UU Astronomy and Space Physics seminar
13th April, 2023

Early kilonova emission from neutron star mergers

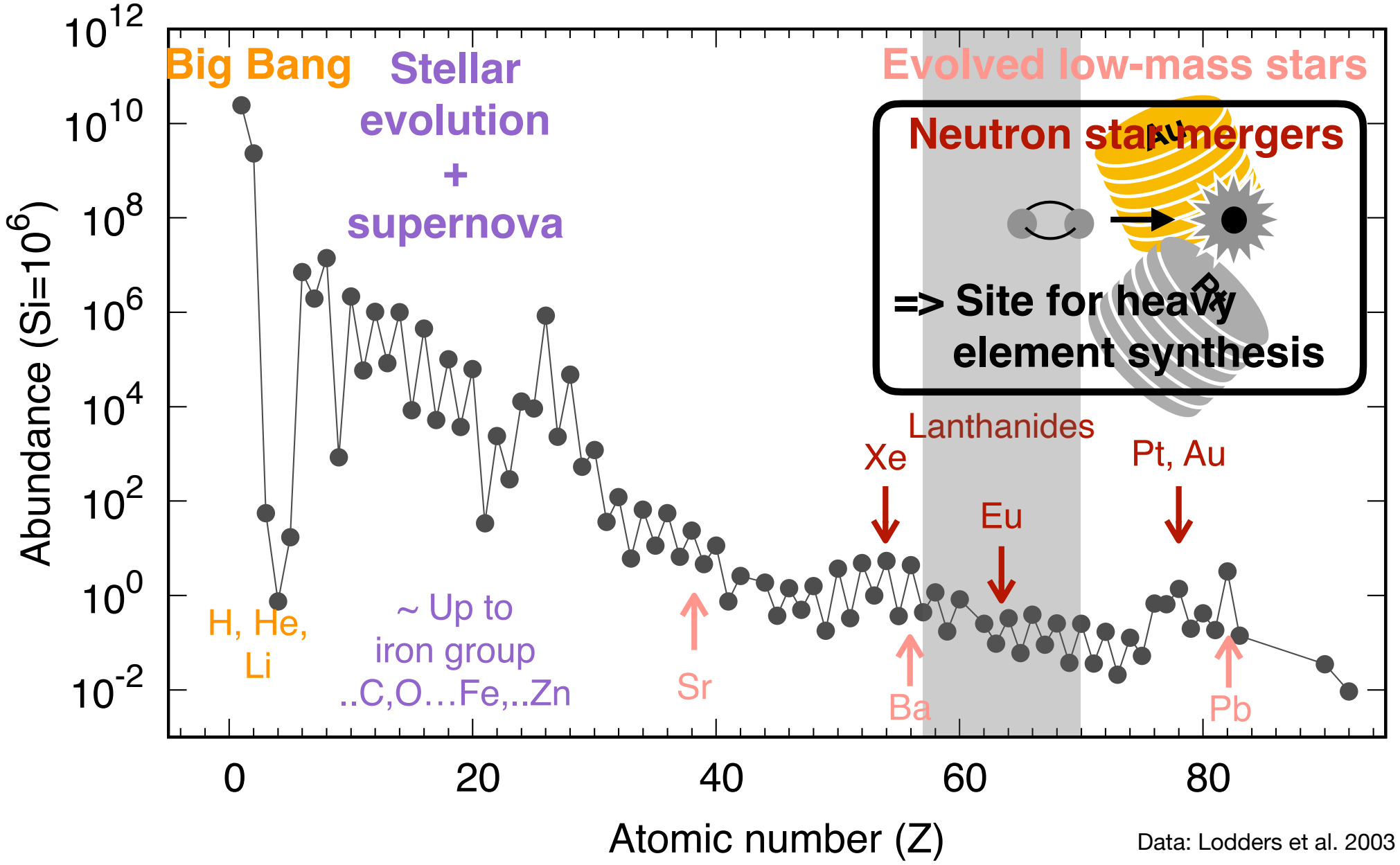
Or

A story of cosmic treasure hunt

Smaranika Banerjee

- Banerjee, Tanaka, Kawaguchi, et al. 2020, ApJ, 901, 29
- Banerjee, Tanaka, Kato, et al. 2022, ApJ, 934, 117
- Banerjee, Tanaka, Kato, Gaigalas, 2023, Submitted to ApJ
  https://arxiv.org/abs/2304.05810

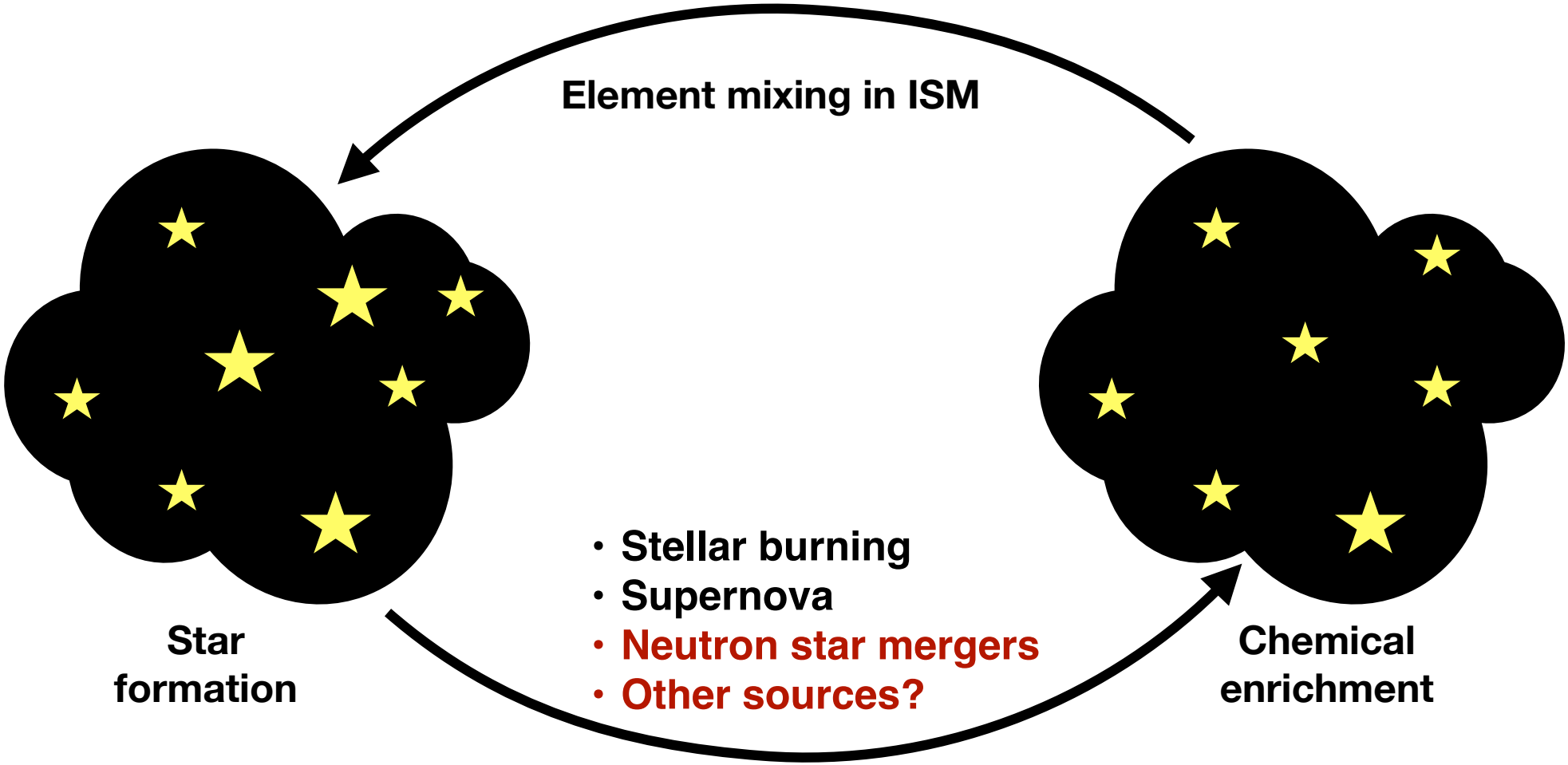
Cosmic treasure hunt



Data: Lodders et al. 2003

Chemical enrichment history

Stars of today bear memory of their origin ⇨ **Galactic chemical evolution**



Outline

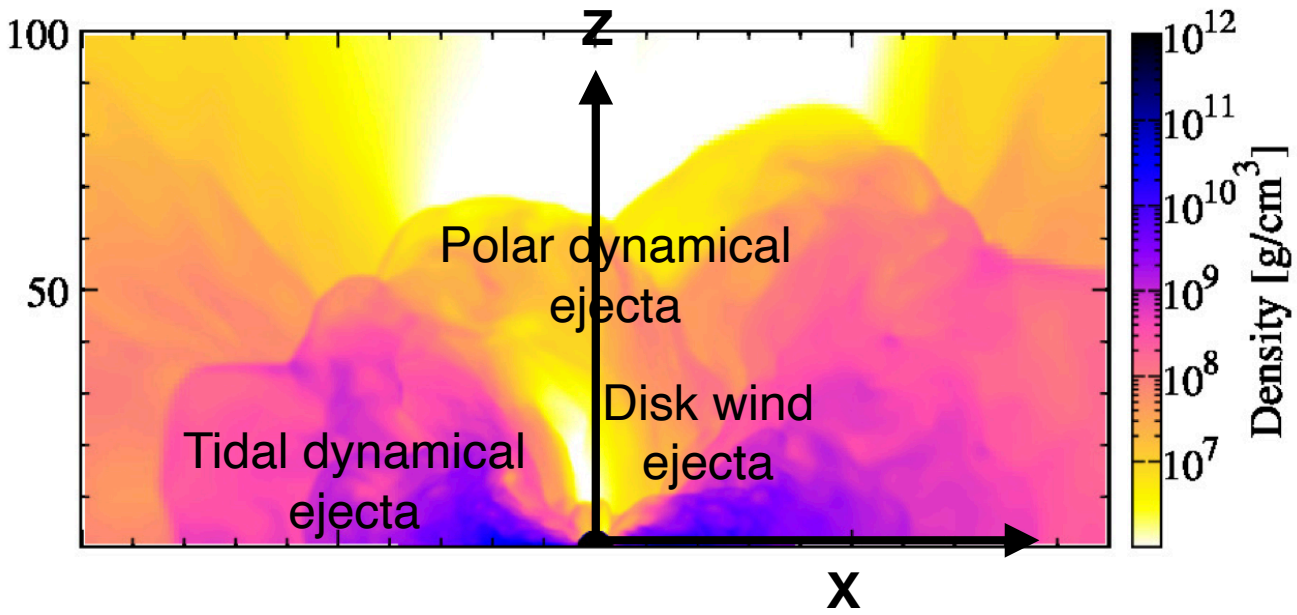
- **Neutron star merger & kilonova**
- **Atomic opacity for kilonova**
- **Kilonova modelling**

Neutron star mergers

Neutron star :
Remnant of massive stars

Mass ~ 1- 2Msun

$$M_{\rm ej} \sim 0.01 M_\odot$$
$$v_{\rm ej} \sim 0.1c$$

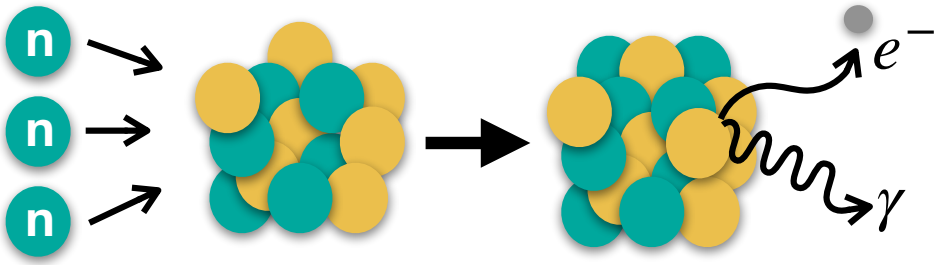


Sekiguchi et al. 2016

Neutron star mergers

Nucleosynthesis by rapid neutron capture

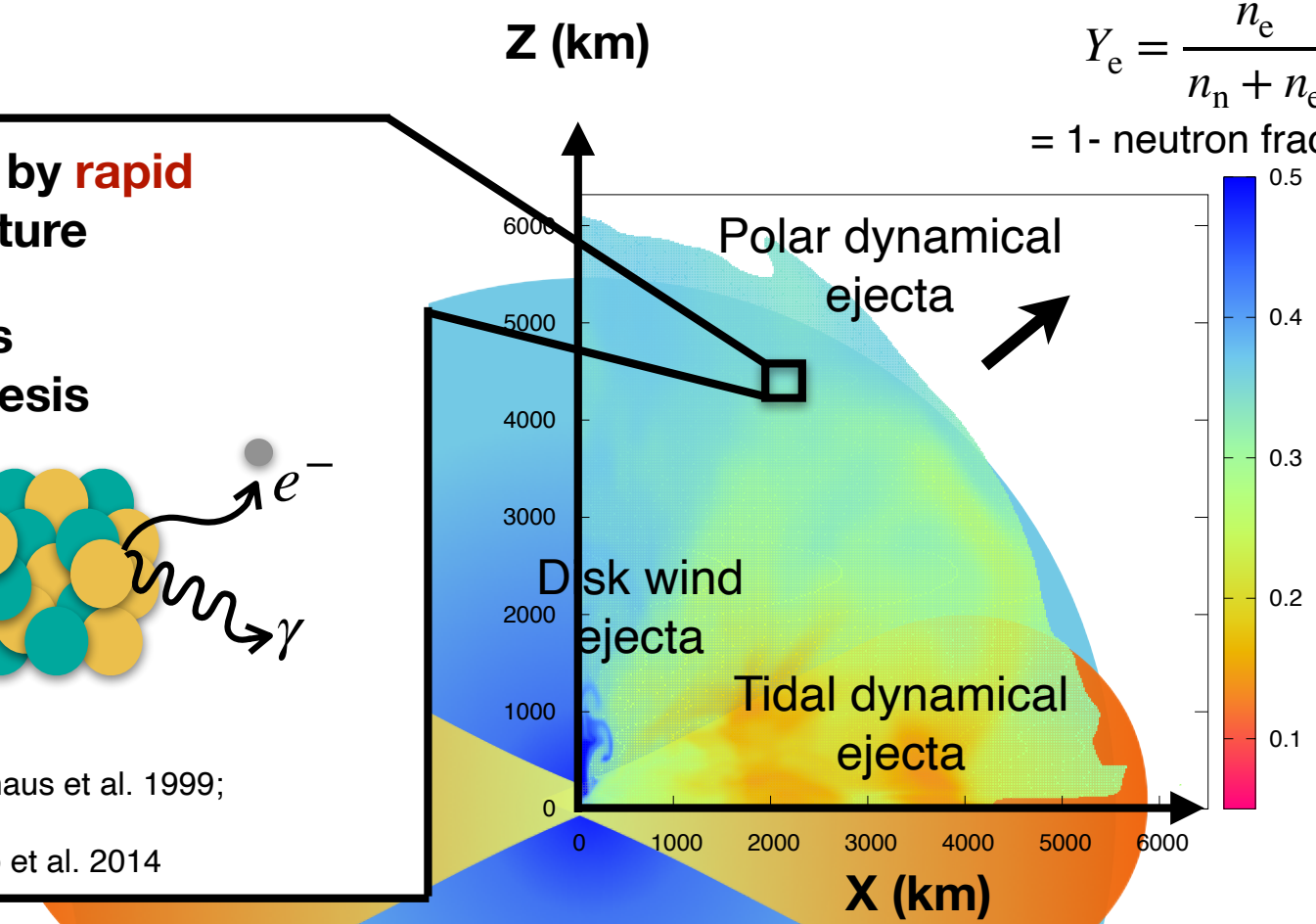
r-process nucleosynthesis



Lattimer & Schramm 1974;
Eichler et al. 1989; Freiburghaus et al. 1999;
Rosswog et al. 1998, 1999,
Korobkin et al. 2012; Wanajo et al. 2014

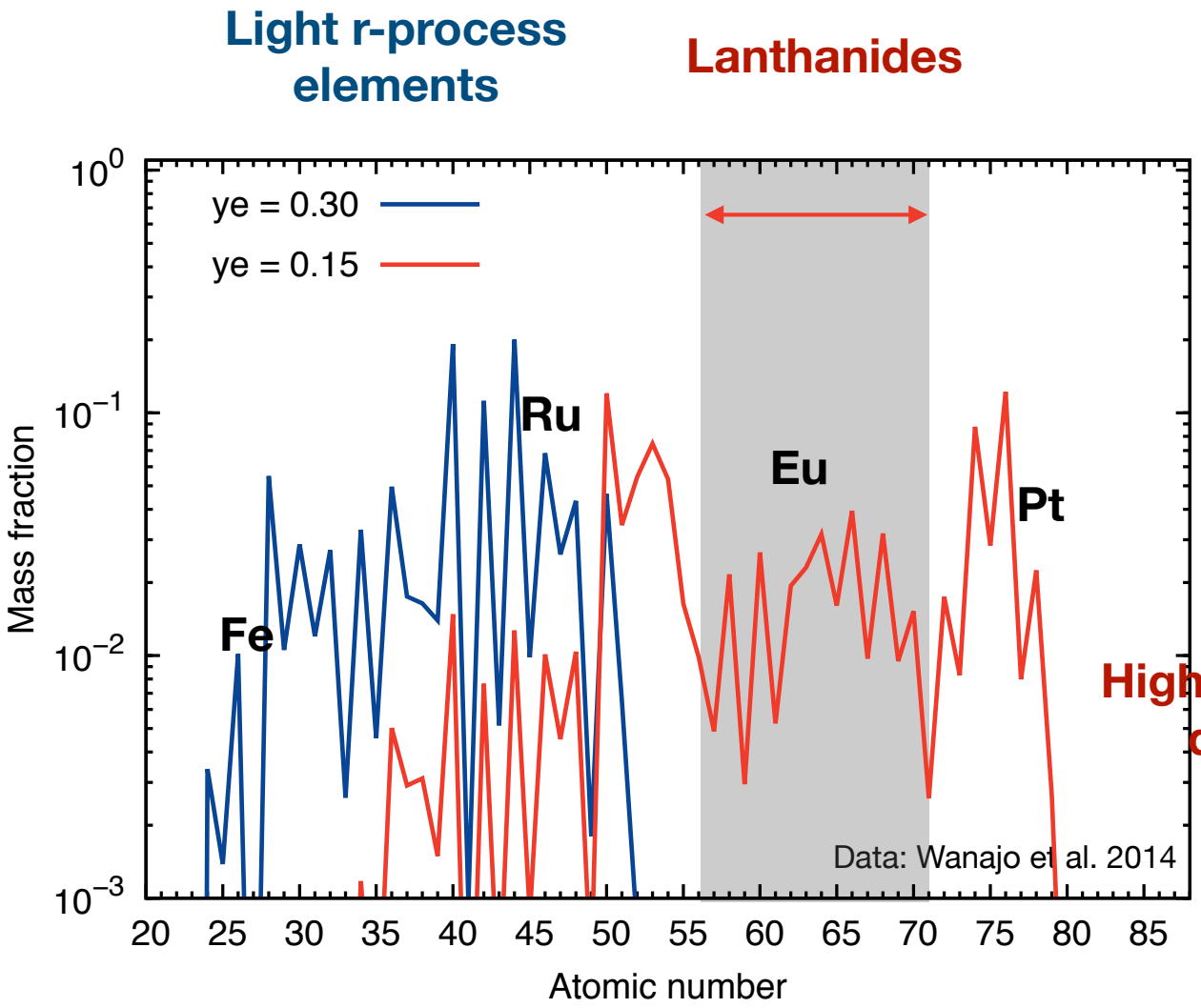
$$Y_e = \frac{n_e}{n_n + n_e}$$

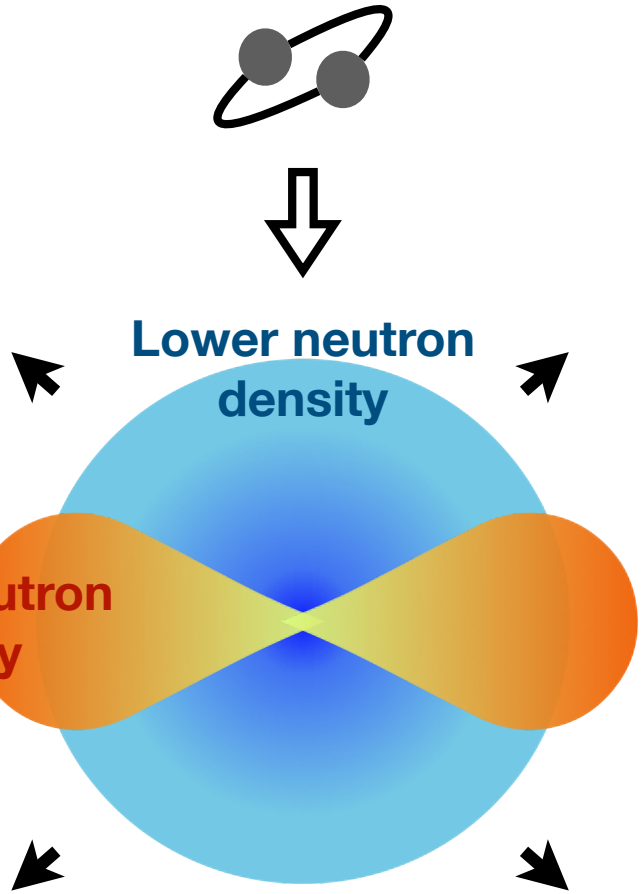
= 1- neutron fraction



Data : Fujibayashi et al. 2022

Abundances





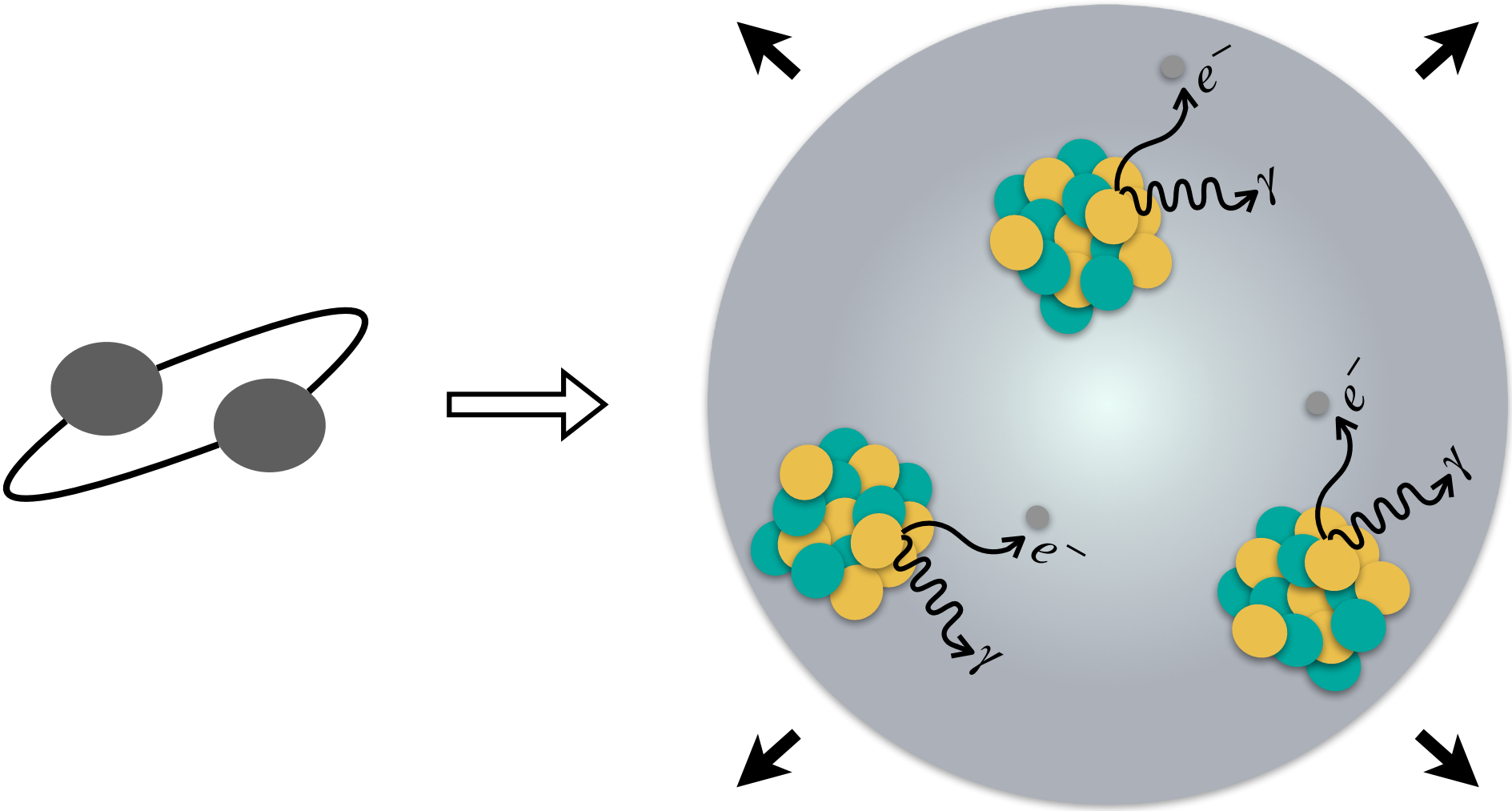
Lanthanide-free abundance
=> Distributed near pole/ isotropically

Lanthanide-rich abundance
=> Distributed towards tidal direction

Kilonova

NS-NS merger

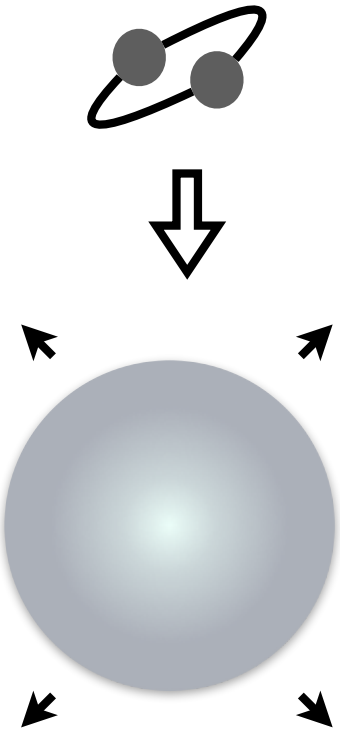
r-process nucleosynthesis



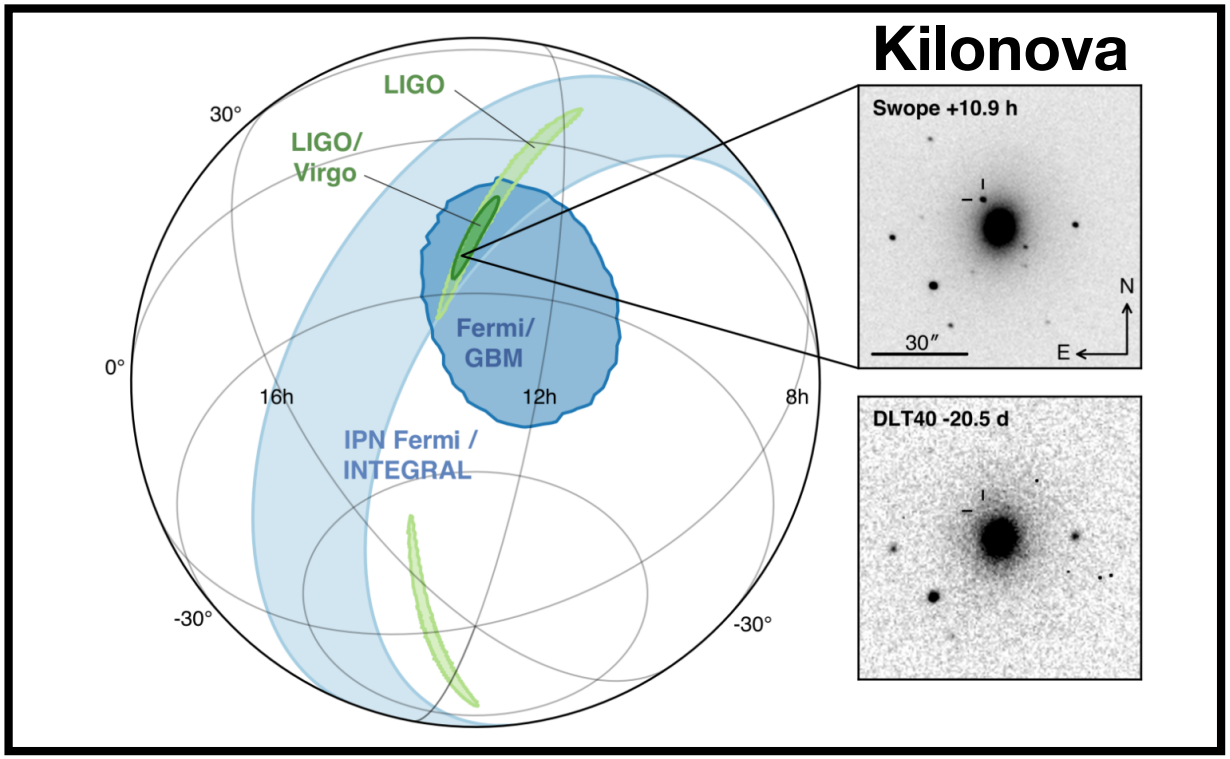
Radioactive decay of heavy elements =>
Thermal radiation => kilonova (~ days - weeks)

Li & Paczynski 1998;
Kulkarni 2005; Metzger et al. 2010

Observations



O2: GW170817



e.g., Coulter et al 2017; Soares-Santos et al 2017; Arcavi et al 2017a; Troja et al 2017; Kilpatrick et al 2017; Smartt et al 2017; Drout et al 2017; Evans et al 2017; Abbott et al 2017d; Utsumi et al 2017; Covino et al 2017

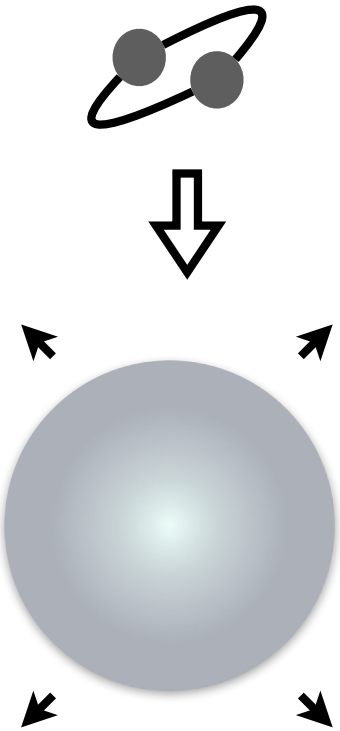
O3: GW190425

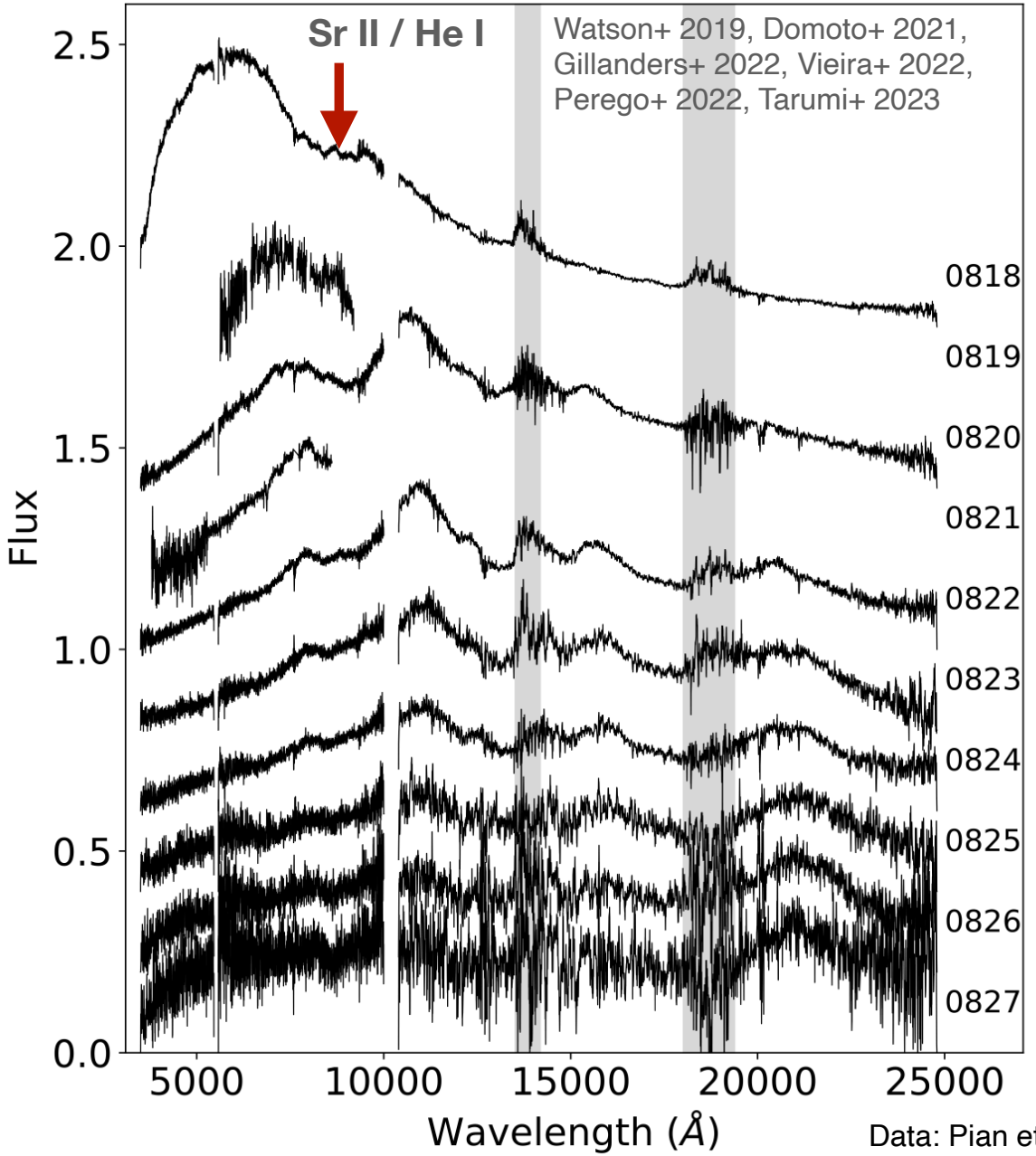
Gravitational wave detected
No electromagnetic counterpart

Coughlin et al 2019; Hosseinzadeh et al. 19; Lundquist et al.2019; Sasada et al. 2021

O4 (starts May, 2023)?

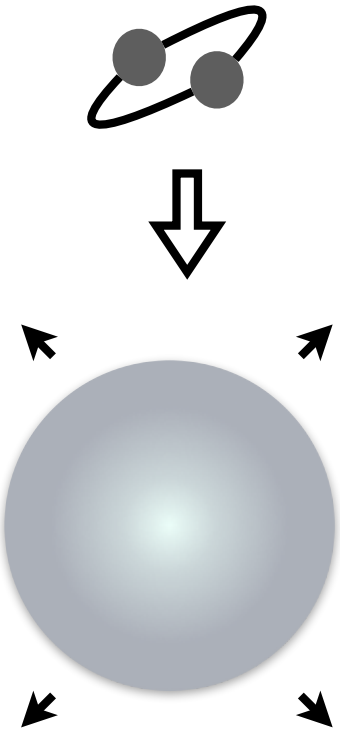
Kilonova AT2017gfo

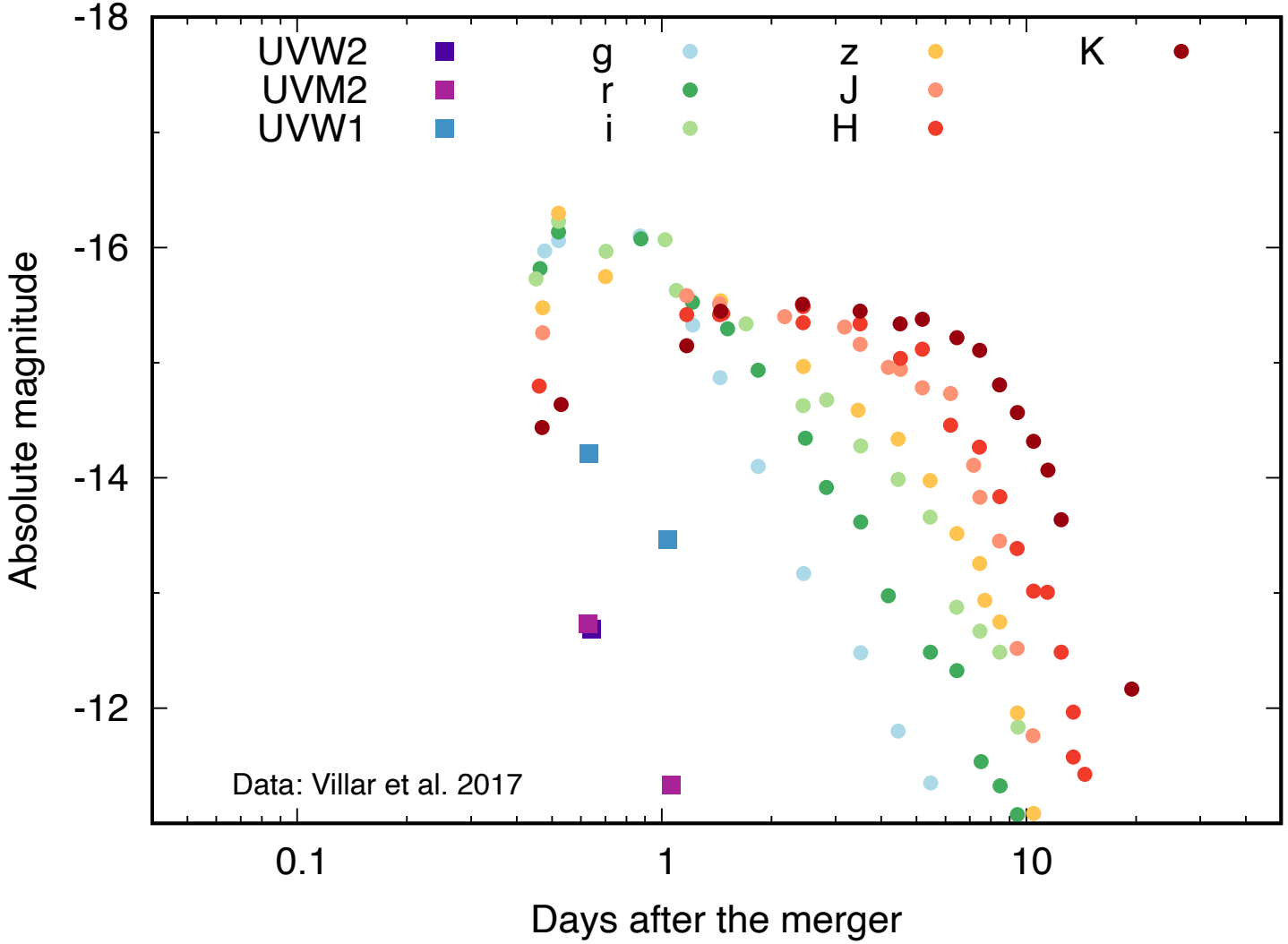




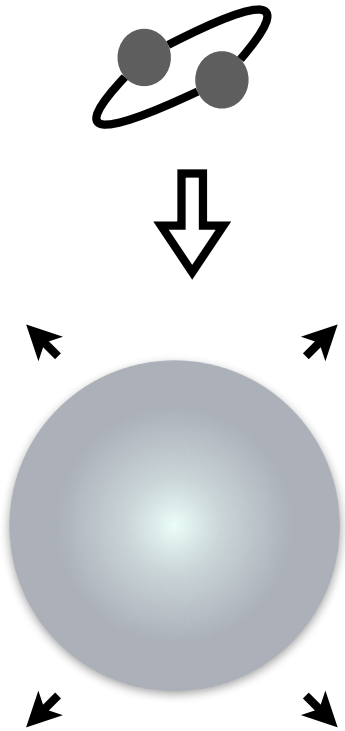
Data: Pian et al. 2017

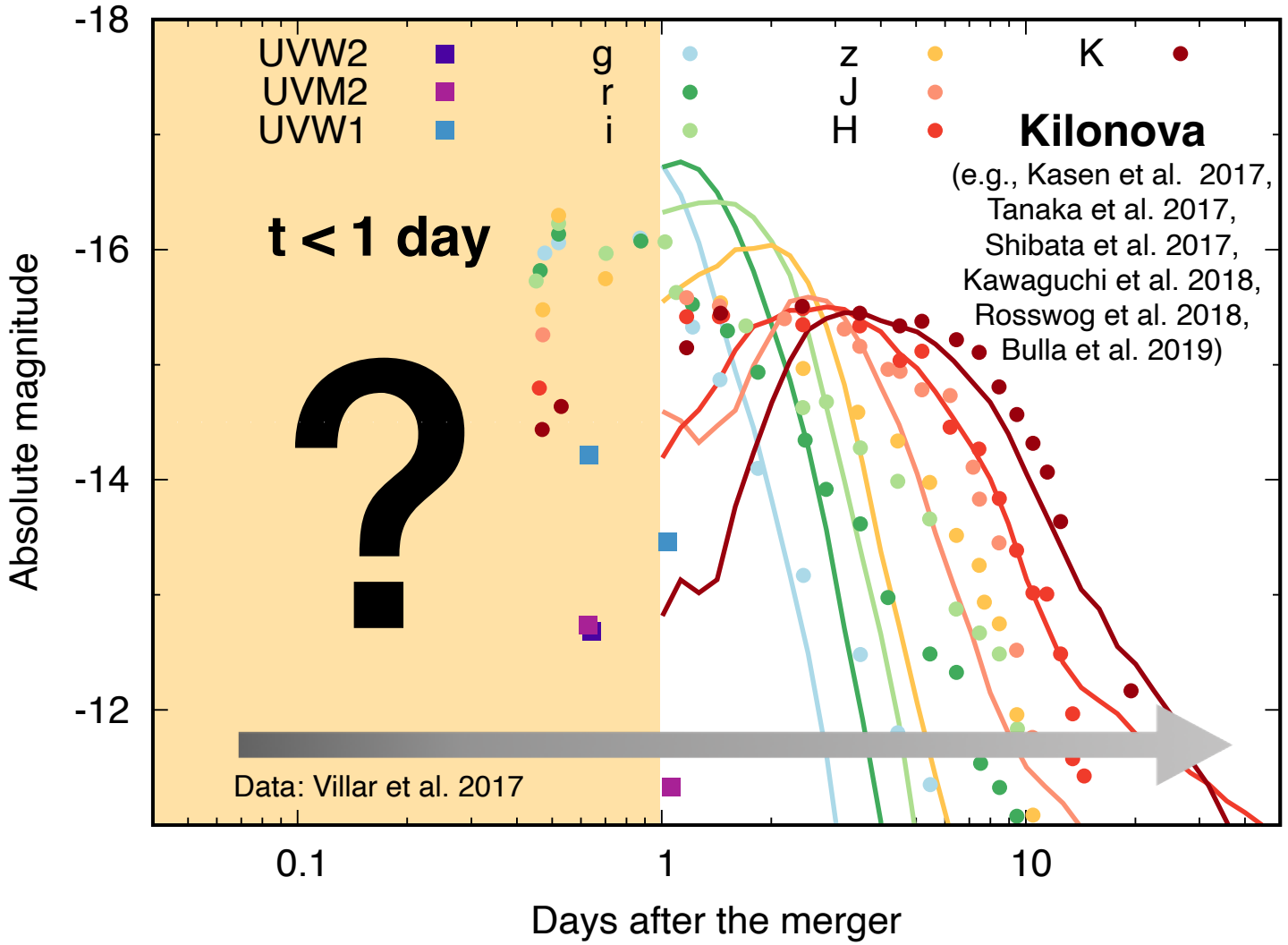
Kilonova AT2017gfo





Kilonova AT2017gfo

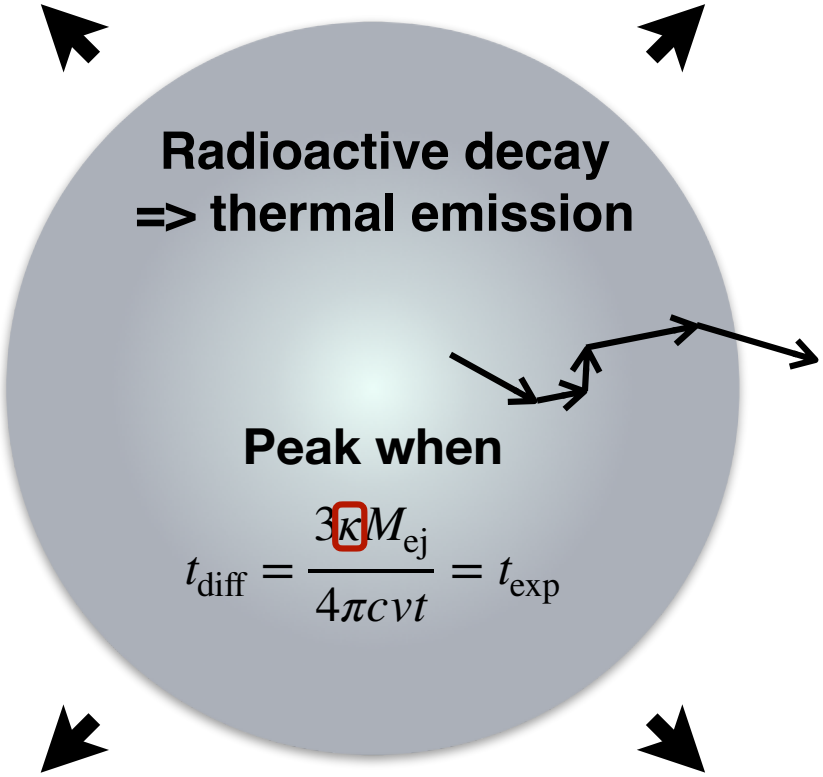


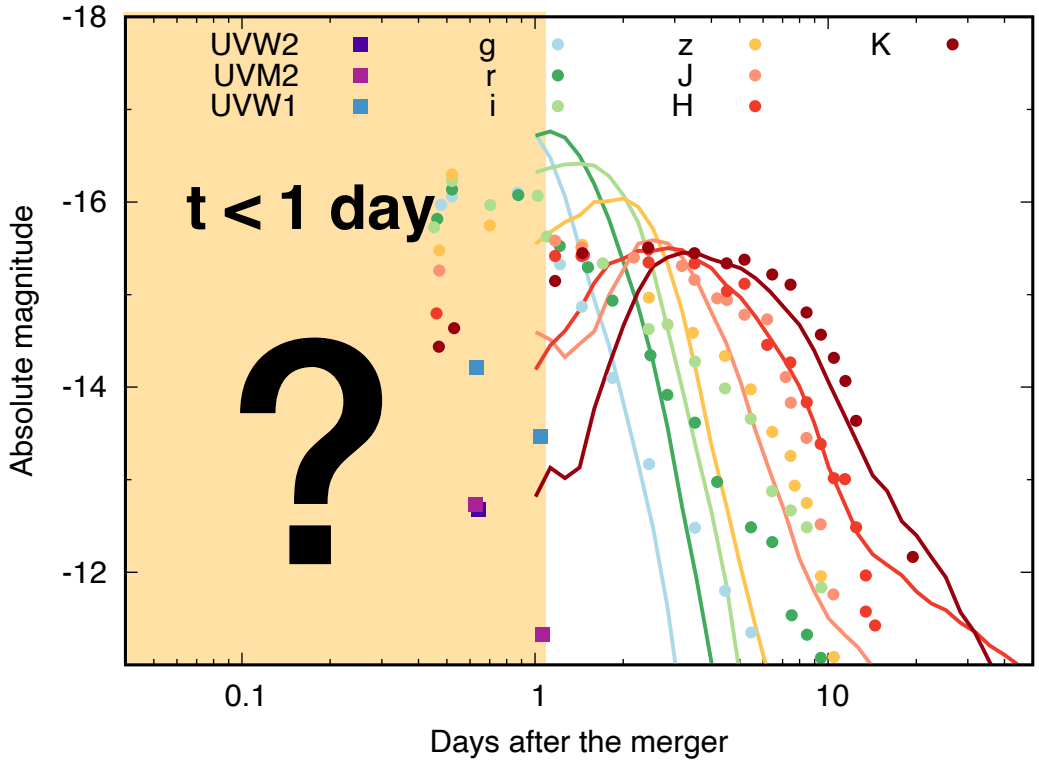


Abundance pattern of **outer** to **inner** ejecta
<- **early** to **late** kilonova

Reproduce solar abundance pattern?
-> Only source?

What do we need?



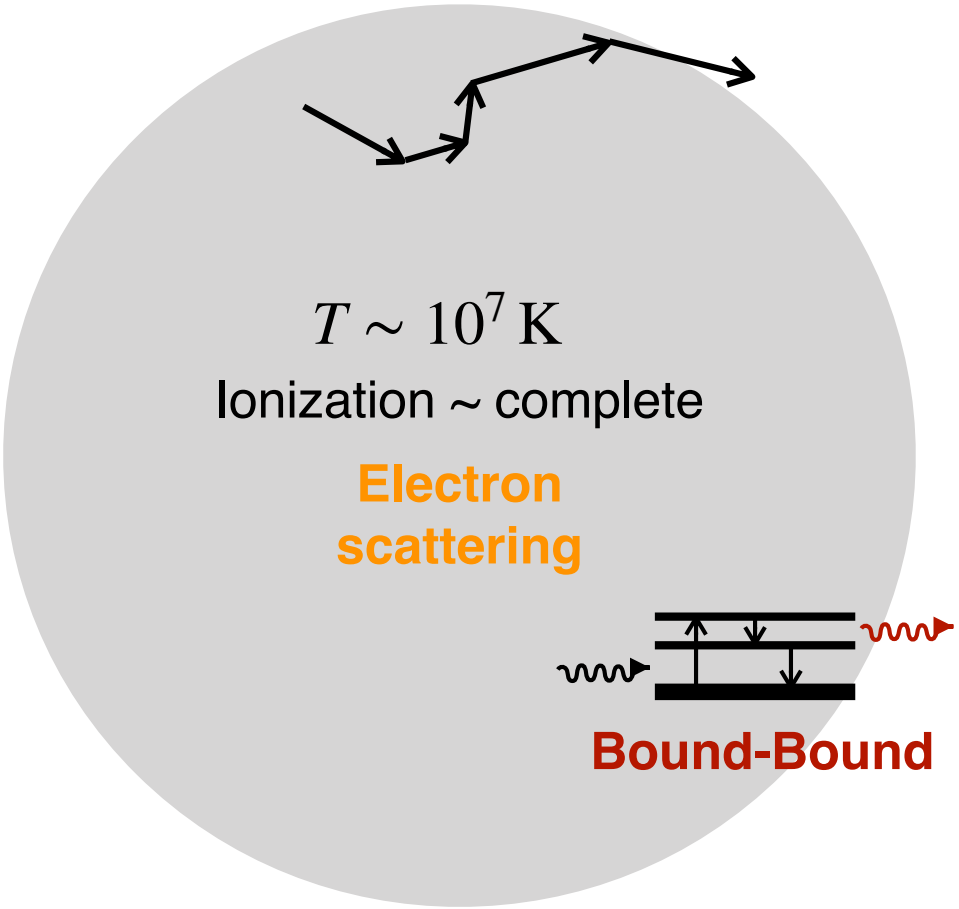


Realistic light curve model at early time

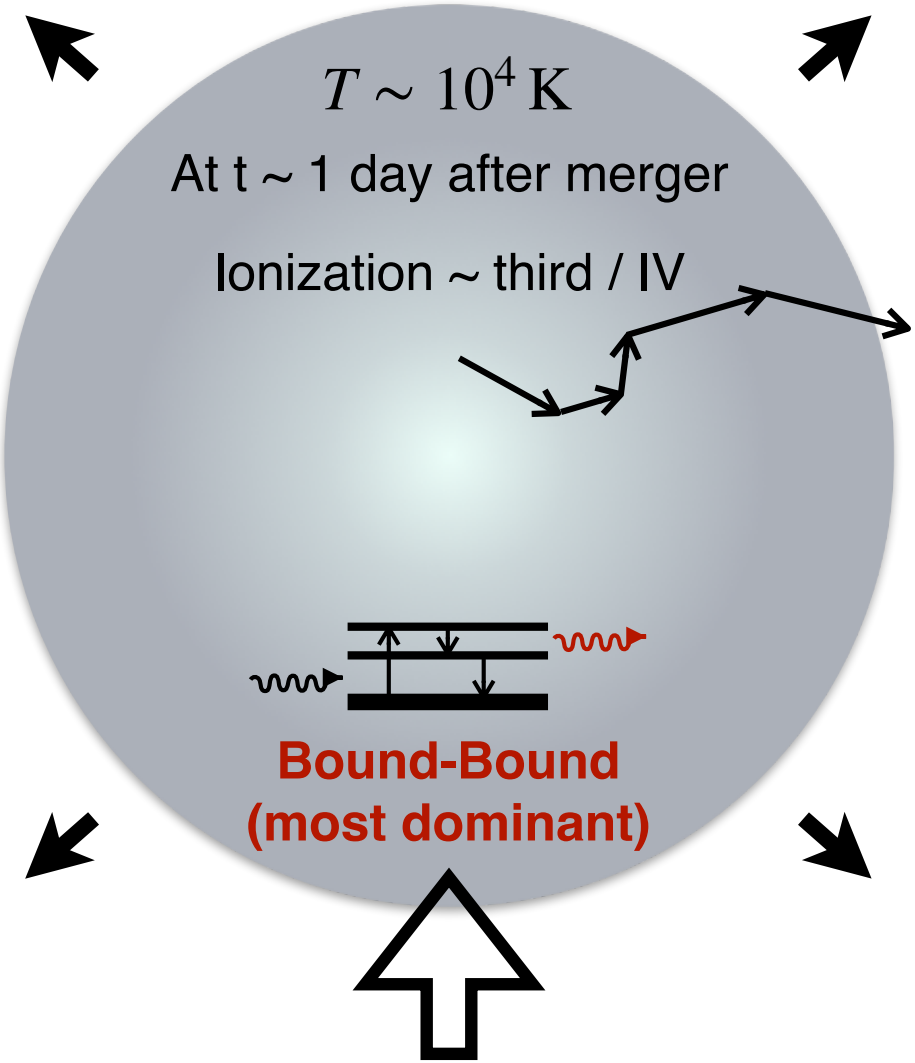
<= Detailed physics at early time?

Opacity

Opacity in a star



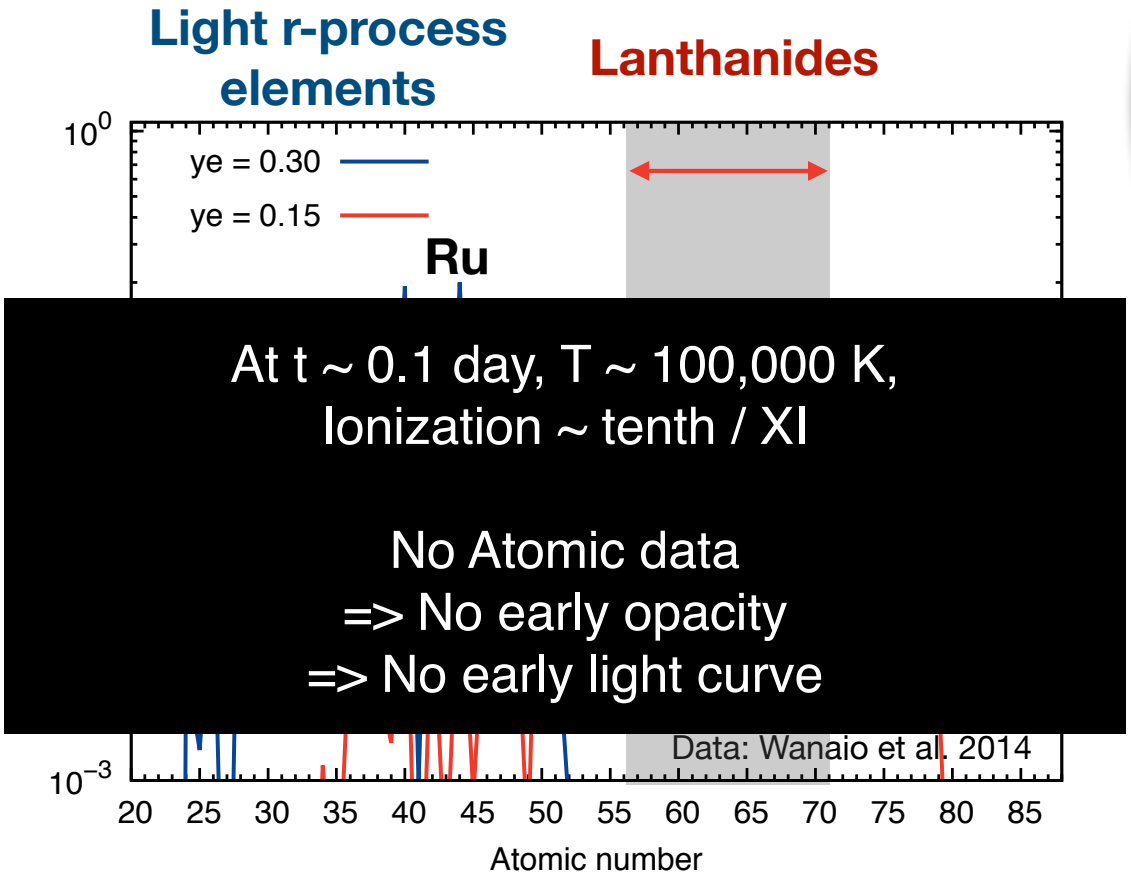
Neutron star merger
=> expansion opacity



Atomic data

Opacity

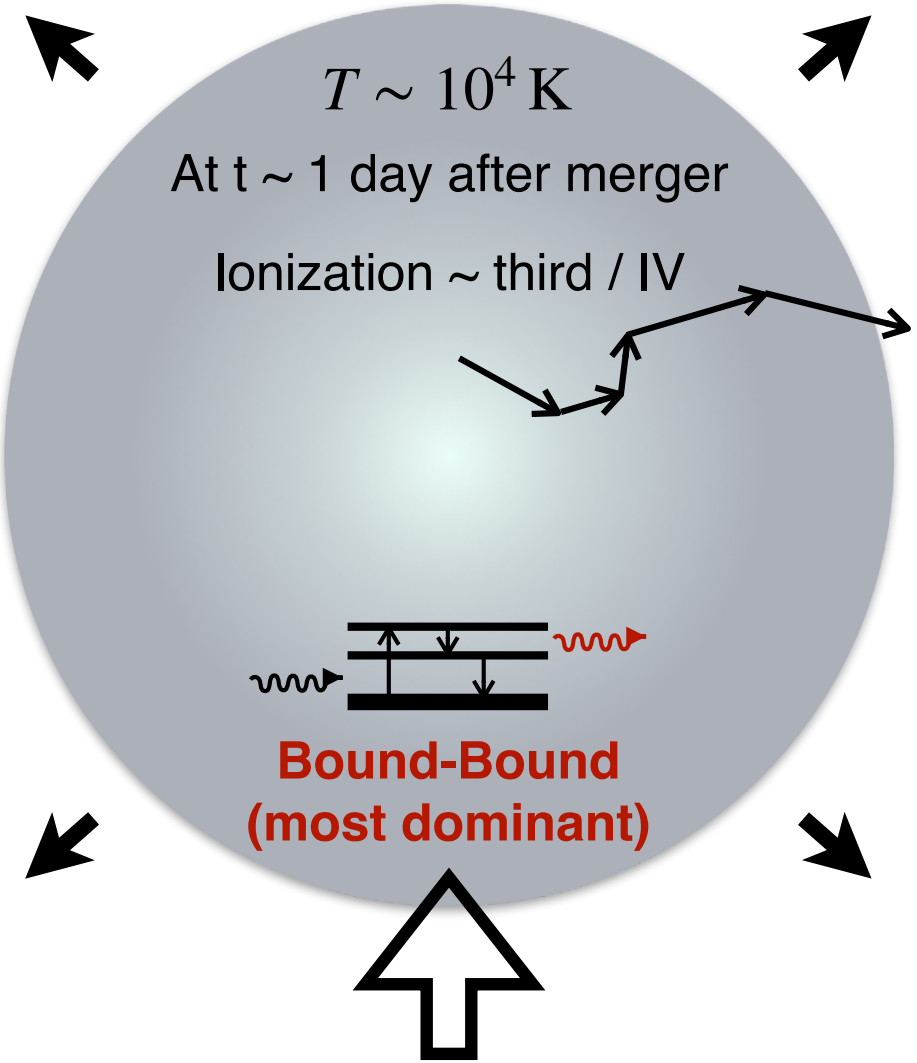
Previous work:
Kasen et al. 2013;
Tanaka & Hotokezaka 2013;
Fontes et al. 2017, 2020;
Wollaeger et al. 2017;
Tanaka et al. 2018, 2020



At t ~ 0.1 day, T ~ 100,000 K,
Ionization ~ tenth / XI

No Atomic data
=> No early opacity
=> No early light curve

Neutron star merger
=> expansion opacity

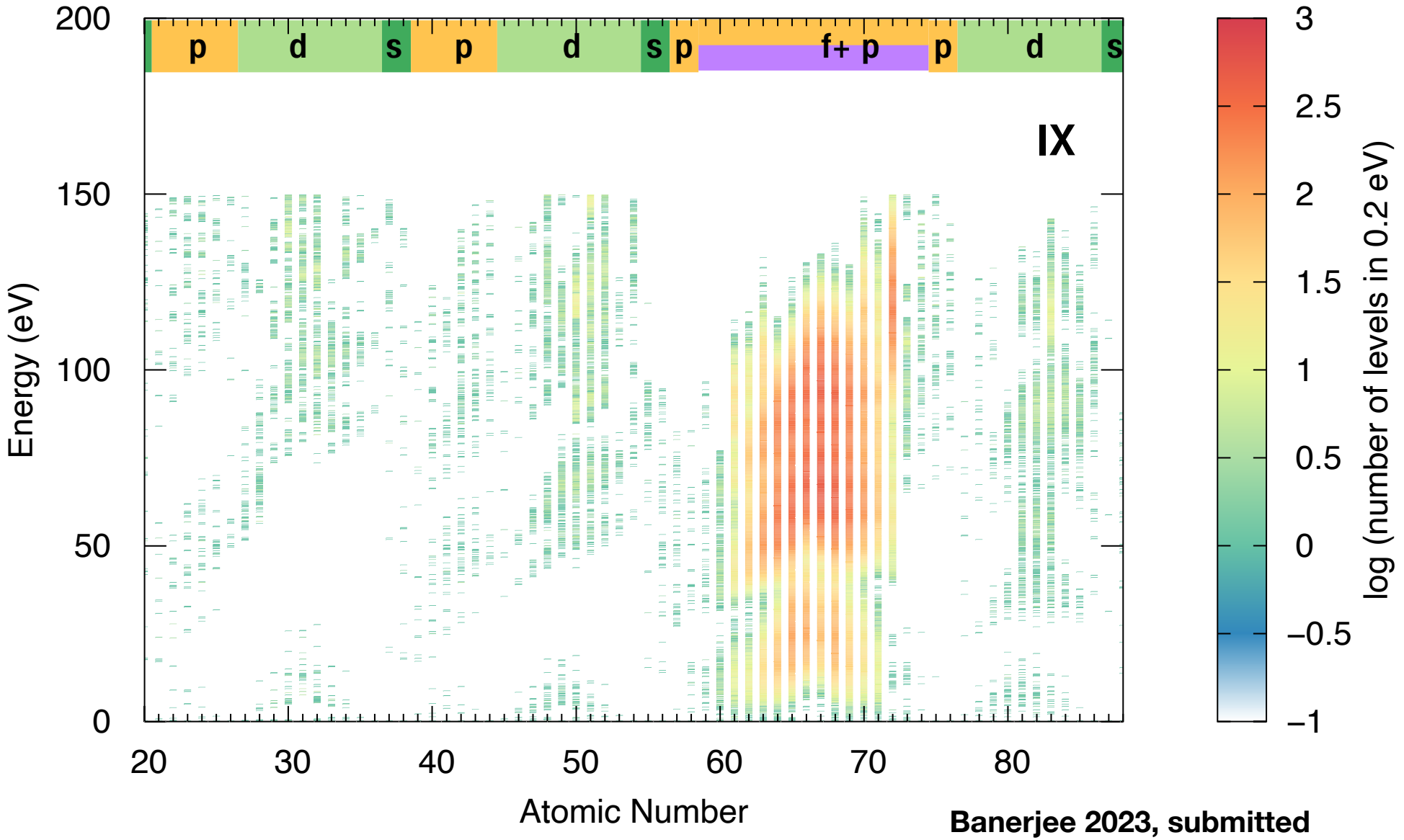


Atomic data

Outline

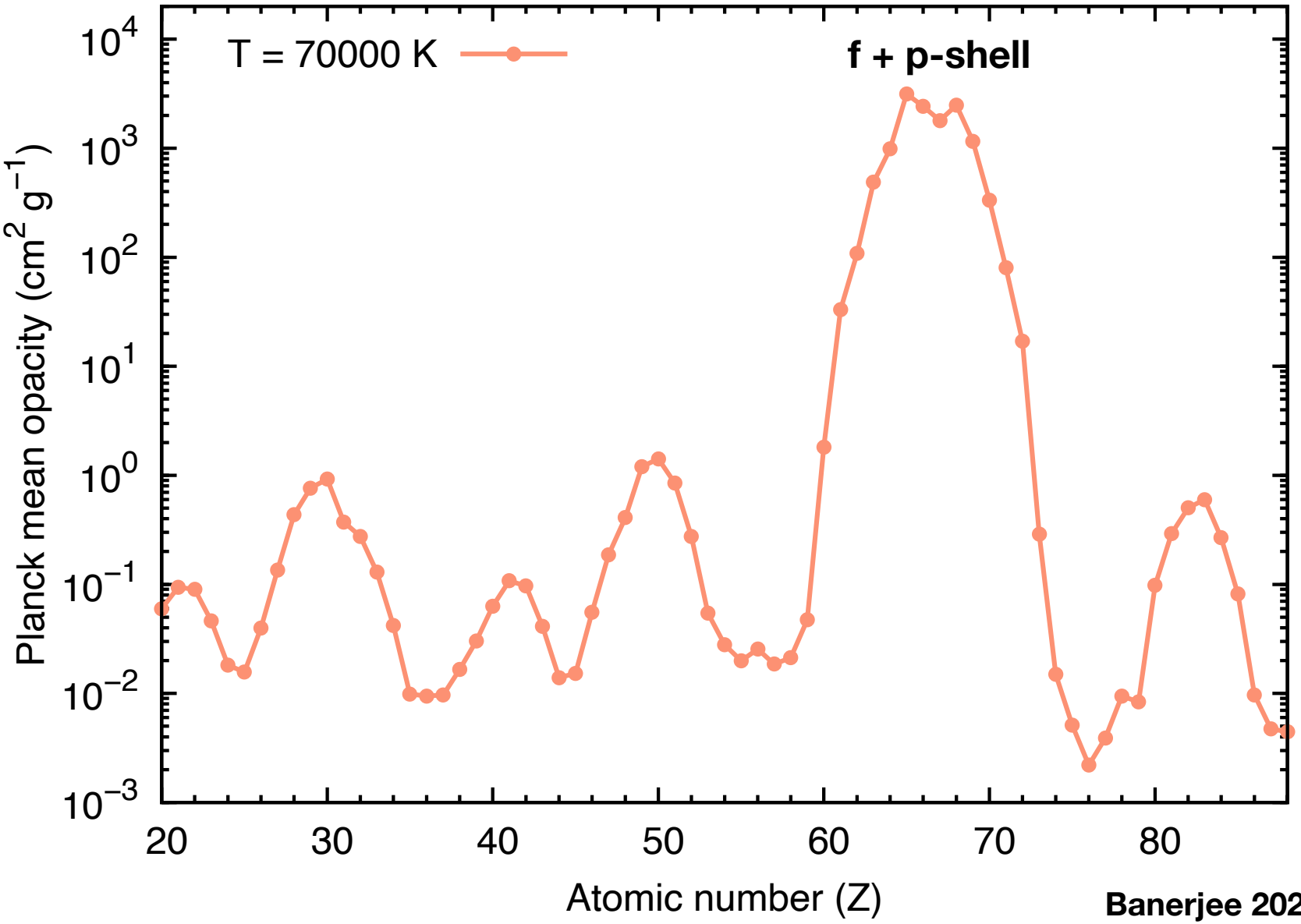
- Neutron star merger & kilonova
- **Atomic opacity for kilonova**
- Kilonova modelling

Energy level



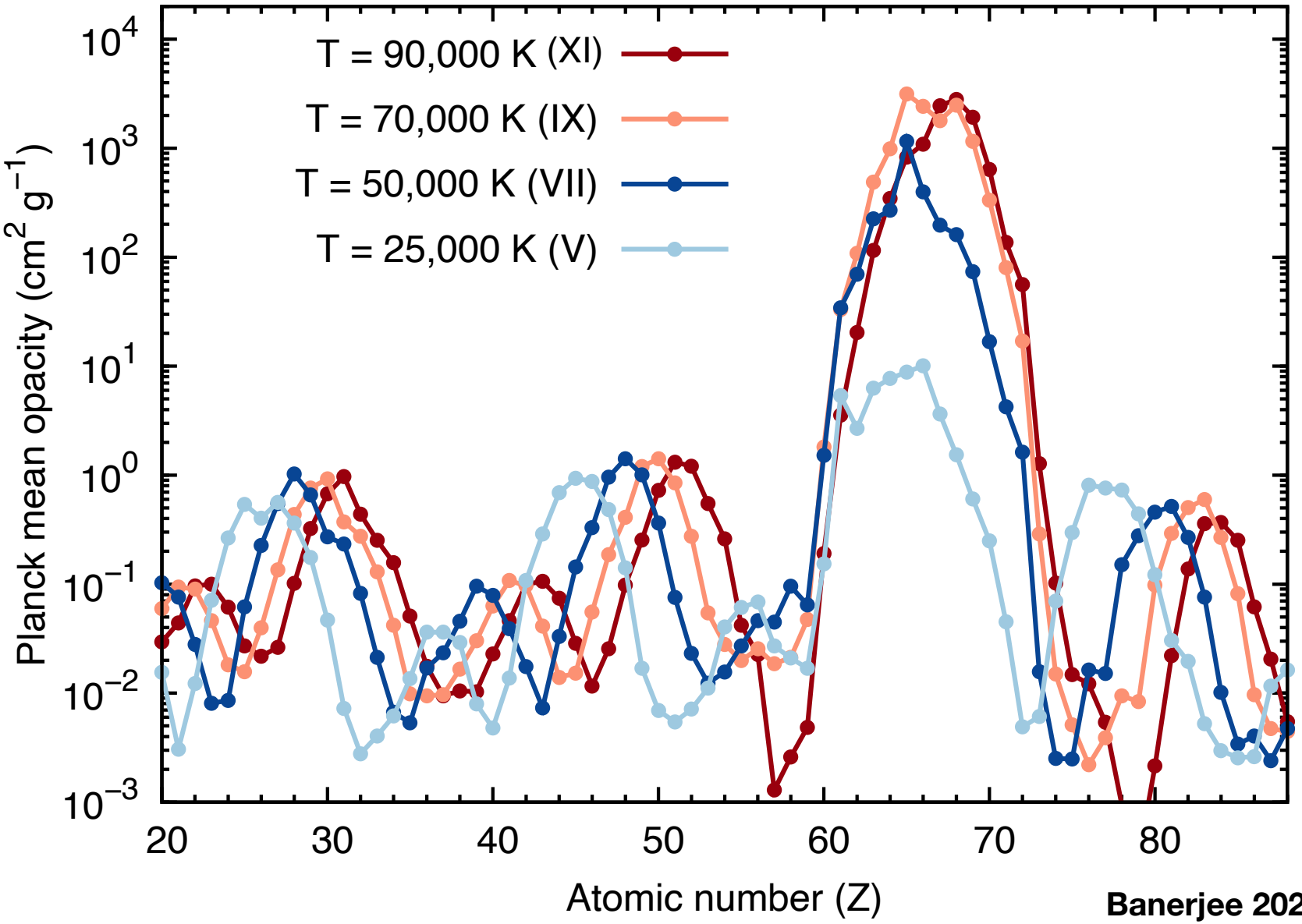
Banerjee 2023, submitted

Opacity



Banerjee 2023, submitted

Opacity



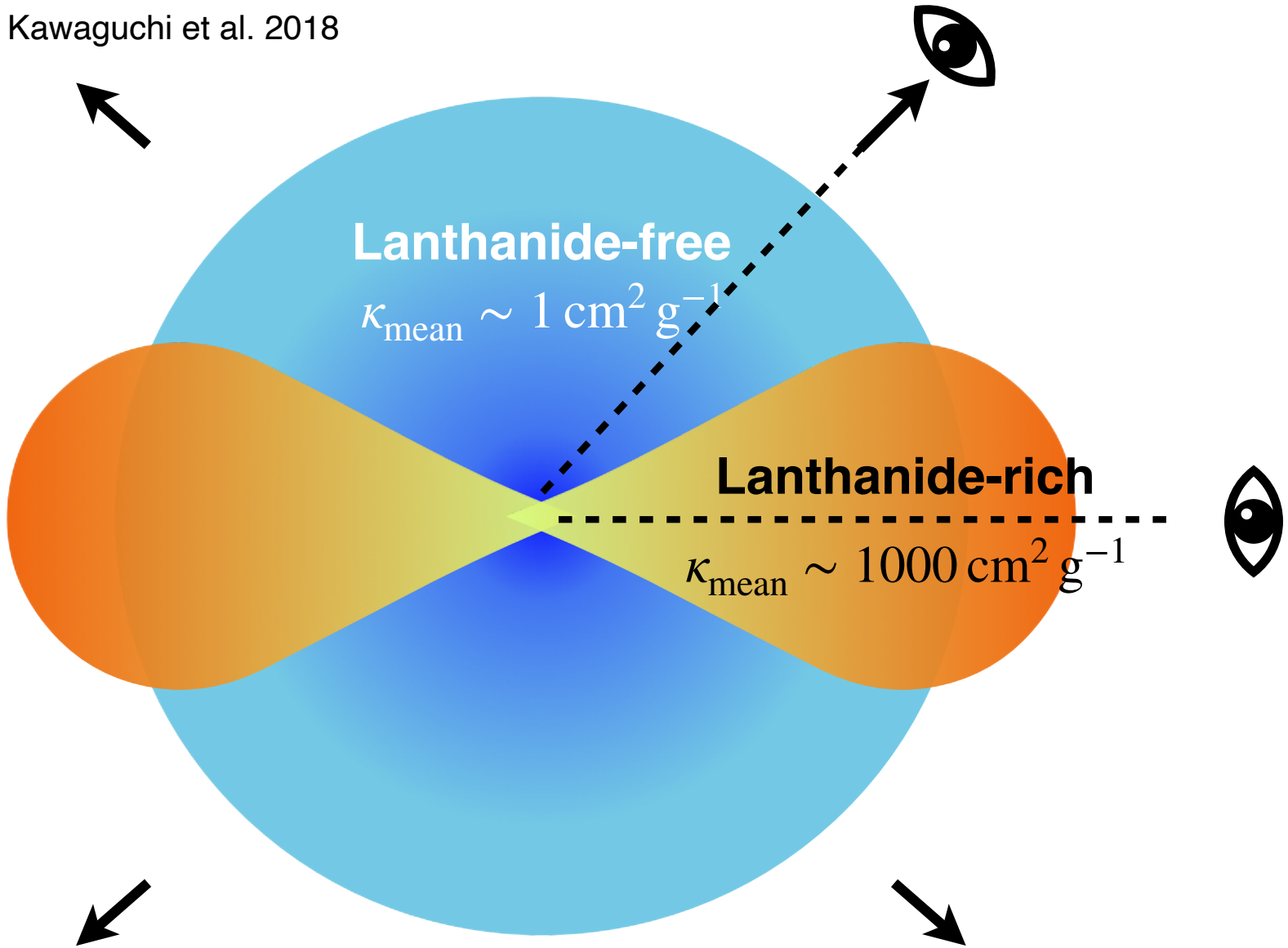
Banerjee 2023, submitted

Outline

- Neutron star merger & kilonova
- Atomic opacity for kilonova
- **Kilonova modelling**

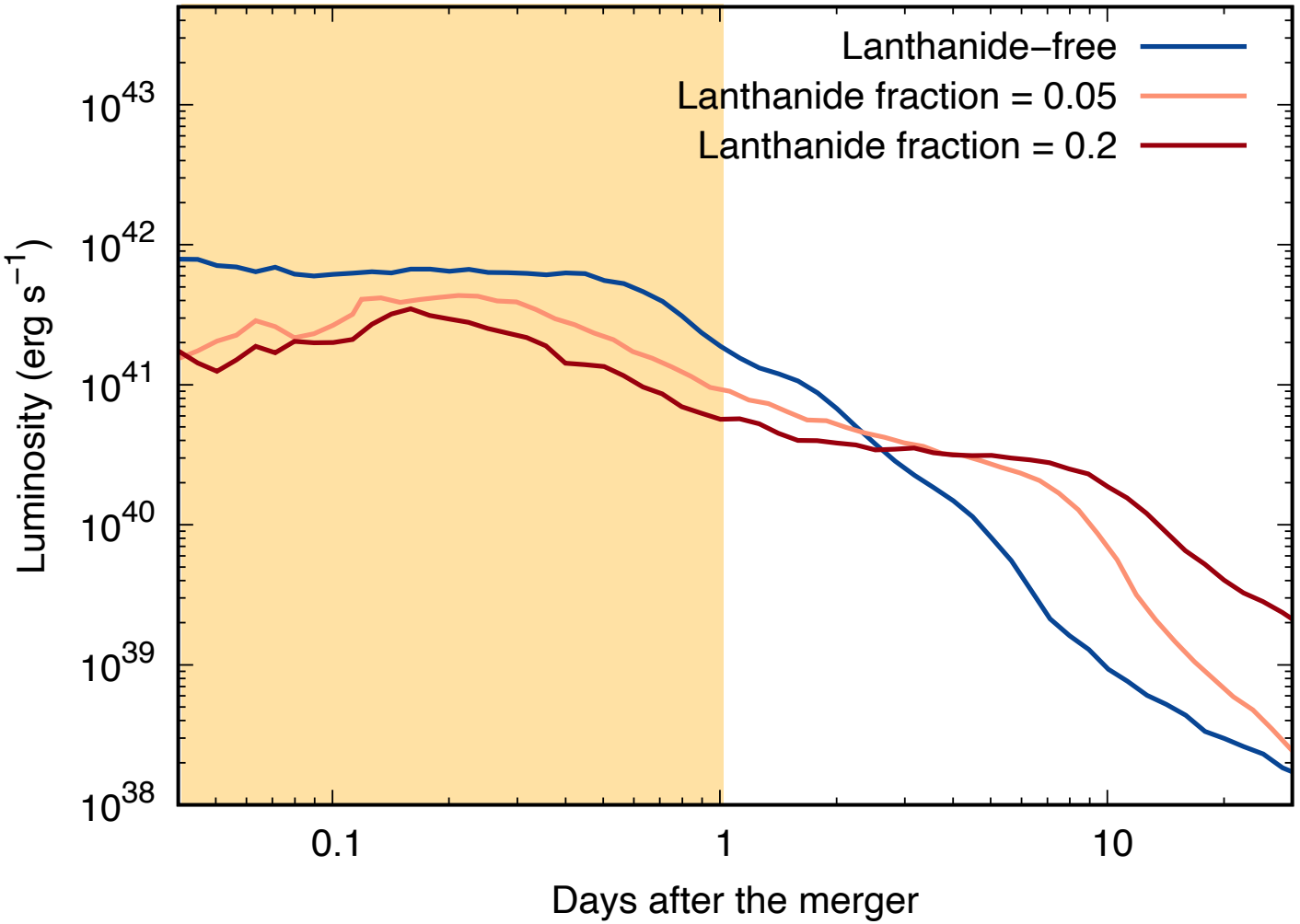
Model

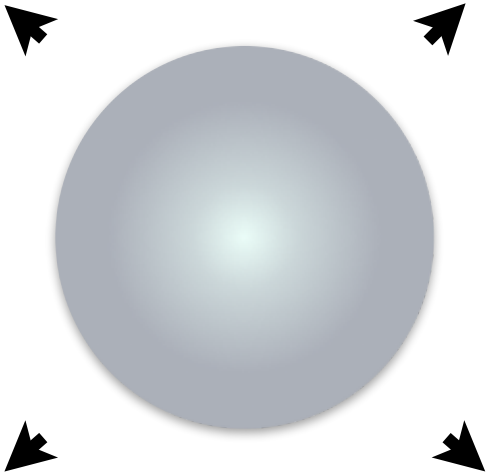
Radiative transfer code:
Tanaka et al. 2013; Kawaguchi et al. 2018



- 1D spherical ejecta model
- Power law density slope

Bolometric light curve



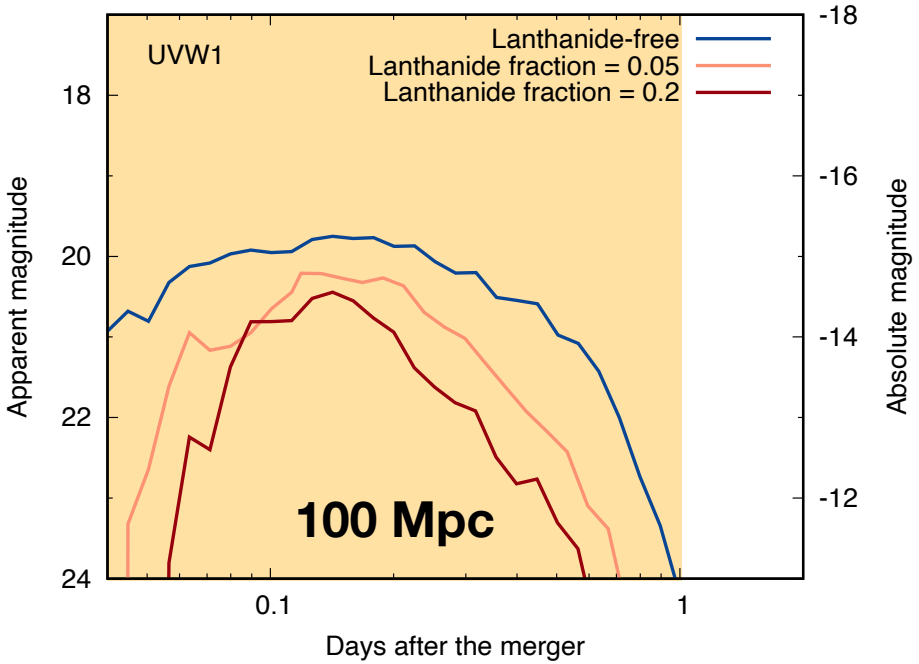


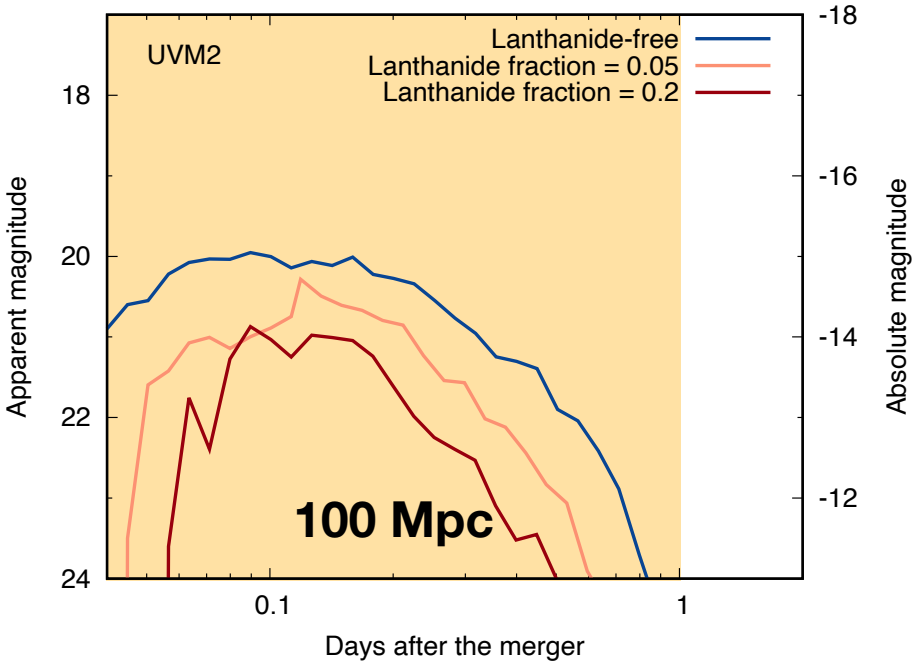
Banerjee+ 2020, 2022, 2023, submitted

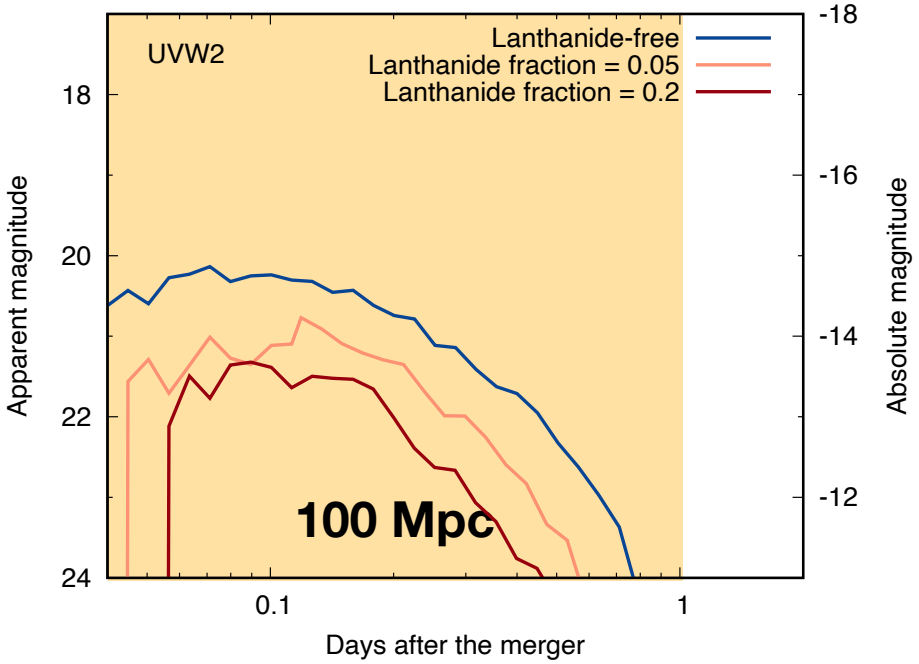
Presence of lanthanides

=> Unique signature in kilonova at first few (~ 4) hours

Multi-color light curve



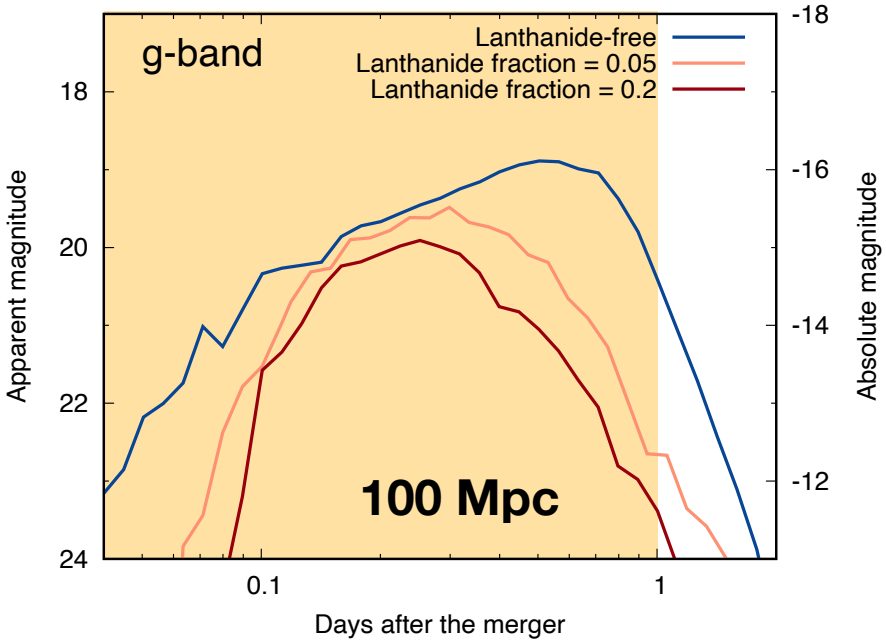


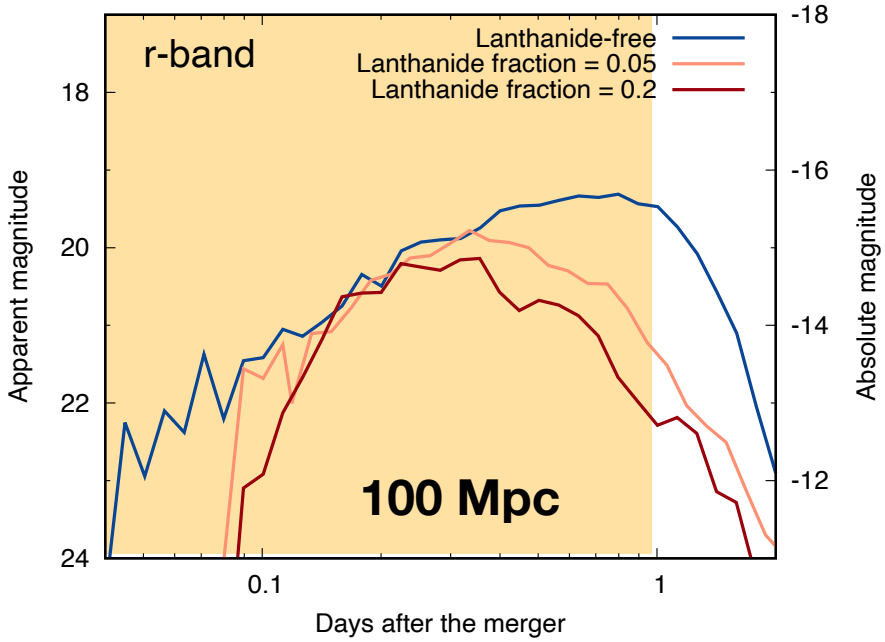


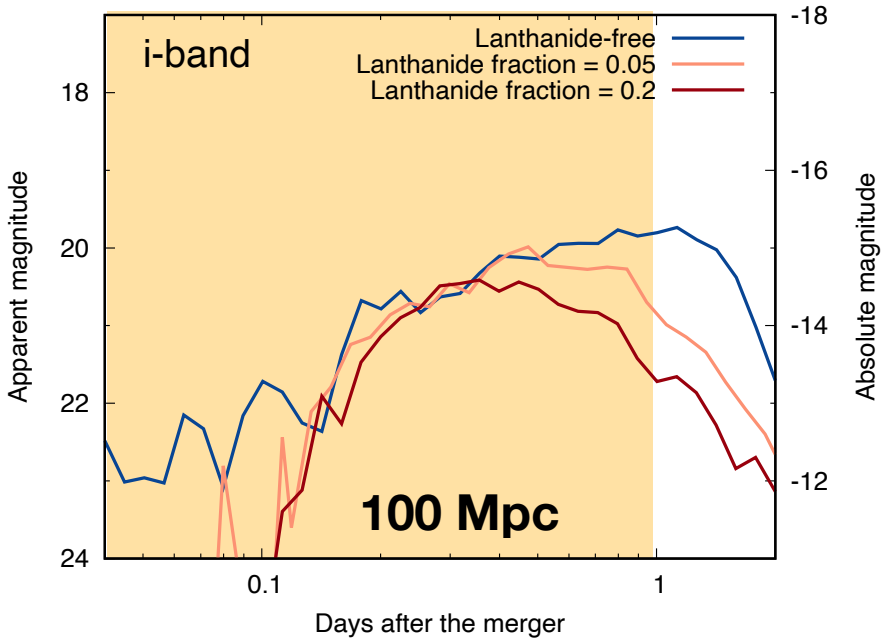
Presence of lanthanides => Dimmer kilonova at first few (~ 4) hours

Detectable by Swift, ULTRASAT

Lanthanide-rich kilonova (optical)



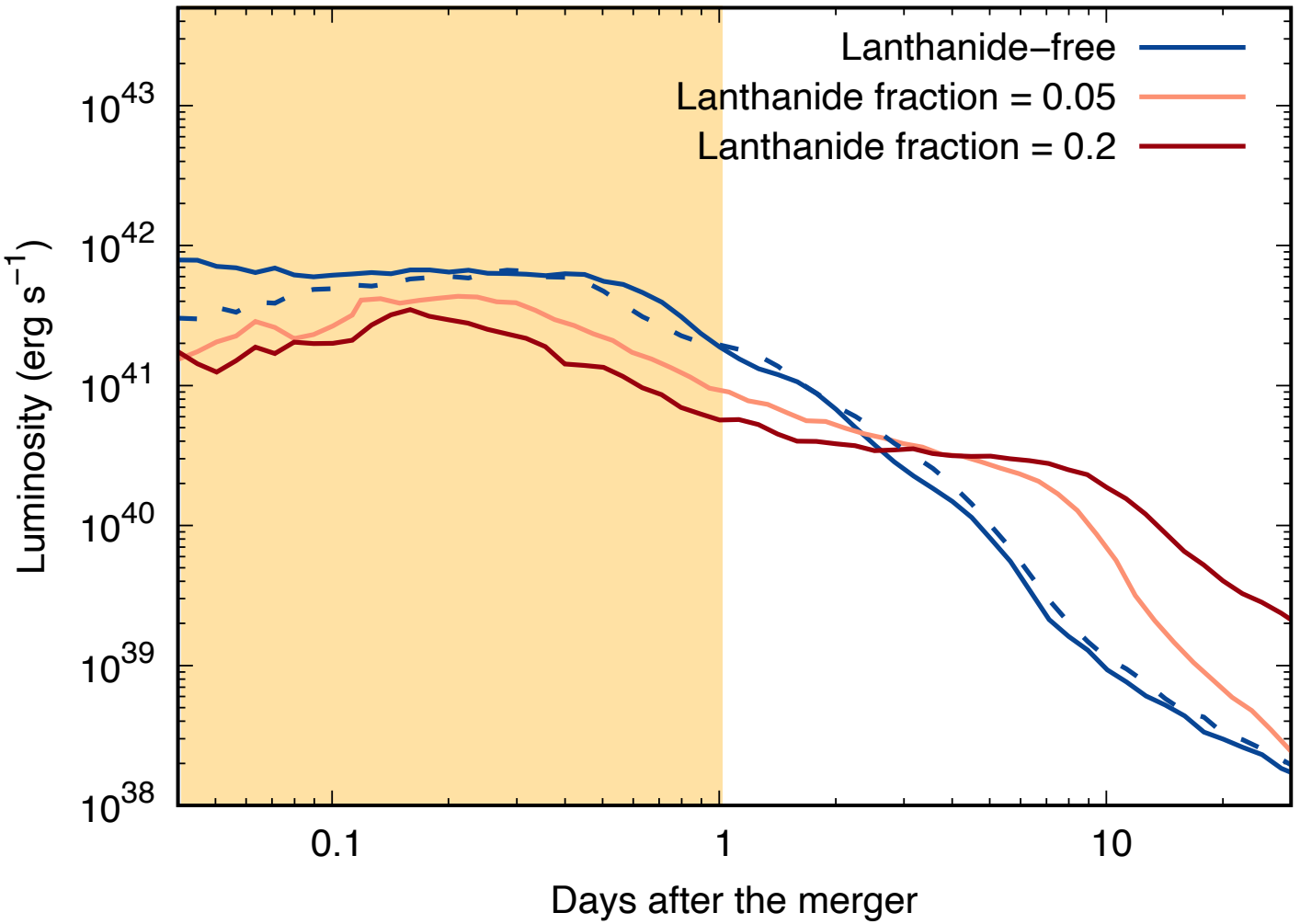


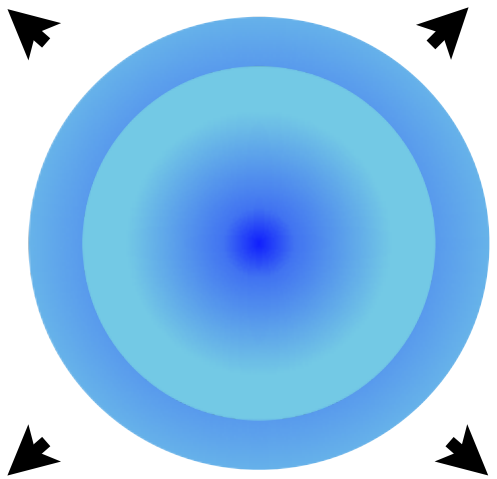


Presence of lanthanides => Dimmer kilonova at first few (~ 4) hours

Detectable by DECam, Subaru/HSC

Bolometric light curve

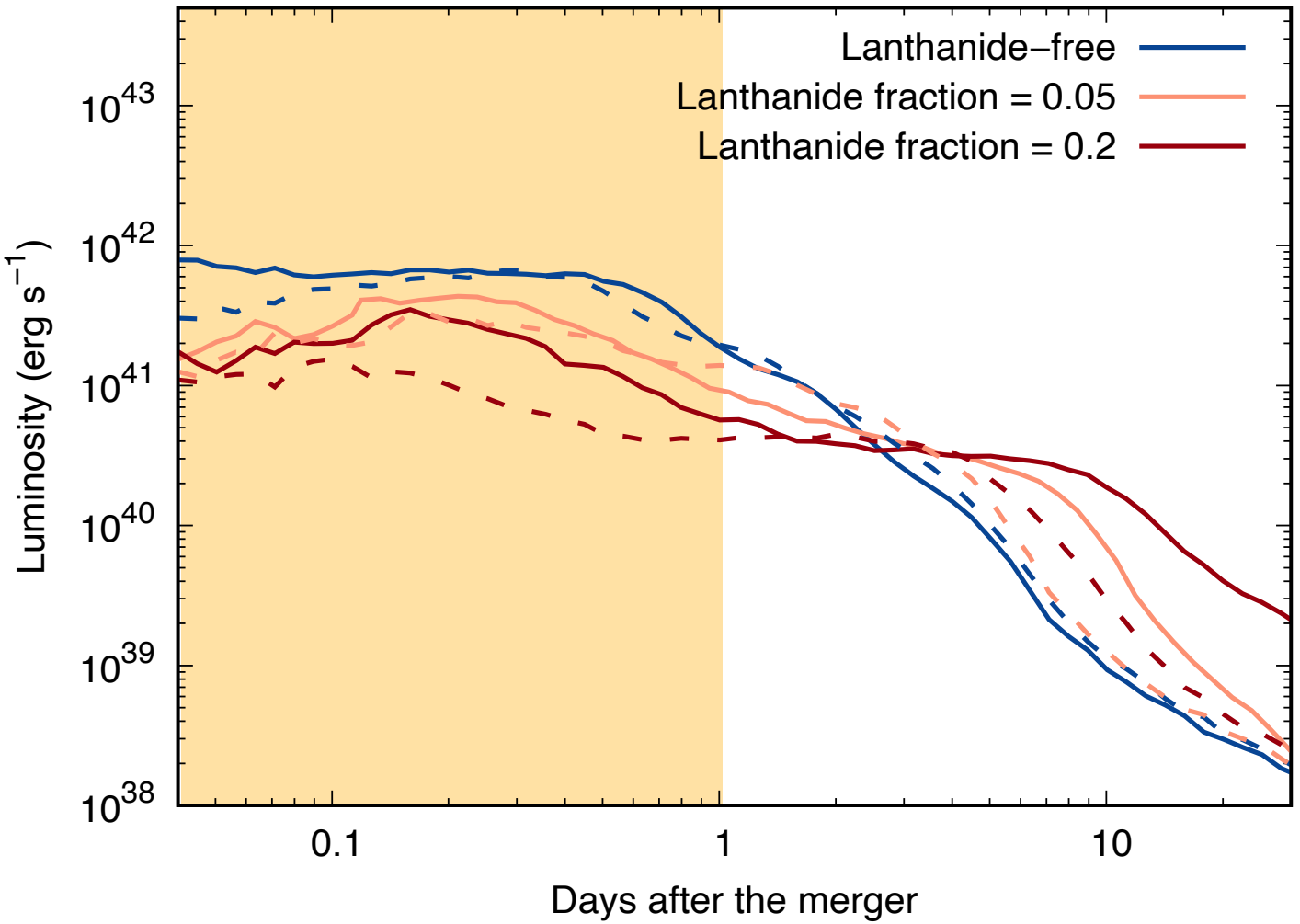


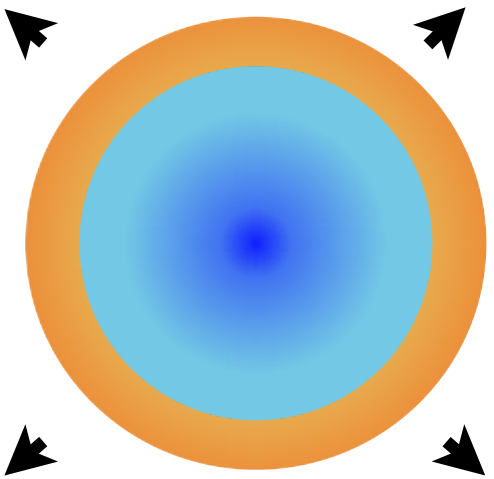


Banerjee+ 2020

Detectable ejecta structure signature in kilonova at first few (~ 4) hours

Bolometric light curve



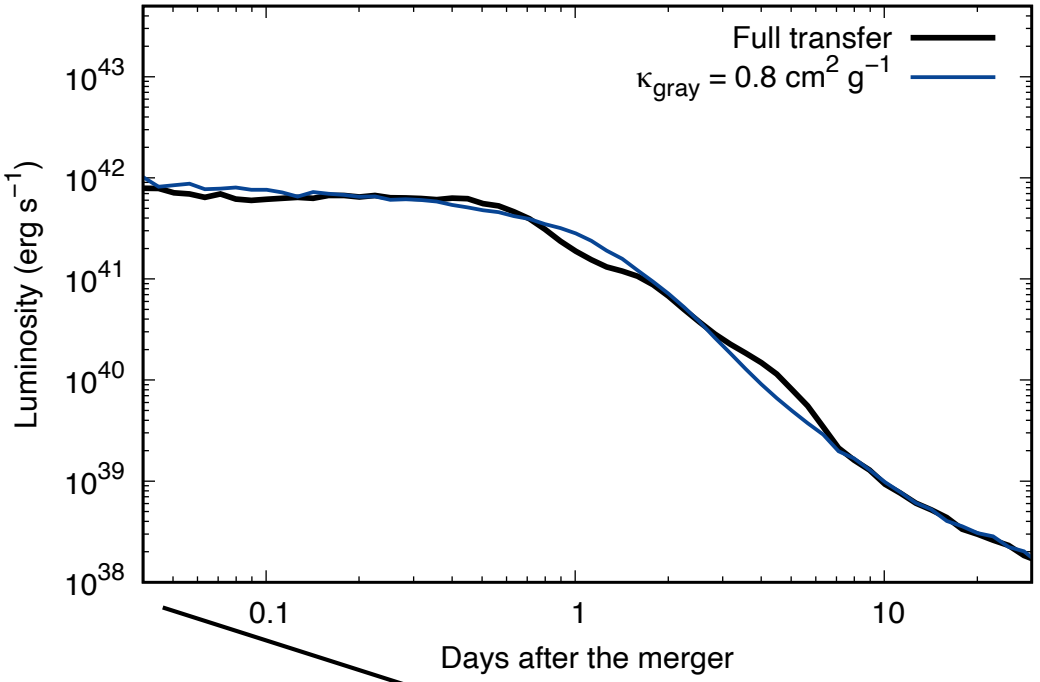


Banerjee+ 2023, submitted

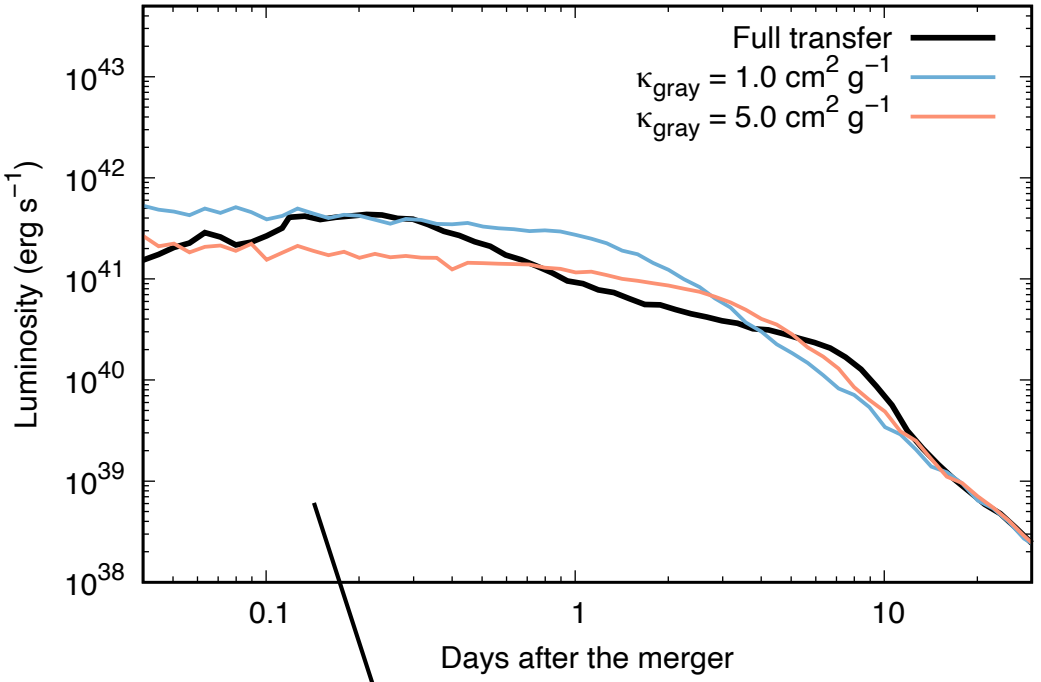
Detectable ejecta structure signature in kilonova at first few (~ 4) hours

Suggested gray opacities

Lanthanide-free



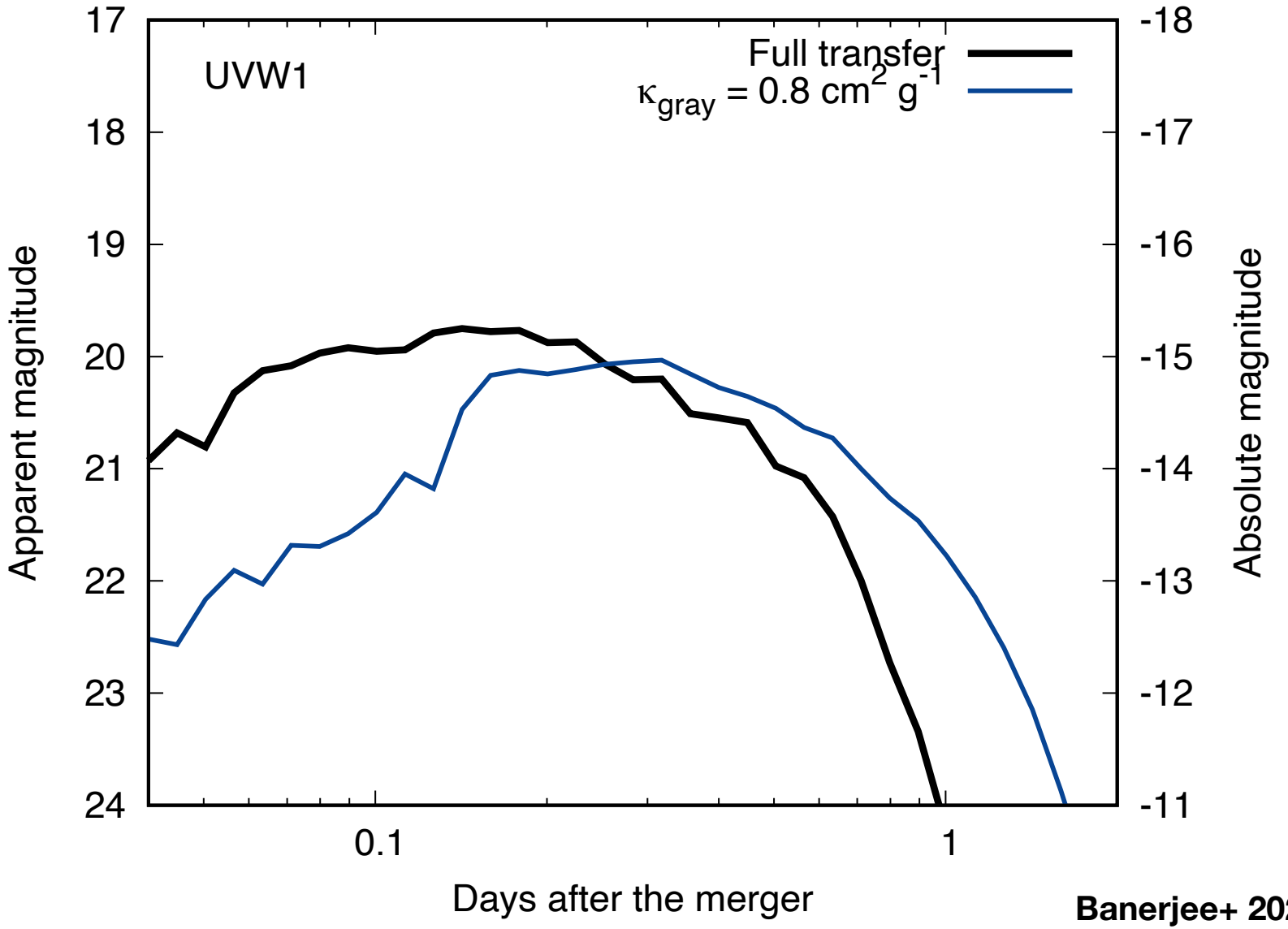
Lanthanide fraction = 0.05



Banerjee+ 2023, submitted

Models	Electron fraction		Suggested gray opacities ($\mathrm{cm^2\,g^{-1}}$)
	$Y_{e,in}$ ($v = 0.05c - 0.2c$, $M_{ej,in} = 0.01M_\odot$)	$Y_{e,out}$ ($v = 0.2c - 0.33c$, $M_{ej,out} = 0.001M_\odot$)	
Model 1	$0.10 - 0.20$	–	$2.0 - 10.0$
Model 2	$0.20 - 0.30$	–	$1.0 - 5.0$
Model 3	$0.30 - 0.40$	–	0.8
Model 4	$0.30 - 0.40$	$0.10 - 0.20$	$5.0 - 20.0$
Model 5	$0.30 - 0.40$	$0.20 - 0.30$	$3.0 - 10.0$
Model 6	$0.30 - 0.40$	$0.30 - 0.40$	$0.8 - 1.0$

Suggested gray opacities

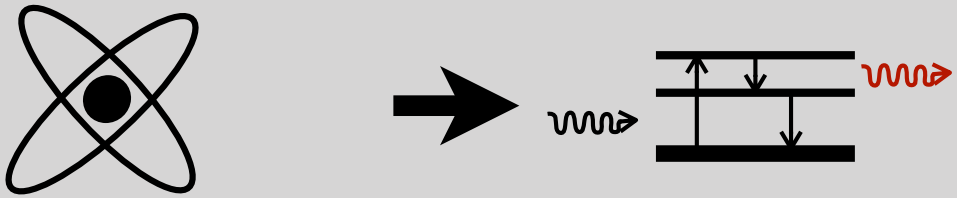


Banerjee+ 2023, submitted

Multi-color light curves cannot be reproduced

Atomic calculation

Opacity calculation

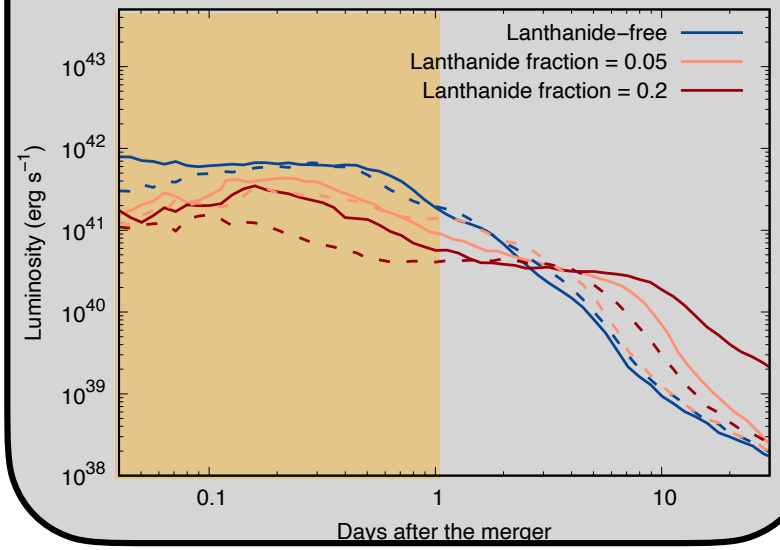


All r-process (Z = 20 - 88), ion up to = XI

$$\kappa_{\mathrm{mean}} \sim 1 - 1000\,\mathrm{cm^2\,g^{-1}}$$

Suitable for early time

Early + late
= Entire kilonova



Comparison with observations
(LIGO O4, May 2023 ~)

Origin of heavy elements


TACK