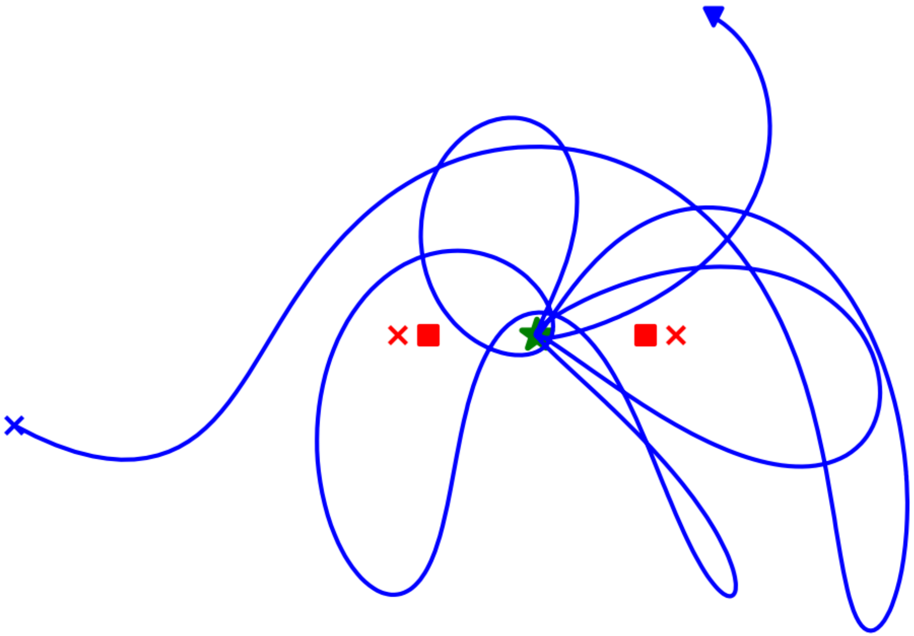
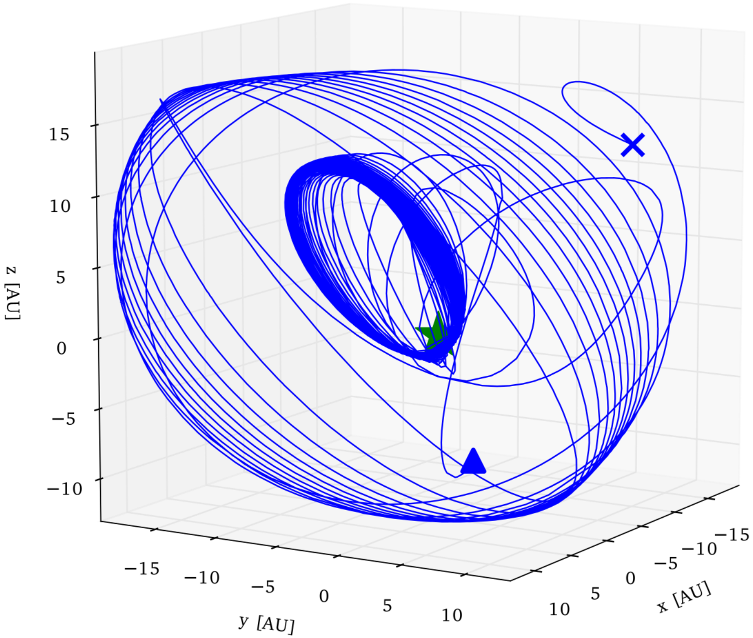
Dynamics of planets and low-mass stars in the Galactic centre: implications for G2





Alessandro A. Trani

Friday 9 December 2016

OSSERVATORIO ASTRONOMICO DI PADOVA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

ma per seguir virtute e canoscenza
SISSA

Collaborators:
Michela Mapelli
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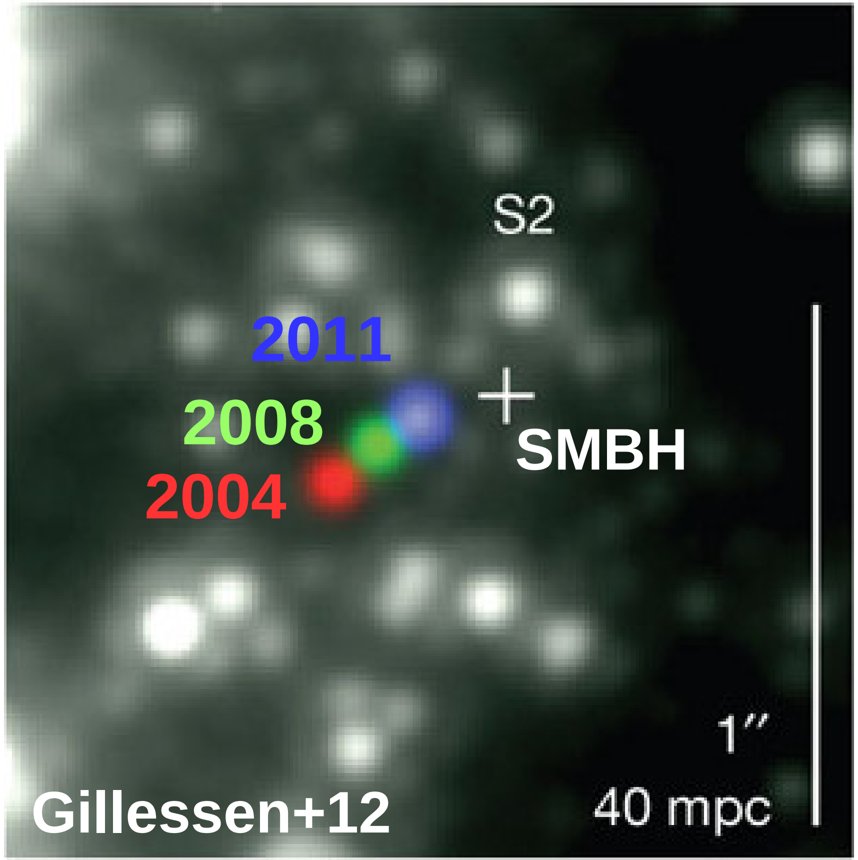
The Galactic Centre: The G2 cloud

- Faint, dusty object visible in Brγ line and L' band
- Radial orbit: $e \simeq 0.98$
- Very close pericenter passage: $p \simeq 200\,\mathrm{AU}$
- Same inclination of the CW disk



Gillessen+12

Debated origin

Compatible with planetary embryo \ low-mass star undergoing photoevaporation

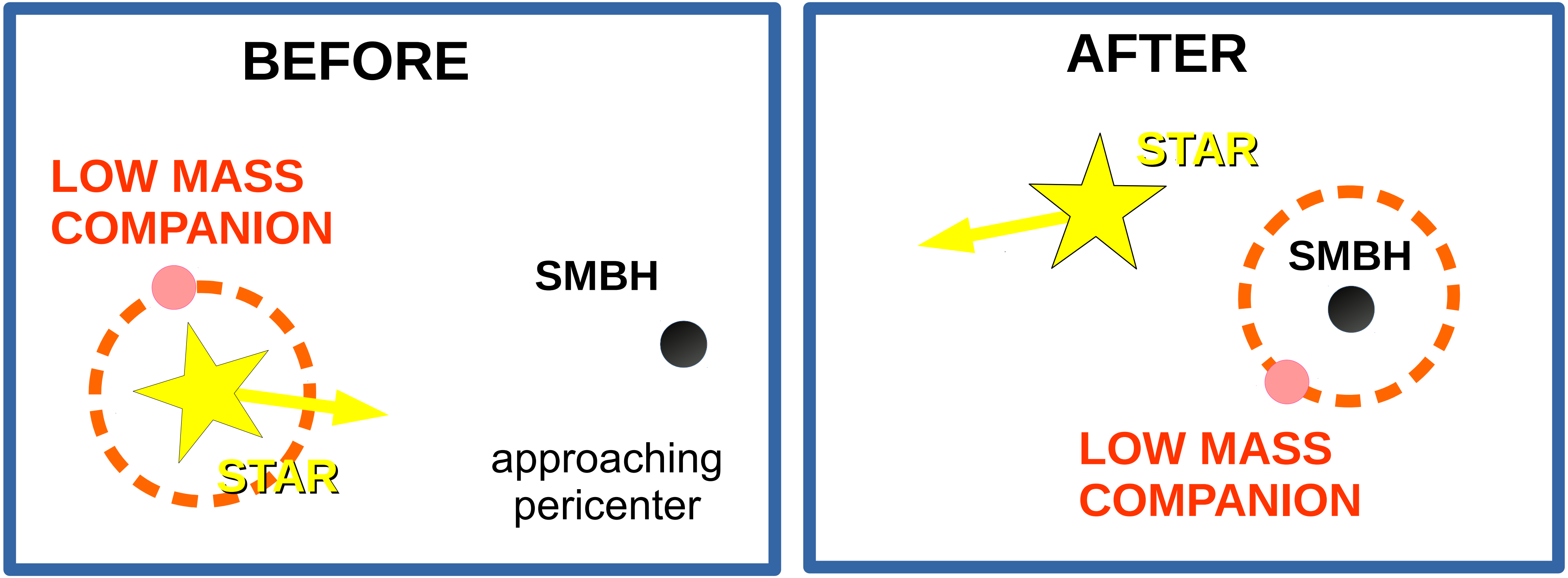
(Murray&Loeb 2012, Mapelli&Ripamonti 2015)

How planets/low mass stars get into such radial orbit?

Planets/low mass stars in the Galactic Center: dynamics

Stars in the CW disk might host planets and protoplanetary disk
(Ginsburg+12, Zubovas+12, Nayakshin+12, Cadez+08)

The SMBH tidal field may capture planets/low-mass stars



BEFORE

LOW MASS COMPANION

SMBH

STAR

approaching pericenter

AFTER

STAR

SMBH

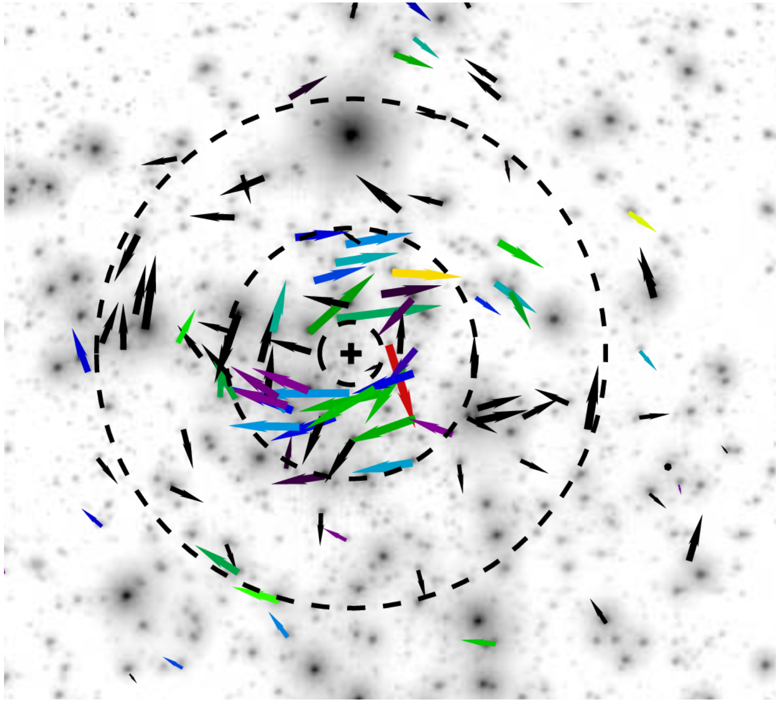
LOW MASS COMPANION

Planets/low mass stars in the Galactic Center: dynamics

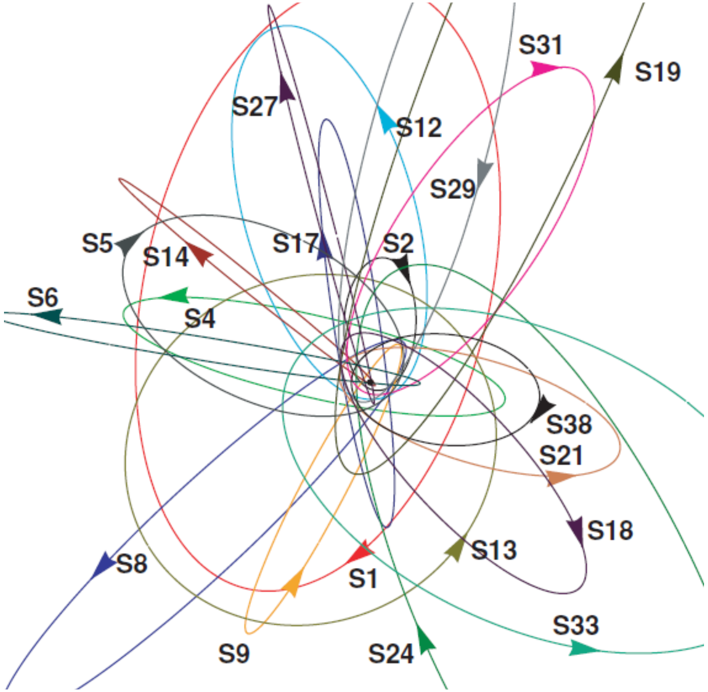
Planets/low mass stars source?

CW disk $a > 0.03\,\mathrm{pc},$ $e \simeq 0.3$

S-star cluster $a < 0.03\,\mathrm{pc},$ $e \simeq 0.4 - 0.99$



Yelda+2014



Gillessen+2009a

Clockwise disk 3-body simulations

3-body simulations of SMBH-star-planet hierarchical systems

- Mikkola's algorithmic regularization (MAR, Mikkola & Tanikawa 1999)

- Masses:

$$M_{\rm SMBH} = 4.3 \times 10^6\,{\rm M}_\odot$$
$$m_{\rm star} = 5\,{\rm M}_\odot$$
$$m_{\rm planet} = 10\,{\rm M}_{\rm Jup}$$

- Star orbit: modelled following the properties of the CW disk inner edge (Yelda+14, Do+13)

- Planet orbit: circular, with $10\,{\rm AU} < {\rm a}_{\rm planet} < 100\,{\rm AU}$

4 sets of 10000 realizations:

- Set A: **coplanar, prograde** orbits
- Set B: **coplanar, retrograde** orbits
- Set C: inclined, prograde orbits
- Set D: inclined, retrograde orbits

Clockwise disk 3-body simulations

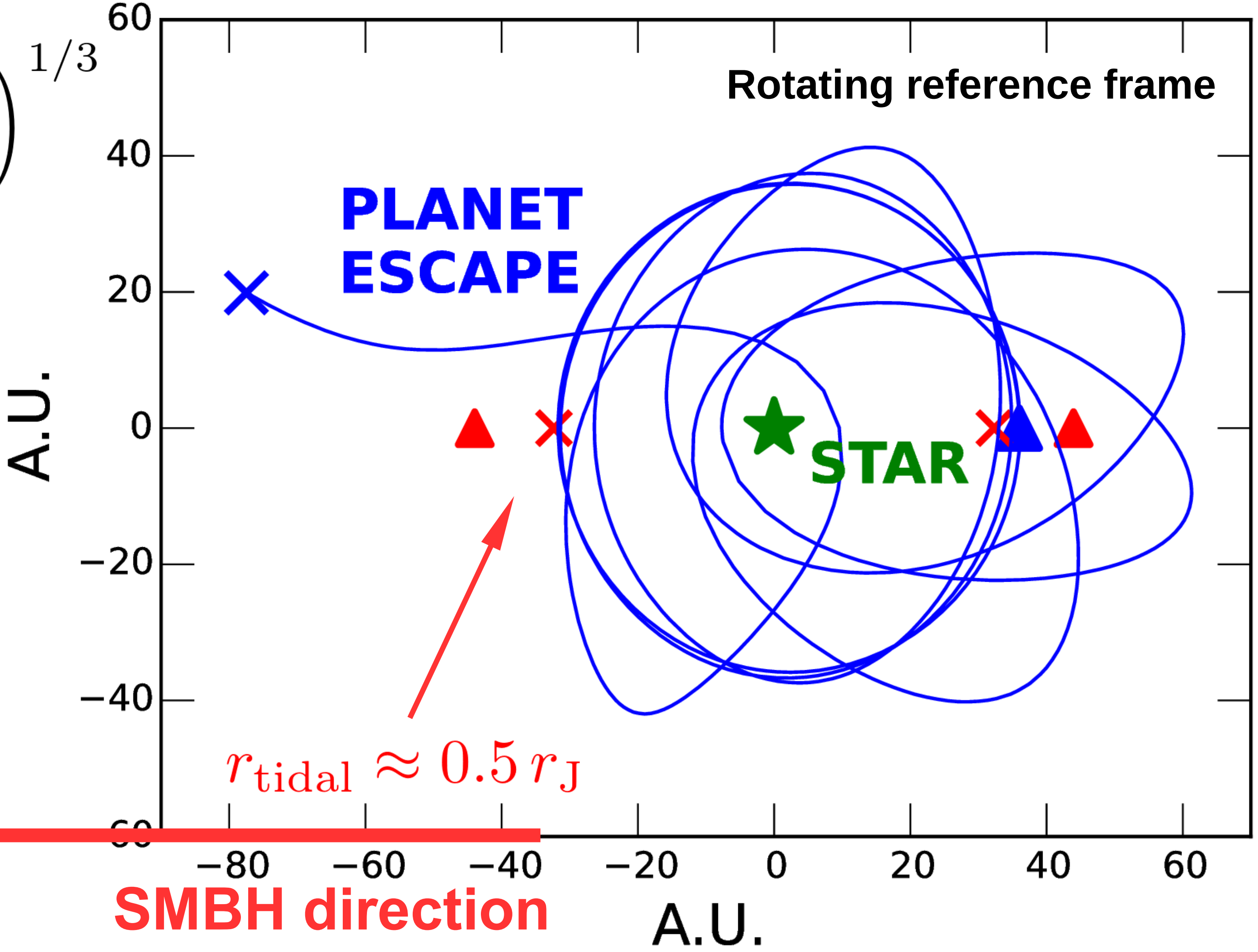
3-body simulations of SMBH-star-planet with regularized code

$$r_{\rm J} = p \left(\frac{m_{\rm star}}{3M_{\rm smbh}} \right)^{1/3}$$

Jacobi radius

$$p = a\,(1 - e)$$

periapsis distance of stellar orbit

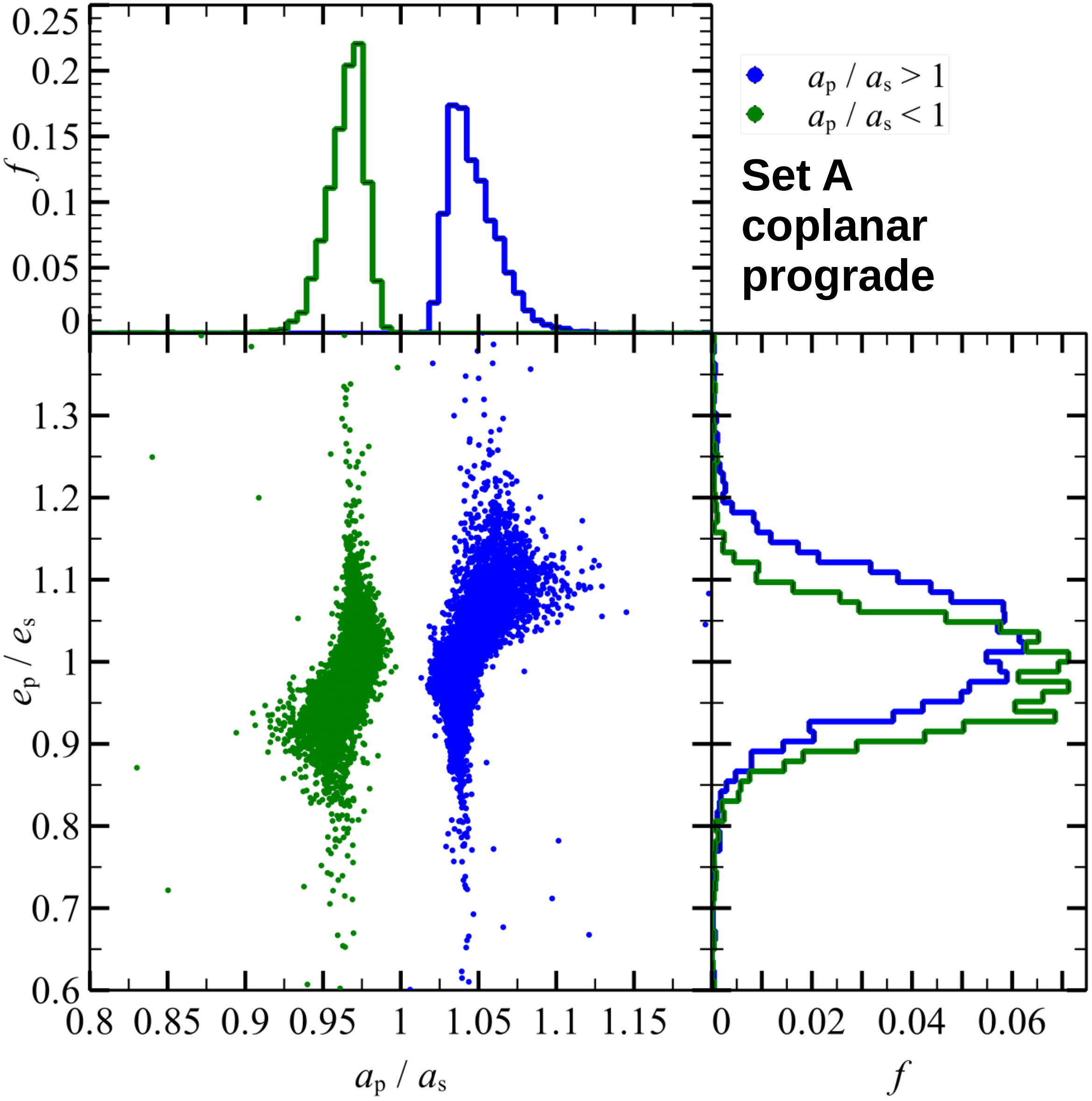


$r_{\rm tidal} \approx 0.5\, r_{\rm J}$

SMBH direction

Clockwise disk 3-body simulations: results

AAT+2016

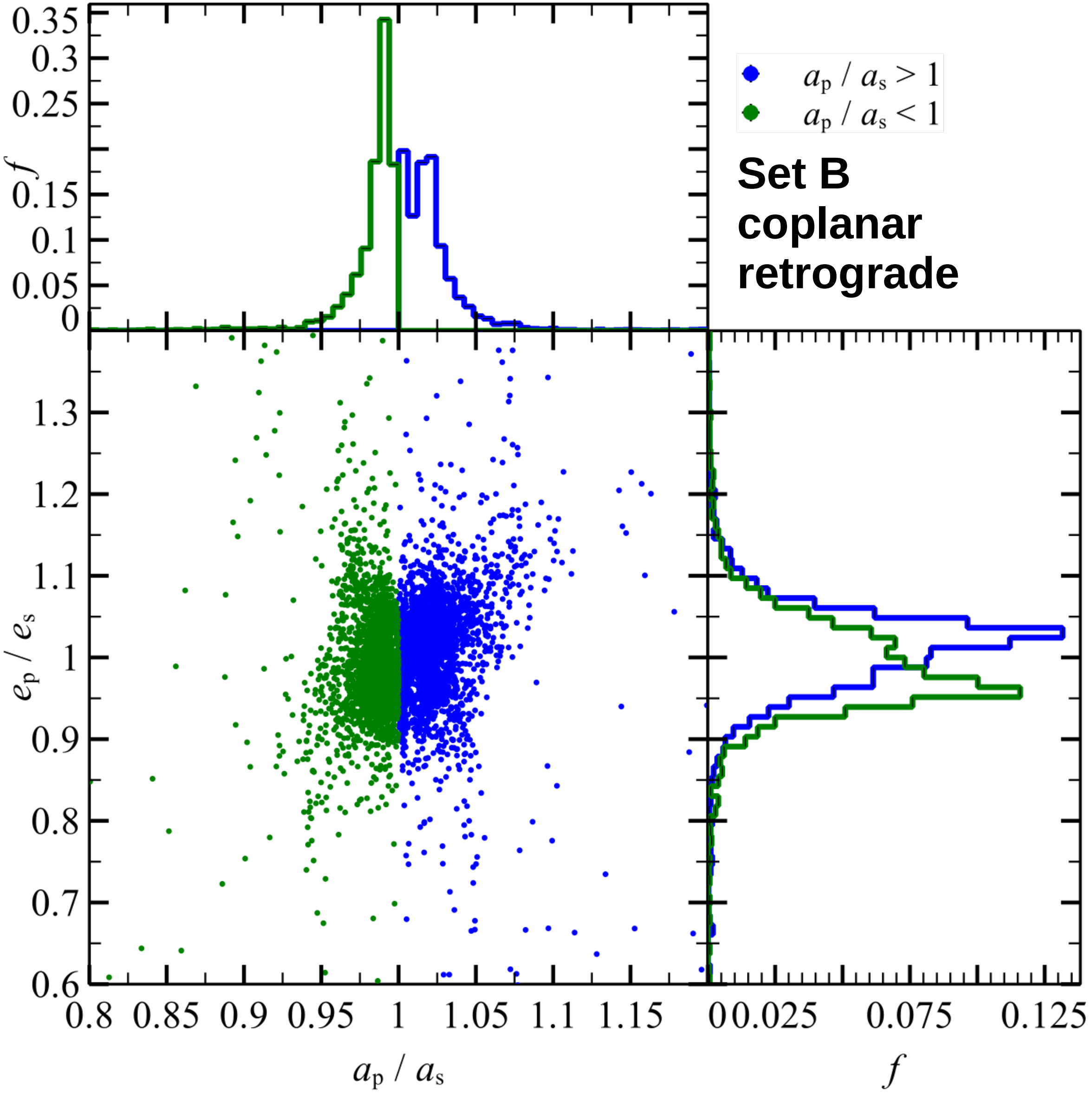


Set A
coplanar
prograde

- Planets remain on orbit similar to the one of their parent star
- Bimodal distribution in normalized semimajor axis: planets never get the same semimajor axis of the parent star
- Looser orbits tend to have higher eccentricity with respect to the parent star orbit, and viceversa

Clockwise disk 3-body simulations: results

AAT+2016



Set B
coplanar
retrograde

- Planets remain on orbit similar to the one of their parent star
- *No bimodal distribution in semimajor axis*
- Looser orbits tend to have higher eccentricity with respect to the parent star orbit, and viceversa

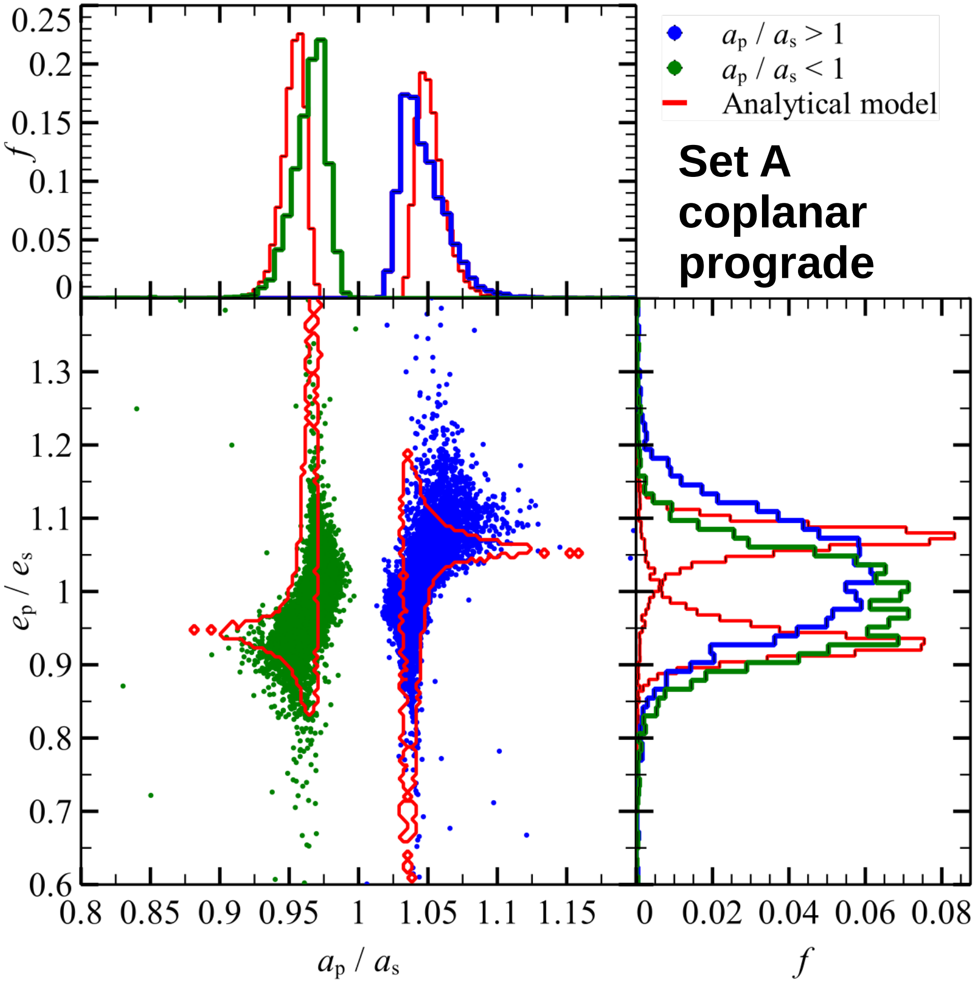
Can we predict analytically?

Clockwise disk 3-body simulations: results

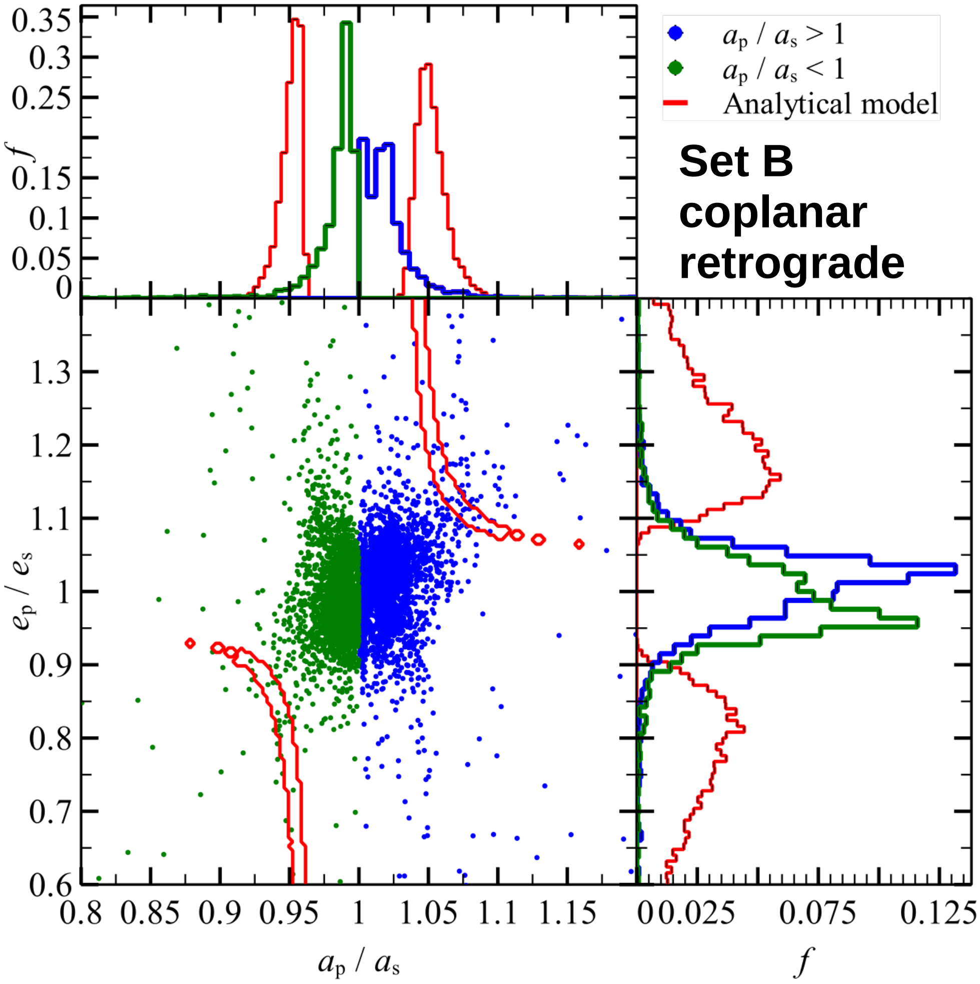
AAT+2016

Prograde orbits:
well predicted analytically

Retrograde orbits:
not well predicted analytically



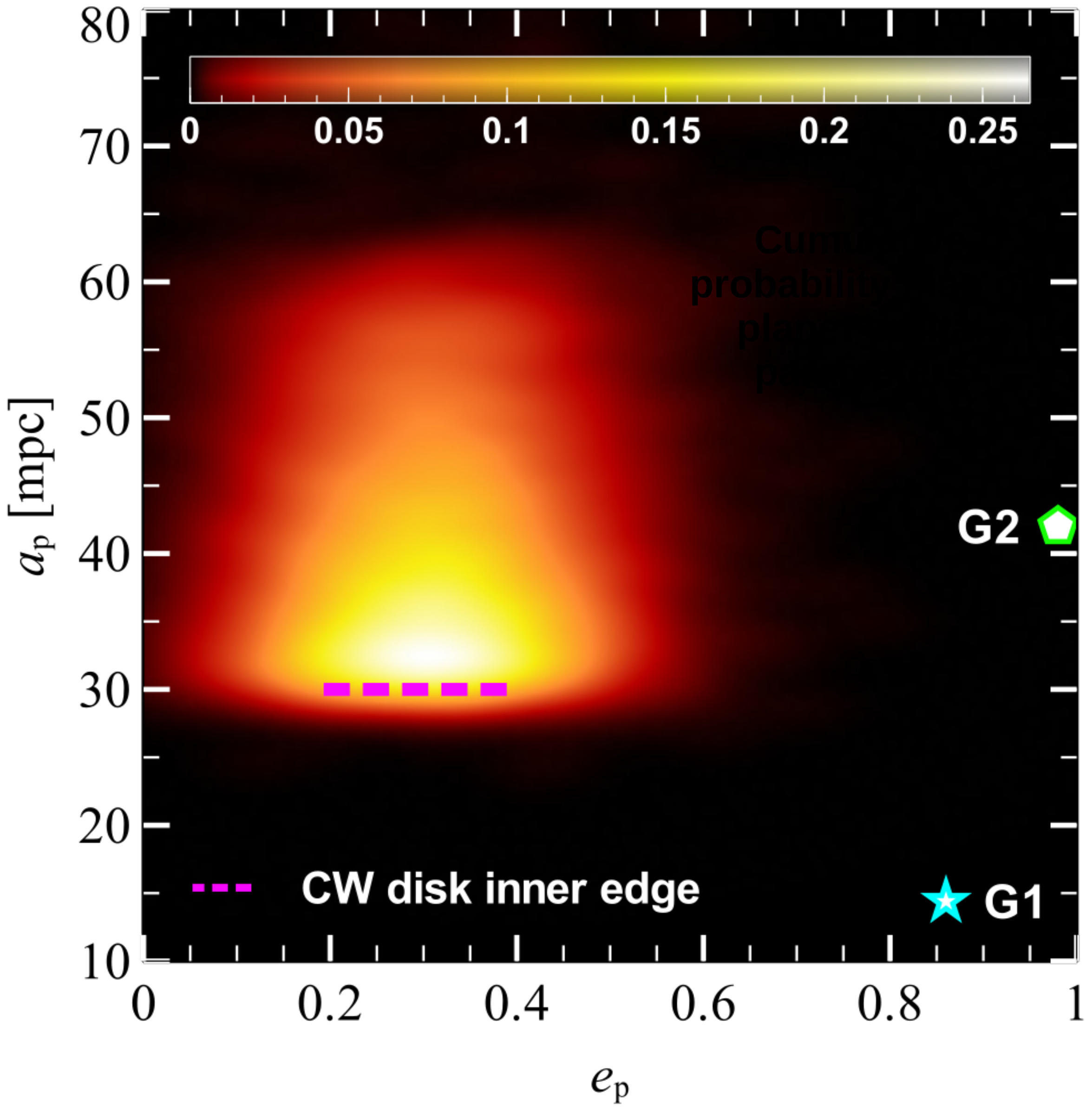
Set A
coplanar
prograde



Set B
coplanar
retrograde

Clockwise disk 3-body simulations: results

AAT+2016



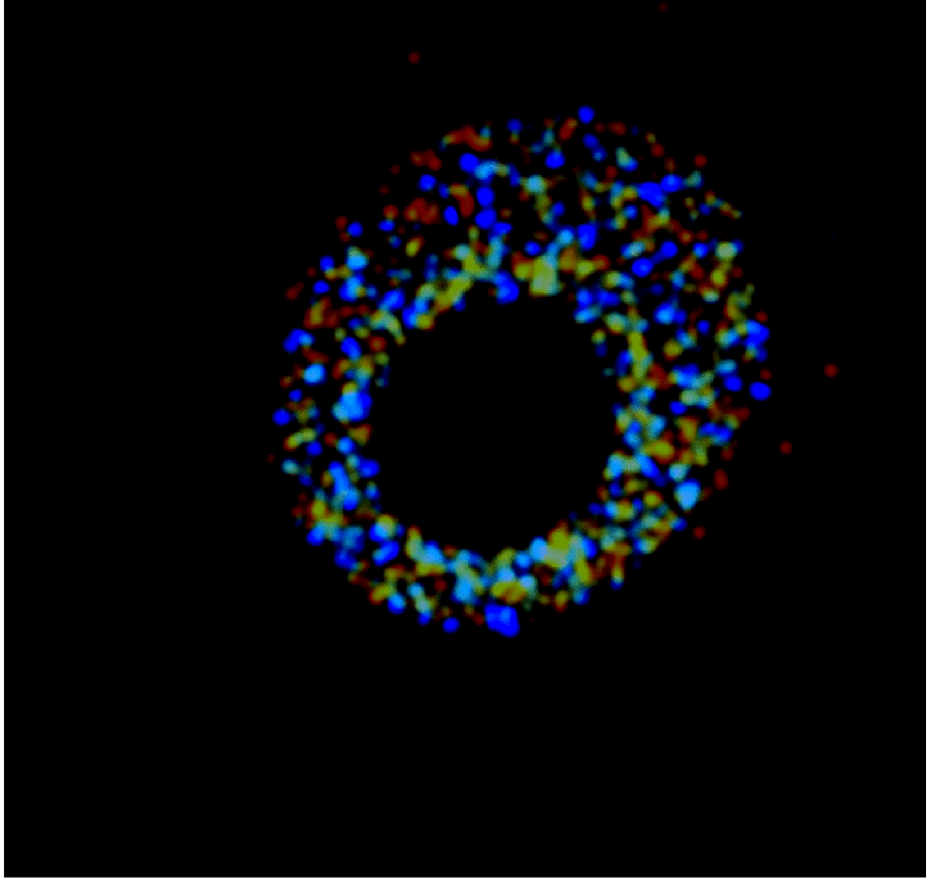
Going back to G2 cloud: is there some planet getting into an orbit around the SMBH similar to the G2 cloud one?

All planets remain in the CW disk

Perturbations from other stars in the disk may bring planets into radial orbits

Clockwise disk simulations

- **GENGA**: hybrid symplectic integrator (Grimm & Stadel 2014)
  - Hamiltonian splitting
  - Runs on GPUs
  - Excellent energy conservation in nearly-Keplerian problems



- **Stellar disk**

Obtained from hydro simulation of an infalling molecular gas cloud (Mapelli+2012)

- **+ planets/low mass stars as test particles (unbound from the stars)** $N_{\rm test} := N_{\rm stars}$

- **Consistent with observations**

(Do+2013, Lu+2013, Yelda+2014)

$N \simeq 10^3$

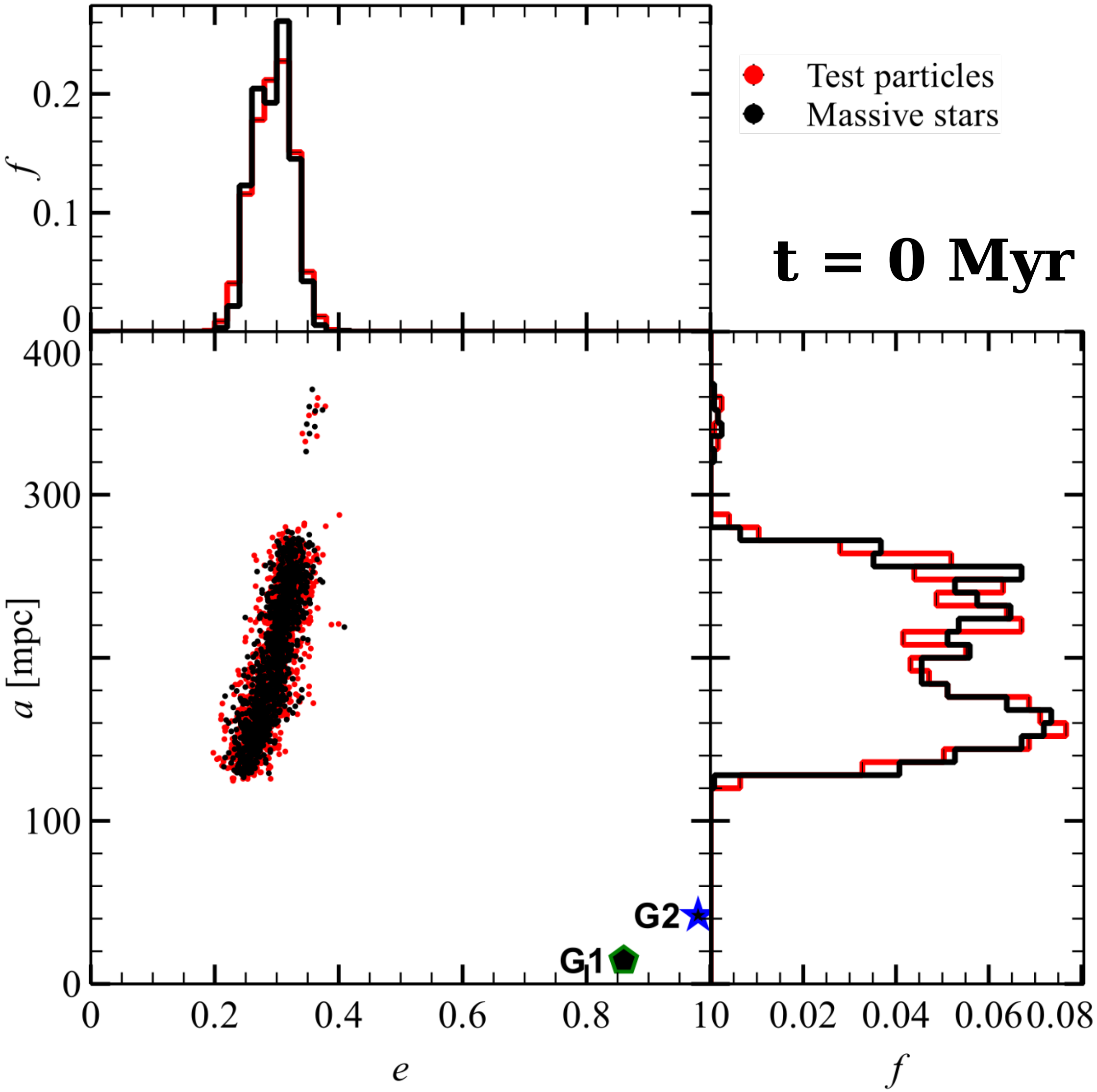
$M_{\rm tot} = 4.3 \times 10^3\,{\rm M}_\odot$

${\rm IMF}(m) \propto m^{-1.5}$

$a \in (0.1, 0.4)\,{\rm pc}$

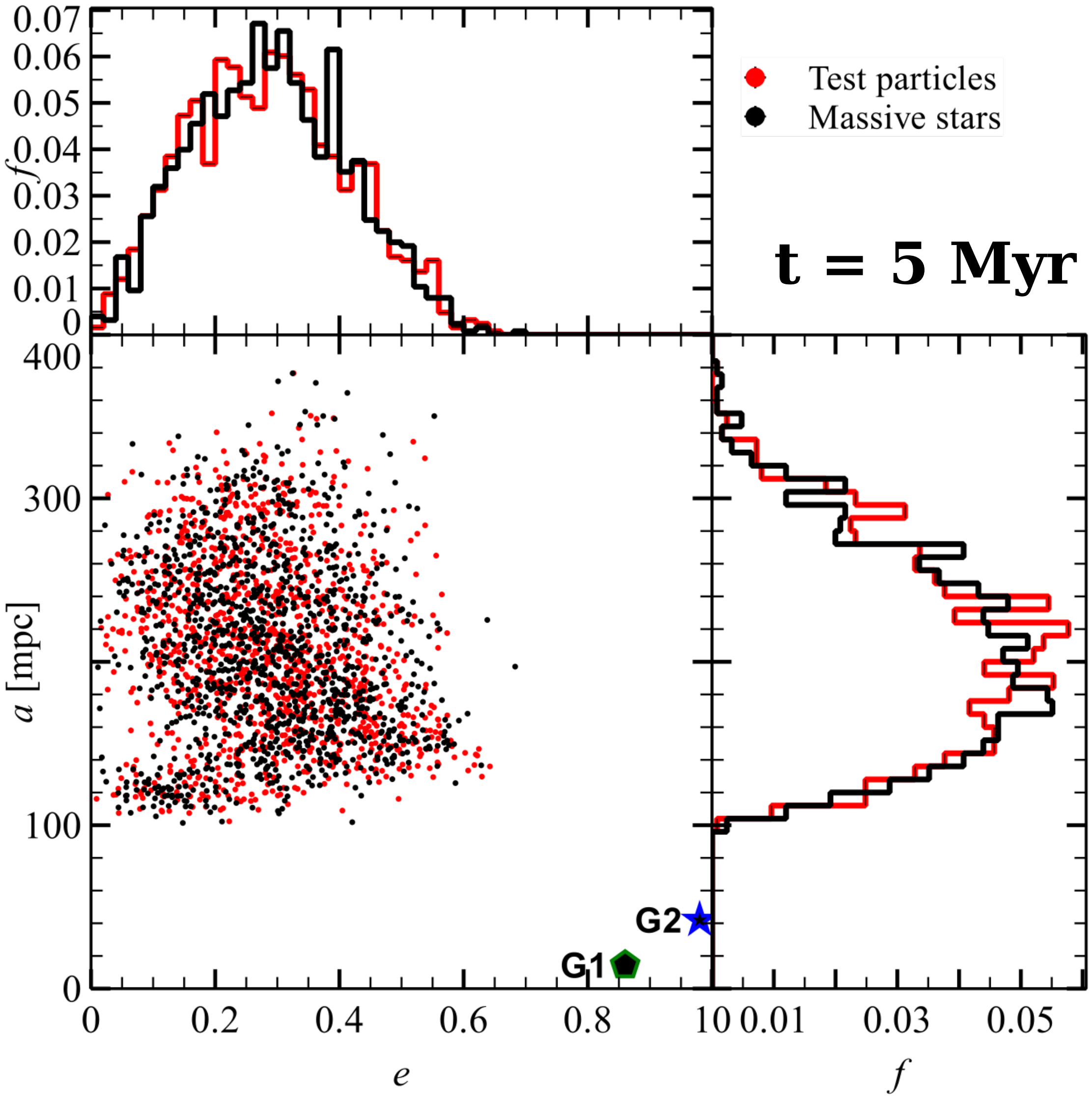
$\langle e \rangle \simeq 0.3$

Clockwise disk simulations: some results



AAT+, in preparation

Clockwise disk simulations: some results



t = 5 Myr

- Both planets and stars diffuse to highly-eccentric orbits
- *BUT NOT ENOUGH*
- No significant difference between test particles and stars distributions

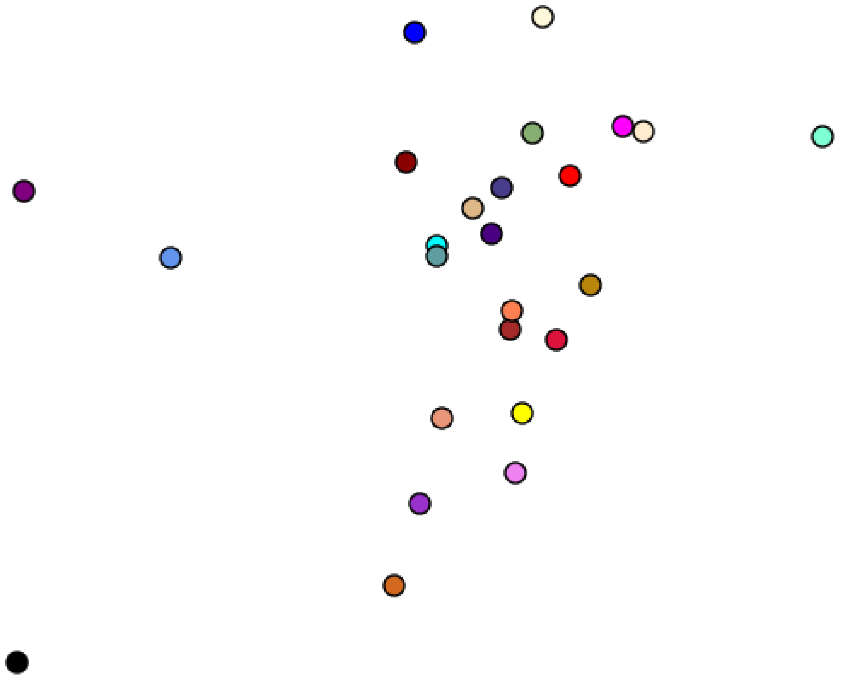
More simulations are coming

AAT+, in preparation

Tidal capture in S-star cluster

What about planets in the S-star cluster?

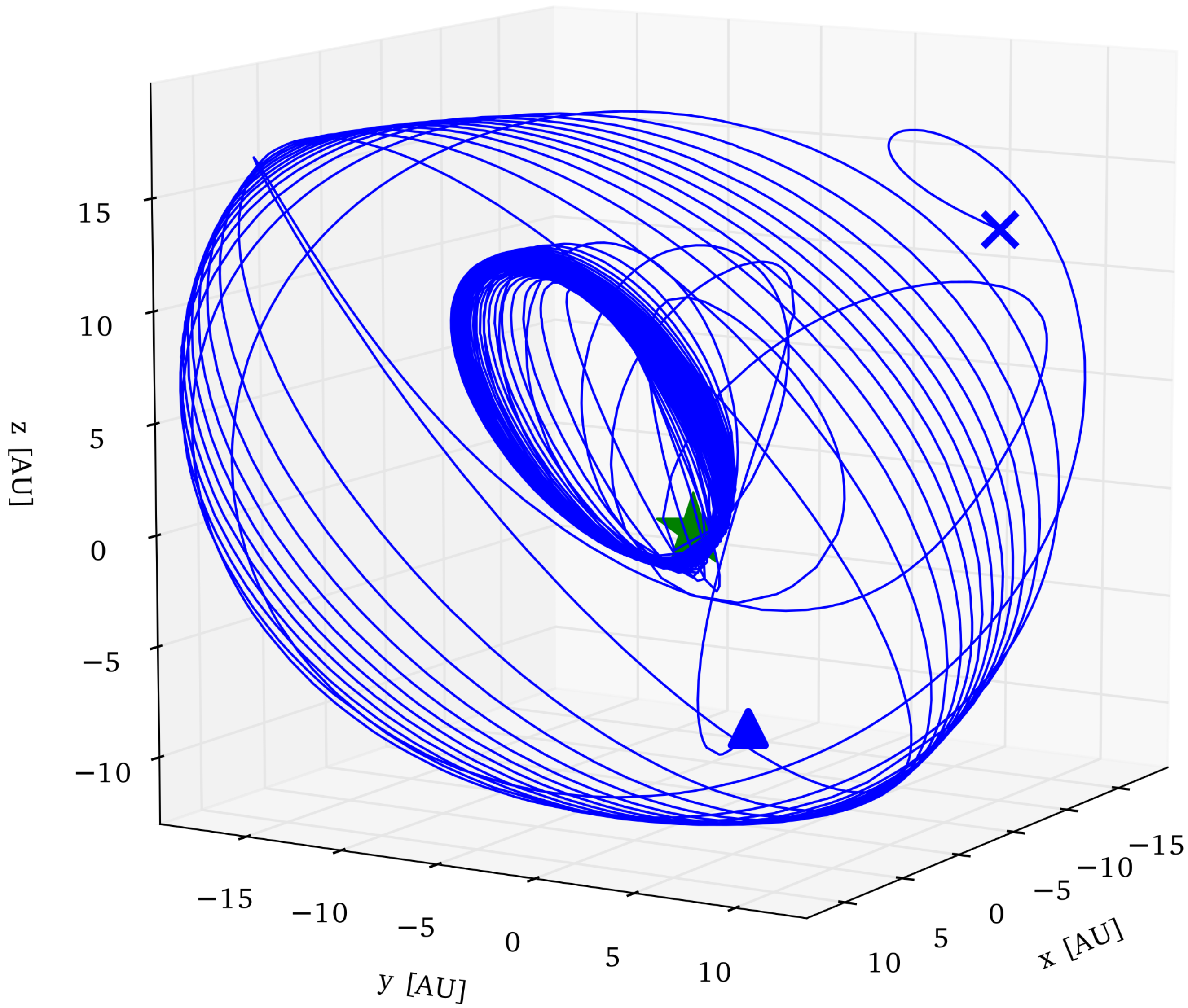
S-stars orbits are more eccentric and tight than CW disk stars:



20000 simulations of 27 S-stars with planets:

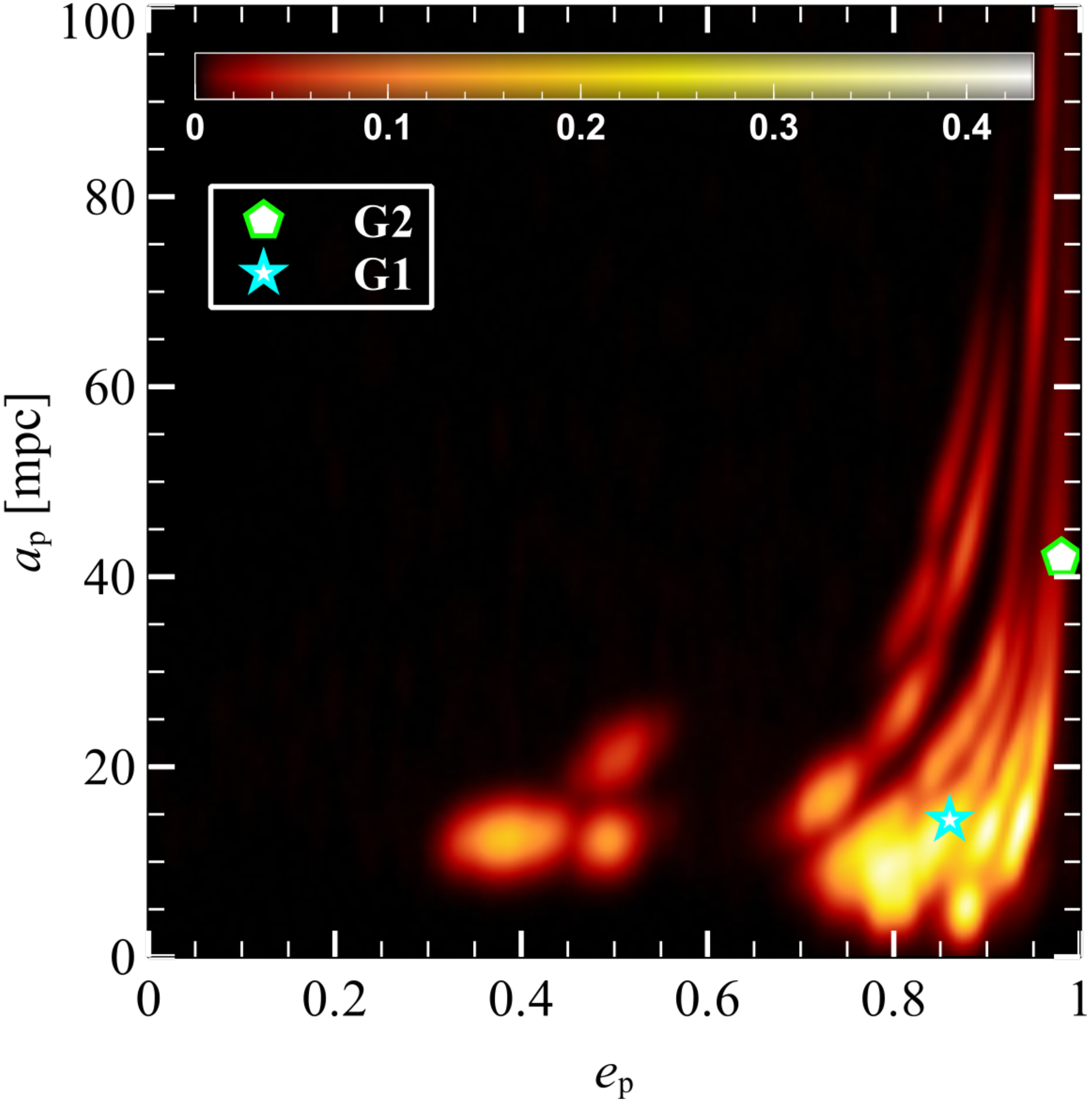
- S-stars orbit parameters taken from observations (Gillessen+09)
- Planet orbits: circular, randomly oriented over the sphere
- Planets semimajor axis: $1 - 20\,\mathrm{AU}$

Tidal capture in S-star cluster



Tidal capture in S-star cluster: results

AAT+2016

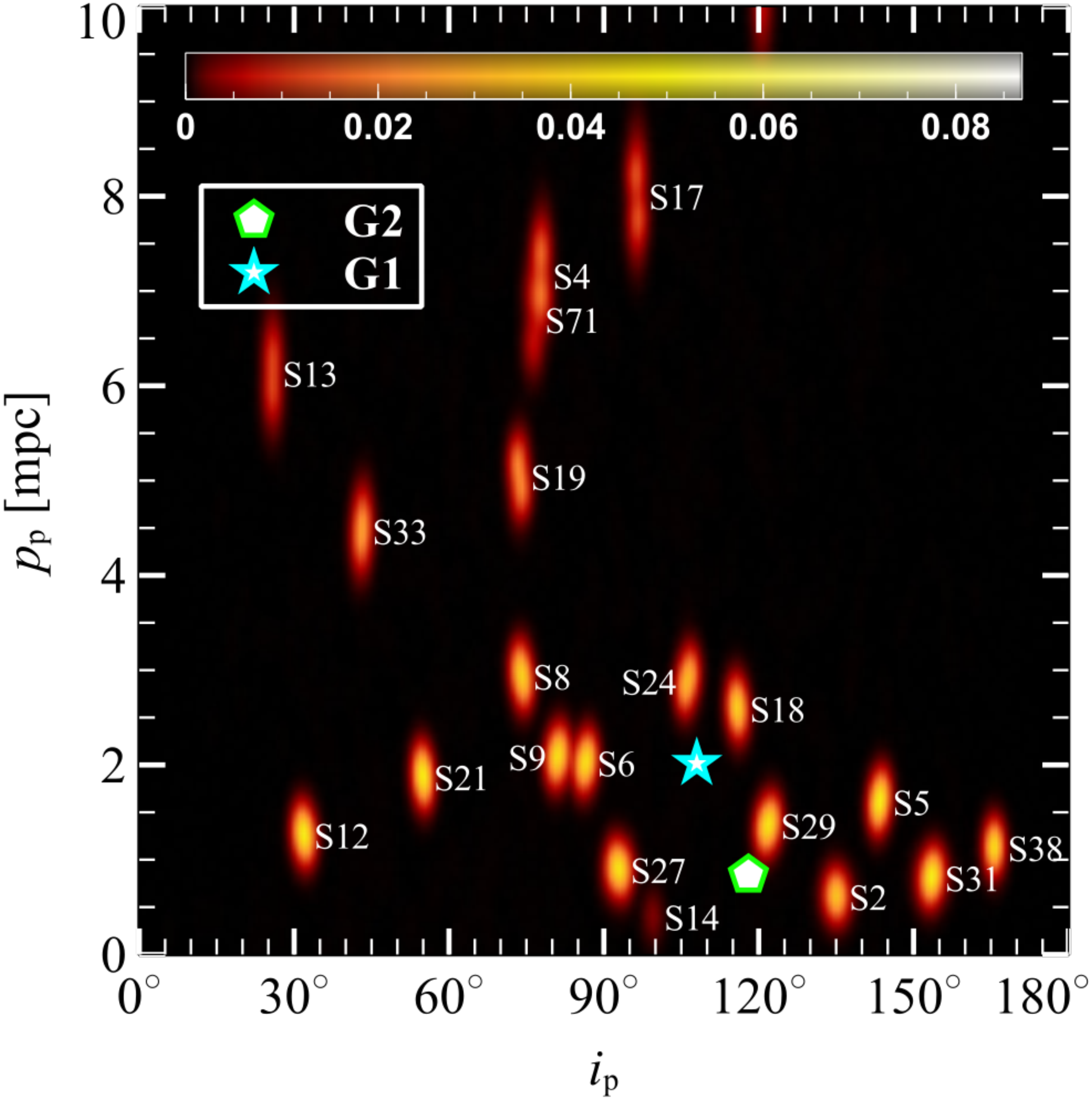


Unbound planets orbital parameters around the SMBH

Semimajor axis and eccentricity are compatible with G1 and G2 cloud...

Tidal capture in S-star cluster: results

AAT+2016



Unbound planets orbital parameters around the SMBH

..orbital orientation is not

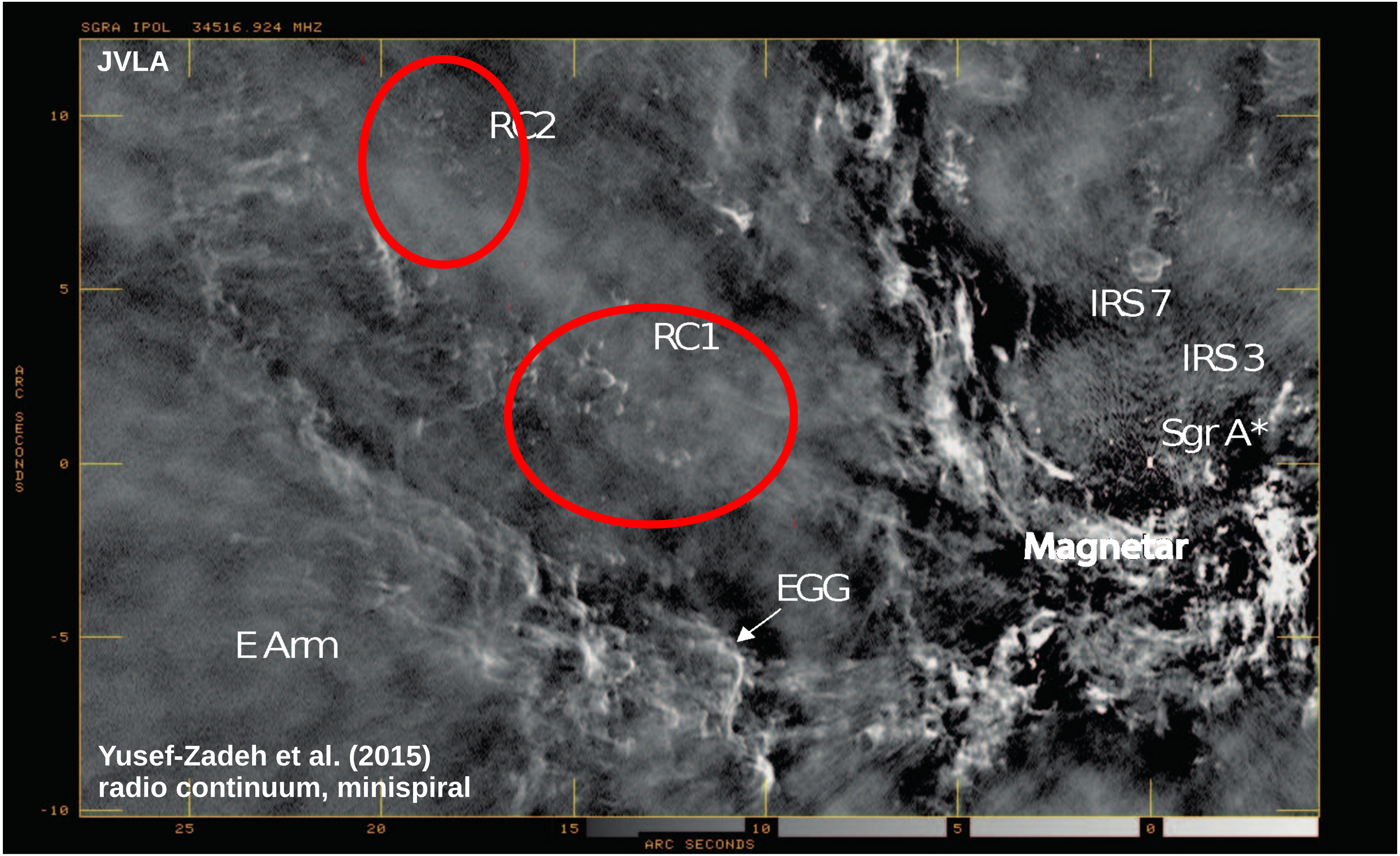
Conclusions

- SMBH tidal field **may split low mass objects from stars**, either in CW disk or S-stars
- Planetary orbital properties around the SMBH can be **predicted with an analytical model** in the case of prograde orbits
- CW low-mass objects **are not compatible** with G2 cloud orbit but:
  - perturbations from other disk stars **might** bring low-mass objects into highly-eccentric orbits (AAT+, in prep.)
- Eccentricity and semimajor axis of **S-stars low-mass objects are compatible** with G2 and G1 cloud orbits, but orientation is not

AAT+2016

http://adsabs.harvard.edu/abs/2016ApJ...831...61T

Planets in the Galactic Center: observations



Yusef-Zadeh et al. (2015)
radio continuum, minispiral

Planets in the Galactic Center: dynamics

How to simulate a SMBH-star-planet system?

- Short interparticle distances, but gravity has singularity in $r \longrightarrow 0$

  Large accelerations lead to too short timestep, halting the integration

- Large mass ratio: $M_{\rm SMBH}/m_{\rm planet} \approx 10^{10}$

  Small errors in acceleration lead to huge errors in planet position and velocity

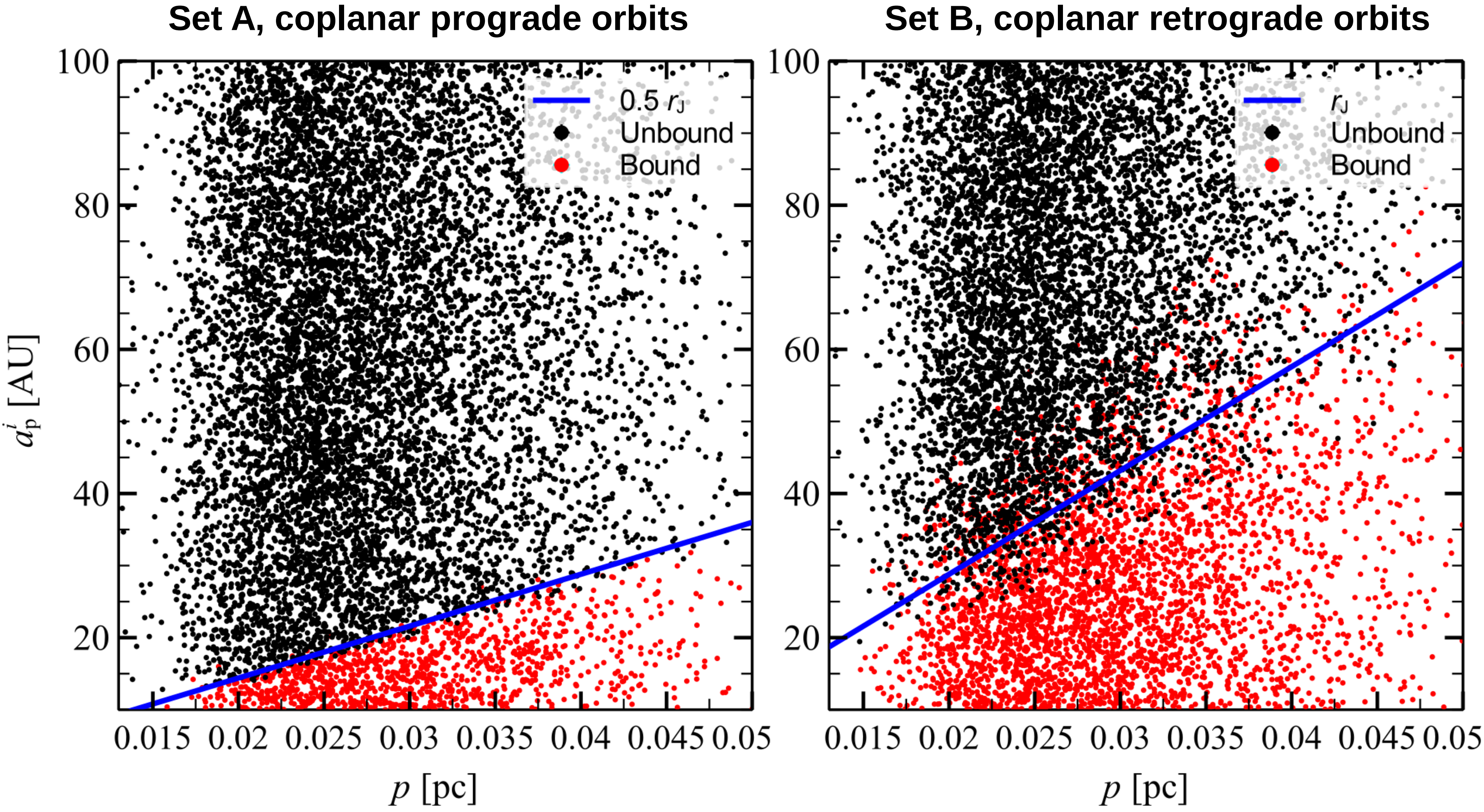
We must employ a regularized algorithm:

Mikkola's algorithmic regularization (MAR, Mikkola&Tanikawa99)

- Removes the singularity of the potential in $r \longrightarrow 0$ by means of coordinate transformations
- Uses coordinate transformation, based on interparticle vectors, reducing round-off errors (Mikkola&Aarseth93)

Planets in CW disk: results

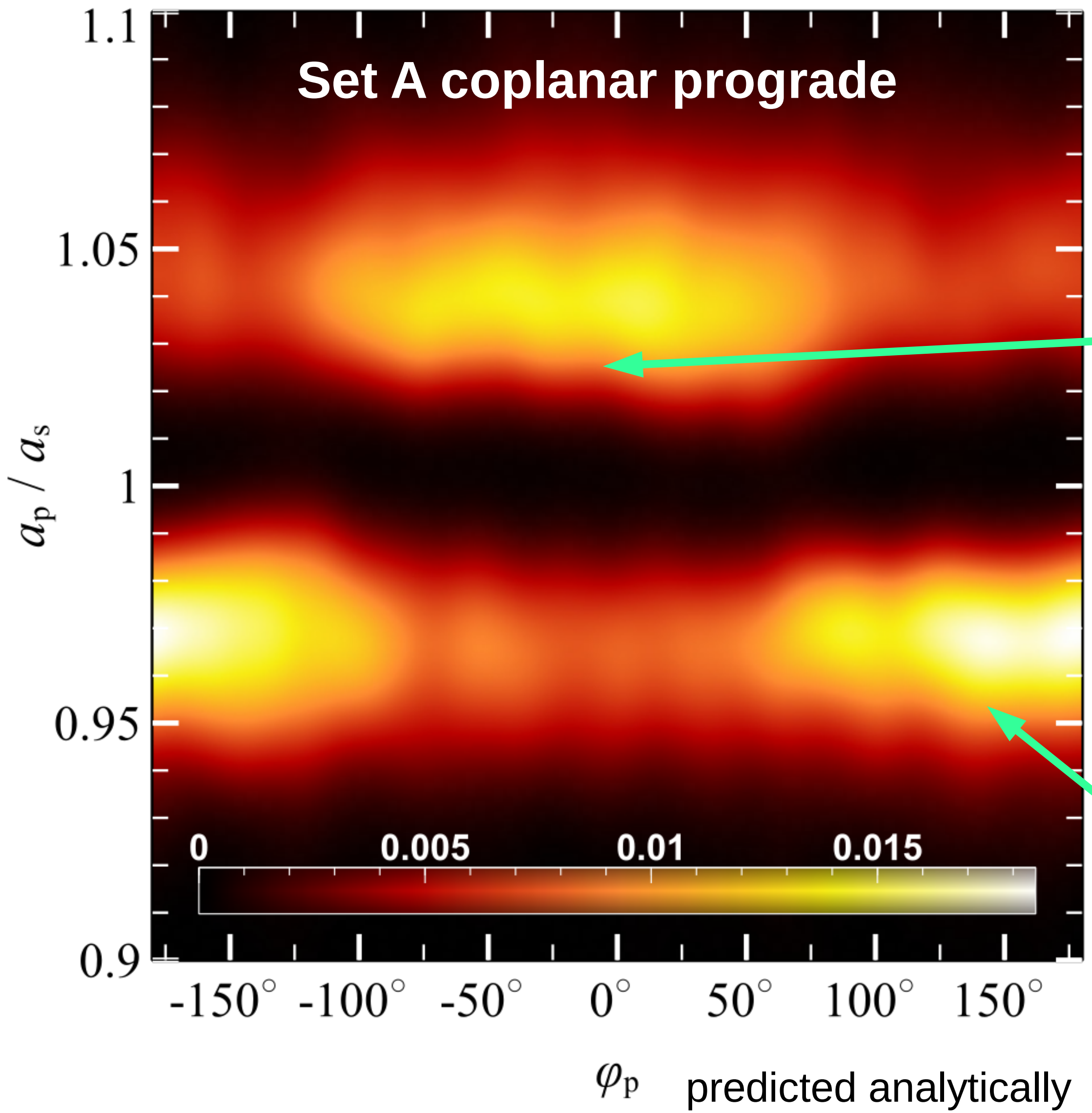
Retrograde orbits are more stable than prograde ones



Set A, coplanar prograde orbits

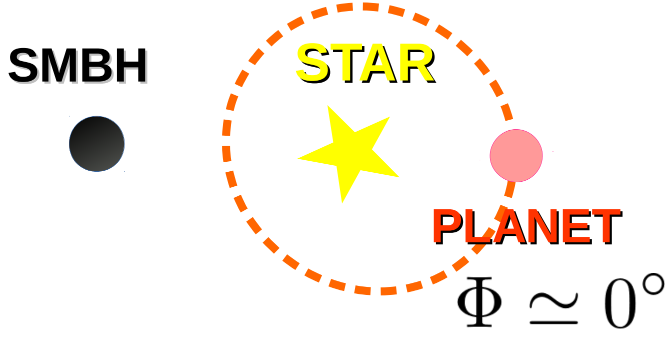
Set B, coplanar retrograde orbits

Planets in CW disk: results



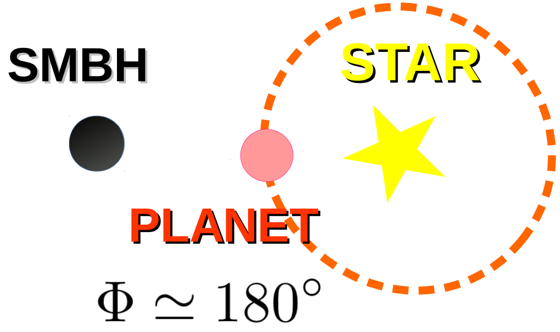
predicted analytically

Planet becomes less bound than parent star if:



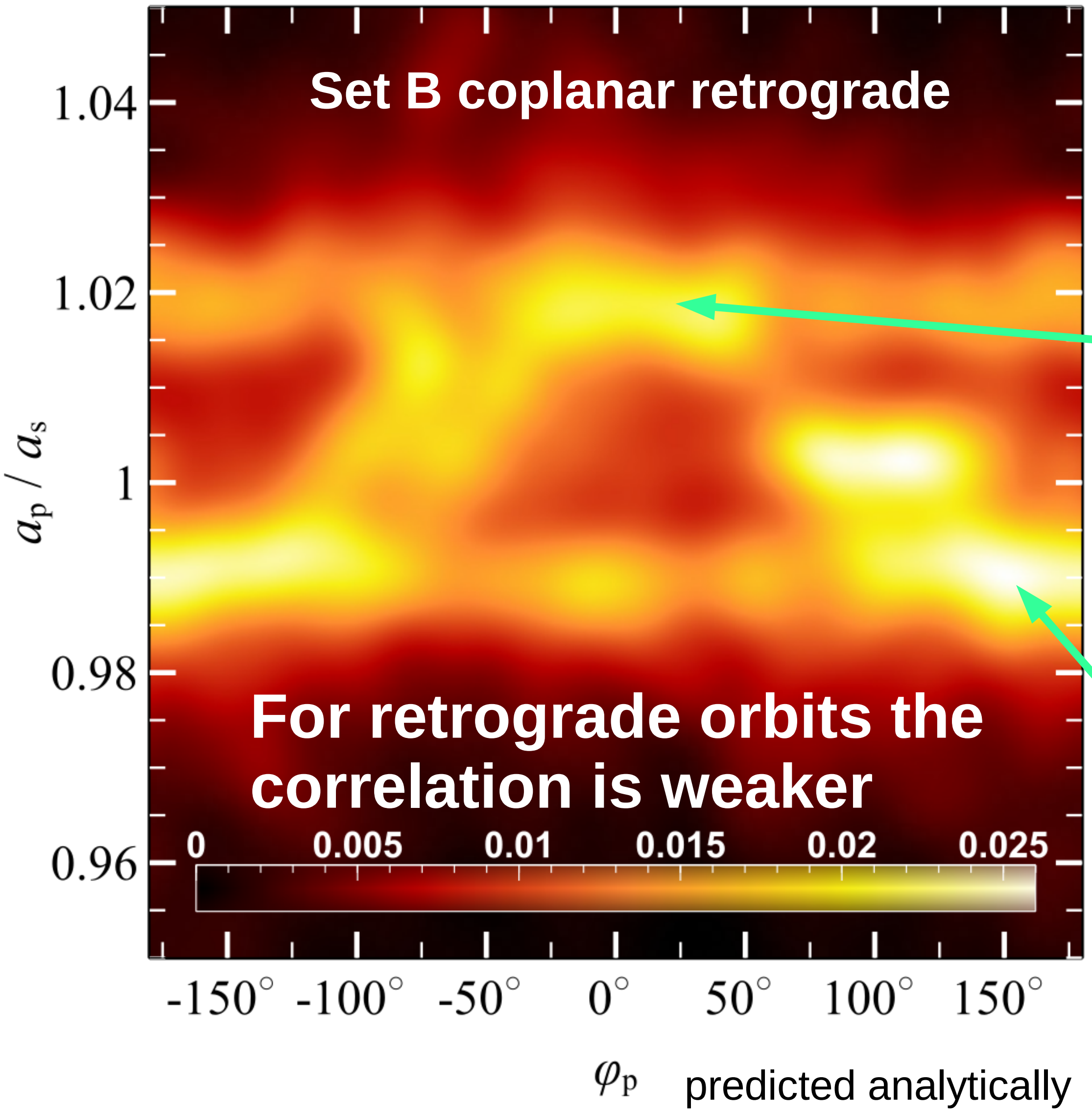
$\Phi \simeq 0^\circ$

Planet becomes more bound than parent star if:



$\Phi \simeq 180^\circ$

Planets in CW disk: results

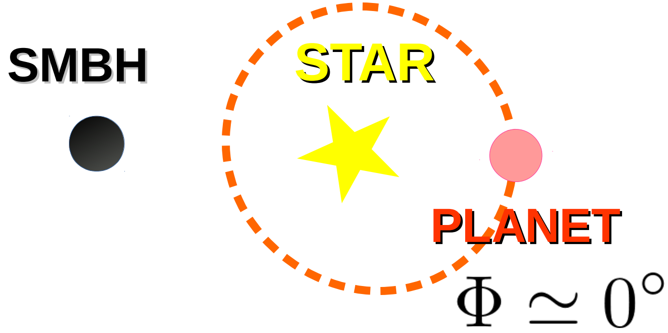


Set B coplanar retrograde

For retrograde orbits the correlation is weaker

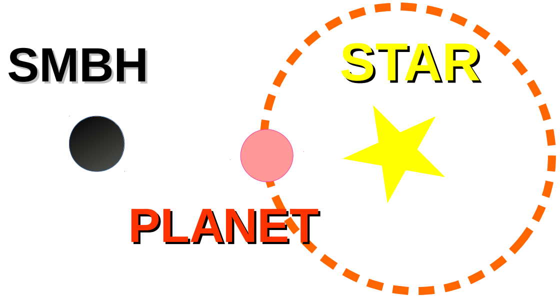
predicted analytically

Planet becomes less bound than parent star if:



$\Phi \simeq 0^\circ$

Planet becomes more bound than parent star if:



The Galactic Centre: a crowded environment

The supermassive black hole (SMBH)

$$M_{\mathrm{BH}} = 4.3 \pm 0.5 \times 10^6\,\mathrm{M}$$

from measurements of the
S2 star orbit

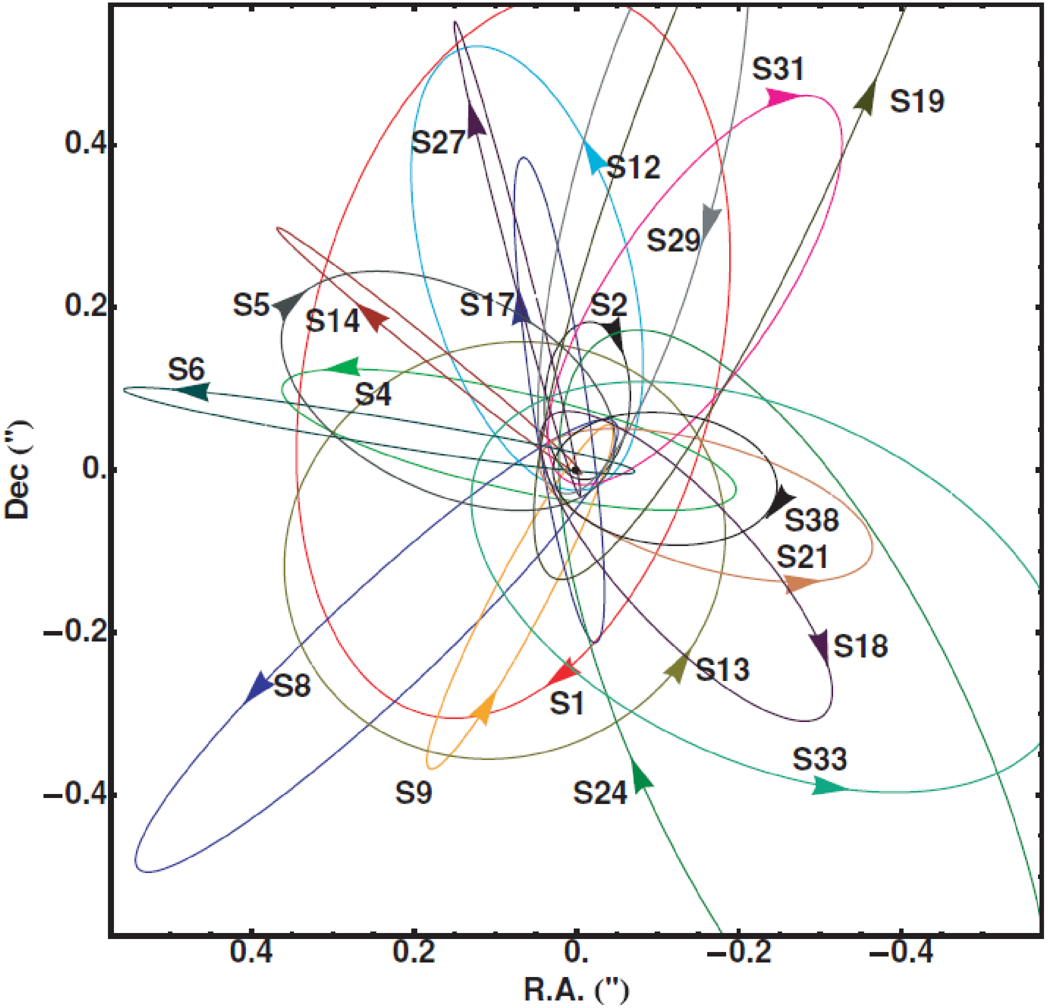
The S-stars

- ~30 stars closest to the SMBH

$$d_{\mathrm{SMBH}} < 0.04\,\mathrm{pc}$$

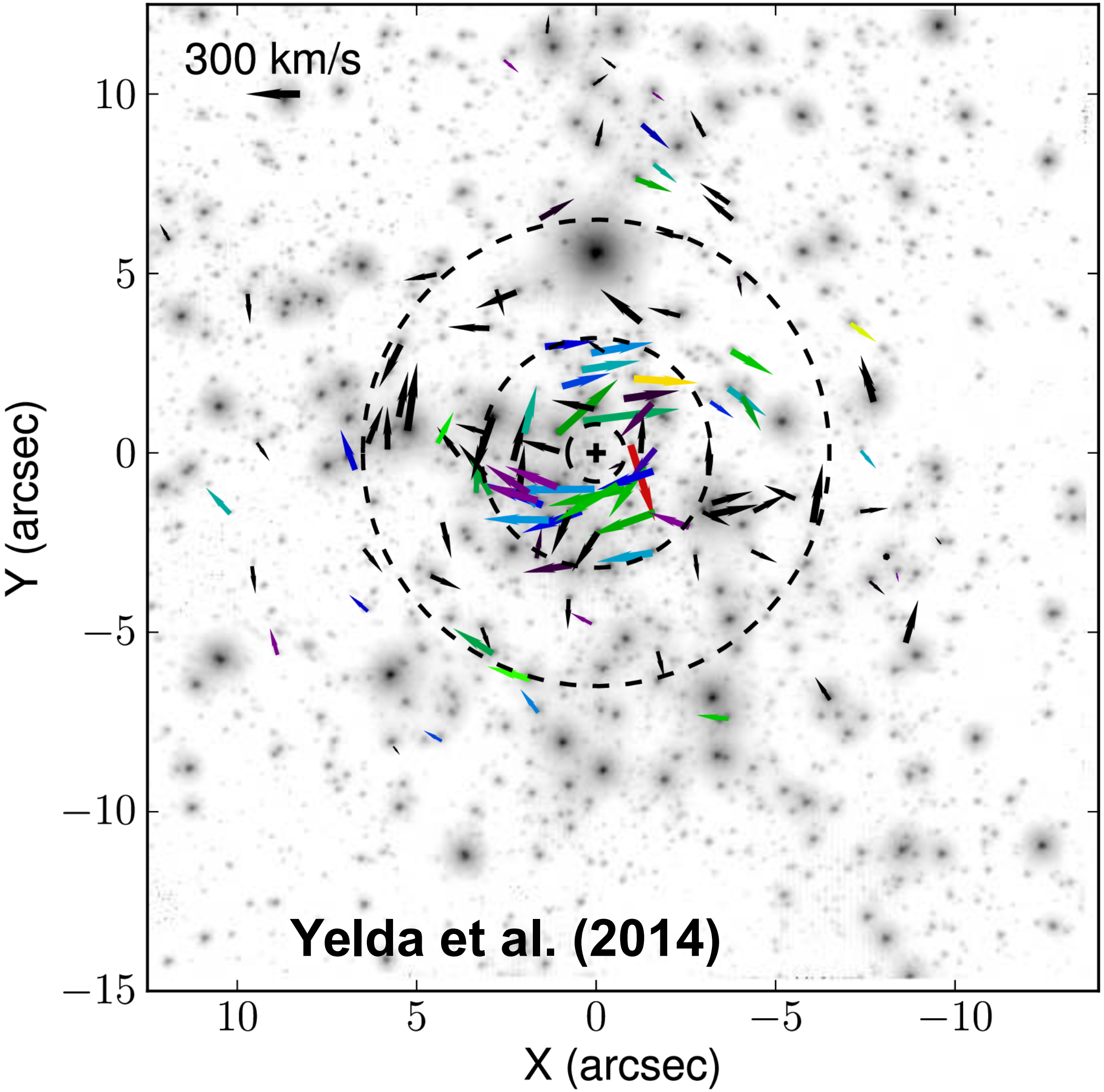
- B-type stars: $t_{\mathrm{age}} \simeq 6 - 400\,\mathrm{My}$
- Randomly oriented orbits
- High eccentricity

Reconstruction of the
S-star orbits
Gillessen et al. (2009a)



The Galactic Centre: The clockwise disc

- O and WR stars:
  $t_{\rm age} \simeq 2.5 - 6\,{\rm Myr}$
- Flat mass function:
  $\propto m^{-1.7\pm0.2}$
- Eccentricity:
  $\langle e \rangle \simeq 0.3$
- Radial extension
  $0.05\,{\rm pc} < {\rm a} < 0.1\,{\rm pc}$
- Only 20% of the young stars lie in the disc (Yelda+14)



Planets in the CW disk: simulations

3-body simulations of SMBH-star-planet hierarchical systems

$$M_{\mathrm{SMBH}} 4.3 \times 10^6\,\mathrm{M}_\odot$$
$$m_{\mathrm{star}} = 5\,\mathrm{M}_\odot$$
$$m_{\mathrm{planet}} = 10\,\mathrm{M}_{\mathrm{Jup}}$$

Star orbit: modelled following the properties of the CW disk (Yelda+14, Do+13)

- Semimajor axis: power-law distribution $\Gamma = -1.93$, range: $0.03\,\mathrm{pc} < \mathrm{a}_{\mathrm{star}} < 0.06\,\mathrm{pc}$
- Eccentricity: Gaussian centred in 0.3, with $\sigma = 0.1$

Planet orbit: circular, with $10\,\mathrm{AU} < \mathrm{a}_{\mathrm{planet}} < 100\,\mathrm{AU}$

4 sets of 10000 realizations:

- Set A: **coplanar, prograde** orbits
- Set B: **coplanar, retrograde** orbits
- Set C: inclined, prograde orbits $-90^\circ < i < 90^\circ$, uniformly distributed
- Set D: inclined, retrograde orbits $90^\circ < i < 270^\circ$, uniformly distributed

Planets in CW disk: results

Considerations:

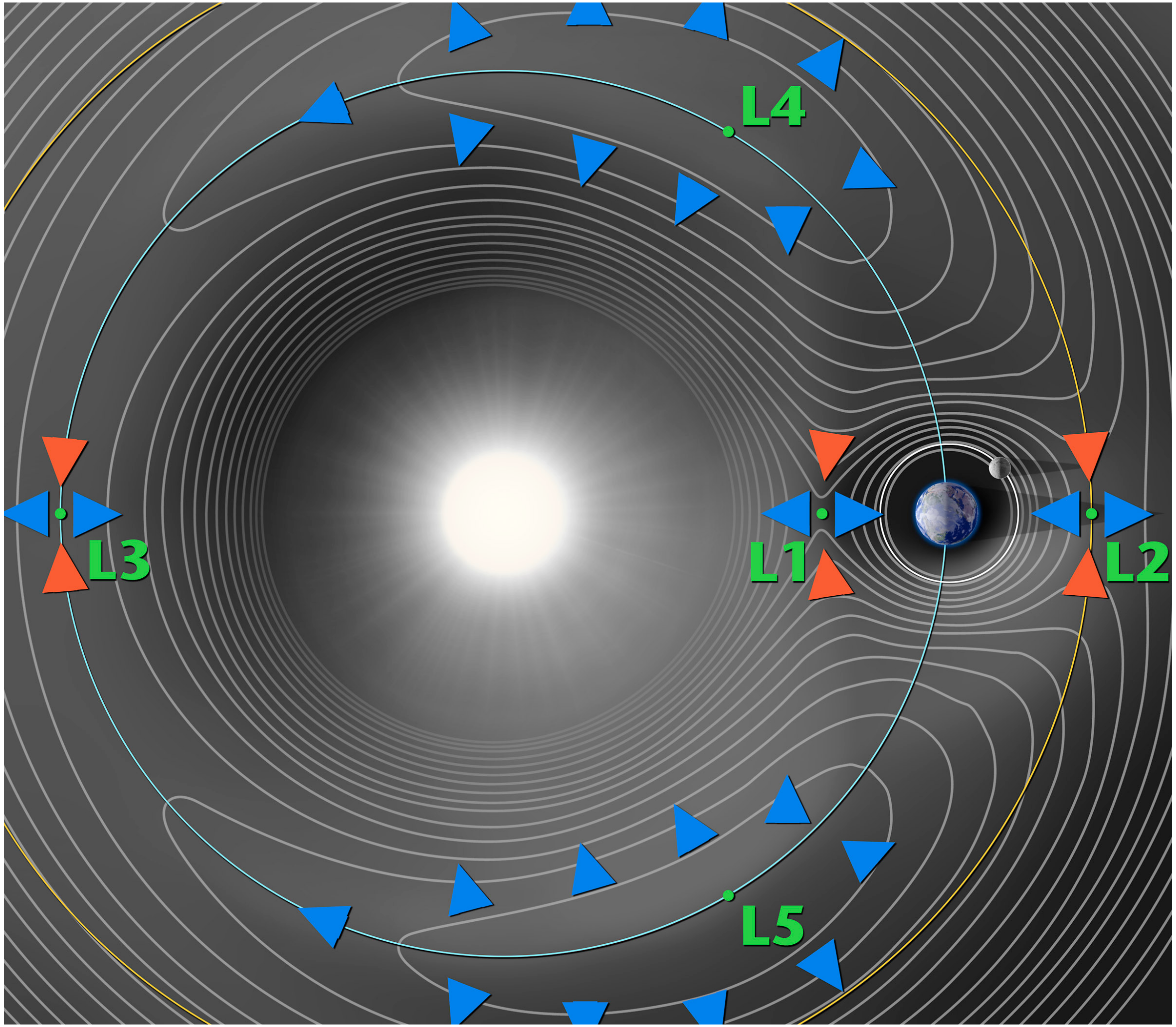
- Planets escaping at 0° or 180° phase have different orbital properties
- Planet orbit remains close to star orbit:

  $\Delta v_{\rm kick} \approx 10\,{\rm km/s}$

  $\ll v_{\rm orb} \approx 700\,{\rm km/s}$

- $m_{\rm planet} \ll m_{\rm star} \ll M_{\rm SMBH}$

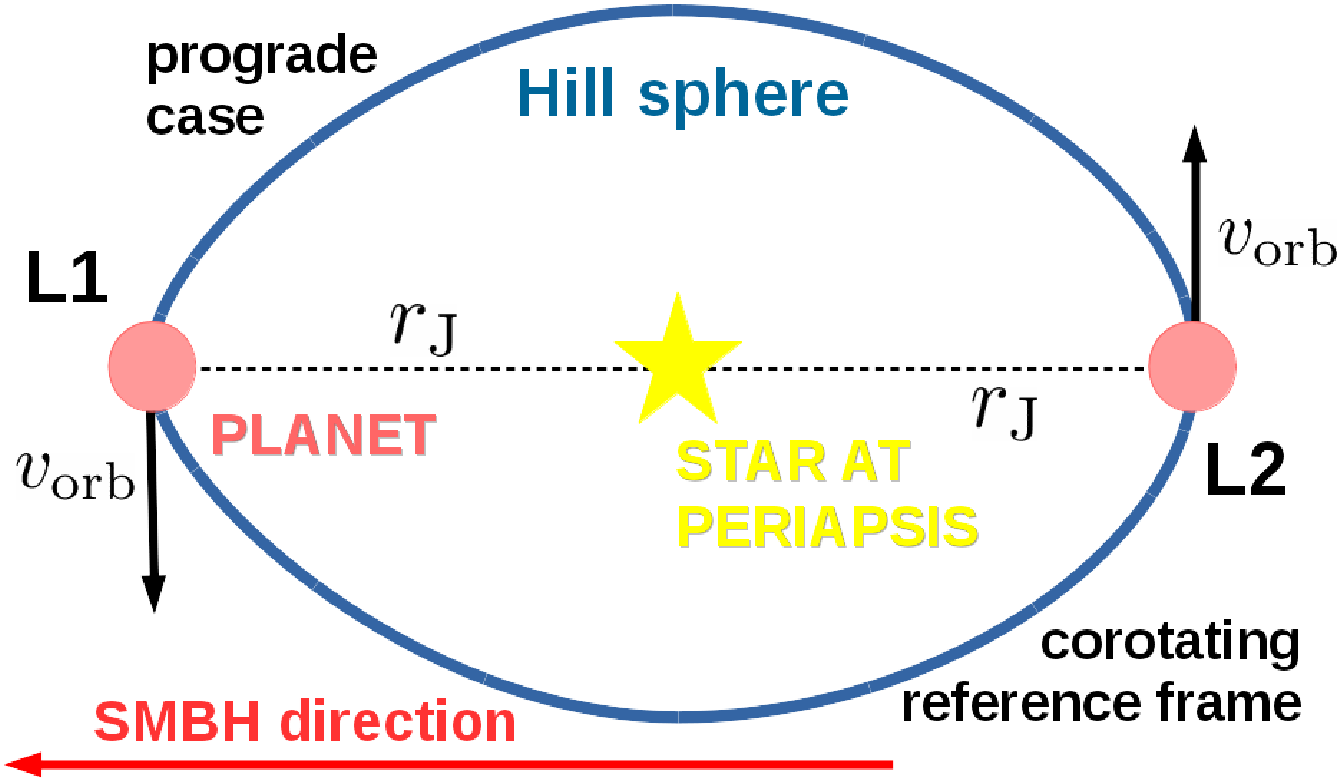
We can adopt the restricted three-body problem formalism to develop a simple analytic model



Planets in CW disk: results

Analytic model assumptions

- Planet becomes unbound during the star pericenter passage
- Planet escapes the star Hill sphere from L1 or L2
- Planet velocity with respect to the rotating frame of reference at the moment of escape equals its orbital velocity



Analytic model equations

$$\Delta E = E_{\mathrm{planet}} - E_{\mathrm{star}} = -\frac{GM_{\mathrm{SMBH}}}{p}\frac{r_{\mathrm{J}}}{p - r_{\mathrm{J}}} - v_{\mathrm{p}}^2 \frac{r_{\mathrm{J}}}{p}\left(1 - \frac{1}{2}\frac{r_{\mathrm{J}}}{p}\right)$$

$$\Delta L = L_{\mathrm{planet}} - L_{\mathrm{star}} = -r_{\mathrm{J}} v_{\mathrm{p}} - p v_{\mathrm{planet}} + r_{\mathrm{J}} v_{\mathrm{planet}}$$

where:

p is periapsis of star orbit

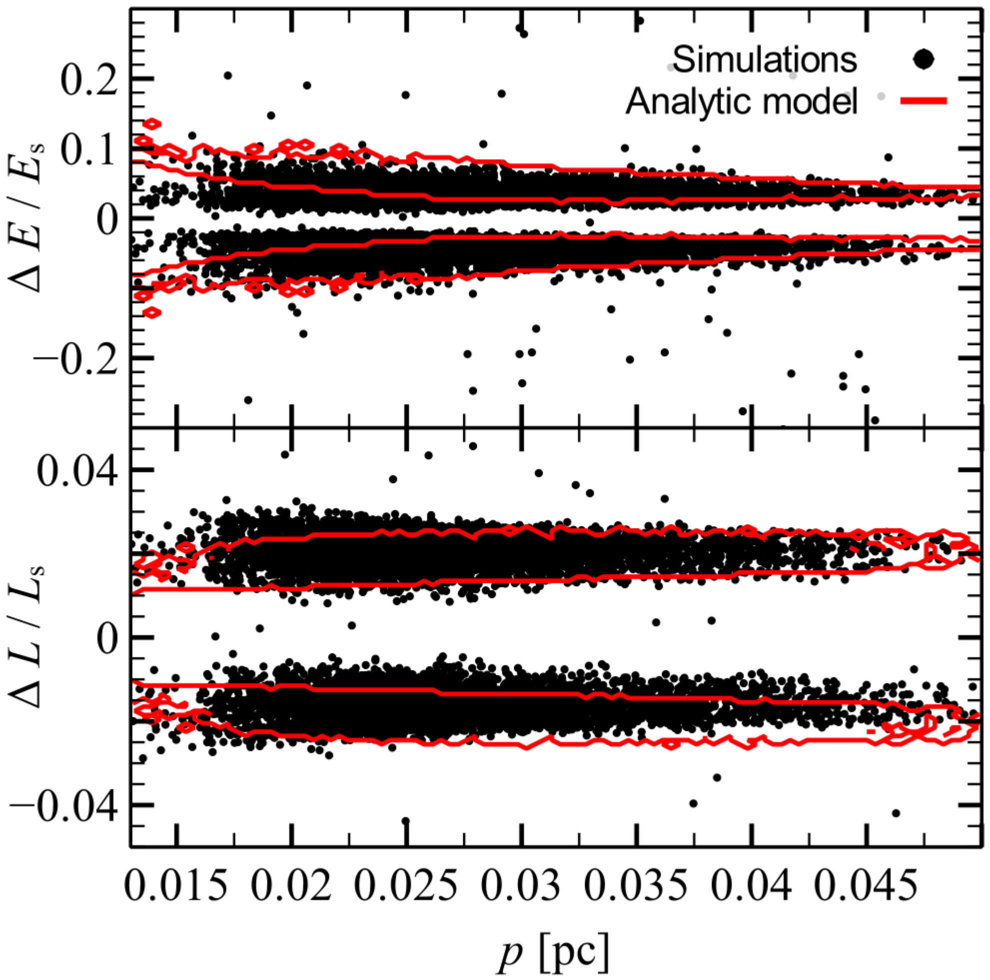
$r_{\mathrm{J}} = p\left(\frac{m_{\mathrm{star}}}{3M_{\mathrm{SMBH}}}\right)^{1/3}$ is the Jacobi radius of star-planet system at star periapsis passage

v_{planet} is the planet orbital velocity aroud the star

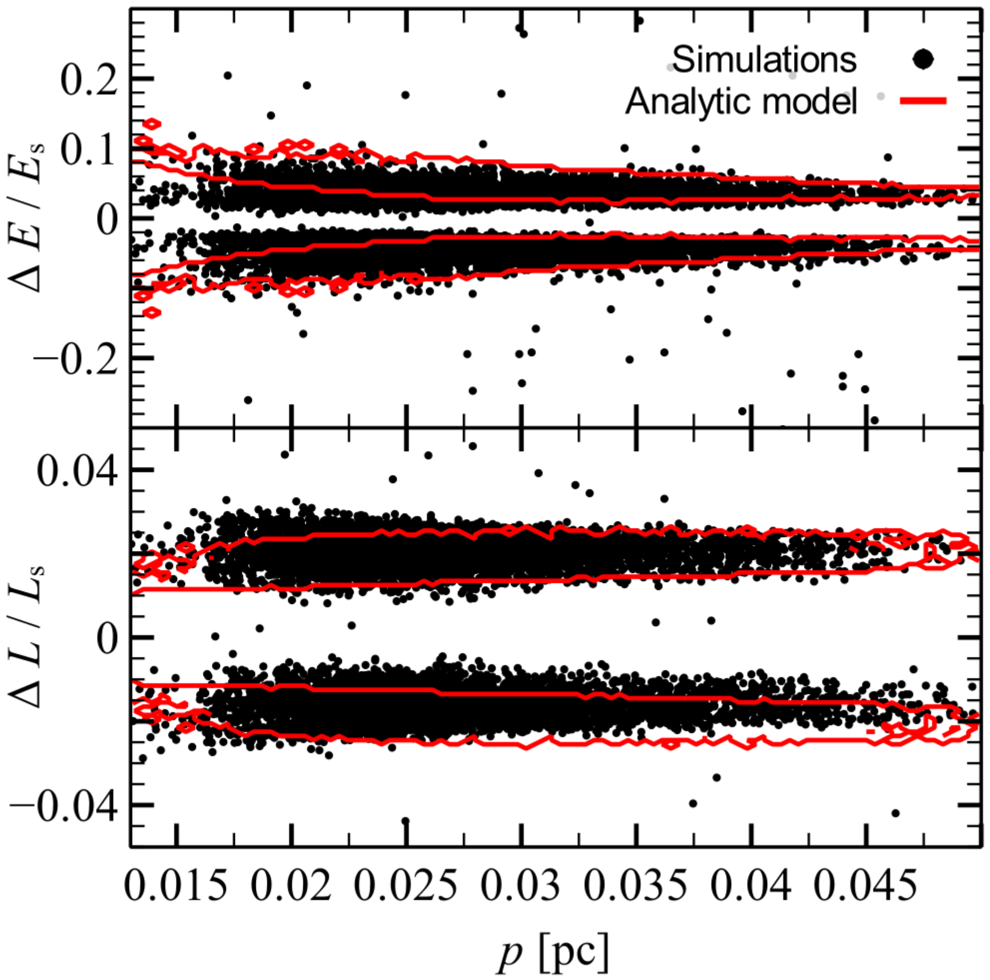
Planets in CW disk: results

Analytic model predicts well energy and angular momentum for planets in the prograde case, but not in the retrograde case

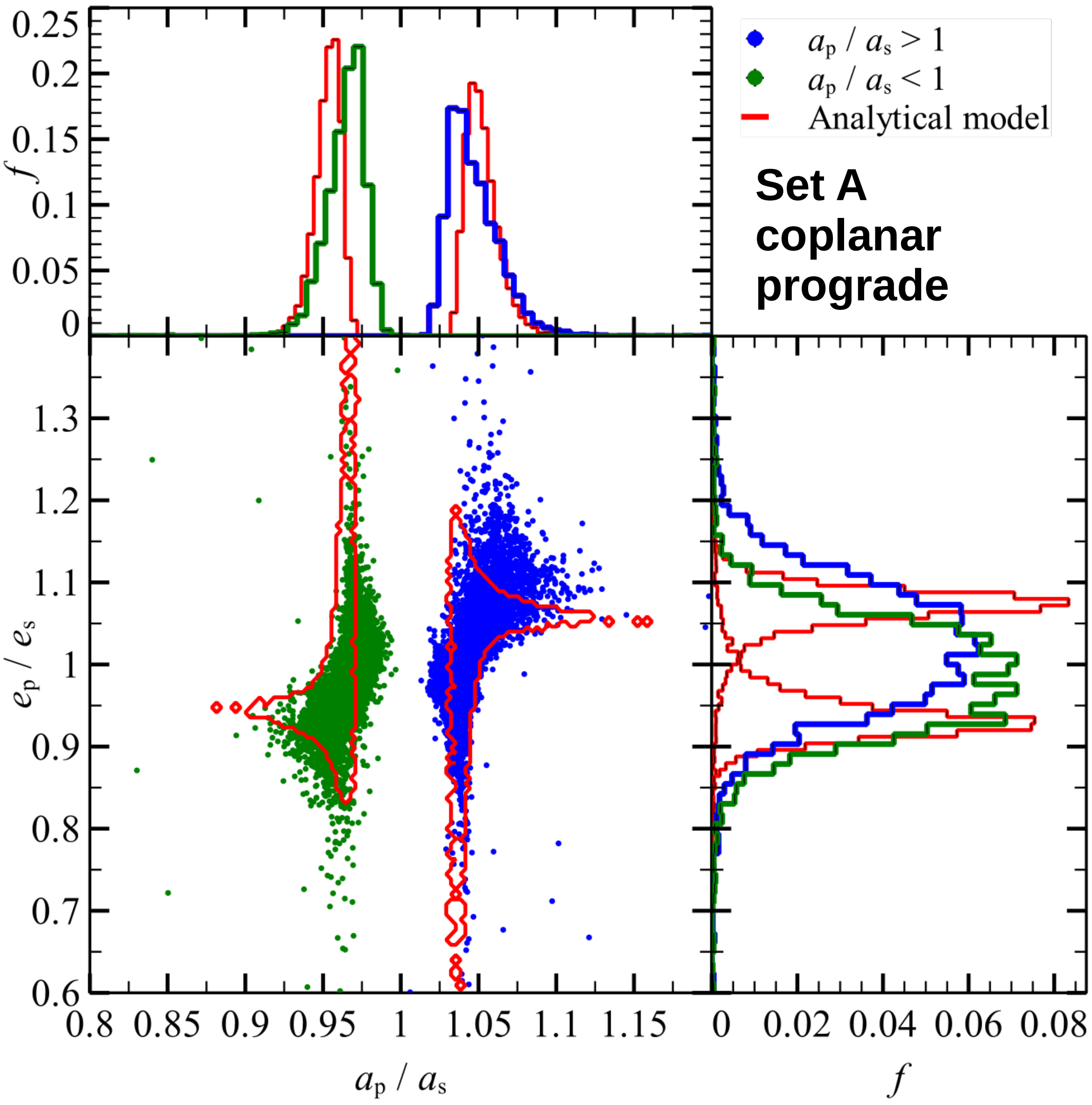
Set A coplanar prograde



Set B coplanar retrograde



Planets in CW disk: results

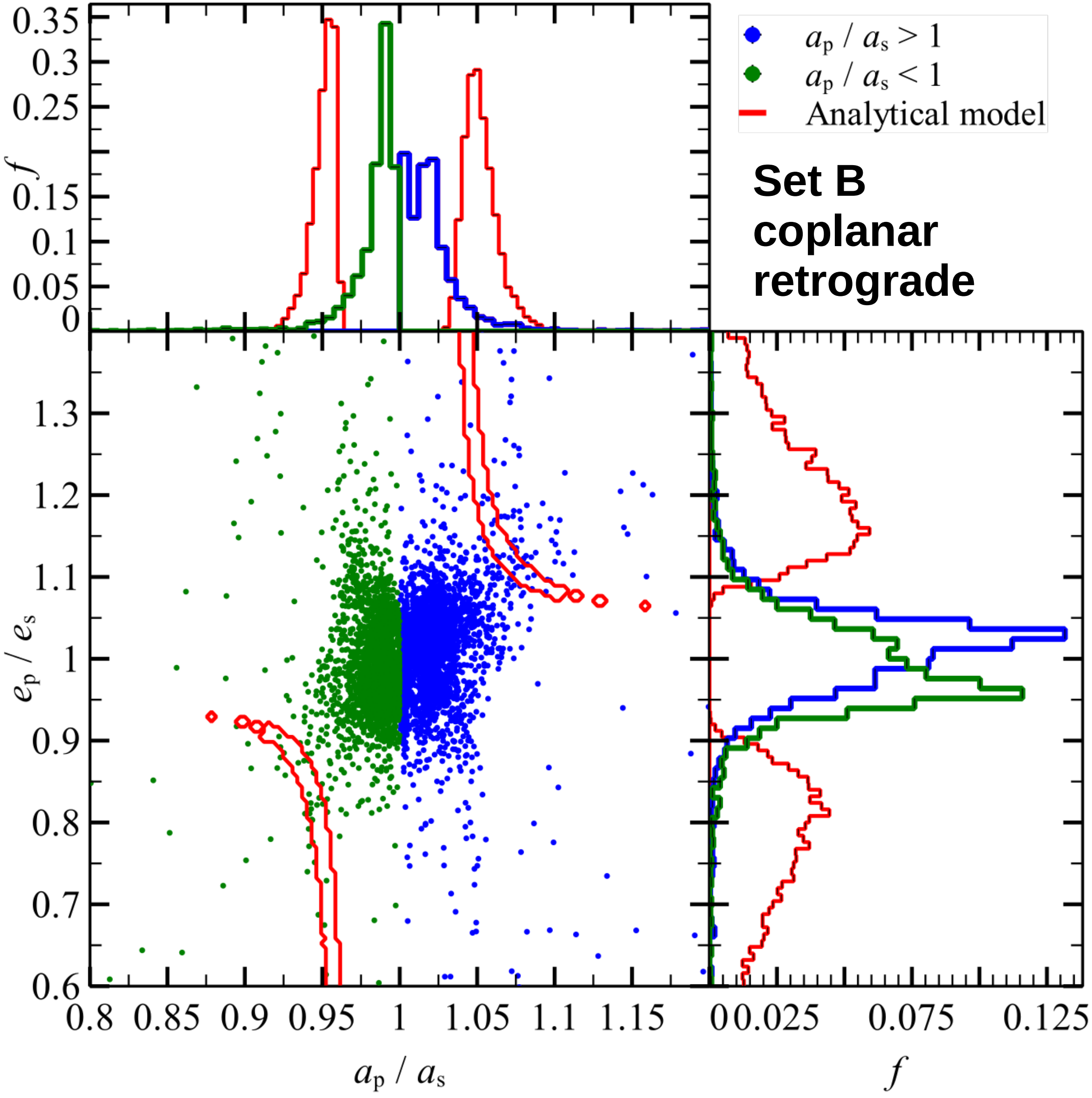


Set A
coplanar
prograde

Analytic model, prograde case:

- Predicts the bimodality in semi-major axis distribution
- Predicts the trend in eccentricity and semimajor axis:
  looser orbits get higher eccentricity,
  tighter orbits get lower eccentricity

Planets in CW disk: results

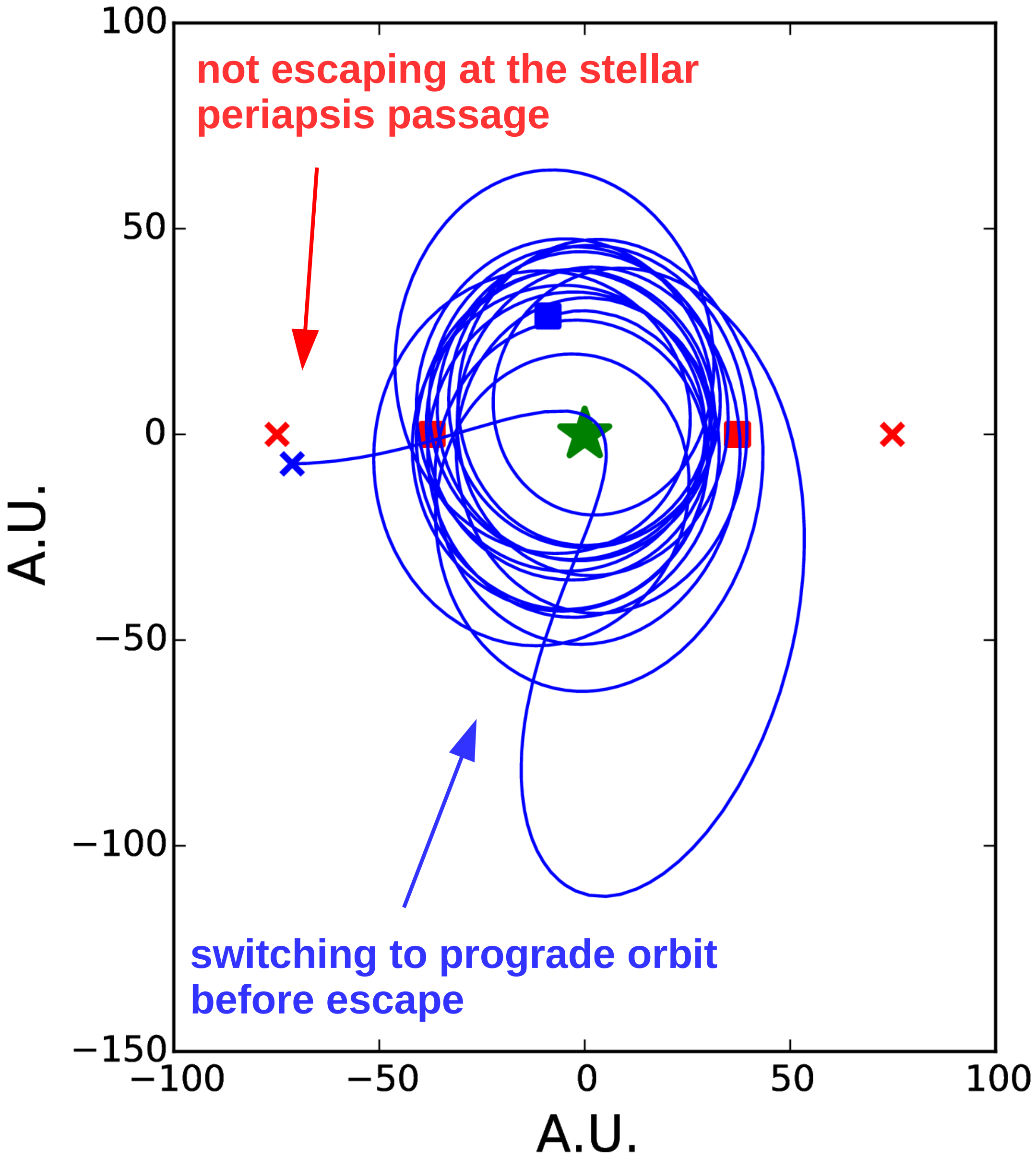


Set B coplanar retrograde

Analytic model, retrograde case:

- Fails to predict simulated distributions

Planets in CW disk: results



Analytic model, retrograde case:

- Fails to predict simulated distributions

Reasons are:

- Retrograde orbits are more convoluted than prograde ones
- Planets can survive many star periapsis passages before getting into unstable orbit
- Planet escape may occur anywhere along the star orbit (breaking the assumption of capture at pericenter distance)

Mikkola's algorithmic regularization

Time transformation: $dt = g(\mathbf{q}, \mathbf{p}, t)\, ds$

Traformation function: $g(\mathbf{q}, \mathbf{p}, t) = \dfrac{1}{U(r_{ij})}$ where $U(r_{ij}) = \sum_{i<j}^{N} \dfrac{m_i m_j}{r_{ij}}$ gravitational potential

$$r_{ij} = |r_i - r_j|$$

Drawback: integrating over *g* to get back physical timestep *t*

$$\Delta t = t_0 - t_1 = \int_{s_0}^{s_1} g\, ds \simeq \frac{g(s_0) + g(s_1)}{2} \Delta s + O(\Delta s^3)$$