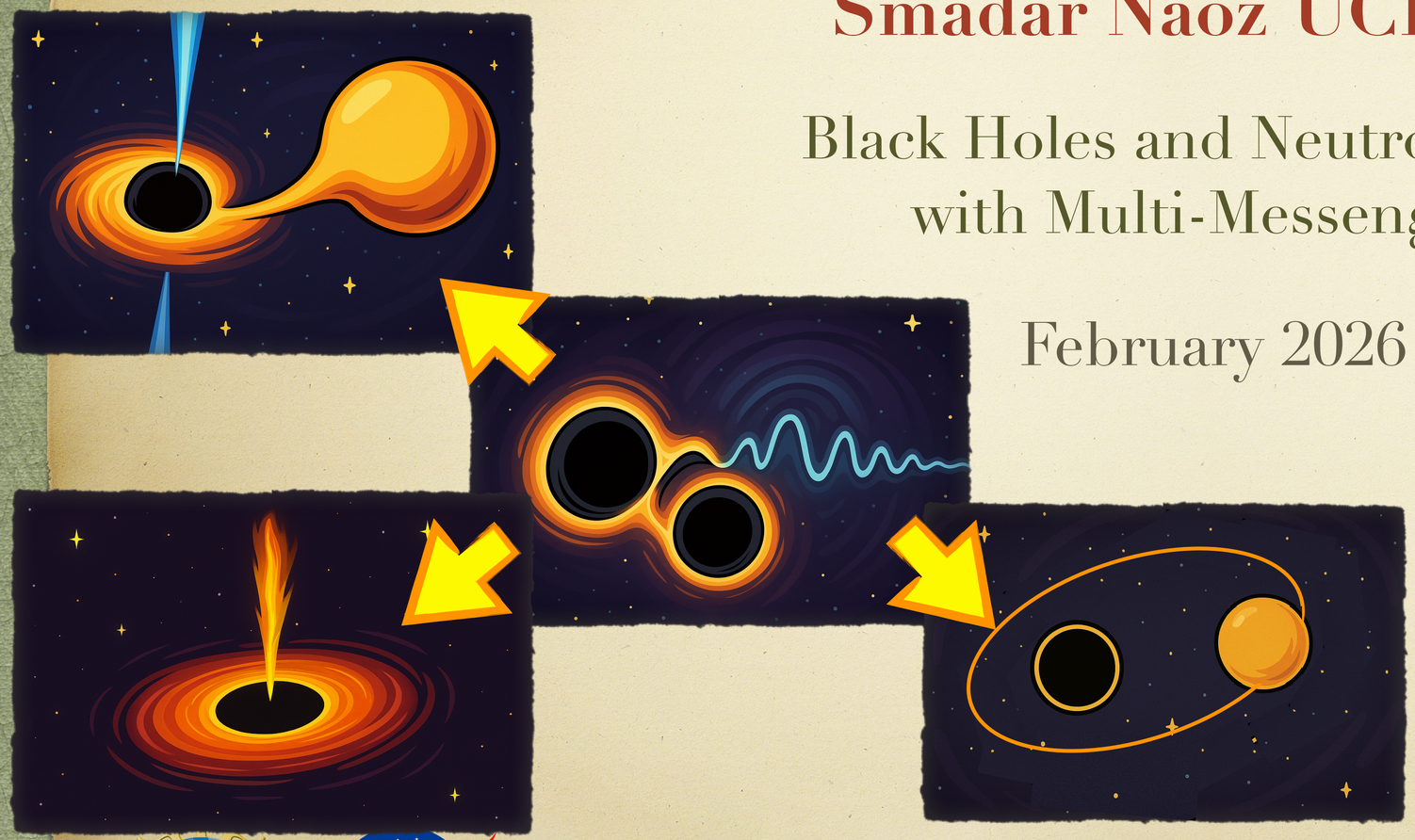
The Triple Connection: Black Hole Mergers, Electromagnetic Signatures, and Galactic Black Holes

Smadar Naoz UCLA



Black Holes and Neutron Stars
with Multi-Messengers

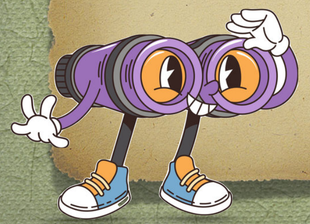
February 2026

Collaborators: Andrea Ghez, Mike Grudić, Anna Ciurlo, Avi Loeb, Bence Kocsis, Blakesley Burkhart, Carl Rodriguez, Cliff Will, Eliot Quataert, Enrico Ramirez-Ruiz, Federico Marinacci, Fred Rasio, Gongjie Li, Jess McIver, Joe Silk, Katie Breivik, Kareem El-Badry, Mark Morris, Mark Vogelsberger, Naoki Yoshida, Tommaso Treu, Tuan Do, Vicky Kalogera, Will Farr, Yoram Lithwick, Zoltan Haiman… + My group

Special thanks to Howard and Astrid Preston for their generous support

Seeing stellar mass black holes

x-ray binary



e.g., Giacconi et al. (1962), Fabbiano (2006), McClintock & Remillard (2006), Corral-Santana et al. (2016), Ingram & Motta (2019), Harrison et al. (2020), Fortin et al. (2024)

Seeing stellar mass black holes

e.g., Abbott et al. (2016), LIGO Scientific Collaboration (2025), etc.

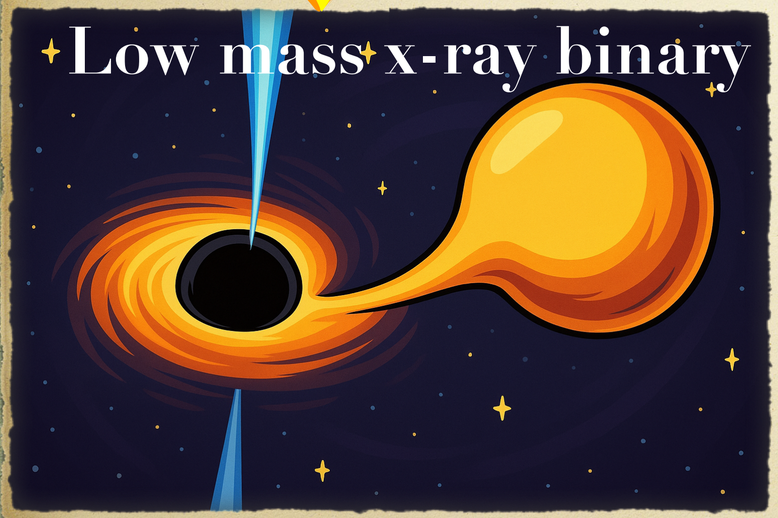
e.g., Agol et al. (2002); Lu et al. (2016), Lam et al. (2022), Sahu et al.(2022)

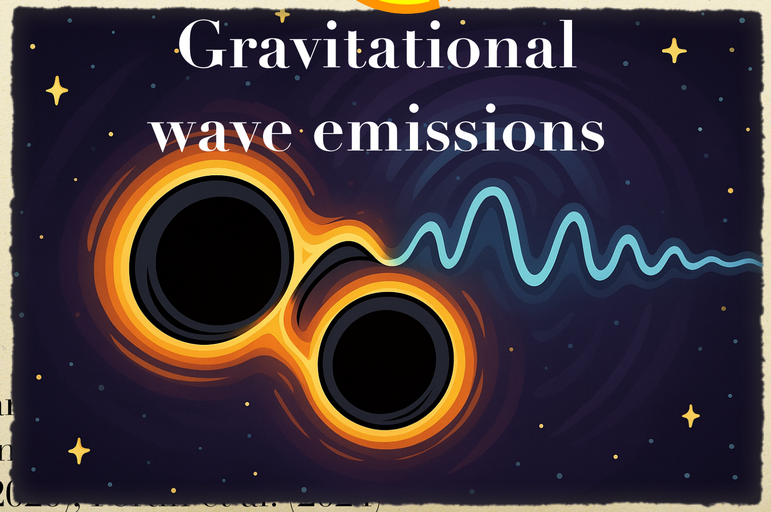
Also: **RVs** + **photometric**, e.g., Thompson et al. 2019; Chawla et al. 2024

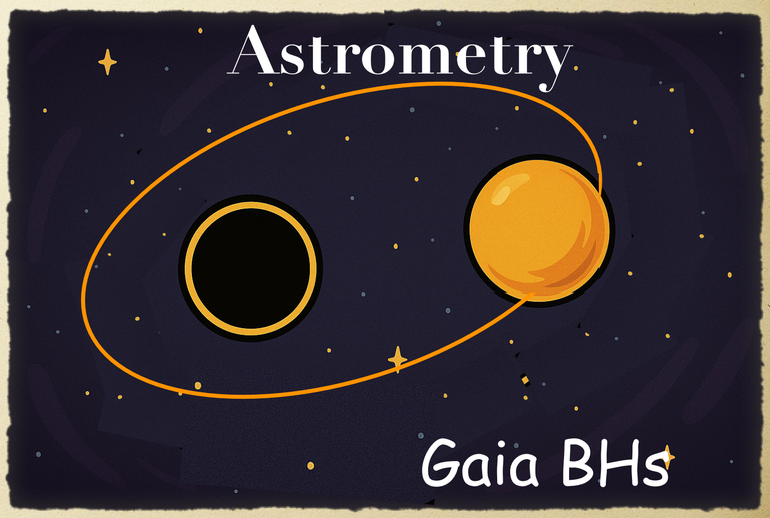
e.g., Zevin et al. (2021), Fishbach & Kalogera (2022), Fishbach et al. (2025).

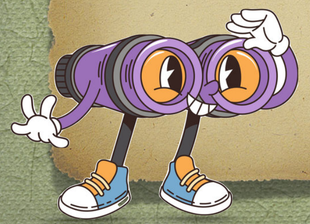
Connection?

Connection?





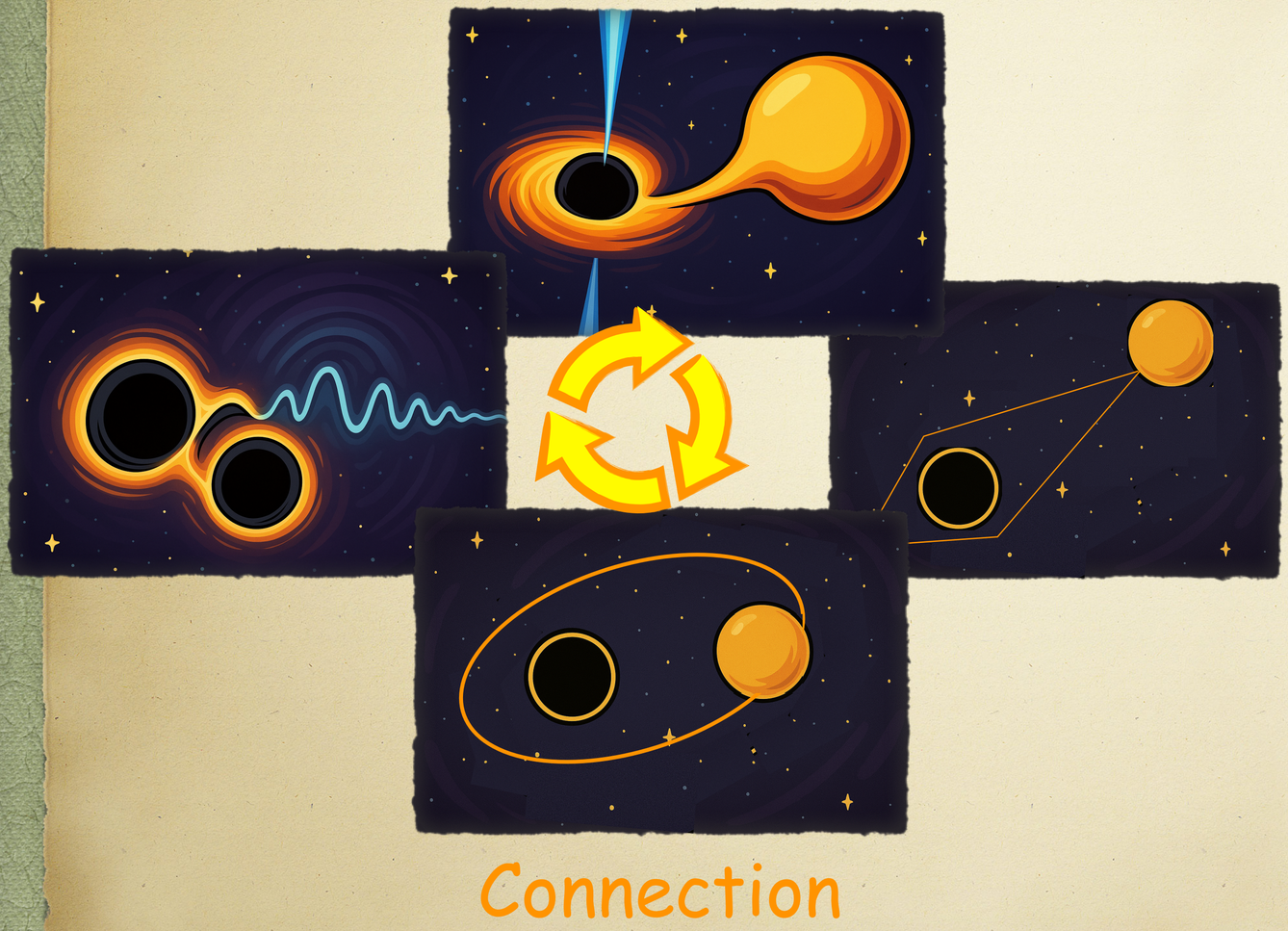




e.g., Giacconi et al. (1962), Fabbian
Remillard (2006), Corral-Santan
& Motta (2019), Harrison et al. (20

e.g., El-Badry et al. (2023), Gaia Collaboration et al. (2024)

Outline



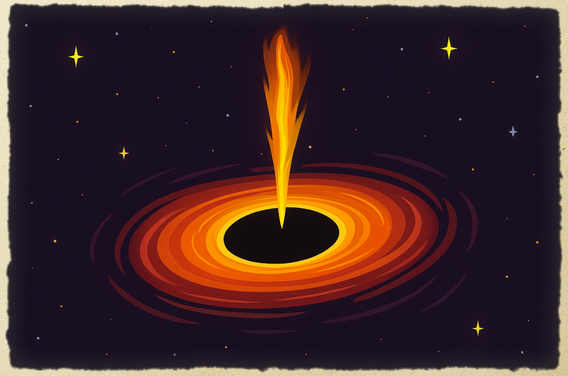
Connection

Possible formation channels

Propose a connection

+

Prediction

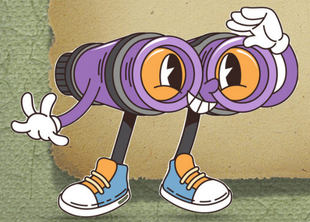


Seeing stellar mass black holes

Low mass x-ray binary

We need a binary!

Formation ideas:



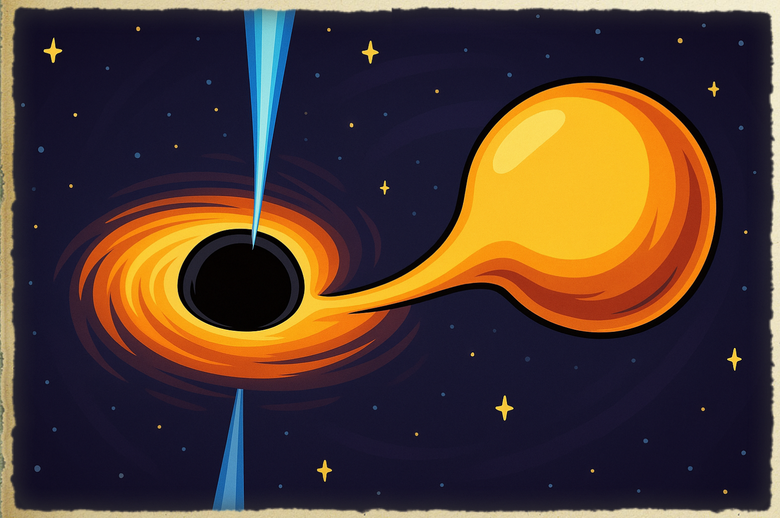
See also: Raghavan et al 2010; Sana et al. 2012; Moe & Di Stefano 2017;

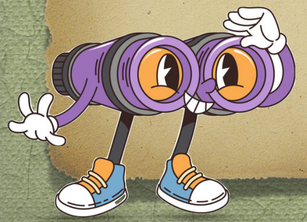
Low mass x-ray binary

Formation ideas:

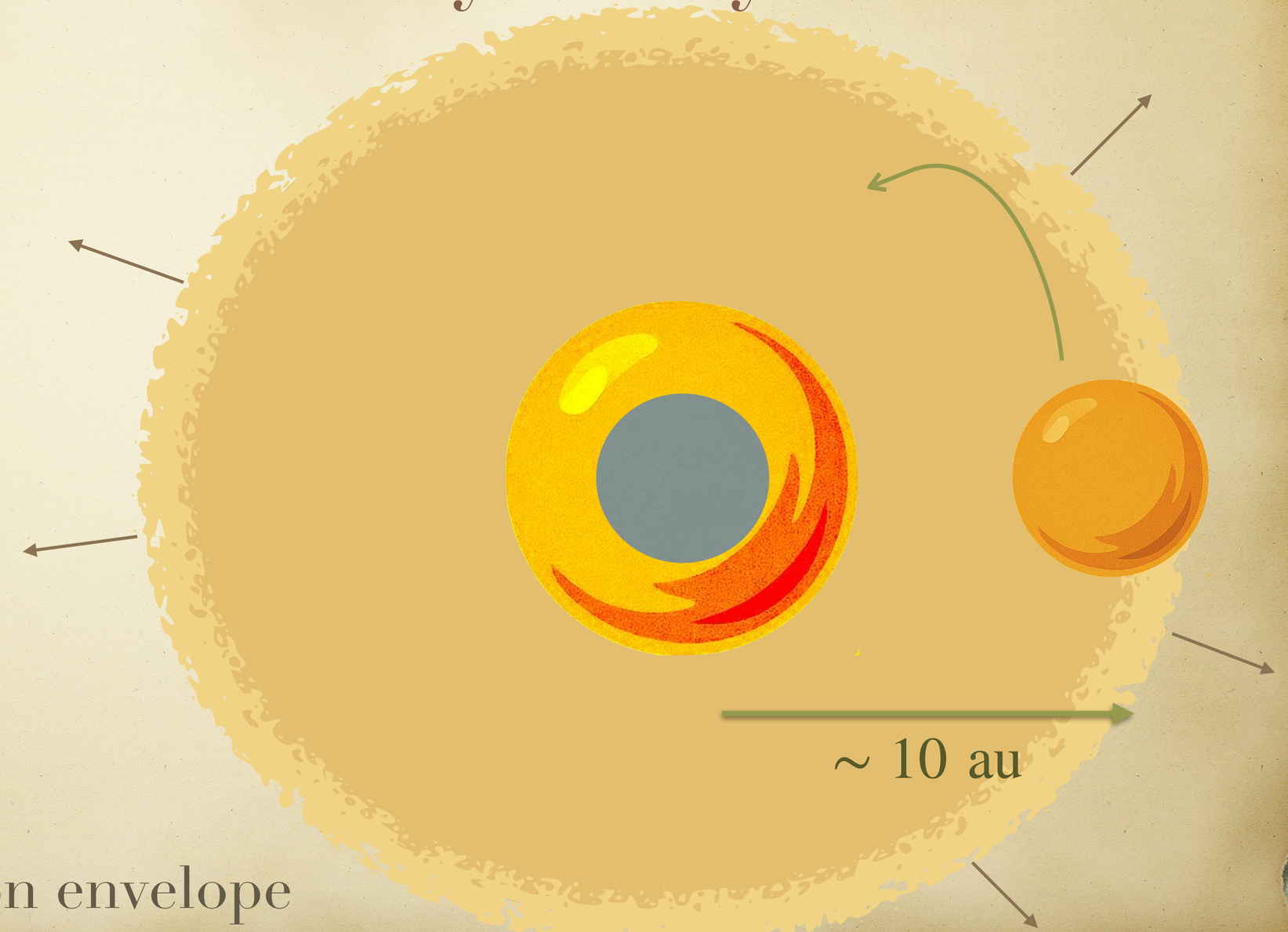
Binary channel

e.g., Podsiadlowski et al. 2003, 2010; Kiel & Hurley 2006; Ivanova et al. 2013; 2015; Wong et al. 2014; Kimball et al. 2023





Common envelope

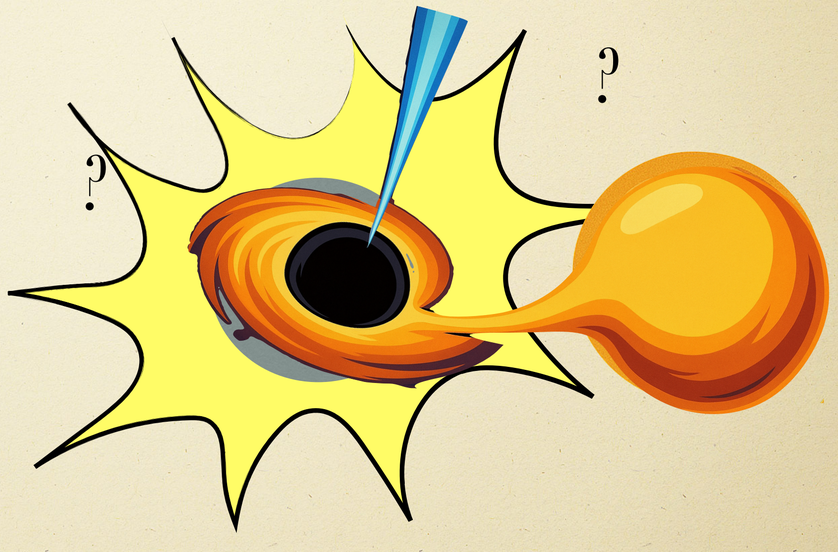


Low mass x-ray binary

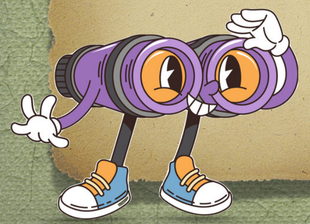
Formation ideas:

Binary channel

e.g., Podsiadlowski et al. 2003, 2010; Kiel & Hurley 2006; Ivanova et al. 2013; 2015; Wong et al. 2014; Kimball et al. 2023



~ much smaller



Low mass x-ray binary

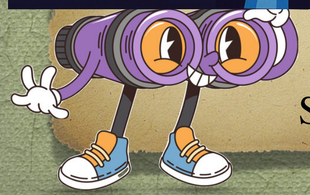
Why triples?

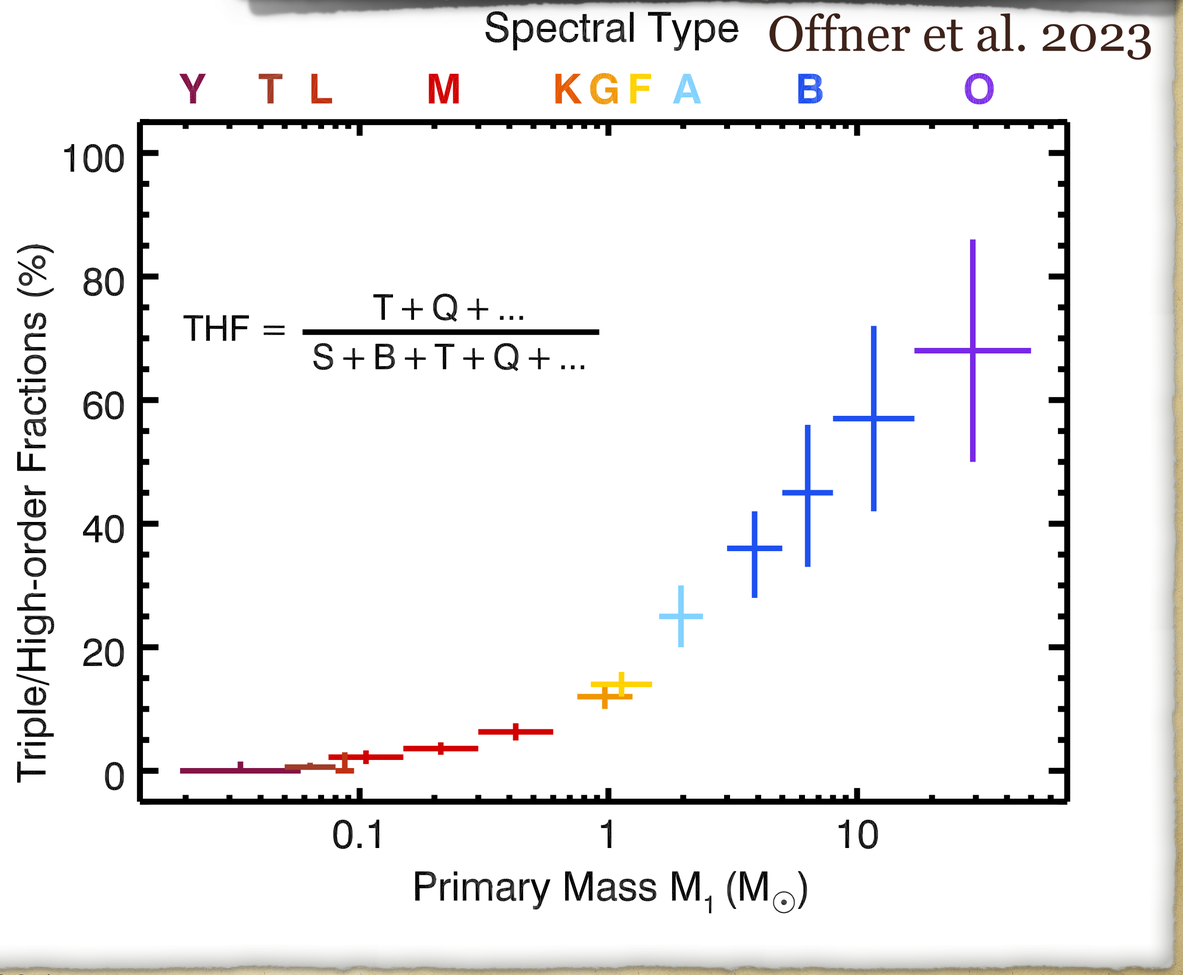
Most (~70%) Massive Stars are Born in Triples+

Formation ideas:

Triple channel

No Common envelope

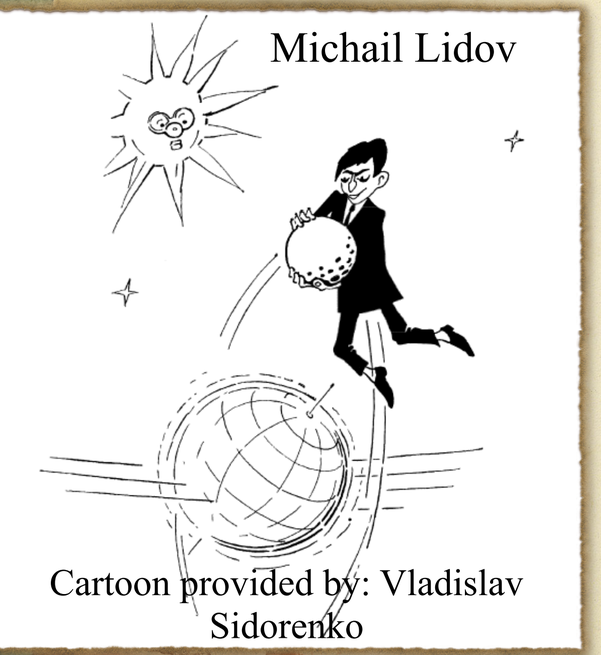




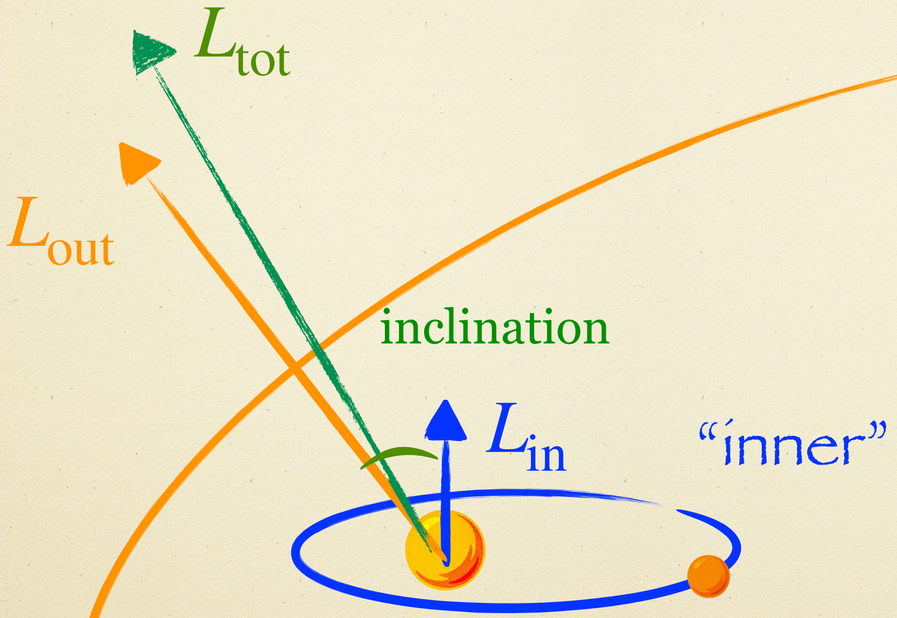
See also: Moe & Di Stefano 2017; Shariat, El-Badry, **Naoz** 2025

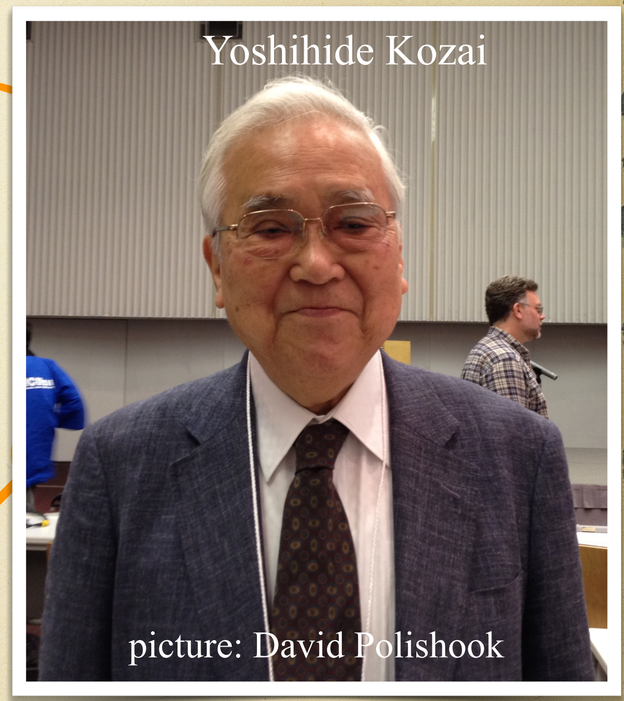
Hierarchical triple system

Kozai 1962, Lidov 1962



Cartoon provided by: Vladislav Sidorenko



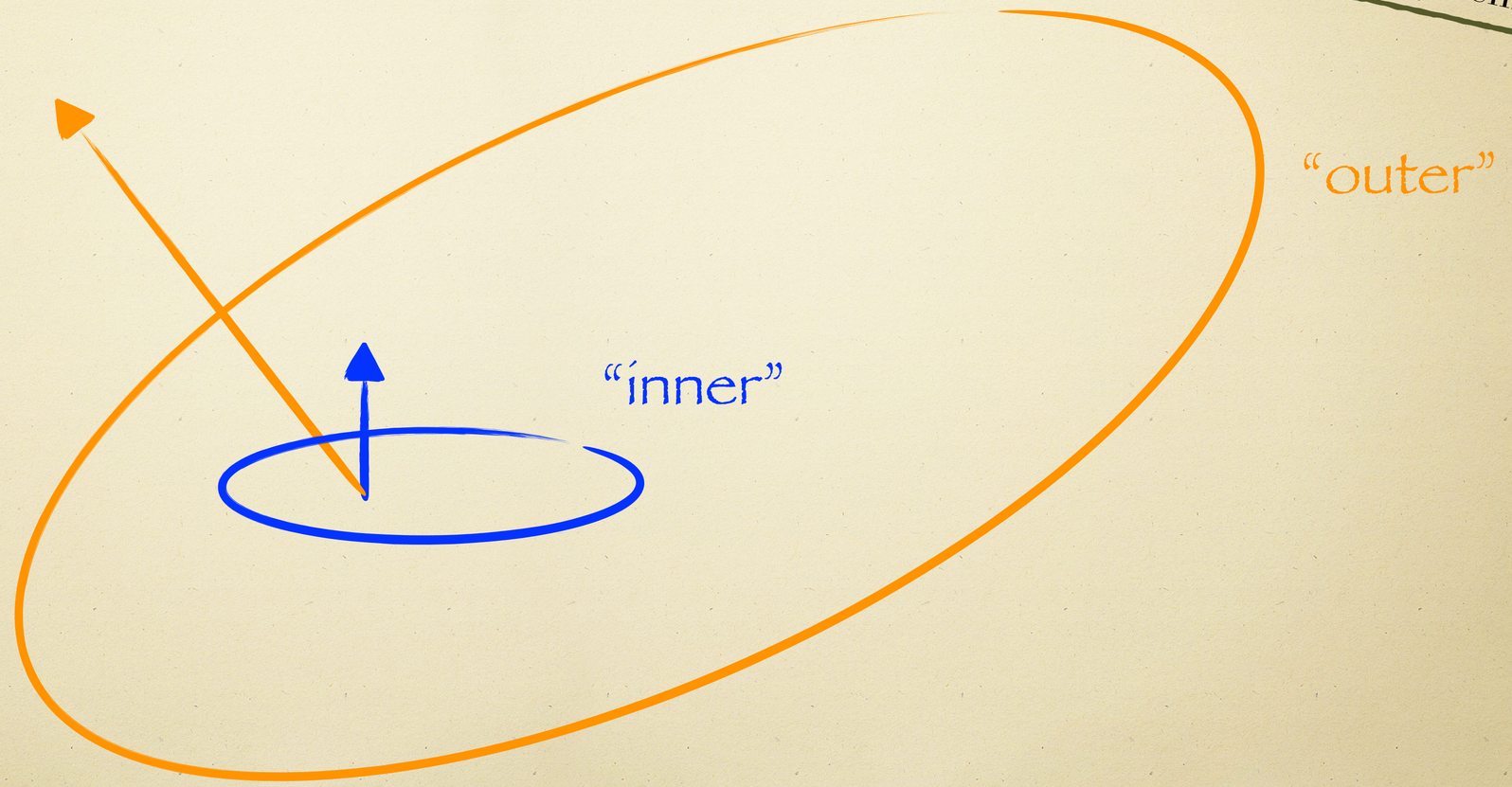


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

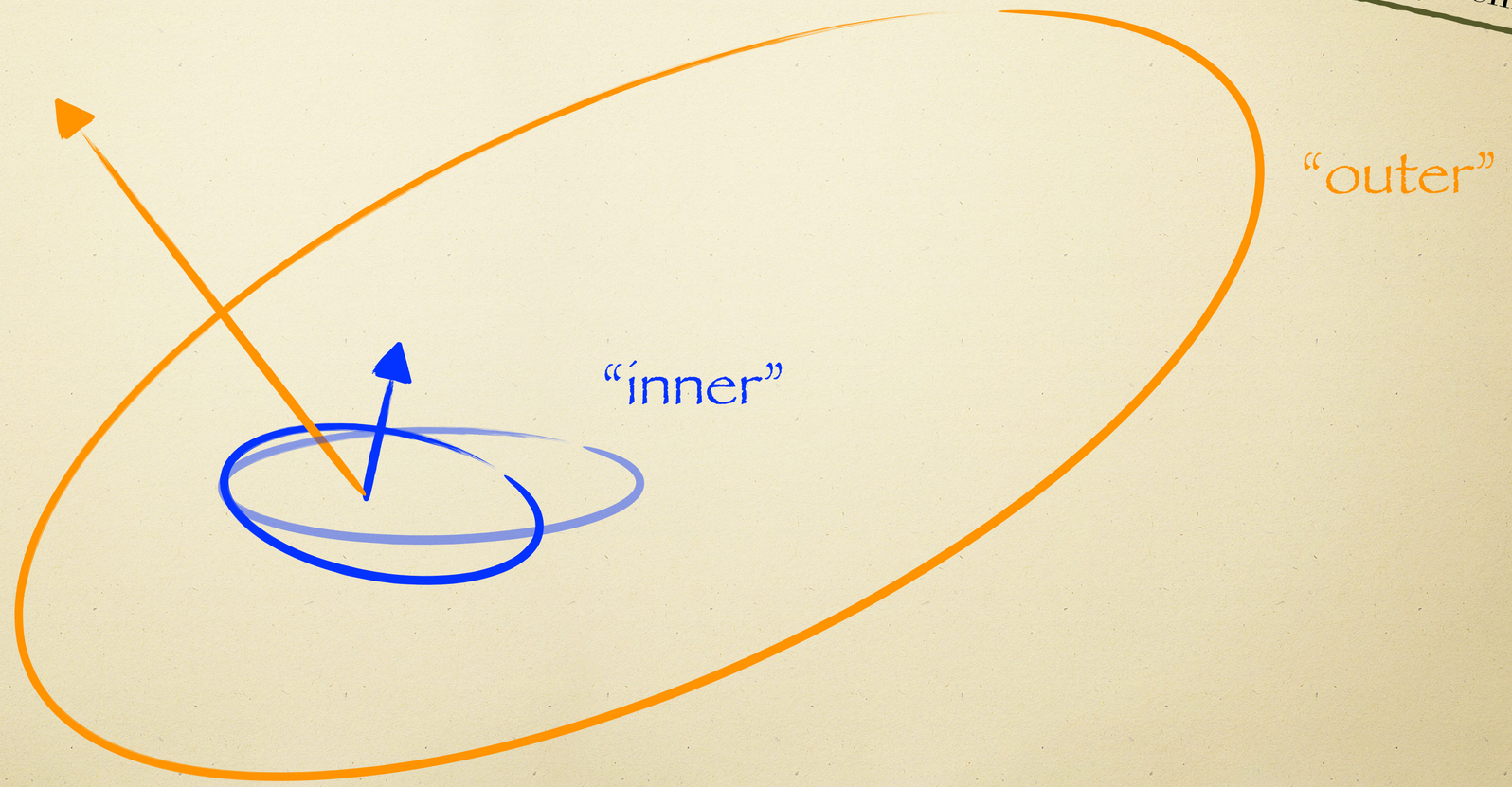


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

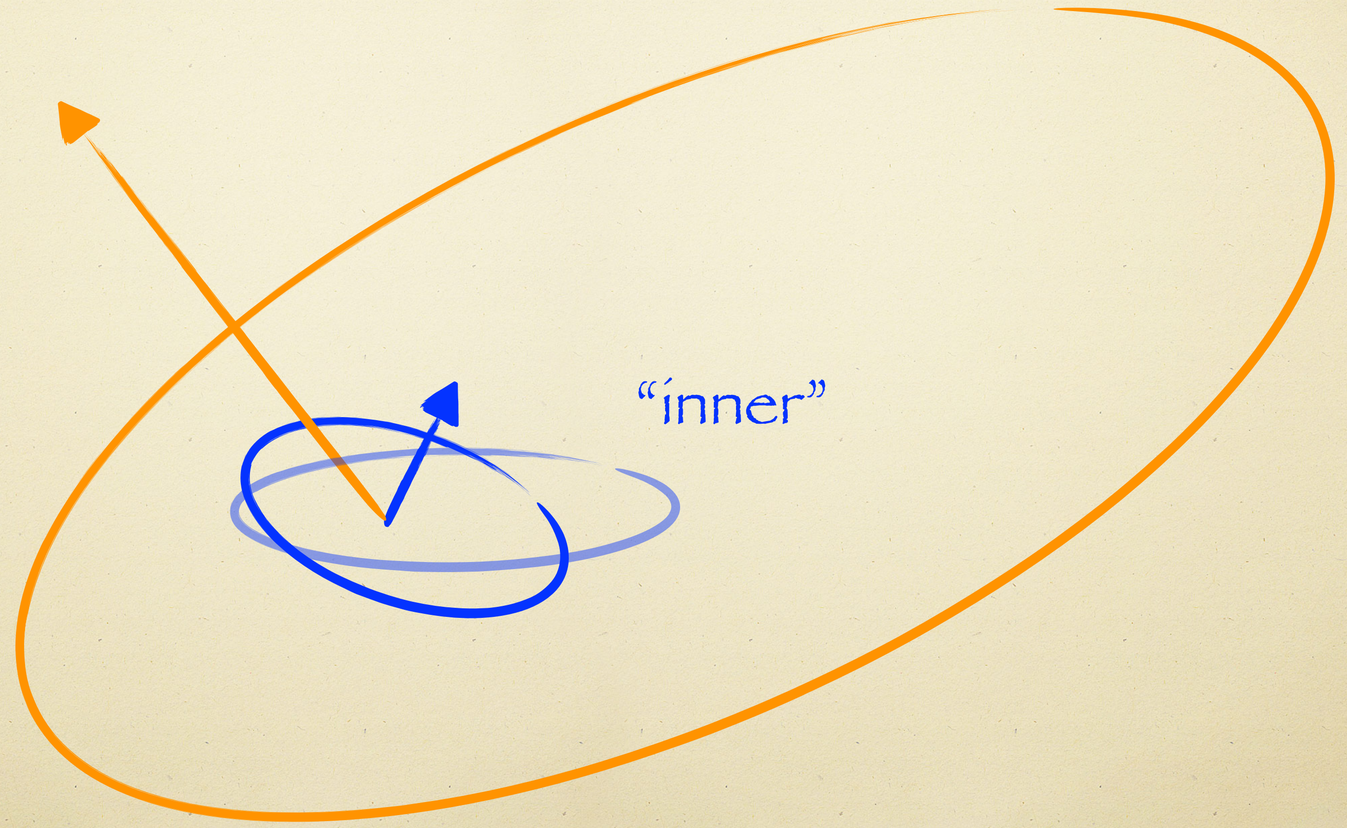


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

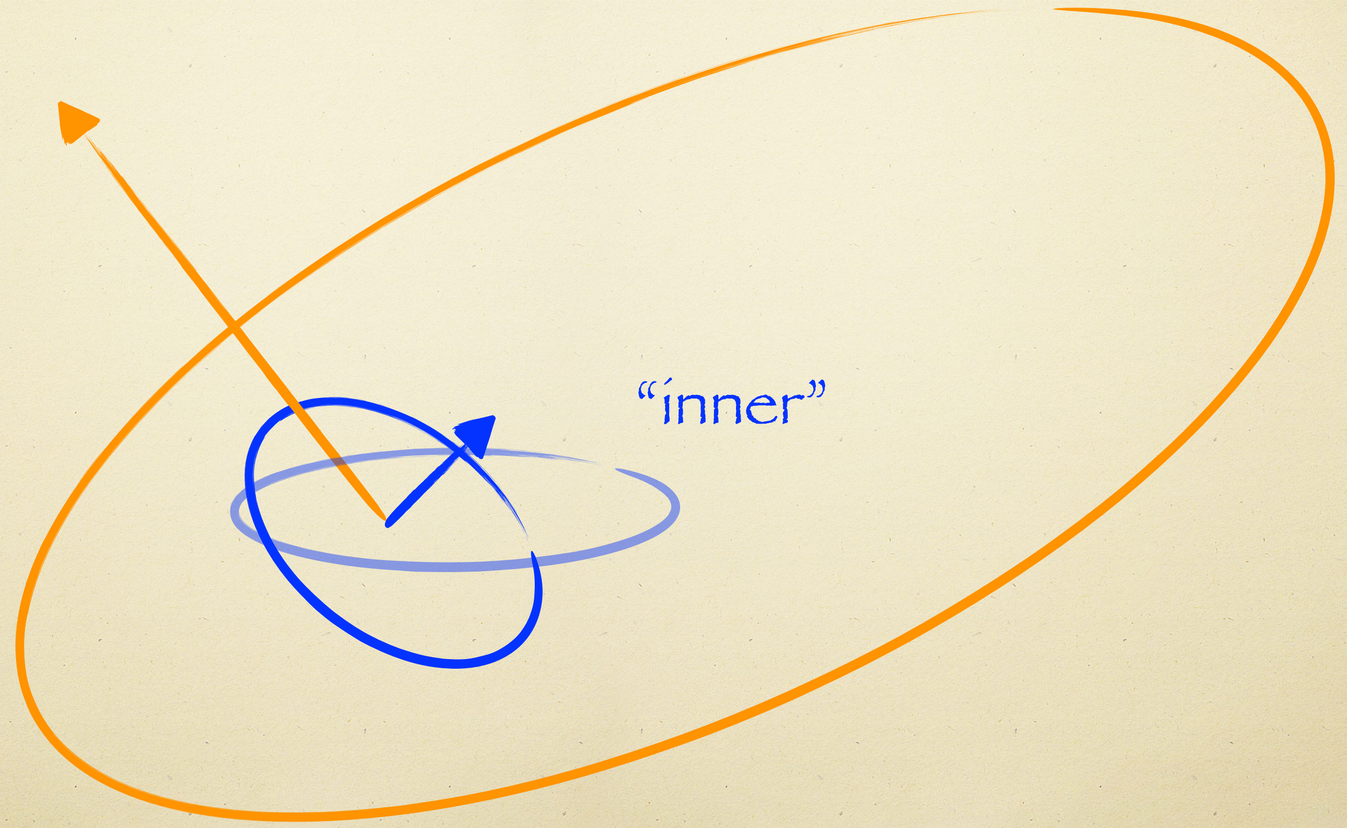


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

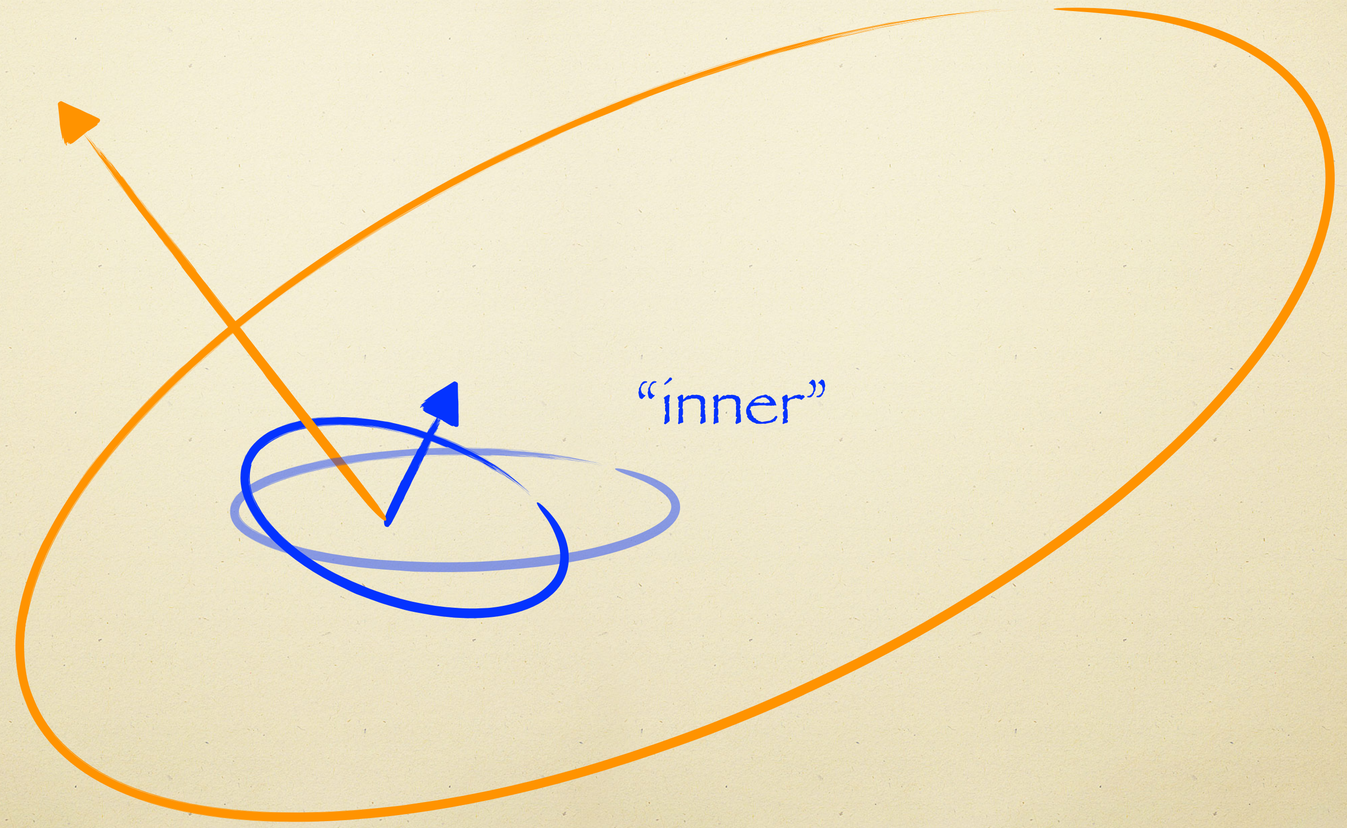


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

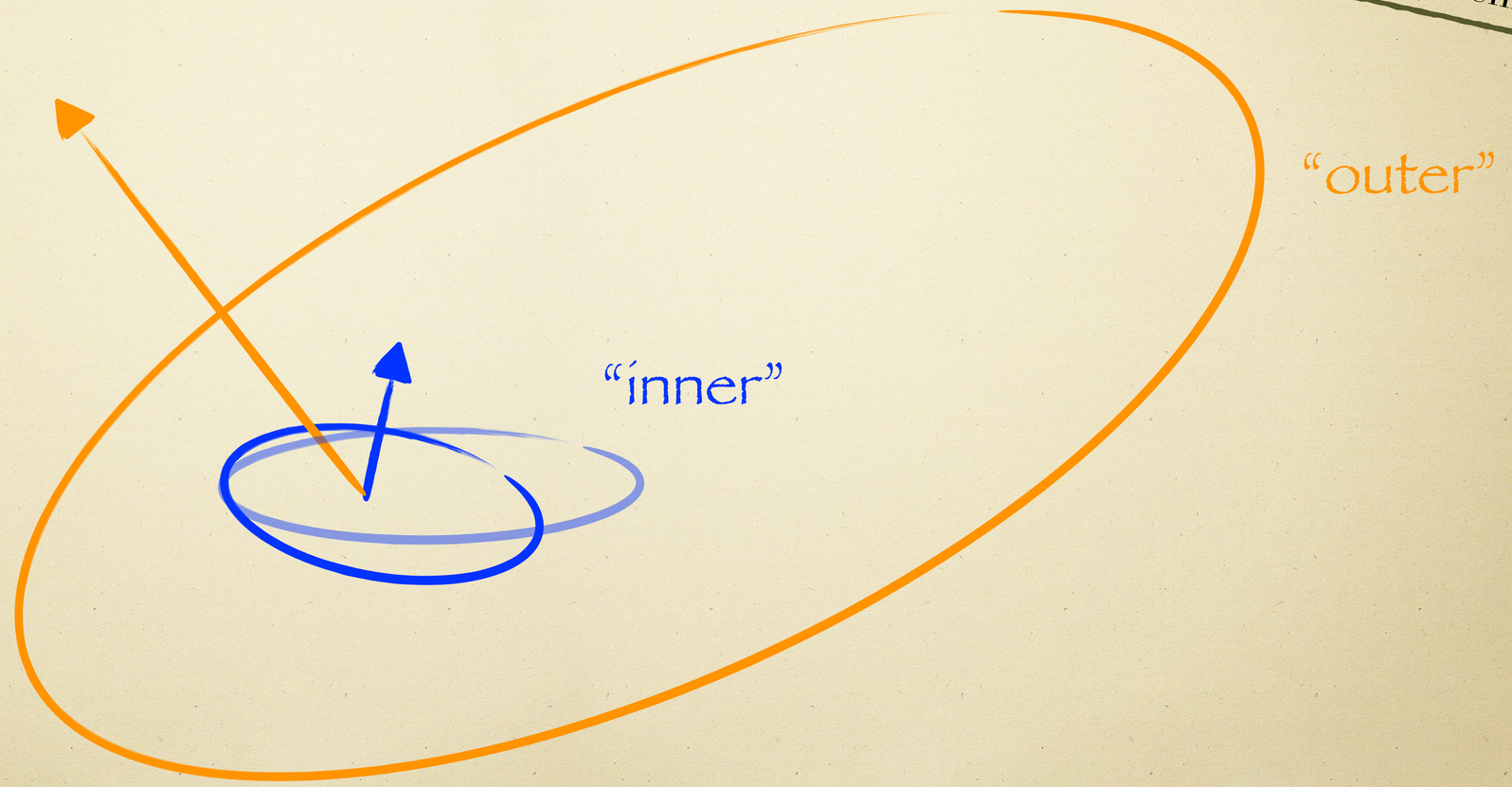


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

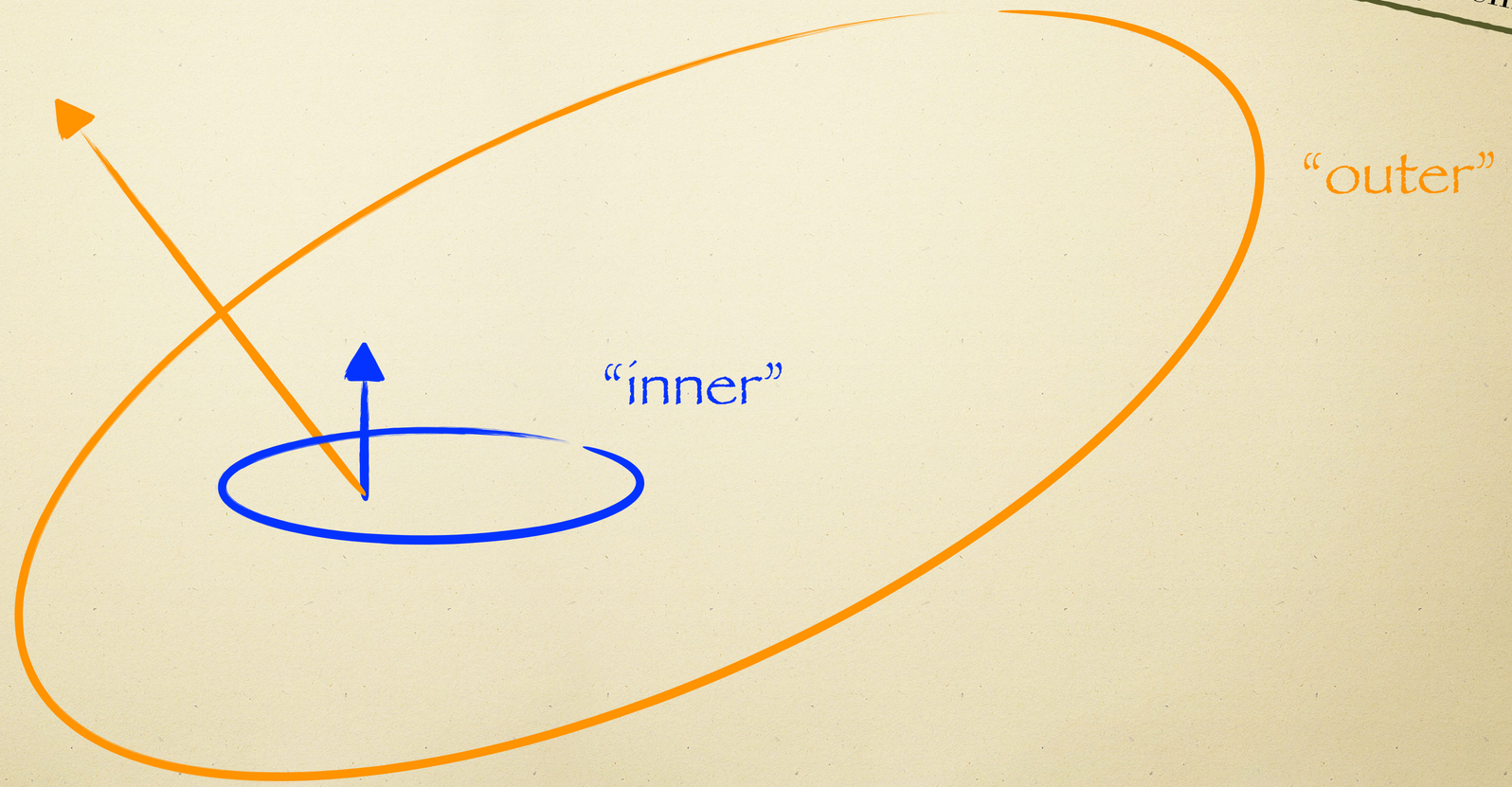


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$

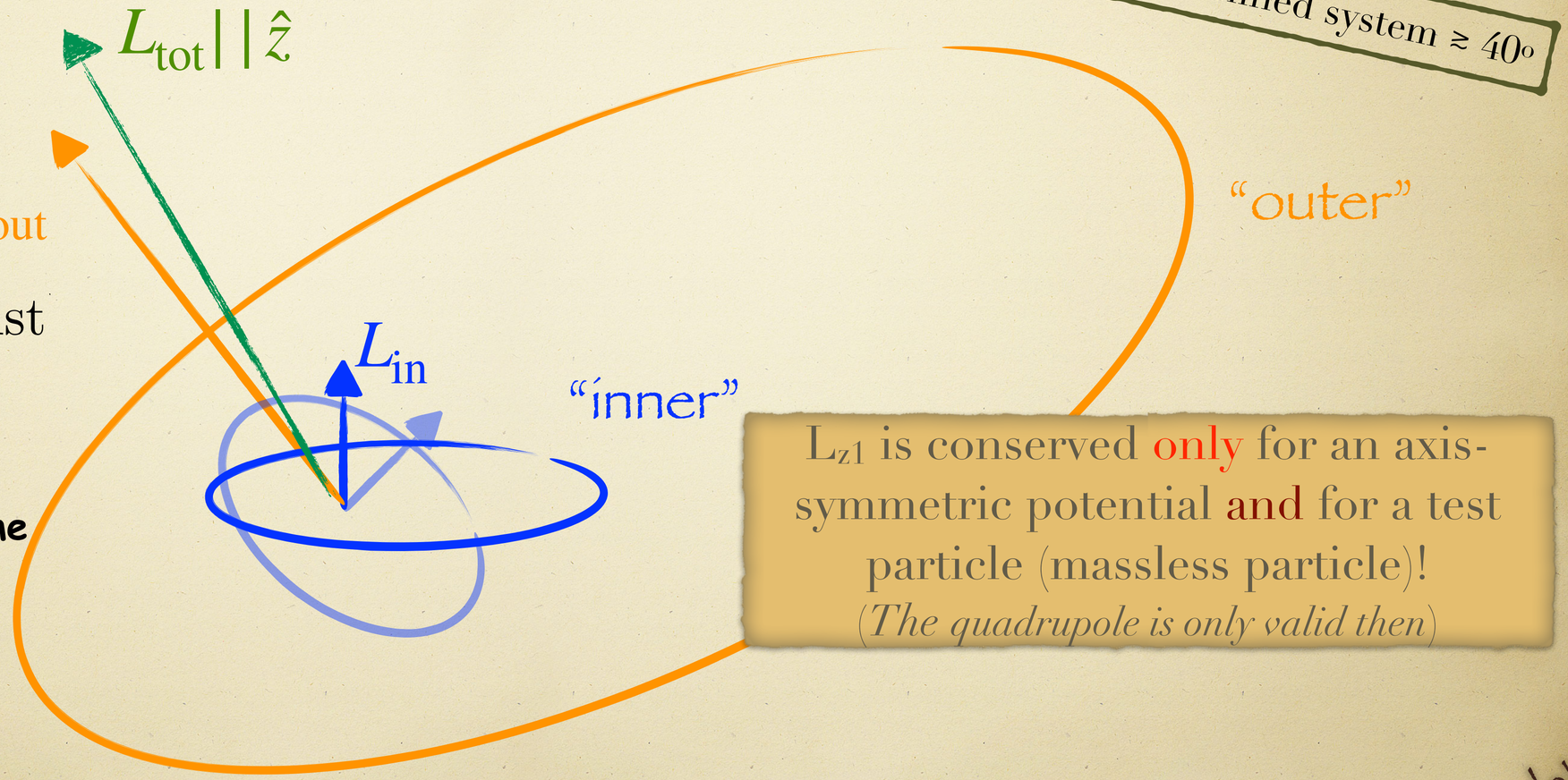


Not to scale!

Hierarchical triple system

Kozai 1962, Lidov 1962

For initially inclined system $\gtrsim 40^{o}$



$L_z \sim \sqrt{1-e^2}\cos i \neq \text{const}$

Prograde orbit cannot become retrograde

L_{z1} is conserved only for an axis-symmetric potential and for a test particle (massless particle)!
(The quadrupole is only valid then)

Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013),MNRAS, arXiv:1107.2414

Not to scale!

Our treatment
The eccentric Kozai-Lidov mechanism

- Allow for the z-component of the angular momenta of the inner and outer orbit to change - already at the quadrupole level.
- Expanding the approximation to the octupole level (e.g., Ford et al, 2000, Blaes et al, 2002 - already done before us.) - hexadecapole-level as needed (e.g., Will 2017; Holzknecht et al. 2026)
- Both the magnitude and orientation of the angular momentum can change

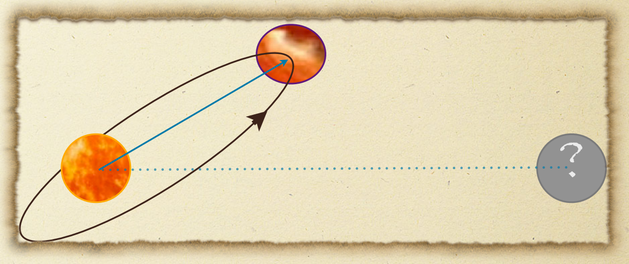
larger parts of the parameter space

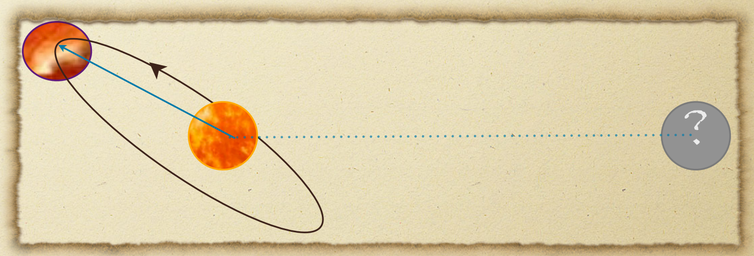
Naoz et al, Nature (2011), arXiv:1011.2501
Naoz et al (2013), MNRAS, arXiv:1107.2414

See Naoz (2016) for review

Exciting, rich, chaotic

i<90 deg - prograde





i>90 deg - retrograde

for test particle approx. see:
Lithwick & **Naoz** (2011), ApJ, arXiv:1106.3329
Katz at al (2011), arXiv:1106.3340

The eccentric Kozai-Lidov mechanism

GR effects: Naoz et al (2013)

$m_1 = 10 M_\odot$

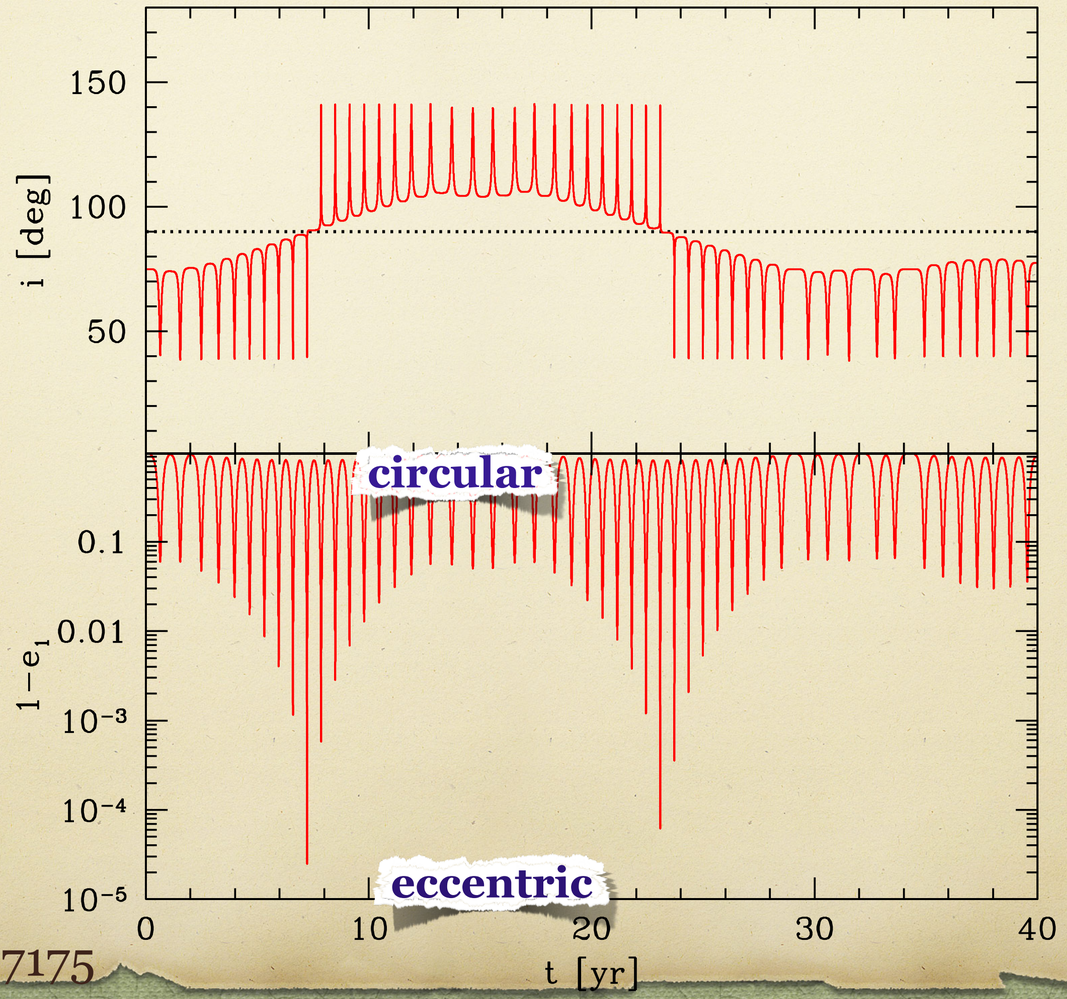
$m_2 = 1 M_\odot$

$M_{SMBH} = 4 \times 10^6 M_\odot$

$a_1 = 10 AU$

$a_2 = 0.003 pc$

$e_2 = 0.8$



Naoz (2016) ARA&A arXiv:1601.07175

The eccentric Kozai-Lidov mechanism

GR effects: Naoz et al (2013)

Compare to: "Standard" (quadrupole) Kozai

$m_1 = 10 M_\odot$

$m_2 = 1 M_\odot$

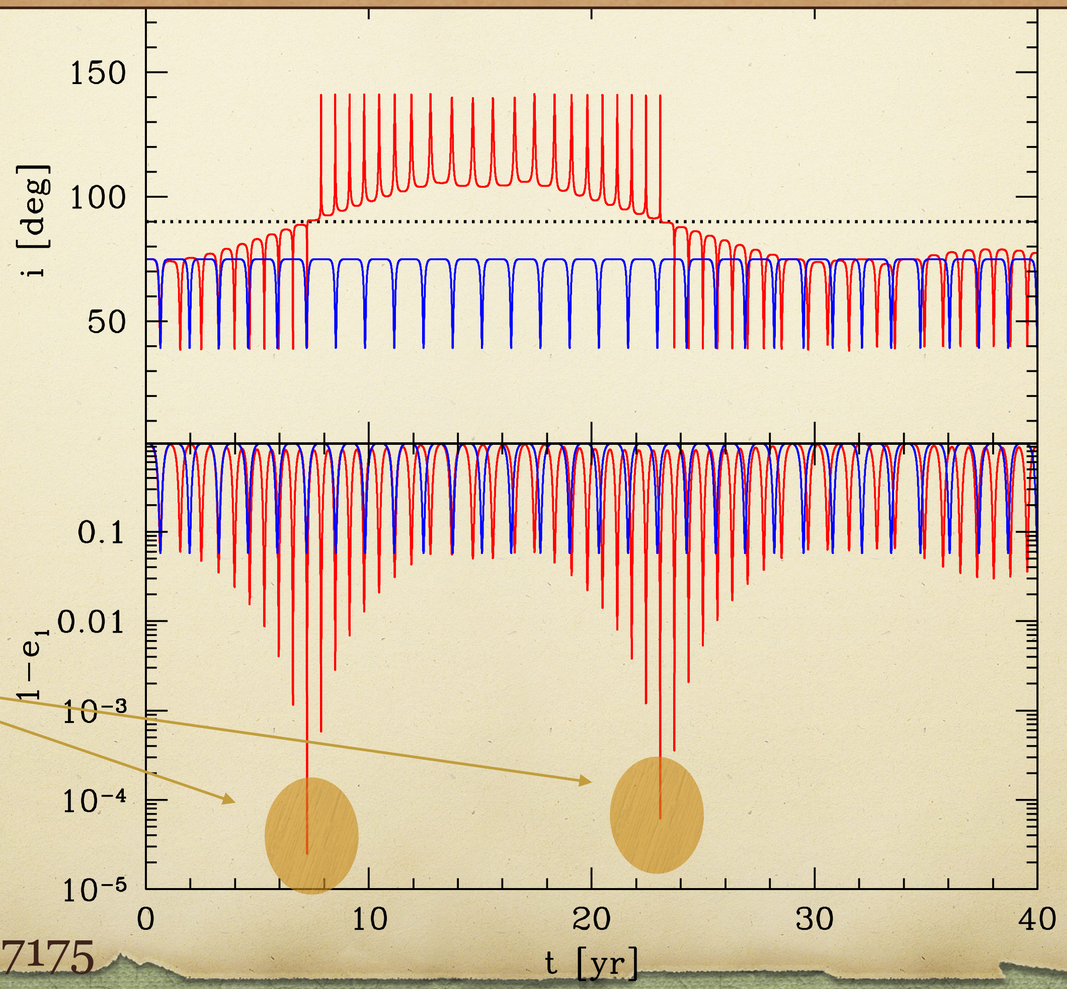
$M_{SMBH} = 4 \times 10^6 M_\odot$

$a_1 = 10 AU$

$a_2 = 0.003 pc$

$e_2 = 0.8$

Extreme eccentricity peaks



Extreme eccentricities are common throughout the parameter space

Teyssandier, **Naoz**, et al. (2013); Li, **Naoz** et al, (2014a,b), Hansen & **Naoz** (2020) Weldon, **Naoz** Hansen (2024)

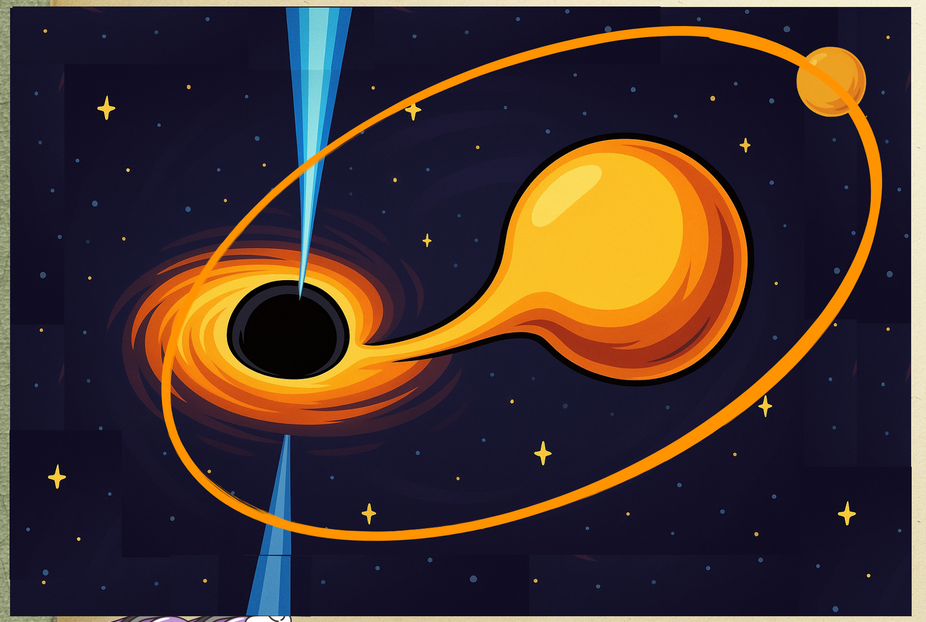
For GR effects see also: Lim & Rodriguez 2020

Naoz (2016) ARA&A arXiv:1601.07175

Low mass x-ray binary

Formation ideas:

Triple channel



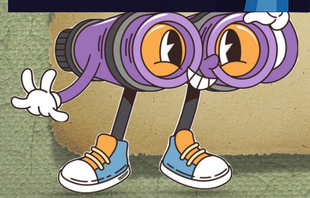
No Common envelope

Low mass x-ray binary

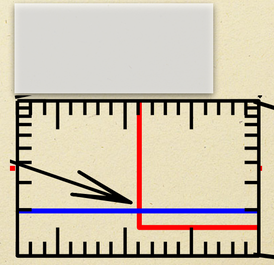
Formation ideas:

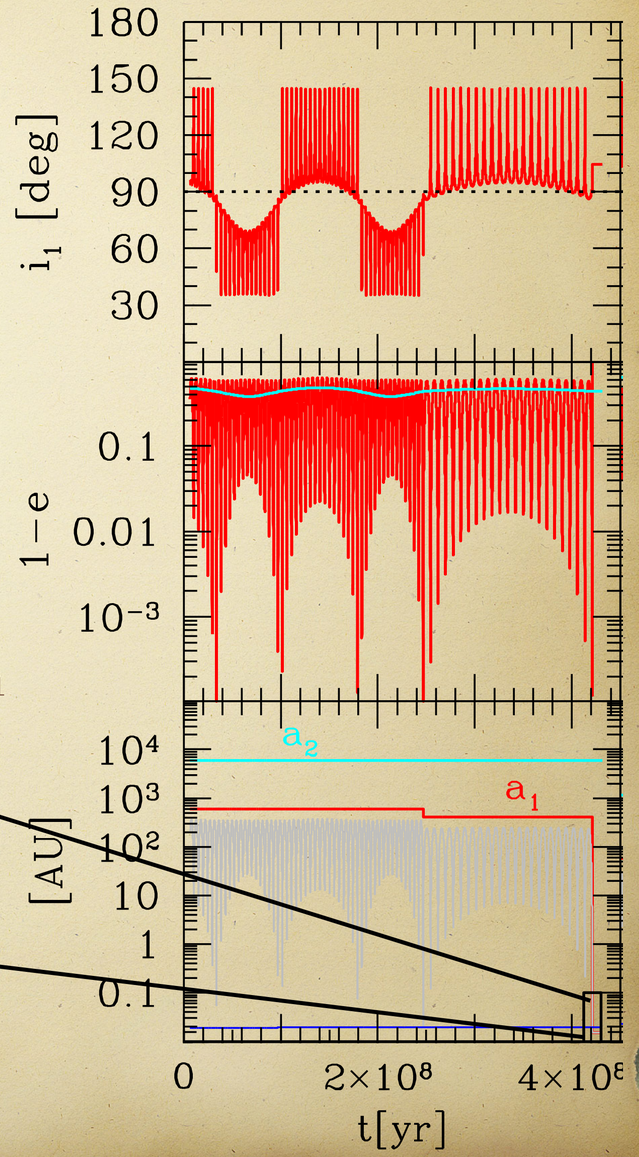
Triple channel

No Common envelope



+ Eccentric Kozai-Lidov (EKL) mechanism (Kozai 1962; Lidov 1962; **Naoz** 2016)
+ General relativity (1pN)
+ Tides
+ Post-main-sequence stellar evolution (SSE, Hurley et al. 2002)





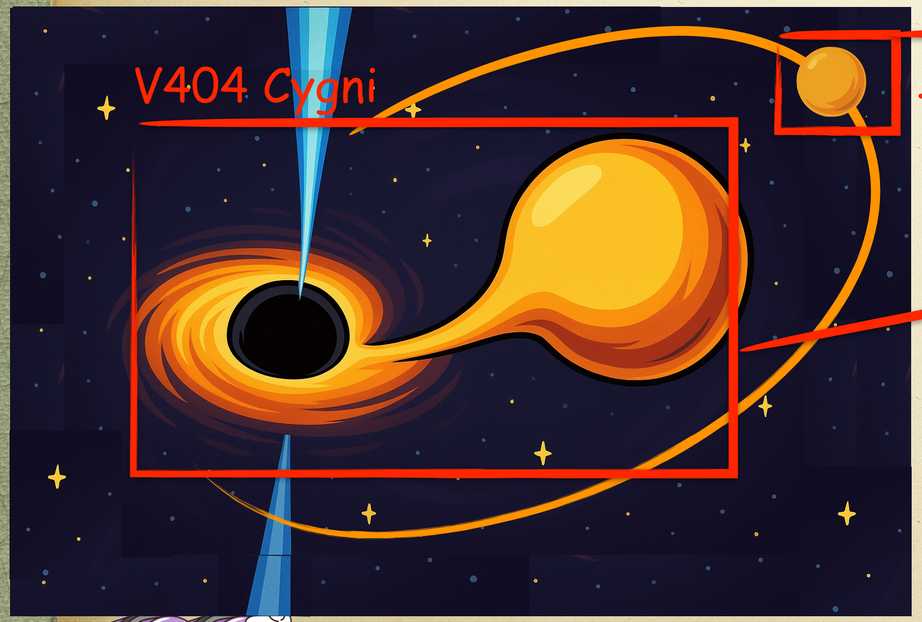
Naoz et al (2016)

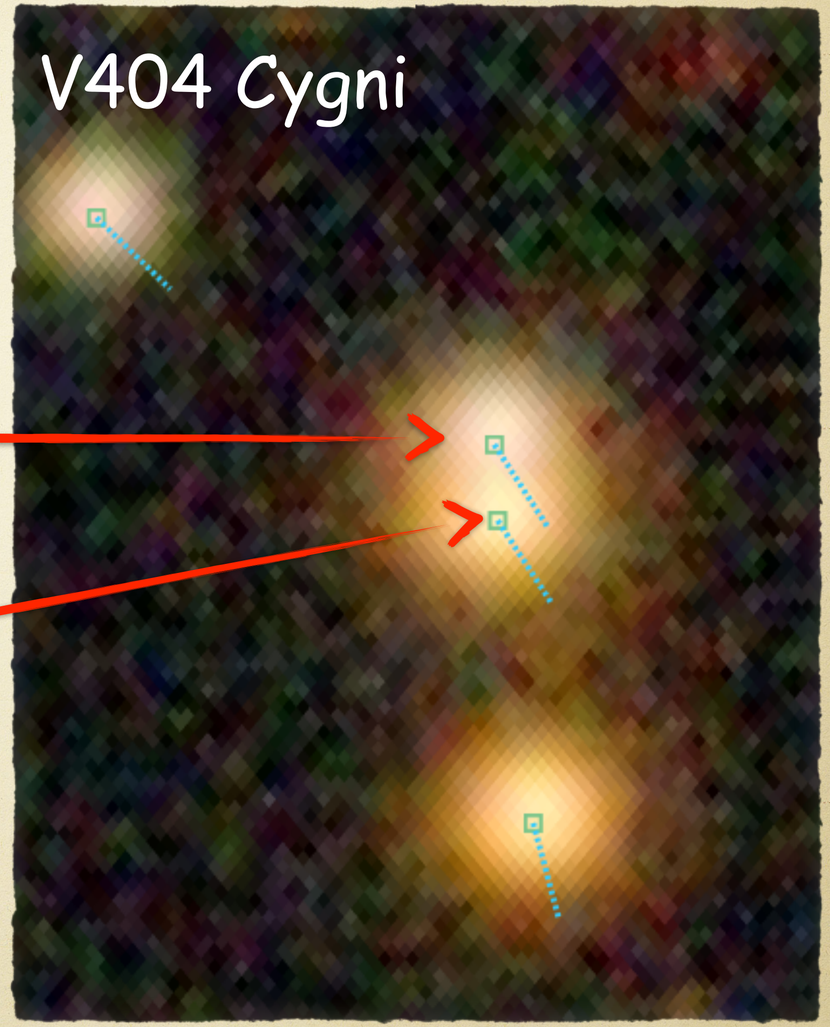
Low mass x-ray binary

Formation ideas:

Triple channel

No Common envelope





Burdge, El-Badry et al. (2024)

Low mass x-ray binary

Cheyanne Shariat

Formation ideas:

Triple channel+ POSYDON

No BH kicks

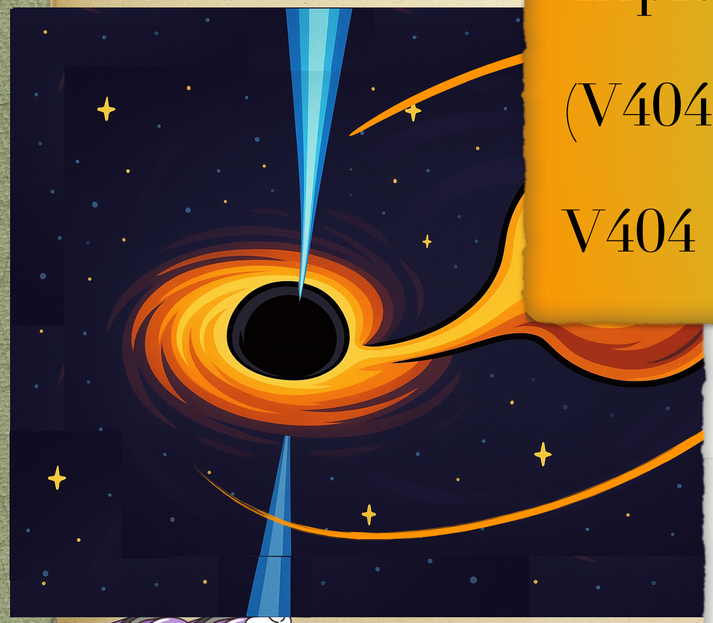
Shariat, **Naoz** et al (2025)

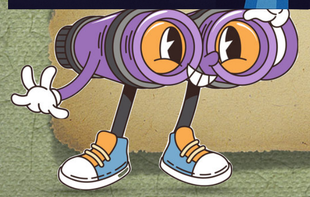
No Common

Triples form BH-LMXBs efficiently, without a common envelope

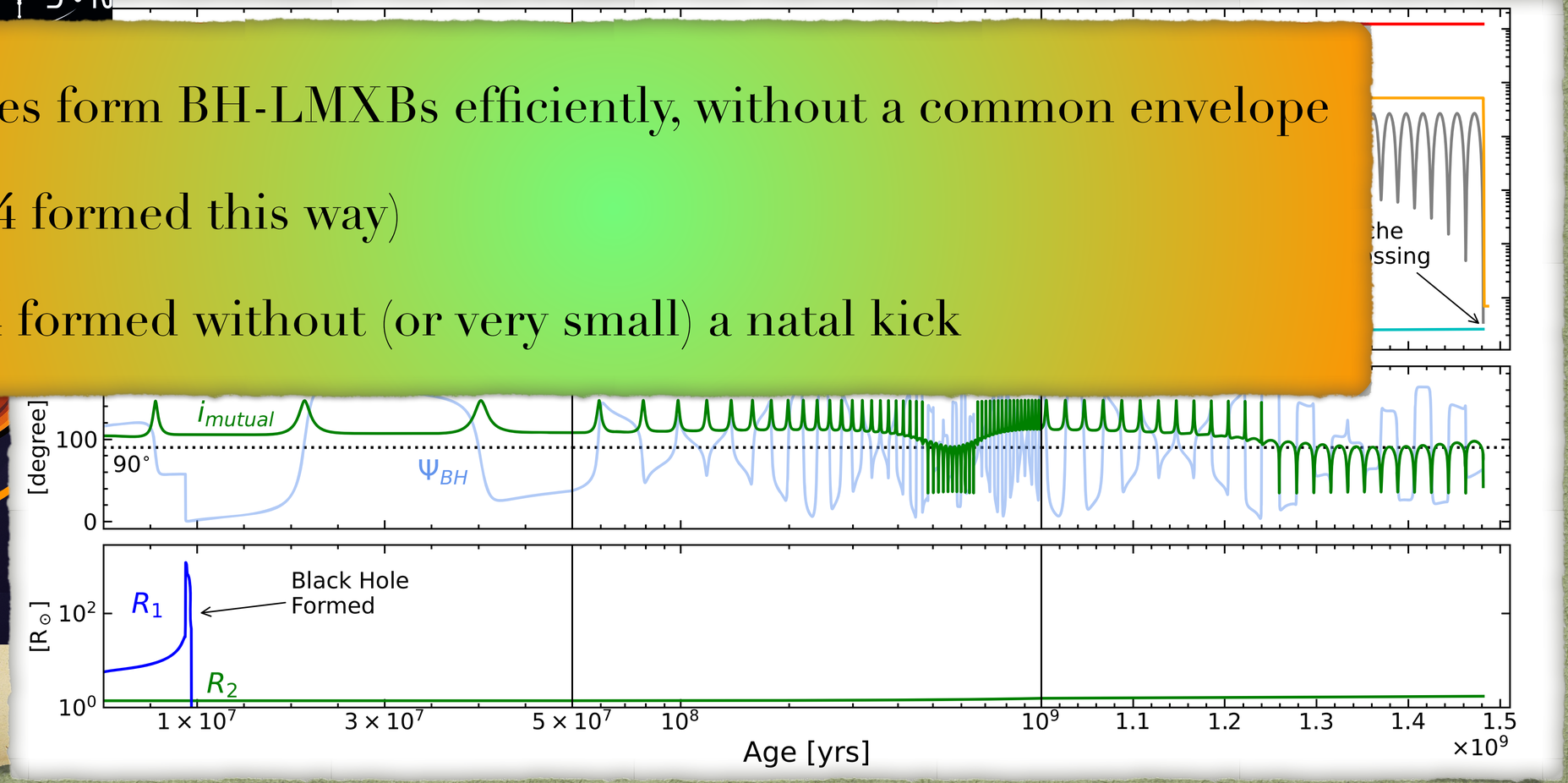
(V404 formed this way)

V404 formed without (or very small) a natal kick





POSYDON,
Fragos et al. 2023



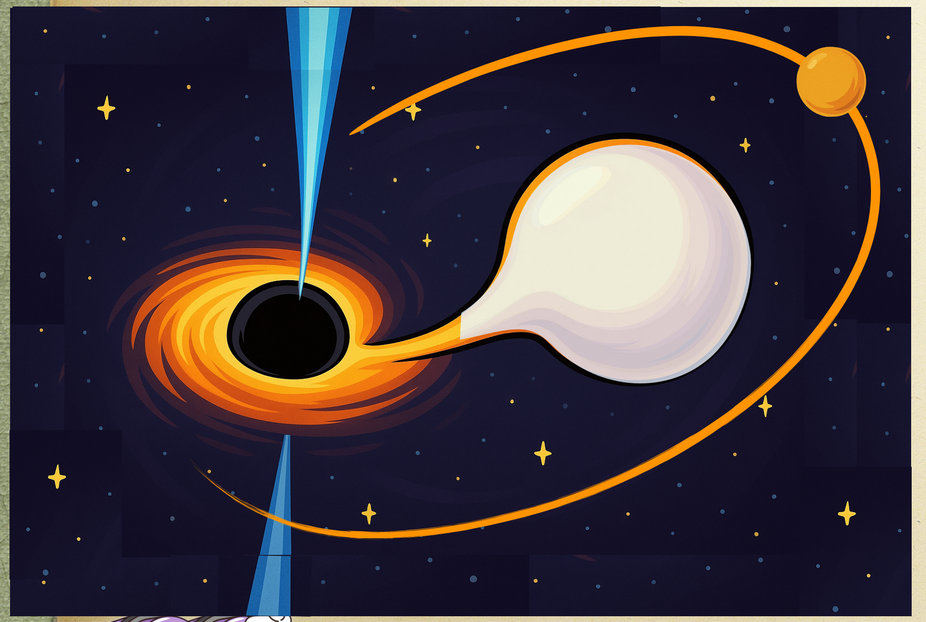
Ultracompact x-ray binary

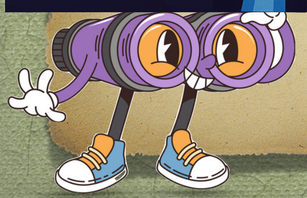
Xuan, Shariat, **Naoz** (2025)

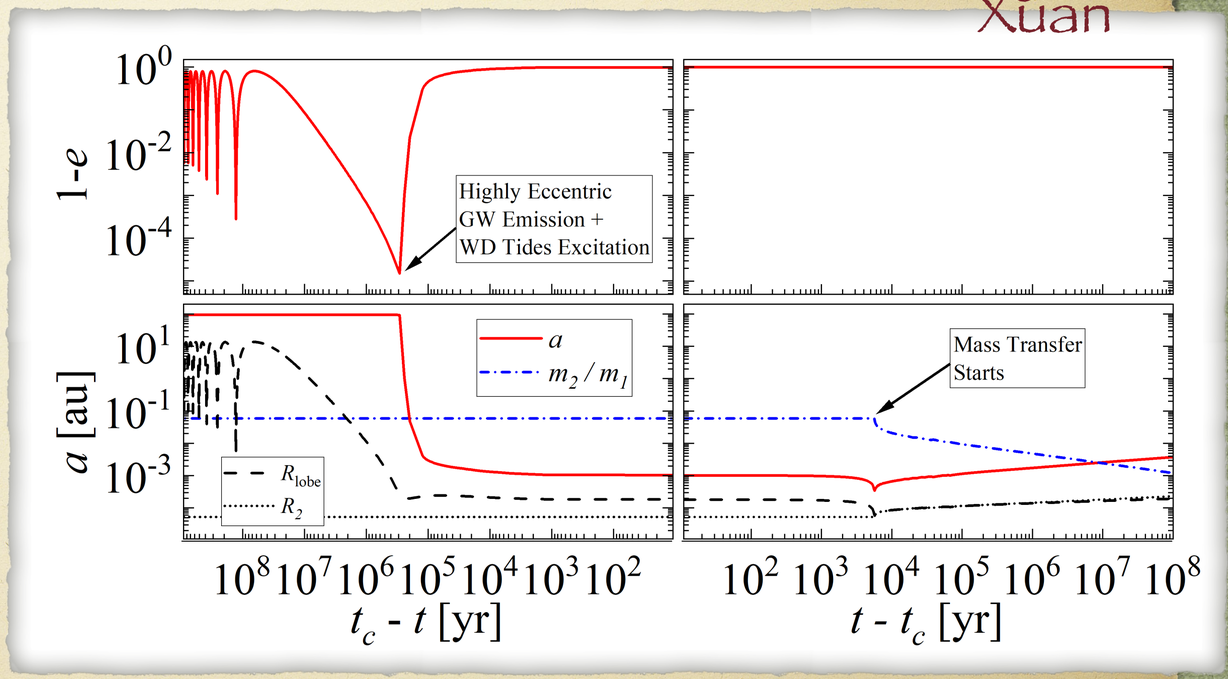
Zeyuan Xuan

- EKL
- General relativity (≤2.5pN)
- WD dynamical tides

No Common envelope







WD dynamical tides following Fuller & Lai (2012a); Vick et al. (2017); Su & Lai (2022)

Ultracompact x-ray binary

Xuan, Shariat, **Naoz** (2025)

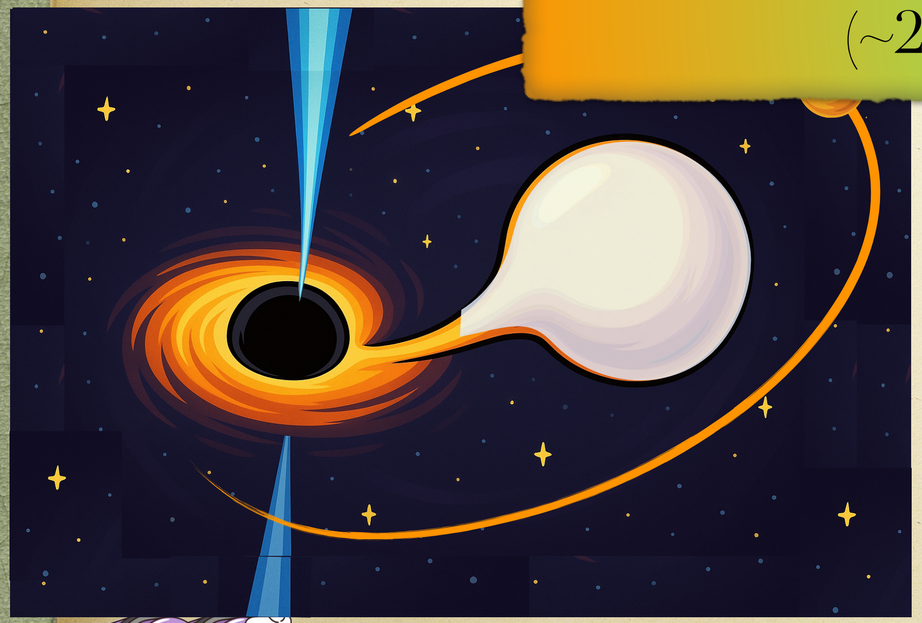
Zeyuan Xuan

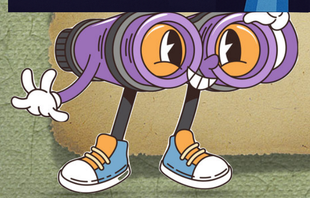
+ EKL
+ General relativity (≤2.5pN)
+ WD dynamical tides

No Common

Produce ~ 3 – 27 detectable UCXBs in the Milky Way

(~20 are observed, e.g., Padilla 2023)



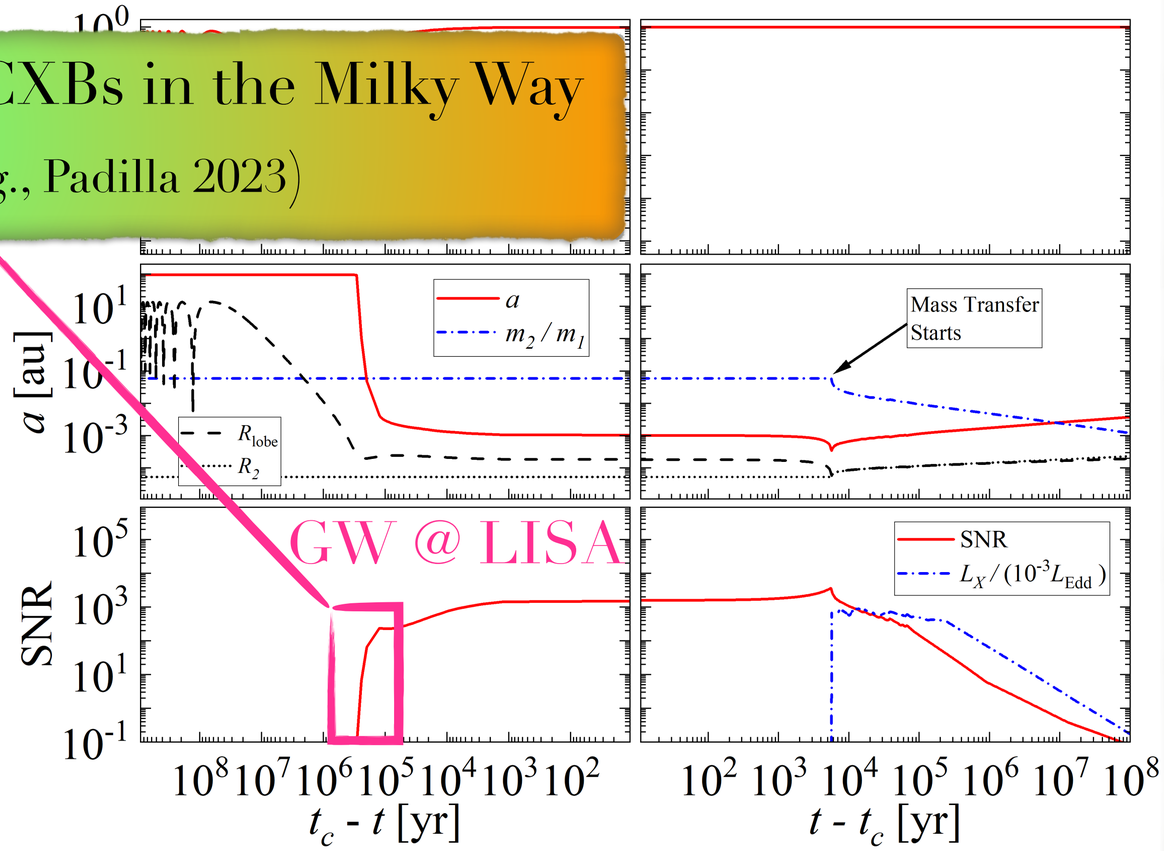


WD dynamical tides following Fuller & Lai (2012a); Vick

Bursting GW

Xuan, **Naoz**,et al. (2024a,b)

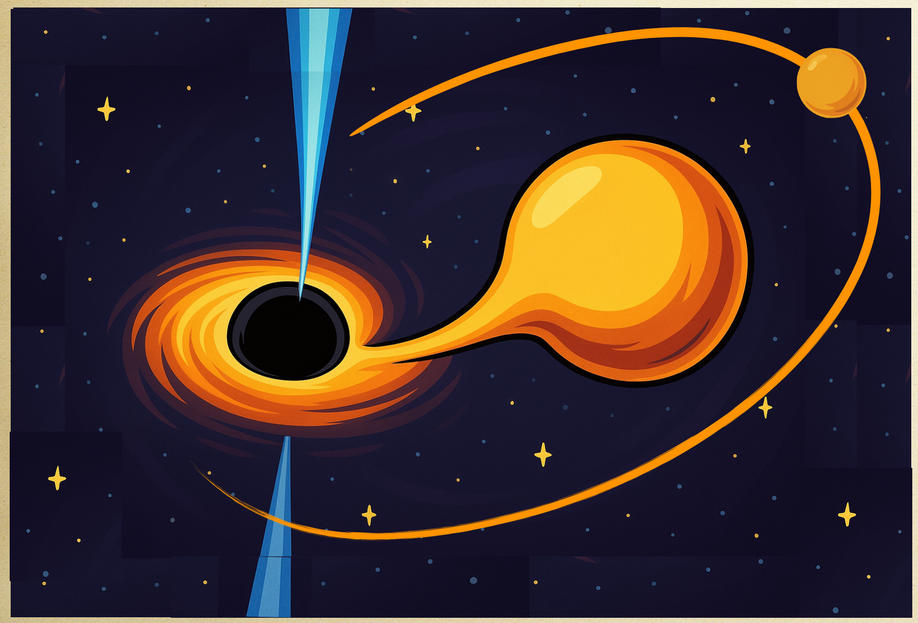
Multimessanger



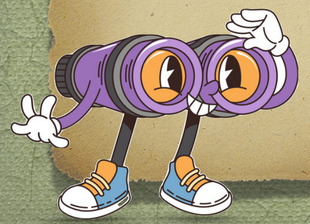
Seeing stellar mass black holes

The Triple Connection:

Low mass x-ray binary



- ☑ Low mass X-ray binaries are efficiently formed via triples
- ☑ Ultracompact X-ray binaries are also efficiently formed through triples (+Multimessanger)
- ☒ No connections to the other BH systems



Seeing stellar mass black holes

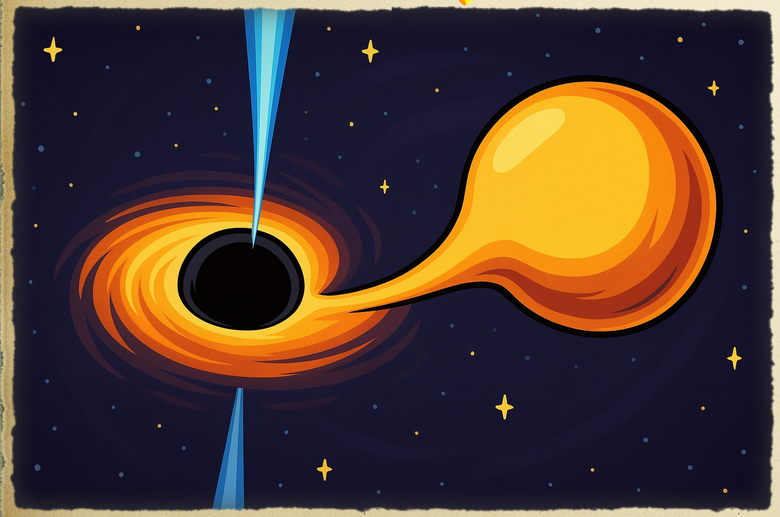
Low mass x-ray binary

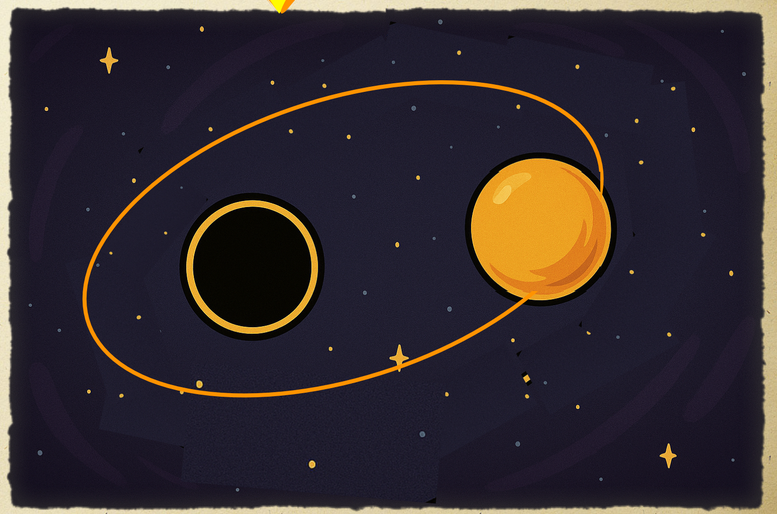
Gravitational wave emissions

Astrometry

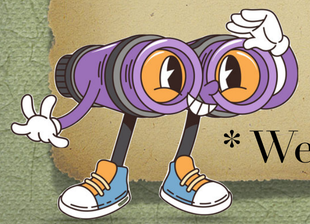
Connection?

Connection?





Gaia BHs

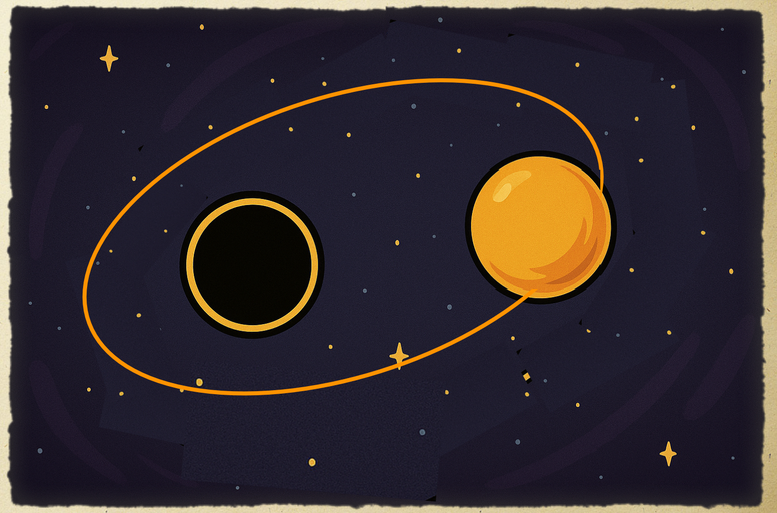


e.g., Zevin et al. (2021), Fishbach & Kalogera (2022), Fishbach et al. (2025).

* We also “see” stellar mass black holes via microlensing

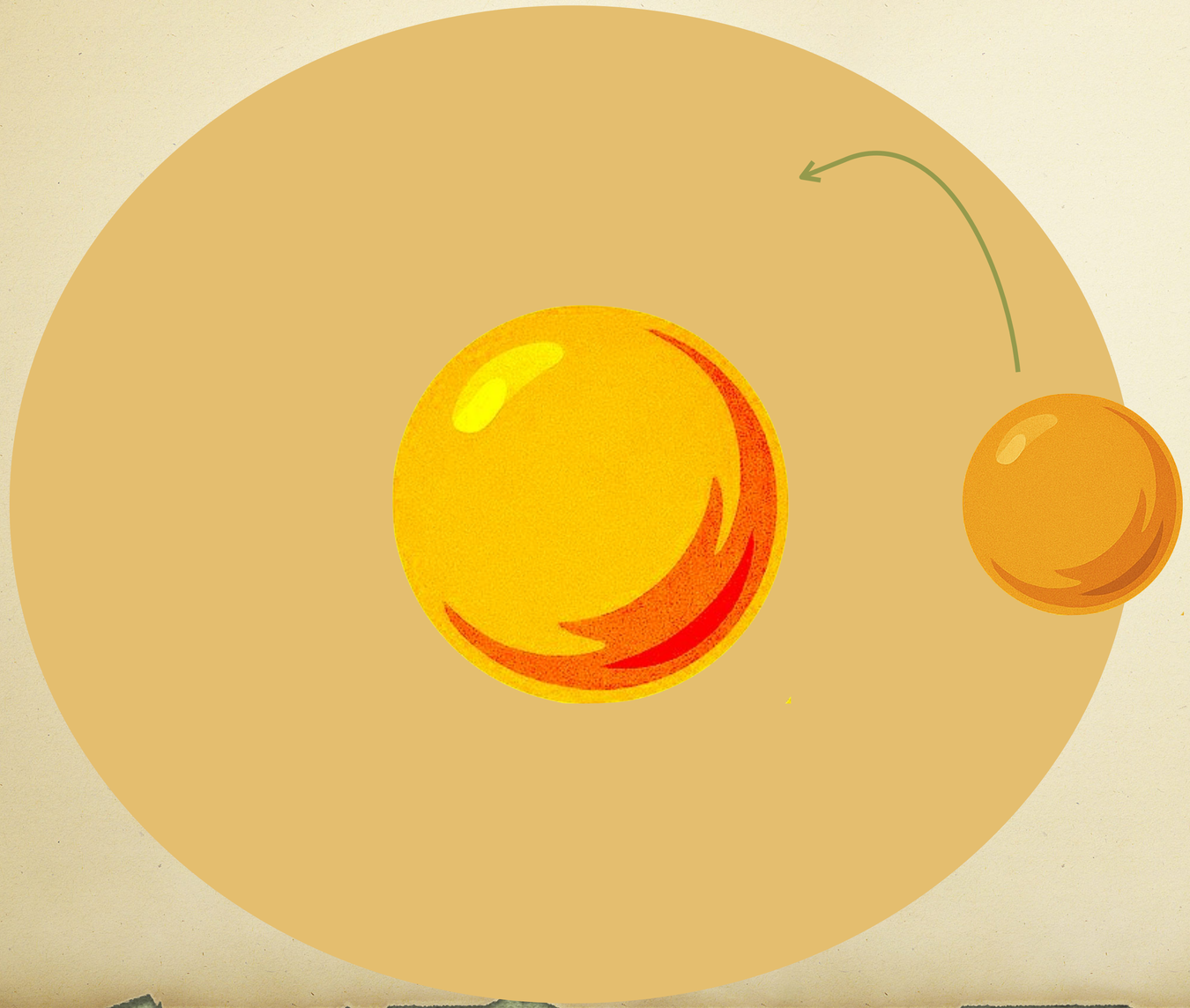
Gaia BHs

Astrometry

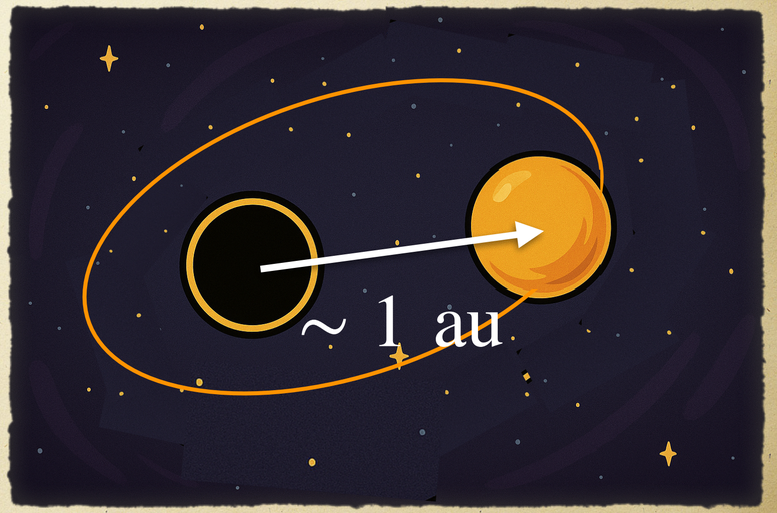


e.g., El-Badry et al. 2023a,b; Gaia Collaboration et al. 2021, 2023, 2024

Gaia BHs



Astrometry



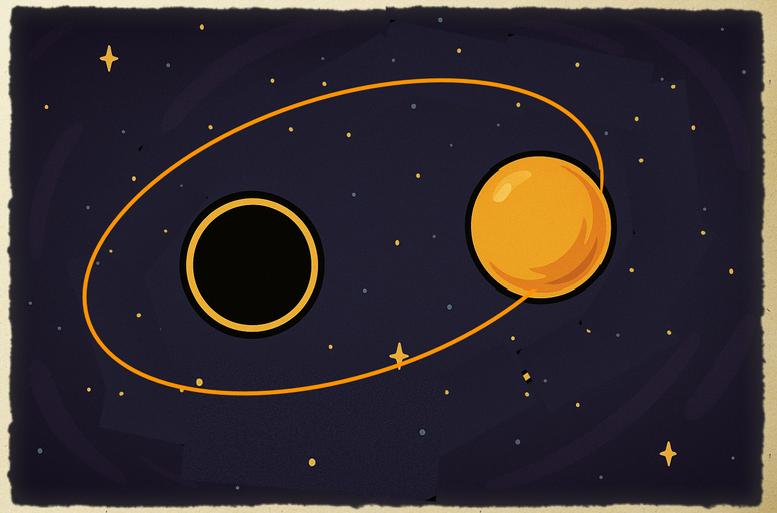
e.g., El-Badry et al. 2023a,b; Gaia Collaboration et al. 2021, 2023, 2024

Gaia BHs

Formation suggestions: fine-tuned mass transfer or envelope ejection, triple-star evolution, and natal BH kicks that reshaped the orbit (e.g., El-Badry et al. 2023b; Generozov & Perets 2024; Li et al. 2024; Fishbach et al. 2025).

20,000 Gaia BH are expected in the MW, e.g., Nagarajan et al. (2025)

Astrometry



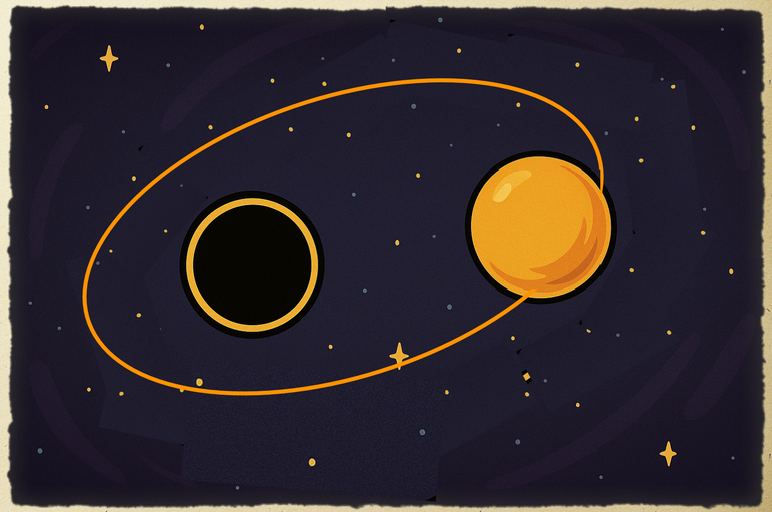
e.g., El-Badry et al. 2023a,b; Gaia Collaboration et al. 2021, 2023, 2024

Seeing stellar mass black holes

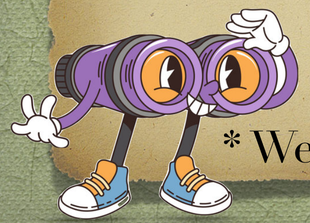
Low mass x-ray binary

Gravitational wave emissions

Astrometry



GAIA BHs



e.g., Zevin et al. (2021), Fishbach & Kalogera (2022), Fishbach et al. (2025).

* We also “see” stellar mass black holes via microlensing

Gravitational wave emissions

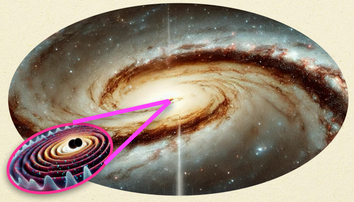
Dynamical channel

- **Globular Clusters**

e.g., Rodriguez et al. 2016, 2018; Miller & Hamilton 02, Portegies Zwart & McMillan 02, Morscher et al. 15, Samsing 18, Samsing & D'Orazio 18, D'Orazio & Samsing 18, Zevin et al. 19, Kremer et al. 19, Gerosa, Vitale et al. 20

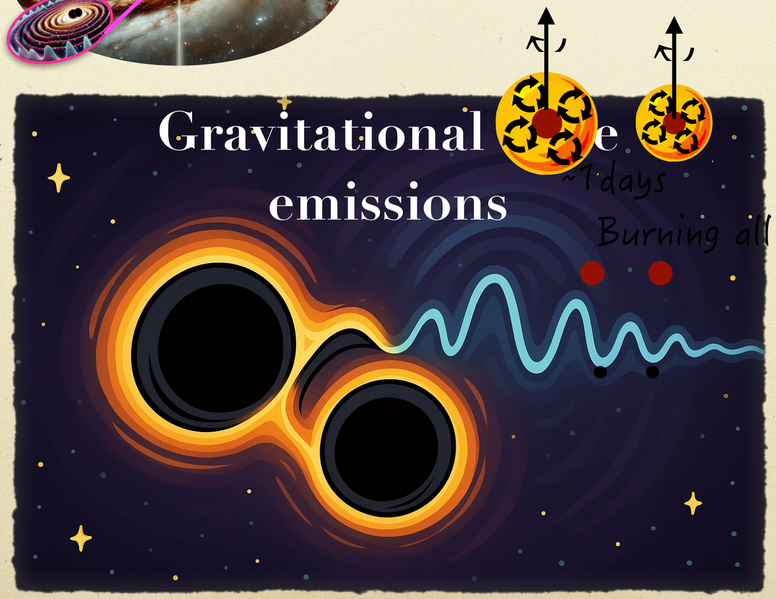
- **Galactic Nuclei**

e.g., **GW capture:** O'Leary et al. 2009; **Naoz** & Sari in prep; **EKL:** Hoang, **Naoz** et al. 2018, 2019; Xuan, **Naoz** et al. 2023, 2024a, 2024b; **Large-scale dynamics:** Petrovich & Antonini 2017; **AGN disks**: Tagawa et al. 2020; Samsing et al. 2022

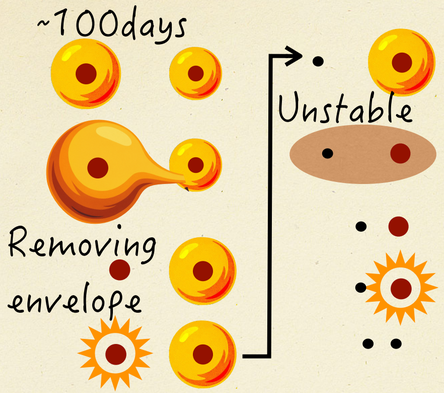


- **Hierarchical triples**

e.g., Thompson 2011; Antonini et al. 2016, 2017; Silsbee & Tremaine 2017; Liu et al. 2019 Dorozsmai et al. 2024; Kummer et al. 2025; Stegmann et al 2025



Isolated binaries



- **Common-envelope**
- **Stable-mass-transfer**

e.g., Van den Heuvel 1976, Kalogera et al. 2007, Dominik et al. (2012, 2013, 2015), Belczynski et al. 2016, 2020, Bavera et al. 2020, 2021, 2022.

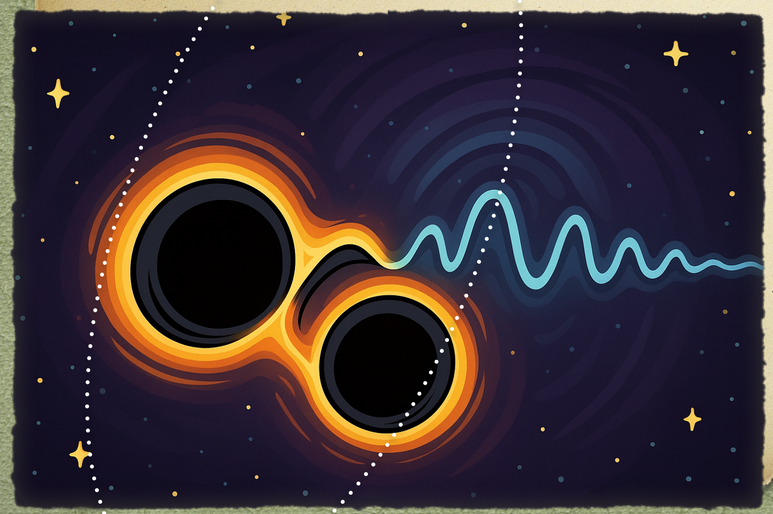
- **Chemically homogeneous**

Chemically homogeneous evolution, e.g., de Mink & Mandel 2016; Mandel & de Mink 2016; Marchant et al. 2016, du Buisspn et al., 2021; Riley et al., 2021; Bavera et al. 2020, 2021, 2022

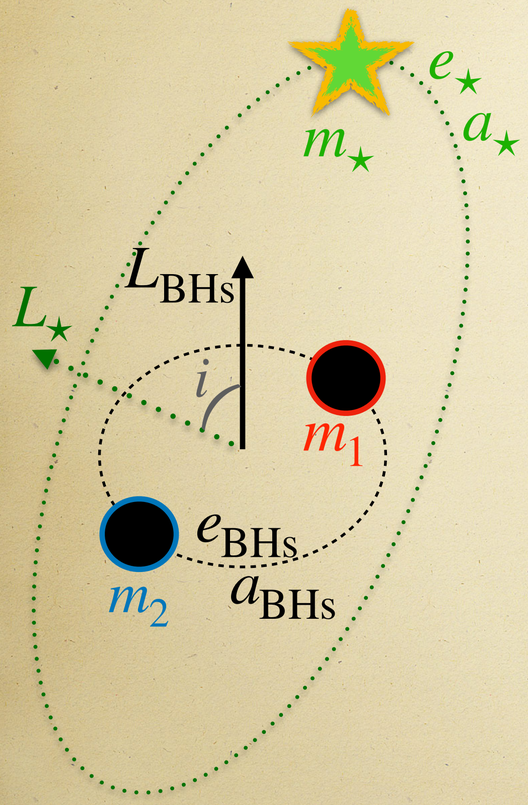
(See also: Nutzman et al. 2004; Belczynski et al. 2002, 2007; Stevenson et al. 2017;Breivik et al. 2016; Gallegos-Garcia et al. 2021).

Isolated binary channel
+ a tertiary

$m_\star = 1\ \mathrm{M}_\odot$



Isolated binary channel + a tertiary

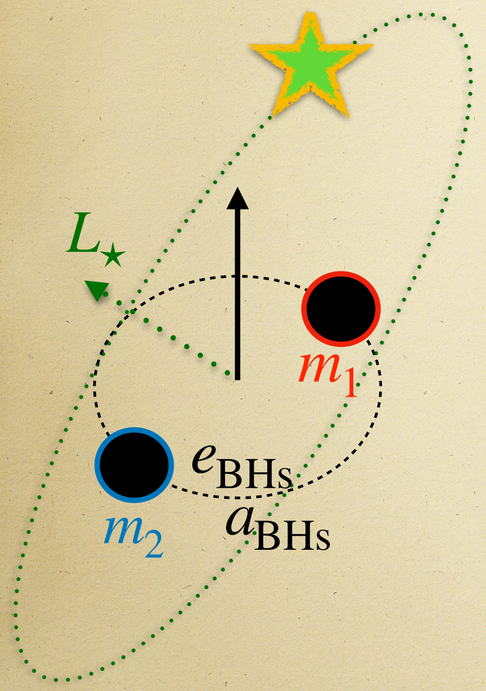


Mostly, the iEKL mechanism, the tertiary doesn't play a big role

Naoz et al (2017)

Isolated binary channel + a tertiary

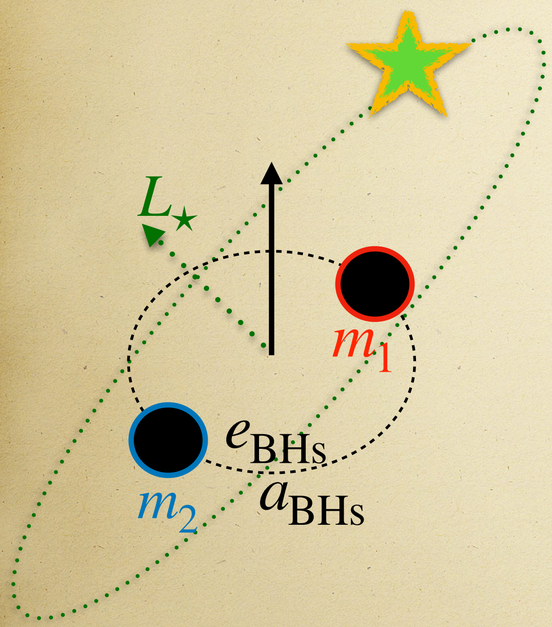
Mostly, the iEKL mechanism, the tertiary doesn't play a big role



Naoz et al (2017)

Isolated binary channel + a tertiary

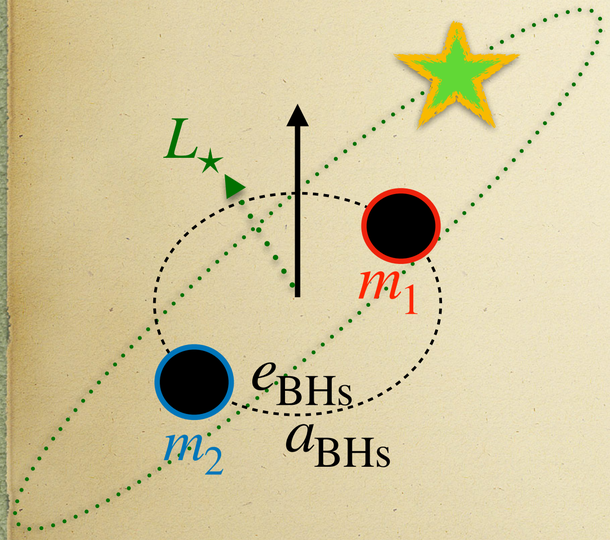
Mostly, the iEKL mechanism, the tertiary doesn't play a big role



Naoz et al (2017)

Isolated binary channel + a tertiary

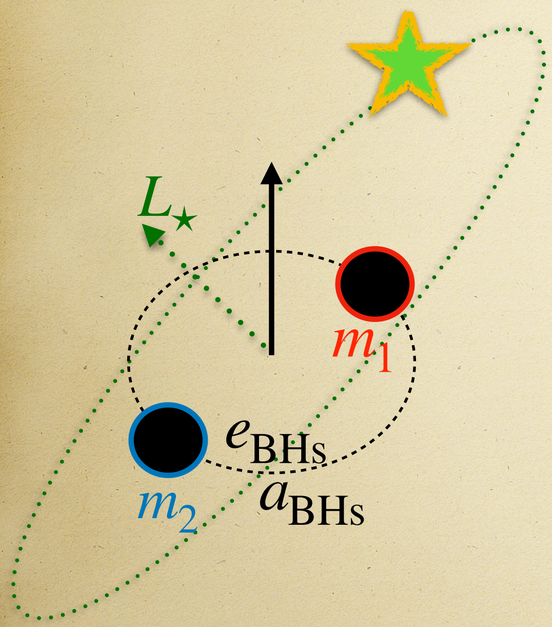
Mostly, the iEKL mechanism, the tertiary doesn't play a big role



Naoz et al (2017)

Isolated binary channel + a tertiary

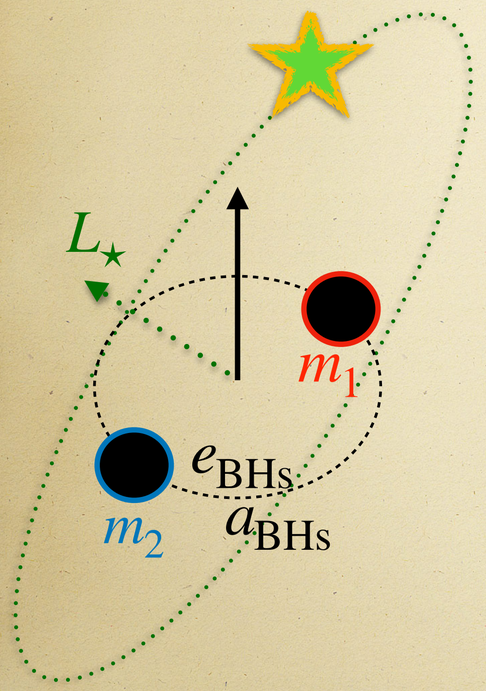
Mostly, the iEKL mechanism, the tertiary doesn't play a big role



Naoz et al (2017)

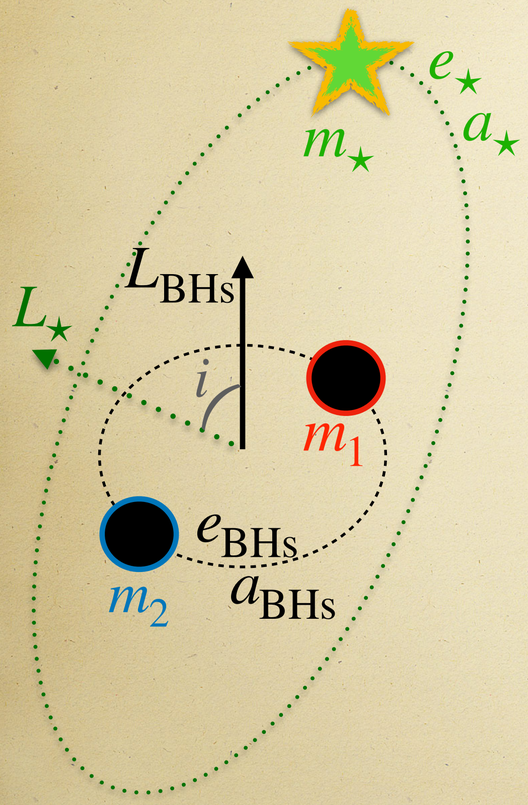
Isolated binary channel + a tertiary

Mostly, the iEKL mechanism, the tertiary doesn't play a big role



Naoz et al (2017)

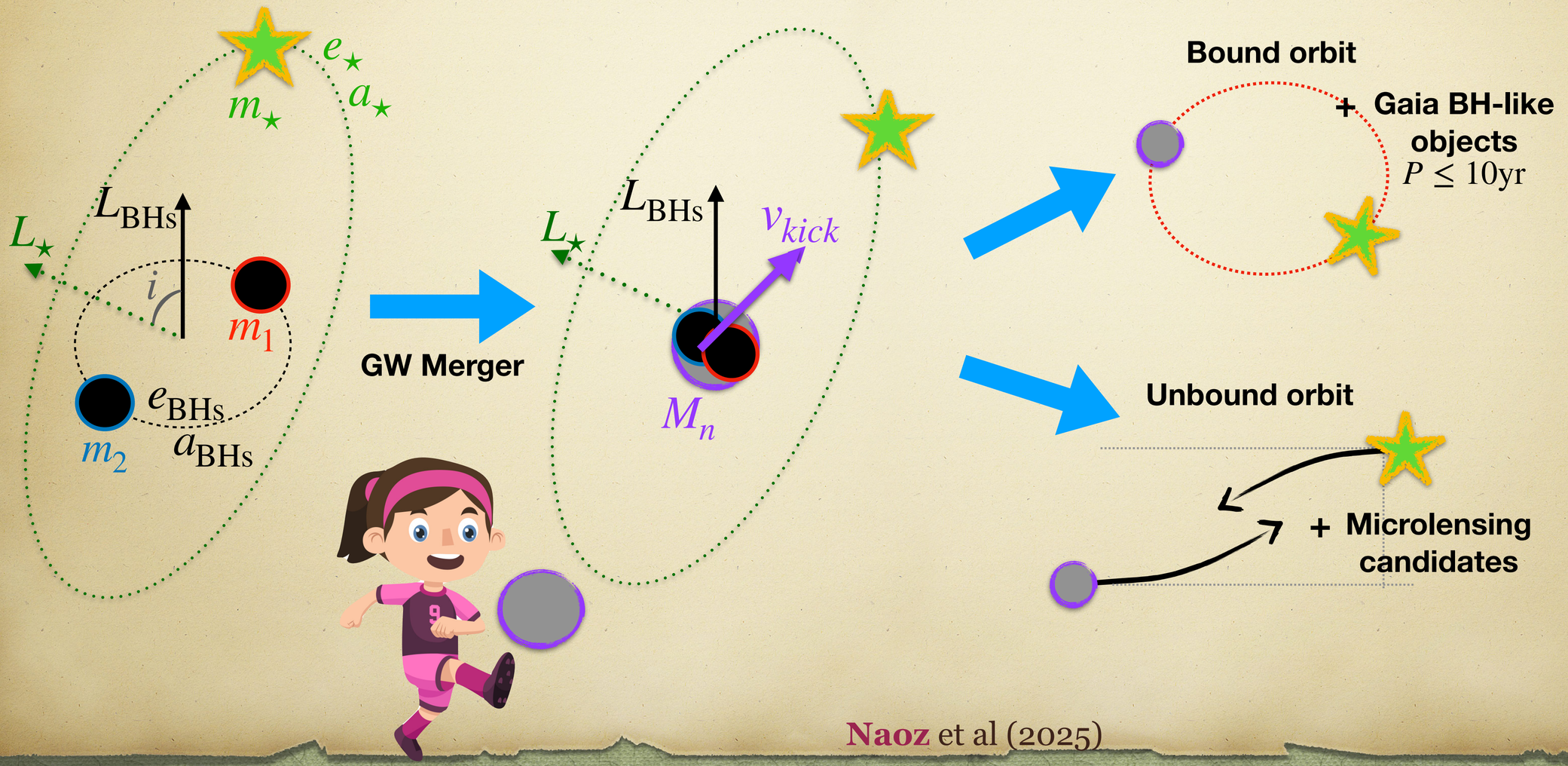
Isolated binary channel + a tertiary



Mostly, the iEKL mechanism, the tertiary doesn't play a big role

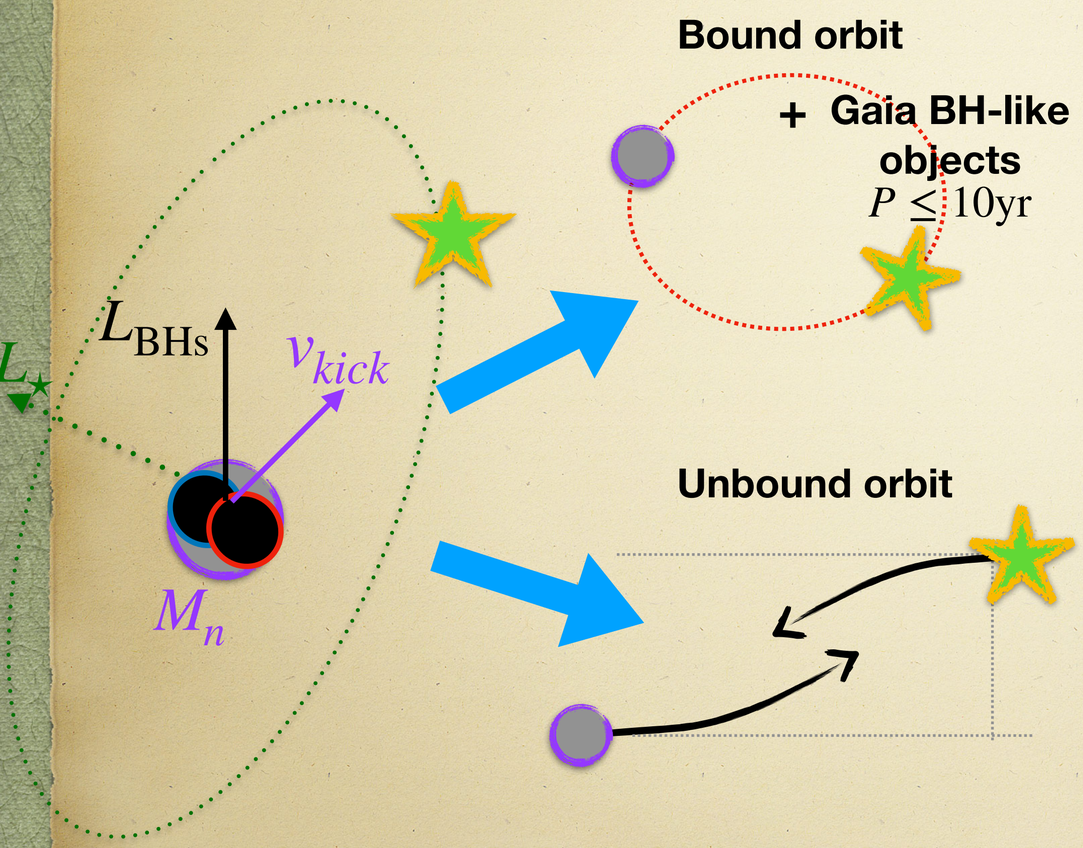
Naoz et al (2017)

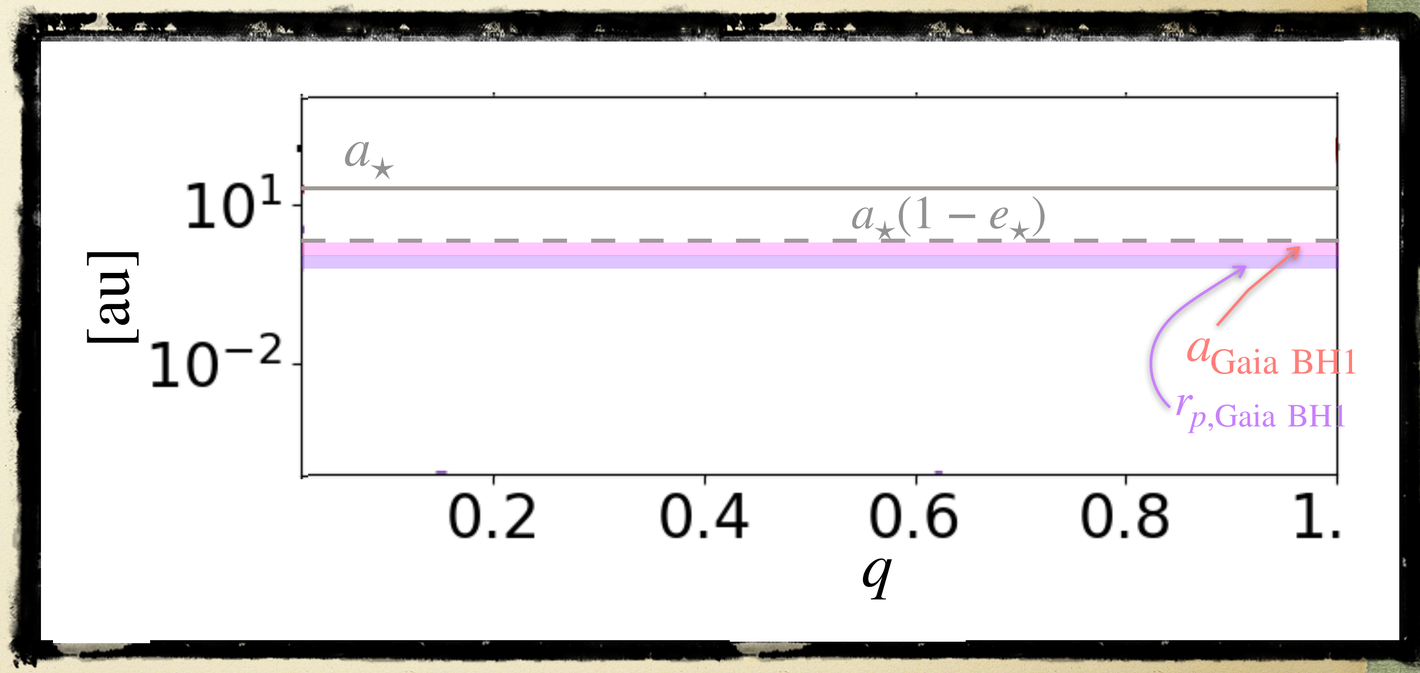
Isolated binary channel + a tertiary



Naoz et al (2025)

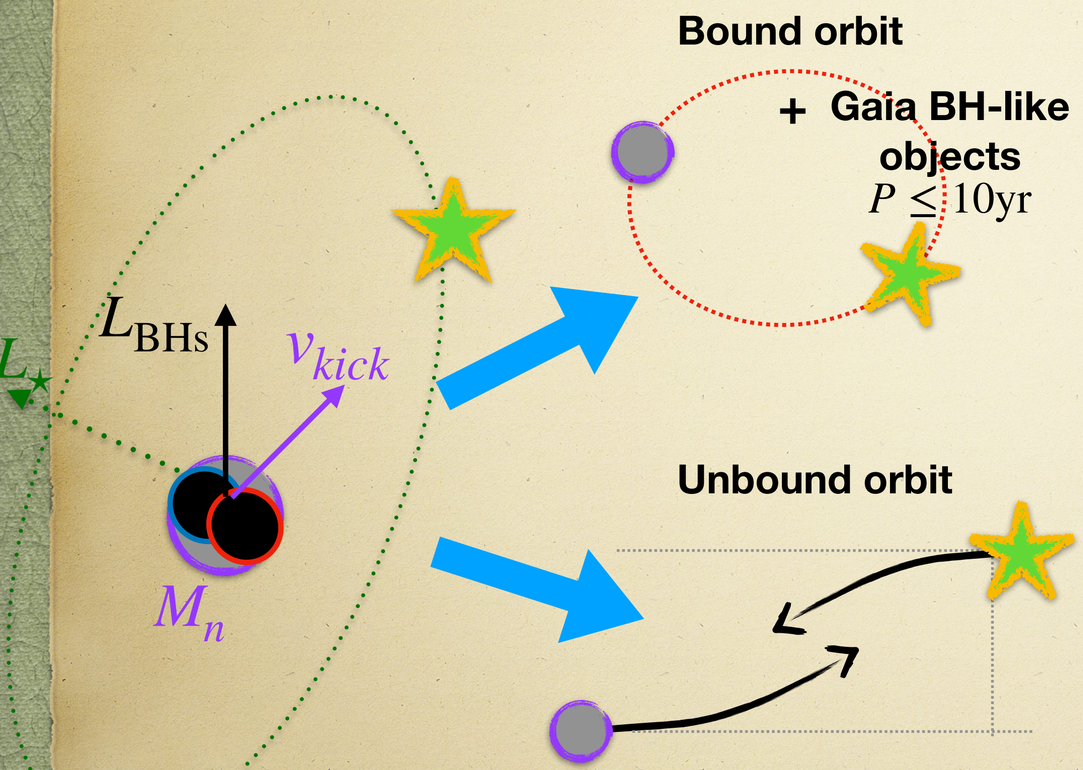
Isolated binary channel + a tertiary

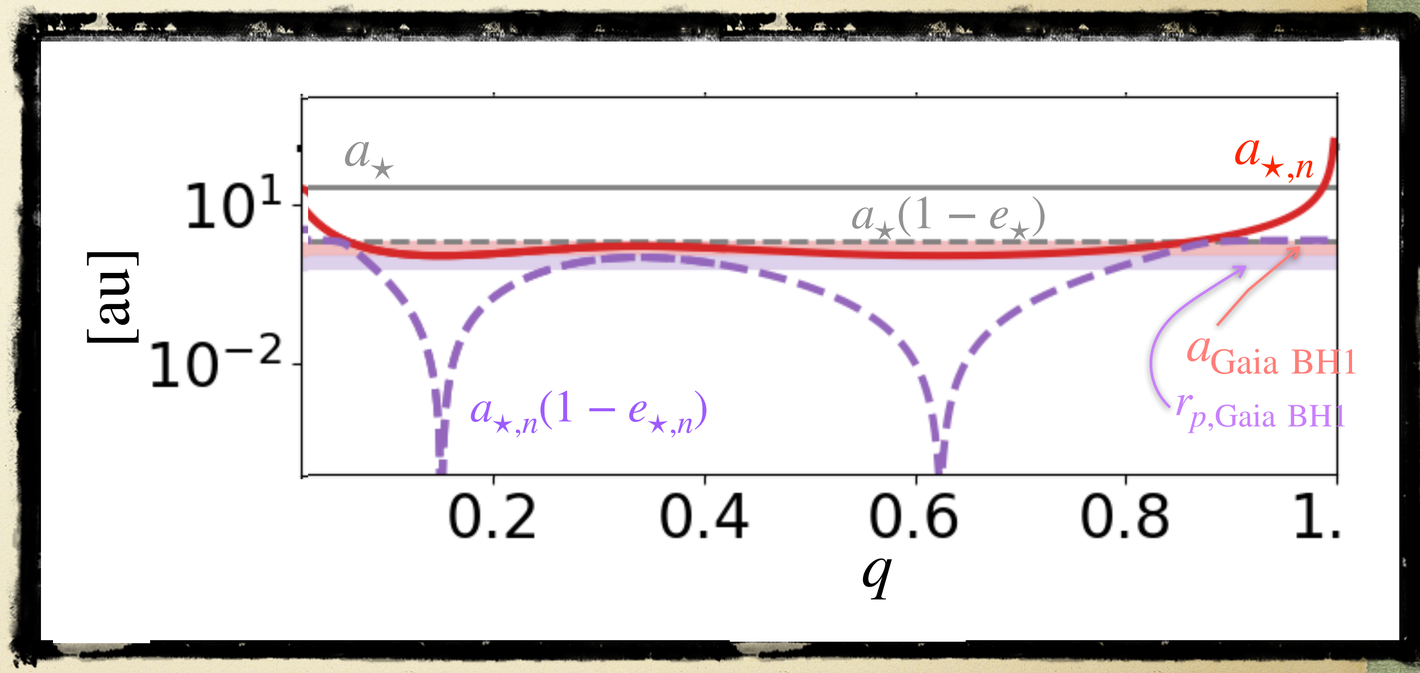




Naoz et al (2025)

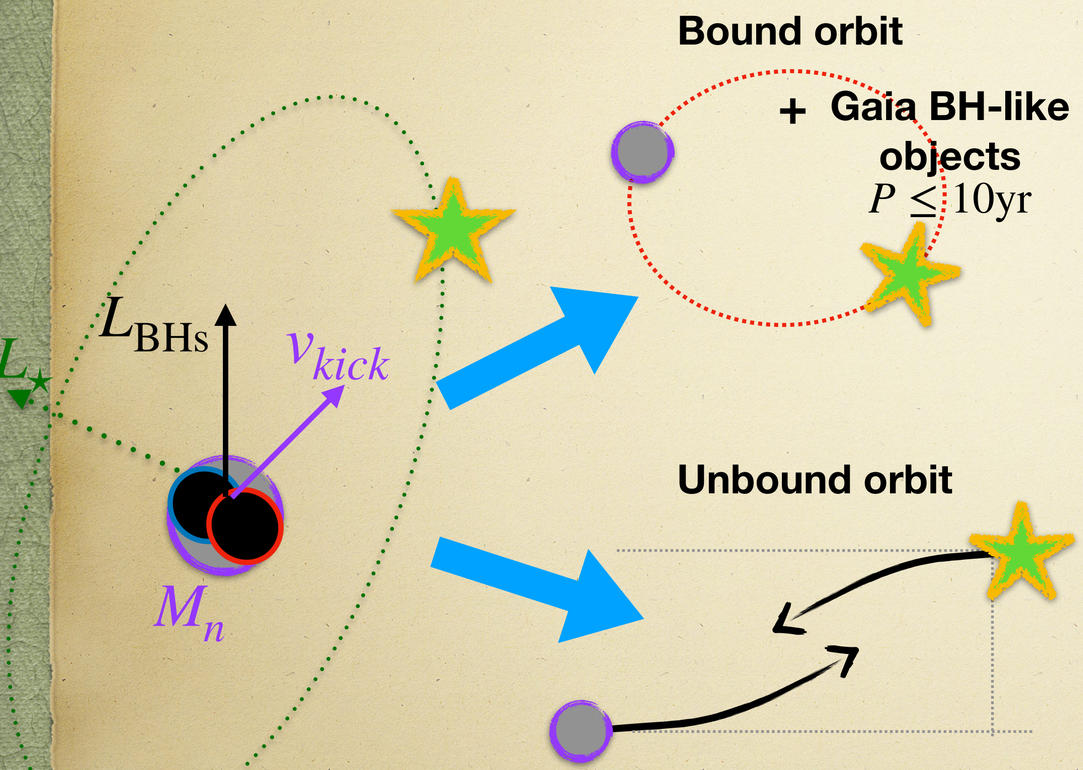
Isolated binary channel + a tertiary

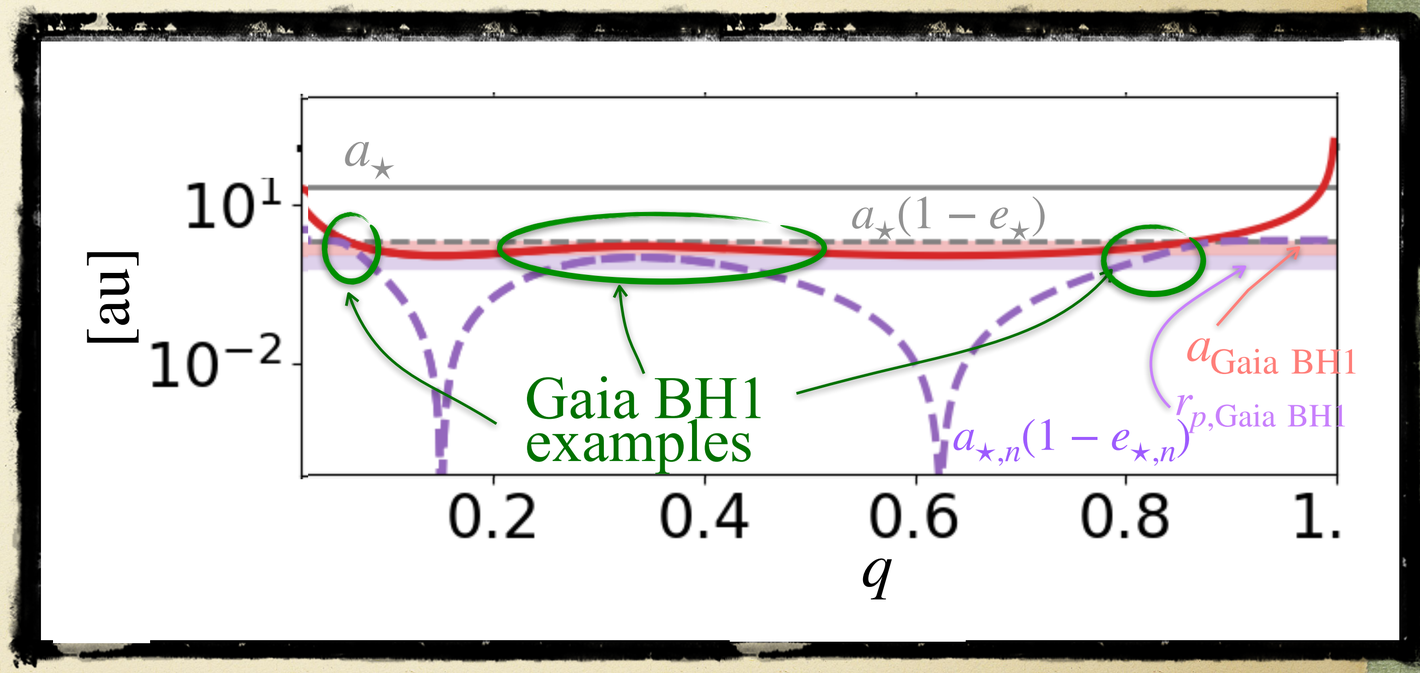




Naoz et al (2025)

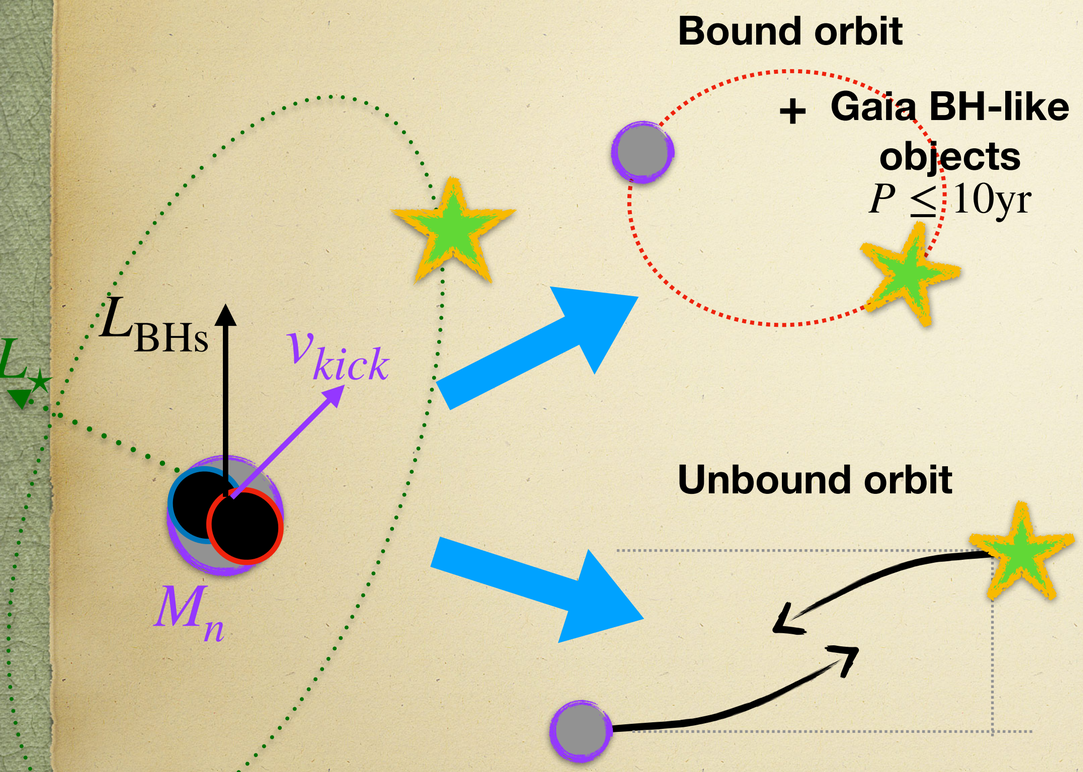
Isolated binary channel + a tertiary

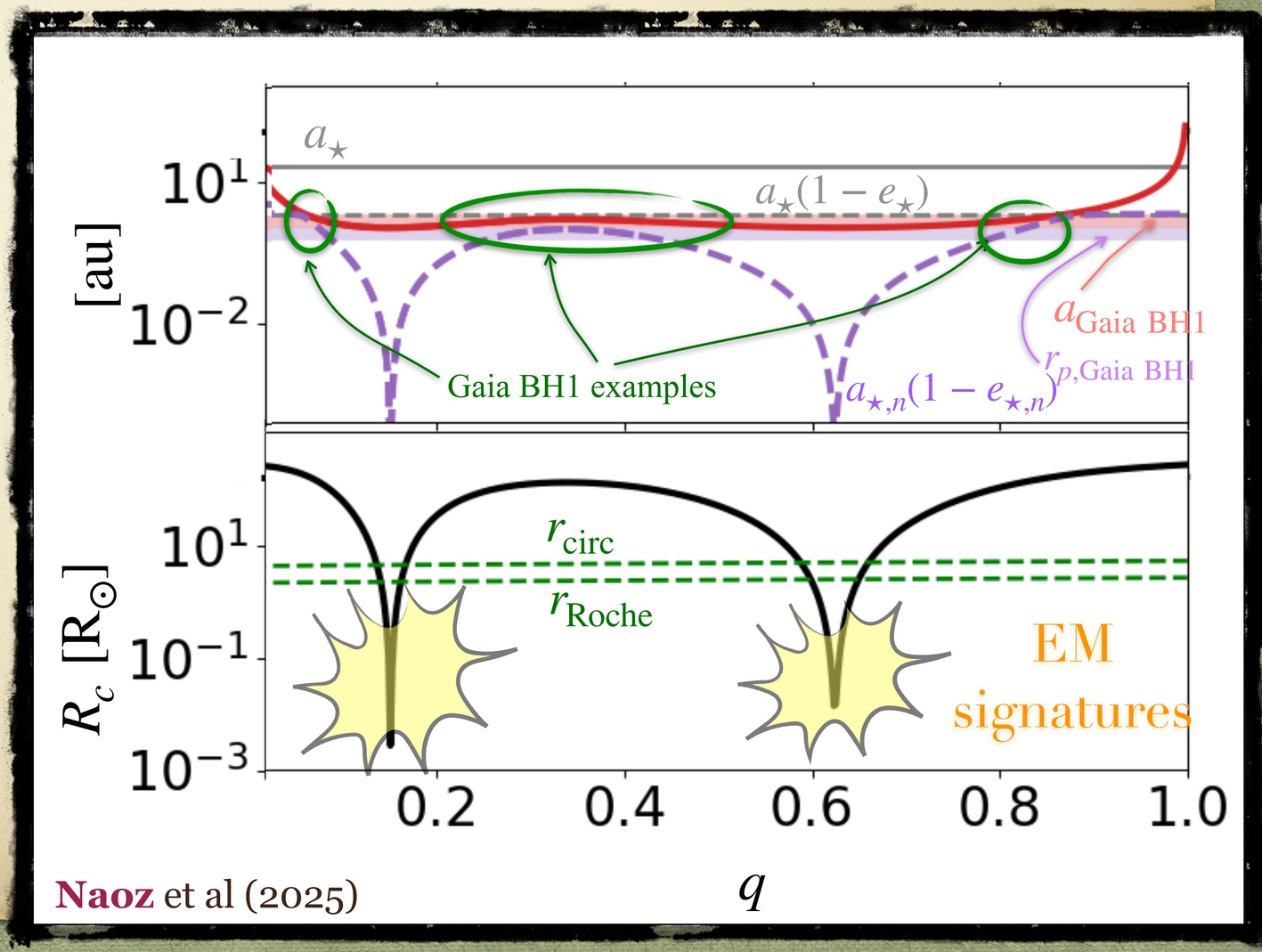




Naoz et al (2025)

Isolated binary channel + a tertiary





Naoz et al (2025)

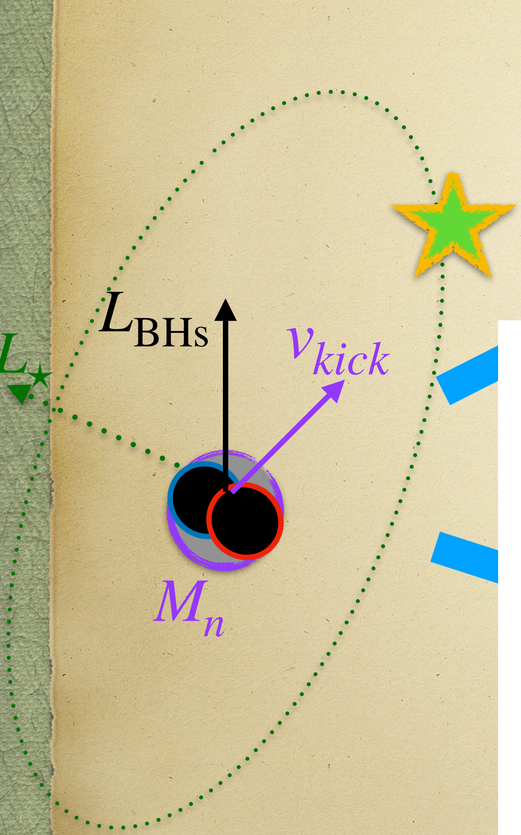
Isolated binary channel + a tertiary

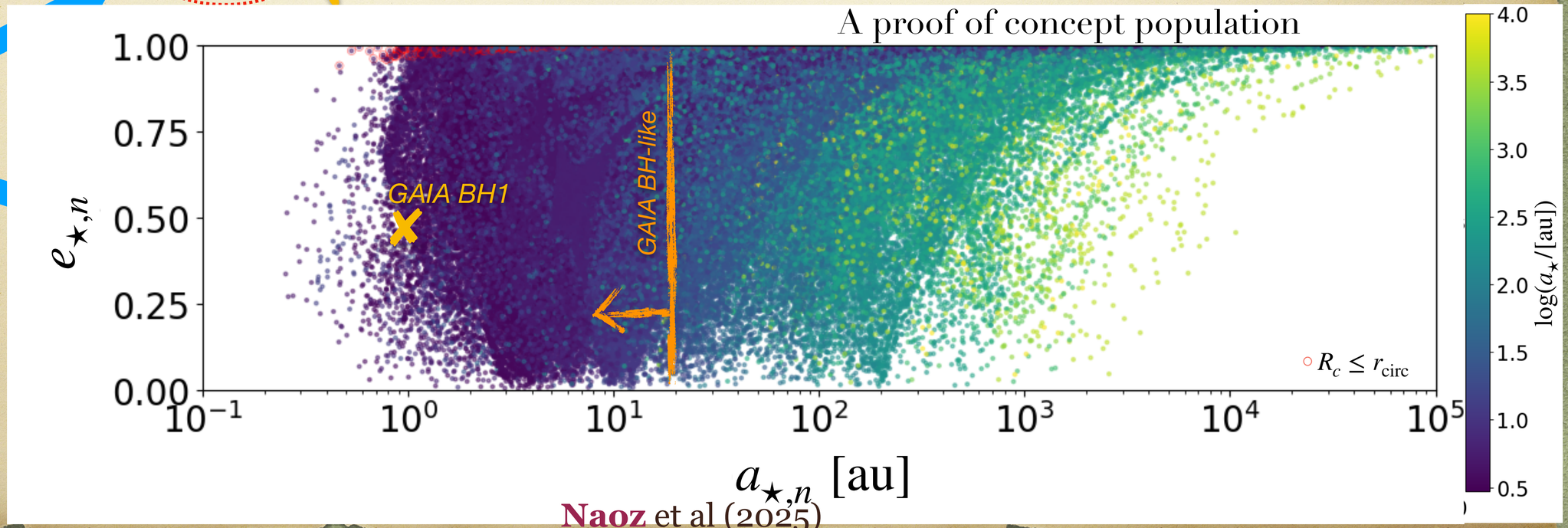
EKL (up to hexadecapole) + GR + GW + recoil kicks

Bin: Pre-merger configurations are motivated by Kruckow et al. (2018); tertiary: Shariat et al. (2025)

If all LVK sources came from isolated binaries

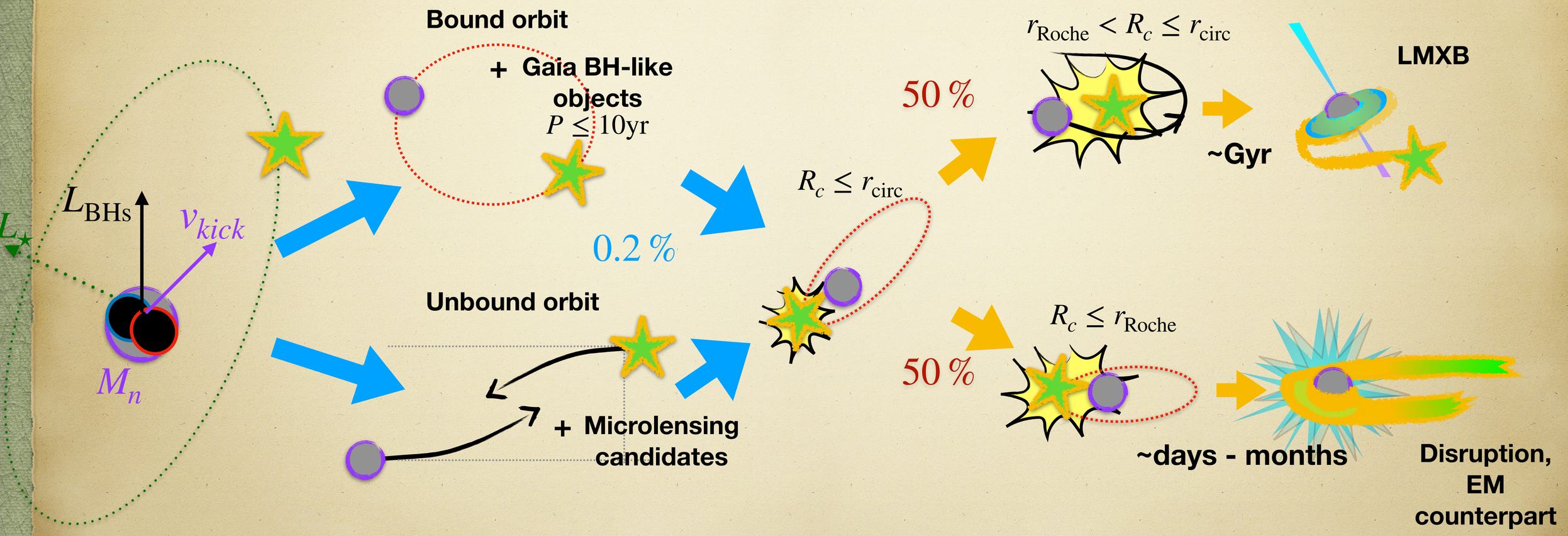
1-10% Gaia BH-like (P≤10yrs)





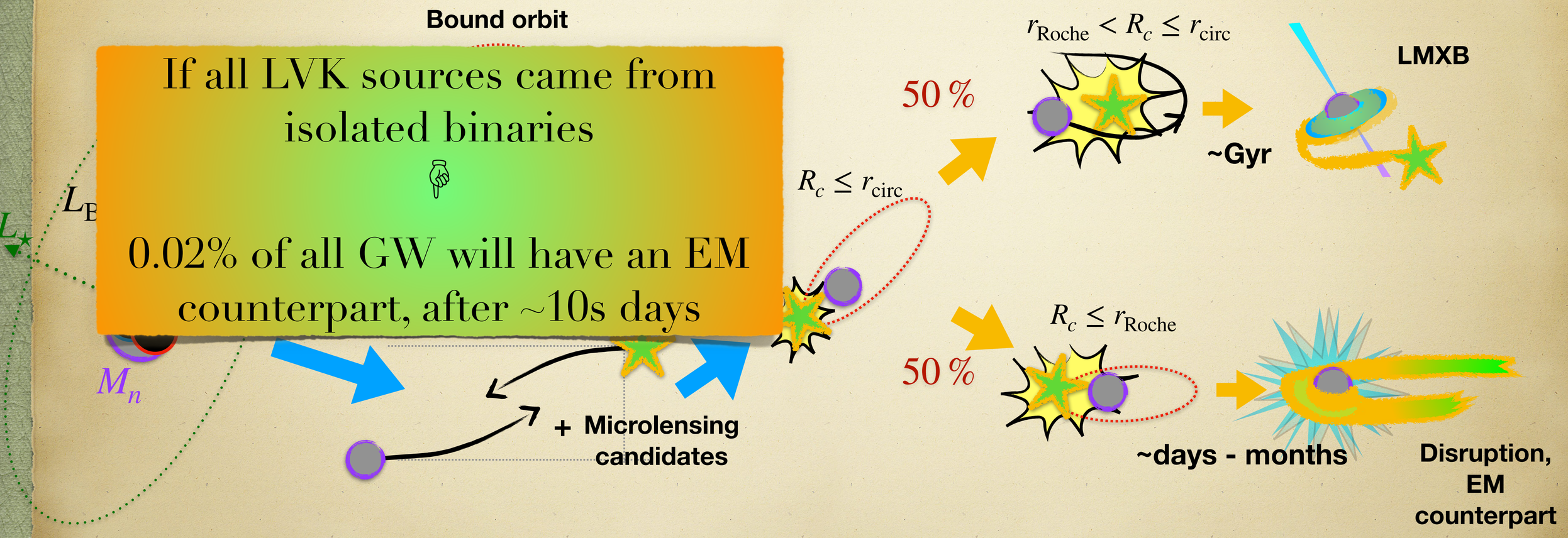
Naoz et al (2025)

Isolated binary channel + a tertiary



Naoz et al (2025)

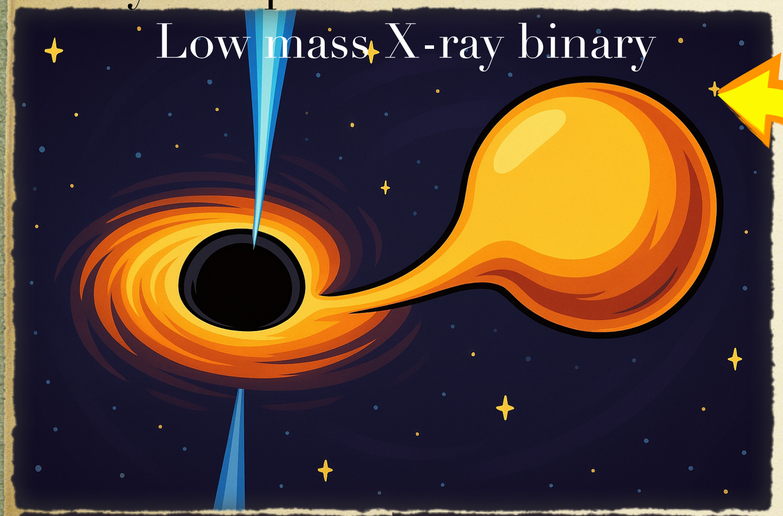
Isolated binary channel + a tertiary

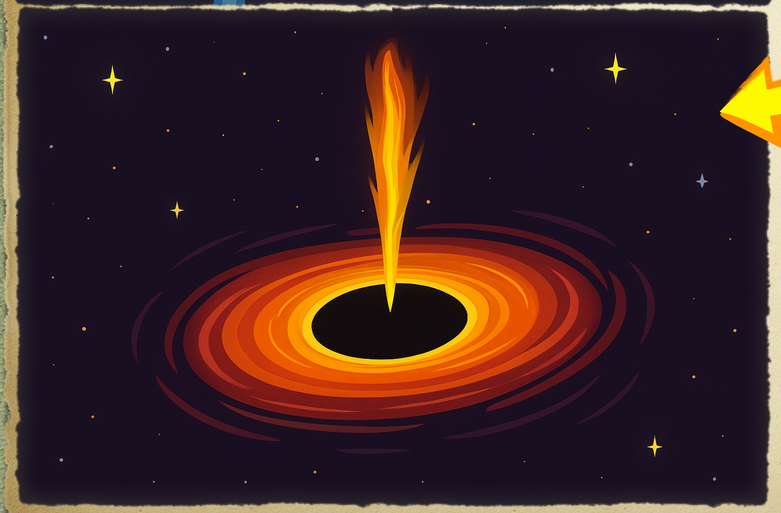


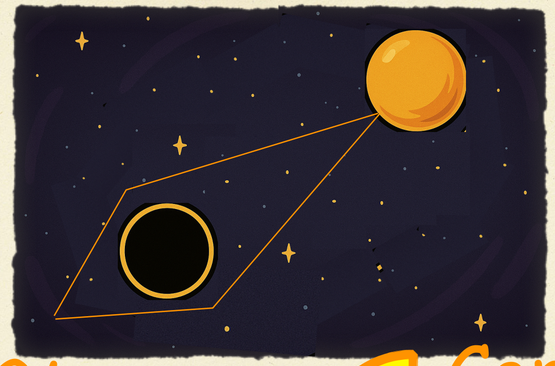
Naoz et al (2025)

The Triple Connection: Black Hole Mergers, Electromagnetic Signatures, and Galactic Black Holes

Binary + Triple formation channel of
Low mass X-ray binary

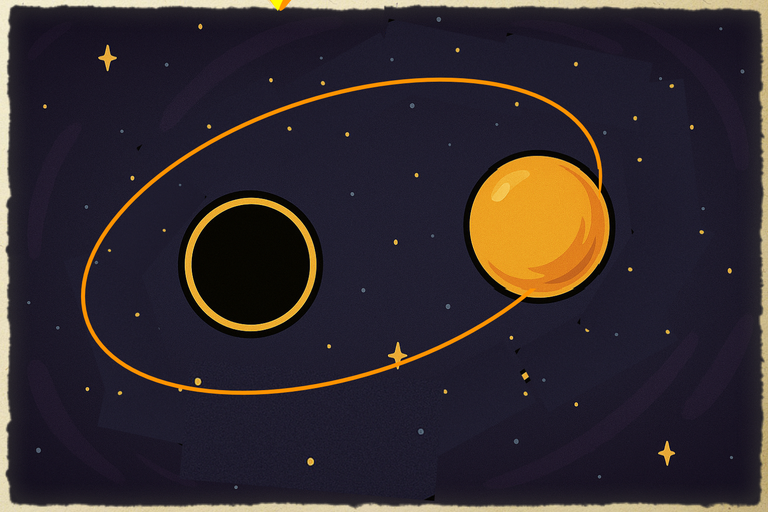






Connection

Connection



Gaia BH-like

Natural connection between different BH-binary systems