The Effect of Jet-Ejecta Interaction on Multi-D Kilonova Light Curves

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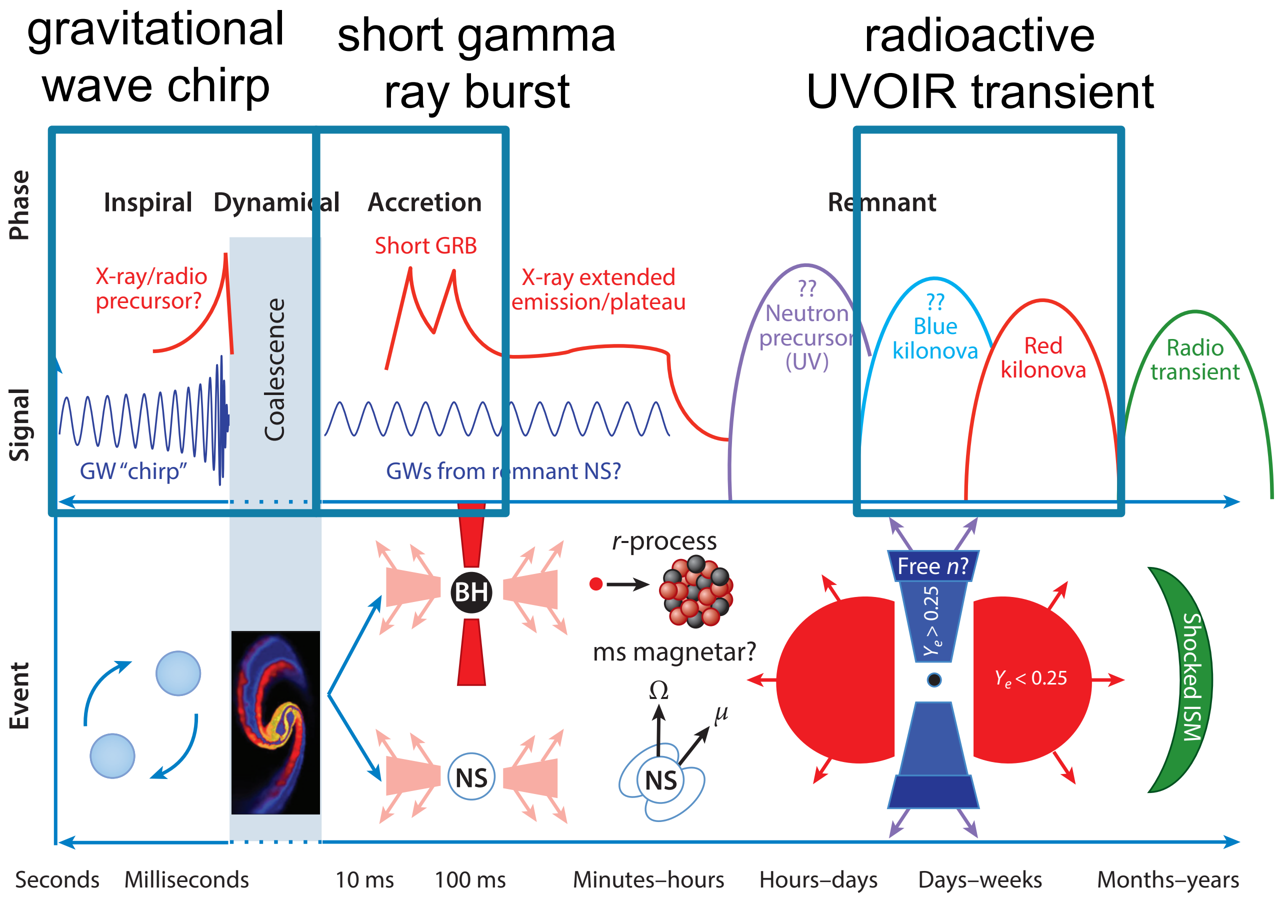
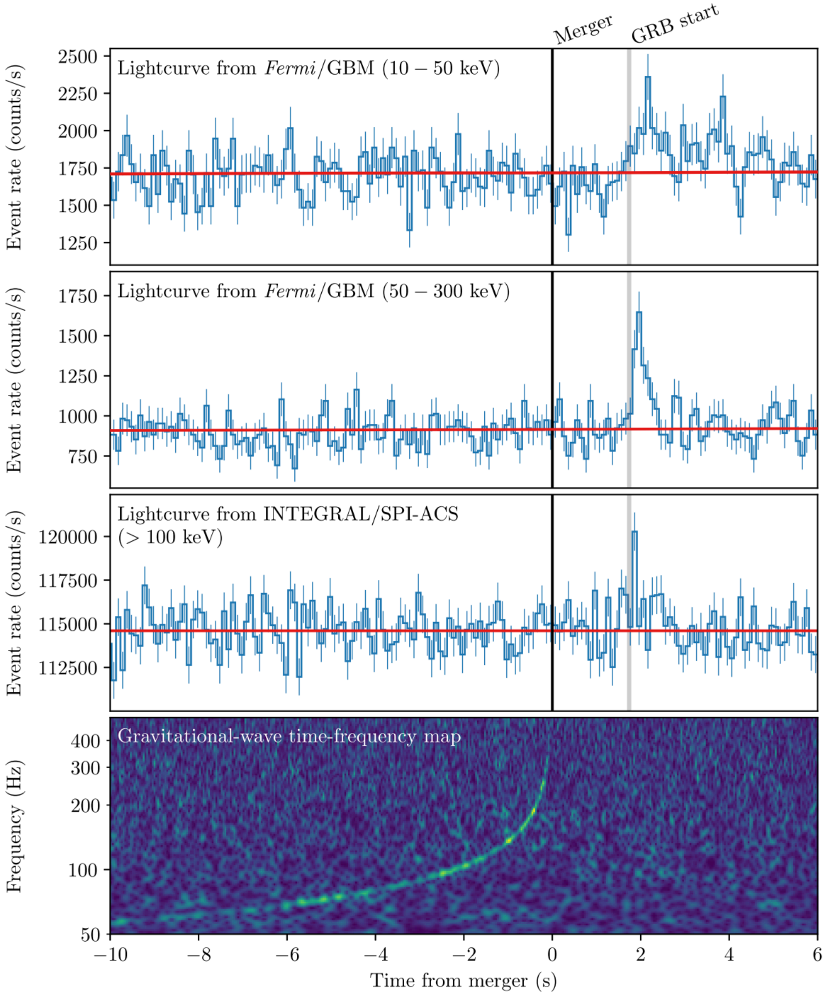
Neutron star mergers are multimessenger events

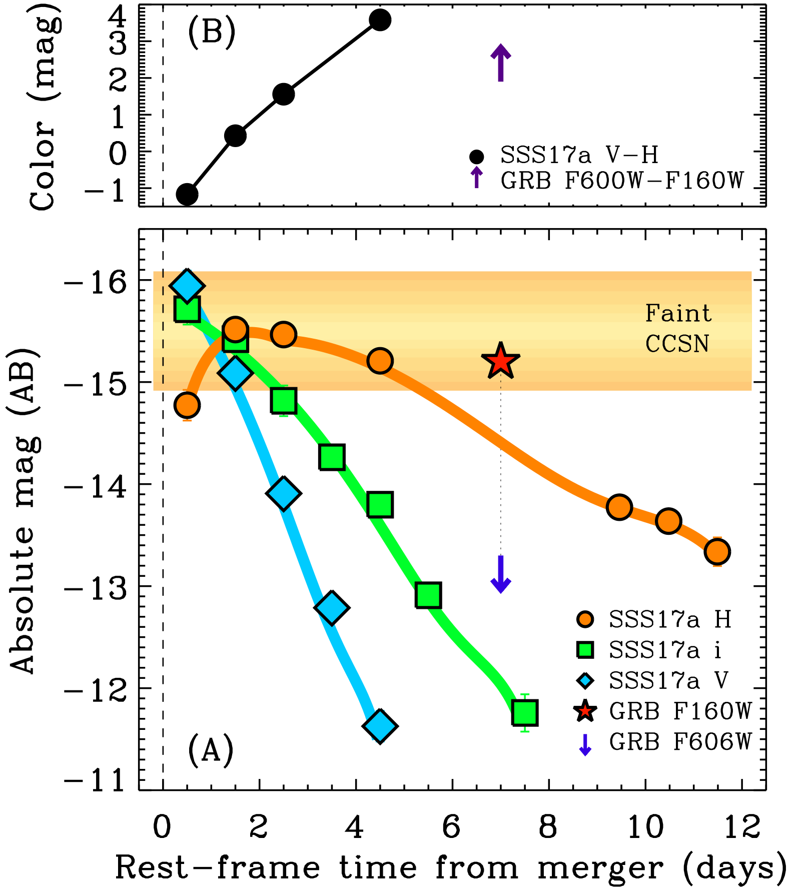


Fernández & Metzger '16

GW170817 / GRB170817A / AT2017gfo



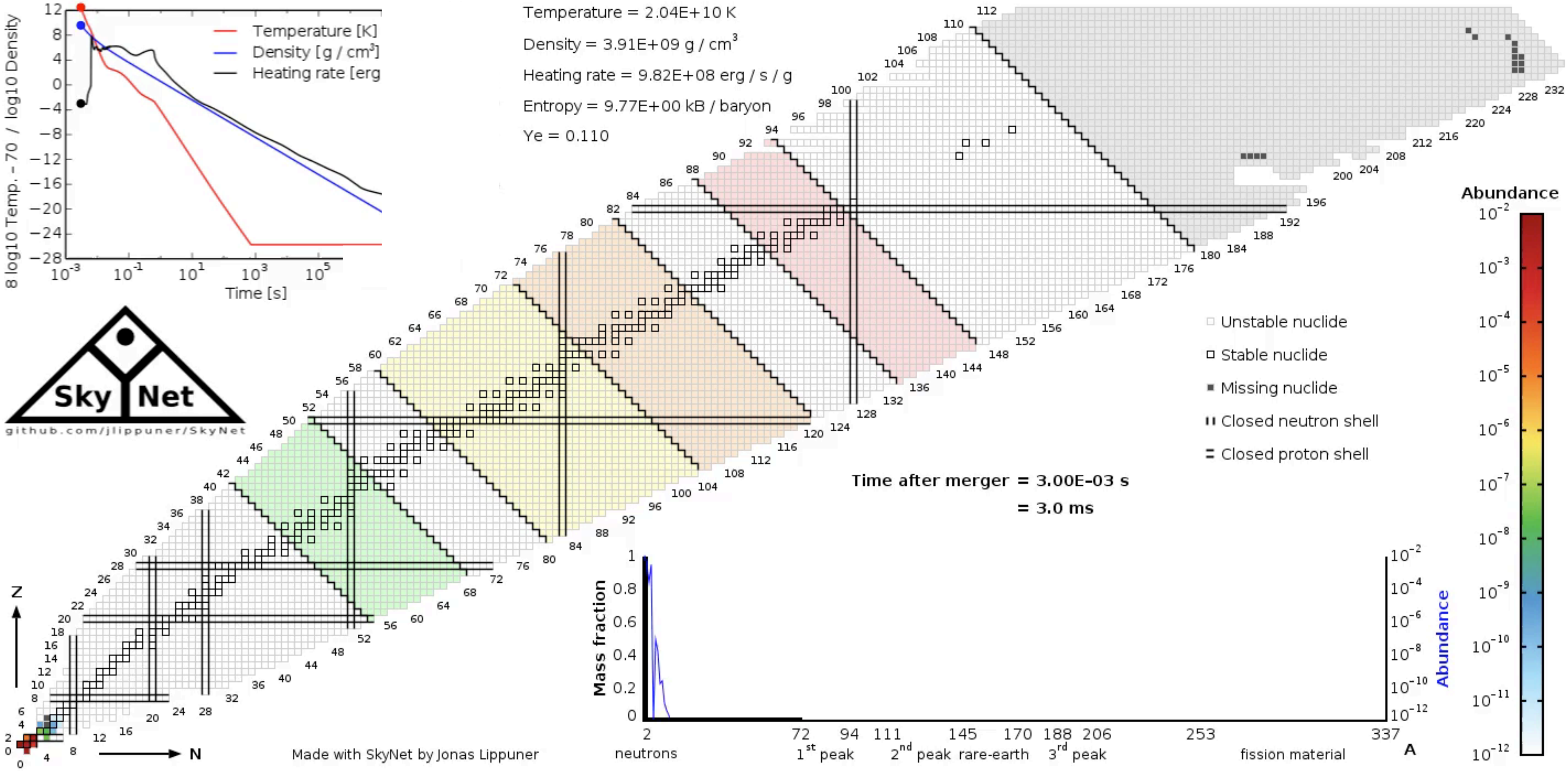
Abbott + '17



Drout + '17

R-Process Nucleosynthesis

$$Y_e \equiv \frac{n_p}{n_p + n_n}$$



Temperature = 2.04E+10 K

Density = 3.91E+09 g / cm^3

Heating rate = 9.82E+08 erg / s / g

Entropy = 9.77E+00 kB / baryon

Ye = 0.110

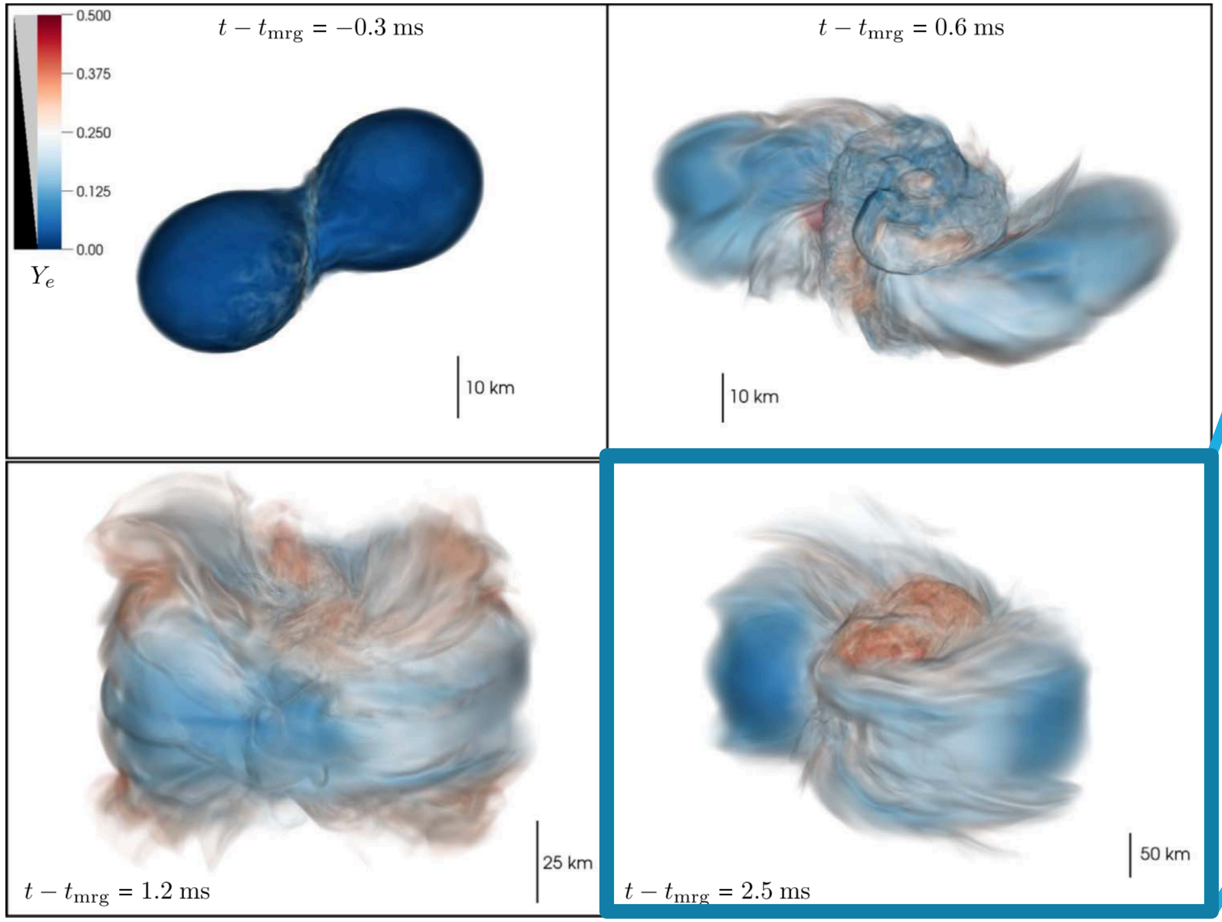
Time after merger = 3.00E-03 s

= 3.0 ms

Made with SkyNet by Jonas Lippuner

Jonas Lippuner

Dynamical ejecta from **tides** and **shocked NS matter**
~10^{-3} $M_\odot$ over ~10 ms



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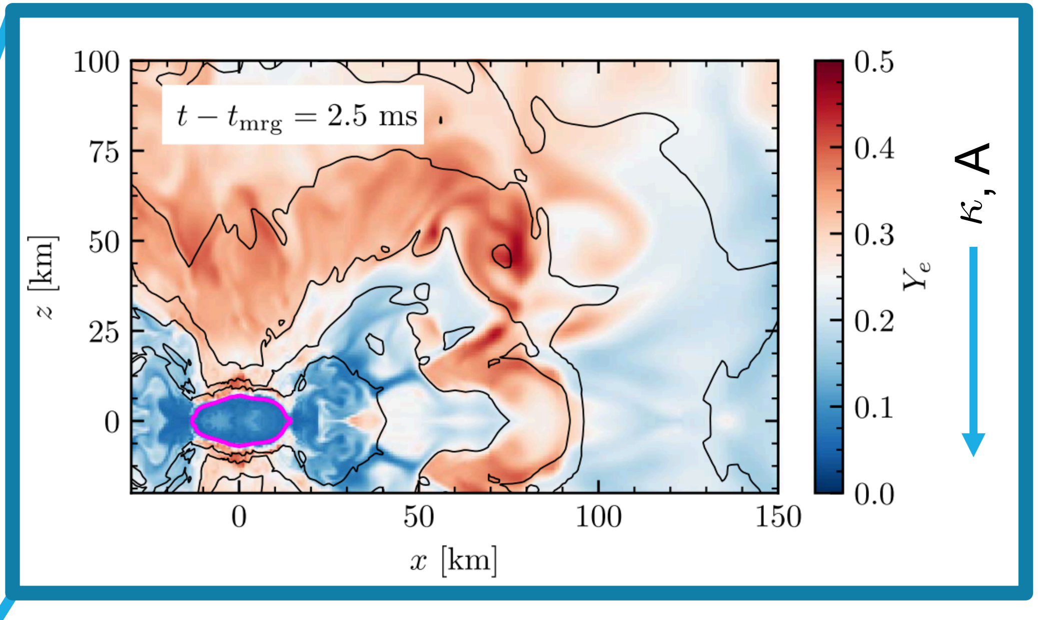
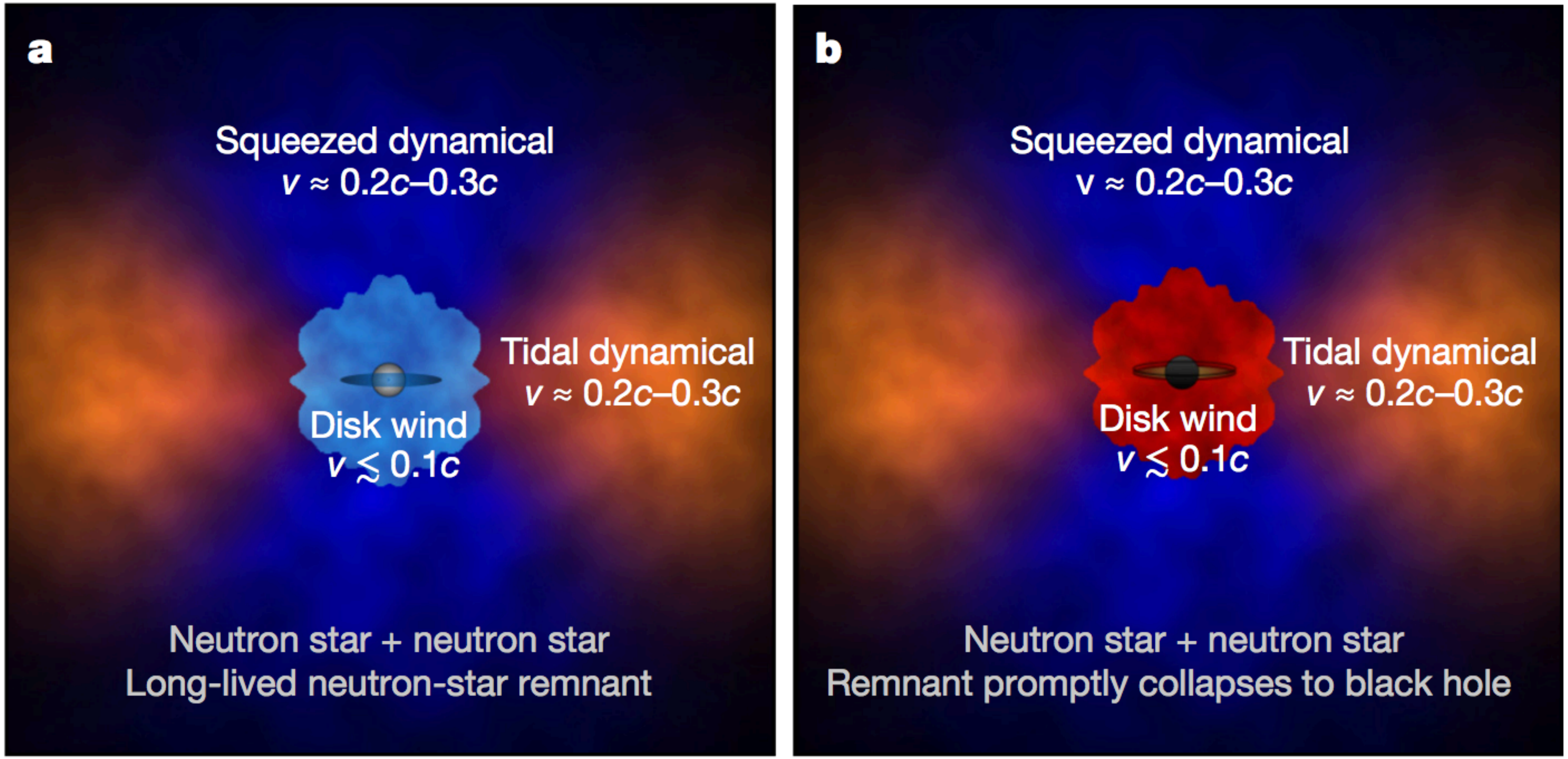


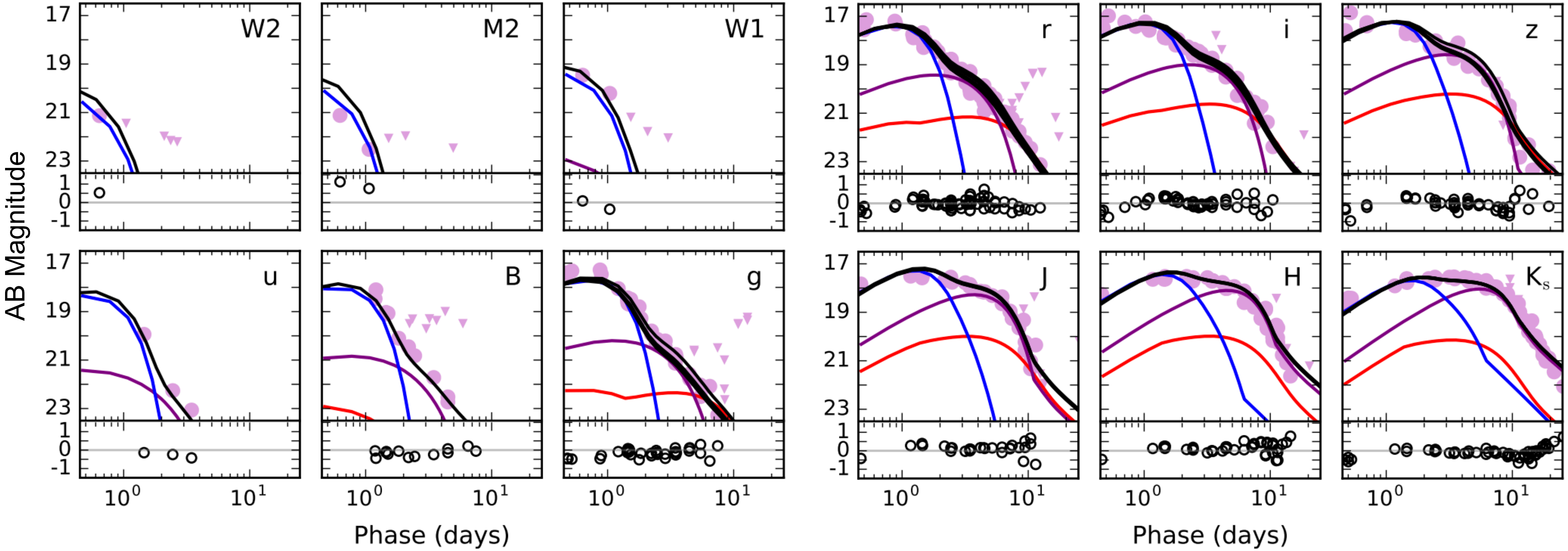
Radice + ‘18

NS mergers produce multiple ejecta components



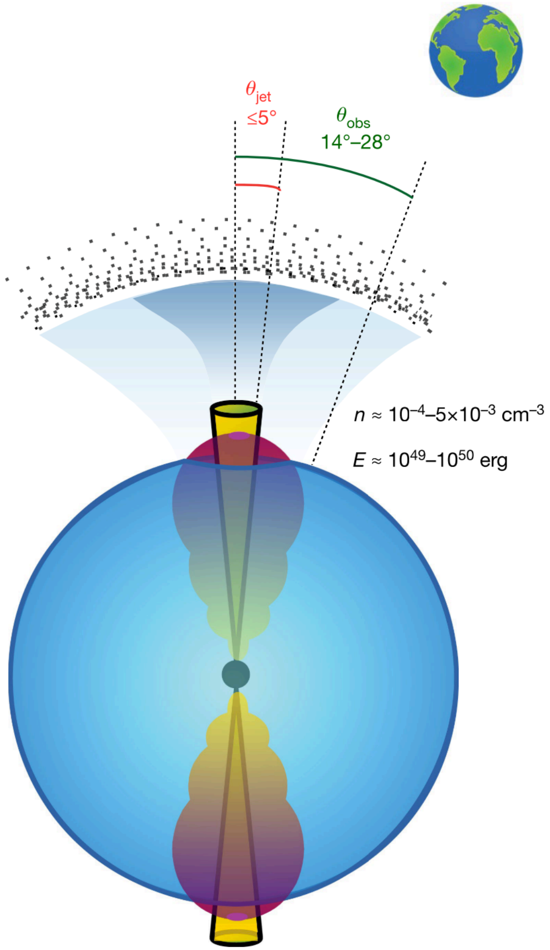
Kasen +’ 17

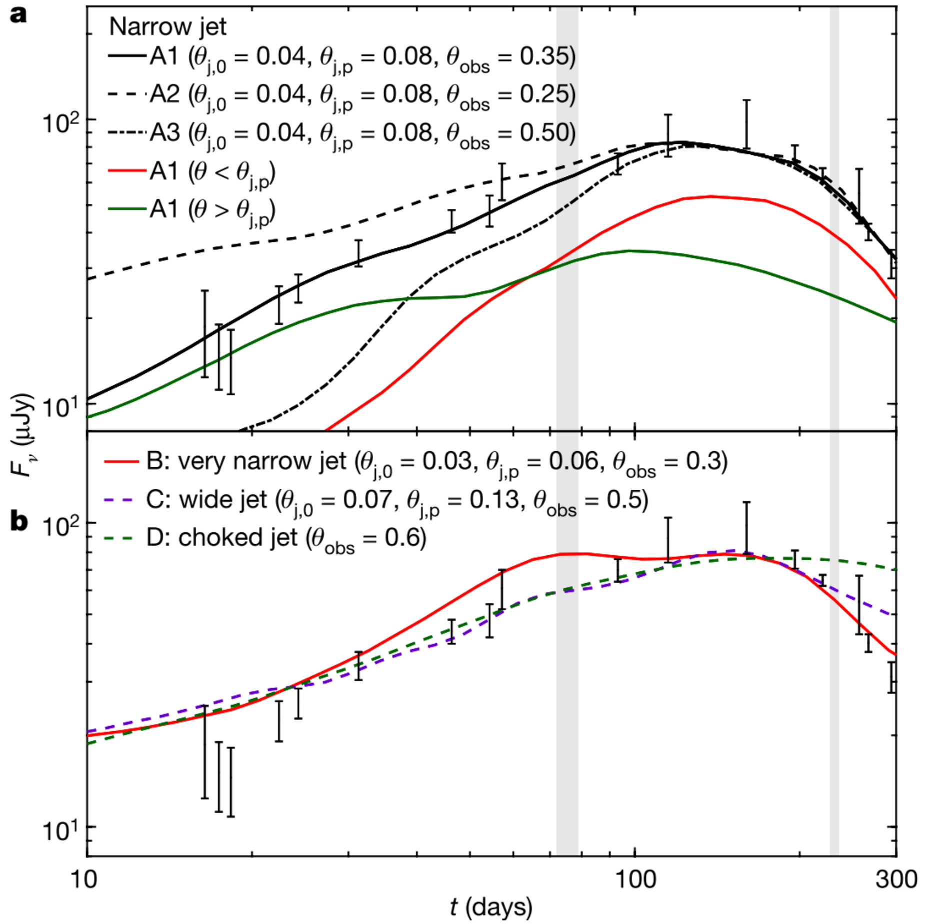
Kilonova consistent with multiple ejecta components



Modified from Villar + 17

GW170817 radio light curve indicates jet





Mooley + ‘18

What next?

What kind of diversity can we expect to see in subsequent kilonovae?

What next?

What are the effects of different viewing angles?

How Does Jet-Ejecta Interaction Affect Kilonova?

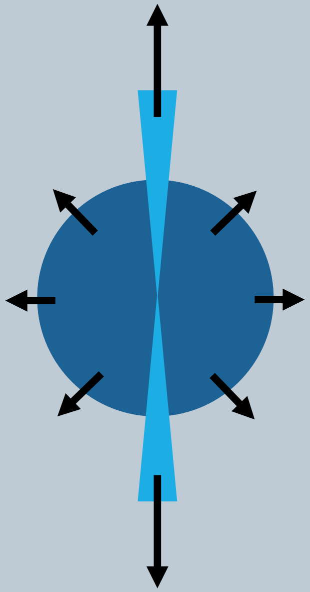
Focusing on **shock-heating** due to a prompt jet and **changes to density structure**

Two of the Possible Sources of Heating for the Optical Transient

Prompt shock heating (from jet?)	**Radioactive decay of nucleosynthesis products**
(incl. Kasliwal+'17, Piro & Kollmeier'17)	**(incl. Metzger+'10)**
~seconds	~seconds to days
10^{49} - 10^{50} erg	10^{50} erg

Approach

t ~ 10 ms to t ~ 100 s

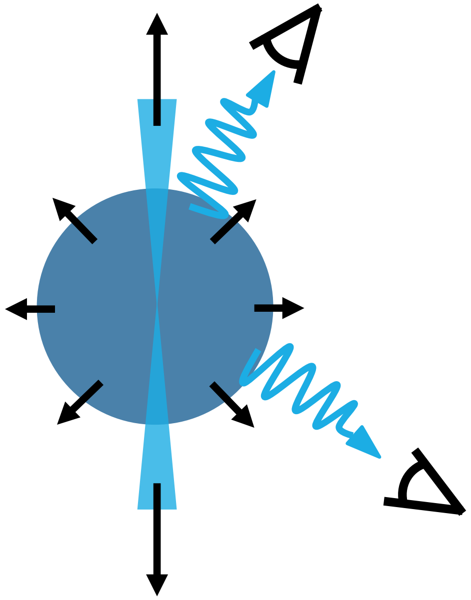


2D relativistic hydrodynamic simulation (in JET) of jet interacting with expanding outflow
(Duffell, Quataert, Kasen, **Klion**) ’18)

adiabatic expansion

r-process heating
(Metzger+’10, Lippuner & Roberts ‘15)

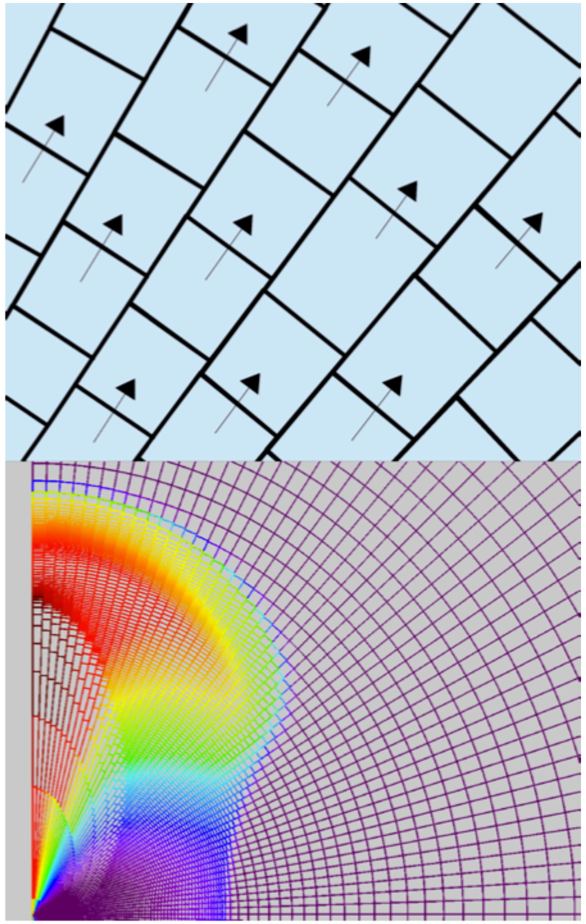
t ~15 min to t ~ 10 days



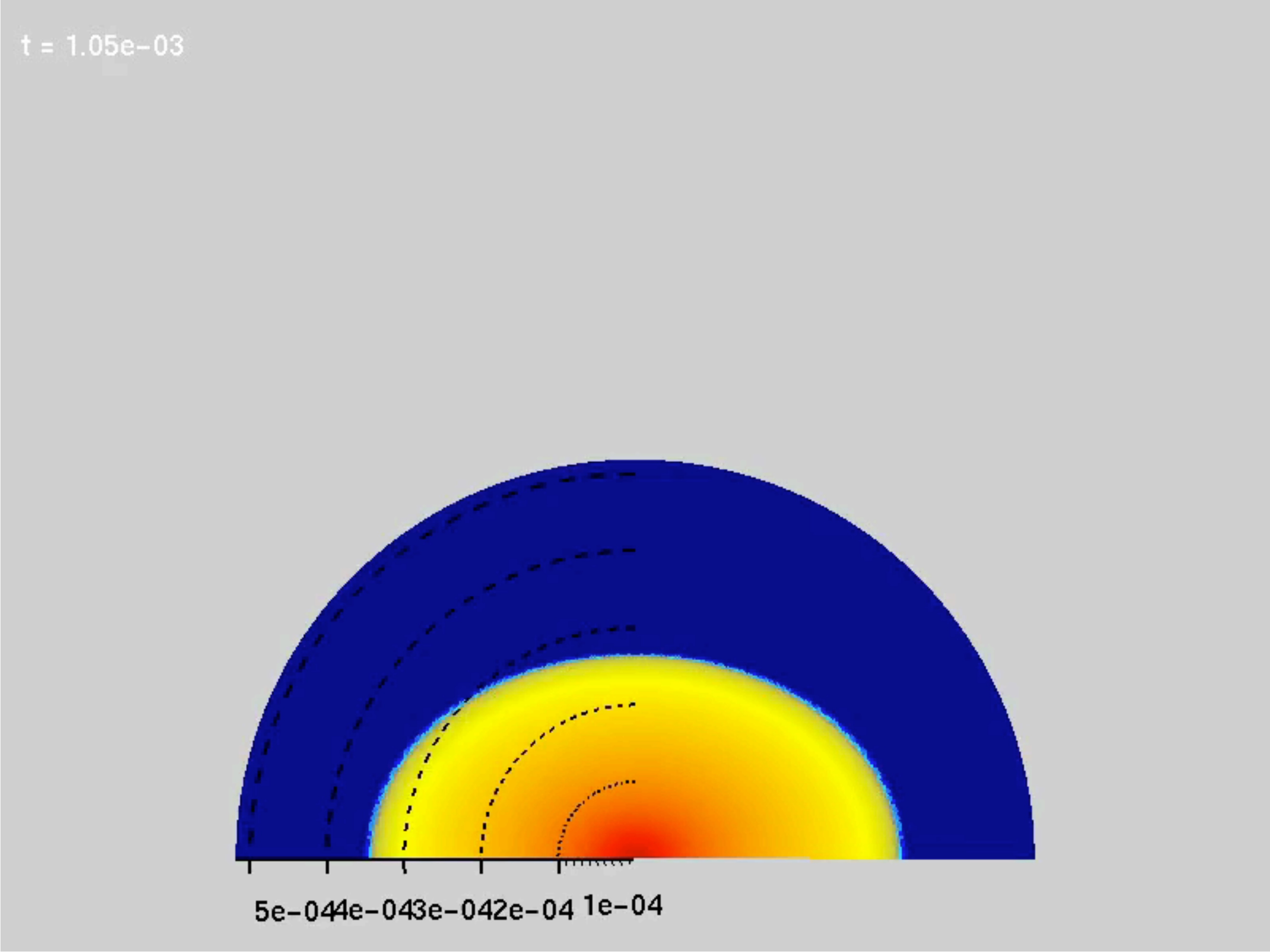
2D Monte Carlo radiation transport simulations with Sedona
(**Klion** + in prep)

Relativistic Hydrodynamic Calculations

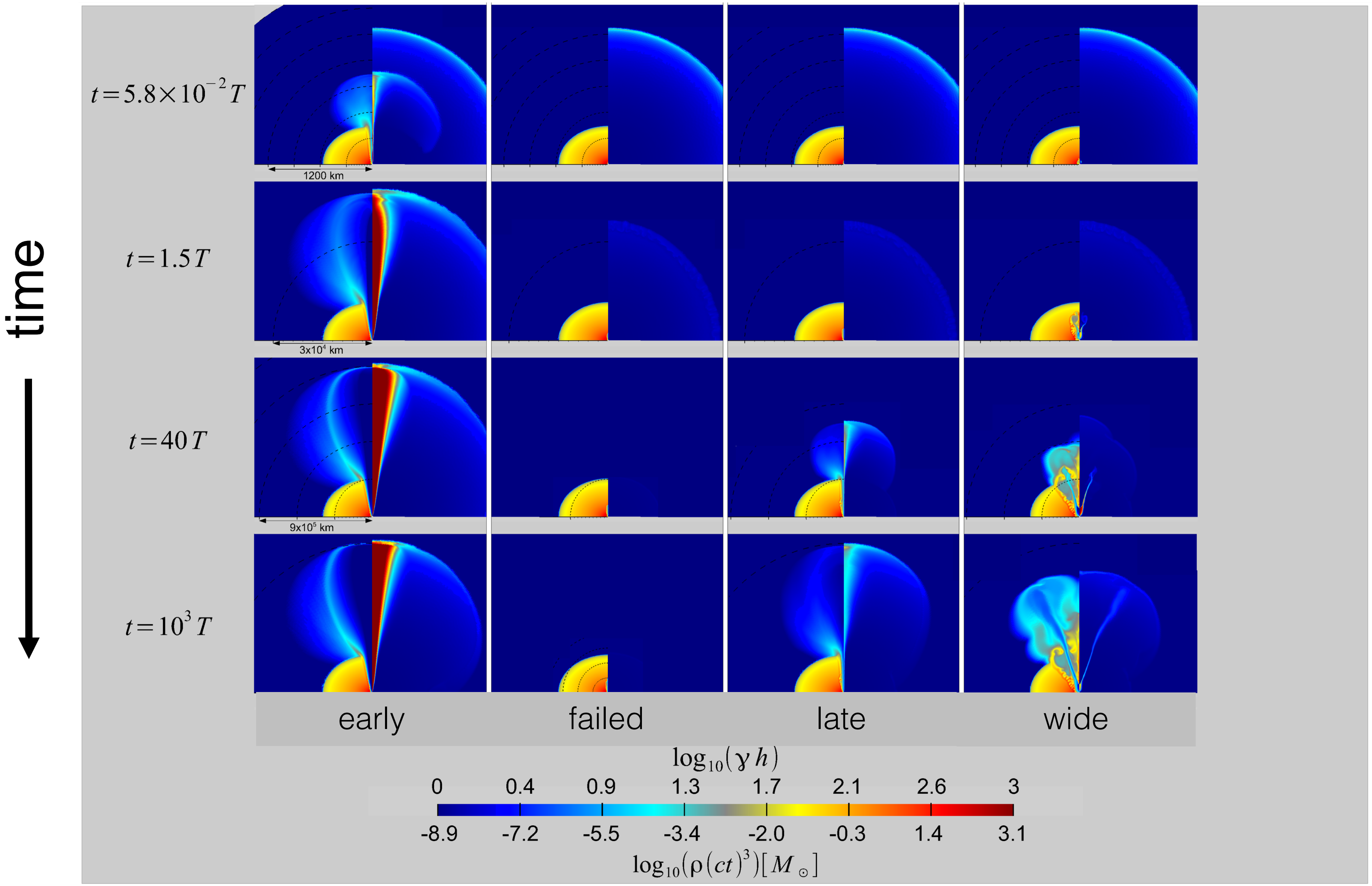
- Initial conditions from numerical NS merger simulations (Hotokezaka +13, Nagakura + 14); ejecta slightly oblate
- Fiducial scales
  - Mass 0.07 $M_\odot$
  - Engine duration $T = 0.1$s
- Using code JET (Duffell & MacFadyen 2011, 2013)
- Lagrangian spherical polar grid, cells can move radially with the flow
- Assume ejecta are homologously expanding. No delay between merger and engine turn on. Inject a jet with some luminosity, engine duration, and opening angle
- Evolve until $1000T \sim 100$s, when mostly homologous



Jet + Ejecta Hydrodynamic Simulations



Four regimes of jet-ejecta interaction



Duffell, Quataert, Kasen, **Klion** ‘18

Jet success depends only on energy scale & angle

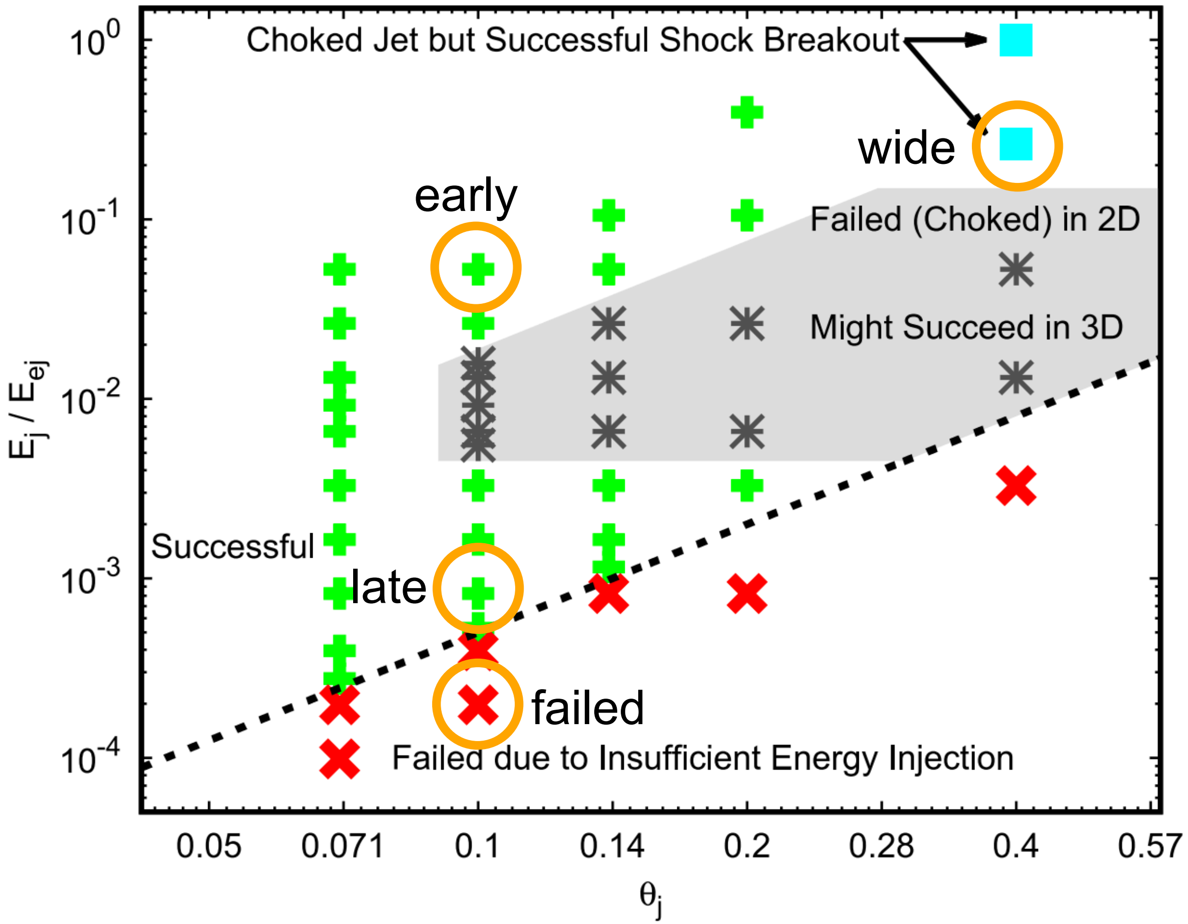
Assumption: ejecta expand homologously – delay between merger and engine is small

Only timescale in the problem is the **engine duration *T***, and success condition cannot independently depend on *T*. Only energy scale and geometry matter.

Success condition:

$$E_j > E_{\rm crit}$$

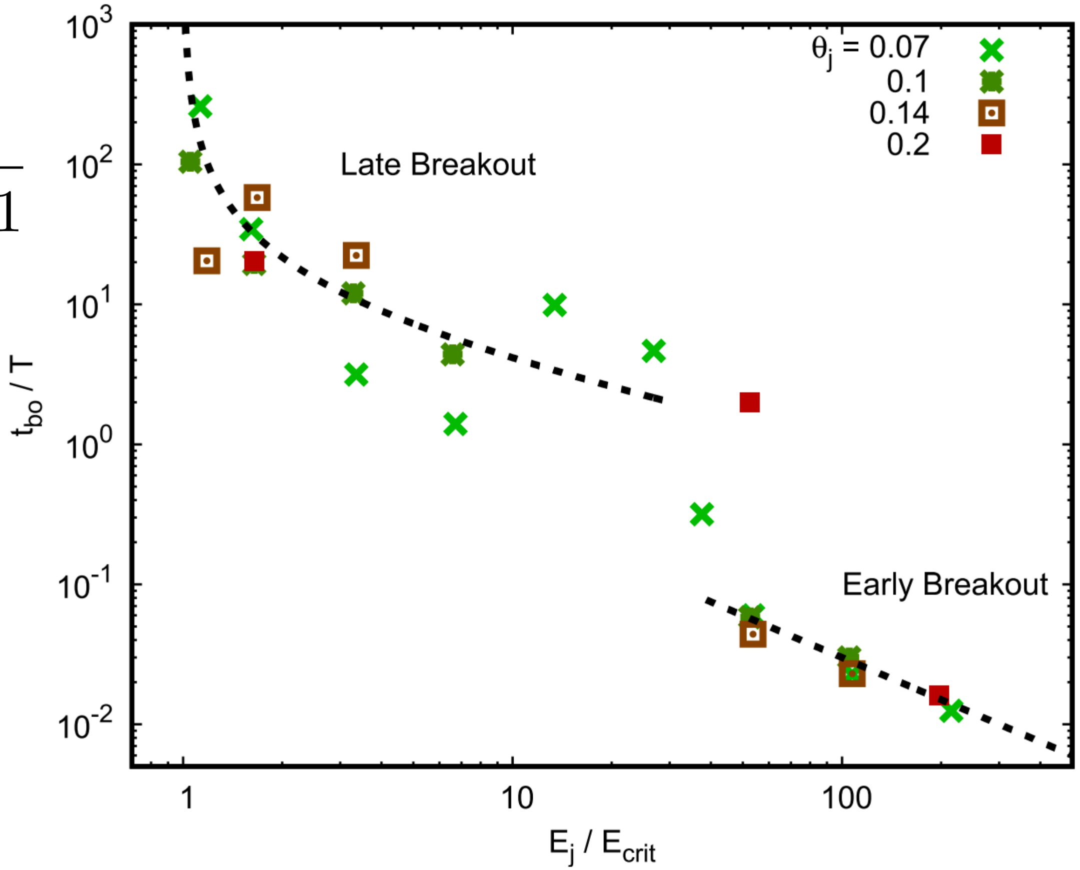
$$E_{\rm crit} \propto \theta_j^2 E_{\rm ej}$$



Duffell, Quataert, Kasen, **Klion** ‘18

Jets can break out on timescales longer than engine duration

$$t_{\rm bo} \sim \frac{T}{\sqrt{E_j/E_{\rm crit}} - 1}$$



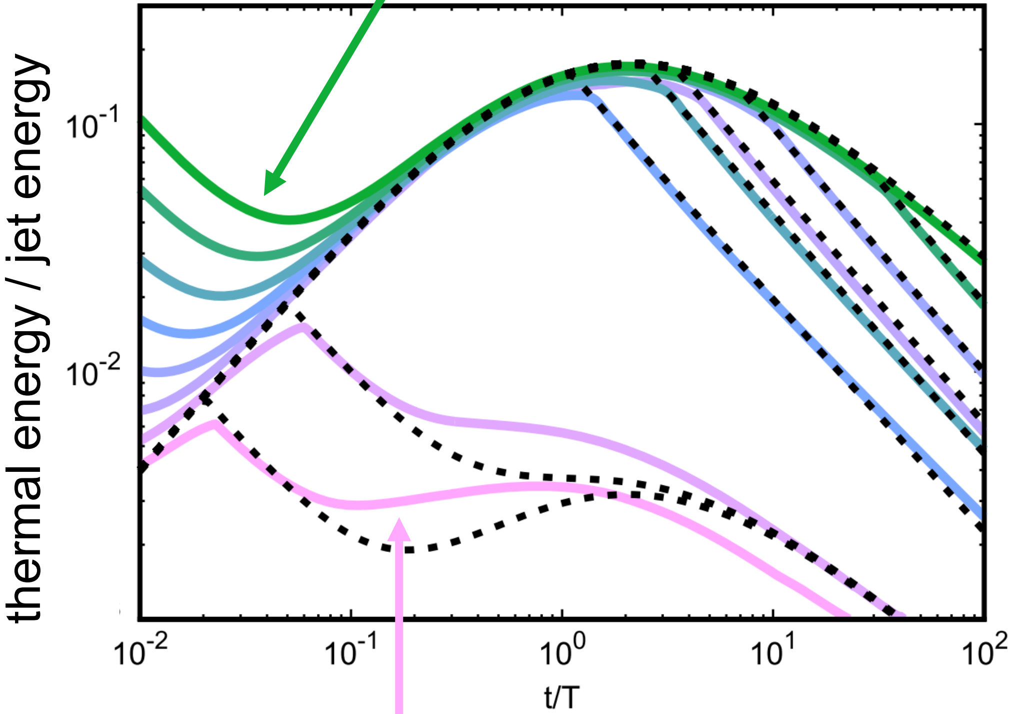
$$E_{\rm crit} = L t_{\rm bo}$$

$$L = E_j/T$$

$$t_{\rm bo} \sim T E_{\rm crit}/E_j$$

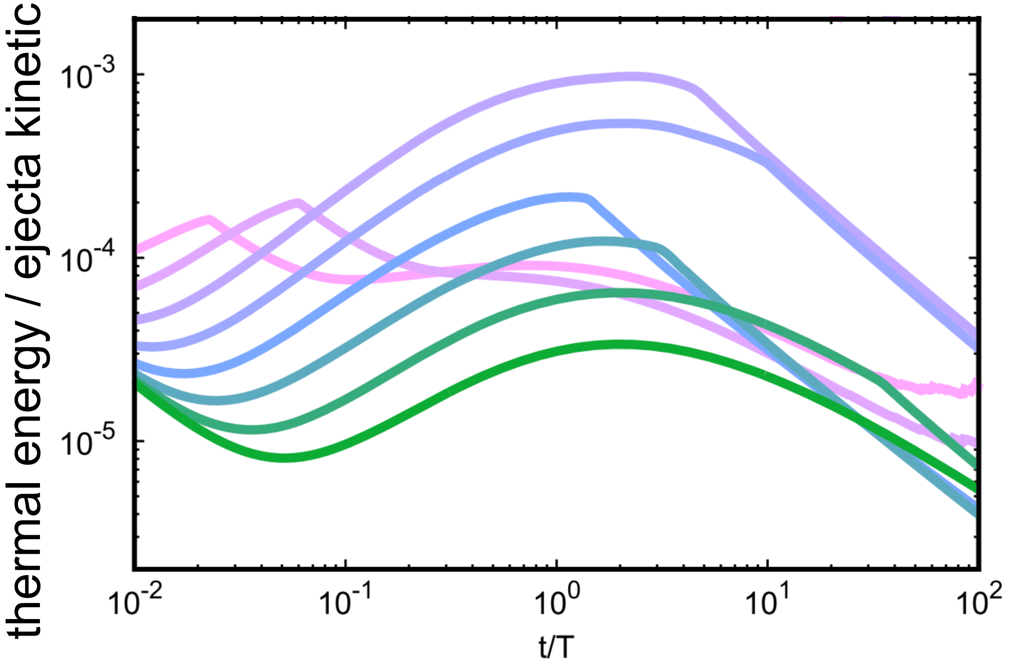
Duffell, Quataert, Kasen, **Klion** ‘18

Higher energy jet does not guarantee more thermal energy



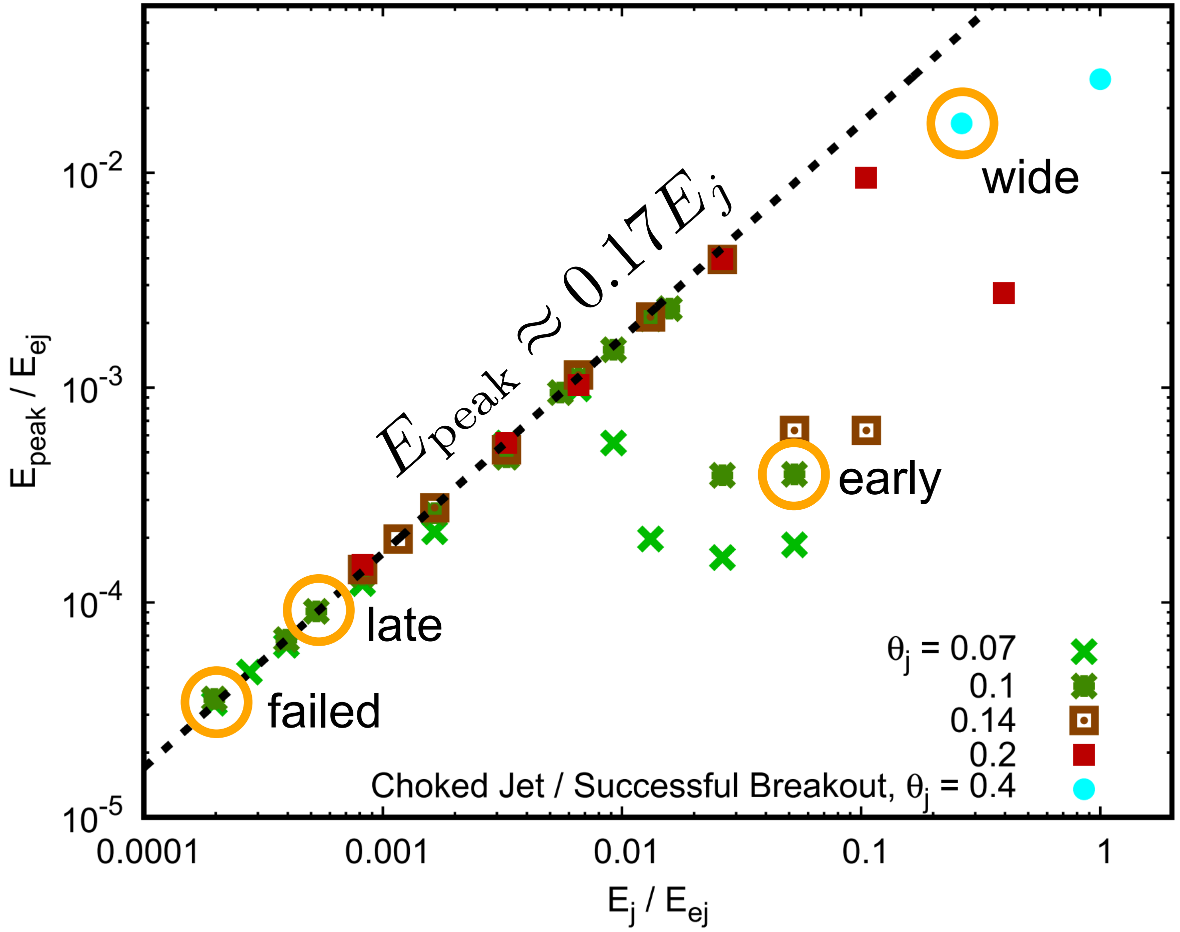
lowest energy jet

highest energy jet



Duffell, Quataert, Kasen, **Klion** ‘18

Jet thermalization efficiency is limited



Duffell, Quataert, Kasen, **Klion** ‘18

Approach

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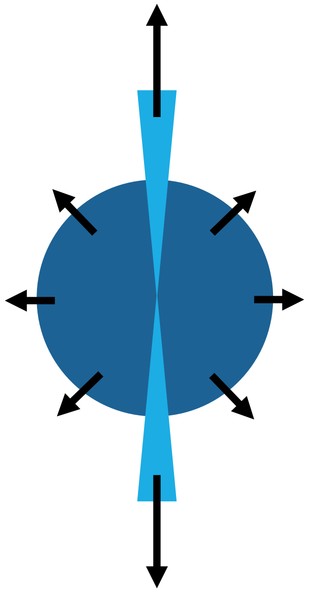

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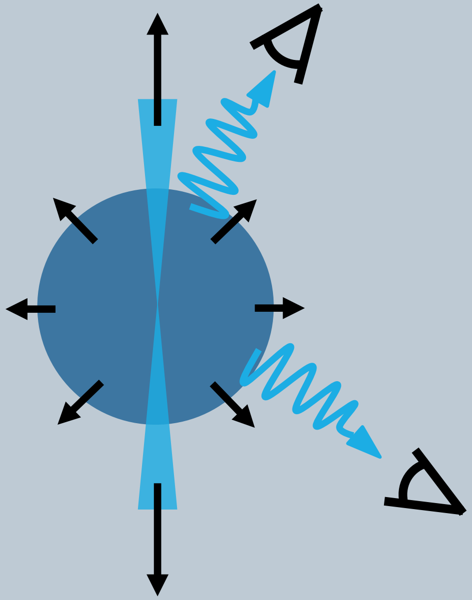

2D Monte Carlo radiation transport simulations with Sedona
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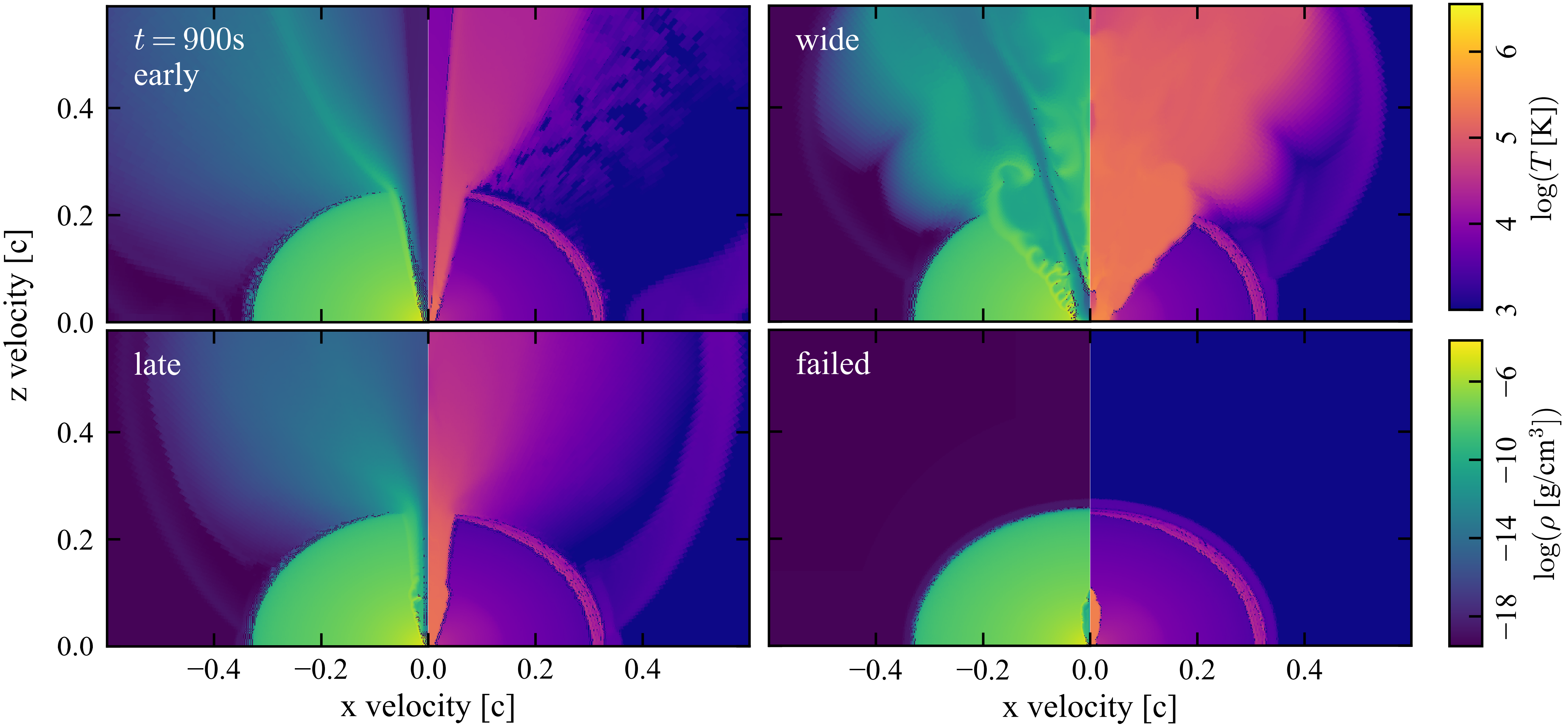
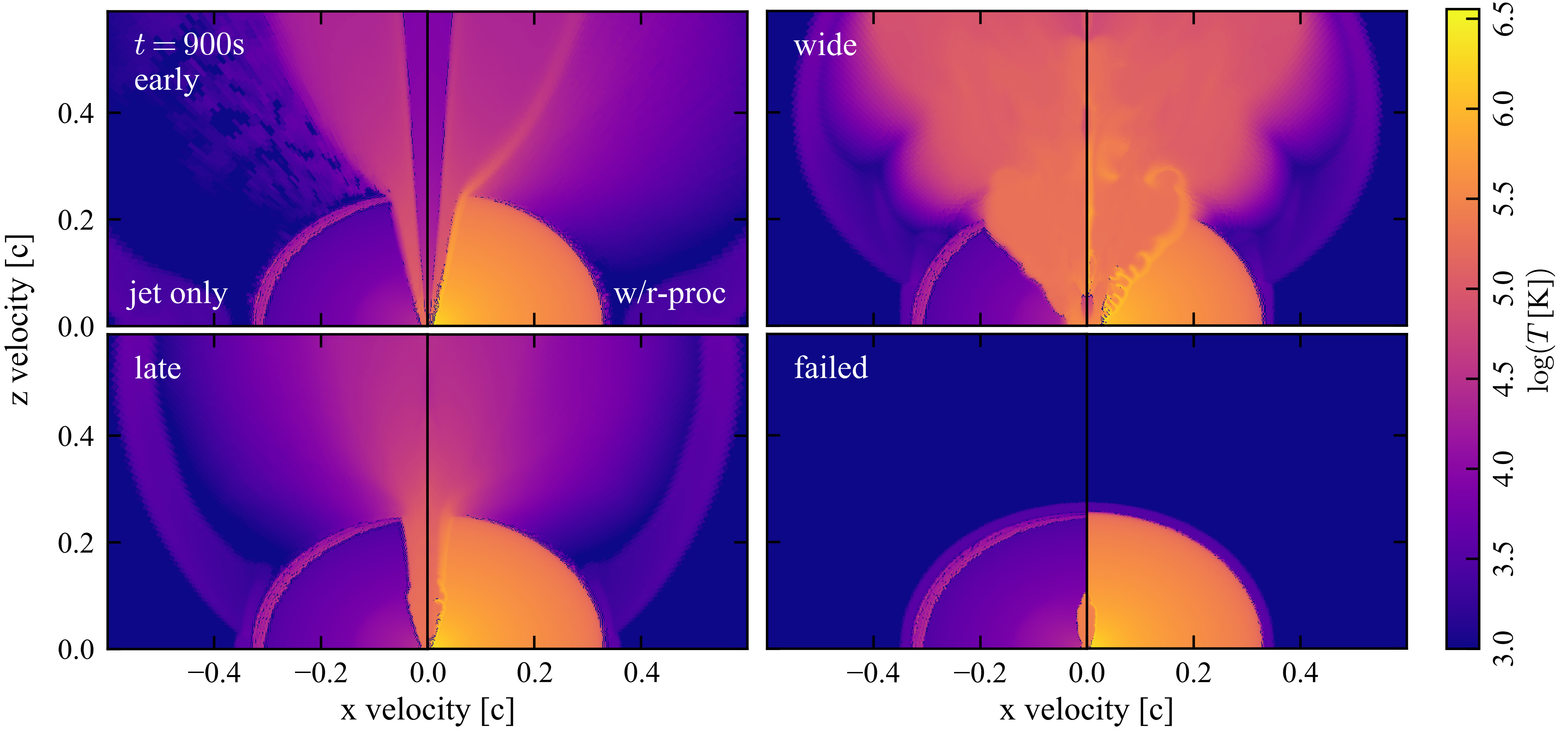
Input Models



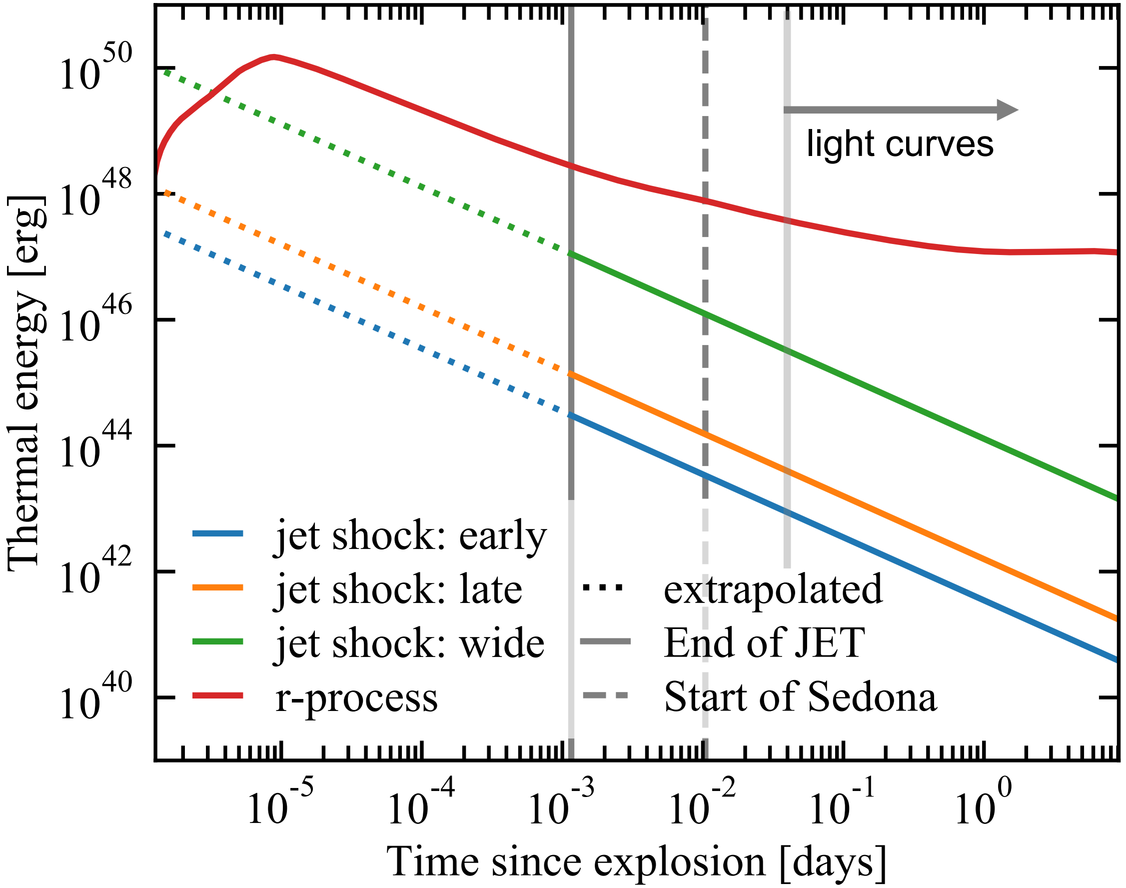
Klion +, in prep

r-process heating > jet shock heating @ 900s



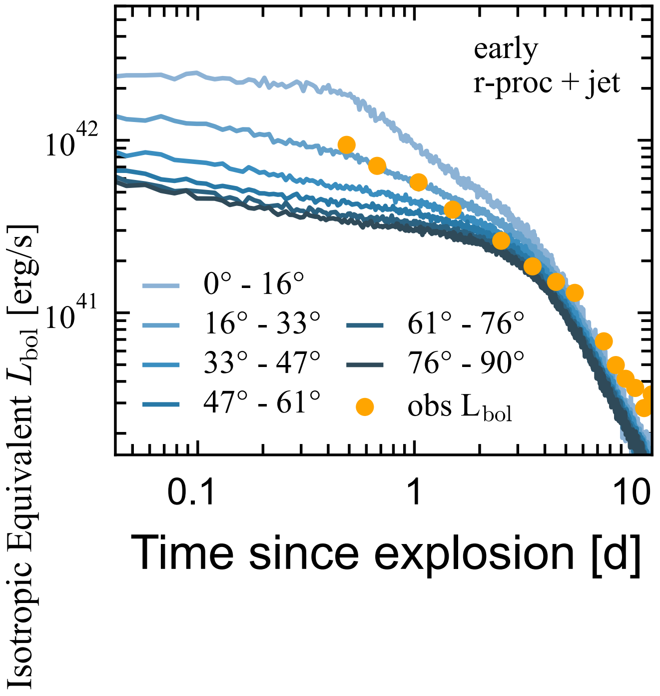
Klion +, in prep

Thermal energy due to r-process heating exceeds jet shock heating throughout



Klion +, in prep

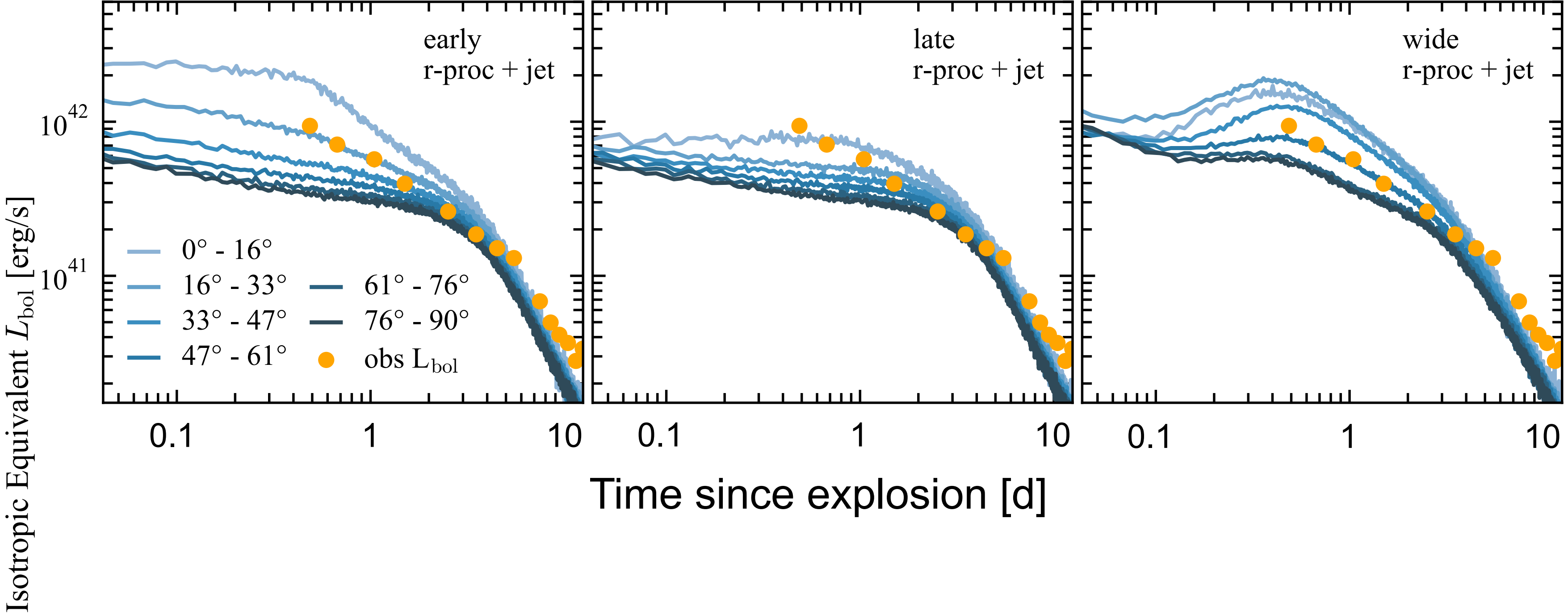
Light curves are brighter on pole than on equator



obs L_{bol} from Drout + ‘17

Klion +, in prep

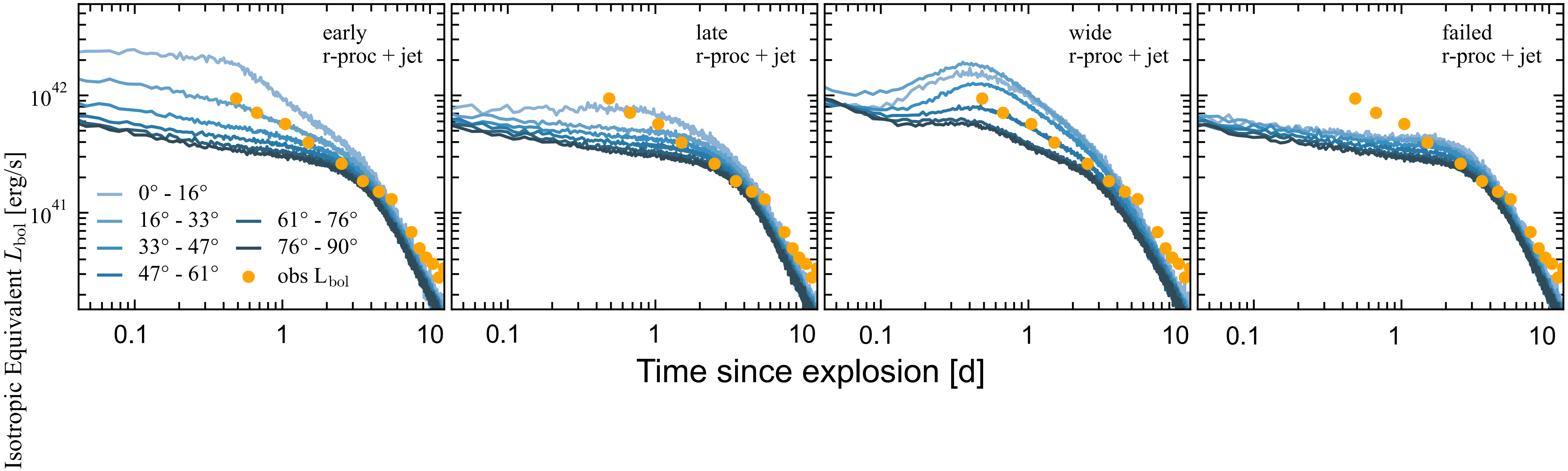
Amount of brightening along jet correlates with how much jet affects density distribution



obs L_{bol} from Drout + '17

Klion +, in prep

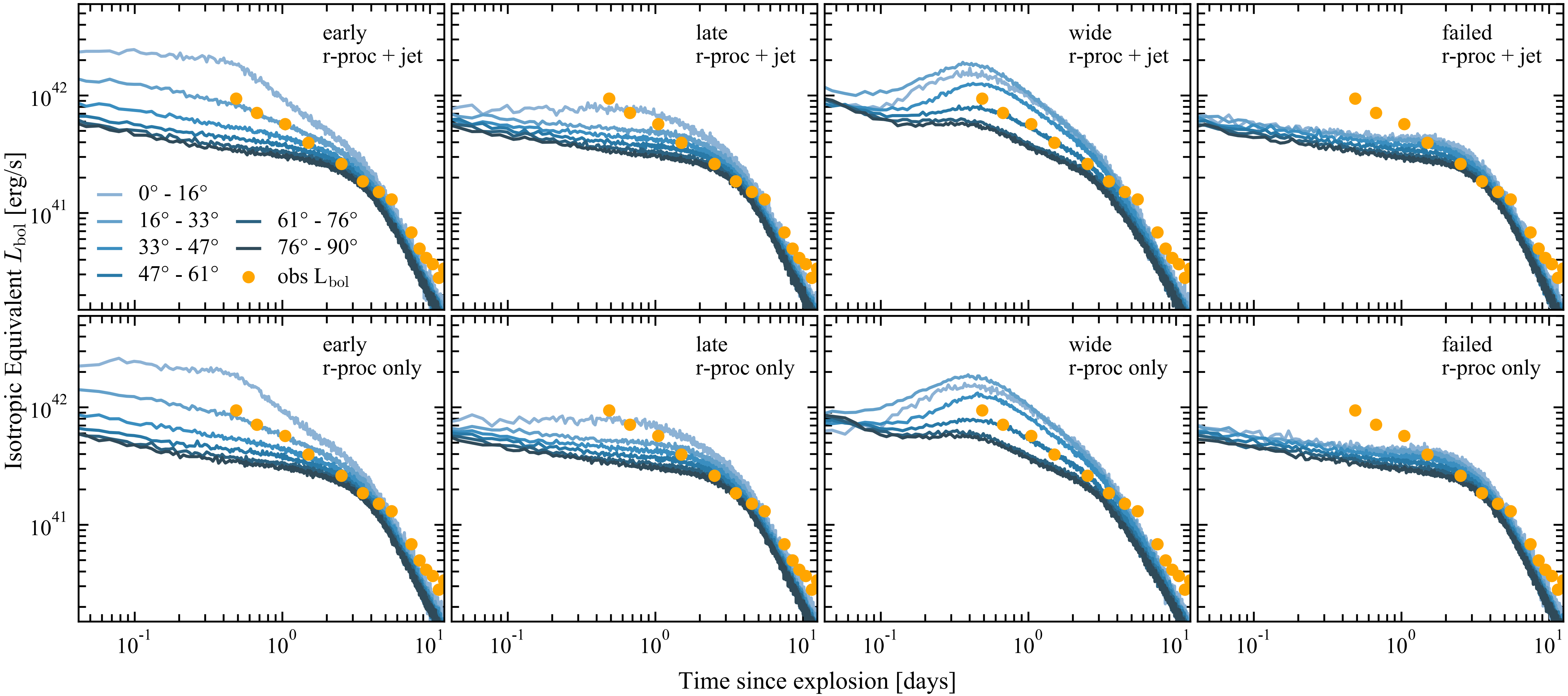
Equatorial light curves match failed jet case



obs L_{bol} from Drout + ‘17

Klion +, in prep

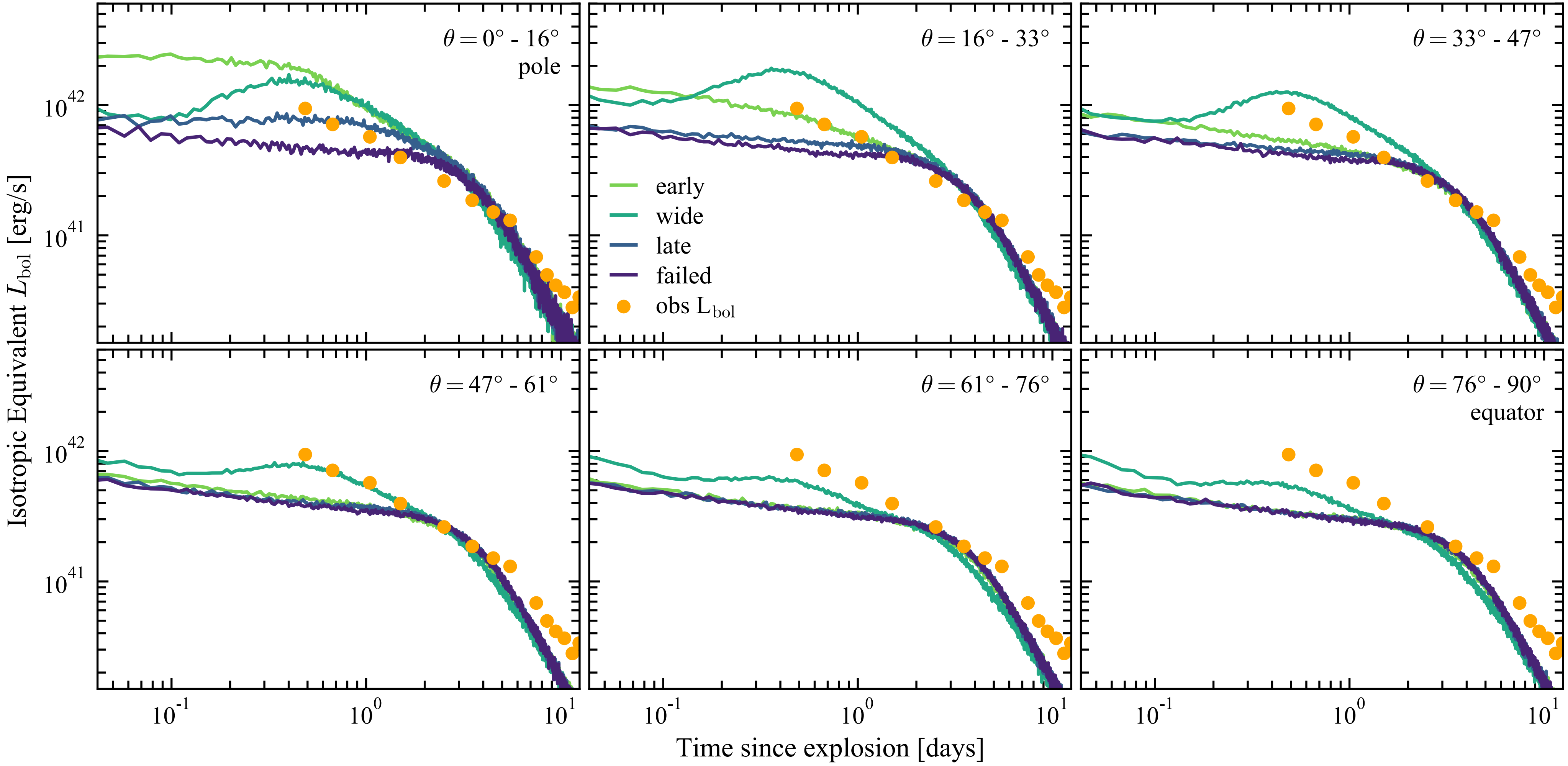
Jet shock heating does not affect light curves



obs L_{bol} from Drout + '17

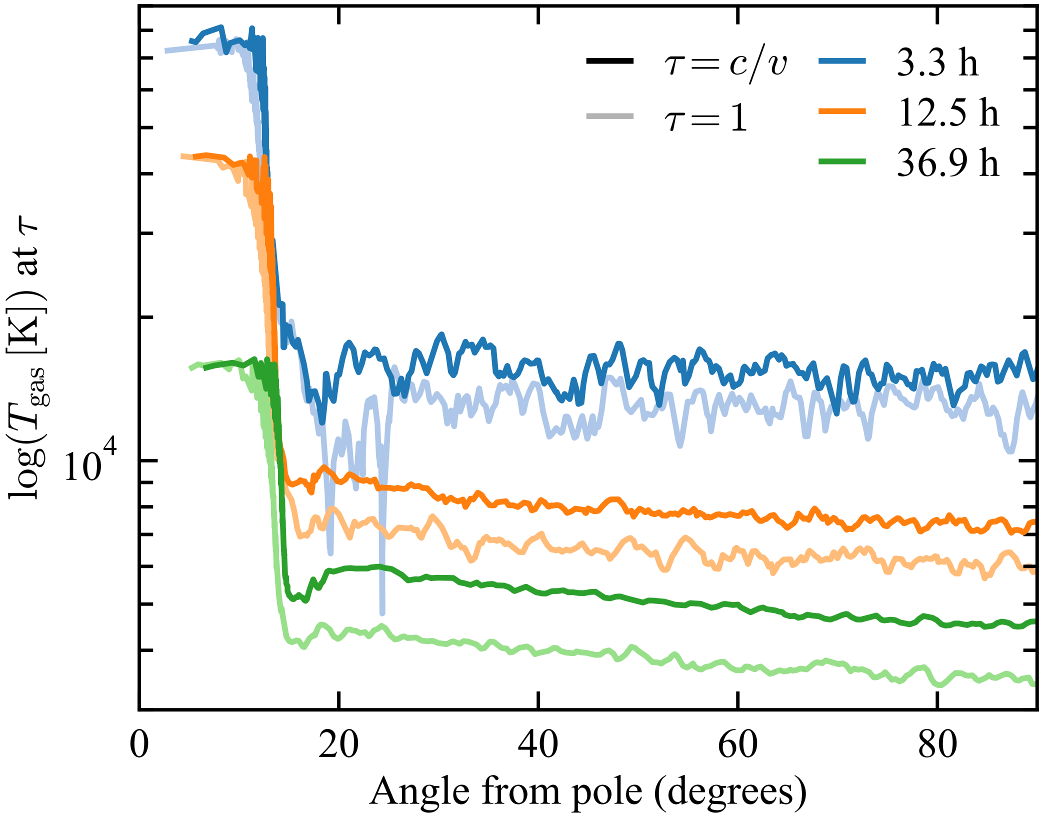
Klion +, in prep

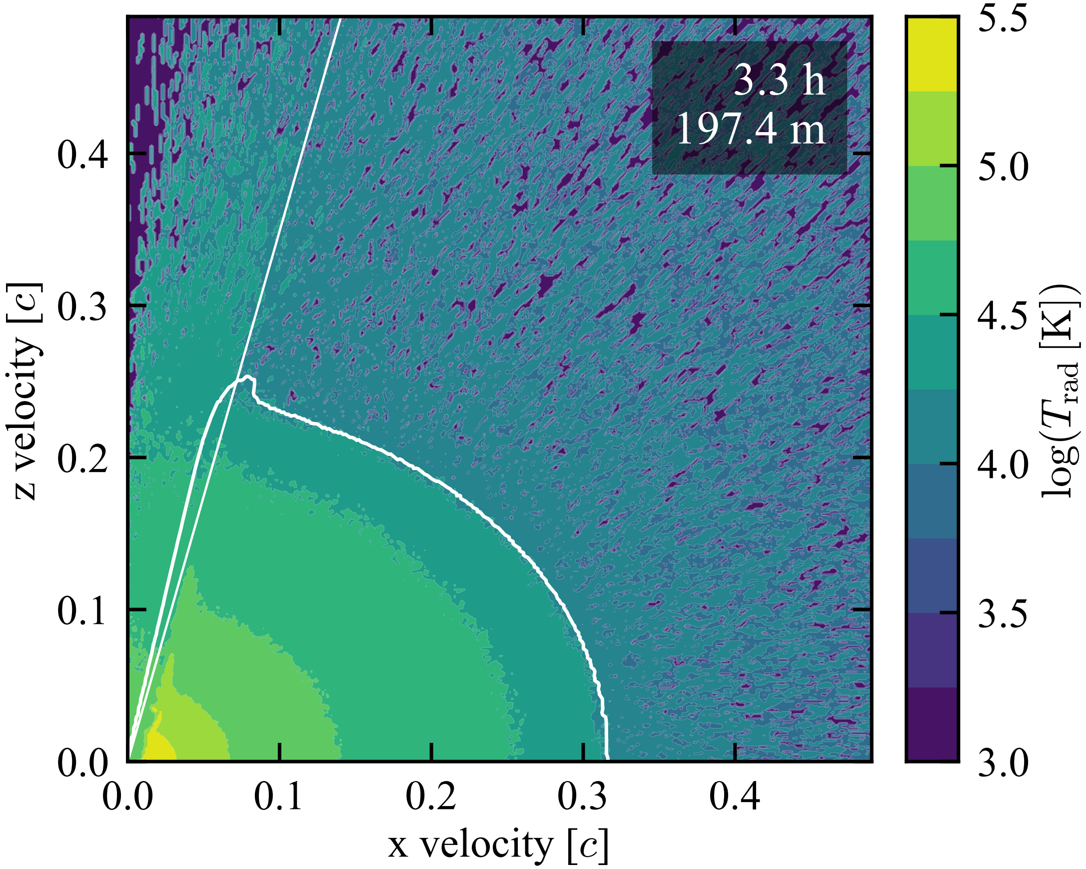
More variation between models at pole than at equator



Klion +, in prep

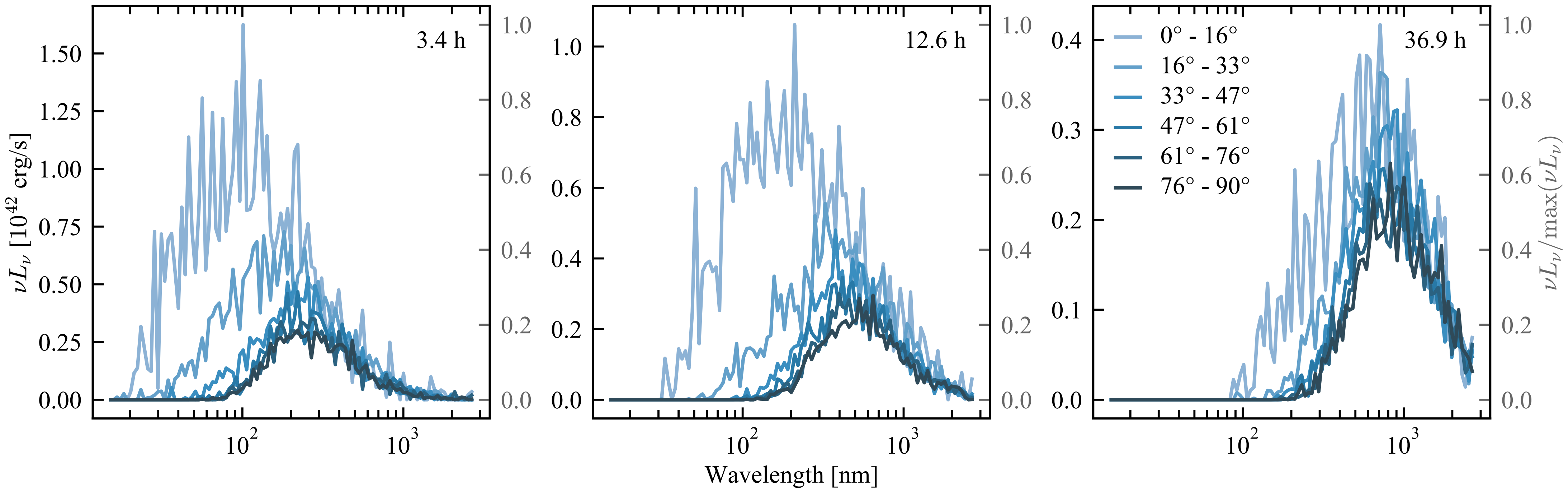
Brighter on pole because greater photospheric temperature





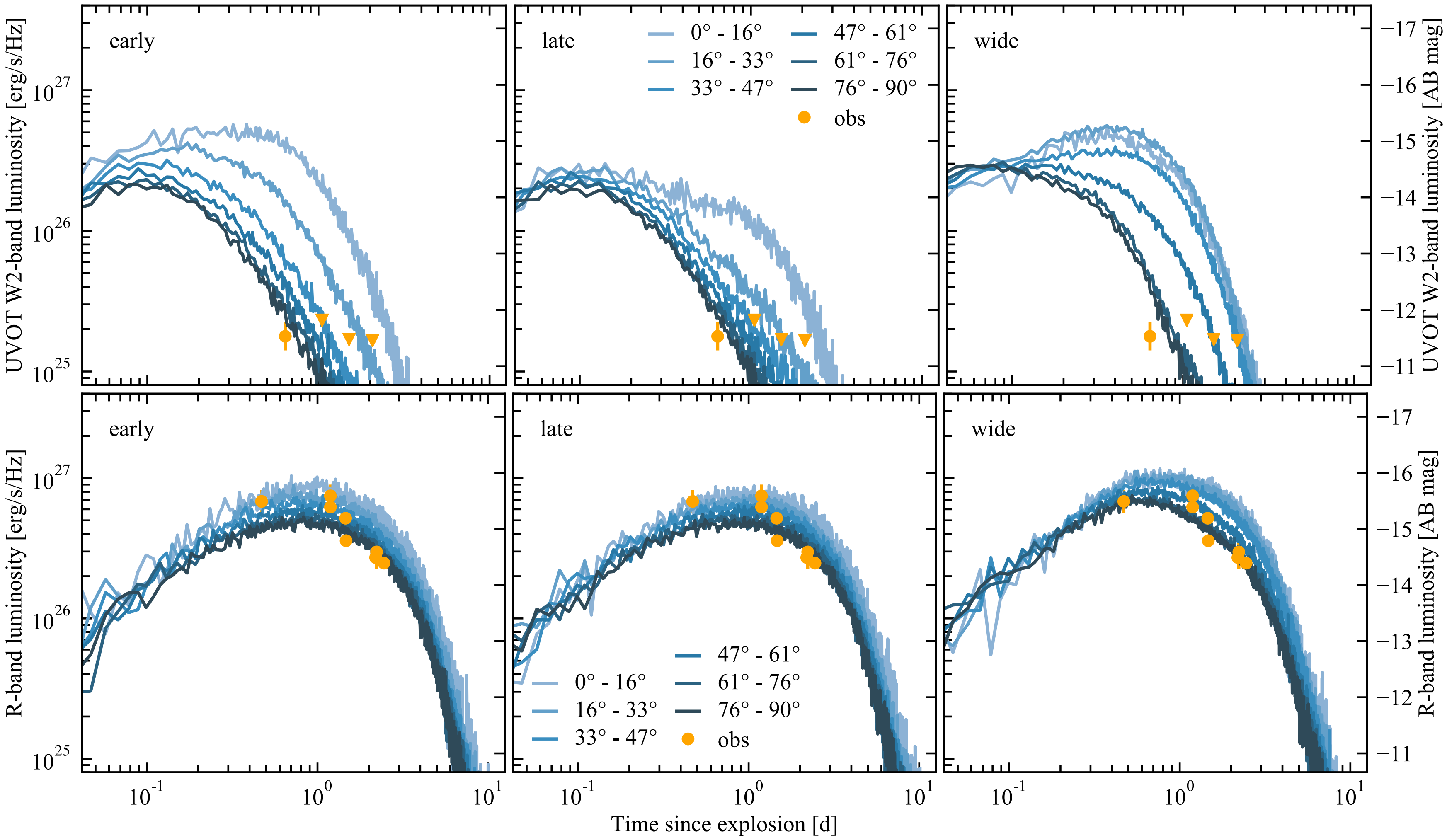
Klion +, in prep

Emission is bluer at poles



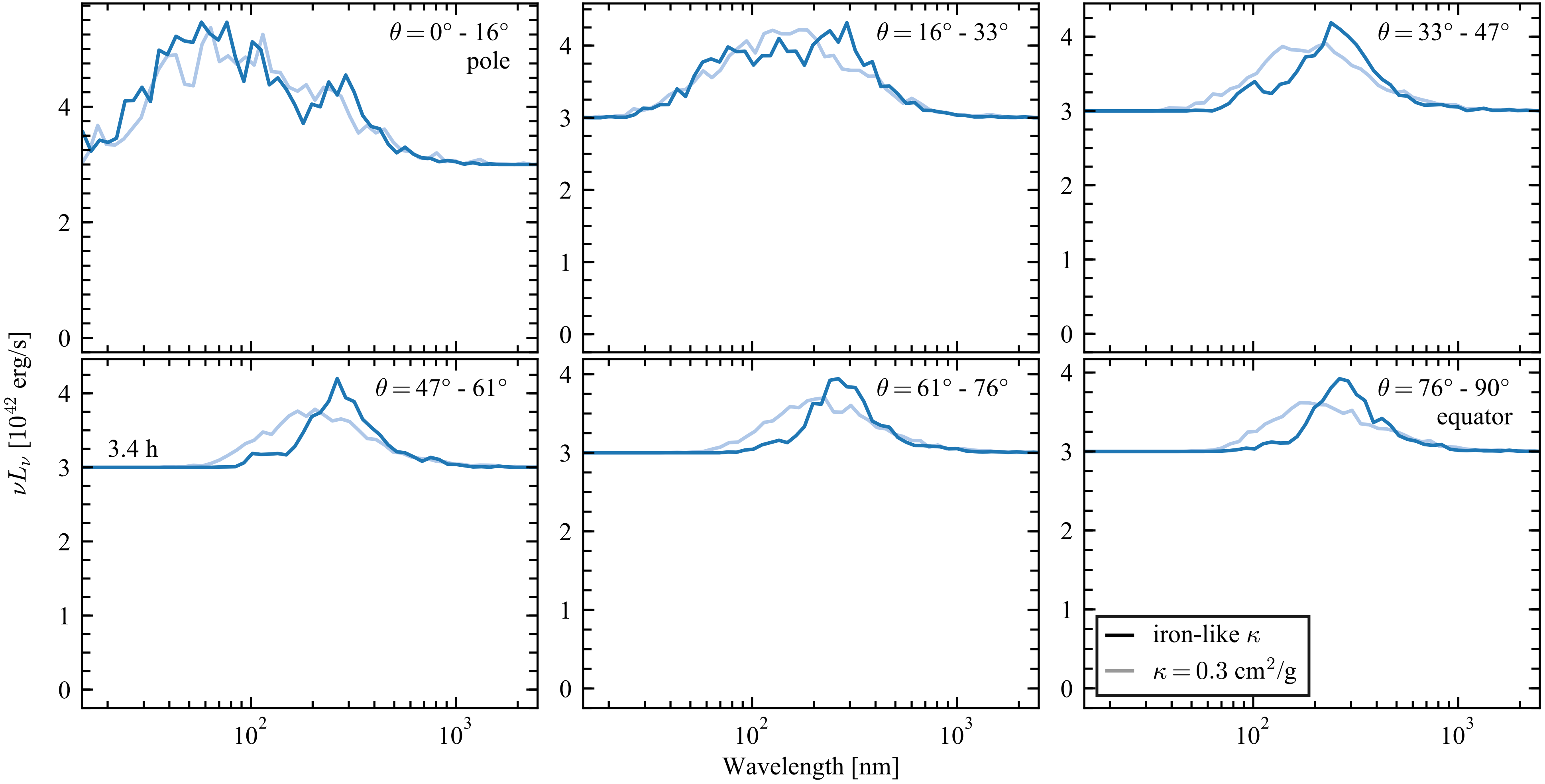
Klion +, in prep

Effect Apparent in Predicted Band Light Curves



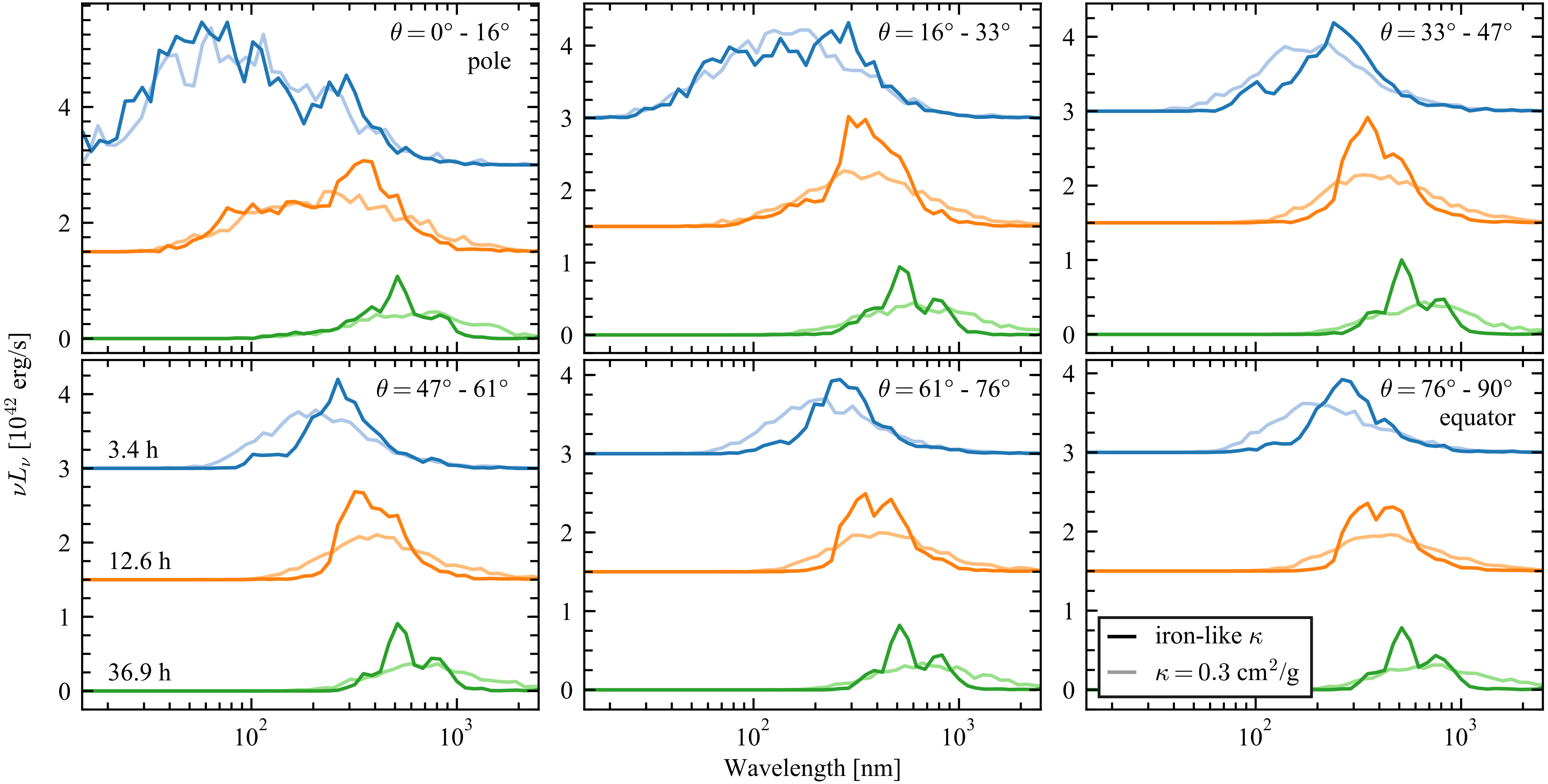
Observed photometry from Kasliwal + ‘17

Early times: iron-like opacities push emission redwards at equator but not near pole



Klion +, in prep

Reddening more apparent at later times



Klion +, in prep

Summary

- Jet thermalization efficiency is limited
- Unlikely that light curve is dominated by (prompt jet) shock heating
- r-process heating greatly exceeds shock heating
- Jet changes the structure of the ejecta, giving viewing-angle effects that depend on jet energy and opening angle
- Jet-affected viewing angles are brighter and possibly somewhat bluer