Natal Kicks on Compact Objects: Insights from Gaia's Precision Astrometry

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Natal kick

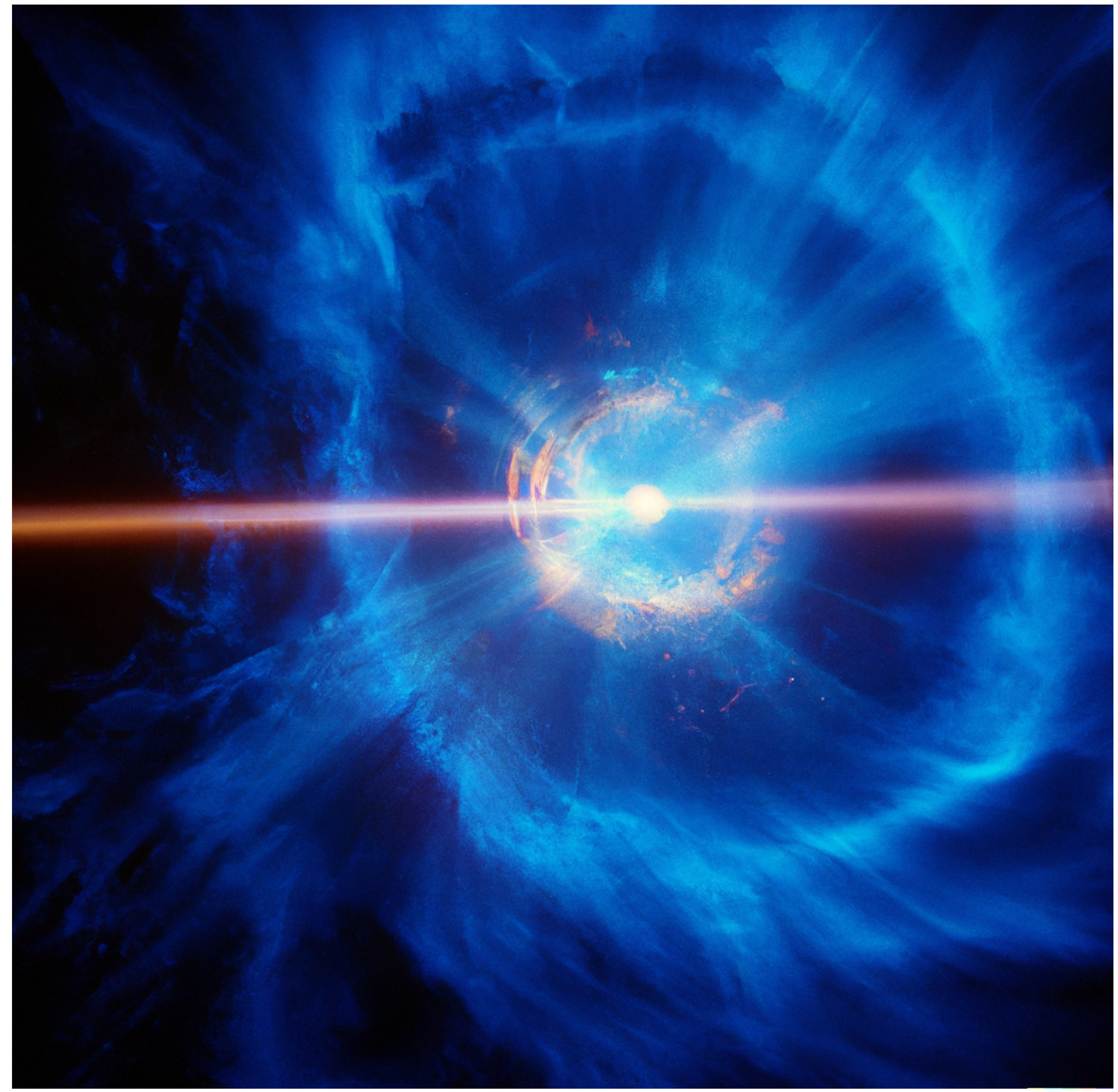
Natal kick (NK):

An impulsive acceleration imparted on a black hole (BH) or a neutron star (NS) due to a supernova.

History

"Runaway" stars (Blaauw 61)

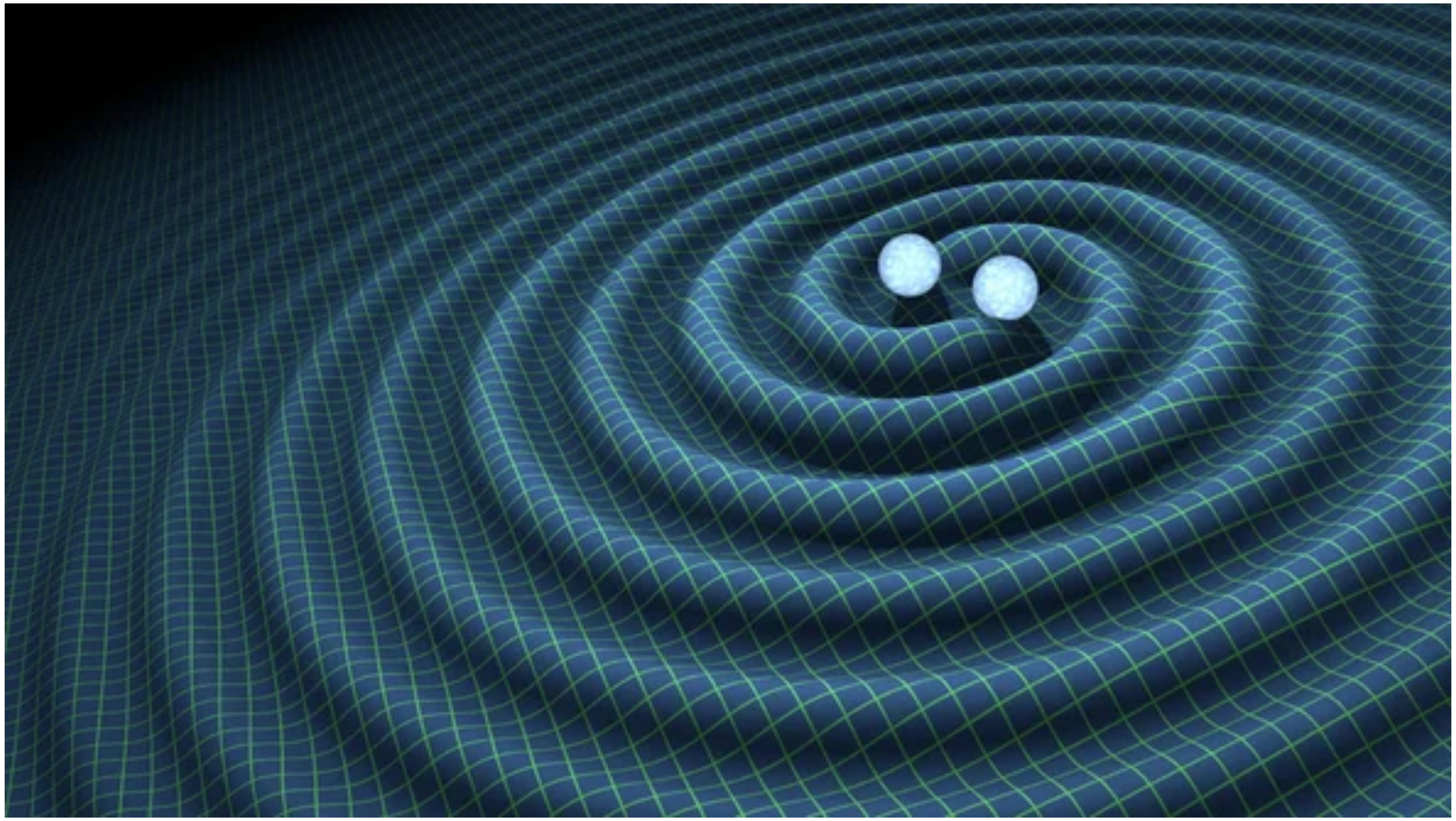
Pulsars' high space velocities: Gunn & Ostriker 70, Lyne & Lorimer 94, Hobbs+05, Verbunt+17



DALLE 2's impression of a hyper-velocity pulsar

Why study NK?

- NK connects to supernova physics (e.g., Lai+04).
- Formation and evolution of compact object binaries (e.g., Kalogera+98).
- Predicting GW source numbers (e.g., Dominik+12, Belczynski+16).



Credit: Caltech

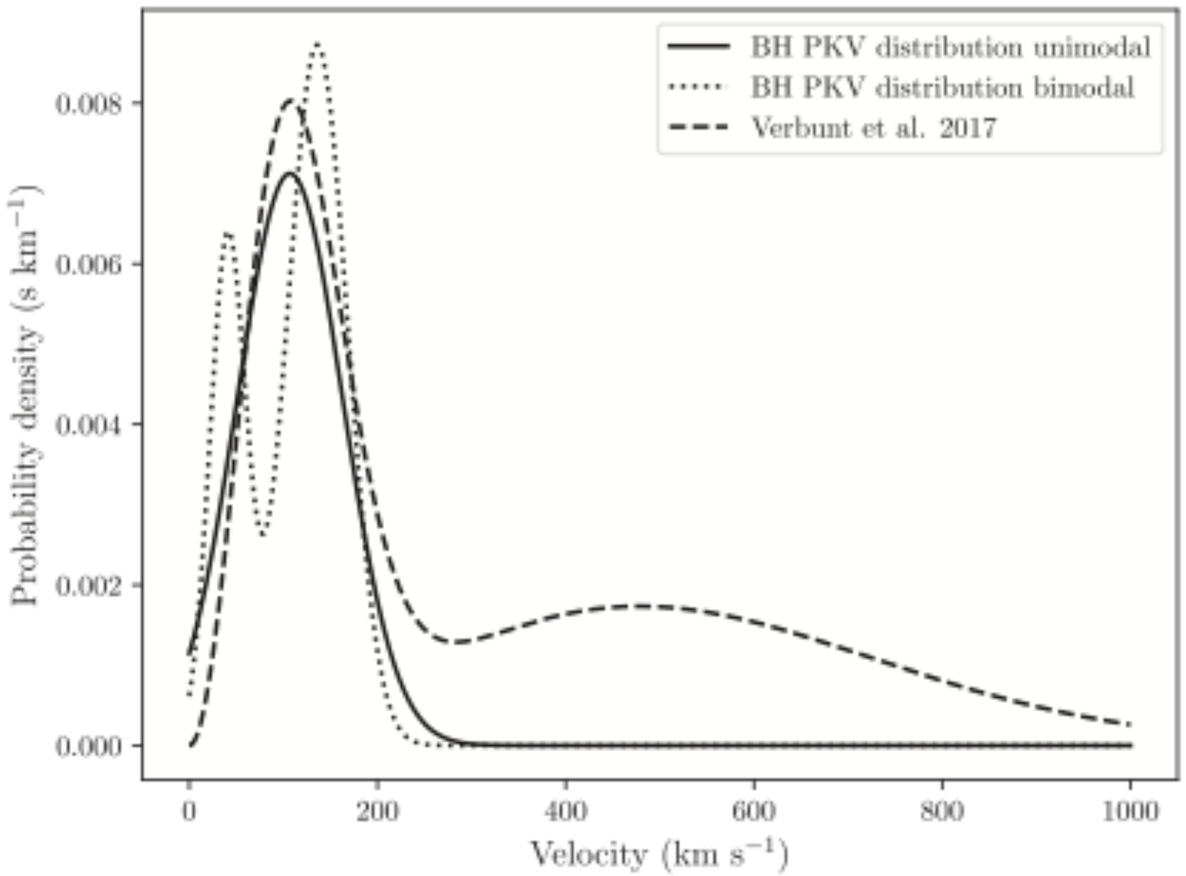
Observational constraints

High velocities (~300 km/s) of pulsars (e.g., Lyne & Lorimer 94, Hobbs+05, Verbunt+17).

Space velocities of binaries hosting BHs or NSs (e.g., Gandhi+19, Atri+19, Fortin+22, O'Doherty+23).

Micro-lensing events for isolated BHs (Sahu+22, Lam+22, Andrews & Kalogera+22).

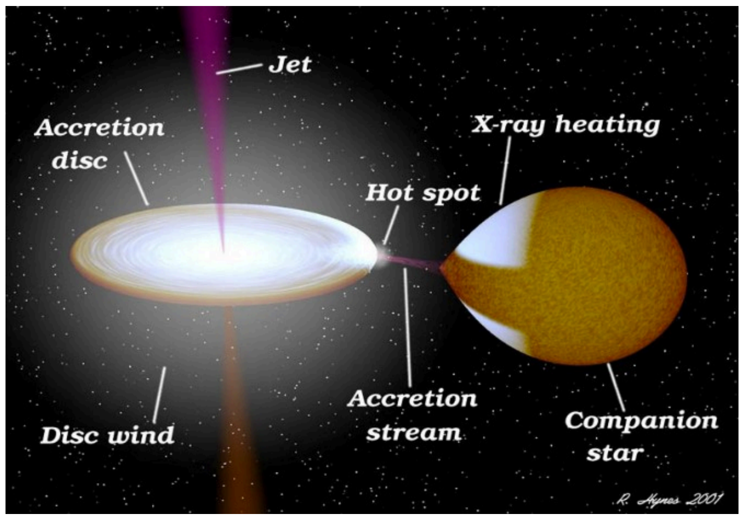
Retention rate of NSs in globular clusters (e.g., Pfahl+02a).



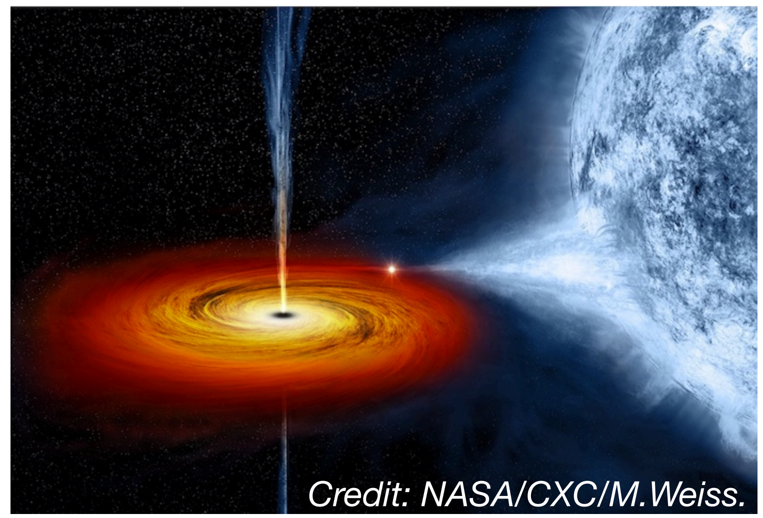
Atri+19. 3D velocity distribution of BH X-ray binaries

The sample: 89 binaries

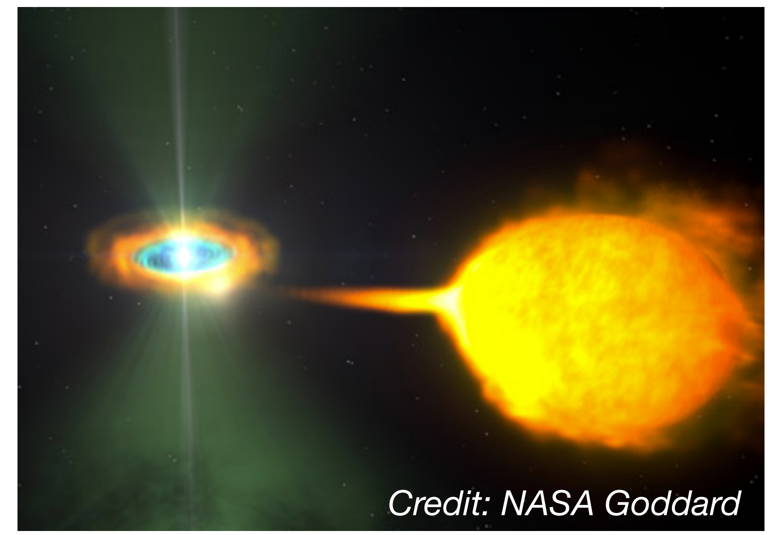
NS, BH low-mass X-ray binaries (NS, BH-LMXBs)



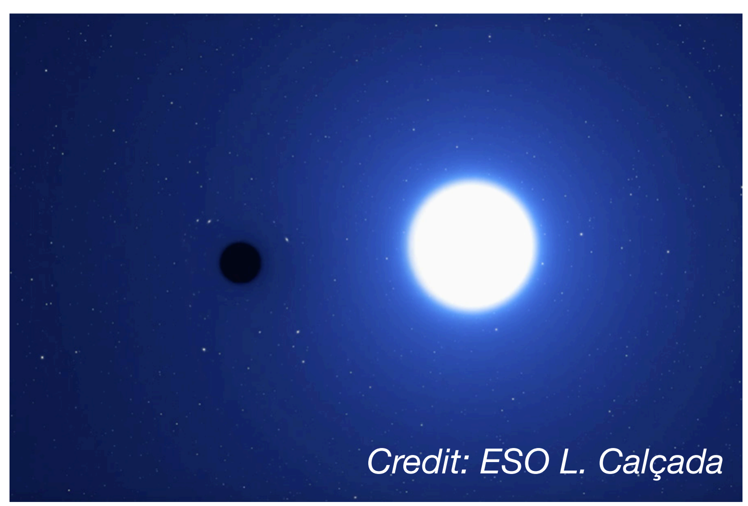
NS, BH high-mass X-ray binaries (NS, BH-HMXBs)



Pulsars in binaries (PSRs)



NS, BH in non-interacting binaries (NIs)



The sample

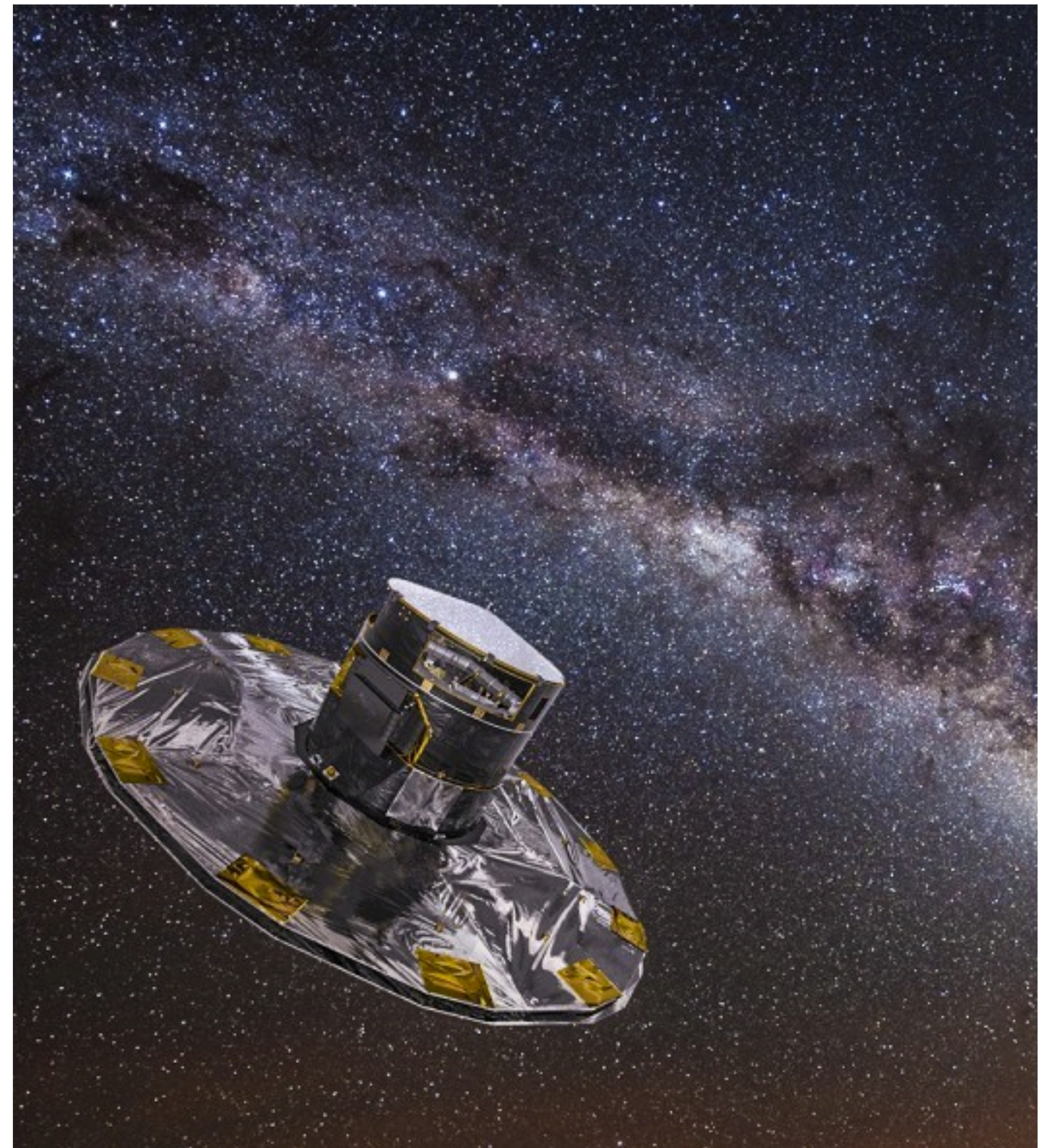
Gaia (E)DR3:

Check for five-parameter astrometry:

- Position (α, δ)
- Parallax (ϖ)
- Proper motion ($\mu_\alpha \cos\delta$, μ_δ)

Radial velocity (γ):

Systemic velocity of the binary in the radial direction.



Credit: ESA

Potential peculiar velocity at birth

Potential peculiar velocity at birth ($v_{\mathrm{pec}}^{z=0}$)

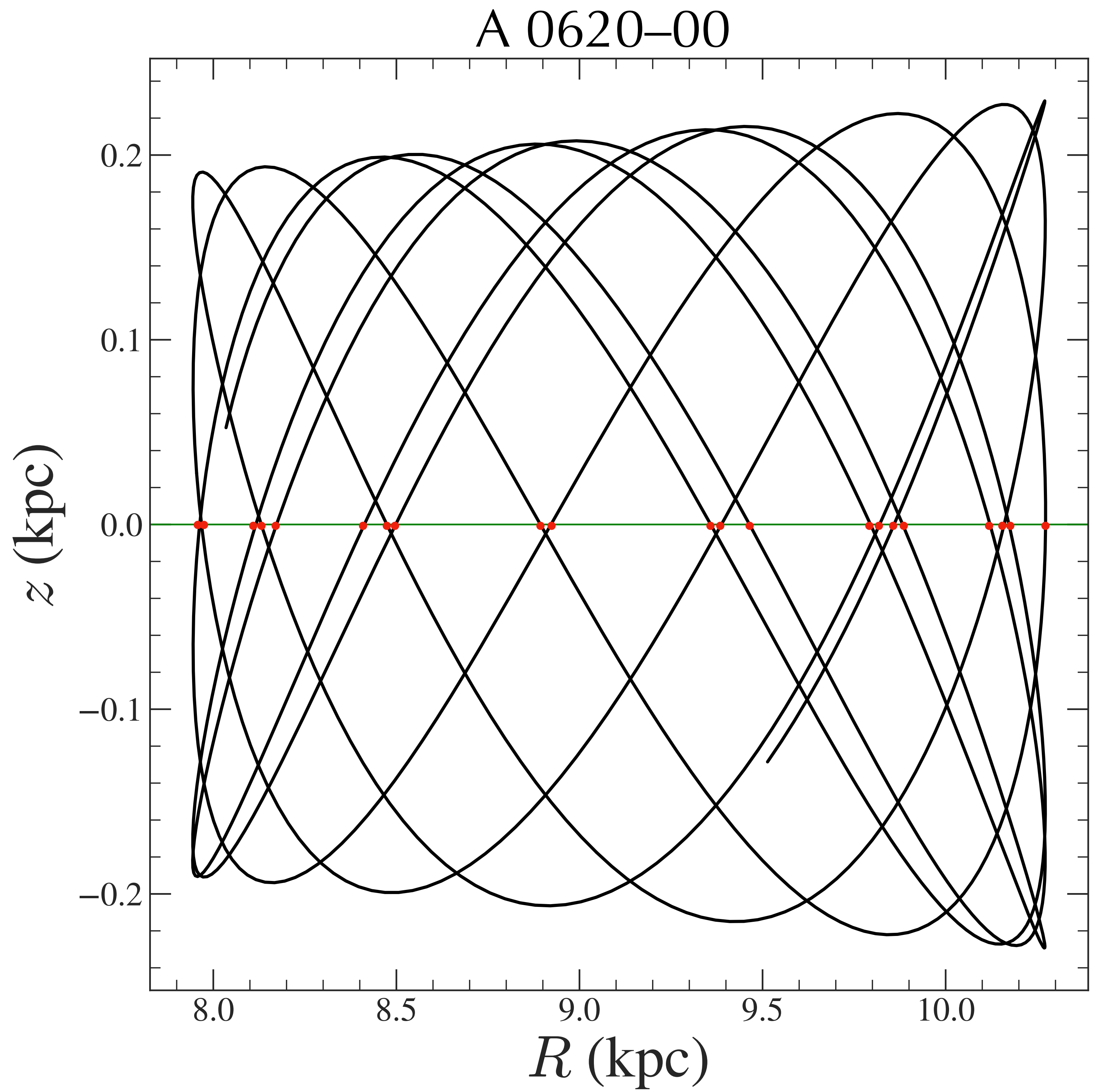
Integrate orbits backward in time.

↓

Collect peculiar velocity at every plane crossing.

↓

Monte Carlo samples of $v_{\mathrm{pec}}^{z=0}$.



Overall distribution

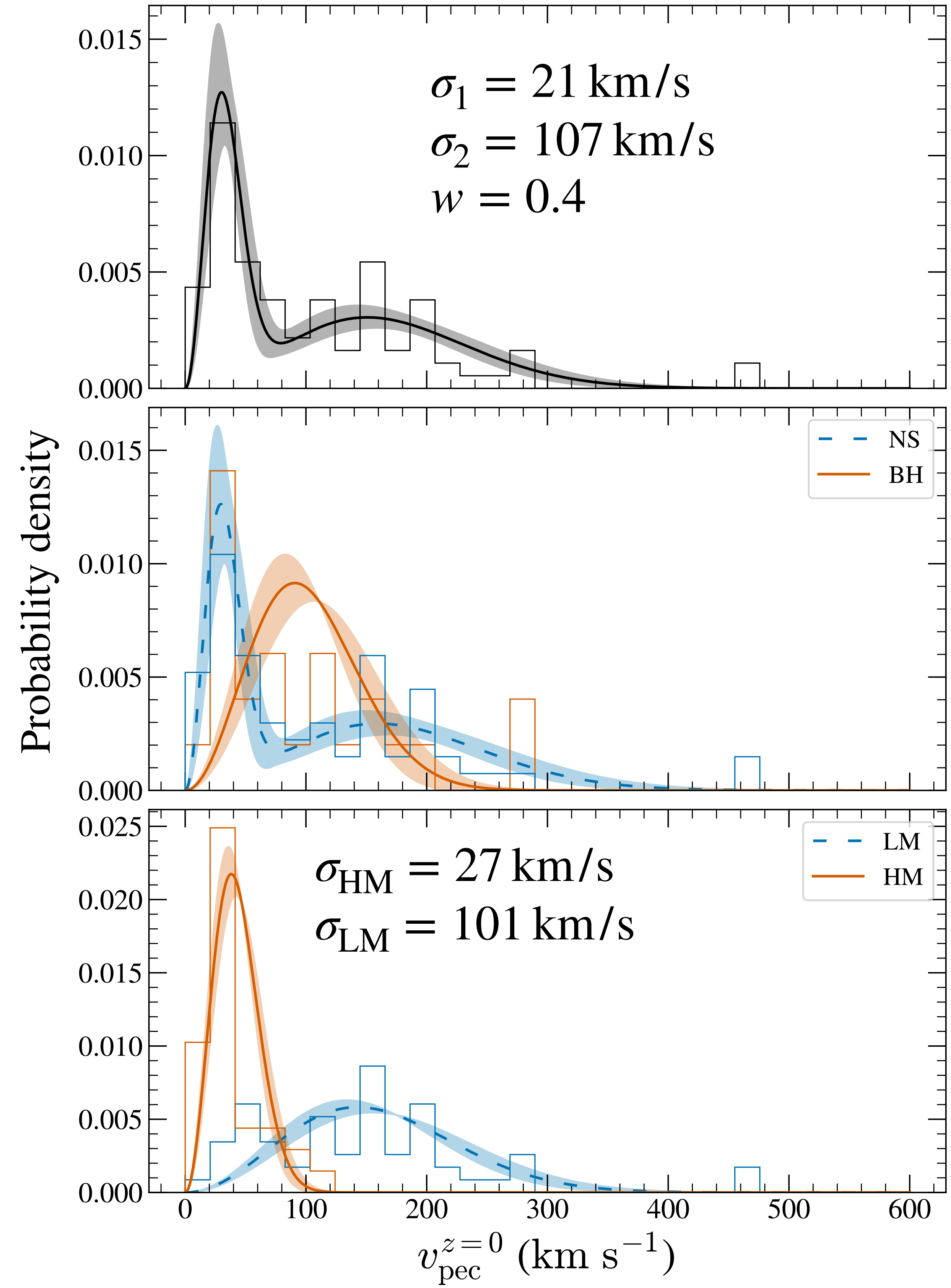
Maxwellian models

Single-component

$$f(v\,|\,\sigma_v) = \sqrt{\frac{2}{\pi}}\frac{v^2}{\sigma_v^3}\exp\left(-\frac{v^2}{2\sigma_v^2}\right)$$

Two-component

$$f(v\,|\,\sigma_{v,1},\sigma_{v,2},w) = wf(v\,|\,\sigma_{v,1}) + (1-w)f(v\,|\,\sigma_{v,2})$$



Distribution comparison

K-S test results ($\alpha = 0.01$):

BHs vs. NSs:

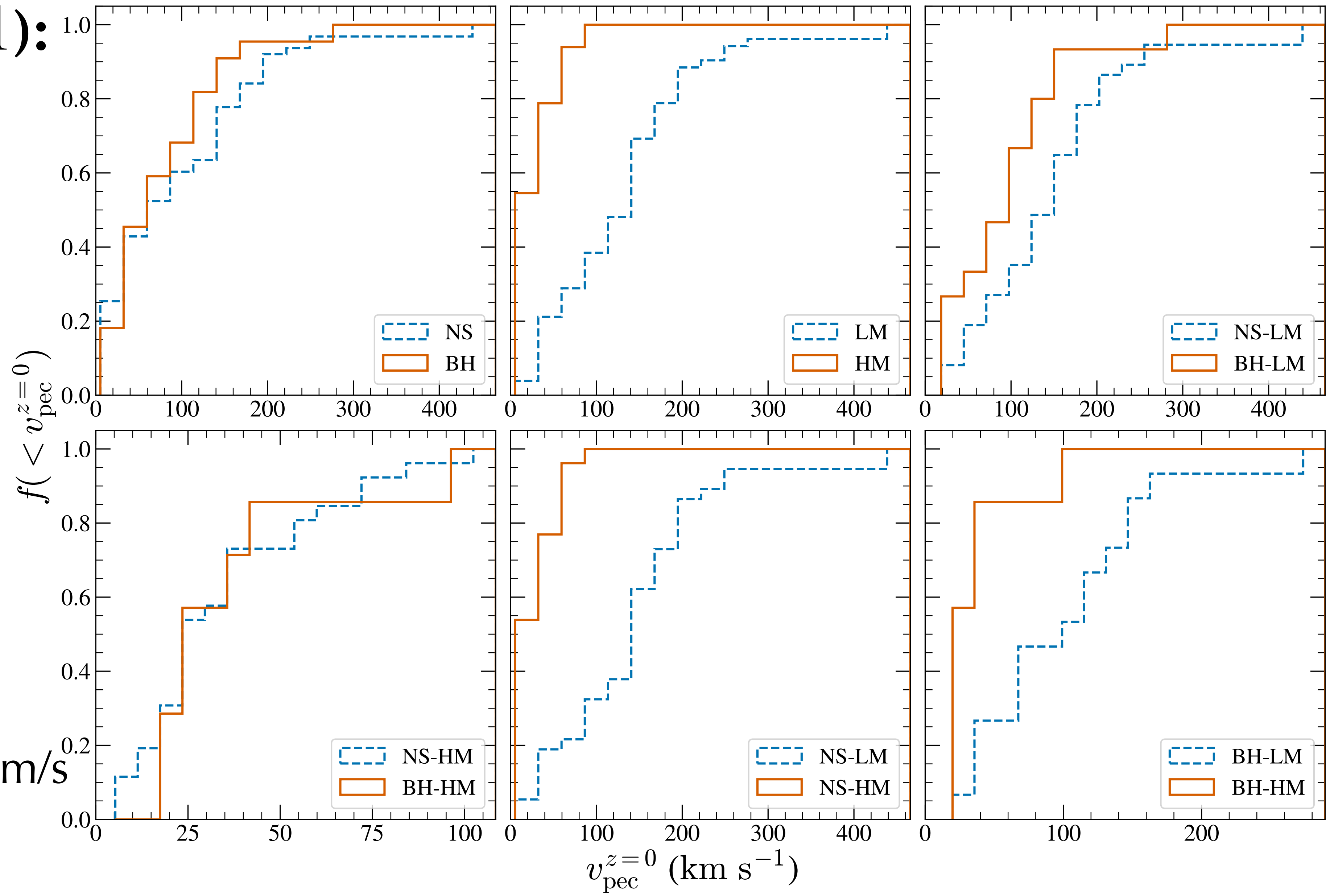
No clear difference

LMs vs. HMs:

Significant difference: all simulations reject the null hypothesis (H_0).

LMs: broader; up to ~400 km/s

HMs: <= 100 km/s



More massive binaries have lower velocities!

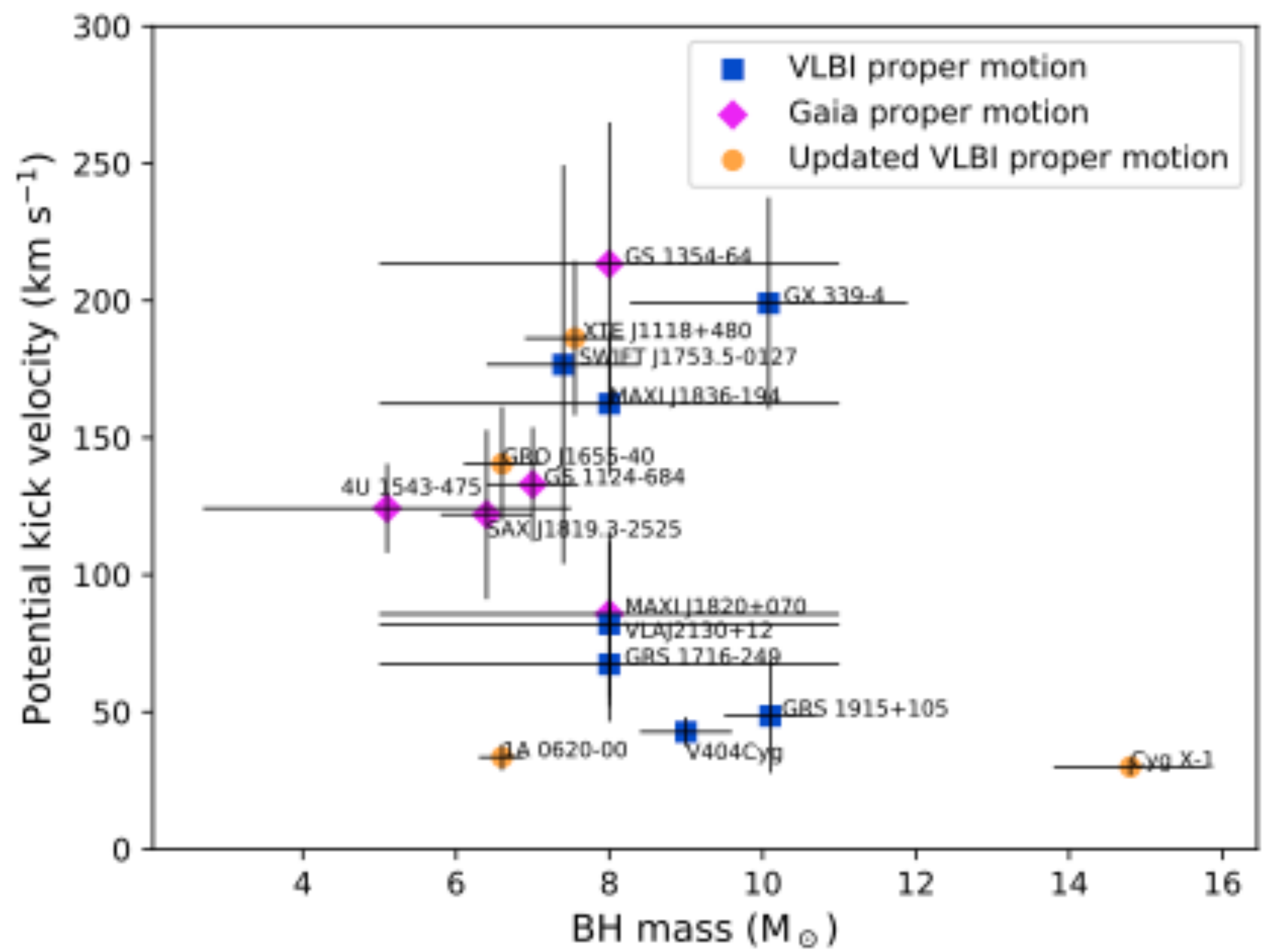
The mass-velocity correlation

Previous studies: Mirabel+16 Gandhi+19, Atri+19, Fortin+22, O'Doherty+23.

How representative are binary systemic velocities of kick strengths?

Only on a subclass of compact object binaries: e.g., BH-XRBs (Gandhi+19), NS-HMXBs (Fortin+22), NS-LMXB and PSR (O'Dherty+23).

Which mass to use?



Atri+19. Potential birth peculiar velocity vs. BH mass.

Kinematic discussion

Kalogera+96: theoretical limits on $v_{\rm pec}^{z=0}$

$$v_{\rm pec,min}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} - \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}},$$

where ΔM is the ejecta mass, and V_r is the relative orbital velocity at SN:

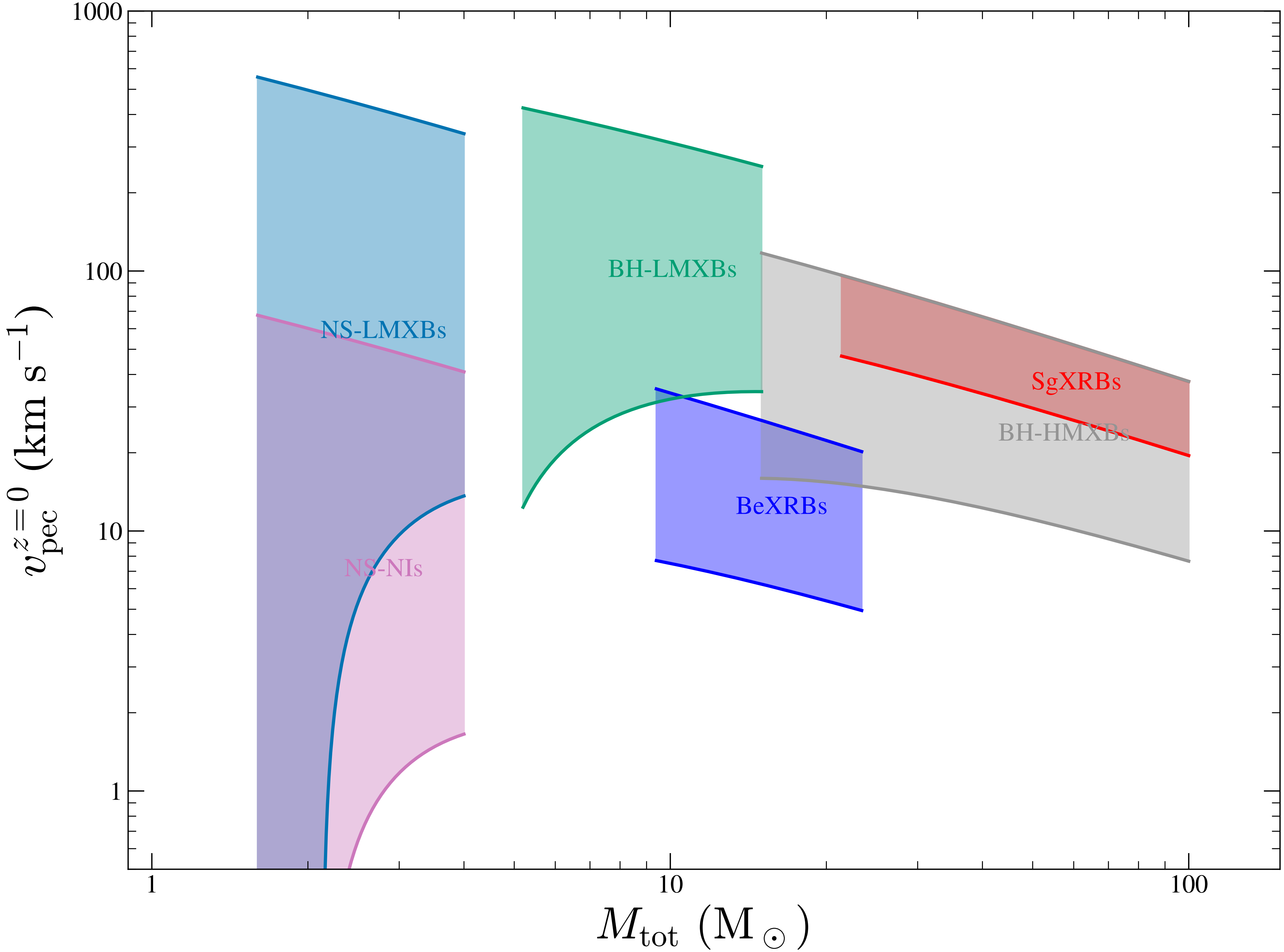
$$V_r = 212.9 \left(\frac{M_{\rm tot} + \Delta M}{M_\odot}\right)^{1/3} \left(\frac{P_{\rm orb,SN}}{\rm day}\right)^{-1/3} \ {\rm km\ s^{-1}}$$

M_1: compact object mass

M_2: mass donor/luminous component mass.

$$M_{\rm tot} = M_1 + M_2$$

Regions of different binary classes

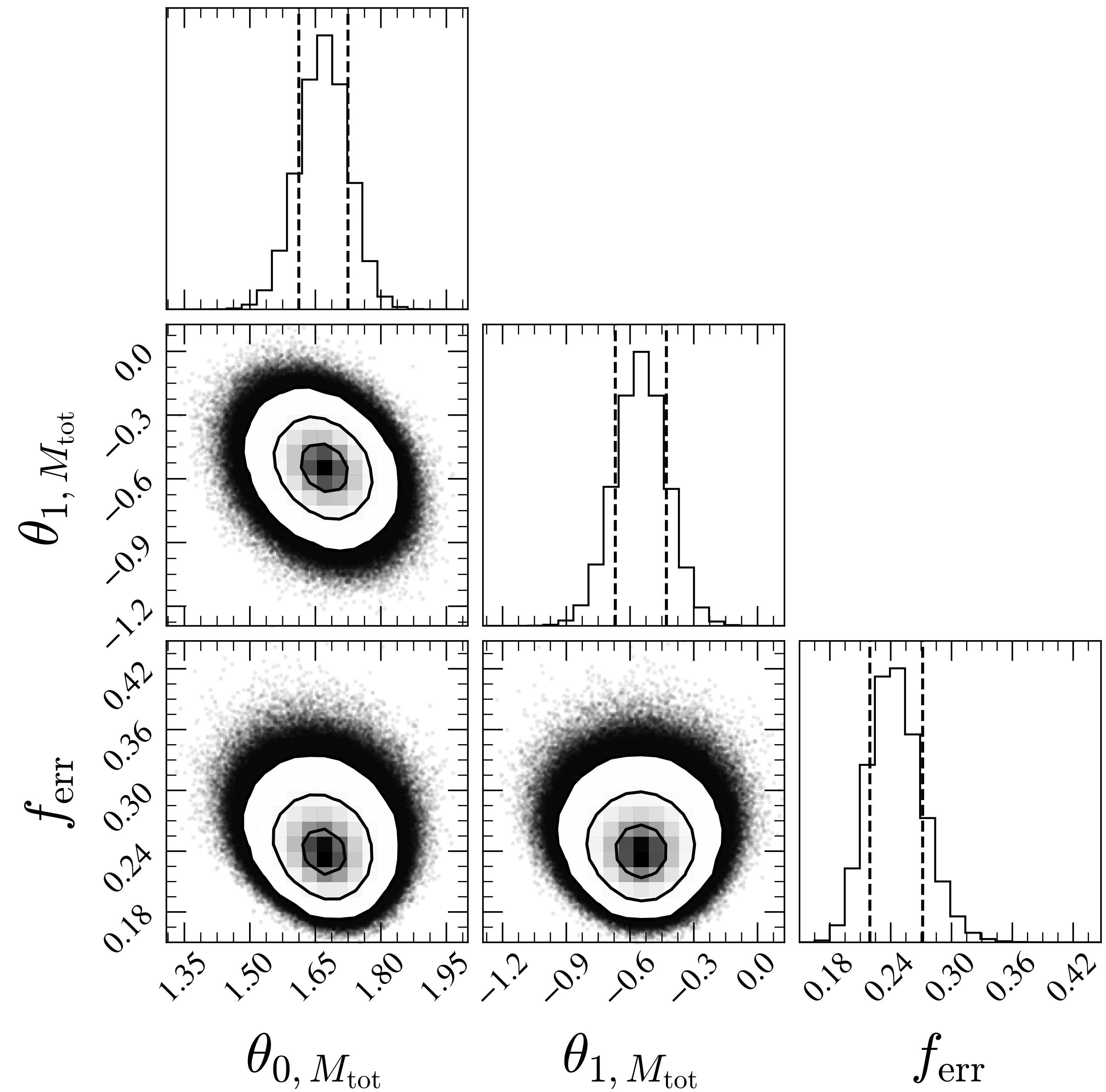


The mass-velocity correlation

$$v_{\rm pec}^{z=0} = \theta_0 + \theta_1(\log M_{\rm tot} - \overline{\log M_{\rm tot}})$$

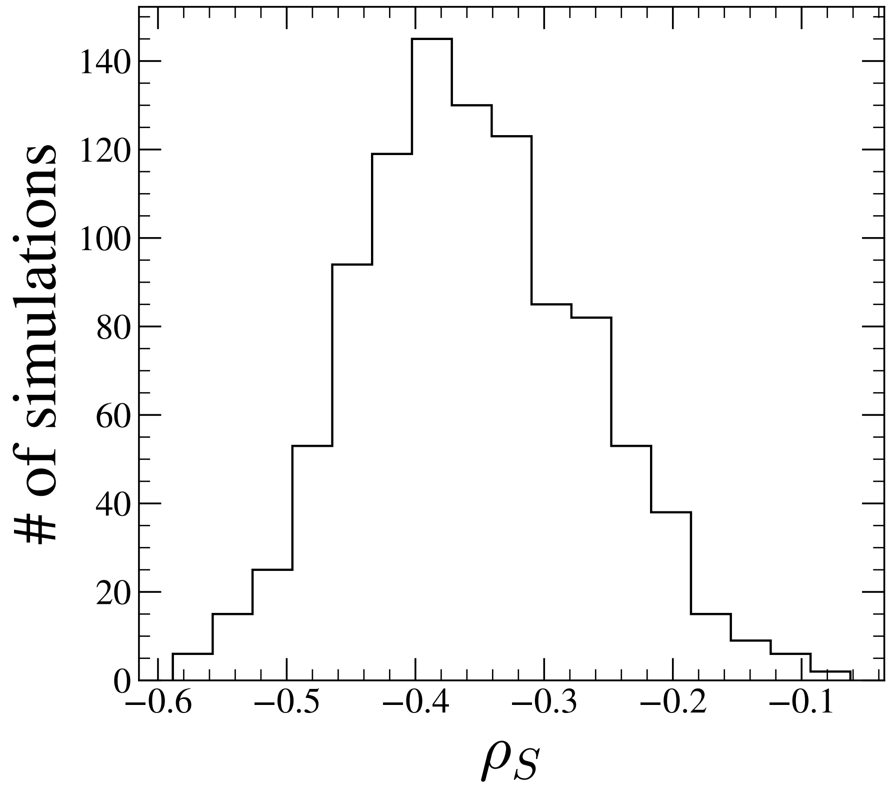
$f_{\rm err}$: The uncertainty on $v_{\rm pec}^{z=0}$ is underestimated by this fraction.

99.7% credible interval for the slope (θ_1): -0.84, -0.16

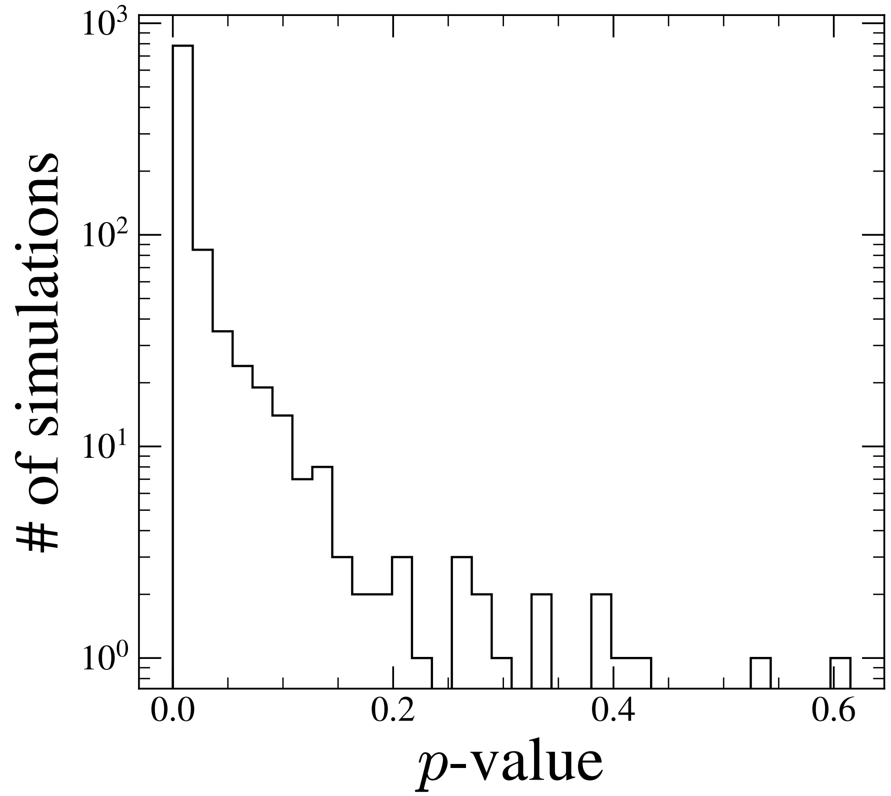


The mass-velocity correlation

Spearman's rank correlation coefficient (ρ_S)



At least 84% of the simulations suggests an anti-correlation (i.e., reject H_0 ($\rho_S = 0$)) at 1% significance.



The anti-correlation is significant even with $f_{\rm err}$.

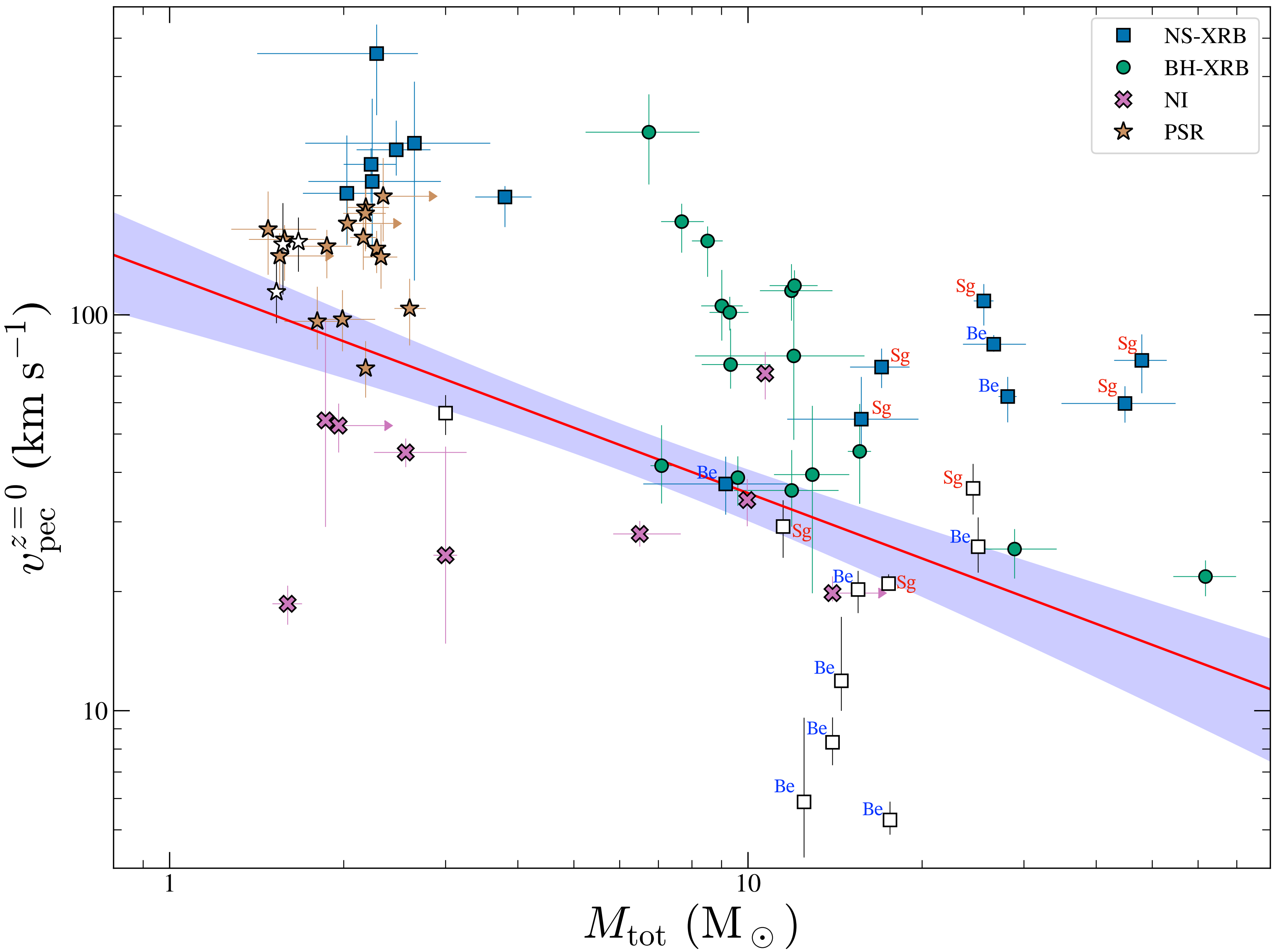
The mass-velocity correlation

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

BeXRBs vs. SgXRBs

BeXRBs are constrained by lower $v_{\rm pec,max}^{z=0}$ than SgXRBs.

- BeXRBs have wider orbits at SNe, and
- BeXRBs ejected fewer mass at SNe (van den Heuvel+00, Pornisara et al. in prep)



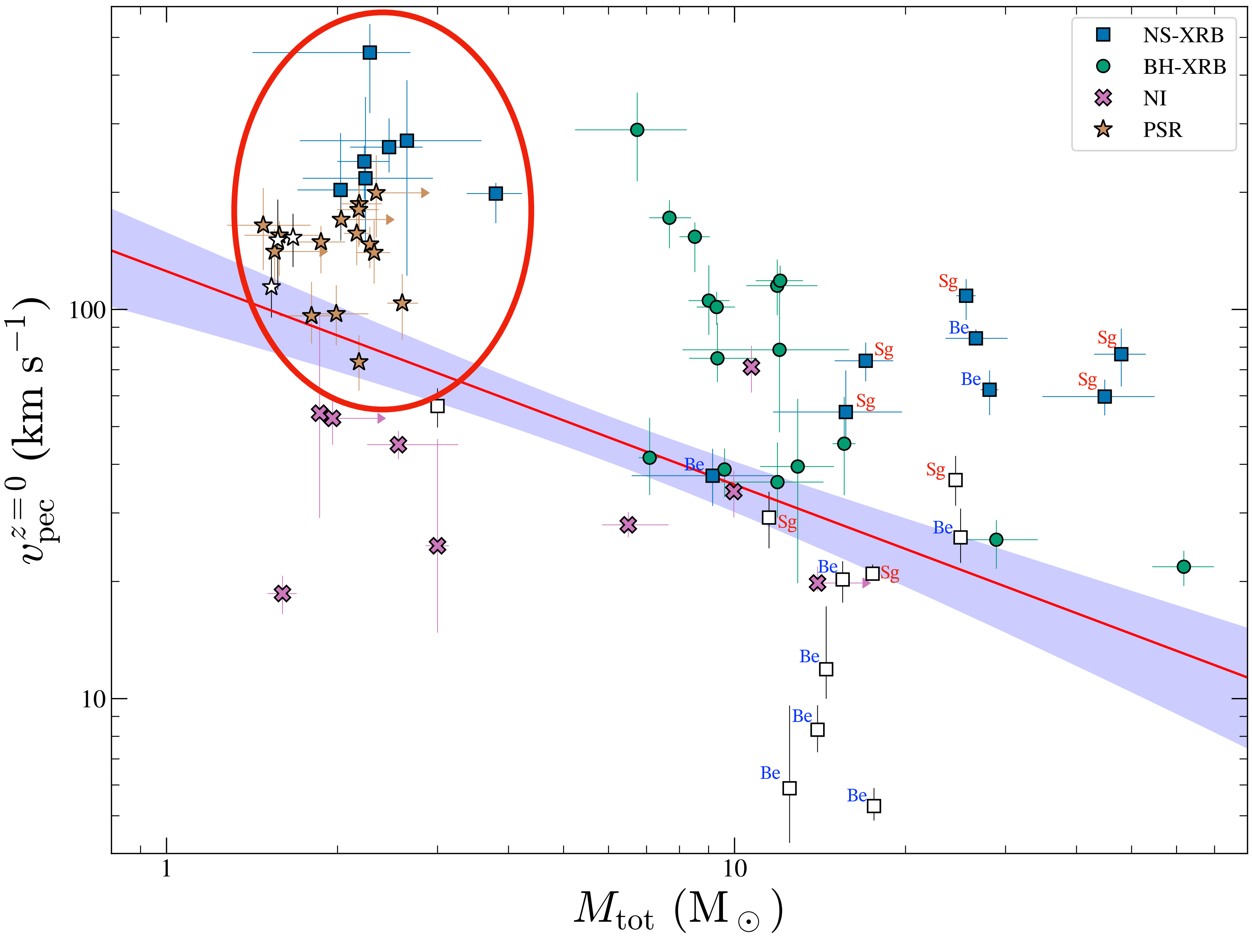
Lack of low-v NS-LMXBs

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

Most NS-LMXBs or PSRs has $v_{\rm pec}^{z=0} \gtrsim 100\,{\rm km/s}$.

To get low $v_{\rm pec}^{z=0}$:

- wide orbits at SNe (e.g., Kalogera+98: "Direct SN"), and/or
- weak NKs (e.g., e-capture SNe, accretion-induced collapse?)

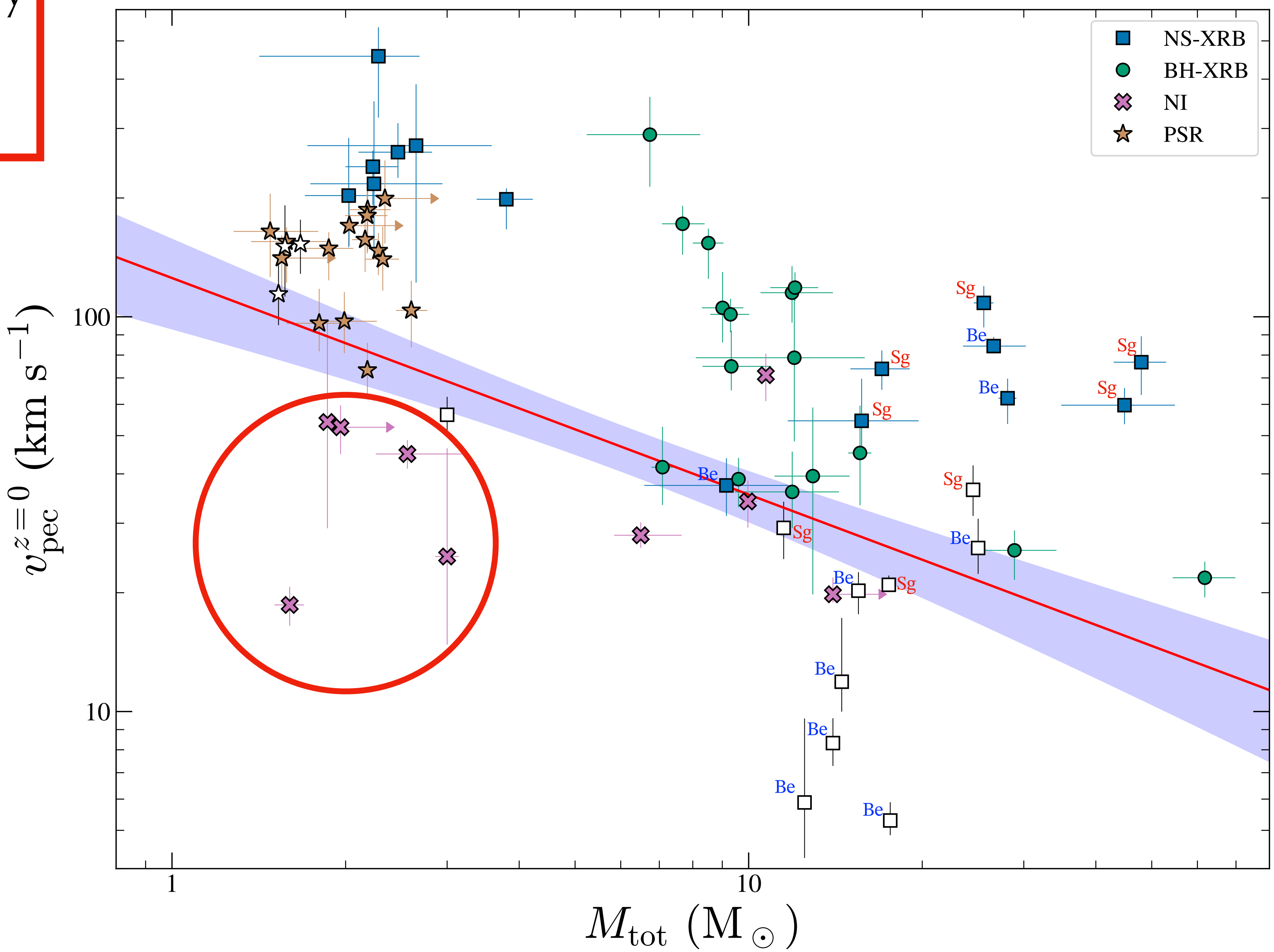


NS-NIs are slower than XRBs

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

NS-NIs seems to have systematically lower $v_{\rm pec}^{z=0}$ than NS-LMXBs and PSRs:

- SNe at much wider orbits?
- Weak NKs?
- Might not be NSs?

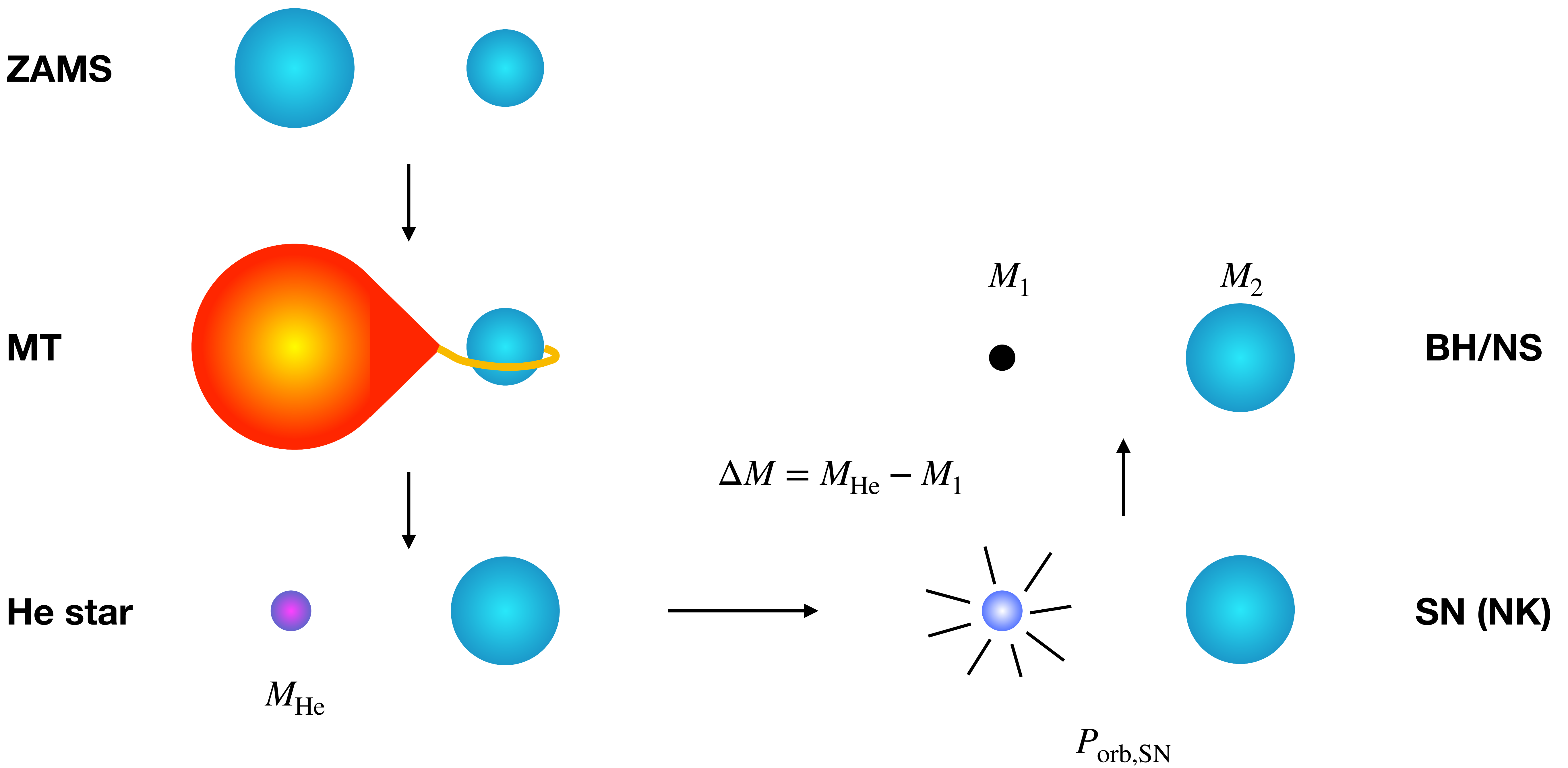


Takeaways

- No significant difference between binaries hosting BHs and those hosting NSs.
- Binaries with LM companions have broader (up to ~400 km/s) distribution compared to those hosting HM companions.
- Anti-correlation between peculiar velocity and M_{tot} is significant.
- The decreasing trend is guided by the Kalogera+96 limits within individual subclasses and also across different classes.

Thank You!

A rough overview of binary evolution



Kinematic discussion

Range of $v_{\rm pec}^{z=0}$ allowed by the limits:

$$v_{\rm pec,max}^{z=0} - v_{\rm pec,min}^{z=0} = \frac{2\sqrt{2}M_1}{M_{\rm tot}^{1/2}\left(M_{\rm tot}+\Delta M\right)^{1/2}}V_r$$

$$\propto M_1 M_{\rm tot}^{-1/2}\left(M_{\rm tot}+\Delta M\right)^{-1/6} P_{\rm orb,SN}^{-1/3}$$

HMs show a narrower distribution compared to LMs one or more of the following:

- apparently larger $M_{\rm tot}$.
- larger ΔM (because of larger progenitor mass).
- wider orbits at SNe (i.e., larger $P_{\rm orb,SN}$).

Kinematic discussion

Comparing $v_{\rm pec}^{z=0}$ of HMXB subtypes:

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

BeXRBs are constrained by lower $v_{\rm pec,max}^{z=0}$ than SgXRBs because

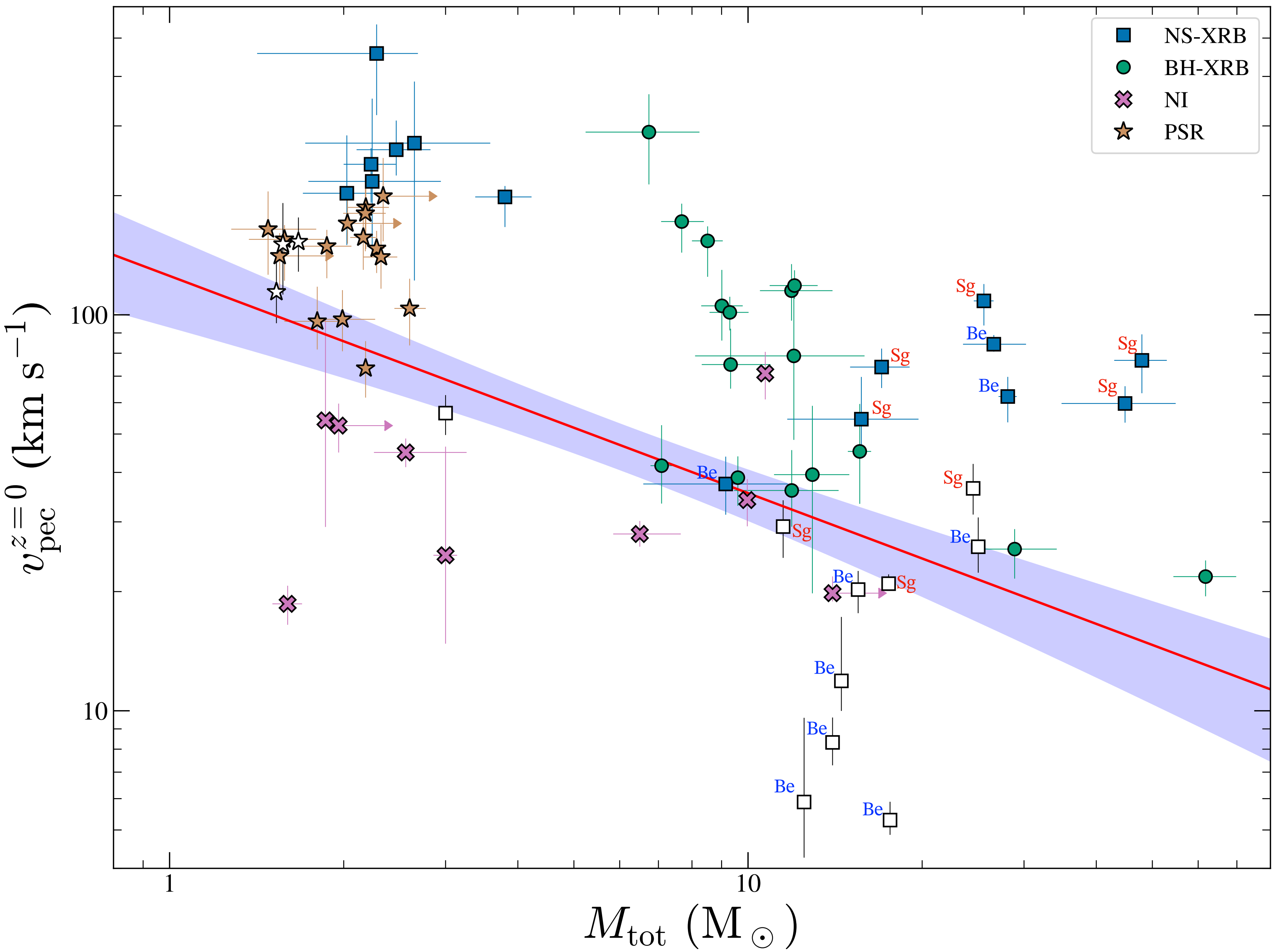
- systematically wider orbits at SNe, and
- less mass is ejected at SNe (also see van den Heuvel+00, Pornisara et al. in prep)

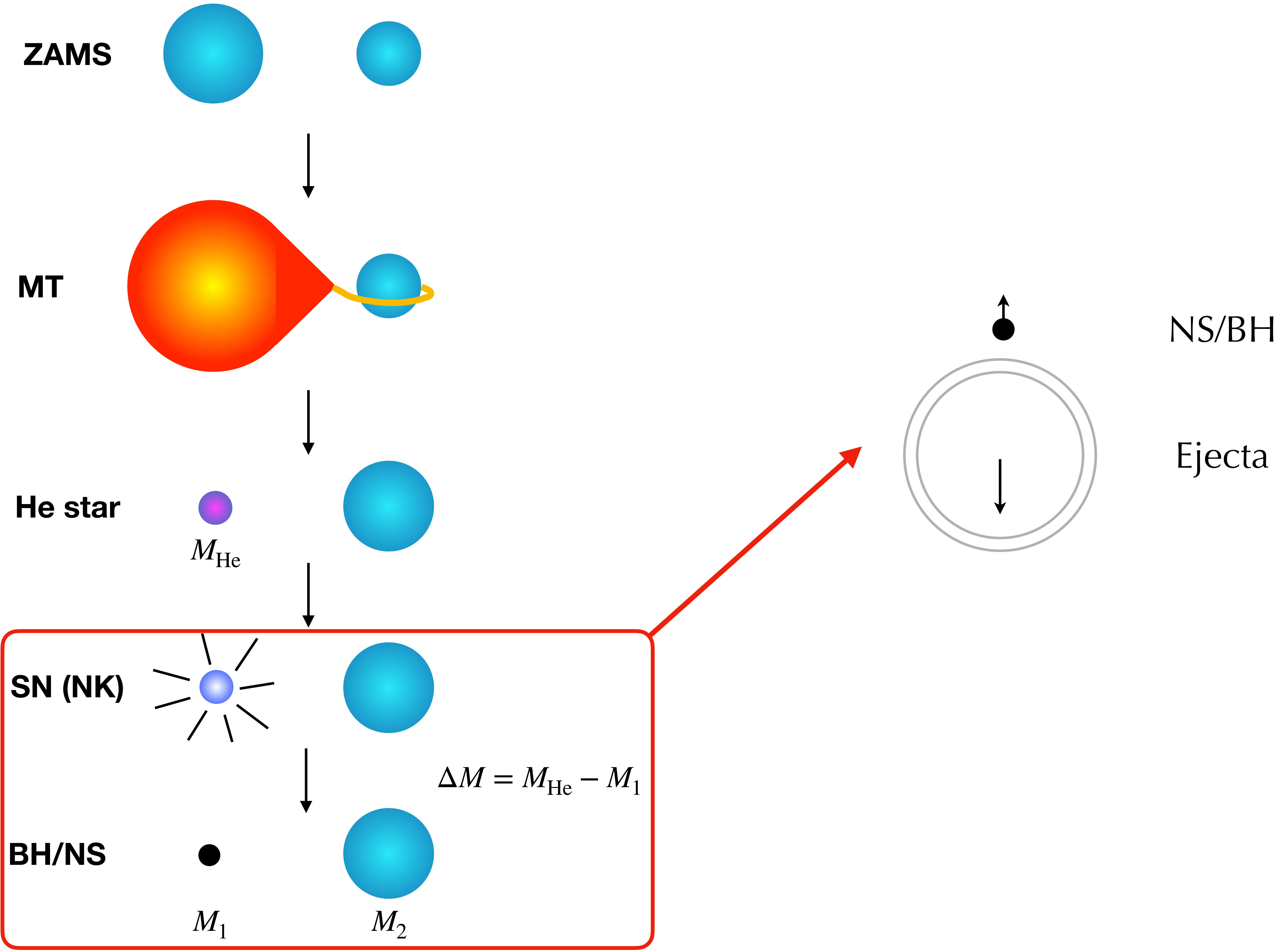
Lack of low-v NS-LMs

$$v_{\rm pec,max}^{z=0}/V_r = \frac{M_1 + \Delta M}{M_{\rm tot} + \Delta M} + \frac{\sqrt{2}M_1}{M_{\rm tot}^{1/2}(M_{\rm tot} + \Delta M)^{1/2}}$$

BeXRBs vs. SgXRBs

BeXRBs are constrained by lower $v_{\rm pec,max}^{z=0}$ than SgXRBs.





ZAMS
MT
He star
M_{He}
SN (NK)
BH/NS
$\Delta M = M_{He} - M_1$
M_1
M_2
NS/BH
Ejecta

Additional slides: Bayesian model for the log-linear fit

Likelihood:

$$D \,|\, f_{\rm err}, \theta_0, \theta_1 \sim \prod_i N\left[\mu_i(\theta_0, \theta_1), \sigma_i(f_{\rm err})\right],$$

where

$$\mu_i = \theta_0 + \theta_1 x_i \text{ and } \sigma_i = \sqrt{\sigma_{v,i}^2 + (f_{\rm err} v_i)^2}\,.$$

Priors:

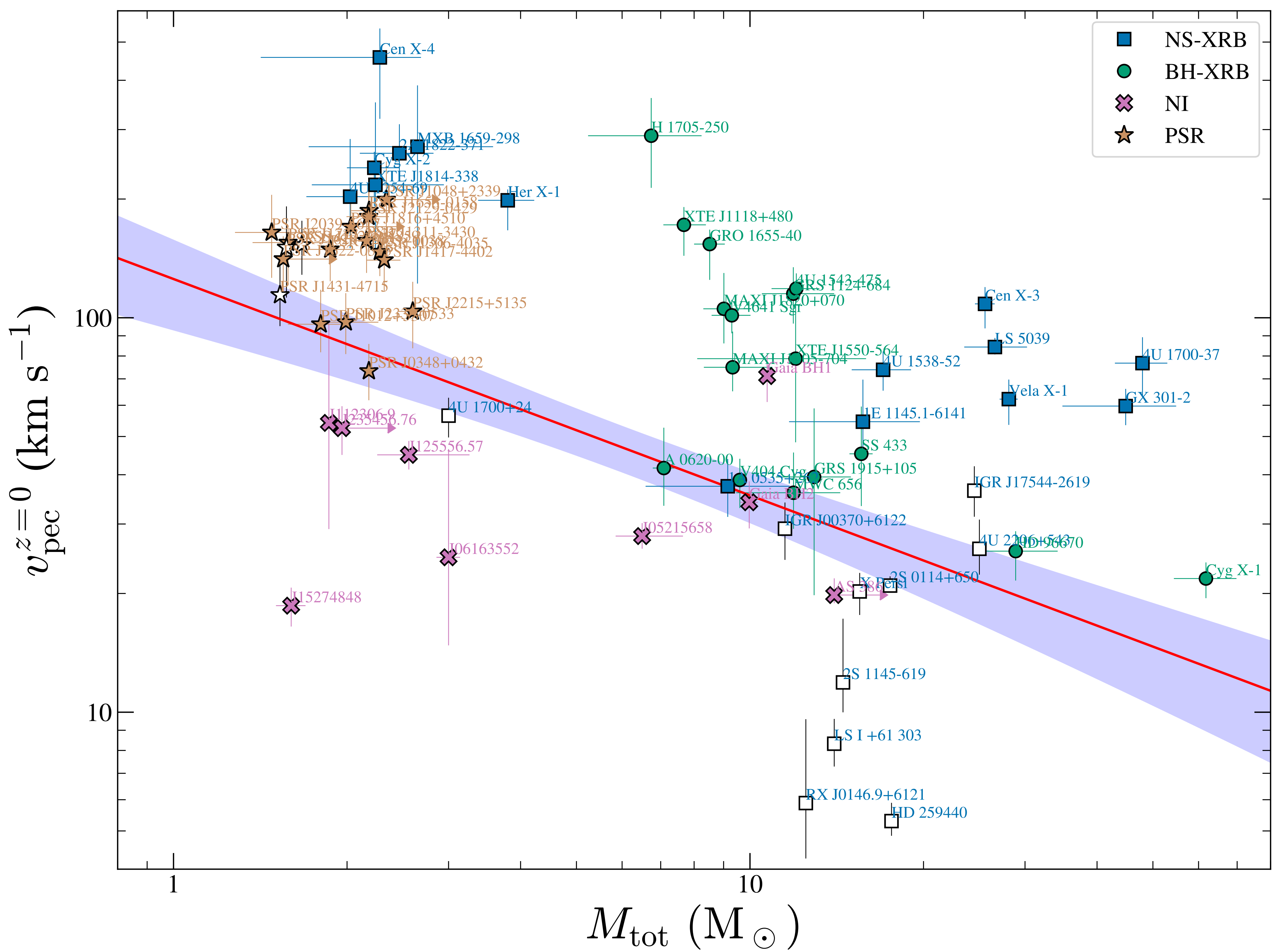
Intercept: $\theta_0 \sim U(-5,5)$ Slope: $\theta_1 \sim U(-5,5)$

Systematic error fraction: $f_{\rm err} \sim U(0,1)$.

Posterior:

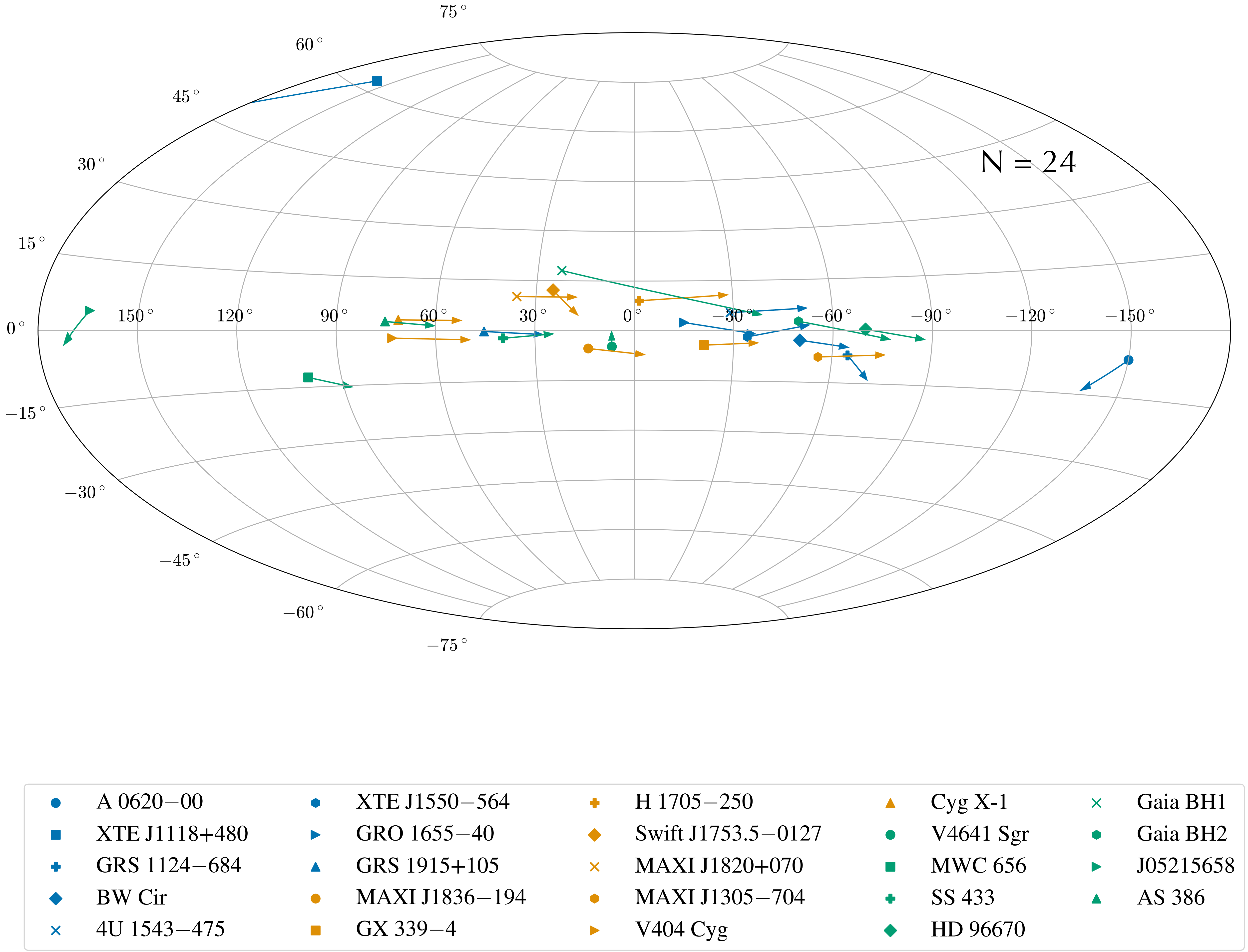
$$p\left(f_{\rm err}, \theta_0, \theta_1 \,|\, D\right) \propto \left[\prod_i N(\mu_i, \sigma_i)\right] p(\theta_0) p(\theta_1) p(f_{\rm err})\,.$$

Additional slides: labelled v vs. M_tot plot

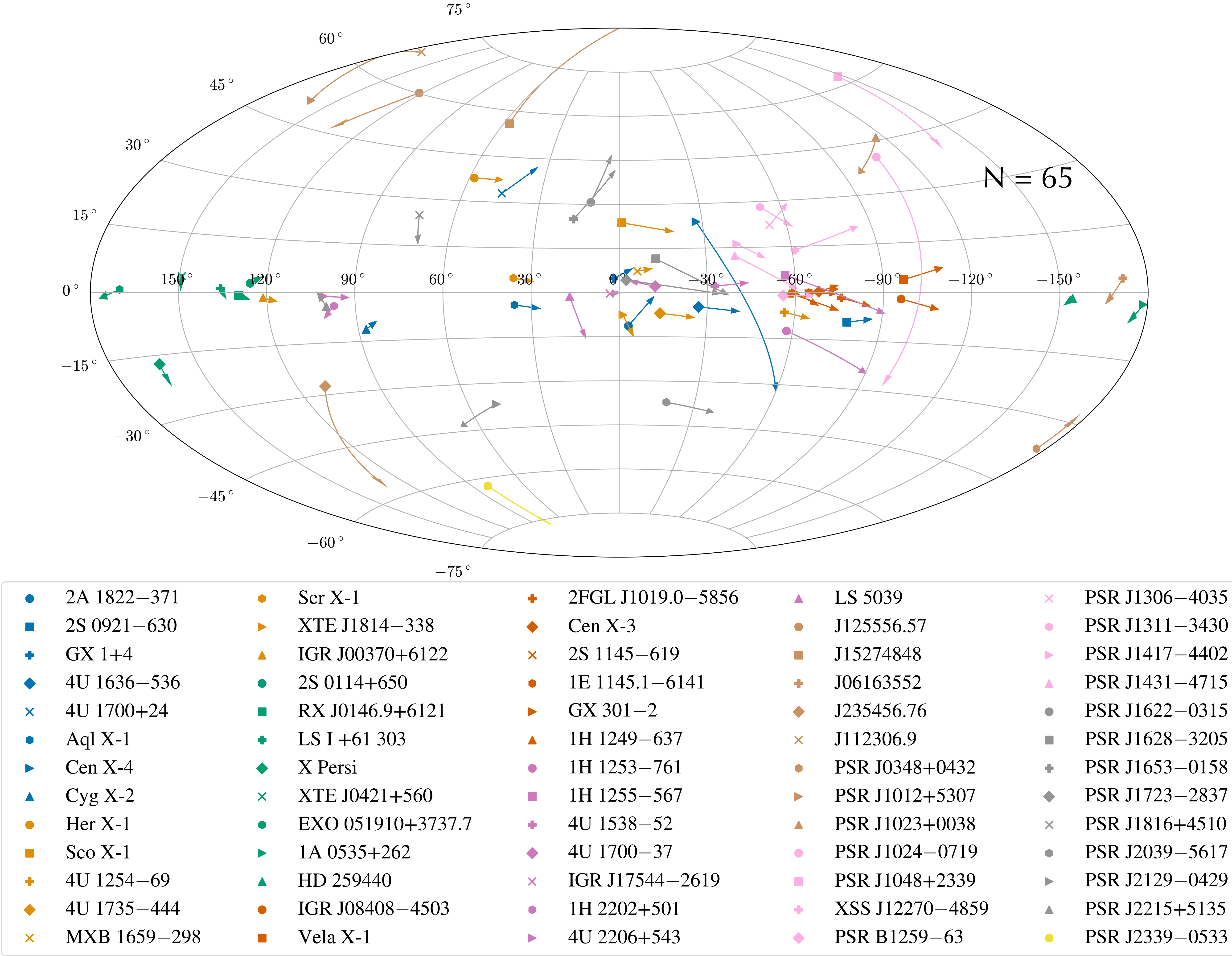


Additional slides: NIs

Name	Type	Ref
AS 386	BH-NI	Khokhlov+18
2MASS J05215658+4359220	BH-NI	Thompson+19
Gaia BH1	BH-NI	El-Badry+23a
Gaia BH2	BH-NI	Tanikawa+22, El-Badry+23b
LAMOST J112306.9+400736	NS-NI	Yi+22
2MASS J15274848+3536572	NS-NI	Lin+23
2MASS J06163552+2319094	NS-NI	Yuan+22
LAMOST J235456.76+335625.7	NS-NI	Zheng+22
2XMM J125556.57+565846.4	NS-NI	Mazeh+22



75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
150°
120°
90°
60°
30°
0°
−30°
−60°
−90°
−120°
−150°
N = 24
A 0620−00
XTE J1118+480
GRS 1124−684
BW Cir
4U 1543−475
XTE J1550−564
GRO 1655−40
GRS 1915+105
MAXI J1836−194
GX 339−4
H 1705−250
Swift J1753.5−0127
MAXI J1820+070
MAXI J1305−704
V404 Cyg
Cyg X-1
V4641 Sgr
MWC 656
SS 433
HD 96670
Gaia BH1
Gaia BH2
J05215658
AS 386



75 °
60 °
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−75 °
150 °
120 °
90 °
60 °
30 °
0 °
−30 °
−60 °
−90 °
−120 °
−150 °
N = 65
2A 1822−371
2S 0921−630
GX 1+4
4U 1636−536
4U 1700+24
Aql X-1
Cen X-4
Cyg X-2
Her X-1
Sco X-1
4U 1254−69
4U 1735−444
MXB 1659−298
Ser X-1
XTE J1814−338
IGR J00370+6122
2S 0114+650
RX J0146.9+6121
LS I +61 303
X Persi
XTE J0421+560
EXO 051910+3737.7
1A 0535+262
HD 259440
IGR J08408−4503
Vela X-1
2FGL J1019.0−5856
Cen X-3
2S 1145−619
1E 1145.1−6141
GX 301−2
1H 1249−637
1H 1253−761
1H 1255−567
4U 1538−52
4U 1700−37
IGR J17544−2619
1H 2202+501
4U 2206+543
LS 5039
J125556.57
J15274848
J06163552
J235456.76
J112306.9
PSR J0348+0432
PSR J1012+5307
PSR J1023+0038
PSR J1024−0719
PSR J1048+2339
XSS J12270−4859
PSR B1259−63
PSR J1306−4035
PSR J1311−3430
PSR J1417−4402
PSR J1431−4715
PSR J1622−0315
PSR J1628−3205
PSR J1653−0158
PSR J1723−2837
PSR J1816+4510
PSR J2039−5617
PSR J2129−0429
PSR J2215+5135
PSR J2339−0533

Peculiar velocity

Peculiar velocity (v_{pec})

Systemic velocity relative to local Galactic rotation.

Reid+09:

$$\alpha, \delta, \varpi, \mu_\alpha \cos\delta, \mu_\delta, \gamma$$

↓

$$U_s, V_s, W_s$$

$$v_{\mathrm{pec}} = \sqrt{U_s^2 + V_s^2 + W_s^2}$$

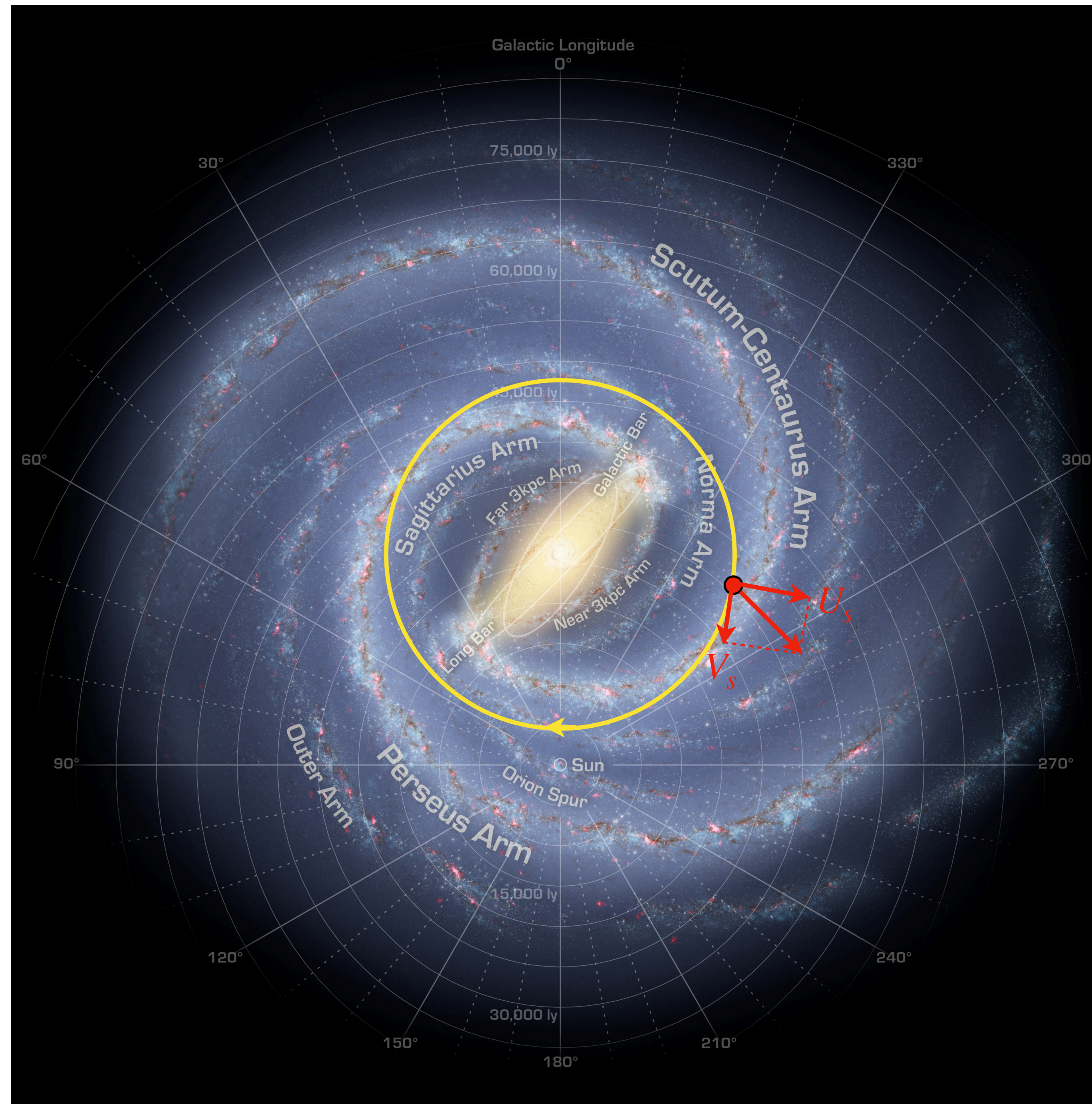


Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Potential peculiar velocity at birth

Potential peculiar velocity at birth ($v_{\rm pec}^{z=0}$)

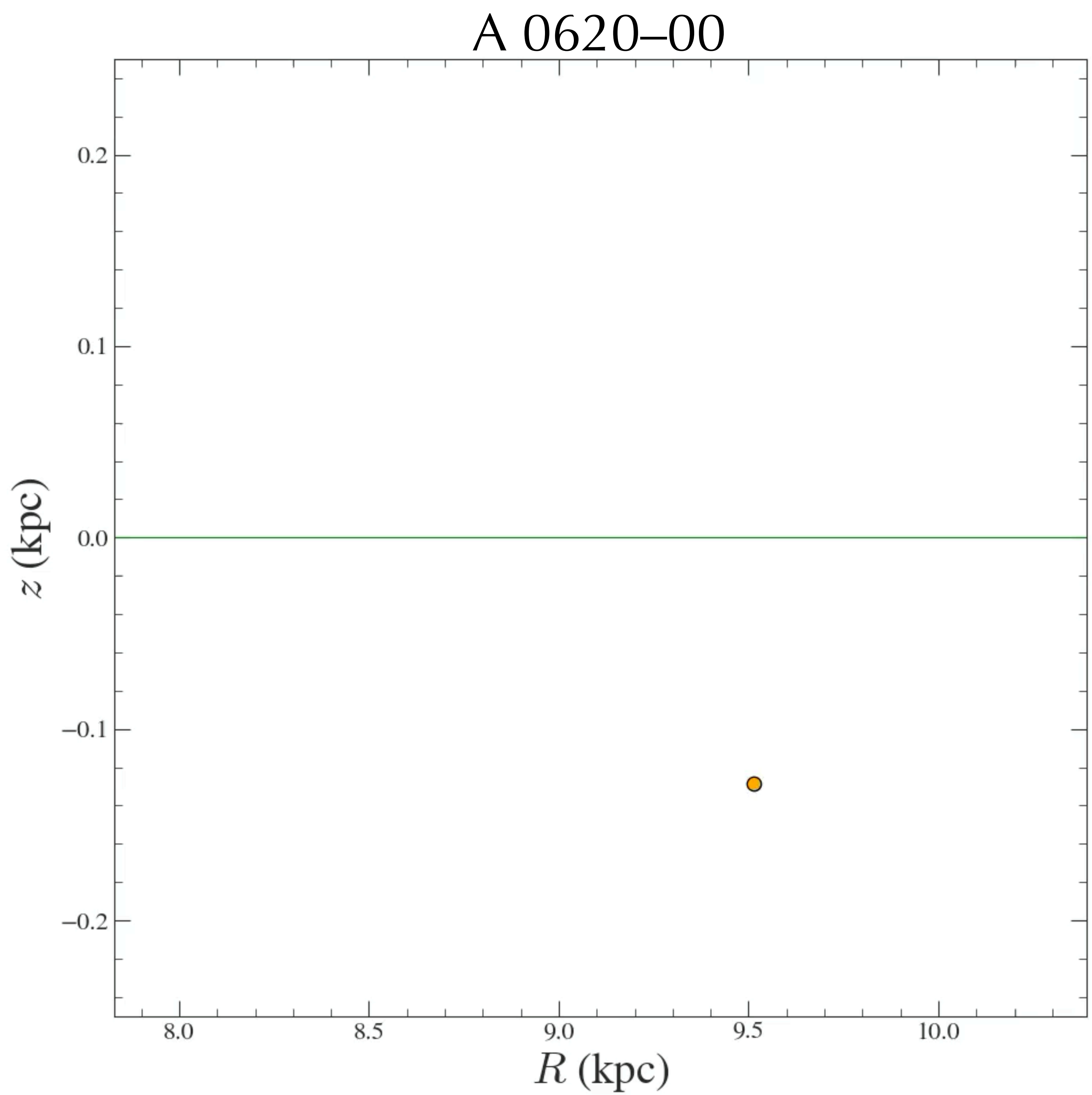
Integrate orbits backward in time.

↓

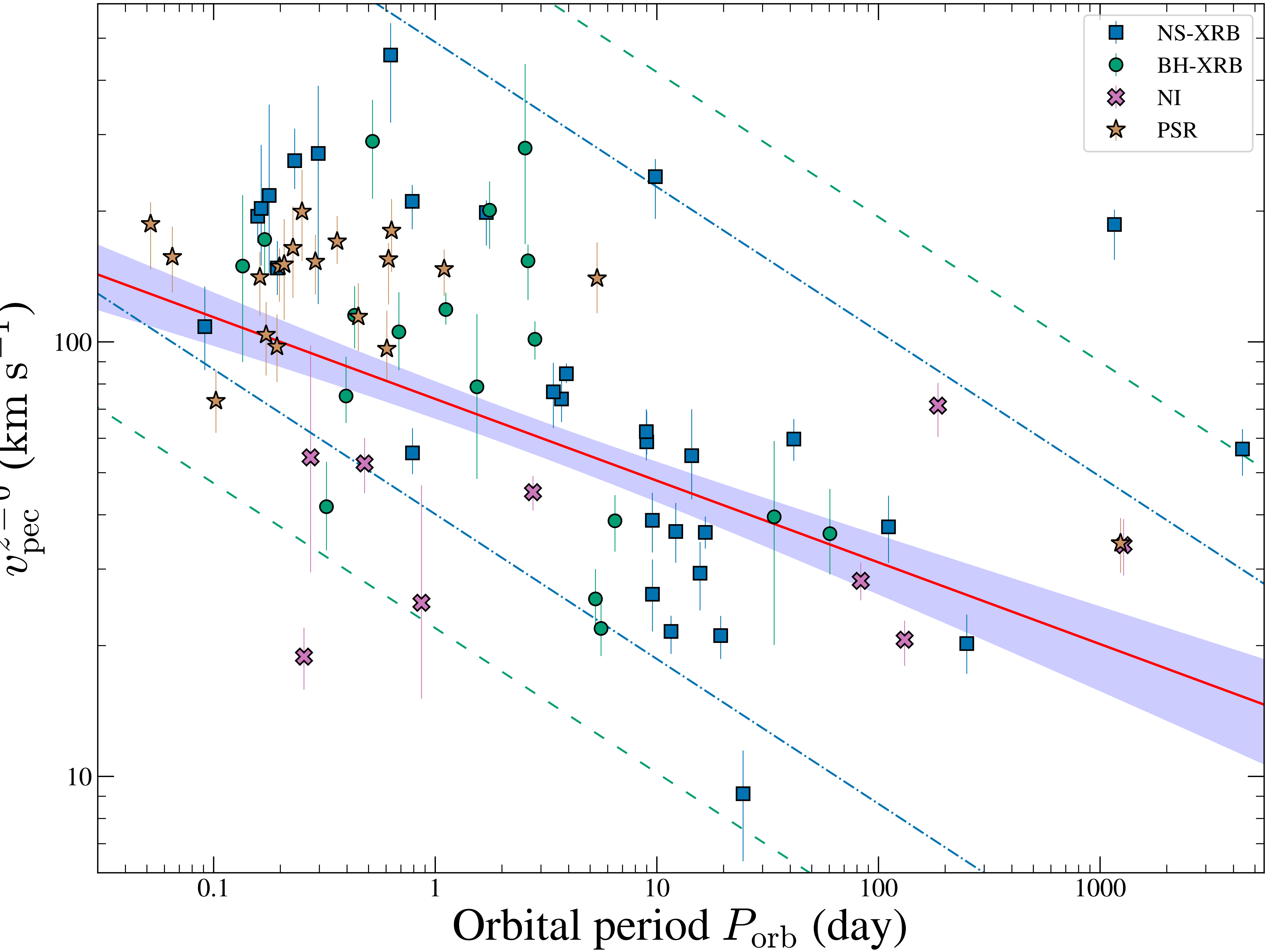
Collect peculiar velocity at every plane crossing.

↓

Monte Carlo samples of $v_{\rm pec}^{z=0}$.



Type	M_1 ($M_\odot$)	ΔM ($M_\odot$)	$P_{\rm orb,SN}$ (day)
NS-LMXB	1.4	1.0	1
BH-LMXB	5.0	6.0	10
BH-HMXB	5.0	6.0	100
SgXRB	1.4	5.0	10
BeXRB	1.4	2.0	300
NS-NI	1.4	1.0	560



NS-XRB
BH-XRB
NI
PSR
100
10
0.1
1
10
100
1000
$v_{\rm pec}^{z=0}$ (km s^{-1})
Orbital period $P_{\rm orb}$ (day)