Supernovae in binary systems

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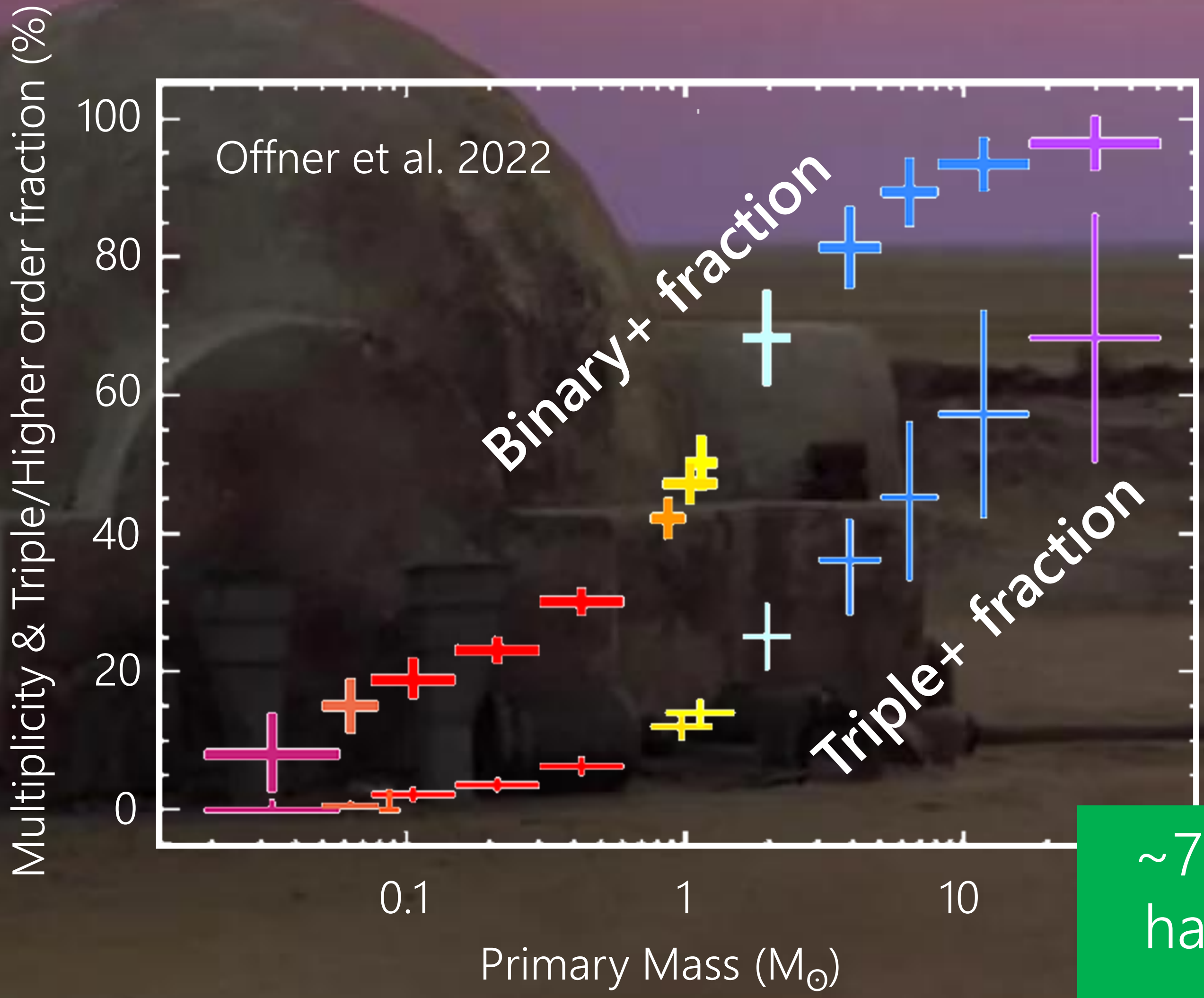
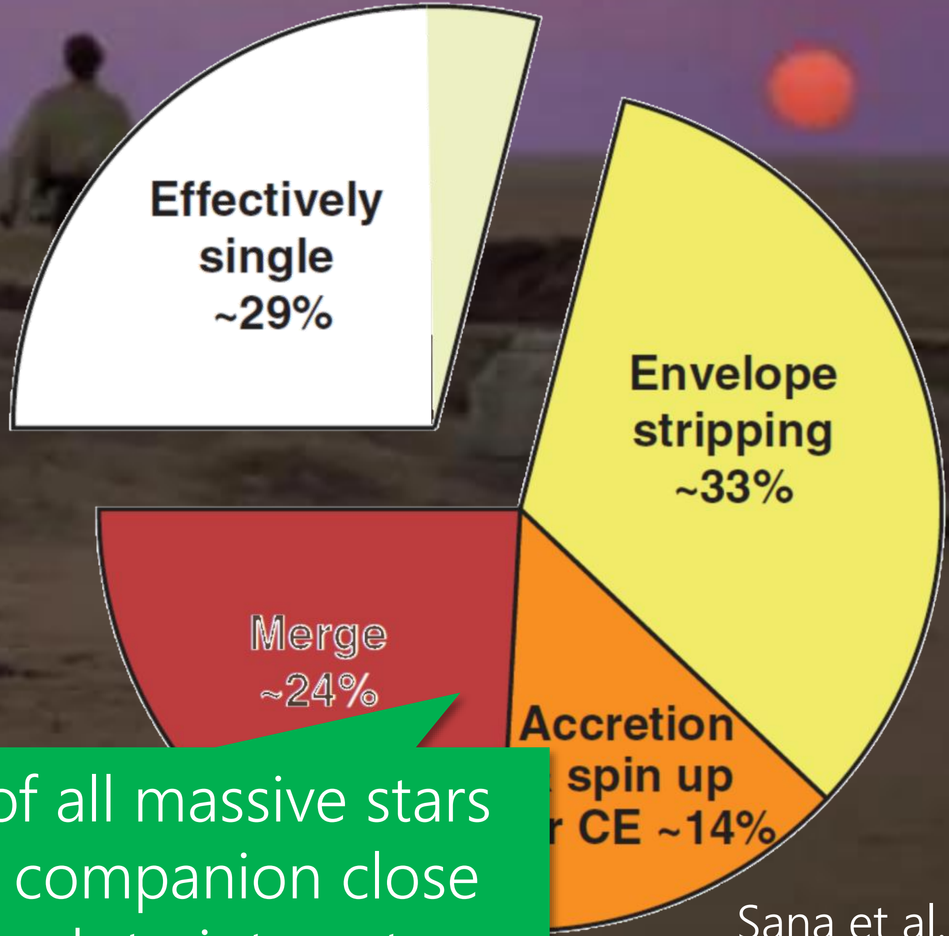
Credit: Star Wars

Binarity of massive stars

Most massive stars have 1 or more companions!

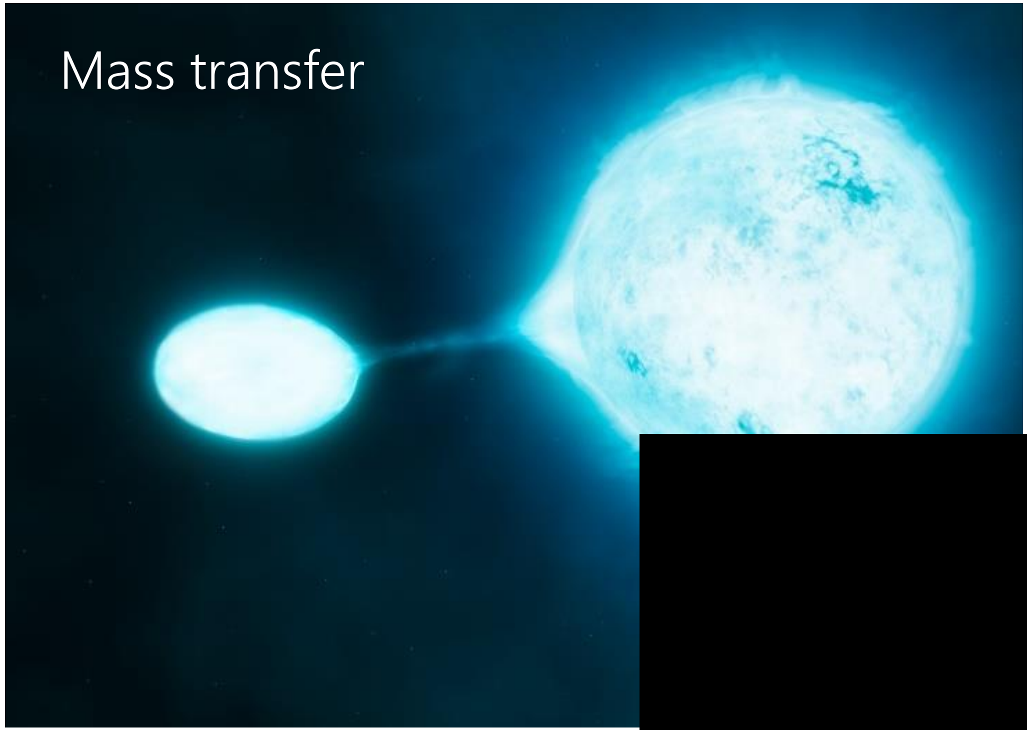


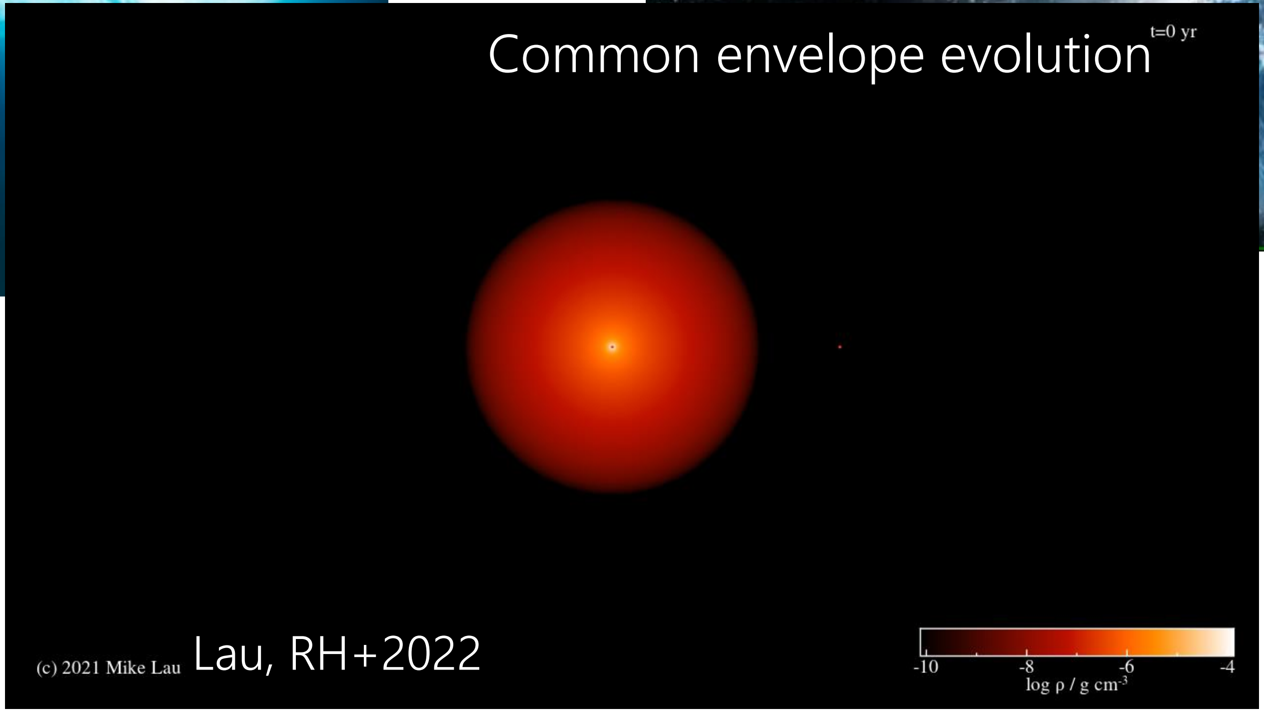


~70% of all massive stars have a companion close enough to interact

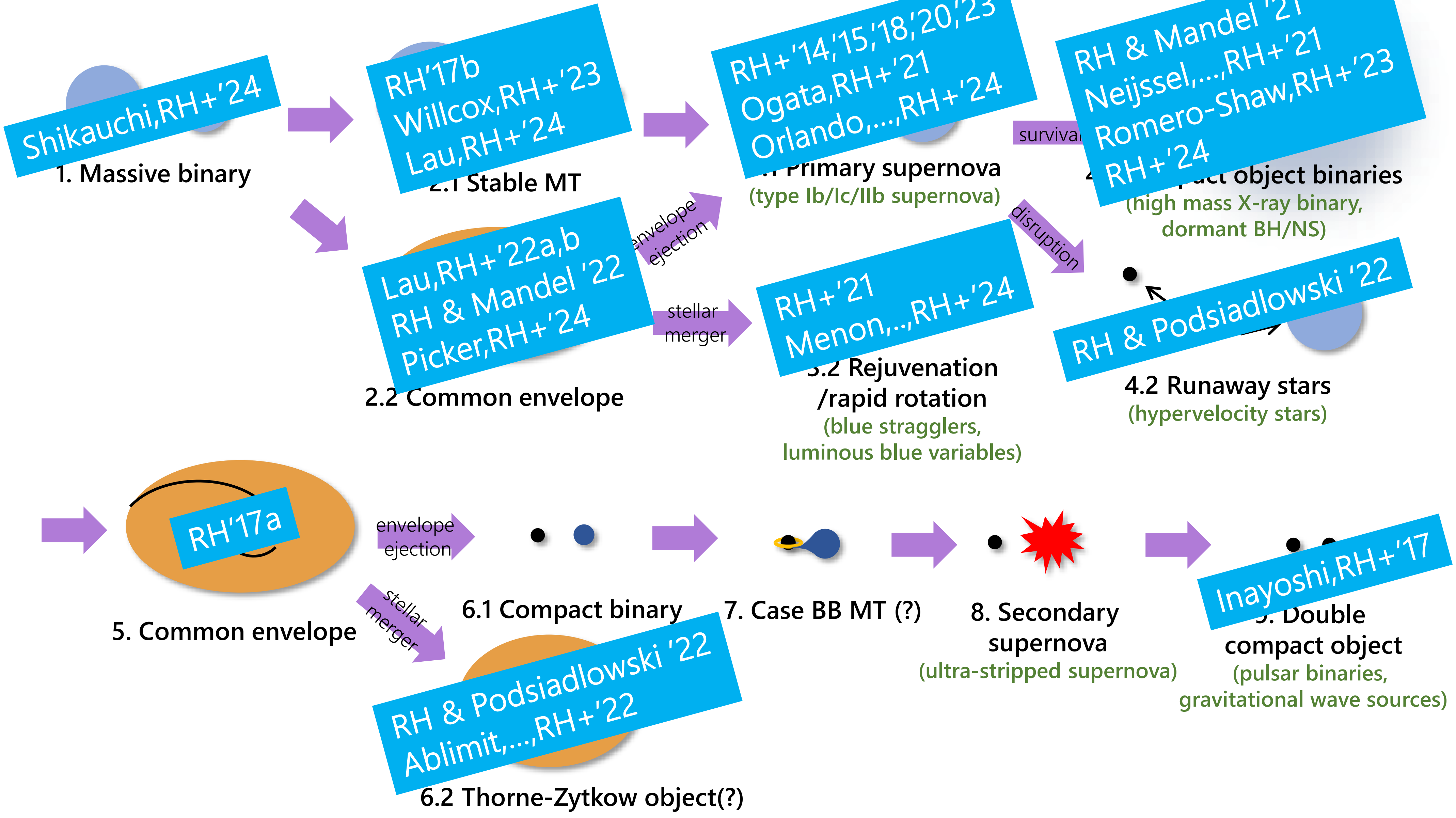
Sana et al. 2012

What are binary interactions?





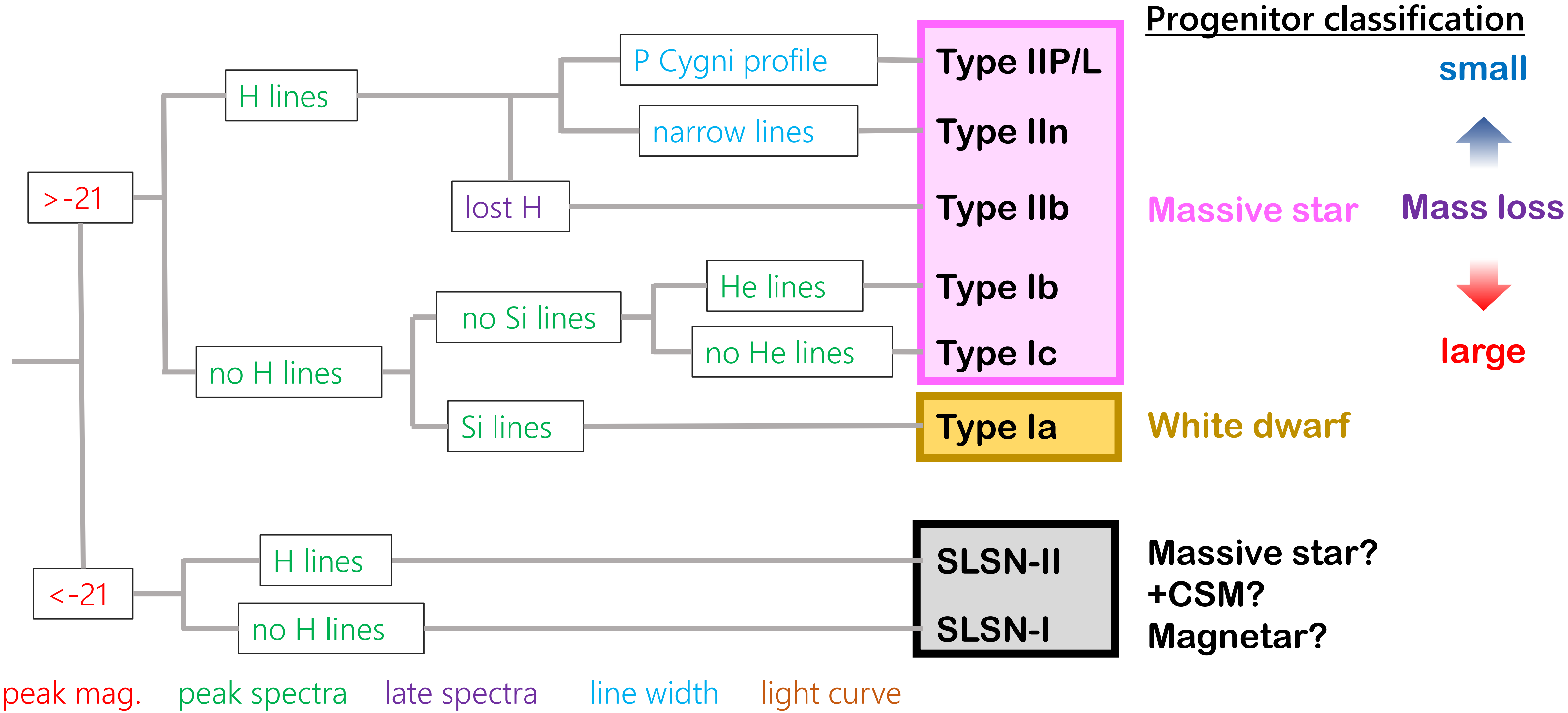
Diversity of massive binary evolution



Outline

- **How can binary evolution influence supernova progenitors?**
- **How can supernova explosions impact binary evolution?**
- **How can we observe effects of binarity in the supernova itself?**

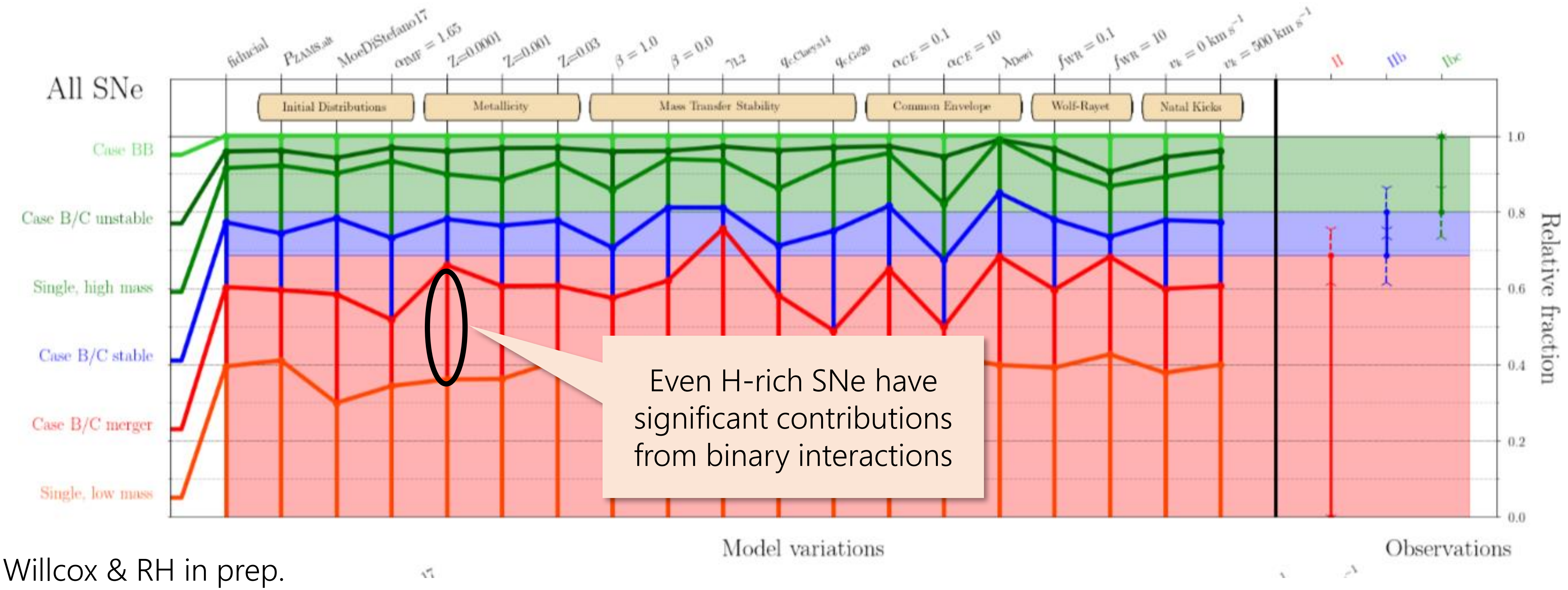
Supernova classification



(sub categories: II-pec, Ibn, Ic-BL, Iax, .Ia, etc)

How can binary evolution influence SN?

Binary interactions are responsible for the diversity of supernova explosions



Willcox & RH in prep.

Outline

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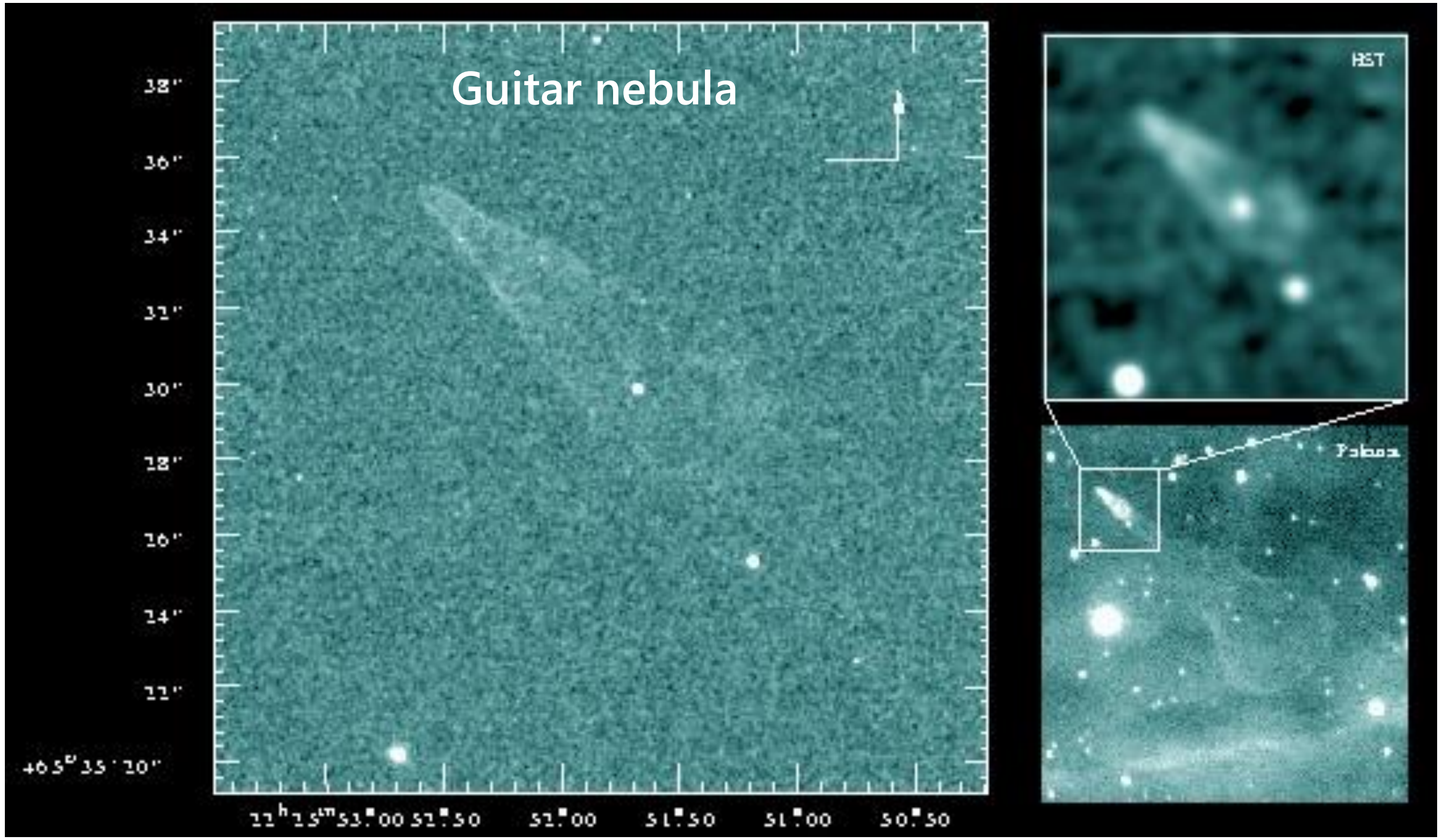
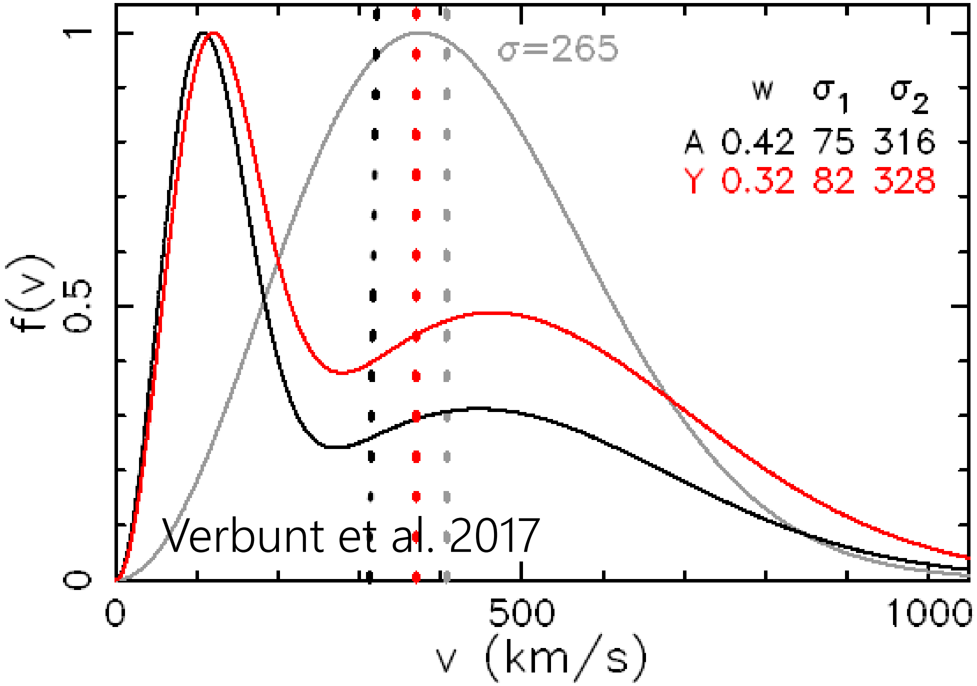
Neutron stars kicks

Pulsars are known to be born with high proper motions

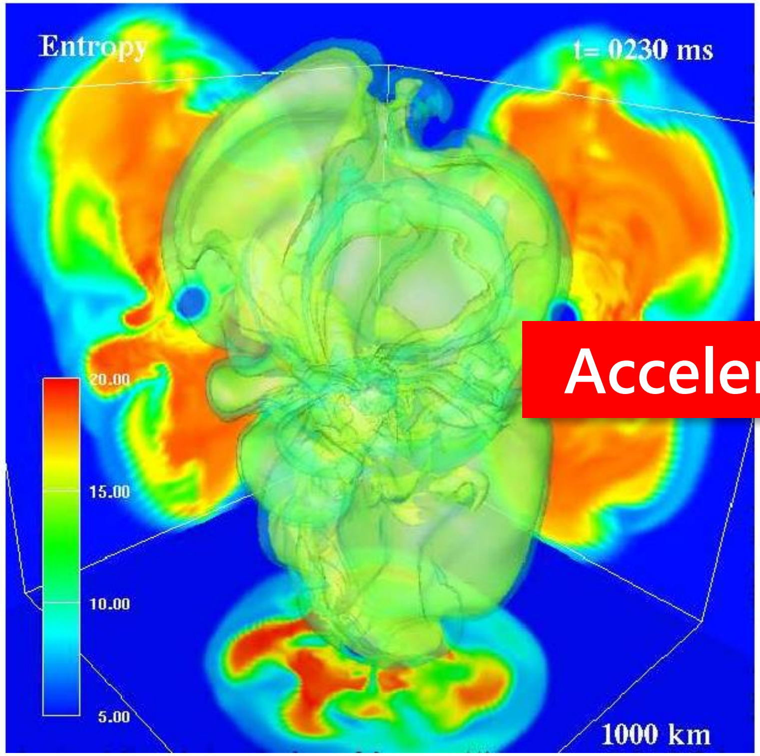




Typical velocities range between 100-1000 km/s

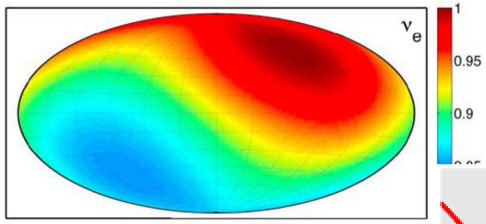
Mainstream NS kick mechanisms

Hydrodynamical instabilities

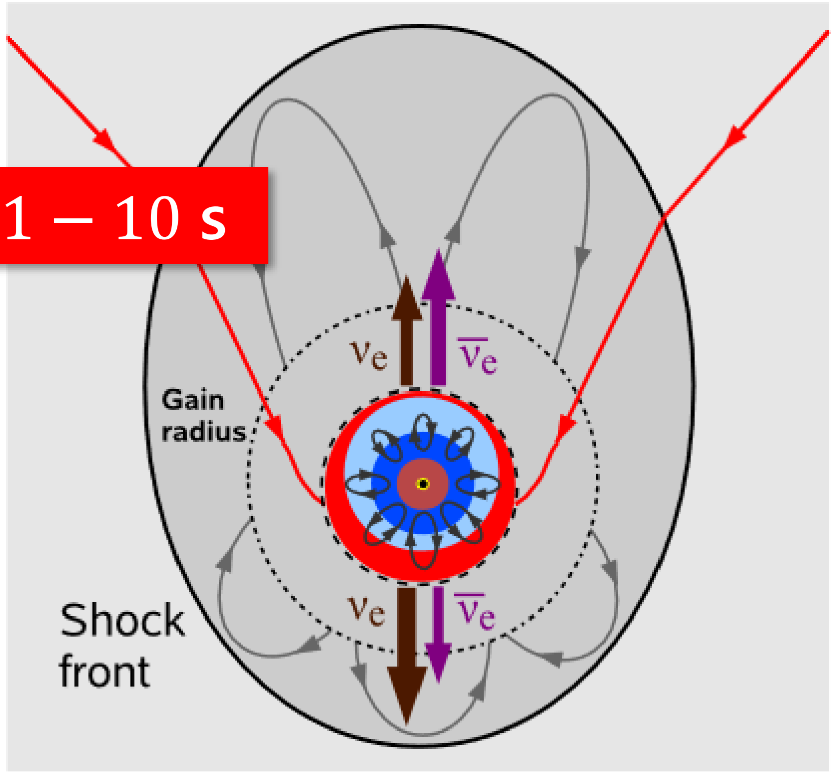


Takiwaki et al. 2012

Neutrino emission asymmetries



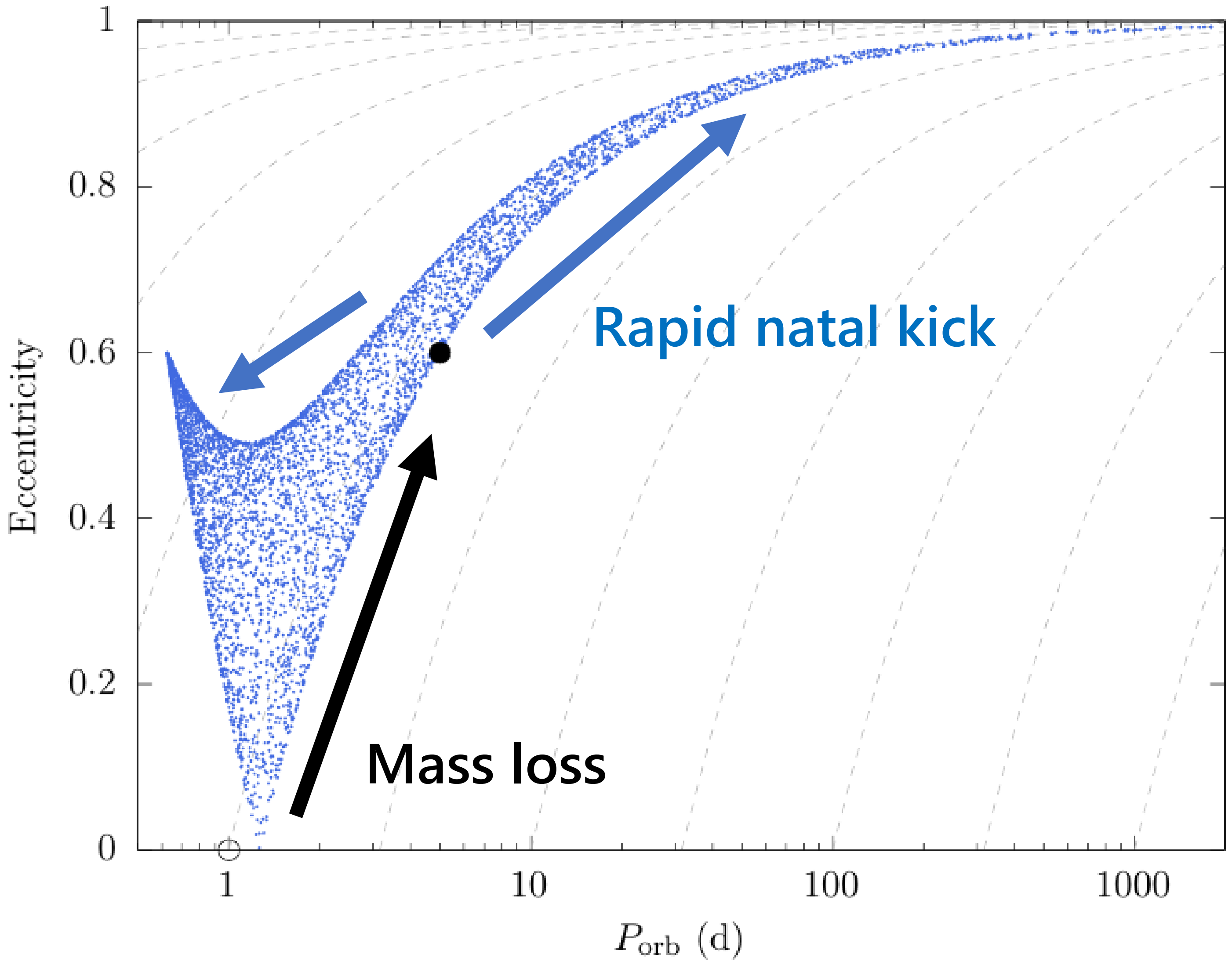
Tamborra et al. 2013

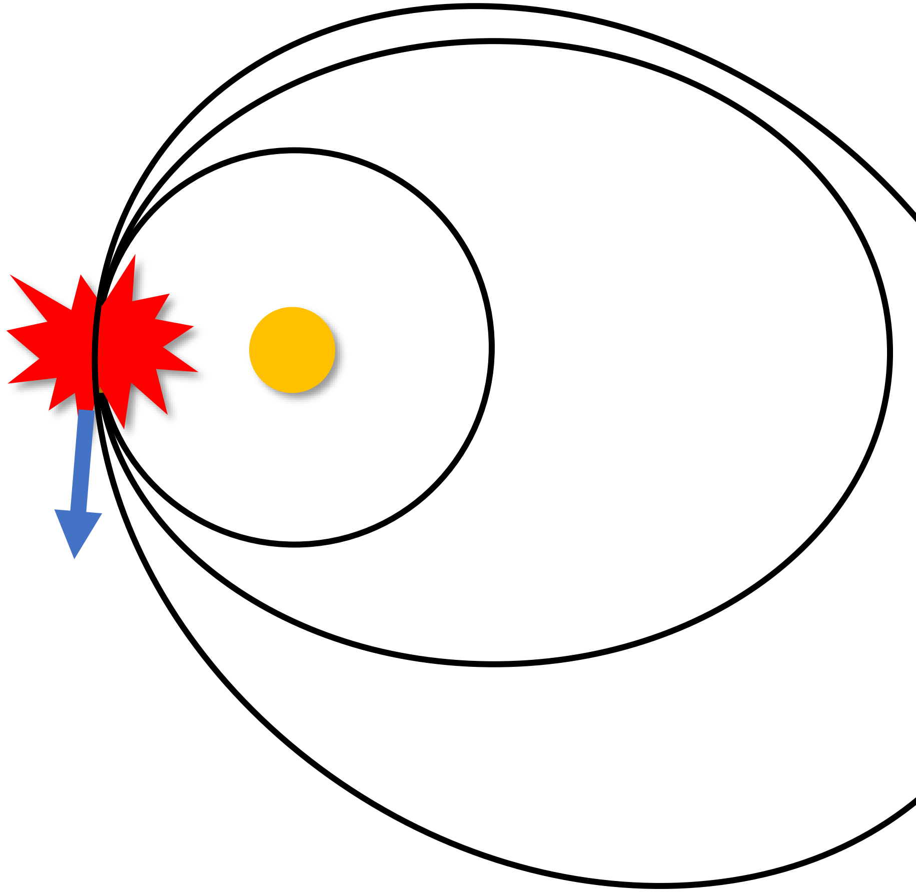


Acceleration timescale: $\tau_{acc} \sim 1 - 10$ s

Supernova kicks in binaries

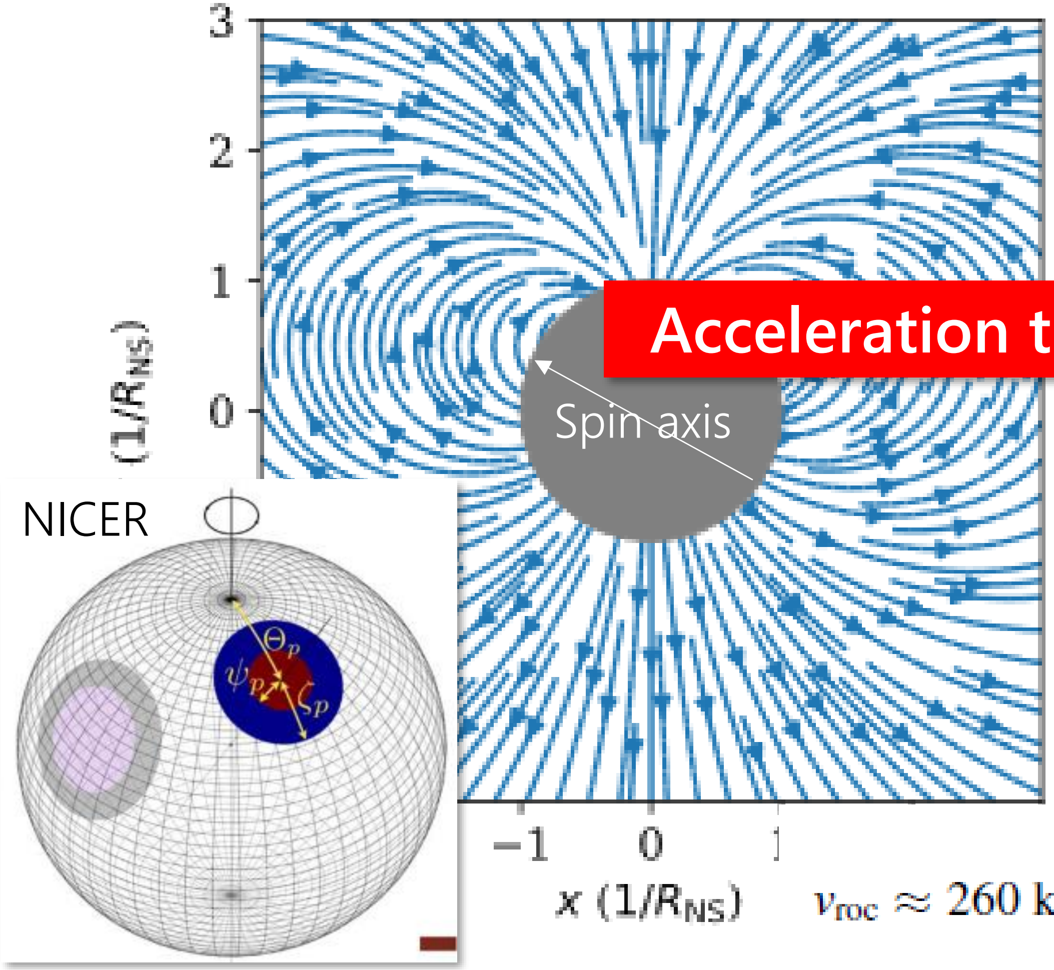
The main result of a supernova in a binary is that the orbit is perturbed



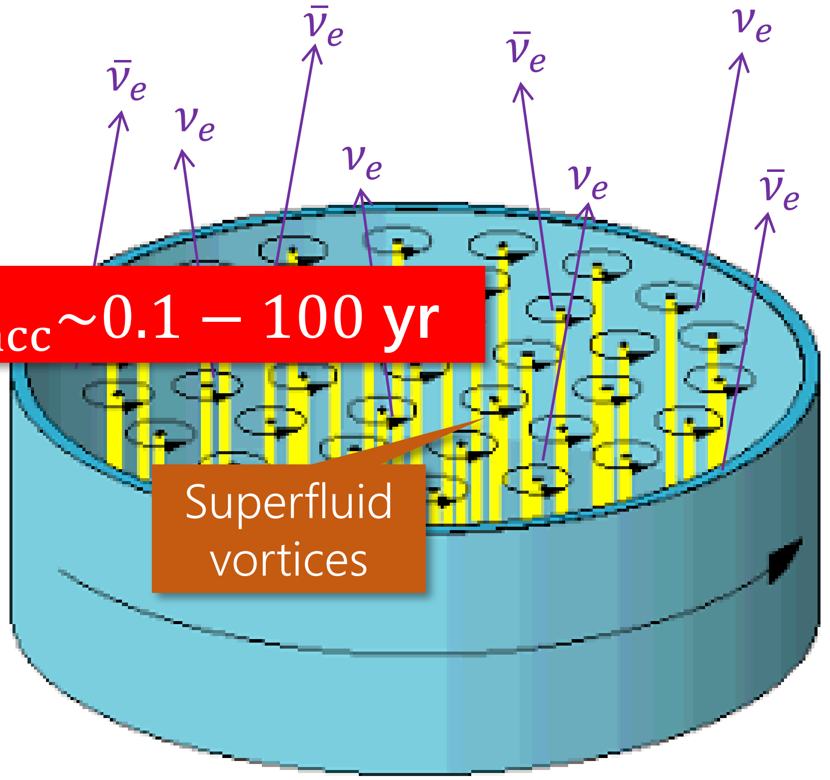


Other NS kick mechanisms

Electromagnetic rocket
(Harrison & Tademaru 1975)



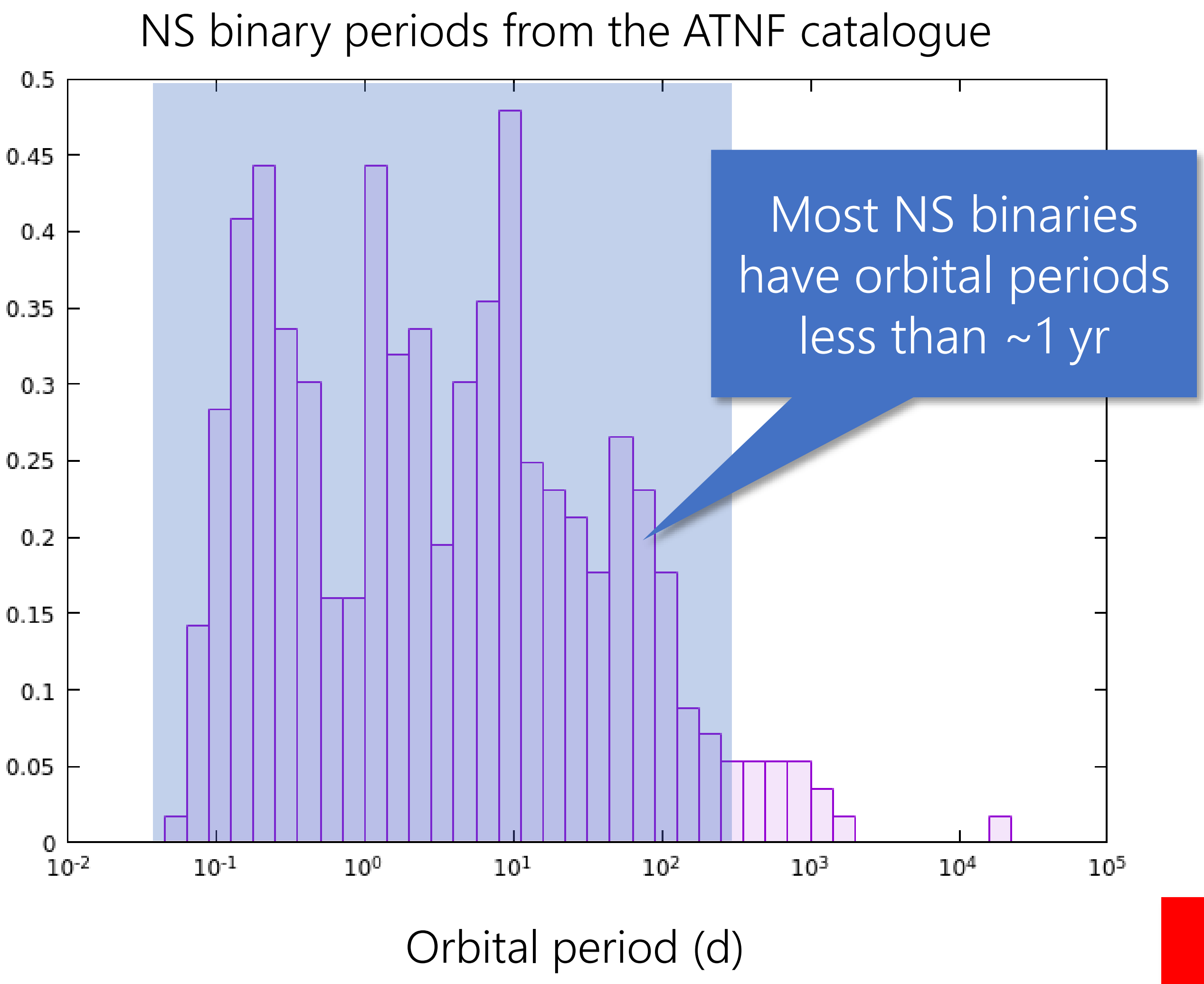
Neutrino rocket
(Peng et al. 1982)



Acceleration timescale: $\tau_{acc} \sim 0.1 - 100$ yr

$$v_{\rm roc} \approx 260\ {\rm km\ s^{-1}} \frac{\bar{\epsilon}}{0.1} \left(\frac{R}{10\ {\rm km}} \right)^2 \left(\frac{P_{\rm spin,ini}}{1\ {\rm ms}} \right)^{-2},$$

Are NS kicks instantaneous?



Mainstream kick models

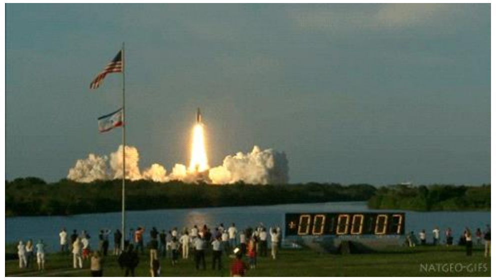
$$\tau_{\rm acc} \ll P_{\rm orb}$$

(~s)

Rocket-like models

$$\tau_{\rm acc} \gg P_{\rm orb}$$

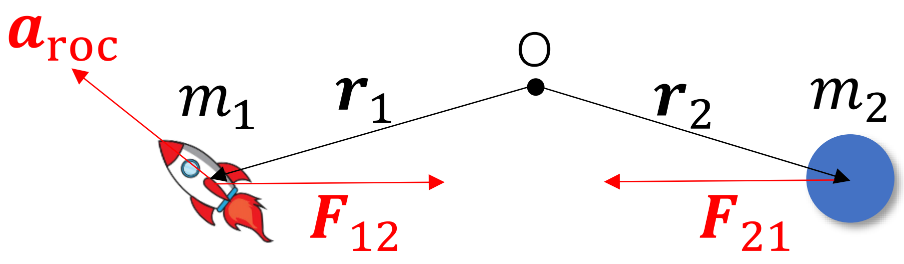
(~yr)



What happens if the kick is not instantaneous?

Analytic solution for rocket binaries

RH+2024



Equation of motion

$$m_1 \ddot{\boldsymbol{r}}_1 = \boldsymbol{F}_{12} + m_1 \boldsymbol{a}_{\mathrm{roc}}$$

$$m_2 \ddot{\boldsymbol{r}}_2 = \boldsymbol{F}_{21}$$

$$\Rightarrow \ \ddot{\boldsymbol{r}} \equiv \ddot{\boldsymbol{r}}_1 - \ddot{\boldsymbol{r}}_2 = \frac{\boldsymbol{F}_{12}}{\mu} + \boldsymbol{a}_{\mathrm{roc}}$$

$$\boldsymbol{F}_{ij} = \frac{G m_i m_j}{\left|\boldsymbol{r}_i - \boldsymbol{r}_j\right|^2} \hat{\boldsymbol{r}}_{ij}$$

"Accelerated Kepler problem" or "Classical Stark problem"

$$\mu \equiv \frac{m_1 m_2}{m_1 + m_2}$$

Assuming

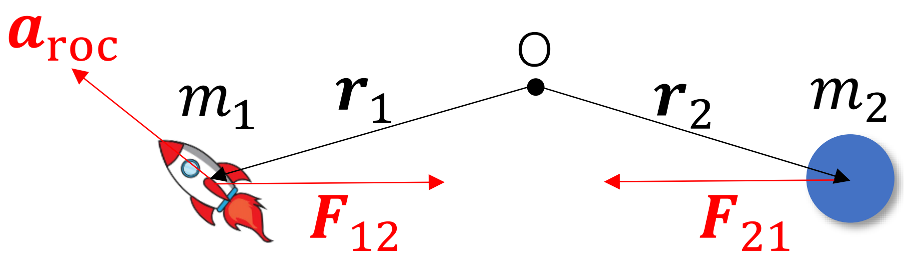
$|\boldsymbol{a}_{\mathrm{roc}}| \ll \frac{|\boldsymbol{F}_{12}|}{m_1}$, (rocket acceleration is a perturbation)

$\frac{|\boldsymbol{a}_{\mathrm{roc}}|}{|\dot{\boldsymbol{a}}_{\mathrm{roc}}|} \gg P_{\mathrm{orb}}$, (rocket acceleration is constant over an orbital period)

we can make the secular approximation (= adiabatic evolution)

Analytic solution for rocket binaries

RH+2024



Orbital angular momentum

$$\boldsymbol{l} \equiv \frac{\bar{v}_{\rm orb}}{G(m_1+m_2)}\,\boldsymbol{r}\times\dot{\boldsymbol{r}}$$

Laplace-Runge-Lenz vector

$$\boldsymbol{e} = \frac{1}{Gm_1m_2}\dot{\boldsymbol{r}}\times\boldsymbol{L} - \frac{\boldsymbol{r}}{|\boldsymbol{r}|}$$

We define a new set of vectors

$$\boldsymbol{h}_\pm \equiv \boldsymbol{e} \pm \boldsymbol{l}$$

Angular momentum and Runge-Lenz vector changes only in direction perpendicular to rocket

Orbital torque

Orbit average

$$\langle \dot{\boldsymbol{h}}_\pm \rangle = \mp \frac{3}{2\bar{v}_{\rm orb}}\boldsymbol{h}_\pm \times \boldsymbol{a}_{\rm roc}$$

EOM: $\ddot{\boldsymbol{r}} \equiv \ddot{\boldsymbol{r}}_1 - \ddot{\boldsymbol{r}}_2 = \dfrac{\boldsymbol{F}_{12}}{\mu} + \boldsymbol{a}_{\rm roc}$

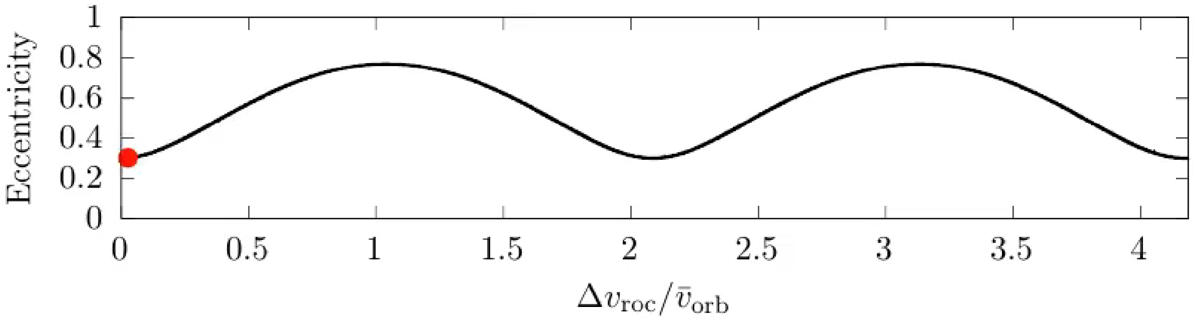
Post-rocket orbit is determined by rotating both vectors around $\boldsymbol{a}_{\rm roc}$

$$\boldsymbol{h}'_\pm = R_z\left(\pm\frac{3\Delta v_{\rm roc}}{2\bar{v}_{\rm orb}}\right)\boldsymbol{h}_\pm$$

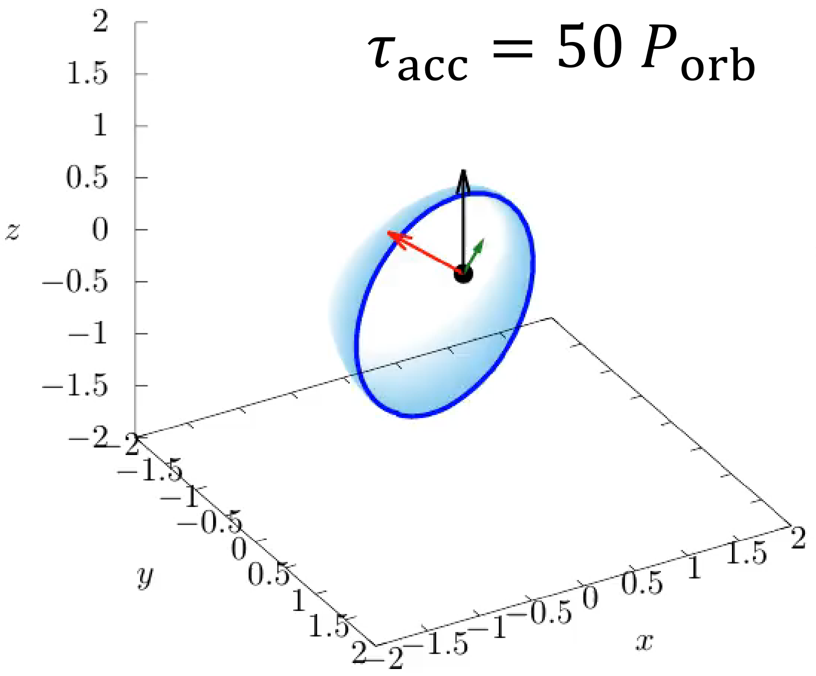
$$\boldsymbol{e}' = \frac{\boldsymbol{h}_+ + \boldsymbol{h}_-}{2},\ \boldsymbol{l}' = \frac{\boldsymbol{h}_+ - \boldsymbol{h}_-}{2}$$

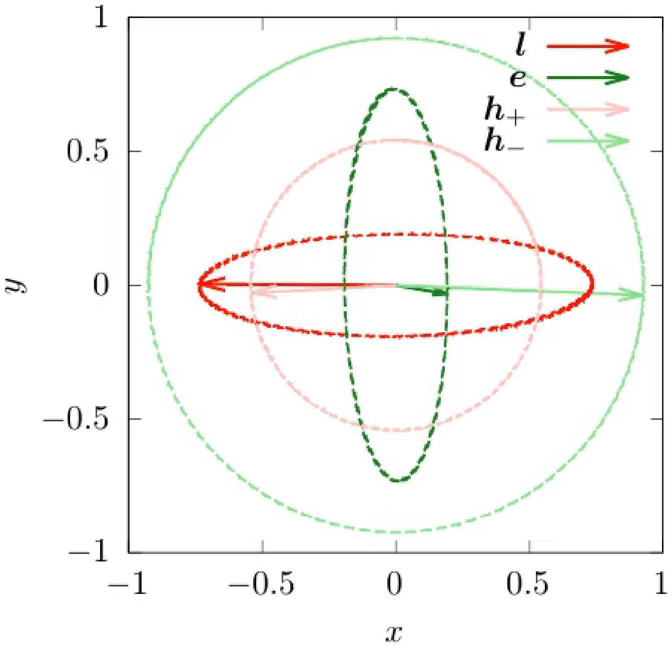
Numerical experiments

As a demonstration, we performed 2-body integrations with rockets attached



$\tau_{\rm acc} = 50\ P_{\rm orb}$





RH+2024

- The orbital period does not change
- The orbit precesses about the direction of acceleration
- The eccentricity oscillates as the orbit rocks around
- The oscillation depends on $\tau_{\rm osc} \sim 2\Delta v_{\rm roc}/\bar{v}_{\rm orb}$
- The maximum and minimum eccentricity depends on (1) initial eccentricity and (2) rocket direction

The "full" post-SN orbital solution

The long-duration kicks do not alter the orbit unless there is

- initial non-zero eccentricity
- misalignment between orbit and rocket

The requirements can be provided from the other forms of natal kicks

Mass loss (Blaauw kick) + **Rapid natal kick** + **Rocket-like kick**

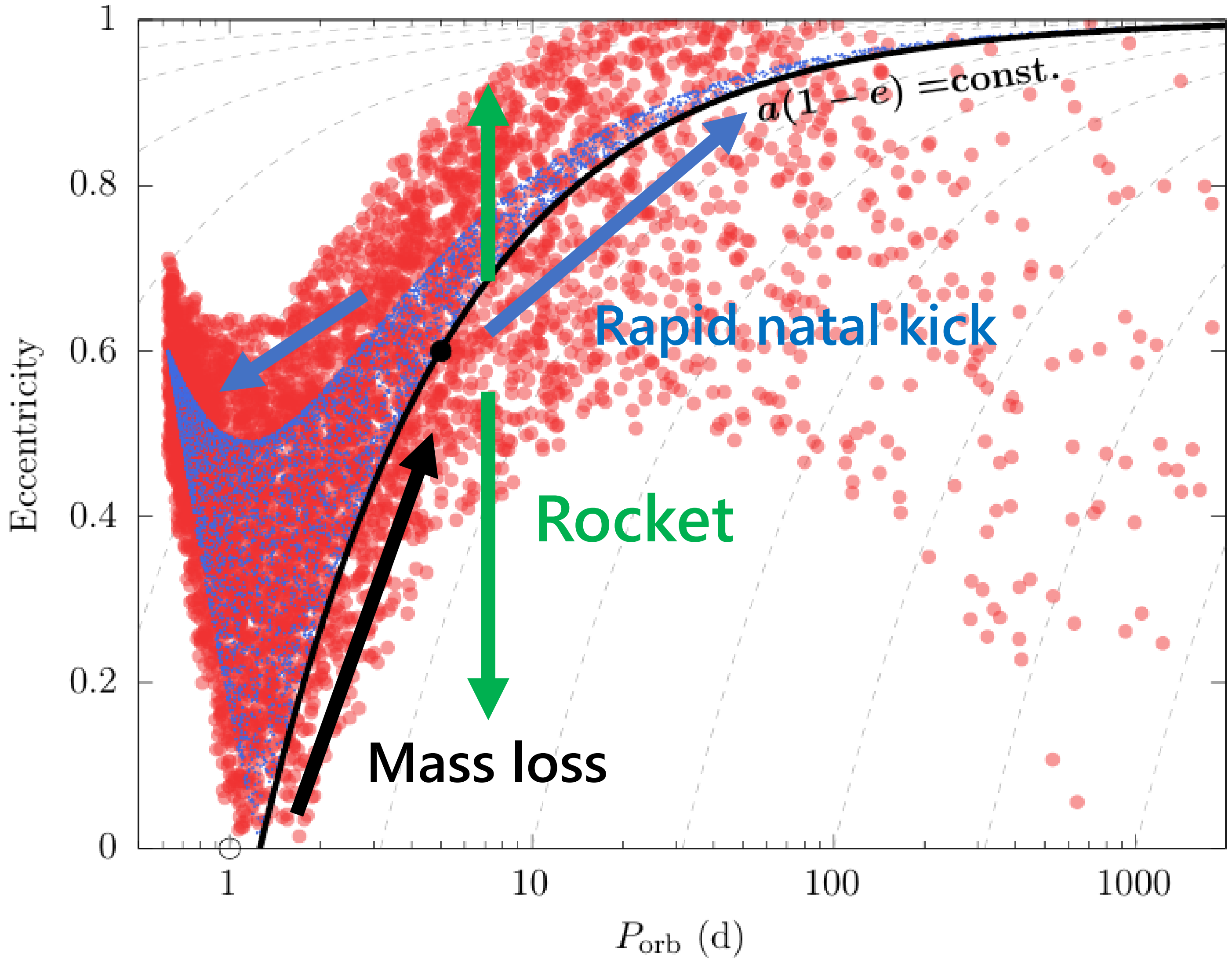
Mass loss (Blaauw kick):
- Eccentricity increase
- Period increase

Rapid natal kick:
- Eccentricity change
- Period change

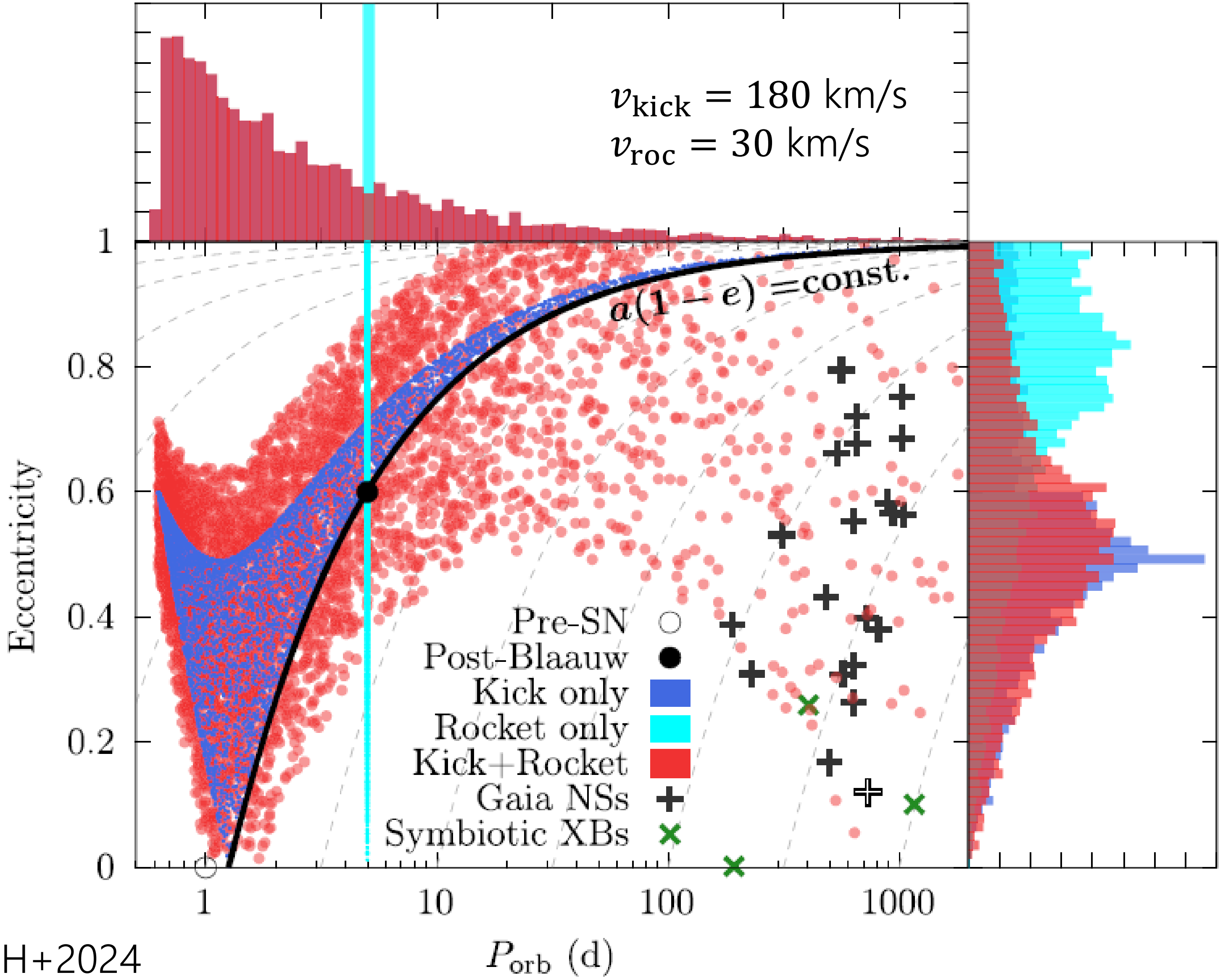
Rocket-like kick:
- Eccentricity change
- Period fixed

Post-SN orbital property distribution

An example of how the kick+rocket can alter the orbit



Gaia NS1 and Symbiotic X-ray binaries



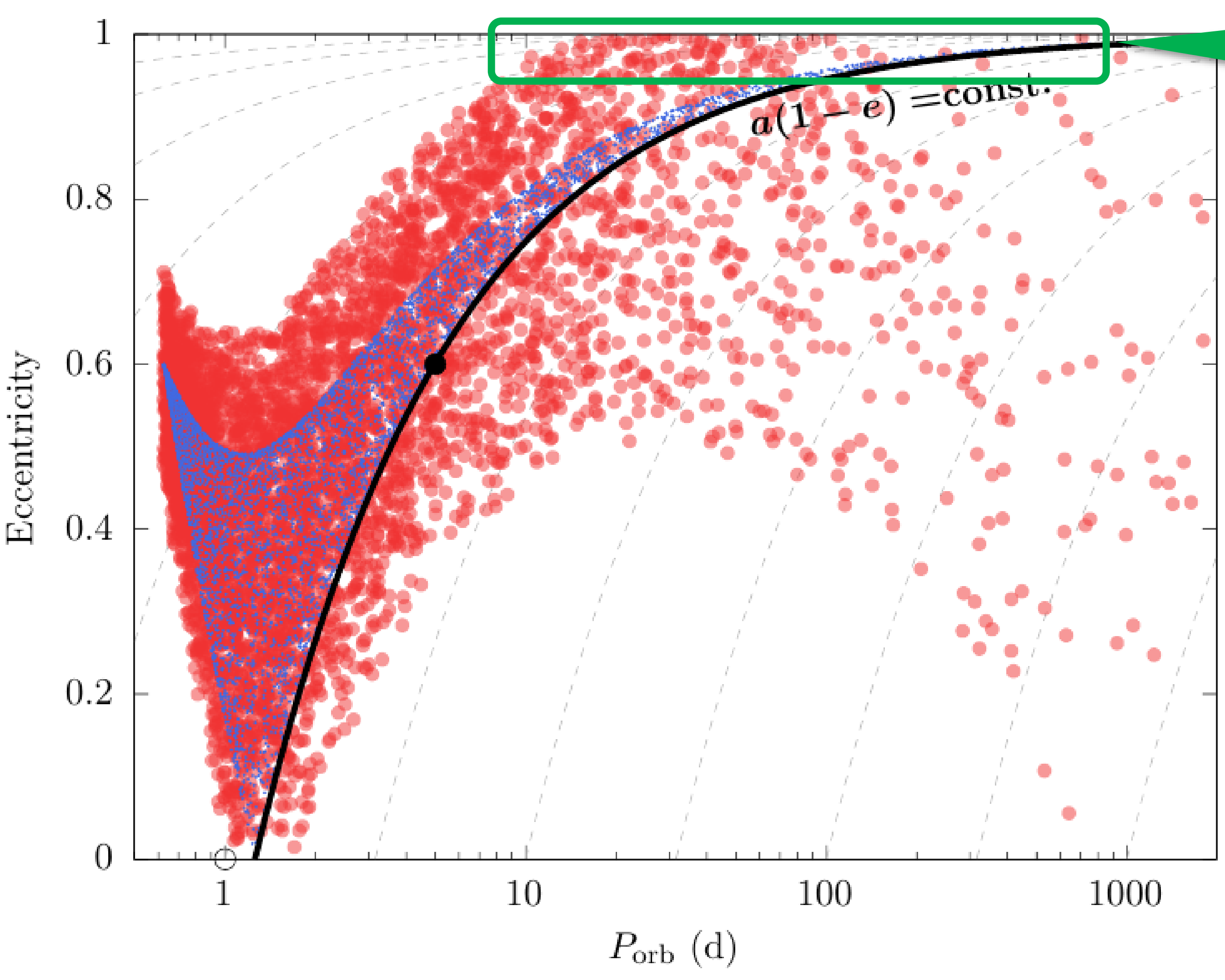
RH+2024

Gaia NSs are impossible to form in traditional kick scenarios nor the dynamical channel

Kicks+rockets may be the only solution to explain the existence of these systems

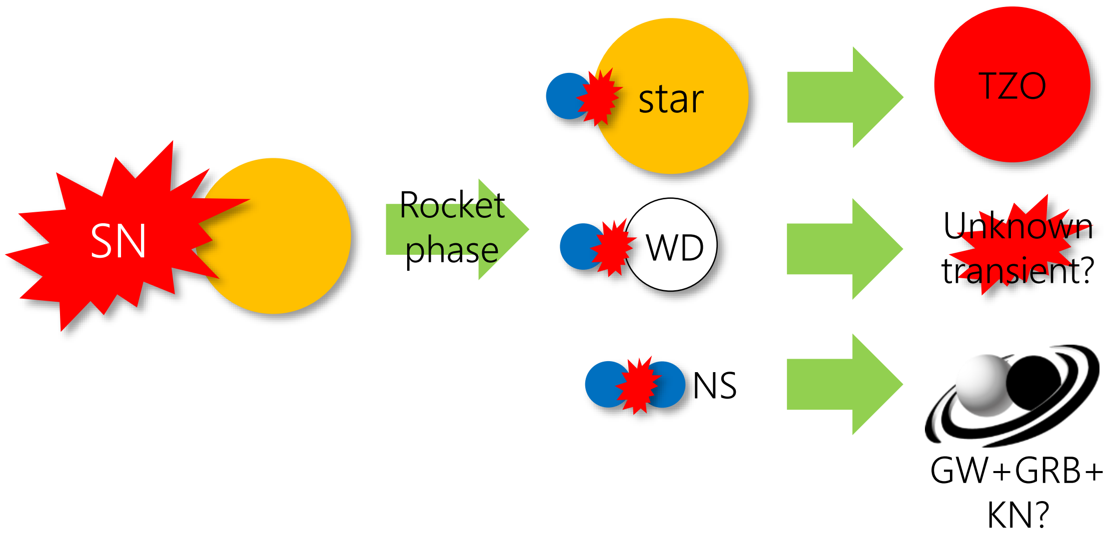
We find that just a modest amount of rocket (~30km/s) is sufficient to explain Gaia NSs

Induced mergers?



Depending on the rocket angle, it is possible to reach e~1

The NS will inevitably merge with the companion at sufficiently high eccentricities



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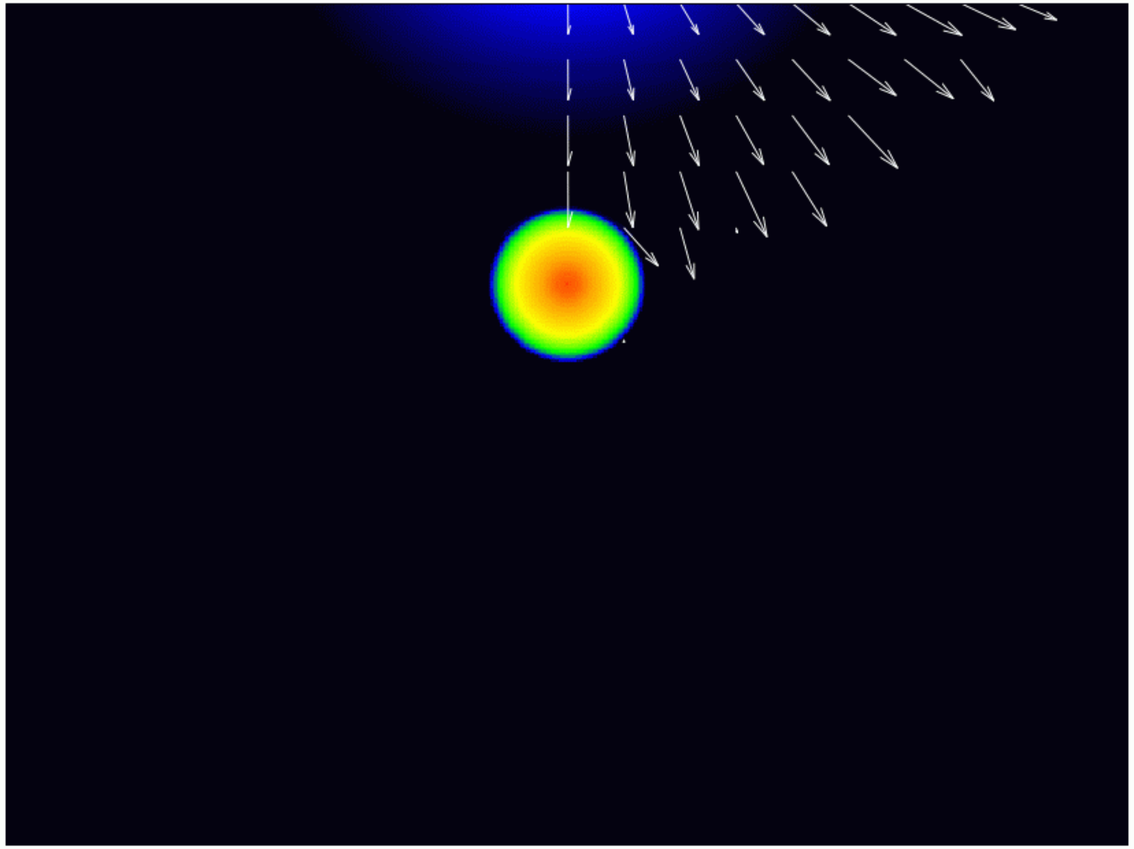
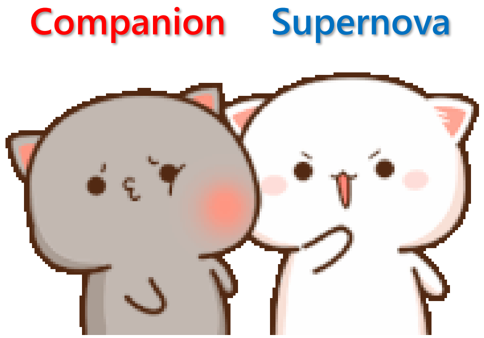
Ejecta-companion interaction

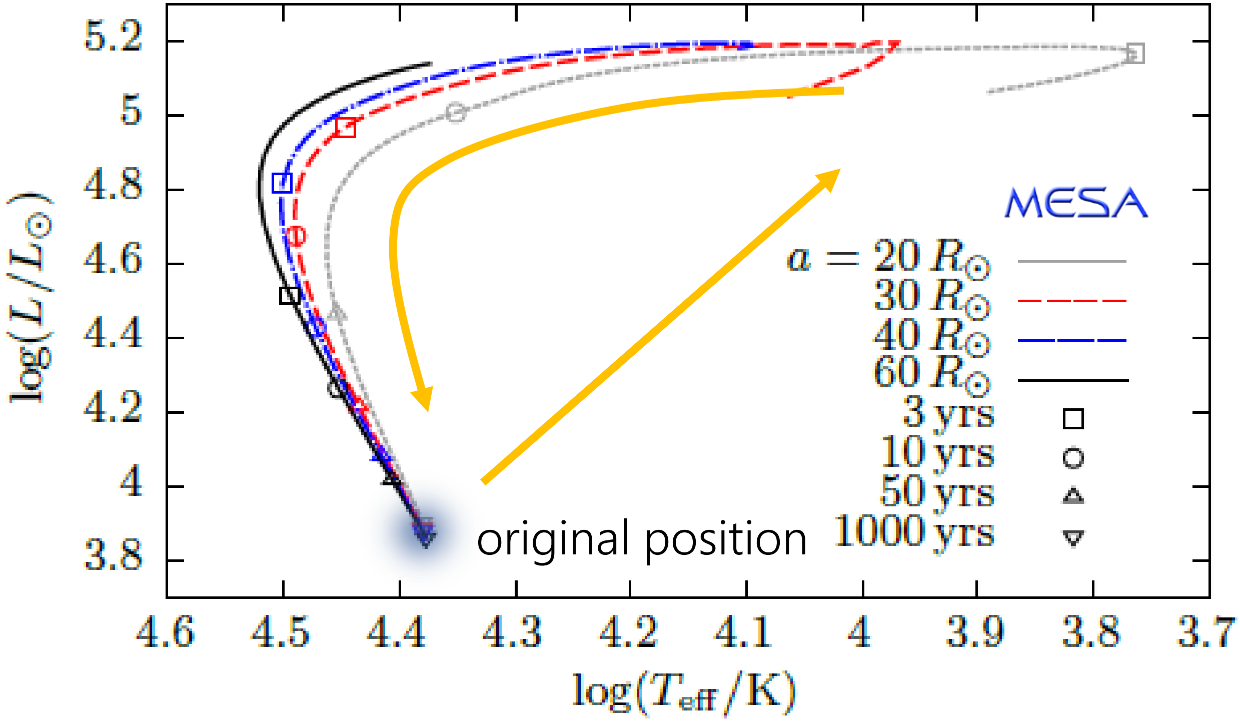
Main sequence companion



The main effect is to inject heat into the companion's envelope and alter its appearance



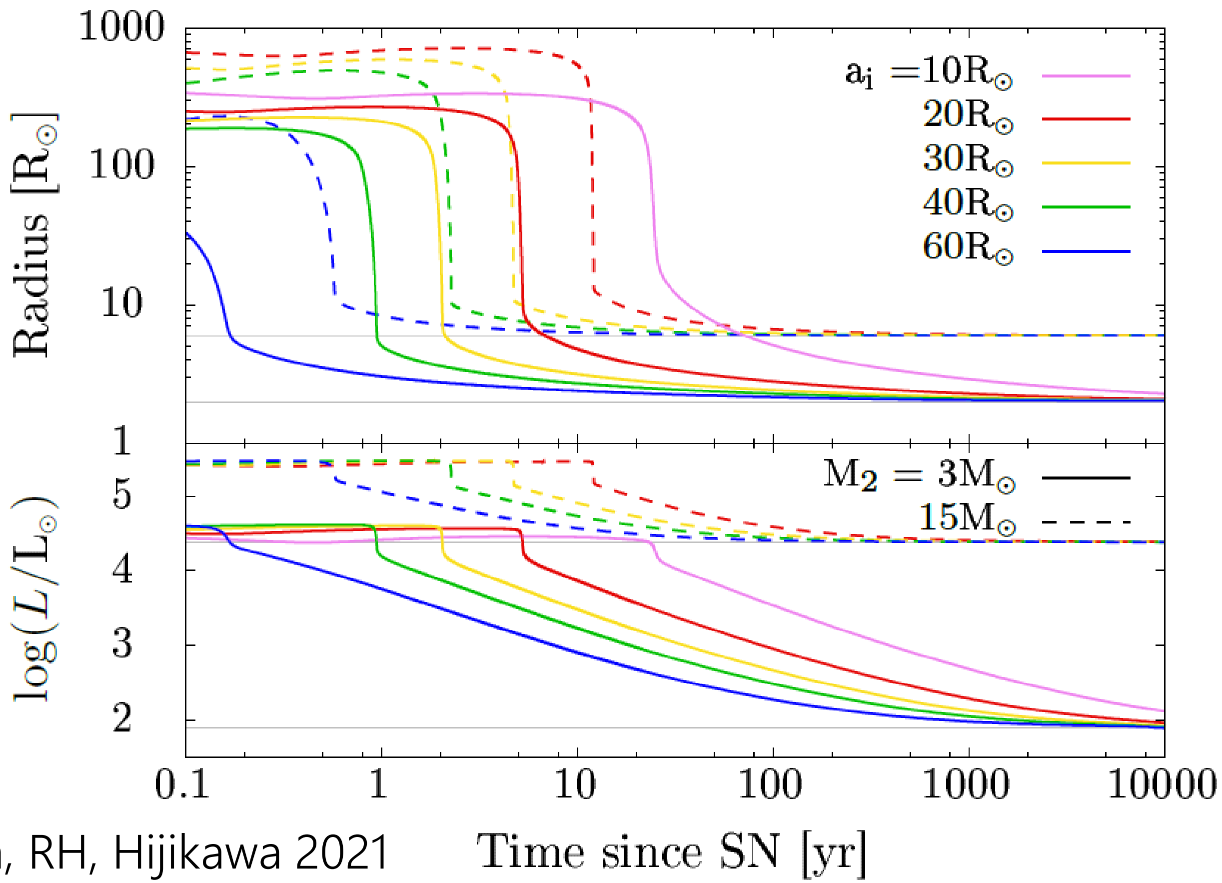
Post-ECI evolution



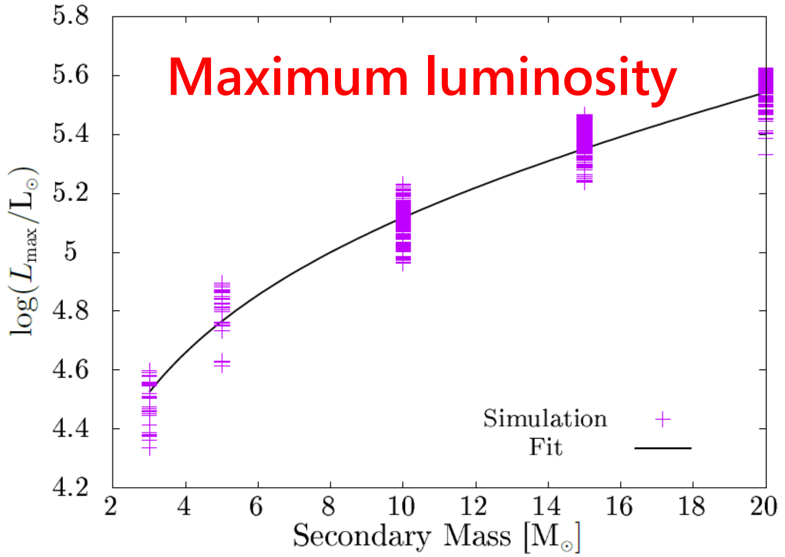
RH & Yamada 2015, RH+2018, Ogata,RH+2021, RH 2023

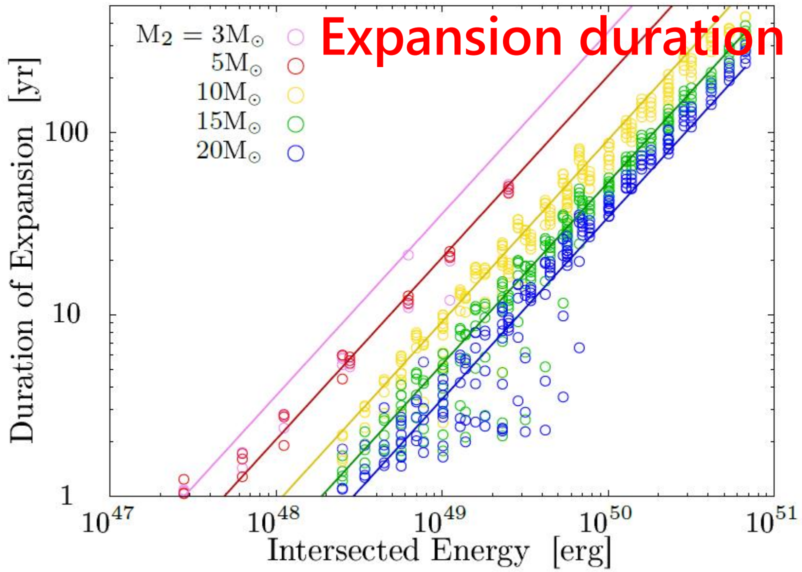
Constraining pre-SN parameters

Time evolution of the stellar properties after being SN-heated



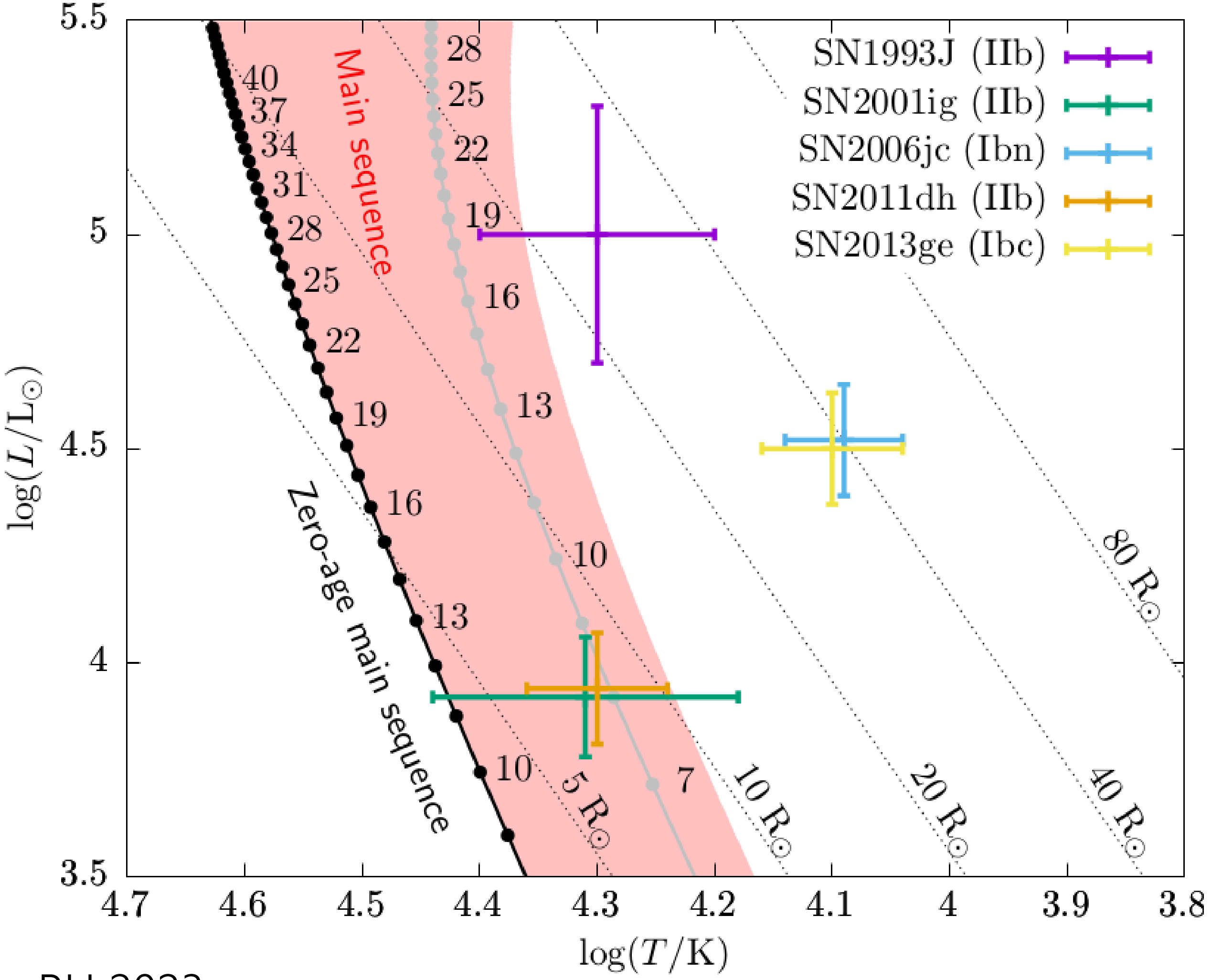
Ogata, RH, Hijikawa 2021



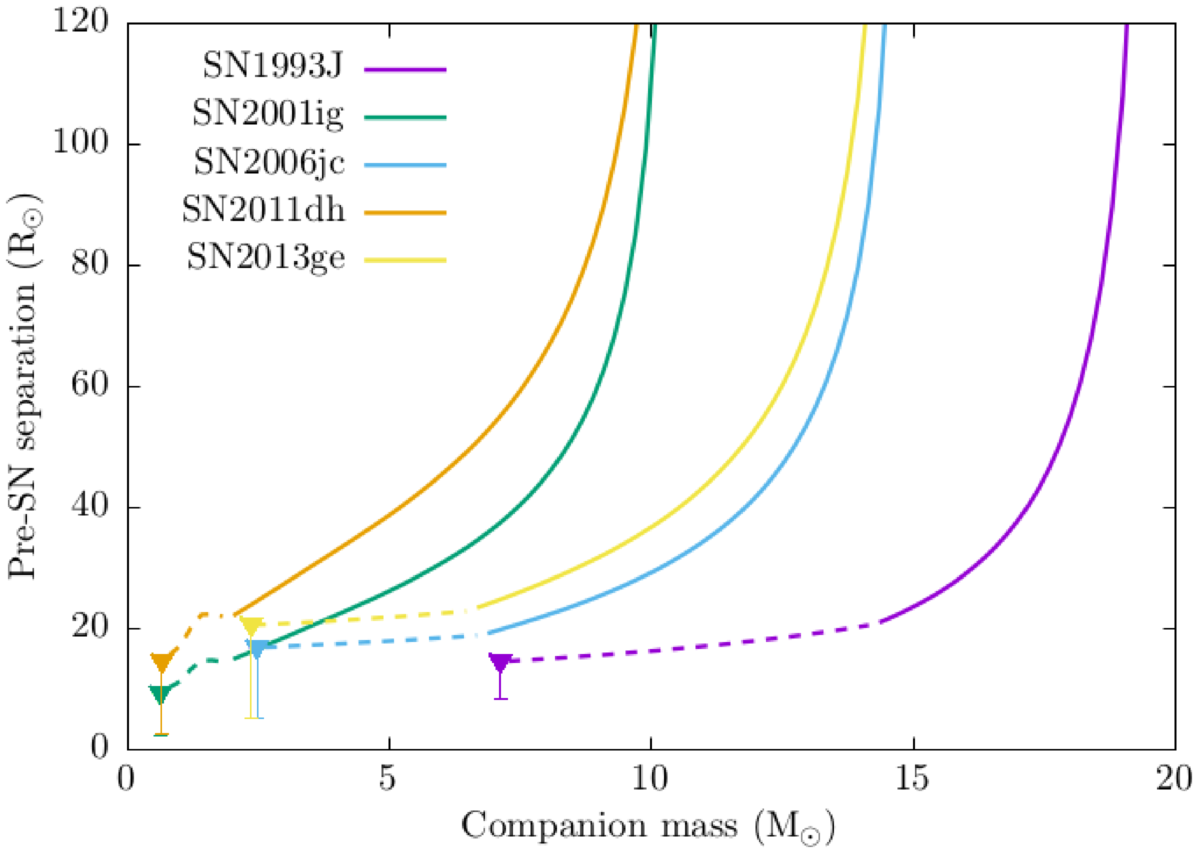


We can constrain the pre-SN binary parameters by observing the post-SN companion!

Inferred pre-SN orbits for observed SNe

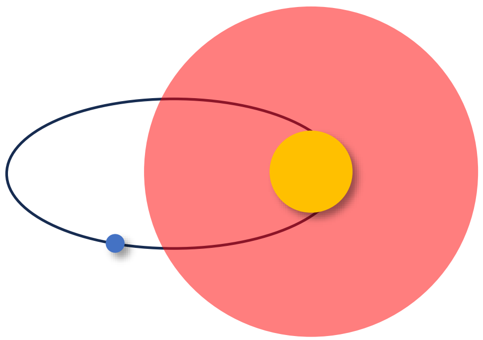


I derived an analytical model that describes the companion response, enabling us to solve the inverse problem

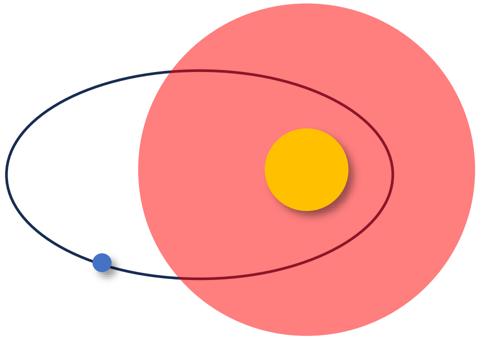


RH 2023

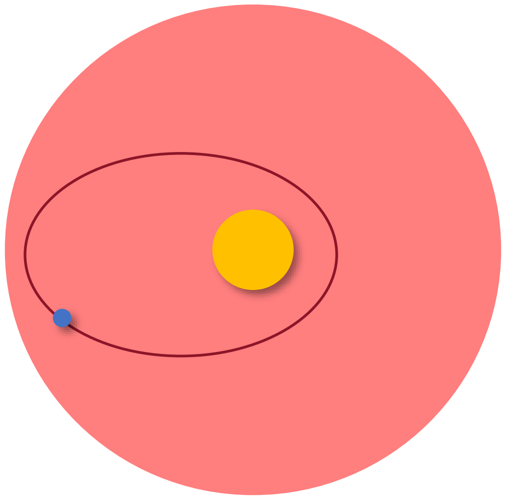
Interaction with SN-heated companions



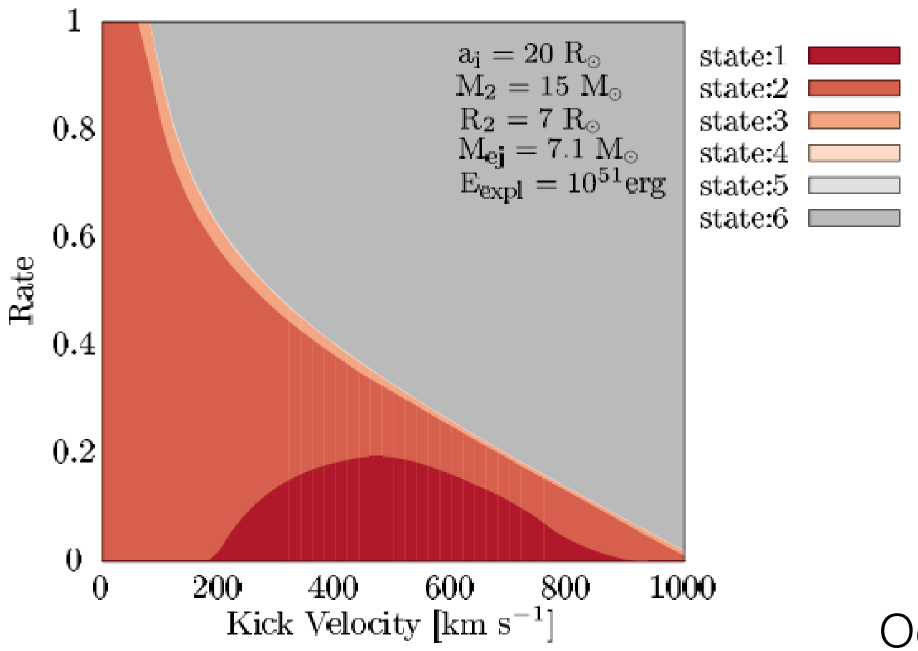
Direct collision



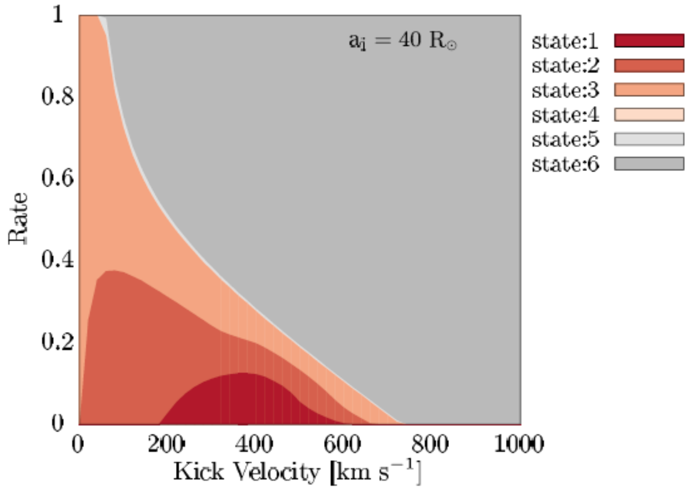
Interaction with inflated envelope

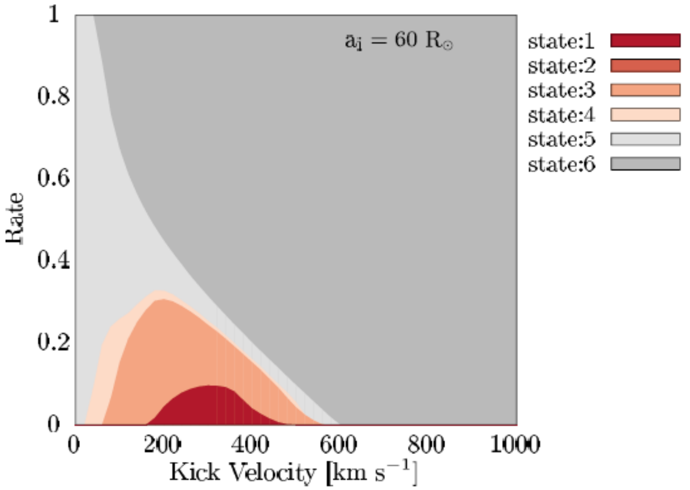


Embedded in inflated envelope



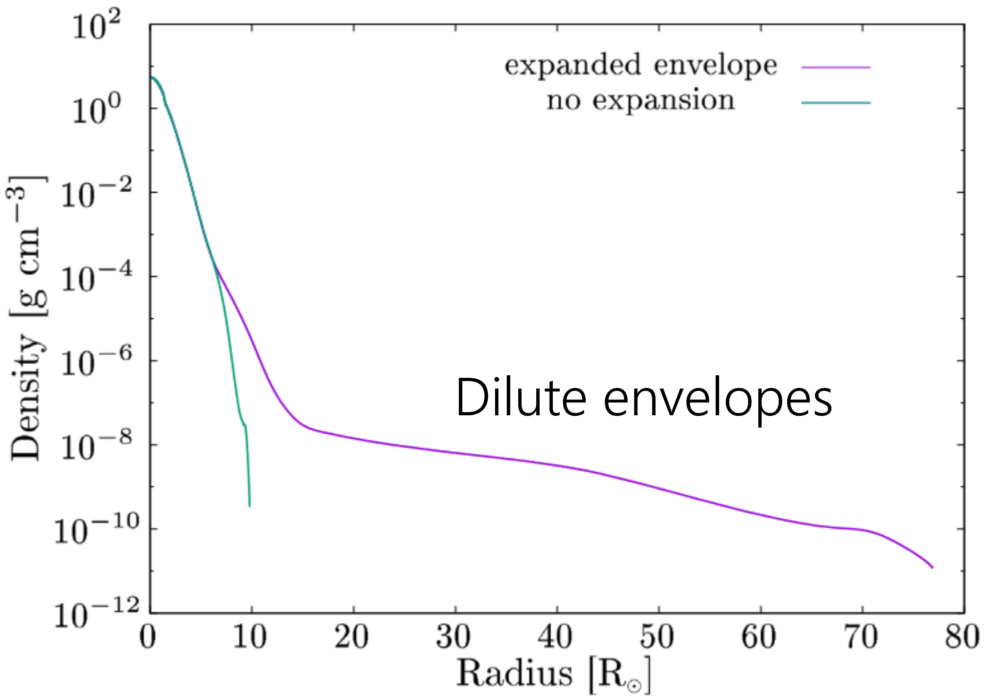
Ogata,RH+2021

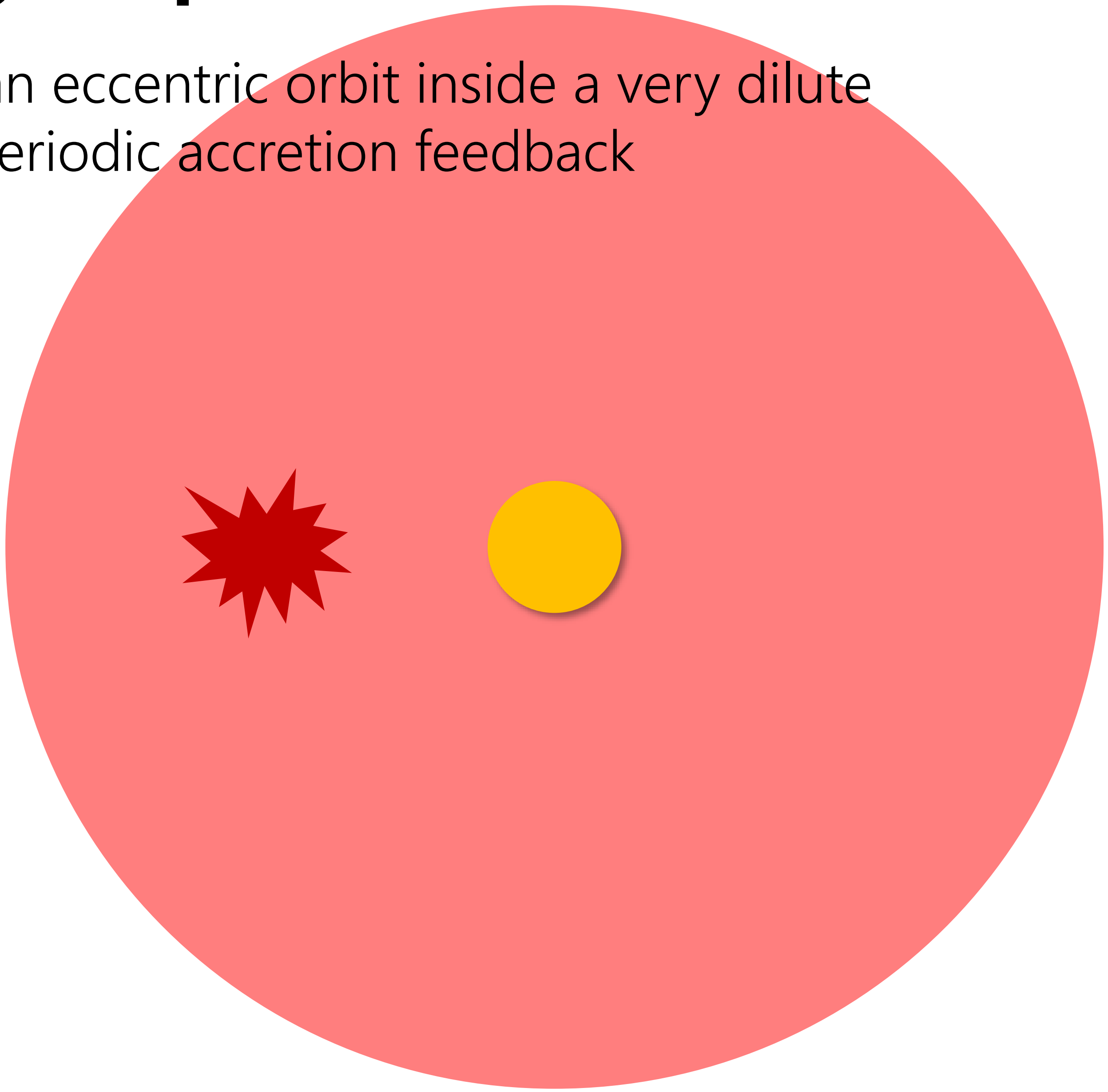




Periodically bumpy supernova?

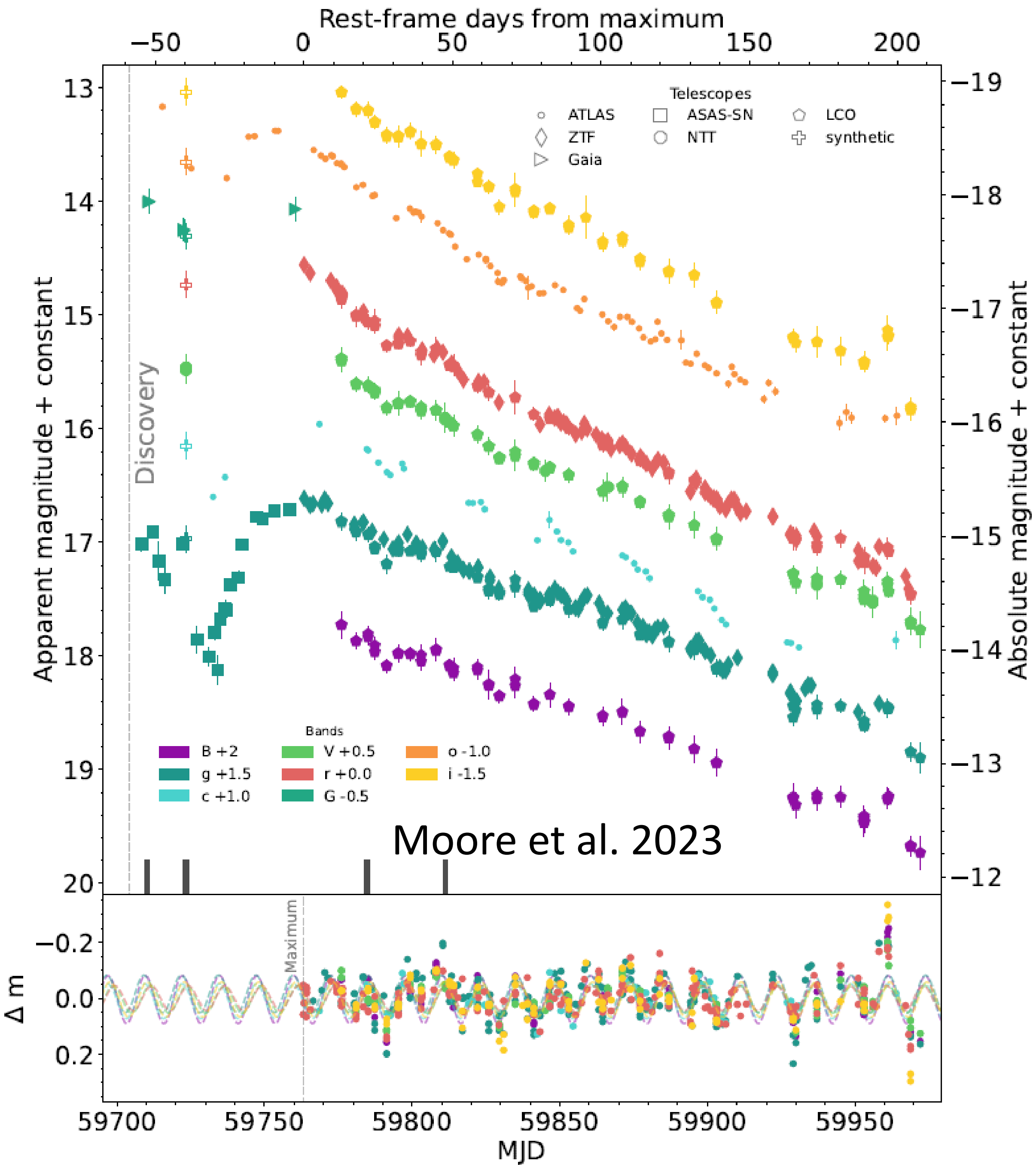
If a new-born neutron star is on an eccentric orbit inside a very dilute inflated envelope, it could have periodic accretion feedback



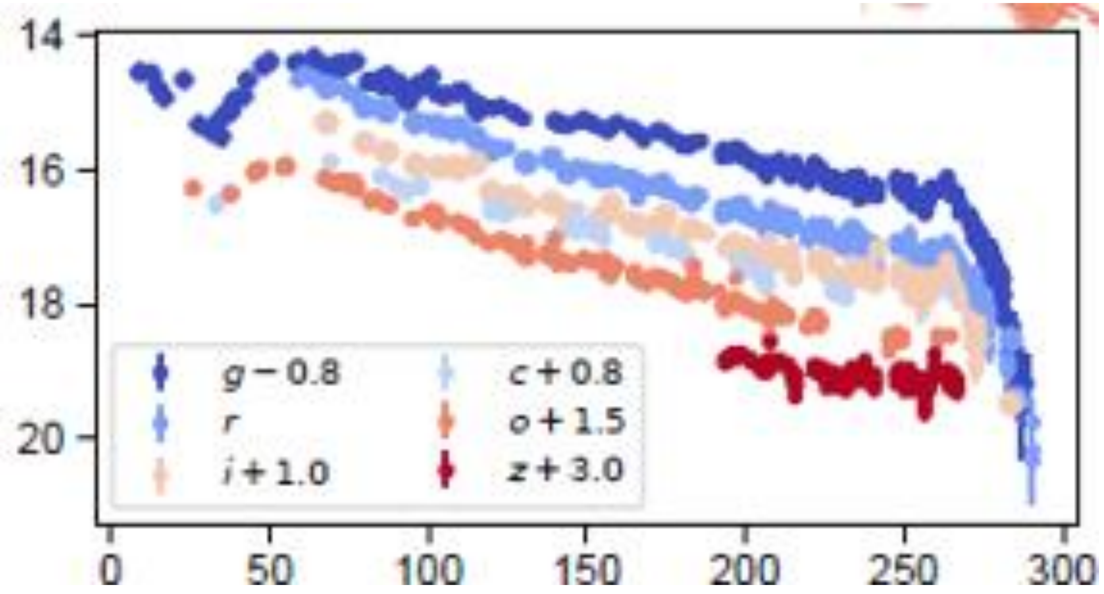


SN2022jli

Type Ic supernova
First time periodic bumps were detected!! (12.5 d periodicity)
At lest 15 cycles were completed

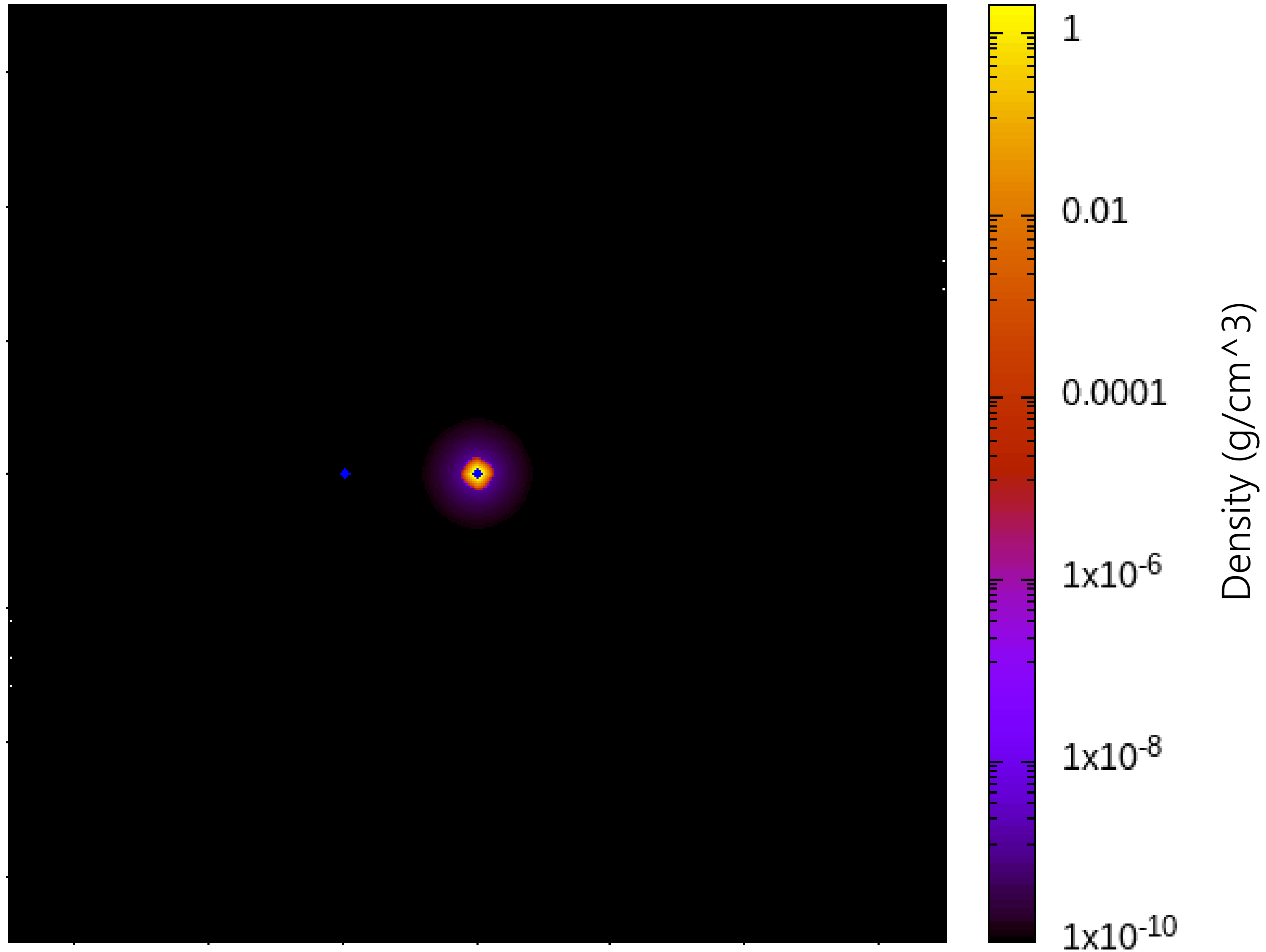


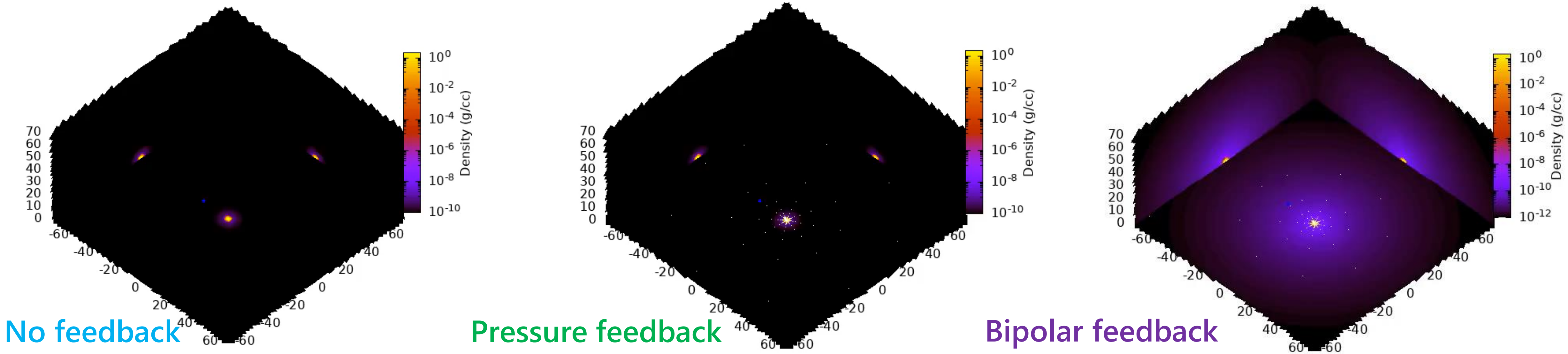
Moore et al. 2023

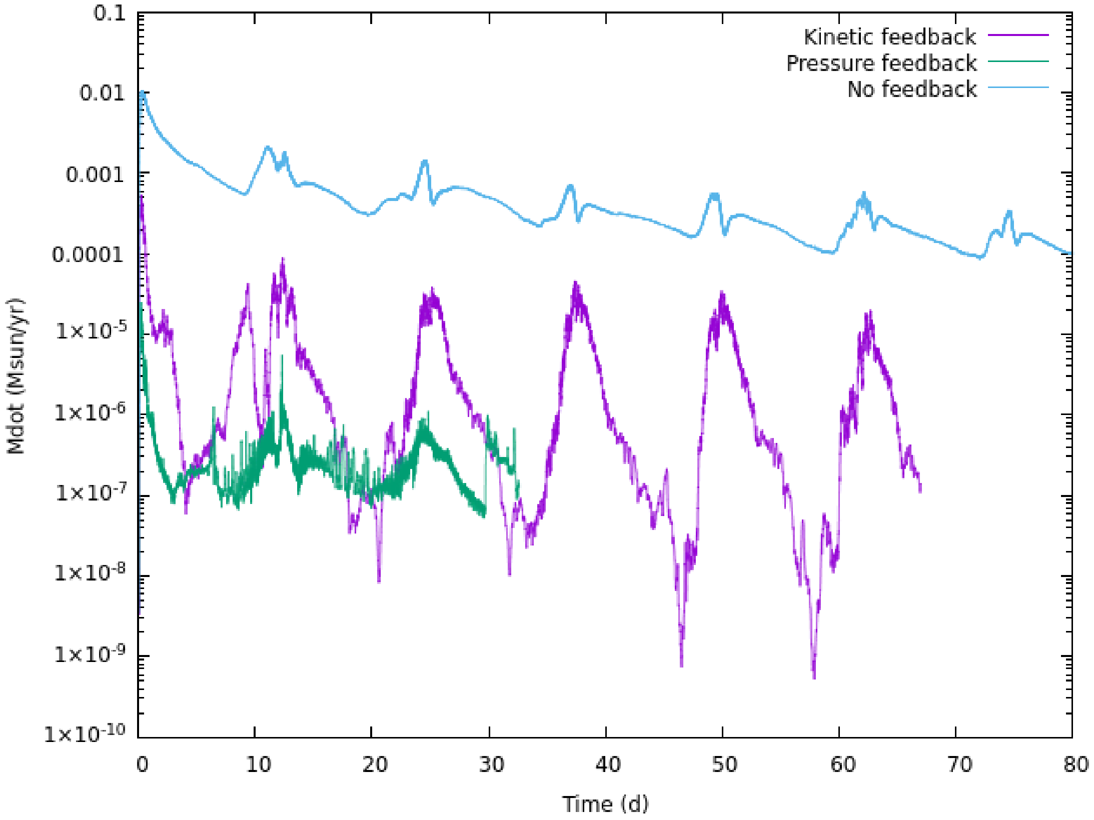


Chen et al. 2024

SN-heating + binary interaction simulation

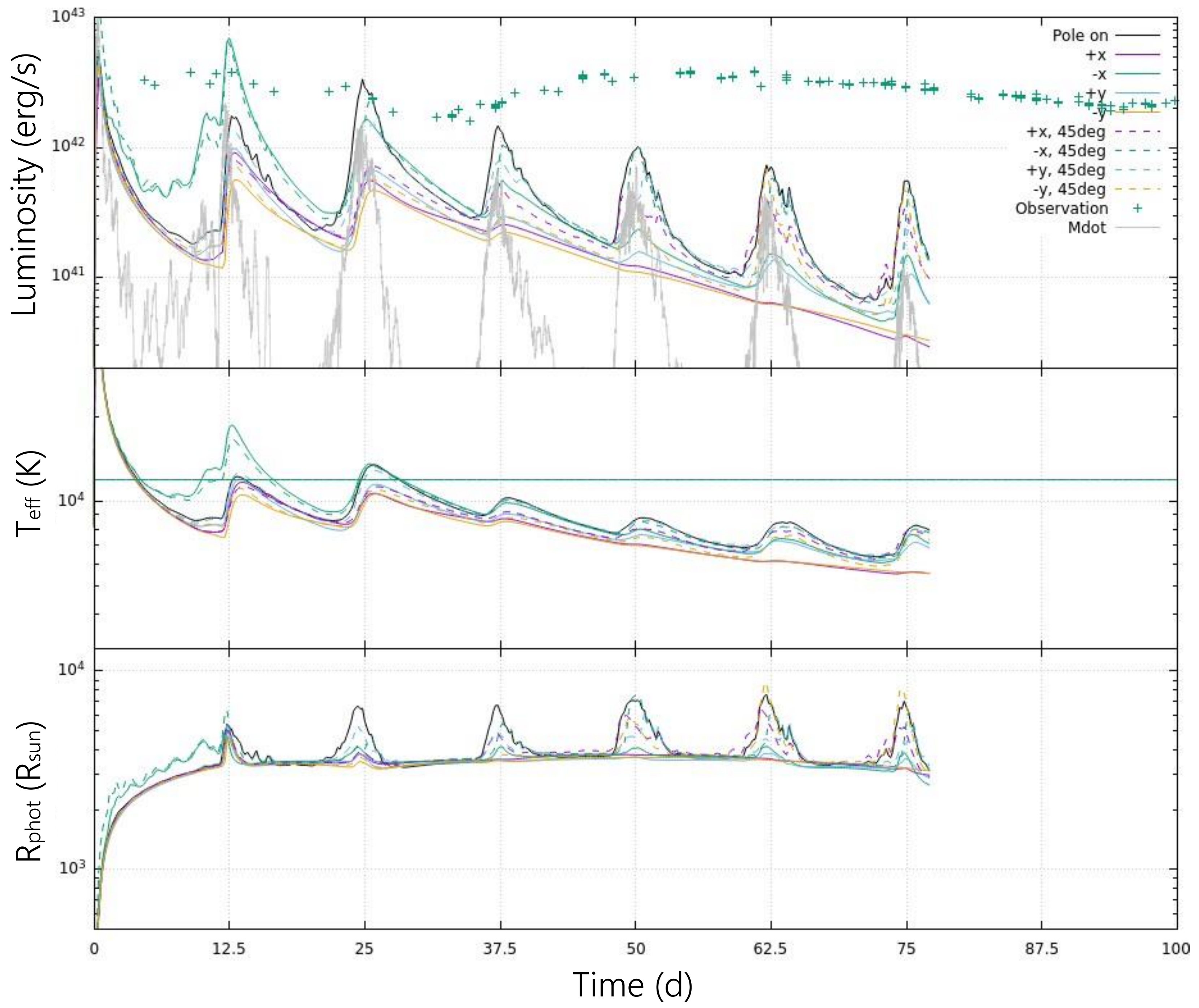






Similar to cosmological simulations, “how” you put in feedback makes a lot of difference

A jet-like bipolar outflow seems to be the best matching model at the moment



We generated mock lightcurves from the bipolar feedback simulations

Main features of SN2022jli are captured:

- Declining but undulating light curve
- Undulation amplitude (from some viewing angles)

But many questions remain:

- ~50d delay to peak
- Absolute luminosity
- Abrupt drop at ~200d

Summary

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- **Binary evolution→Supernovae**
  - Binary interactions are responsible for the diversity of SNe, even for the H-rich SNIIP/L's
- **Supernovae→Binary evolution**
  - SN kicks have drastic impacts on the orbit
  - NS rocket mechanism unlocks a whole new parameter space and could resolve many issues in binary evolution
- **Observing binarity in supernovae**
  - Ejecta-companion interaction can cause companions to temporarily inflate. Inflation timescales can be used to constrain pre-SN orbital properties
  - Accretion from inflated envelopes could periodically power SN light curves, like in SN2022jli