Kilonova

Observations and Modeling of GW170817/AT2017gfo

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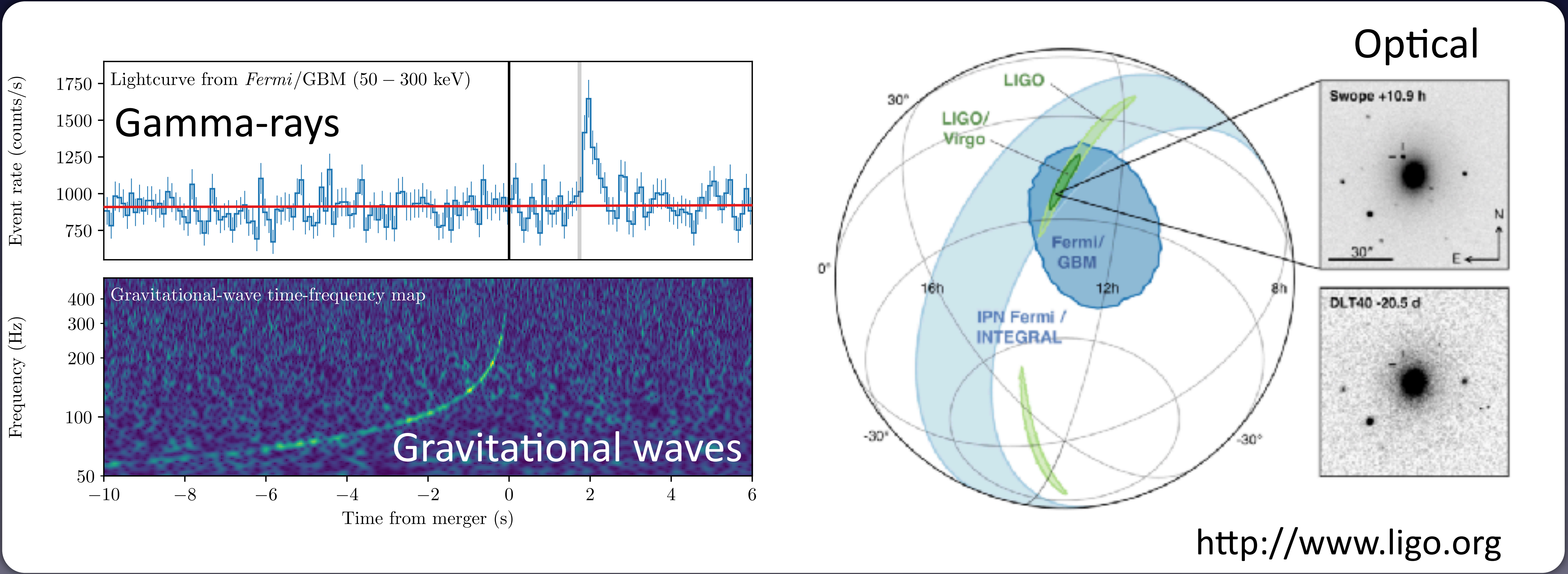
GW170817

* The first detection of gravitational waves (GWs) from neutron star merger

* The first detection of electromagnetic (EM) signals from GW sources



Dawn of "multi-messenger" astronomy

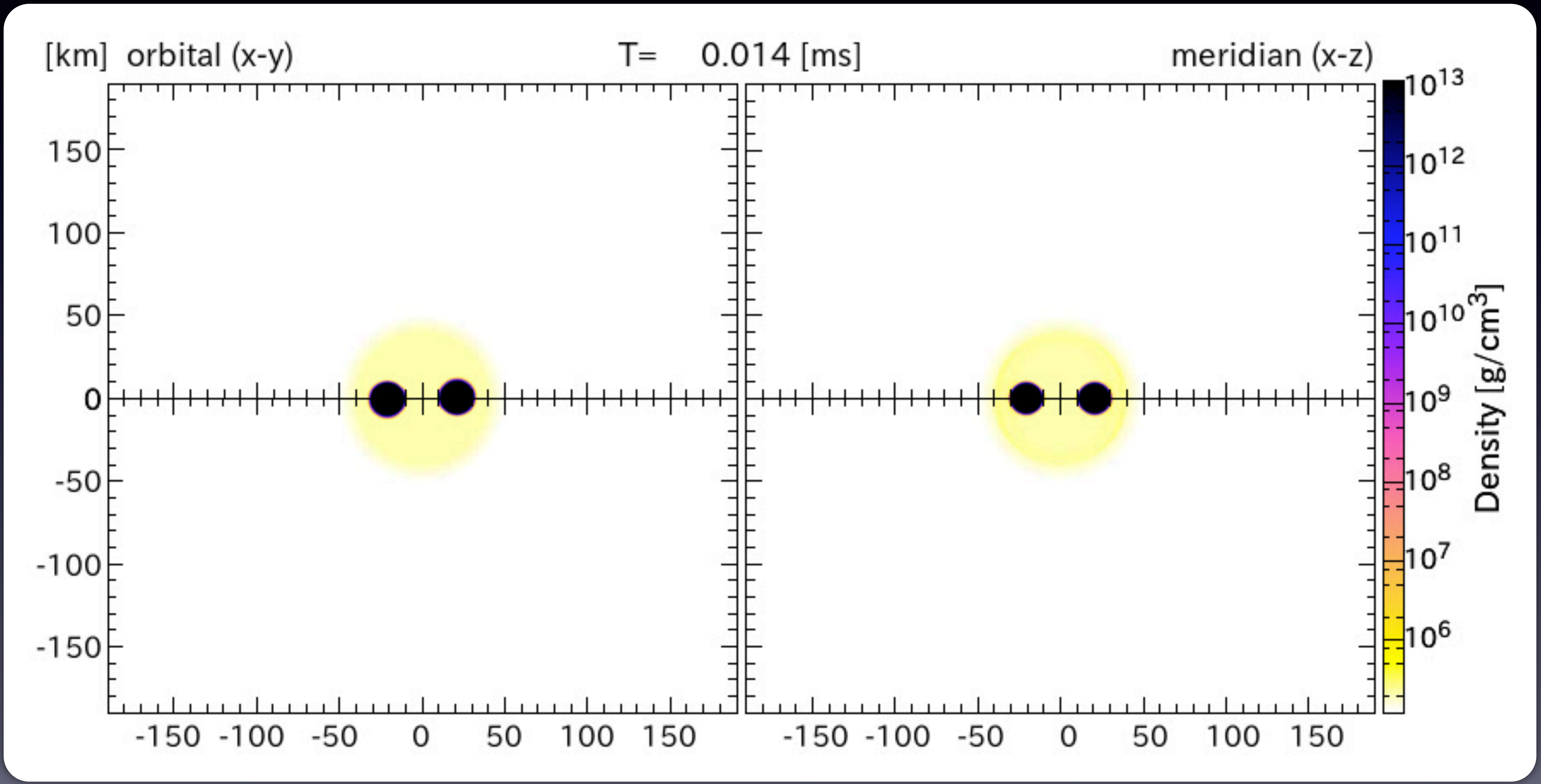
Kilonova

Observations and Modeling of GW170817/AT2017gfo

- Neutron star mergers and kilonova
- GW170817/AT2017gfo
- Open issues

Mass ejection from NS merger

Top view **Side view**



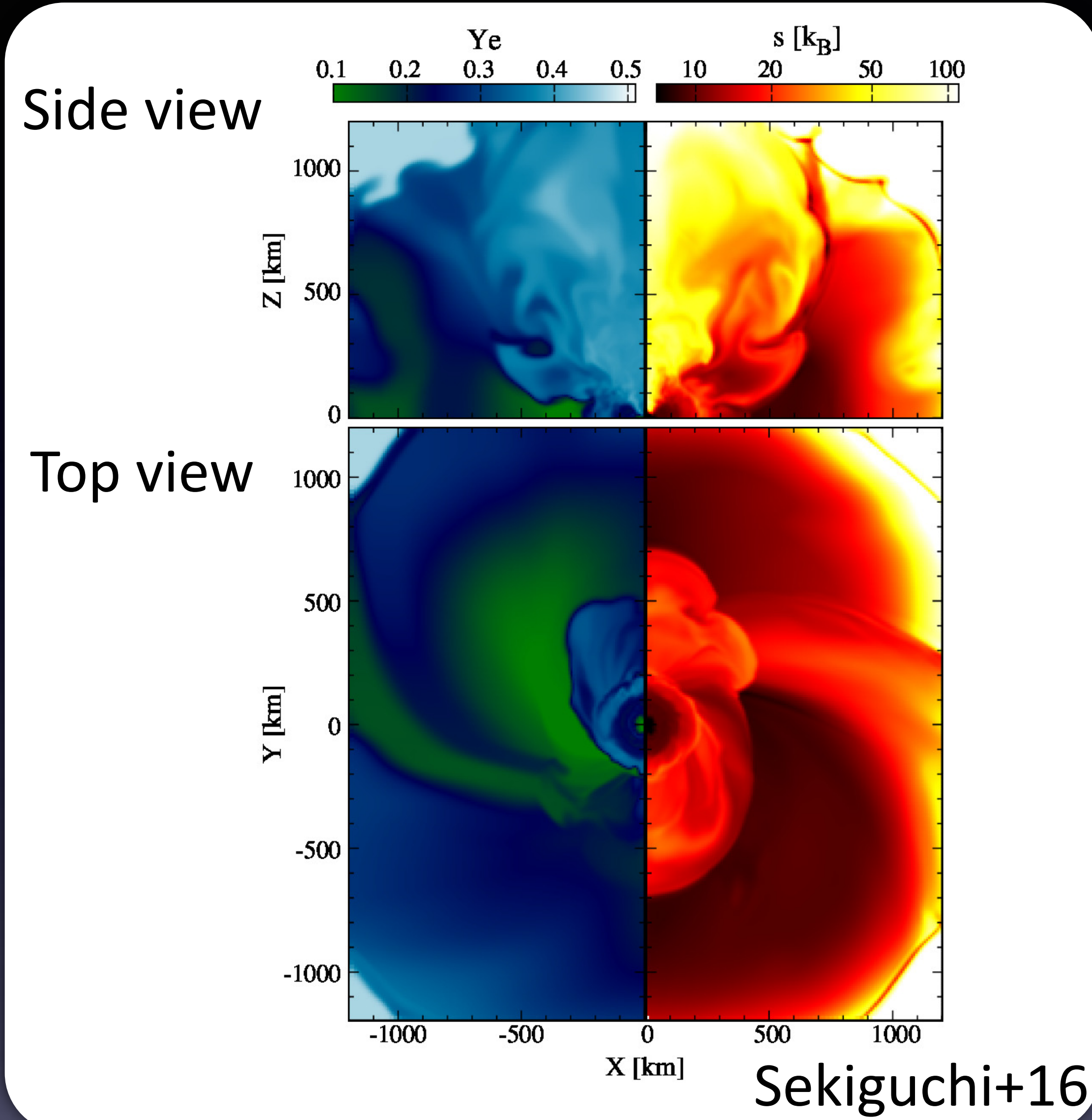
Sekiguchi+15, 16

- Tidal disruption
- Shock heating

$M \sim 10^{-3} - 10^{-2}$ Msun

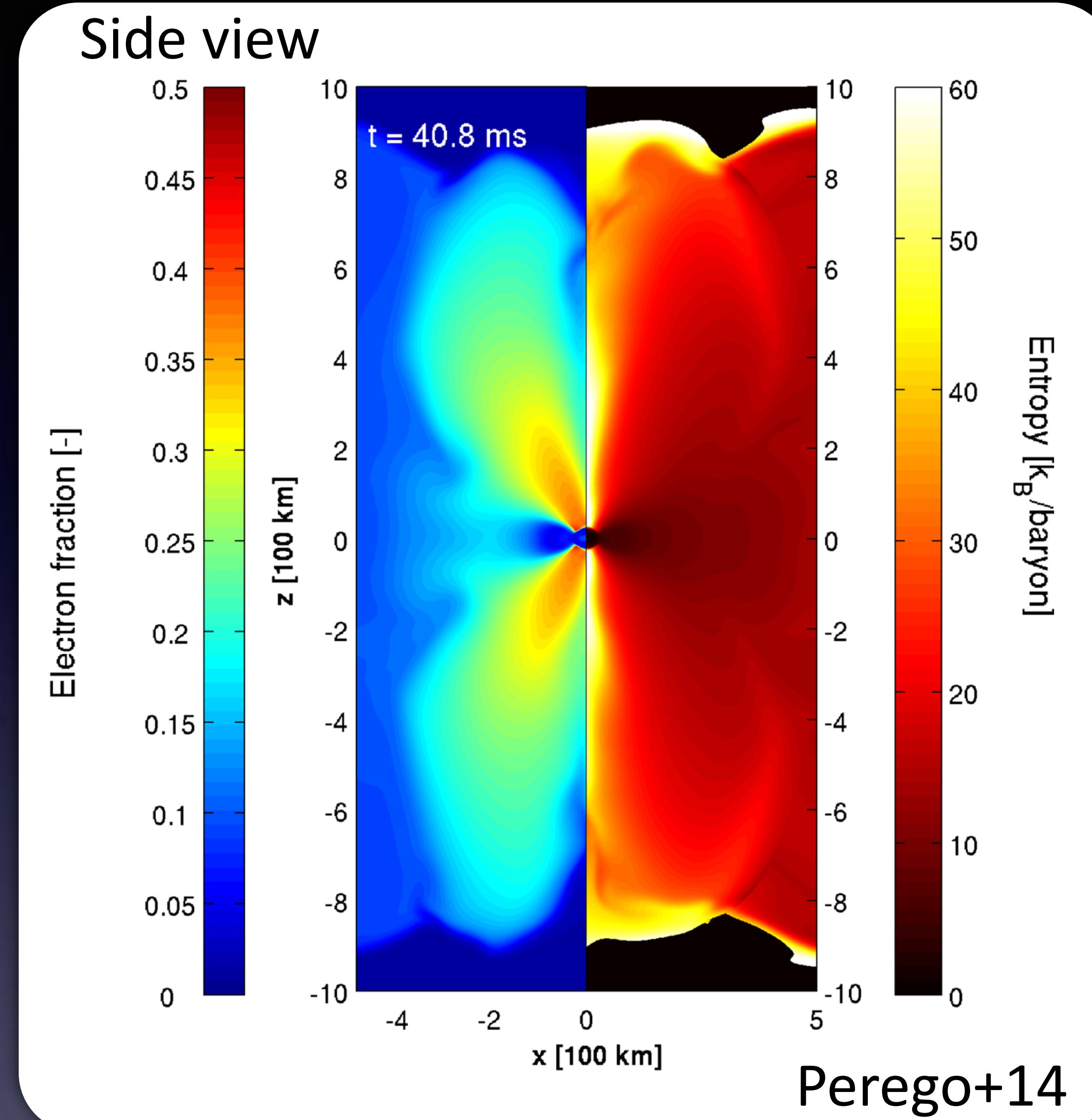
$v \sim 0.1 - 0.2$ c

Dynamical ejecta (~< 10 ms)



- Mej ~ 10^{-3} - 10^{-2} Msun
- v ~ 0.1-0.2 c
- Low Ye (w/ wide distr.)

Post-merger ejecta (~< 100 ms)

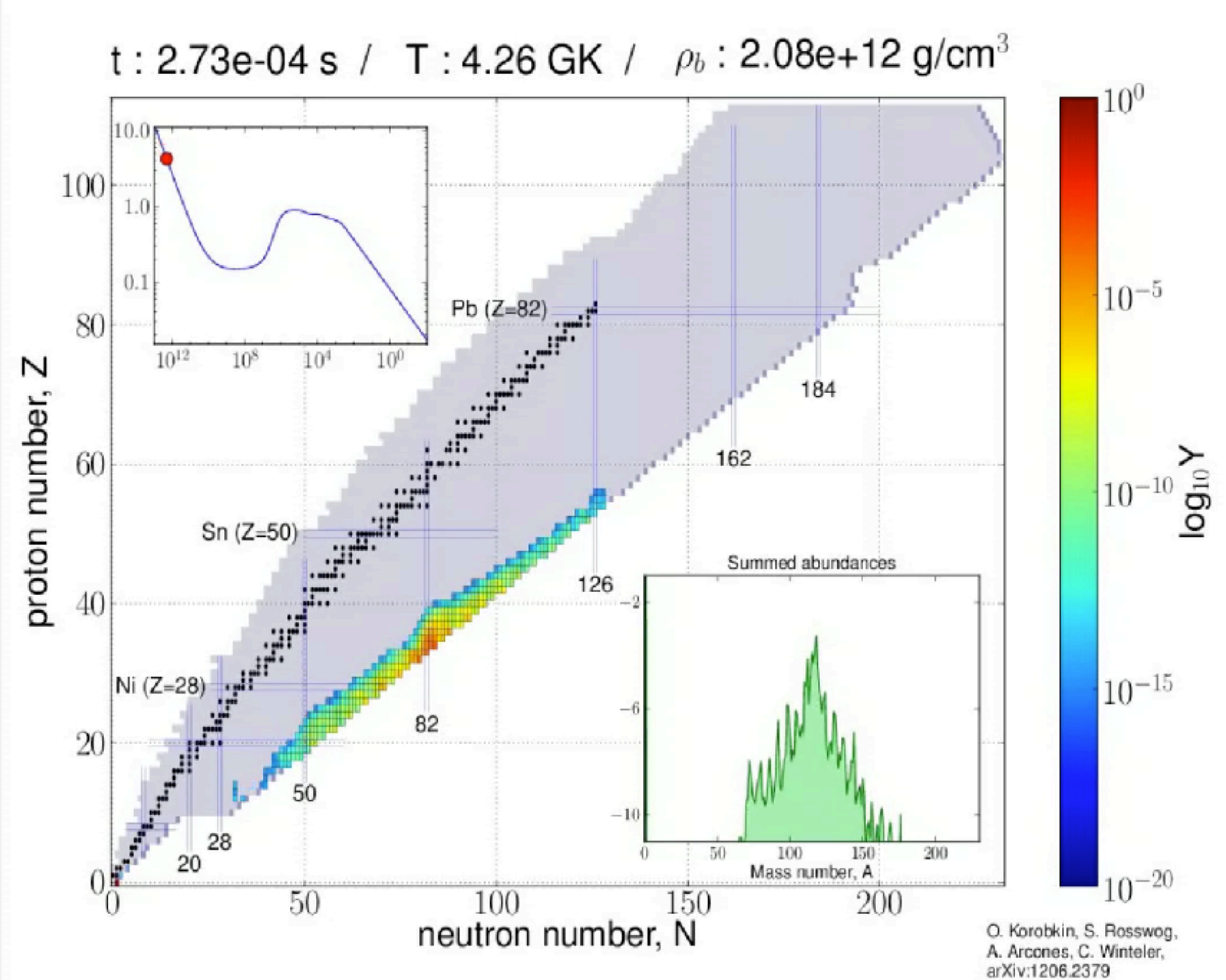


- Mej >~ 10^{-2} Msun
- v ~ 0.05 c
- Relatively high Ye

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

r-process nucleosynthesis in NS merger

Nuclear physics



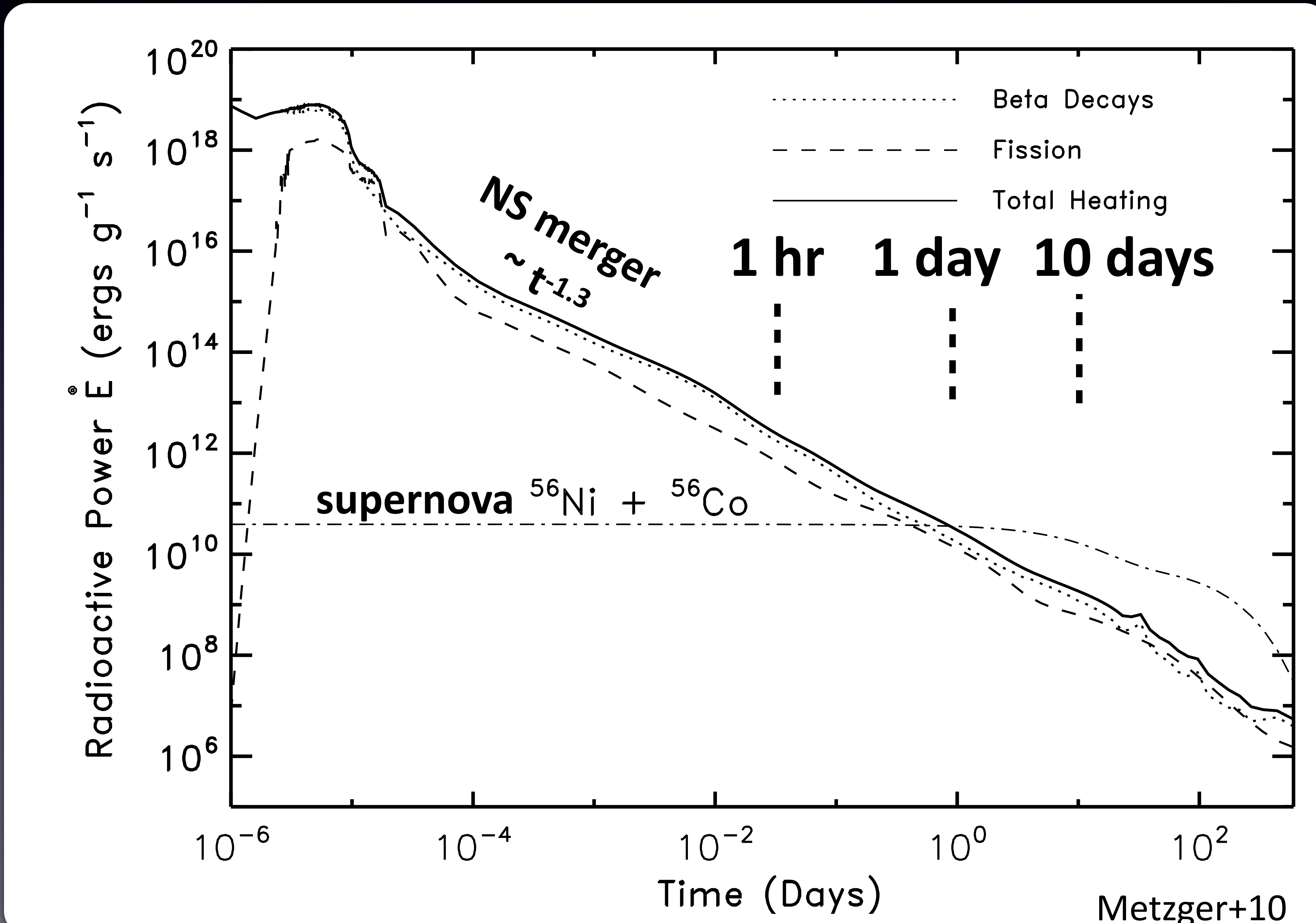
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

Radioactive heating

decay of many r-process nuclei

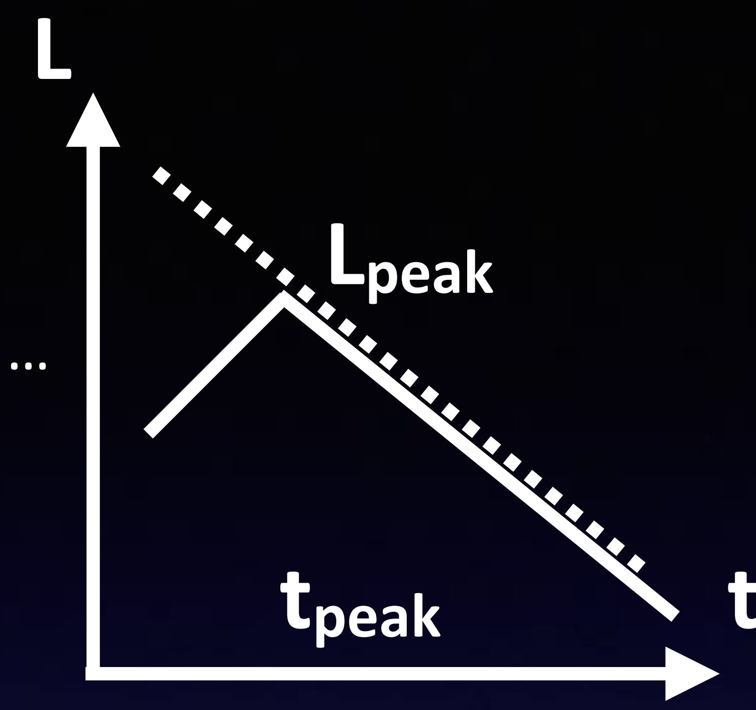
=> β decay (γ, β), α decay, fission

Nuclear physics



“Kilonova/Macronova"

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



Timescale

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

Luminosity

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

*assuming 50% thermalization

Temperature ~ 5000 K => bound-bound transitions of heavy elements

Atomic physics

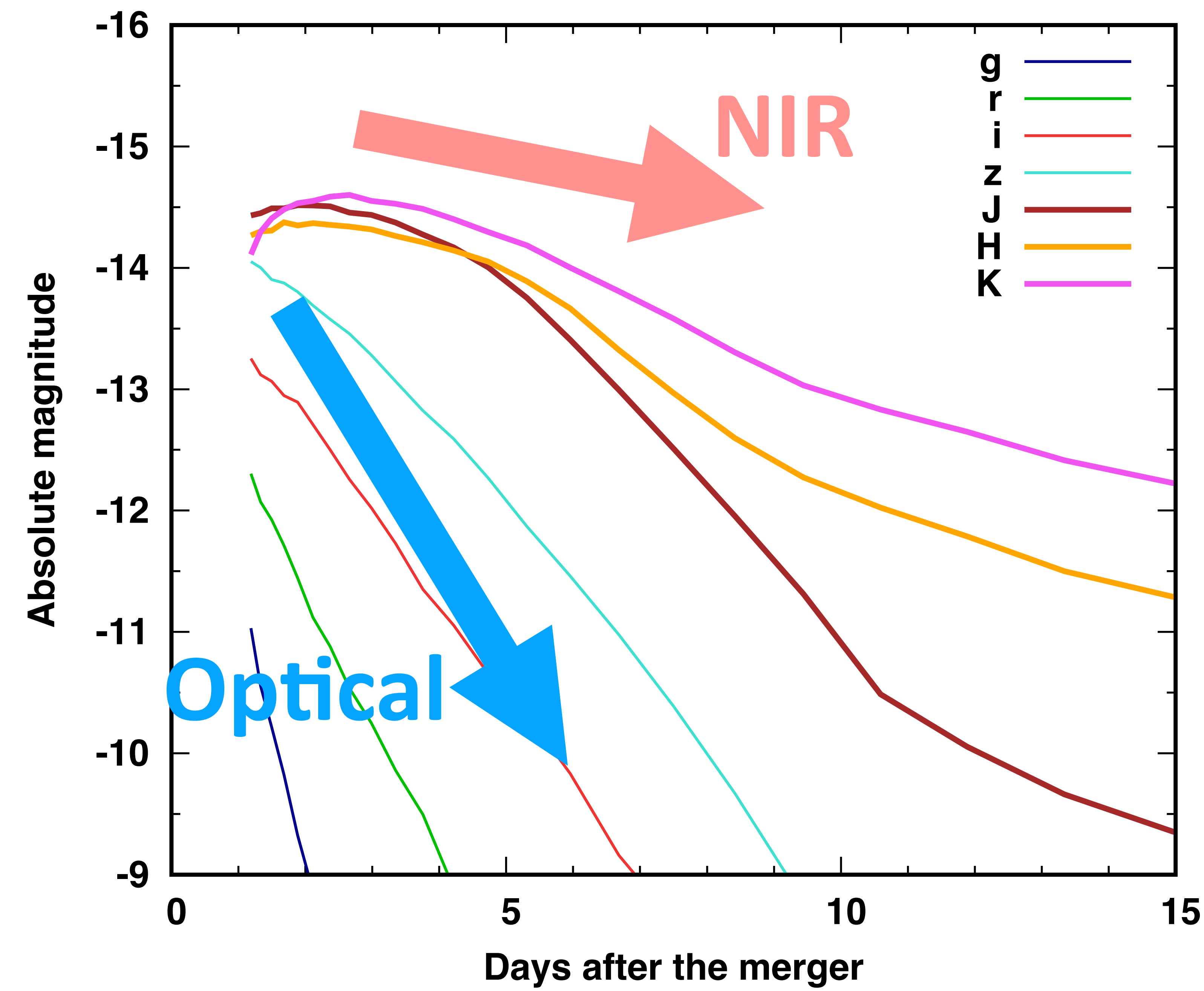
Light curves of kilonova

Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13

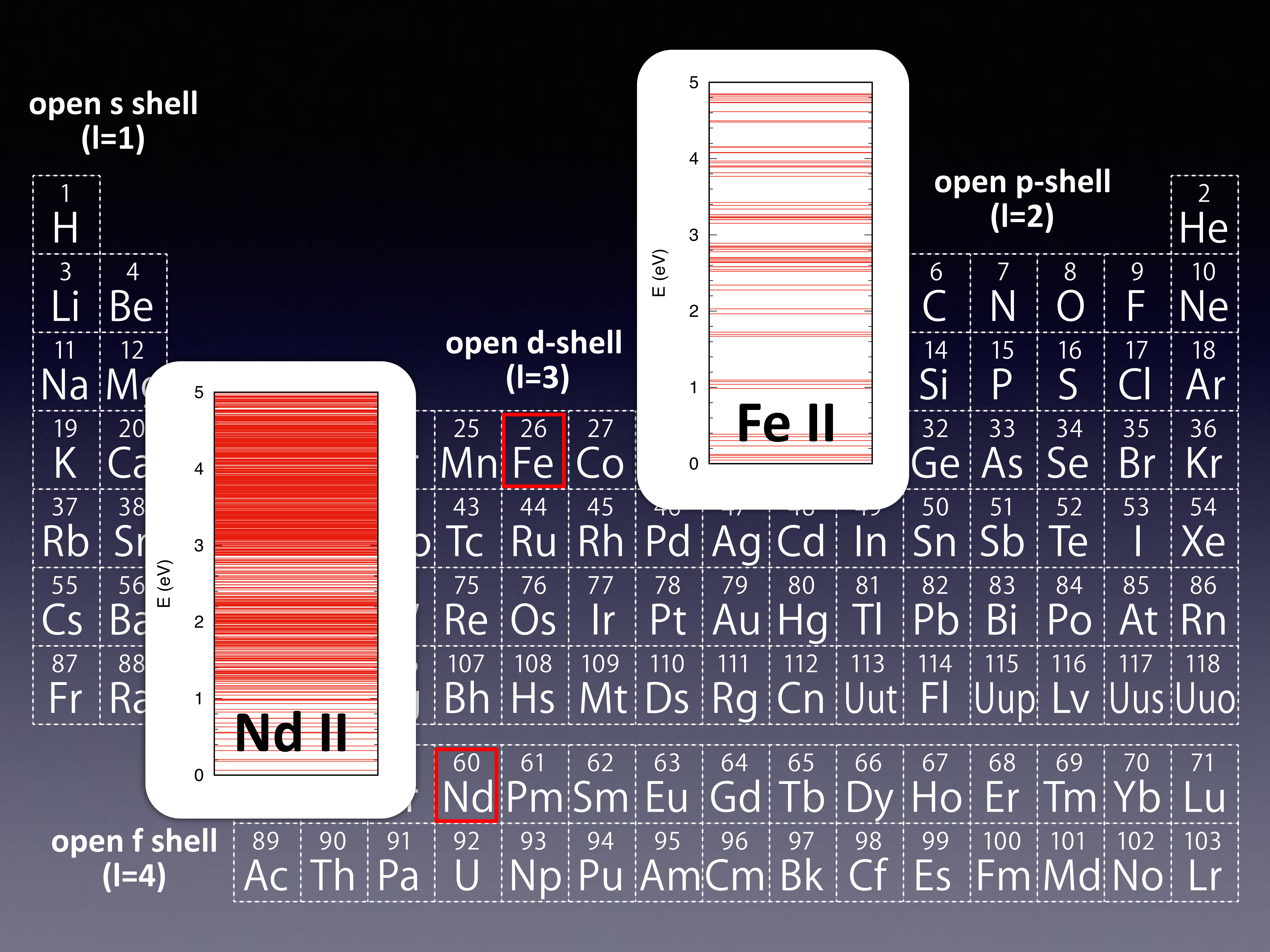
L ~ 10^{40}-10^{41} erg s^{-1}

t ~ weeks

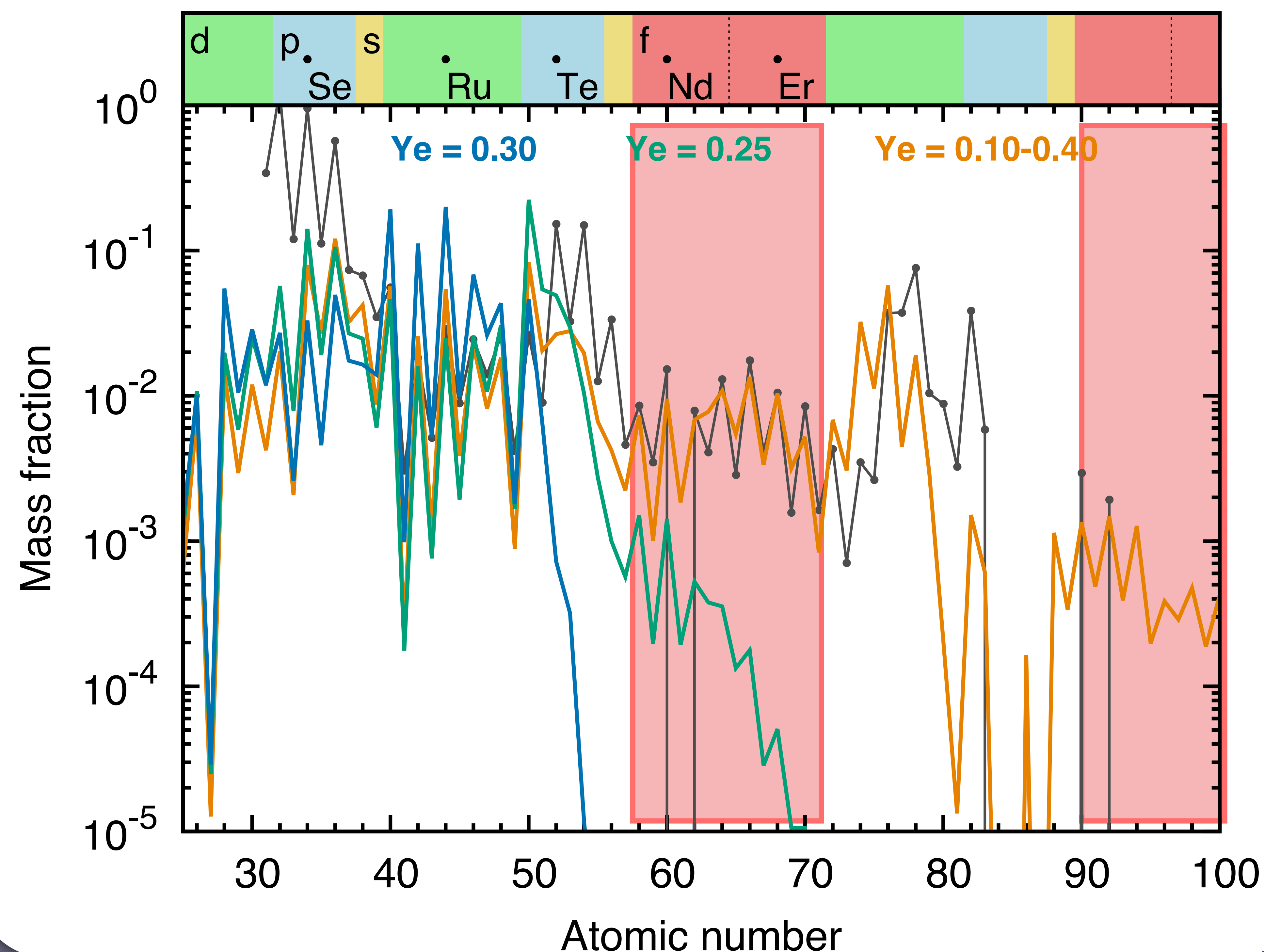
NIR > Optical



Model: MT+17a



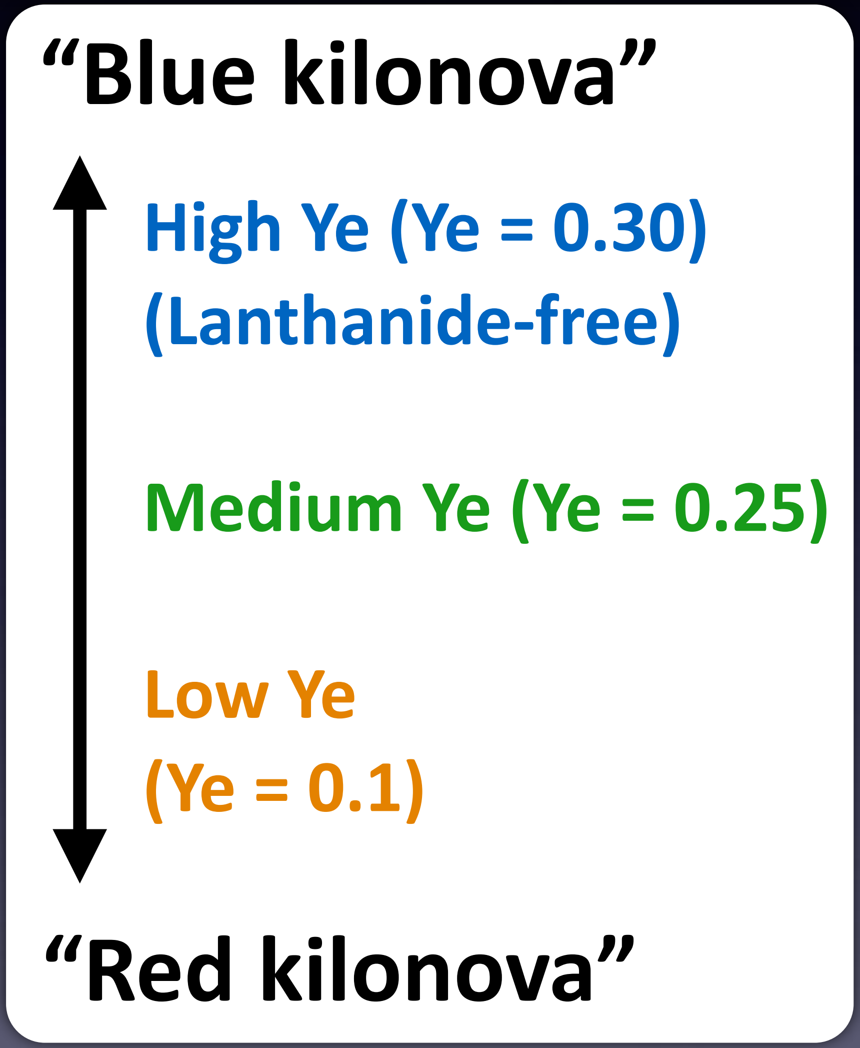
open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
Fe II
E (eV)
Nd II
E (eV)

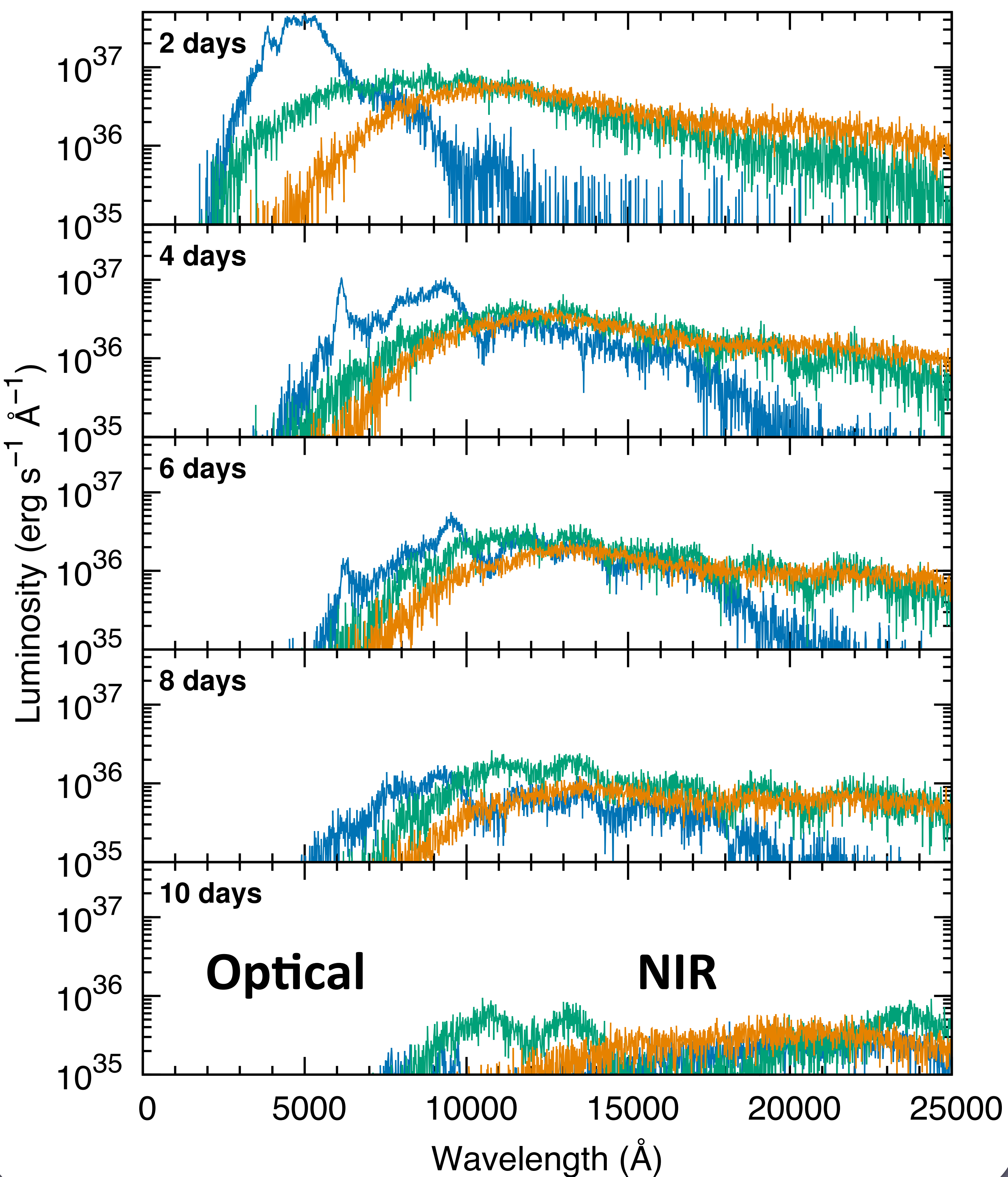


If post-merger ejecta is Lanthanide-free (Ye >~ 0.25)
=> low opacity => "blue kilonova"

Metzger+14, Kasen+15

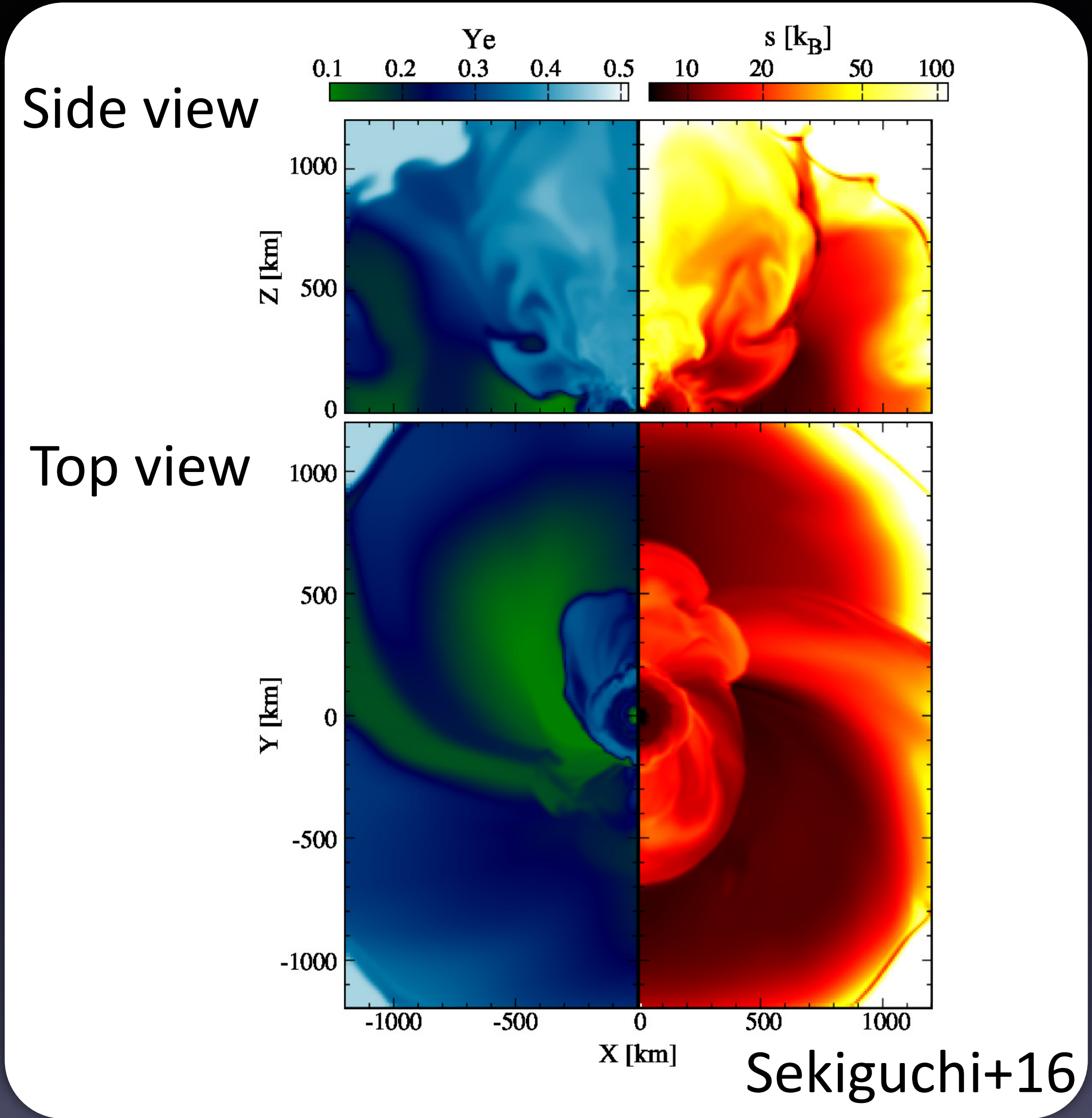
Nucleosynthesis is imprinted in the spectra





MT+18

Dynamical ejecta (~< 10 ms)



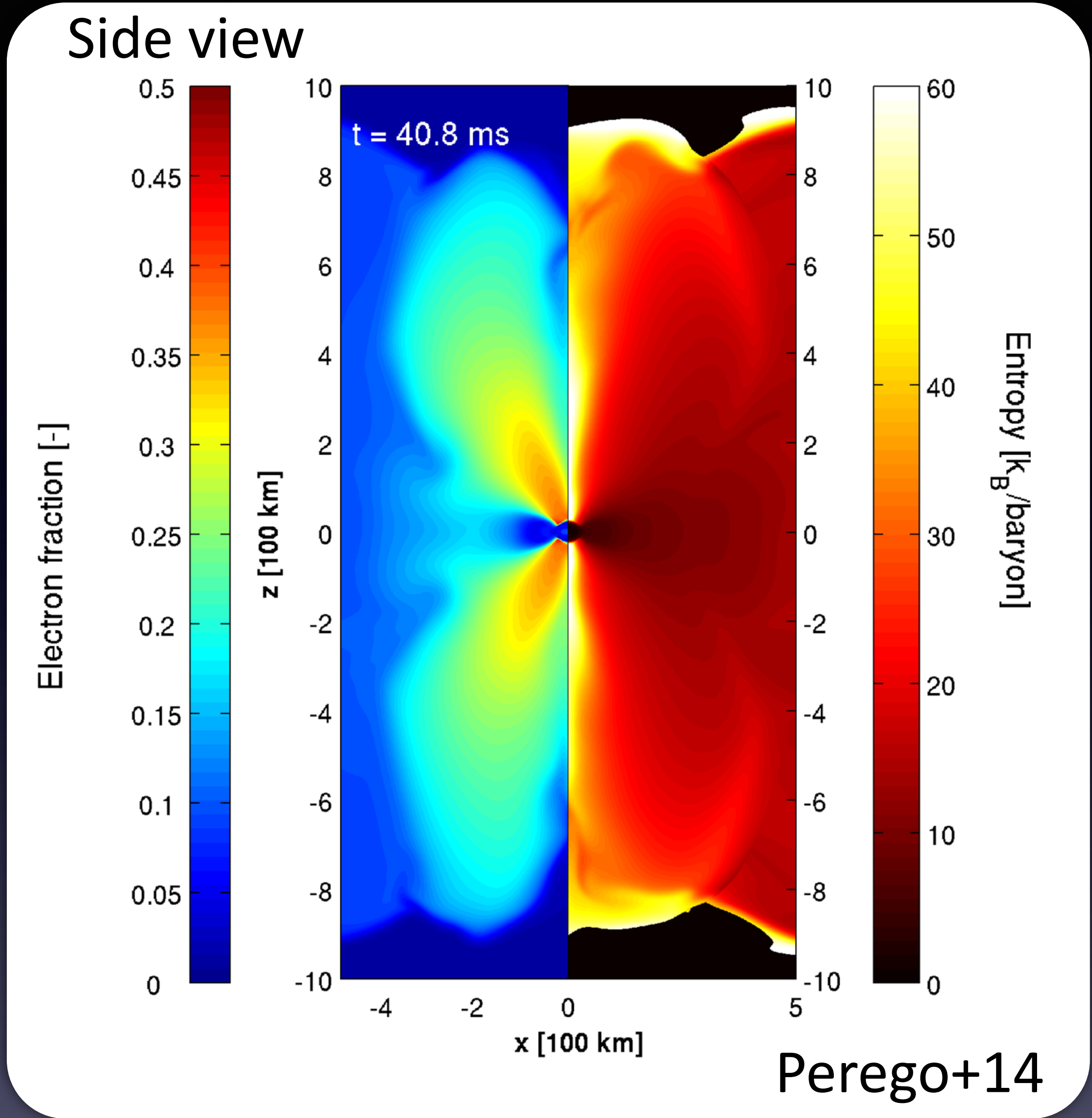
Mej ~ 10^{-3} - 10^{-2} Msun

v ~ 0.1-0.2 c

Low Ye (w/ wide distr.)

=> Red kilonova?

Post-dynamical ejecta (~< 100 ms)



Mej >~ 10^{-3} Msun

v ~ 0.05 c

Relatively high Ye

=> Blue kilonova?

Kilonova

Observations and Modeling of GW170817/AT2017gfo

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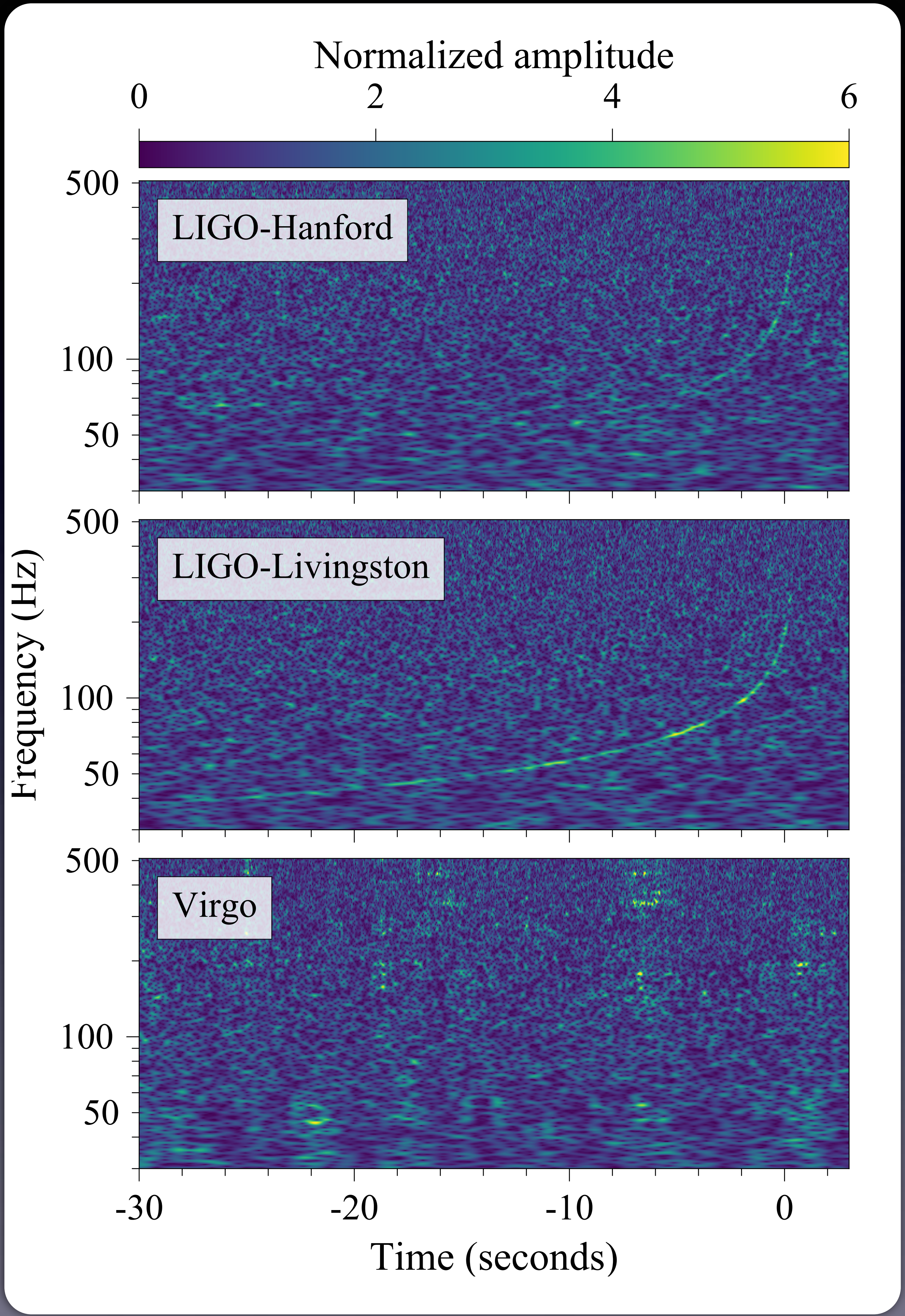
- GW170817/AT2017gfo
- Open issues

2017 Aug 17

GW170817:
The first detection of GWs from a NS merger

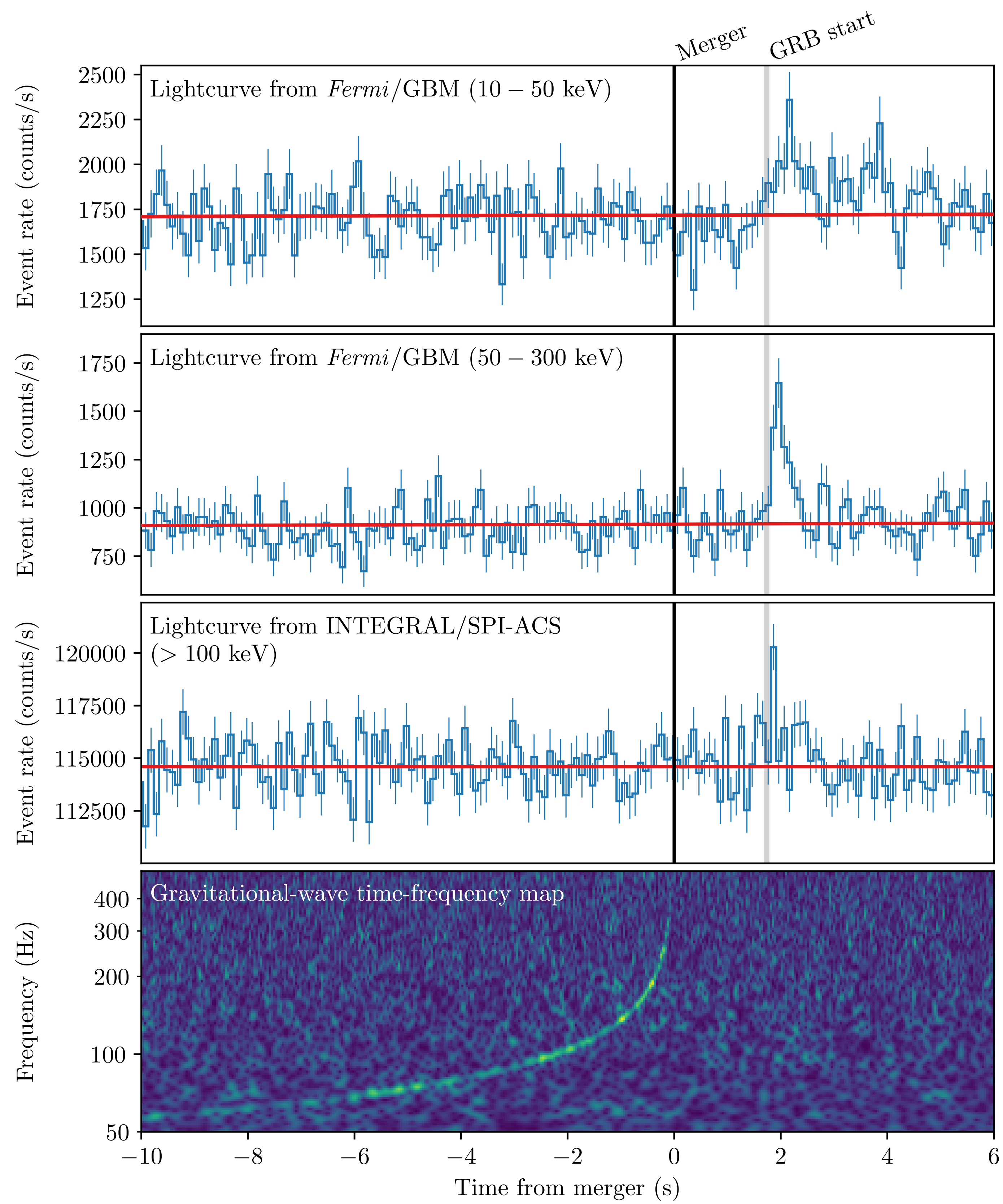


LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

Abbott et al. 2017, ApJ

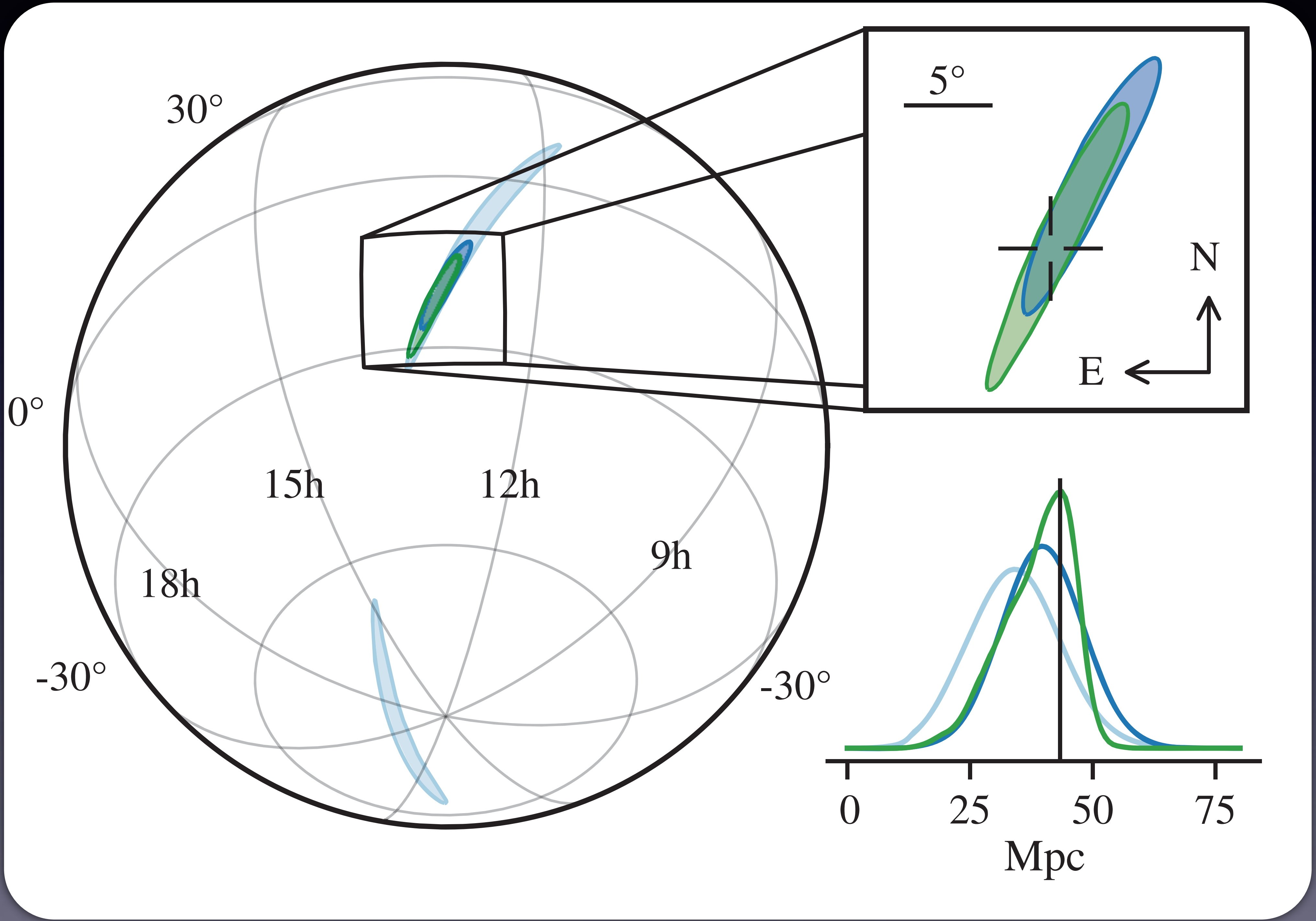
Gamma-rays
@ ~2 sec after the merger

Gamma-ray burst (GRB)
- NS merger connection



But the luminosity is lower than usual by $>10^3$

Skymap from 3 detectors (LIGO x 2 + Virgo)
==> 30 deg^2 (~40 Mpc)



LIGO Scientific Collaboration and Virgo Collaboration, 2017

Coulter+17, Soares-Santos+17, Valenti+17, Arcavi+17, Tanvir+17, Lipunov+17

Movie: Utsumi, MT+17, Tominaga, MT+18

Summary of multi-messenger observations

Abbott+17

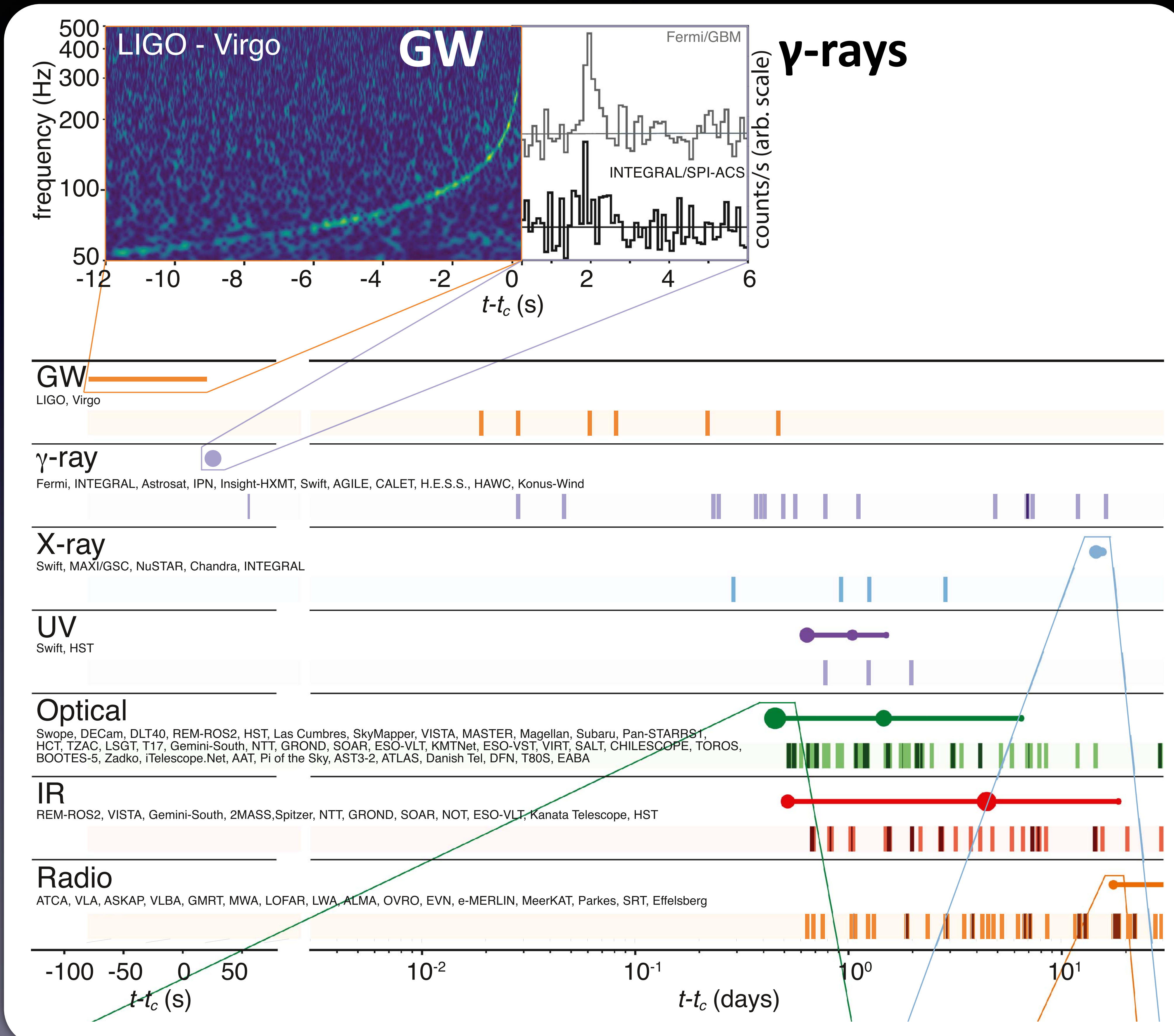
GWs

GRB

X-ray

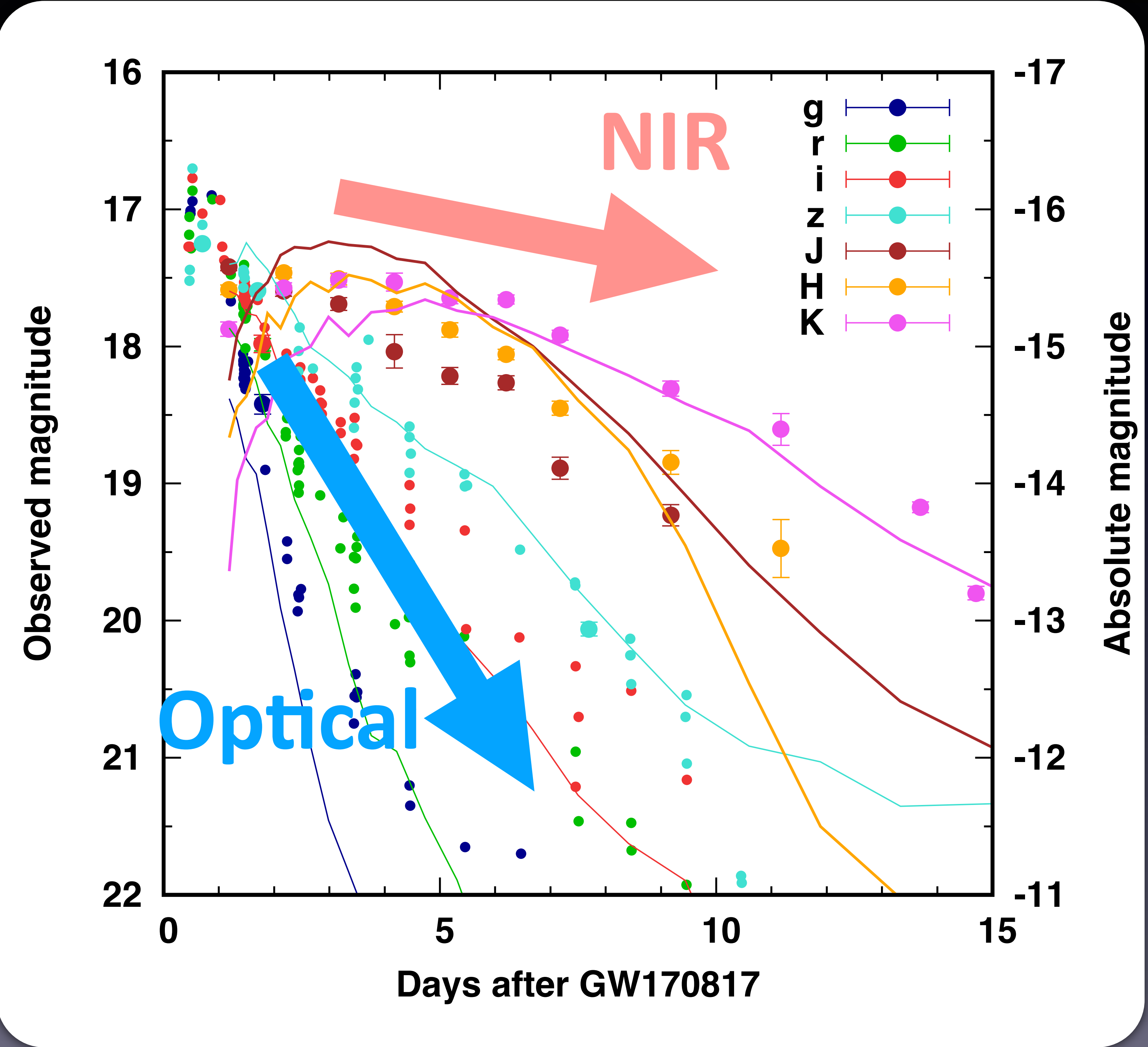
UV/optical/infrared (kilonova)

Radio



GW170817: optical/infrared light curves

- Brightness
- Timescale
- SED

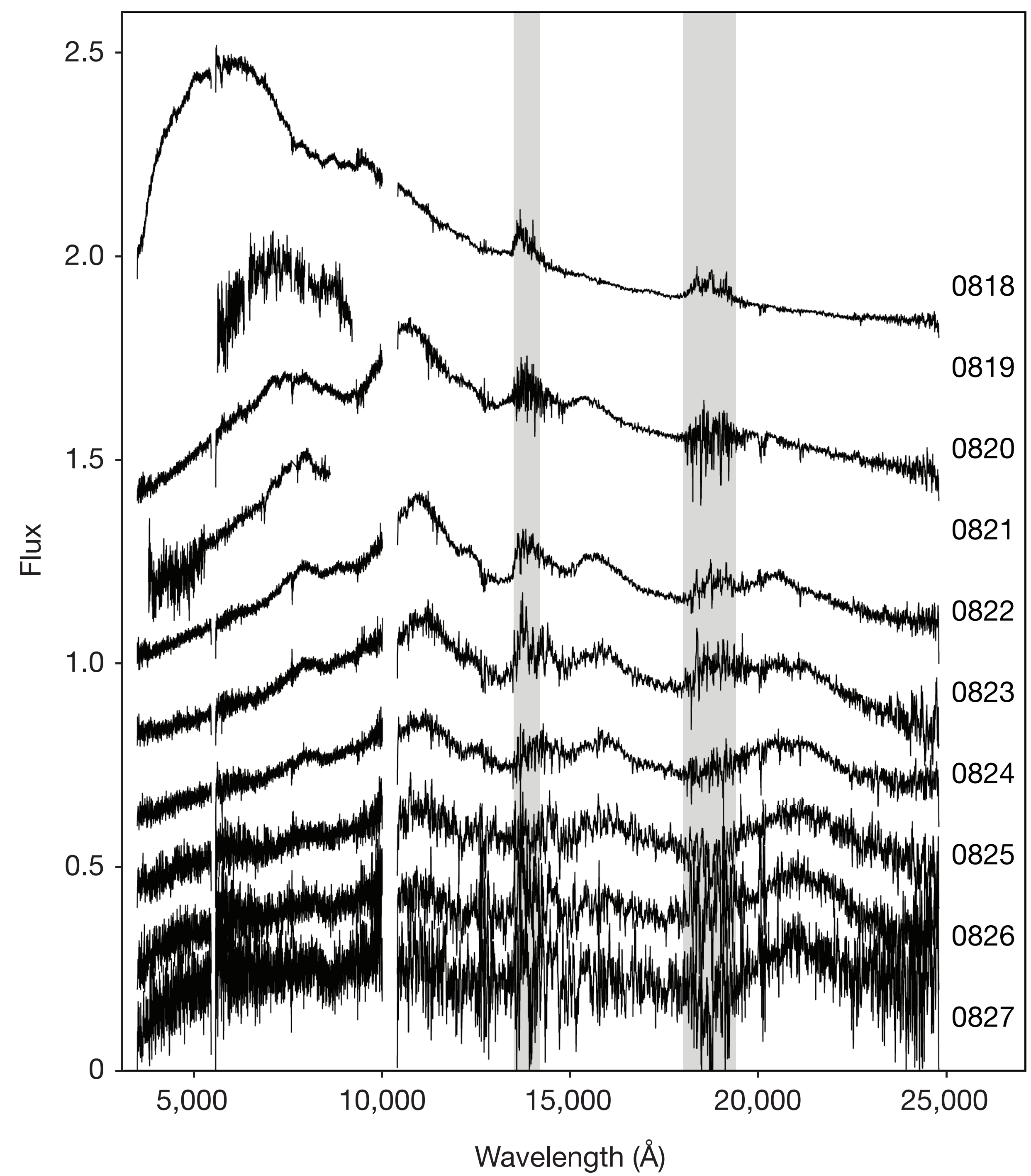


Arcavi+17, Cowperthwaite+17, Diaz+17, Drout+17,Evans+17, Kasliwal+17,Pian+17, Smartt+17, Tanvir+17, Troja+17, Utsumi, MT+17, Valenti+17

Signature of lanthanide production
Ejecta mass ~0.03 Msun (w/ ~1% of lanthanides)

GW170817: Spectra

- Smooth spectra
  (high velocity)
- Not similar to any
  kind of known supernovae

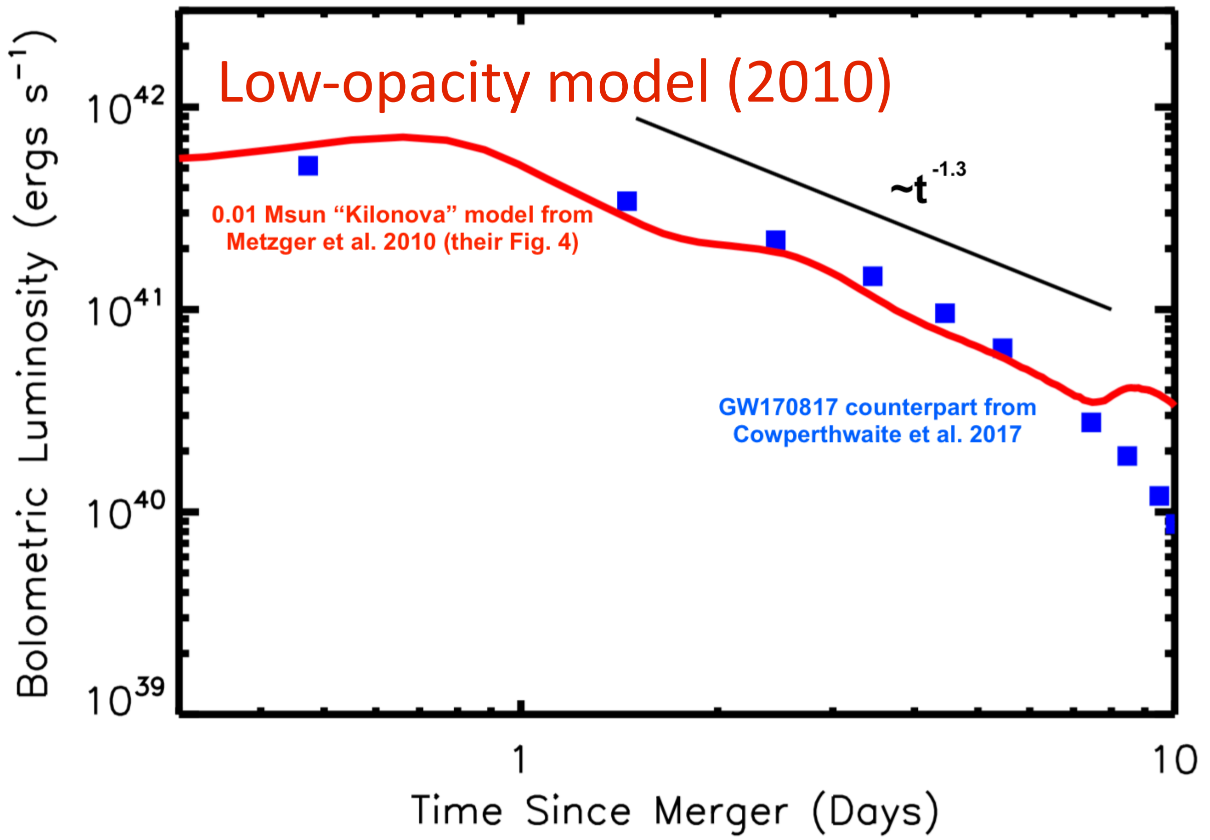


Andreoni+17, Chornock+17, Kilpatrick+17
McCully+17, Nicholl+17, Pian+17,
Shappee+17, Smartt+17

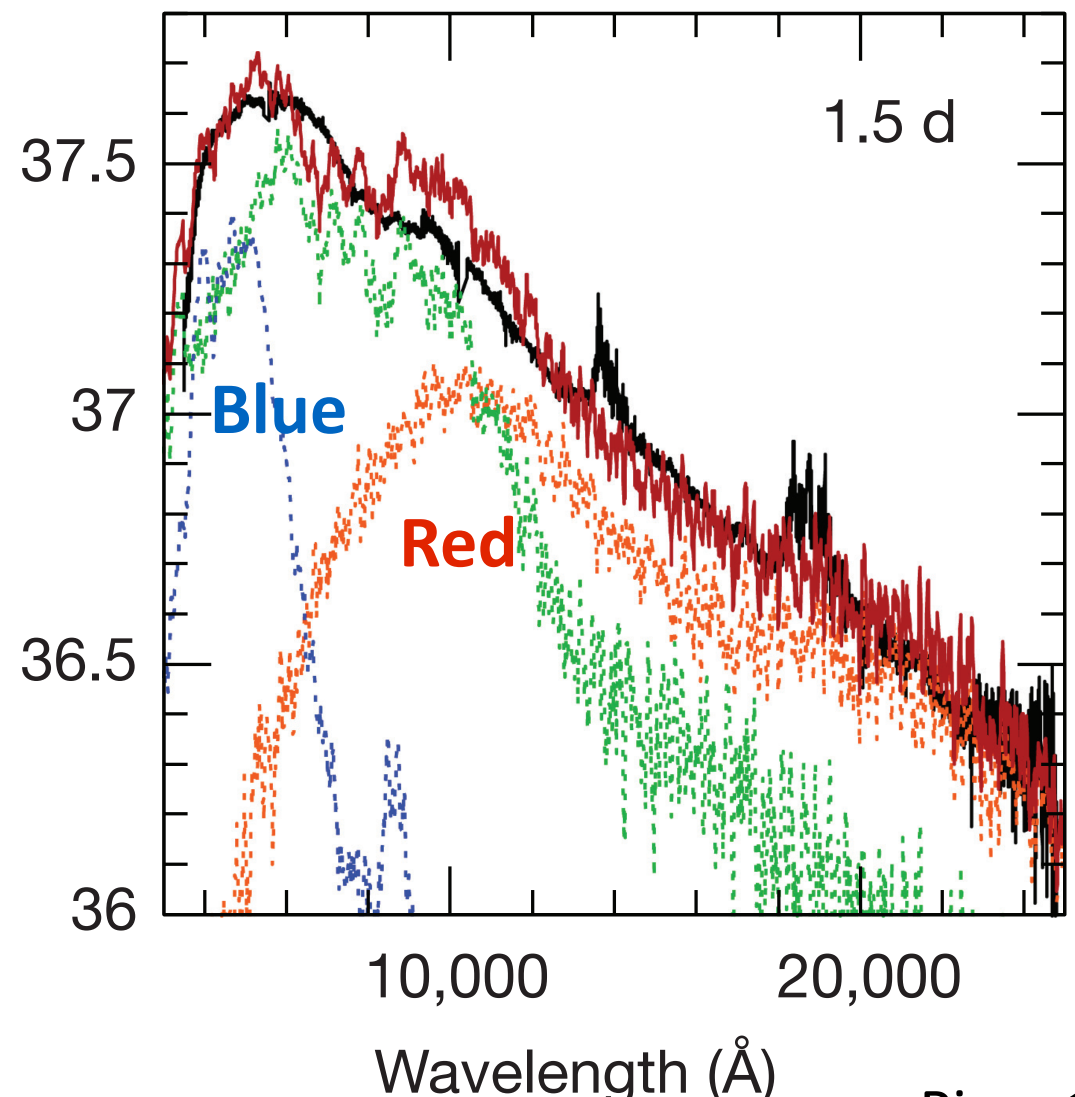
Pian+17

Presence of blue component

Kasen+17, Metzger 17, MT+17



Metzger 17

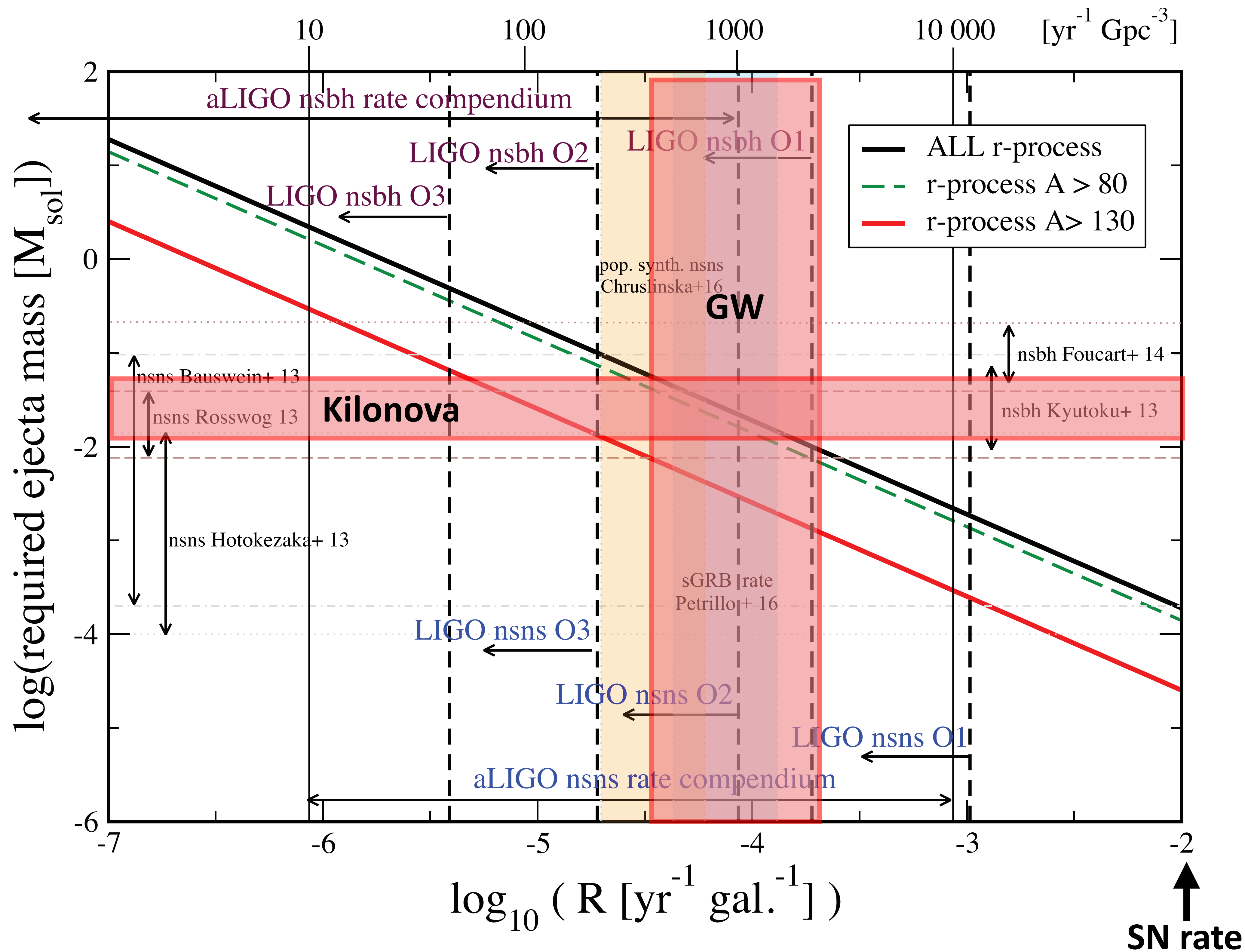


Pian+17

Signature of high Ye material => wide range of r-process

M ~ 0.02 Msun

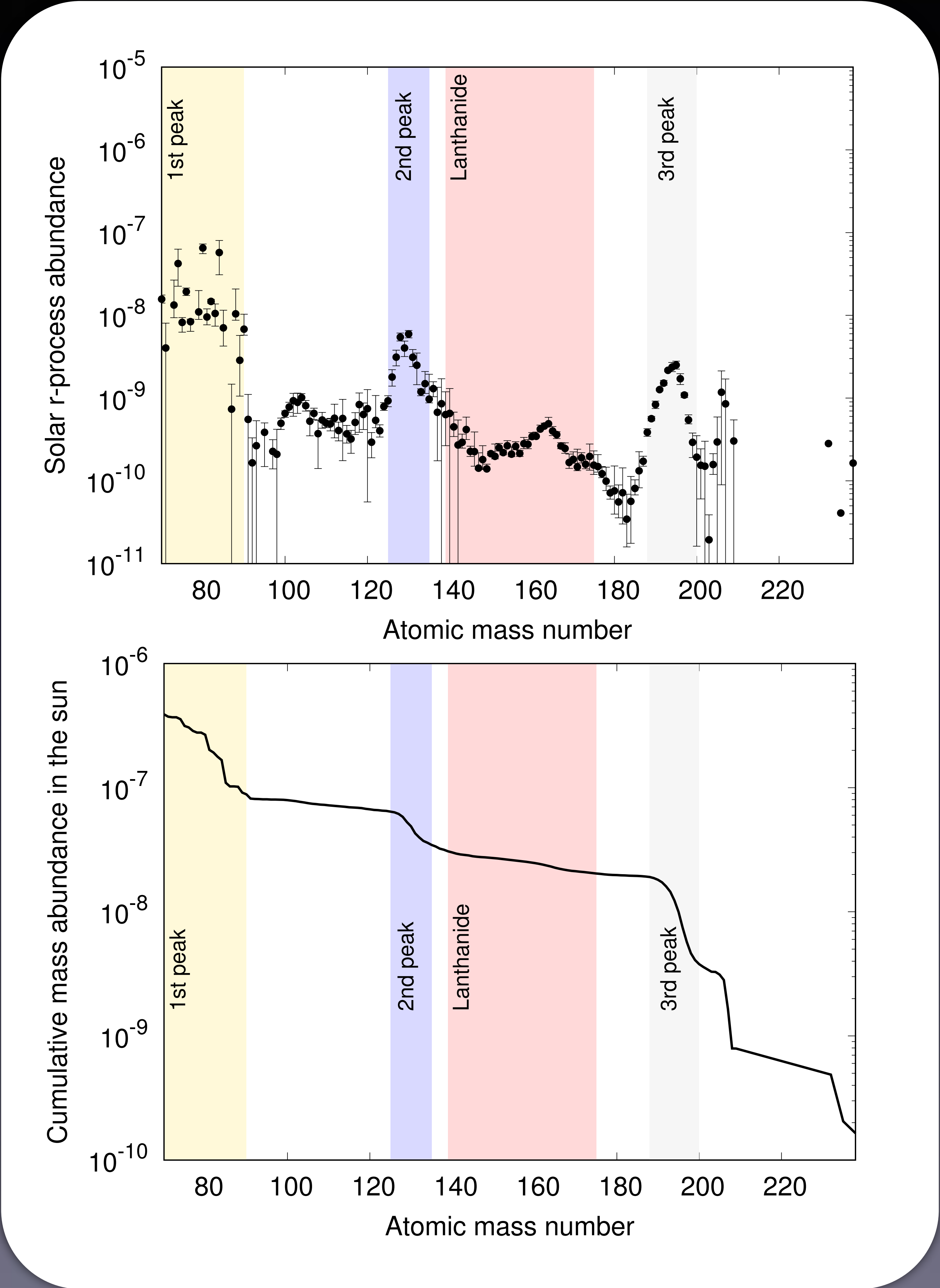
Origin of r-process elements



Rosswog+17, Hotokezaka+15, 18

Not clear whether GW170817 produced solar ratios

Observational signatures
- some lanthanides
- some lighter elements



Hotokezaka+18

Kilonova

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- Neutron star mergers and kilonova
- GW170817/AT2017gfo
- Open issues

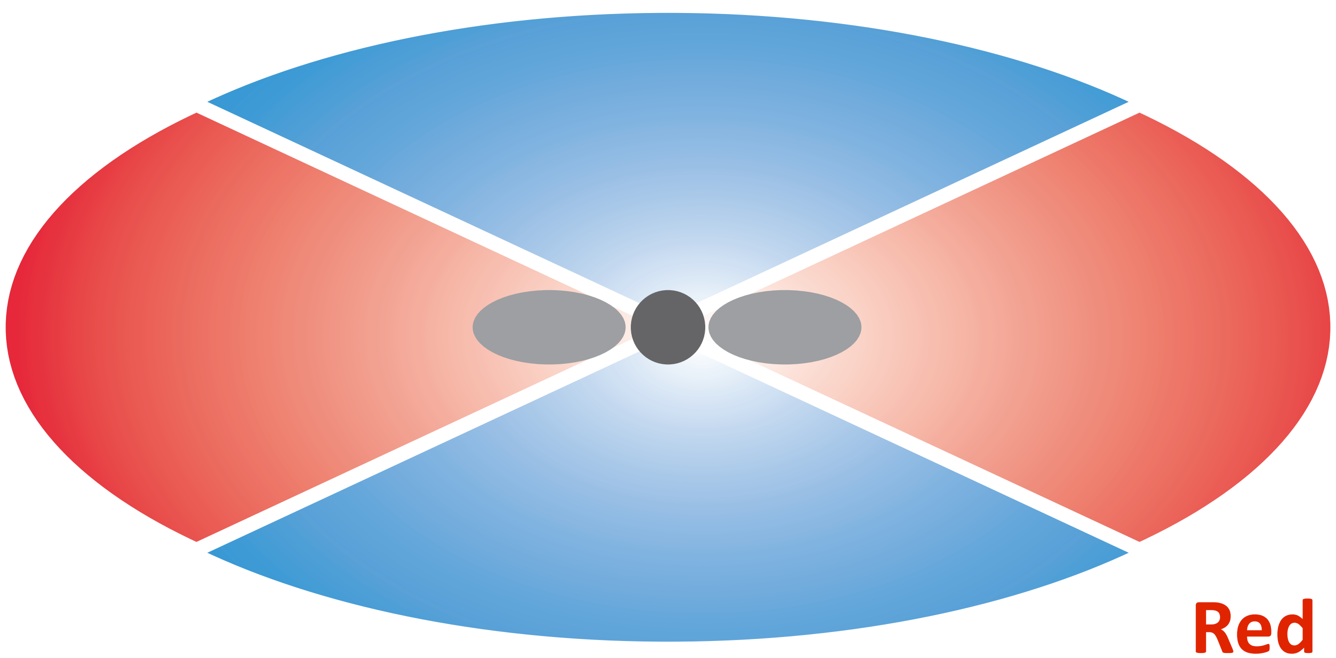
Open questions (only a part)

1. **Mass ejection**
   - Origins of red/blue components?
   - Uncertainty in estimated masses?
2. **Abundance pattern**
   - Similar to solar abundances?
     (Produce 1st peak? 3rd peak?)
   - How to identify spectral features?

Blue kilonova <= post-merger ejecta

v ~ 0.25c v ~ 0.05-0.1c

M ~ 0.02 Msun M ~> 0.01 Msun



Red kilonova <= dynamical ejecta

v ~ 0.1 c v ~ 0.1-0.2c

M ~ 0.03 Msun M ~< 0.01 Msun

Tension between observations and theory?

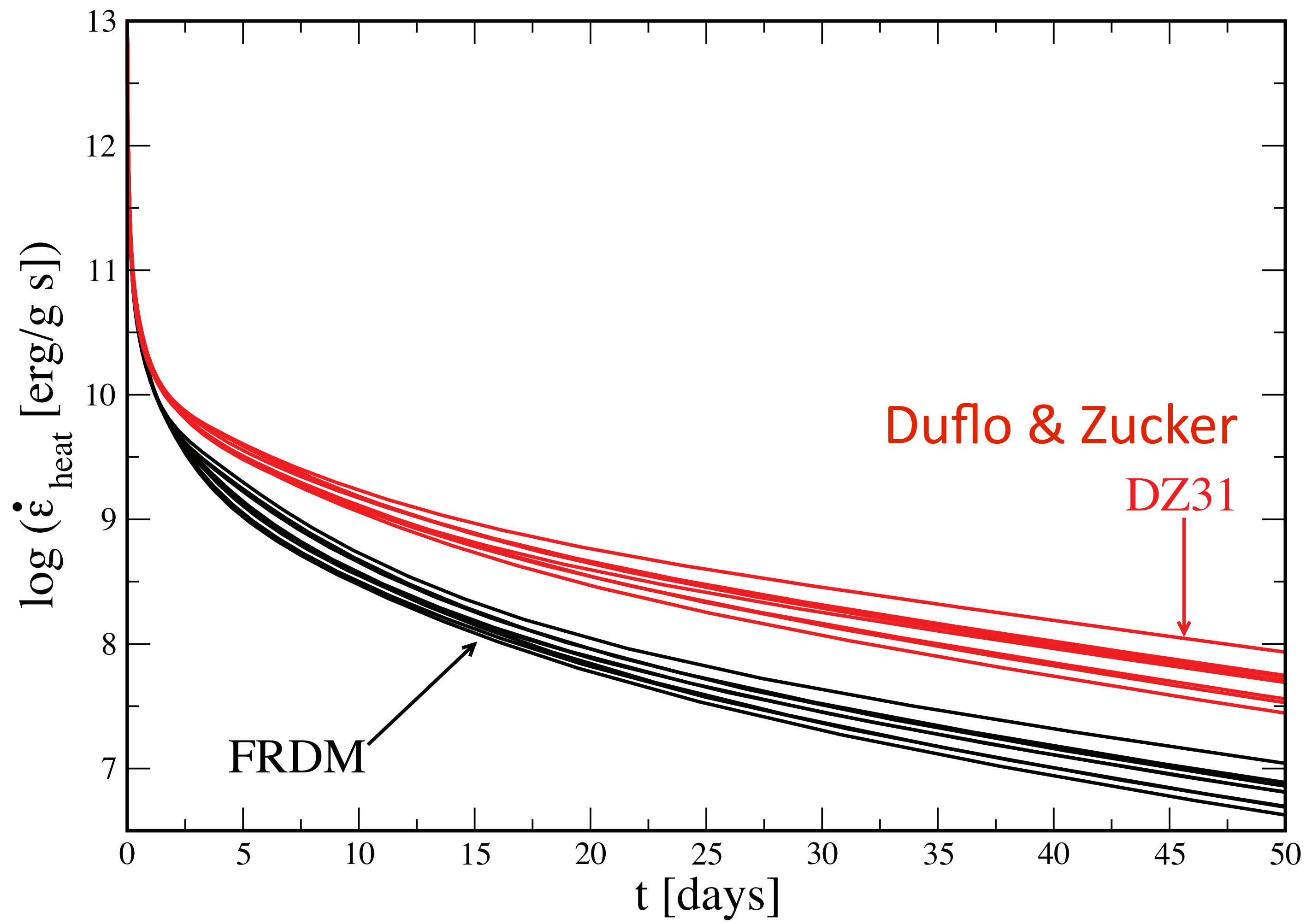
Blue kilonova: too fast as post-merger ejecta

Red kilonova: too massive as dynamical ejecta

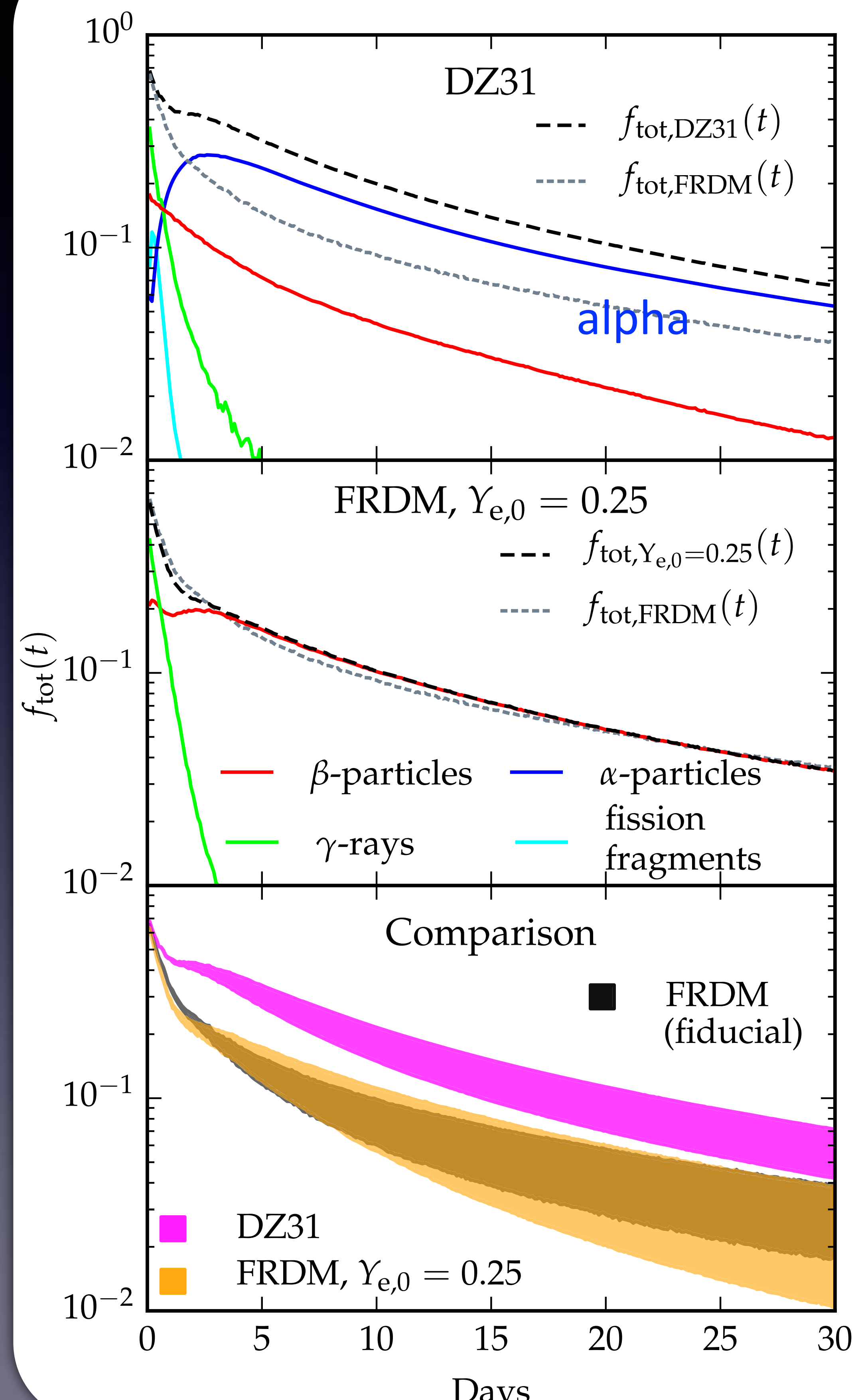
See e.g., Metzger+18, Waxman+18

Mass estimate: how accurate??

Nuclear physics



Rosswog+17

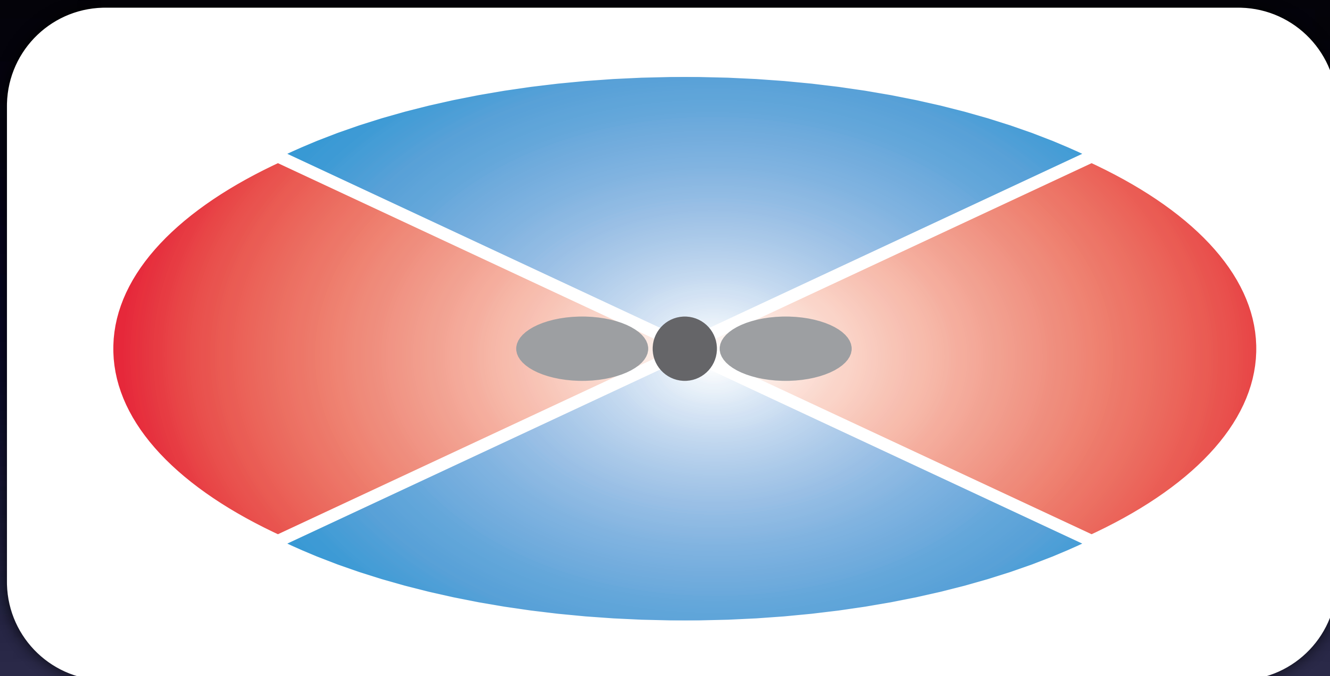


Energy deposition rate might differ up to by a factor 5?

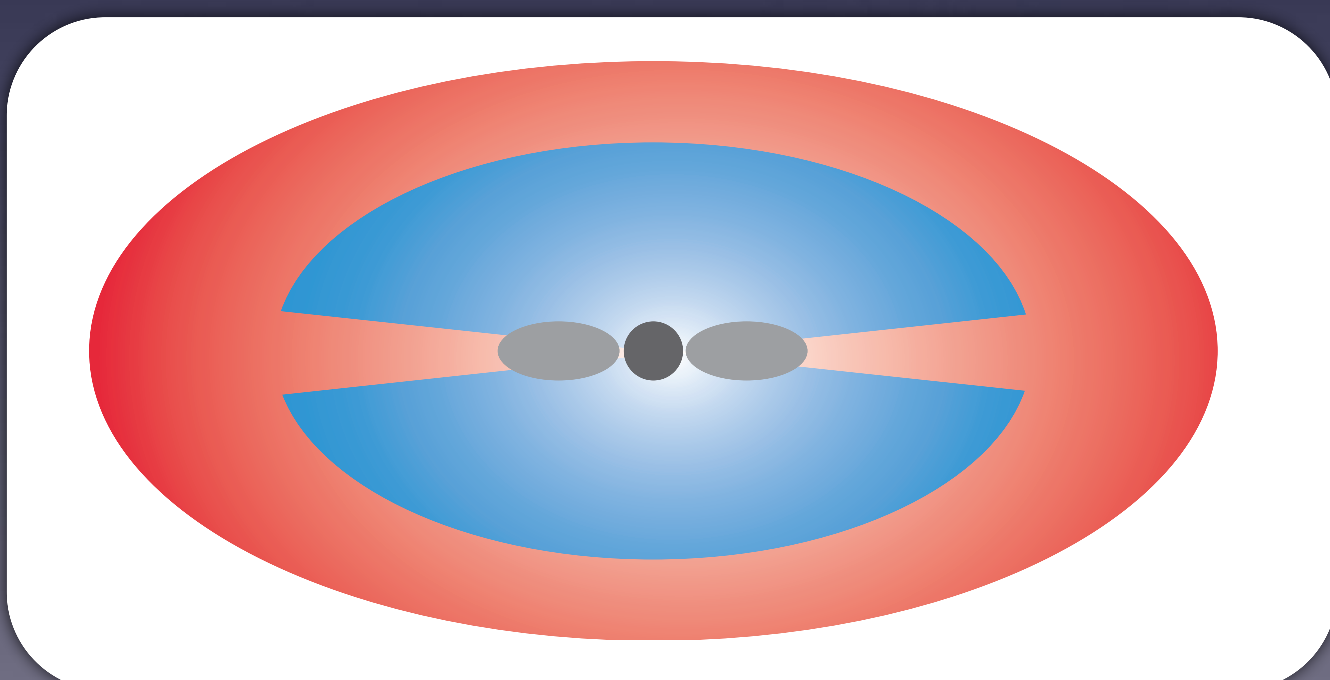
Barnes+16

Multi-D interplay of multiple ejecta

By Kyohei Kawaguchi



Separated blue + red components



Photons from post-merger ejecta can interact with dynamical ejecta

See also Kasen+15

Open questions (only a part)

1. Mass ejection

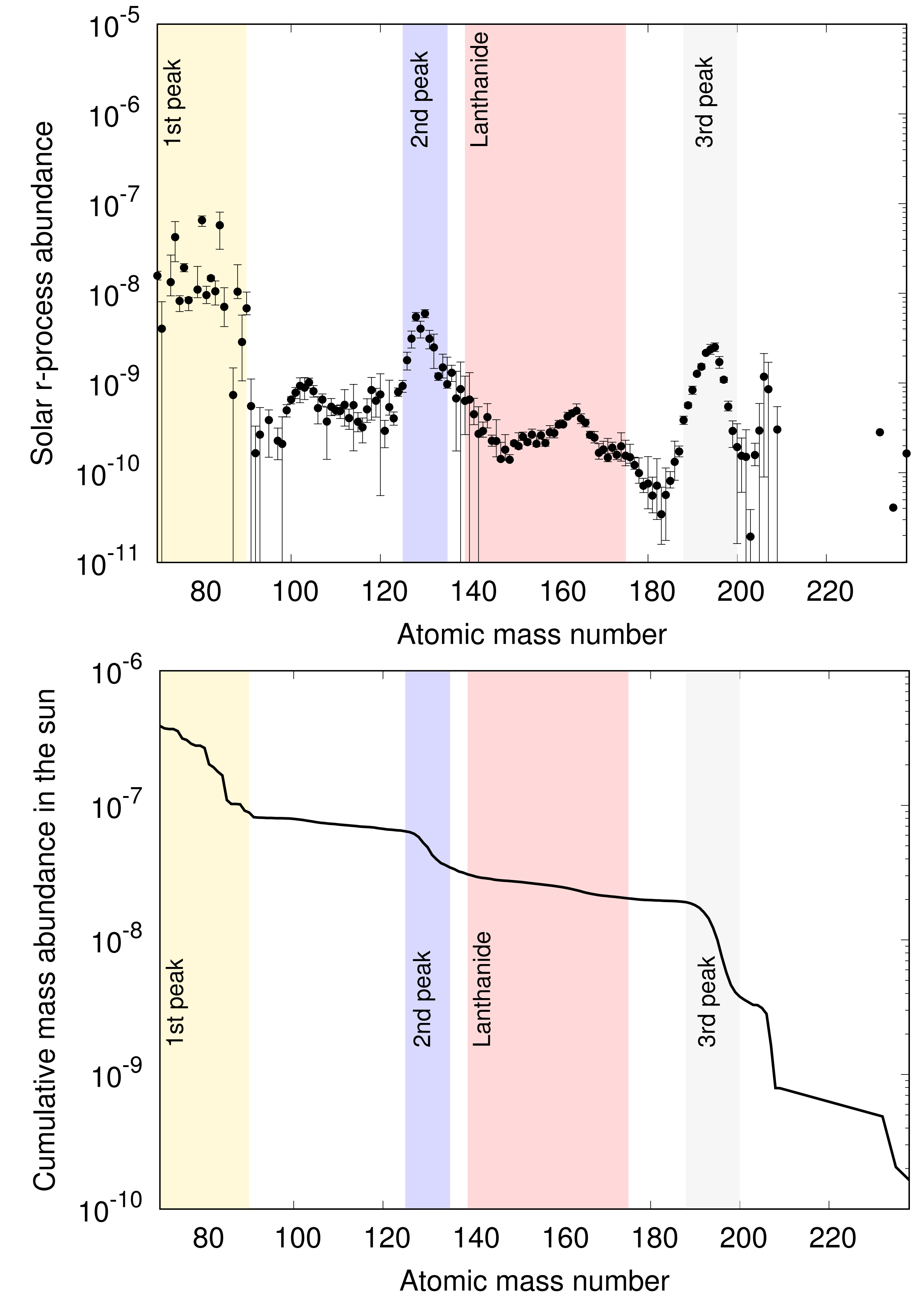
- Origins of red/blue components?
- Uncertainty in estimated masses?

2. Abundance pattern

- Similar to solar abundances?
  (Produce 1st peak? 3rd peak?)
- How to identify spectral features?

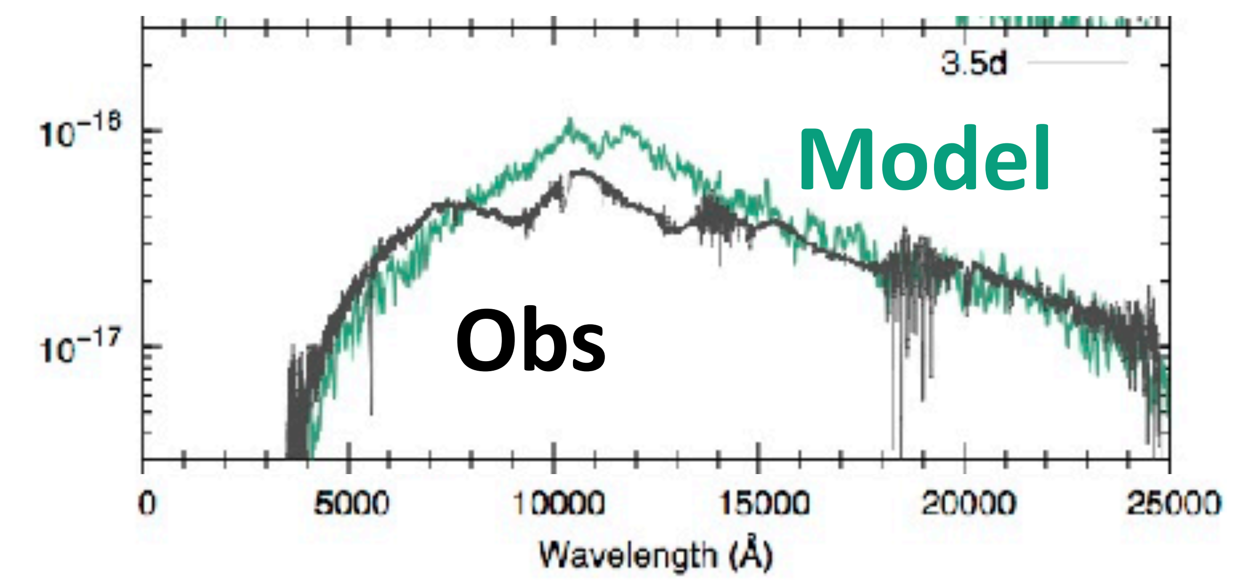
Not clear whether GW170817 produced solar ratios

Observational signatures
- some lanthanides
- some lighter elements



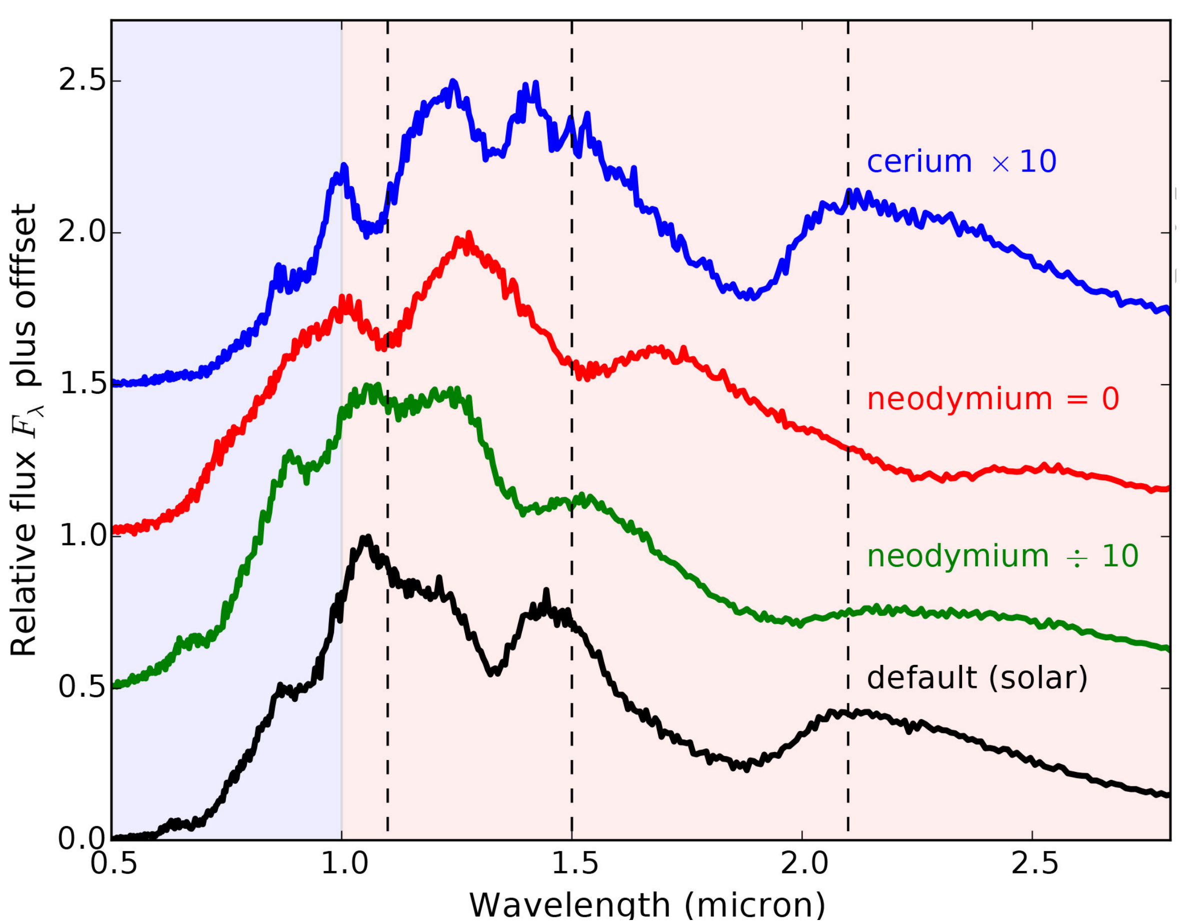
Hotokezaka+18

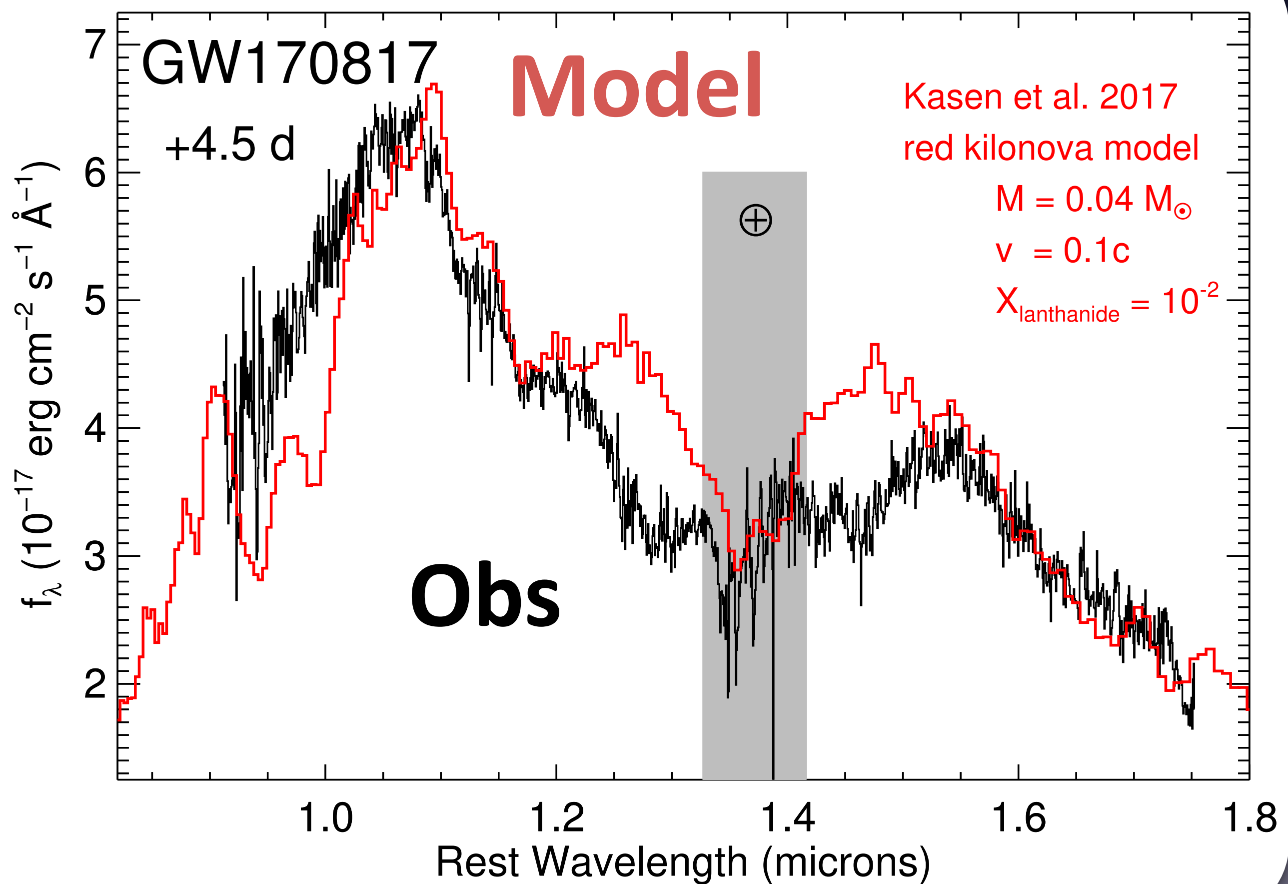
Possible element features
In the spectra??
=> Not very conclusive
(lack of atomic data!)



MT+17

Model





Kasen+17

Chornock+17

Atomic calculations

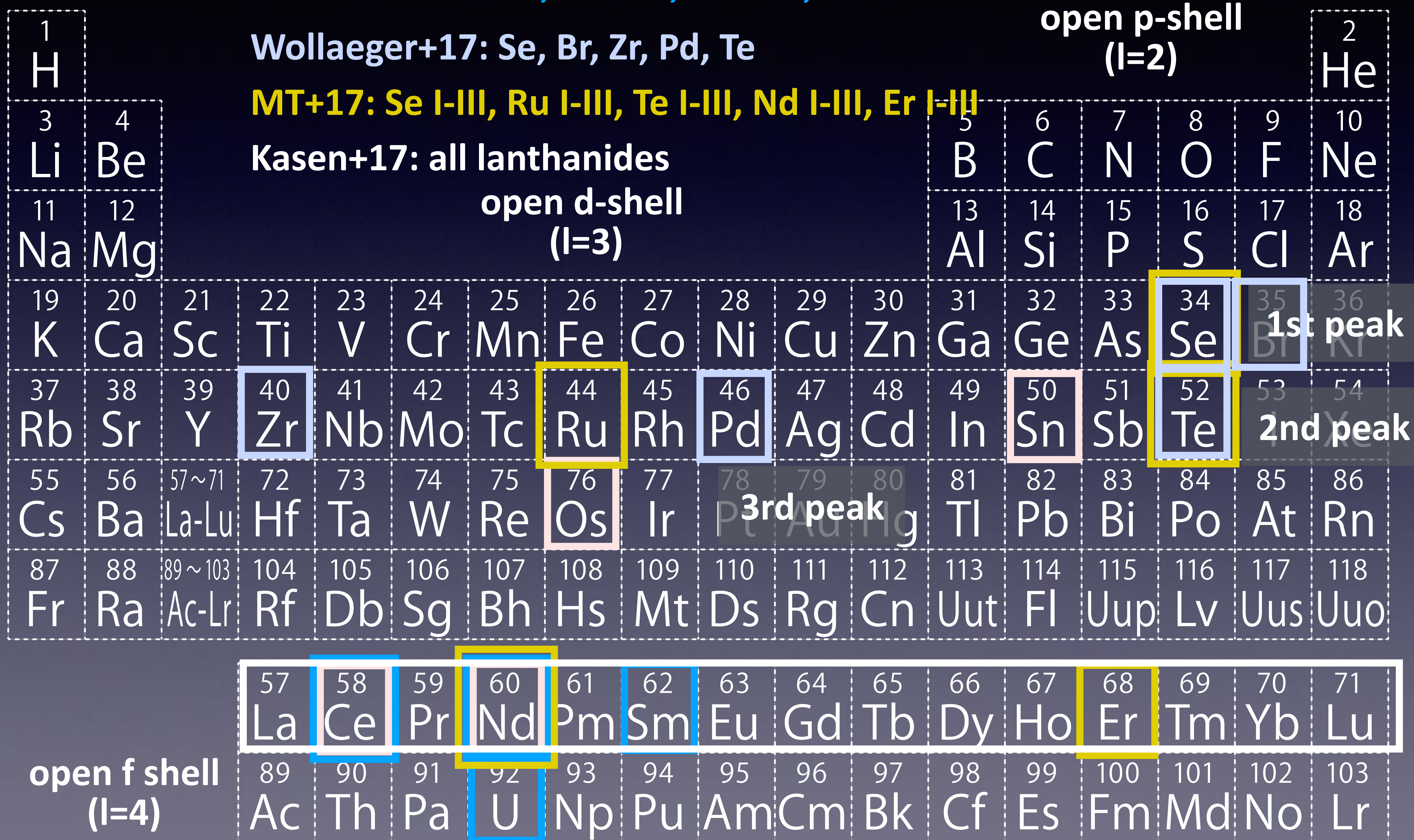
Kasen+13: Sn II, Ce II-III, Nd I-IV, Os II

Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV

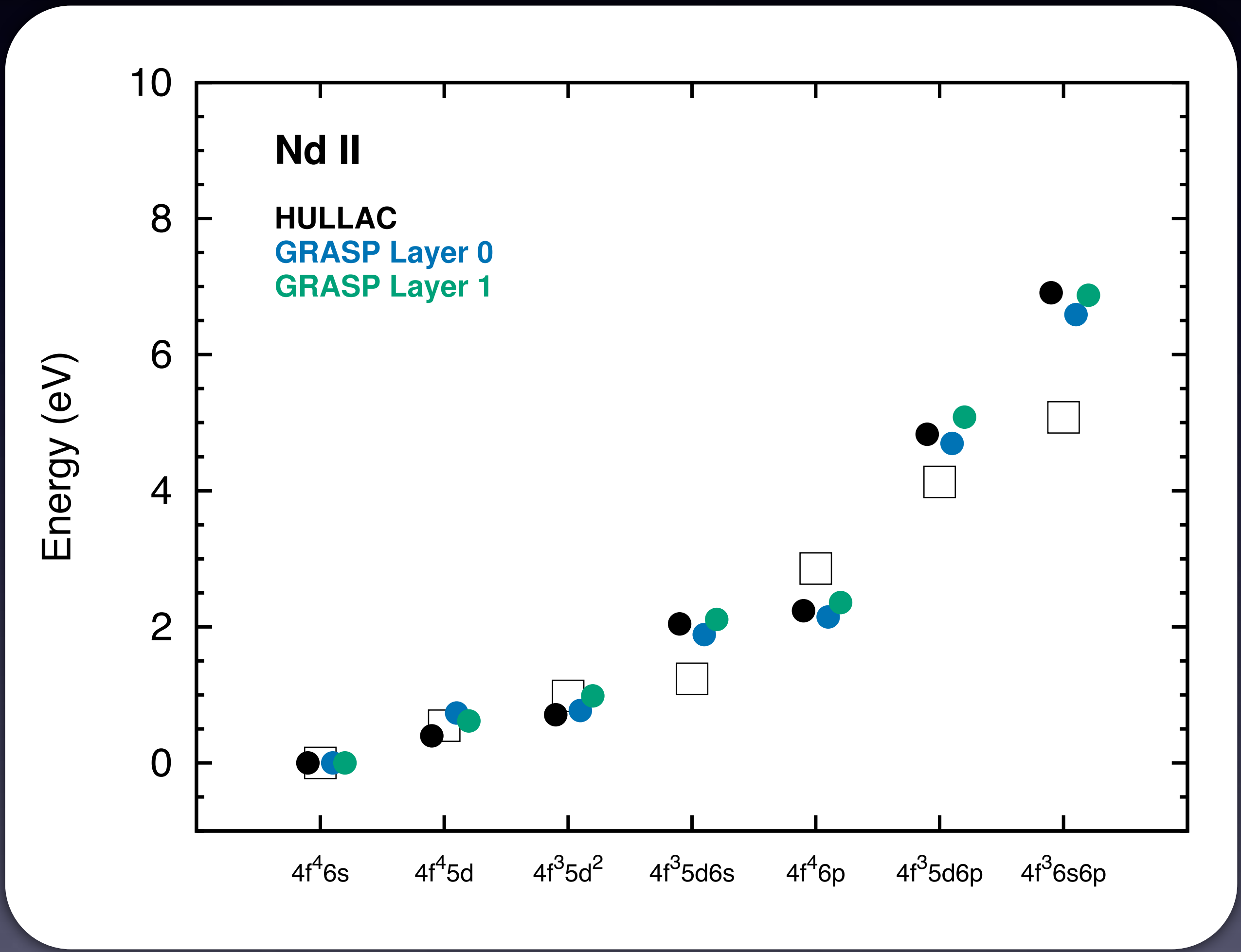
Wollaeger+17: Se, Br, Zr, Pd, Te

MT+17: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III

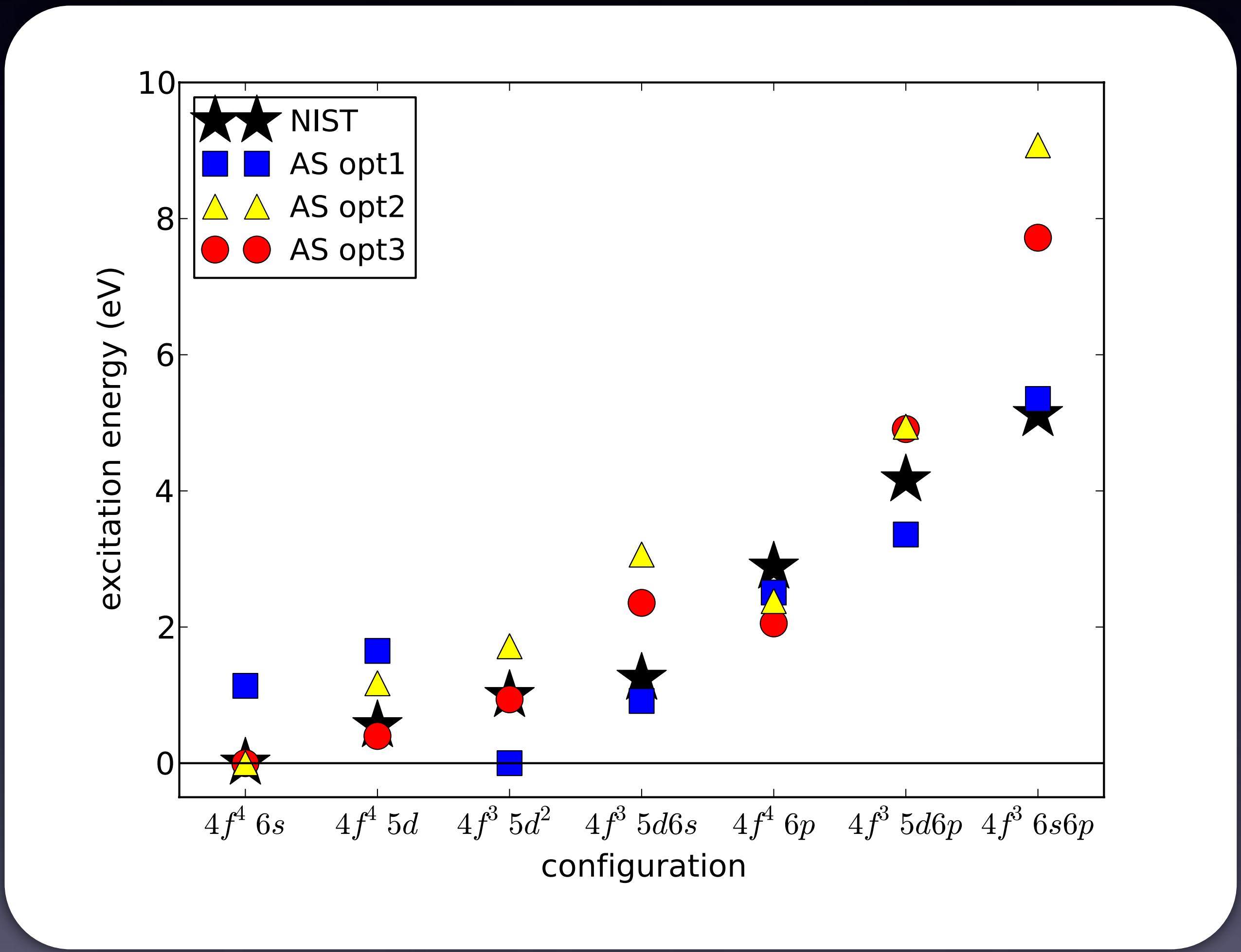
Kasen+17: all lanthanides



Calculations of energy levels (Nd II, Z = 60)



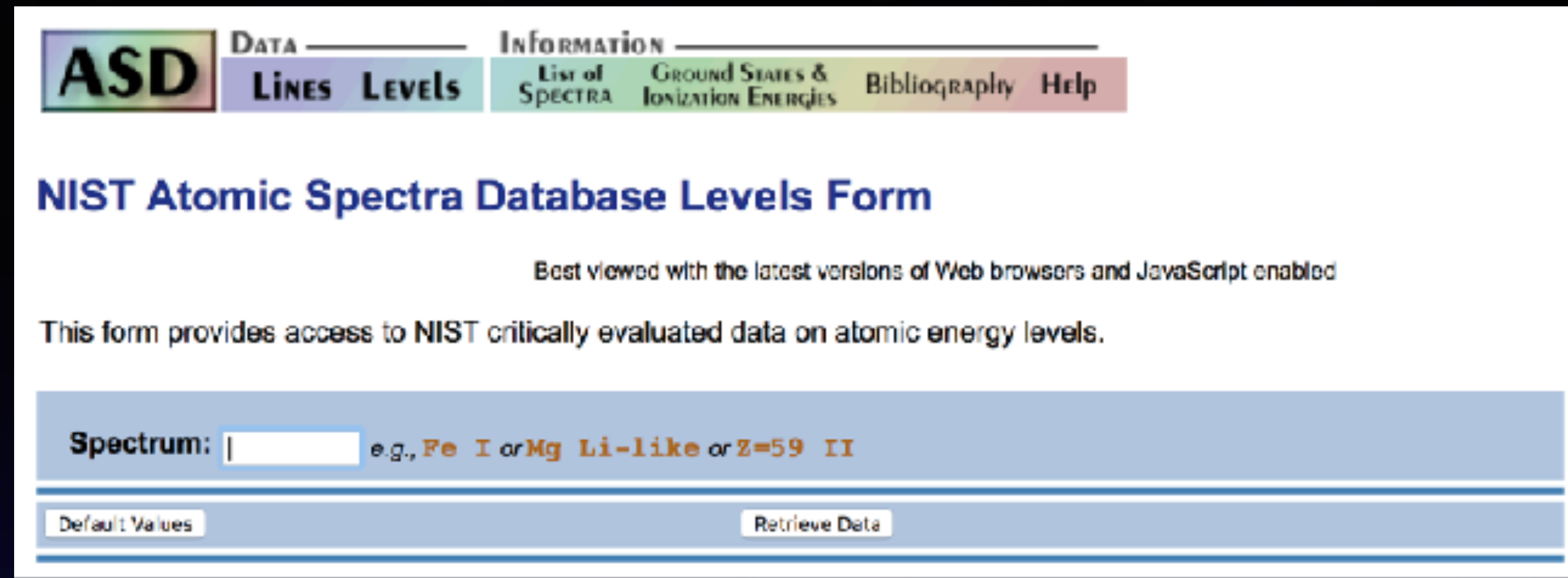
MT+17 (HULLAC, GRASP2K)

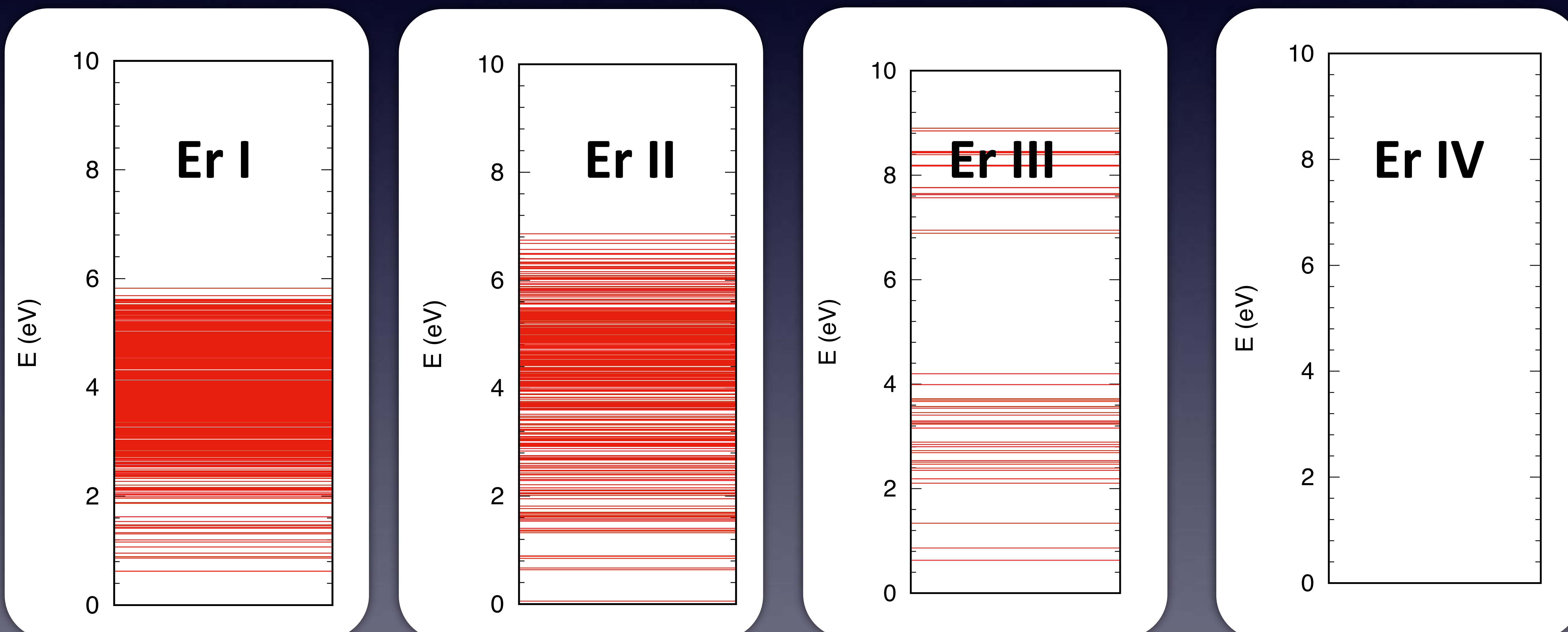


Kasen+13 (Autostructure)

Not very accurate for transition wavelengths

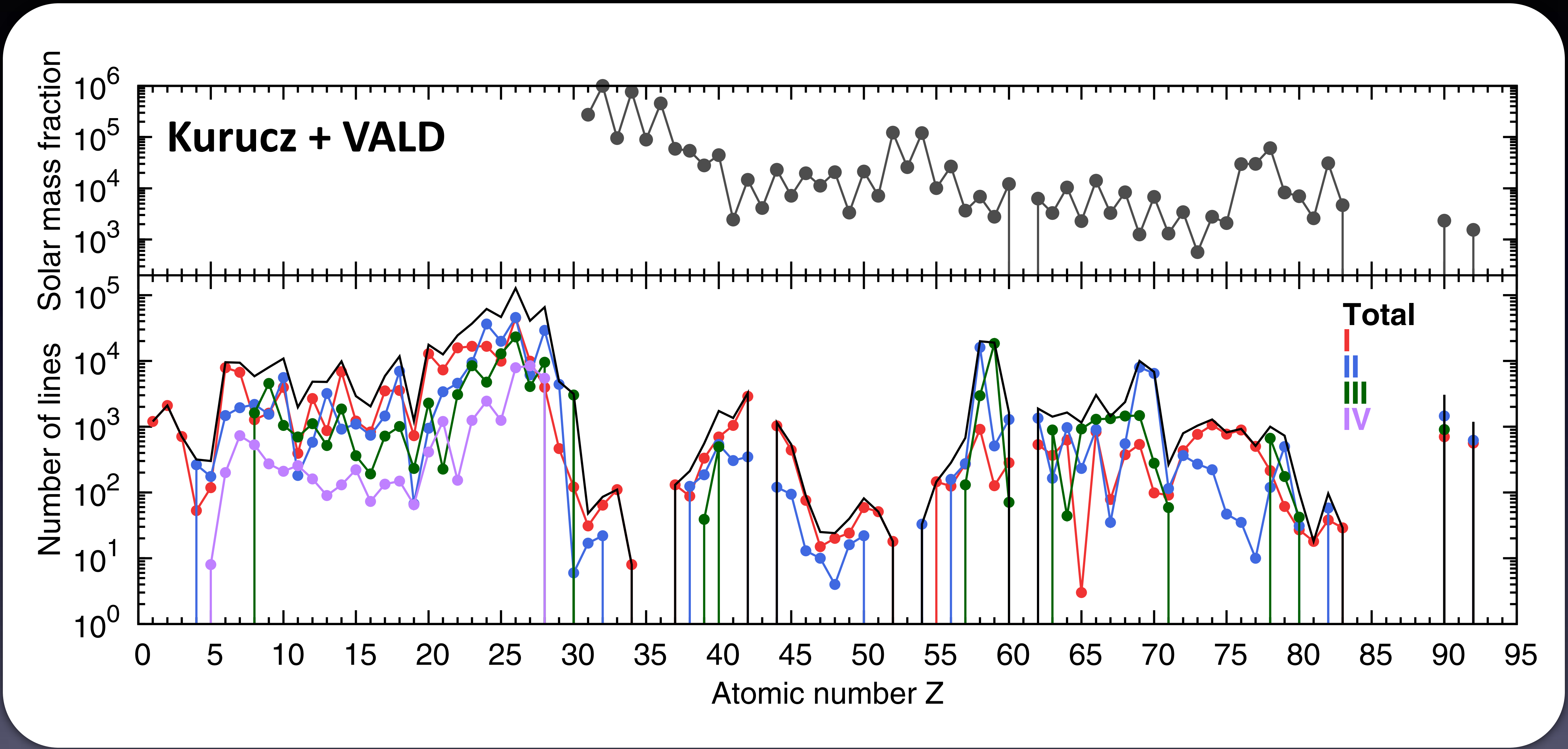
Er (Z=68) Energy levels





Need experimental data

Good data for strong transitions



MT & Hotokezaka 13

Not complete for "opacity"
but probably enough for line identification
(similar to stellar abundance analysis)

Summary

- **GW170817/AT2017gfo**
  - Signature of kilonova
  - Both red and blue components
    => Production of lanthanide and higher elements
  - Production rate fulfills the necessary condition
- **Open issues**
  - Origins of blue/red components
    - Uncertainty in the ejecta mass => nuclear physics
    - Multi-D models
  - Composition in the ejecta: solar ratios?
    - Lack of atomic data (both calculations and experiments)
      => atomic physics