# Electromagnetic signatures of r-process nucleosynthesis

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# Electromagnetic signatures of r-process nucleosynthesis

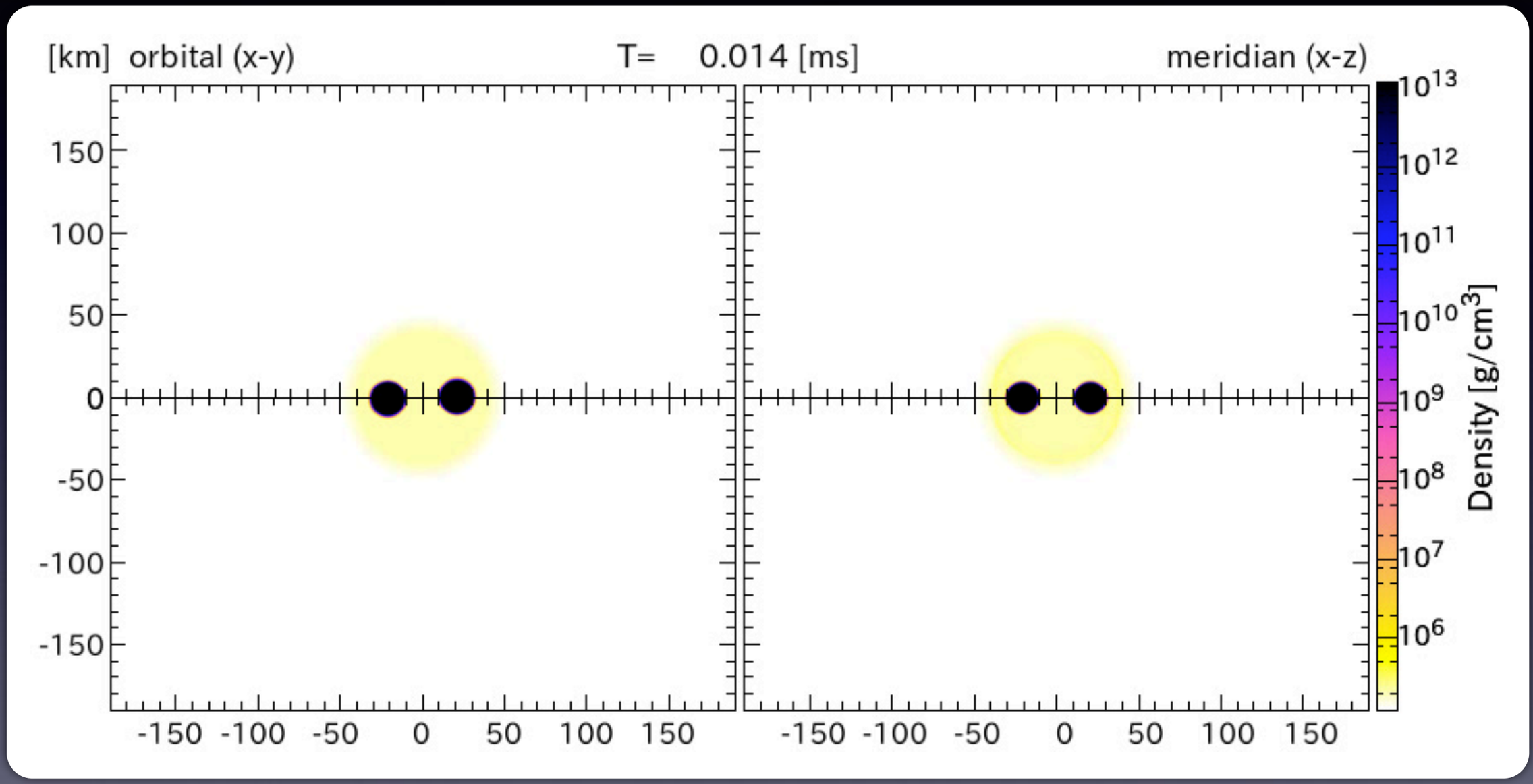
- Kilonova: Electromagnetic signal from NS merger
- GW170817 and observations of kilonova
- Origin of the r-process elements

# Mass ejection from NS merger

M. Shibata's talk

## Top view

## Side view




**Ejected material**

**M ~ $10^{-3}$ - $10^{-2}$ Msun**

**v ~ 0.1 - 0.2 c**

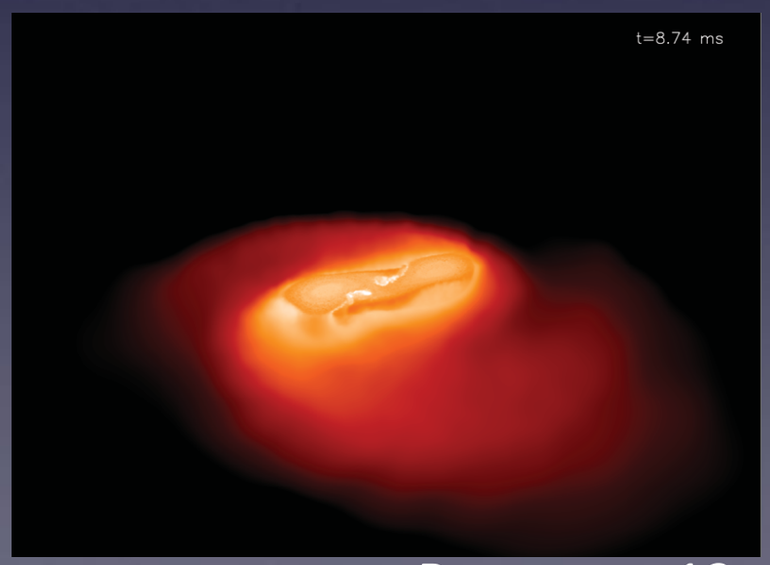
Sekiguchi+15, 16

M. Shibata's talk

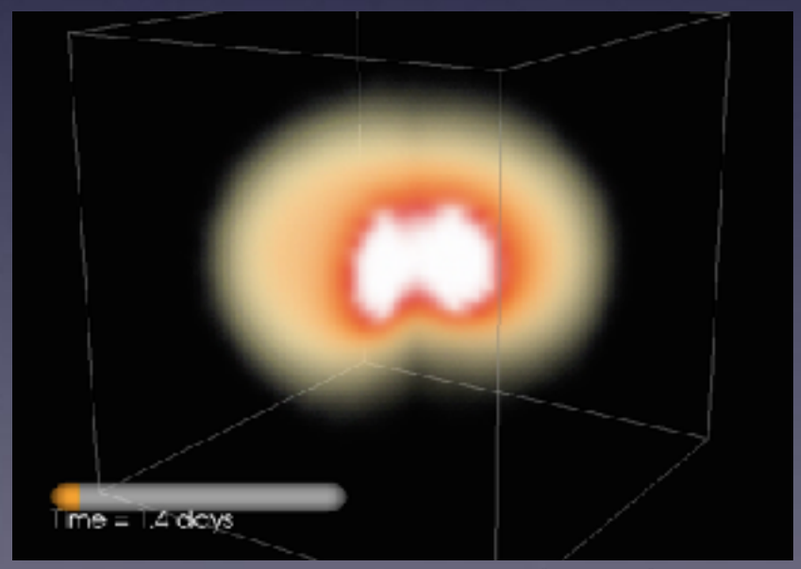
J. Lattimer's
A. Arcones's talks

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

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

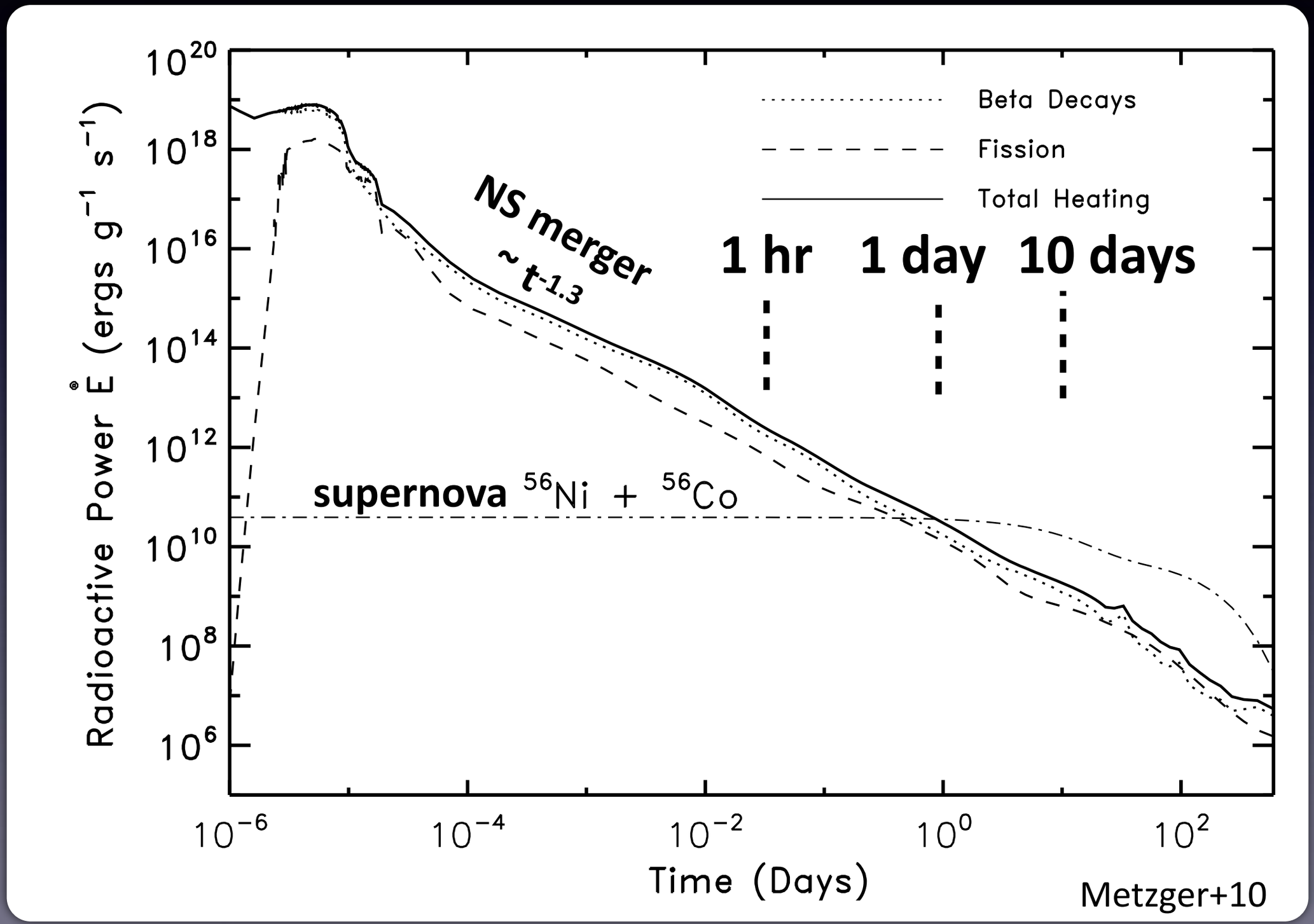


Rosswog+ 13


MT & Hotokezaka 13

# Decays of r-process nuclei

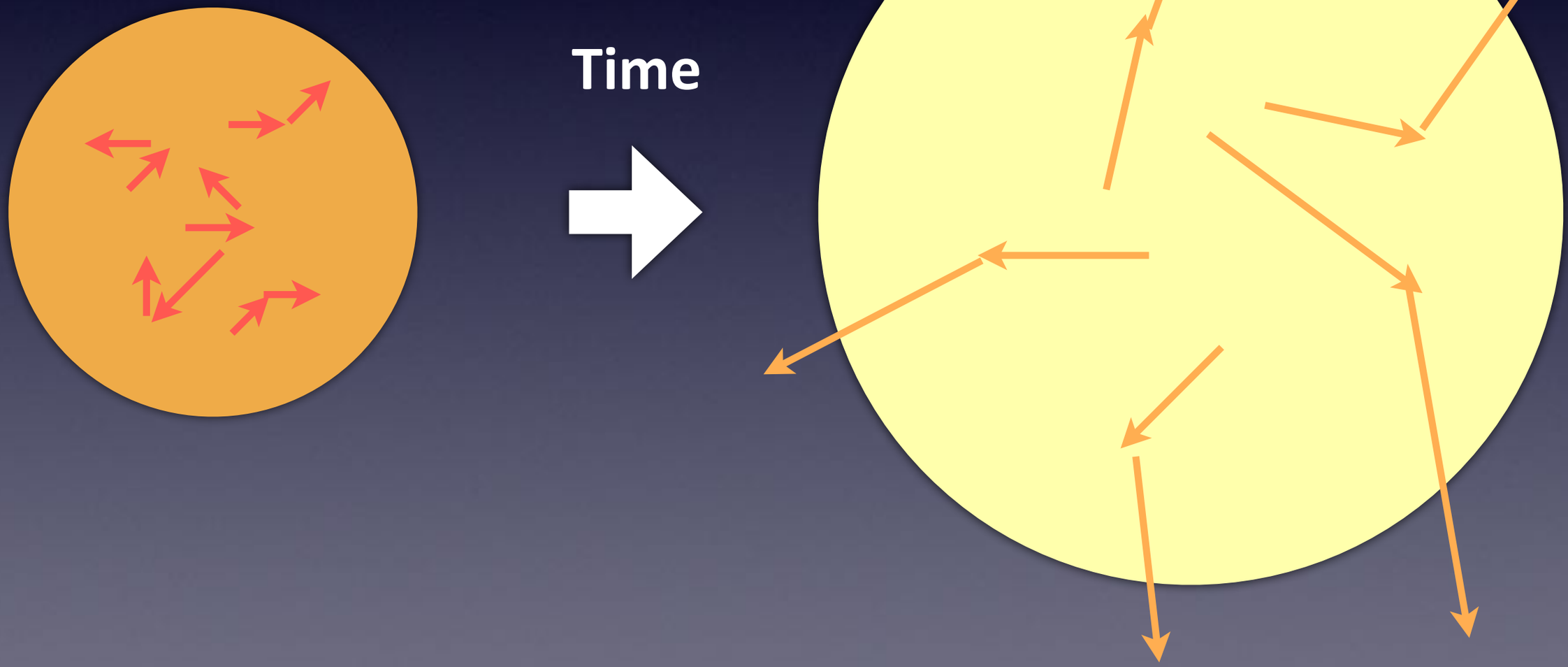
# β decay (γ, β), α decay, fission => heating up the ejecta




Metzger+10

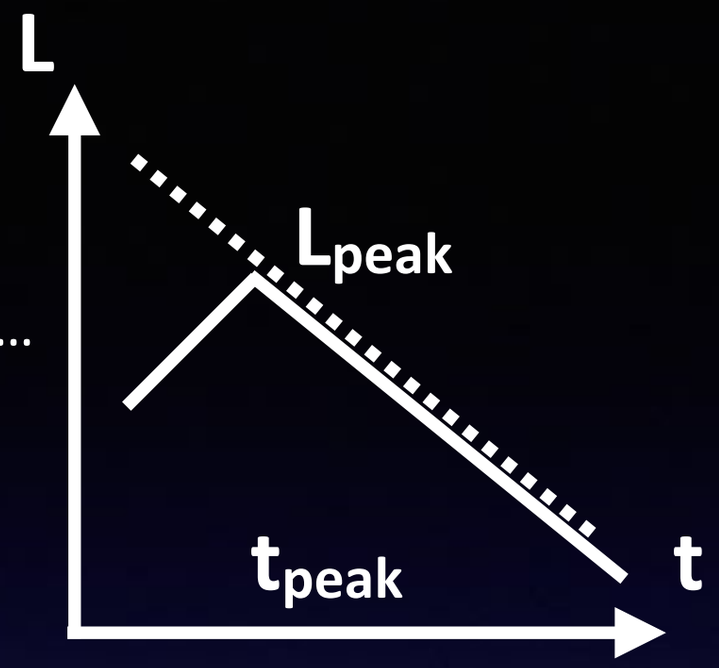
# “Kilonova” = Electromagnetic transient powered by decays of r-process nuclei

Li & Paczynski 98, Kulkarni 05, Metzger+10



# “Kilonova"

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




## Timescale

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

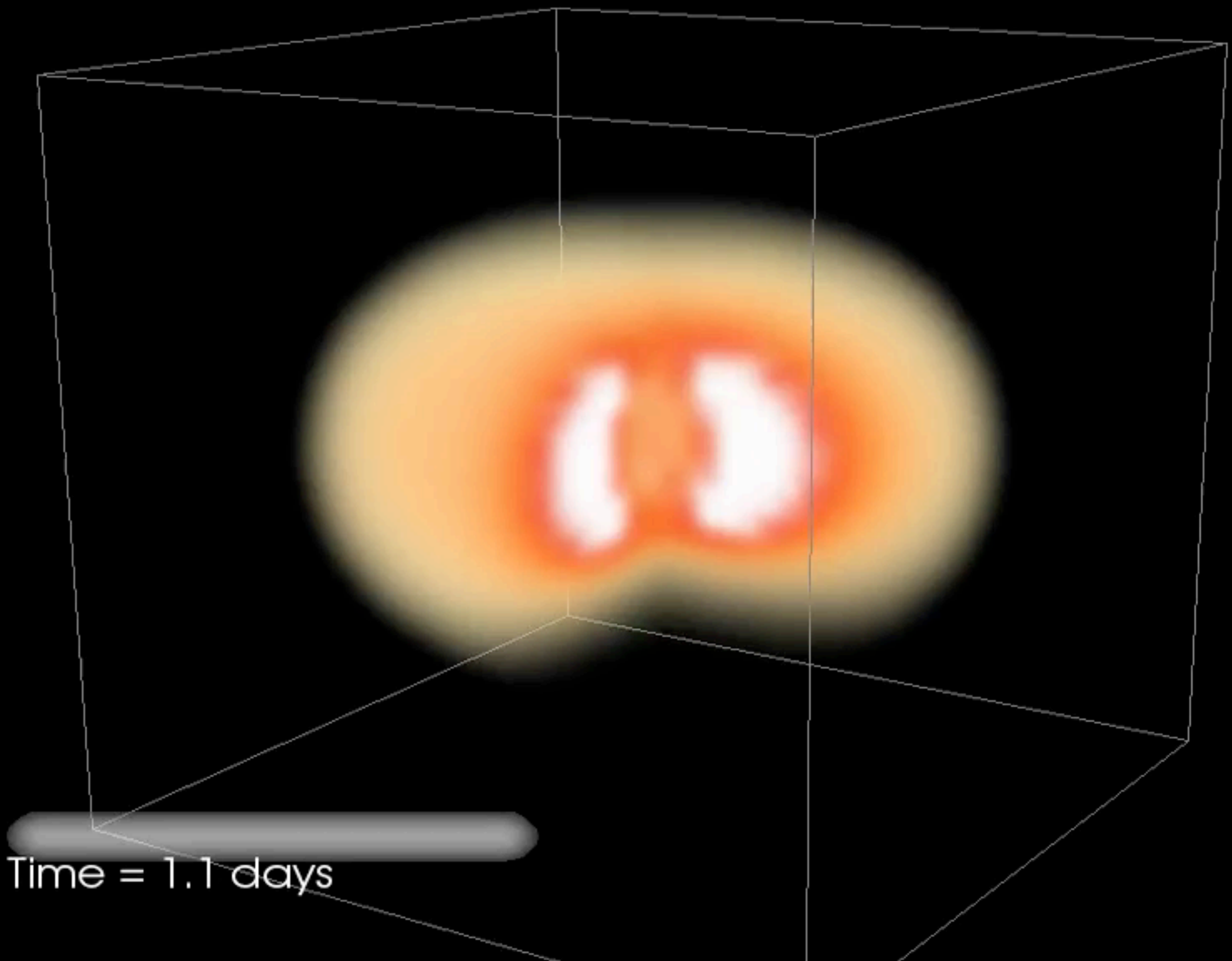
## Luminosity

*assuming 50% thermalization

$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$
$$\simeq 1.3\times10^{40}\ {\rm erg\ s^{-1}} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10\ {\rm cm^2\ g^{-1}}}\right)^{-0.65}$$

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

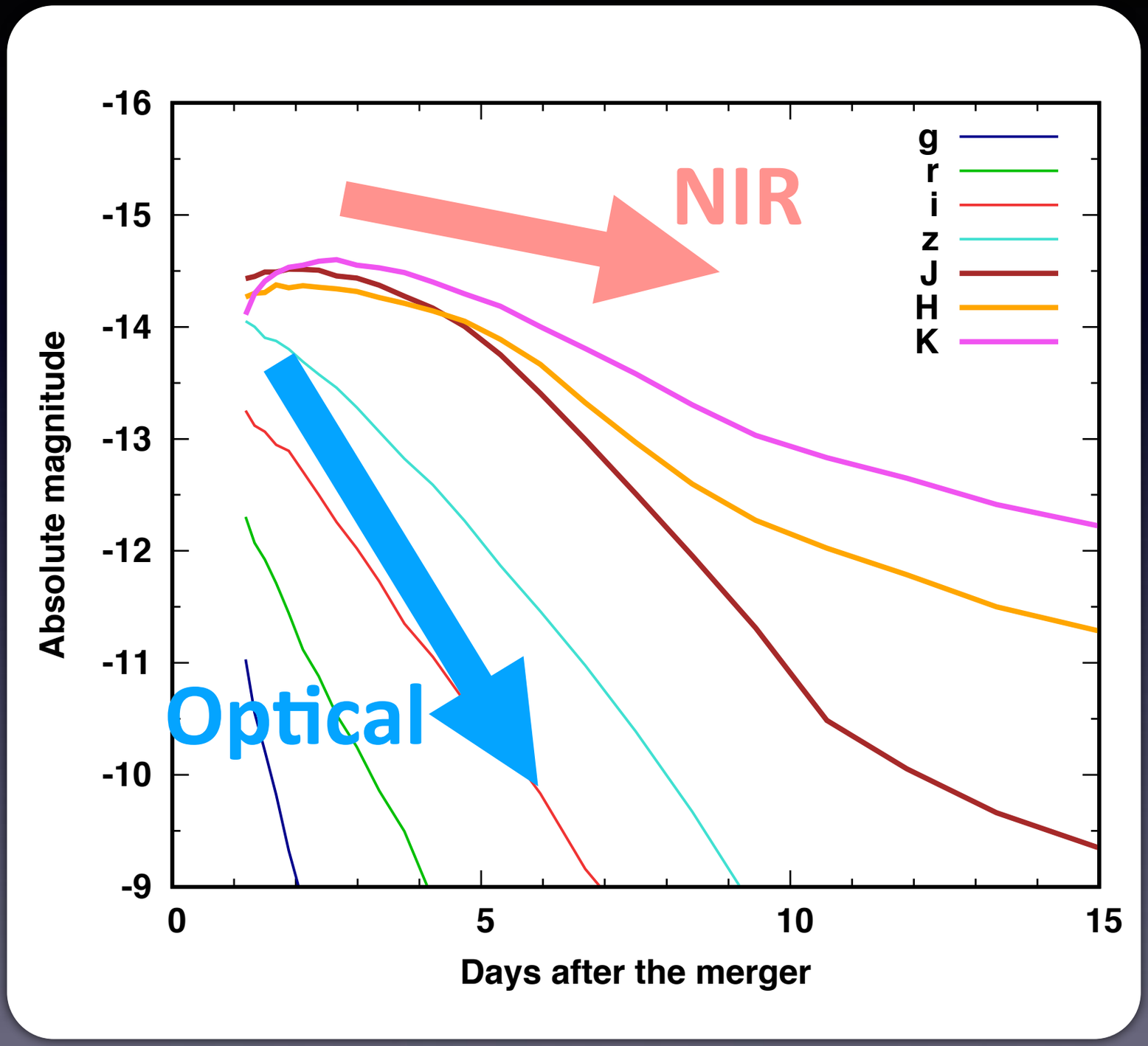
# Radiation transfer simulations of kilonova



# Light curves of kilonova

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

**L ~ $10^{40}$-$10^{41}$ erg $s^{-1}$**
**t ~ weeks**
**NIR > Optical**



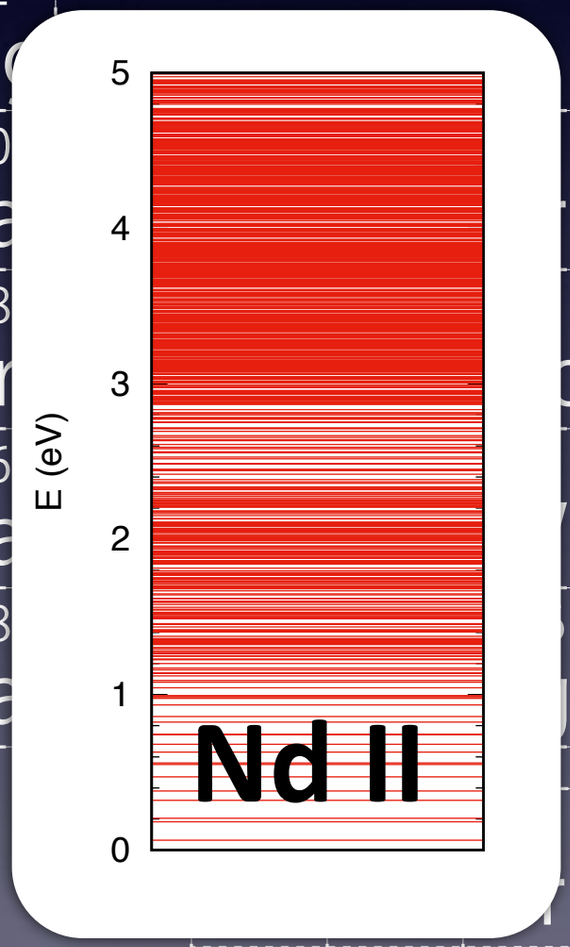

Model: MT+17a

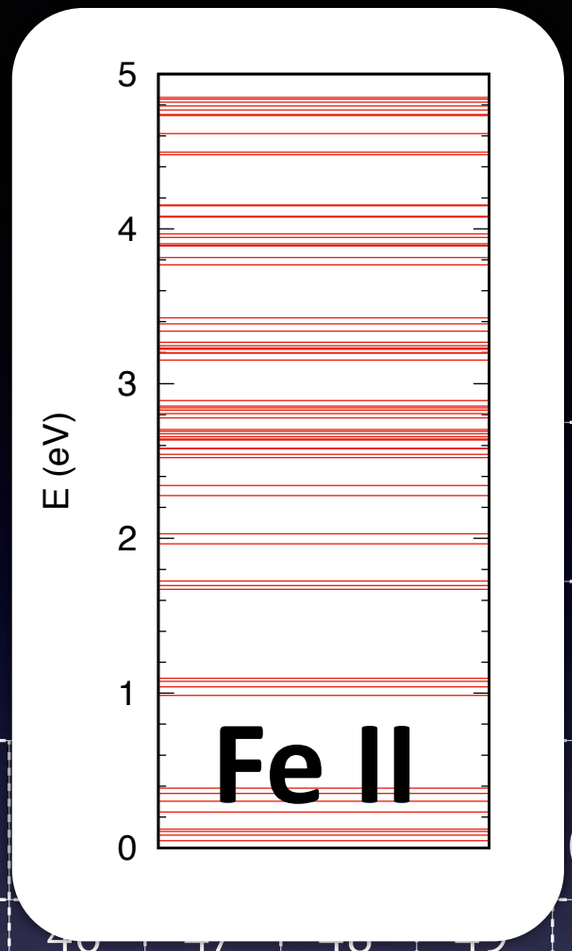
**open s shell (l=1)**

**open d-shell (l=3)**

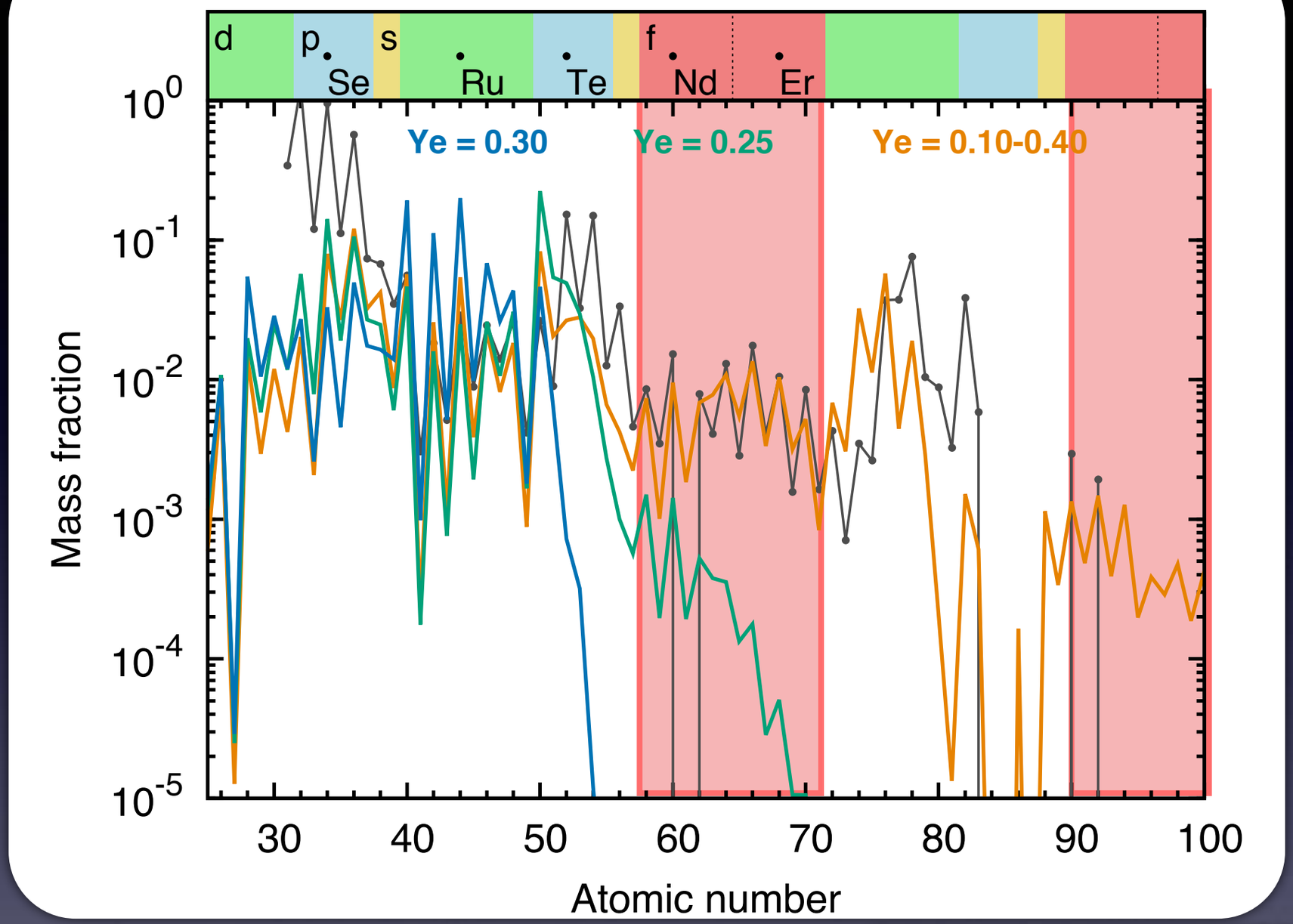
**open p-shell (l=2)**

**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 | 12 Mg | | | | | | | | | | | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar | |
| 19 K | 20 Ca | | | | | 25 Mn | 26 Fe | 27 Co | | | | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr | |
| 37 Rb | 38 Sr | | | | | 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 | | | | | 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 | | | | | 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 | |




**M. Shibata's**
**and A. Arcones's talks**

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

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

Metzger+14, Kasen+15

# Electromagnetic signatures of r-process nucleosynthesis

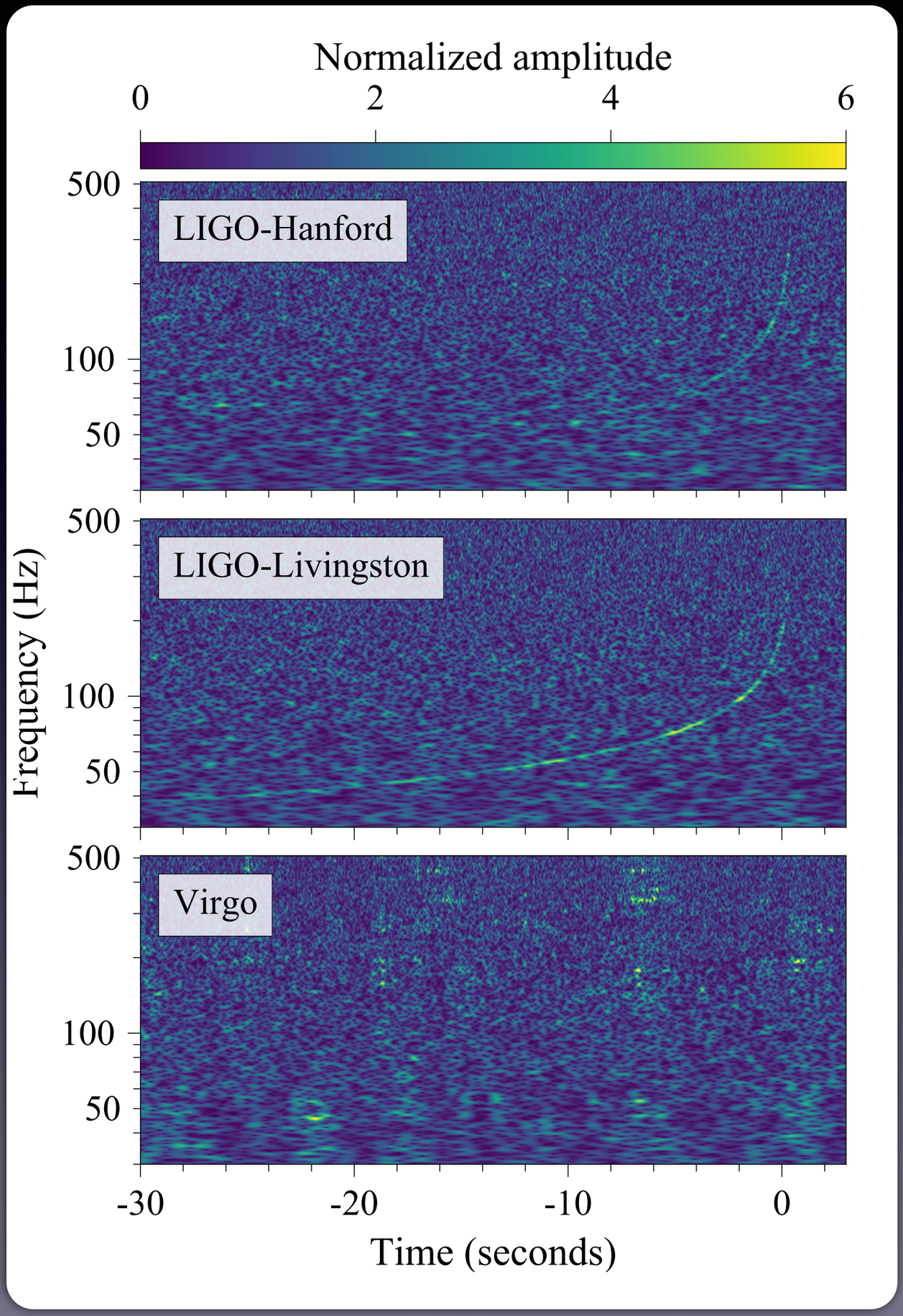
- Kilonova: Electromagnetic signal from NS merger
- GW170817 and observations of kilonova
- Origin of the r-process elements

# GW170817

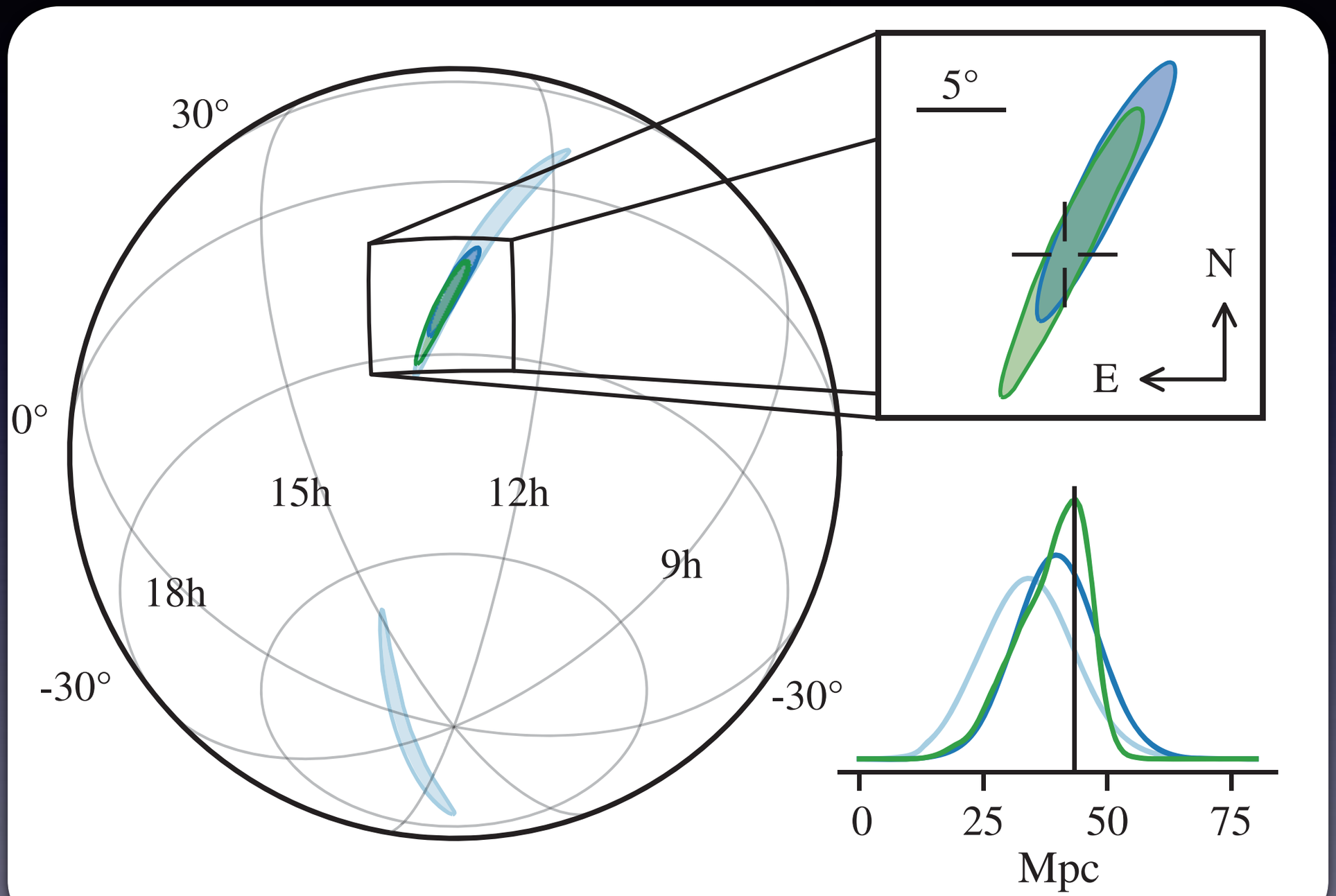
## The first detection of GWs from a NS merger

**B. Sathyaprakash's and T. Hinderer's talks**

LIGO Scientific Collaboration and Virgo Collaboration, 2017, PRL



# Skymap from 3 detectors (LIGO x 2 + Virgo)
# ==> 30 deg² (~40 Mpc)



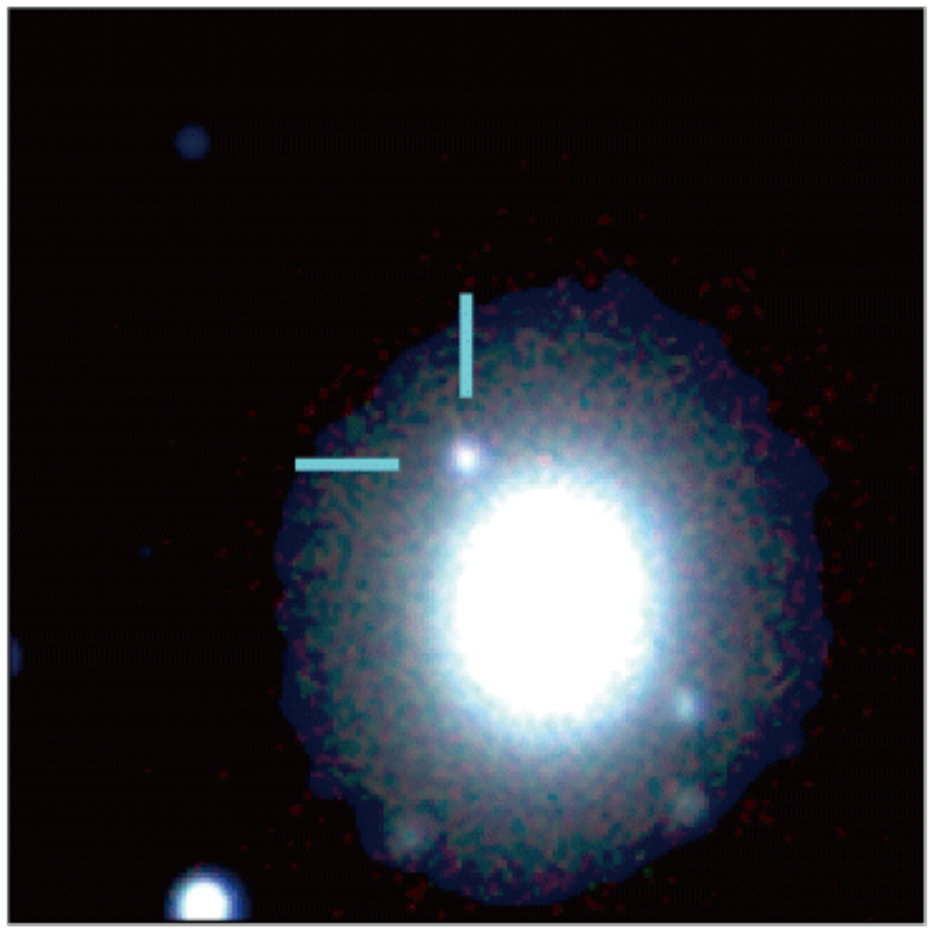

LIGO Scientific Collaboration and Virgo Collaboration, 2017


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

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

# Electromagnetic counterpart of GW170817 @ 40 Mpc

Day 1

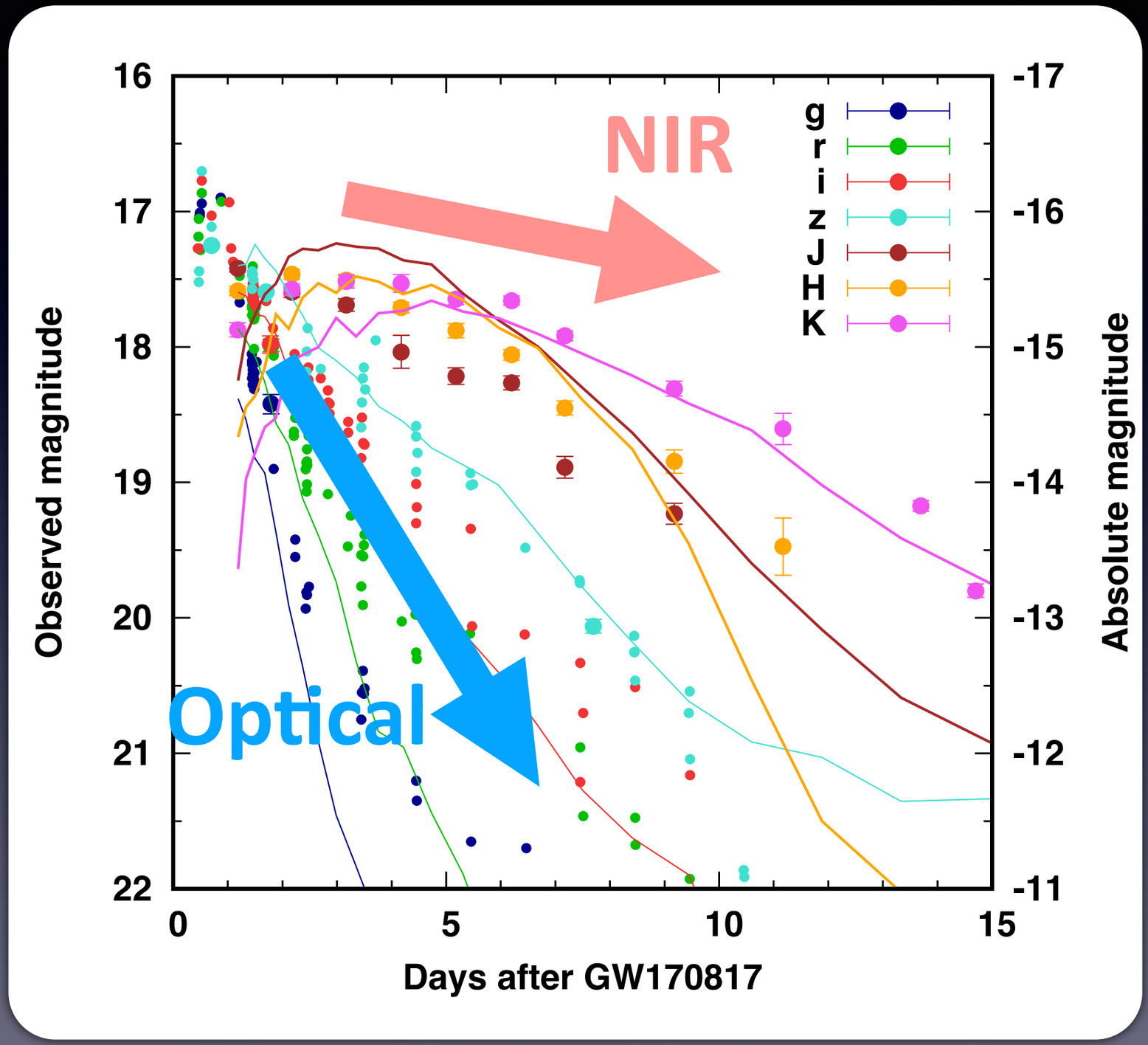


Day 7

Optical (z)  near IR (H)  near IR (Ks)

Utsumi, MT+17

# GW170817: optical/infrared light curves



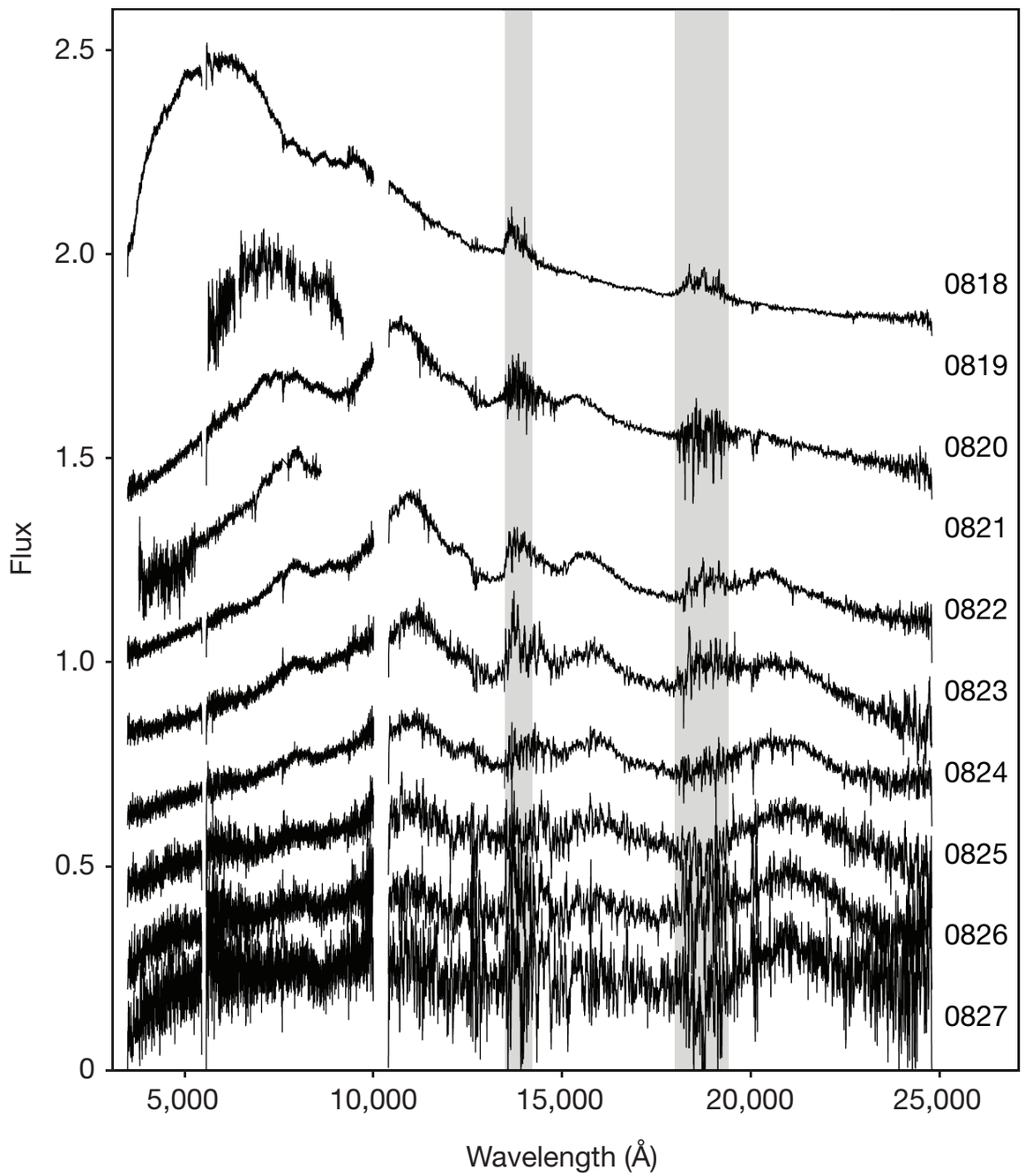

Arcavi+17, Cowperthwaite+17,
Diaz+17, Drout+17,Evans+17,
Kasliwal+17,Pian+17,
Smartt+17, Tanvir+17, Troja+17,
Utsumi, MT+17, Valenti+17

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

# GW170817: Spectra

- Smooth spectra (high velocity)
- Not similar to known transients

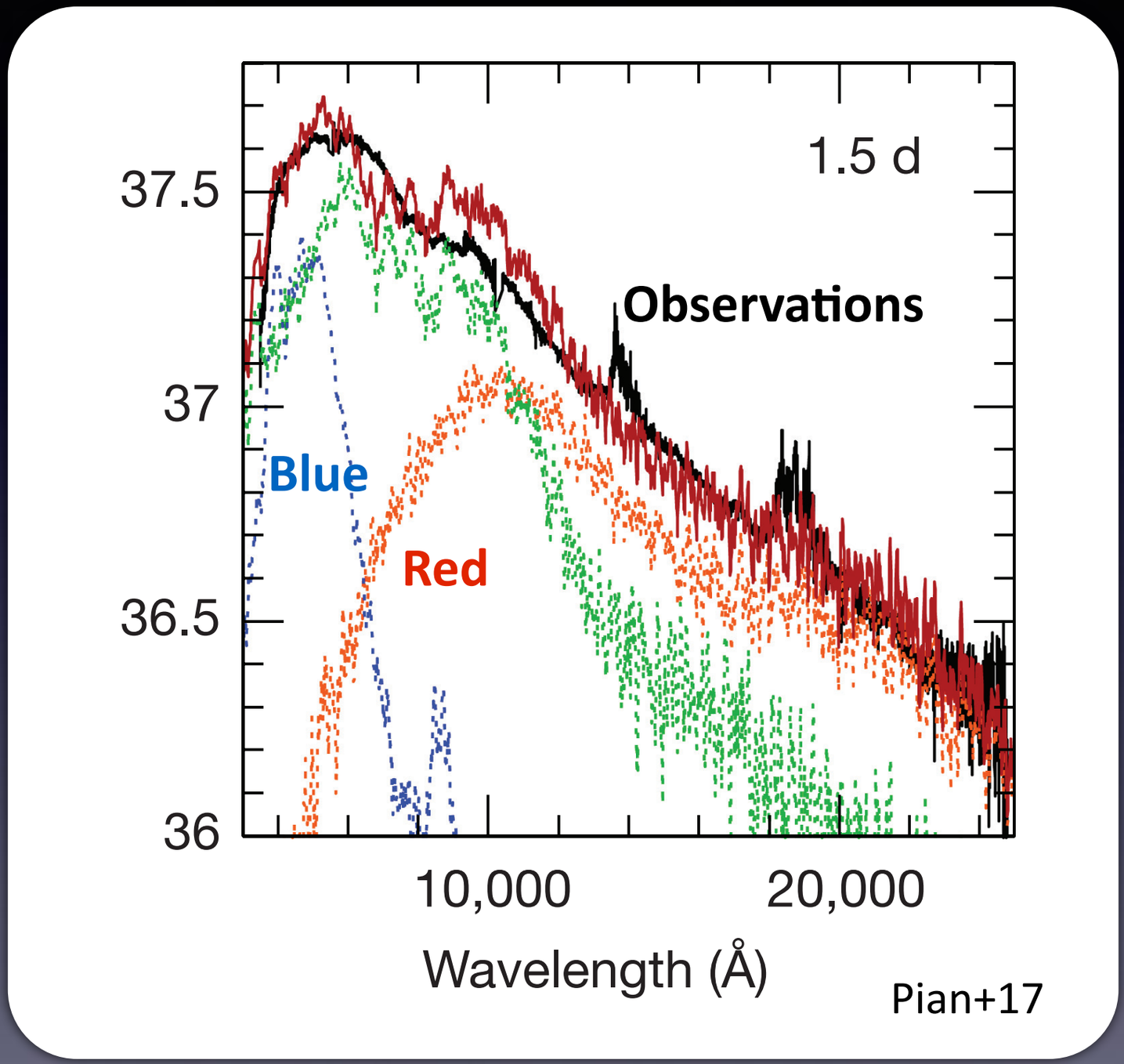
Andreoni+17, Chornock+17, Kilpatrick+17
McCully+17, Nicholl+17, Pian+17,
Shappee+17, Smartt+17




Pian+17

# Presence of blue kilonova

Kasen+17, Metzger 17, MT+17




**Signature of lighter r-process elements**
**M ~ 0.02 Msun**

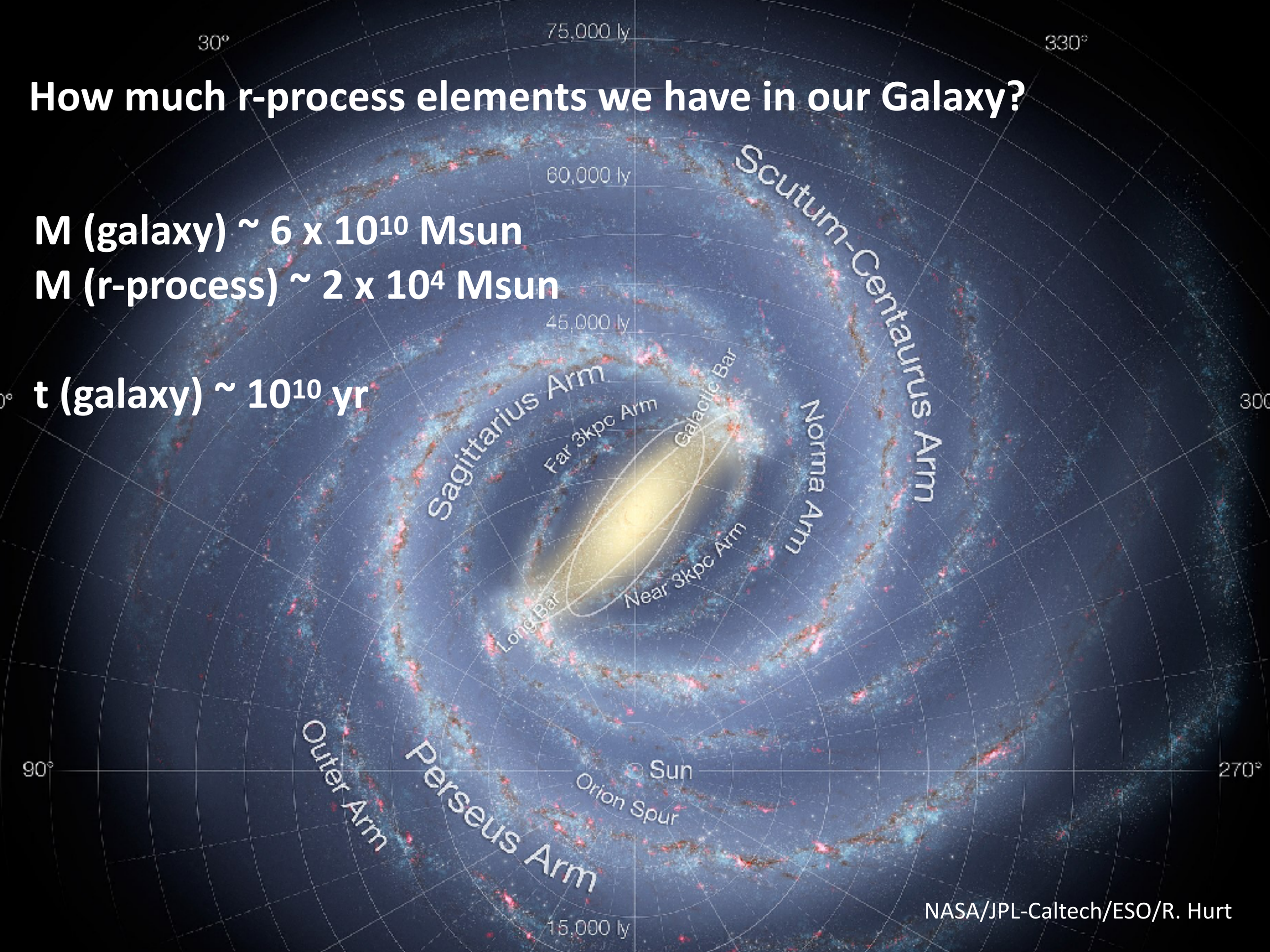
# Electromagnetic signatures of r-process nucleosynthesis

- Kilonova: Electromagnetic signal from NS merger
- GW170817 and observations of kilonova
- Origin of the r-process elements

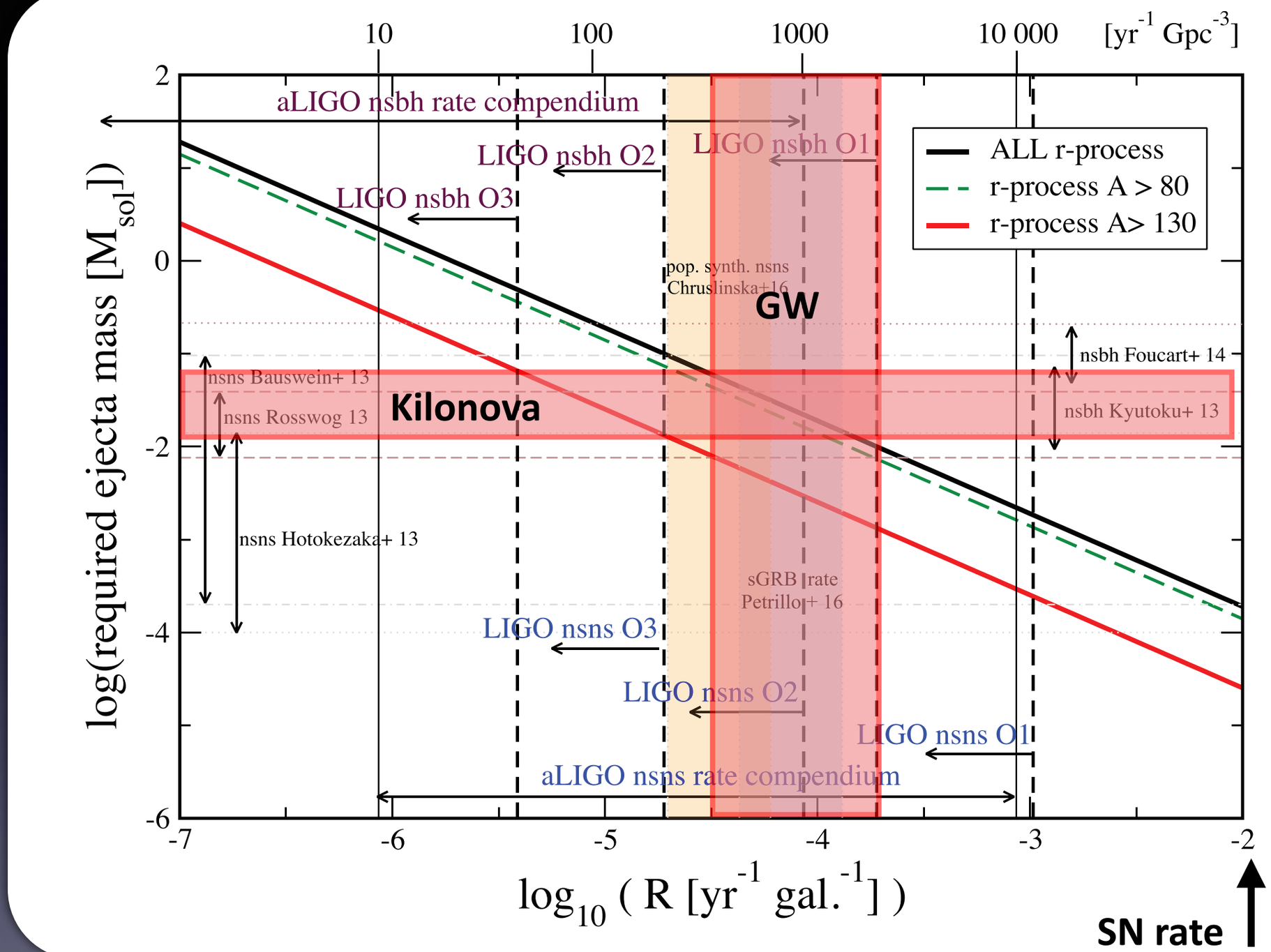
# How much r-process elements we have in our Galaxy?

**M (galaxy) ~ 6 x $10^{10}$ Msun**
**M (r-process) ~ 2 x $10^{4}$ Msun**

**t (galaxy) ~ $10^{10}$ yr**




NASA/JPL-Caltech/ESO/R. Hurt




Rosswog+17, Hotokezaka+15, 18

Caveat: constant event rate over time, “closed box” galaxy, …

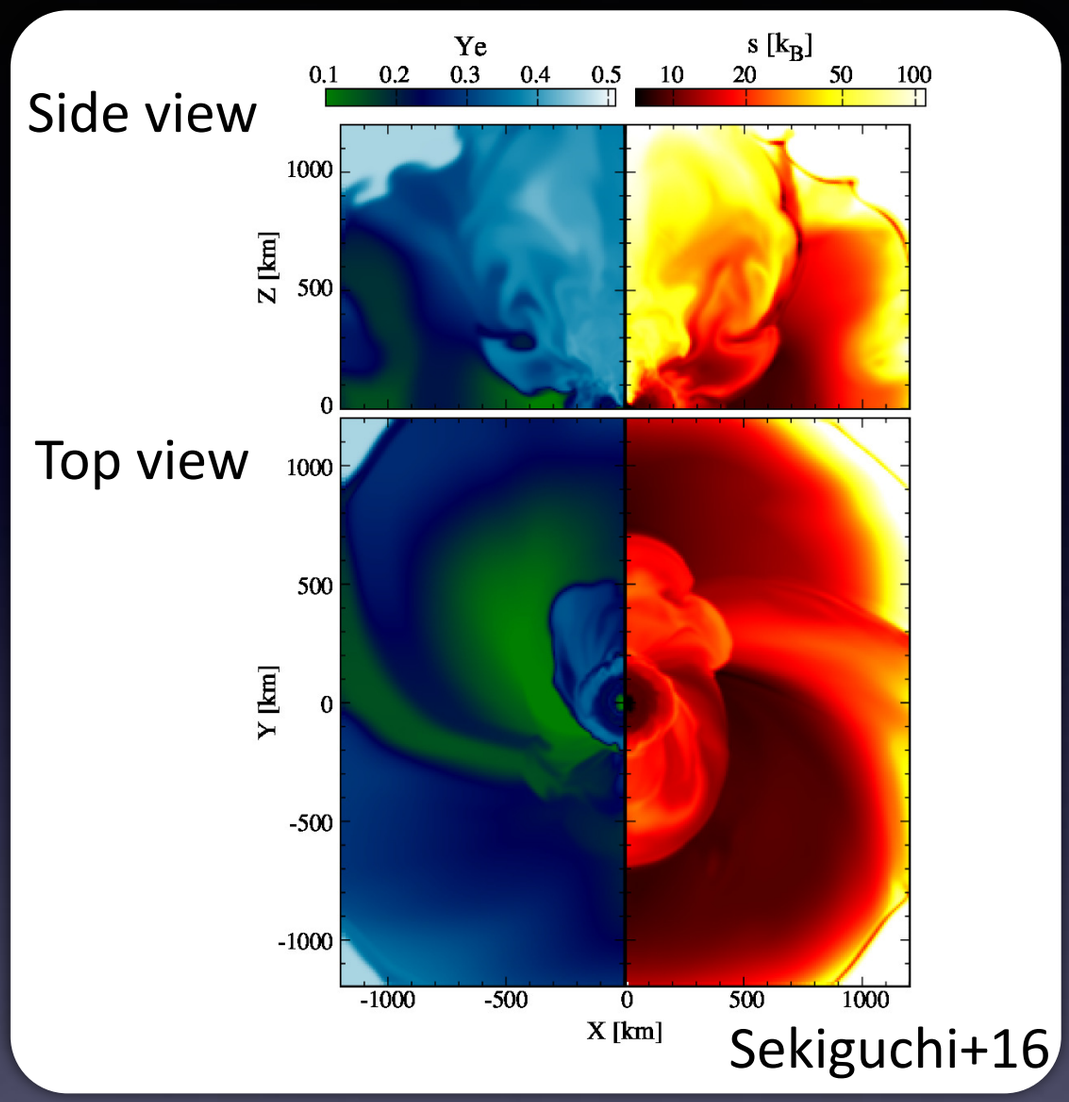
## What we have learned from GW170817

- Red kilonova => production of lanthanide elements
- Blue kilonova => production of lighter r-process elements
- Production rate (rate x yield) explains the total abundance

## Open issues

- What is the origins of blue/red kilonova?
- Which is element abundance pattern?
  Similar to solar abundance ratios?

# Dynamical ejecta (~< 10 ms)

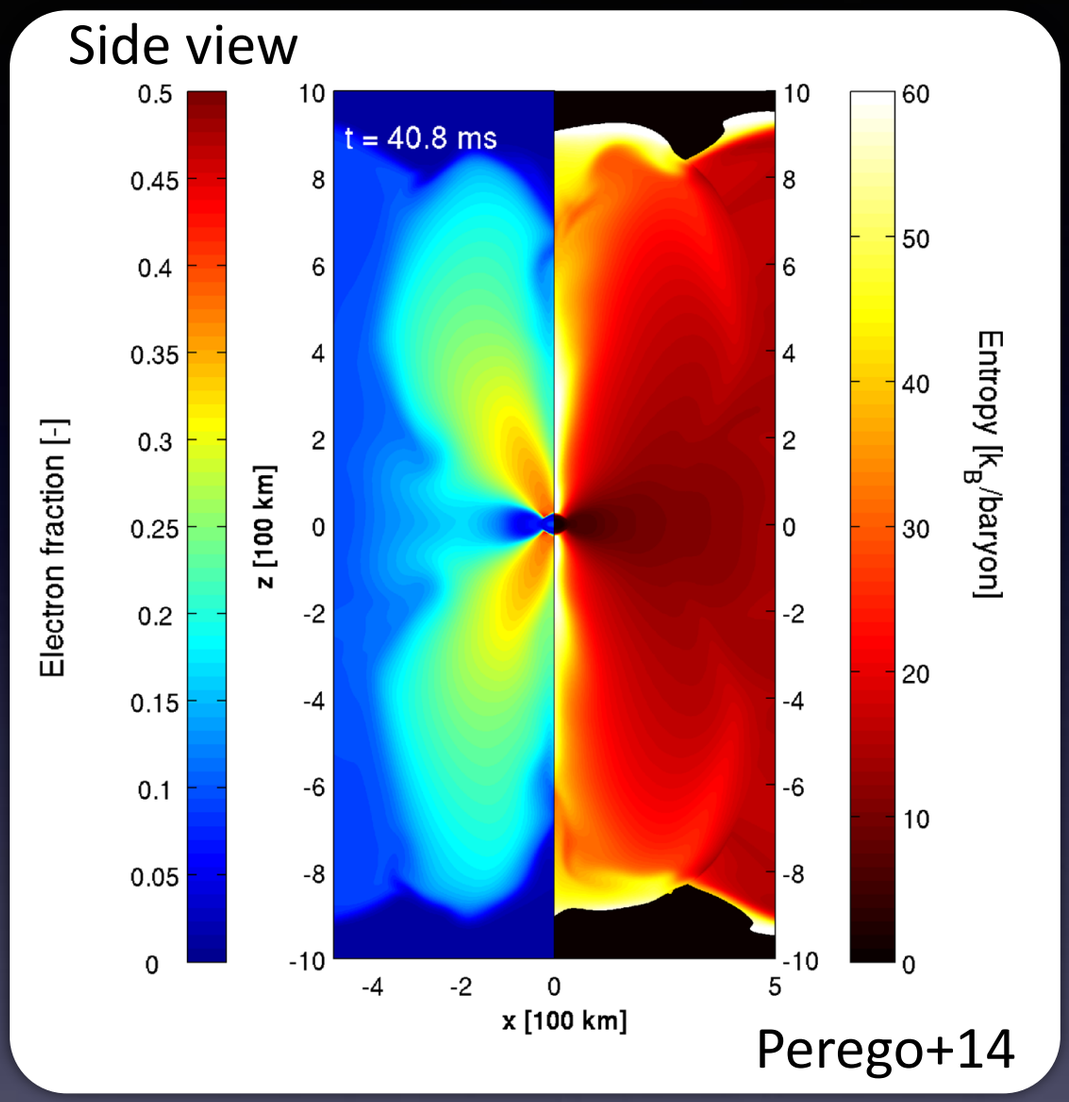



Sekiguchi+16

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

**=> Red kilonova?**

# Post-dynamical ejecta (~< 100 ms)




Perego+14

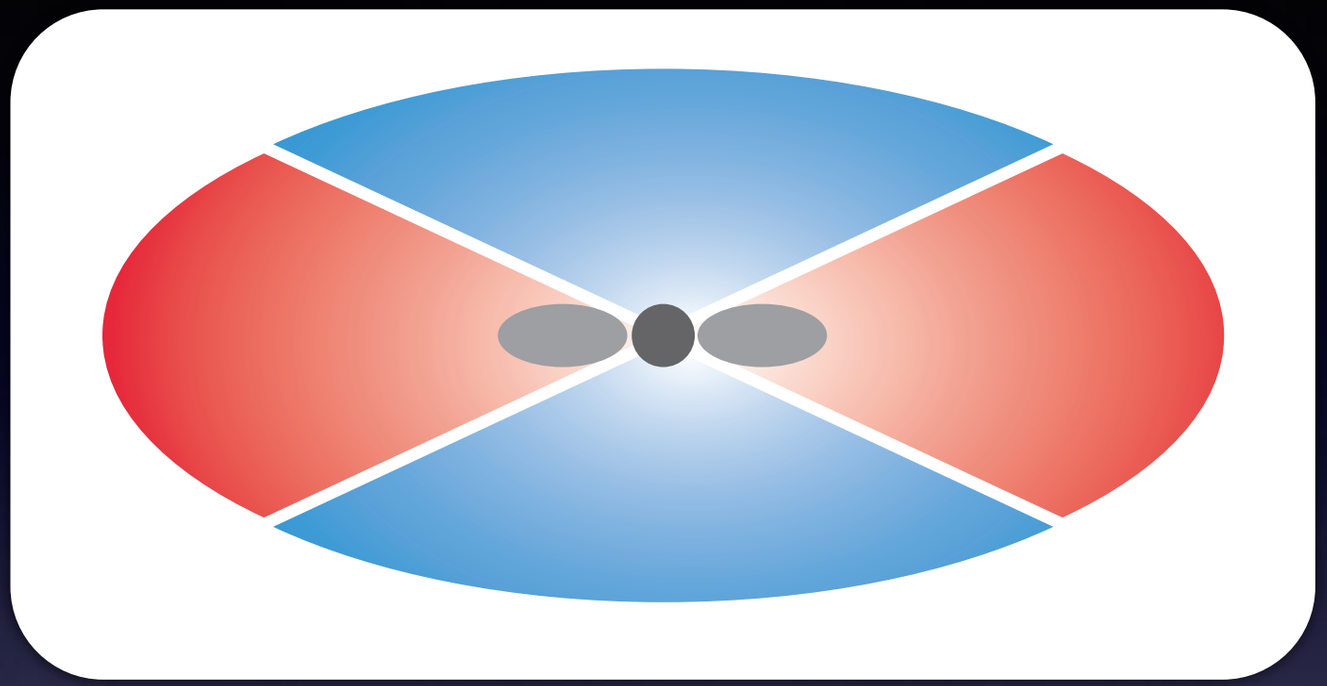
**Mej >~ $10^{-3}$ Msun**
**v ~ 0.05 c**
**Relatively high Ye**

**=> Blue kilonova?**

**M. Shibata's and A. Arcones's talks**

# What is the origin of blue/red kilonova?

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



**Blue kilonova**

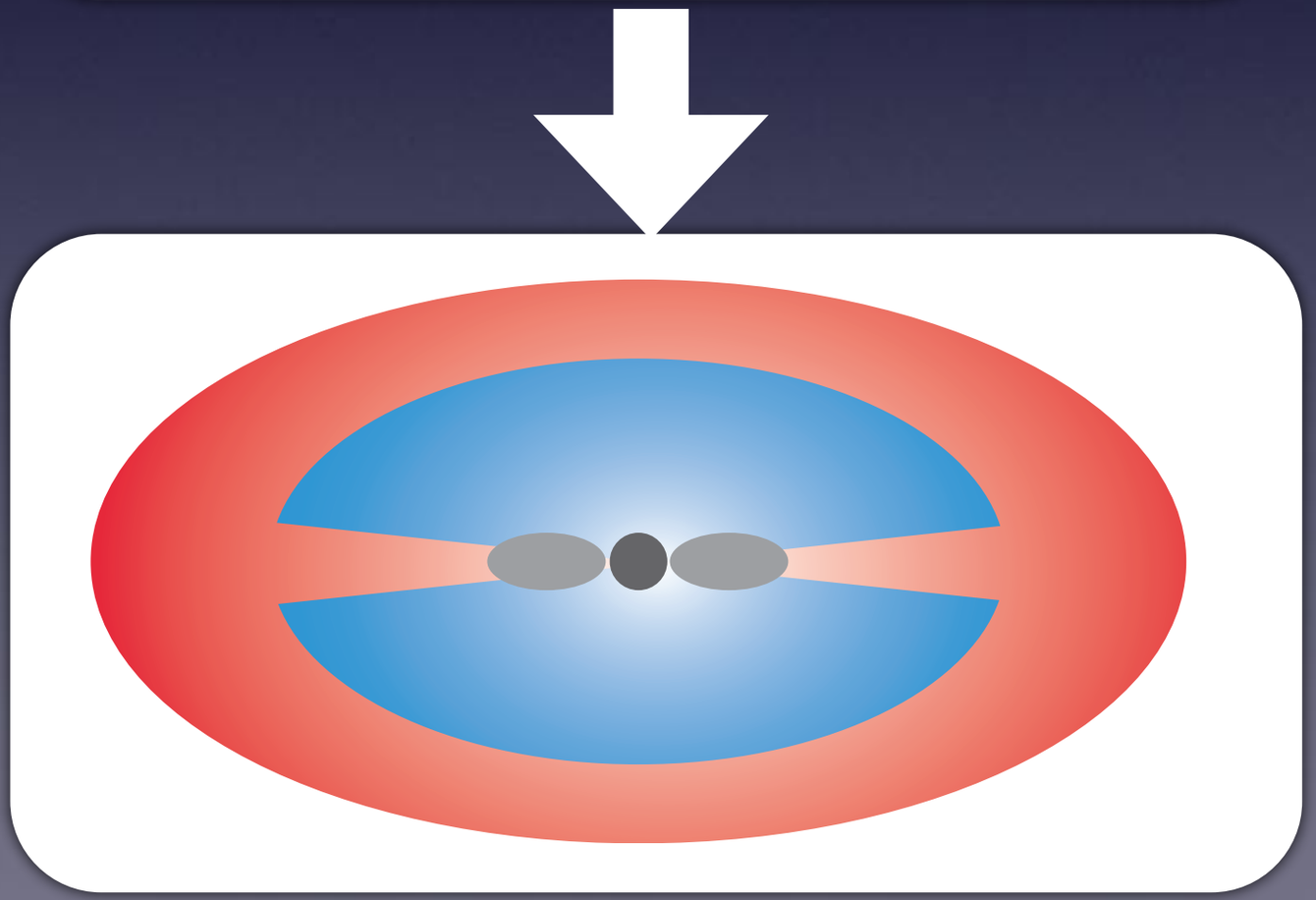
**M ~ 0.02 Msun**

**v ~ 0.25c** Too fast as post-merger ejecta??

**Red kilonova**

**M ~ 0.03 Msun**

**v ~ 0.1 c** Too massive as dynamical ejecta??

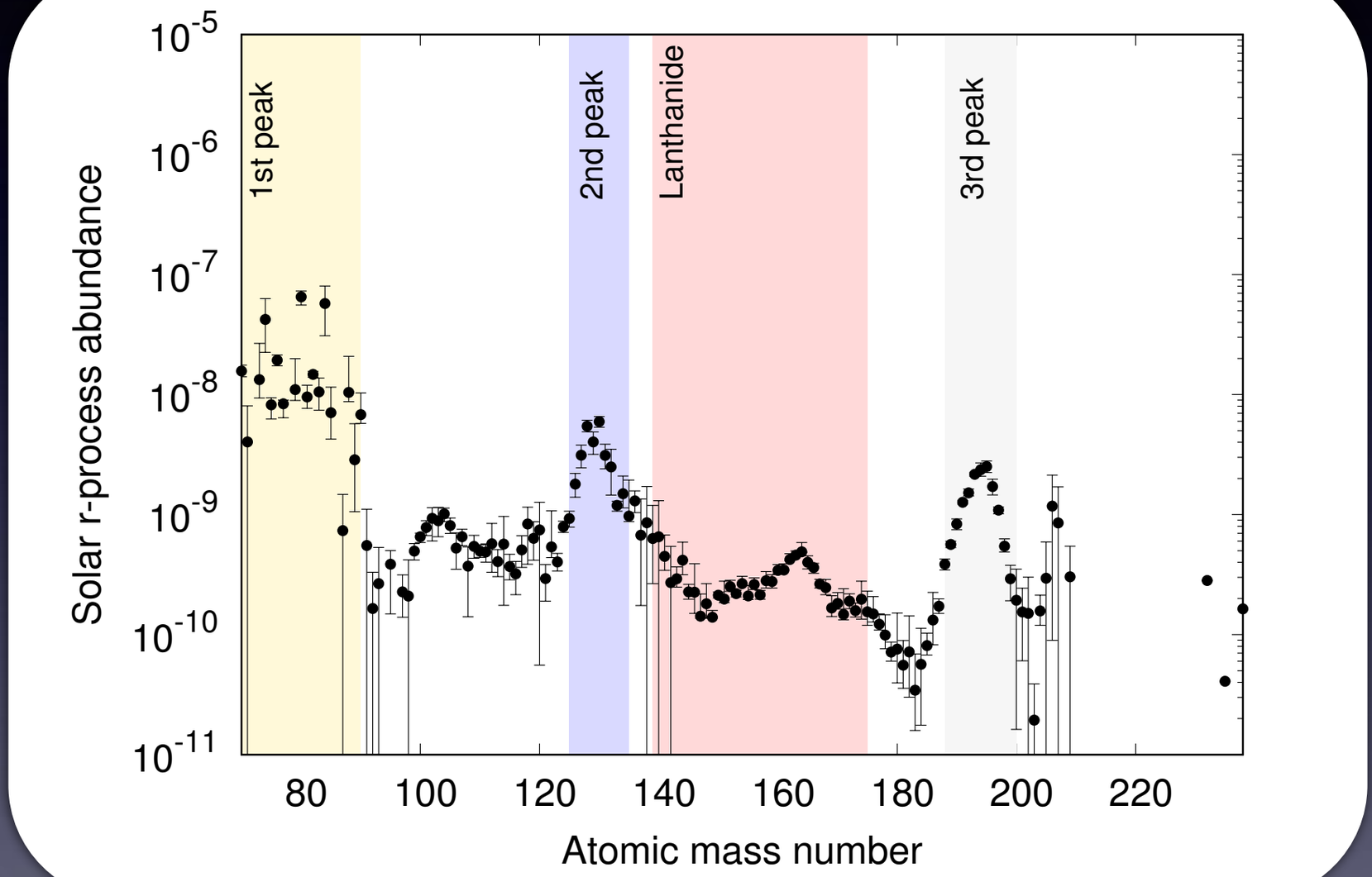


**Post-merger ejecta**
**Inside of dynamical ejecta**
(less dynamical ejecta near the pole)

**What is the abundance pattern that NS merger produces?**

**see J. Lattimer's And A. Frebel's talk**

**Solar abundance ratios**




Hotokezaka+18

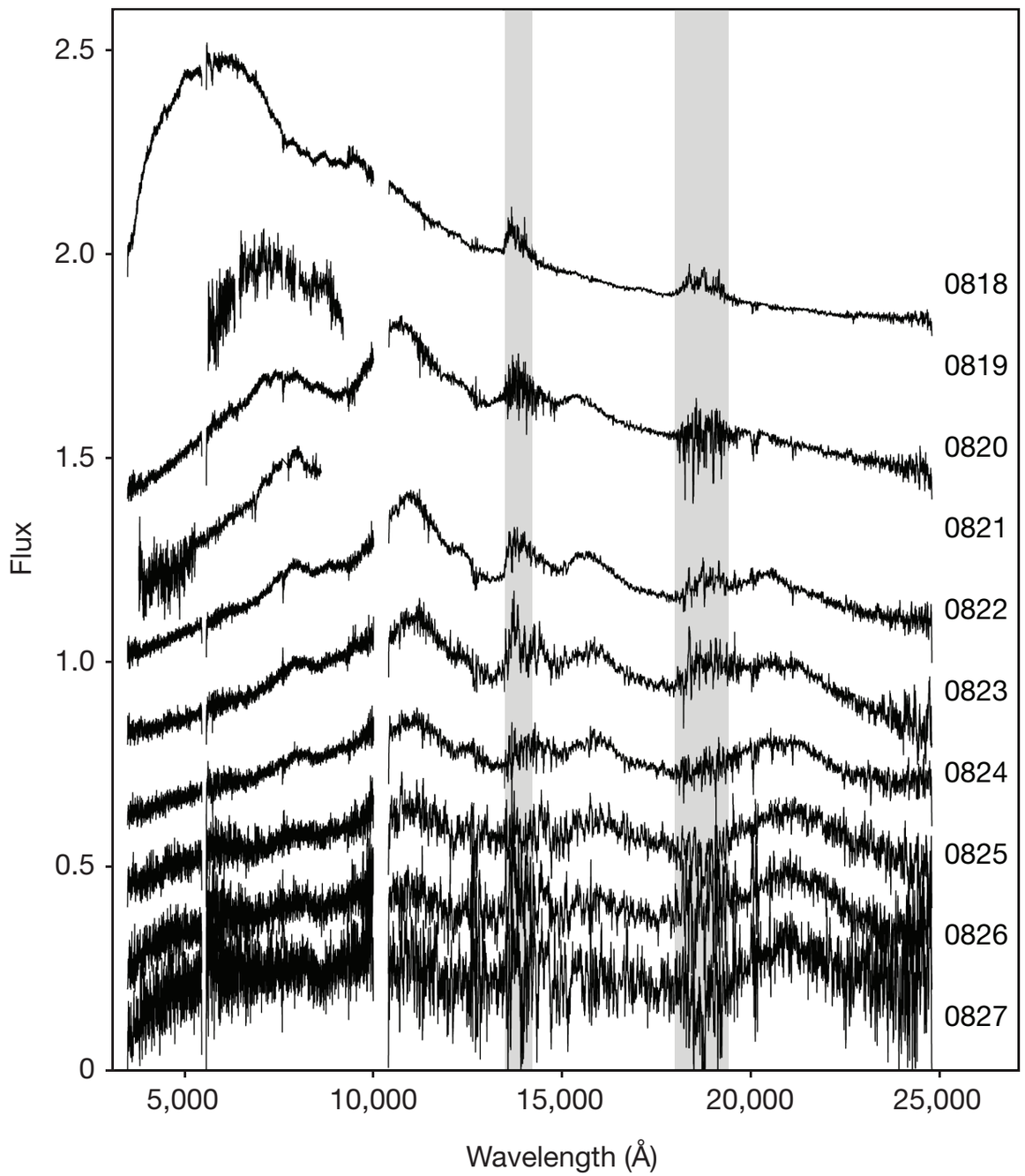
**GW170817**
**- lanthanides**
**- lighter elements**

**Not yet clear if NS mergers reproduce solar abundance ratios**

# GW170817: Spectra

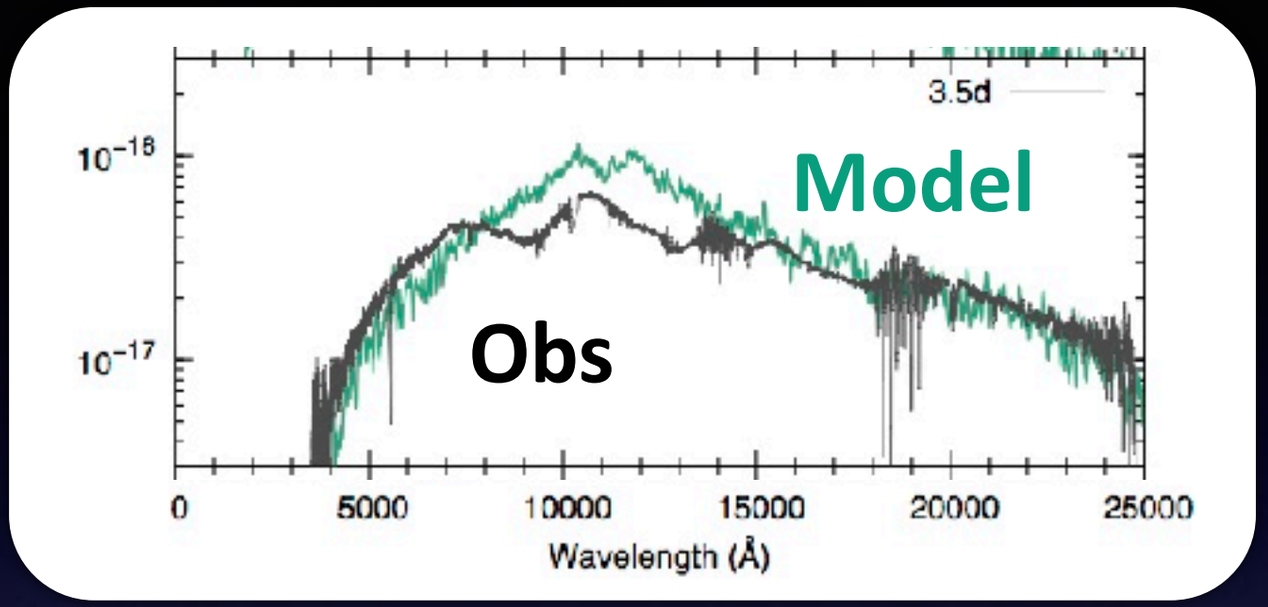
- Smooth spectra (high velocity)
- Not similar to known transients

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



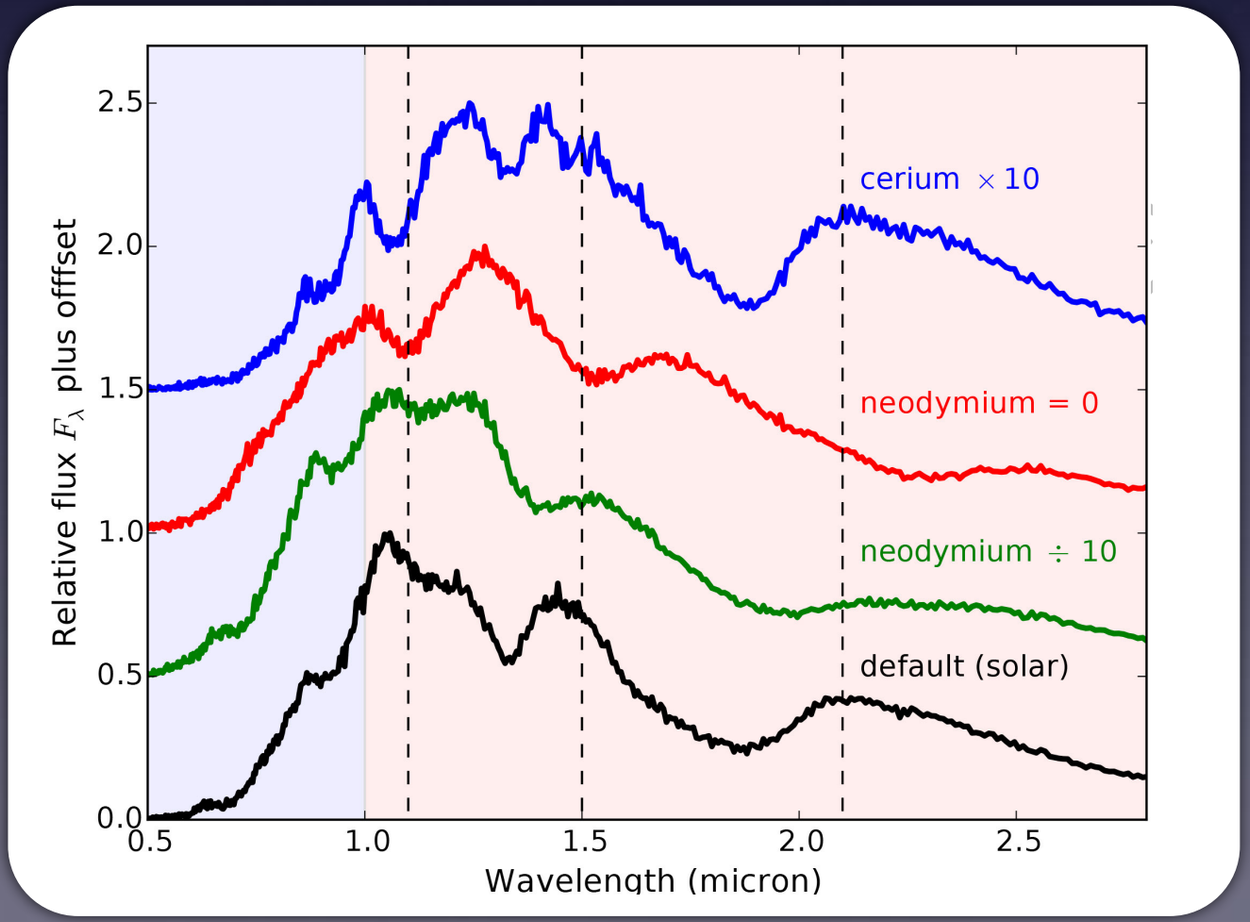

Pian+17

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

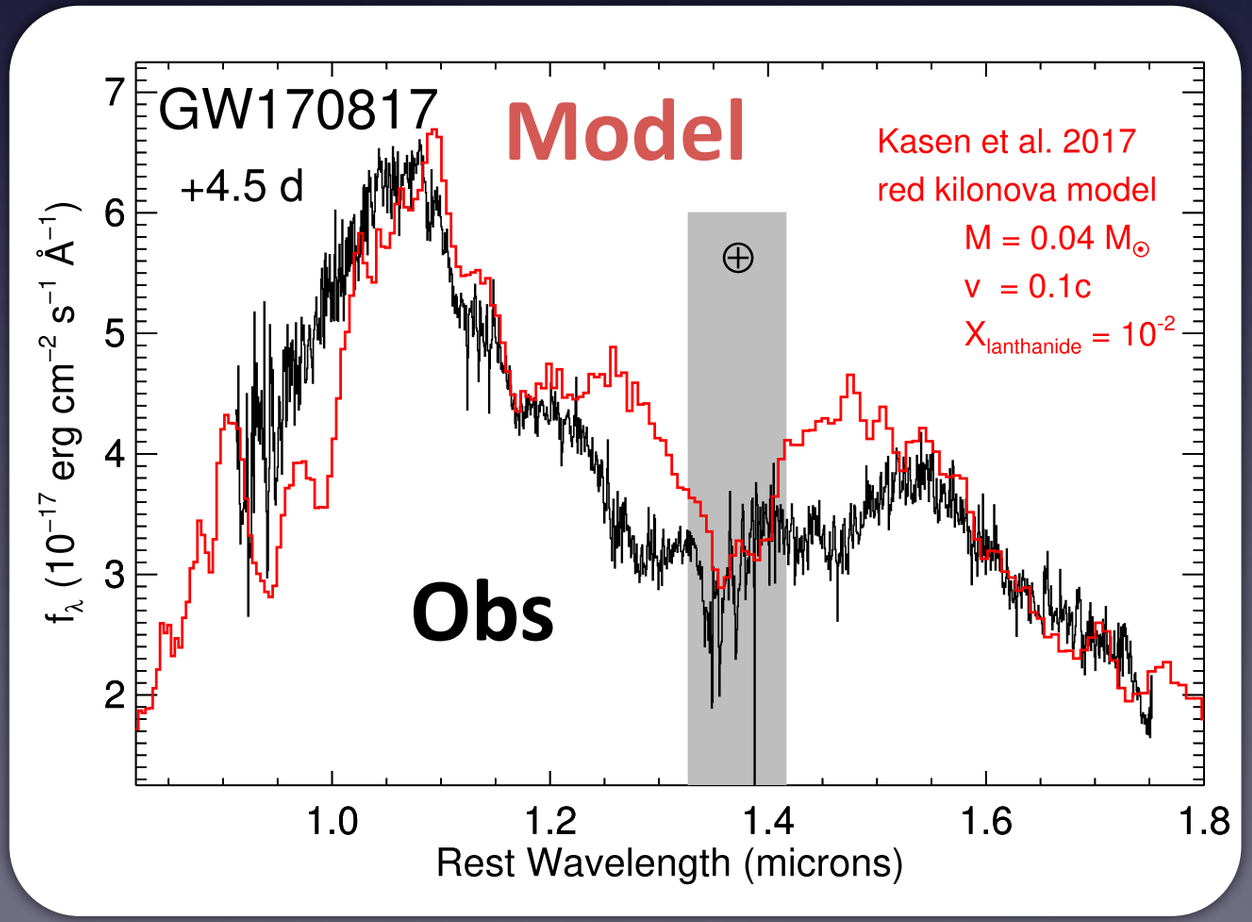



MT+17

**Model**




Kasen+17




Chornock+17

# Atomic calculations

**open s shell (l=1)**

**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**

**open p-shell (l=2)**

**open d-shell (l=3)**

**open f shell (l=4)**

**1st peak**

**2nd peak**

**3rd peak**

# Summary

- **Kilonova: signature of r-process nucleosynthesis**
  - Detected for GW170817
  - Both red and blue components
    => Production of lanthanide and higher elements
  - Production rate fulfills the necessary condition
    (but abundance patterns are not well constrained)
- **Future prospects**
  - Astrophysics: Consistent modeling from merger to kilonova
  - Atomic physics: Improvement in heavy element data
  - Test with future GW + EM observations
    Event rate, yield, and abundance patterns
    (with different masses and viewing angles)