# Stellar dynamics around SgrA*

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# Kinetic Theory @IAP

Particular thanks to the following graduate students

Sofia Flores
Renormalisation

Kerwann Tep
Eccentricity relaxation

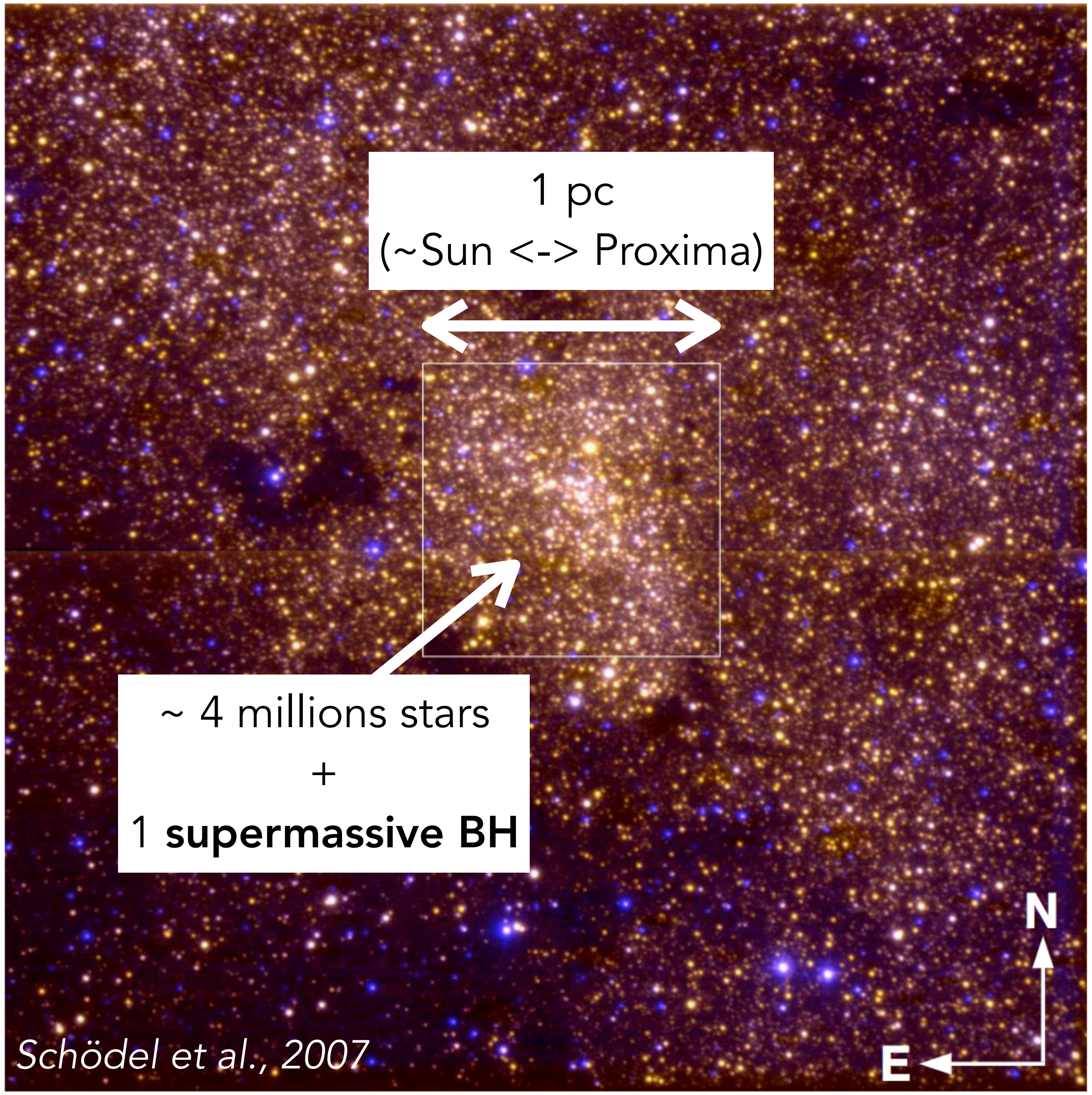
Mathieu Roule
Kinetic blockings

Juan Giral
Neighbor separation

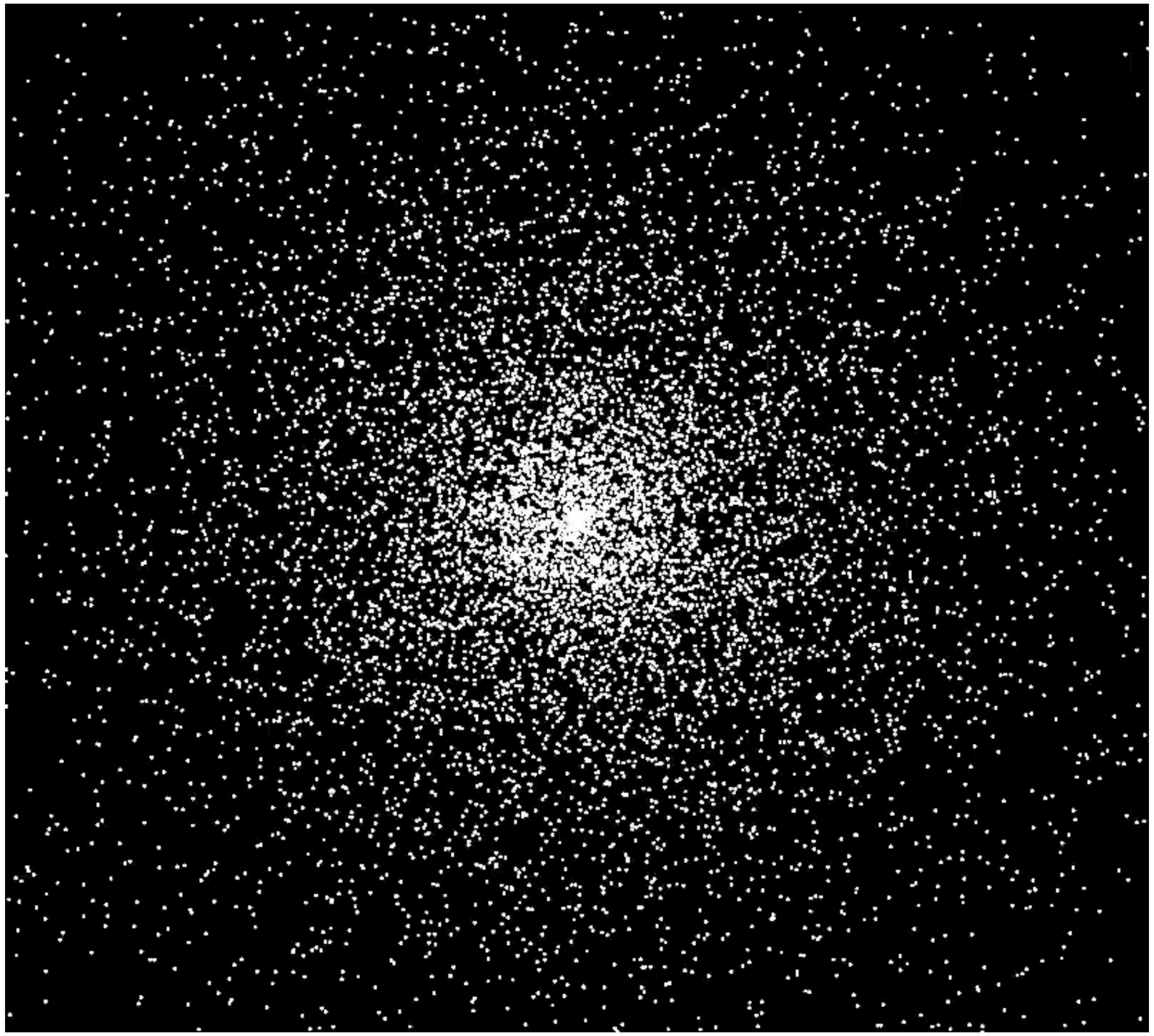
Nathan Magnan
Thermodynamical Eq.

# Extremely dense environment

Behaves like a **gas of stars**




**VLT observations**

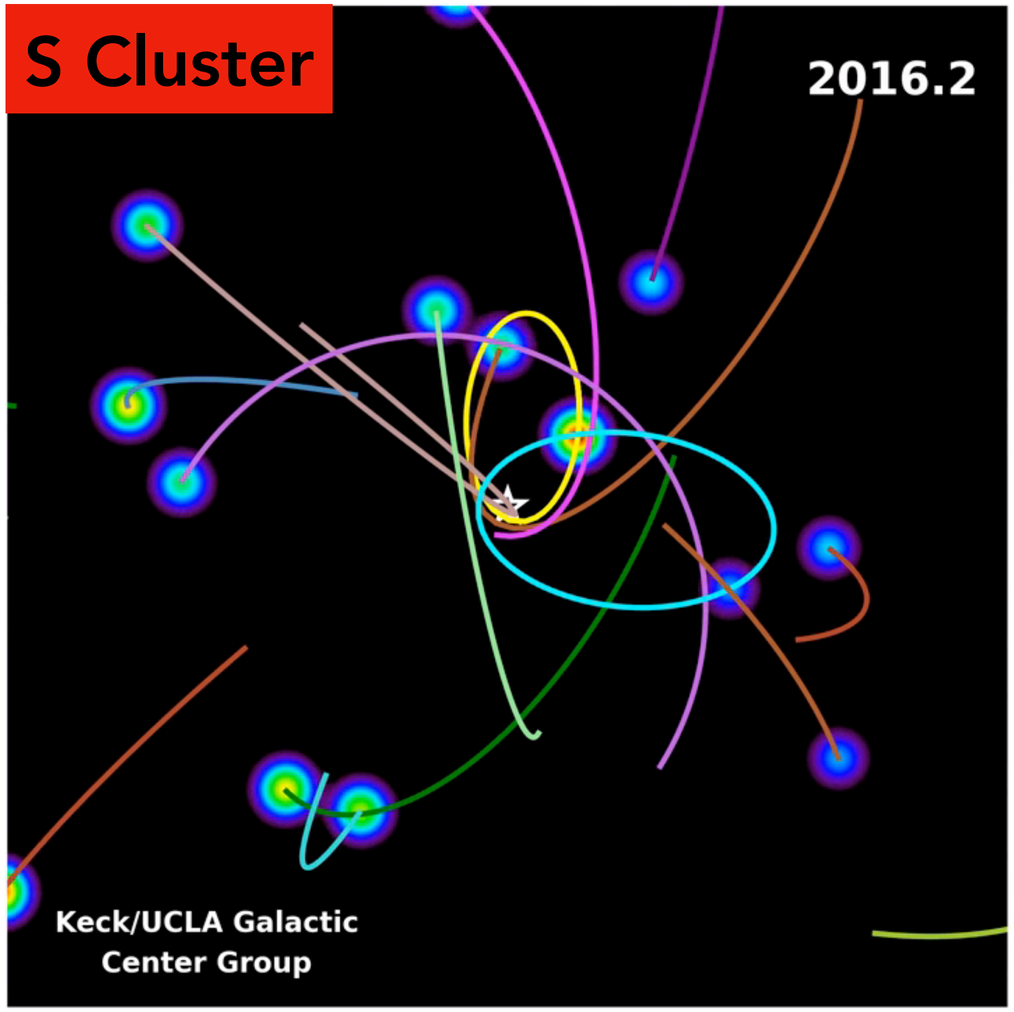


**Numerical simulations**

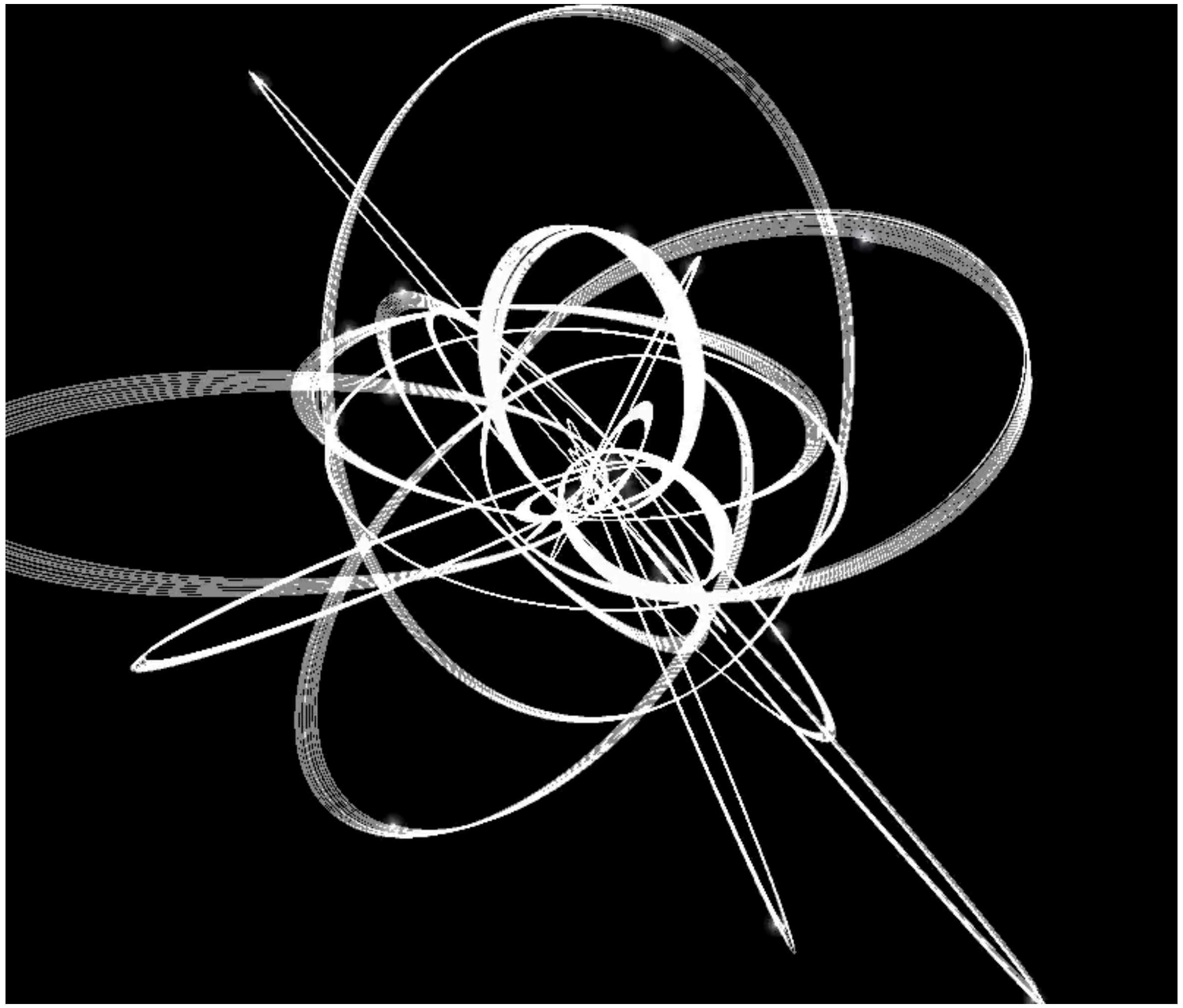
# A simple dynamics?

The central BH is **supermassive**

$M_{\mathrm{SgrA}} \simeq 4{,}200{,}000 \times M_{\mathrm{Sun}}$ vs. $M_{\mathrm{Sun}} \simeq 330{,}000 \times M_{\mathrm{Earth}}$




Keck observations

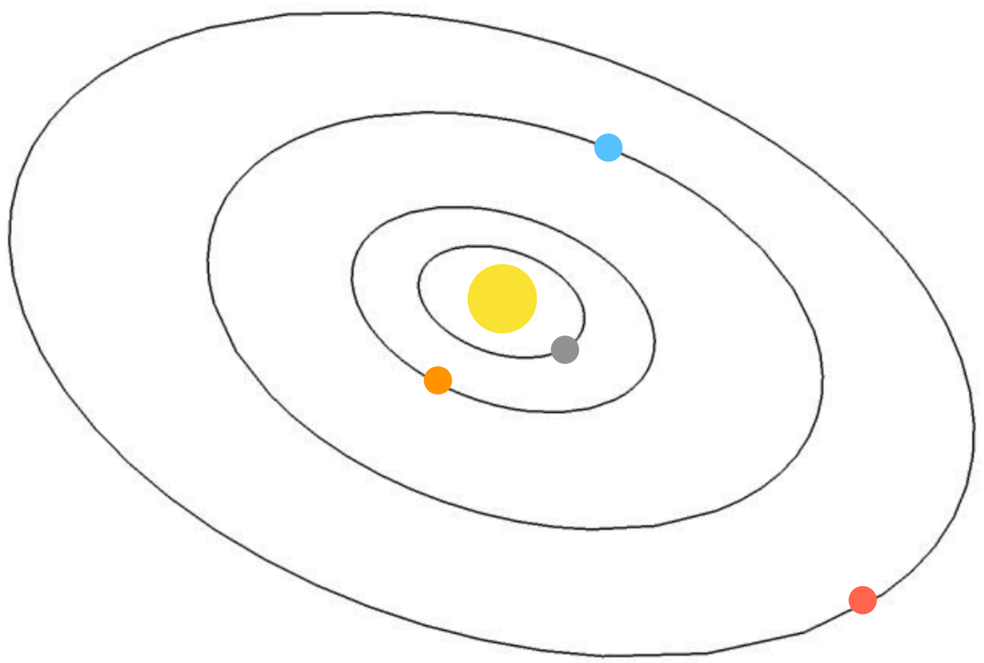


Numerical simulations

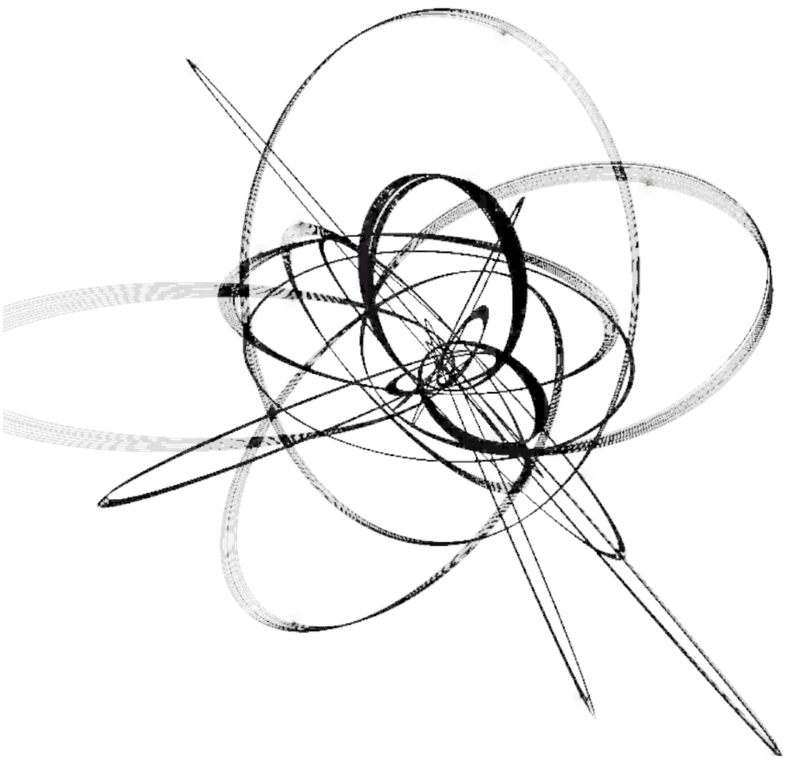
Like the Earth around the Sun, stars follow **Keplerian orbits**

# Keplerian systems

## Solar system



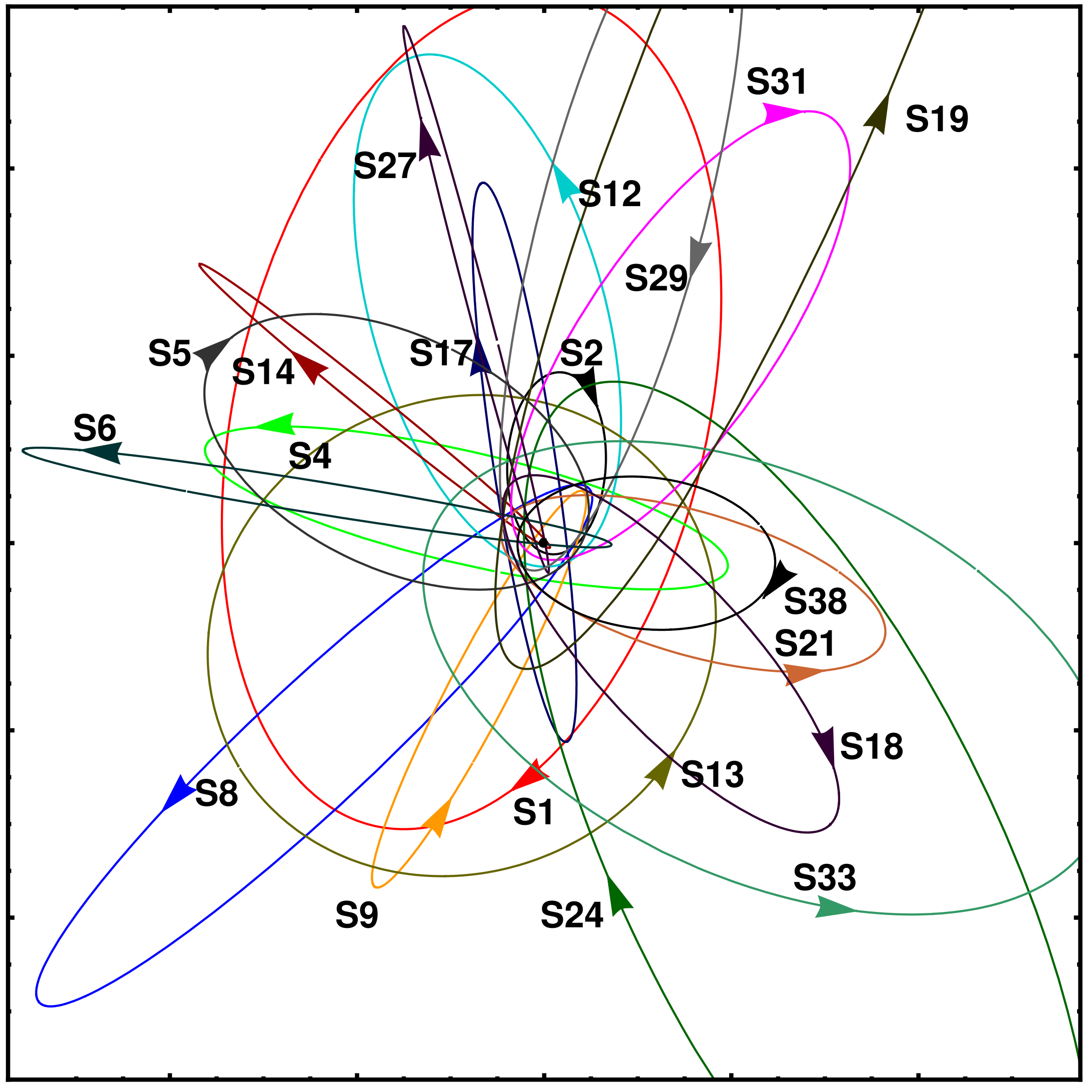
## Galactic centre



| Solar system | Comparison | Galactic centre |
| --- | --- | --- |
| **Planets** | Light object | **Stars** |
| **Sun** | Heavy object | **Black hole** |
| $N \simeq 10$ | Number of ``particles" | $N \simeq 10^6$ |
| **Planar** symmetry | Shape of the system | **Spherical** symmetry |
| **Quasi-circular** orbits | Shape of the orbits | **Very eccentric** orbits |

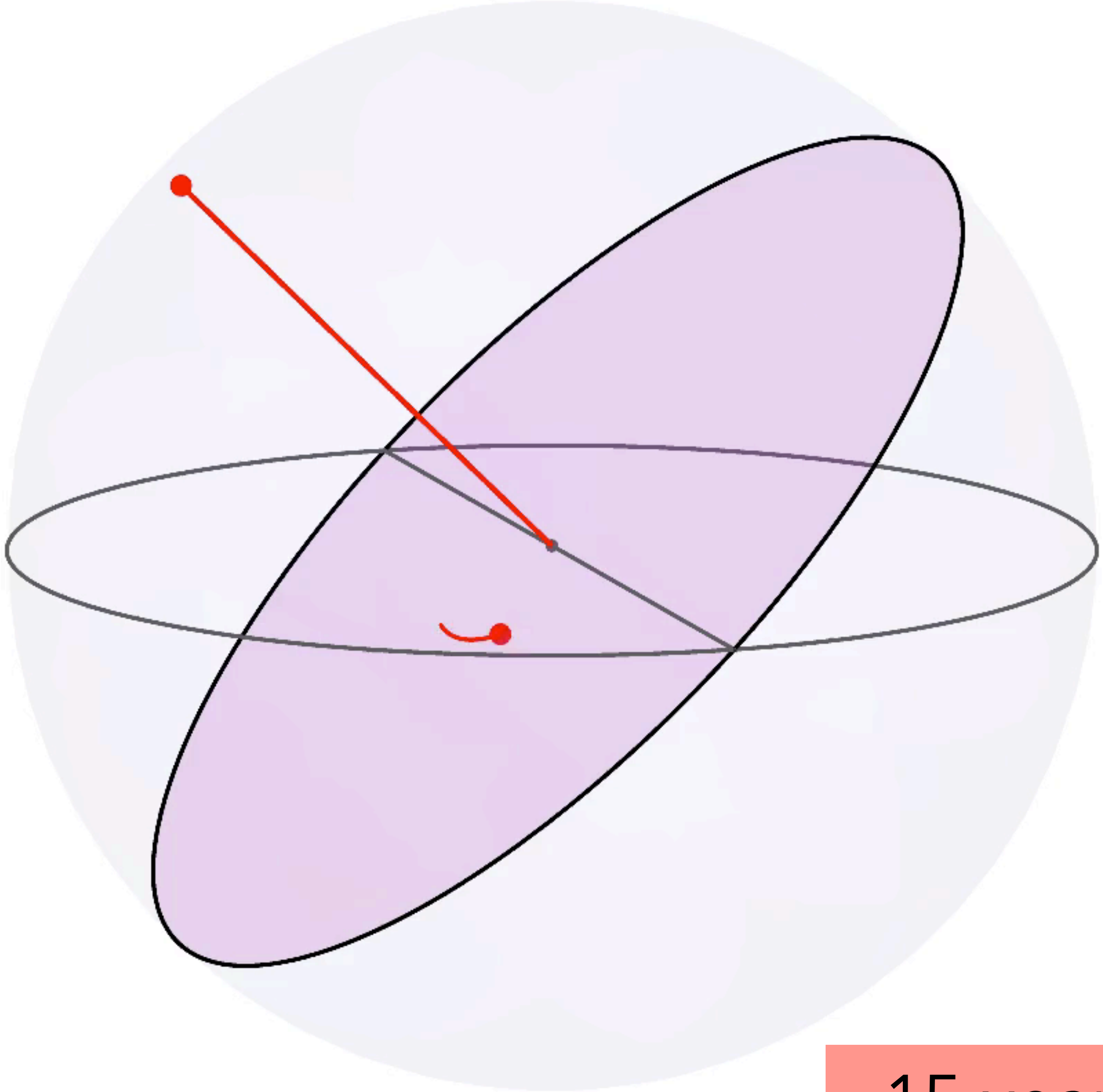
# Keplerian orbits

The BH dominates the stars' dynamics




*Gillessen et al., 2009*

VLT observations



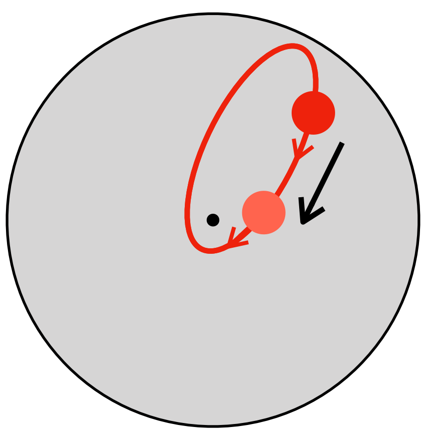
Typical orbit

~15 years for S2

# What is an orbit?

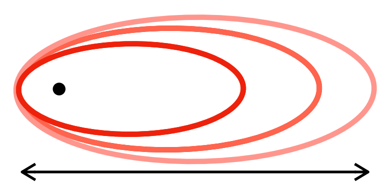
## Describing an **orbit**

**Position** of the star

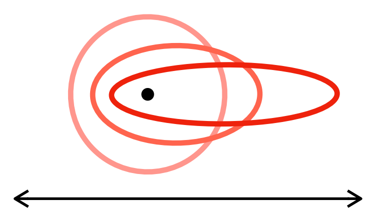


Dynamical motion

**Shape** of the orbit

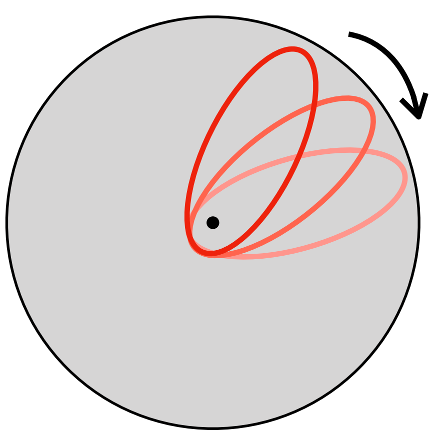


Semi-major axis



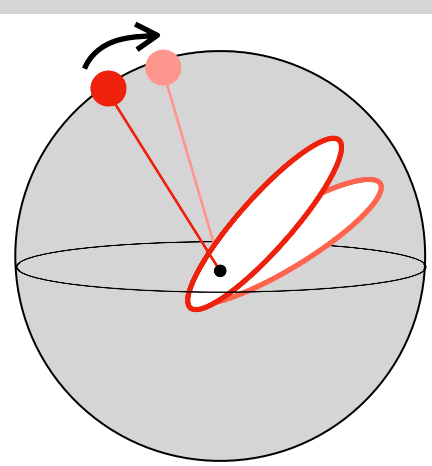
Eccentricity

**Phase** of the orbit

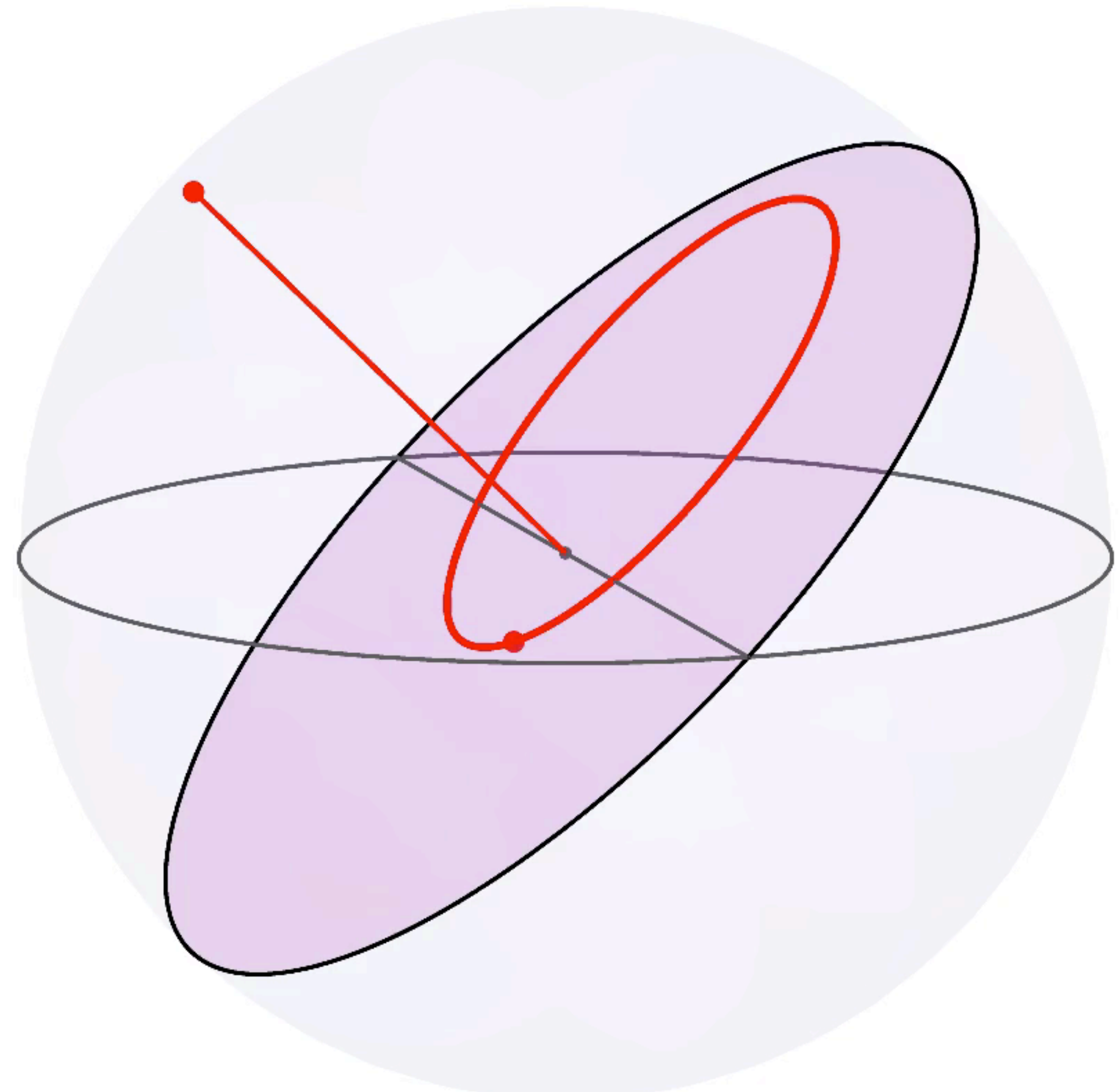


Phase of the pericentre

**Orientation** of the orbit



Spatial orientation



**Keplerian orbit**

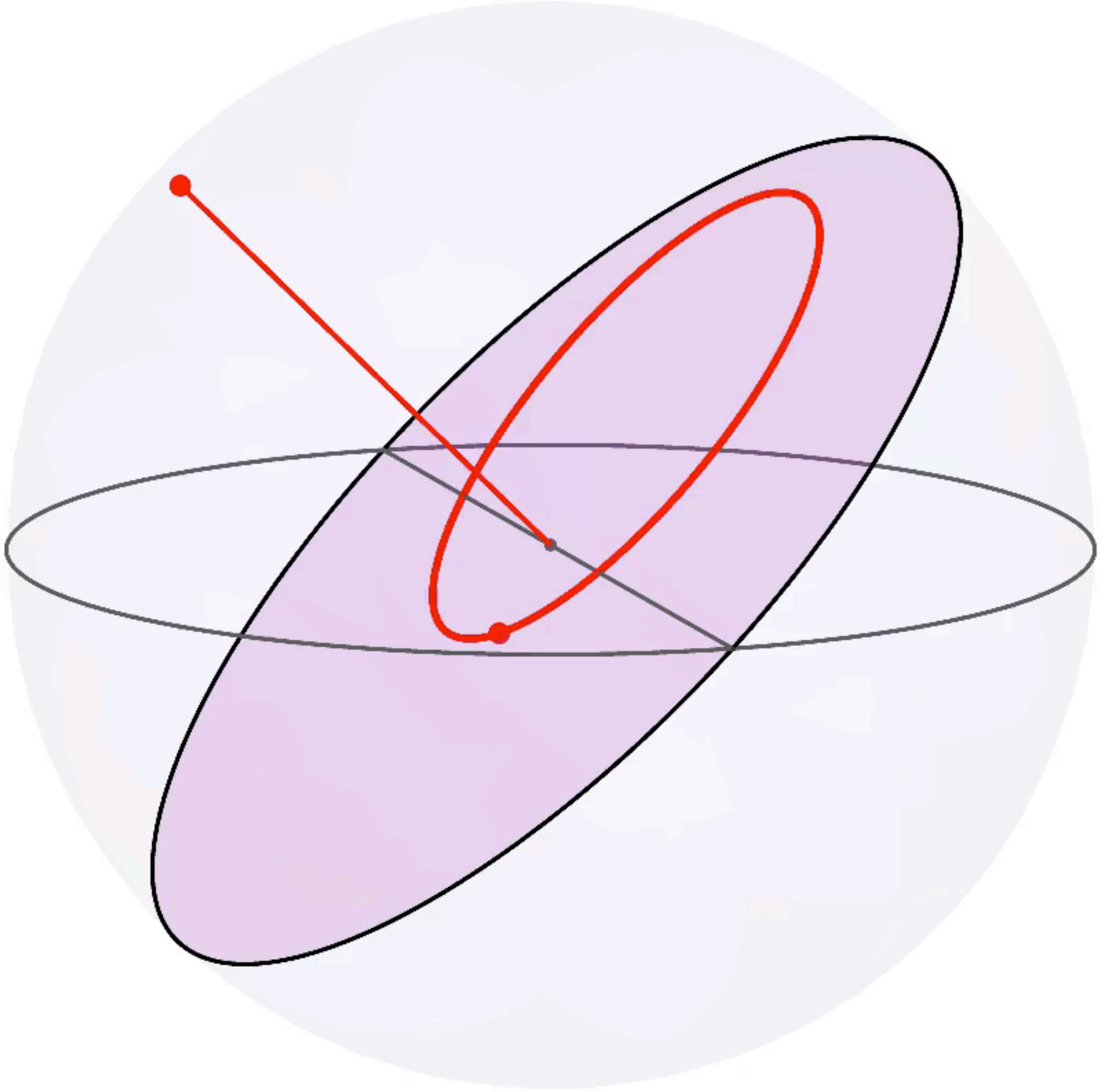
What is the dynamics of **Keplerian orbits**?

# Pericentre precession

Origins of the **precession**:

+ **Relativistic** effects from the BH
+ **Potential** from the other stars

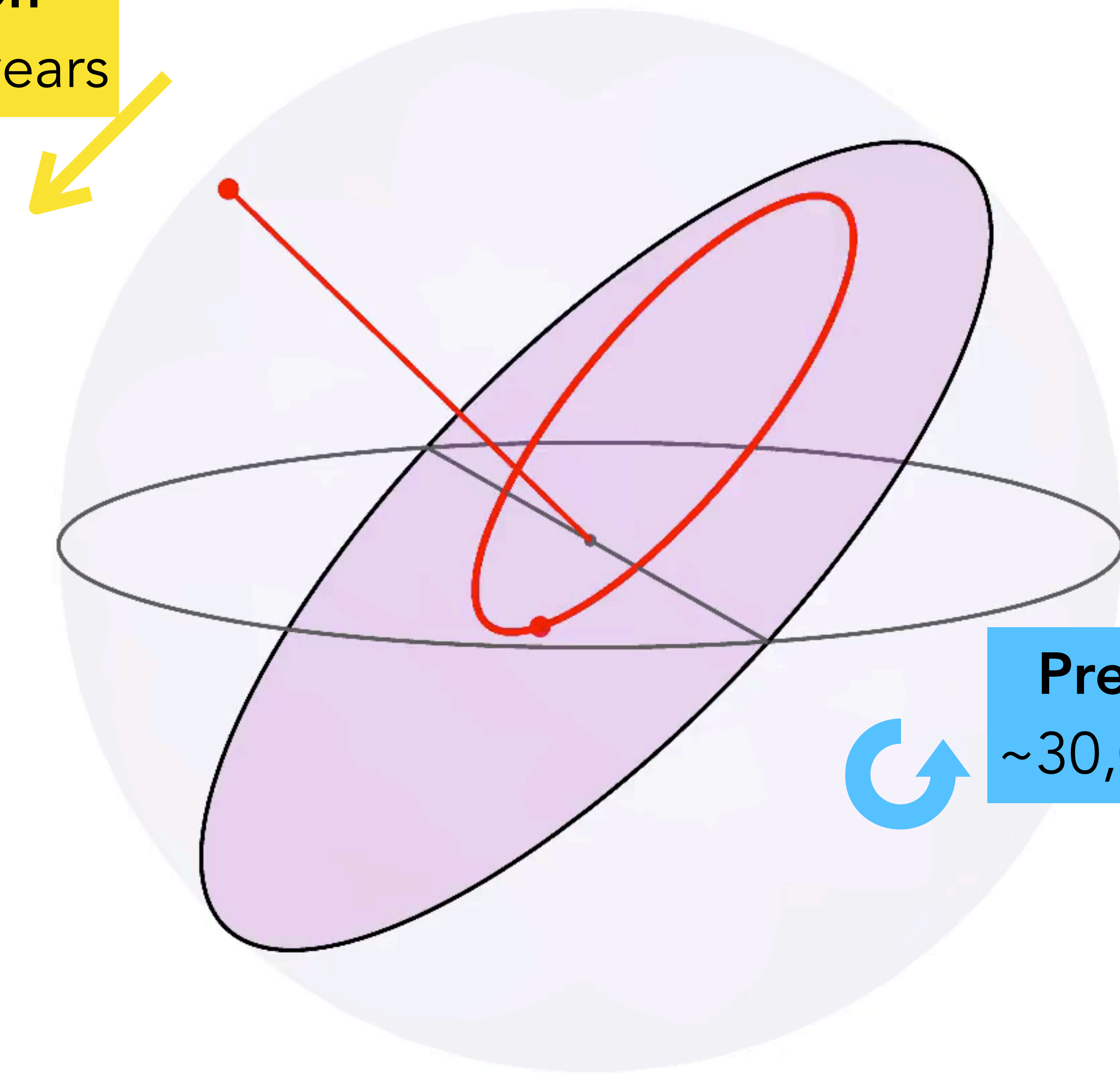
~30,000 years for S2



Orbits **precess** in their planes

# Orbits also change in orientations

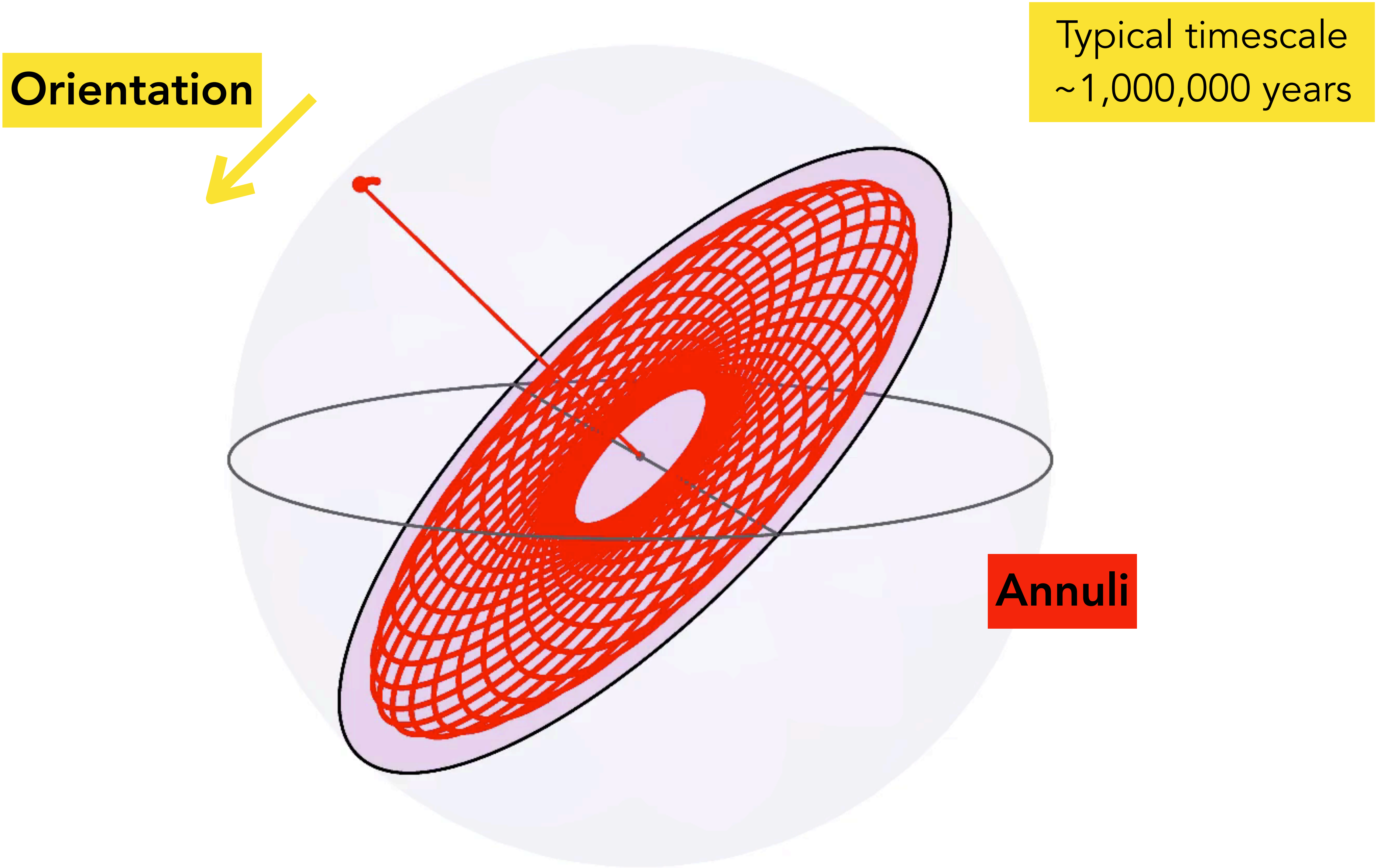
**Orientation**
~1,000,000 years



**Precession**
~30,000 years

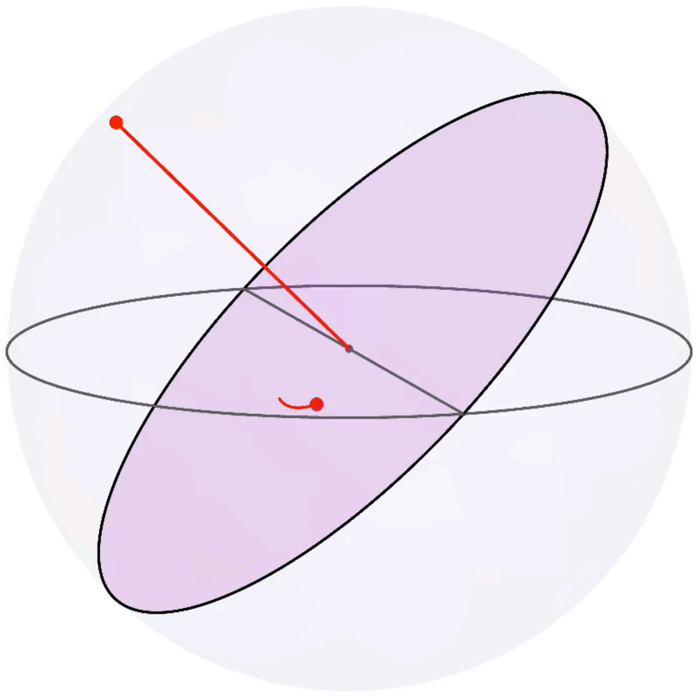
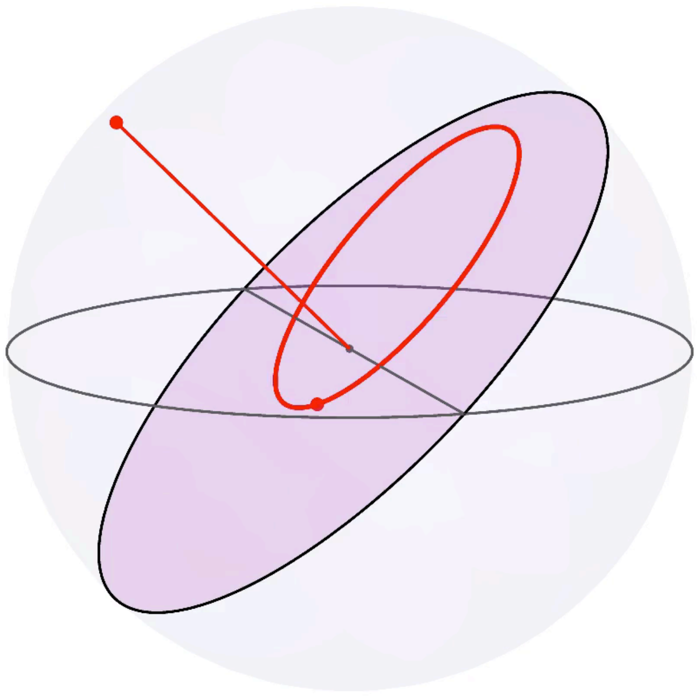
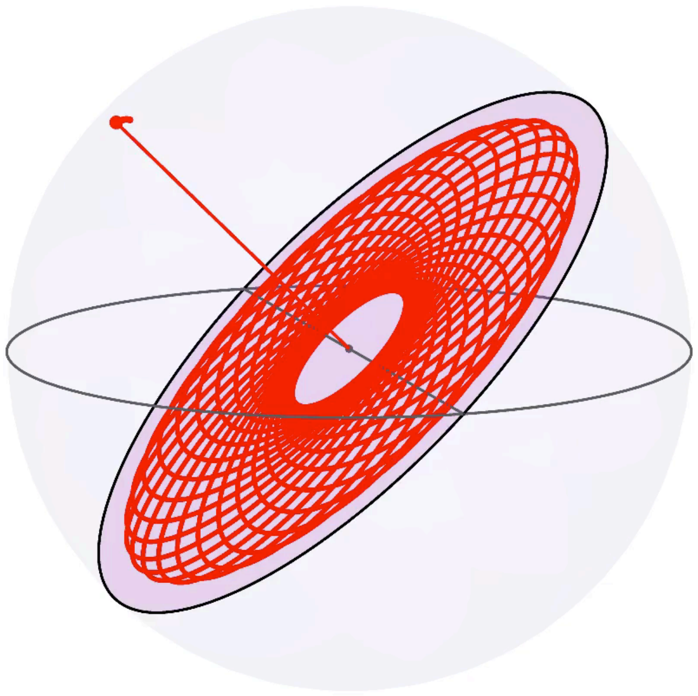
Two timescales: **Precession** ≪ **Orientation**

# Stellar orientations




After a full precession, **ellipses** become **annuli**

# Stellar dynamics

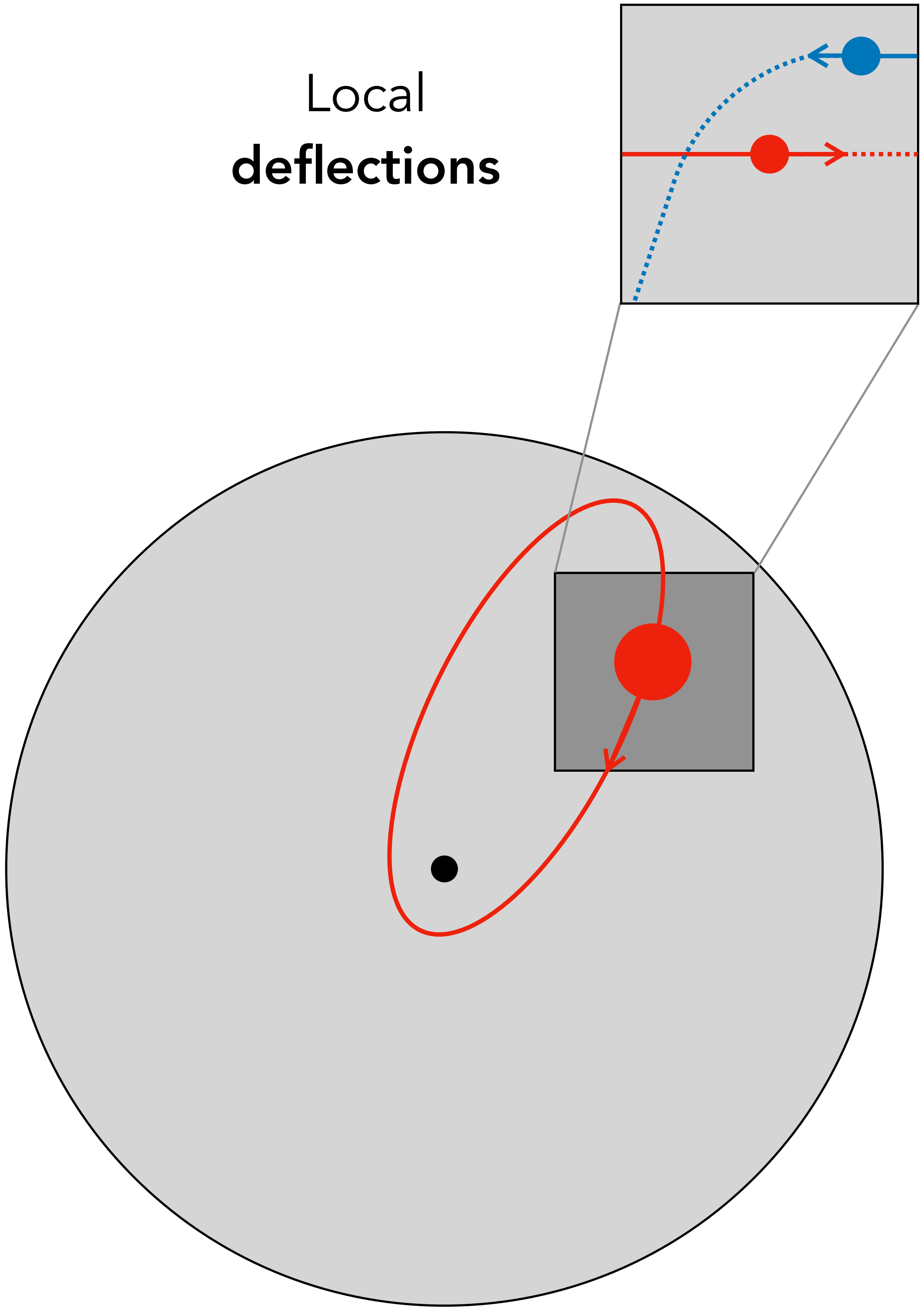
| Stars | Ellipses | Annuli |
| --- | --- | --- |
|  |  |  |
| ~10 years | 30,000 years | ~1,000,000 years |
| **Orbital** motion | **Pericentre** precession | **Orientation** precession |

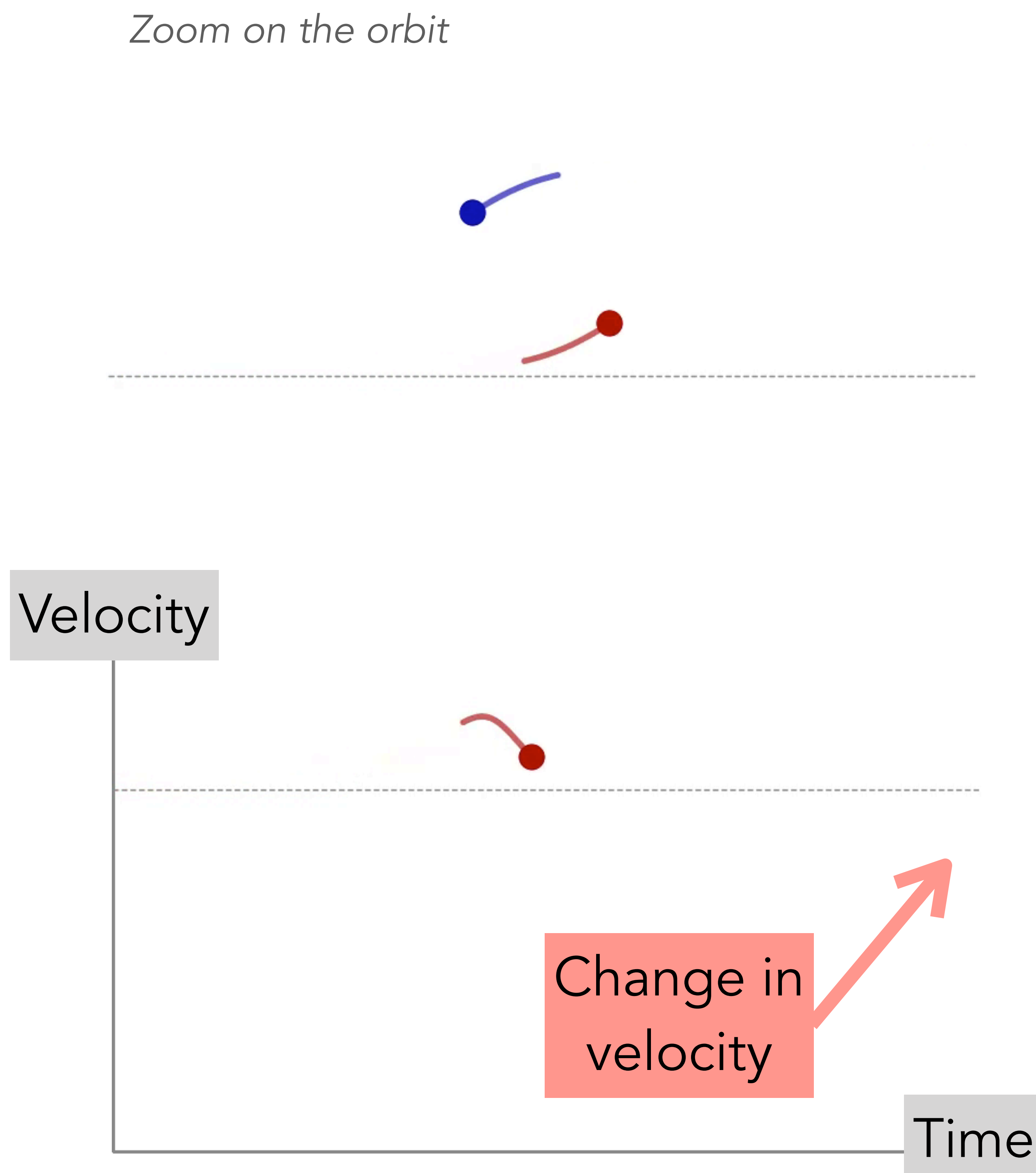
SgrA* is 10 Gyr orld. We can wait longer

# Stellar energy

Orbital distortions sourced by instantaneous **kicks and deflections**

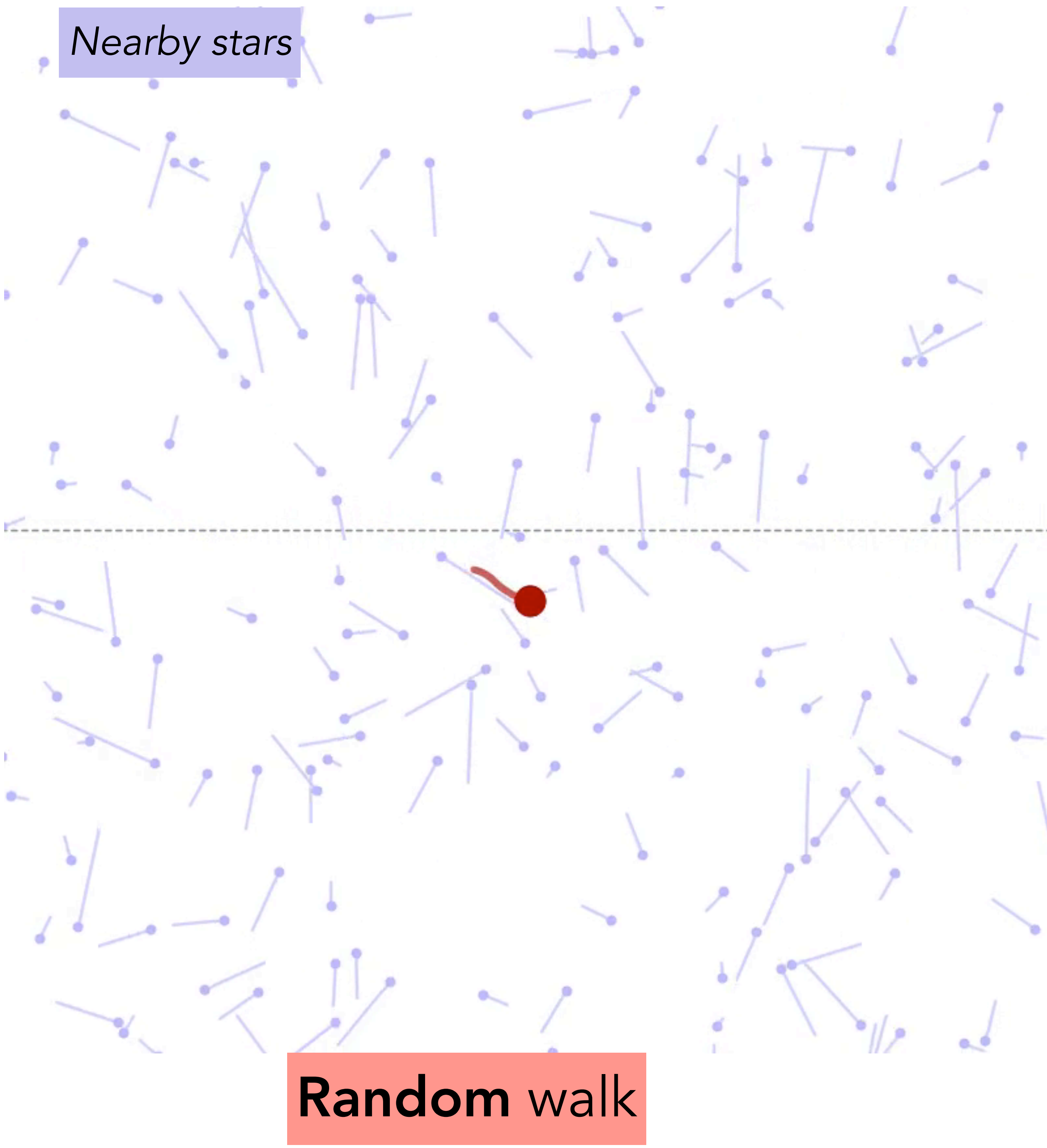
Local
**deflections**

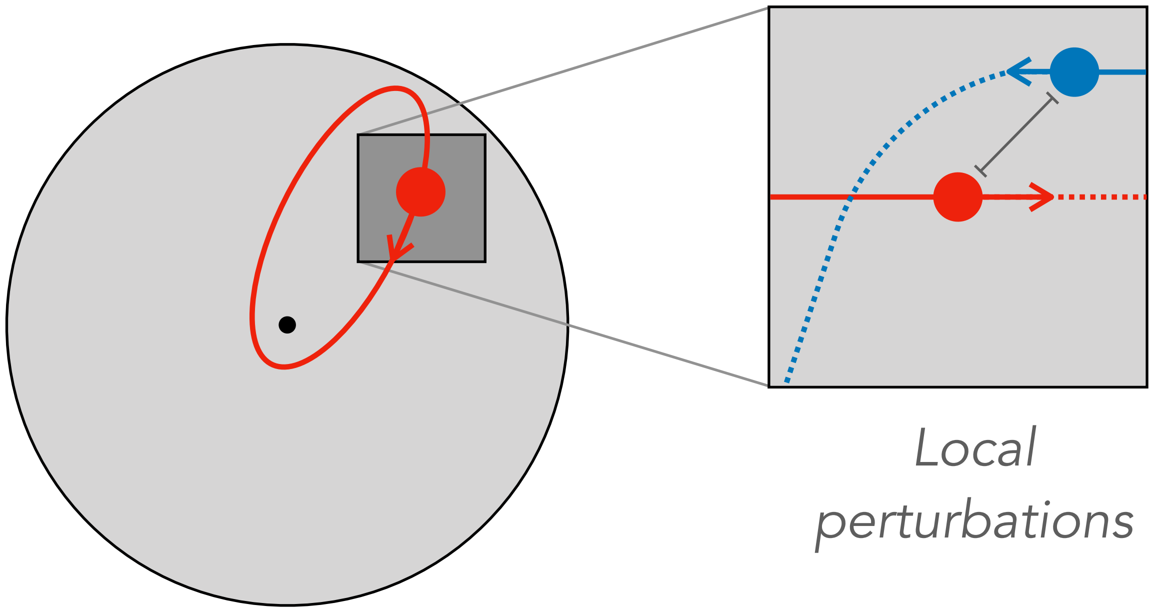


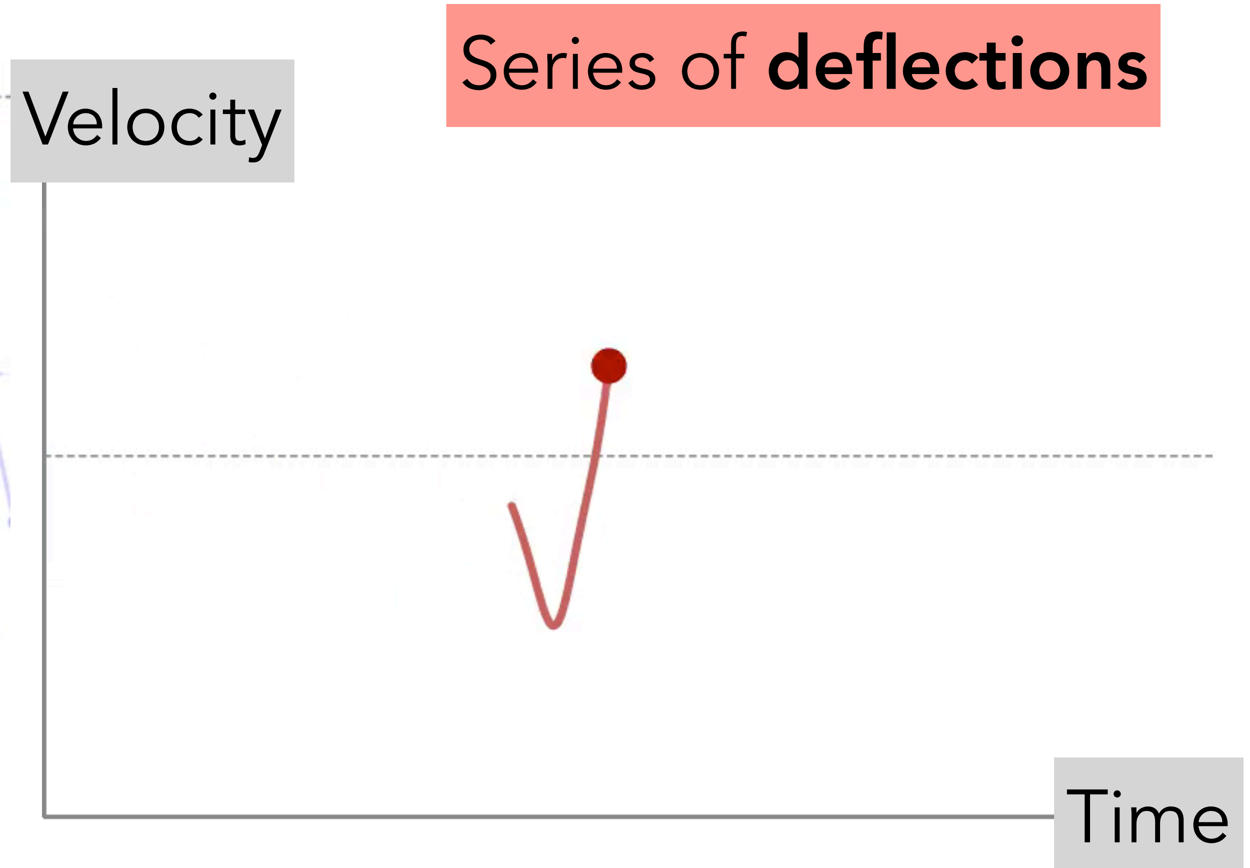


# Deflections

The star has a lot of **close neighbours**

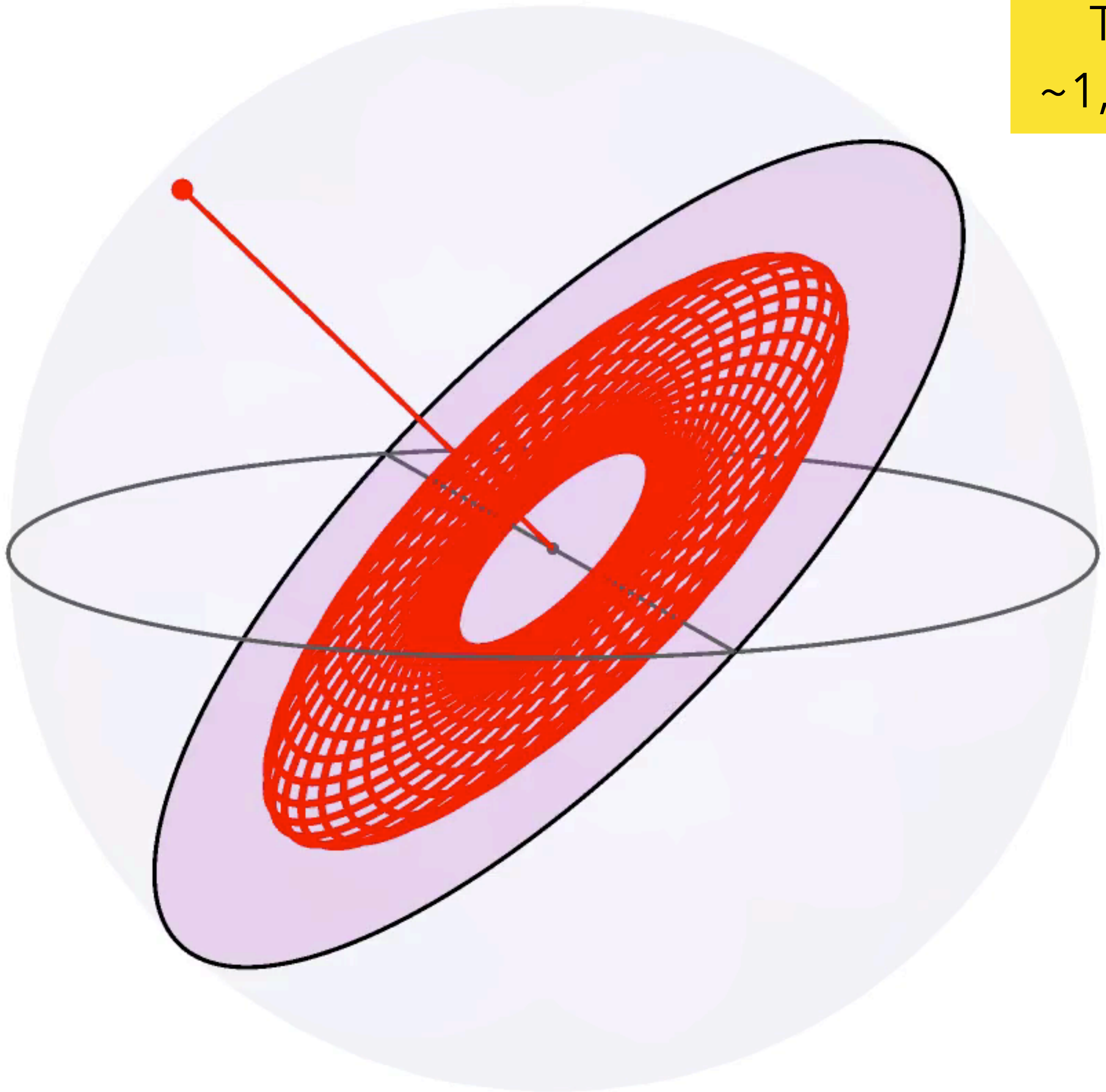


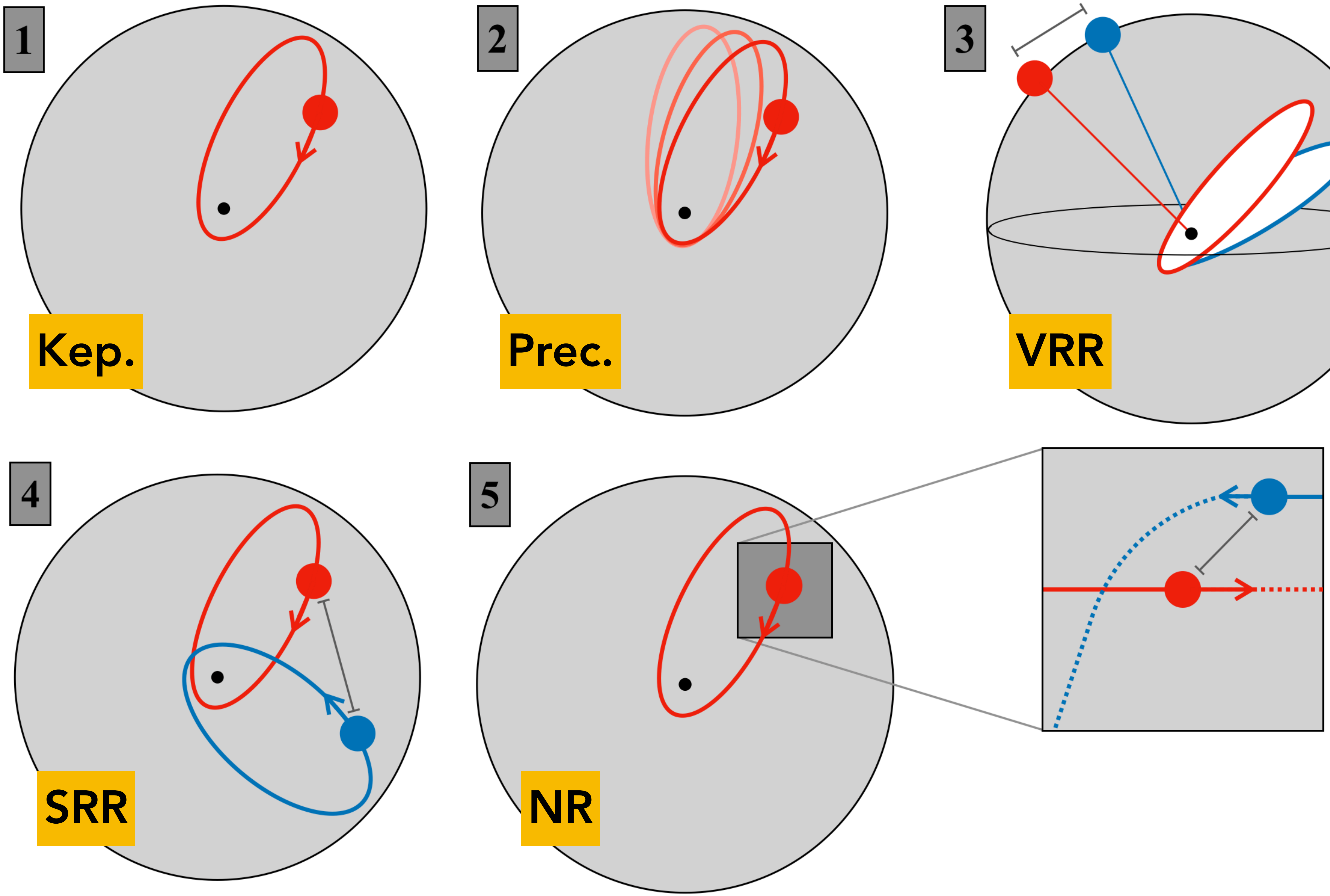
# Stellar energy

Typical timescale
~1,000,000,000 years



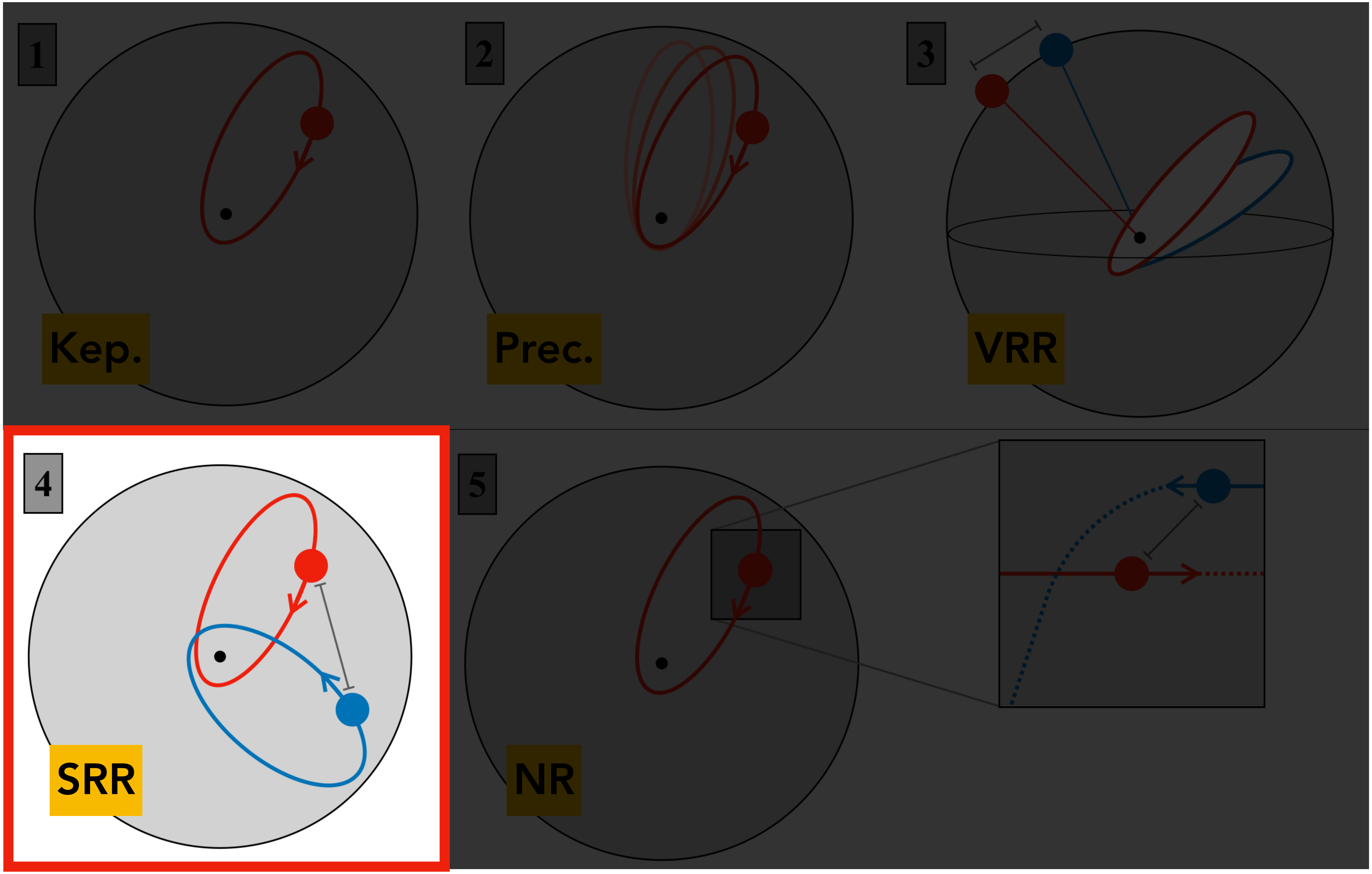
**Deflections** drive a slow change in the Keplerian energy

# A wealth of dynamical processes




An extremely **hierarchical system**

# Scalar Resonant Relaxation

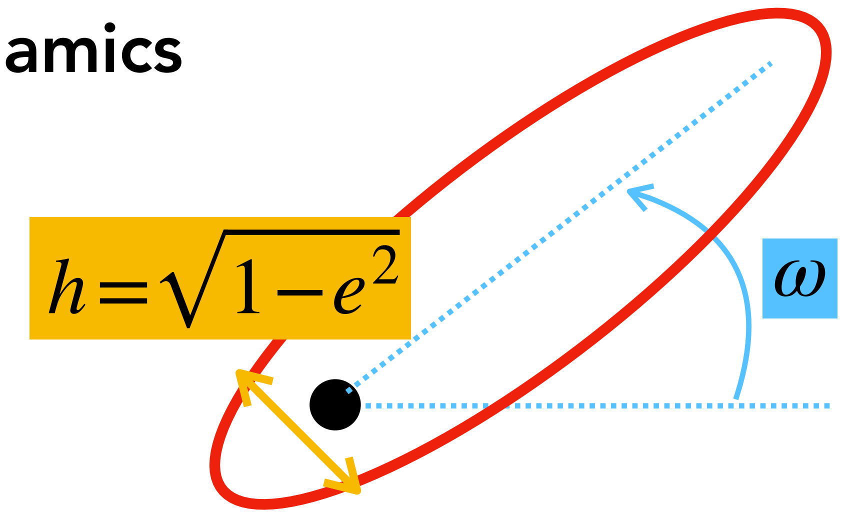


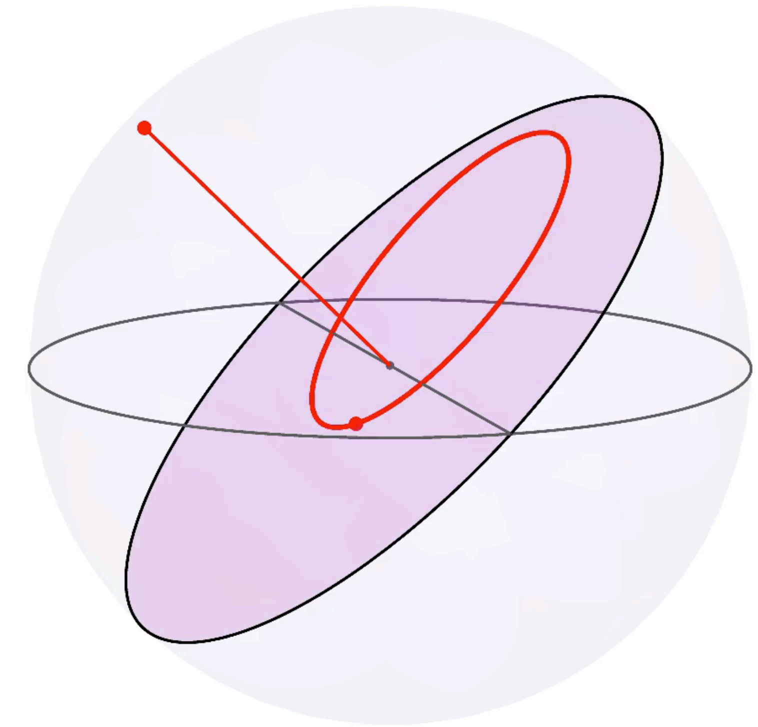

The (resonant) dynamics of **eccentricities**

# Scalar Resonant Relaxation

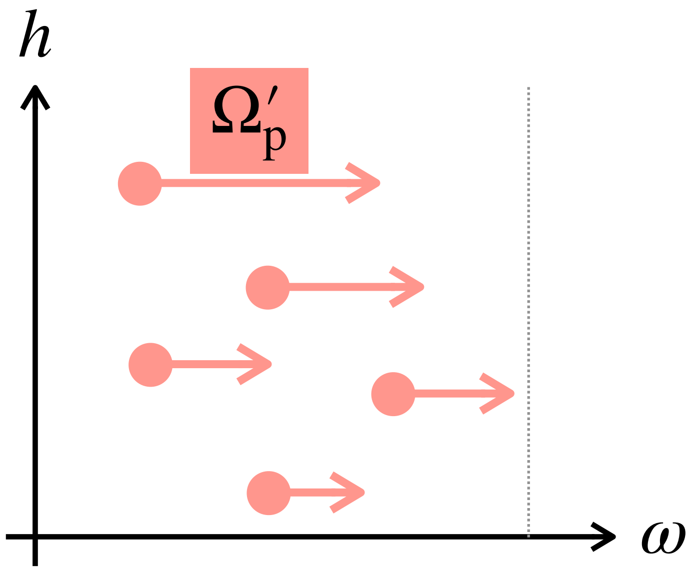
A simple **unperturbed dynamics**

$$\begin{cases} \dot{\omega} \simeq \Omega_{\mathrm{p}}(h) \\ \dot{h} \simeq \eta(t, \omega, h) \end{cases}$$

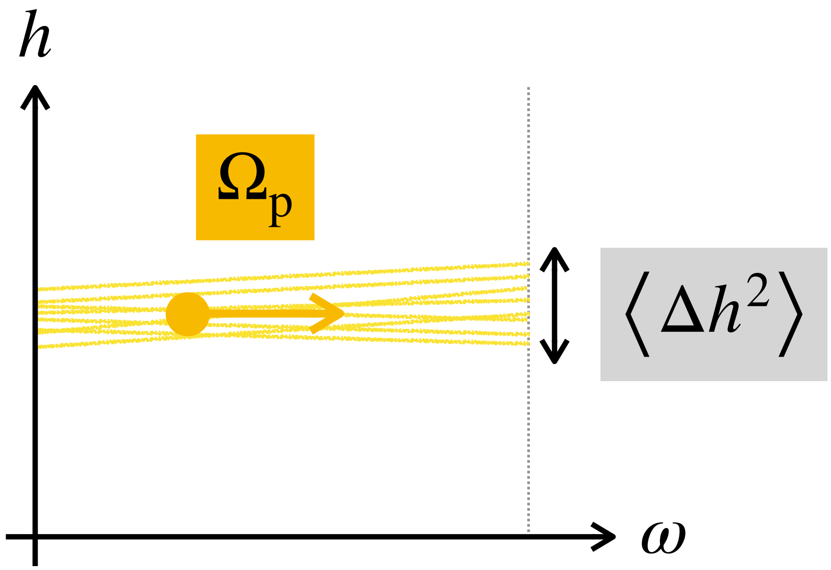


**Phase-space** dynamics




**Background cluster**




**Test particle**

Relaxation occurs at **resonance**

$$k\, \Omega_{\mathrm{p}}(a, h) = k'\, \Omega_{\mathrm{p}}(a', h')$$

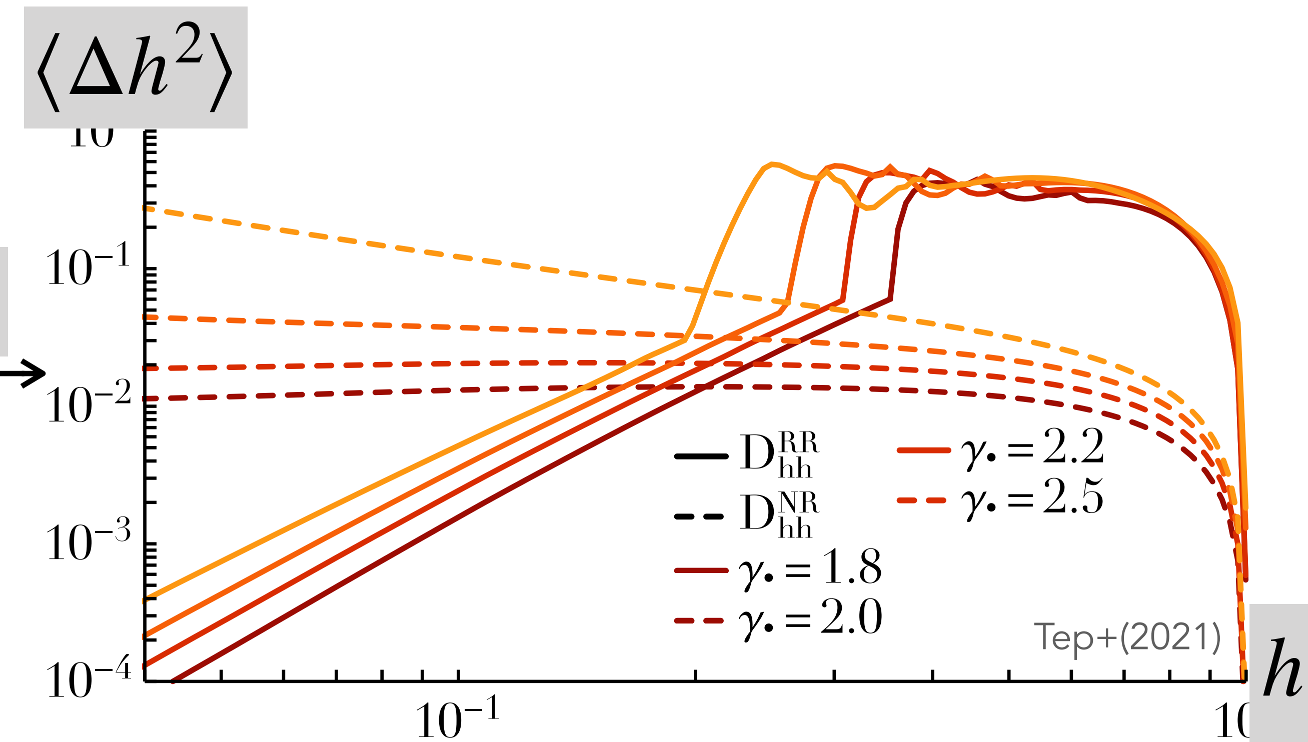
*Balescu-Lenard equation*

# SRR around SgrA*

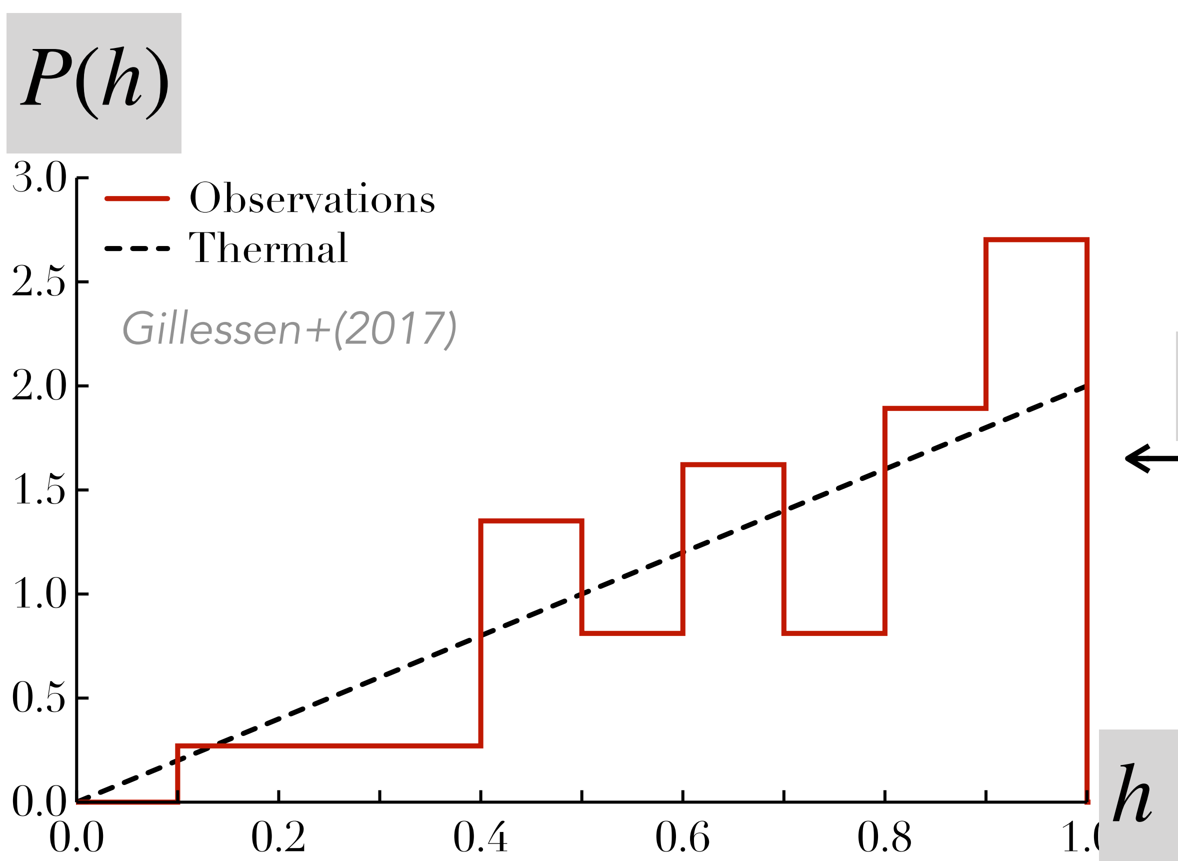
## Model

- Old stars
  *(unresolved but relaxed)*
- **IMBHs**
  *(strong source of Poisson noise)*
- S-stars ICs
  *(Tidal disruption vs disc formation)*

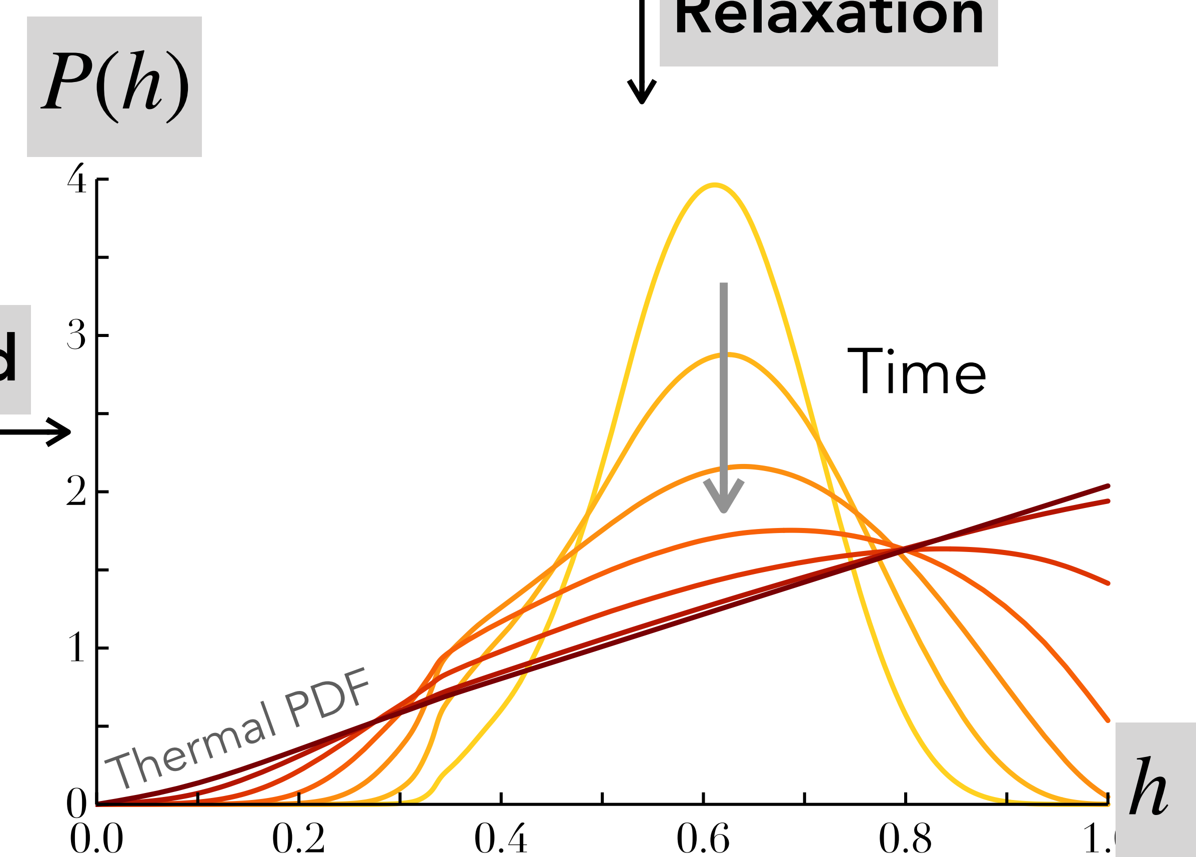
**Kinetic theory** →




↕ **Relaxation**

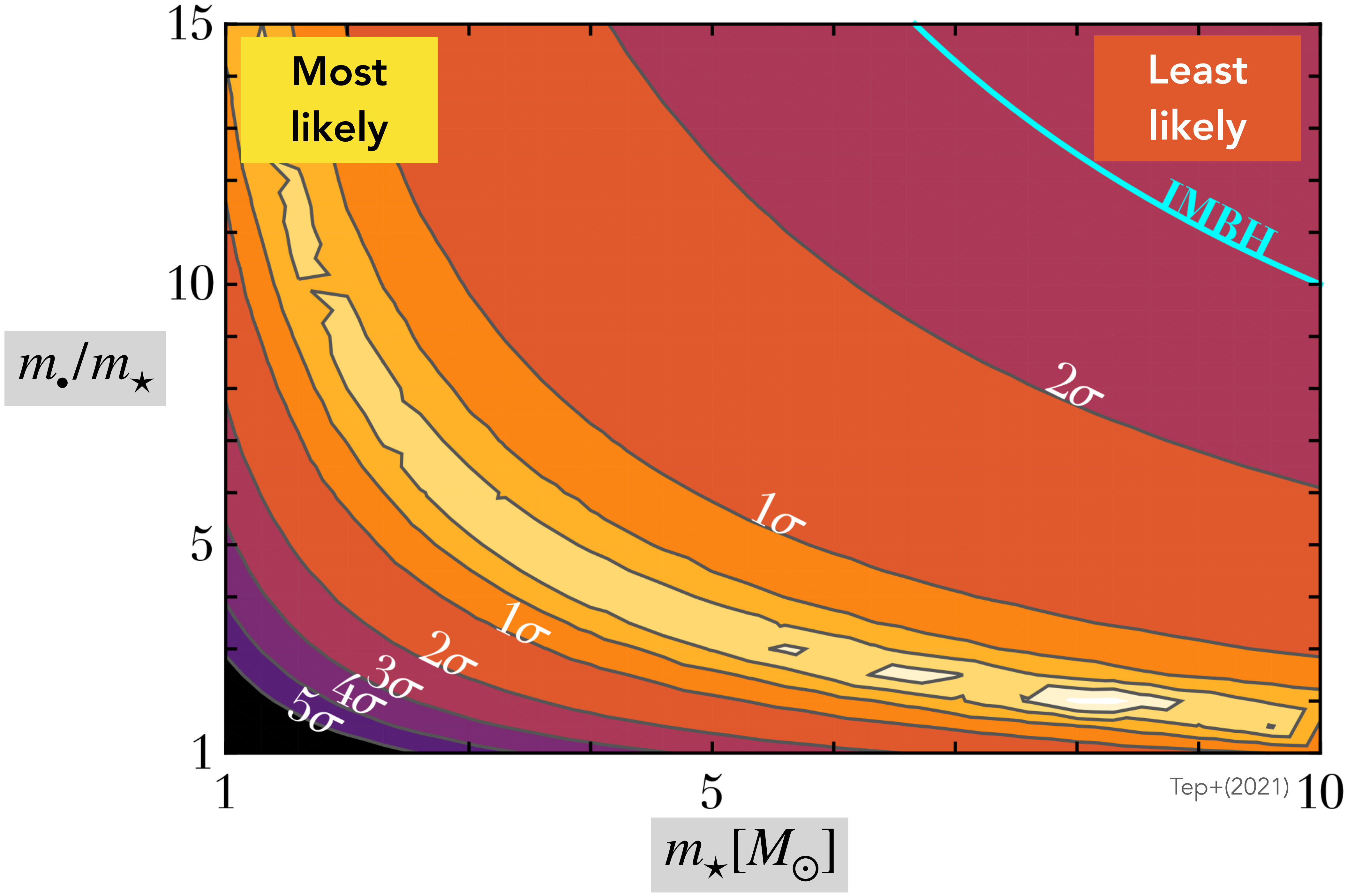



↔ **Likelihood**



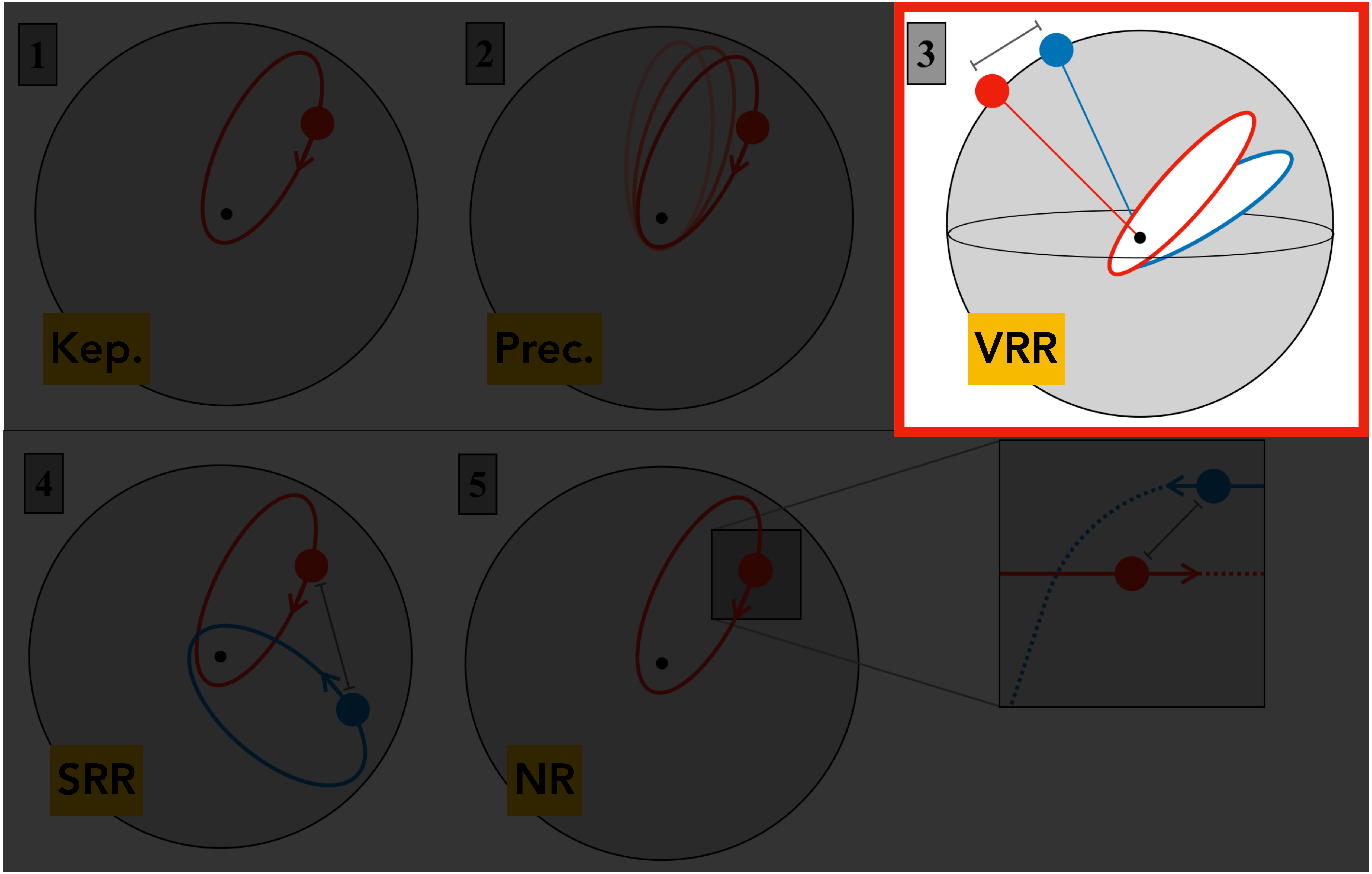
# Constraining IMBHs from SRR

2-population model (stars+IMBHs)




IMBHs population hard to reconcile with a **thermal eccentricity distribution**

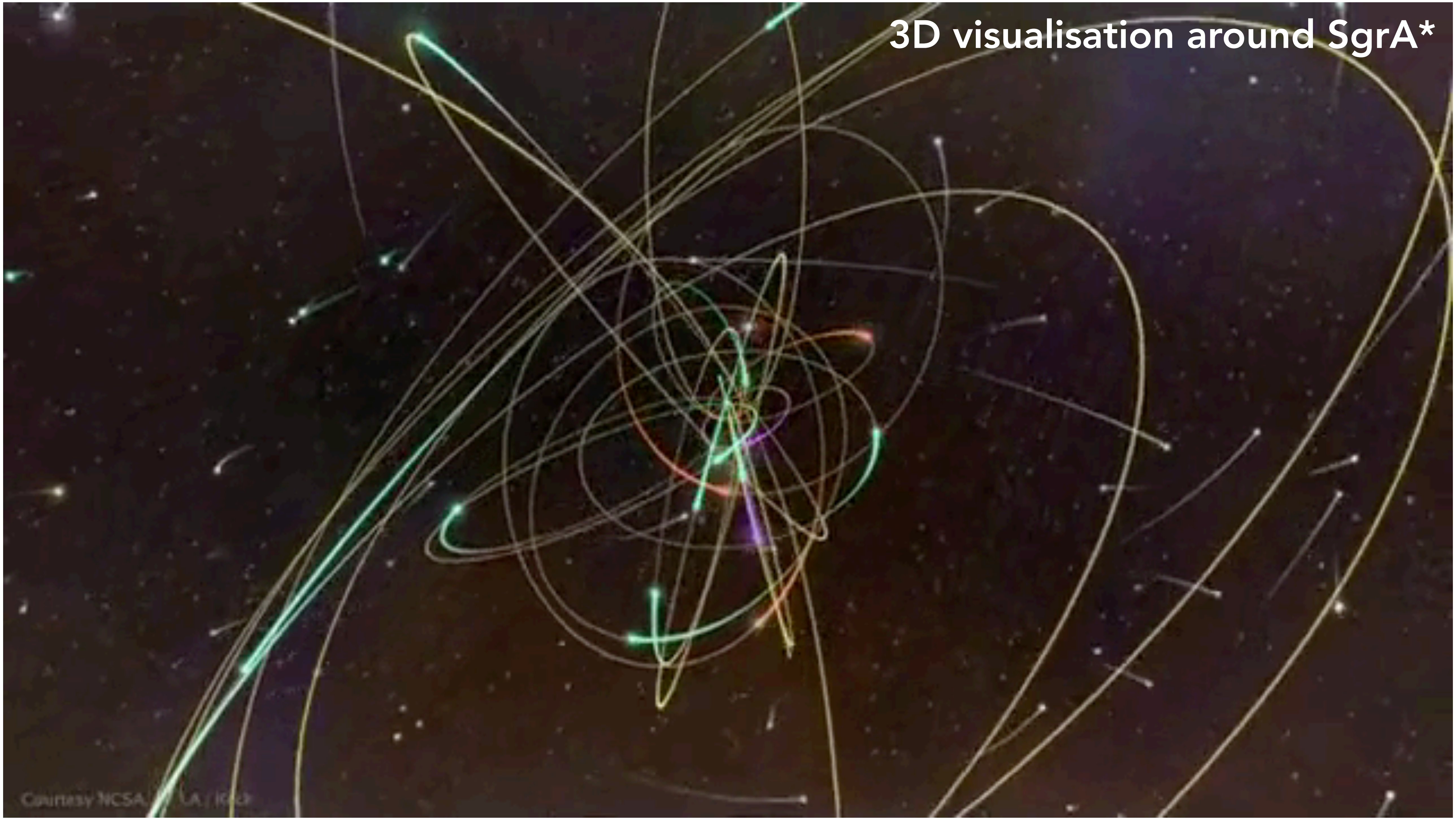
# Vector Resonant Relaxation




The coherent dynamics of **orientations**

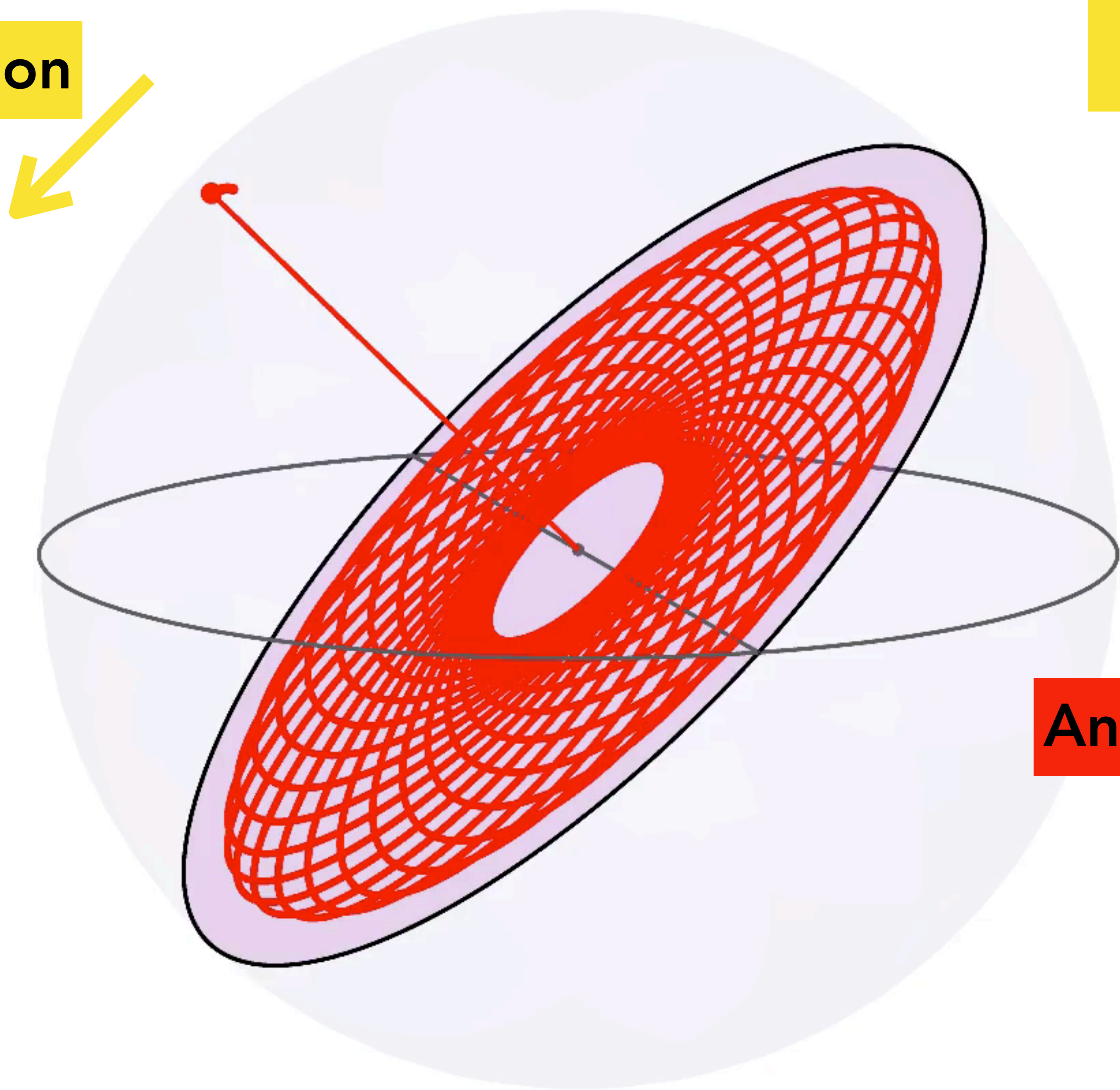
# Stellar orientations

Orbits are in **all directions**




What is the origin of the clockwise stellar disc?

# Stellar orientations



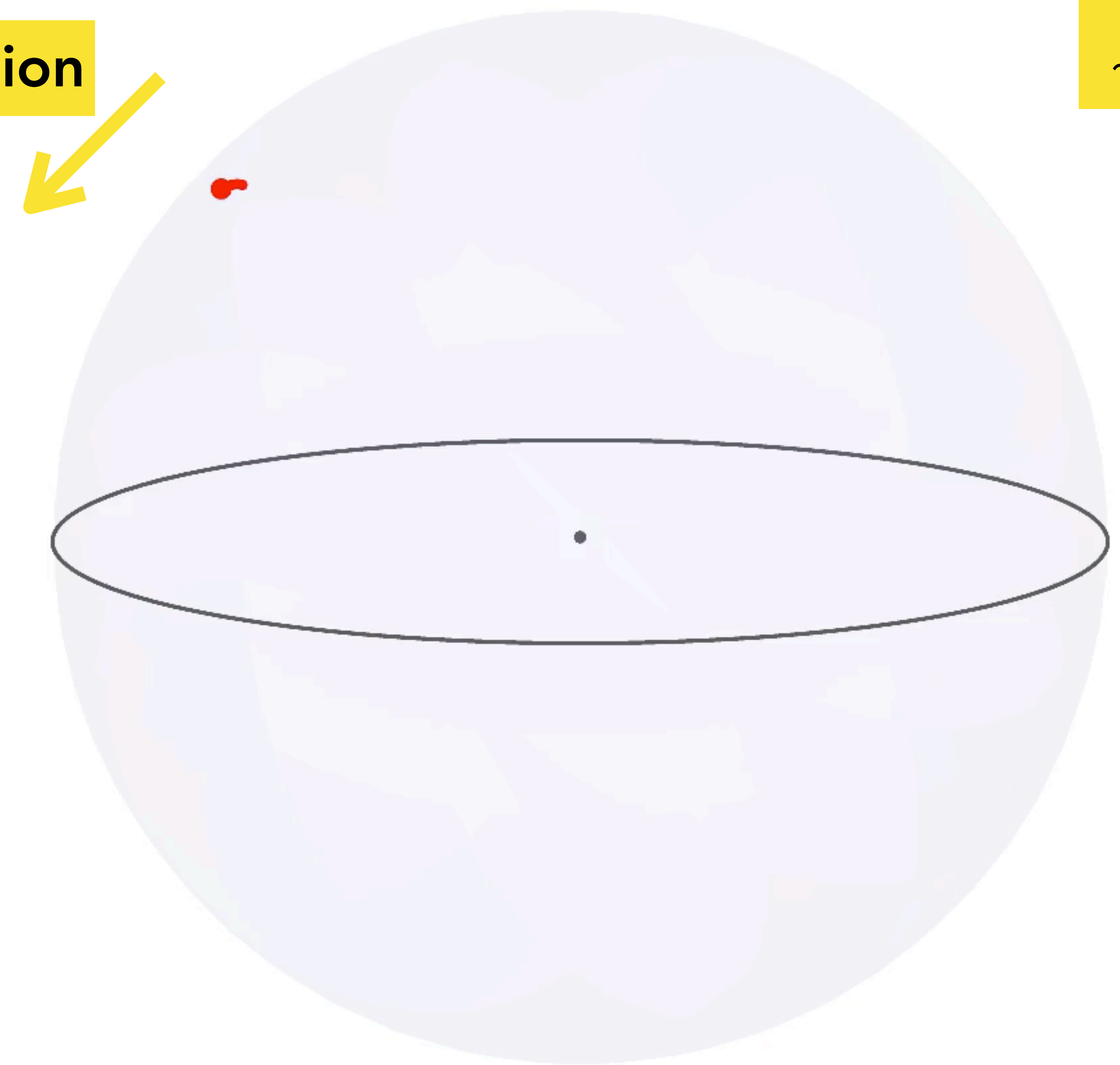

After a full precession, **ellipses** become **annuli**

# Orbital orientations

**Orientation**

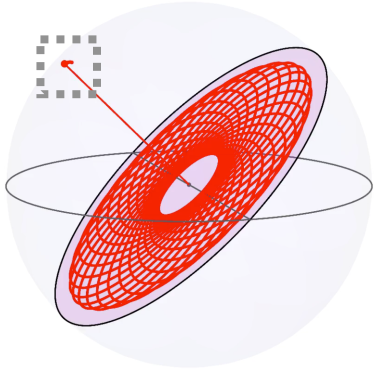
$\hat{\mathbf{L}}$

Typical timescale
~1,000,000 years



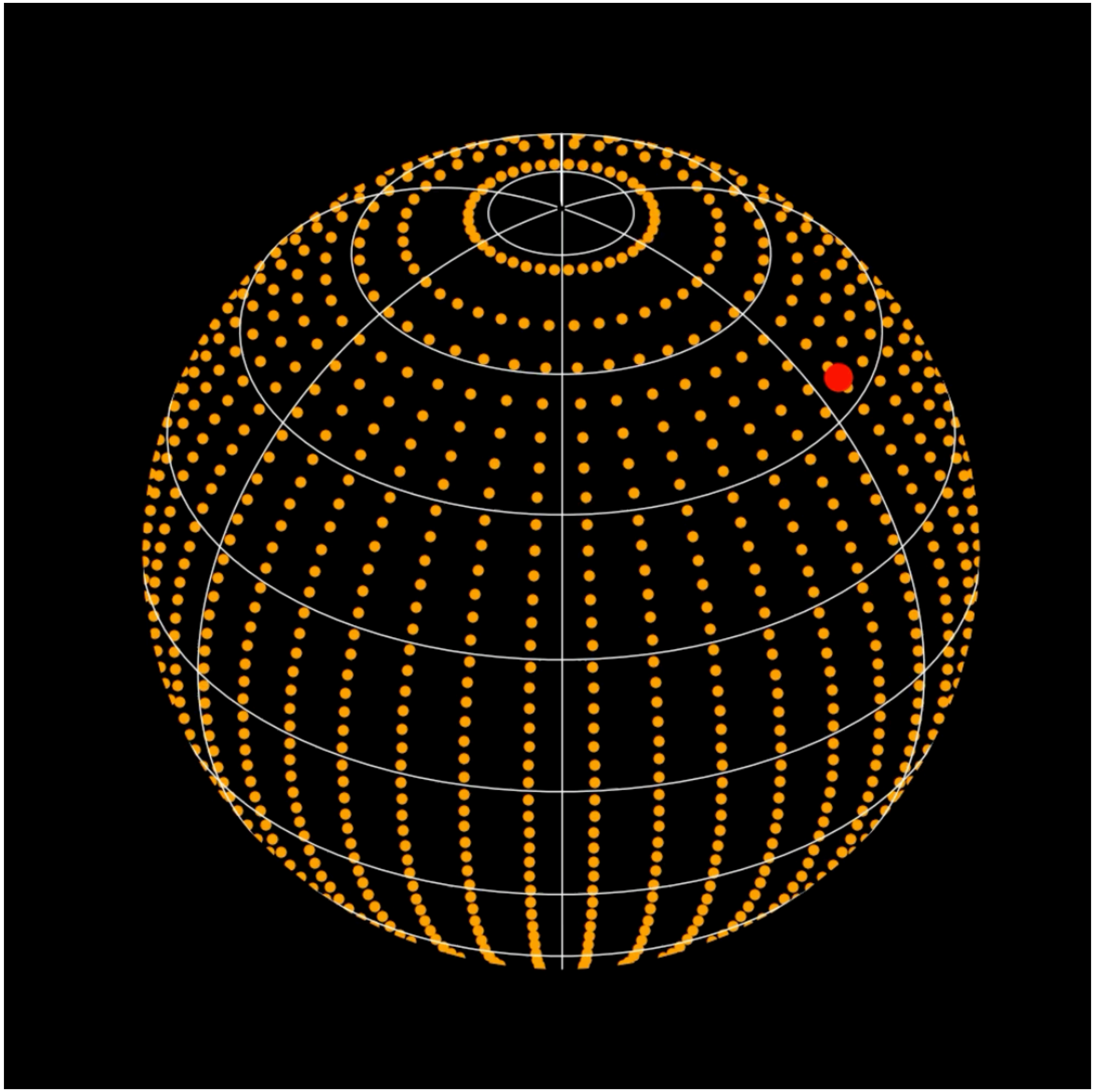
One orientation becomes a single point on the **unit sphere**

# Restricted 2-body problem



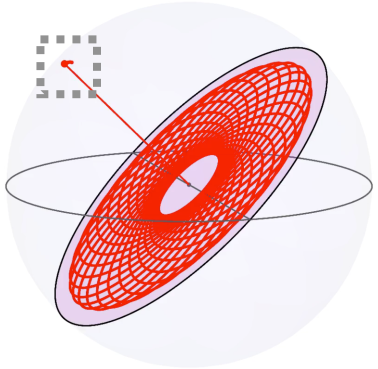
Heavy star

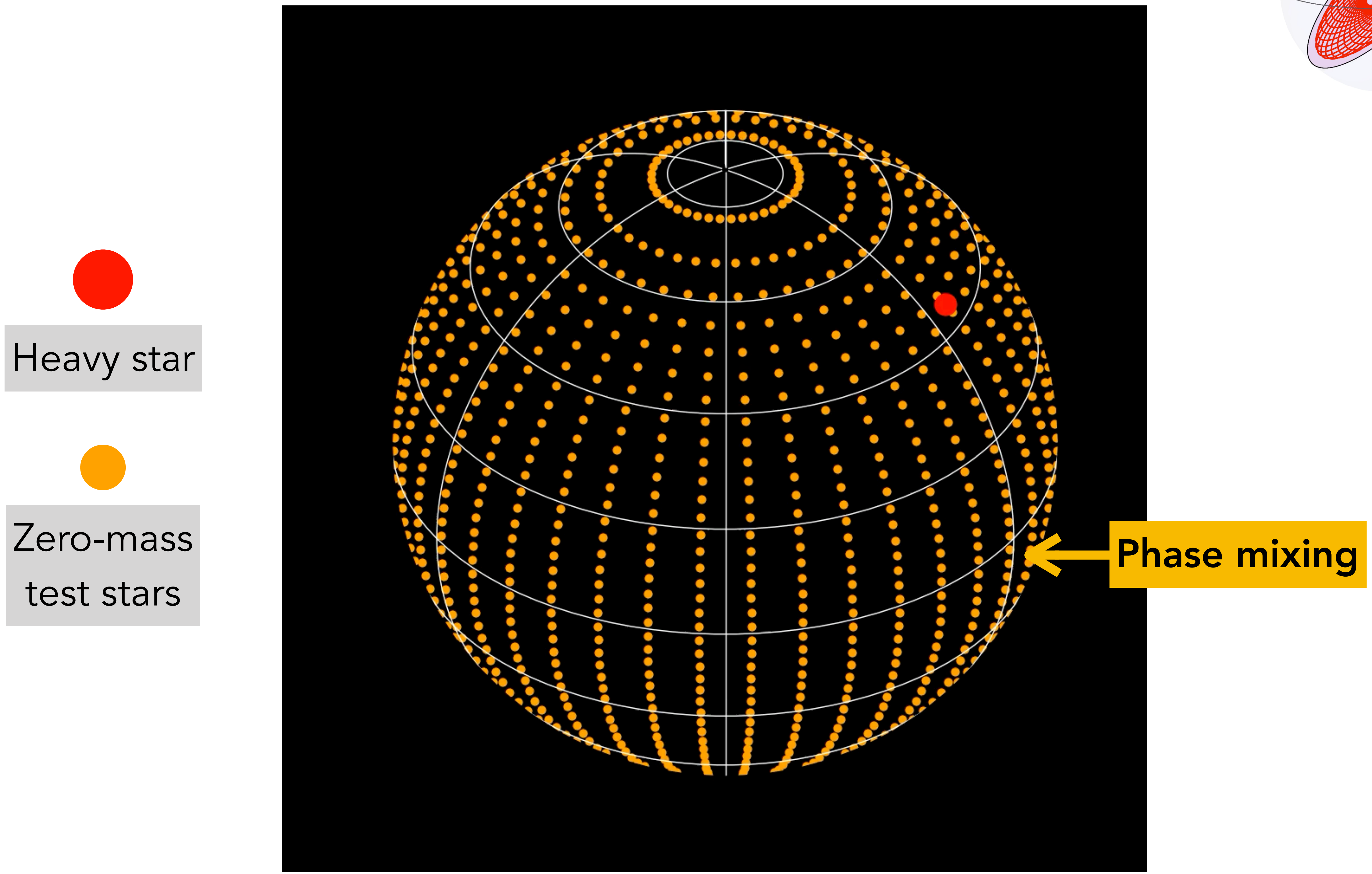
Zero-mass test stars



Dynamics induced by a single massive star

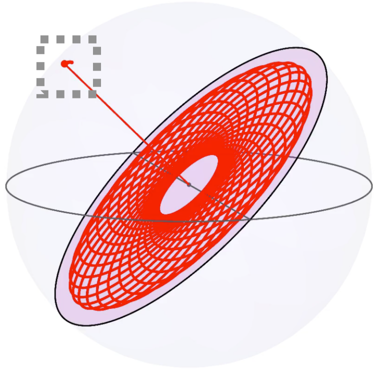
# Restricted 2-body problem






Simple **orbits** around the massive object

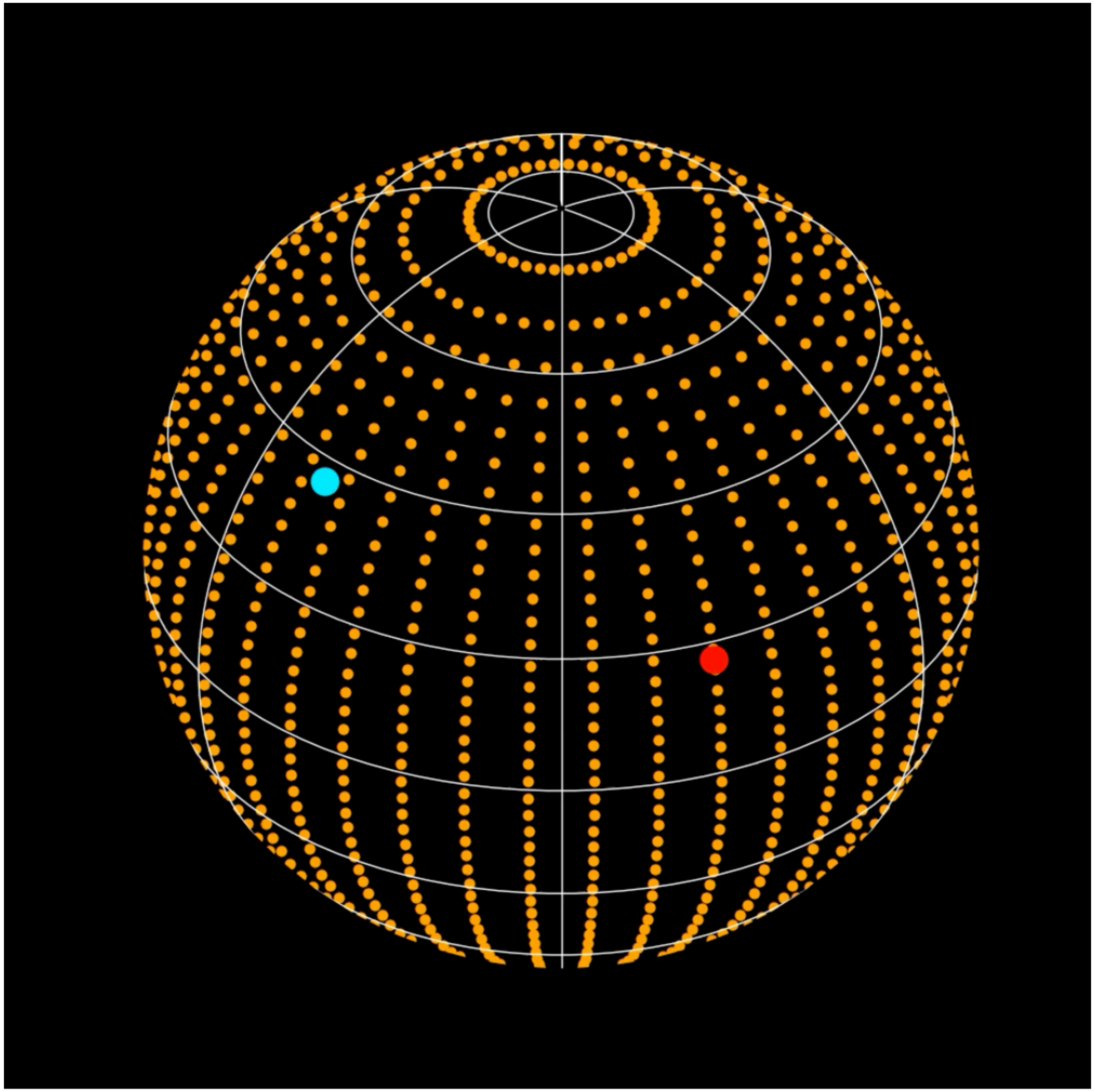
# Restricted 3-body problem



Heavy star

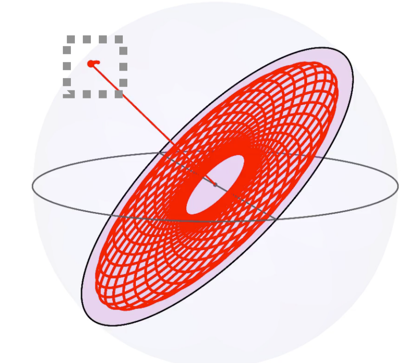
Heavy star

Zero-mass test stars



Dynamics induced by **two fixed massive stars**

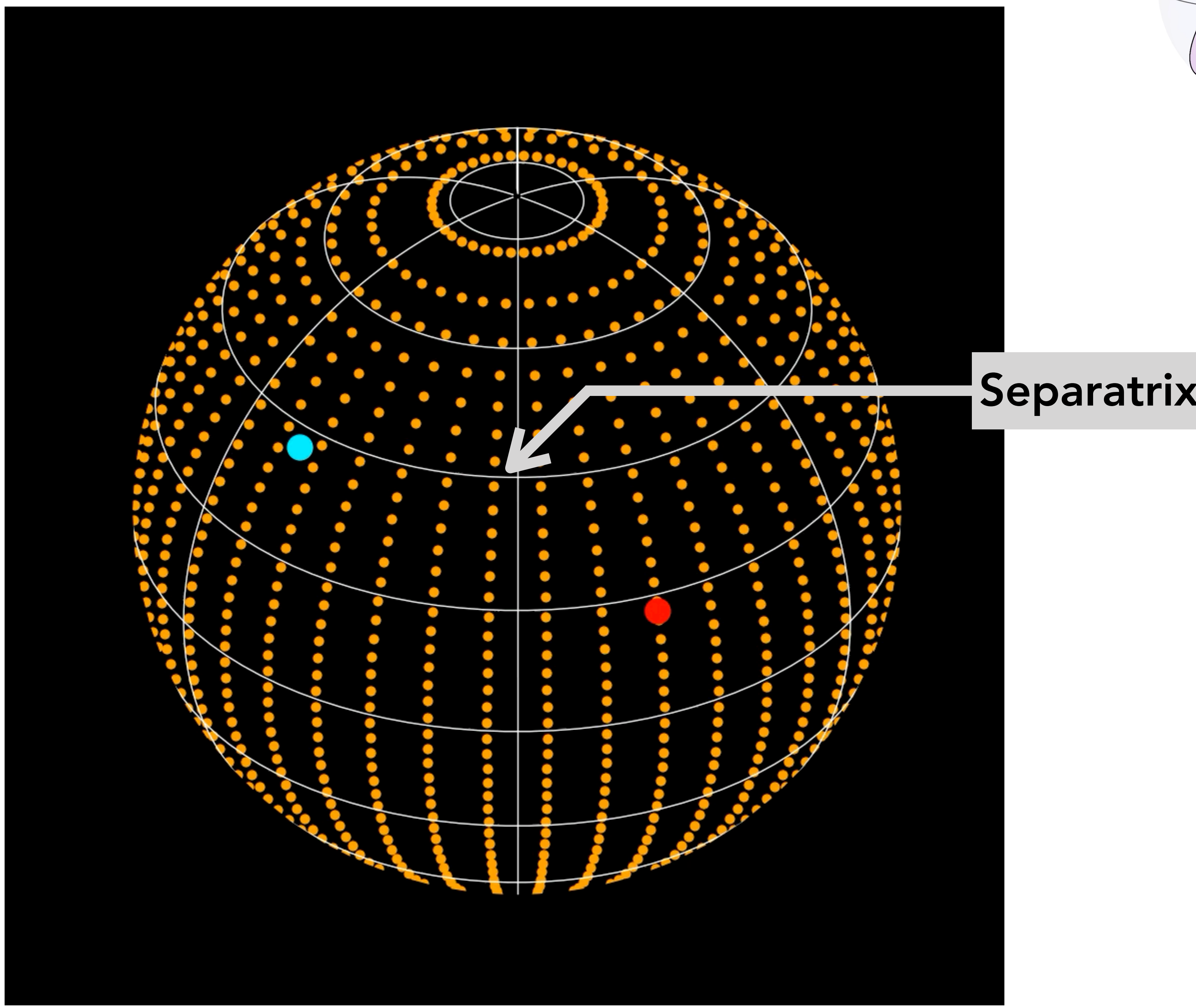
# Restricted 3-body problem



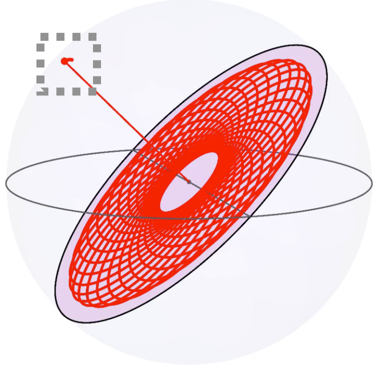
Heavy star

Heavy star

Zero-mass test stars



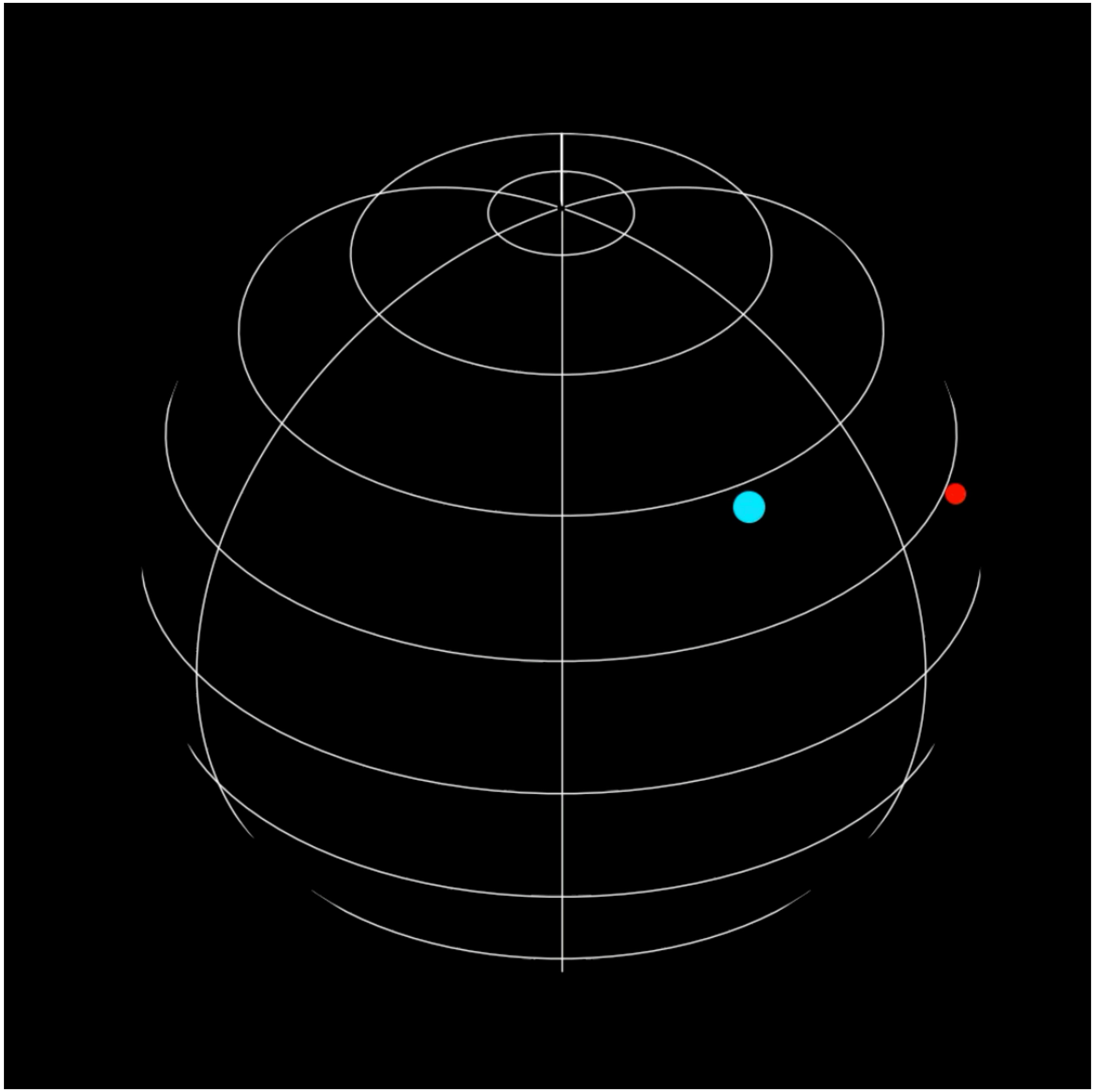

Test stars attracted by **each star respectively**



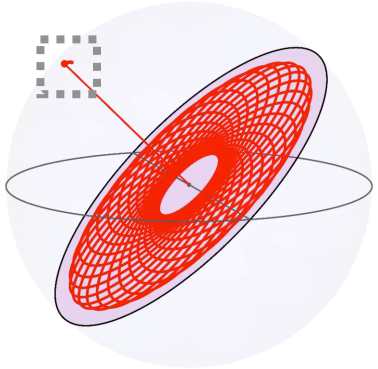
# Real 2-body problem

**Less**
massive star

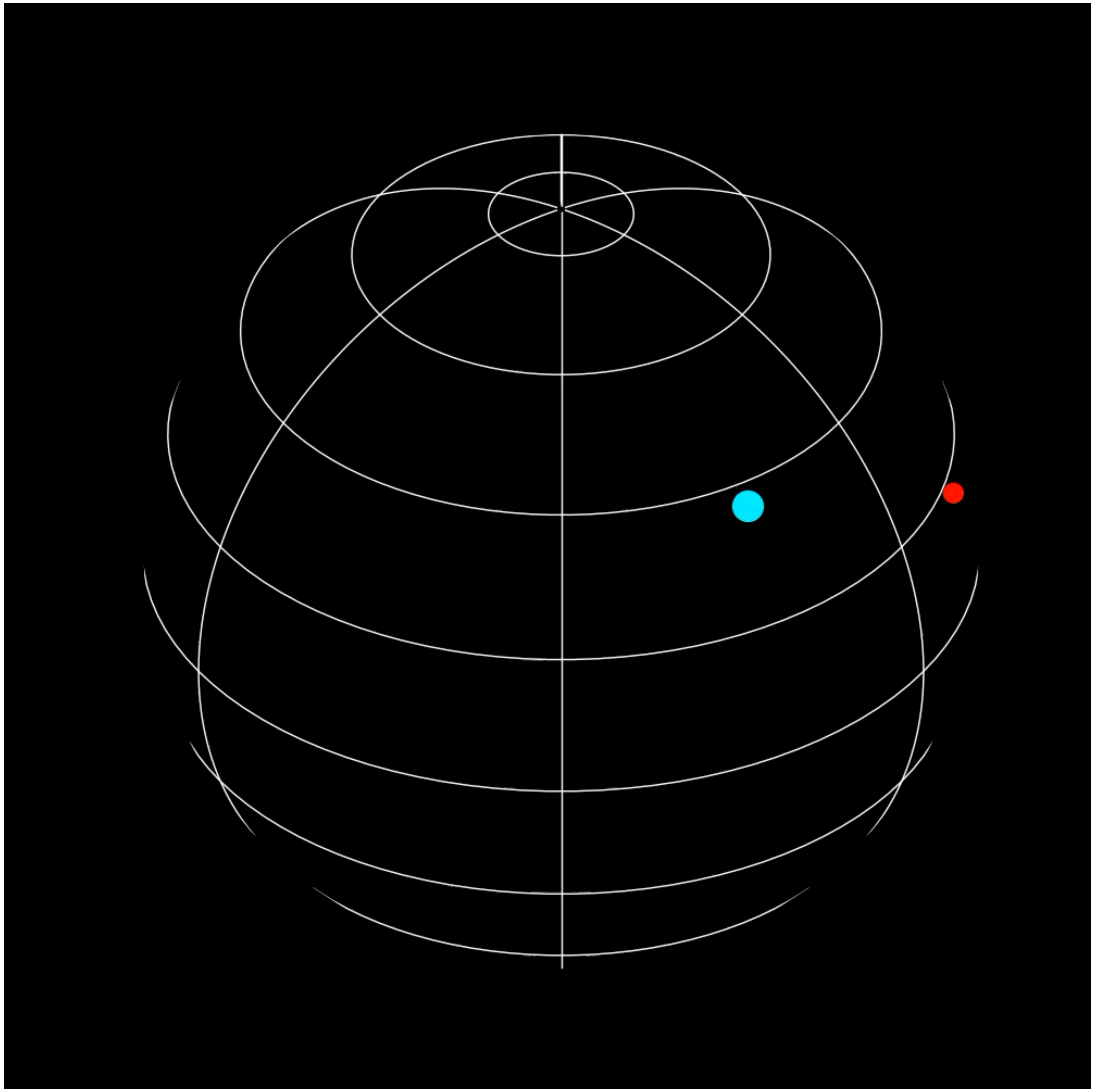
**More**
massive star



**Two massive** stars together



# Real 2-body problem

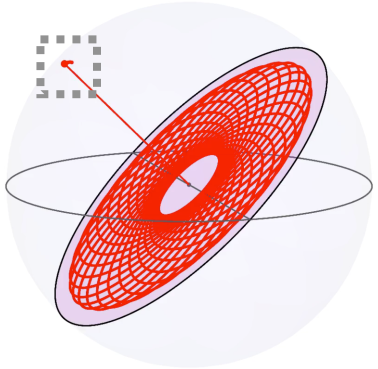


**Less** massive star

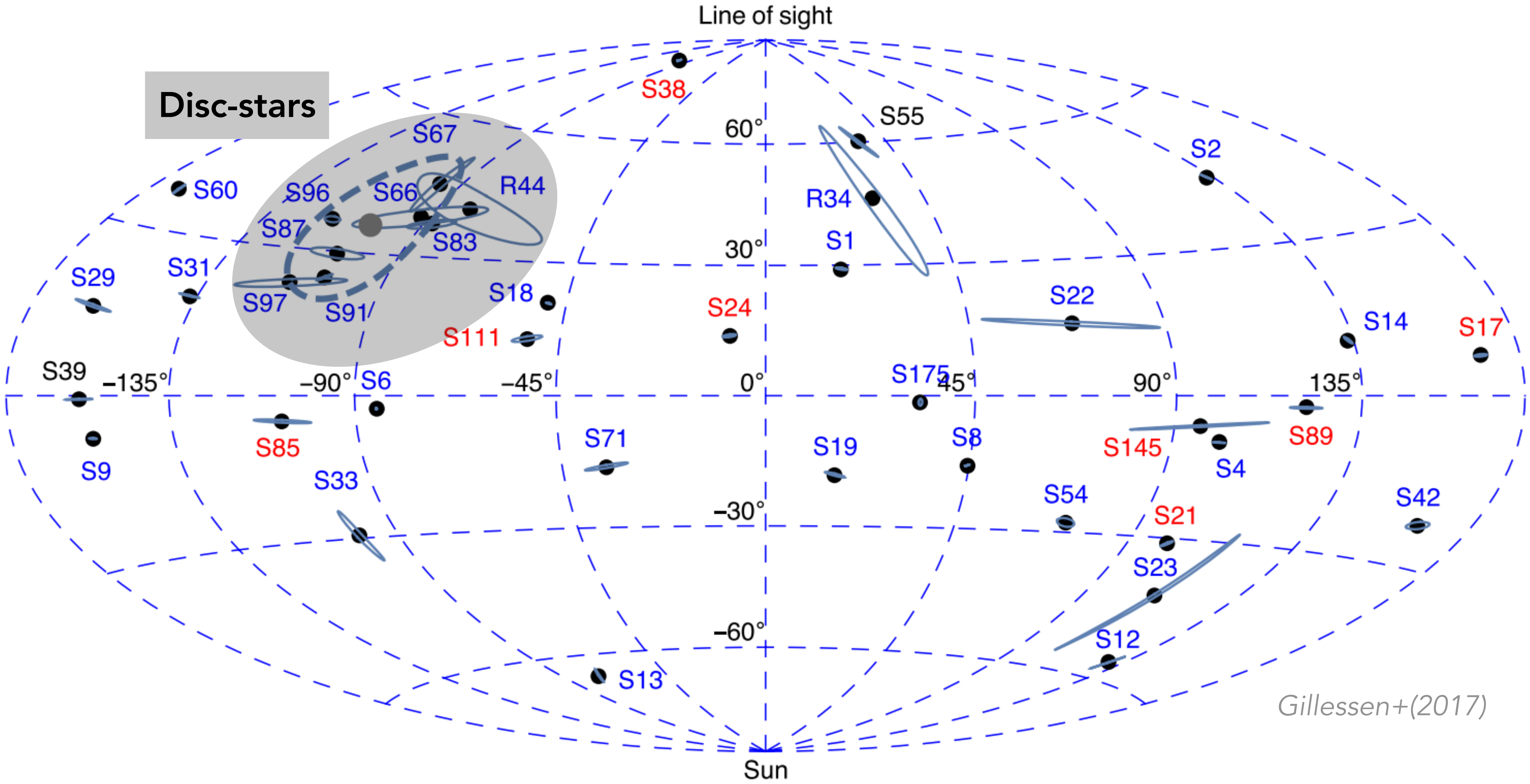
**More** massive star

Stars orbit around their common ``**centre of mass**''

# A “turbulent” dynamics

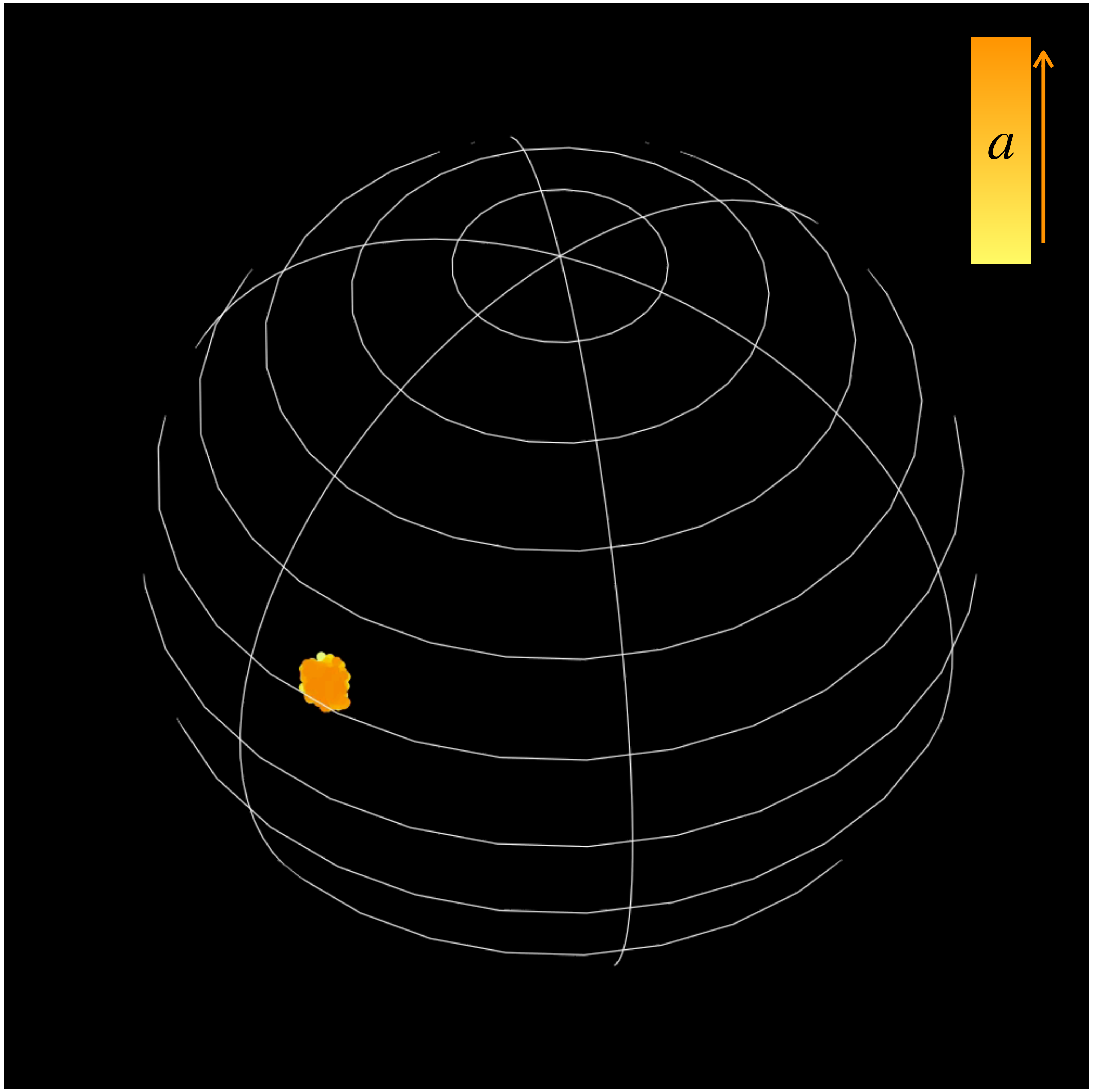
# Vector Resonant Relaxation can affect the disc-stars




How long should these stars stay ``**neighbors**''?

Are they **young enough**?

# Is the stellar disc the imprint from ICs?




+ How ``**neighbors**'' get separated

$$\frac{\mathrm{d}\hat{\mathbf{L}}_i}{\mathrm{d}t} = \eta(a_i, \hat{\mathbf{L}}_i, t)$$

+ Two joint sources of **separation**

- **Parametric** separation

$$a_i \neq a_j$$

- **Angular** separation

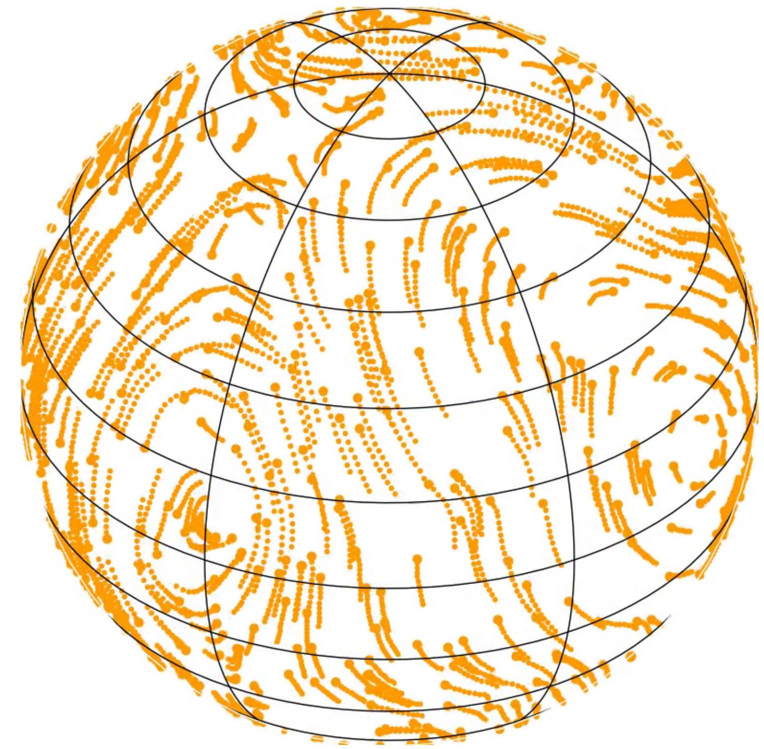
$$\hat{\mathbf{L}}_i \neq \hat{\mathbf{L}}_j$$

# VRR around SgrA*

**Model**

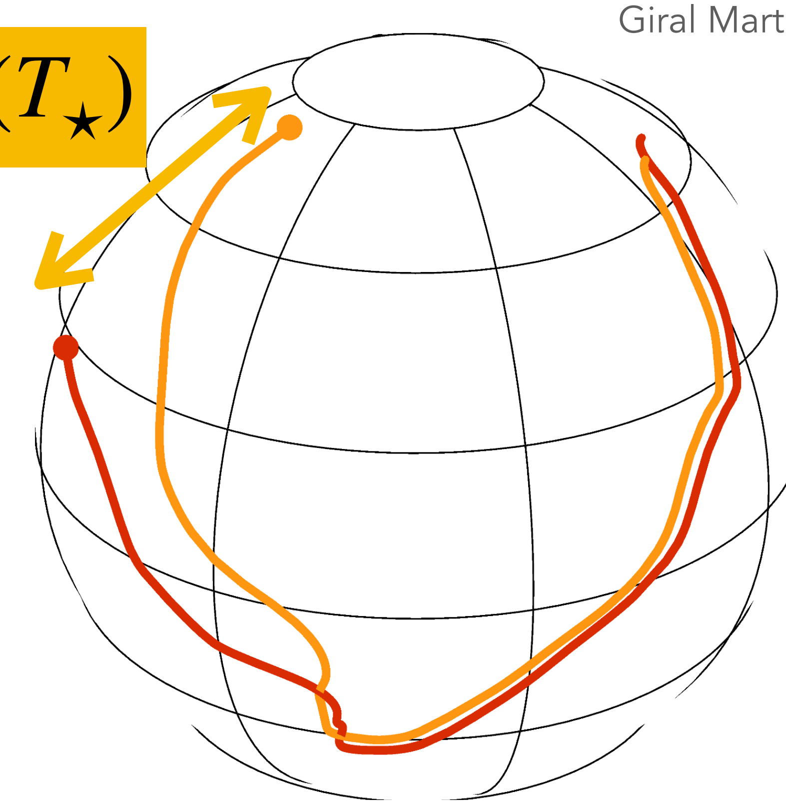
- Old stars
*(unresolved but relaxed)*
- **IMBHs**
*(strong source of Poisson noise)*
- S-stars disc ICs
*(initial angular dispersion)*

Kinetic theory →

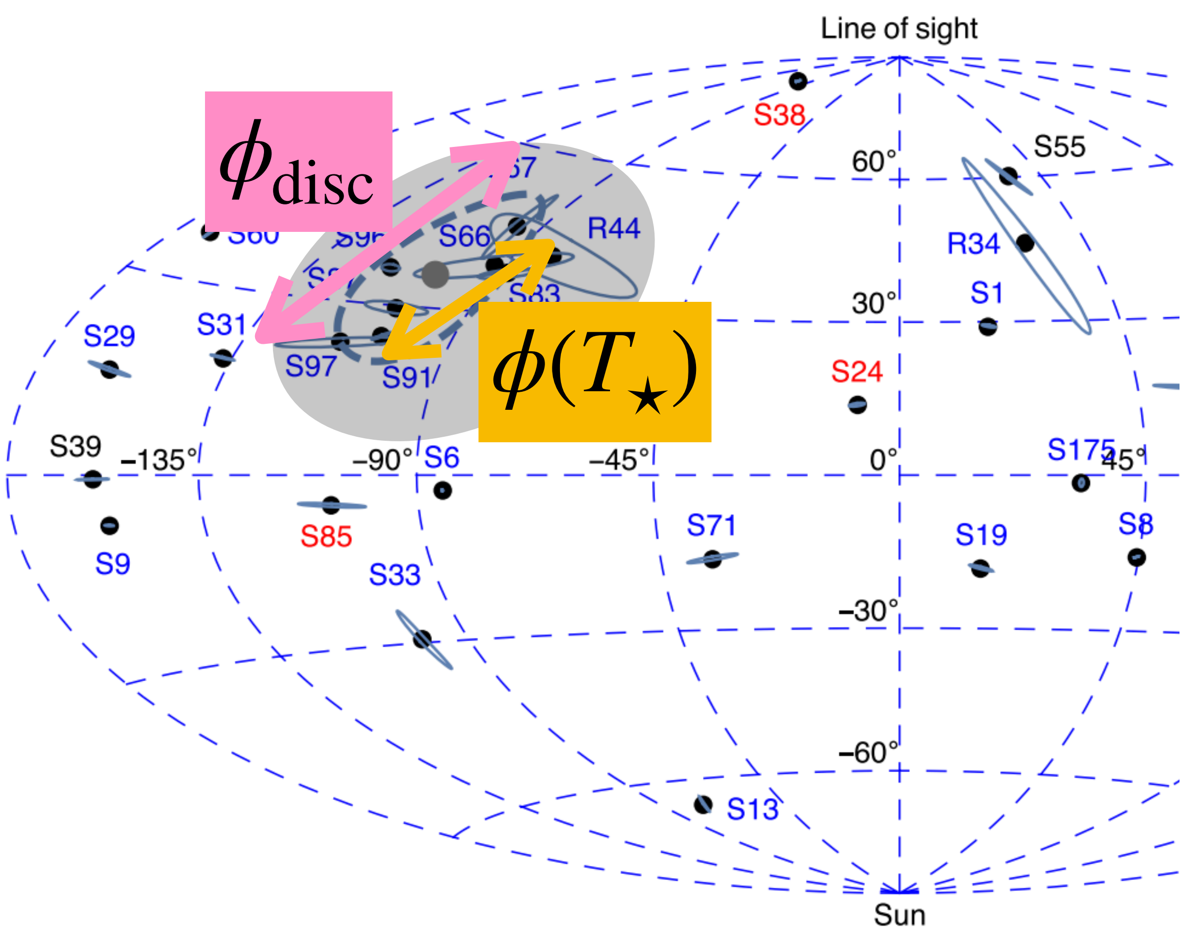


↕ Dilution

Giral Martinez+(2020)

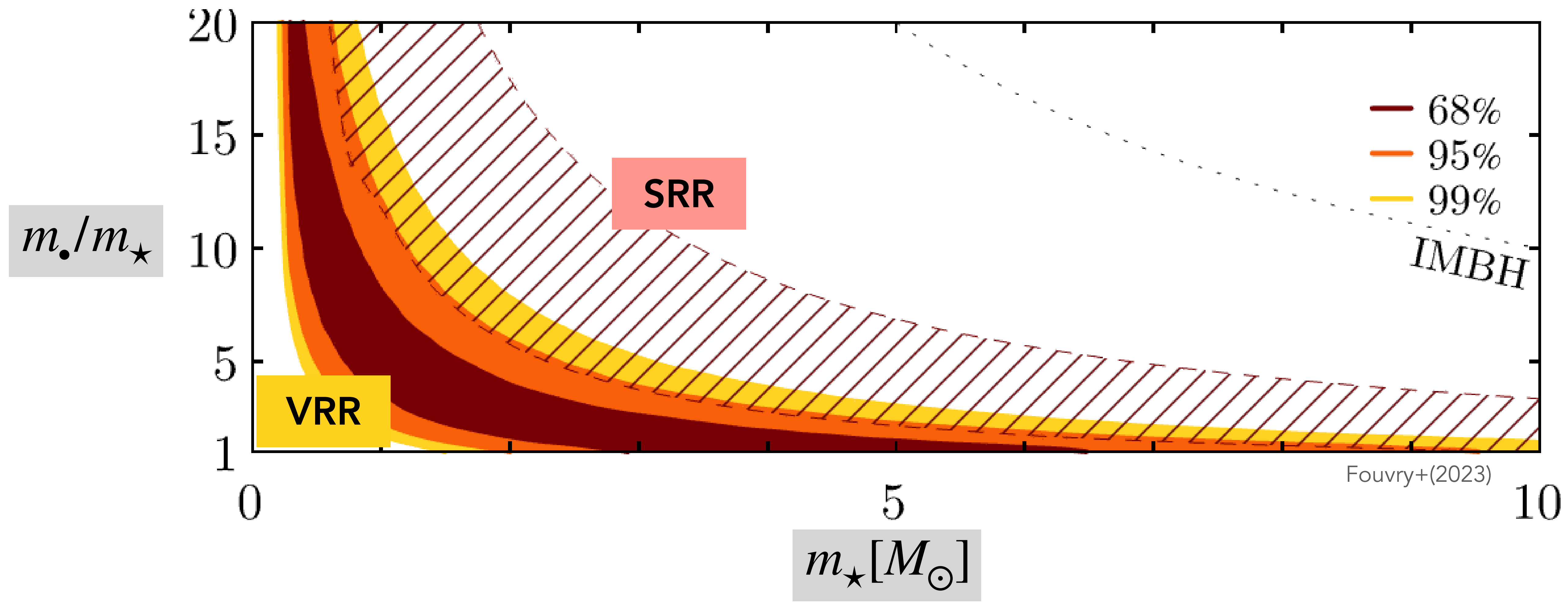



Likelihood ↔



# Constraining IMBHs with VRR

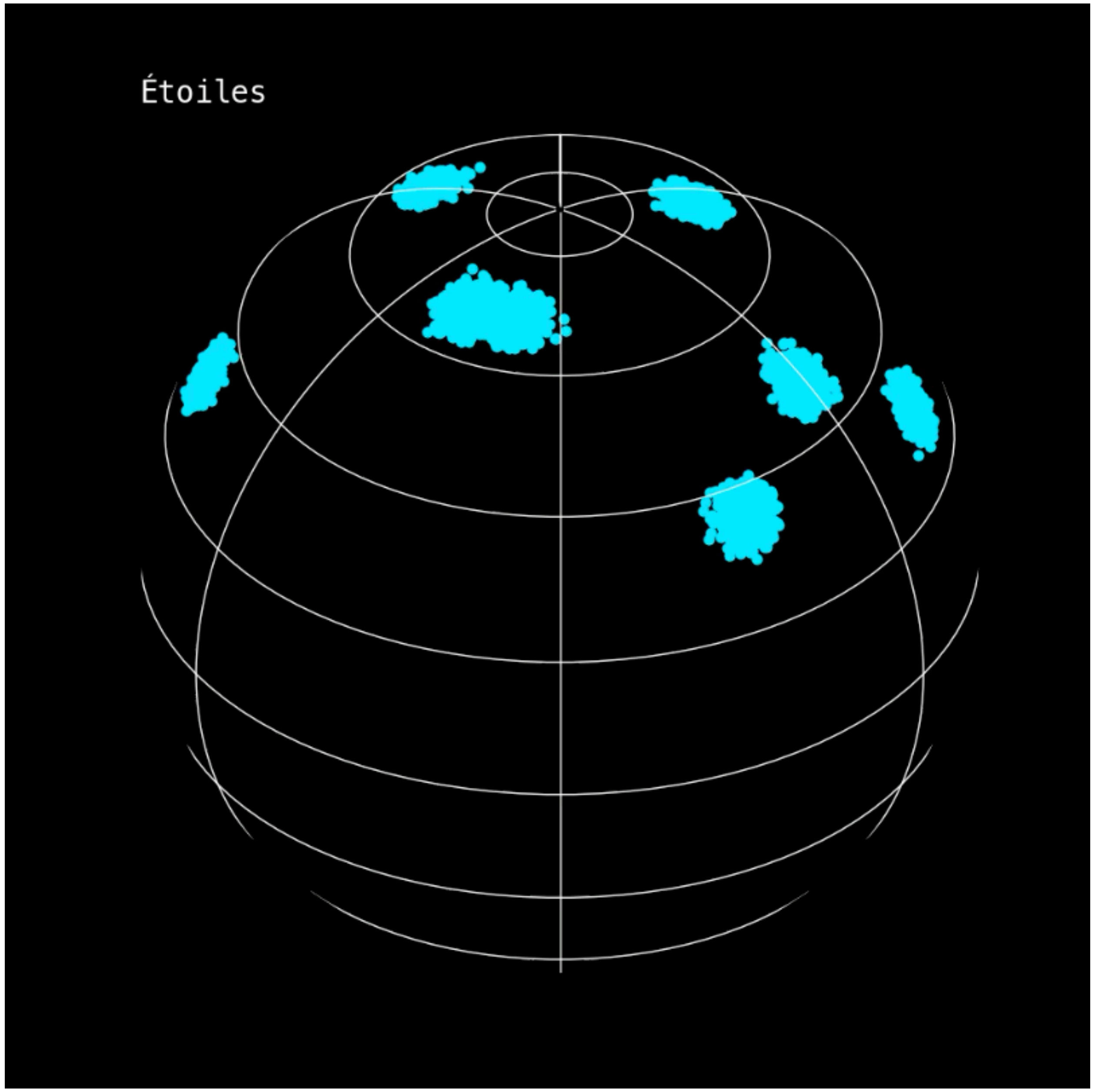
2-population model (stars+IMBHs)



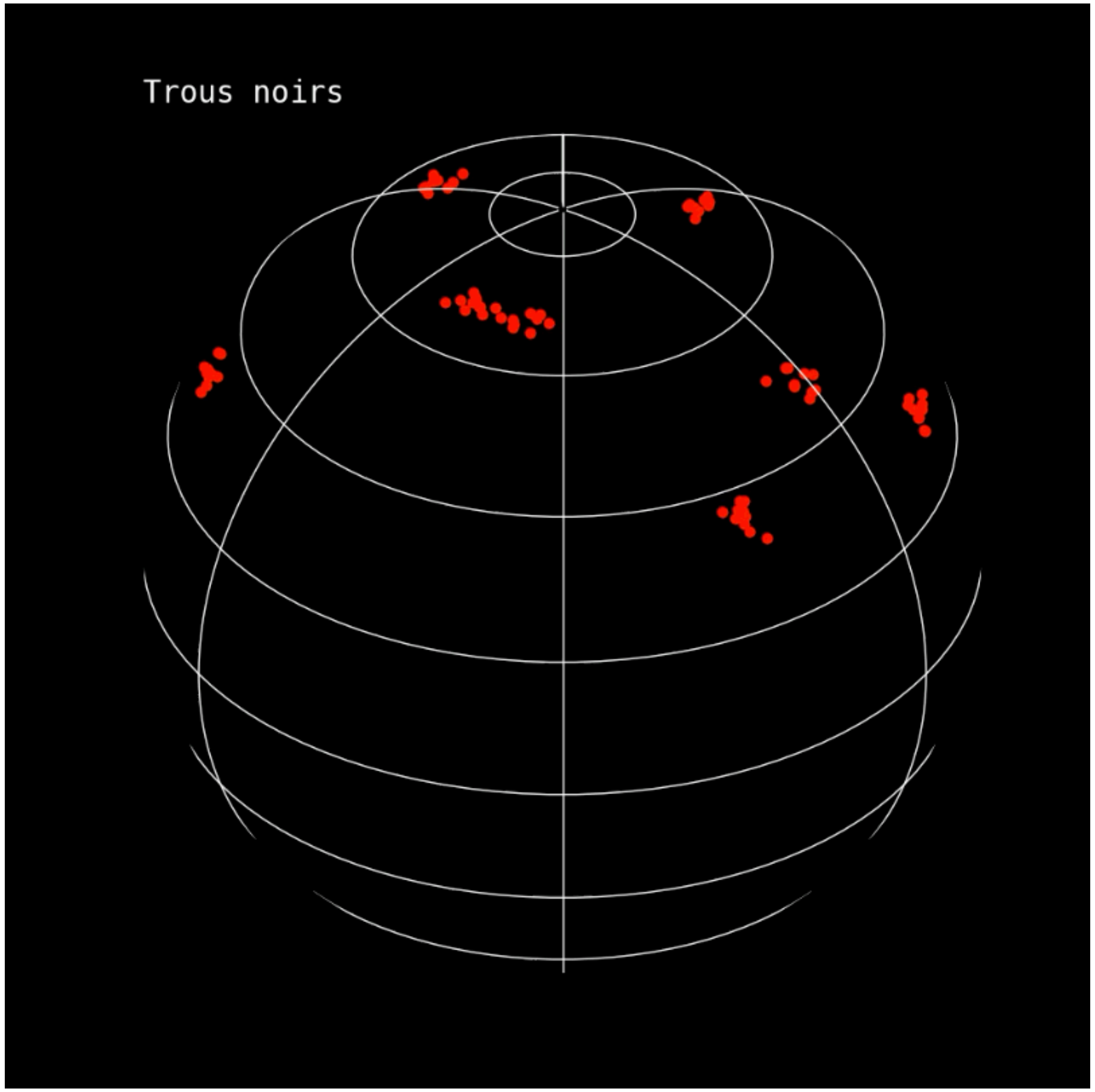

IMBHs population hard to reconcile with the **disc's survival**

# A spontaneous disc?

Stars




Intermediate mass black holes

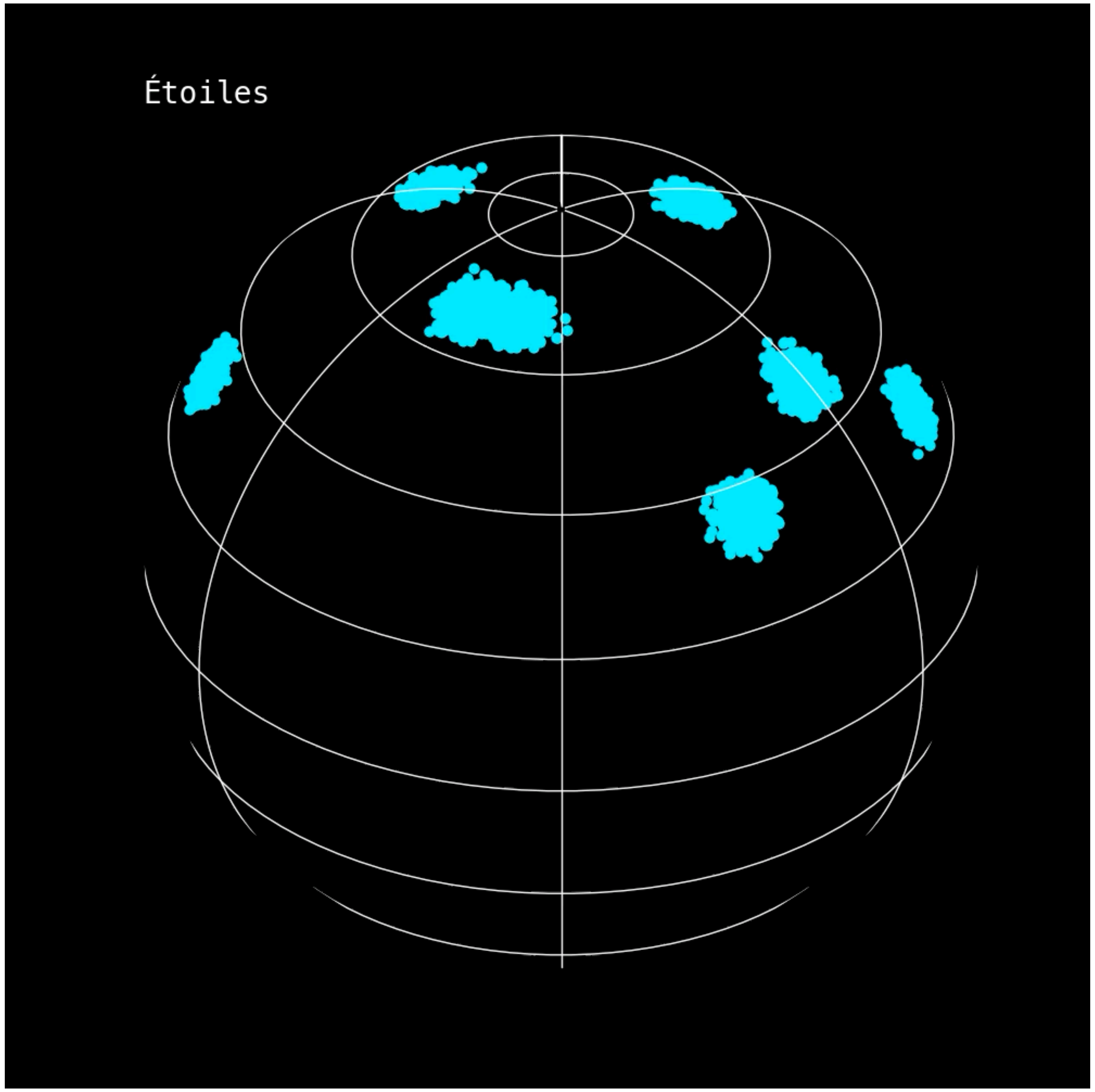


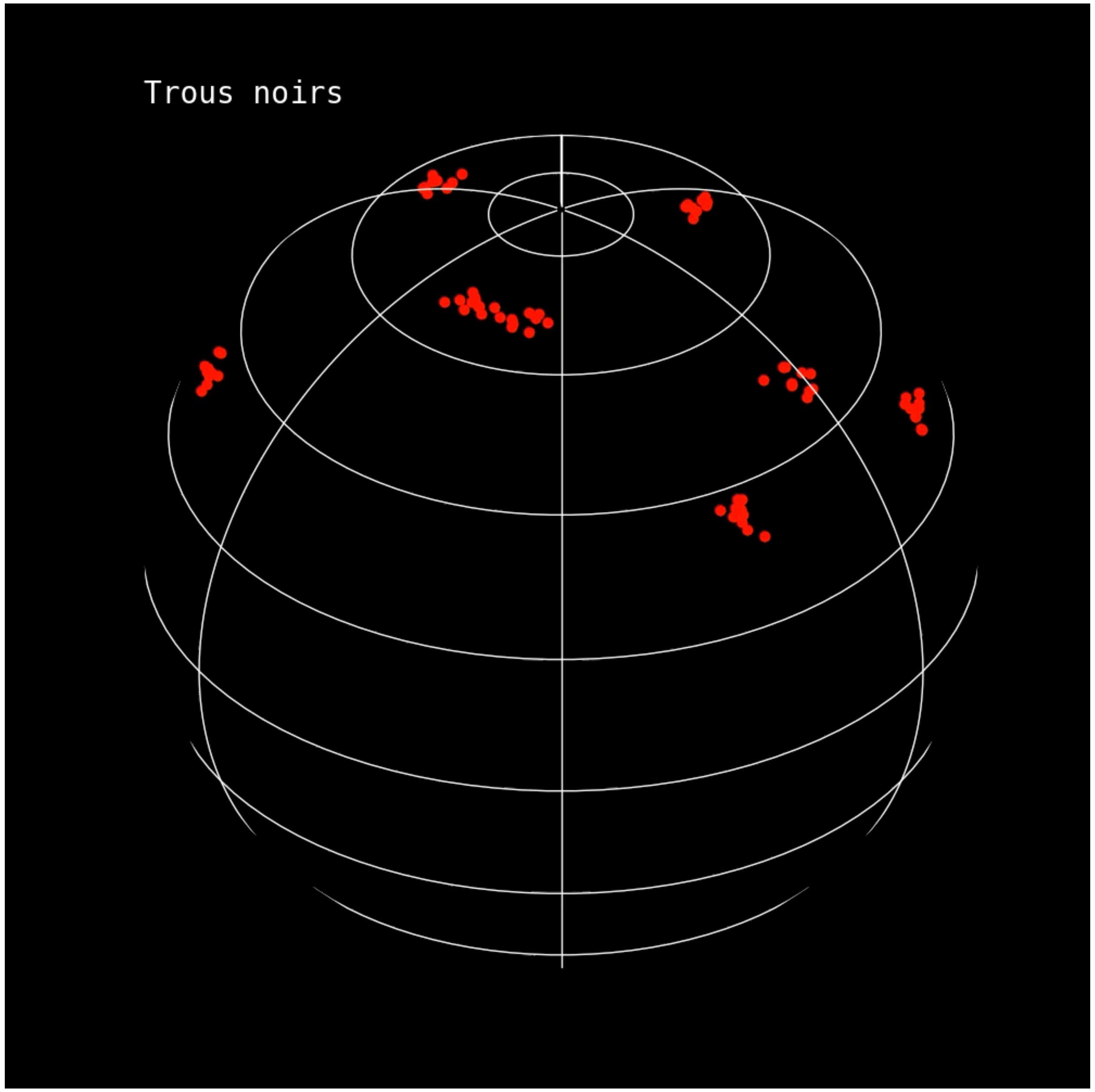

**Anisotropic distribution** from gas infall

# A spontaneous disc?

Stars

Intermediate mass black holes



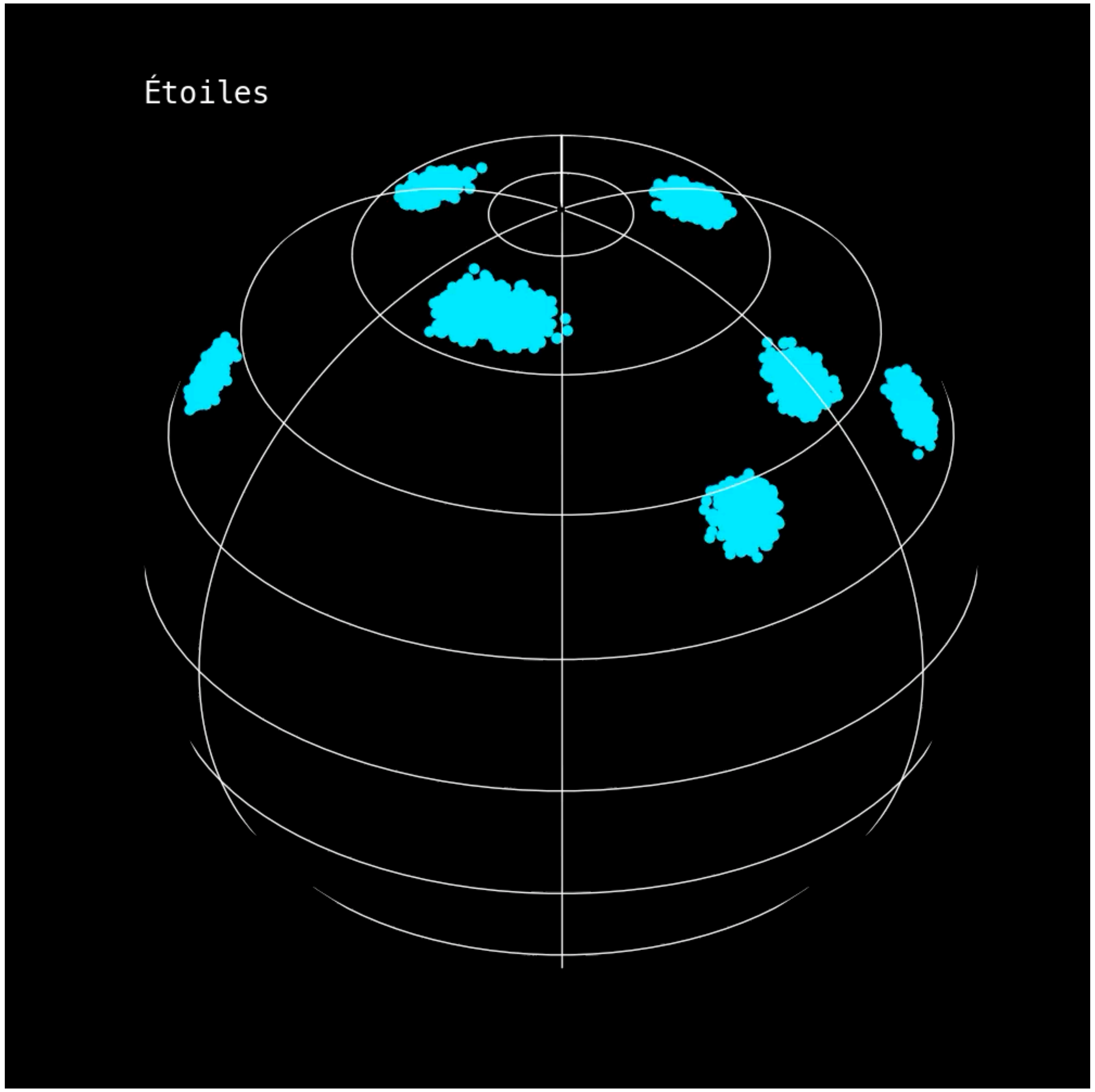



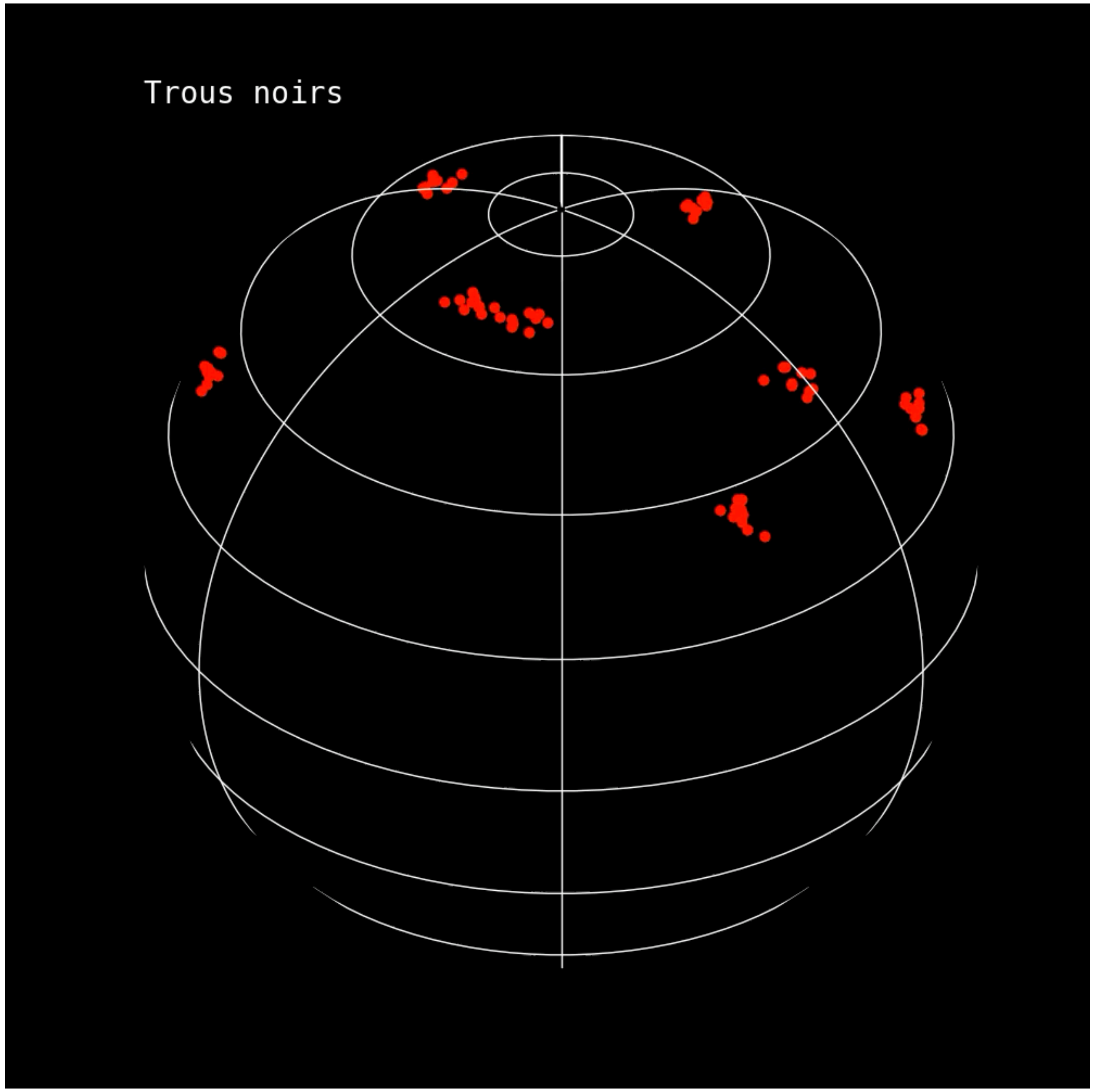

Relaxation on **short timescales**

# A spontaneous disc?

Stars

Intermediate mass black holes

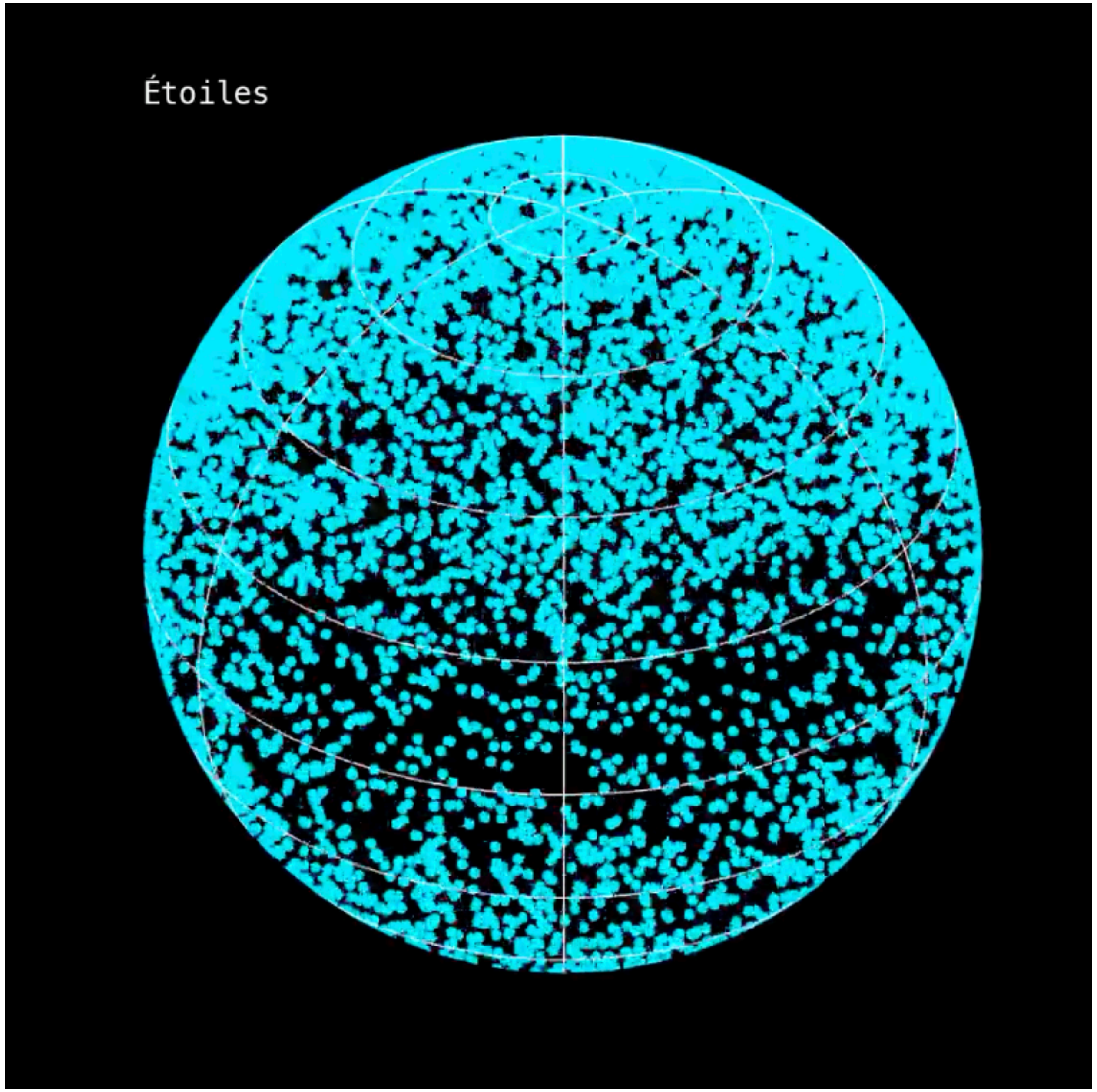


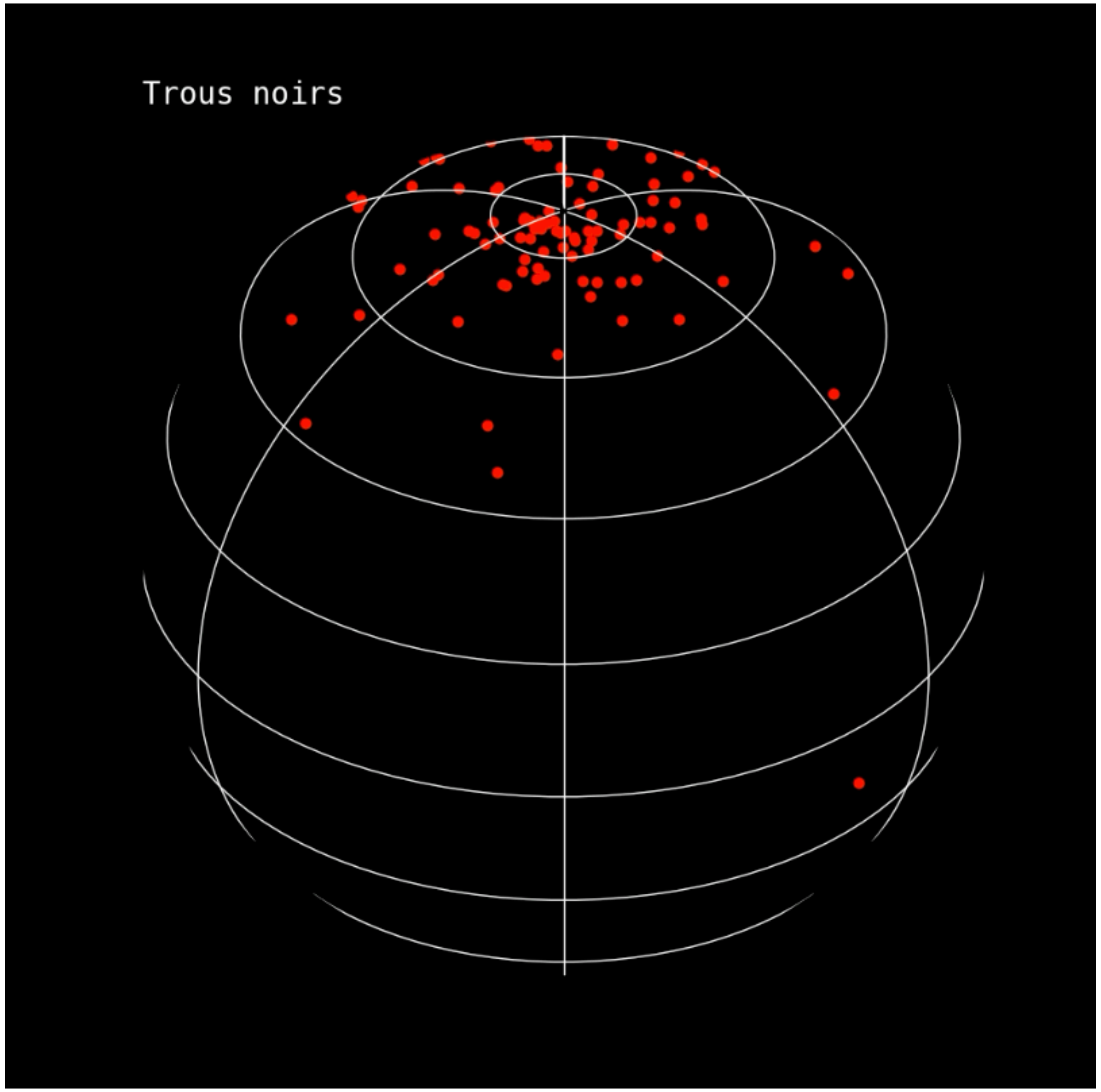

Relaxation on **long timescales**

# A spontaneous disc?

Stars

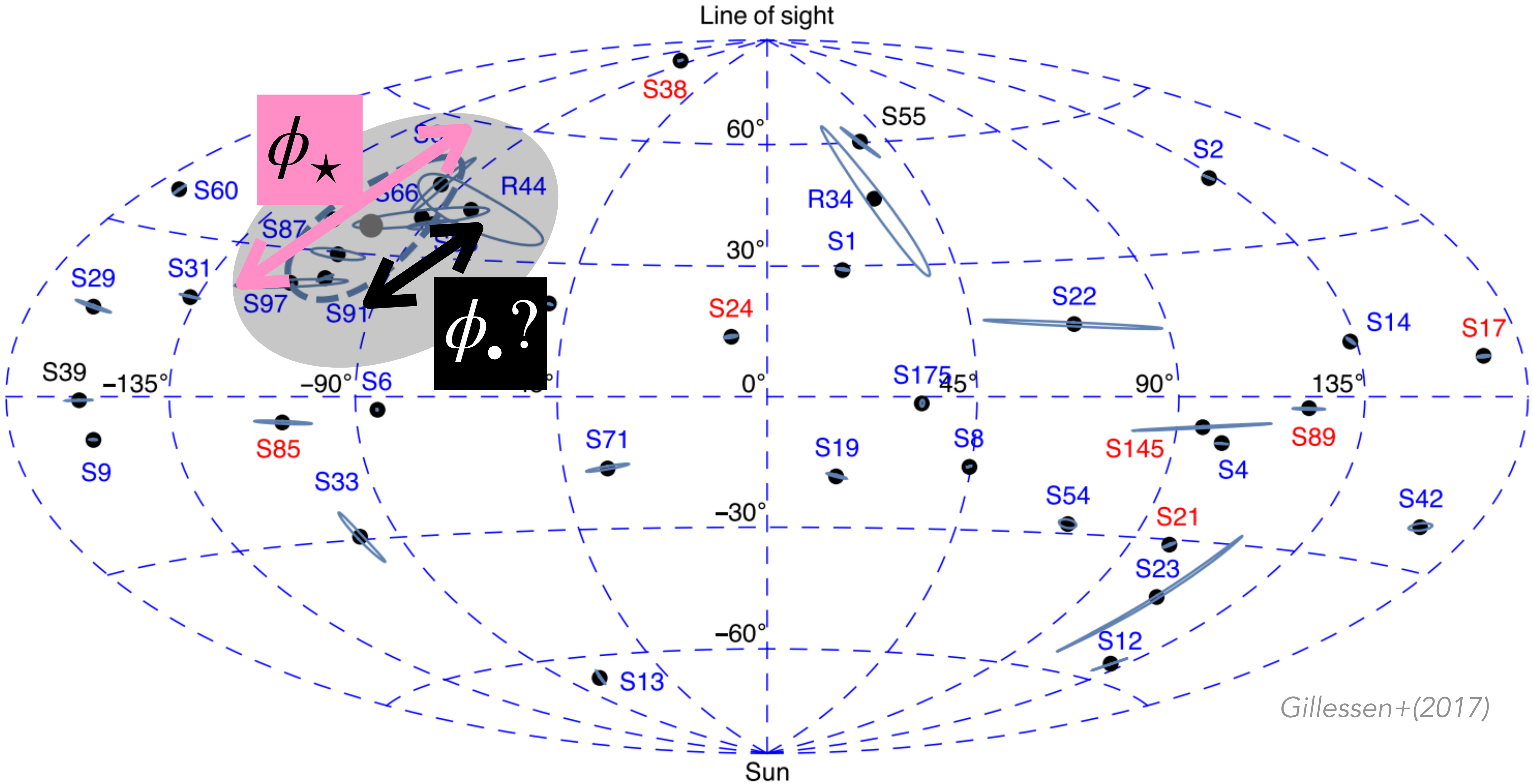



Intermediate mass black holes




**Anisotropic** equilibria

# A disc of IMBHs?

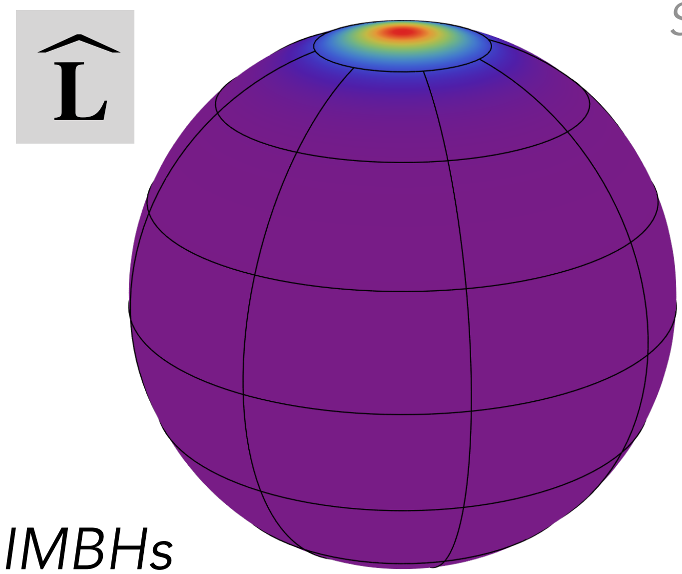



Are there aligned IMBHs around SgrA*?

# Next steps — Dynamical modelling

## Anisotropic orientations

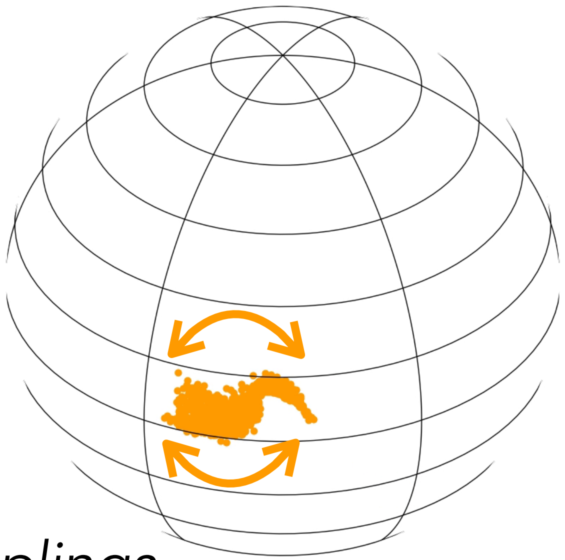
Szolgyen+(2018)




*Disc of IMBHs*

## Self-gravity

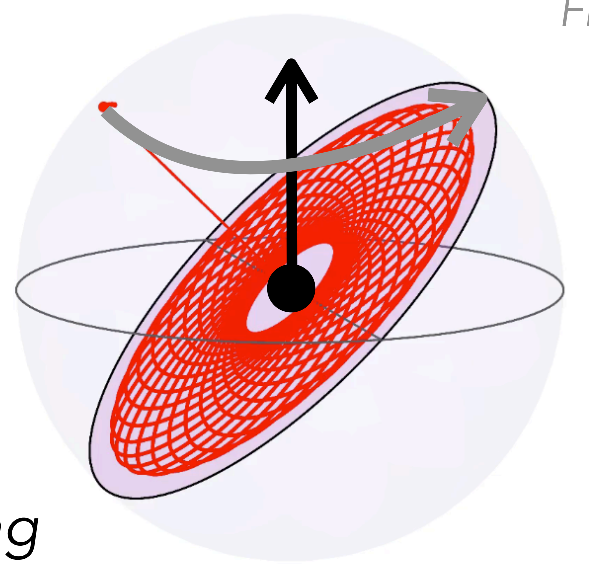
Kocsis+(2011)



*Pairwise couplings*

## Lense-Thirring

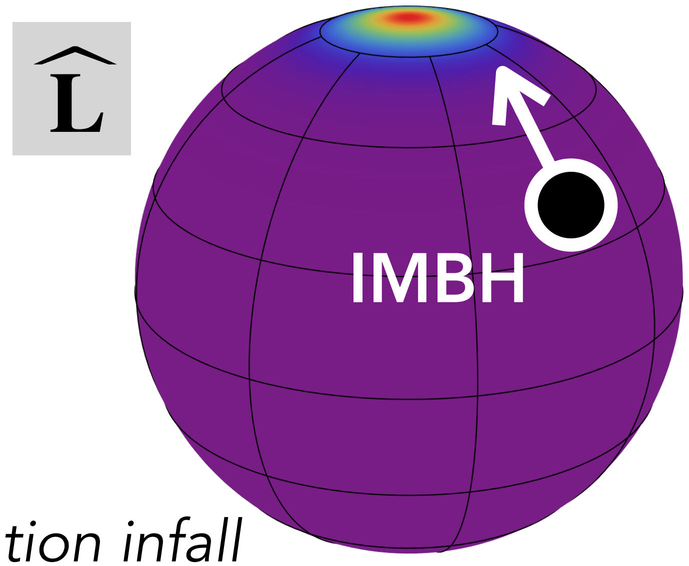
Fragione+(2022)



*Phase mixing*

## Dynamical Friction

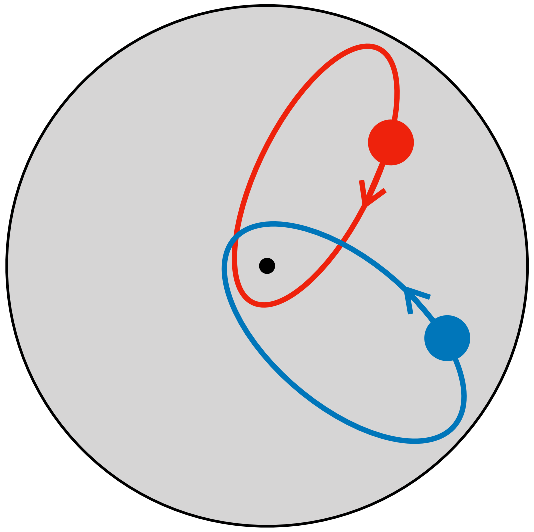
Ginat+(2023)



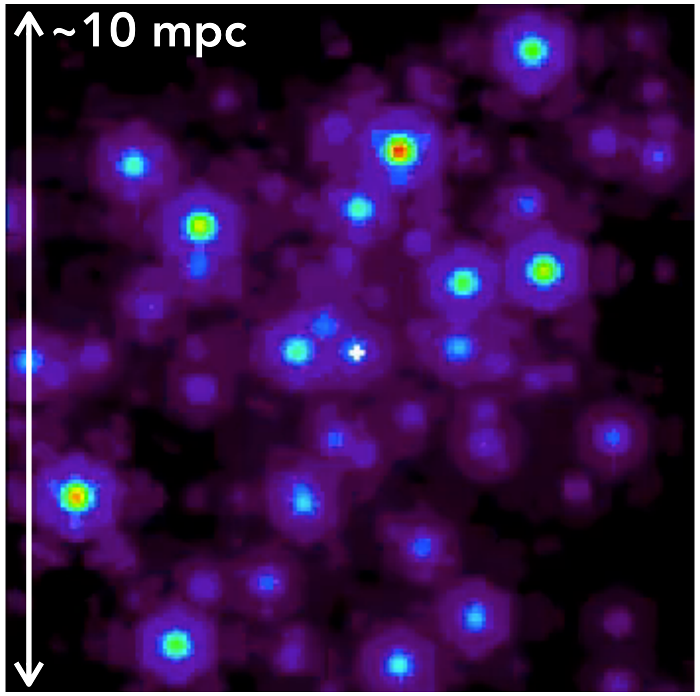

*Orientation infall*

# Next steps — Observations

New stellar orbits



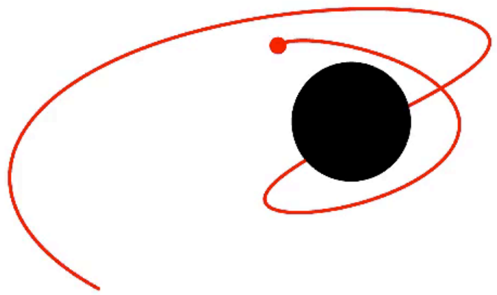
TMT and ELT



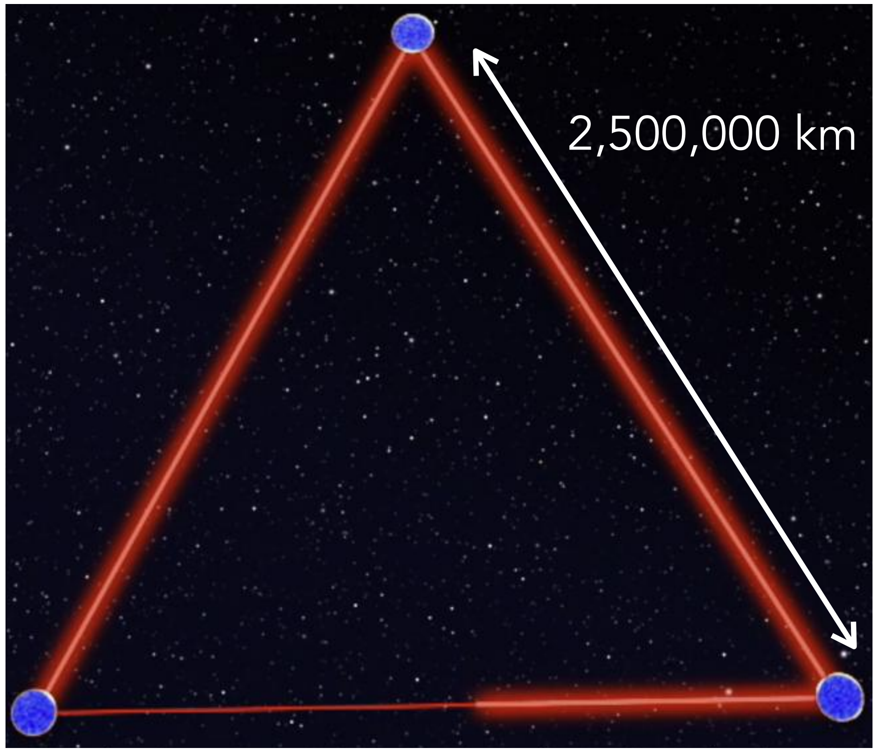

UCLA

Expected observations

Infall of **compact objects**



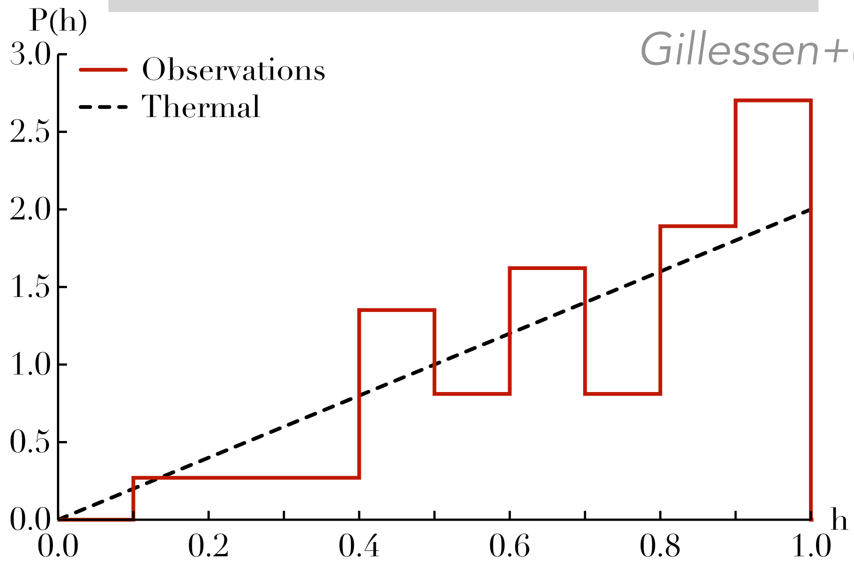
LISA spatial interferometer



# Next steps — SgrA* & Observations

## SRR & Eccentricity

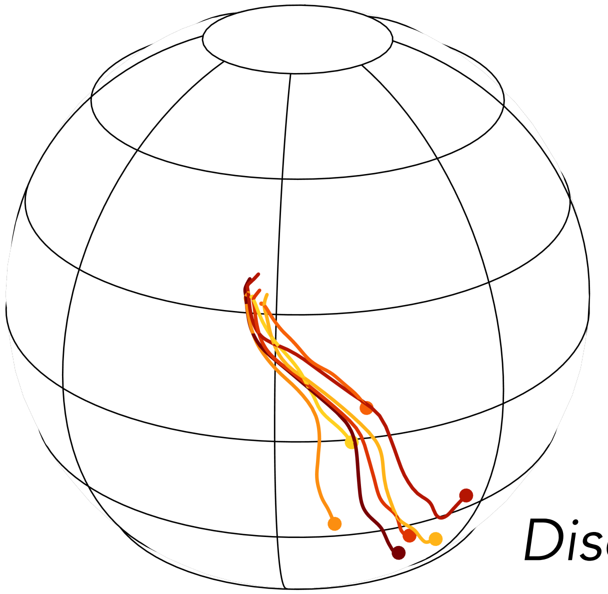
Gillessen+(2017)




*Eccentricity thermalisation*

## VRR & Stellar Discs

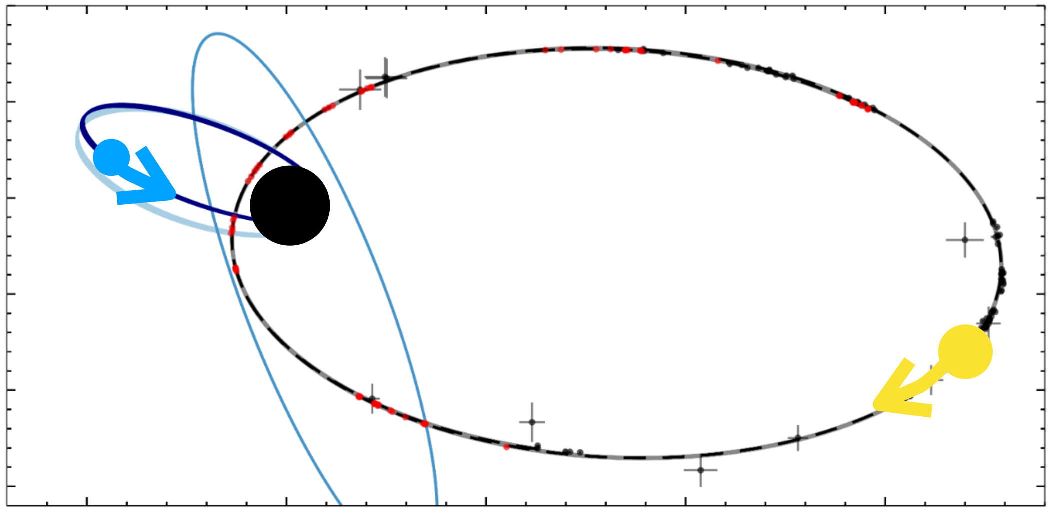
*VLT, Keck*



*Disc dilution*

## S2's kinematics

*Gravity+(2023)*
*Will+(2023)*



*Local perturbations?*

## Future observations

$$P = P(a, h, \widehat{\mathbf{h}}, T)$$

*Full PDF statistics*

# 4-body problem for VRR