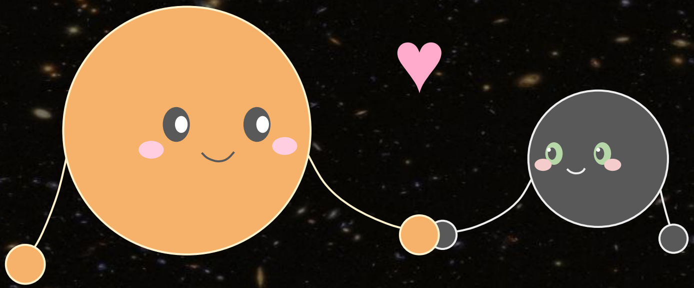
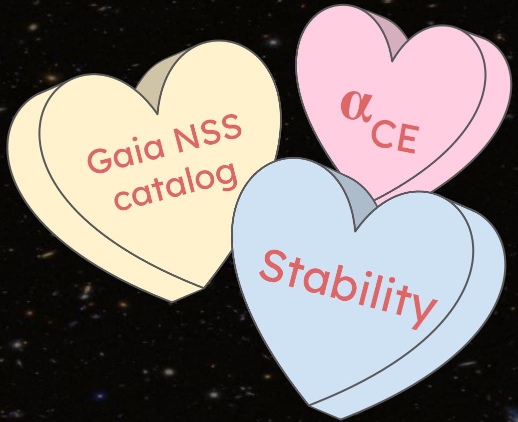
WD + MS binaries as probes of binary interactions

Natsuko Yamaguchi
(G3, Astrophysics)

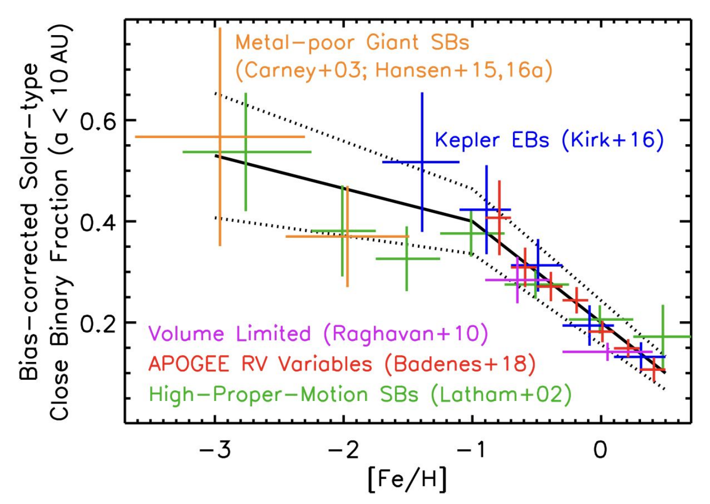


Happy Valentine's Day!



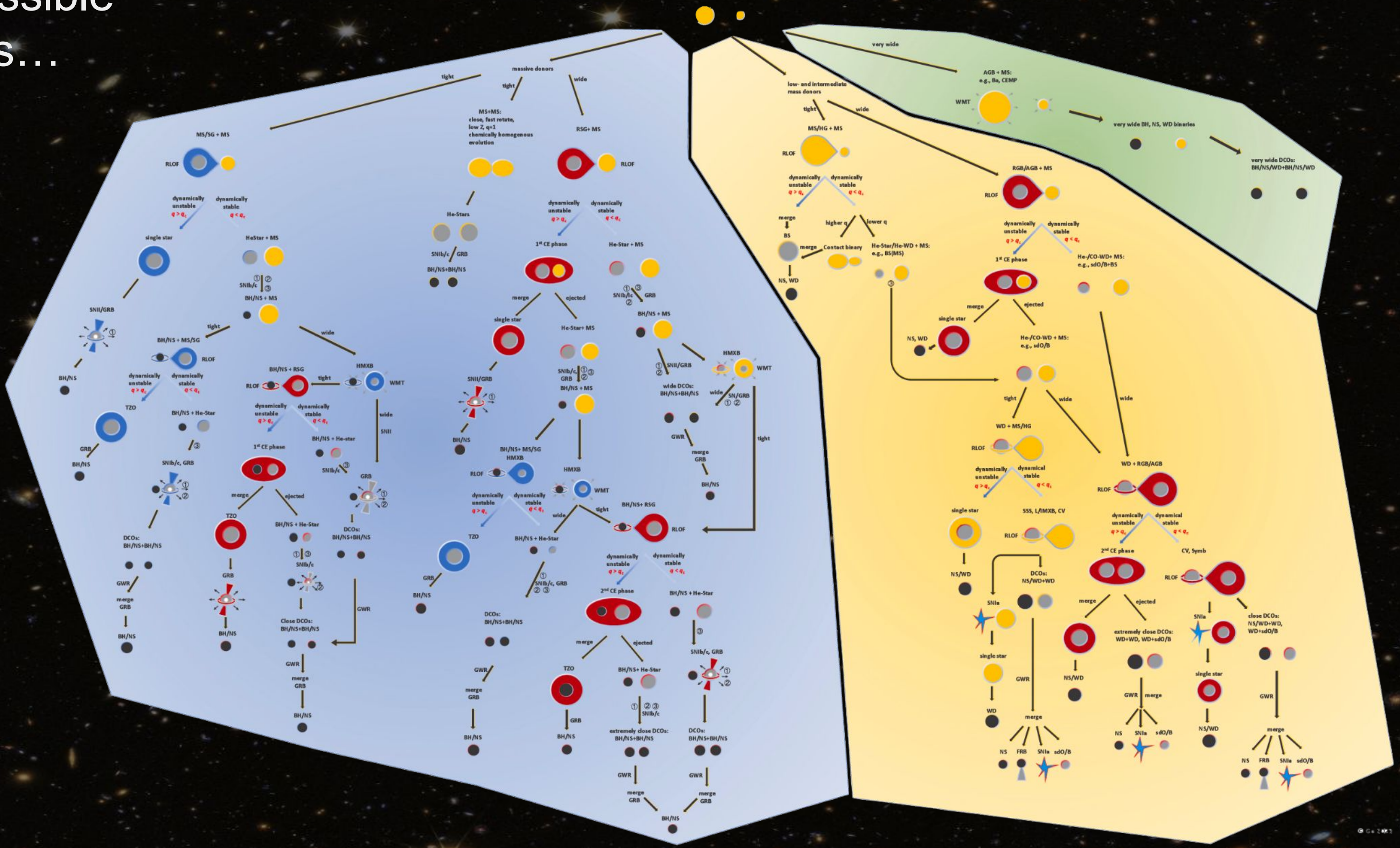
Binary interactions are ubiquitous.

- Many stars will interact with a companion in their lifetime
- These interactions are critical to the formation of many important and exotic astrophysical phenomena
- But these processes can get complicated



Moe et al. (2019)

Many possible pathways…

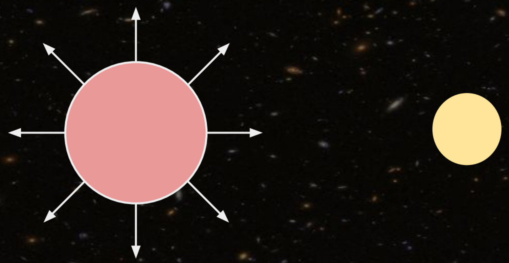


Han et al. (2020)

There are many types of binary mass transfer.

1. Wind accretion

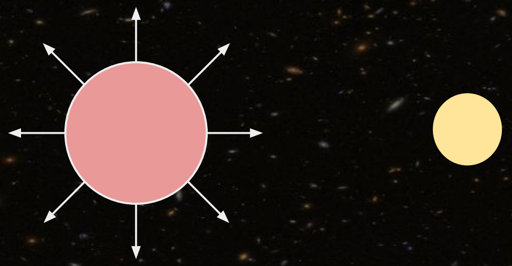
- Wide separations, giants



There are many types of binary mass transfer.

1. Wind accretion

- Wide separations, giants



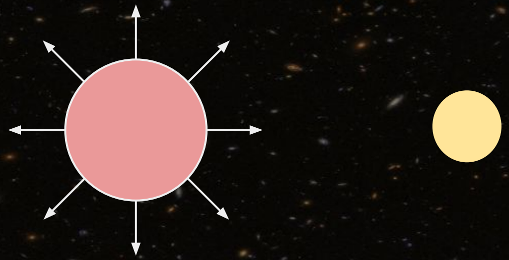
2. Roche Lobe Overflow (RLOF)

- Conservative vs. Non-conservative MT

There are many types of binary mass transfer.

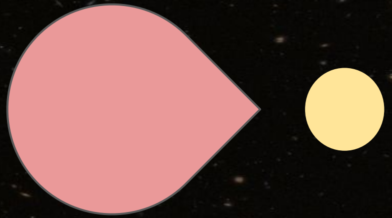
1. Wind accretion

- Wide separations, giants



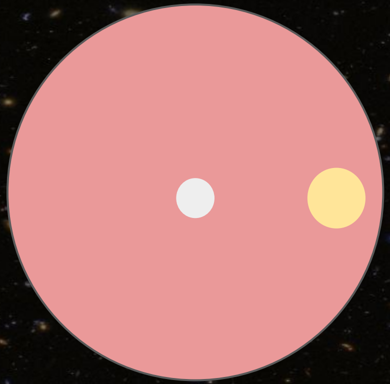
2. Roche Lobe Overflow (RLOF)

- Conservative vs. Non-conservative MT



3. Common Envelope Evolution (CEE)

- Unstable MT
- Can end in stellar merger or form post-common envelope binary (PCEB)



Unresolved questions remain regarding these processes.

Common Envelope Evolution (Paczynski 1976; Ivanova 2013)

- How much does the orbit shrink? (Livio and Soker 1988; Zorotovic et al. 2010; Davis et al. 2011; Zorotovic and Schreiber 2022; Scherbak and Fuller 2024)

$$E_{bind} = \alpha \, \Delta E_{orbital}$$

Unresolved questions remain regarding these processes.

Common Envelope Evolution (Paczynski 1976; Ivanova 2013)

- How much does the orbit shrink? (Livio and Soker 1988; Zorotovic et al. 2010; Davis et al. 2011; Zorotovic and Schreiber 2022; Scherbak and Fuller 2024)

$$E_{grav} + E_{int} + E_{rec} + E_{jet} + \ldots ? = E_{bind} = \alpha \, \Delta E_{orbital}$$

- What physics do we need to consider?
  - Recombination energy? (Lucy 1967; Paczyński and Ziółkowski 1968; Sabach 2017; Ivanova et al. 2015; Ivanova 2018; Grichener et al. 2018)
  - Jets from accretor? (Armitage and Livio 2000; Soker 2004, 2014; Moreno-Mendez 2017; Sabach 2017)

Unresolved questions remain regarding these processes.

Common Envelope Evolution (Paczynski 1976; Ivanova 2013)

- How much does the orbit shrink? (Livio and Soker 1988; Zorotovic et al. 2010; Davis et al. 2011; Zorotovic and Schreiber 2022; Scherbak and Fuller 2024)

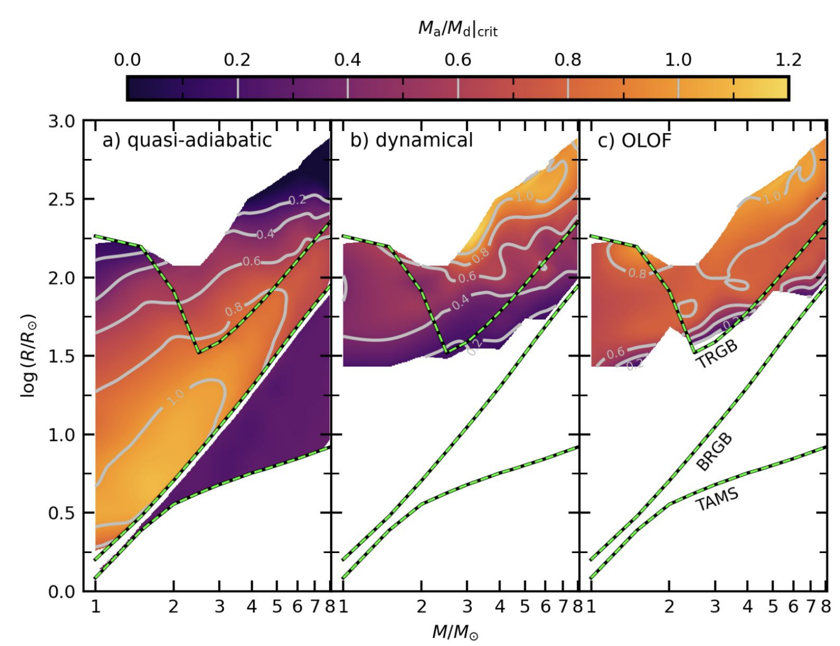
$$E_{grav} + E_{int} + E_{rec} + E_{jet} + \ldots ? = E_{bind} = \alpha \Delta E_{orbital}$$

- What physics do we need to consider?
  - Recombination energy? (Lucy 1967; Paczyński and Ziółkowski 1968; Sabach 2017; Ivanova et al. 2015; Ivanova 2018; Grichener et al. 2018)
  - Jets from accretor? (Armitage and Livio 2000; Soker 2004, 2014; Moreno-Mendez 2017; Sabach 2017)
- Does the orbit circularize completely? (Glanz and Perez 2021, Trani et al. 2022, Sand et al. 2020, Bronner et al. 2024)

Unresolved questions remain regarding these processes.

Stable mass transfer

- What is the stability boundary? (i.e. the critical mass ratio; Paczynski 1965; Webbink 1985; Hjellming and Webbink 1987; Passy et al. 2012; Pavlovskii and Ivanova 2015; Ge et al. 2015, 2020; Temmink et al. 2022)



Temmink at al. (2022)

Unresolved questions remain regarding these processes.

Stable mass transfer

- What is the stability boundary? (i.e. the critical mass ratio; Paczynski 1965; Webbink 1985; Hjellming and Webbink 1987; Passy et al. 2012; Pavlovskii and Ivanova 2015; Ge et al. 2015, 2020; Temmink et al. 2022)
- How much mass is accreted onto the companion vs. lost from the system? (i.e. β parameter; Paczyński and Ziółkowski 1967; Sarna 1993; Langer 2003; Tauris and van den Heuvel 2006; de Mink et al. 2007)

Unresolved questions remain regarding these processes.

Stable mass transfer

- What is the stability boundary? (i.e. the critical mass ratio; Paczynski 1965; Webbink 1985; Hjellming and Webbink 1987; Passy et al. 2012; Pavlovskii and Ivanova 2015; Ge et al. 2015, 2020; Temmink et al. 2022)
- How much mass is accreted onto the companion vs. lost from the system? (i.e. β parameter; Paczyński and Ziółkowski 1967; Sarna 1993; Langer 2003; Tauris and van den Heuvel 2006; de Mink et al. 2007)
- How do we deal with eccentric RLO? (Hadjidemetriou 1969; Sepinsky et al. 2007; Hamers and Dosopoulou 2019; Kyle et al. 2024)

My approach: WD + MS binaries

Close ($P_{orb} \lesssim 10^3$ days) WD + MS binaries

→ interacted prior to the formation of the WD

→ post-MT binaries

Goal: Use their properties to constrain MT models

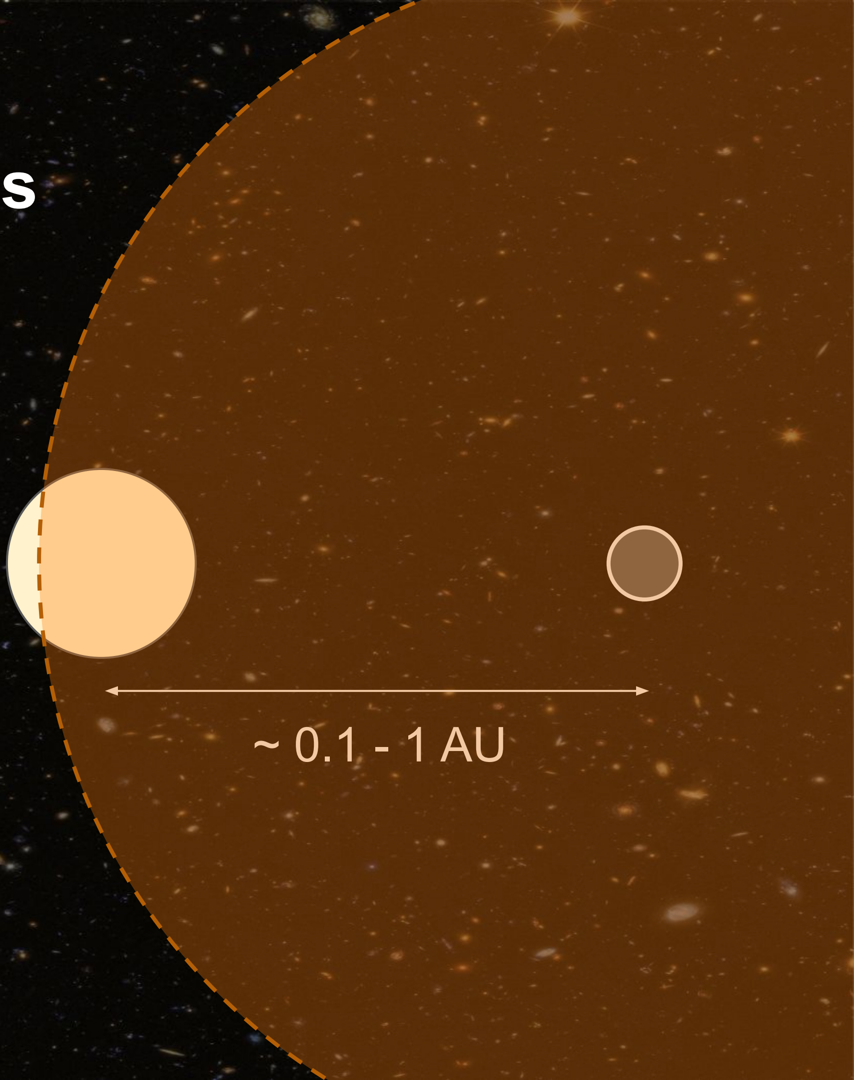
My approach: WD + MS binaries

Close ($P_{orb} \lesssim 10^3$ days) WD + MS binaries

→ interacted prior to the formation of the WD

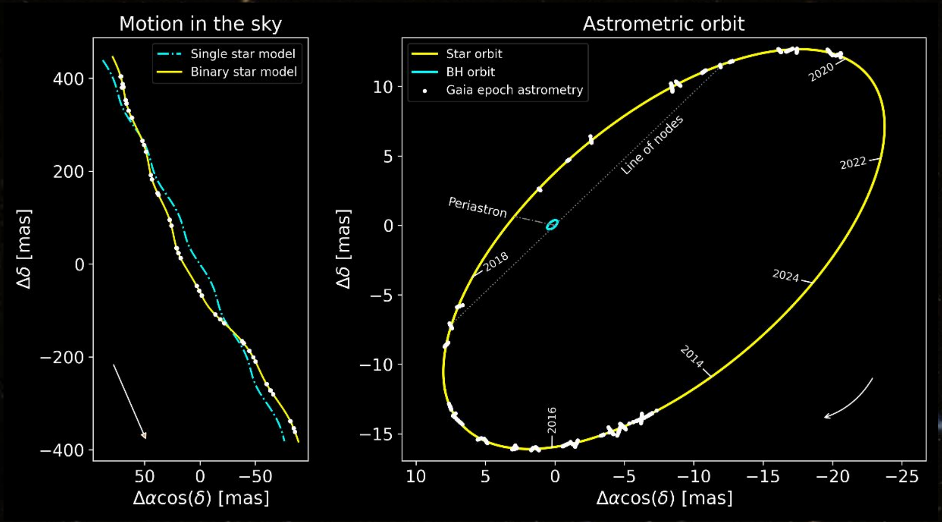
→ post-MT binaries

Goal: Use their properties to constrain MT models



Gaia DR3 Non-Single Stars (NSS) catalog: a treasure box of binaries

> > 160,000 astrometric orbital solutions

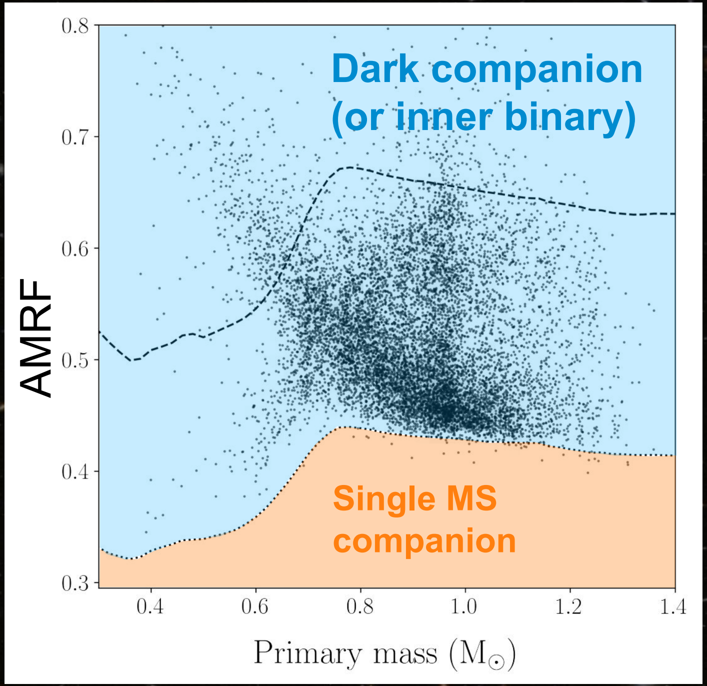


Gaia Collaboration, P. Panuzzo, et al. (2024)

Gaia DR3 Non-Single Stars (NSS) catalog: a treasure box of binaries

> 160,000 astrometric orbital solutions

+ Astrometric Mass Ratio Function (AMRF; Shahaf et al. 2019, 2024)



Shahaf et al. (2024)

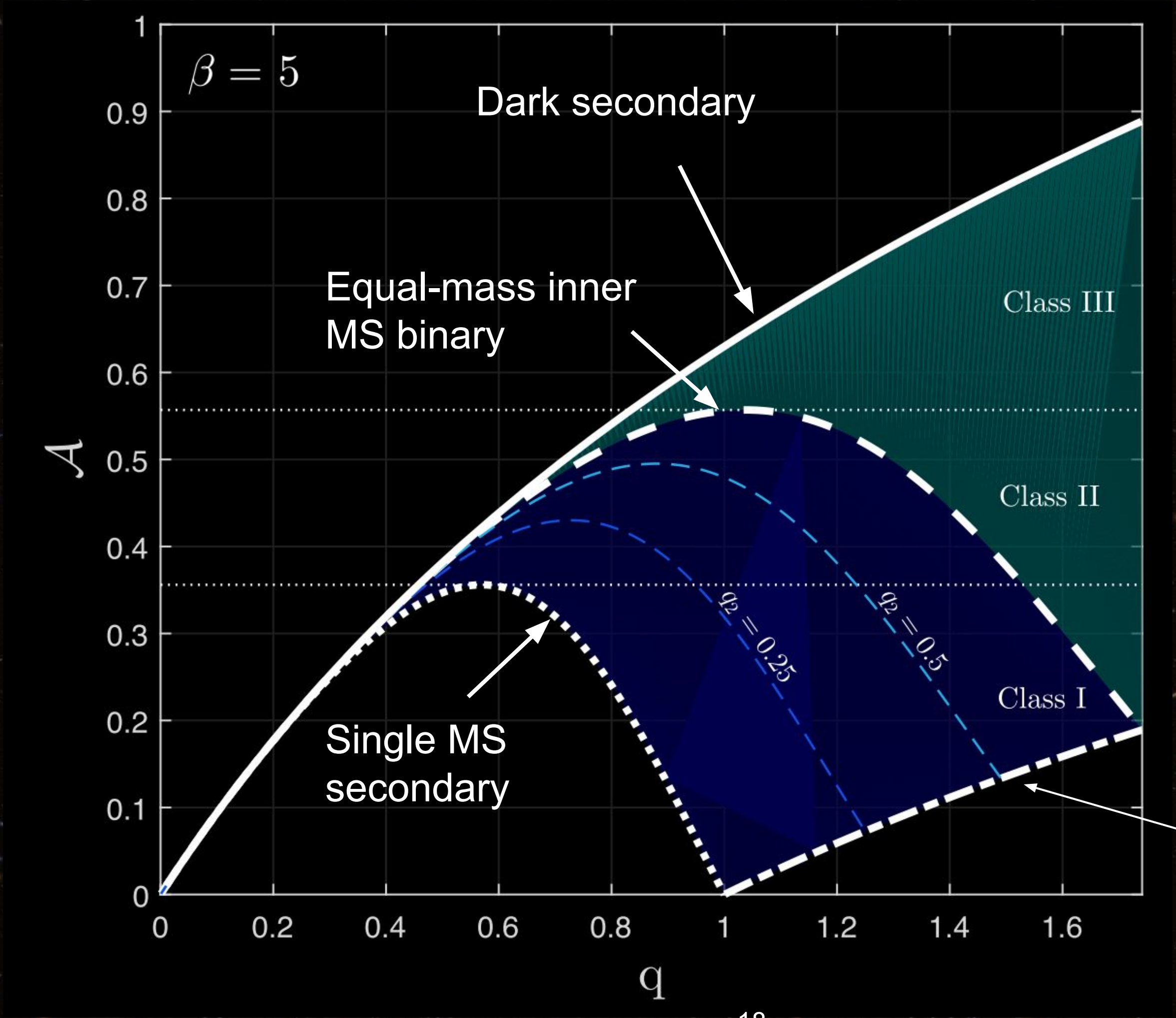
A little tangent about the "triage" technique… (Shahaf et al. 2019, 2022, 2024)

Astrometric mass ratio function:

$$\mathcal{A} = \frac{\alpha}{\varpi}\left(\frac{M_1}{\mathrm{M}_\odot}\right)^{-1/3}\left(\frac{P}{\mathrm{yr}}\right)^{-2/3}$$

$$= \frac{q}{(1+q)^{2/3}}\left(1 - \frac{\mathcal{S}(1+q)}{q(1+\mathcal{S})}\right)$$

Consider three possible types of secondaries:
(1) Dark compact object: $S = 0$
(2) Single MS star or (3) Inner MS binary → need MLR, $I \propto M^{\beta}$, to get S(q)



S_{triple} = 1 limiting case (inner binary becomes as bright at the primary star)

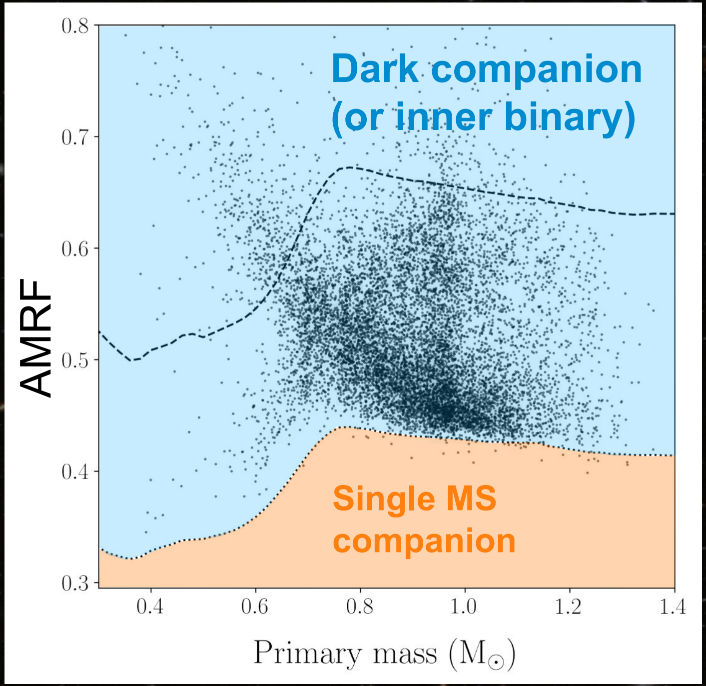
Gaia DR3 Non-Single Stars (NSS) catalog: a treasure box of binaries

> 160,000 astrometric orbital solutions

+ Astrometric Mass Ratio Function (AMRF; Shahaf et al. 2019, 2024)

⇒ **> 3000 WD + MS binary candidates!**

Probing a unique region of parameter space



Shahaf et al. (2024)

Gaia DR3 Non-Single Stars (NSS) catalog: a treasure box of binaries

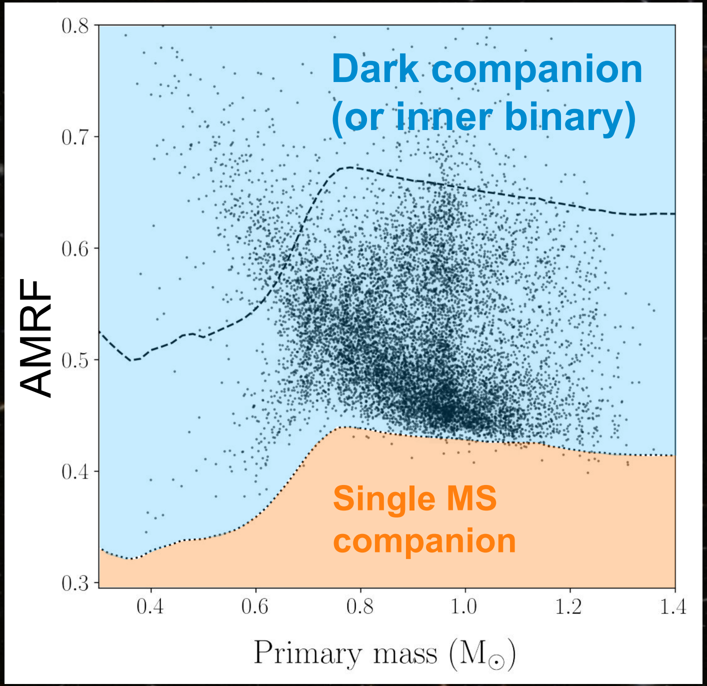
> 160,000 astrometric orbital solutions

+ Astrometric Mass Ratio Function (AMRF; Shahaf et al. 2019, 2024)

⇒ **> 3000 WD + MS binary candidates!**

Probing a unique region of parameter space

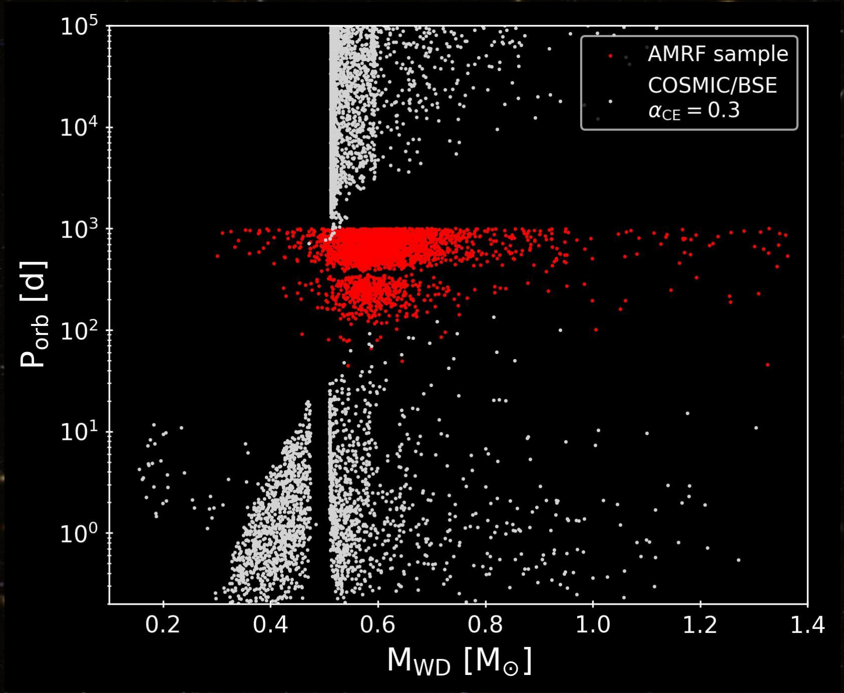
Also, > 180,000 SB1/SB2 solutions



Shahaf et al. (2024)

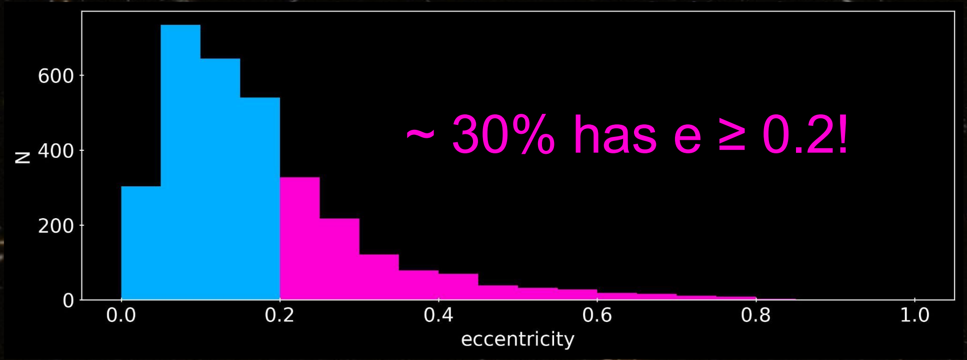
Gaia DR3 WD + MS binaries weren't as expected.

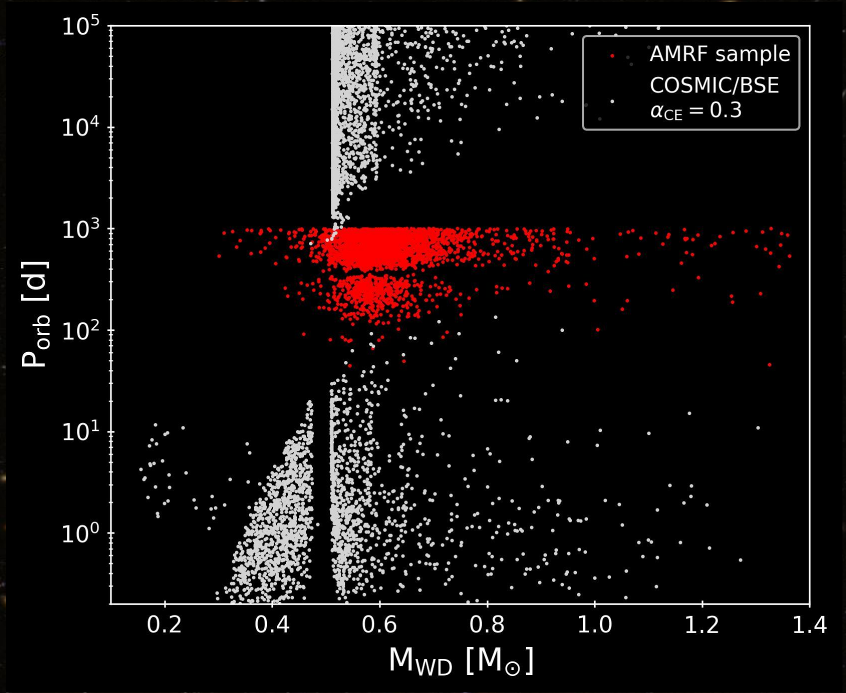
- Lots of systems with P_{orb} ~ 100 - 1000 d
  - PCEB? Post - stable RLOF?

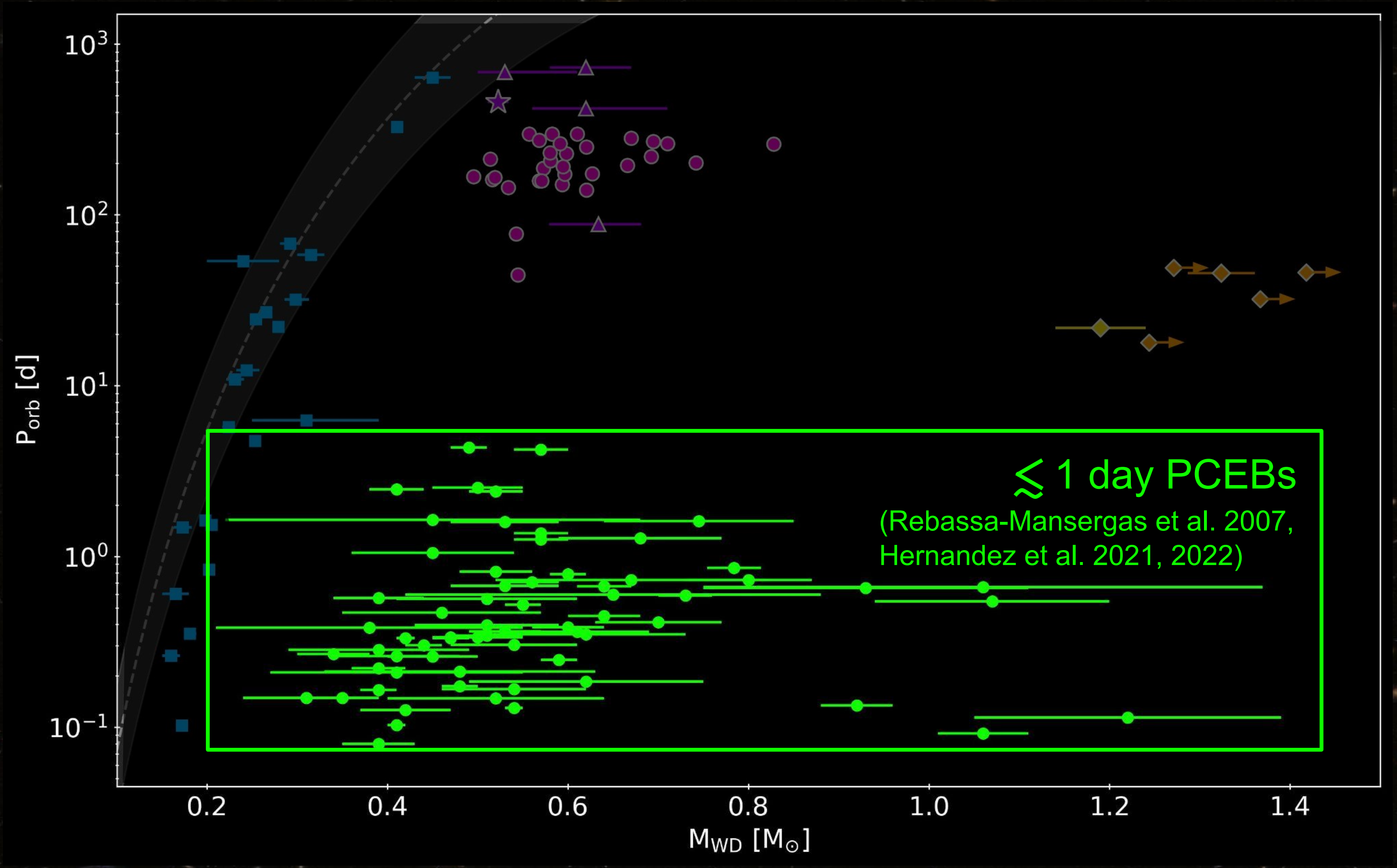


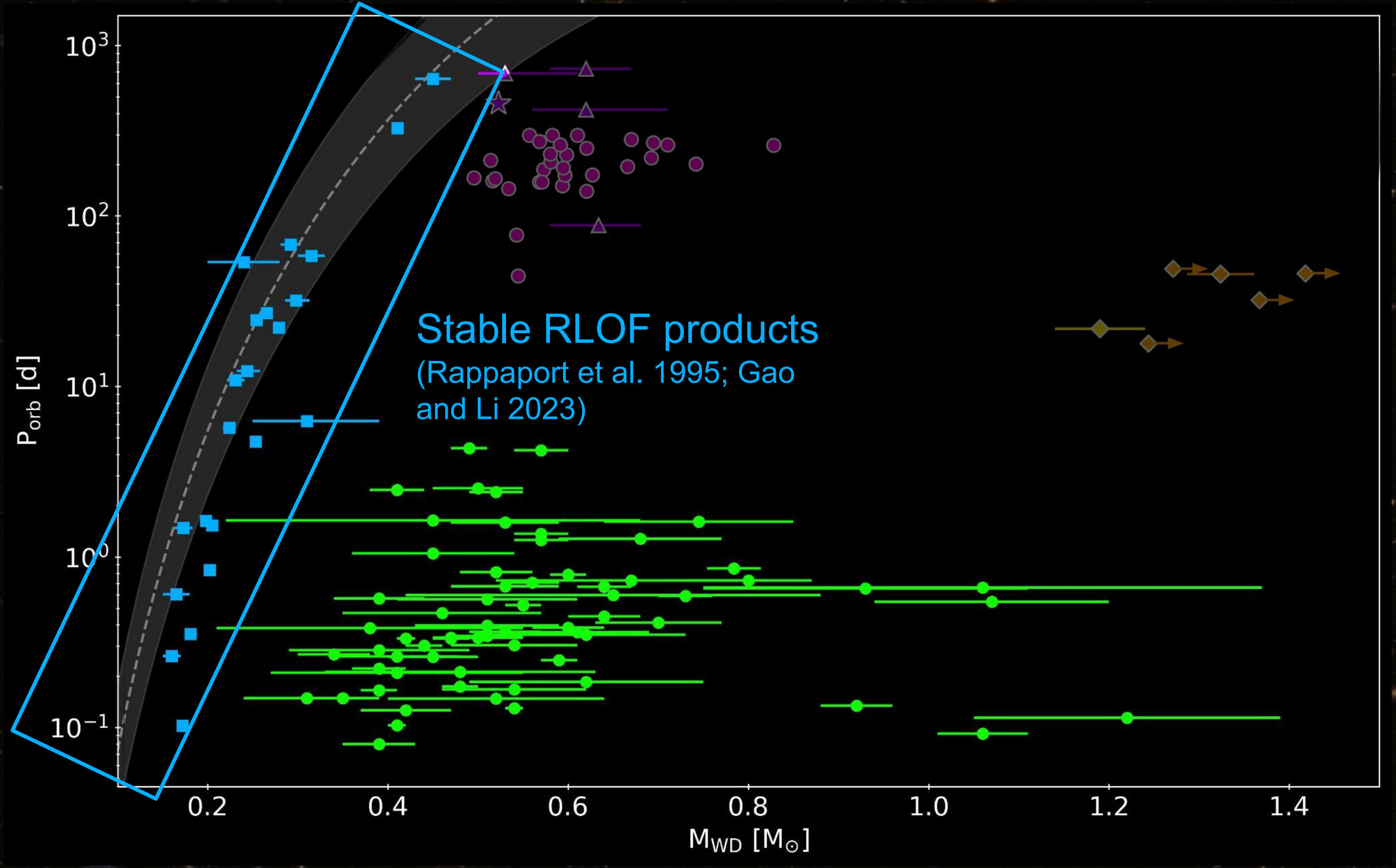
Gaia DR3 WD + MS binaries weren't as expected.

- Lots of systems with P_{orb} ~ 100 - 1000 d
  - PCEB? Post - stable RLOF?
- Many eccentric systems!
  - Inefficient tidal circularization? Eccentricity pumping?

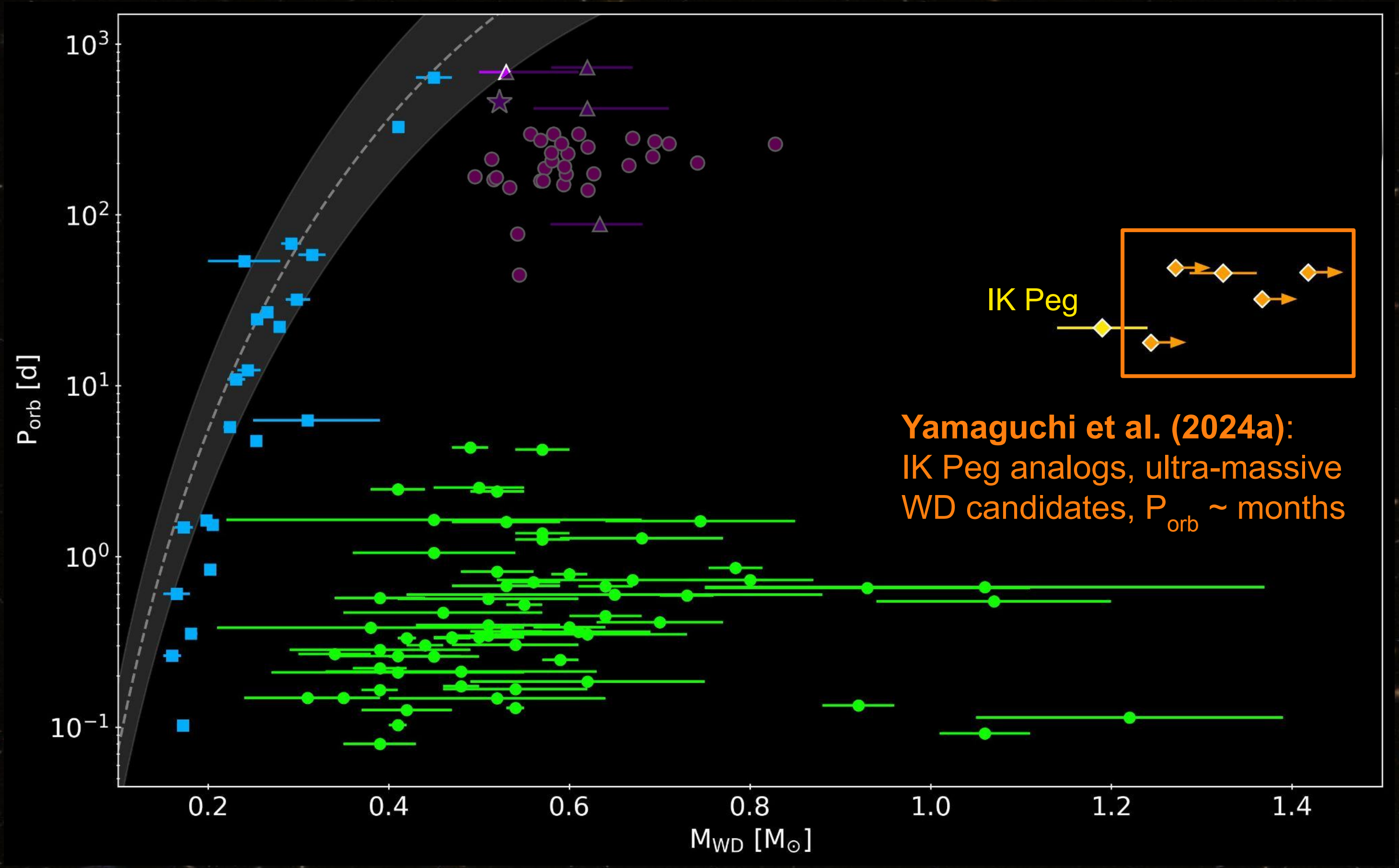




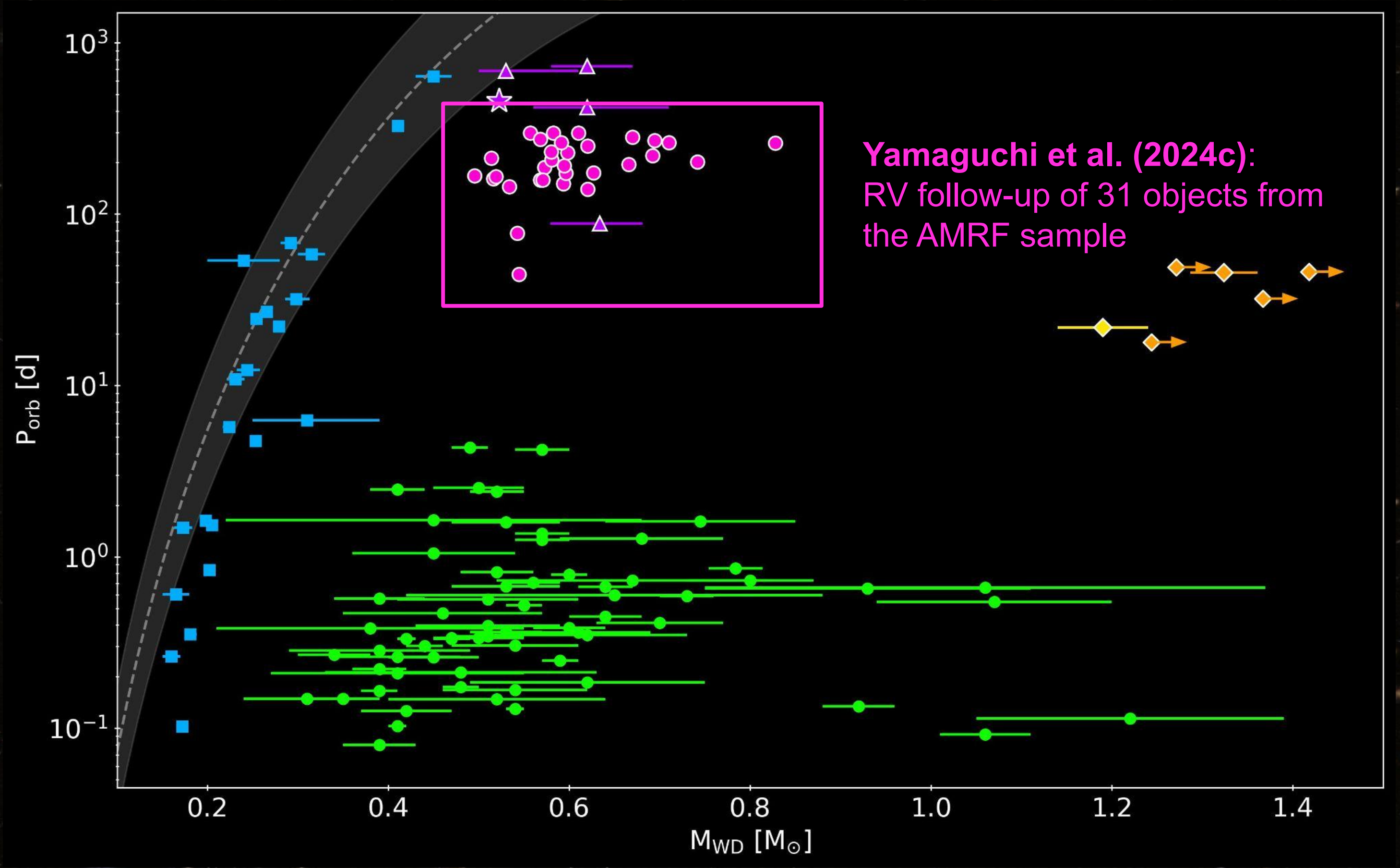

$\lesssim$ 1 day PCEBs
(Rebassa-Mansergas et al. 2007,
Hernandez et al. 2021, 2022)
P_{orb} [d]
M_{WD} [$M_\odot$]



Stable RLOF products
(Rappaport et al. 1995; Gao and Li 2023)
P_{orb} [d]
M_{WD} [$M_\odot$]
10^3
10^2
10^1
10^0
10^{-1}
0.2
0.4
0.6
0.8
1.0
1.2
1.4

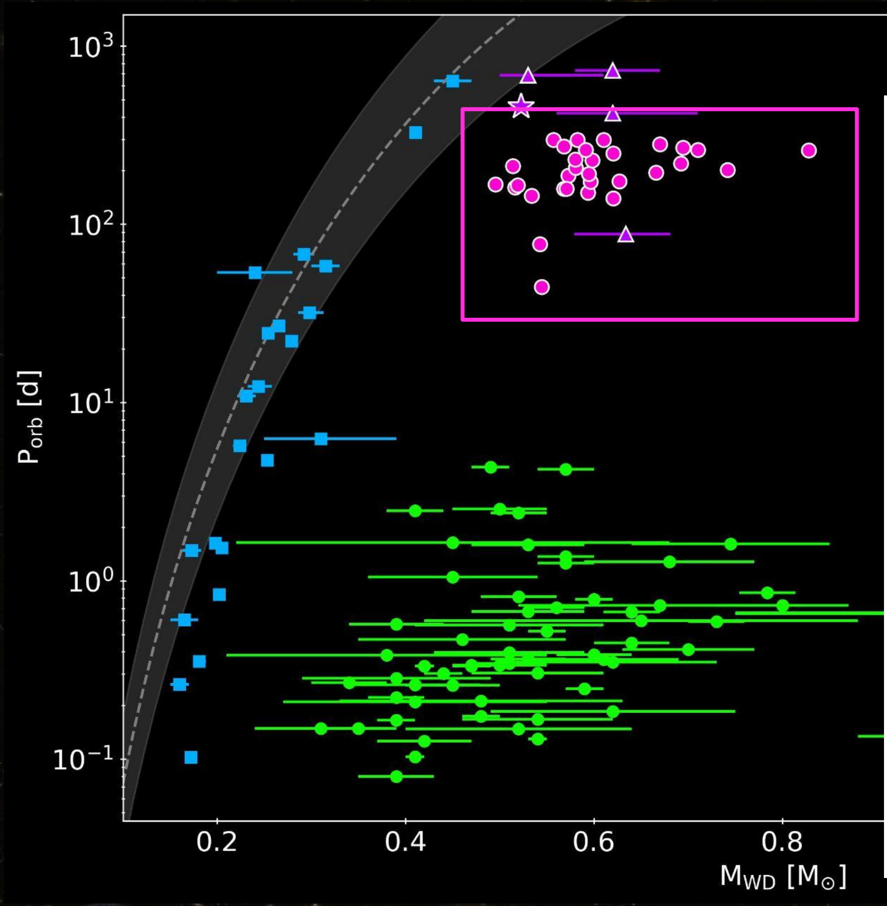


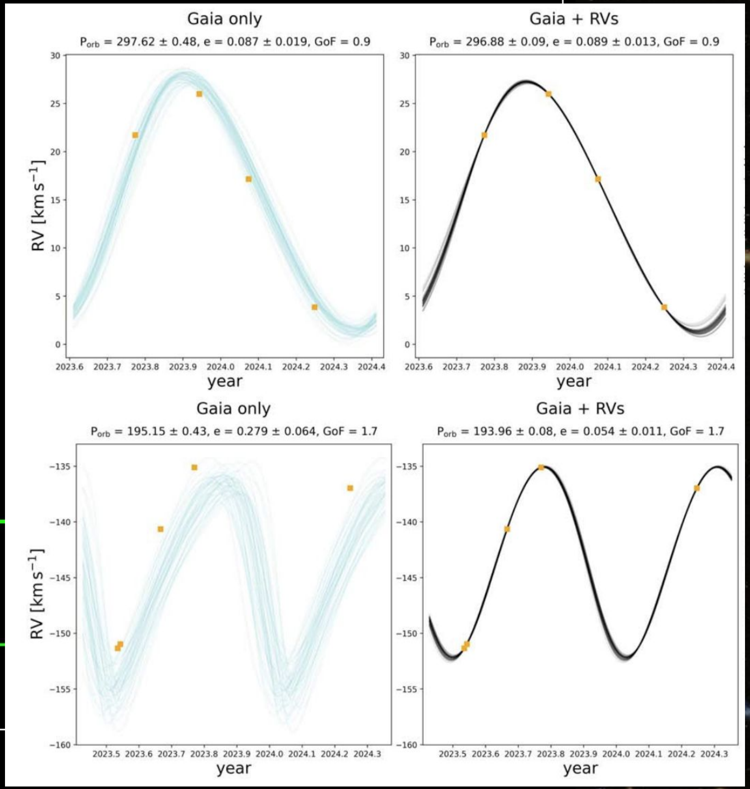
10^3
10^2
10^1
10^0
10^{-1}
P_{orb} [d]
0.2
0.4
0.6
0.8
1.0
1.2
1.4
M_{WD} [$M_\odot$]
IK Peg
Yamaguchi et al. (2024a):
IK Peg analogs, ultra-massive WD candidates, P_{orb} ~ months

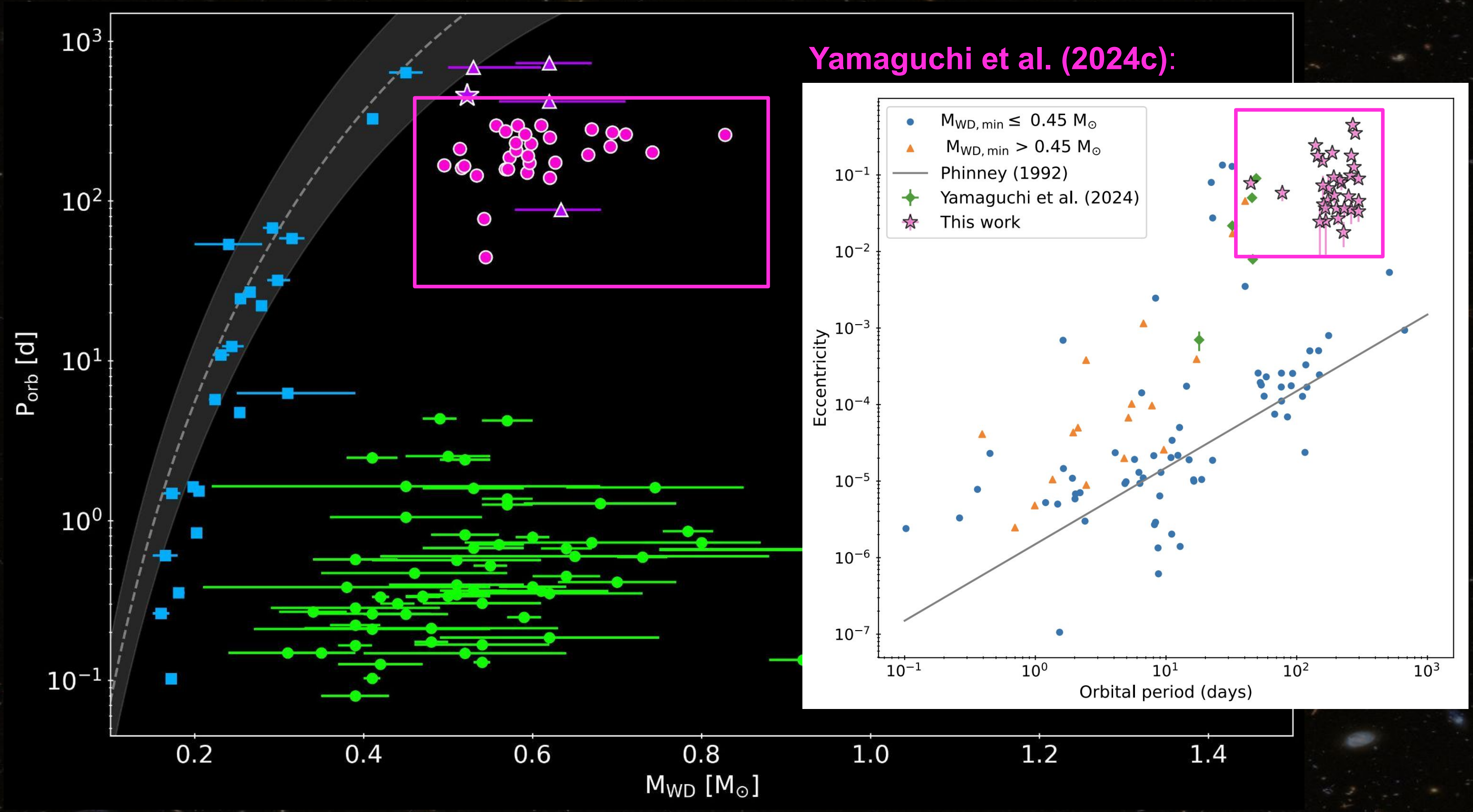


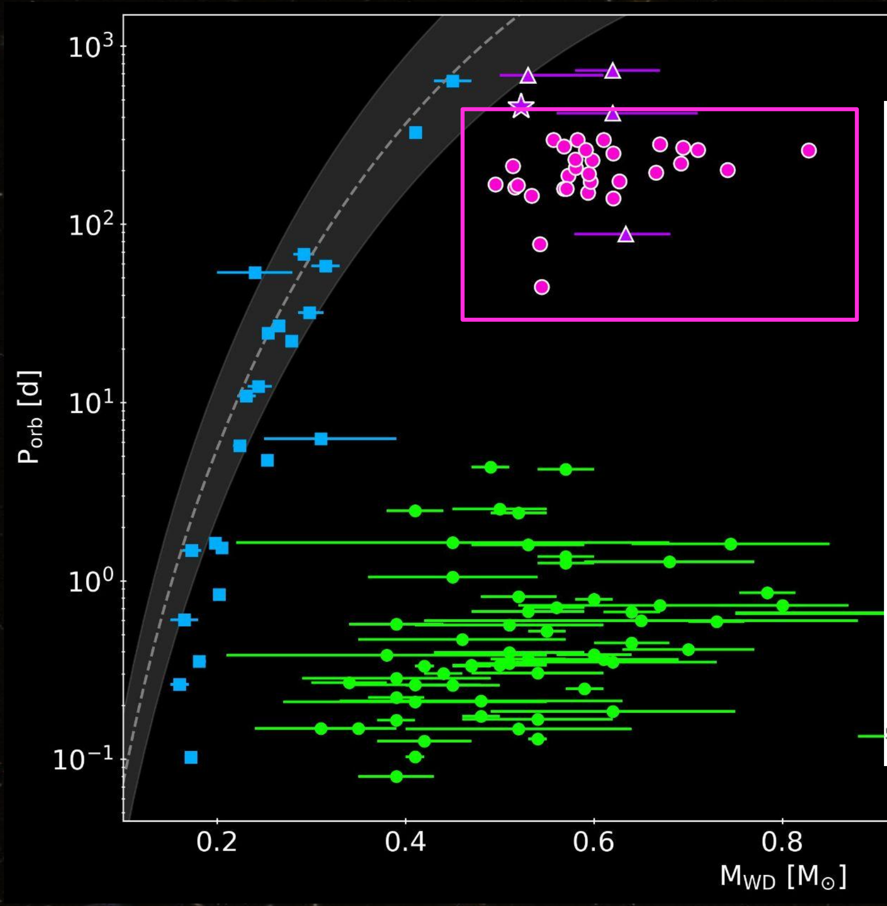
Yamaguchi et al. (2024c):
RV follow-up of 31 objects from the AMRF sample

Yamaguchi et al. (2024c):

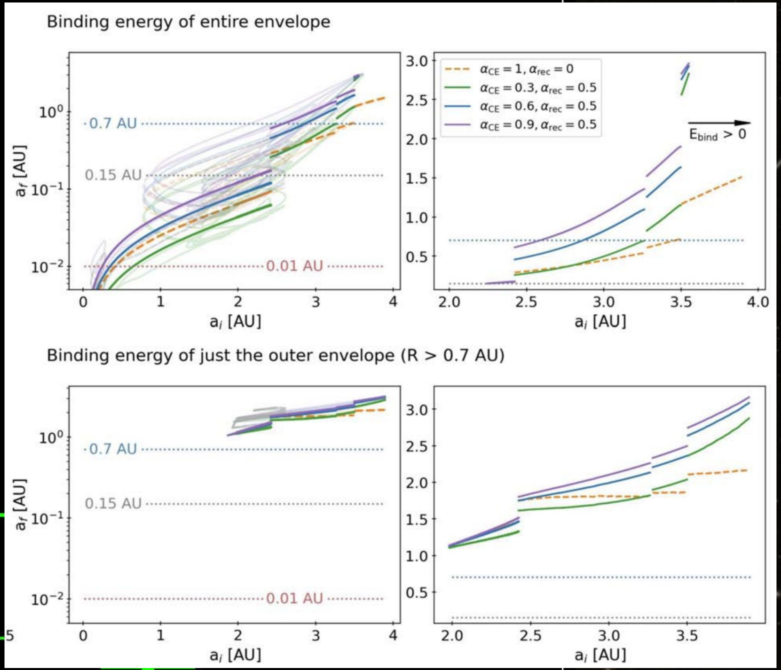





P_{orb} [d]
10^3
10^2
10^1
10^0
10^{-1}
0.2
0.4
0.6
0.8
1.0
1.2
1.4
M_{WD} [$M_\odot$]
Yamaguchi et al. (2024c):
$M_{WD, min} \leq$ 0.45 $M_\odot$
$M_{WD, min}$ > 0.45 $M_\odot$
Phinney (1992)
Yamaguchi et al. (2024)
This work
Eccentricity
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-1}
10^0
10^1
10^2
10^3
Orbital period (days)



Yamaguchi et al. (2024c):



Ongoing work: Constructing a mock AMRF Sample

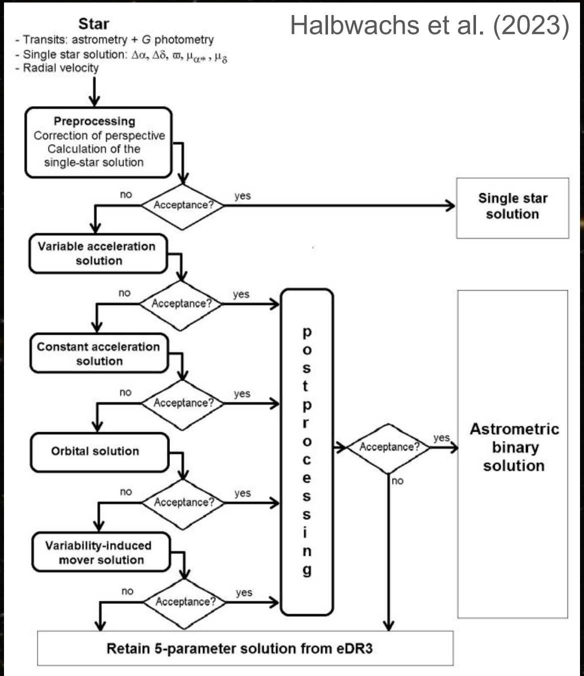
Lots of interesting systems discovered from Gaia DR3 NSS astrometric binaries catalog

…But how can we learn about the intrinsic population from these?

Ongoing work: Constructing a mock AMRF Sample

Lots of interesting systems discovered from Gaia DR3 NSS astrometric binaries catalog

…But how can we learn about the intrinsic population from these?

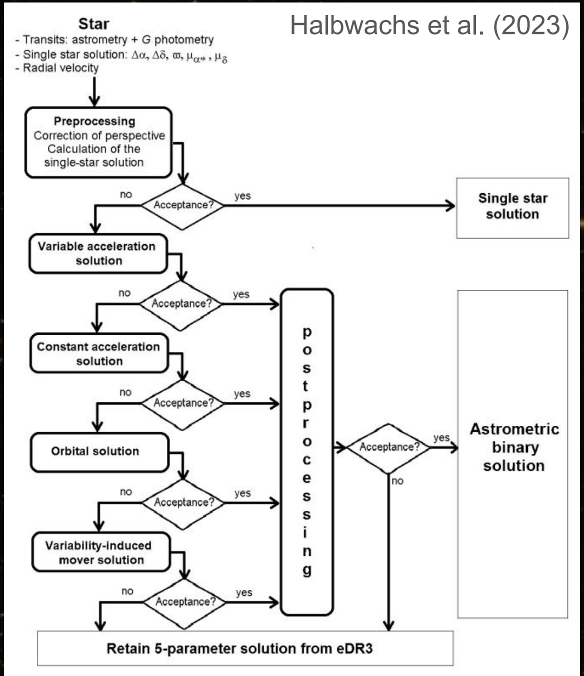


Ongoing work: Constructing a mock AMRF Sample

Lots of interesting systems discovered from Gaia DR3 NSS astrometric binaries catalog

…But how can we learn about the intrinsic population from these?

→ El-Badry et al. (2024): Forward model of the catalog



Synthetic stellar population
Galaxia + COSMIC

→ Gaia scanning law + noise →

Mock observations

→ Fit epoch astrometry, make cuts →

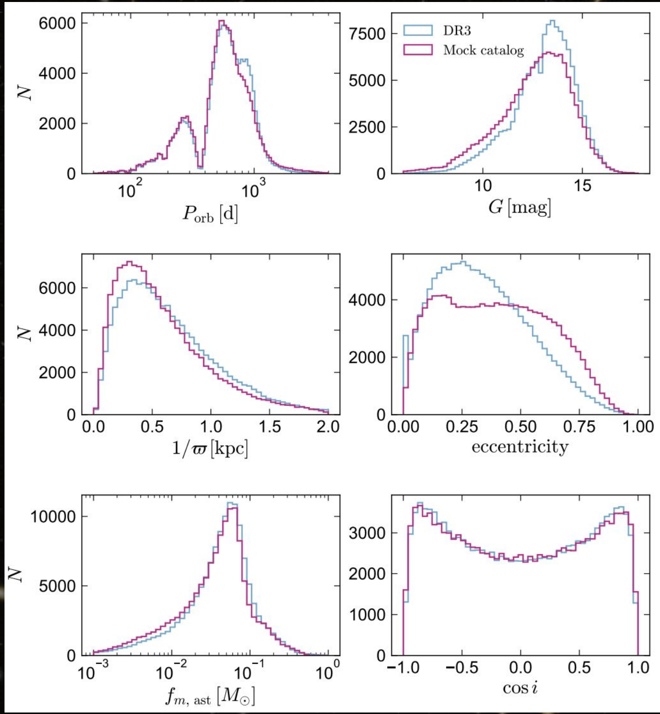
Mock NSS Catalog

Ongoing work: Constructing a mock AMRF Sample

Lots of interesting systems discovered from Gaia DR3 NSS astrometric binaries catalog

…But how can we learn about the intrinsic population from these?

→ El-Badry et al. (2024): Forward model of the catalog



Synthetic stellar population
Galaxia + COSMIC

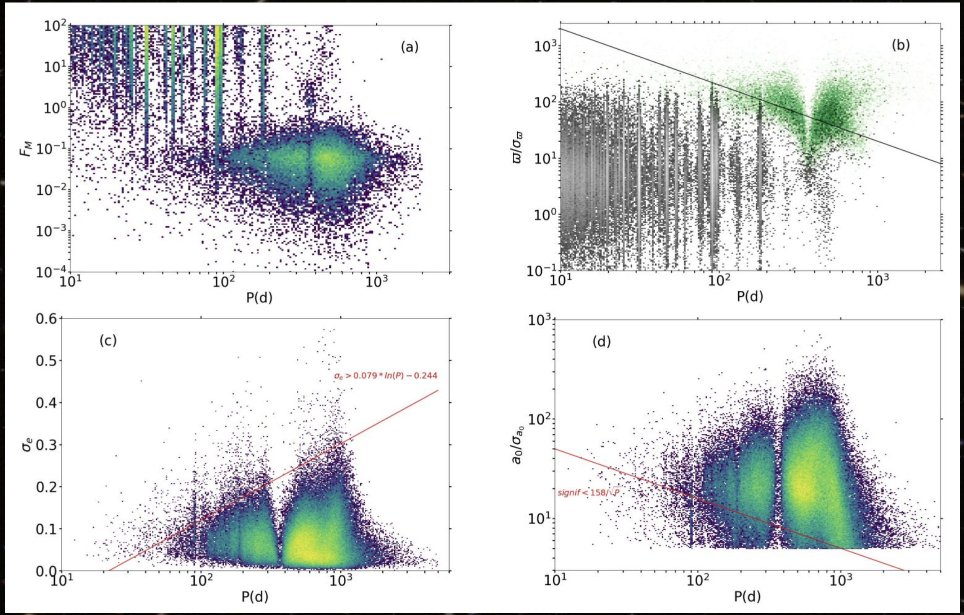
→ Gaia scanning law + noise →

Mock observations

→ Fit epoch astrometry, make cuts →

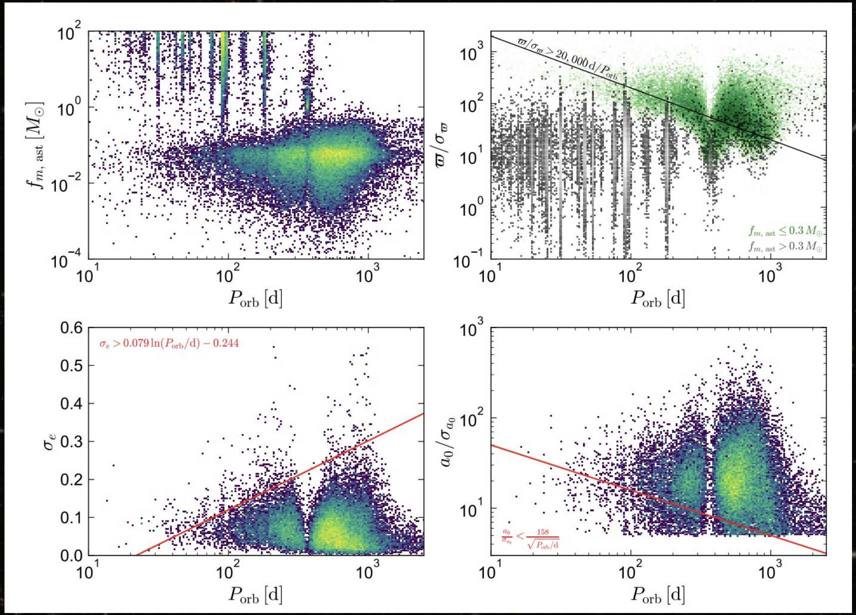
Mock NSS Catalog

REAL



(a)
(b)
(c)
(d)
F_M
ϖ/σ_ϖ
σ_e
a_0/σ_{a_0}
P(d)
$\sigma_e > 0.079 * ln(P) - 0.244$
$signif < 158/\sqrt{P}$

MOCK



$f_{m,\,\mathrm{ast}}\,[M_\odot]$
ϖ/σ_ϖ
$\varpi/\sigma_\varpi > 20,000\,\mathrm{d}/P_{\mathrm{orb}}$
$f_{m,\,\mathrm{ast}} \leq 0.3\,M_\odot$
$f_{m,\,\mathrm{ast}} > 0.3\,M_\odot$
σ_e
$\sigma_e > 0.079\ln(P_{\mathrm{orb}}/\mathrm{d}) - 0.244$
a_0/σ_{a_0}
$\frac{a_0}{\sigma_{a_0}} < \frac{158}{\sqrt{P_{\mathrm{orb}}/\mathrm{d}}}$
$P_{\mathrm{orb}}\,[\mathrm{d}]$

Ongoing work: Constructing a mock AMRF Sample

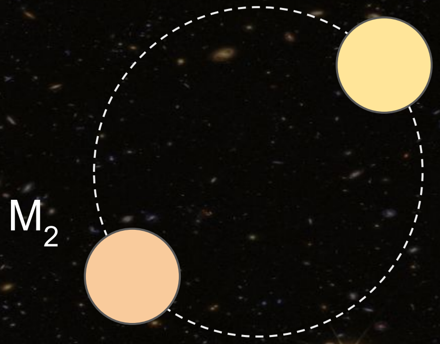
My plan: Extend this work to reproduce AMRF sample

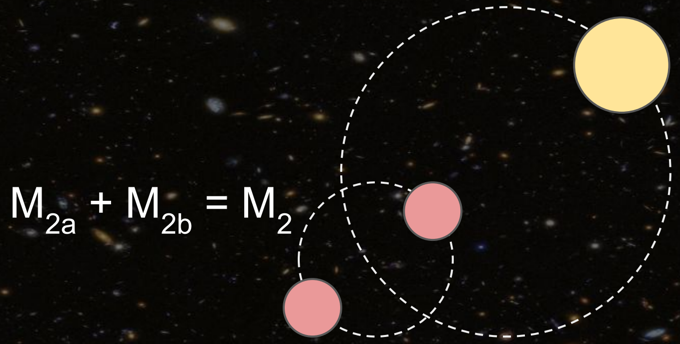
Ongoing work: Constructing a mock AMRF Sample

My plan: Extend this work to reproduce AMRF sample

Questions:

1. How many false candidates make it in? How many real ones are excluded?





Ongoing work: Constructing a mock AMRF Sample

My plan: Extend this work to reproduce AMRF sample

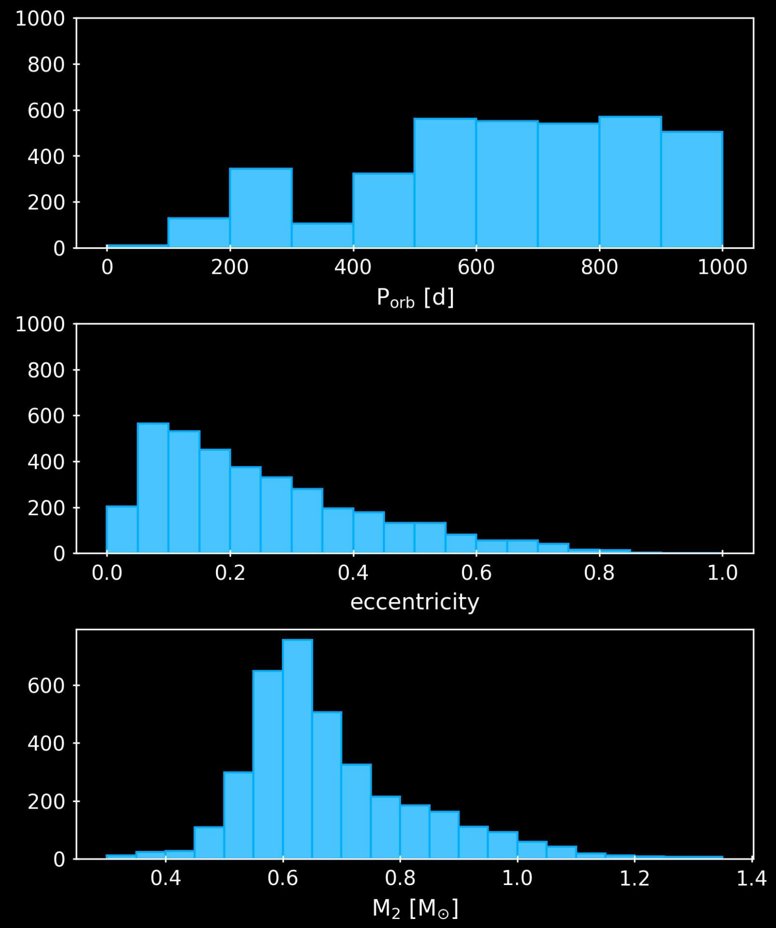
Questions:

1. How many false candidates make it in? How many real ones are excluded?
2. What period, eccentricity, and WD mass distributions best reproduce features of the real catalog?
3. Can we physically motivate these distributions?

Ongoing work: Constructing a mock AMRF Sample

Key properties of AMRF catalog:

- Large population with P_{orb} ~ 100 - 1000 d
- Many eccentric systems
- Deficit of high-mass WDs (Hallakoun et al. 2024)

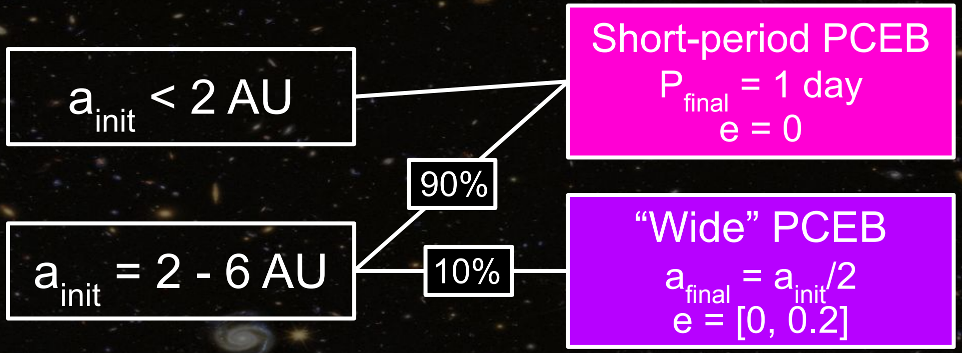


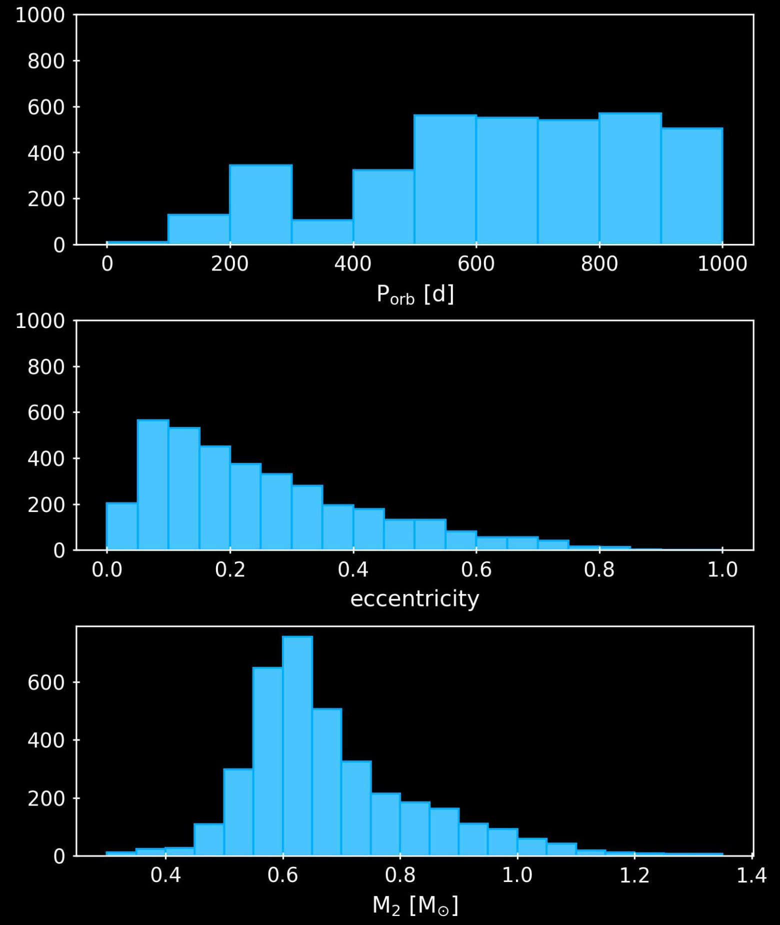
Ongoing work: Constructing a mock AMRF Sample

Key properties of AMRF catalog:

- Large population with P_{orb} ~ 100 - 1000 d
- Many eccentric systems
- Deficit of high-mass WDs (Hallakoun et al. 2024)

How was CEE handled in the original model?



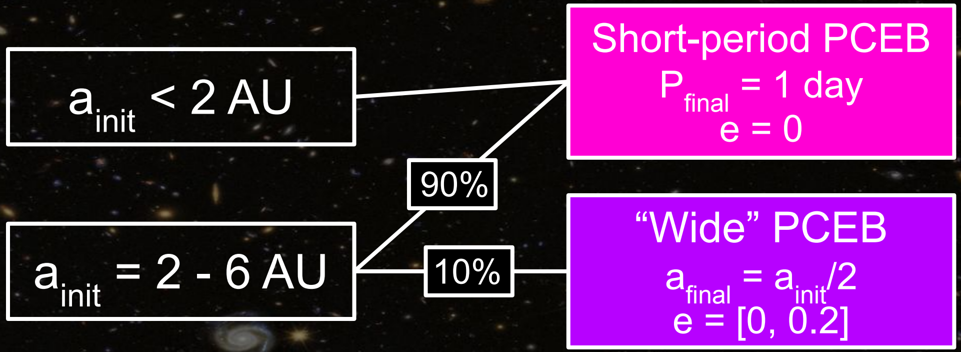


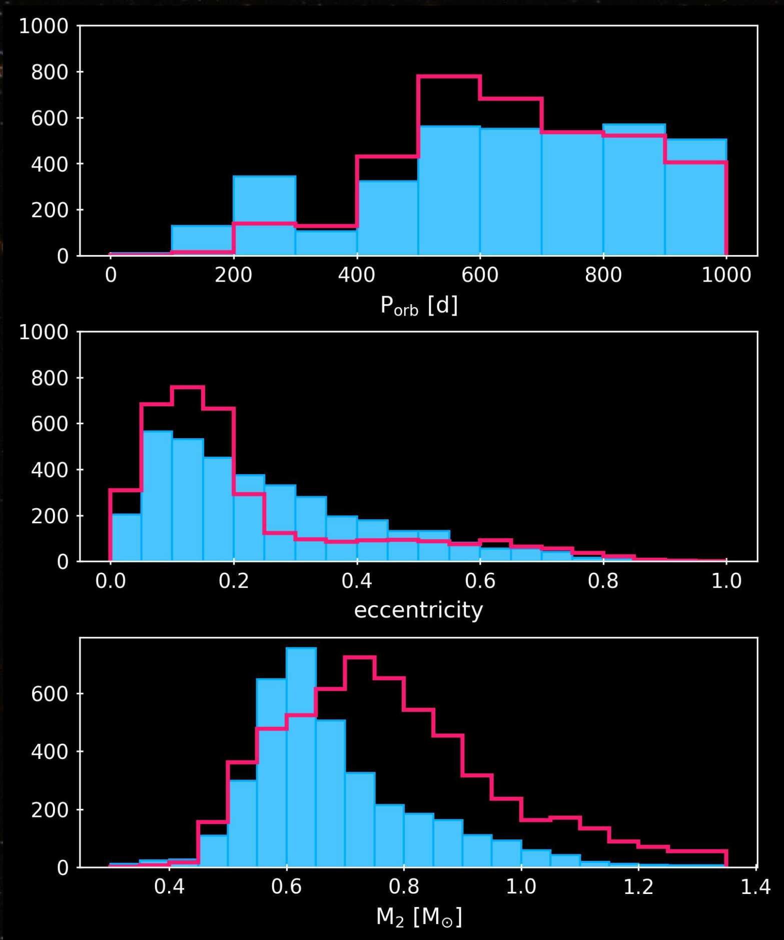
Ongoing work: Constructing a mock AMRF Sample

Key properties of AMRF catalog:

- Large population with P_{orb} ~ 100 - 1000 d
- Many eccentric systems
- Deficit of high-mass WDs (Hallakoun et al. 2024)

How was CEE handled in the original model?



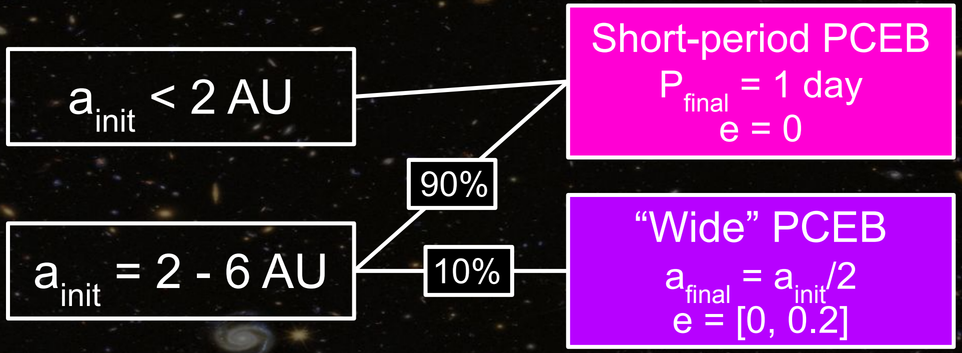


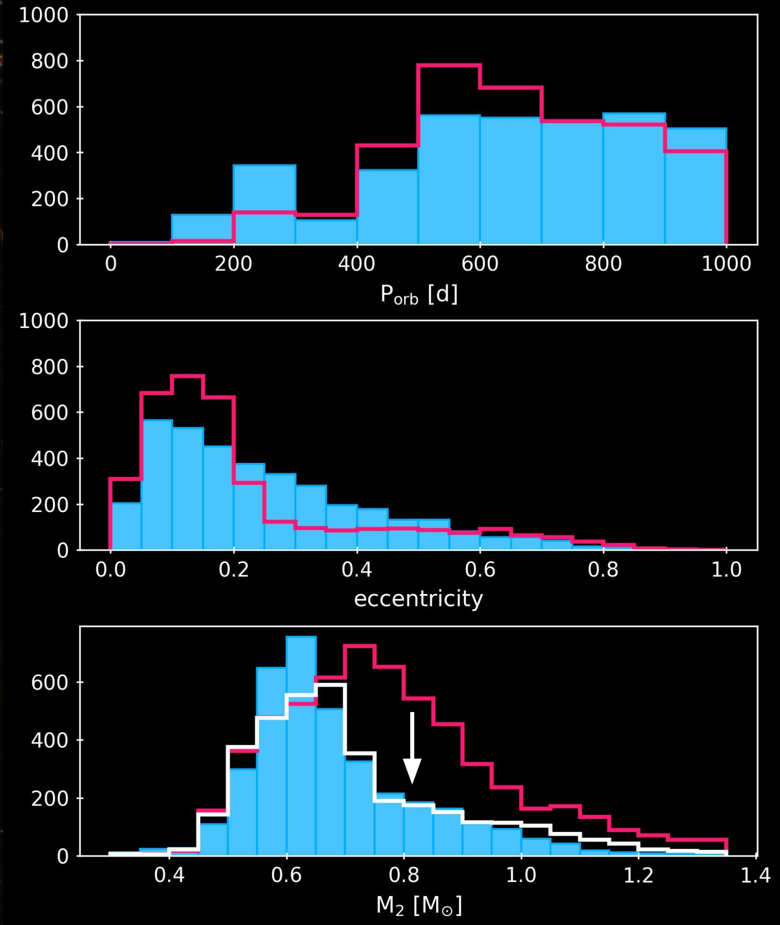
Ongoing work: Constructing a mock AMRF Sample

Key properties of AMRF catalog:

- Large population with P_{orb} ~ 100 - 1000 d
- Many eccentric systems
- Deficit of high-mass WDs (Hallakoun et al. 2024)

How was CEE handled in the original model?

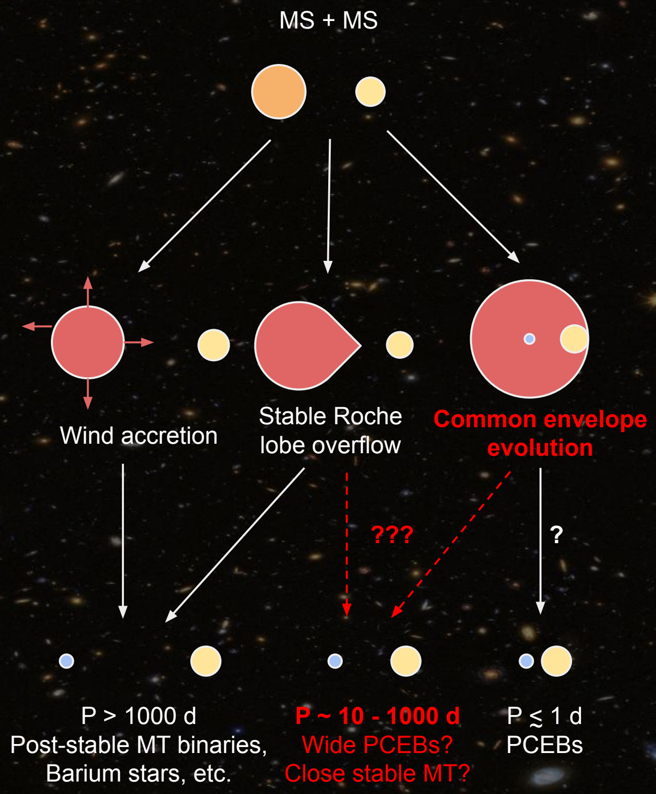





Ongoing wo
mock AMRF
Key properties of AM
Large populati
Many ecce
Deficit of hi
How was CEE ha
a init < 2 AU
a init = 2 - 6 AU
A forward model of Gaia DR3 WD + MS binaries
Natsuko Yamaguchi 1 and Kareem El-Badry 1
1 Department of Astronomy, California Institute of Technology, 1200 E. California Blvd, Pasadena, CA, 91125, USA
ABSTRACT
The third data release of the Gaia mission included astrometric orbital
binaries – an unparalleled dataset in which to look for hosts of
to the discovery of an abundance of white dwarf (WD)
orbital periods ranging from ~ 100 – 1000 d.
transfer is expected to have occ
but which is intermedi
envelope bi
The abundance of these AU-scale WD + MS binaries were unexpected, given the standard picture of binary evolution. While their separations are too close to have avoided interaction when the WD progenitor was on the asymptotic giant branch (AGB), implying they are post-mass transfer (MT) systems, their orbits are
are made
utions and where a
model is only fit if simpler solu-
provide a sufficiently good fit to the data.
means that while the published orbits have been shown to be largely reliable (Yamaguchi et al. 2024a), many true binaries do not make it into the NSS catalog. Therefore, the selection function of this catalog, as well as any of its products, is complex.
However, recently, El-Badry et al. (2024a) took a forward modeling approach to tackle this problem. Starting with a model of the galactic stellar population, they got synthetic Gaia observations for each source which they ran through an analysis pipeline similar to that used by the collaboration to end up with a mock NSS catalog. They showed that the distributions of orbital
dwarf
with orbital pe-
days, corresponding to
COMING SOON!
600
800
1000
P orb [d]
0.6
0.8
1.0
eccentricity
0.8
1.0
1.2
1.4
M 2 [M ⊙]

To summarize…

- Close WD + MS binaries are useful probes of binary evolution
- Gaia DR3 lead to the discovery of a large population of AU-scale WD + MS binaries
  - Intermediate to standard predictions of stable vs. unstable MT
- My work aims to explore various aspects of this population to learn about their MT histories
  - Spectroscopic follow-up
  - 1D stellar evolution models
  - Forward modeling



References

Akira Rocha K., et al., 2024, arXiv e-prints, p. arXiv:2411.11840
Bhat A., Bauer E. B., Pakmor R., Shen K. J., Caiazzo I., Rajamuthukumar A. S., El-Badry K., Kerzendorf W. E., 2024, arXiv e-prints, p. arXiv:2407.03424
Bidelman W. P., Keenan P. C., 1951, , 114, 473
Breivik K., et al., 2020, , 898, 71
Bronner V. A., Schneider F. R. N., Podsiadlowski P., Röpke F. K., 2024, , 683, A65
Busso M., Gallino R., Wasserburg G. J., 1999, , 37, 239
Davis P. J., Kolb U., Knigge C. ., 2011, in Schmidtobreick L., Schreiber M. R., Tappert C., eds, Astronomical Society of the Pacific Conference Series Vol. 447, Evolution of Compact Binaries. p. 115
Delfosse X., Forveille T., Beuzit J. L., Udry S., Mayor M., Perrier C., 1999, , 344, 897
El-Badry K., Rix H.-W., Weisz D. R., 2018, , 860, L17
El-Badry K., et al., 2023a, The Open Journal of Astrophysics, 6, 28
El-Badry K., et al., 2023b, , 518, 1057
El-Badry K., et al., 2023c, , 521, 4323
El-Badry K., et al., 2024a, The Open Journal of Astrophysics, 7, 58
El-Badry K., et al., 2024b, The Open Journal of Astrophysics, 7, 58
El-Badry K., Lam C., Holl B., Halbwachs J.-L., Rix H.-W., Mazeh T., Shahaf S., 2024c, The Open Journal of Astrophysics, 7, 100
Escorza A., et al., 2019, , 626, A128
Foreman-Mackey D., Morton T. D., Hogg D. W., Agol E., Schölkopf B., 2016, , 152, 206
Gao S.-J., Li X.-D., 2023, , 525, 2605
Ge H., Webbink R. F., Chen X., Han Z., 2015, , 812, 40
Glanz H., Perets H. B., 2021, , 507, 2659
Grichener A., Sabach E., Soker N., 2018, , 478, 1818
Grondin S. M., Webb J. J., Leigh N. W. C., Speagle J. S., Khalifeh R. J., 2023, , 518, 4249
Grondin S. M., Drout M. R., Nordhaus J., Muirhead P. S., Speagle J. S., Chornock R., 2024, , 976, 102
Hadjidemetriou J. D., 1969, , 3, 31
Halbwachs J.-L., et al., 2023, , 674, A9
Hallakoun N., Shahaf S., Mazeh T., Toonen S., Ben-Ami S., 2024, , 970, L11
Hamers A. S., Dosopoulou F., 2019, , 872, 119
Hernandez M. S., et al., 2021, , 501, 1677
Hernandez M. S., et al., 2022, , 517, 2867
Hjellming M. S., Webbink R. F., 1987, , 318, 794
Hurley J. R., Tout C. A., Pols O. R., 2002, , 329, 897
Ivanova N., 2018, , 858, L24
Ivanova N., et al., 2013, , 21, 59
Ivanova N., Justham S., Podsiadlowski P., 2015, , 447, 2181
Jorissen A., Mayor M., 1988, , 198, 187
Käppeler F., Gallino R., Bisterzo S., Aoki W., 2011, Reviews of Modern Physics, 83, 157
Kawahara H., Masuda K., MacLeod M., Latham D. W., Bieryla A., Benomar O., 2018, , 155, 144
Kharchenko N. V., Piskunov A. E., Schilbach E., Röser S., Scholz R. D., 2013, , 558, A53
Kruse E., Agol E., 2014, Science, 344, 275
Langer N., Wellstein S., Petrovic J., 2003, in van der Hucht K., Herrero A., Esteban C., eds, IAU Symposium Vol. 212, A Massive Star Odyssey: From Main Sequence to Supernova. p. 275
Leibovitz C., Hube D. P., 1971, , 15, 251
Liu Z.-W., Röpke F. K., Han Z., 2023, Research in Astronomy and Astrophysics, 23, 082001
Livio M., Soker N., 1988, , 329, 764
Lucy L. B., 1967, , 72, 813
Maeder A., 1973, , 26, 215
Masuda K., Kawahara H., Latham D. W., Bieryla A., Kunitomo M., MacLeod M., Aoki W., 2019, , 881, L3
McClure R. D., 1983, , 268, 264
McClure R. D., Woodsworth A. W., 1990, , 352, 709
McClure R. D., Fletcher J. M., Nemec J. M., 1980, , 238, L35
Moe M., Kratter K. M., Badenes C., 2019, , 875, 61
Paczyński B., 1965, , 15, 89
Paczynski B., 1976, in Eggleton P., Mitton S., Whelan J., eds, IAU Symposium Vol. 73, Structure and Evolution of Close Binary Systems. p. 75
Paczyński B., Ziółkowski J., 1967, , 17, 7
Paczyński B., Ziółkowski J., 1968, in Osterbrock D. E., O'Dell C. R., eds, IAU Symposium Vol. 34, Planetary Nebulae. p. 396
Passy J.-C., Herwig F., Paxton B., 2012, , 760, 90
Pavlovskii K., Ivanova N., 2015, , 449, 4415
Raddi R., Hollands M. A., Gänsicke B. T., Townsley D. M., Hermes J. J., Gentile Fusillo N. P., Koester D., 2018, , 479, L96
Rappaport S., Podsiadlowski P., Joss P. C., Di Stefano R., Han Z., 1995, , 273, 731
Rebassa-Mansergas A., et al., 2017, , 472, 4193
Rekhi P., Ben-Ami S., Hallakoun N., Shahaf S., Toonen S., Rix H.-W., 2024, , 973, L56
Sabach E., Hillel S., Schreier R., Soker N., 2017, , 472, 4361
Sana H., et al., 2012, Science, 337, 444
Sand C., Ohlmann S. T., Schneider F. R. N., Pakmor R., Röpke F. K., 2020, , 644, A60
Sarna M. J., 1993, , 262, 534
Scherbak P., Fuller J., 2023, , 518, 3966
Sepinsky J. F., Willems B., Kalogera V., Rasio F. A., 2007, , 667, 1170
Shahaf S., Mazeh T., Faigler S., Holl B., 2019, , 487, 5610
Shahaf S., Bashi D., Mazeh T., Faigler S., Arenou F., El-Badry K., Rix H. W., 2023, , 518, 2991
Shahaf S., Hallakoun N., Mazeh T., Ben-Ami S., Rekhi P., El-Badry K., Toonen S., 2024, , 529, 3729
Shen K. J., et al., 2018, , 865, 15
Tauris T. M., van den Heuvel E. P. J., 2006, in Lewin W. H. G., van der Klis M., eds, , Vol. 39, Compact stellar X-ray sources. pp 623–665, doi:10.48550/arXiv.astro-ph/0303456
Temmink K. D., Pols O. R., Justham S., Istrate A. G., Toonen S., 2023, , 669, A45
Tout C. A., Aarseth S. J., Pols O. R., Eggleton P. P., 1997, , 291, 732
Trani A. A., Rieder S., Tanikawa A., Iorio G., Martini R., Karelin G., Glanz H., Portegies Zwart S., 2022, , 106, 043014
Webbink R. F., 1985, in Pringle J. E., Wade R. A., eds, , Interacting Binary Stars. p. 39
Wonnacott D., Kellett B. J., Stickland D. J., 1993, , 262, 277
Yamaguchi N., El-Badry K., Ciardi D. R., Latham D. W., Masuda K., Bieryla A., Clark C. A., Condon S. S., 2024a, , 136, 074201
Yamaguchi N., El-Badry K., Rees N. R., Shahaf S., Mazeh T., Andrae R., 2024b, , 136, 084202
Yamaguchi N., et al., 2024c, , 527, 11719
Zorotovic M., Schreiber M., 2022, , 513, 3587
Zorotovic M., Schreiber M. R., Gänsicke B. T., Nebot Gómez-Morán A., 2010, , 520, A86
de Mink S. E., Pols O. R., Hilditch R. W., 2007, , 467, 1181