New-born neutron stars colliding with companion stars

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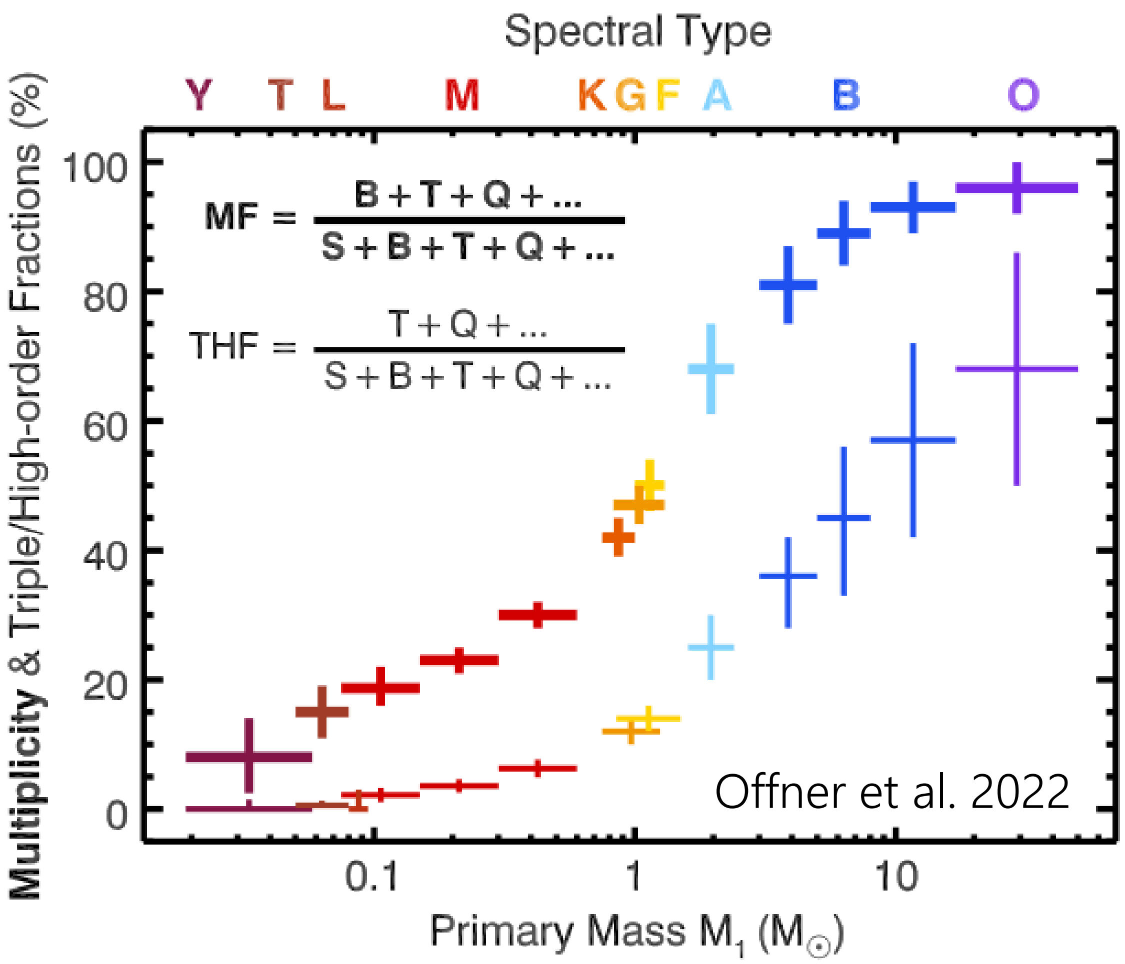
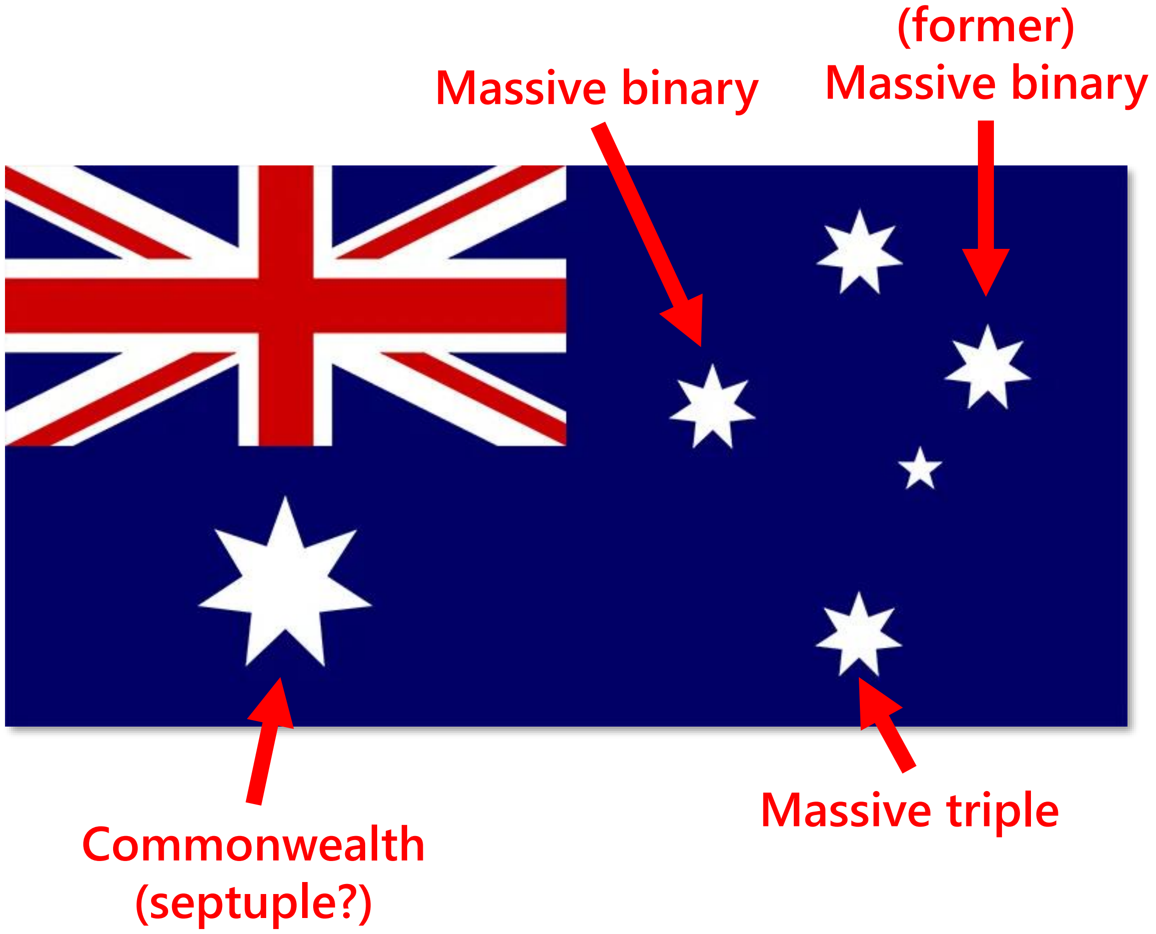
Massive binaries are important

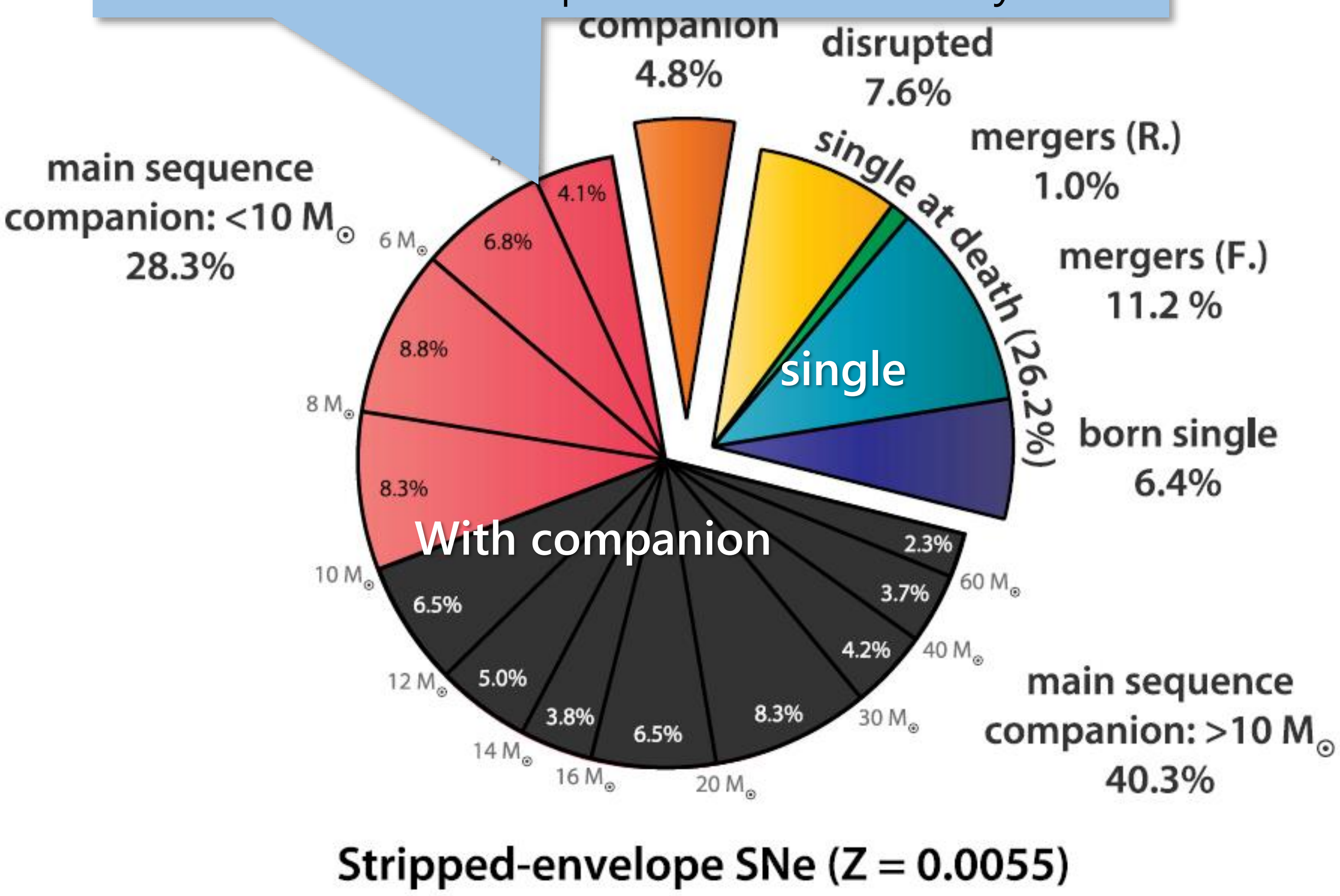
Most massive stars have 1 or more companions!





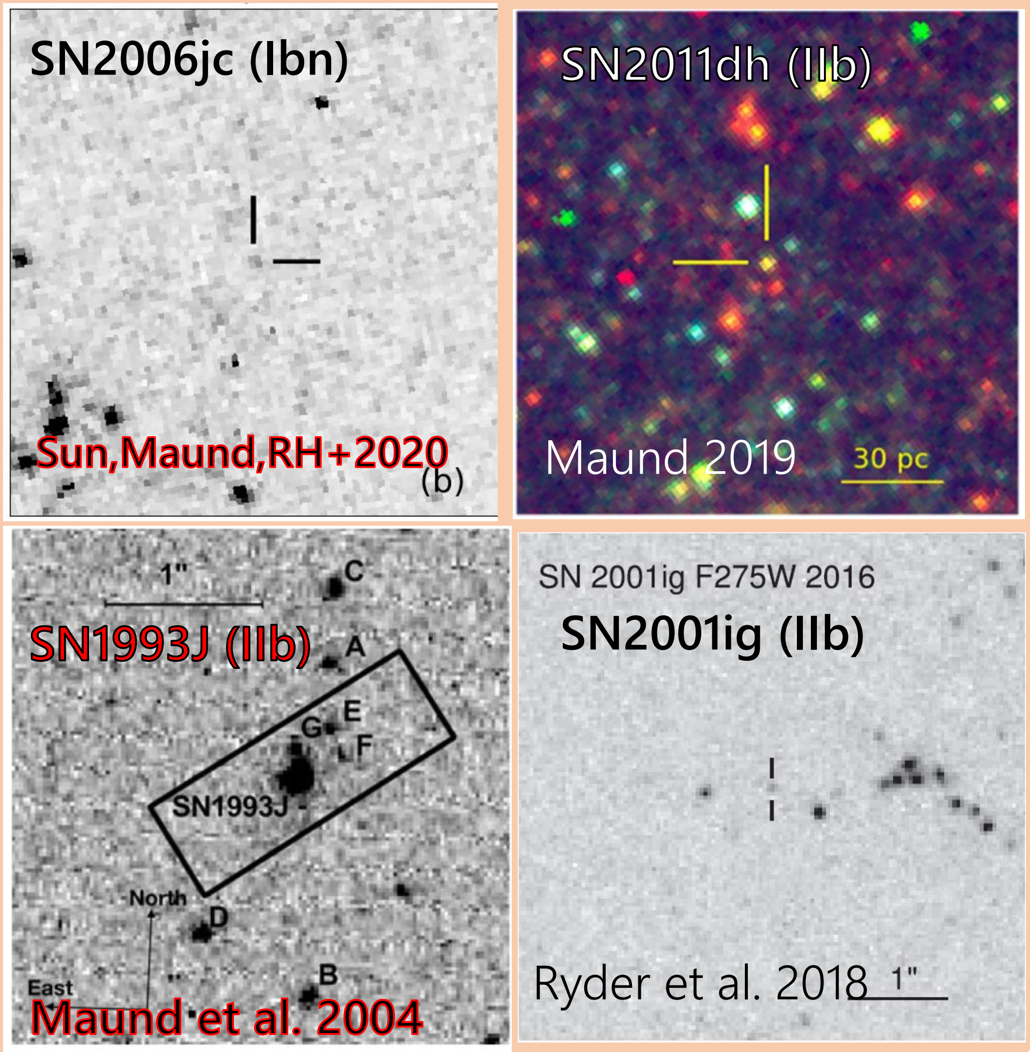
Supernovae in binaries

Many core-collapse supernovae are expected to occur with a companion star close-by

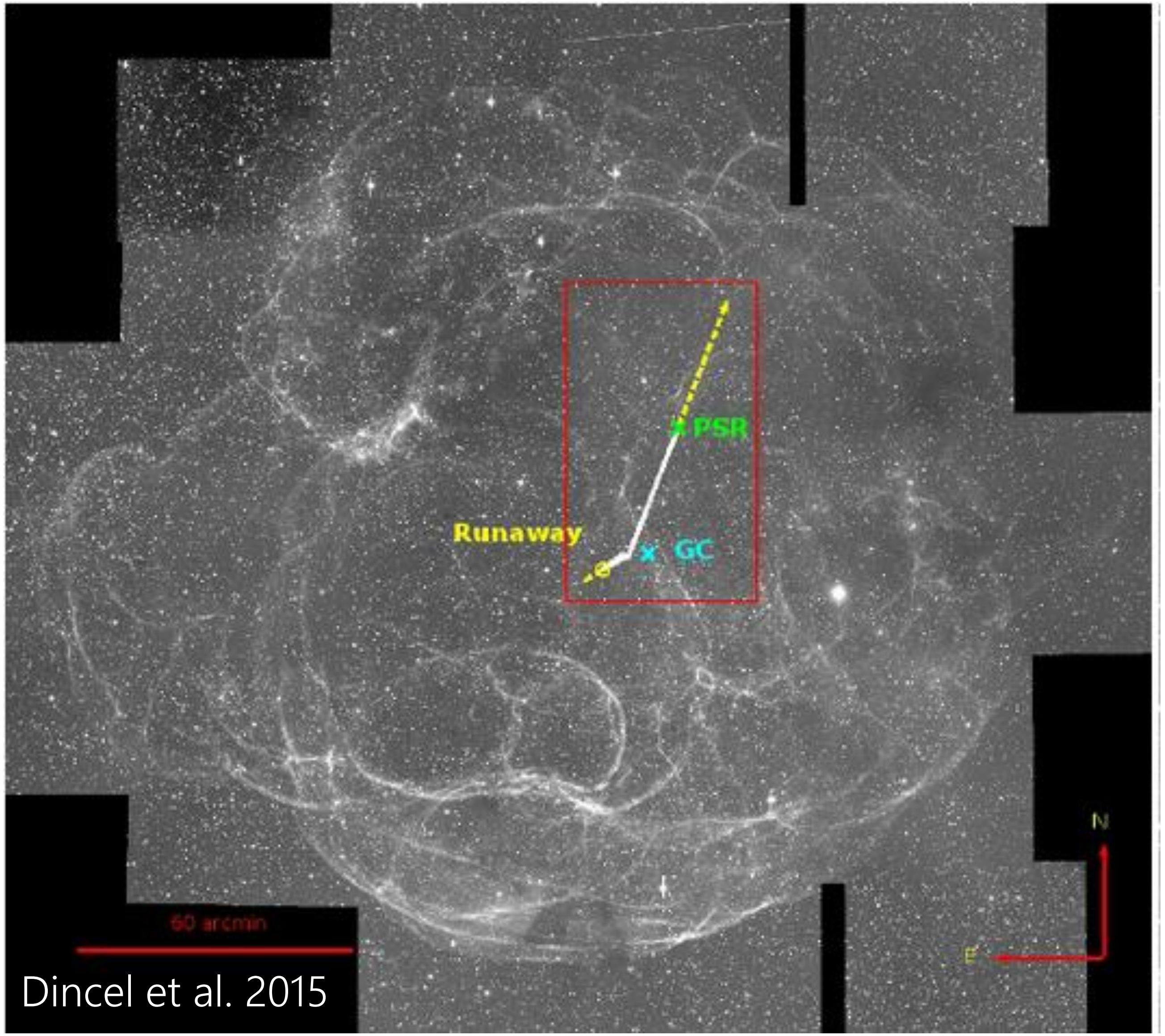


Zapartas et al. 2017

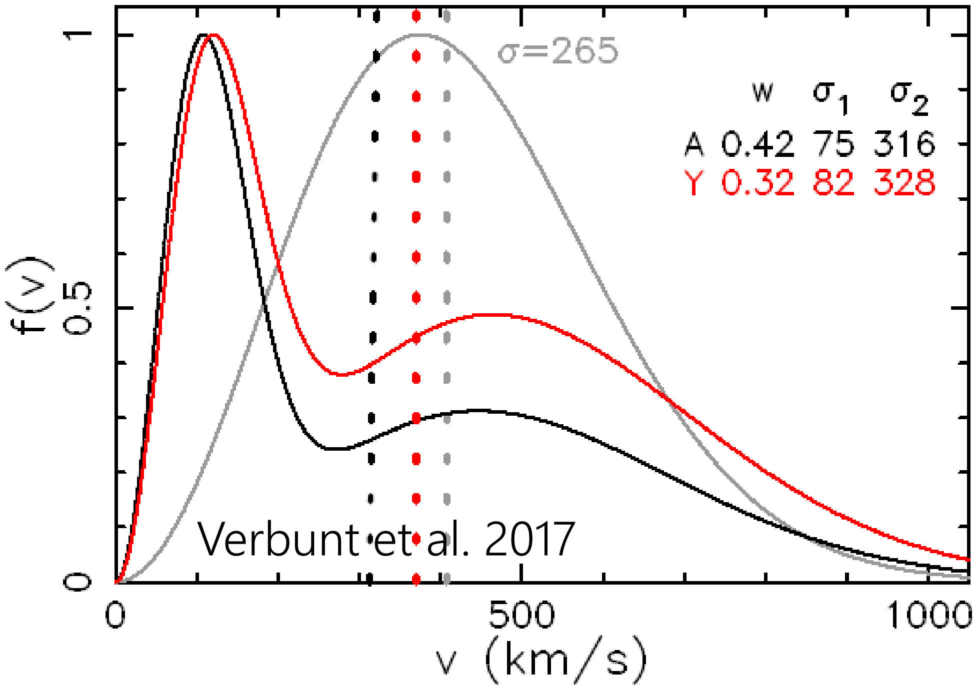
Companion detections

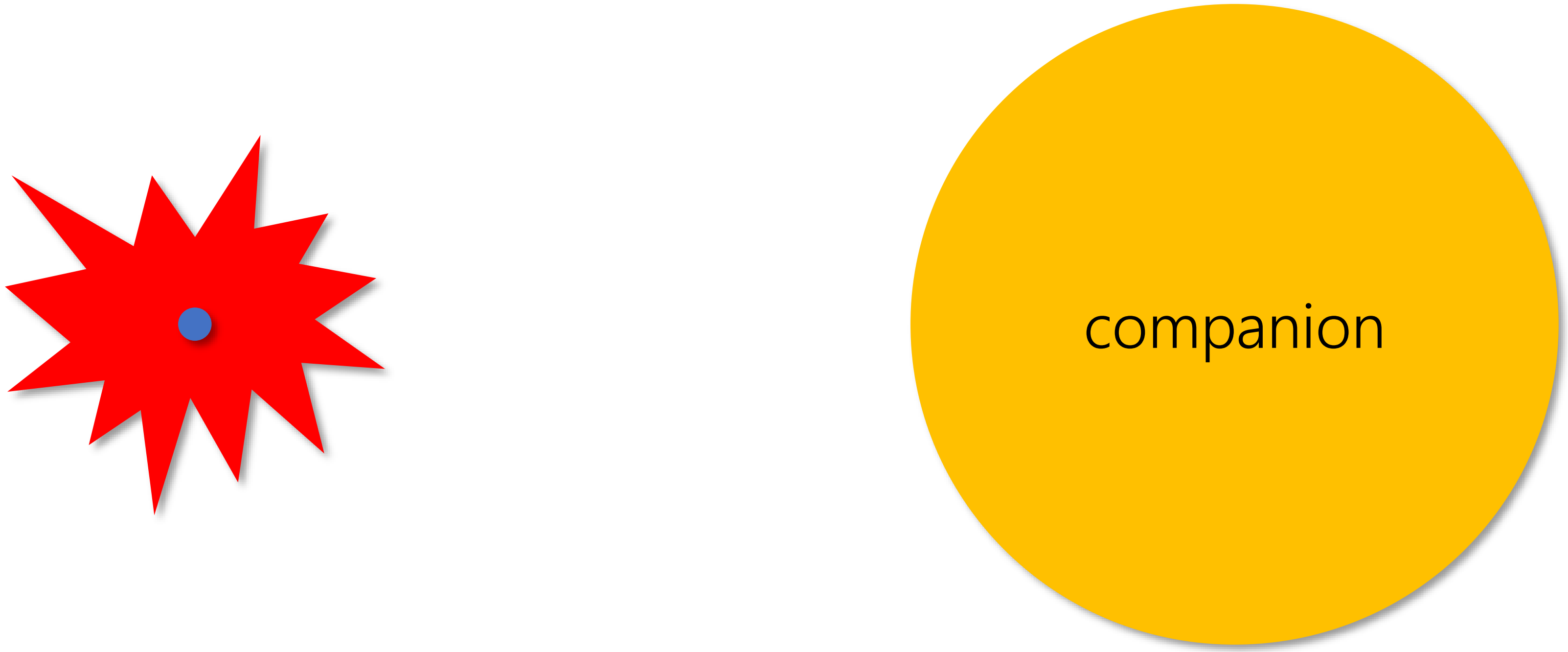


Neutron star natal kicks



New-born neutron stars receive “kicks” due to the asymmetry in the explosion
Asymmetries may be caused by:
- Hydrodynamical stochasticity
- Neutrino emission





What happens when neutron stars are kicked *into* the companion star?

HORMONE

(High ORder Magnetohydrodynamic cOde with Numerous Enhancements)

Unofficial logo

- 3D MHD code
- Finite volume scheme (Godunov-type)
- HLLD fluxes + 9-wave method
- openMP parallel
- Cartesian/Cylindrical/Spherical coordinates
- Hyperbolic self-gravity (~O(N), Hirai et al. 2016)
- Optically thin radiative cooling (Townsend 2009)
- Customized flux limiter
- Original EoS solver for recombination (Hirai et al. 2020) → PHANTOM
- Working on AMR and RT…

Hydrodynamical simulations

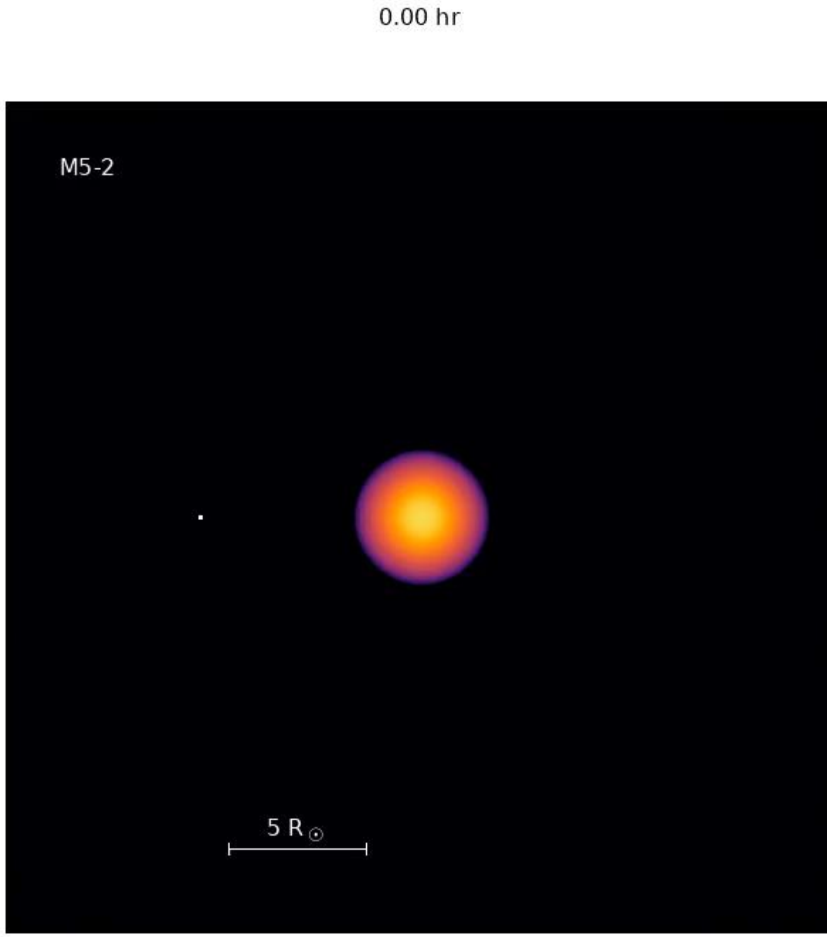
I performed 3D hydro simulations of collisions between new-born NSs and companions

<u>Model parameters</u>

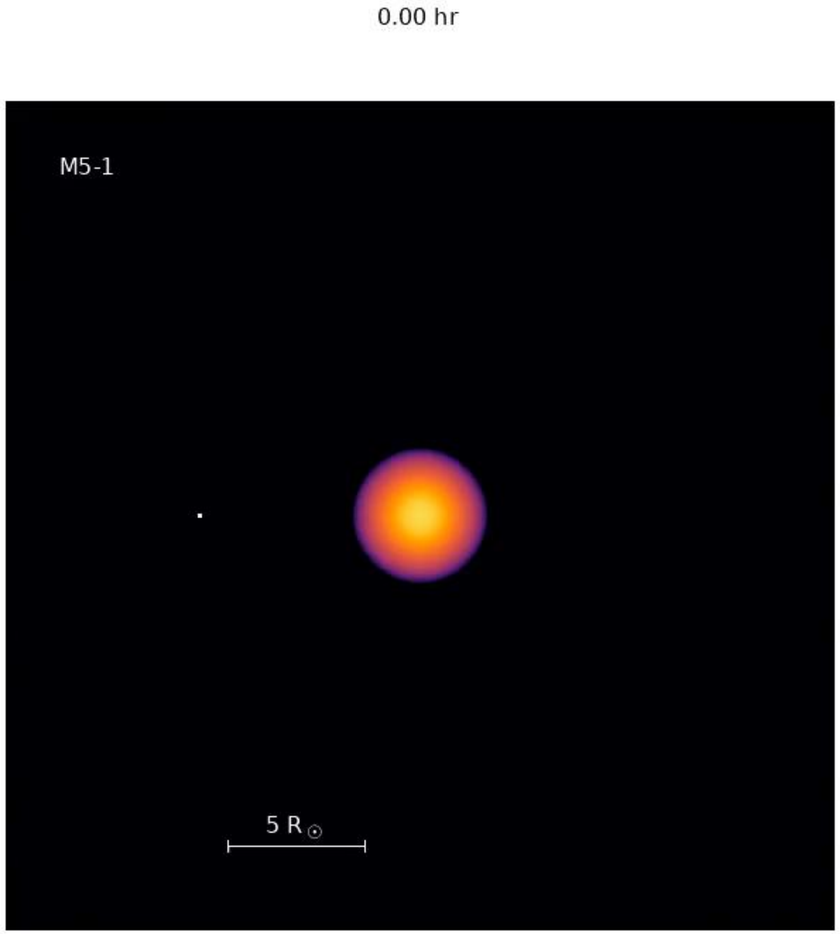
- Progenitor mass：6 $M_\odot$
- NS mass：1.4 $M_\odot$
- Companion mass：1,5,10 $M_\odot$
- Orbital separation：3,8,15 $R_\odot$
- Kick velocity：1000 km/s
- Kick direction：various

Similar setup to:

- Stellar flybys
- Tidal disruption events
- Common-envelopes

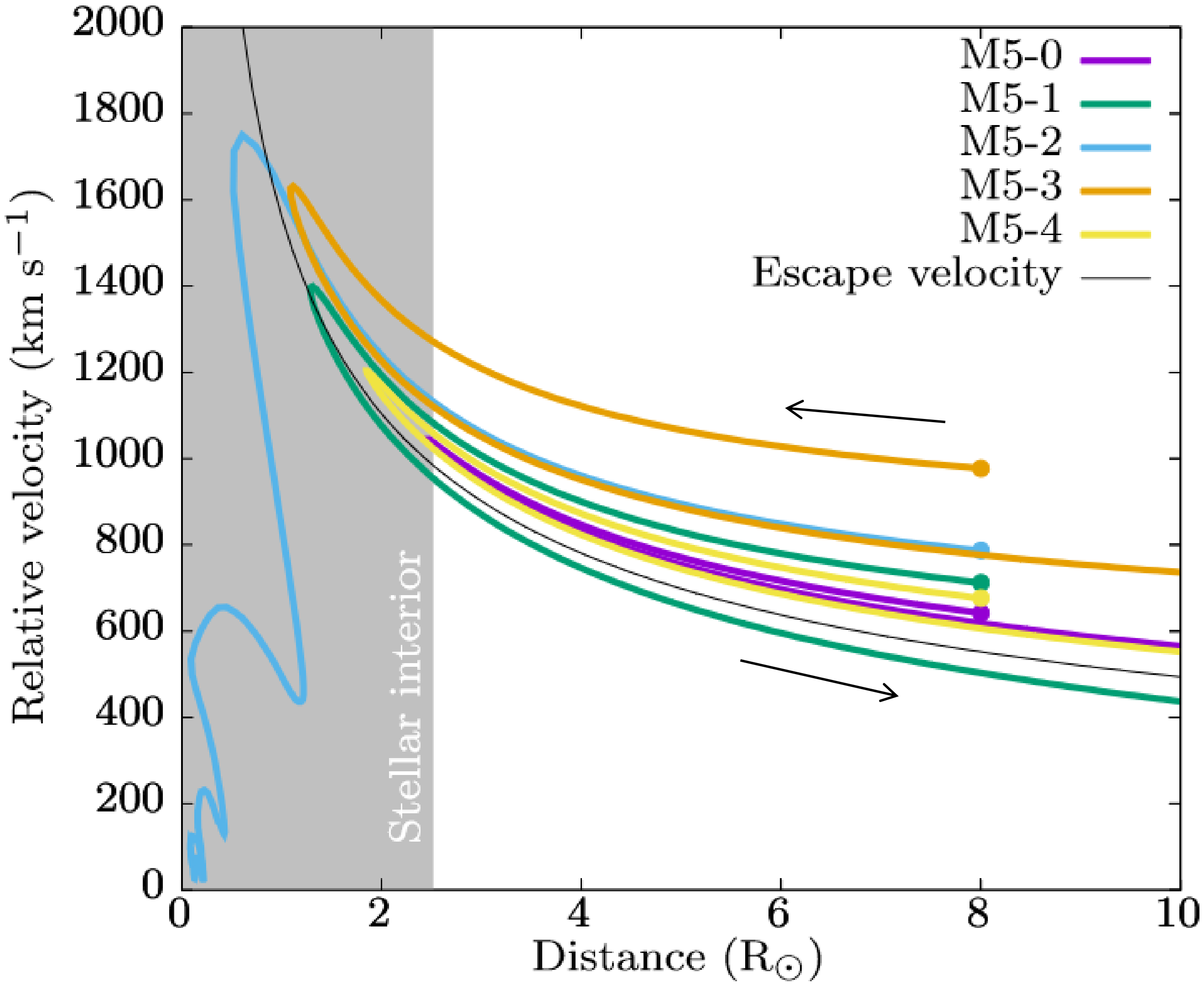


Immediate merger



Envelope penetration

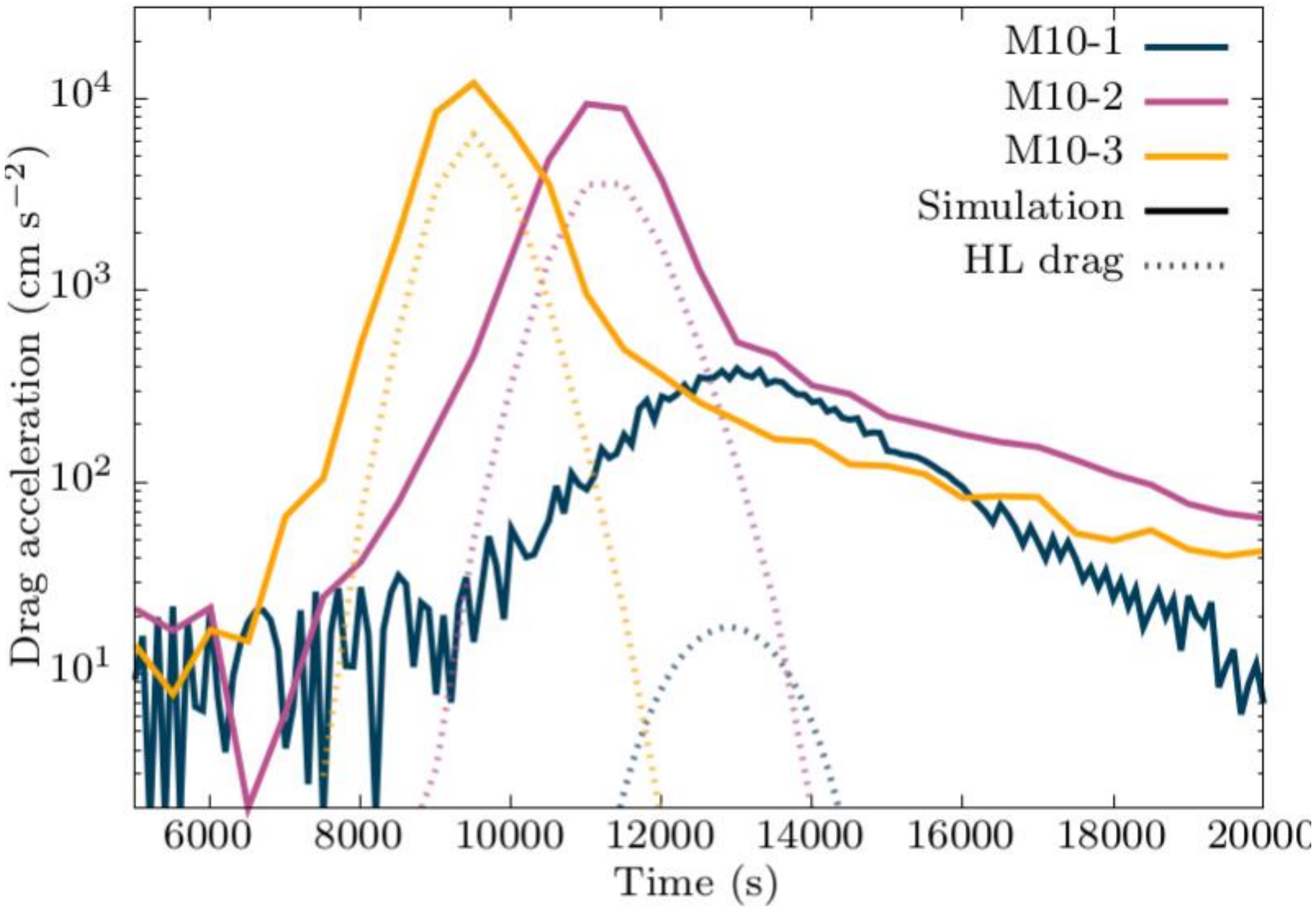
Results – deceleration in the envelope



- On completely ballistic trajectories, the ingoing and outgoing curves should exactly agree
- As the NS enters the stellar envelope, the gravitational drag causes the NS to decelerate
- The deceleration is sometimes large enough to put the NS on a bound orbit

Semi-analytical modelling

We create a new analytical model for gravitational drag to enable more rapid modelling



Hoyle-Lyttleton drag

$$f_{\mathrm{drag,HL}} = \frac{4\pi G^2 M_{\mathrm{NS}} \rho}{v_{\mathrm{rel}}^2}$$

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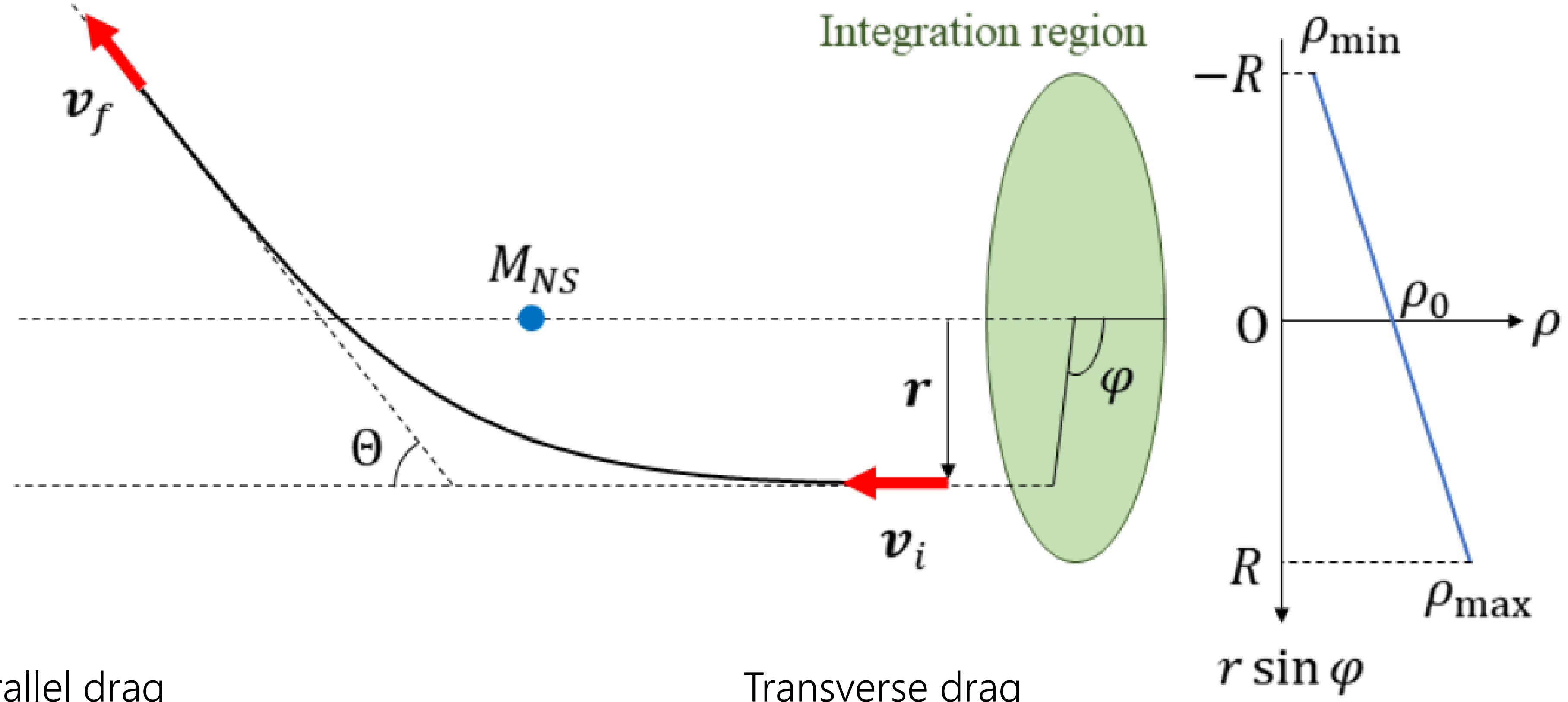

Parallel drag

$$f_{\mathrm{d},\parallel} = \pi \rho_0 v_\infty^2 R_\mathrm{b}^2 \cdot \frac{1}{2} \ln\left[\left(\frac{2R}{R_\mathrm{b}}\right)^2 + 1\right]$$

$$R_\mathrm{b} \equiv 2GM_\mathrm{NS}/v_\infty^2$$

Transverse drag

$$f_{\mathrm{d},\perp} = \pi(\rho_{\max} - \rho_{\min}) v_\infty^2 R_\mathrm{b}^2 \cdot \frac{1}{16}\left[\frac{2R}{R_\mathrm{b}} - \frac{R_\mathrm{b}}{2R}\ln\left(1 + \left(\frac{2R}{R_\mathrm{b}}\right)^2\right)\right]$$

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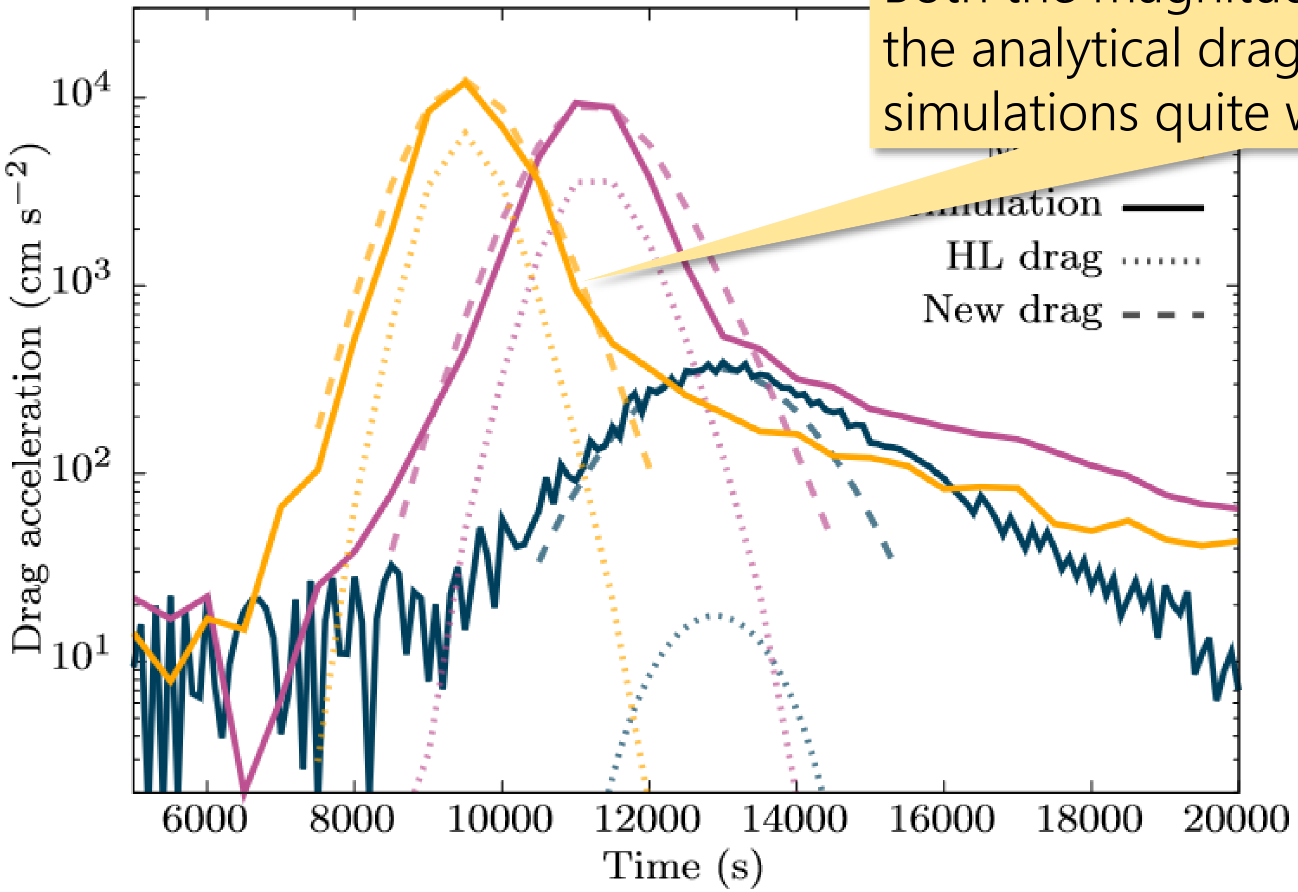
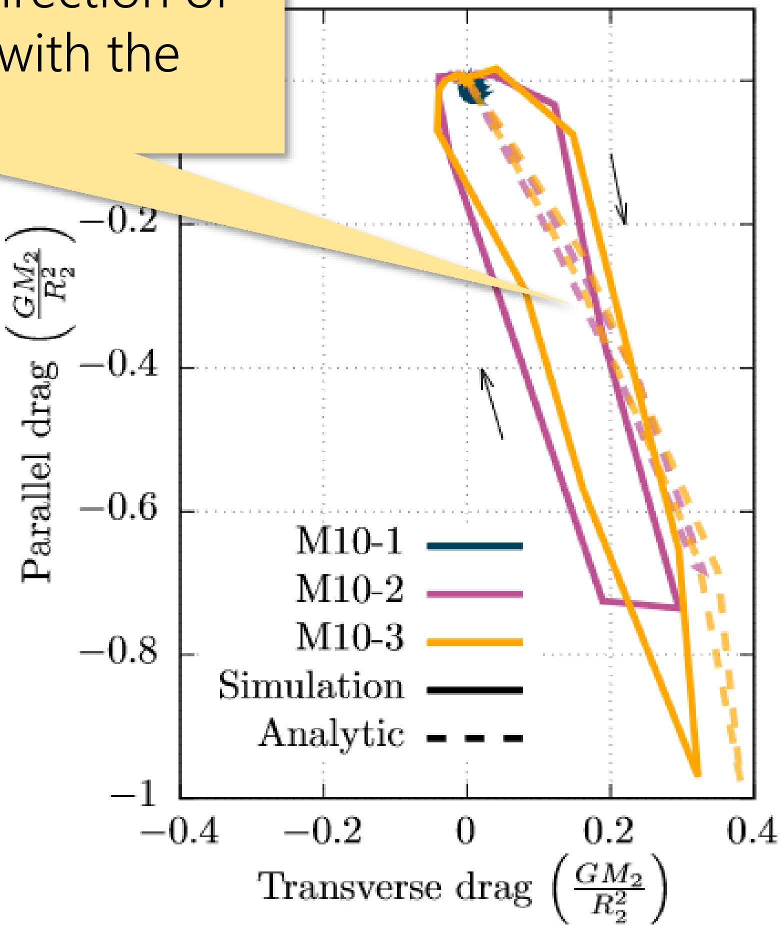
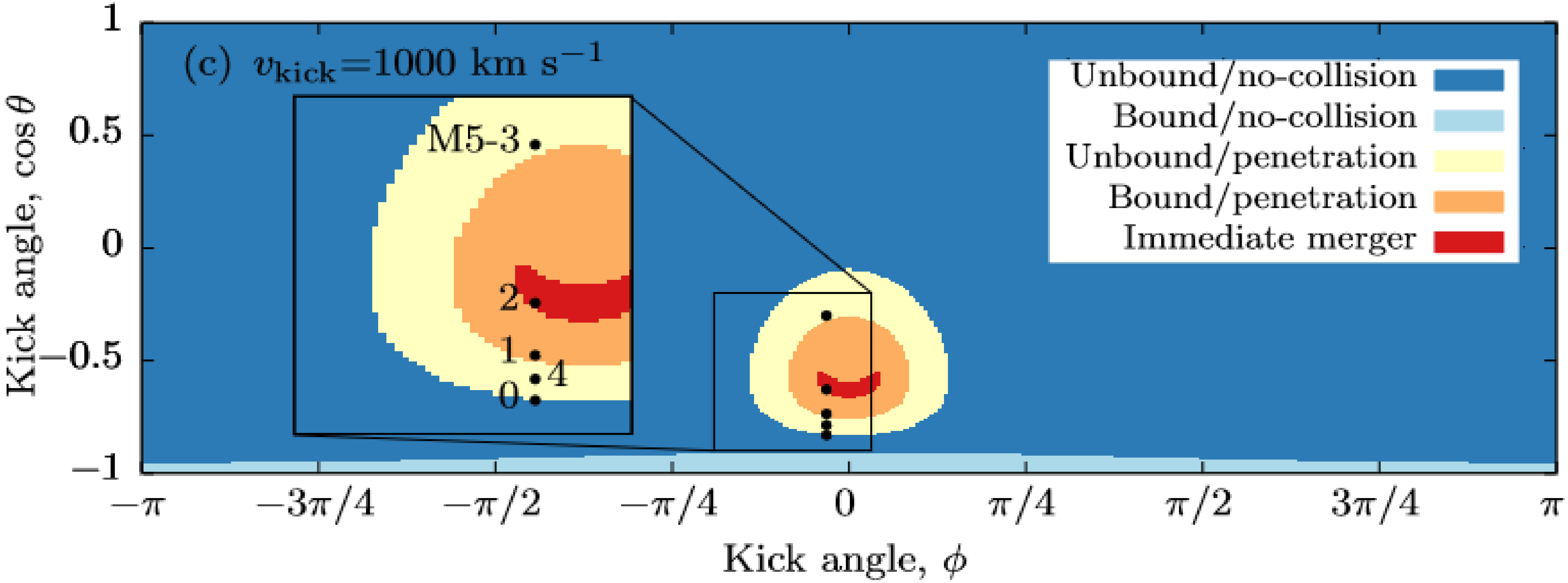


Both the magnitude and direction of the analytical drag agrees with the simulations quite well



Classifying the outcomes

We classify the outcomes into 5 different groups



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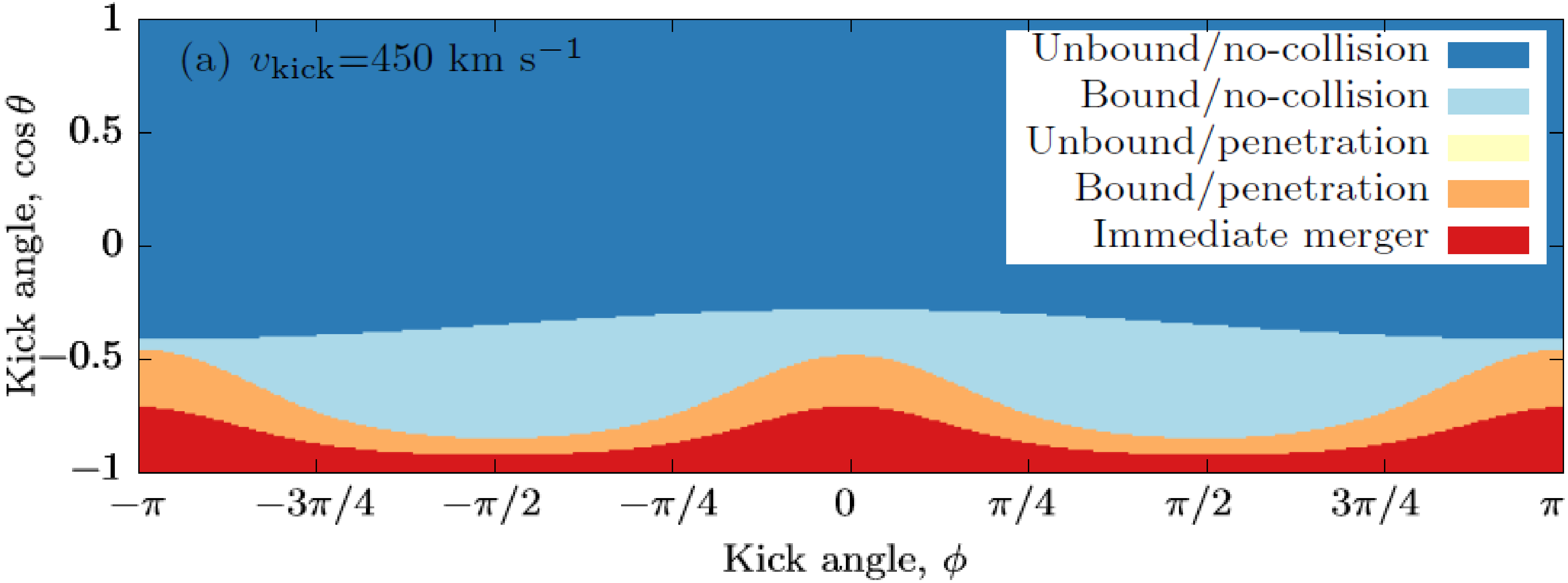

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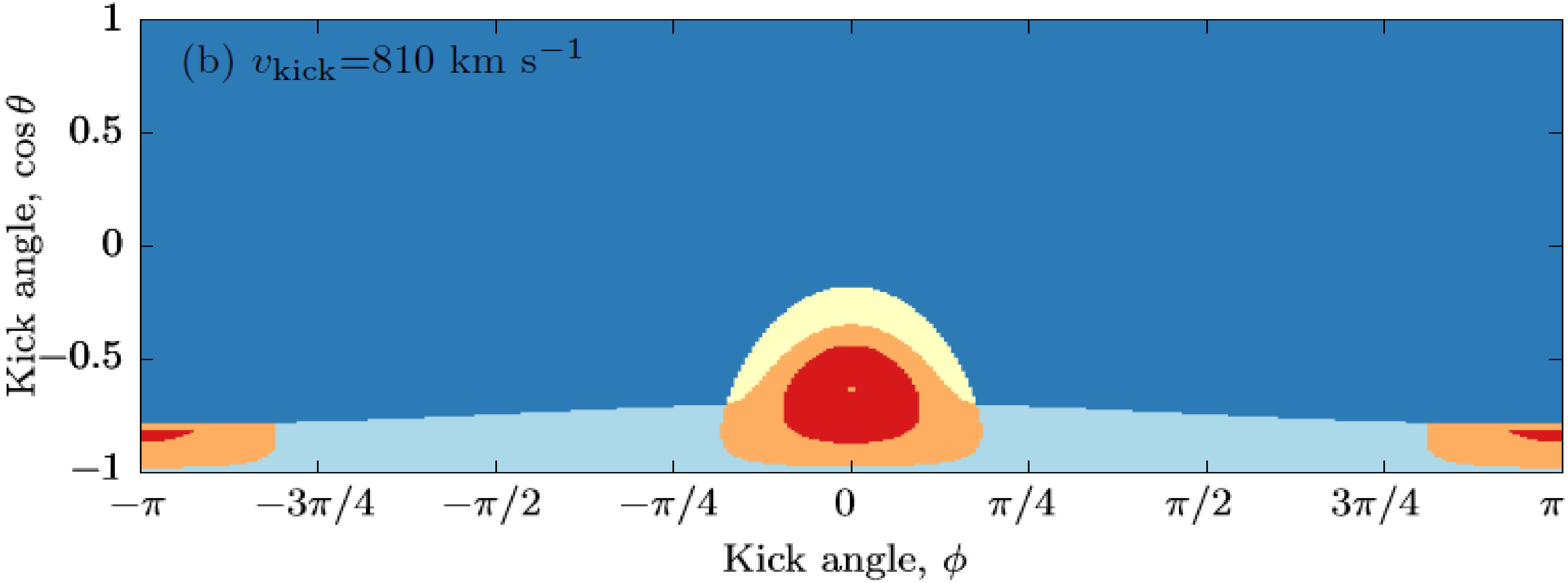

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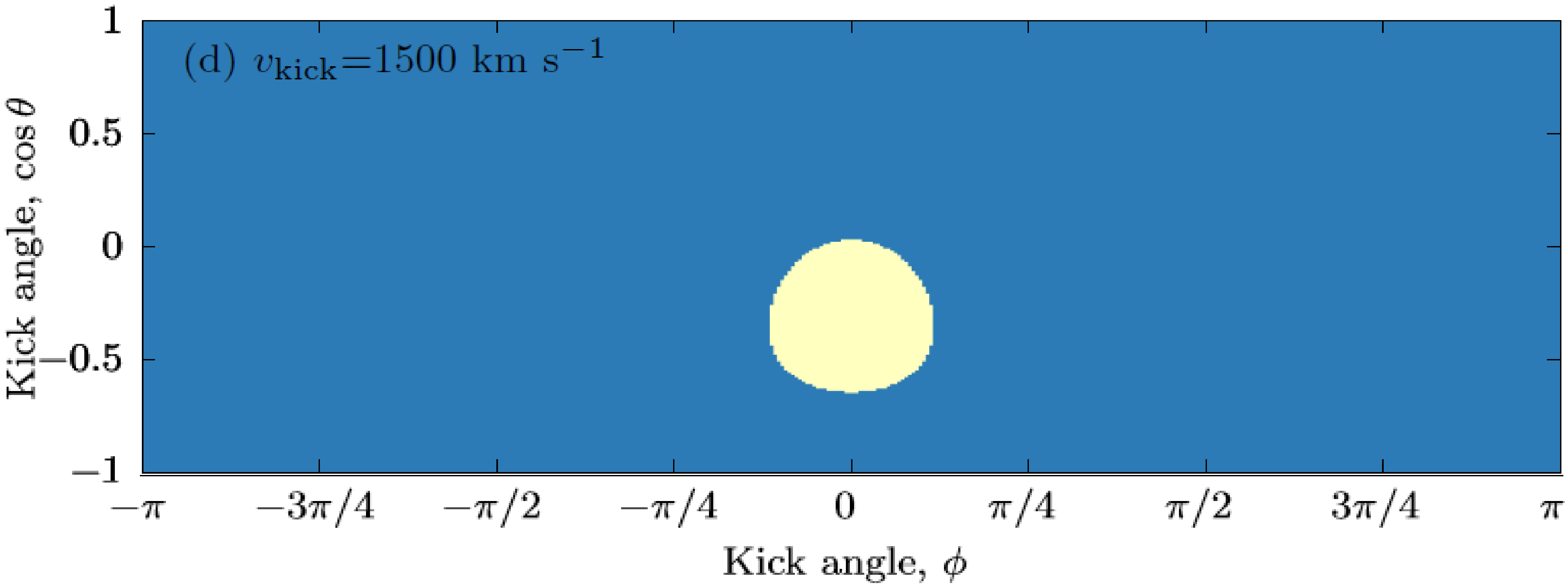
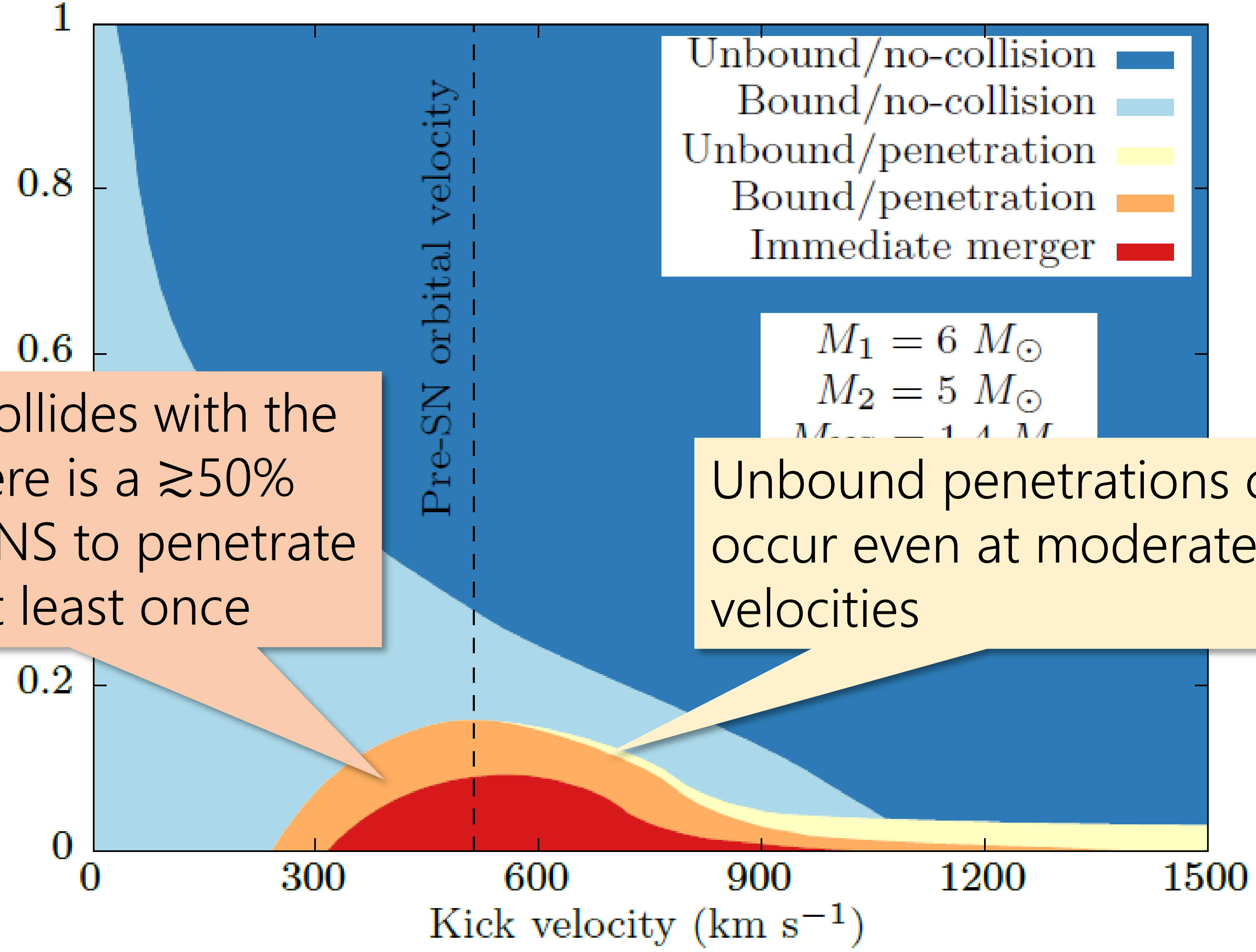


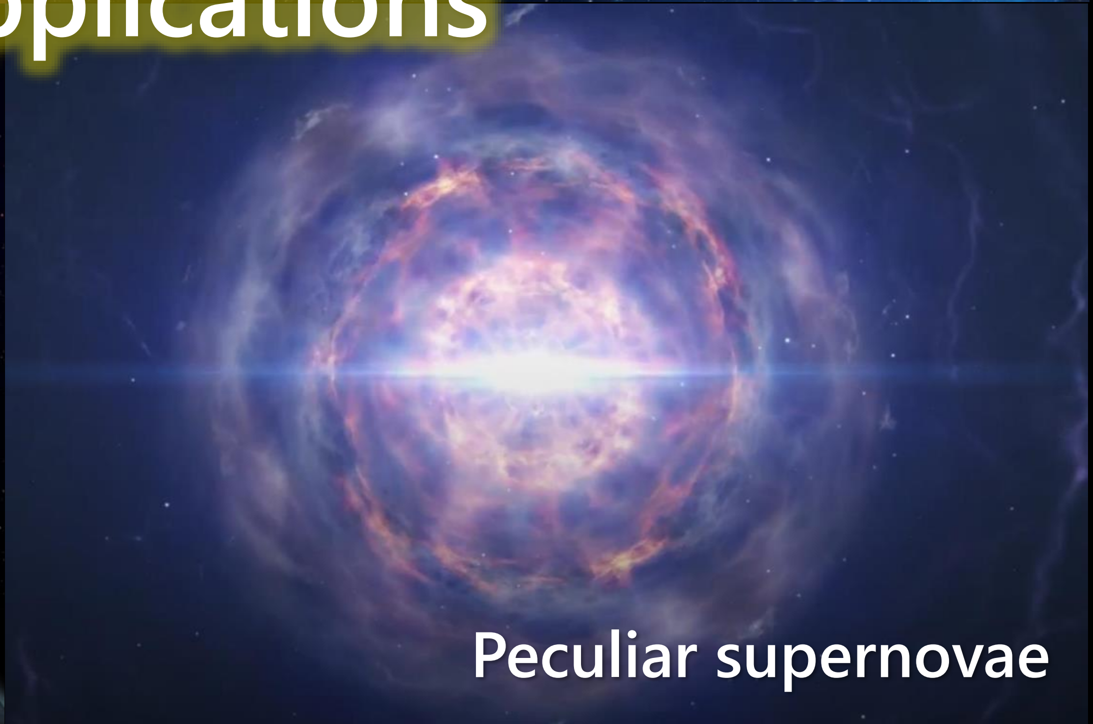
Probabilities of each outcome



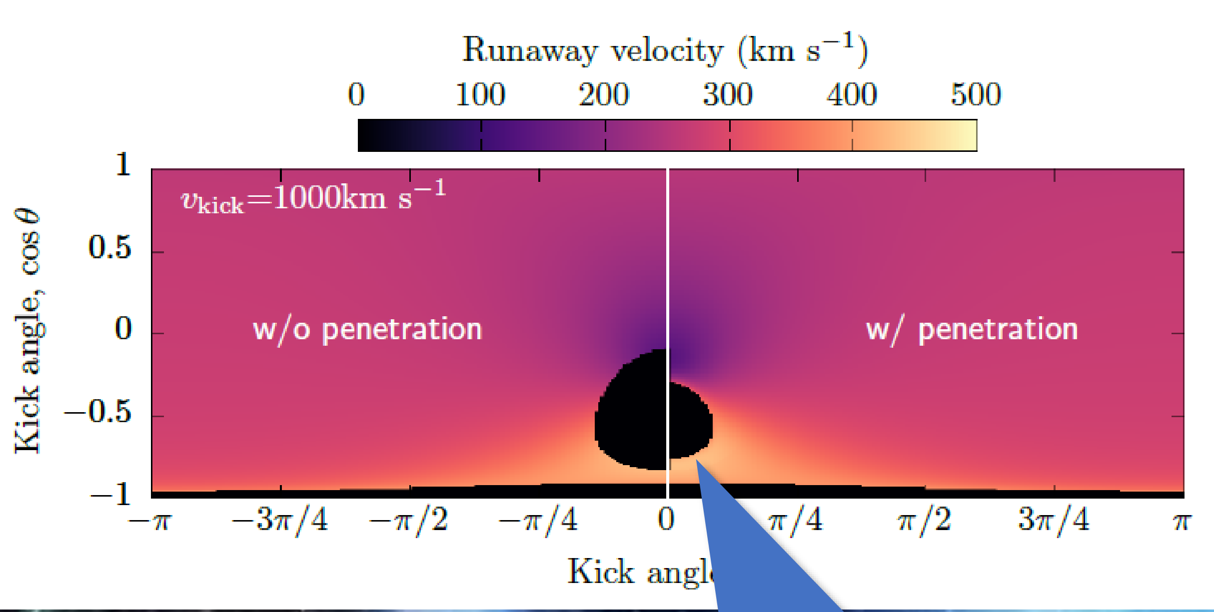
When the NS collides with the companion, there is a ≳50% chance for the NS to penetrate the envelope at least once

Unbound penetrations can occur even at moderate kick velocities

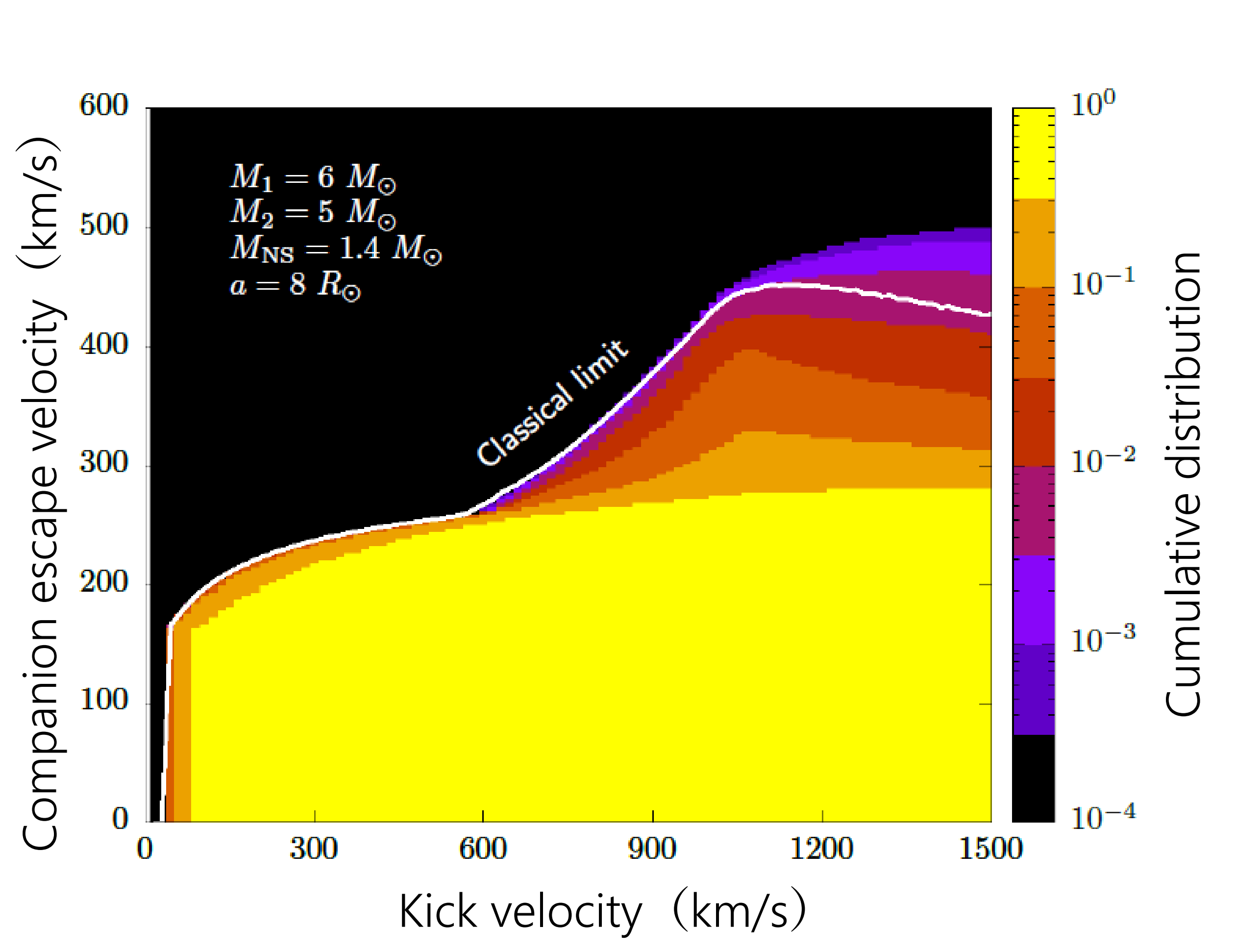
Possible applications



New upper limit for hypervelocity stars



We can exceed the classical limit by ~10% by allowing envelope penetrations



Origin of pulsar planets

The first exoplanets were discovered around pulsars

>10 pulsar planets discovered so far
Some pulsars even have proto-planetary disks

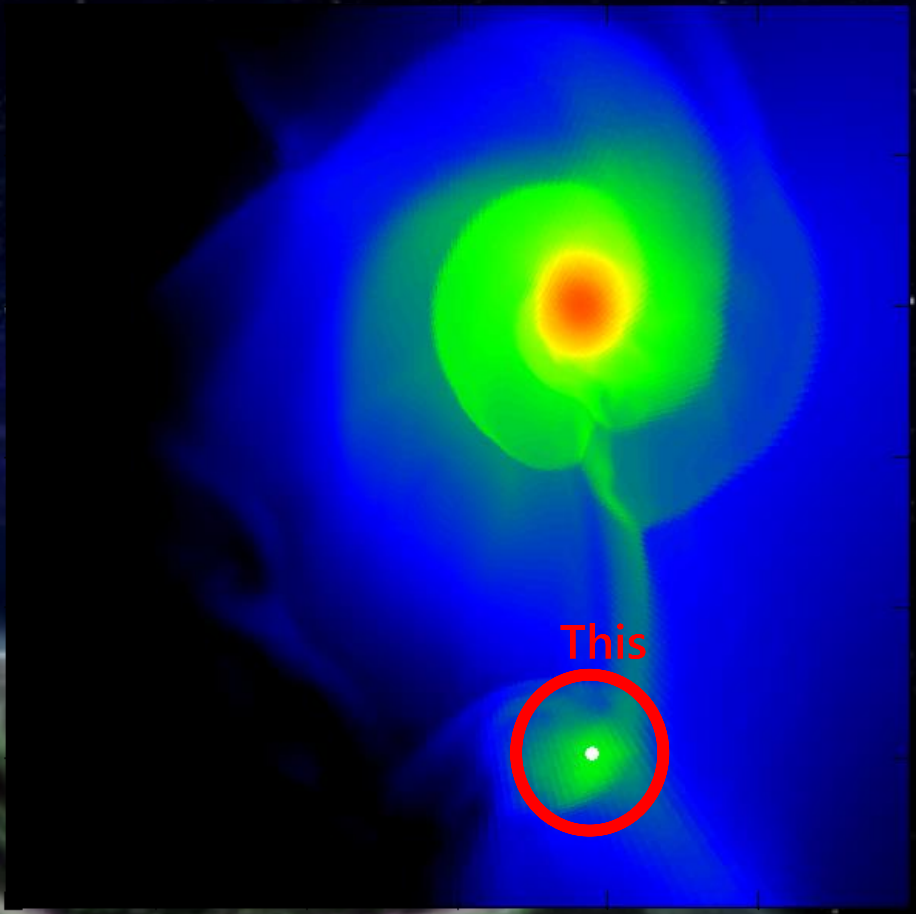
<u>Origin scenarios</u>

1. **Dynamical capture**
   Steal planets from other stars in dense clusters

2. **Evaporated companion**
   Evaporate the companion star via pulsar winds

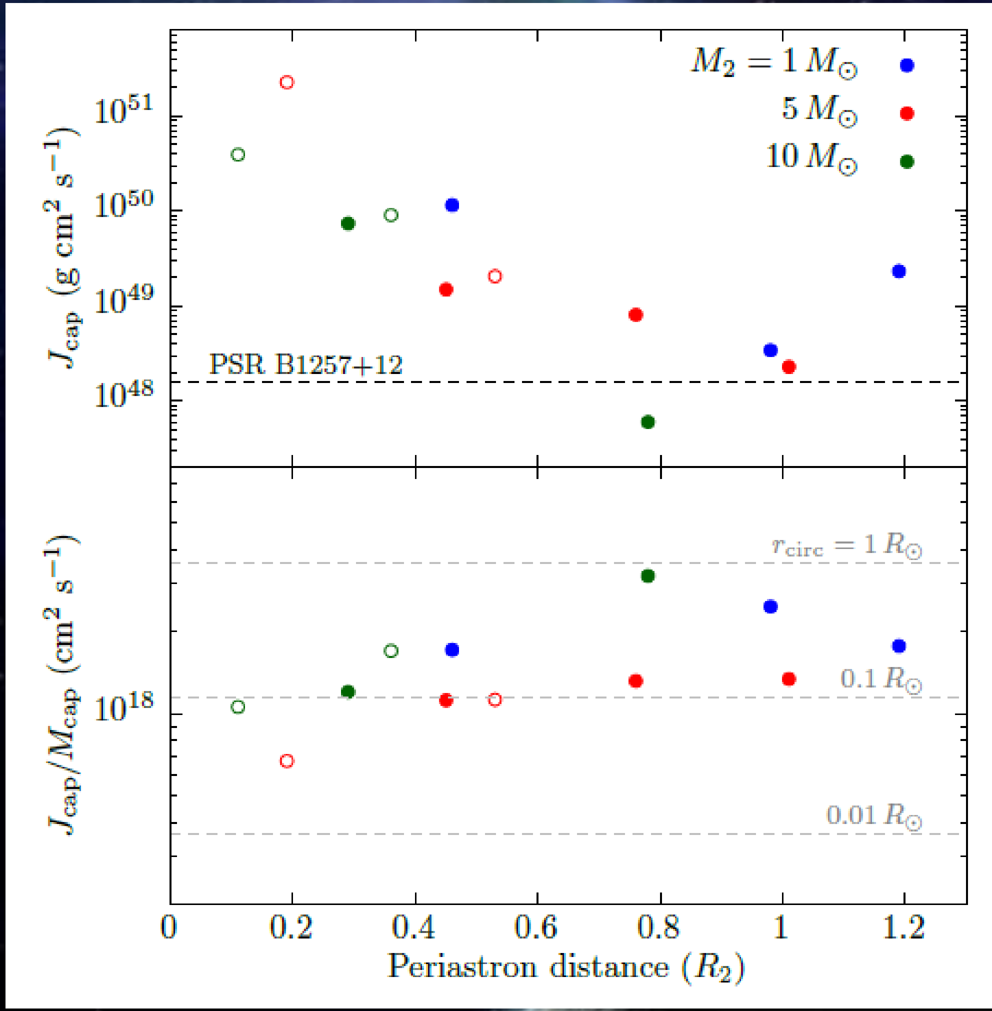
3. **NS-WD merger**
   Tidally disrupt a WD to create proto-planetary disks

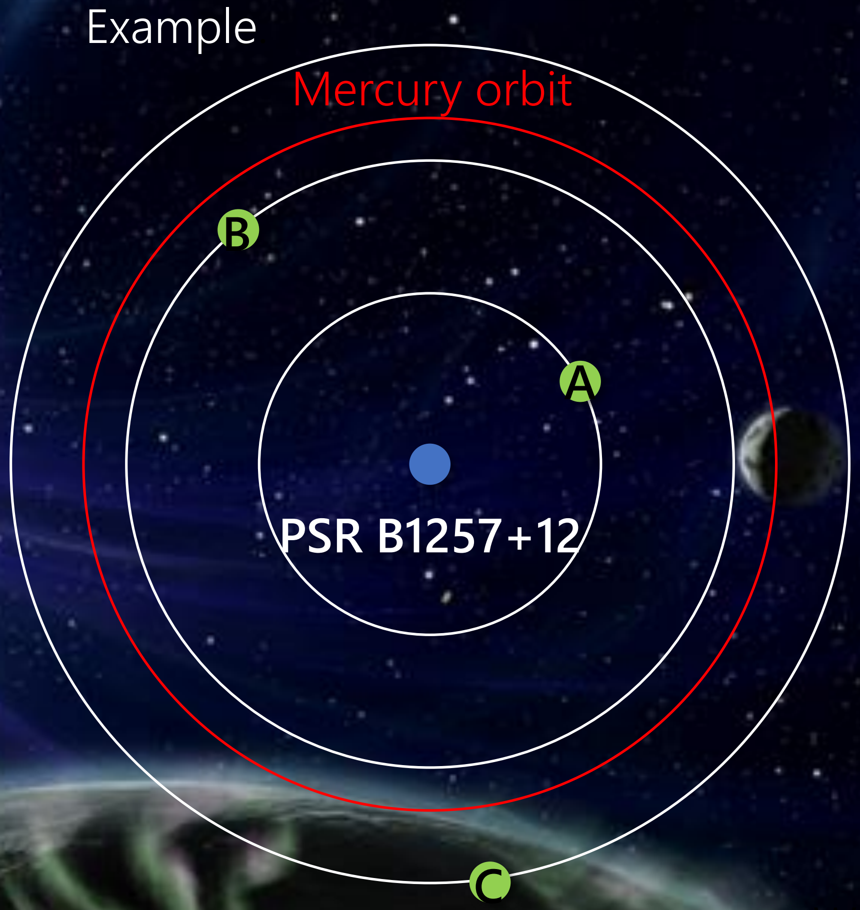
4. **Matter capture from companion**
   Accrete matter from companion to create proto-planetary disk



Captured mass by the neutron star

The NS captured 1-10M_J of mass from the companion in our simulations

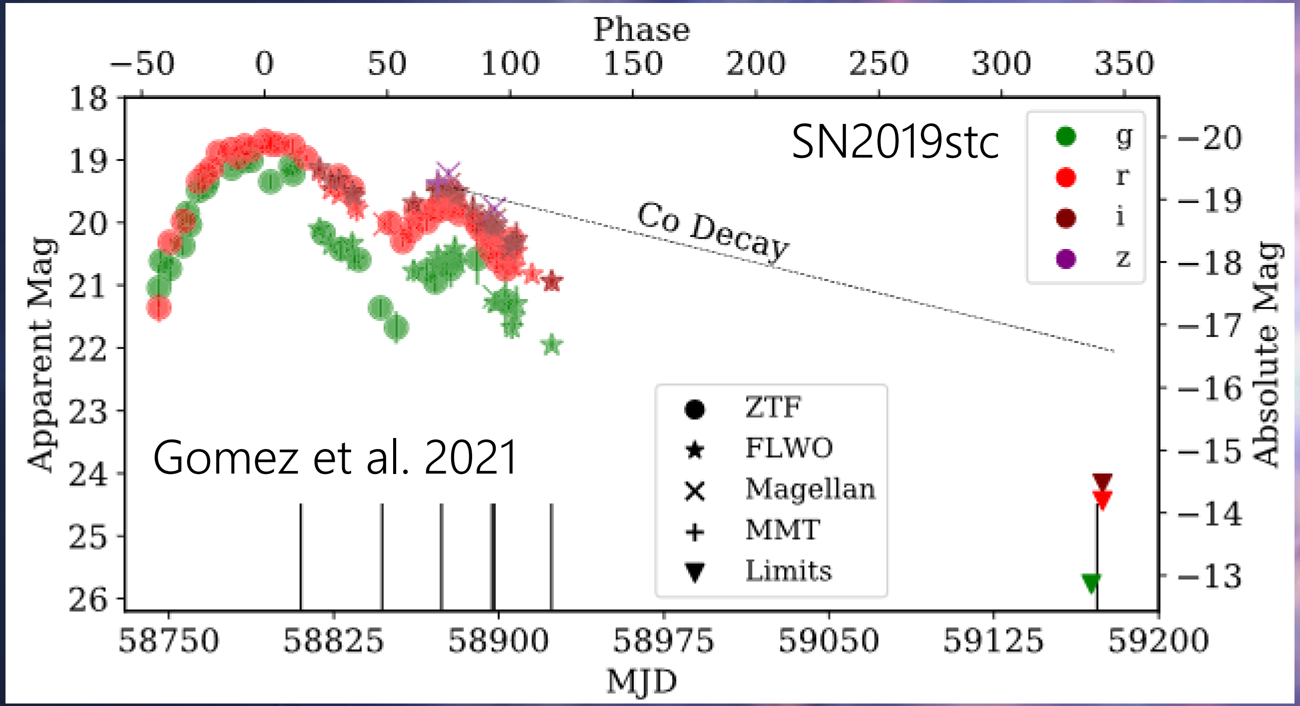


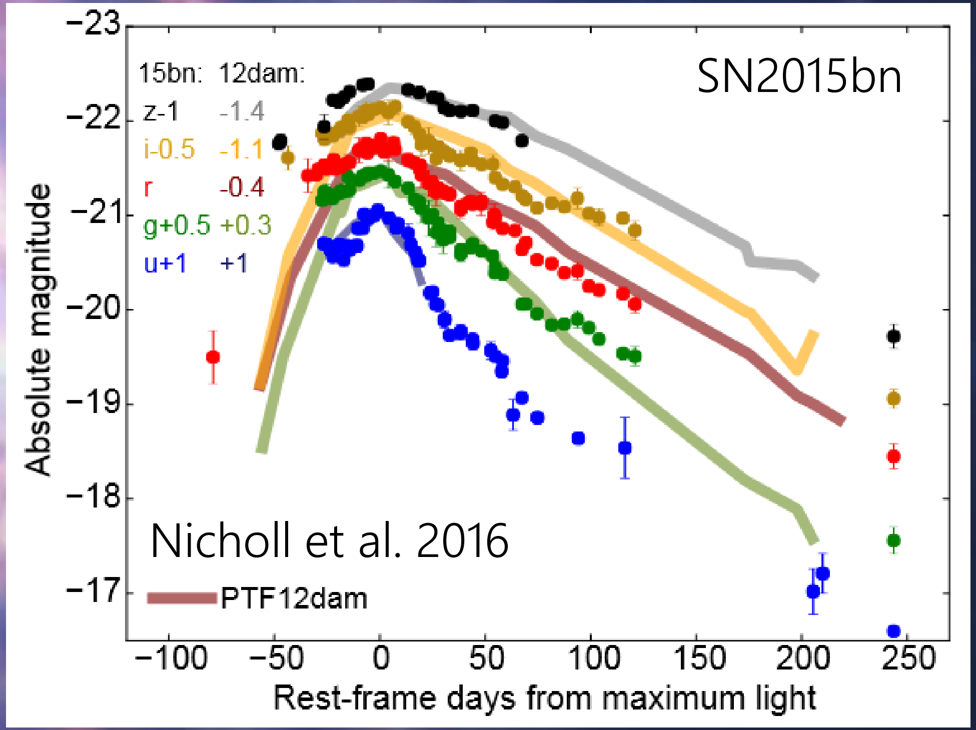


Mass and angular momentum captured by the NS is sufficient for pulsar planet formation

Bumpy superluminous supernovae?

Recently, some stripped-envelope superluminous SNe are showing very bumpy light curves





For our bound+penetration models, the NS can interact with the companion multiple times
Each time, the NS can take away some matter and accrete it to power the light curve from inside

Summary

- Stripped-envelope supernovae can have non-zero chances for the NS being kicked into the companion
- When the kick is strong enough, the NS can sometimes penetrate through the companion's envelope, taking away some matter at the same time
- Envelope penetration could explain the origin of the following phenomena
  - Thorne-Żytkow objects
  - Hypervelocity stars
  - Pulsar planets
  - Peculiar supernovae (bumpy SESN)

Phantom is definitely more suitable for this
Anyone want to follow up?