Overview: Kilonova

1. Basics
2. Prospects for EM observations
3. Signatures of r-process nucleosynthesis

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References (Reviews)

- **Rosswog, S. 2015**
  "The multi-messenger picture of compact binary mergers"
  International Journal of Modern Physics D, 24, 1530012-52
- **Fernandez, R. & Metzger, B. D. 2016**
  "Electromagnetic Signatures of Neutron Star Mergers in the Advanced LIGO Era"
  Annual Review of Nuclear and Particle Science, 66, 23
- **Tanaka, M. 2016**
  "Kilonova/Macronova Emission from Compact Binary Mergers"
  Advances in Astronomy, 634197
- **Metzger, B. D. 2017**
  "Kilonovae"
  Living Reviews in Relativity, 20, 3

Timeline

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

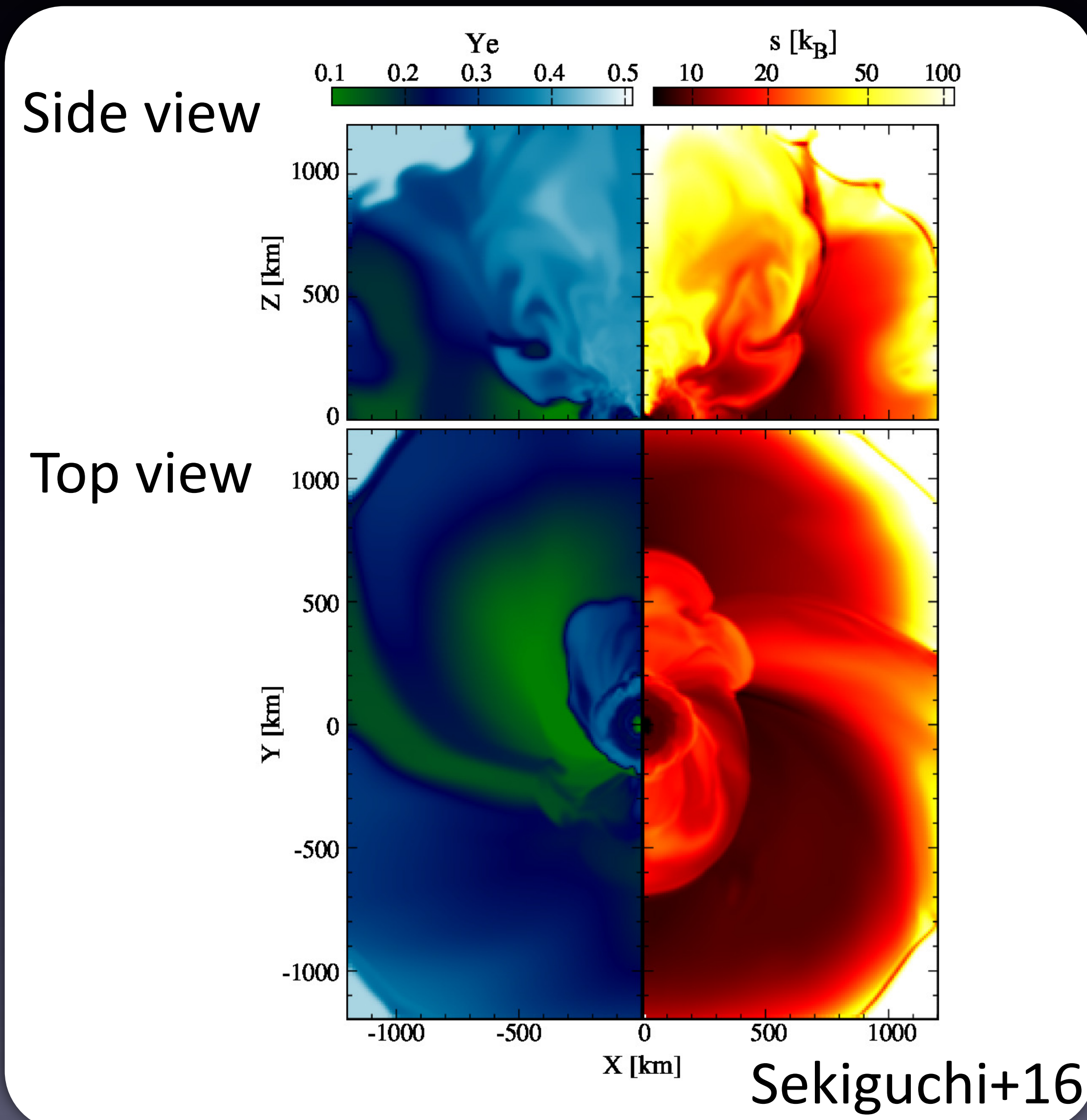
Dynamical | Wind

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

Masaru's talk (Thursday) | Francois's talk (Monday) | My talk (today)

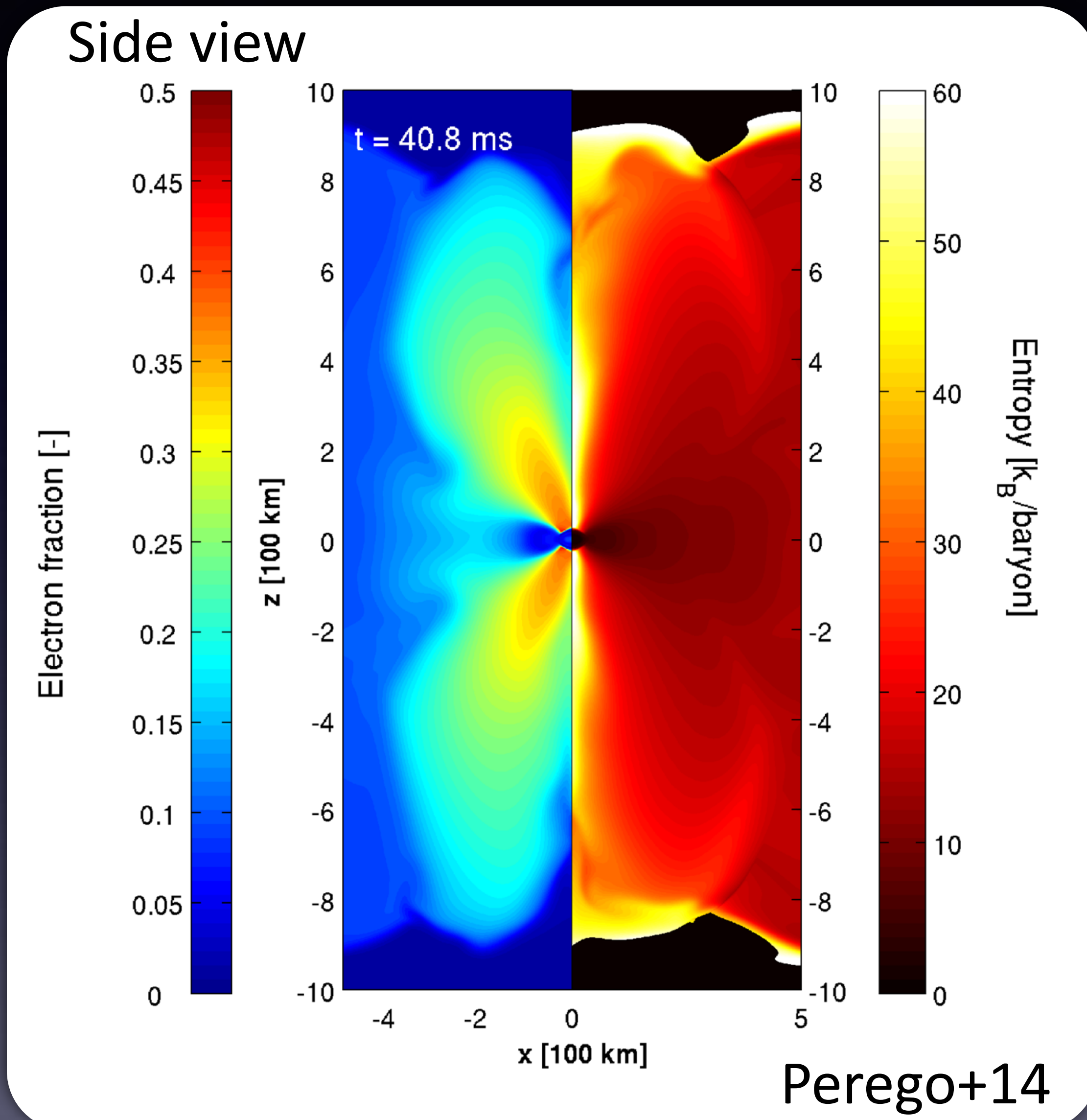
Merger => see Masaru's talk

Dynamical ejecta (~< 10 ms)



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

Post-dynamical ejecta (~< 100 ms)

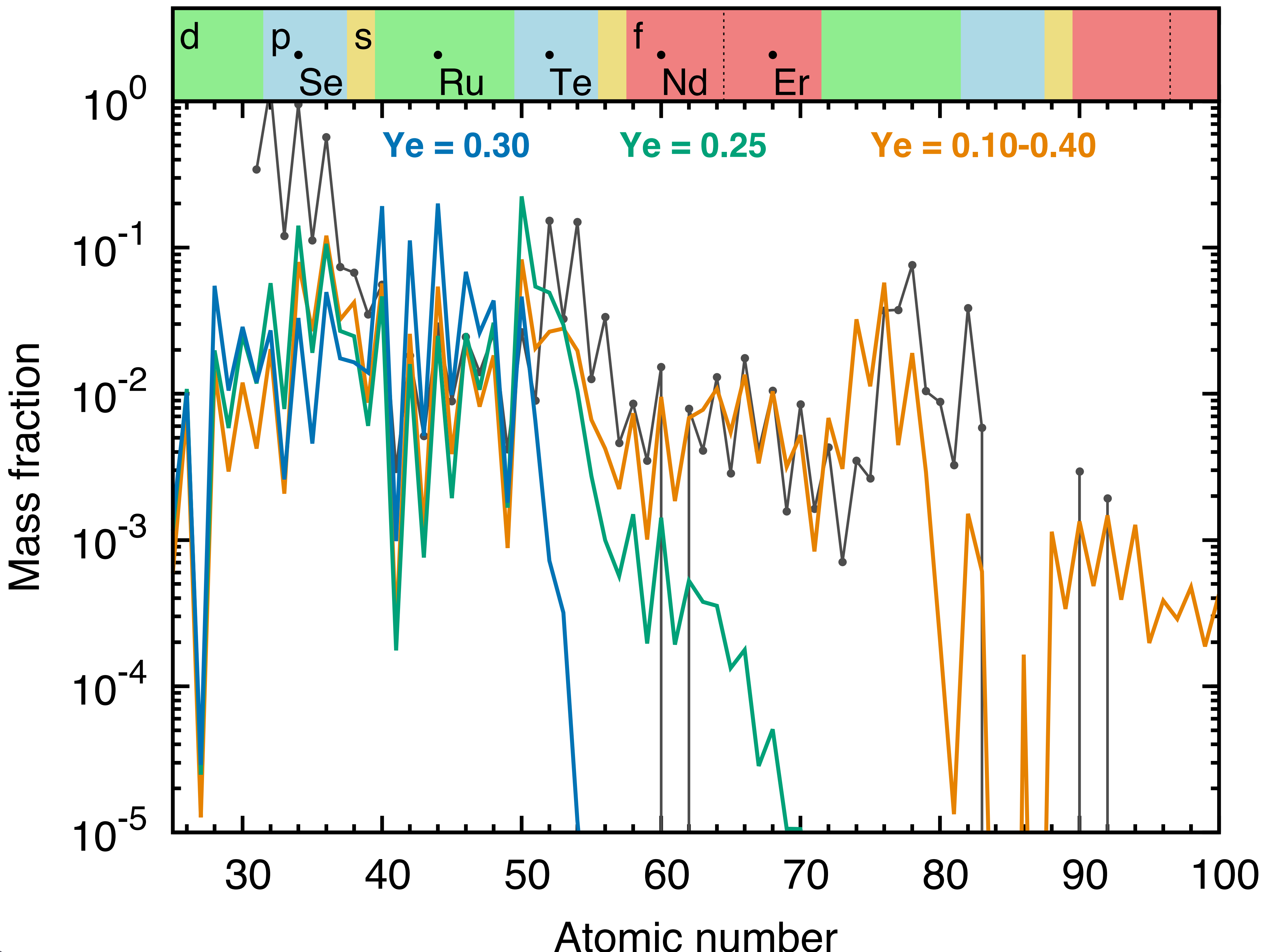


- Mej >~ 10^{-3} Msun
- v ~ 0.05 c
- relatively high Ye

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

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

Nucleosynthesis (< 1 sec) => see Francois's talk



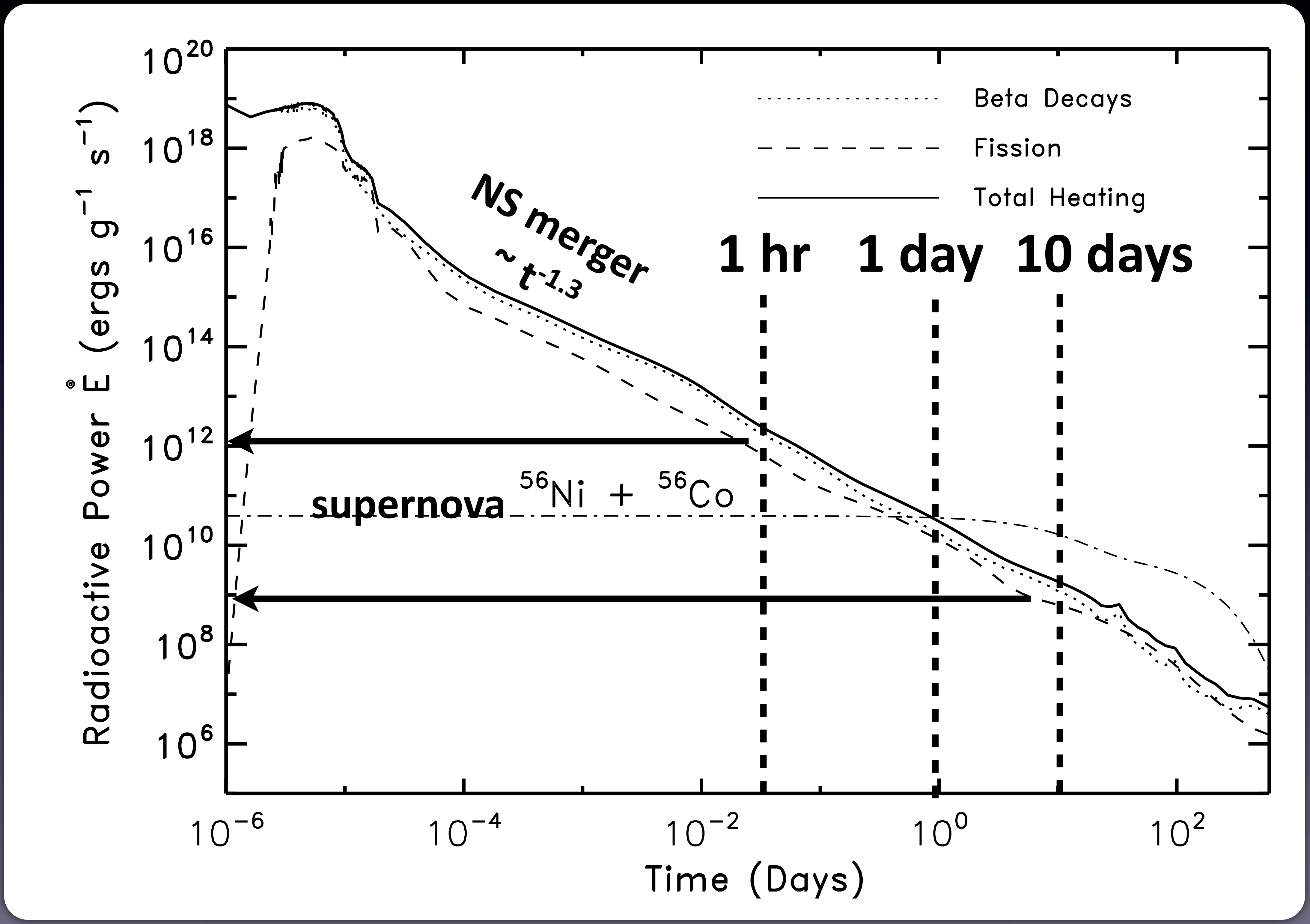
=> Solar abundance? (Discussion yesterday)

(from Wanajo+14)

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

Physical properties of NS merger ejecta at ~1 day

(Blackboard)

“Kilonova/Macronova"

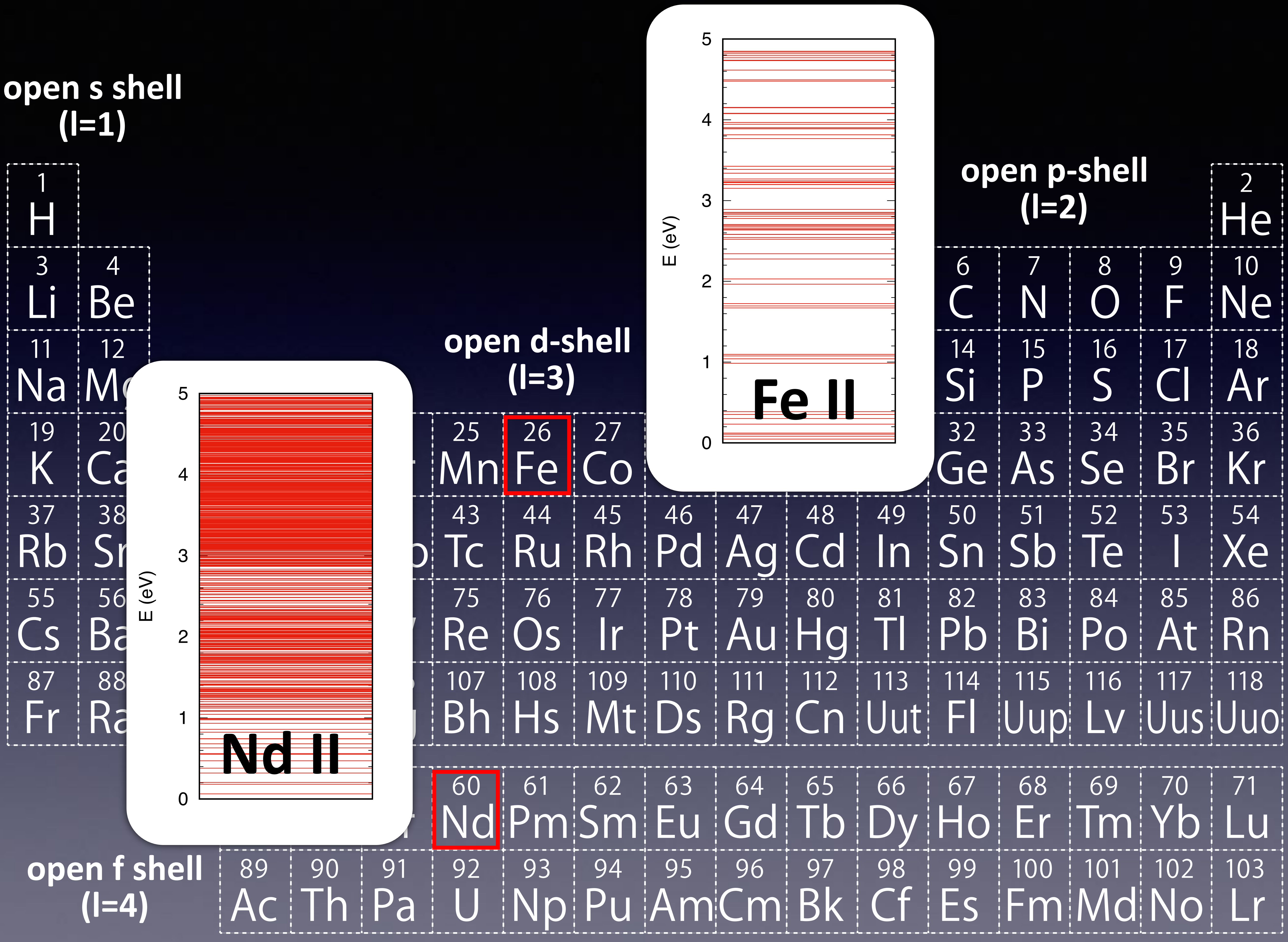
Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, …
High opacity: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, …

Timescale

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

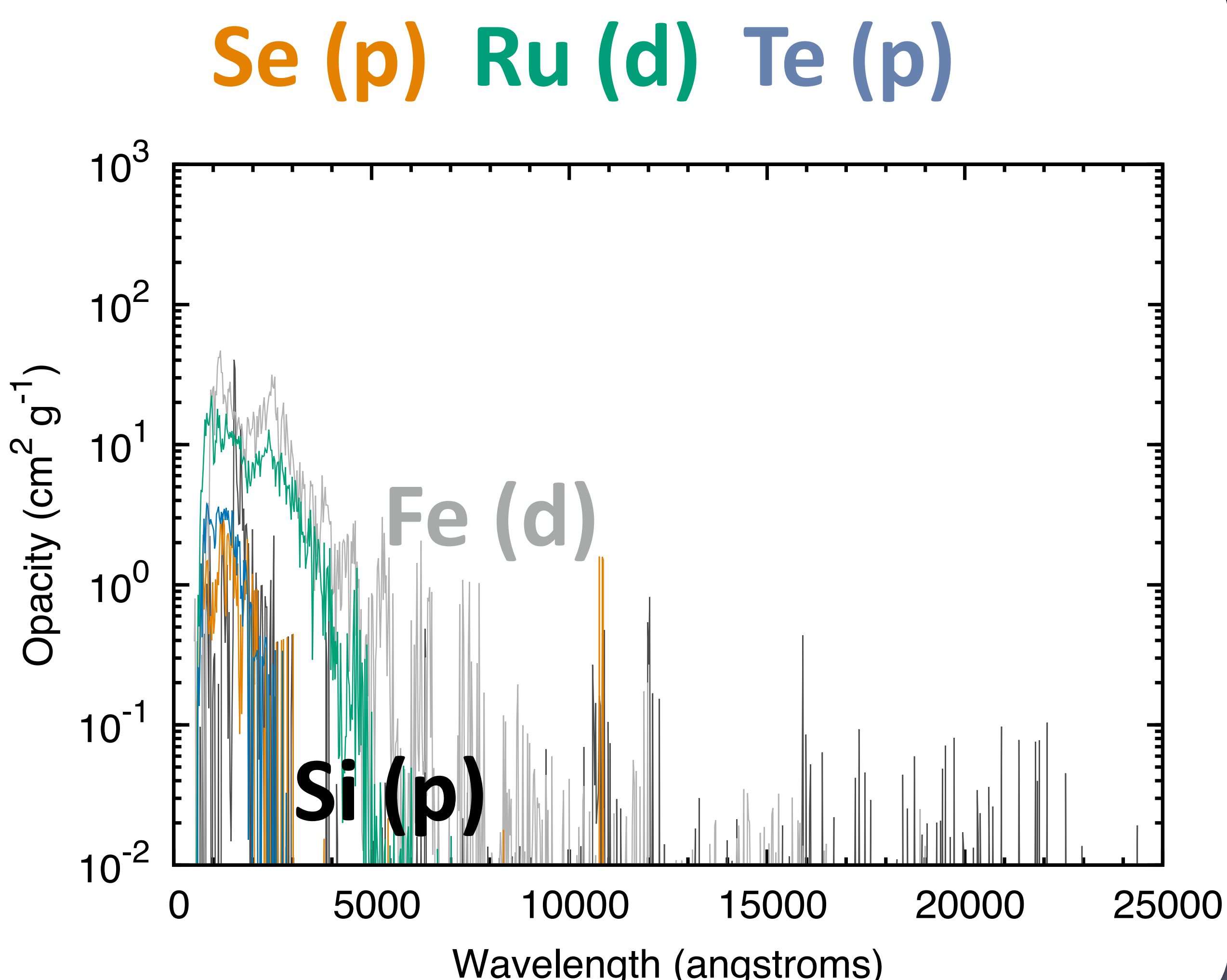
Luminosity

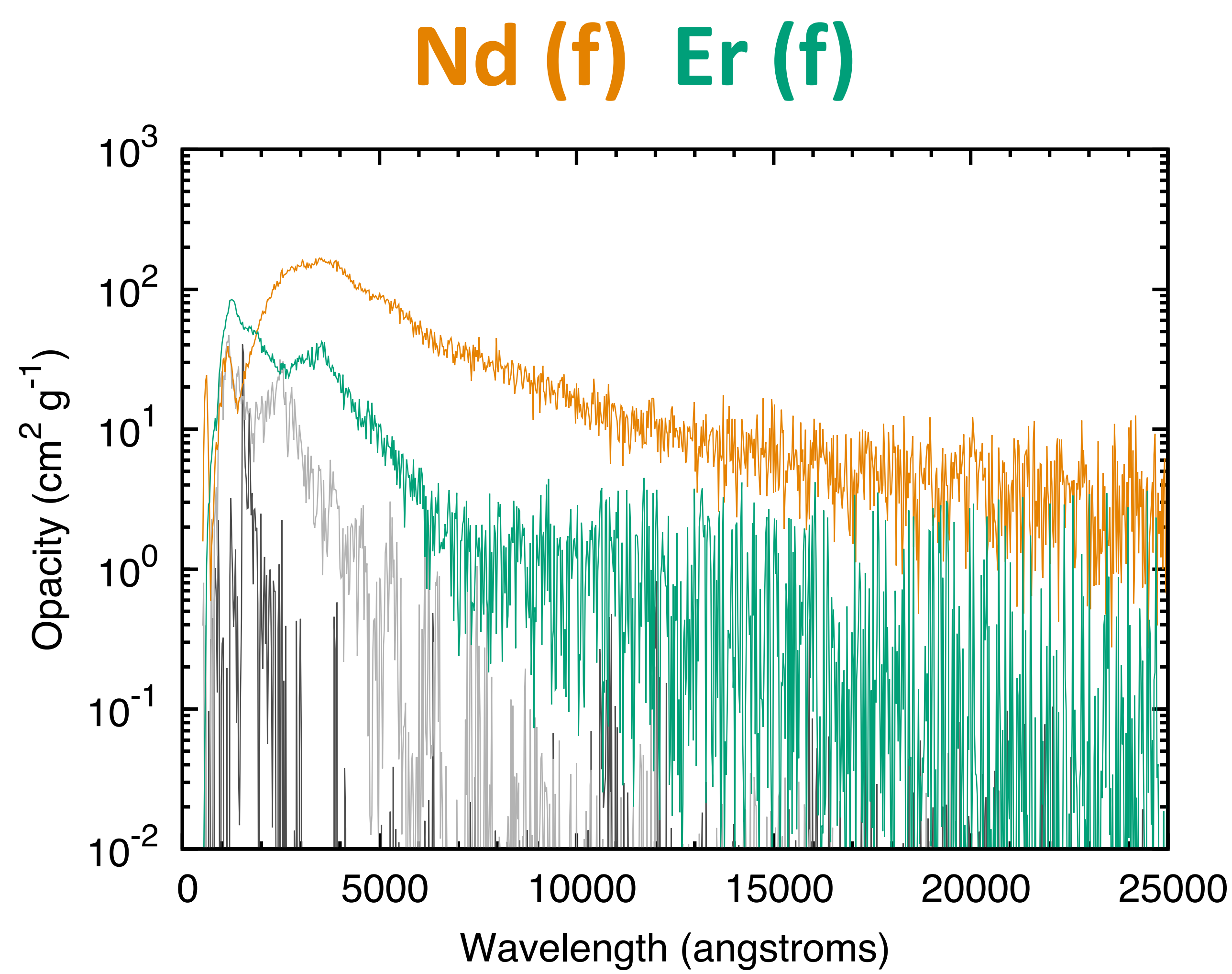
$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$
$$\simeq 1.3 \times 10^{40}\ {\rm erg\ s^{-1}} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10\ {\rm cm^2\ g^{-1}}}\right)^{-0.65}$$


open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
Fe II
Nd II
E (eV)
0 1 2 3 4 5
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

Opacity

Atomic structure calculation
with HULLAC code (relativistic, local radial potential, Bar-Shalom+99)
and GRASP code (relativisitic, e-e interaction, Jonsson+07)





MT+ in prep.

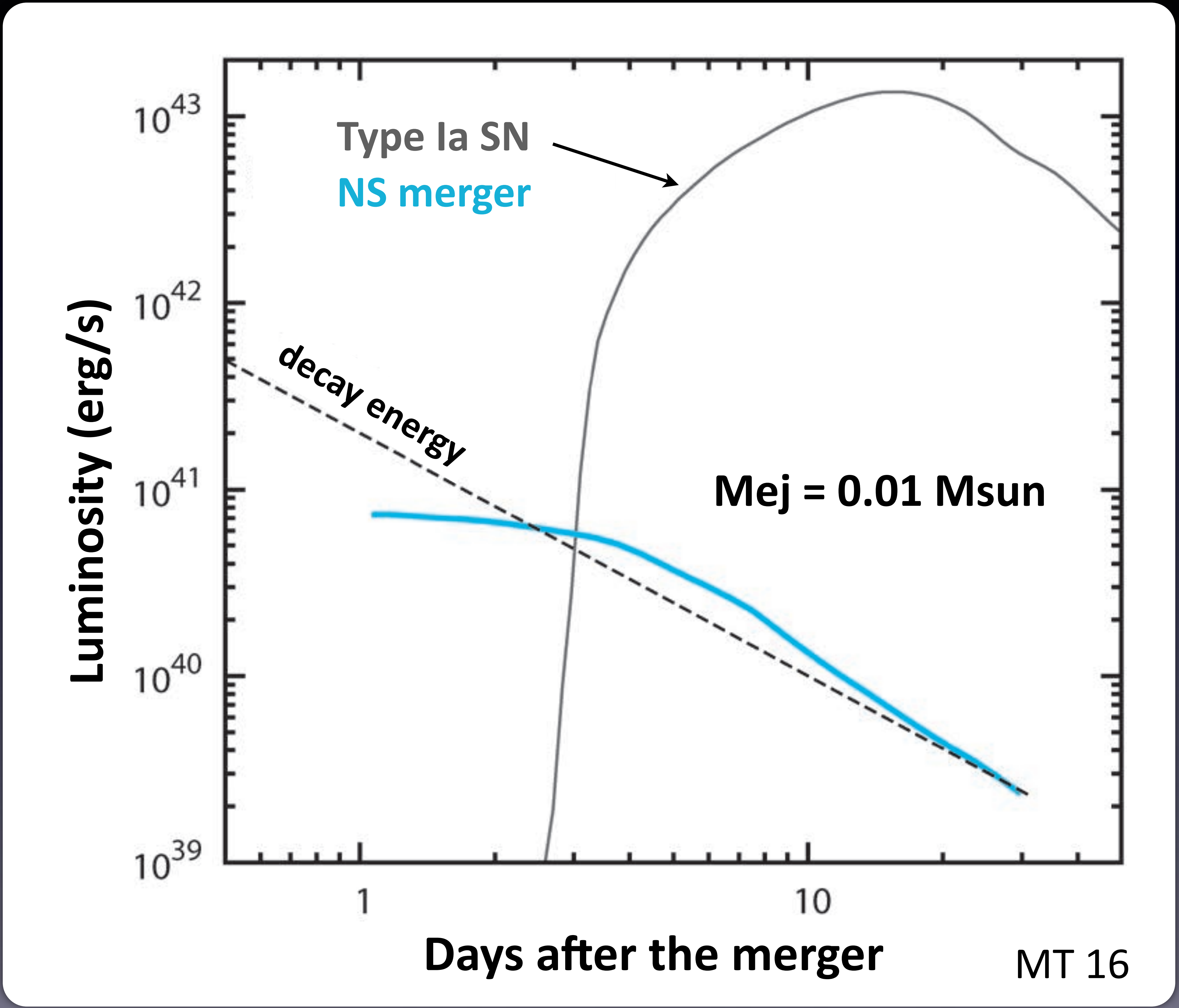
κ (p shell) < κ (d shell) < κ (f shell)

κ (Lanthanide) ~ 10 cm^2 g^{-1}

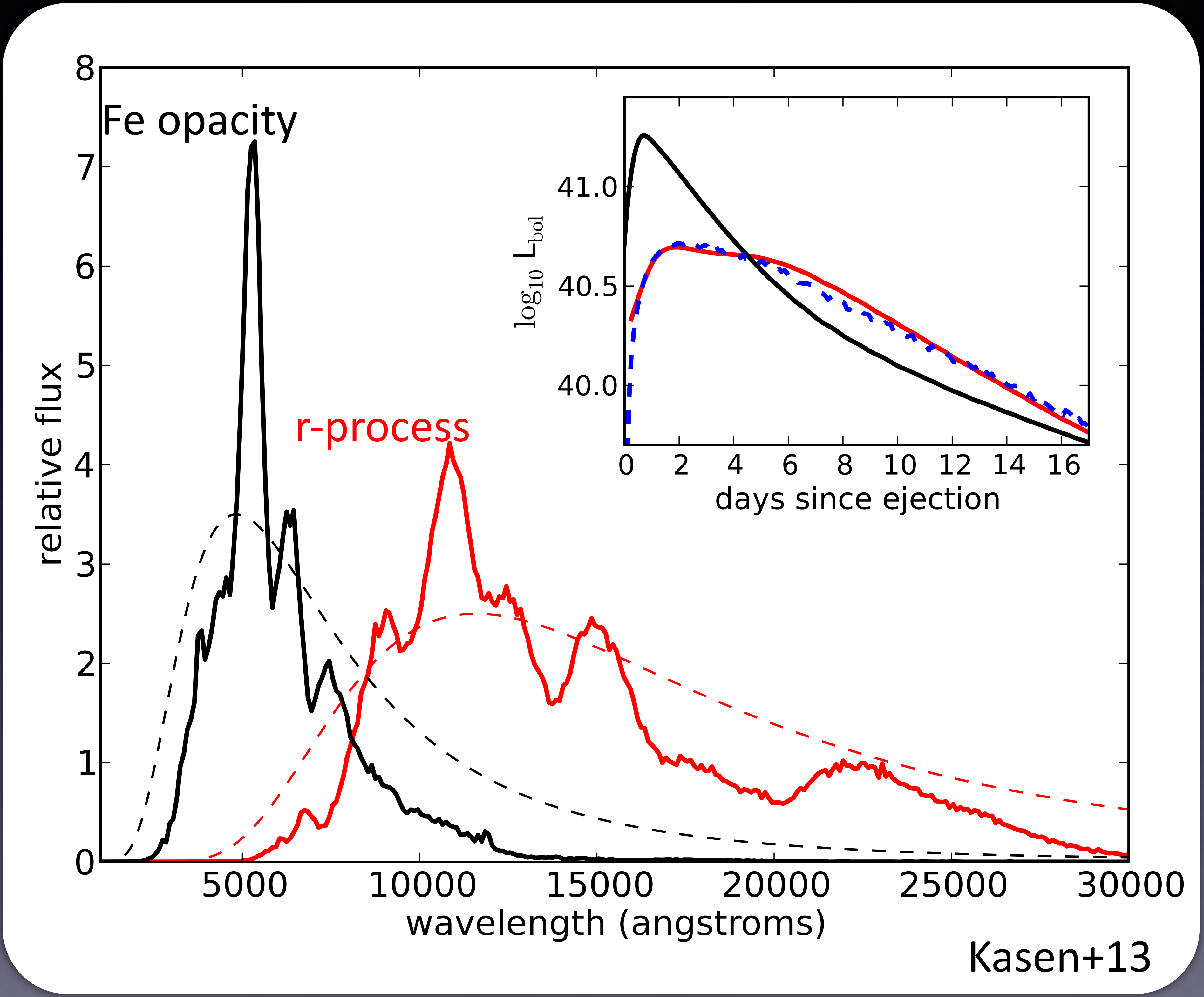
Kasen+13, MT & Hotokezaka 13

Light curve

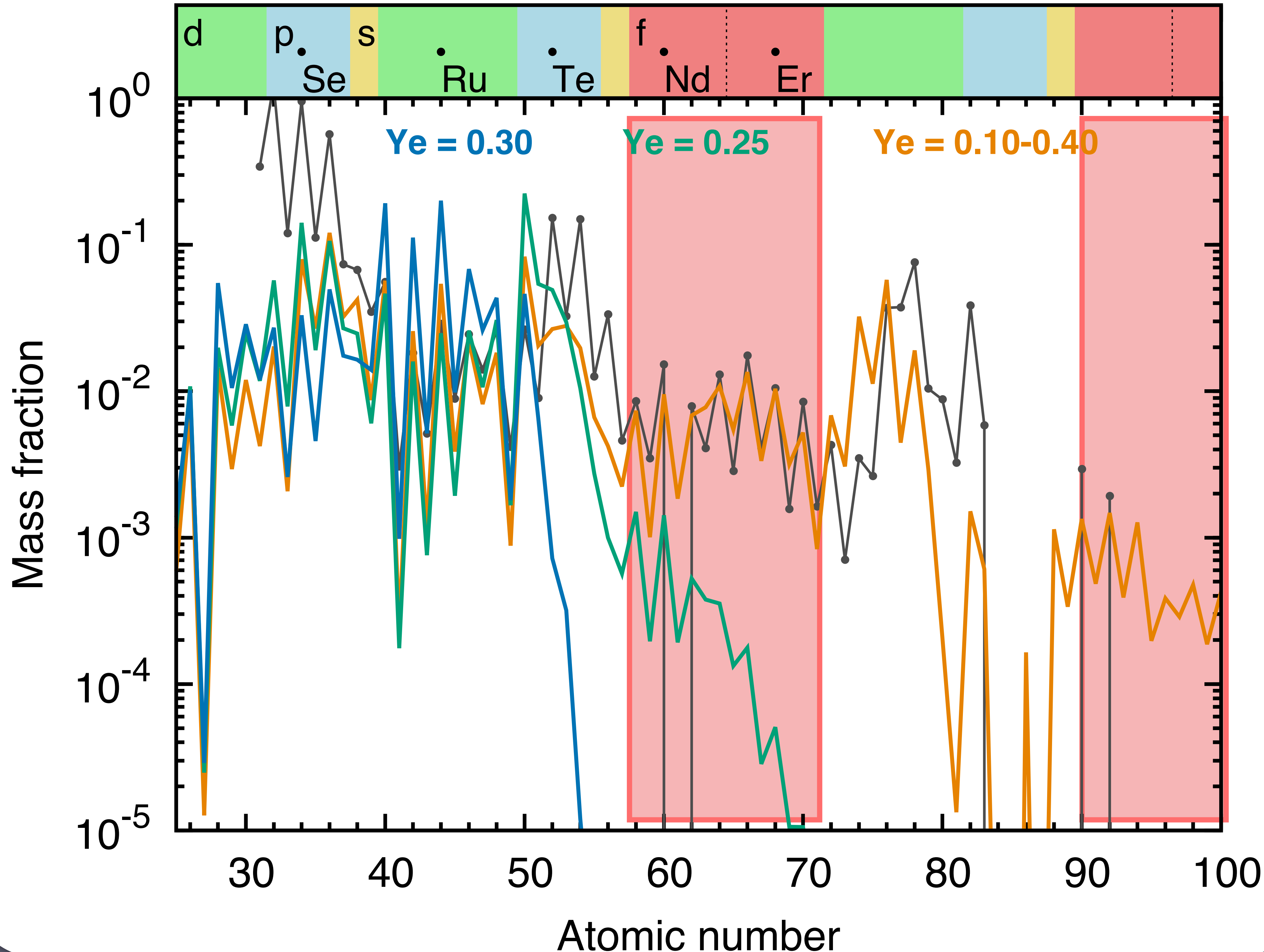
a few x 10^{40} erg/s
@ ~1 week



Spectra



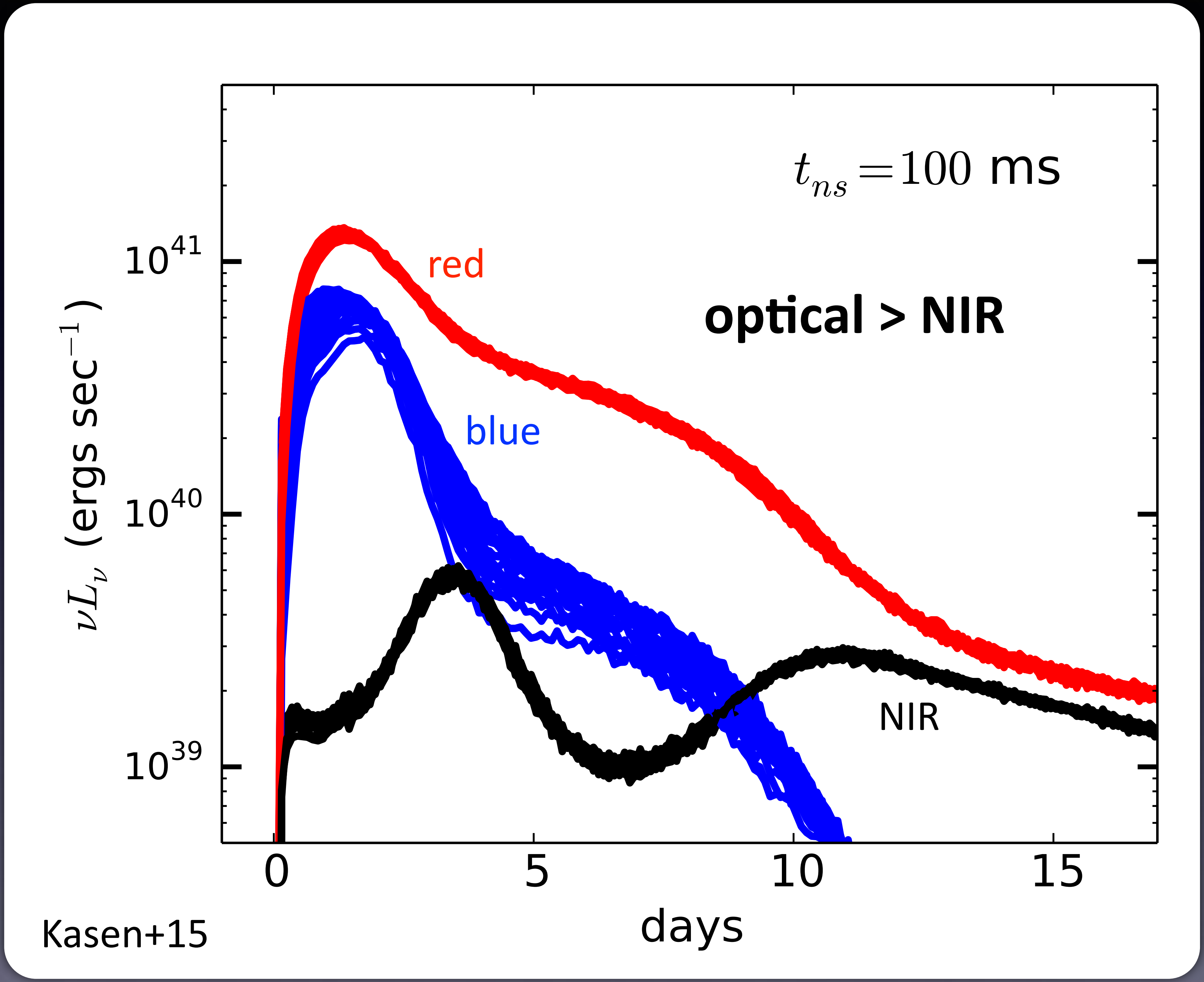
Extremely red spectra (peaks at near infrared wavelengths)



If post-dynamical ejecta is Lanthanide-free (Ye >~ 0.25)
=> low opacity => “blue kilonova”

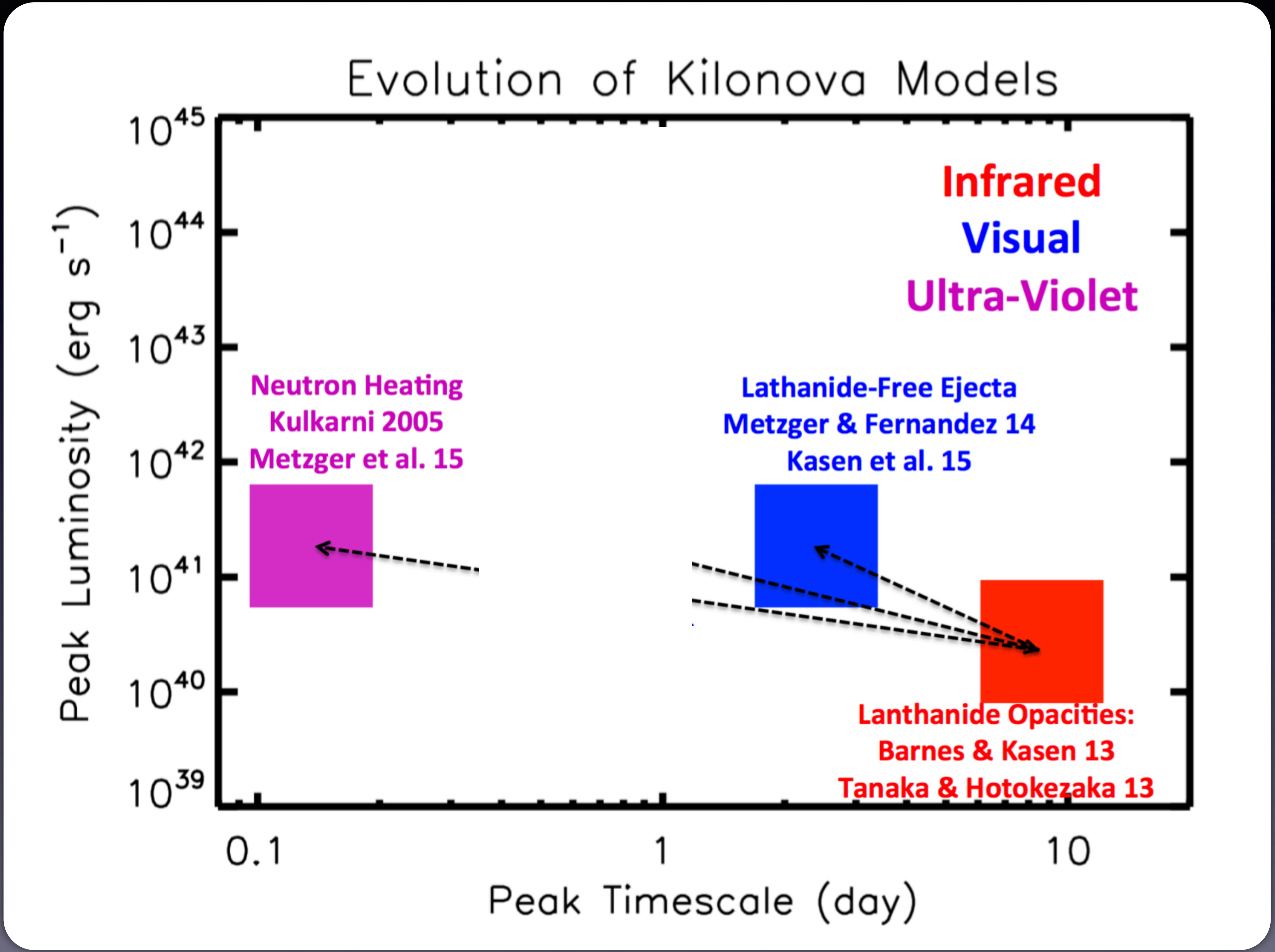
(Metzger+14, Kasen+15)

“Blue kilonova"



L ~ 10^{41} erg/s, t ~ a few days, Optical

Summary



Metzger 17

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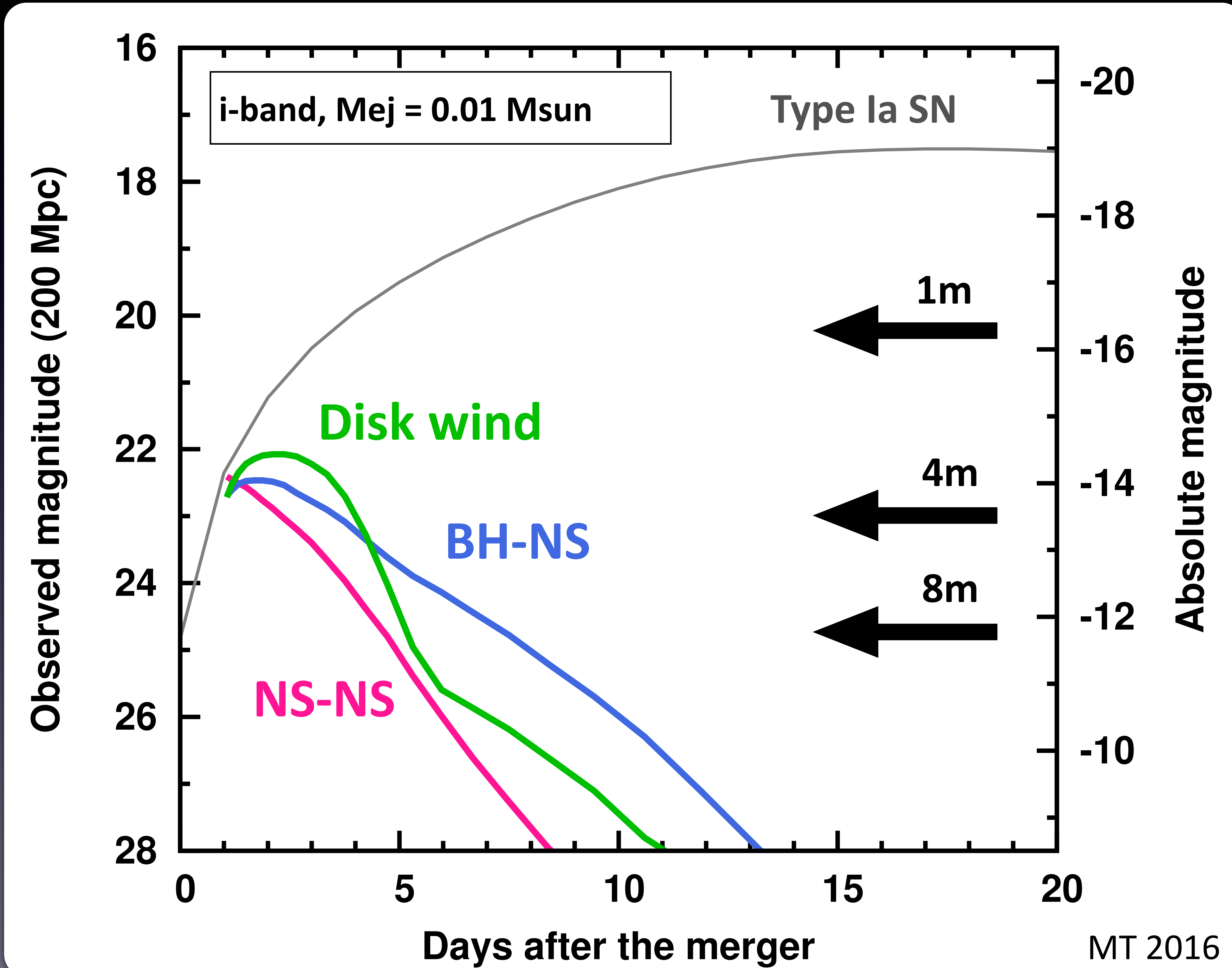
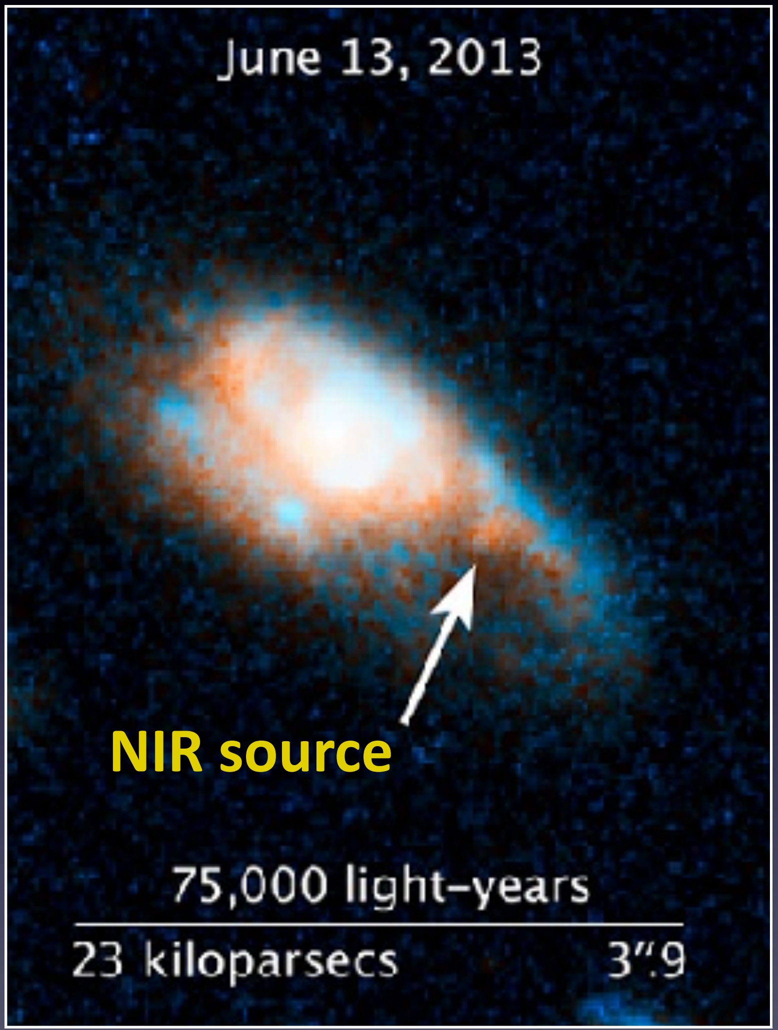
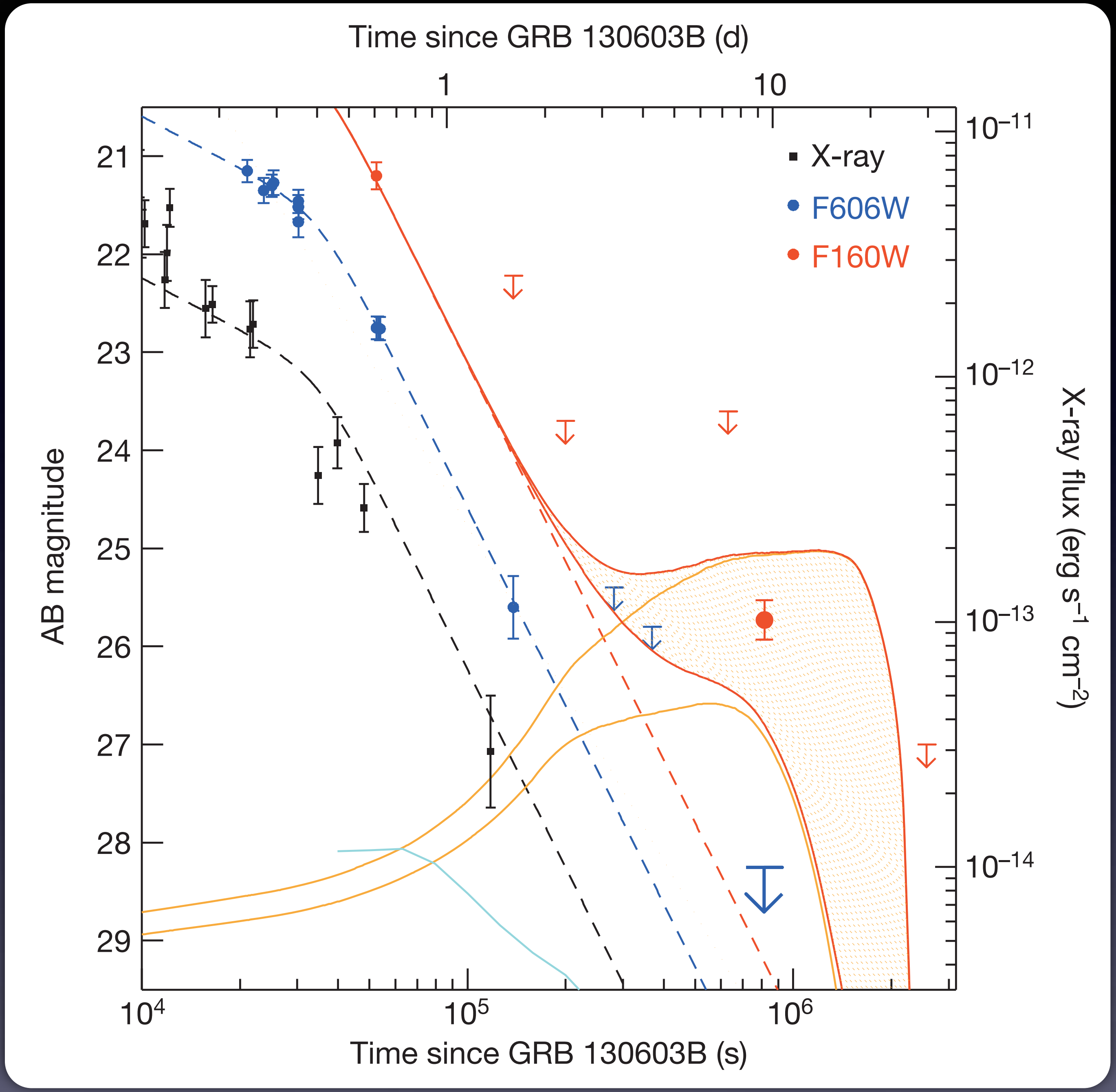
Optical light curves in observed magnitudes



Constraints from short GRBs (1/2)

GRB 130603B





Tanvir+2013, Berger+2013

1 + 1(?) more cases
GRB 060614 & GRB 050709

Ejection of ~0.06 Msun Hotokezaka+13, Barnes+16

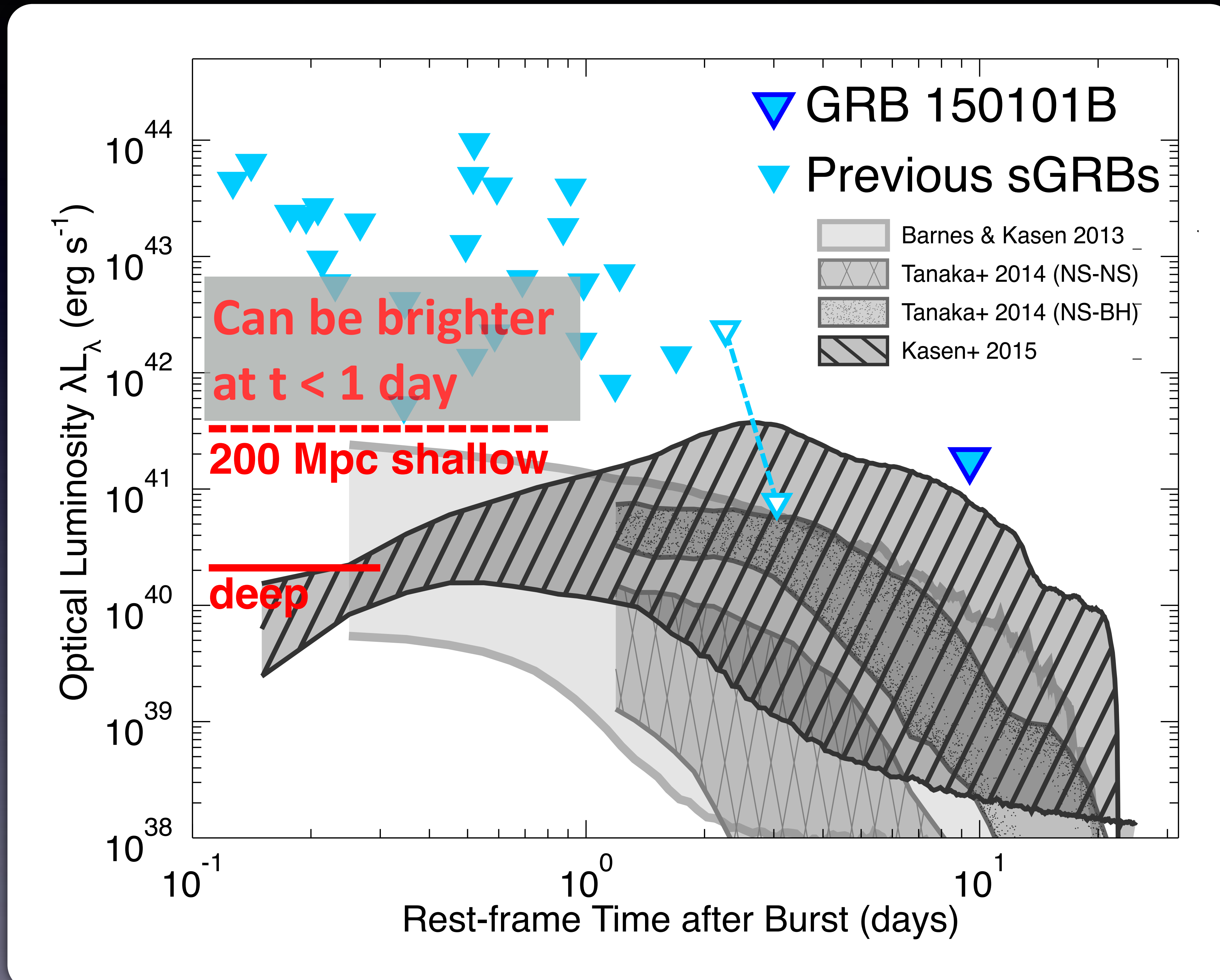
GRB 160821B: ~ 0.01 Msun? (Troja+16)

Constraints from short GRBs (2/2)

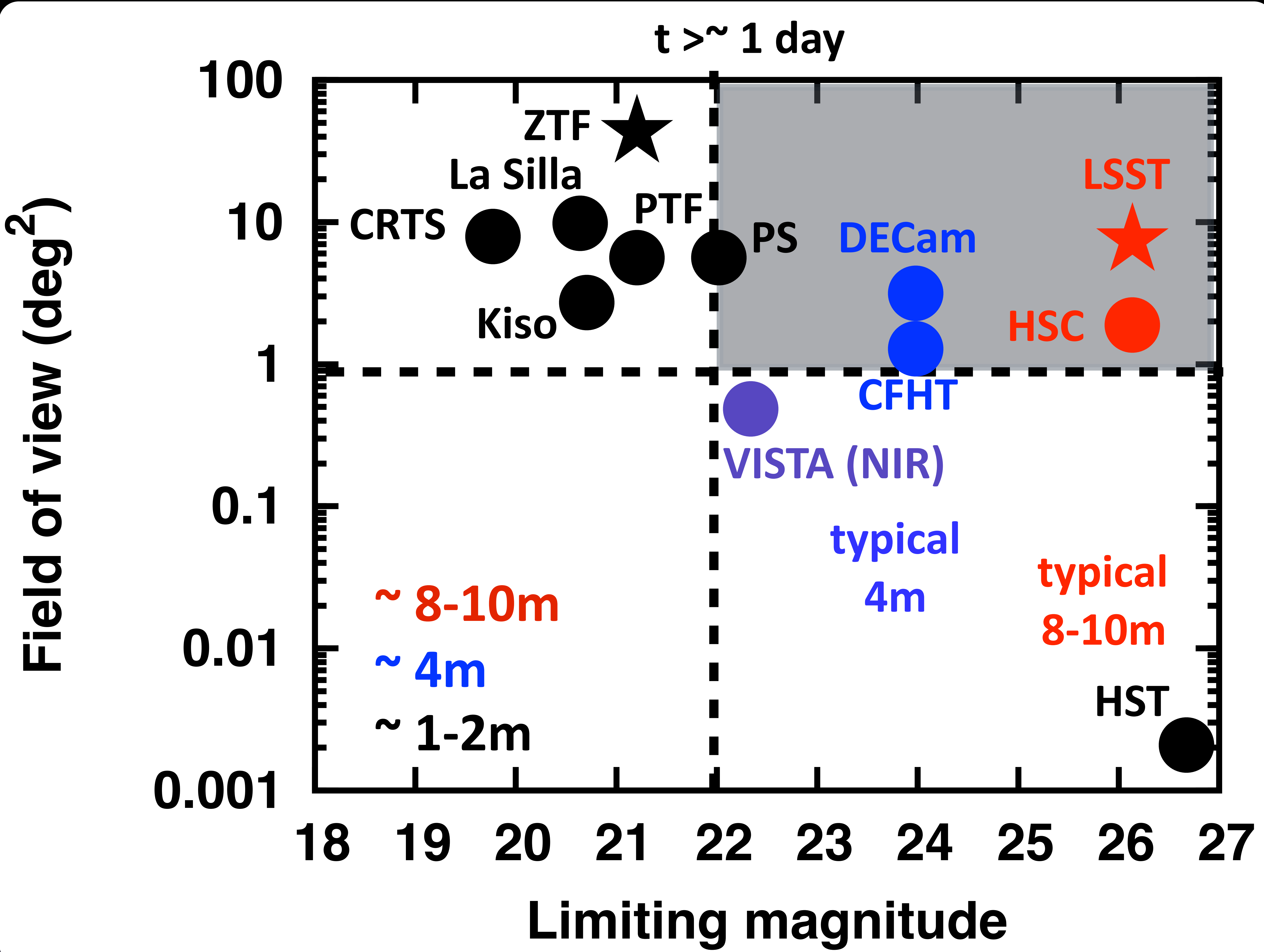
@ 200 Mpc

21 mag

24 mag



Fong+16

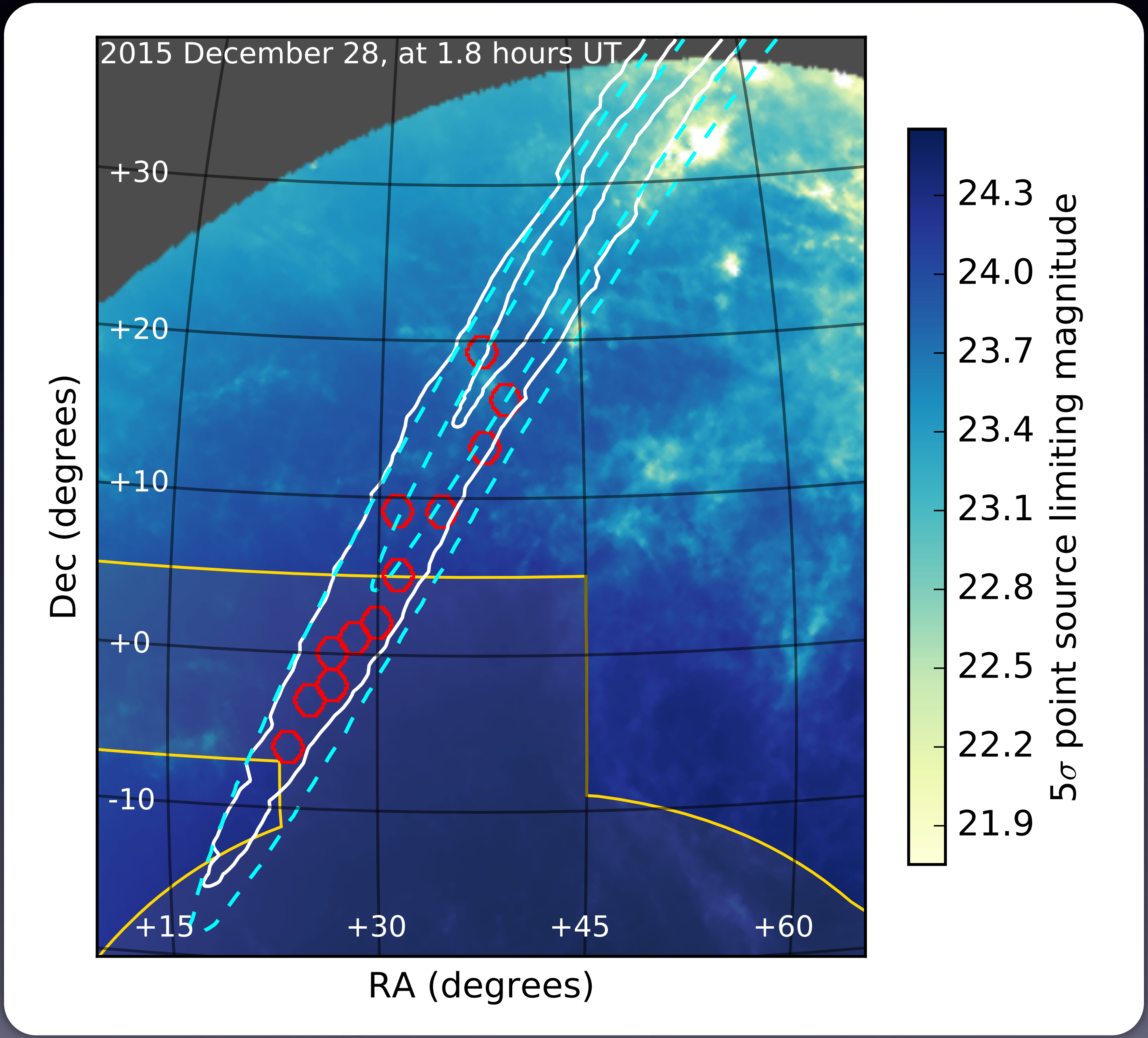


t >~ 1 day
100
10
1
0.1
0.01
0.001
Field of view (deg2)
18
19
20
21
22
23
24
25
26
27
Limiting magnitude
ZTF
La Silla
CRTS
PTF
PS
Kiso
DECam
LSST
HSC
CFHT
VISTA (NIR)
typical
4m
typical
8-10m
HST
~ 8-10m
~ 4m
~ 1-2m

DECam observations of GW151226

Cowperthwaite+16

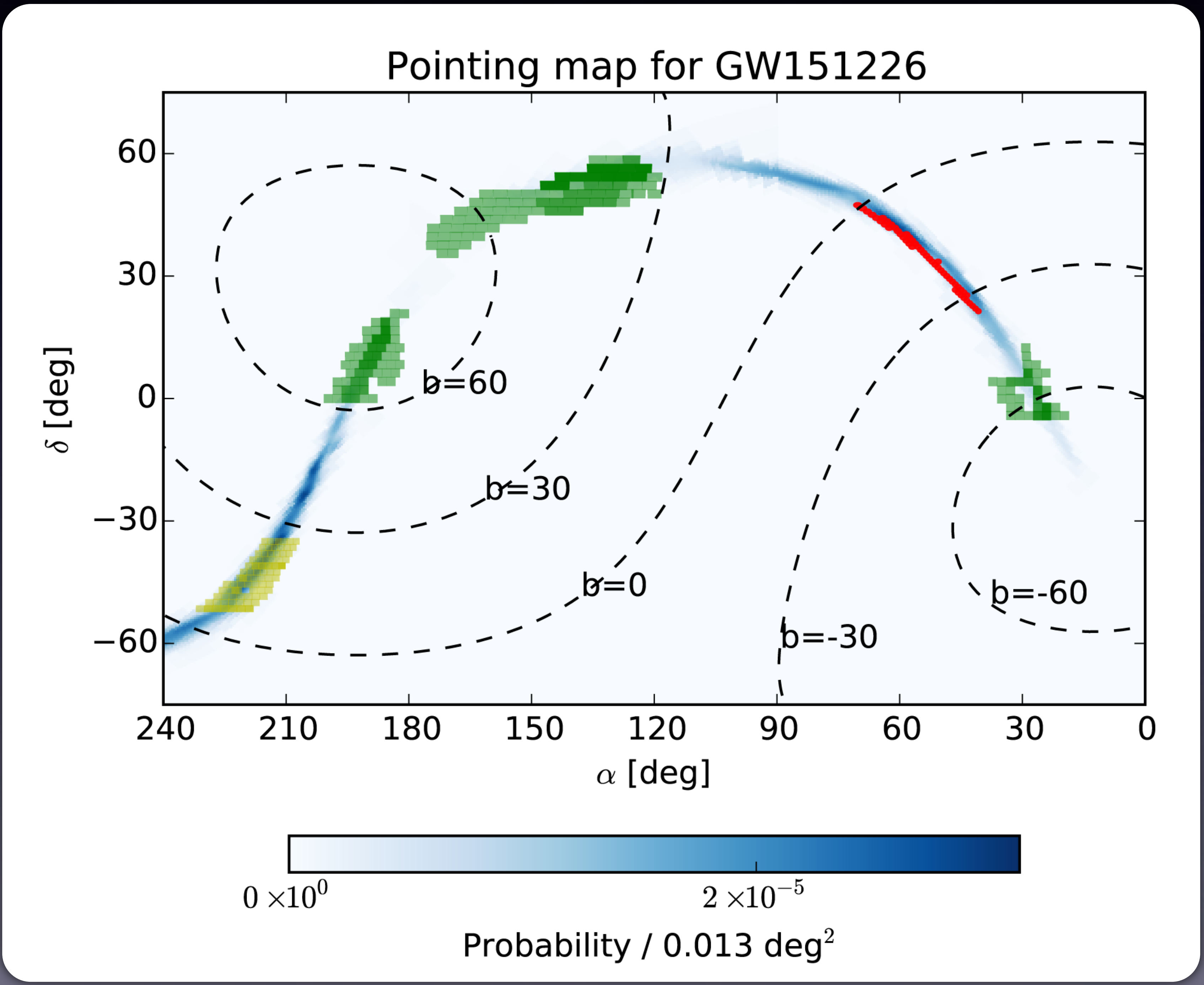
=> see Philip's talk



J–GEM observations of GW151226

Yoshida, Utsumi, Tominaga, Morokuma, MT et al. 2017
Utsumi, Tominaga, MT in prep.

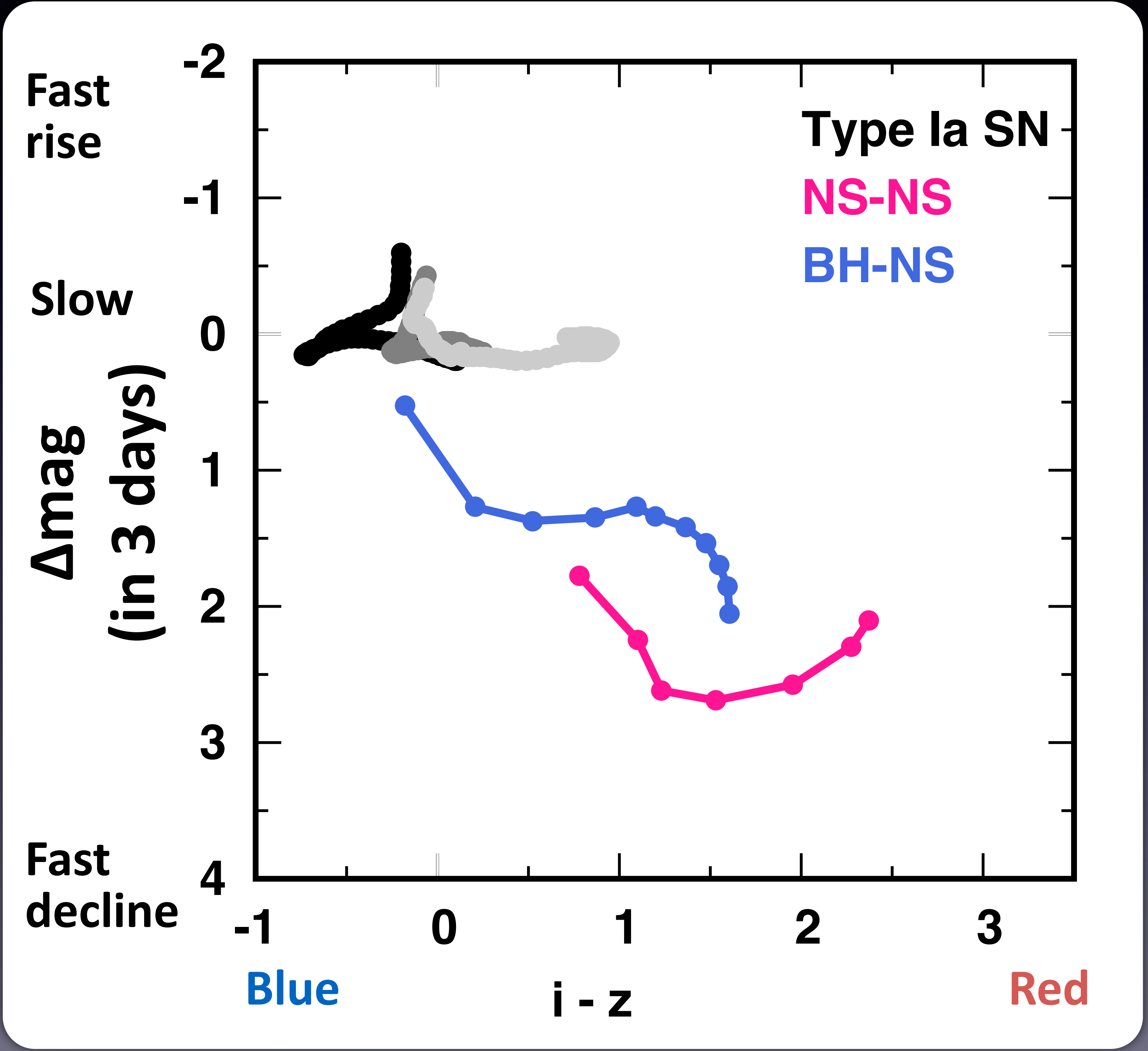
=> see Nozomu's talk (next week)



987 deg^2

- Subaru/HSC: 64 deg^2
- Kiso: 778 deg^2
- MOA: 145 deg^2

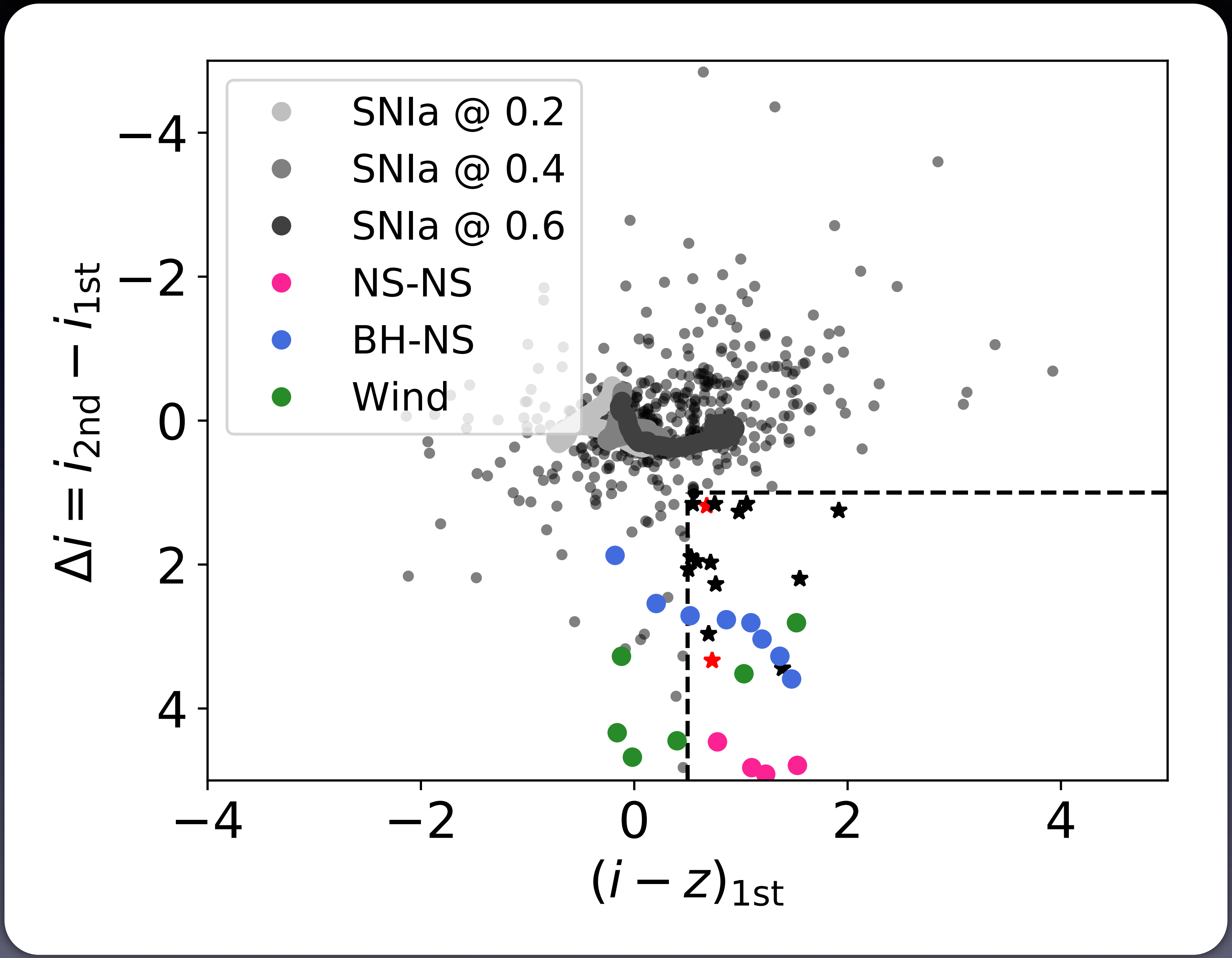
Heavy contamination of supernovae, AGNs, and variable stars
=> How to select NS mergers?



- Association with nearby galaxies
- Faintness
- Rapid evolution
- Red color

MT+14, MT 16

Candidate selection for Subaru/HSC survey (~ 23-24 mag)



- Association with nearby galaxies
- Faintness
- Rapid evolution
- Red color

0 remaining candidate

Utsumi, Tominaga, MT+ in prep.

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Supernova vs NS merger

	Supernova	NS merger
M (r-process)	10^{-2} Msun (?)	10^{-2} Msun
M (total)	~10 Msun	10^{-2} Msun
Heating source	^{56}Ni	r-process
Spectra	H, He, α elements, Iron group	r-process (w/ heavy blend)

We can "measure" r-process mass with kilonova

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

NS merger as a possible origin of r-process elements

Event rate

$R_{NSM} \sim 10^2\text{-}10^3$ Gpc^{-3} yr^{-1}
~ 3-30 GW events yr^{-1}
(w/ Adv. detectors, < 200 Mpc)

GW

LIGO O1
$R_{NSM} < 10^4$ Gpc^{-3} yr^{-1}

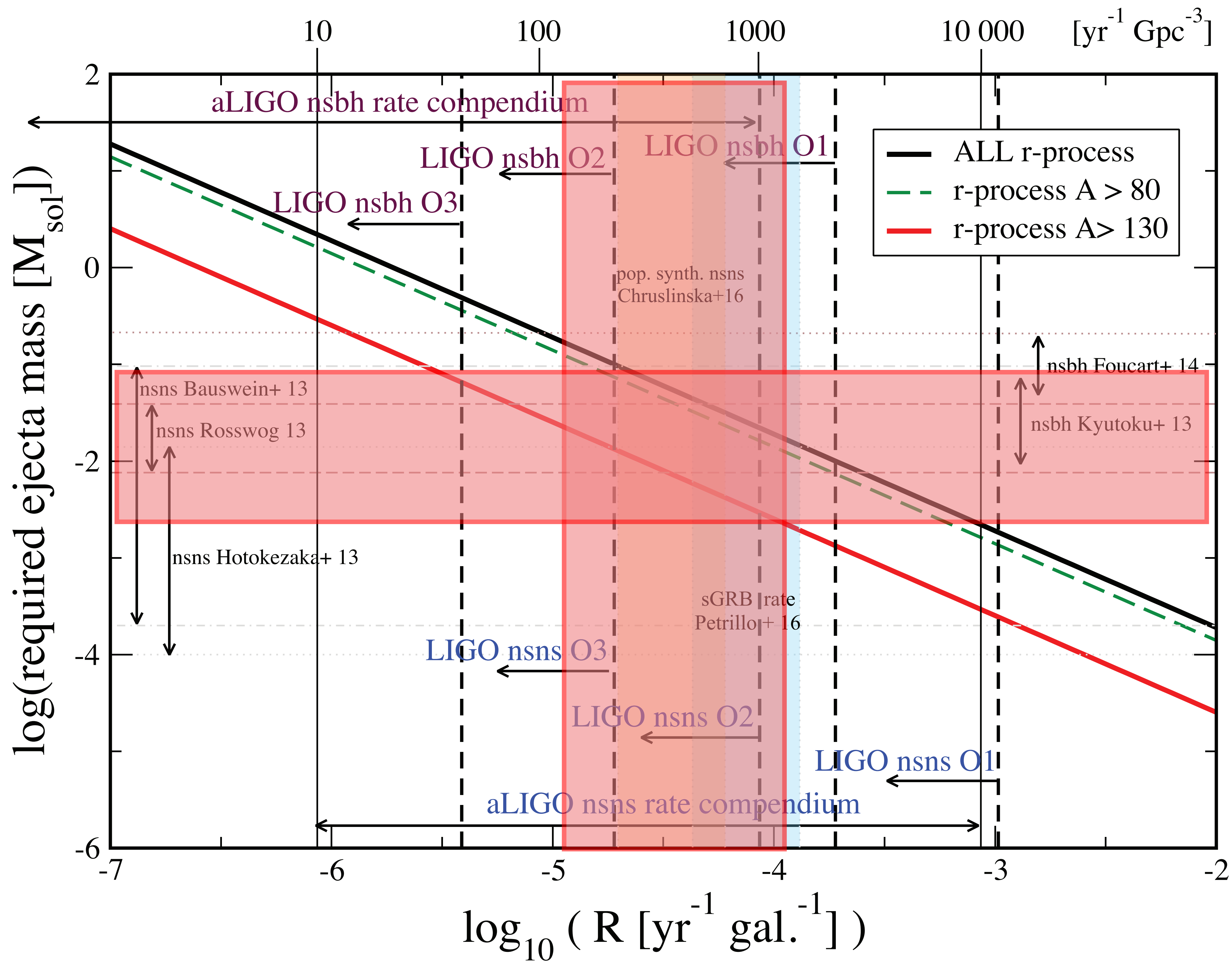
Ejection per event

M_{ej}(r-process) ~ 10^{-2} Msun

EM

Enough to explain the r-process abundance in our Galaxy

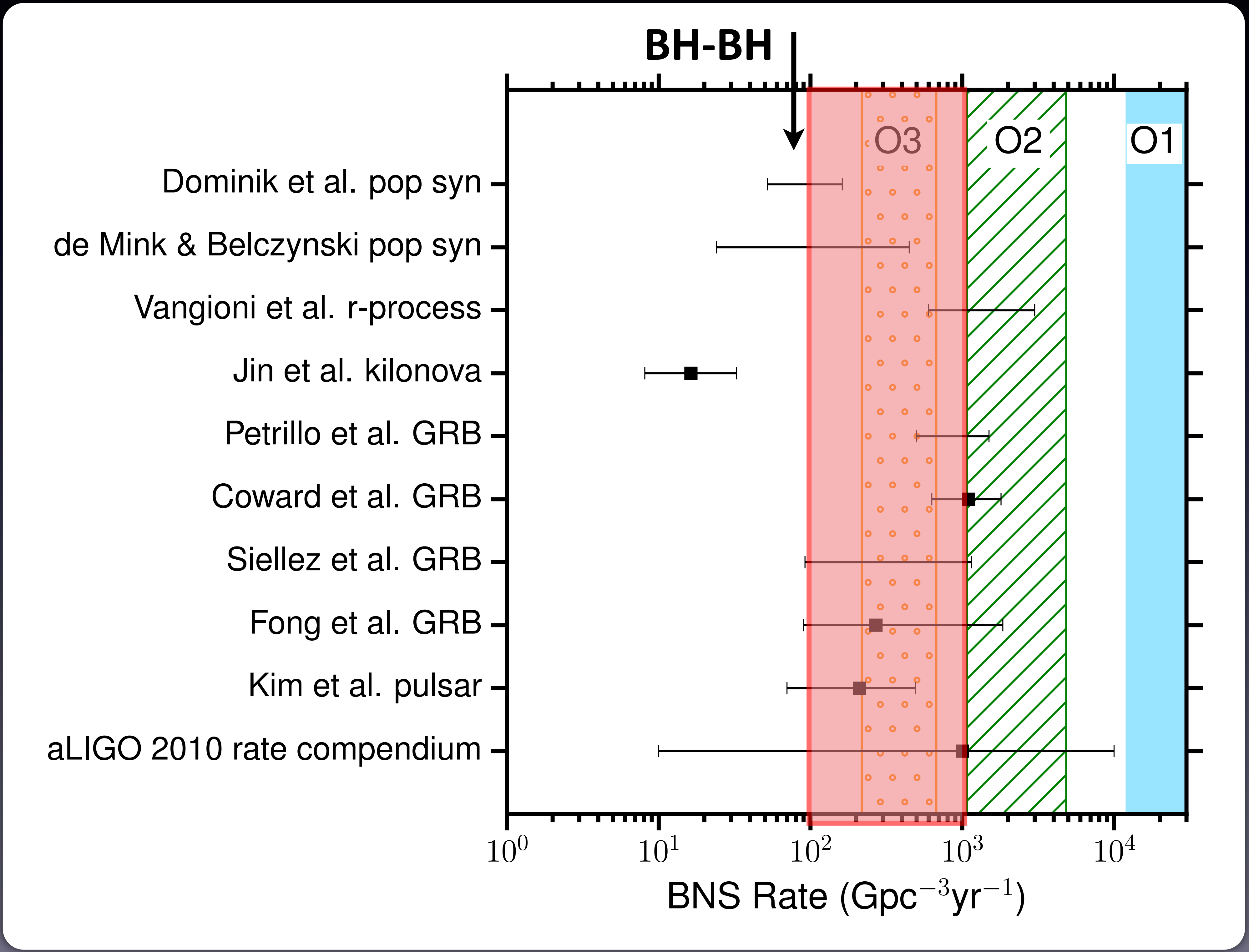
M(Galaxy, r-process) ~ $M_{ej}(r)$ x (R_{NSM} x t_G)
~ 10^{-2} x 10^{-4} x 10^{10} ~ 10^4 Msun



Rosswog+17, see also Hotokezaka+15

Constraints on the NS-NS merger rate

Expected event rates



O1: 2015-2016

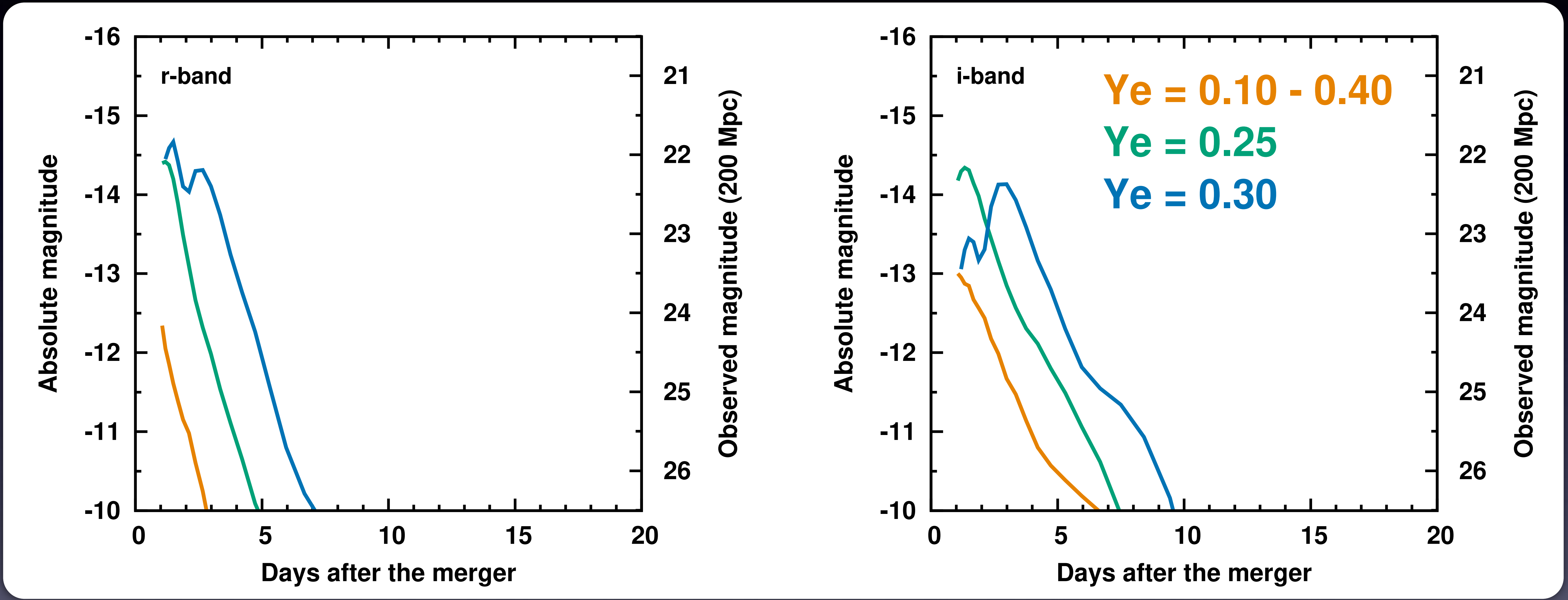
O2: 2016-2017

O3: 2018

arXiv:1607.07456

How good we can estimate ejected mass?

Mej = 0.01 Msun



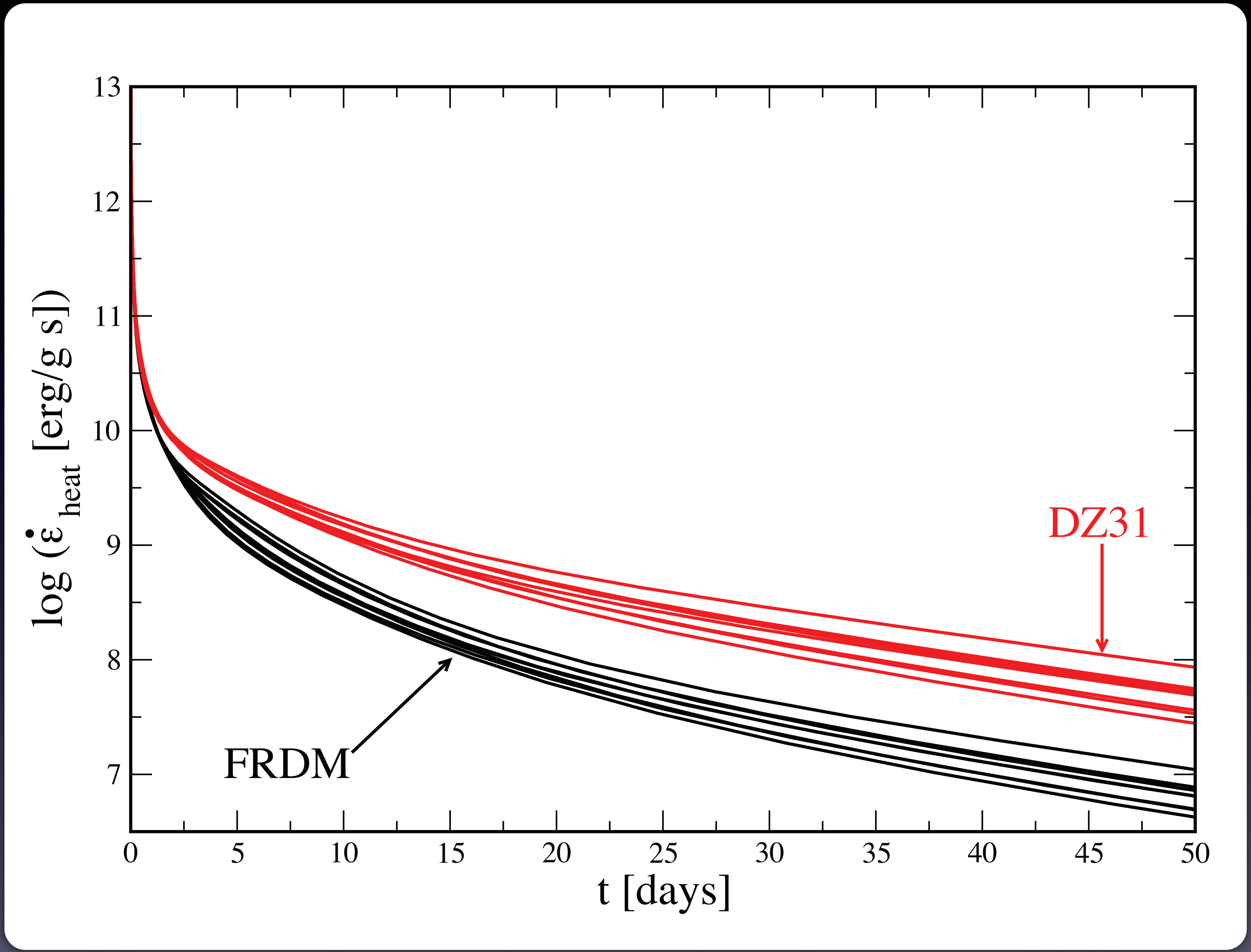
MT+ in prep.

We need (1) multi-color observations, and

(2) good theoretical models for spectra

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

Nuclear mass model => heating rate



FRDM:
Finite range droplet model

DZ31:
31-parameter mass model
(Duflo and Zuker 95)

Rosswog+17

We need (1) multi-color observations, and
(2) good theoretical models for spectra

- mergers and nucleosynthesis (long-term simulations)
- heating rate (nuclear physics)
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Summary

- **Kilonova**
  - **Dynamical ejecta** (Lanthanide-rich)
    => L ~ $10^{40\text{-}41}$ erg s^{-1} for a week, red spectrum
  - **Post-dynamical ejecta** (IF Lanthanide-free)
    => L ~ 10^{41} erg s^{-1} for a few days, blue spectrum
- **For EM follow-up observations**
  - **At >~ 1 day**: Likely to be fainter than 22 mag @ 200 Mpc
    => >4m-class telescopes
  - **At ~< 1 day**: Can be brighter than 21 mag @ 200 Mpc
    => 1-2m-class telescopes
- **Measurements of r-process mass**
  - Need multi-color observations
  - Need good theoretical models to predict spectra/color