EMMI + IReNA workshop 2022, GSI

Opacity of the highly ionized heavy elements and the effect on the early kilonova

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In collaboration with

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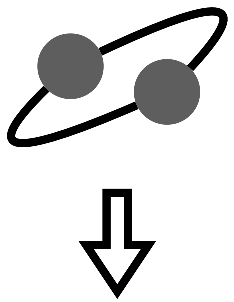
Banerjee, Tanaka, Kawaguchi, et al. 2020, ApJ, 901, 29

Banerjee, Tanaka, Kato, et al. 2022, ApJ, 934, 117

EMMI+IReNA Workshop "Remnants of neutron-star mergers – Connecting hydrodynamics models to nuclear, neutrino, and kilonova physics"

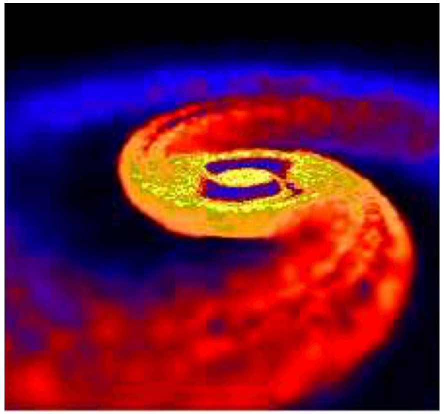
EMMI

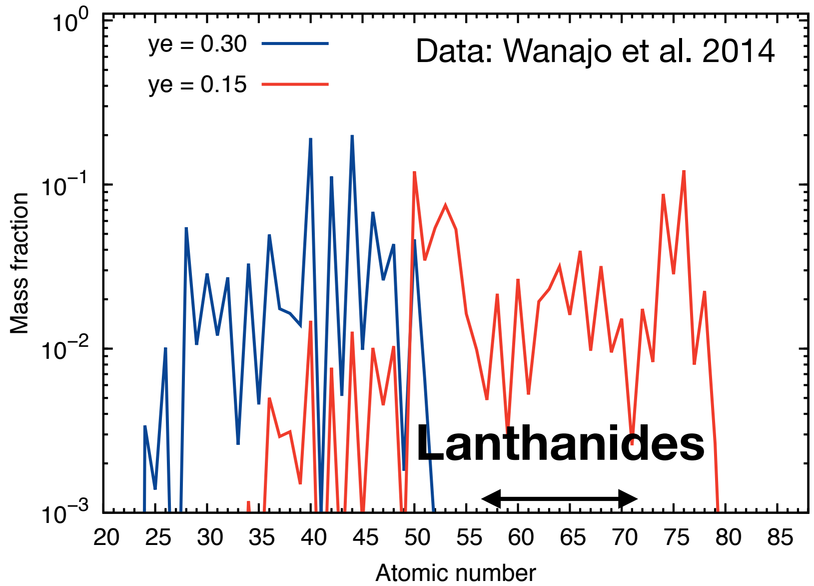
Mon 17/10 | Tue 18/10 | Wed 19/10 | **Thu 20/10** | All days

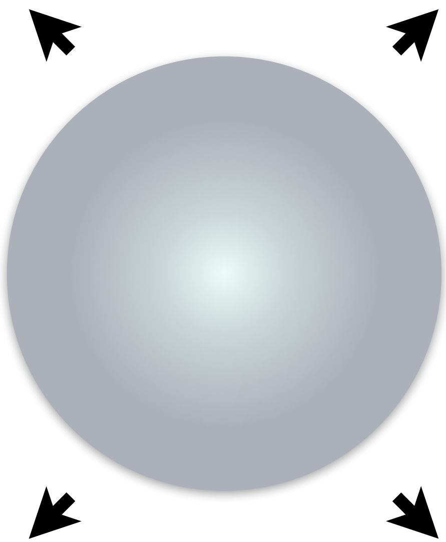


ms - s

days-weeks







Mass ejection

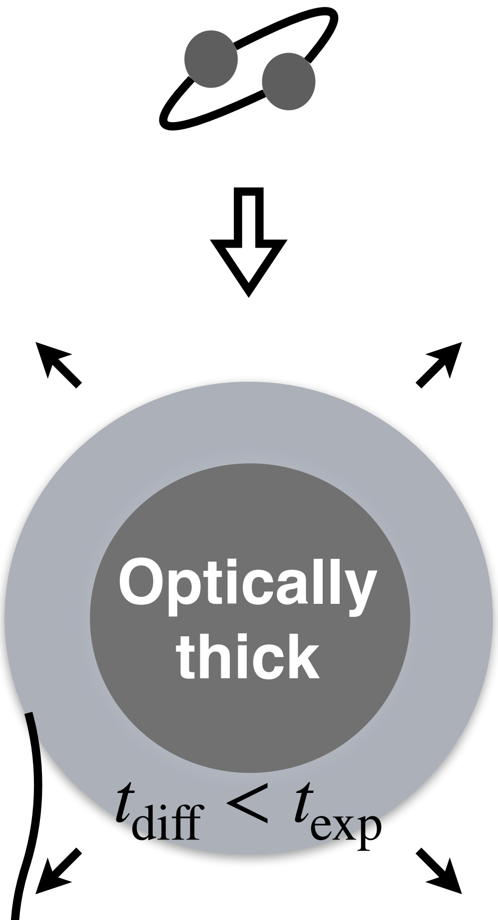
r-process nucleosynthesis

Radioactive decay of heavy elements => kilonova

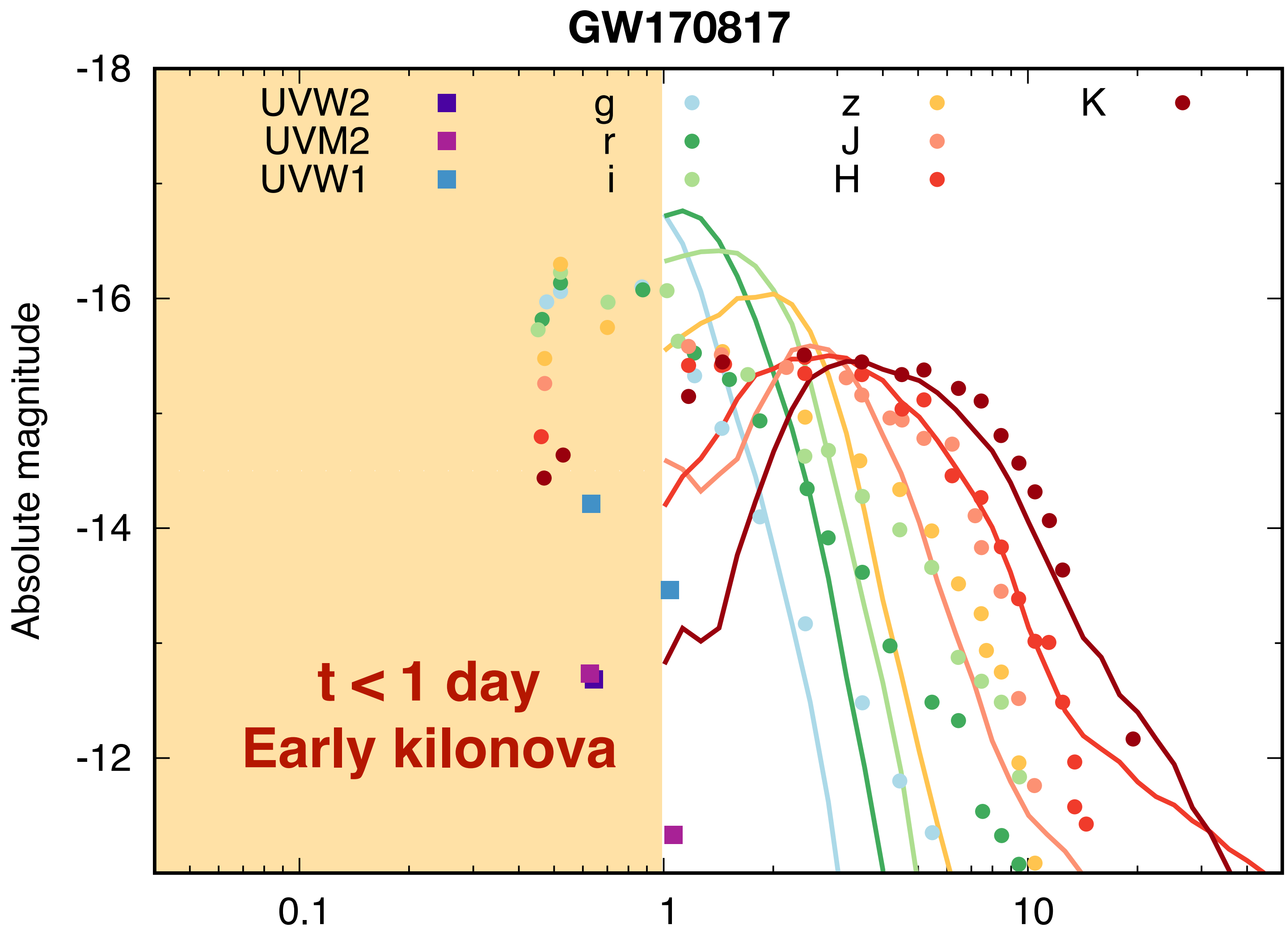
Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010

e.g, Lattimer & Schramm 1974; Eichler et al. 1989; Freiburghaus et al. 1999; Rosswog et al. 1998, Hotokezaka et al 2013a; Radice et al 2016a, 2018b; Ciolfi et al 2017

Early kilonova



Abundance pattern of **outer** ejecta

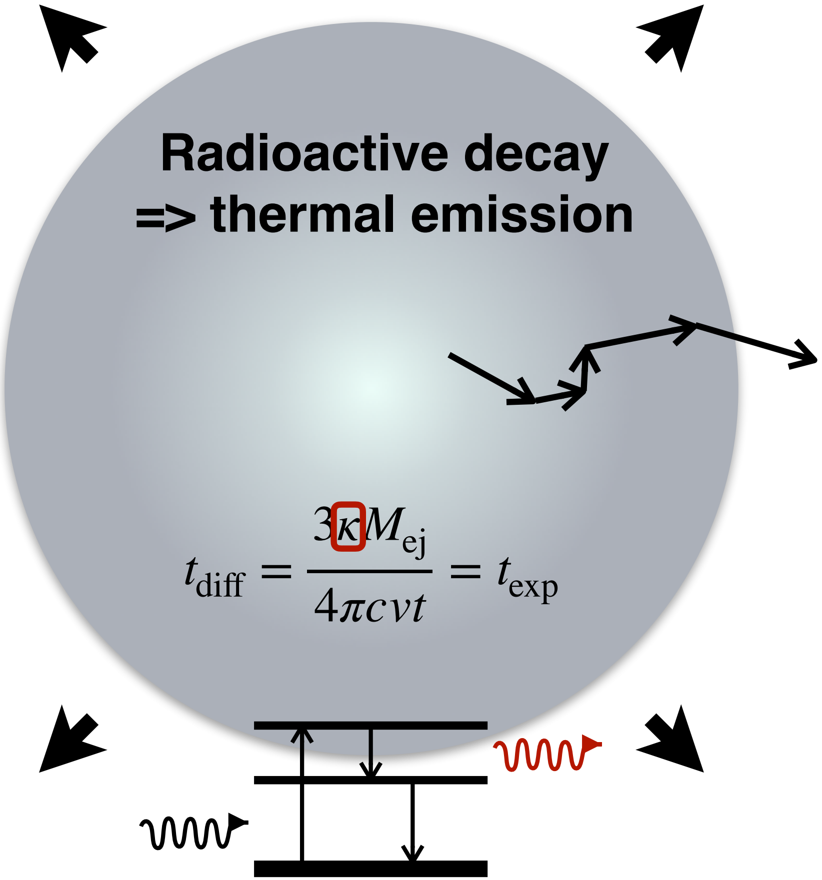


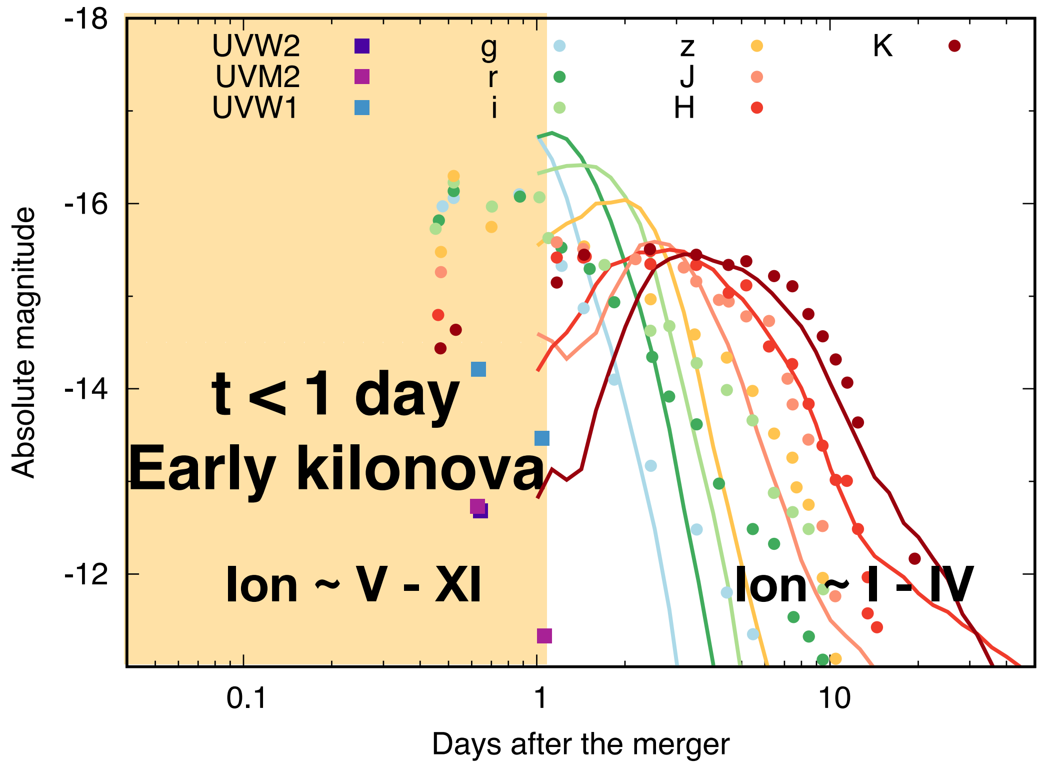
Coulter et al 2017; Soares-Santos et al 2017; Arcavi et al 2017a; Troja et al 2017; Kilpatrick et al 2017; Smartt et al 2017; Drout et al 2017; Evans et al 2017; Abbott et al 2017d; Utsumi et al 2017; Covino et al 2017

What do we need?

Realistic light curve model at early time

<= Detailed opacity at early time?



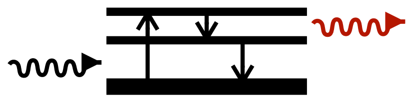


Bound-Bound (most dominant) ⇦ **Atomic data (Highly ionized heavy elements)**

Challenges in atomic calculation

Atomic energy levels and transition rates

ASD | DATA: LINES LEVELS | INFORMATION: LIST OF SPECTRA, GROUND STATES & IONIZATION ENERGIES, BIBLIOGRAPHY



NIST Atomic Spectra Database Levels Data

Spectra: Eu VI

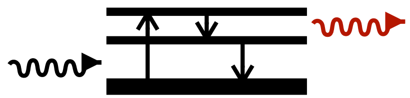
e.g., Fe I *or* Na *or* H-Ds I *or* Mg+ *or* Al3+ *or* mg iv,vi-VIII; S V-xii *or* Fe ne-like-S-like *or* Ne-Fe I-III *or* Ni-like *or* H-like-Ne-like

Default Values | Retrieve Data

Challenges in atomic calculation

Atomic energy levels and transition rates

ASD | Data: Lines, Levels | Information: List of Spectra, Ground States & Ionization Energies, Bibliography



NIST Atomic Spectra Database Levels Data

Eu VI 2 Levels Found

***Z* = 63, Ce isoelectronic sequence**

Primary data source		Query NIST Bibliographic Database for **Eu VI** (new window)
		Literature on Eu VI Energy Levels

Configuration	Term	*J*	Level (cm^{-1})	Uncertainty (cm^{-1})	Reference
$4f^5 5s^2 5p^5$			0	10	L582
Eu VII ($4f^5 5s^2 5p^{4\circ}$)	Limit	---	(714 000)	36 000	L582

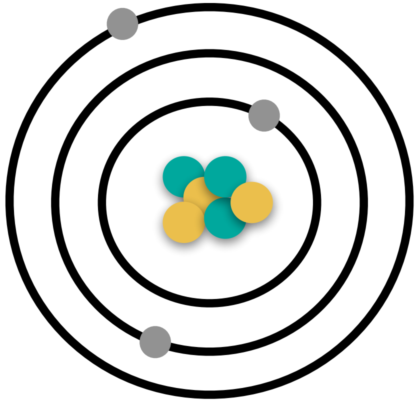
Also problem for t > 1 day

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

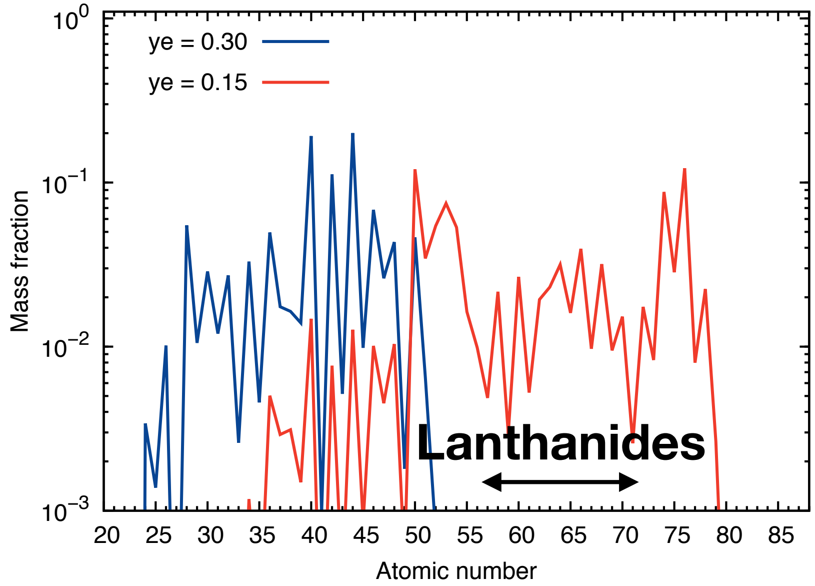
However,

Challenges in atomic calculation

~~Ground configurations~~ ⇒ **Theoretical atomic calculations**



Sp. Name.	Ground Shells a	Ground Level
Eu I	[Xe]$4f^7 6s^2$	$^8S°_{7/2}$
Eu II	[Xe]$4f^7 6s$	$^9S°_4$
Eu III	[Xe]$4f^7$	$^8S°_{7/2}$
Eu IV	[Xe]$4f^6$	$^7F_0$
Eu V	[Xe]$4f^5$	$^6H°_{5/2}$
Eu VI	[Cd]$4f^5 5p^5$	
Eu VII	[Cd]$4f^5 5p^4$	°
Eu VIII	[Cd]$4f^5 5p^3$	
Eu IX	[Cd]$4f^5 5p^2$	°
Eu X	[Cd]$4f^5 5p$	
Eu XI	[Cd]$4f^5$	°



Early kilonova (t < 1 day)

Opacity calculation

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

Atomic calculation

- Atomic energy levels and transition rates?
- **Ground configurations?**

Energy level

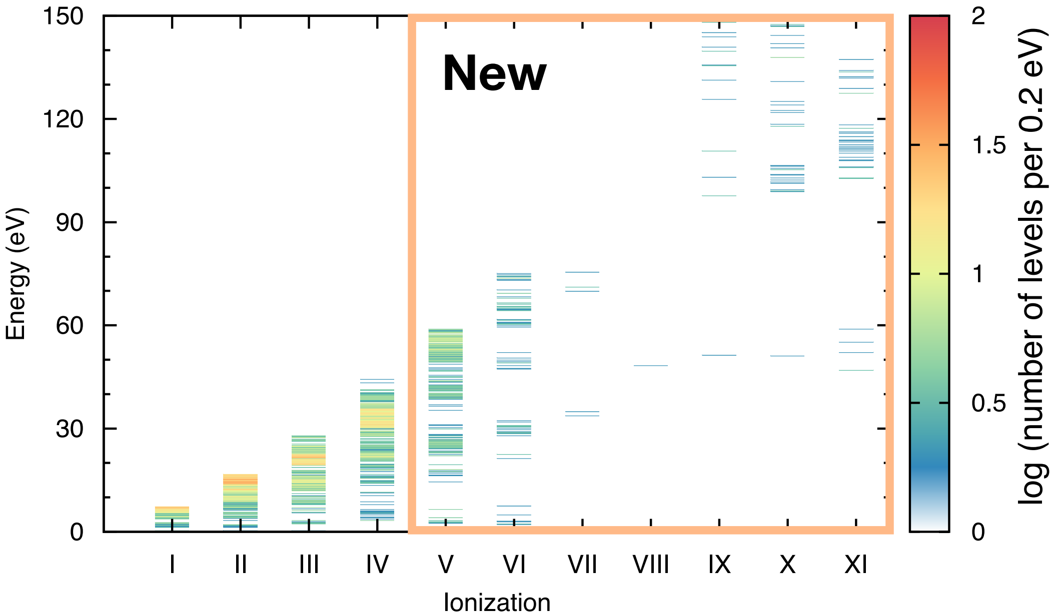
Code: HULLAC (Hebrew University Lawrence Livermore Atomic Code)

Bar-Shalom et al. 2001

We developed a methodology to systematically find the ground states

Non-lanthanide Ru (Z = 44)

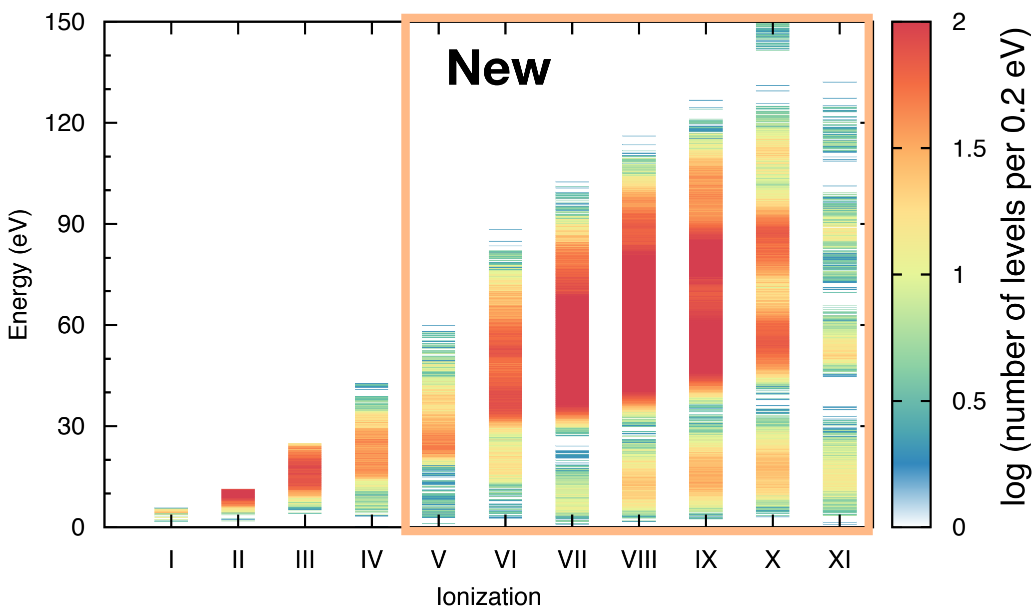
Open d-shell



Temperature

Lanthanide Eu (Z =63)

Open f-shell + open p-shell

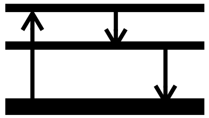


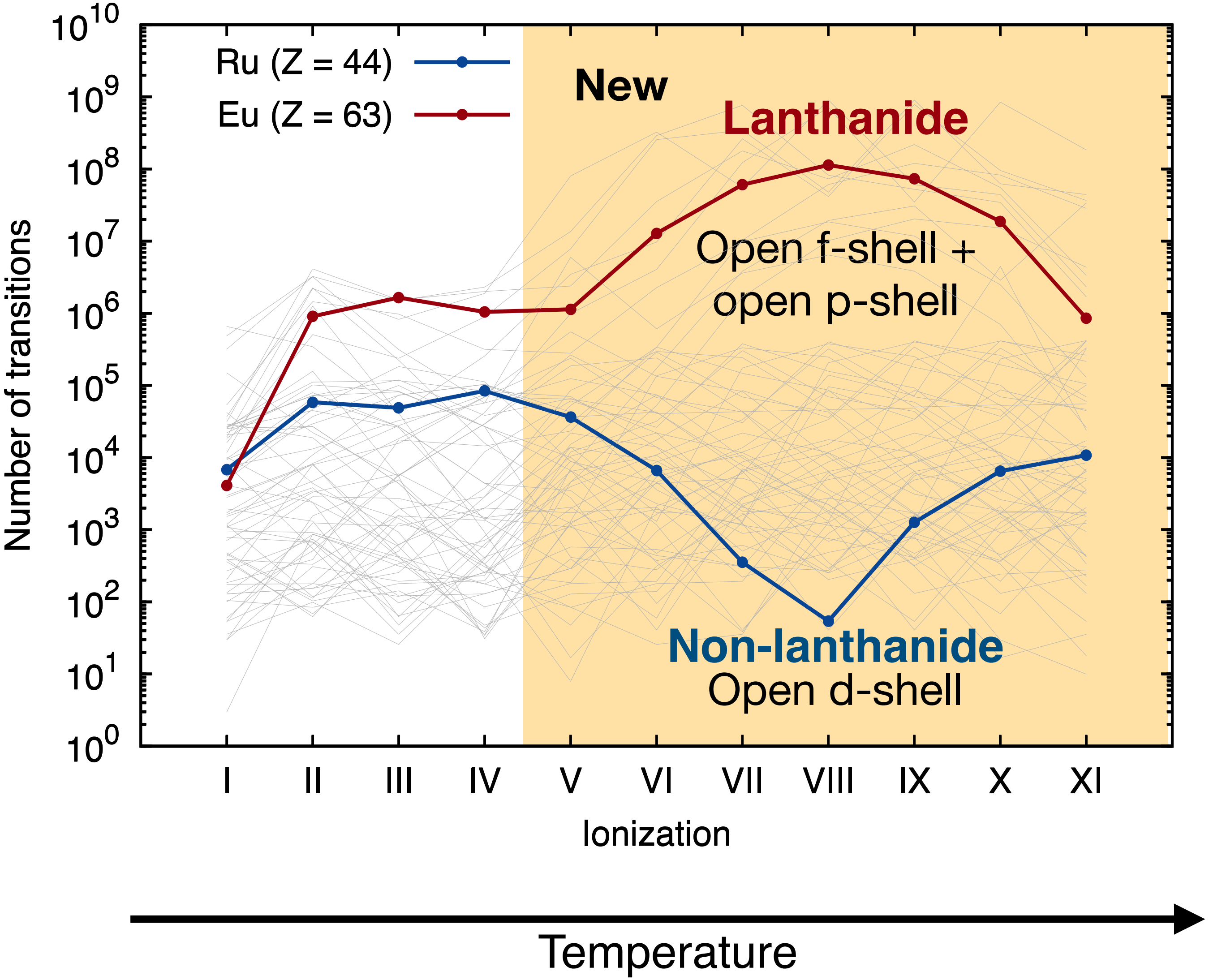
Temperature

Transitions

All r-process elements including Lanthanides (Z = 20 - 88),
maximum ionization = XI (10^{th})

=> suitable for ejecta condition at t ~ 0.1 day





Early opacity

Atomic data

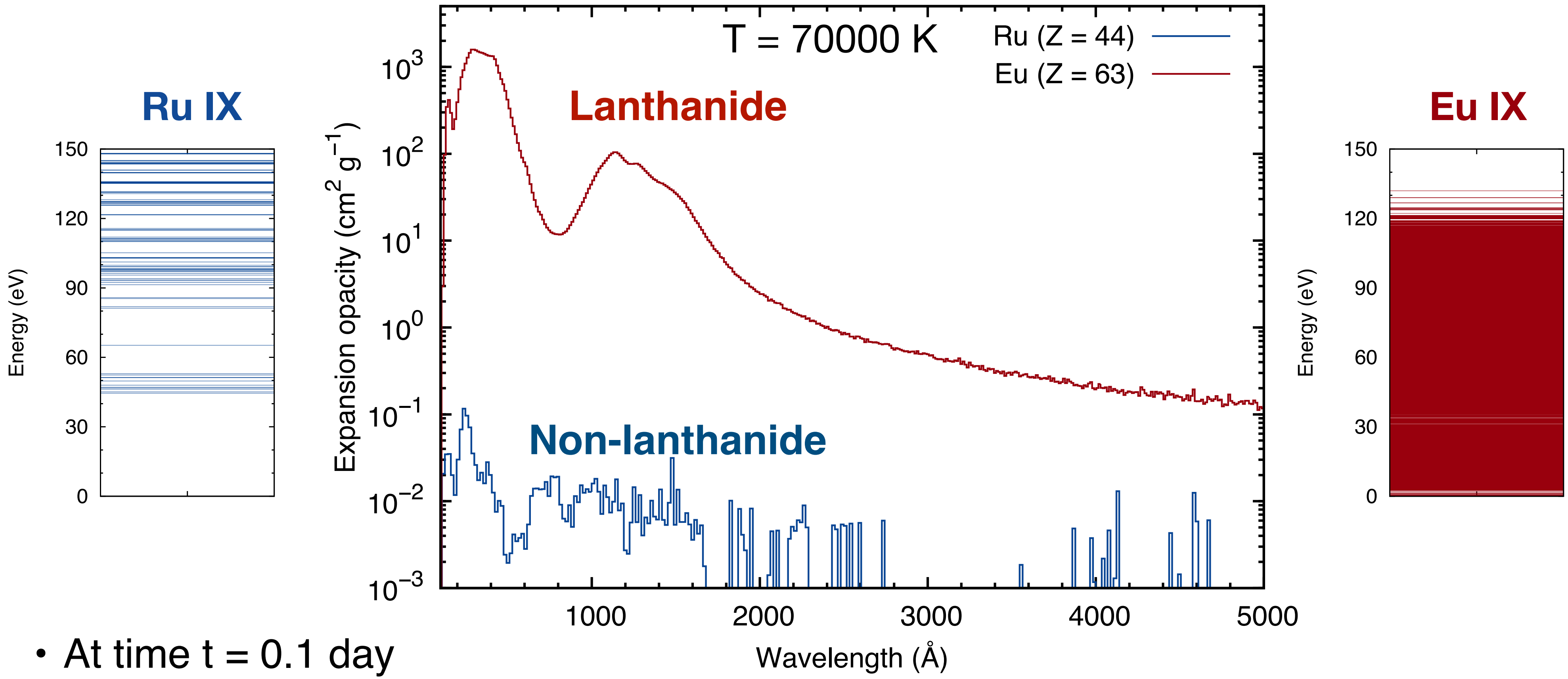
- Energy levels
- Transitions

⇨

Expansion opacity

$\kappa_{\mathrm{exp}}(\lambda)$

Sobolev 1960; Karp et al. 1977;
Eastmann and Pinto 1993



- At time t = 0.1 day
- Single element ejecta,
- Constant density $10^{-10}\,\mathrm{g\,cm^{-3}}$

Early opacity

Atomic data

- Energy levels
- Transitions

⇨

Expansion opacity

$\kappa_{\rm exp}(\lambda)$

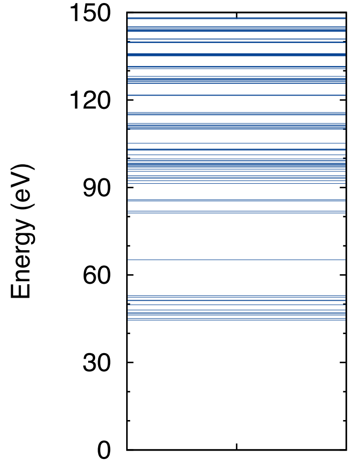
Sobolev 1960; Karp et al. 1977;
Eastmann and Pinto 1993

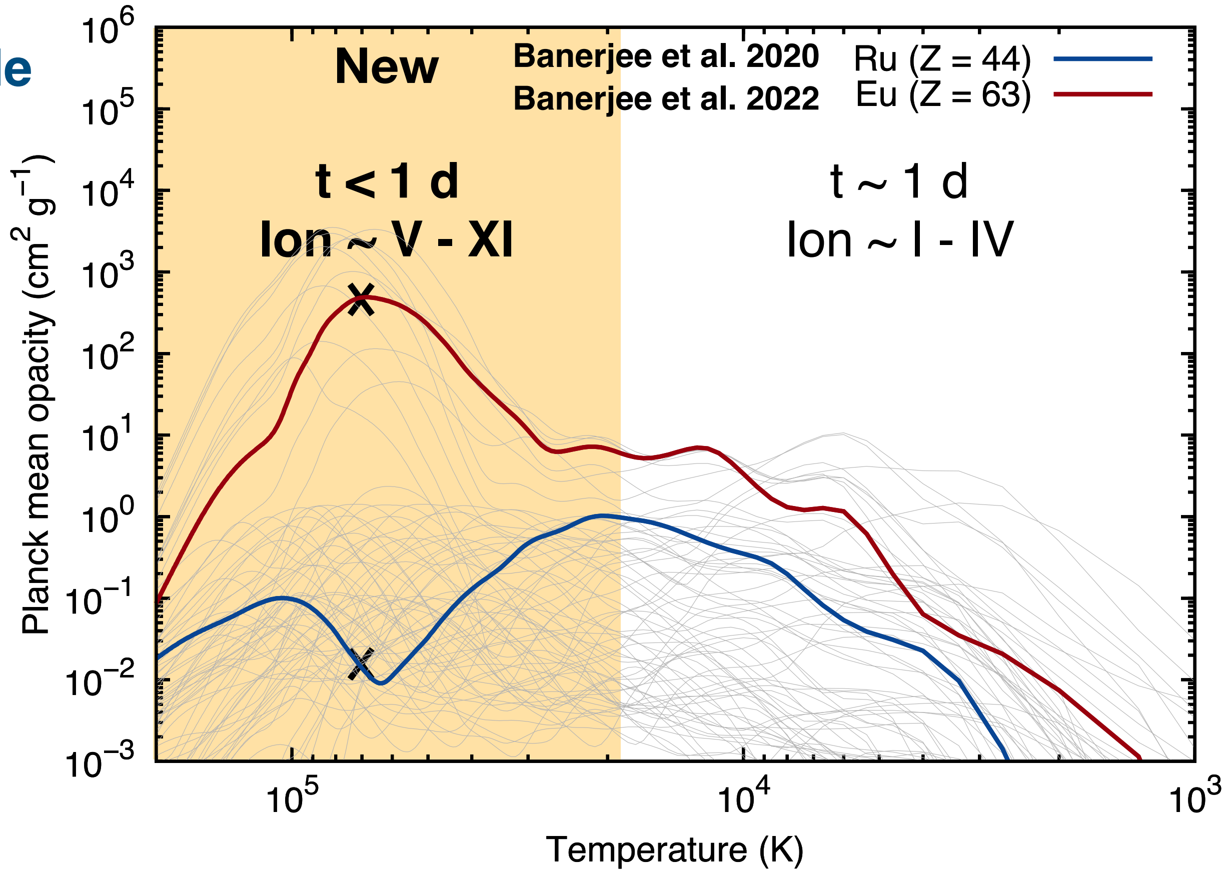
⇨

$$\kappa_{\rm mean} = \frac{\int_0^\infty \kappa_{\rm exp}(\lambda)\, B_\lambda(T)\, d\lambda}{\int_0^\infty B_\lambda(T)\, d\lambda}$$

Non-lanthanide

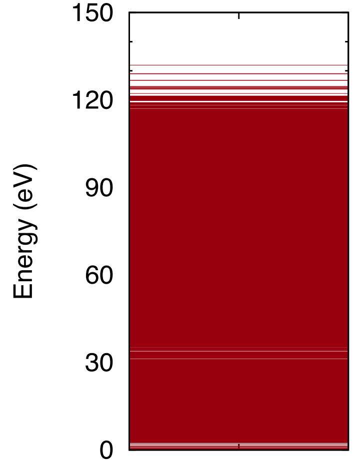
Ru IX





Lanthanide

Eu IX

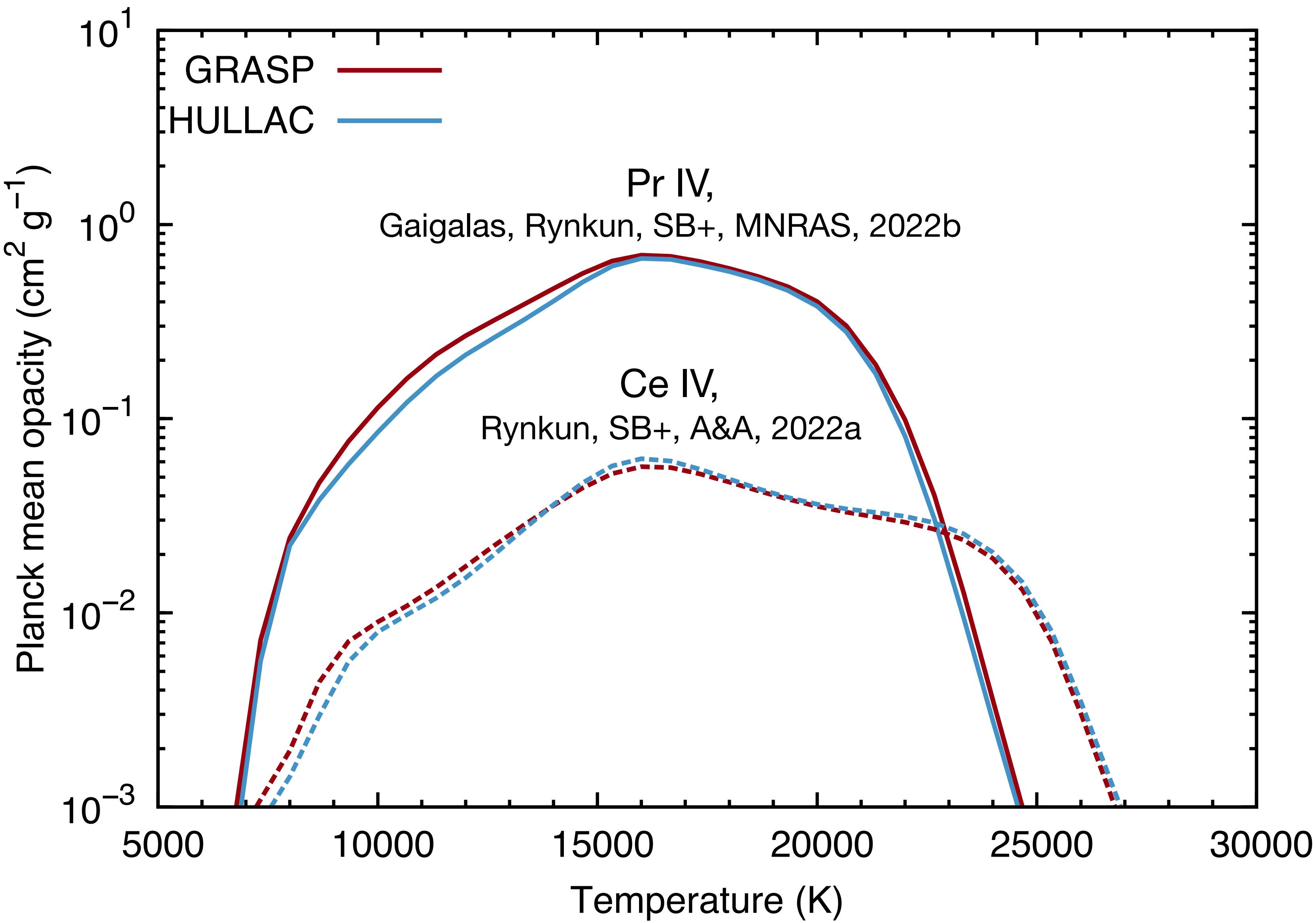


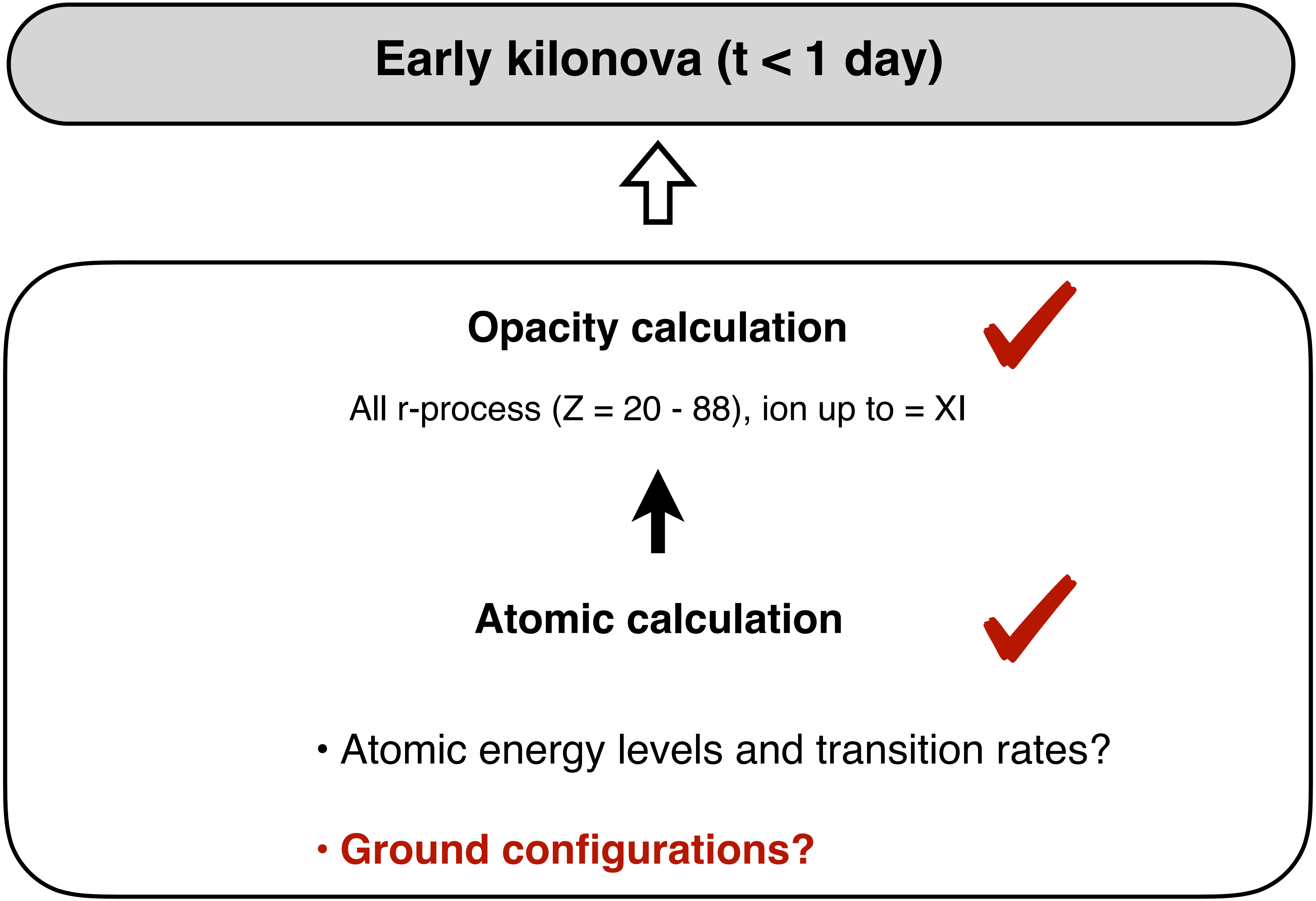
Time

This work provides the foundation to assess kilonova in early time

Uncertainties

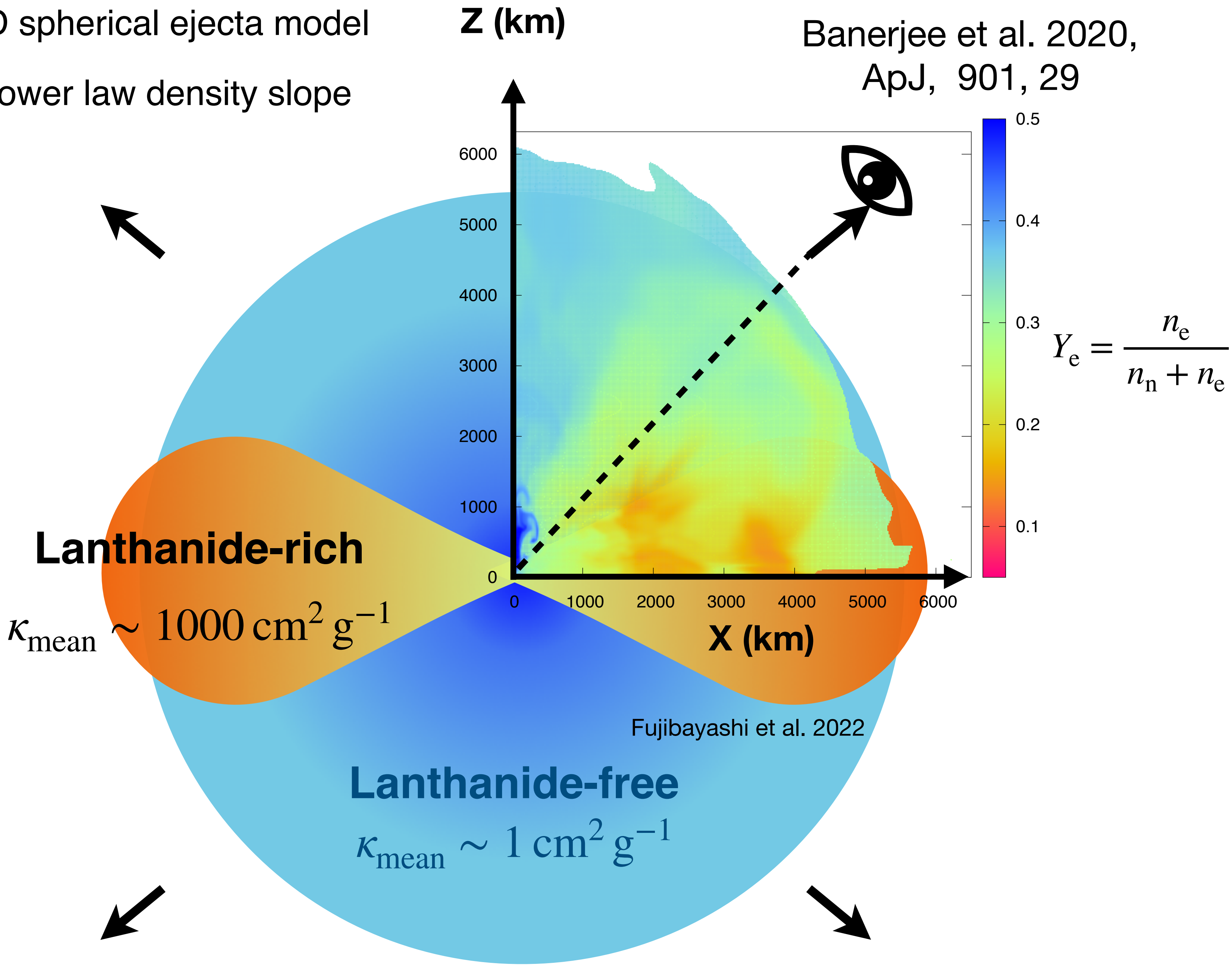
Calculations between different atomic calculations matches well



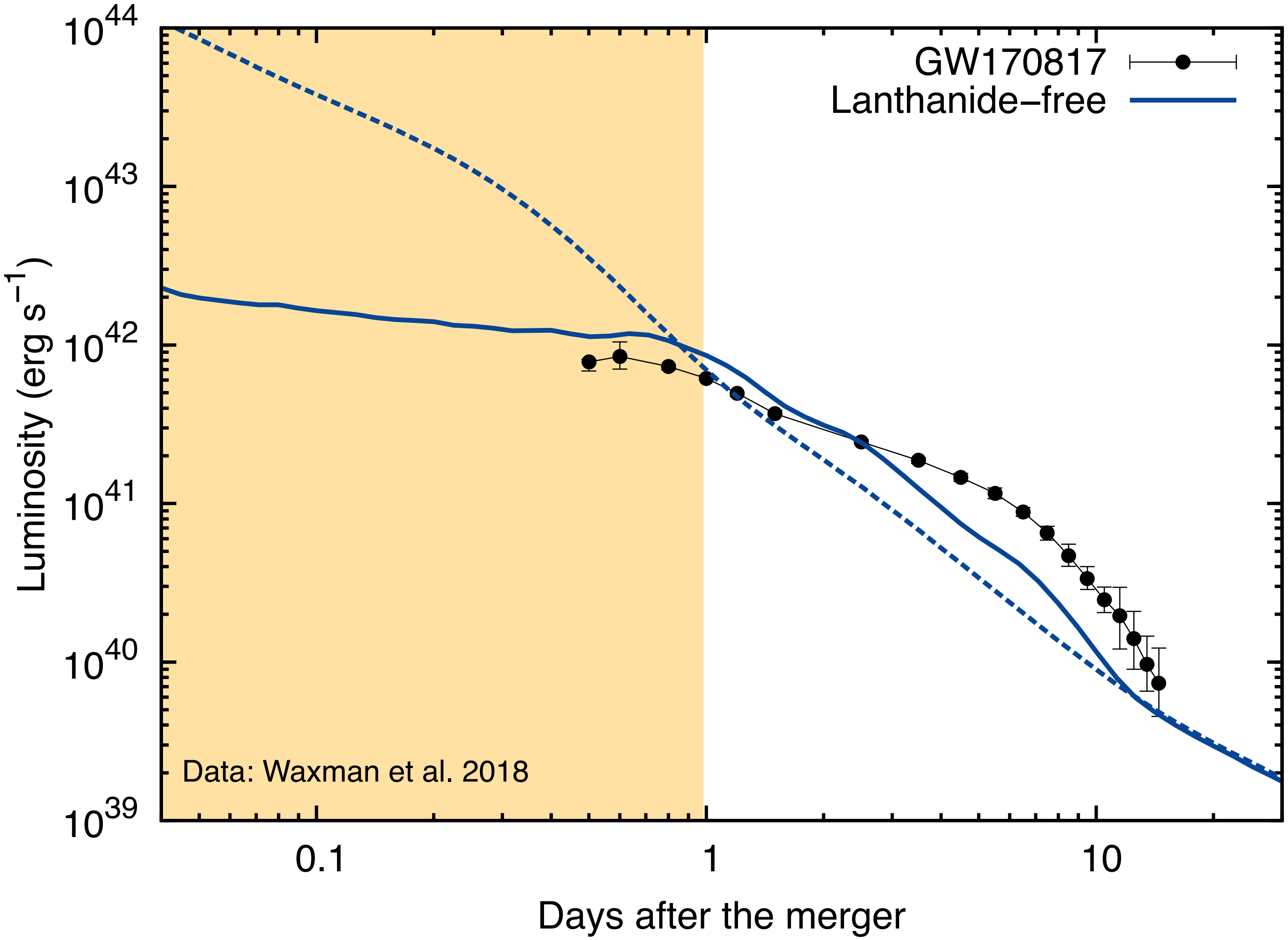

Early kilonova (t < 1 day)
Opacity calculation
All r-process (Z = 20 - 88), ion up to = XI
Atomic calculation
• Atomic energy levels and transition rates?
• Ground configurations?

Model

- 1D spherical ejecta model
- Power law density slope



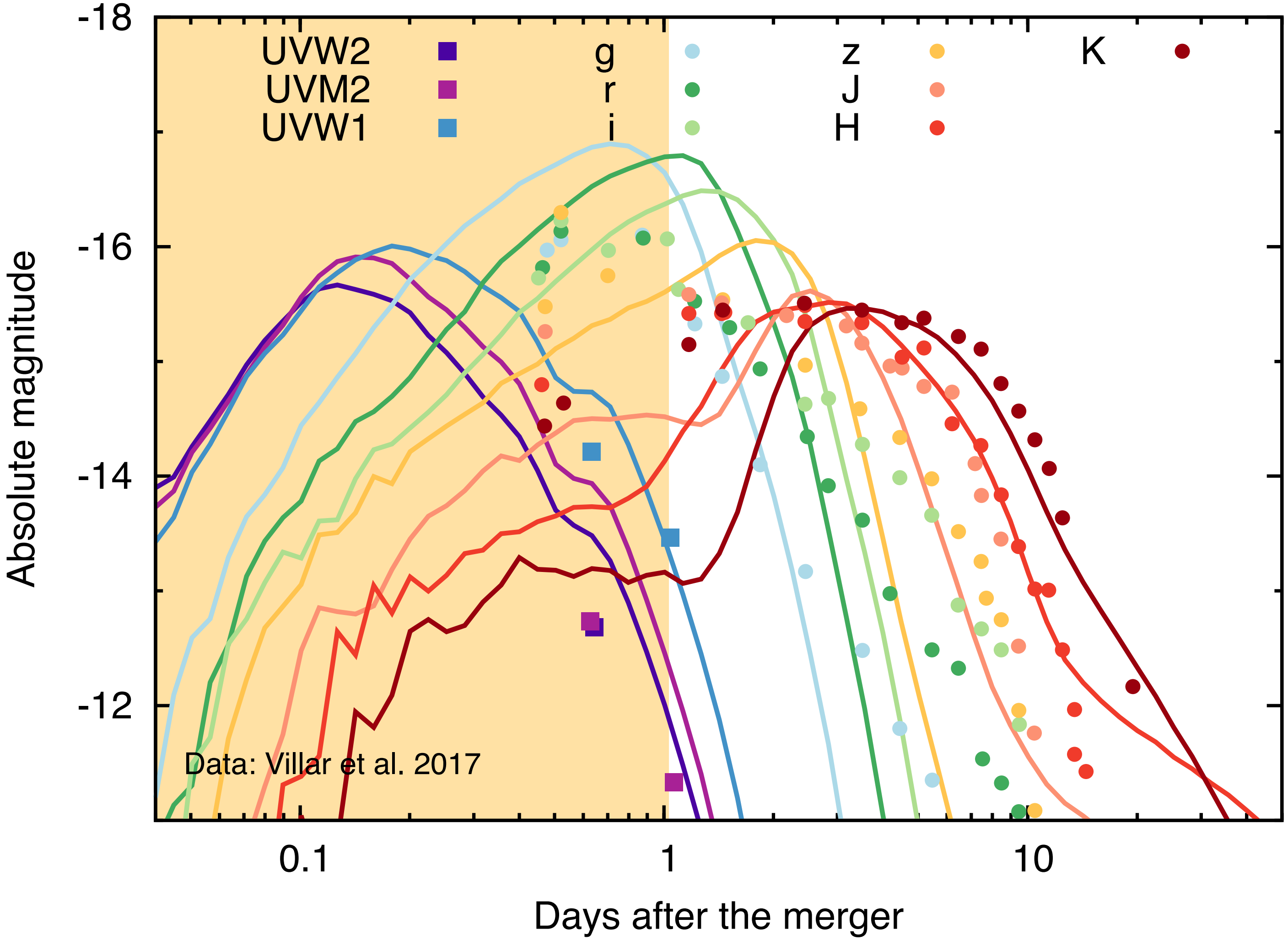
Lanthanide-free kilonova



- Light r-process element abundance
- Mass ~0.05Msun
- v ~ 0.05c - 0.2c

Radioactive model can reproduce early light curve for kilonova with GW170817

Application to GW170817



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Model

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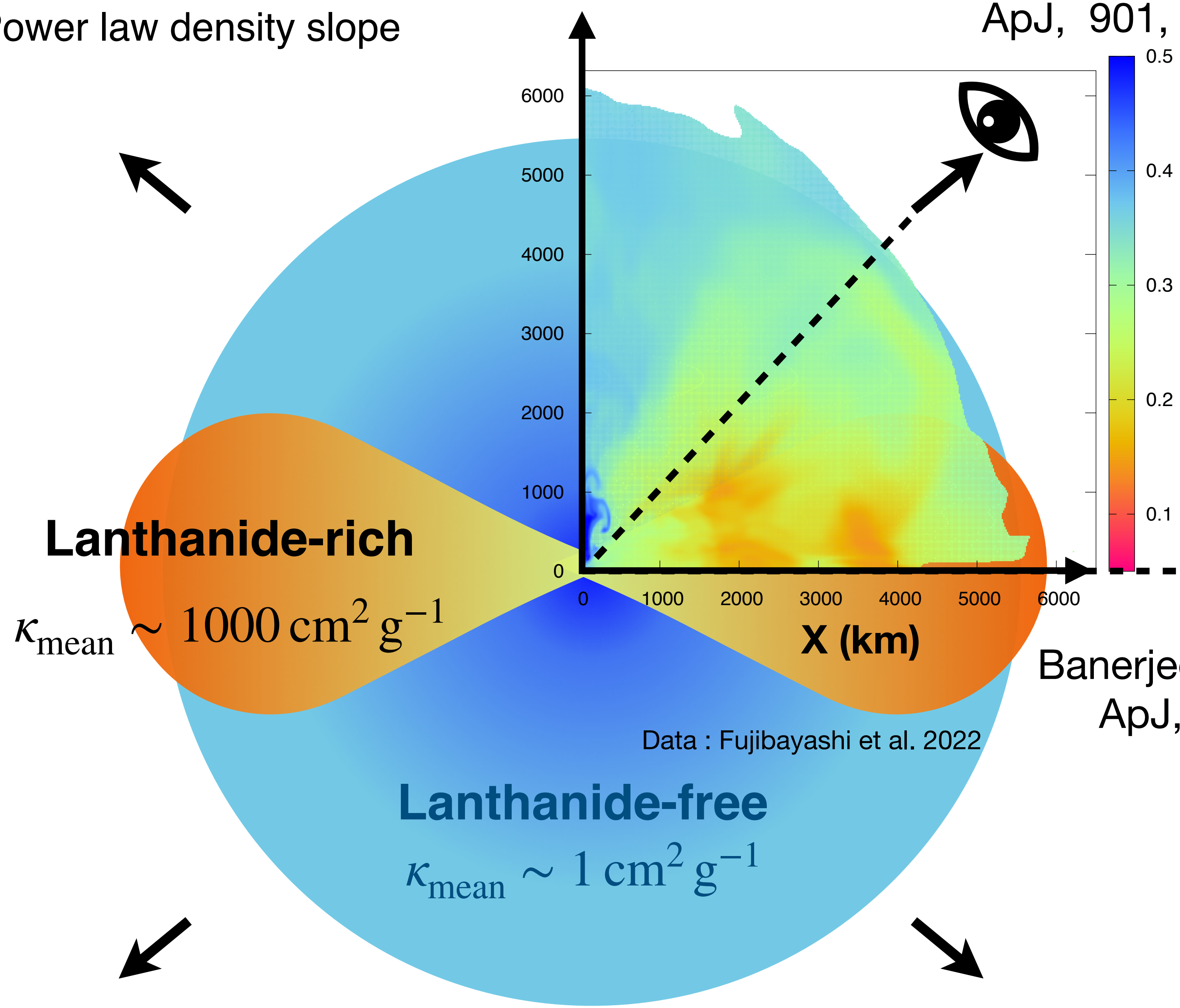
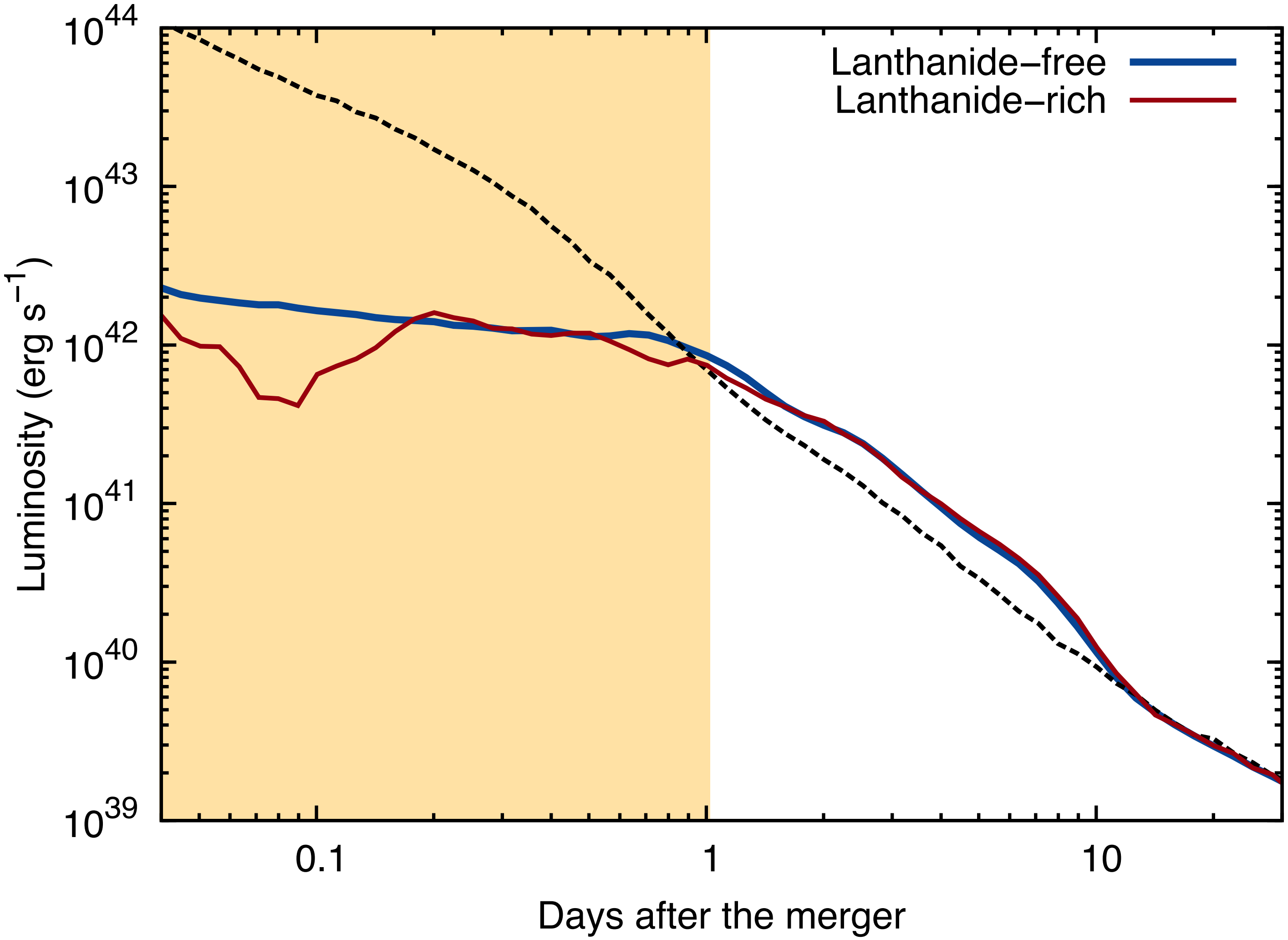


Banerjee et al. 2020, ApJ, 901, 29

$$Y_{\rm e} = \frac{n_{\rm e}}{n_{\rm n} + n_{\rm e}}$$

Banerjee et al. 2022, ApJ, 934, 117

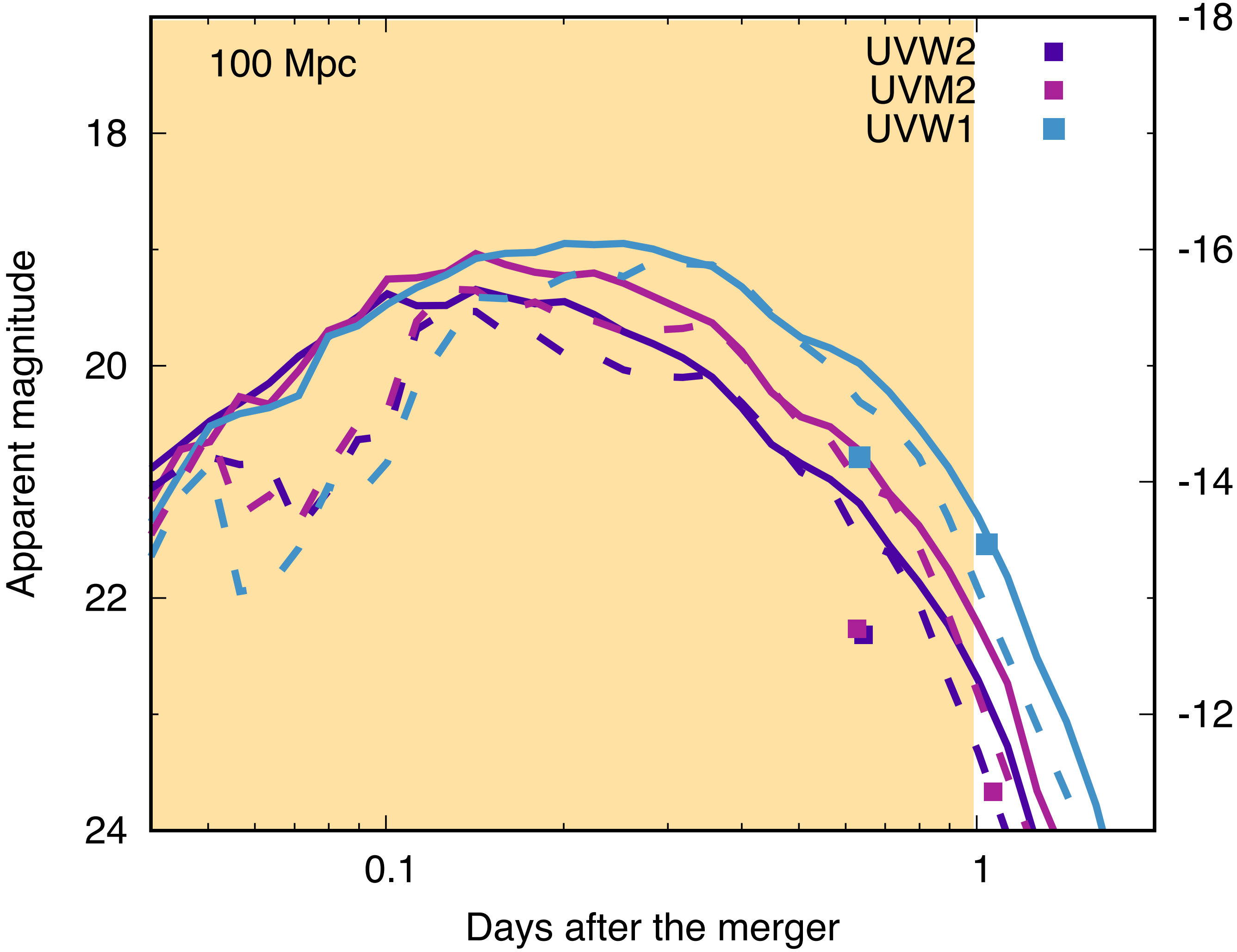
Lanthanide-rich kilonova



- Light r-process element abundance + La fraction (0.1)
- Mass ~ 0.05Msun
- v ~ 0.05c - 0.2c

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

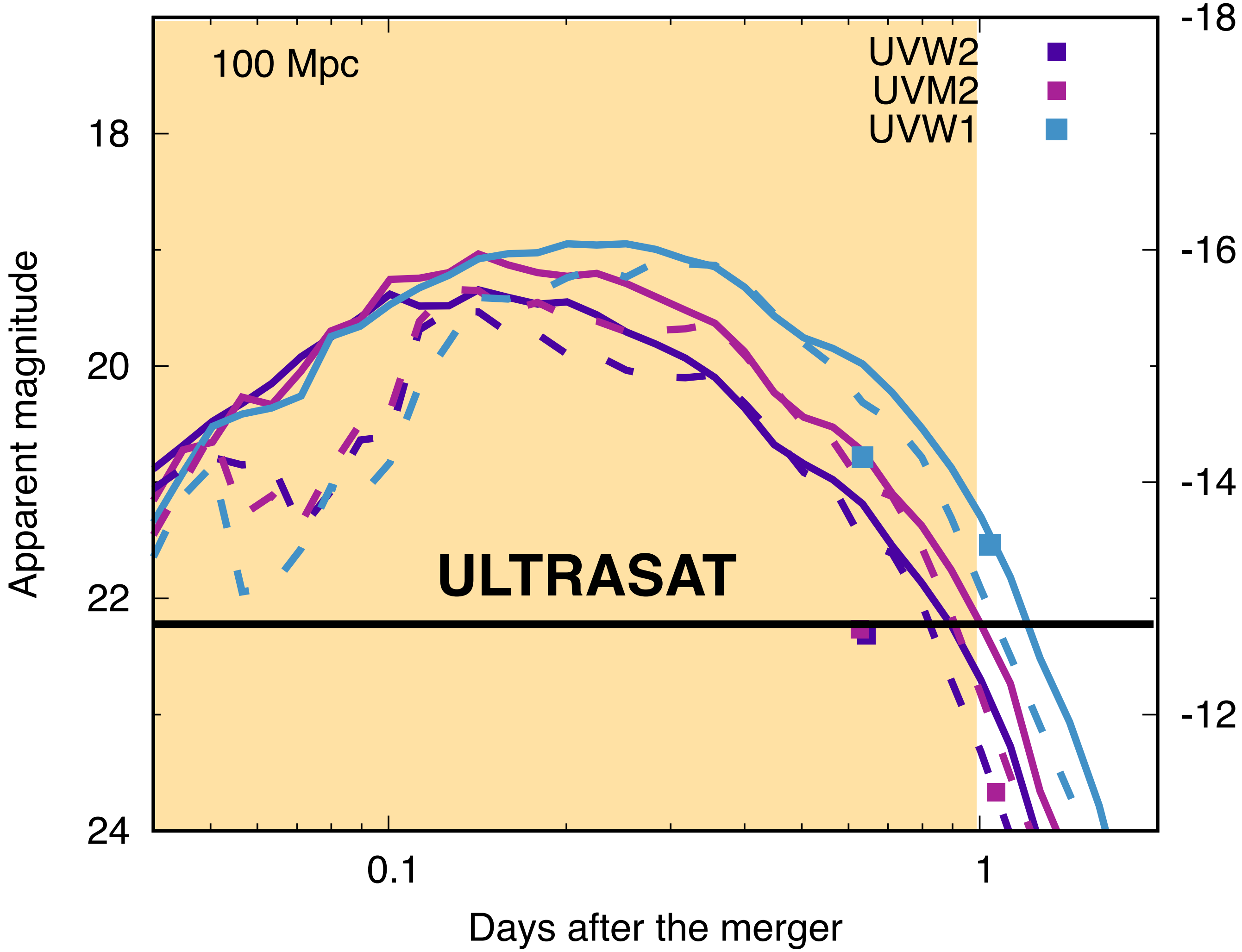
Lanthanide-rich kilonova



- Light r-process element abundance
  + La fraction (0.1)
- Mass ~ 0.05Msun
- v ~ 0.05c - 0.2c

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

Future prospects



Mission	5σ (AB)
Dorado	20.5 (10 min. exp.)
ULTRASAT	22.3 (15 min. exp.)
UVEX	25 (15 min. exp.)

Dorsman et al. 2022

Multiple upcoming UV missions: ULTRASAT, Dorado, UVEX

Our model predicts detectable early bright UV emission

Early kilonova (t < 1 day)

Opacity calculation

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

Atomic calculation

- Atomic energy levels and transition rates?
- **Ground configurations?**

Summary

First systematic atomic opacity suitable for early time

- For all r-process elements including lanthanides (Z = 20 - 88) for ionization up to 10^{th}
- Lanthanide opacity is order of magnitude high

First radiative transfer simulation with detailed opacity

(1) light r-process abundance => equivalent to polar kilonova

- Explains kilonova observation of GW170817

(2) lanthanide abundance => equivalent to equatorial kilonova

- Strong suppression of luminosity in early time

Predicts bright UV emission detectable by future UV satellites

This work provides the foundation to assess early kilonova from future observations