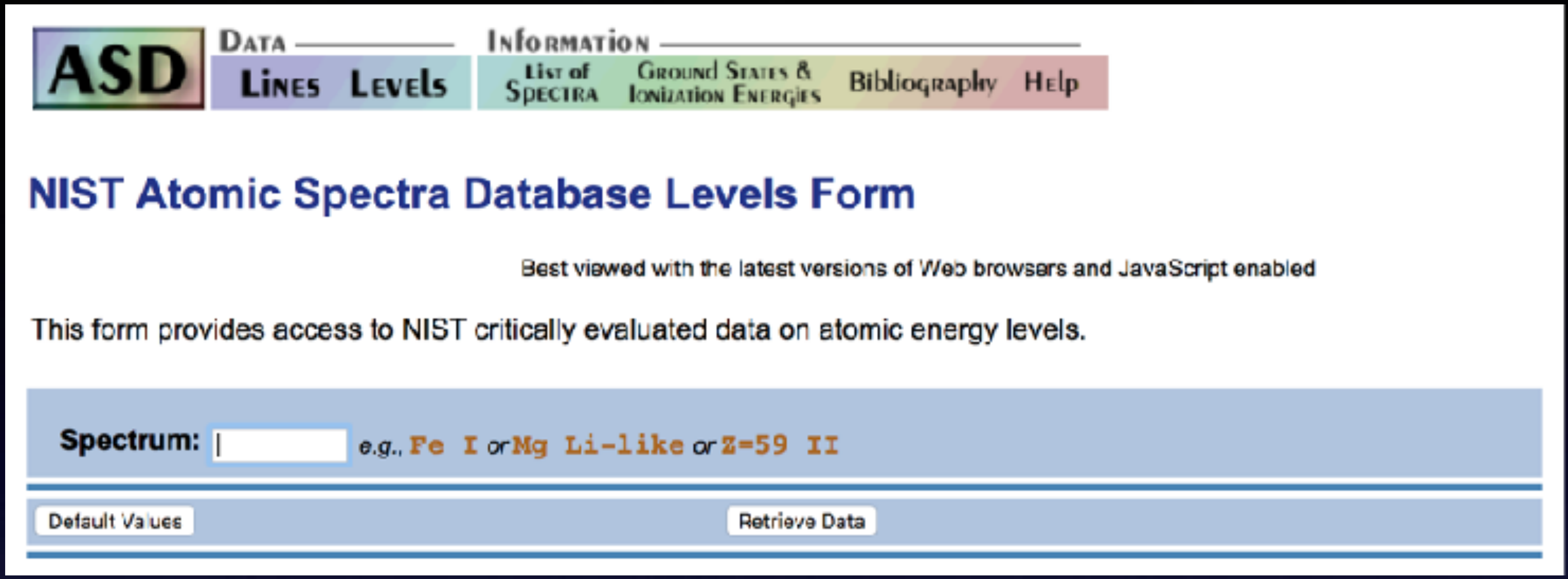


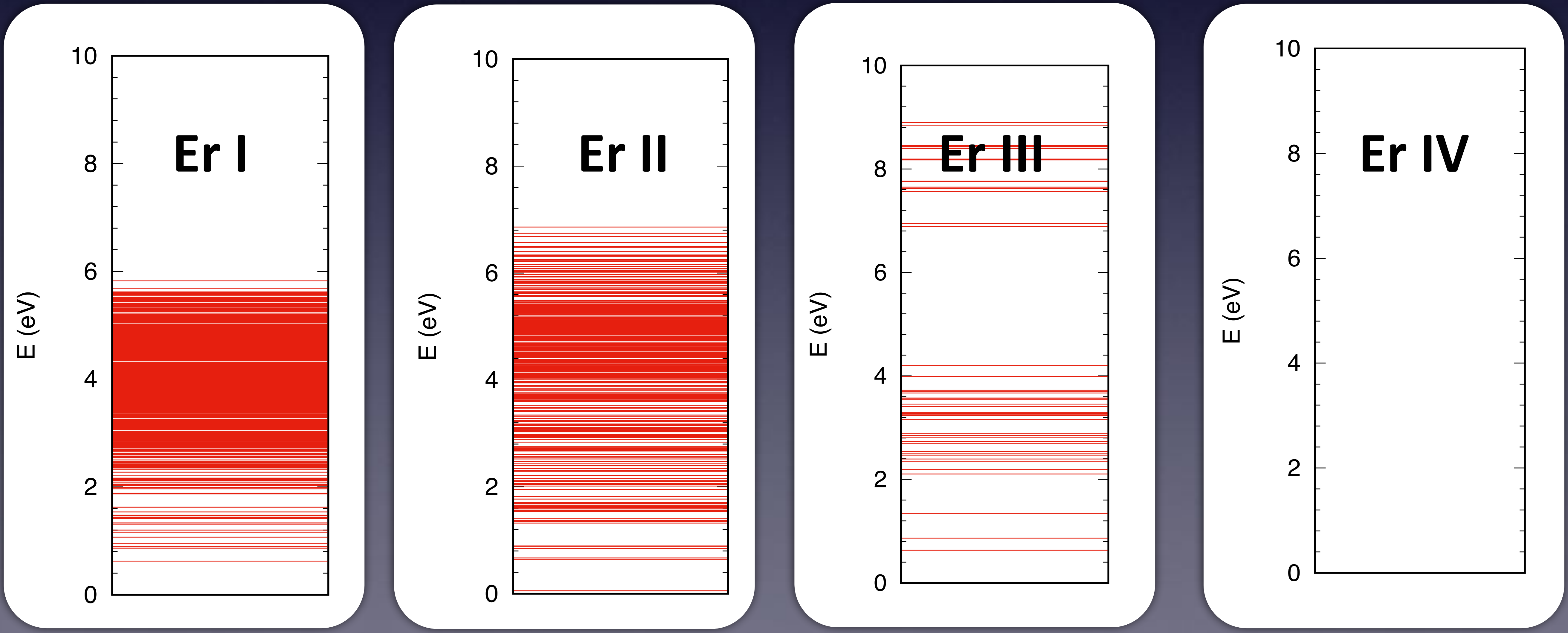
MT+ in prep.

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

see Kasen+13, Fontes+17

Er (Z=68)
Energy levels





Spectroscopic experiments for Er (Z=68)

Collaboration with

Nobuyuki Nakamura,
Hajime Tanuma,
Hiroyuki Sakaue, and
Izumi Murakami

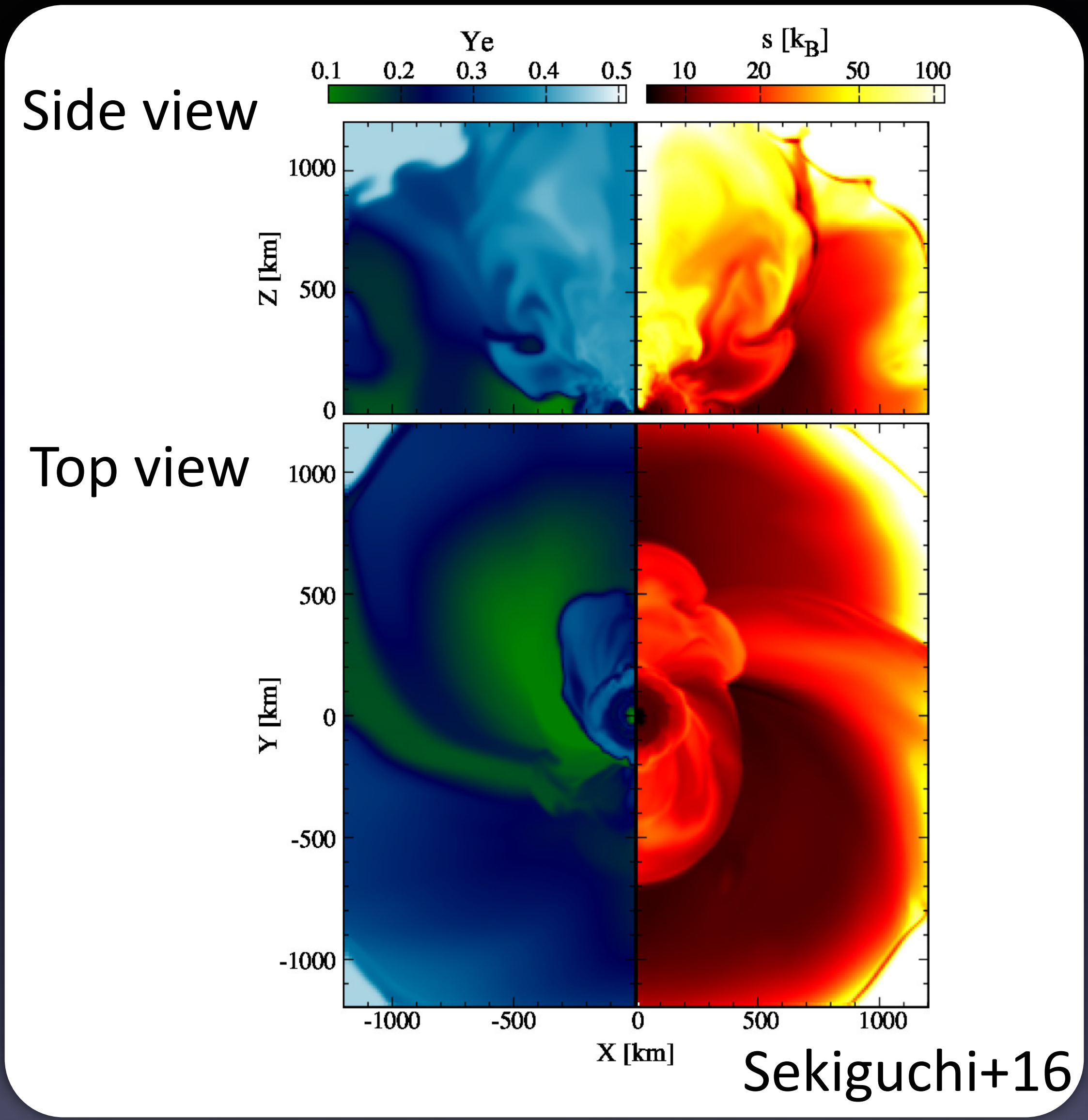
- Atomic and opacity calculations
- Kilonova light curves

Collaboration with

Shinya Wanajo (Sofia University, Japan) and

Yuichiro Sekiguchi (Toho University, Japan)

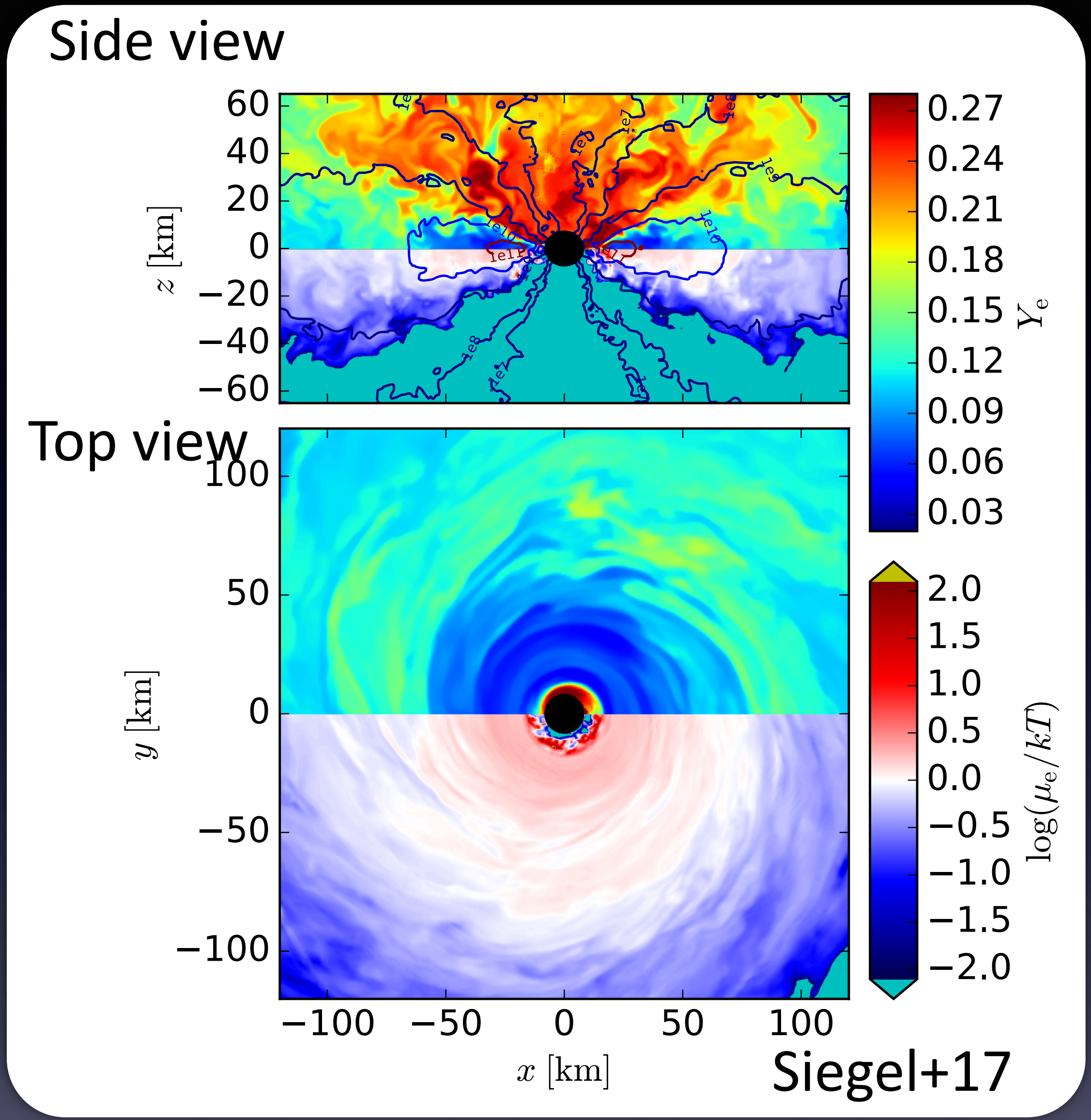
Dynamical ejecta (~< 10 ms)



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-merger ejecta (~< 100 ms)

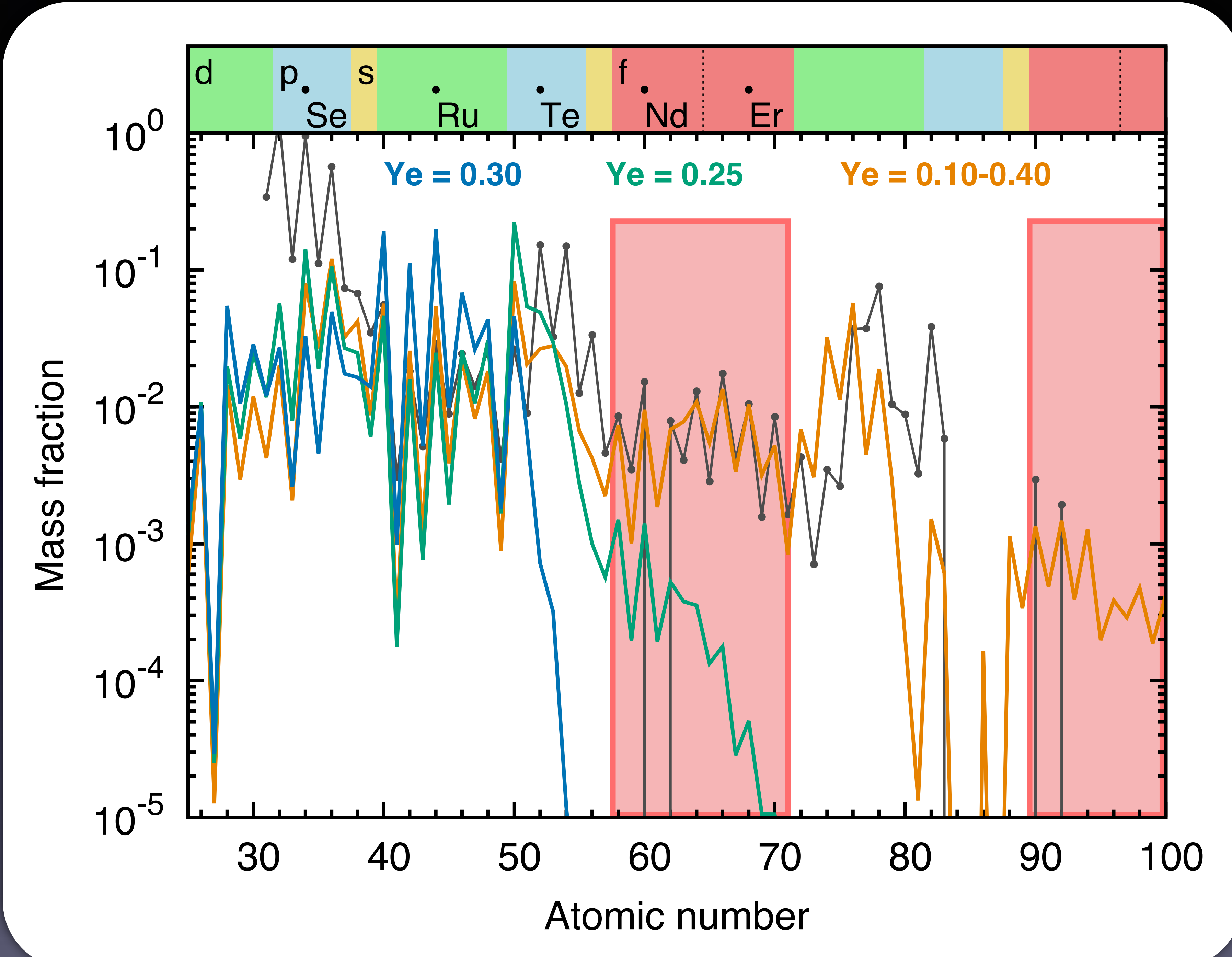


Fernandez+13,15, Perego+14, Kiuchi+14,15, Martin+15, Just+15, Wu+16, Siegel & Metzger 17…

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

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

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



@ 1 day (Wanajo+14)

"Blue" kilonova?

Simulations with Fe opacity or gray opacity

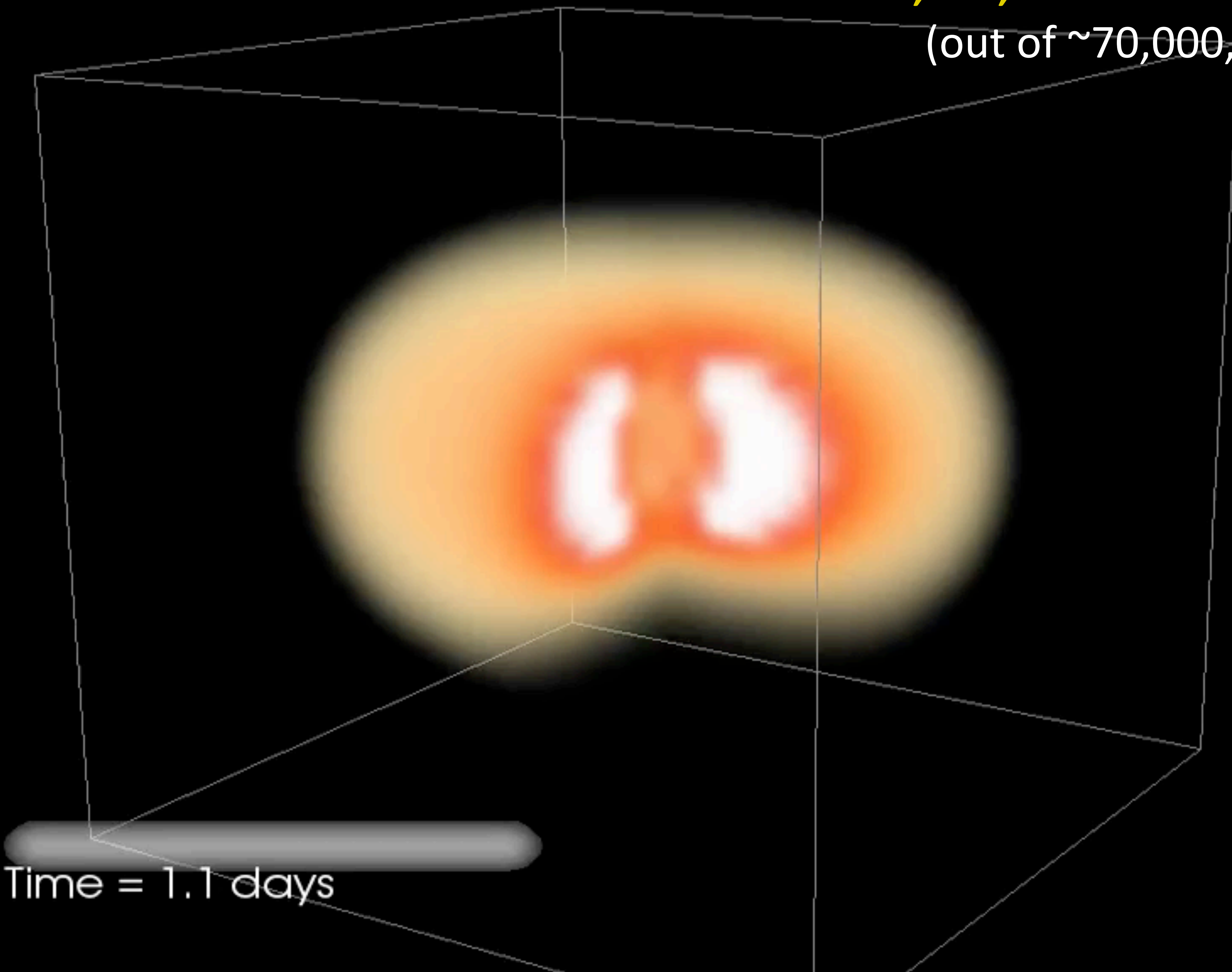
Metzger+14, Kasen+15, Fernandez & Metzger 16, Metzger 16

3D Monte-Carlo frequency-dependent radiation transfer

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

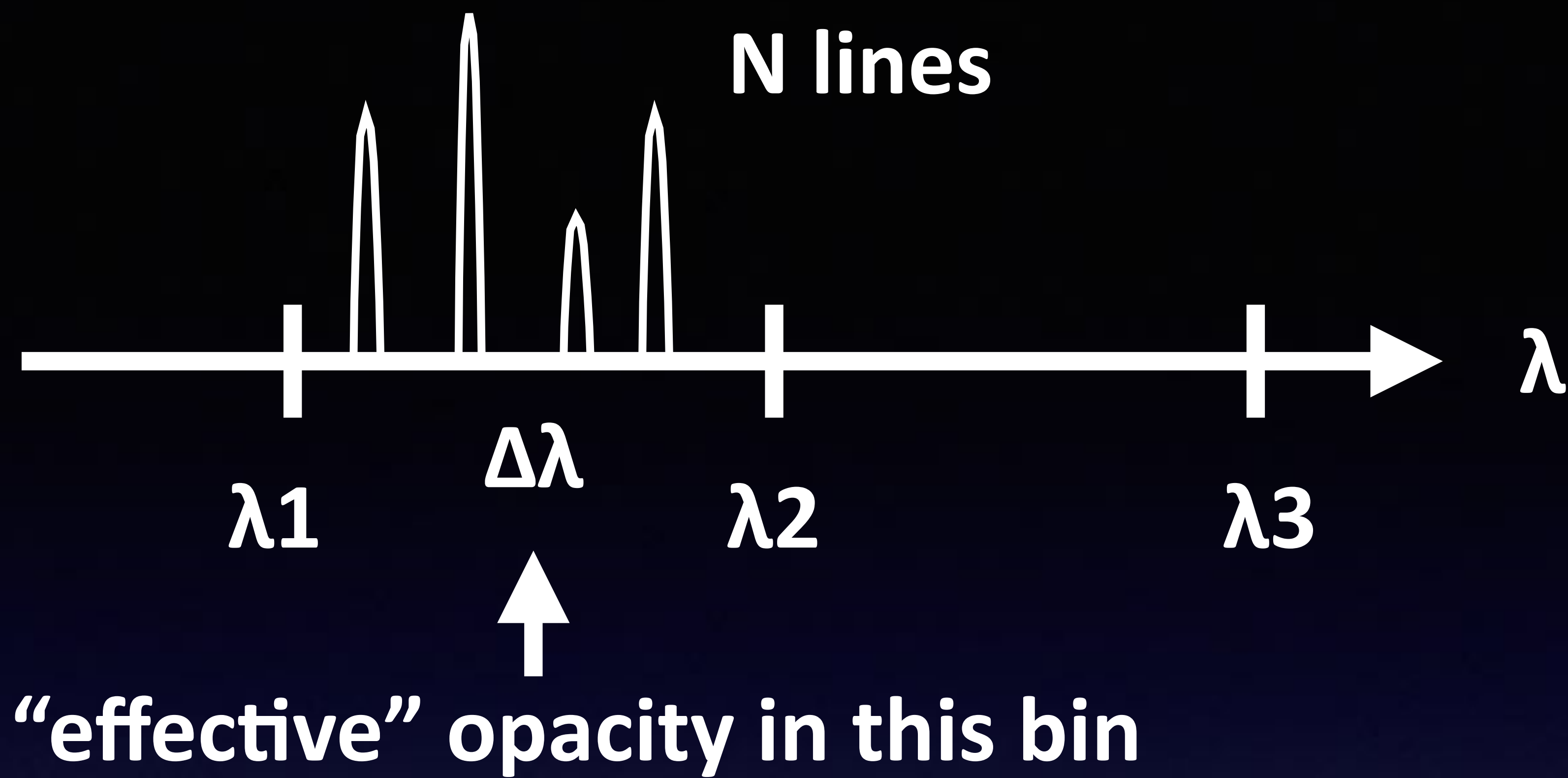
~6,000,000 b-b transitions

(out of ~70,000,000)



Expansion opacity

Pinto & Eastman 2000
Kasen+06, Kasen+13
MT+13



Line spacing

$$\frac{\Delta\lambda}{N}$$

"Effective" mean free path

$$l = \frac{\Delta\lambda}{N}\frac{1}{\lambda}ct$$

$$\tau_{\rm sob} = \frac{\pi e^2}{mc} n_1 f_{\rm osc} t \lambda$$

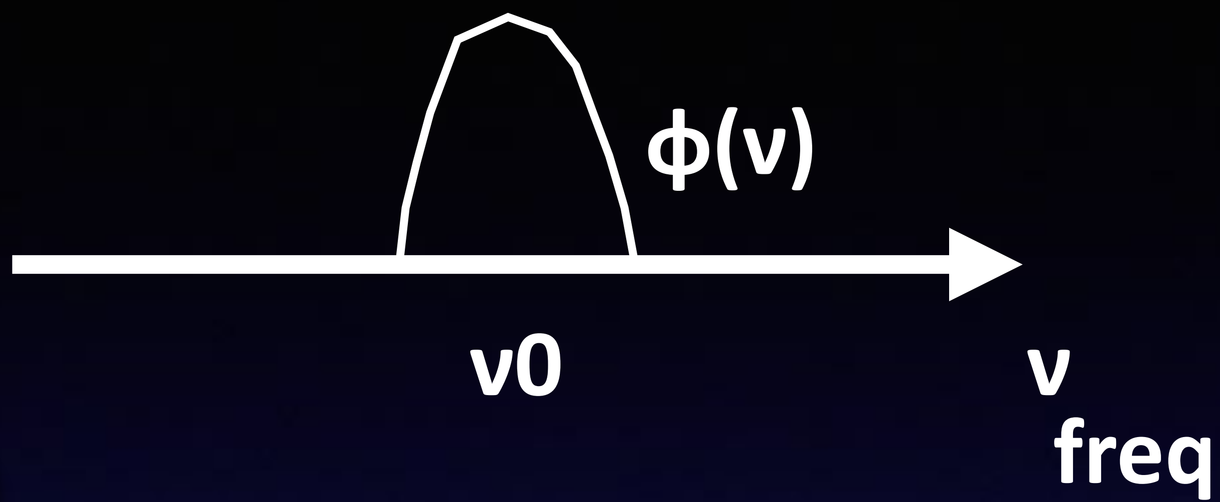
"Effective" absorption coefficient $\alpha_{\rm exp}$ (cm^{-1})

$$\alpha_{\rm exp} = \frac{1}{l} = \frac{\lambda}{\Delta\lambda}\frac{1}{ct}N$$

$$\alpha_{\rm exp} = \frac{\lambda}{\Delta\lambda}\frac{1}{ct}\Sigma(1 - e^{-\tau_{\rm sob}})$$

Sobolev optical depth

$$\alpha = \frac{\pi e^2}{mc} n_1 f_{\rm osc} \phi(\nu)$$



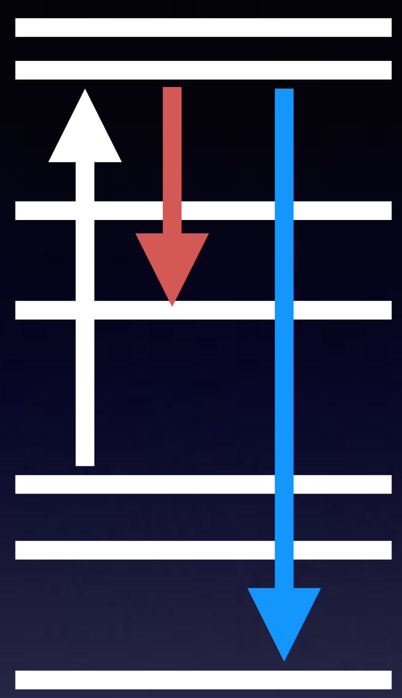
$$\tau_{\rm sob} = \int \alpha dr$$
$$= \int \alpha \frac{dr}{dv} \frac{c}{\nu_0} d\nu$$
$$= \int \frac{\pi e^2}{mc} n_1 f_{\rm osc} \phi(\nu) \frac{dr}{dv} \frac{c}{\nu_0} d\nu$$
$$= \frac{\pi e^2}{mc} n_1 f_{\rm osc} \frac{dr}{dv} \frac{c}{\nu_0}$$
$$= \frac{\pi e^2}{mc} n_1 f_{\rm osc} t \lambda$$

$$\frac{d\nu}{\nu_0} = \frac{dv}{c} = \frac{1}{c} \frac{dv}{dr} dr$$

if velocity dominated by radial motion ($v_{th} << v_{rad}$)

$$\int \phi(\nu) d\nu = 1$$

Fluorescence



When photons interact with line,

*** Full treatment**

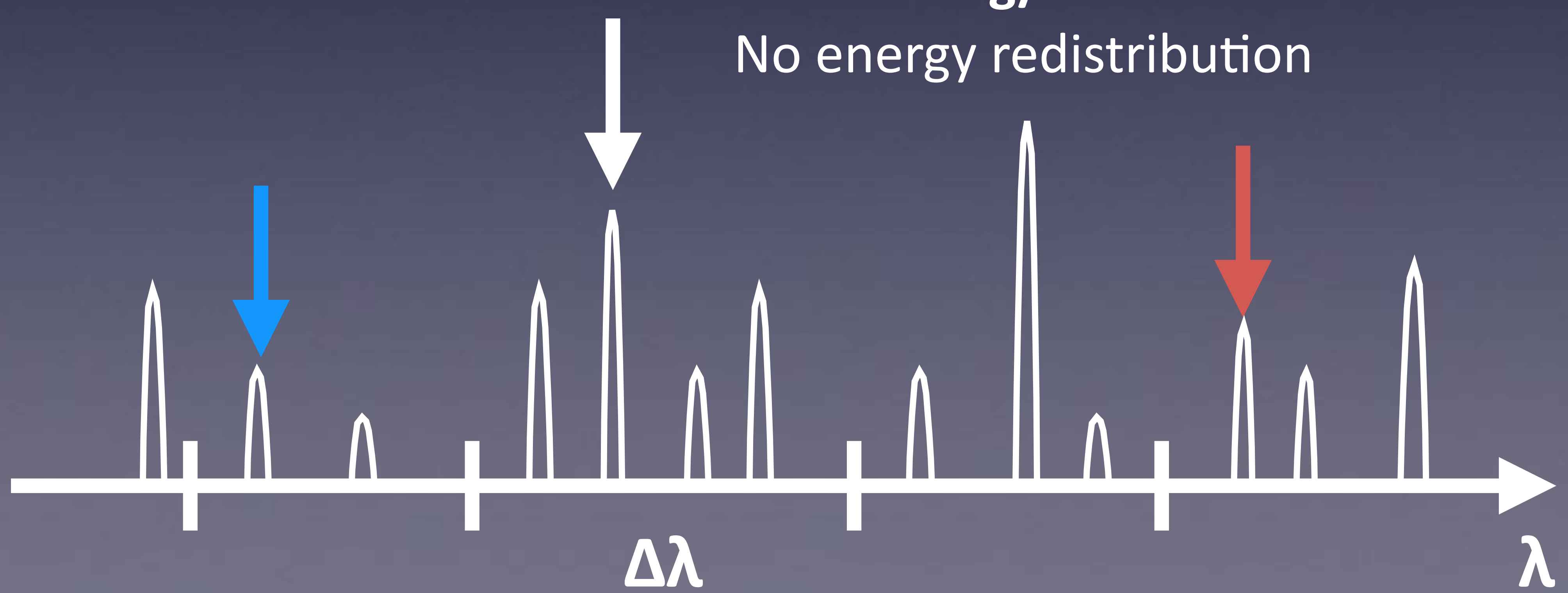
Redistribute photon energy
according to branching ratios
(Lucy, Mazzali & Lucy, Kasen+06)

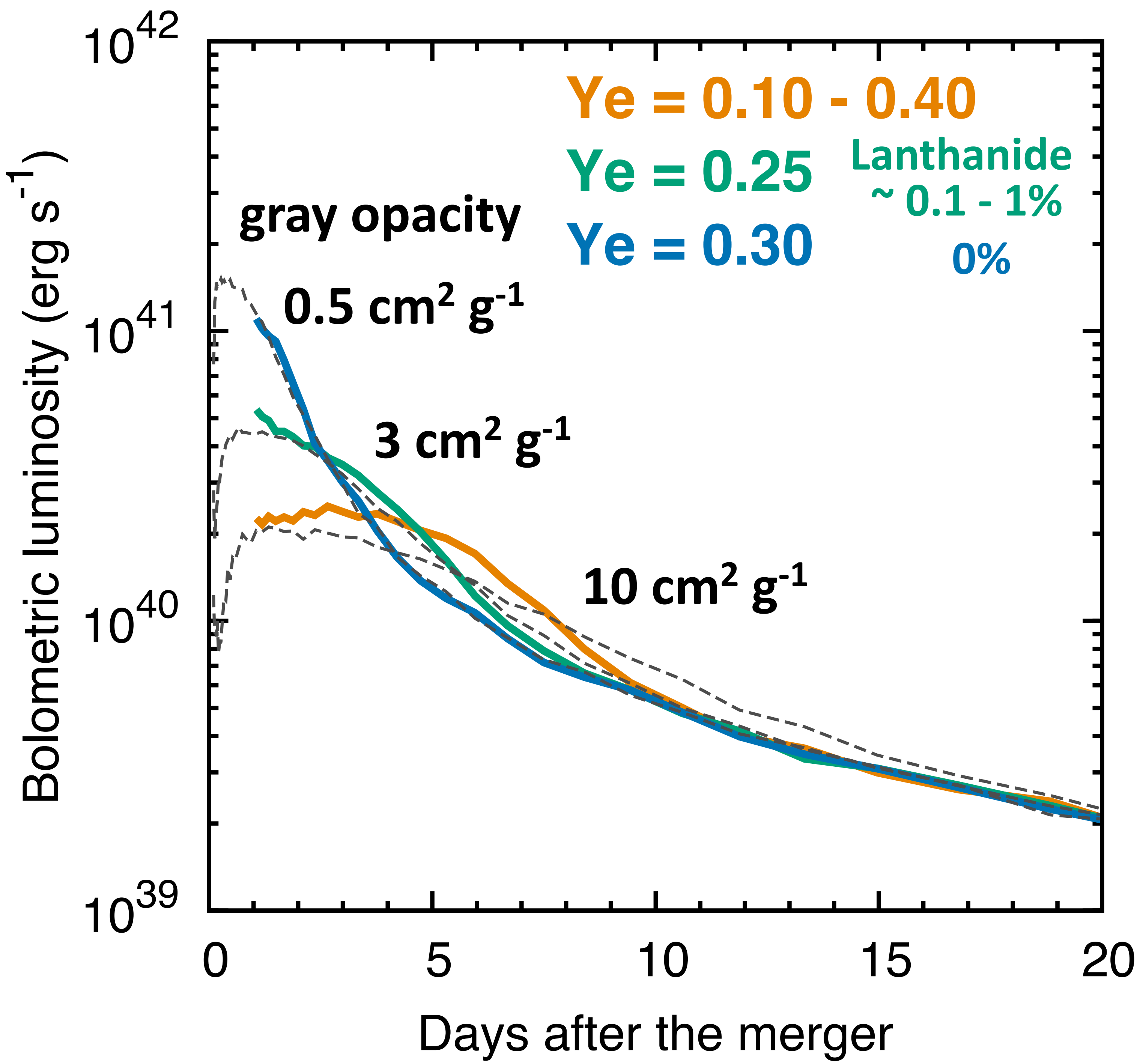
*** Absorptive**

Redistribute photon energy
according to thermal distribution $j = \alpha B(T)$
(Kasen+13, Tanaka & Hotokezaka 13,
Fontes+17, Wollaeger+17)

*** Scattering/resonance**

No energy redistribution



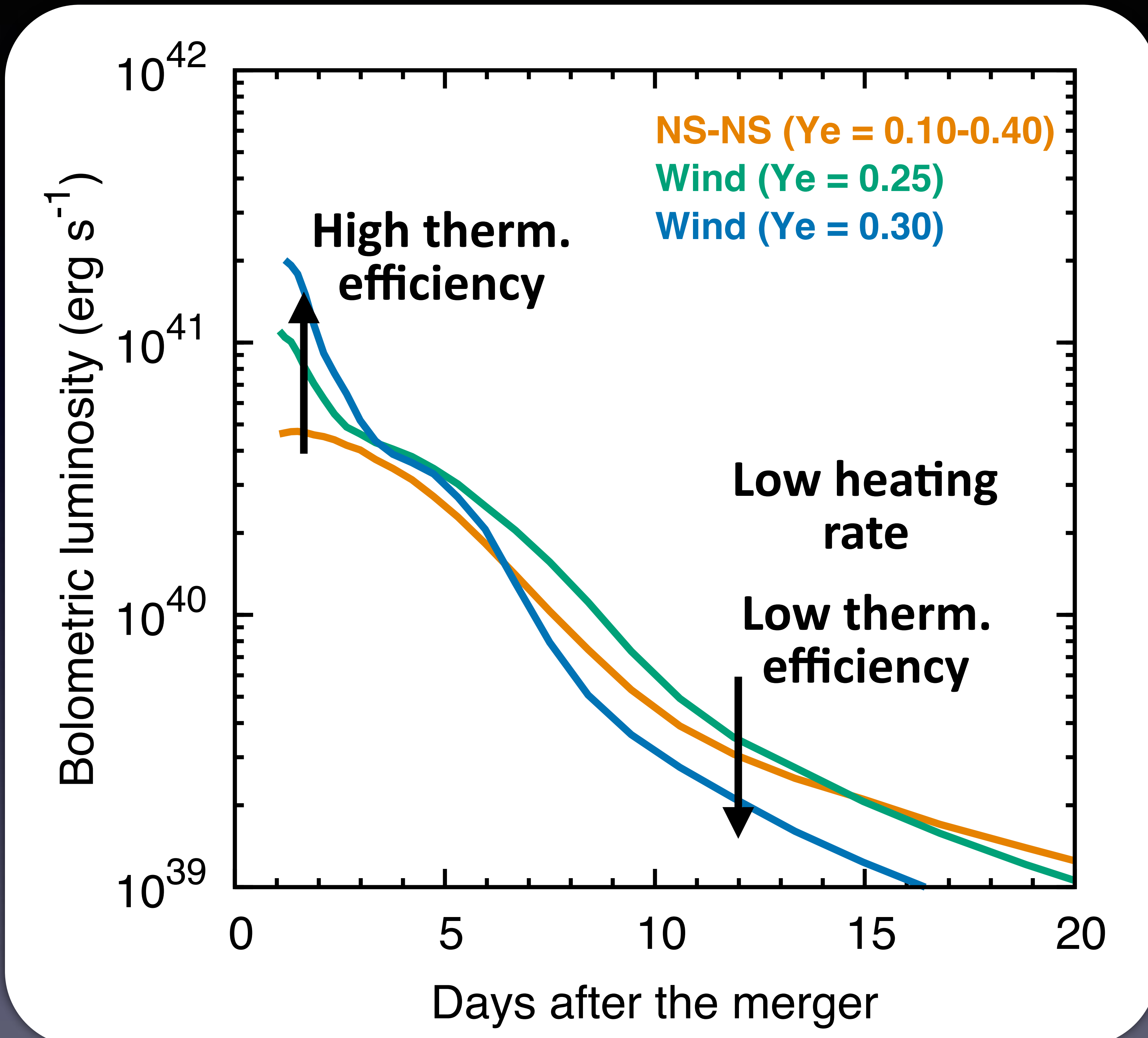


Simple model

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

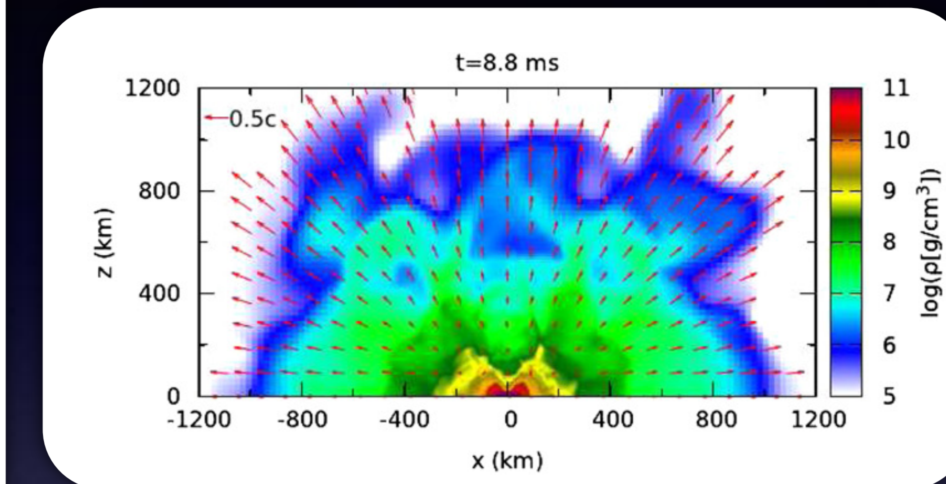
Depends sensitively on Ye

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

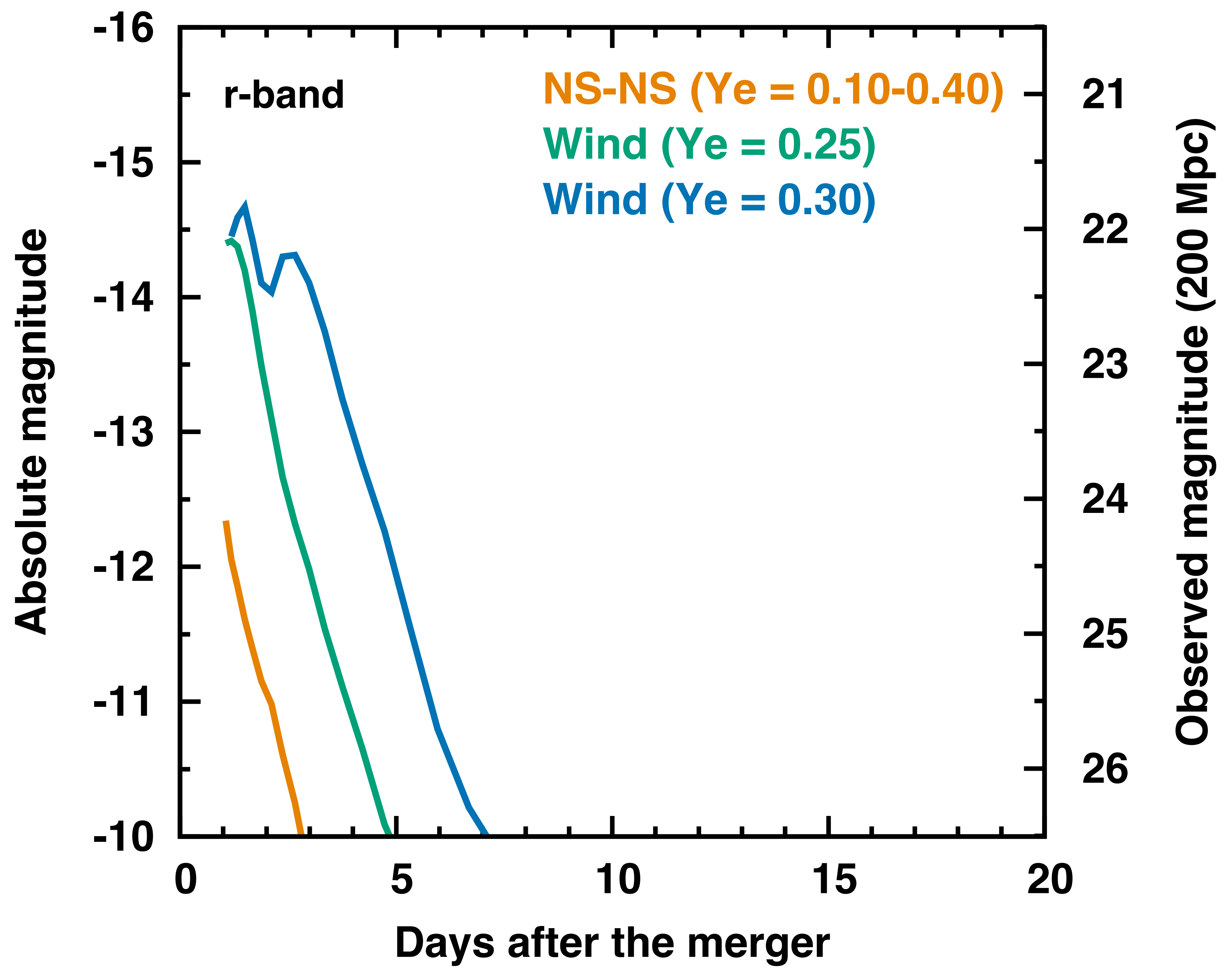
Wind

- Mej = 0.01 Msun
- v = 0.05c

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

Optical (r-band)

Mej = 0.01 Msun



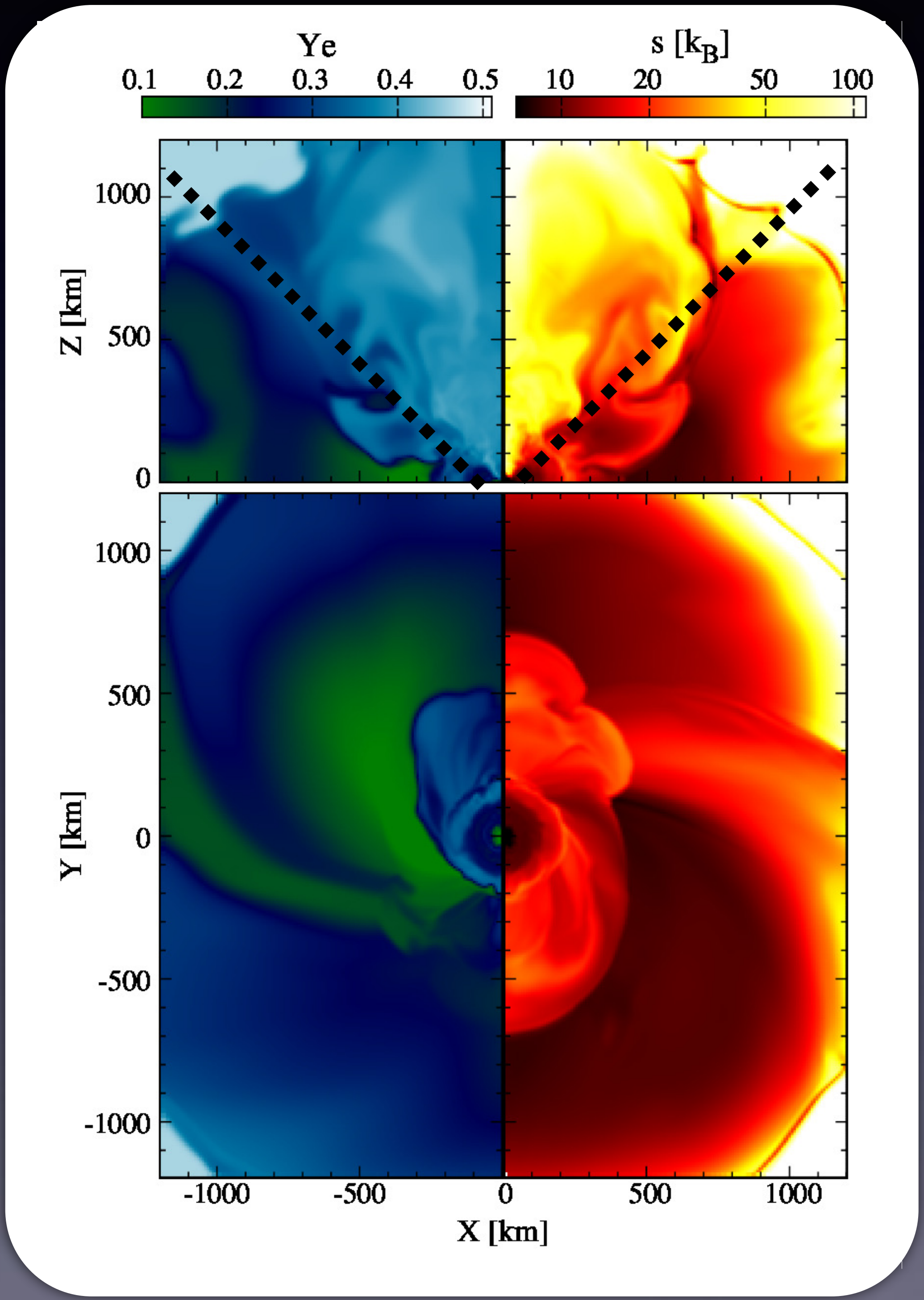
MT+ in prep.

Wide variety even for the same ejecta mass

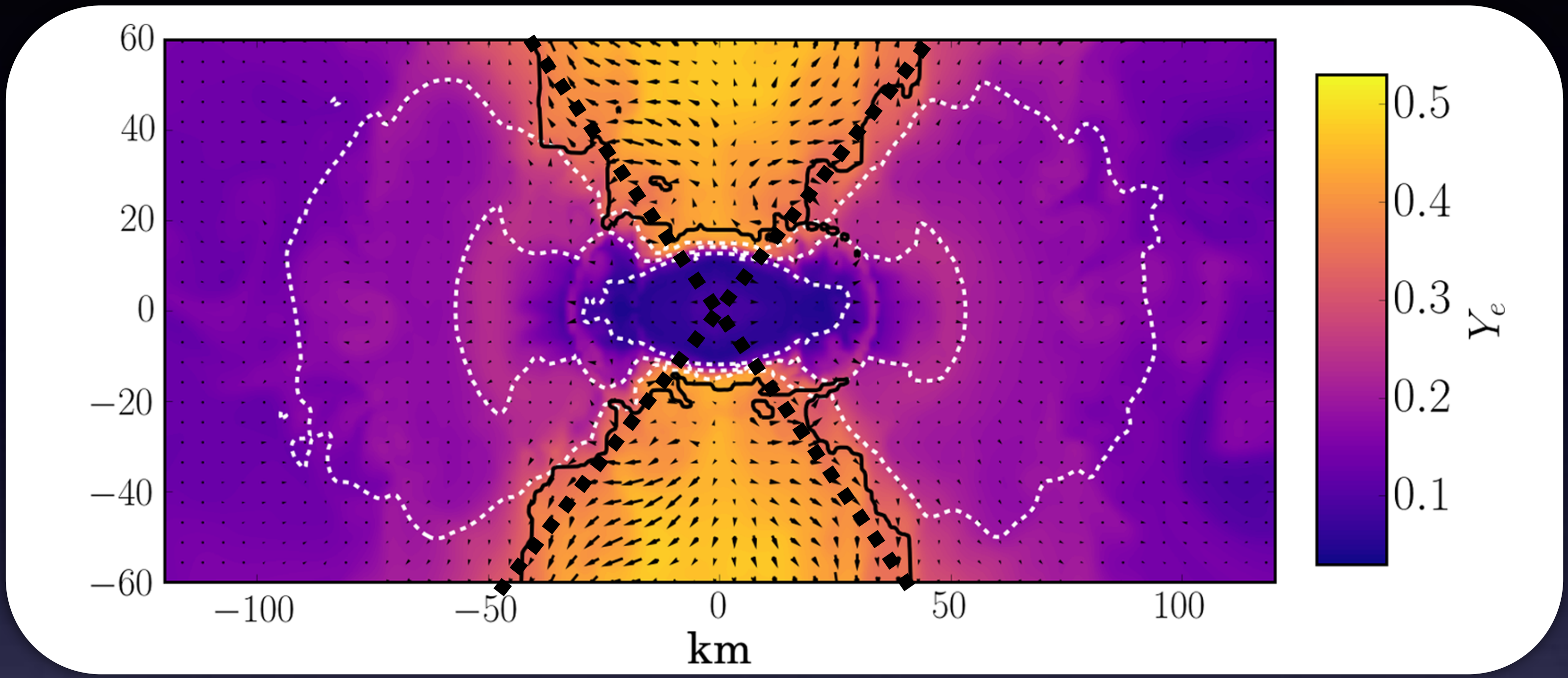
=> Accurate estimate of Ye is crucial

Blue component may be absorbed by dynamical ejecta?

e.g., Kasen+15, Metzger 17



Sekiguchi+16

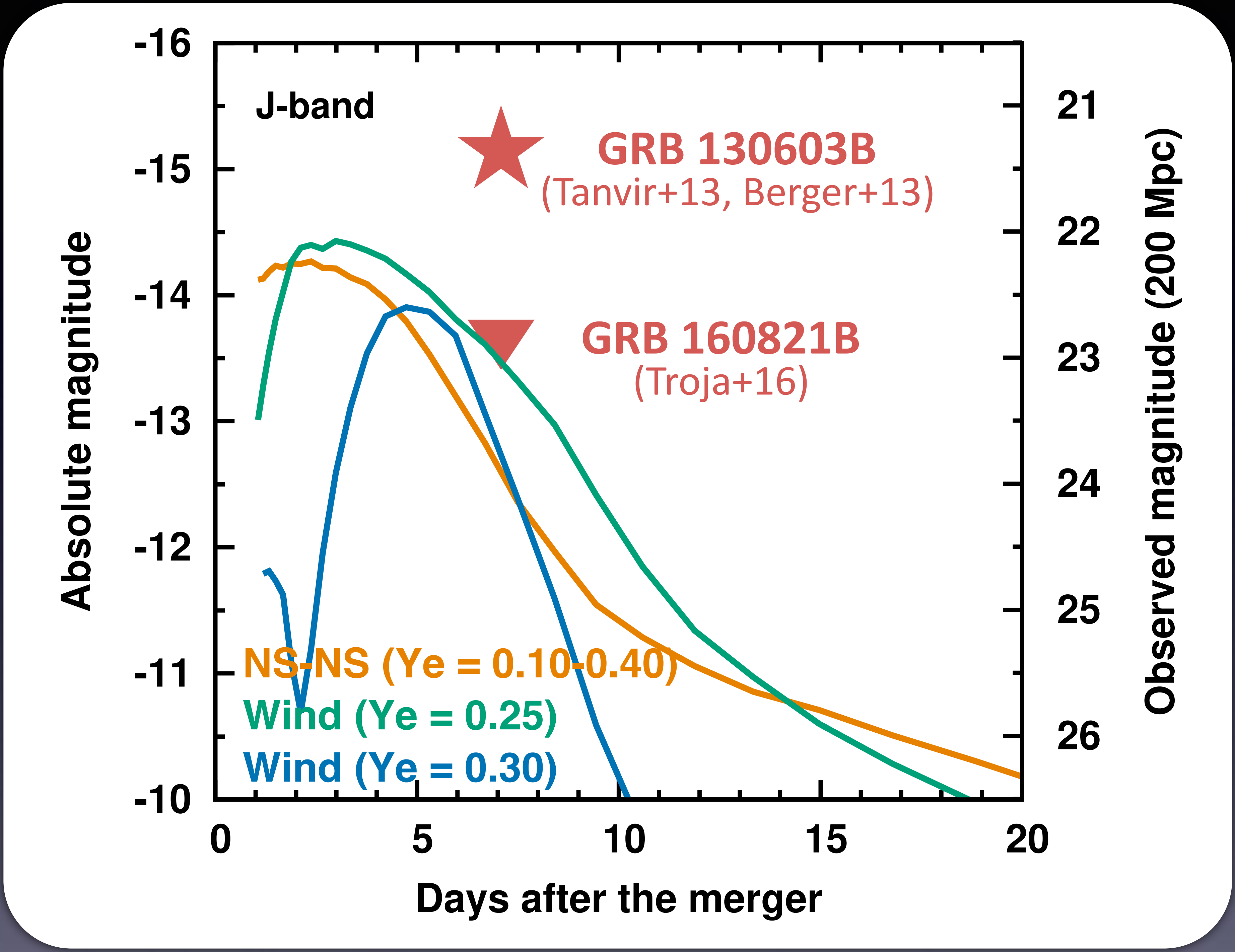


Foucart+16

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

NIR (J-band)

Mej = 0.01 Msun

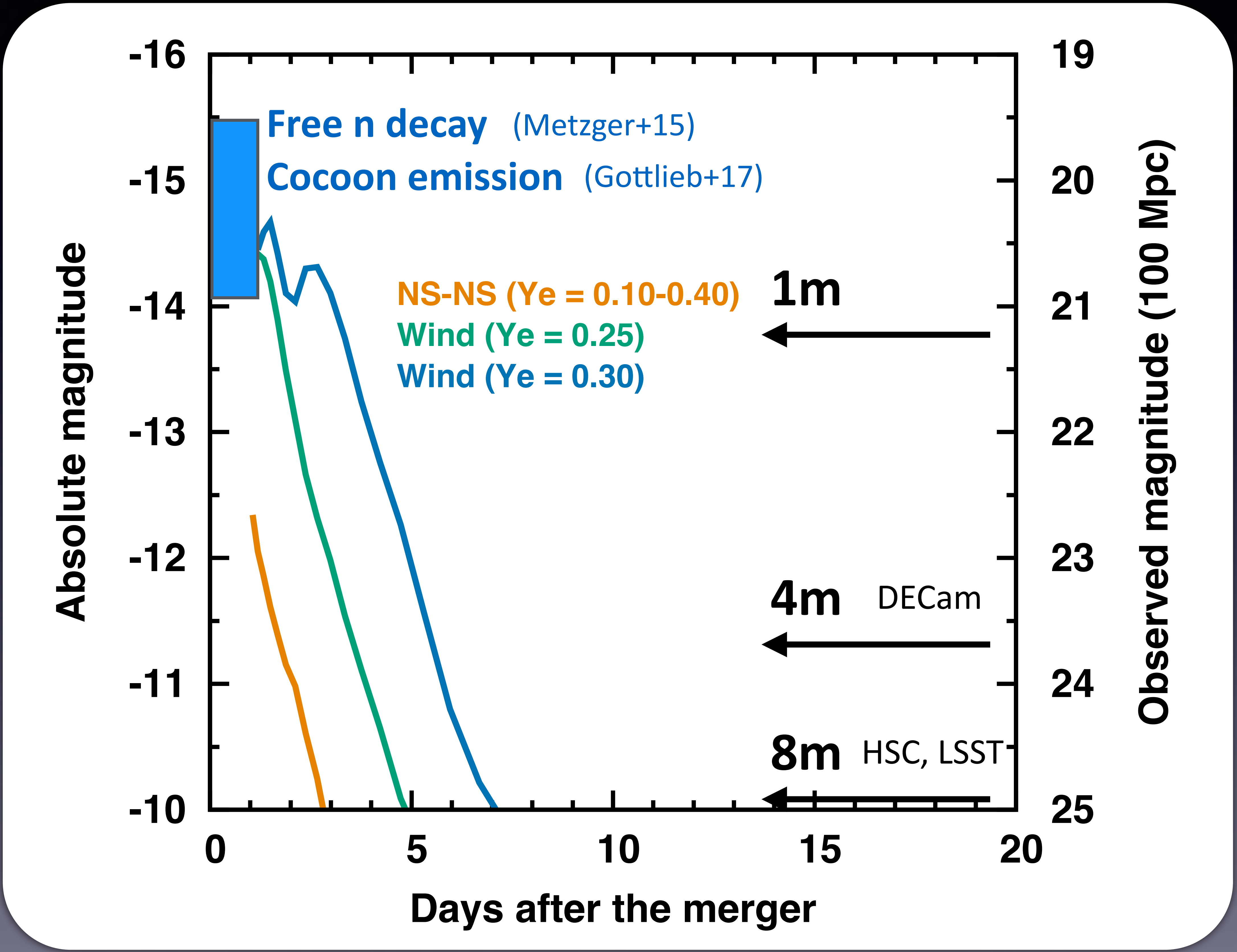


see also Kasliwal+17

M ~ 0.06 Msun for GRB 130603B Barnes+16

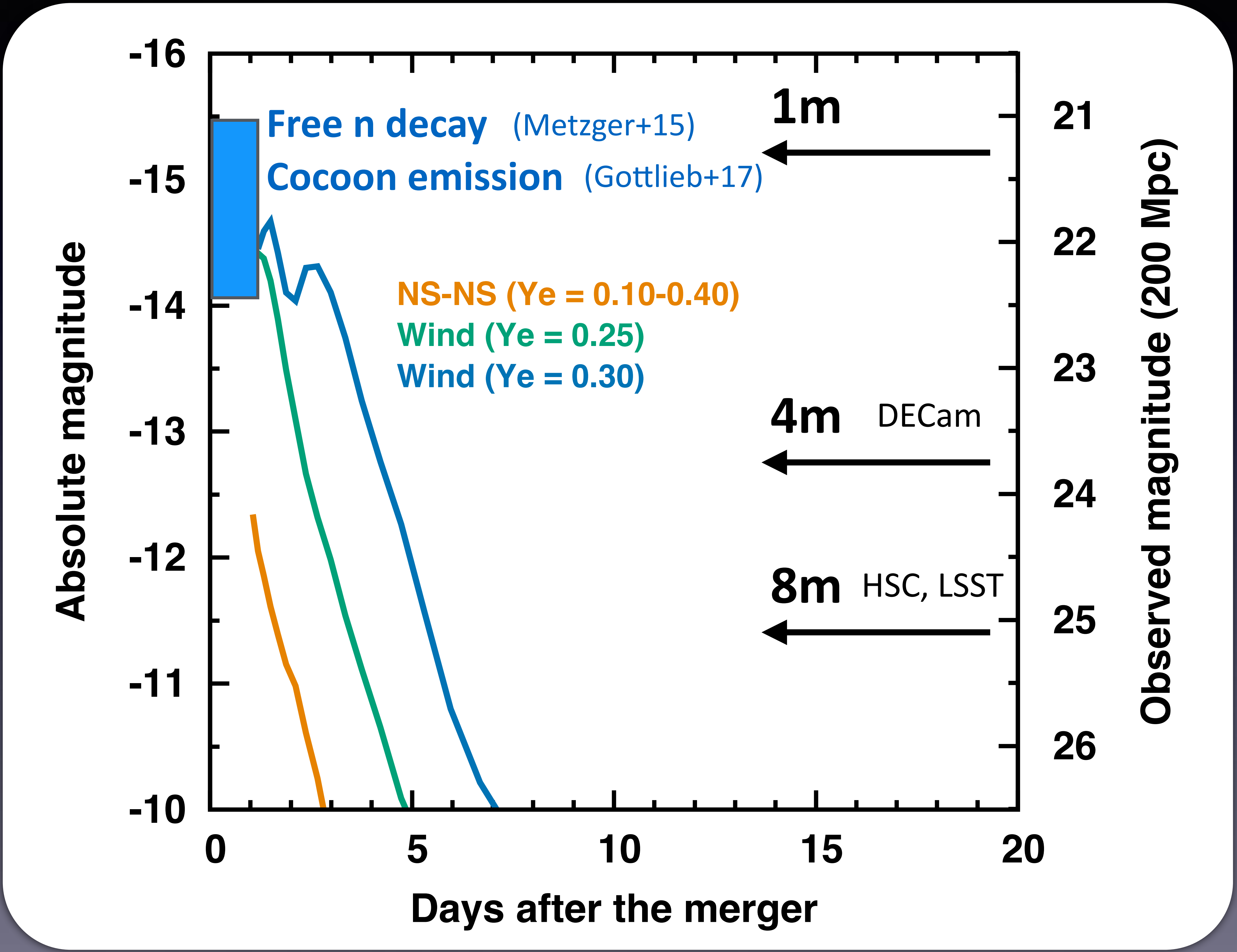
r-band magnitude @ 100 Mpc

Mej = 0.01 Msun



r-band magnitude @ 200 Mpc

Mej = 0.01 Msun



Summary

- **Guides from theory are important for observations**
- **New opacity calculations for Se, Ru, Te, Nd, and Er**
- **Opacity sensitively depends on compositions**
  - $\kappa \sim 0.5$ cm^2 g^{-1} for Ye ~ 0.3 (Lanthanide free)
  - $\kappa \sim 10$ cm^2 g^{-1} for solar abundance
- **Kilonova brightness depends 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)
- **Accurate estimate of Ye in merger simulations is critical**