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Stellar Dynamics in Galactic Nuclei

Jean-Baptiste Fouvry

in collaboration with K. Tep, J. Giral Martinez, N. Magnan
C. Pichon, P.-H. Chavanis, W. Dehnen, S. Tremaine, B. Bar-Or

TUG meeting, ENS Paris
October 2023

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and constraining IMBHs around SgrA*

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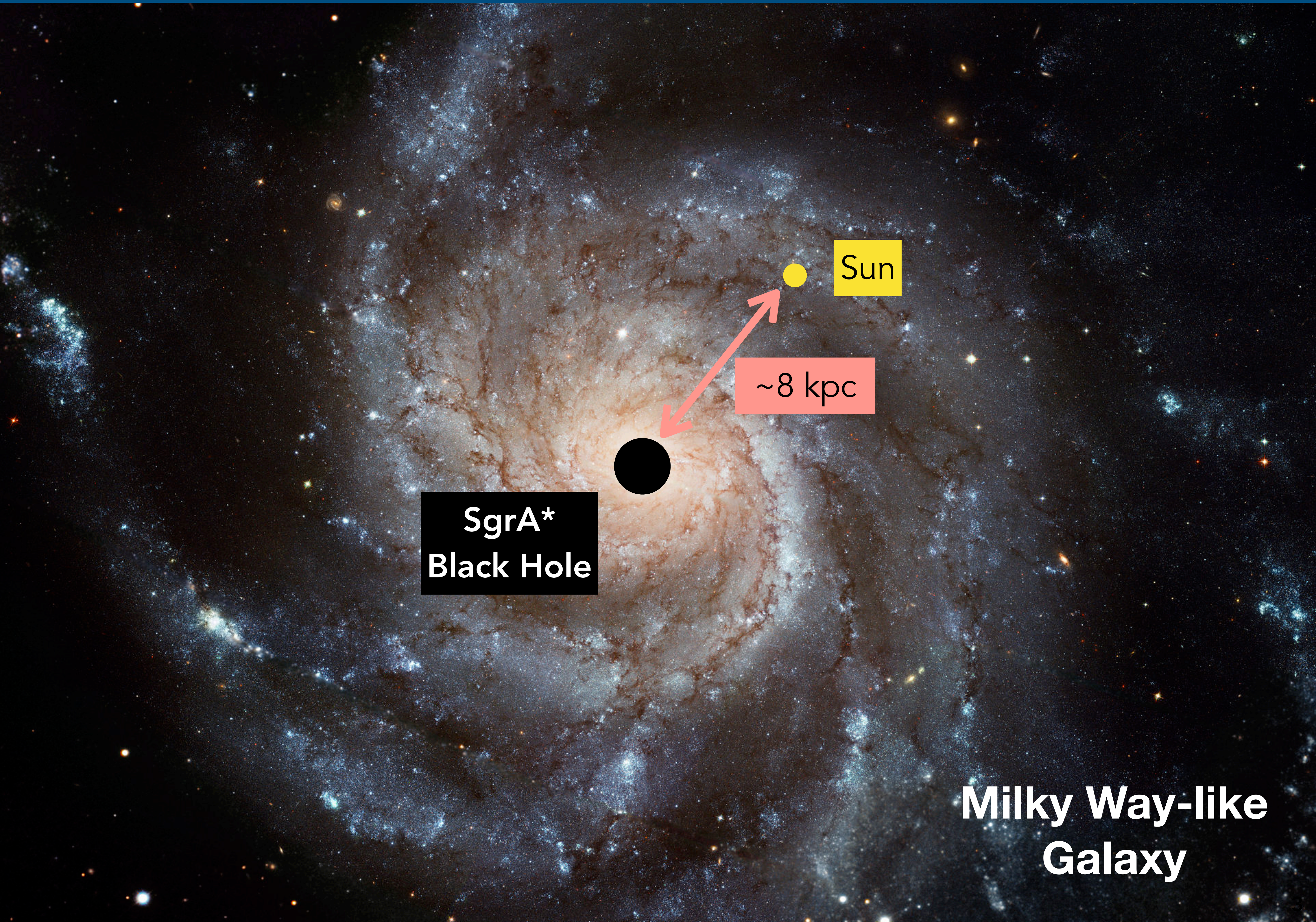
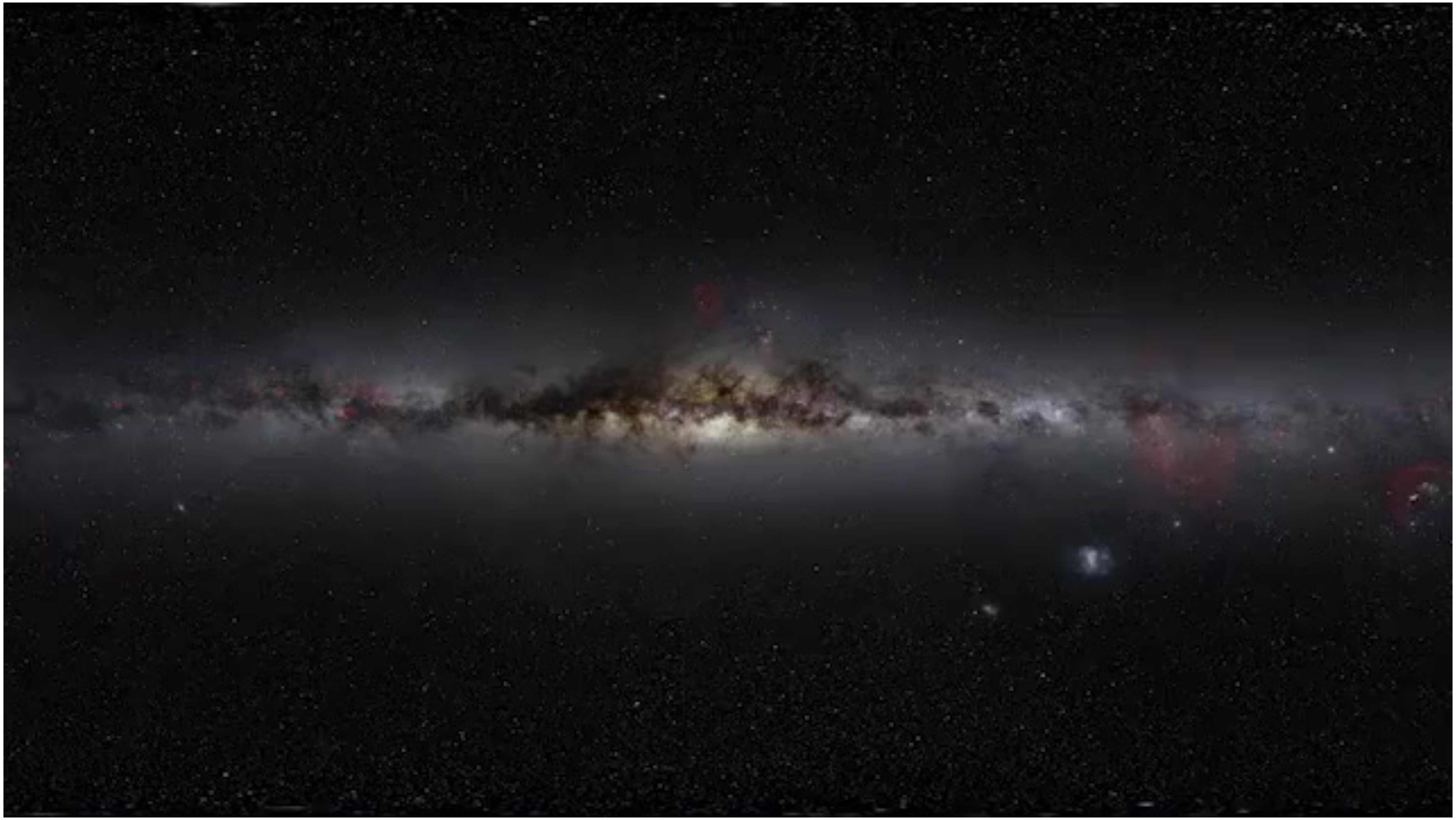

Sun
~8 kpc
SgrA*
Black Hole
Milky Way-like
Galaxy

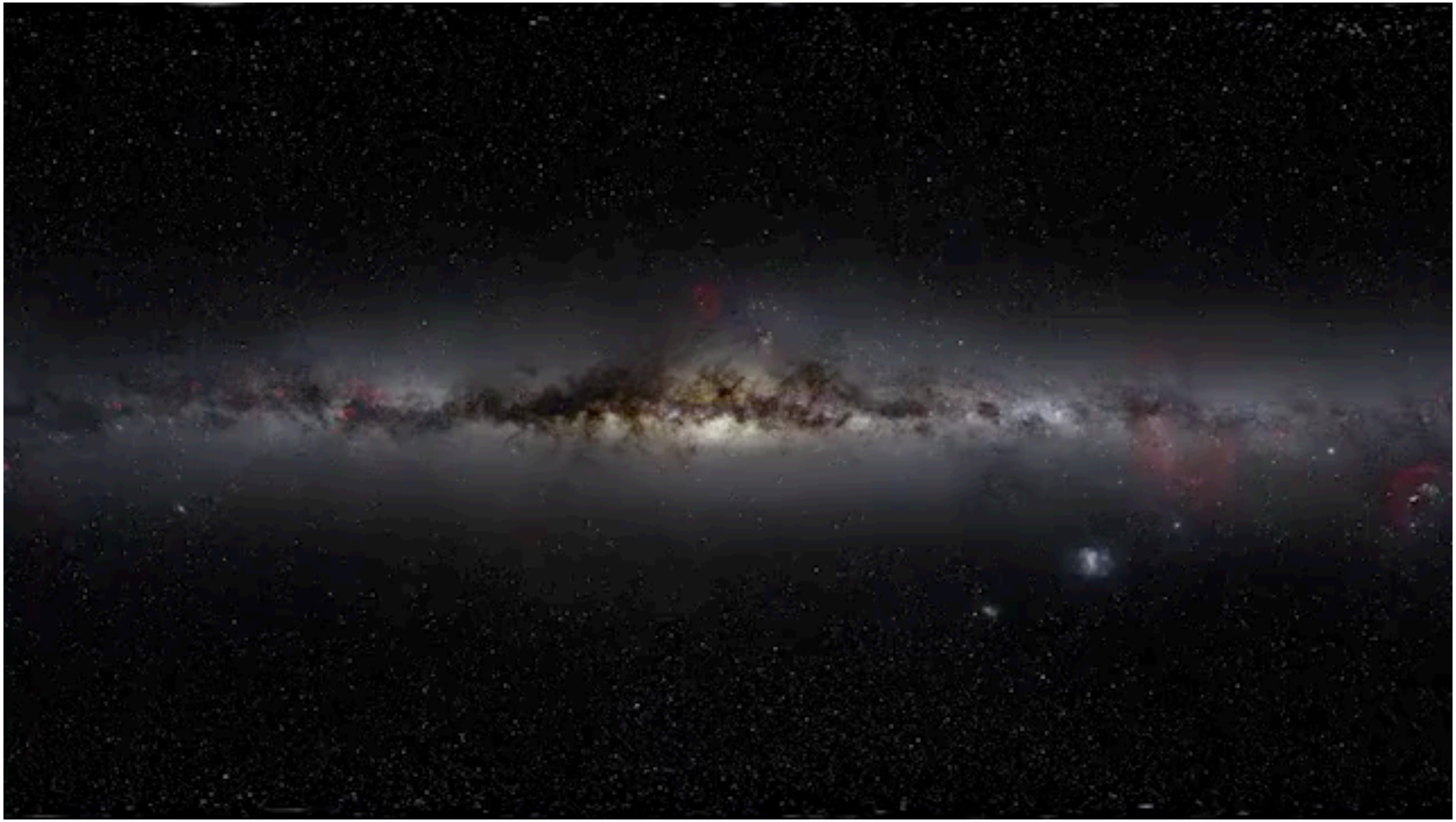
SgrA*, our Galactic Centre



ESO

Milky Way (10^{17} km)

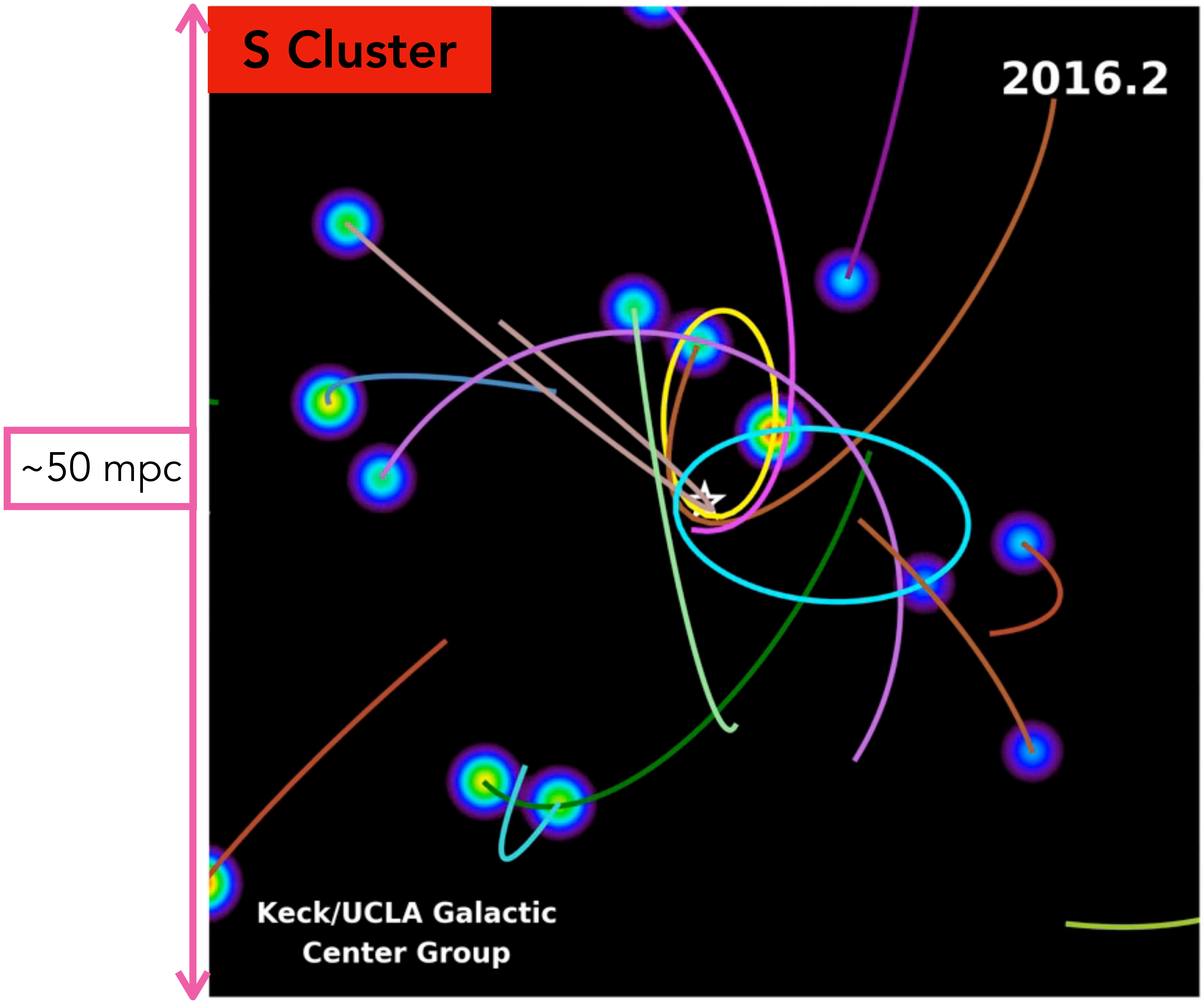
SgrA*, our Galactic Centre



ESO

Zoom (x10,000,000)

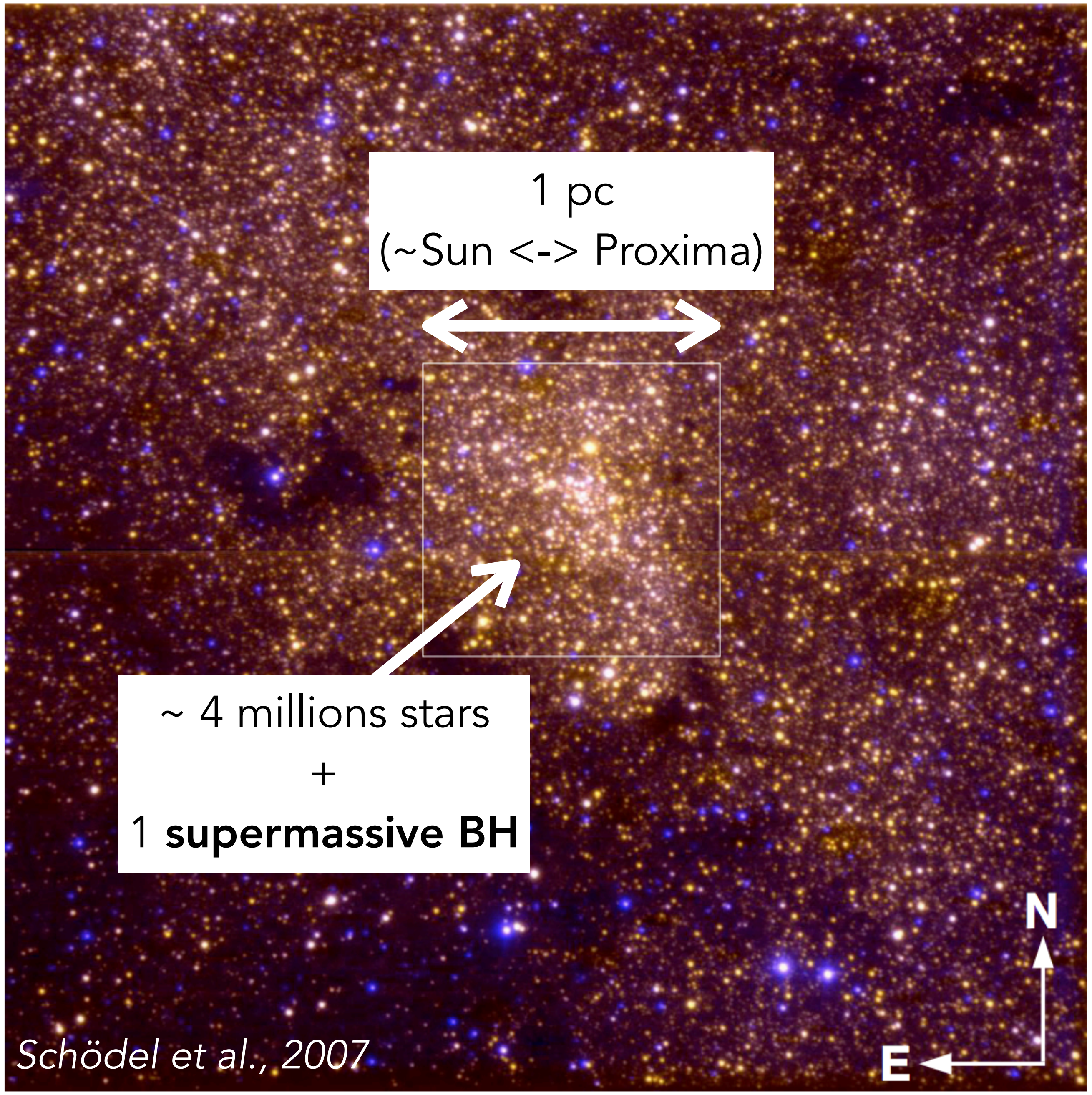
SgrA*, at the heart of the Milky Way



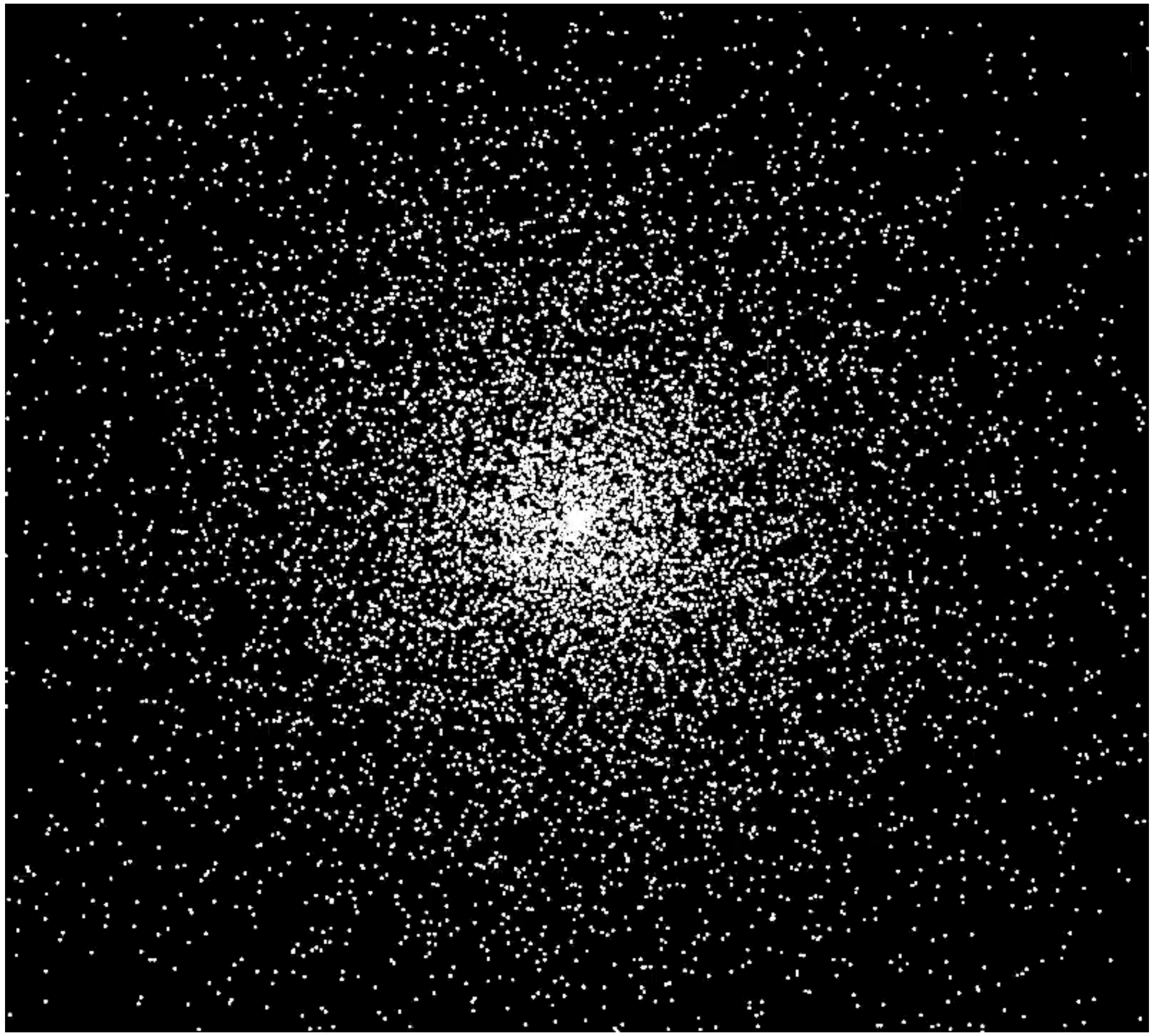
What is the diet of **supermassive black holes**?

Extremely dense environment

Behaves like a **gas of stars**



VLT observations

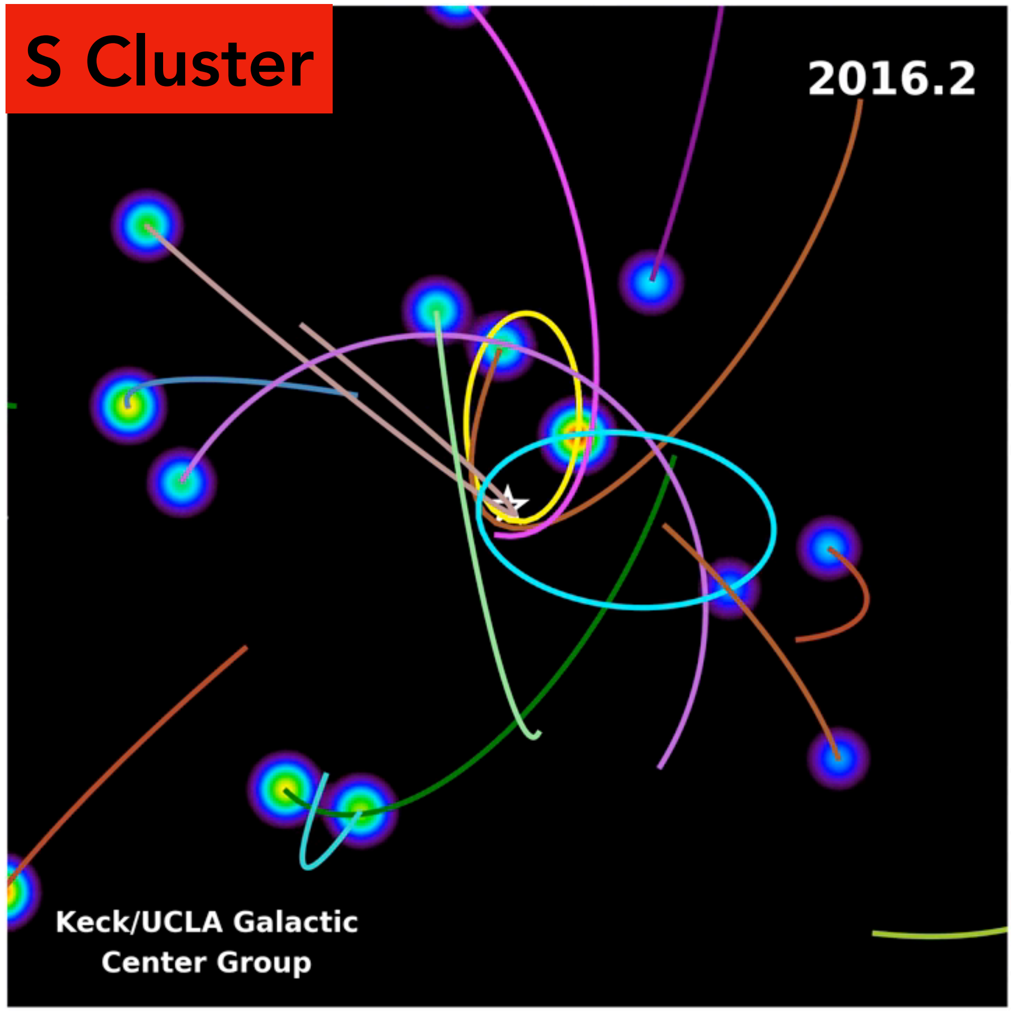


Numerical simulations

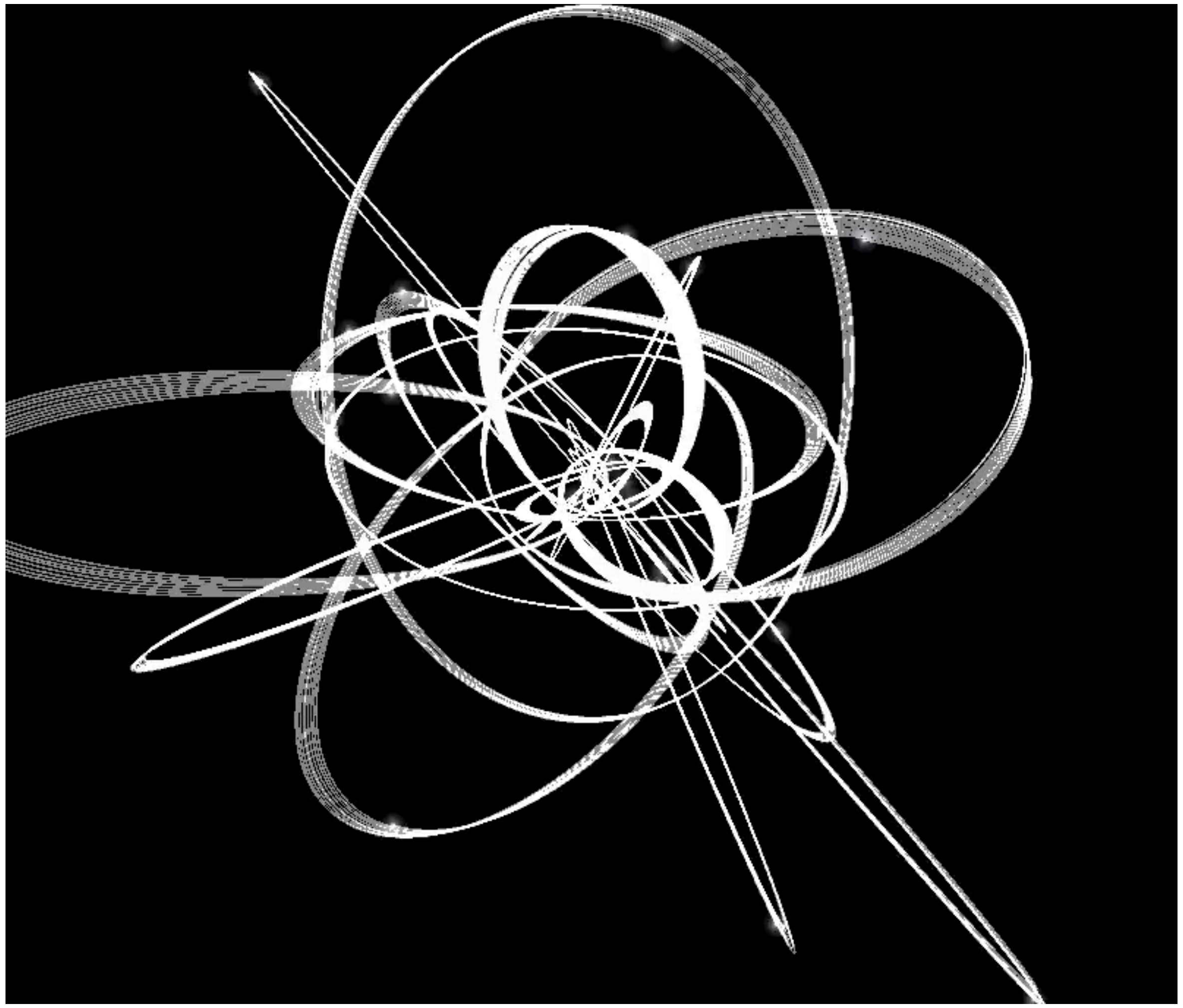
A simple dynamics?

The central BH is **supermassive**

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



Keck observations

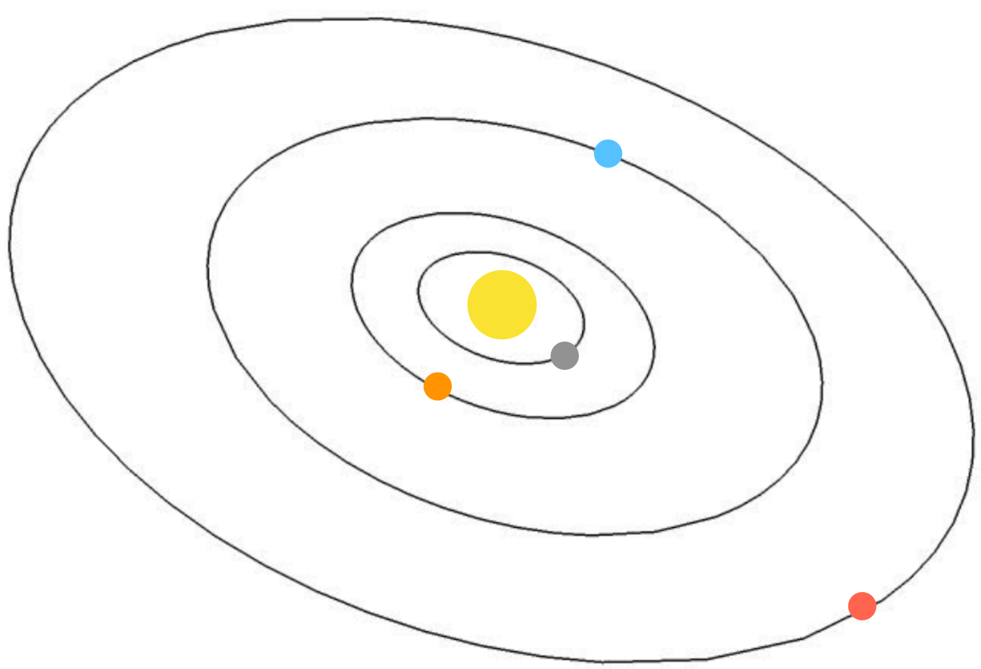


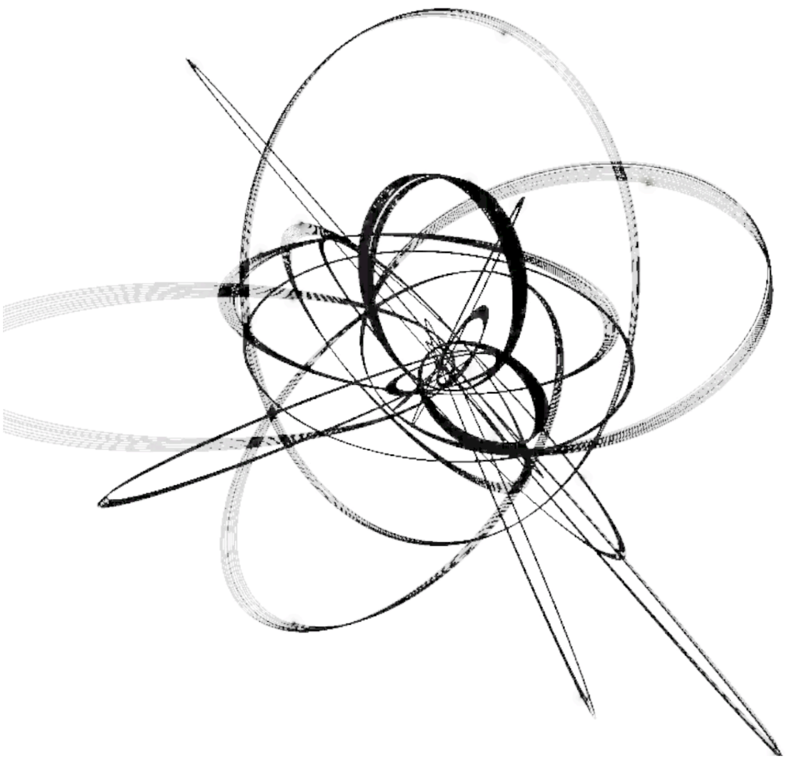
Numerical simulations

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

Keplerian systems

Solar system	Galactic centre

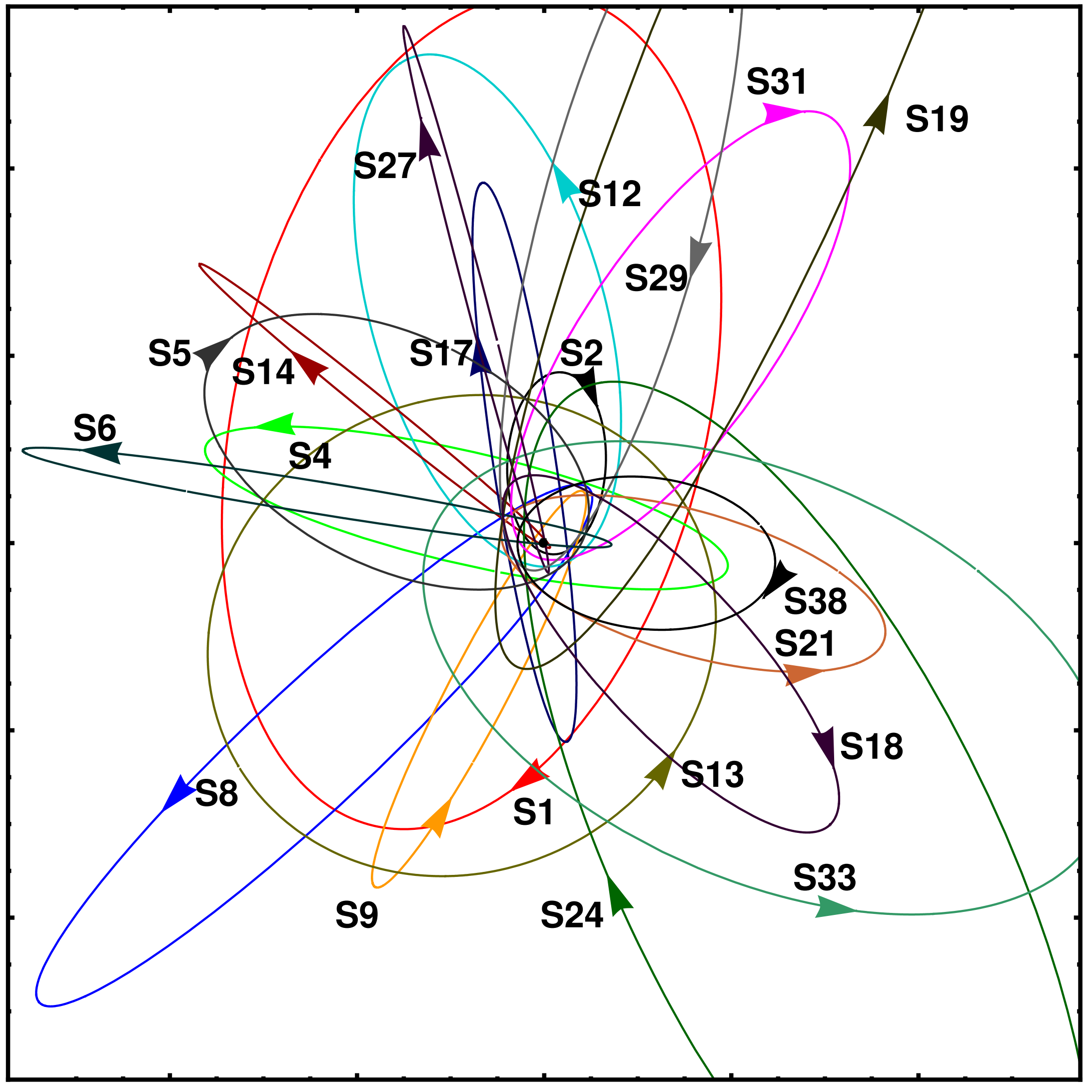




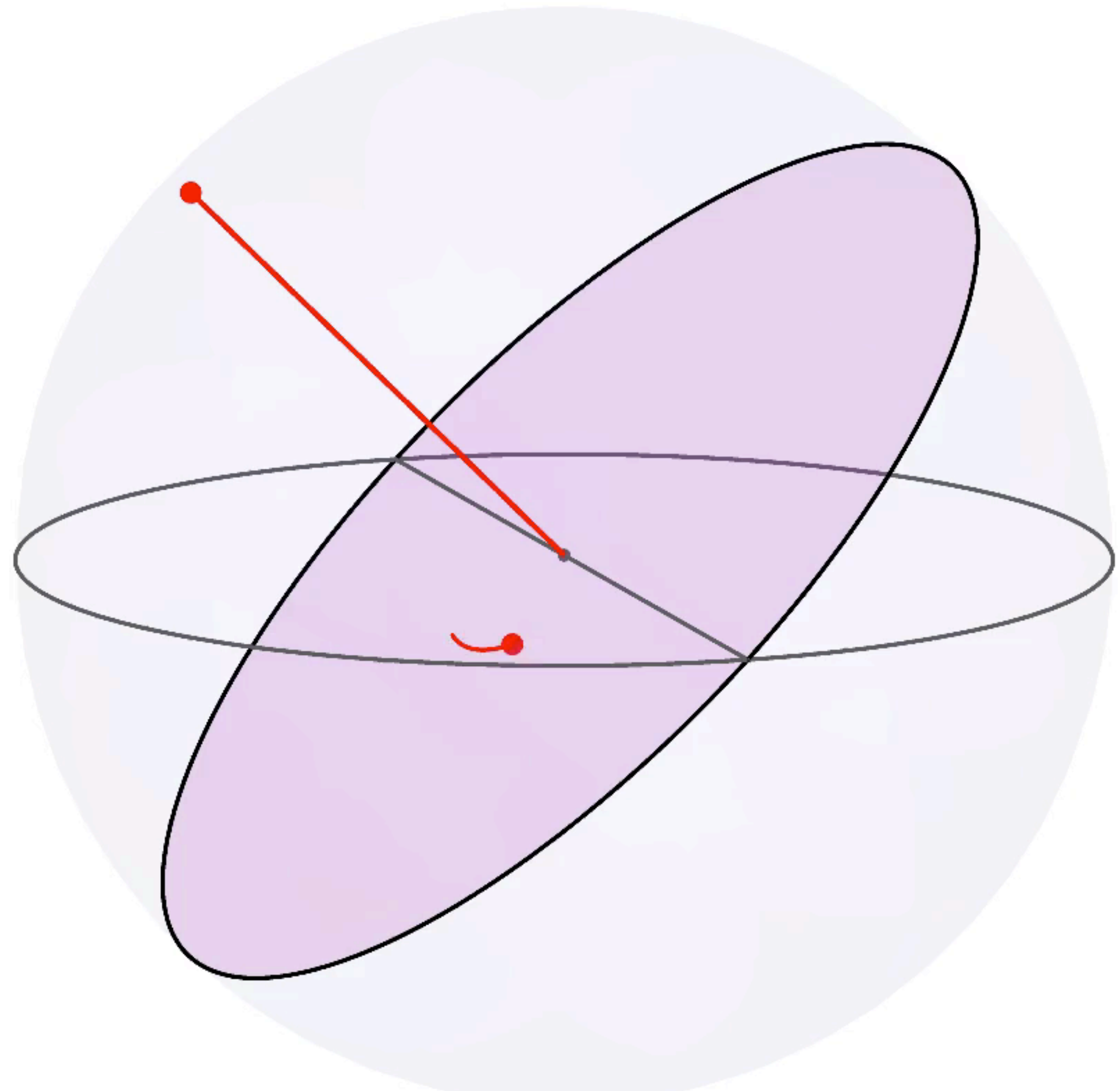
Solar system		Galactic centre
Planets	⟷ Light object	**Stars**
Sun	⟷ Heavy object	**Black hole**
$N \simeq 10$	⟷ Number of "particles"	$N \simeq 10^6$
Planar symmetry	⟷ Shape of the system	**Spherical** symmetry
Quasi-circular orbits	⟷ Shape of the orbits	**Very eccentric** orbits

Keplerian orbits

The BH dominates the stars' dynamics



Gillessen et al., 2009



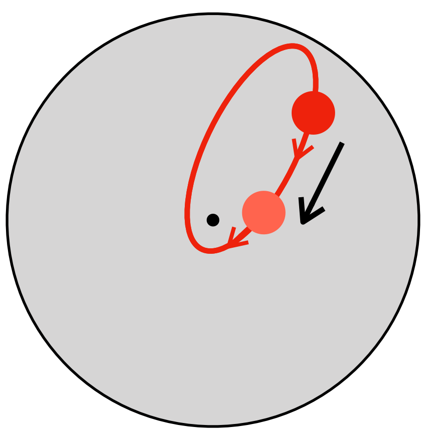
VLT observations

Typical orbit

What is an orbit?

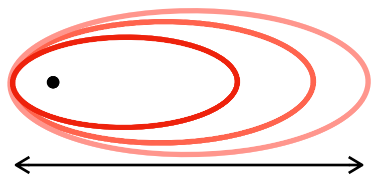
Describing an **orbit**

Position of the star

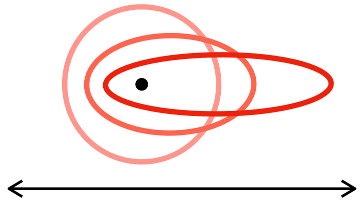


Dynamical motion

Shape of the orbit

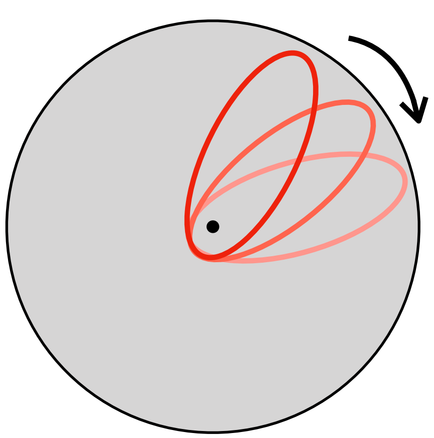


Semi-major axis



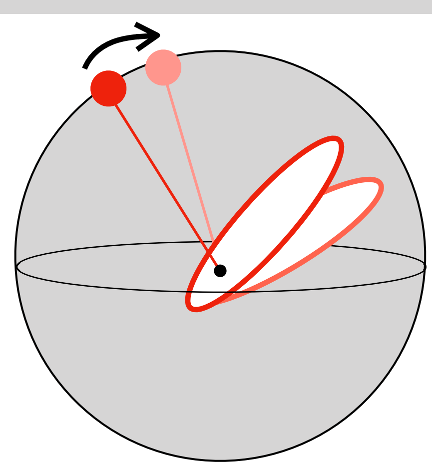
Eccentricity

Phase of the orbit

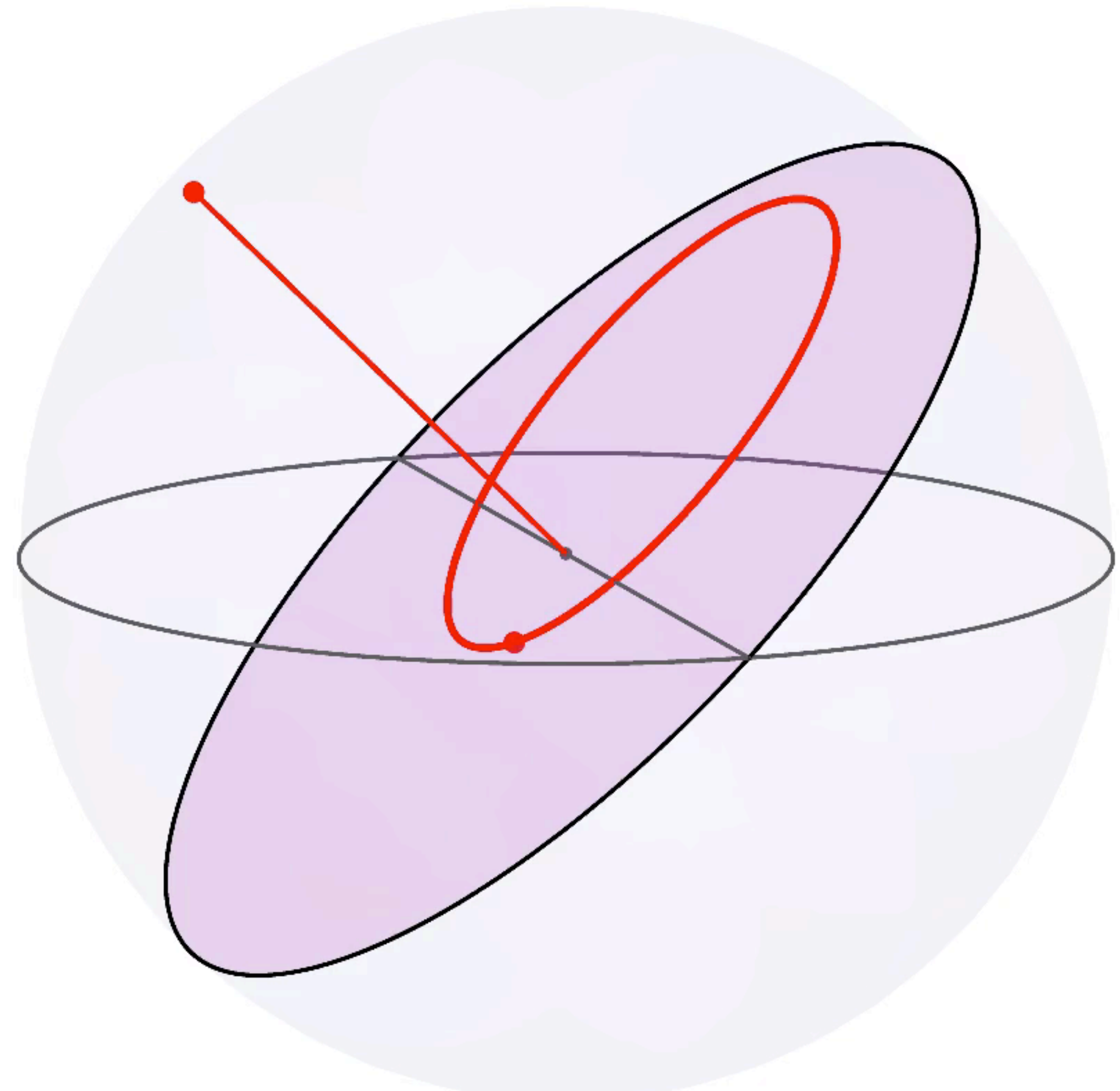


Phase of the pericentre

Orientation of the orbit



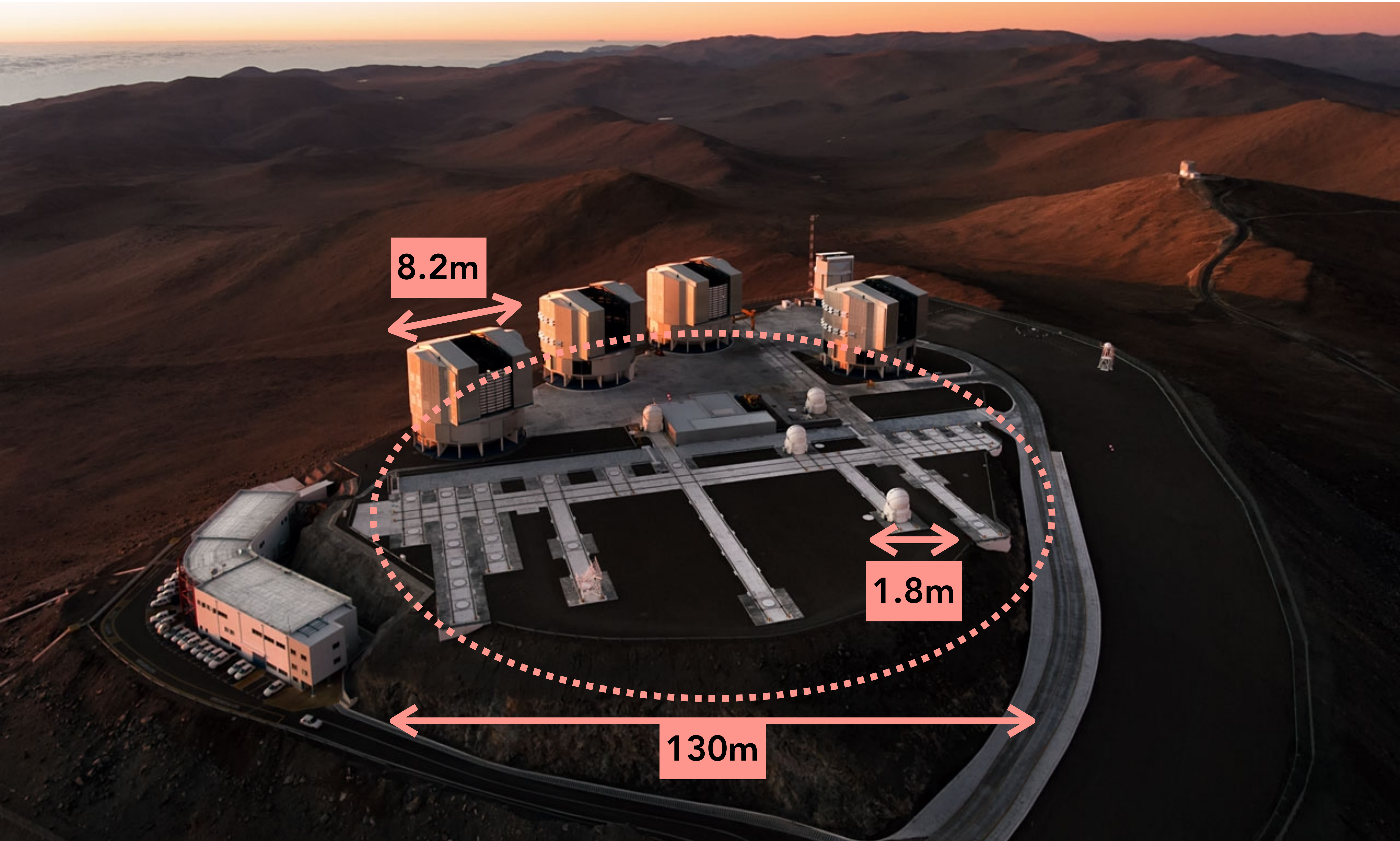
Spatial orientation



Keplerian orbit

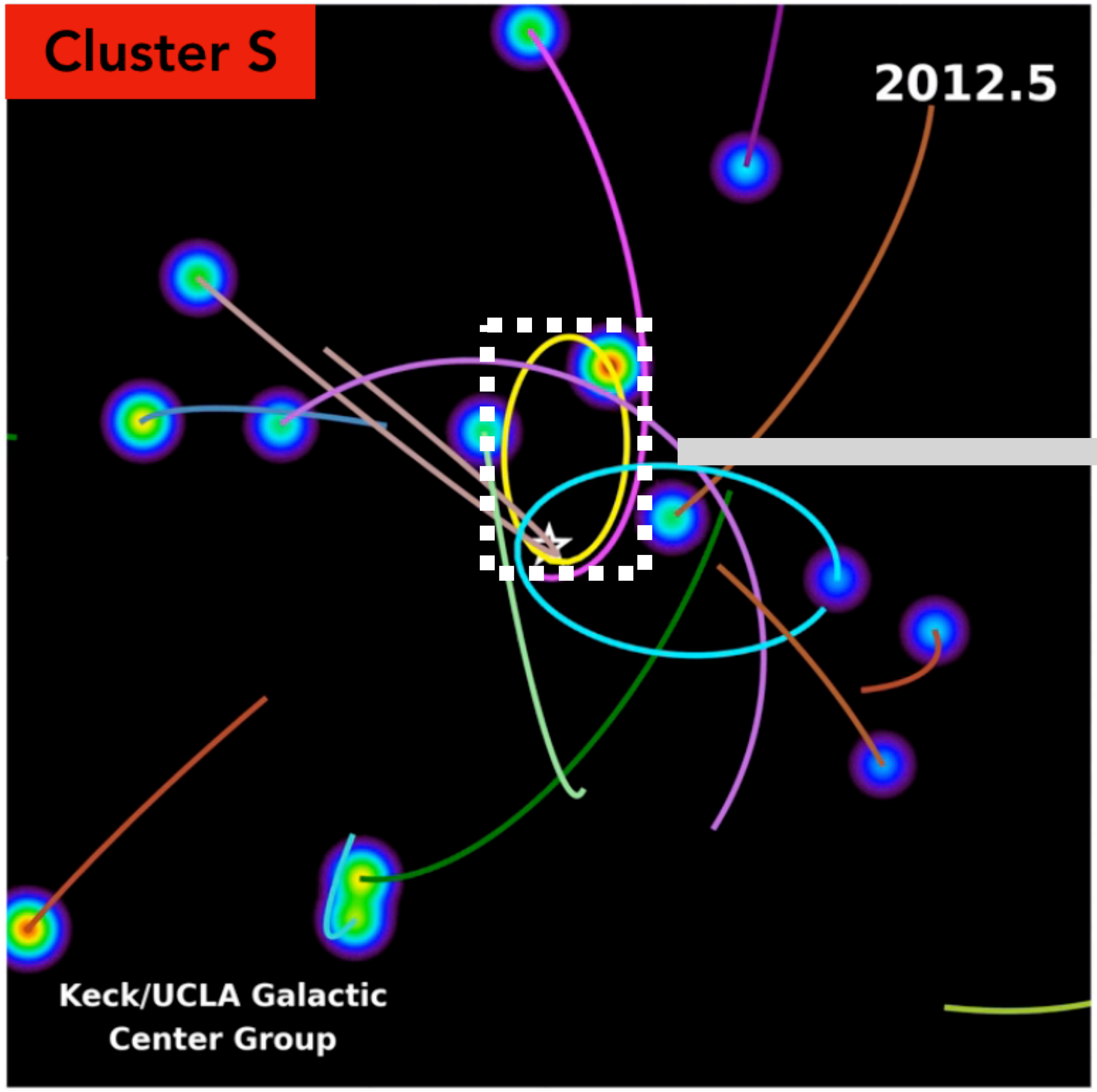
What is the dynamics of **Keplerian orbits**?

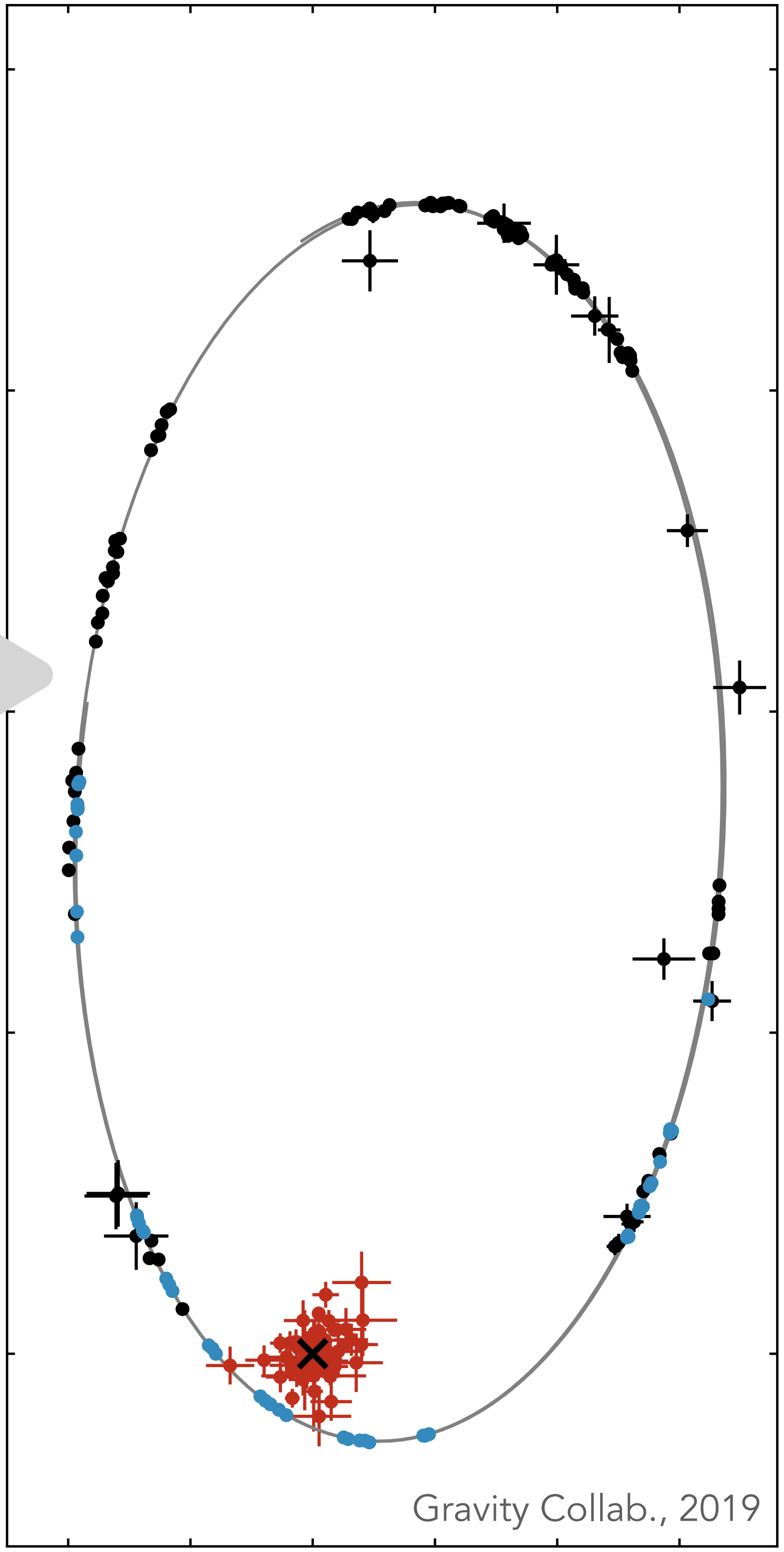
Gravity Interferometer — VLTI — Chili



S2's observation

S2's observations (Gravity)

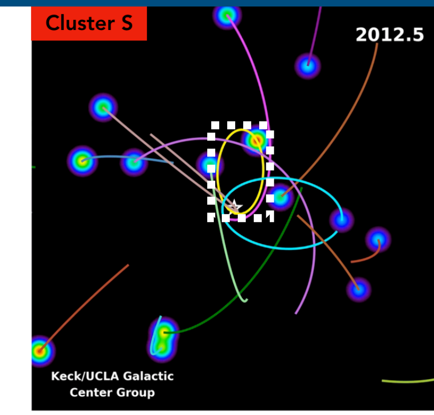




Classical (adaptative) telescope

Interferometric telescope

S2's observation (Gravity)

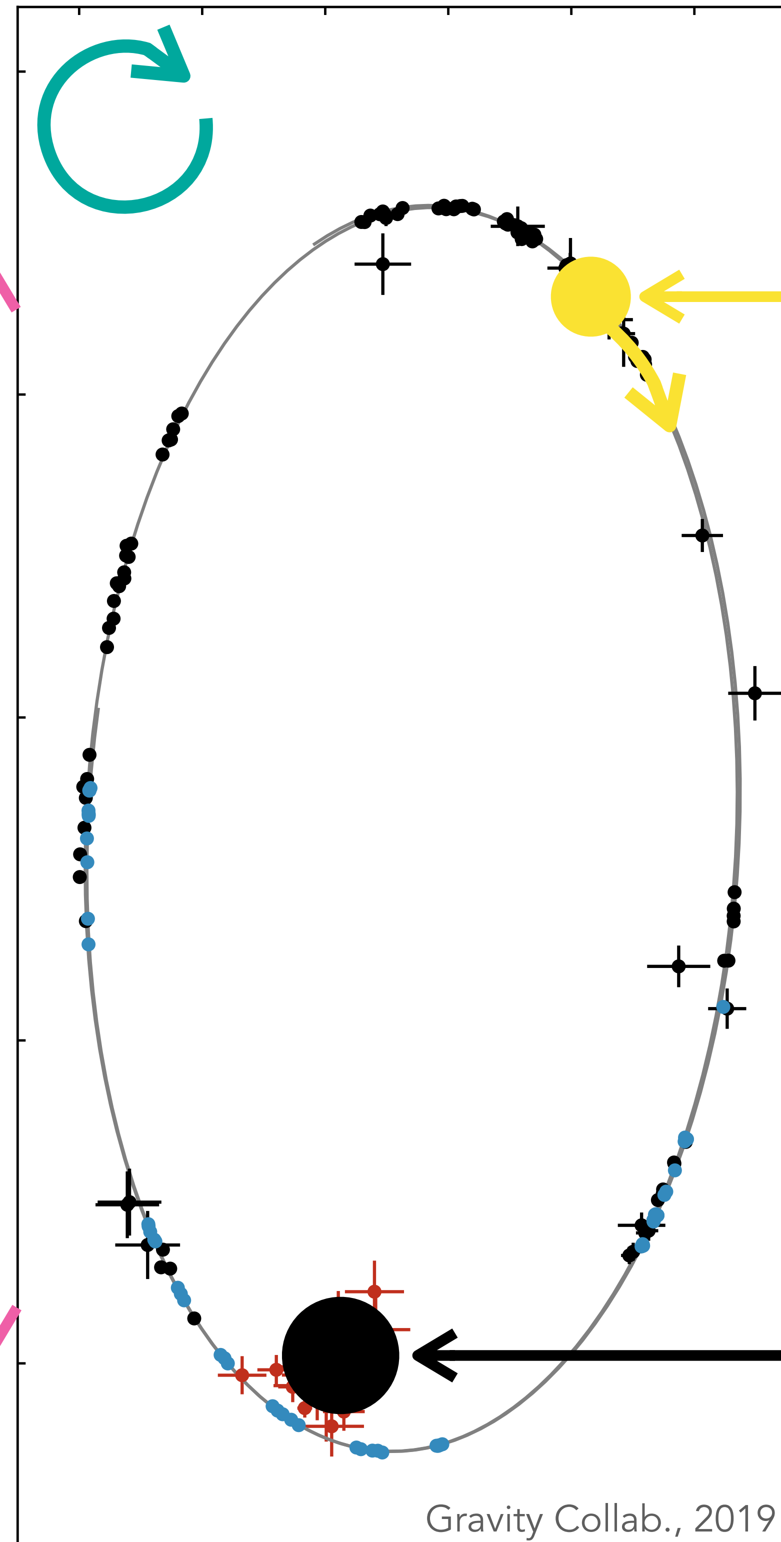


~15 years
(~ Jupiter's period)

Earth

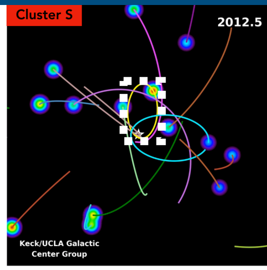
~10^9 ua

~1000 ua
(~1% Sun <-> Proxima)



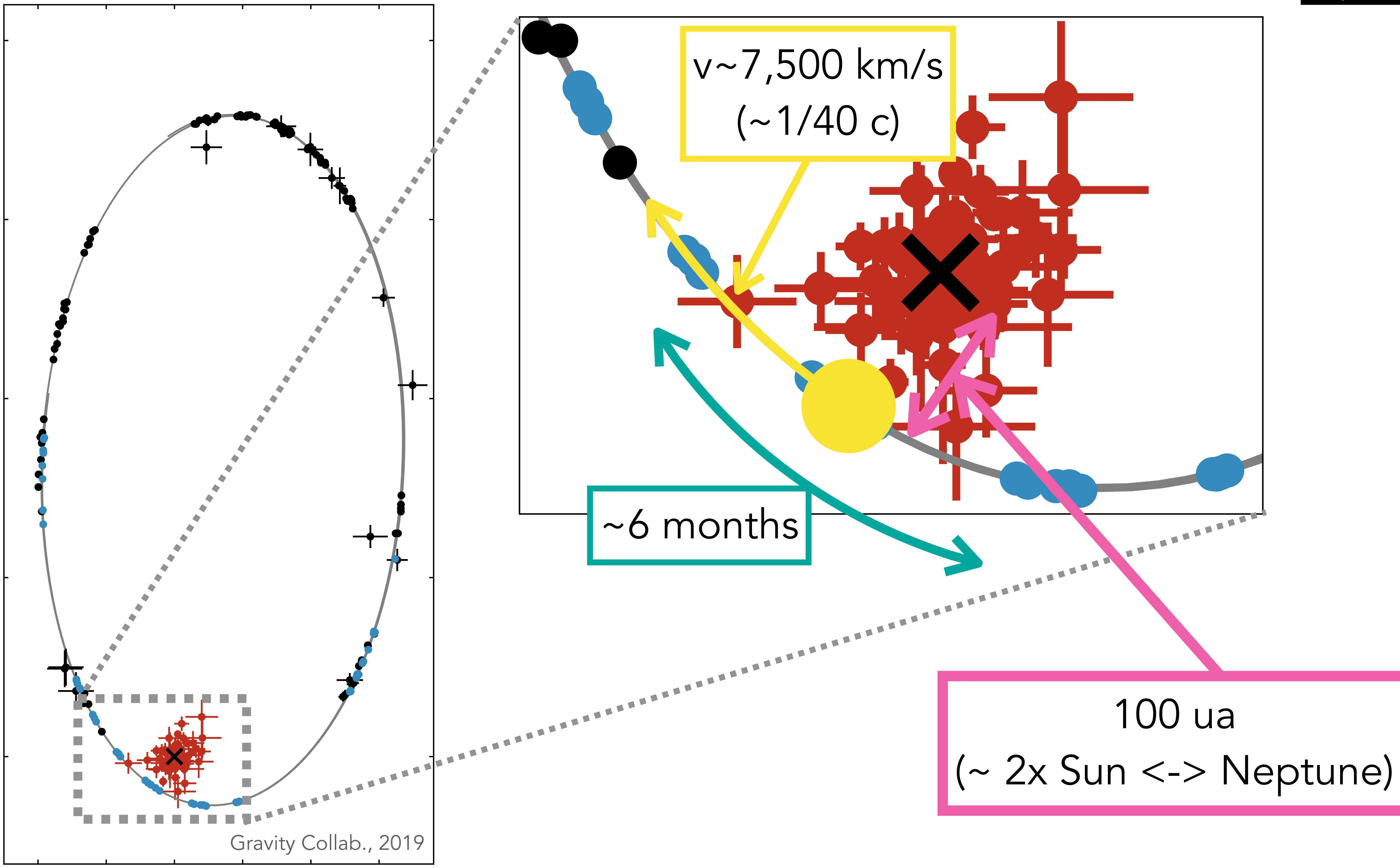
S2 star
~10 M_{Sun}

BH SgrA*
~4x10^6 M_{Sun}



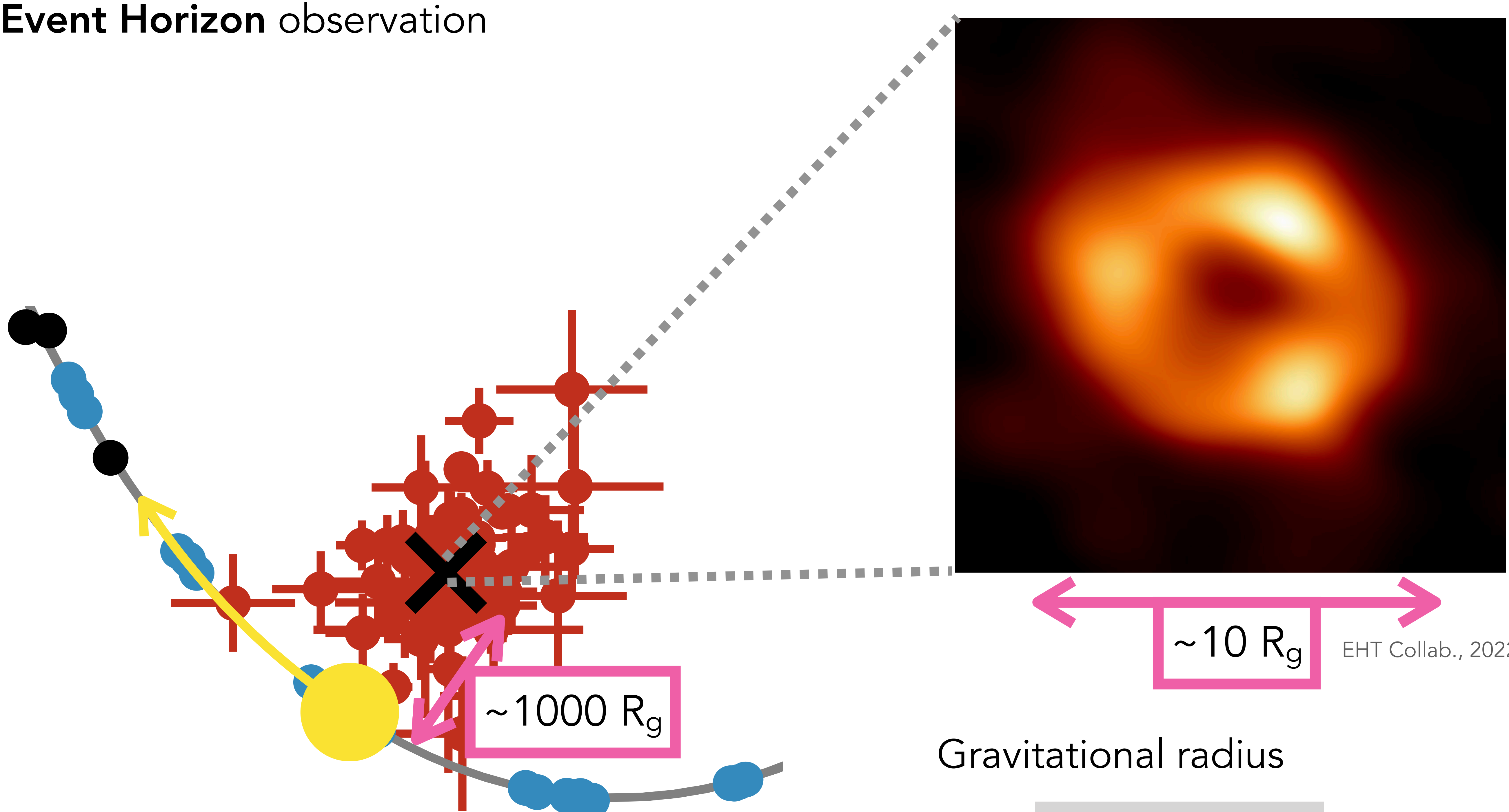
Pericentre passage

S2's observations (Gravity)



Black hole's shadow

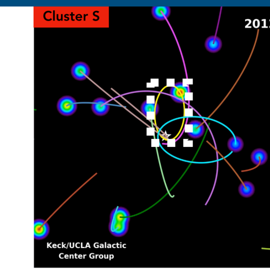
Event Horizon observation



EHT Collab., 2022

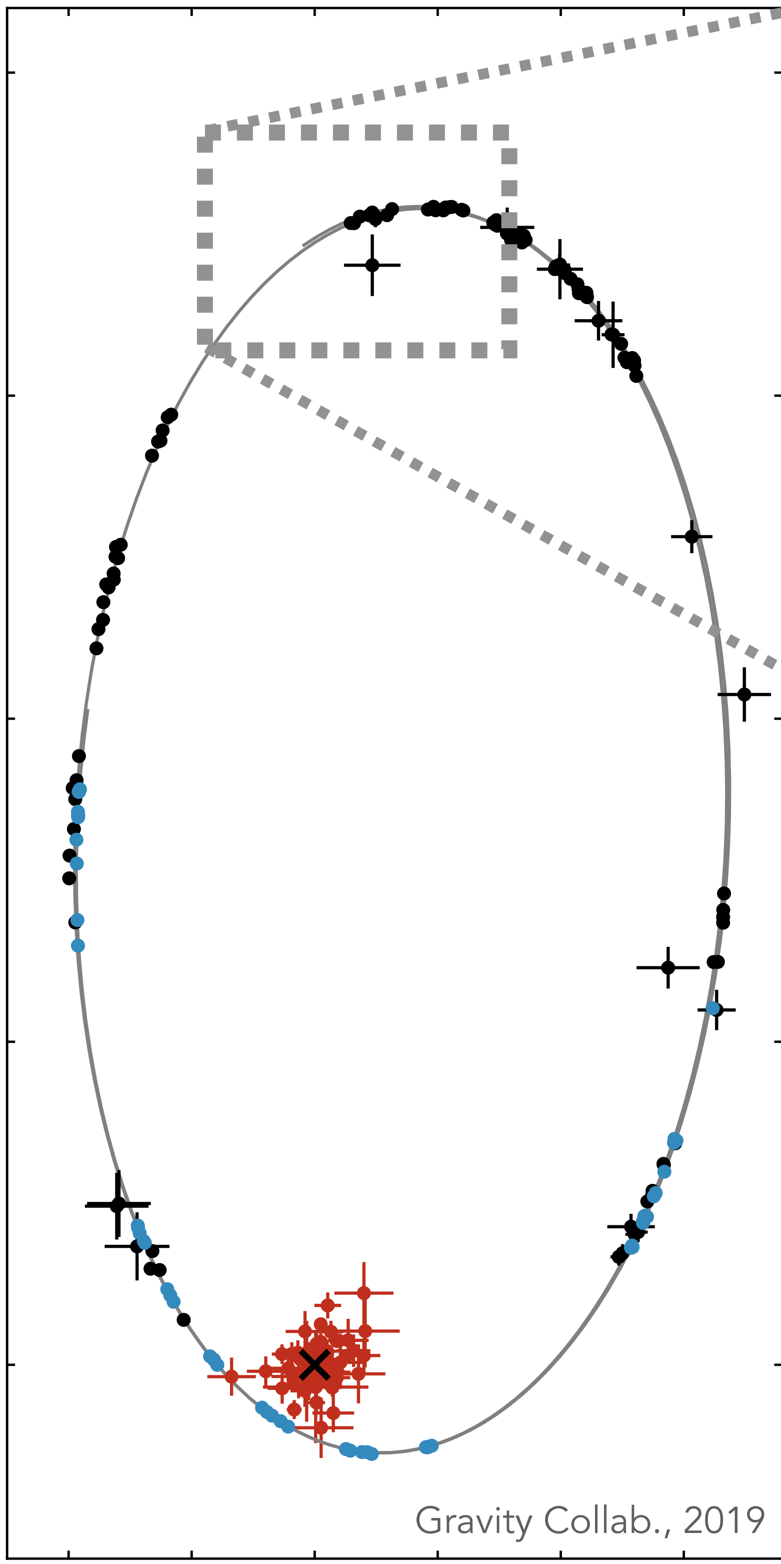
Gravitational radius

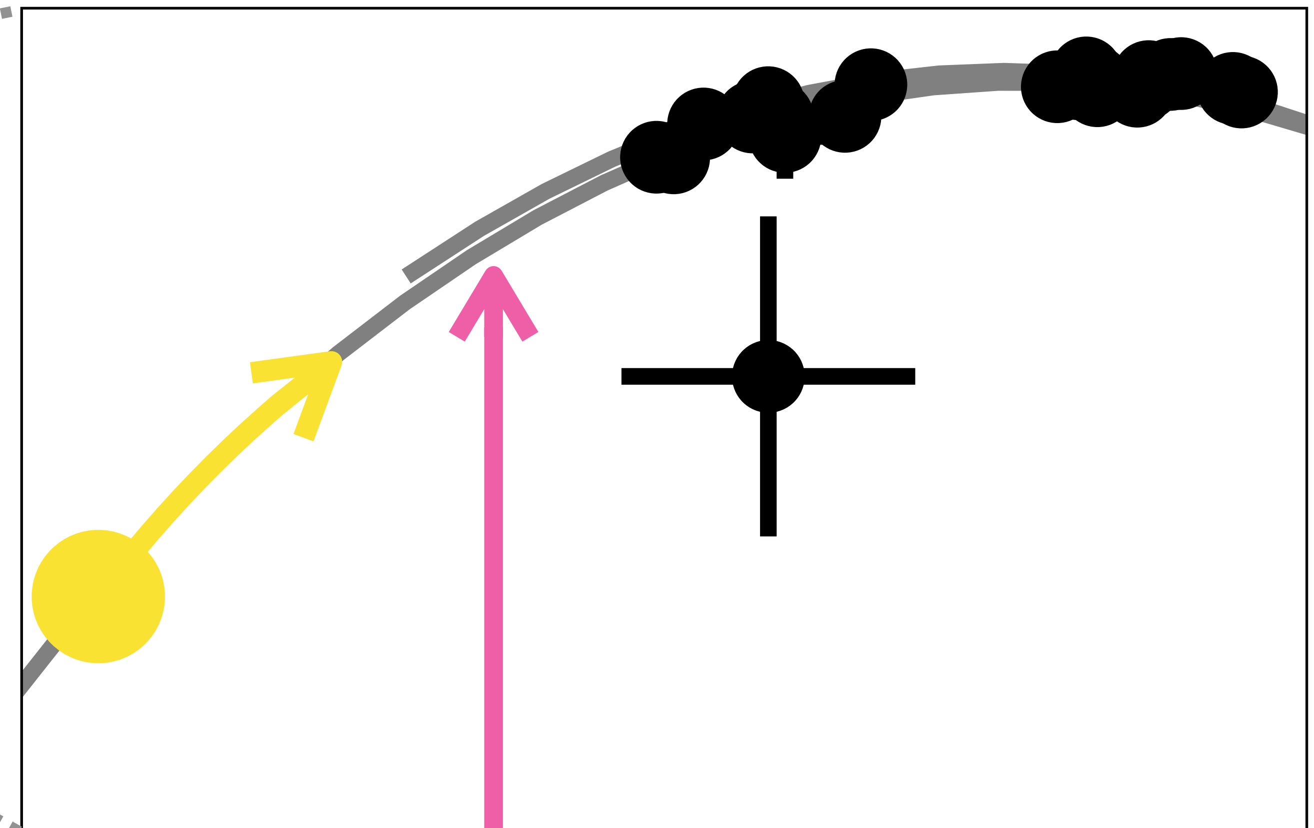
$$R_g = \frac{GM_\bullet}{c^2}$$



Relativistic precession

Observation of S2 (Gravity)



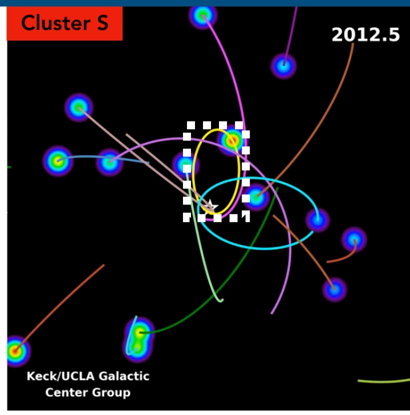


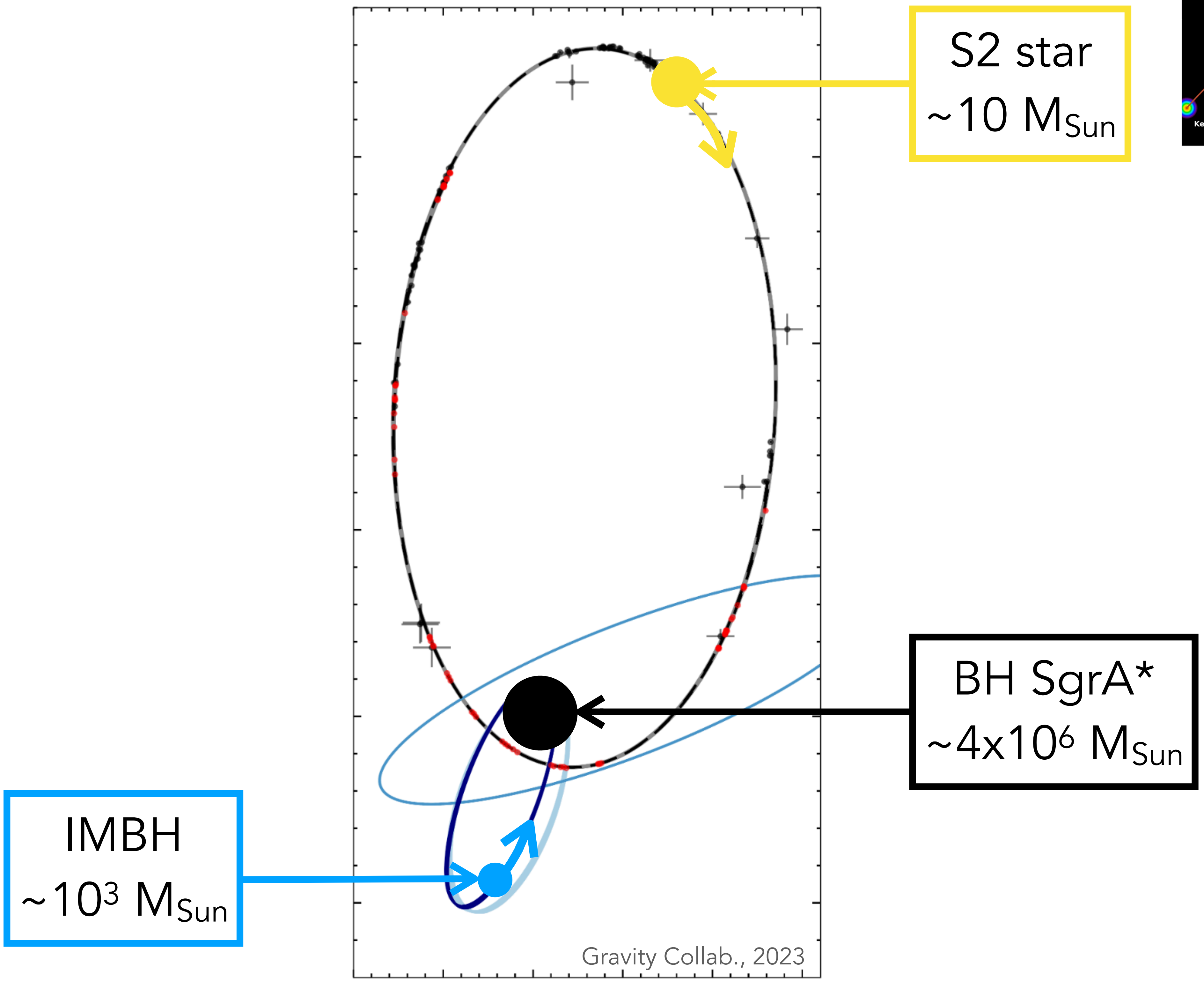
Precession of the orbit
12′ (=0.2°) per orbit

S2 arrived early:
- + Orbit is **non-closed**
- + **Prograde** precession

→ **Relativistic effects**

What about an IMBH?





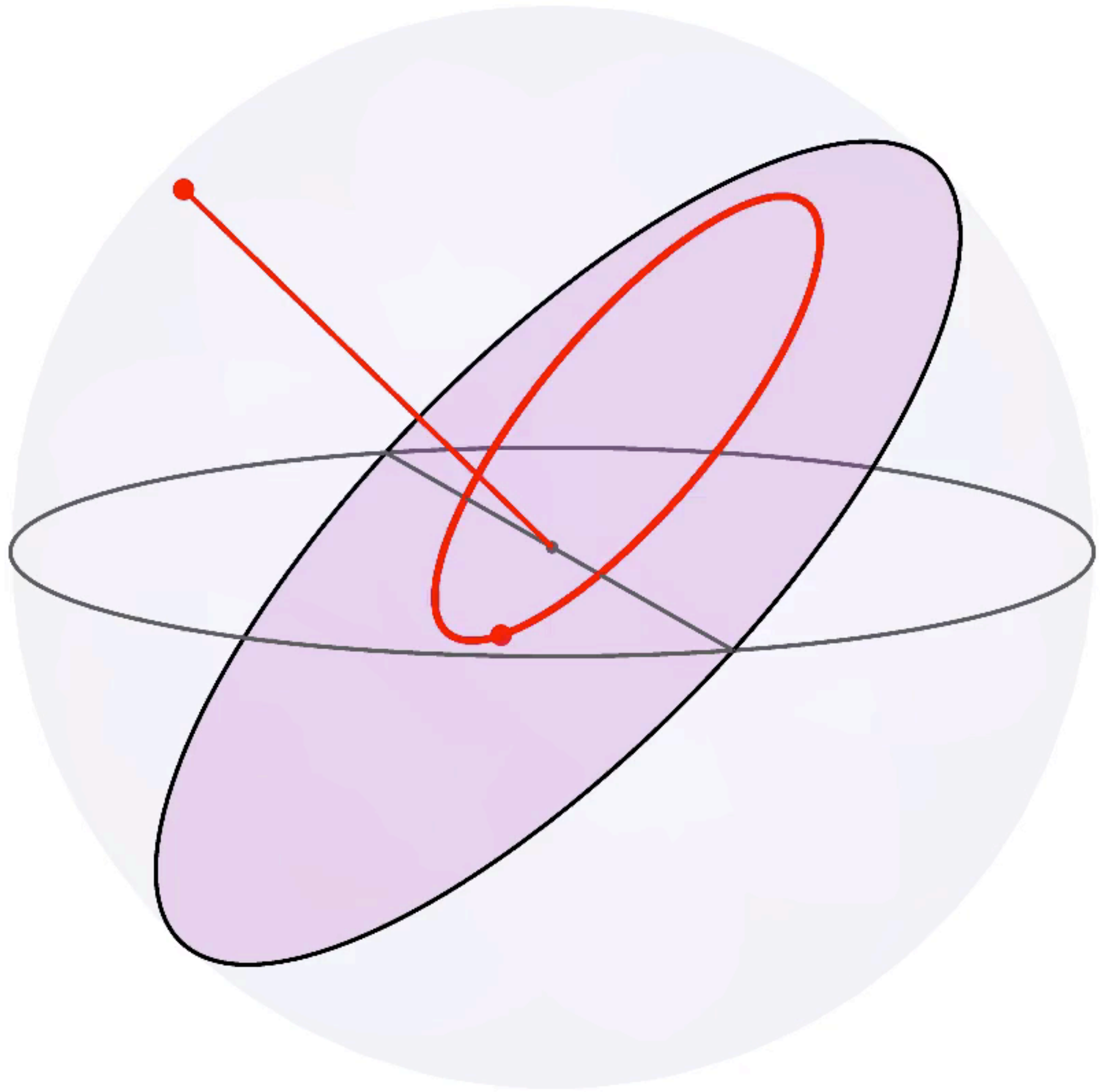
An inner IMBH hard to reconcile with **S2's orbit**

Pericentre precession

Origins of the **precession**:

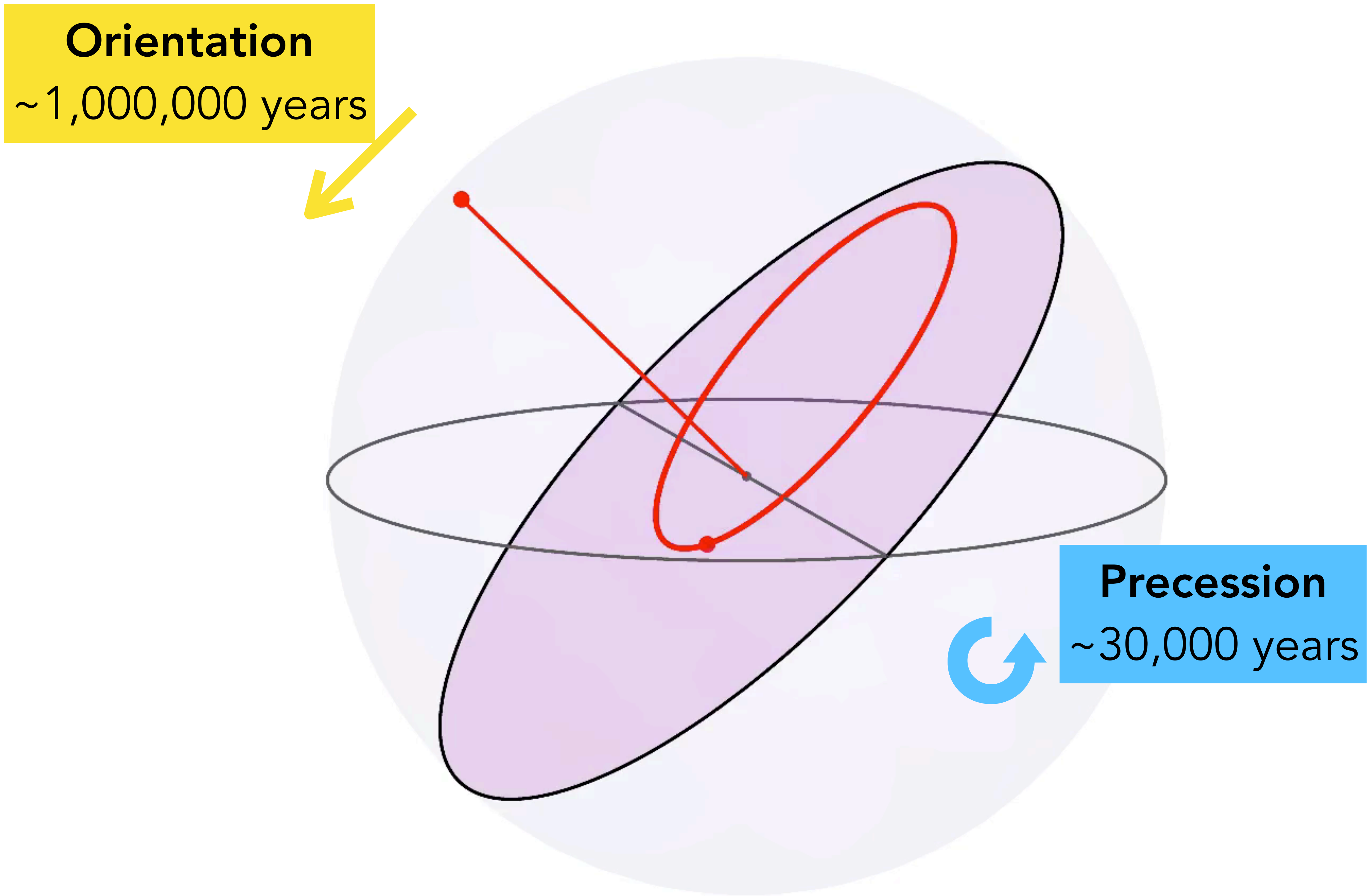
+ **Relativistic** effects from the BH
+ **Perturbations** from other stars

~30,000 years for S2



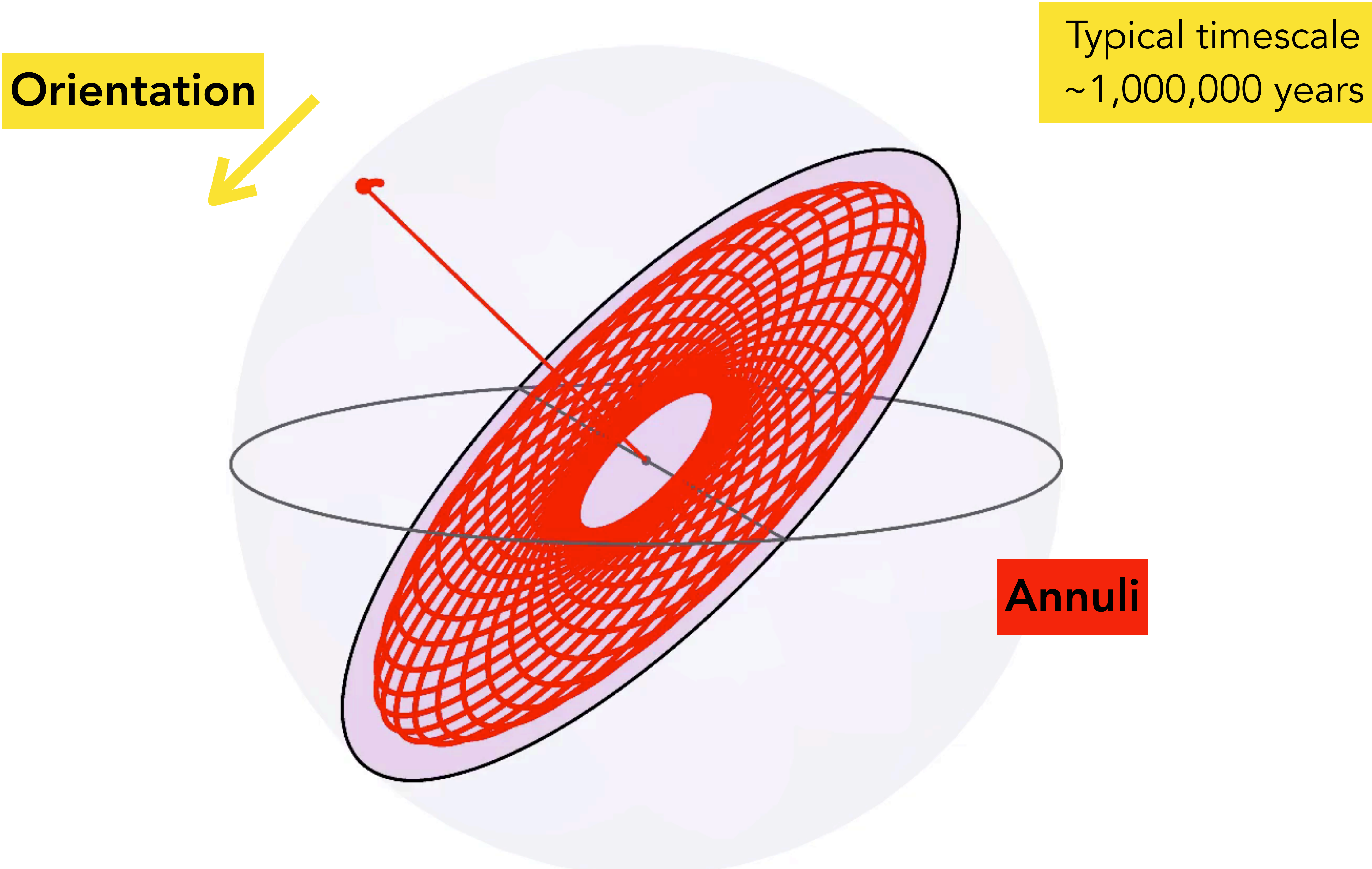
Orbits **precess** in their planes

Orbits also change in orientations



Two timescales: Precession $\ll$ Orientation

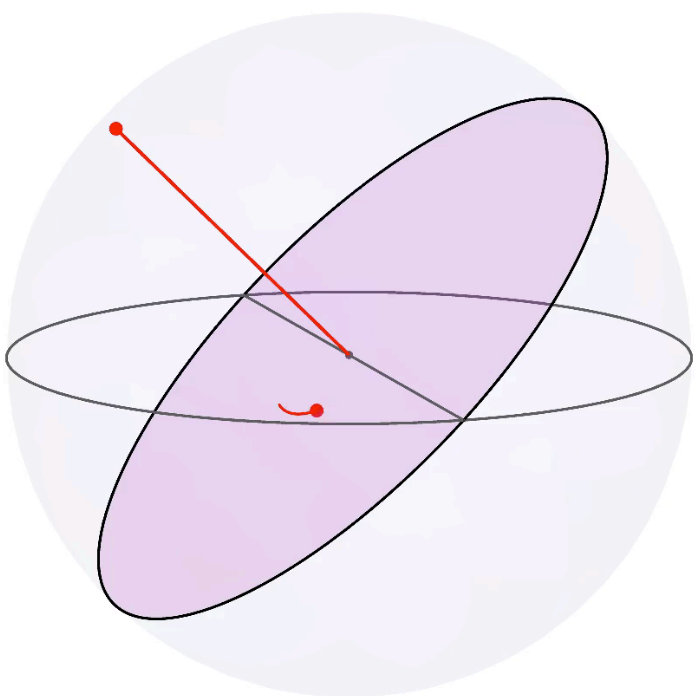
Stellar orientations



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

Stellar dynamics

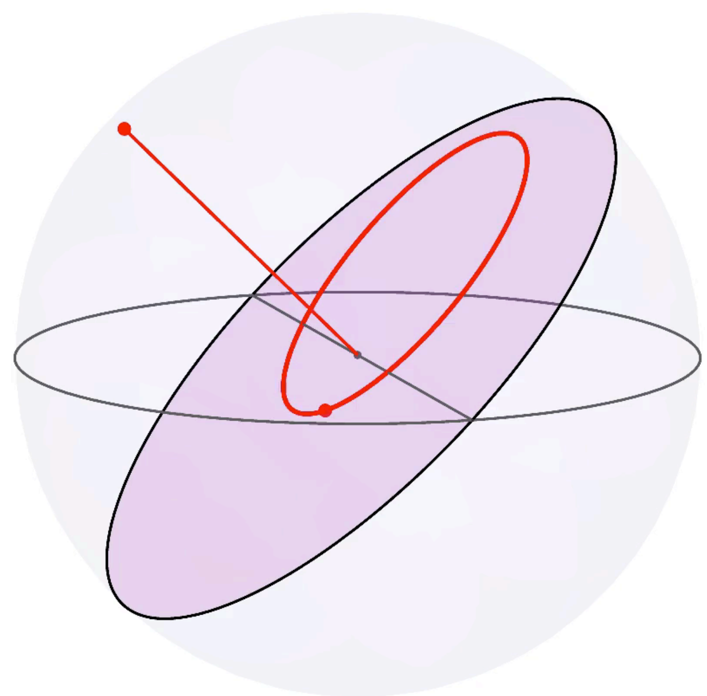
Stars



~10 years

Orbital motion

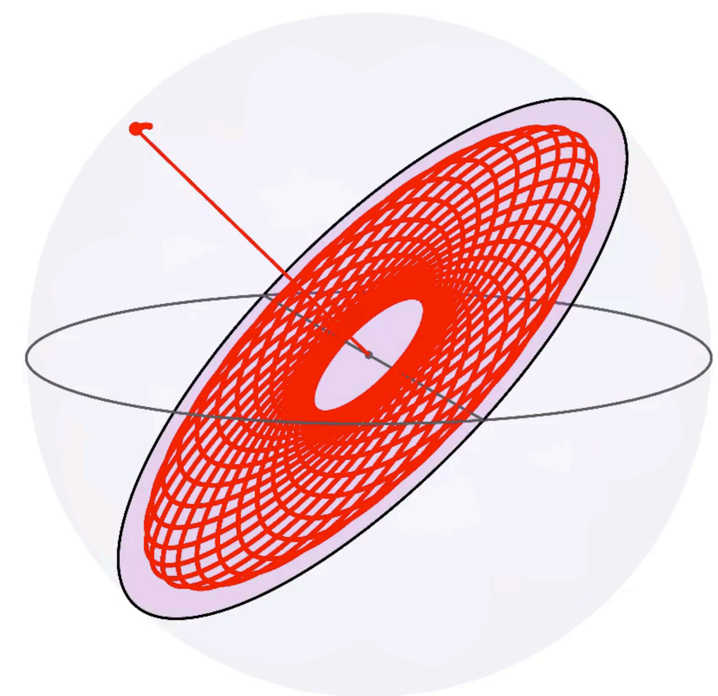
Ellipses



30,000 years

Pericentre precession

Annuli



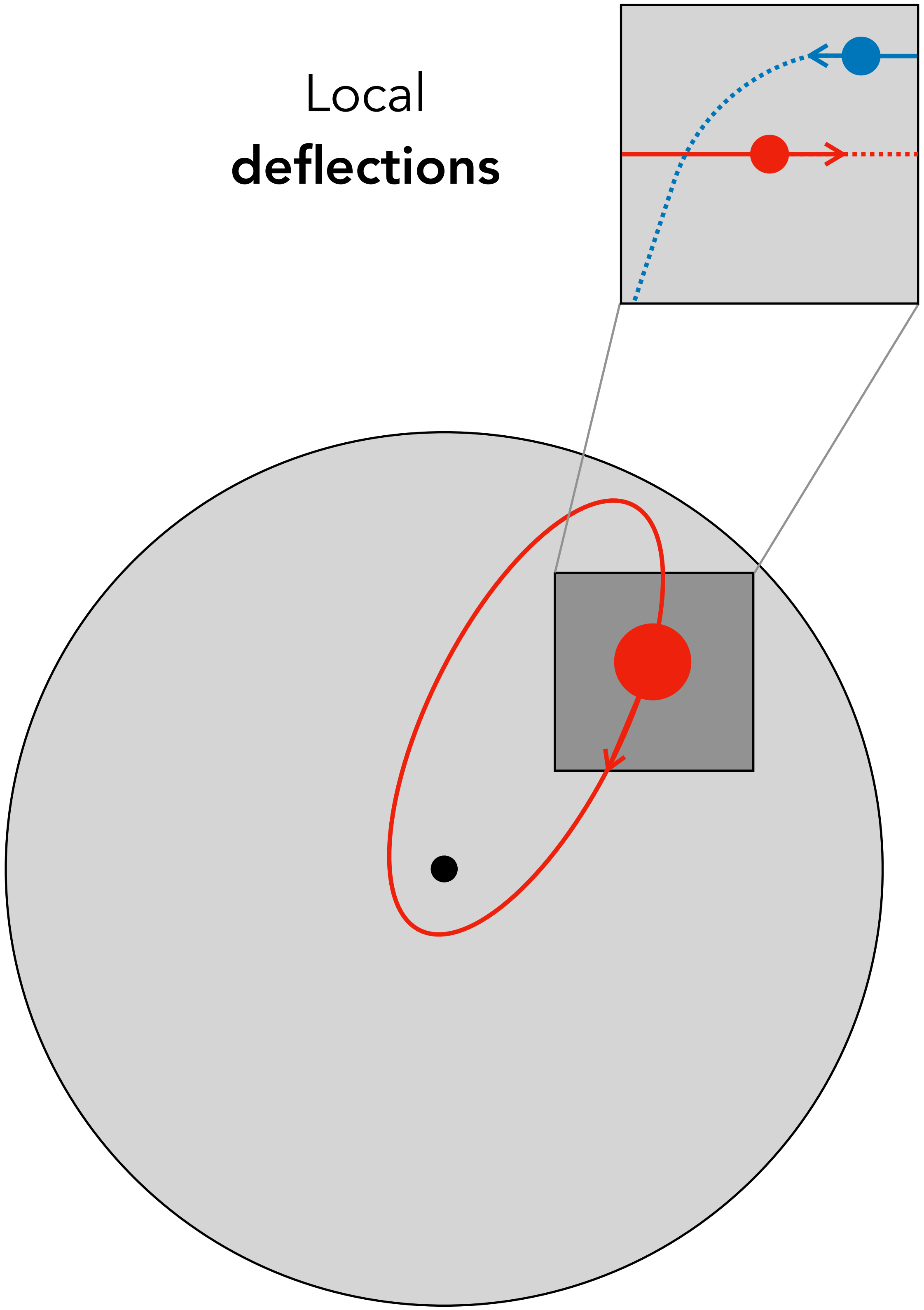
~1,000,000 years

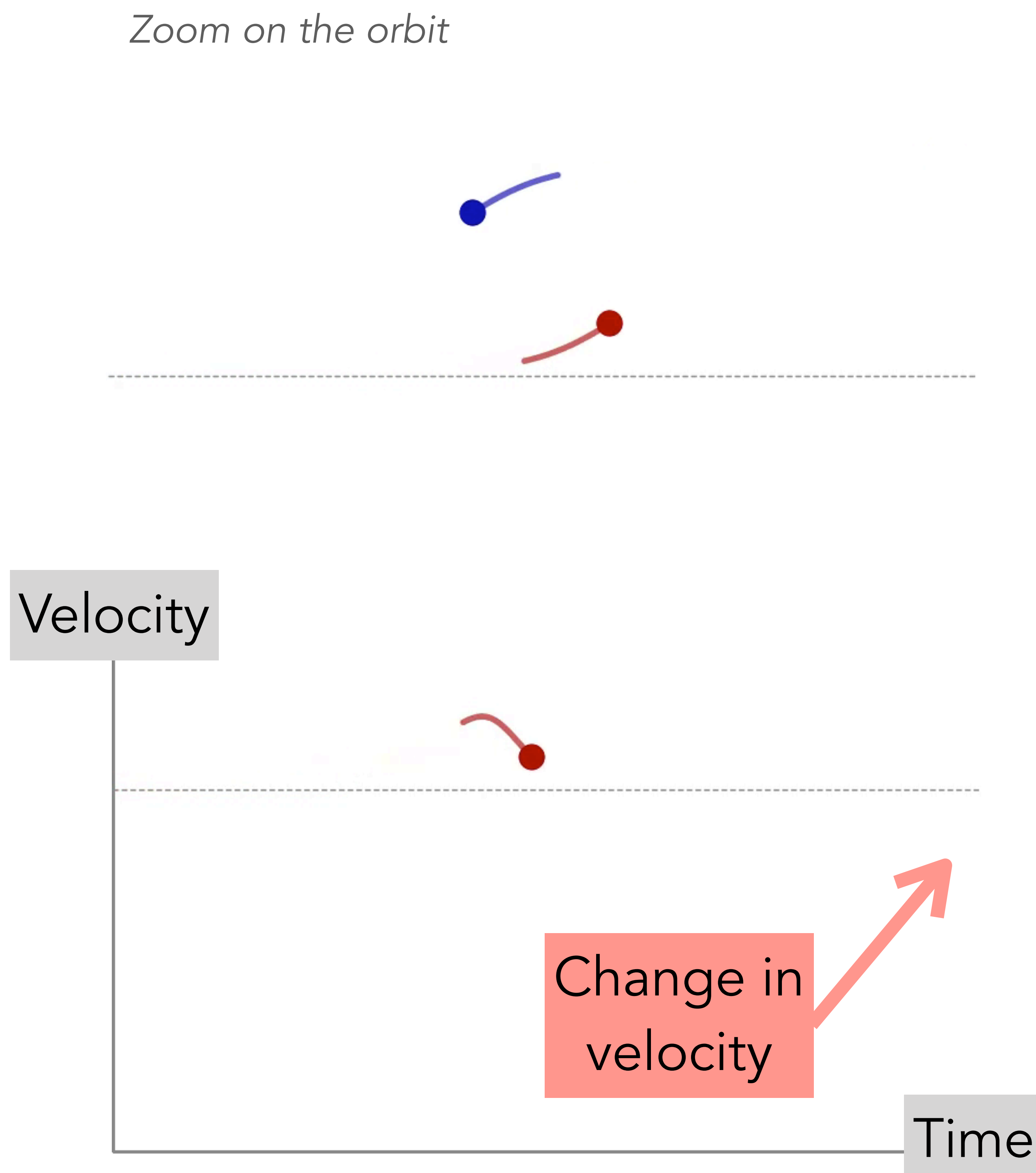
Orientation precession

SgrA* is 10 Gyr orld. We can wait longer

Stellar energy

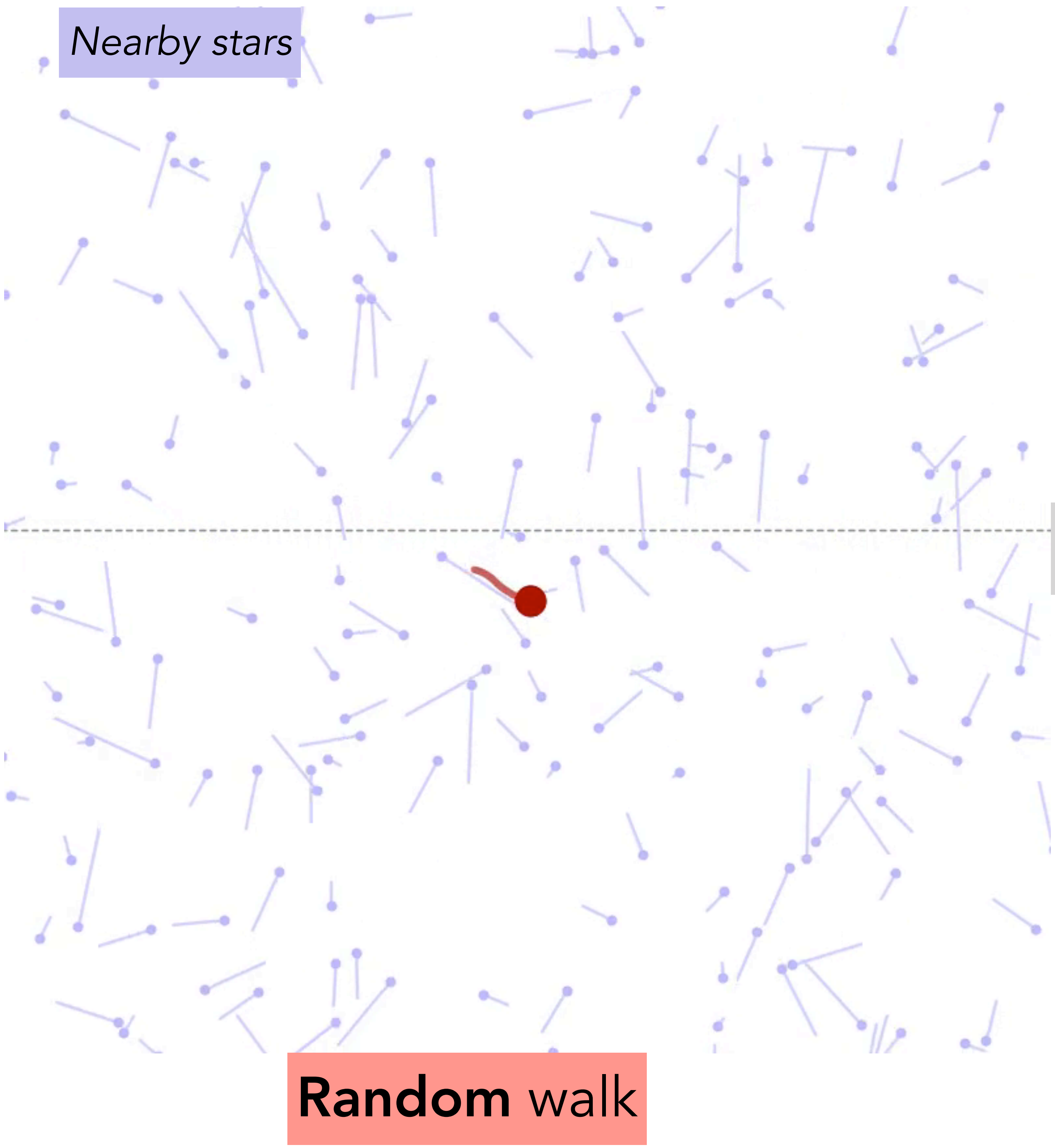
Orbital distortions sourced by instantaneous **kicks and deflections**

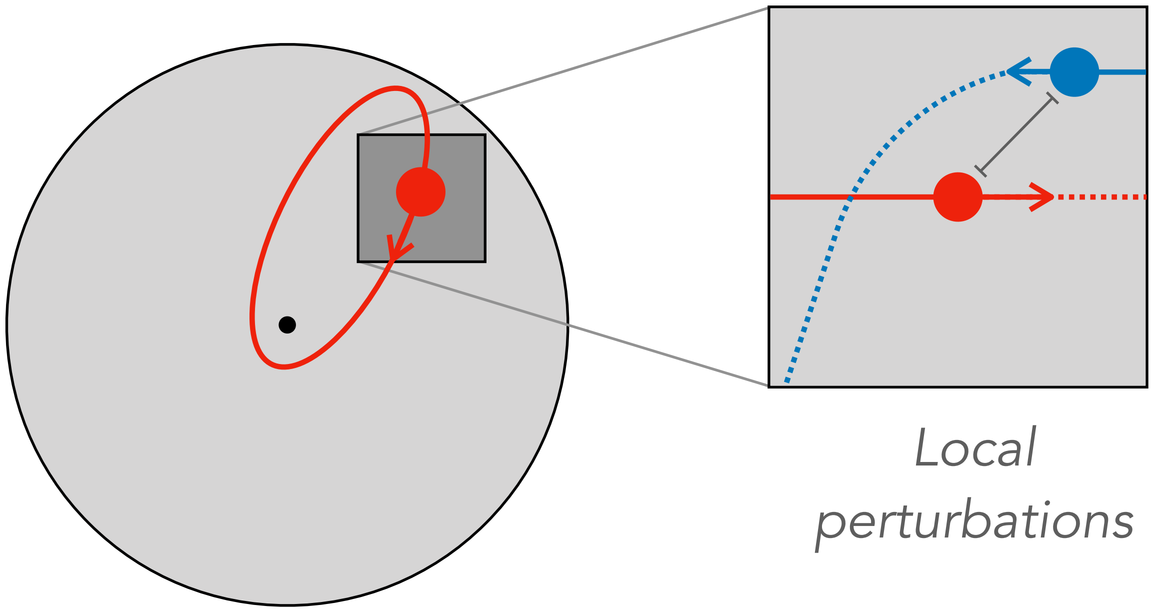


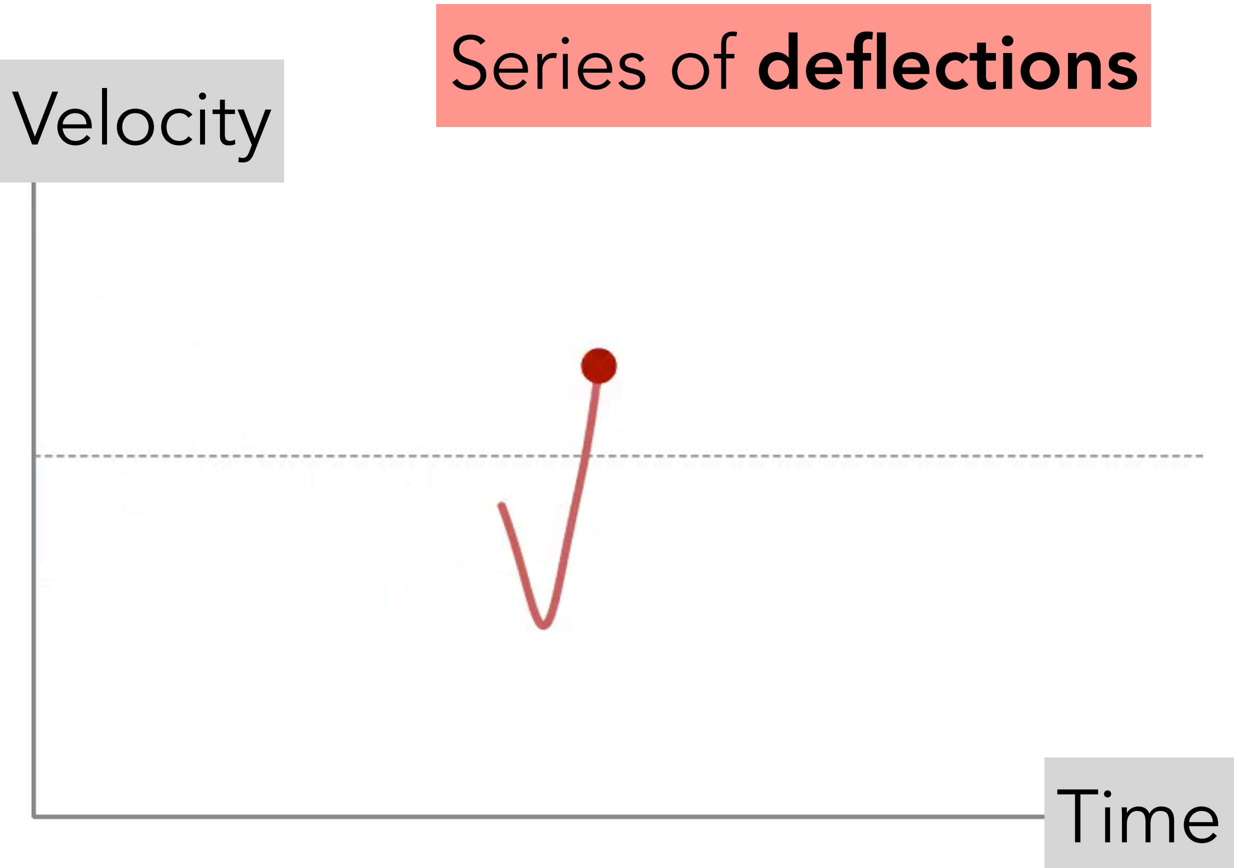


Deflections

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

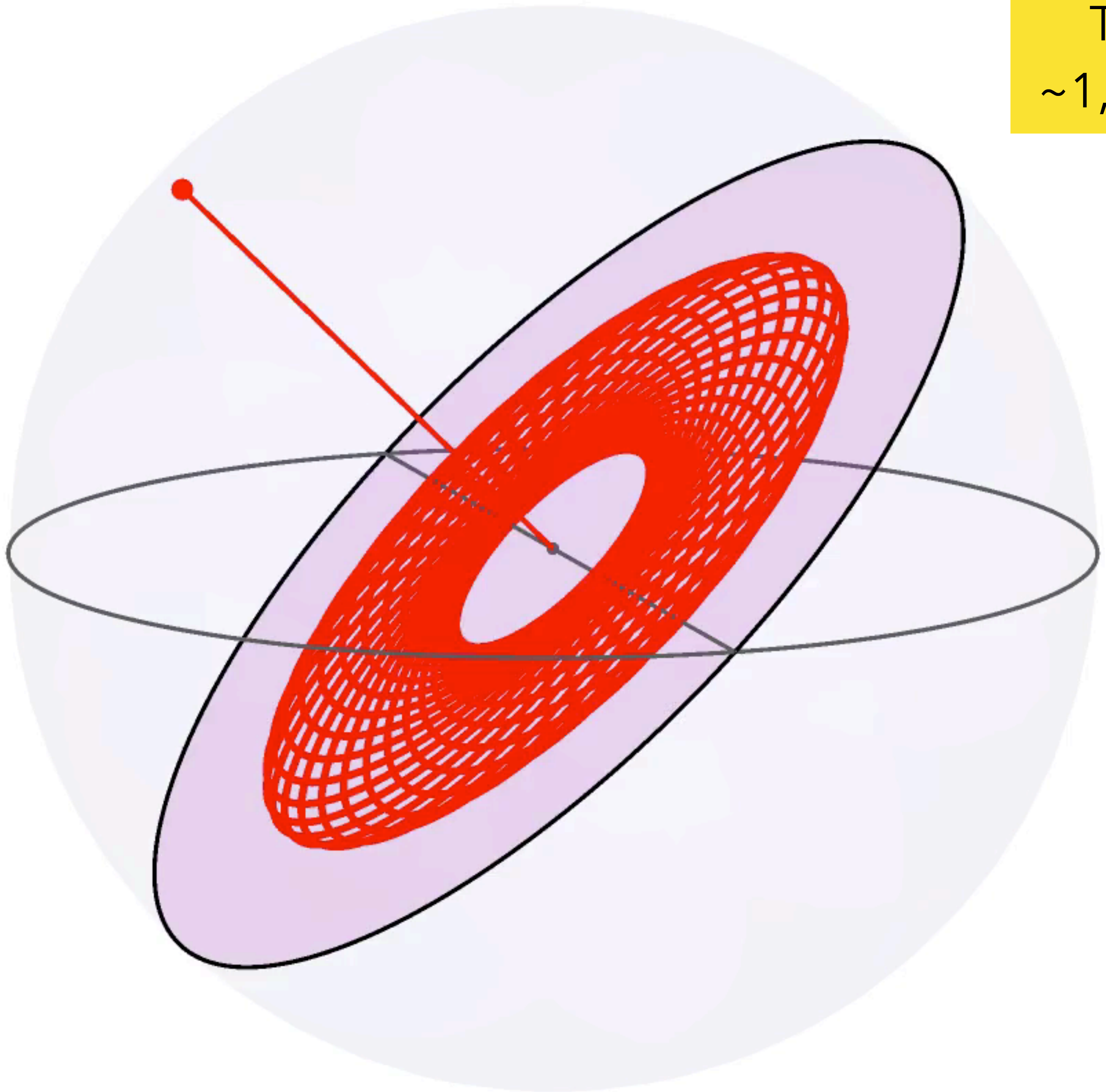






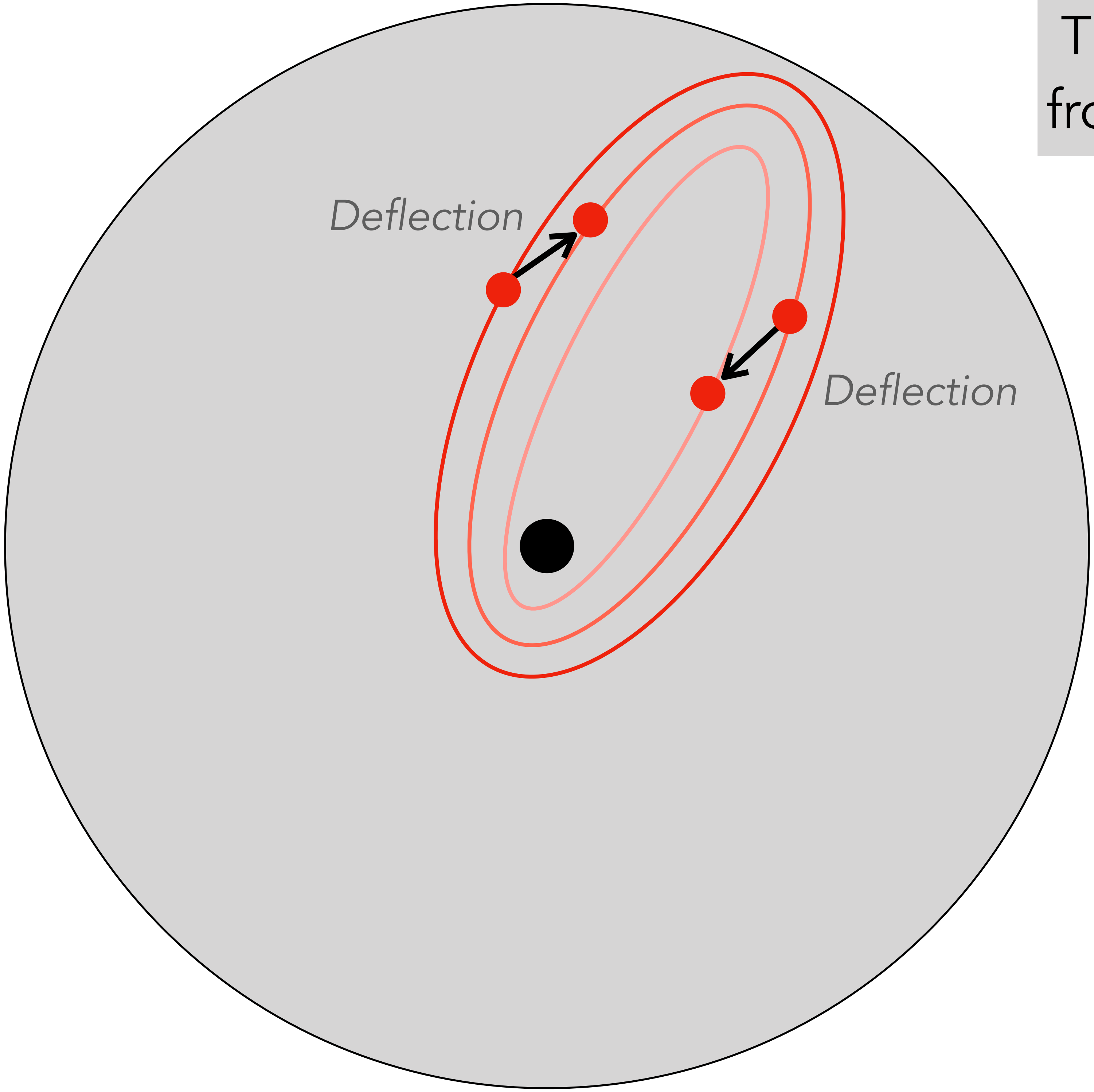
Stellar energy

Typical timescale
~1,000,000,000 years



Deflections drive a slow change in the Keplerian energy

Deflections

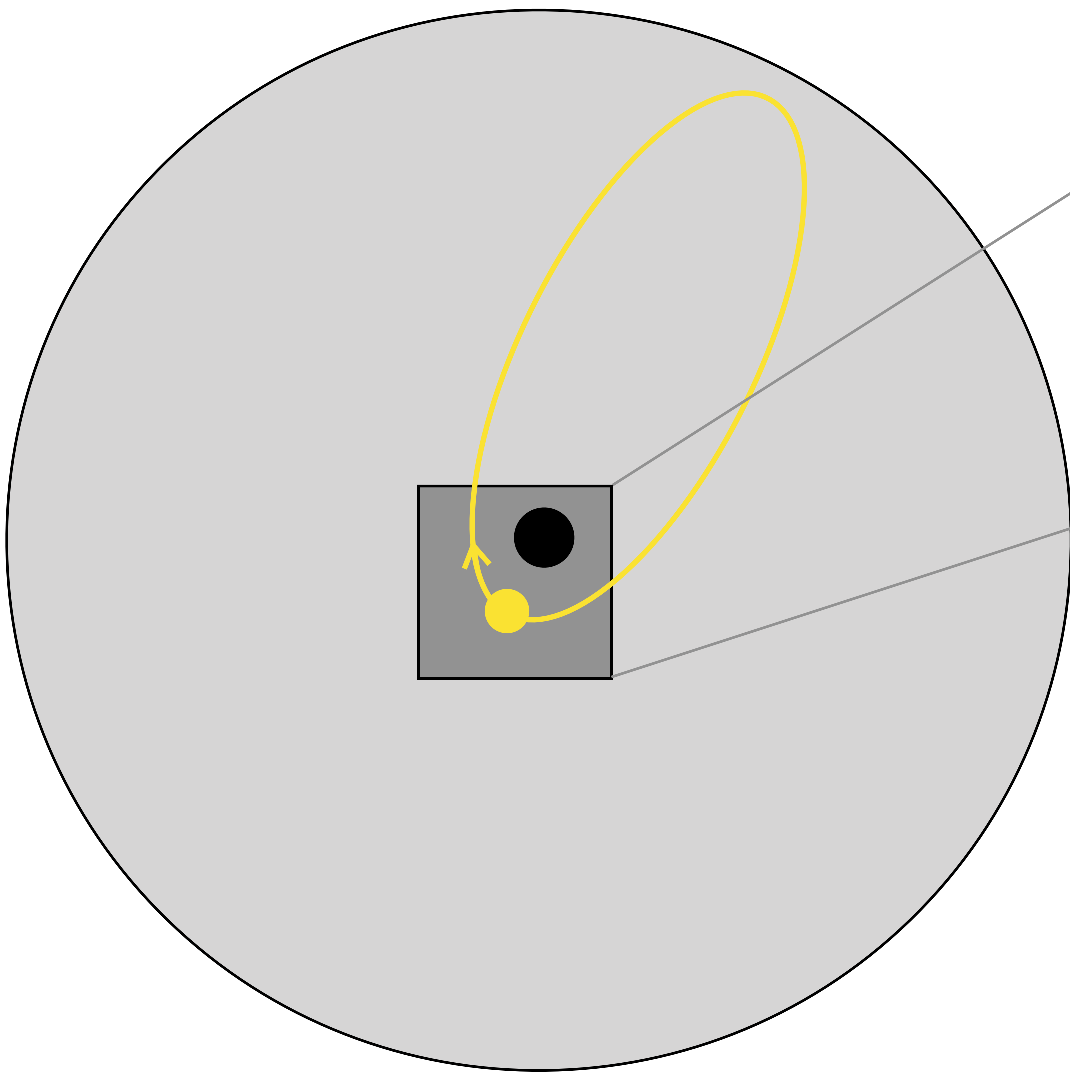


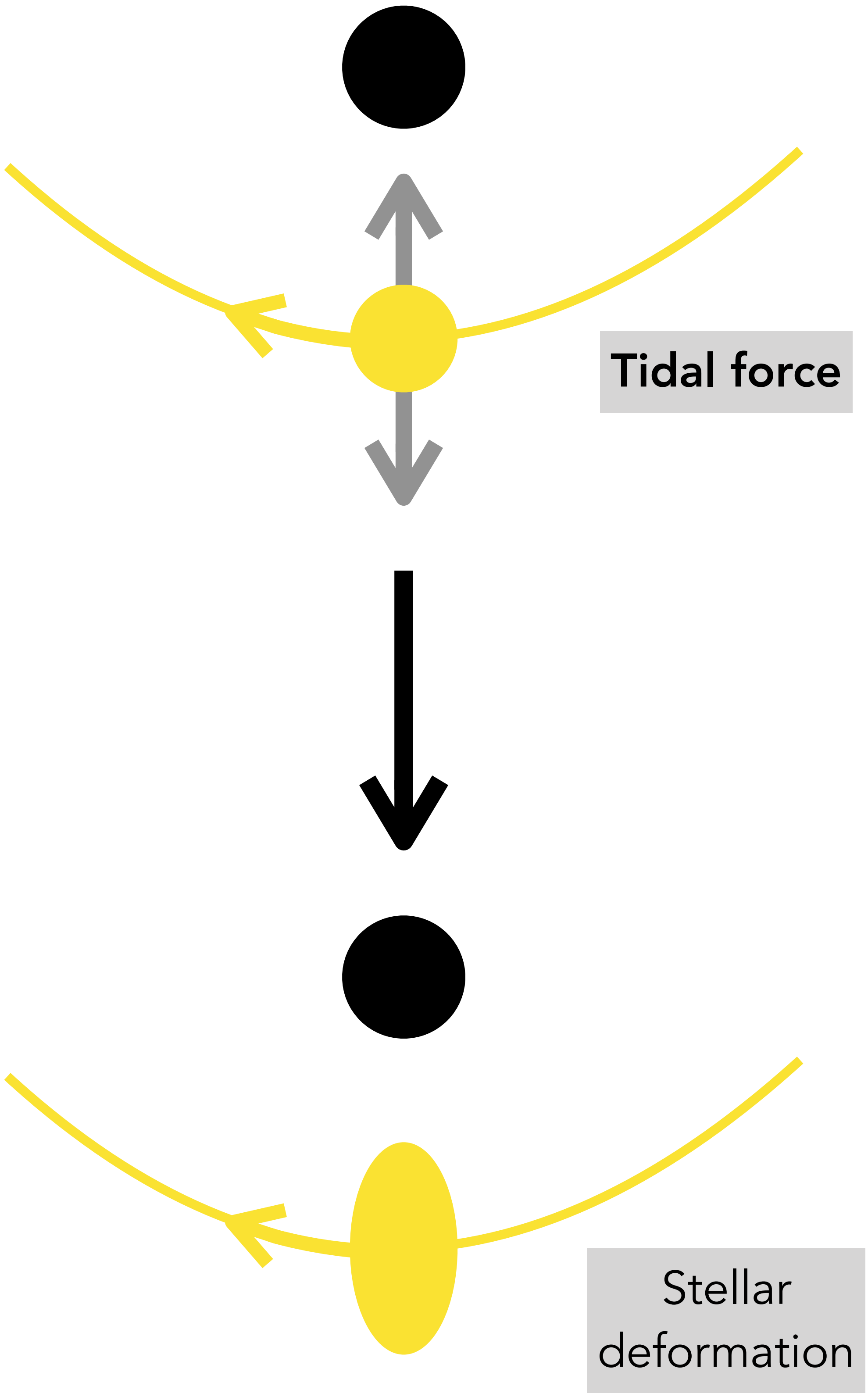
The star ``jumps" from orbit to orbit

Deflections allow the star to get even closer to the **central BH**

The neighborhood of the BH

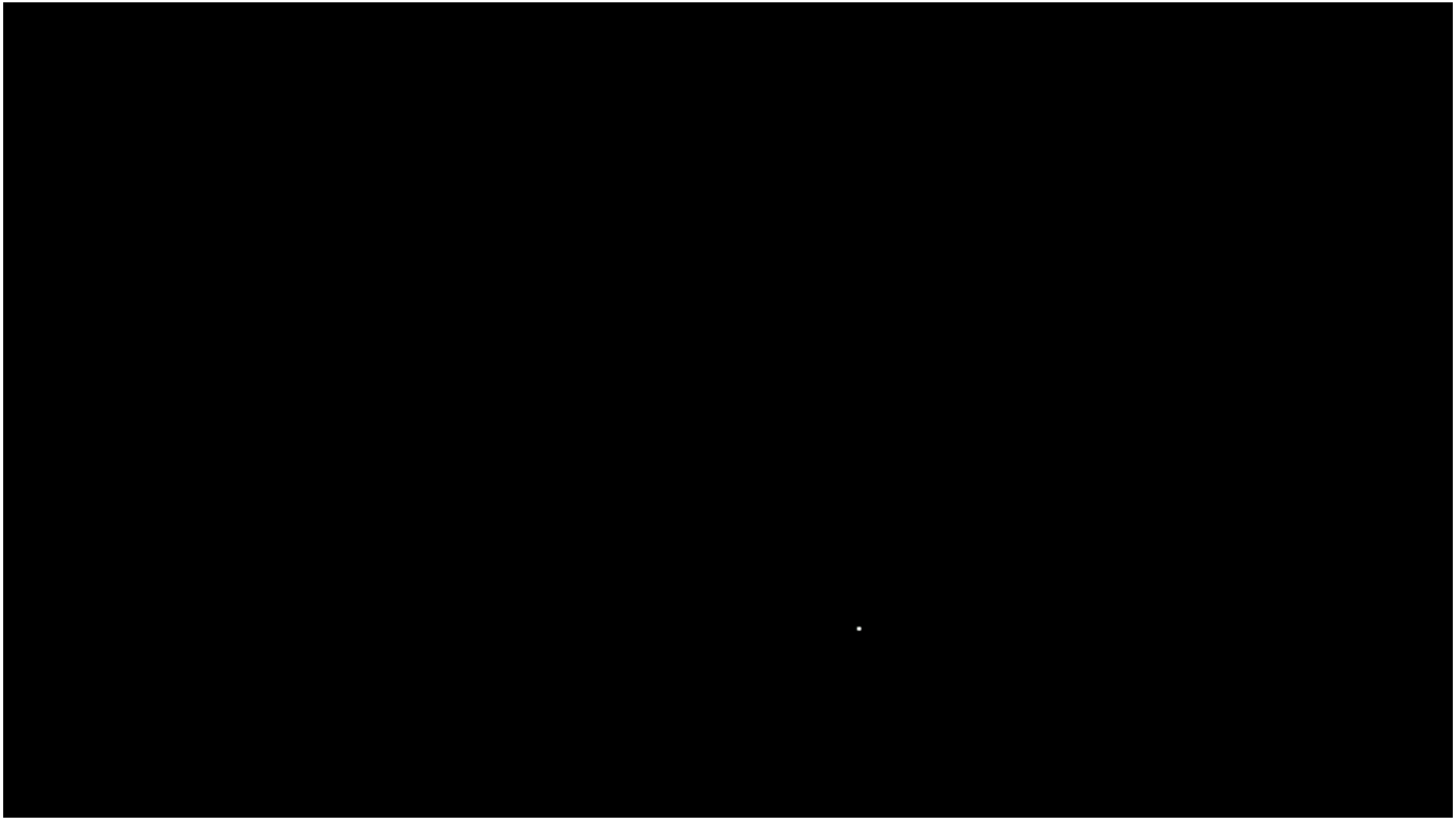
What does a star feel close to the BH?





Very close to the BH,
the star is no more a point

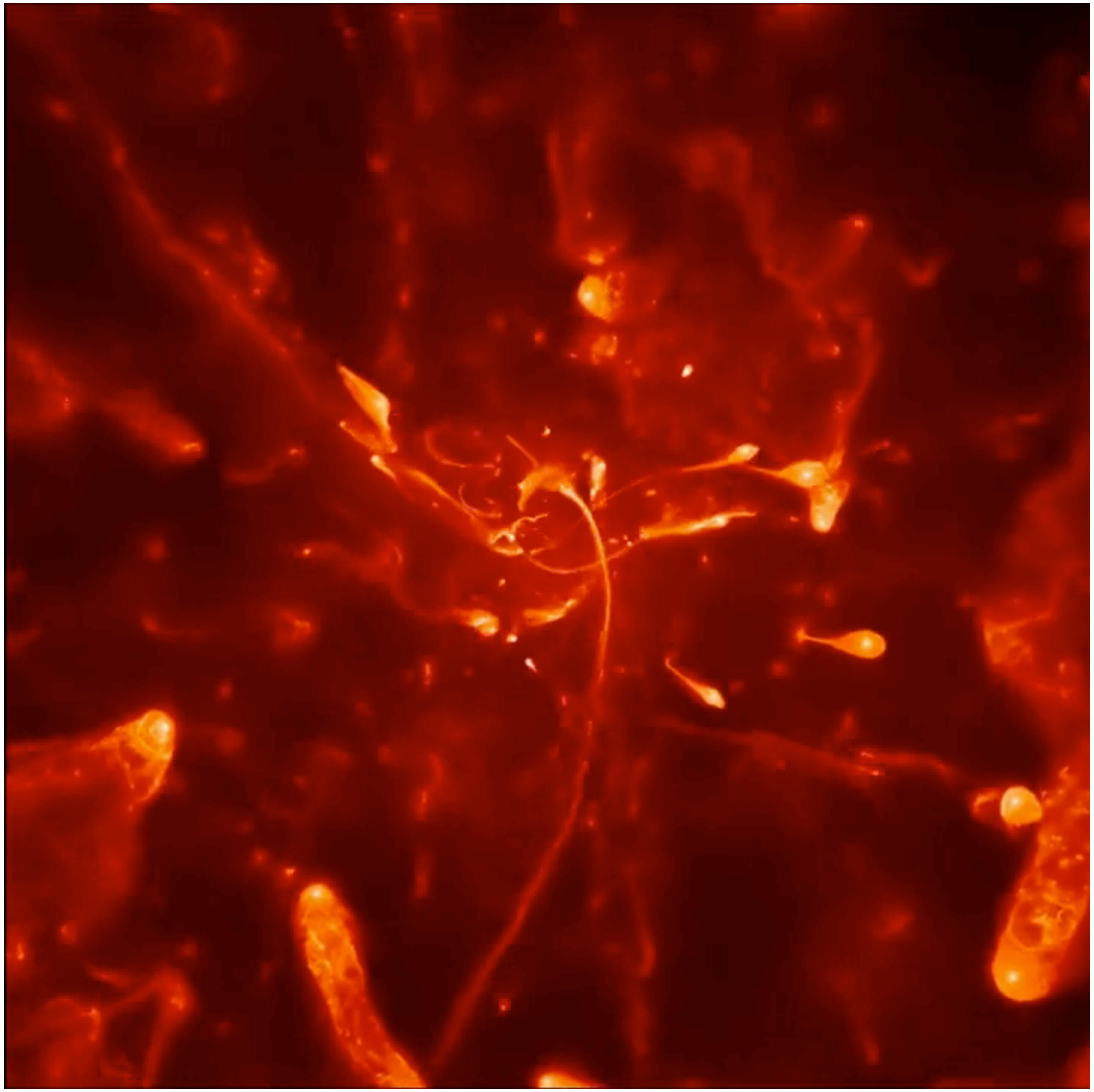
Tidal disruption events



J. Guillochon

Stars get **disrupted** by the BH’s force field

Stellar winds

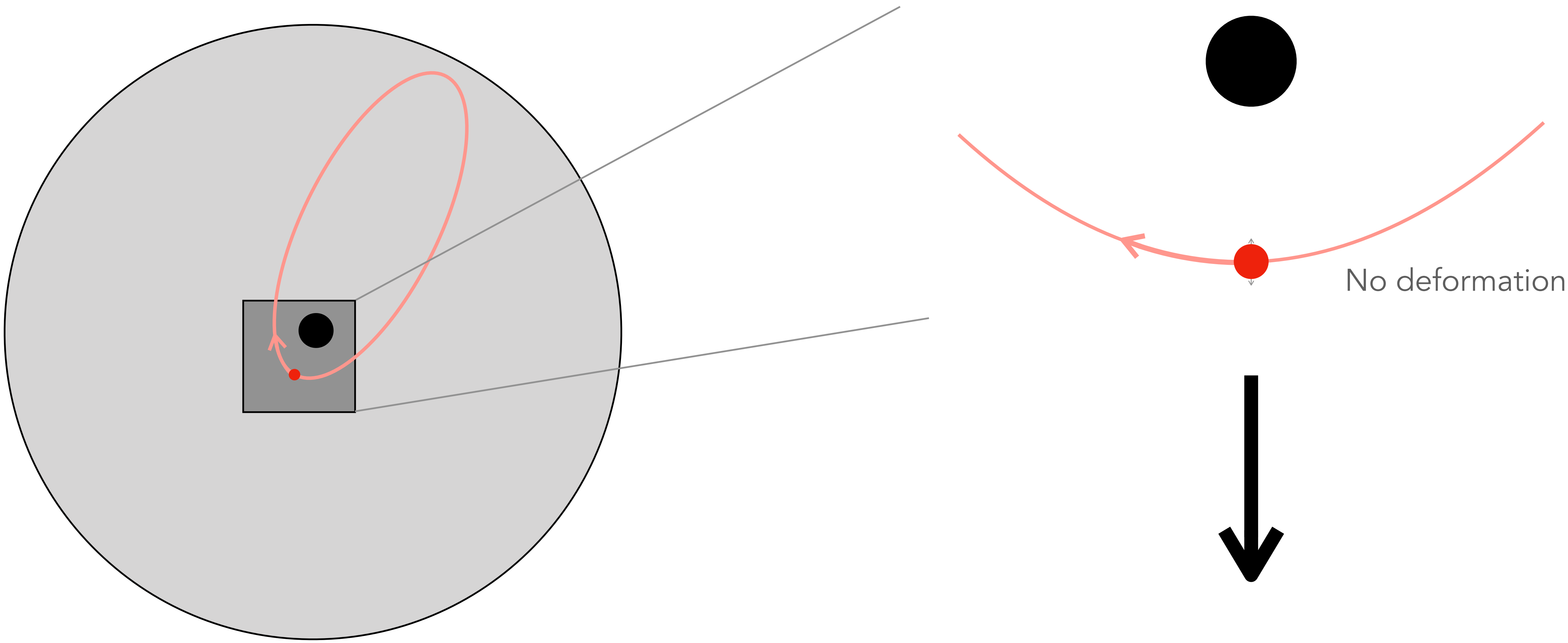


N. Luetzgendorf

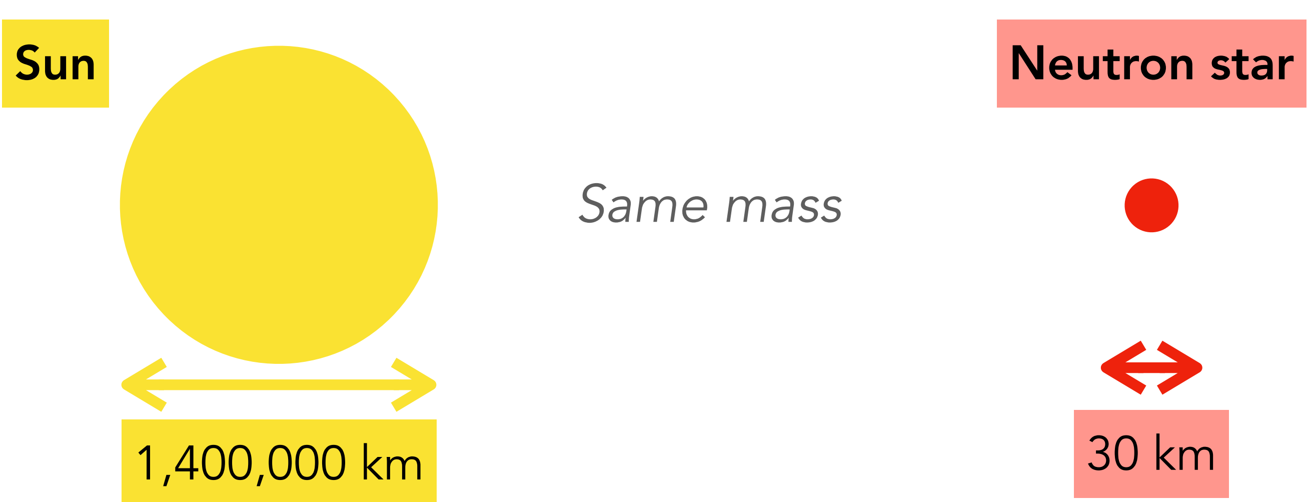
Gas is **striped** from stars close to the BH

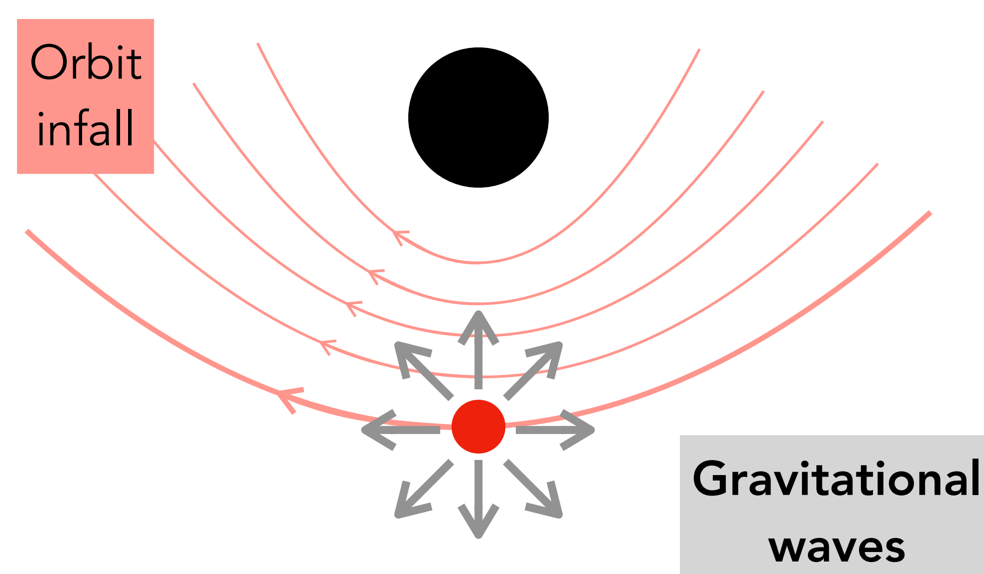
Even closer to the BH

What does a **compact object** feel close to the BH?



Compact objects (neutron stars, BHs) are **really small**





Extreme mass ratio inspirals

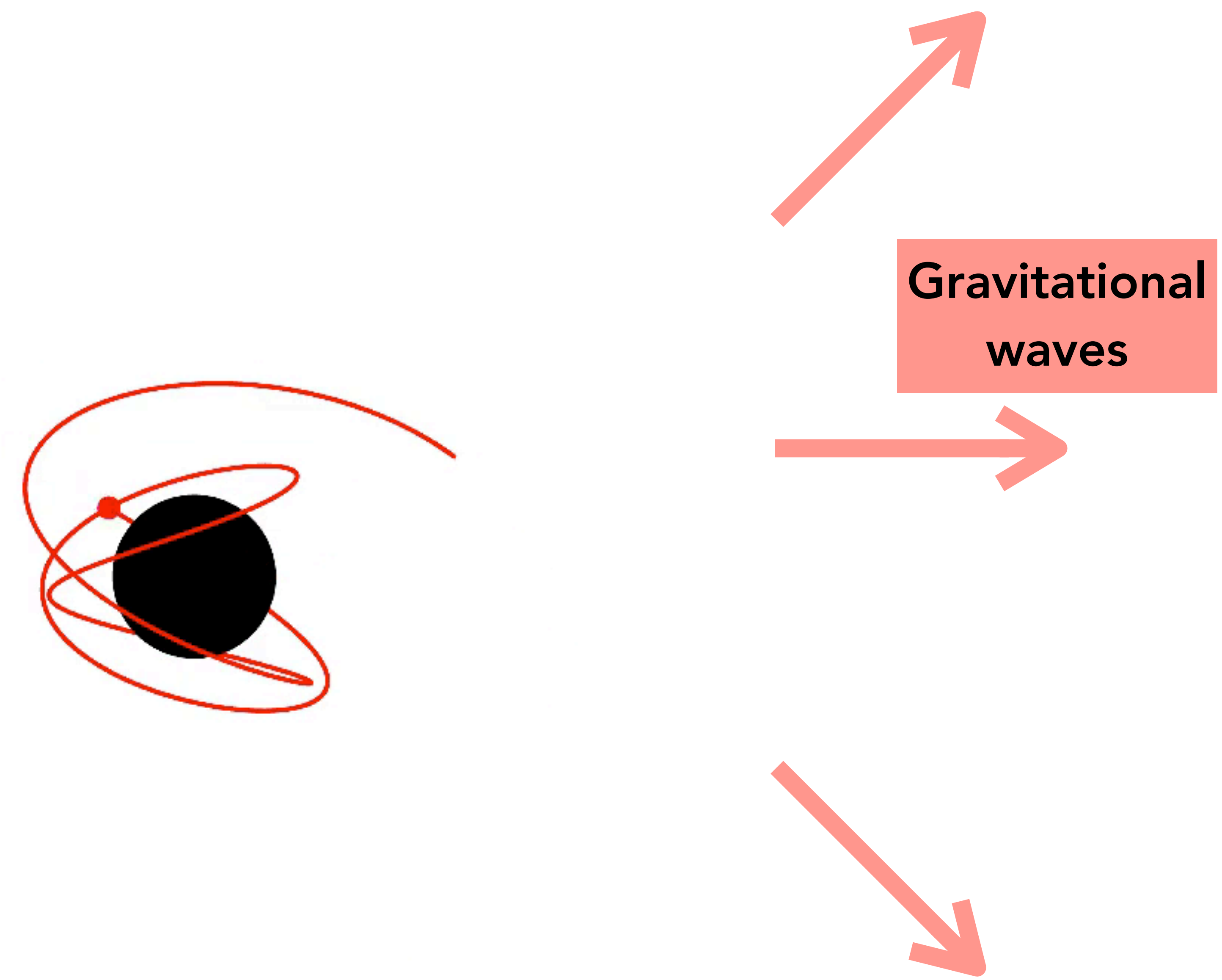
Typical time
~a few months

Supermassive BH

~4,000,000 M_{Sun}

Neutron star

~2 M_{Sun}



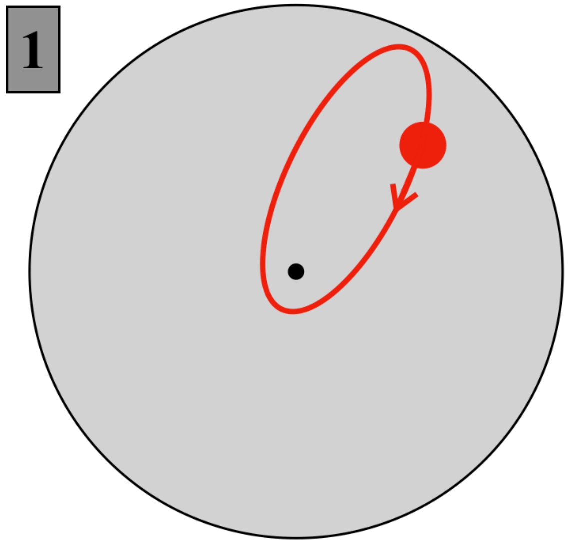
The emission of gravitational waves leads to an **unavoidable infall**

Timescales are highly hierarchical

1. Dynamical time

Fast orbital motion induced by the BH

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \Omega_{\mathrm{Kep}}$$



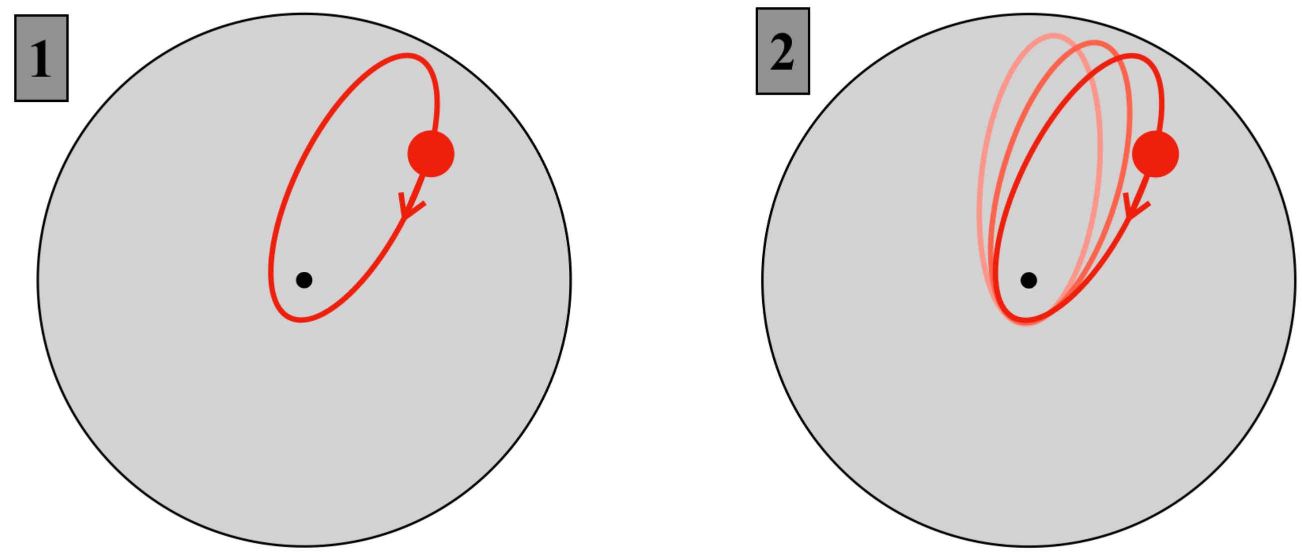
Timescales are highly hierarchical

1. Dynamical time
Fast orbital motion induced by the BH

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \Omega_{\mathrm{Kep}}$$

2. Precession time
In-plane precession (mass + relativity)

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \Omega_{\mathrm{p}}$$



Timescales are highly hierarchical

1. Dynamical time
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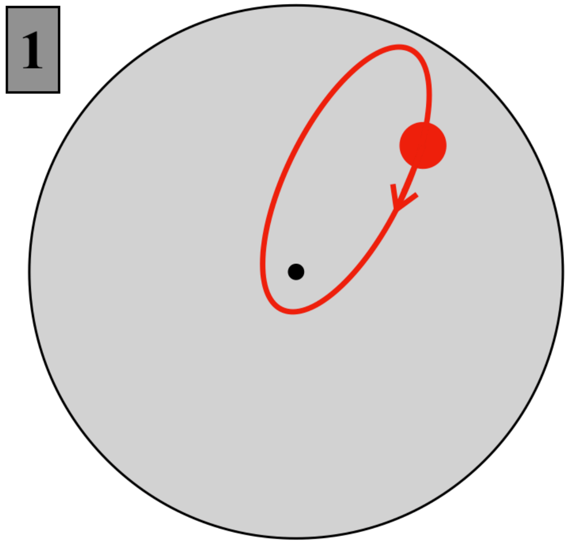
$$\frac{\mathrm{d}M}{\mathrm{d}t} = \Omega_{\mathrm{Kep}}$$

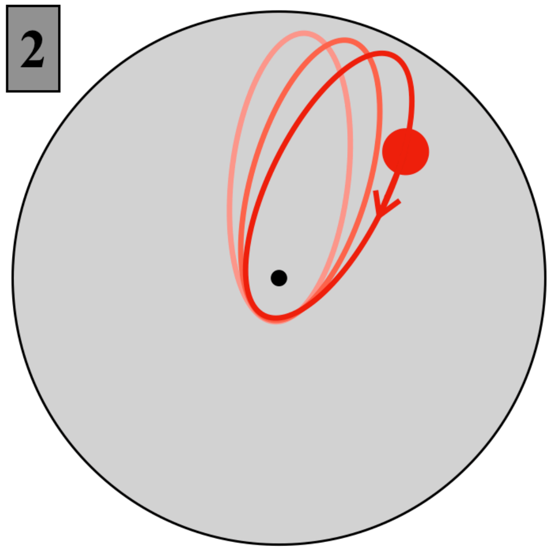
2. Precession time
In-plane precession (mass + relativity)

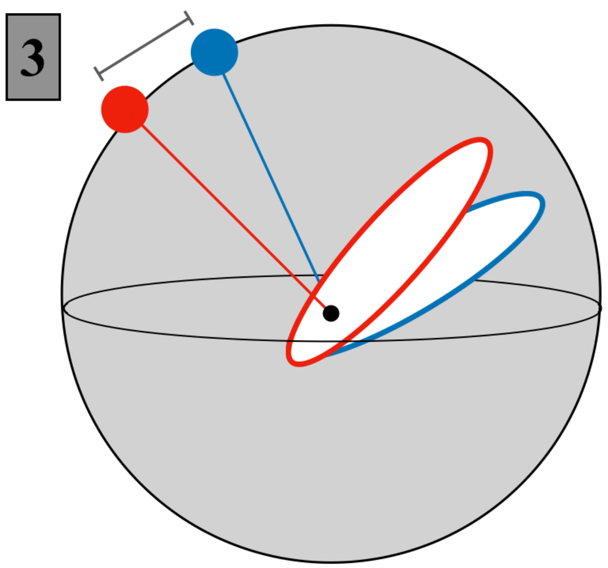
$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \Omega_{\mathrm{p}}$$

3. Vector Resonant Relaxation
Non-spherical torque coupling

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







Timescales are highly hierarchical

1. Dynamical time
Fast orbital motion induced by the BH

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \Omega_{\mathrm{Kep}}$$

2. Precession time
In-plane precession (mass + relativity)

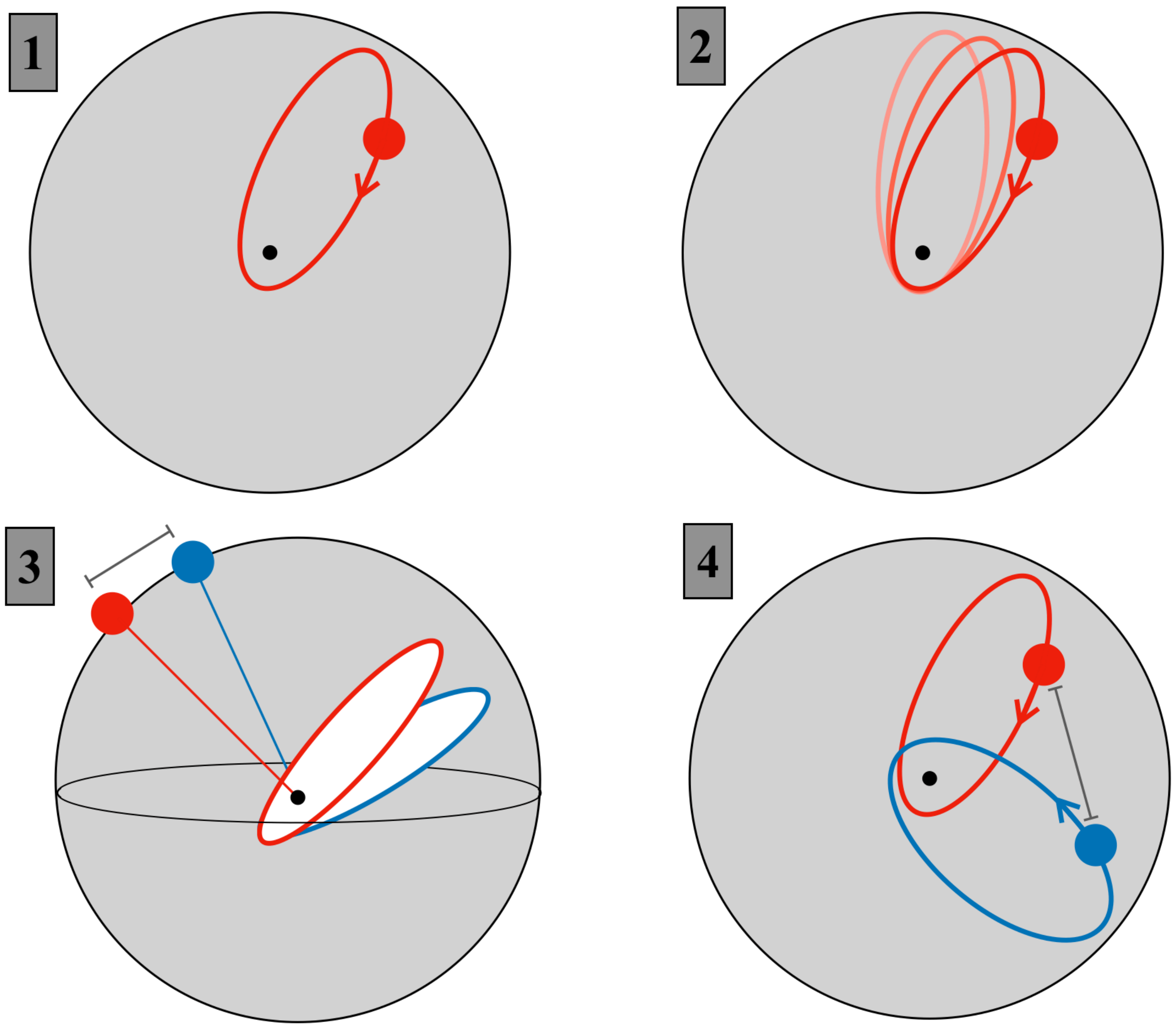
$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \Omega_{\mathrm{p}}$$

3. Vector Resonant Relaxation
Non-spherical torque coupling

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

4. Scalar Resonant Relaxation
Resonant coupling on precessions

$$\frac{\mathrm{d}e}{\mathrm{d}t} = \eta(e, t)$$



Timescales are highly hierarchical

1. Dynamical time
Fast orbital motion induced by the BH

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \Omega_{\mathrm{Kep}}$$

2. Precession time
In-plane precession (mass + relativity)

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \Omega_{\mathrm{p}}$$

3. Vector Resonant Relaxation
Non-spherical torque coupling

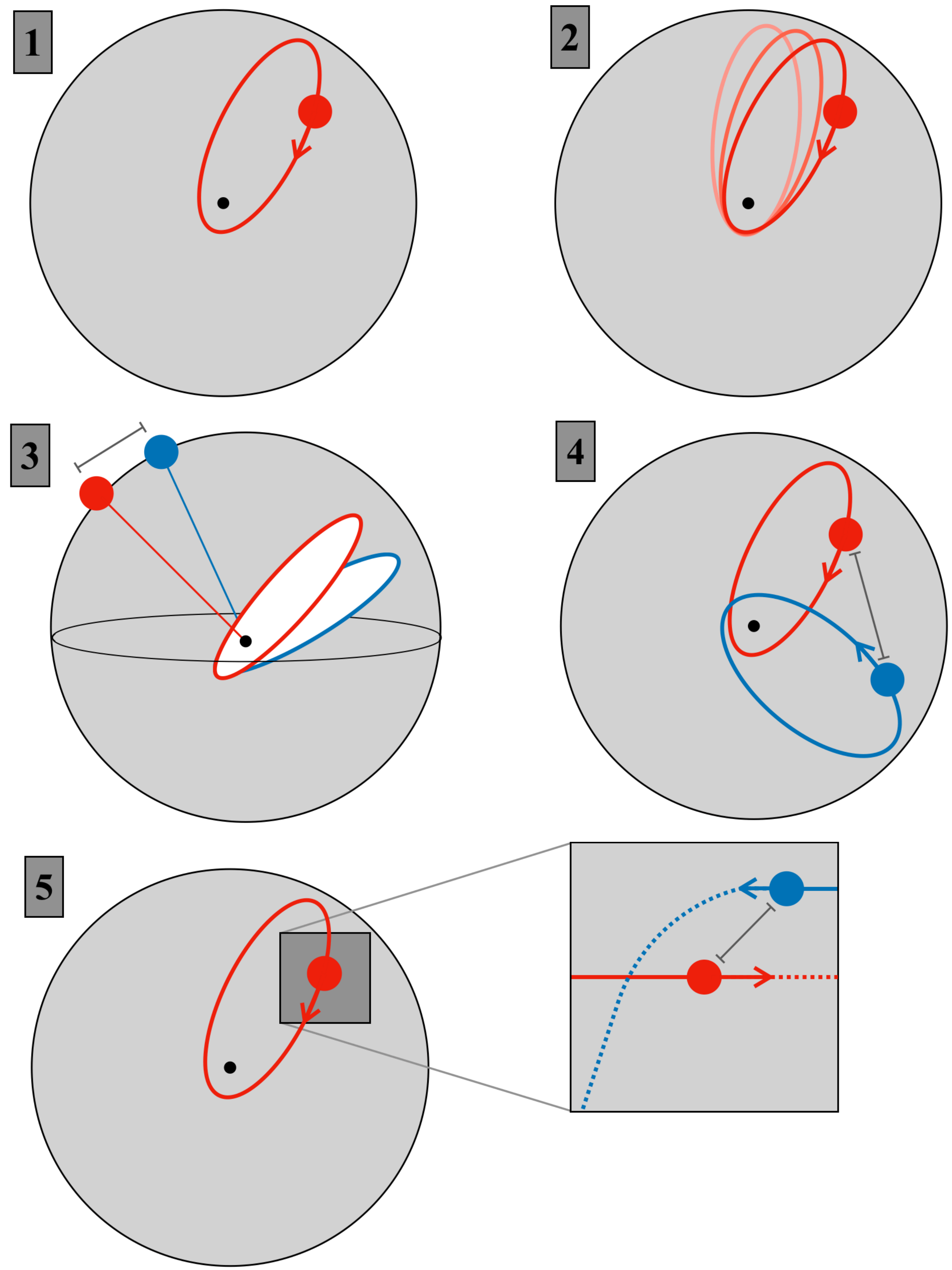
$$\frac{\mathrm{d}\hat{\mathbf{L}}}{\mathrm{d}t} = \eta(\hat{\mathbf{L}}, t)$$

4. Scalar Resonant Relaxation
Resonant coupling on precessions

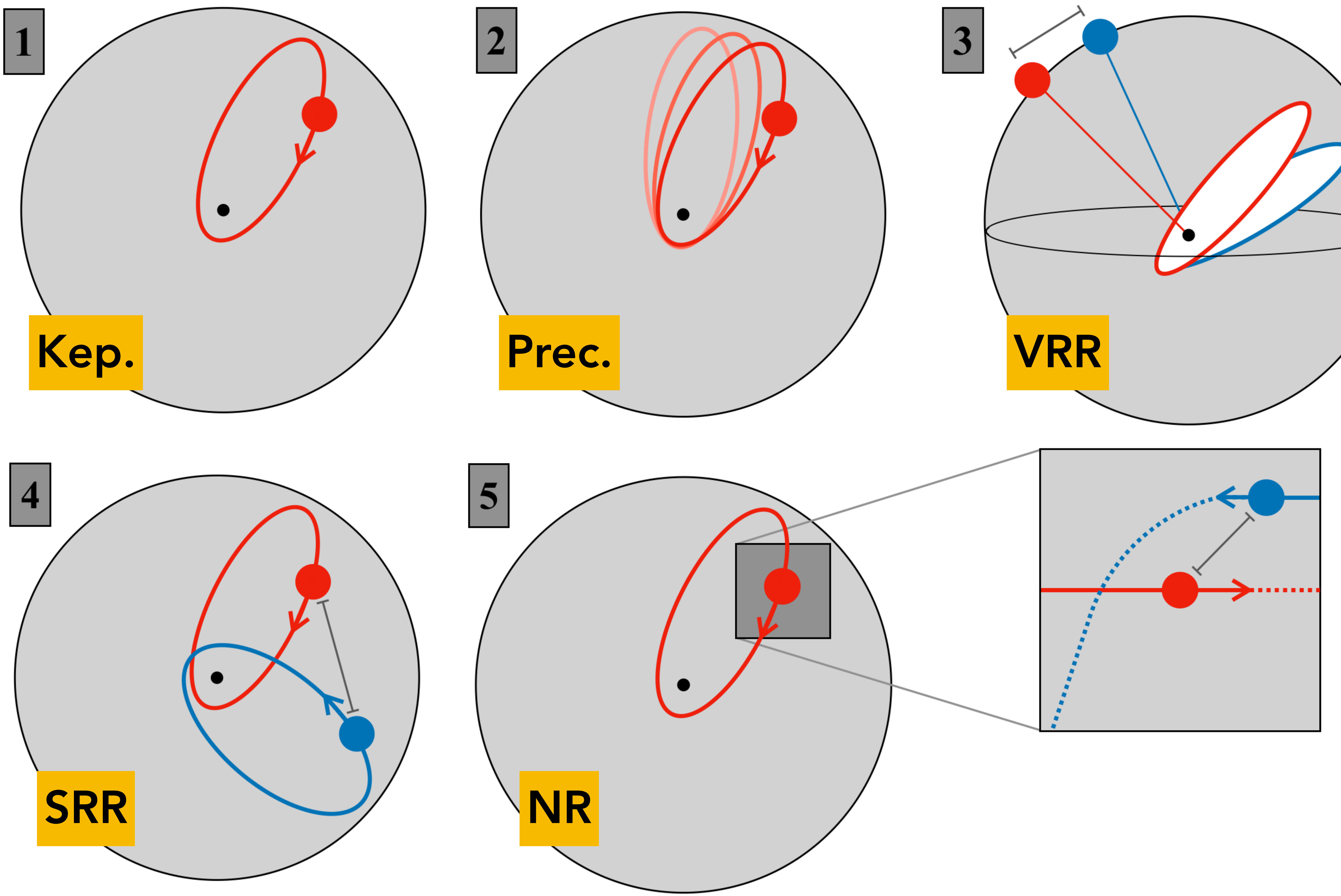
$$\frac{\mathrm{d}e}{\mathrm{d}t} = \eta(e, t)$$

5. Non-Resonant Relaxation
Local two-body encounters

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \eta(a, t)$$

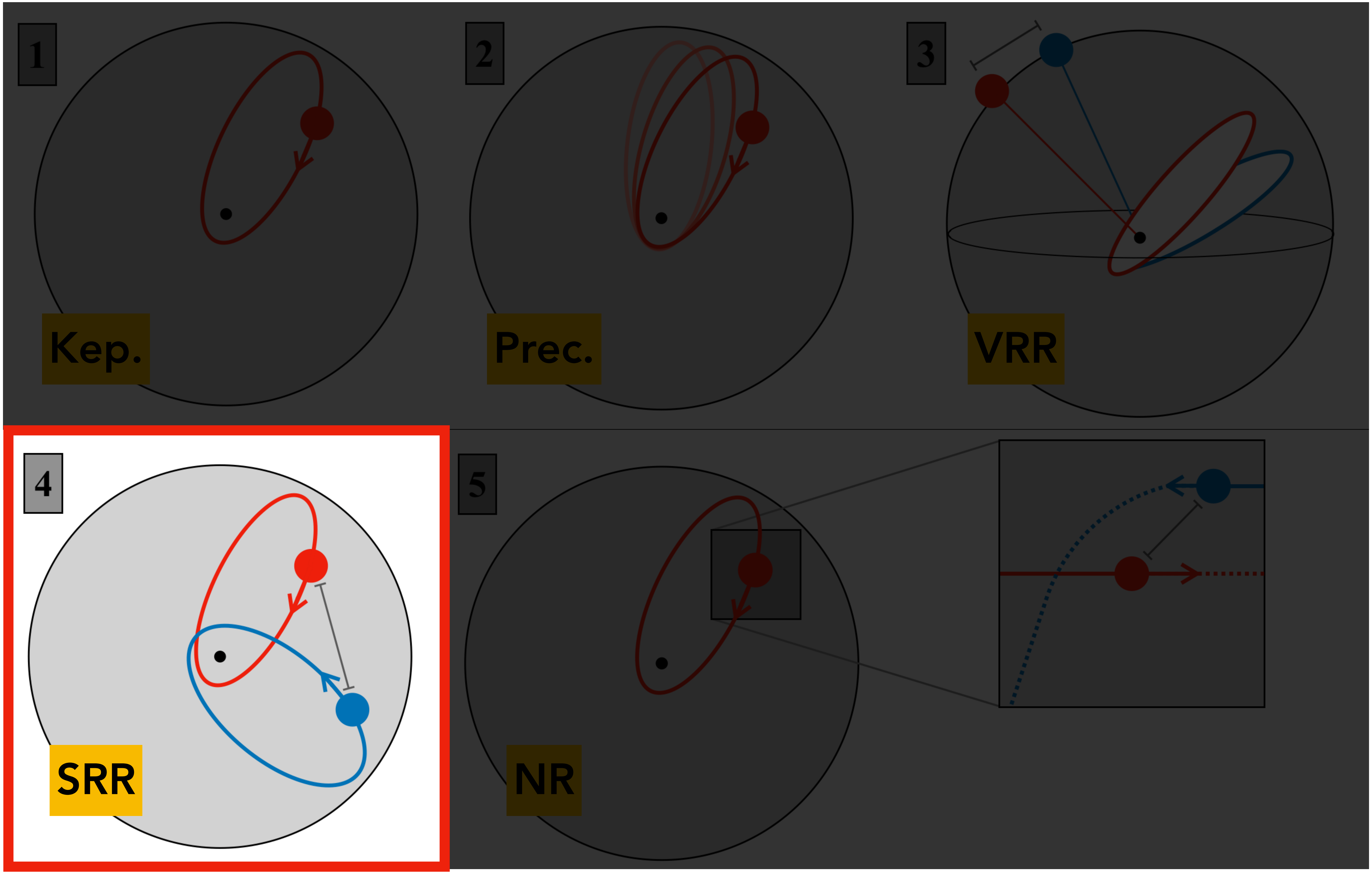


A wealth of dynamical processes



An extremely **hierarchical system**

Scalar Resonant Relaxation

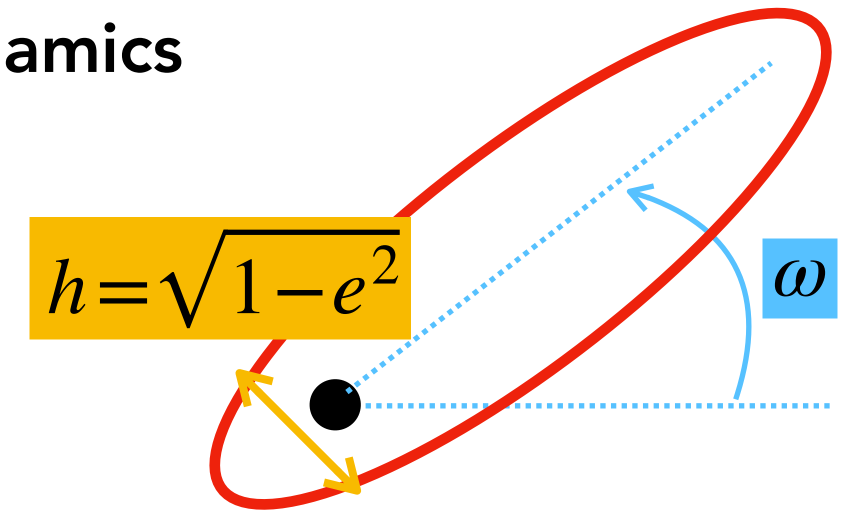


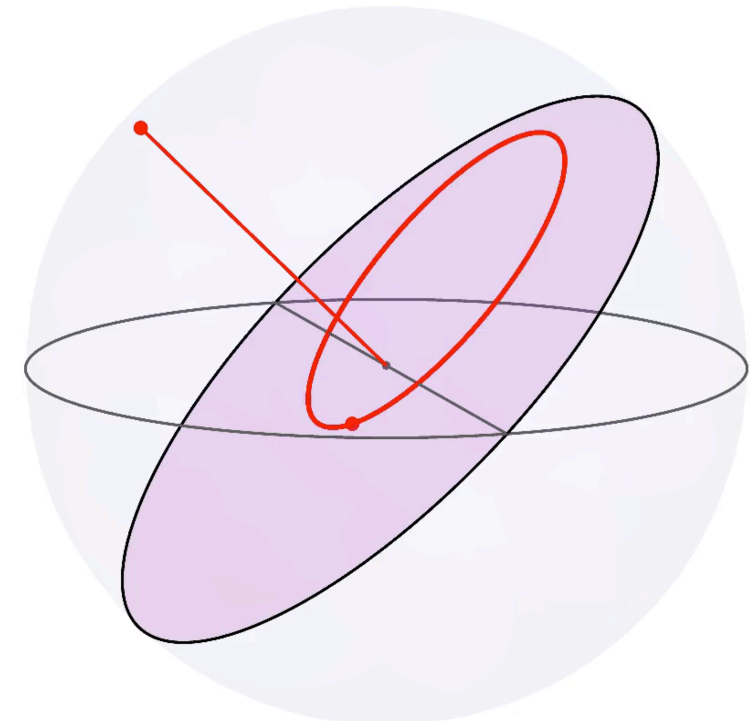
The (resonant) dynamics of **eccentricities**

Scalar Resonant Relaxation

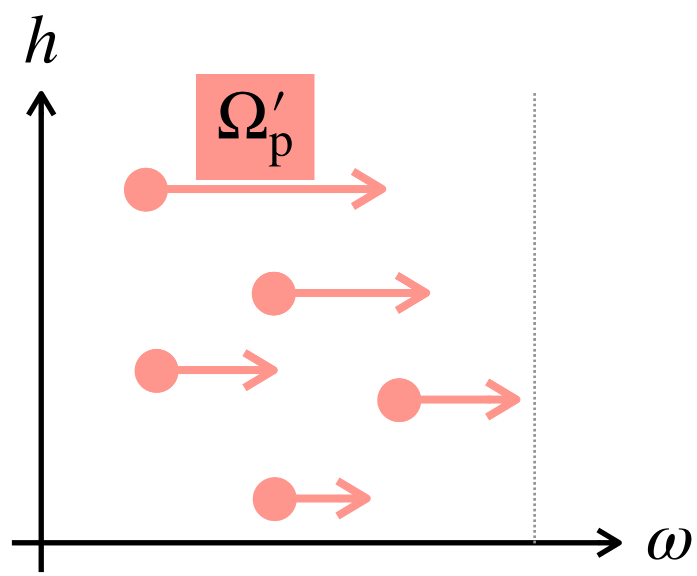
A simple **unperturbed dynamics**

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

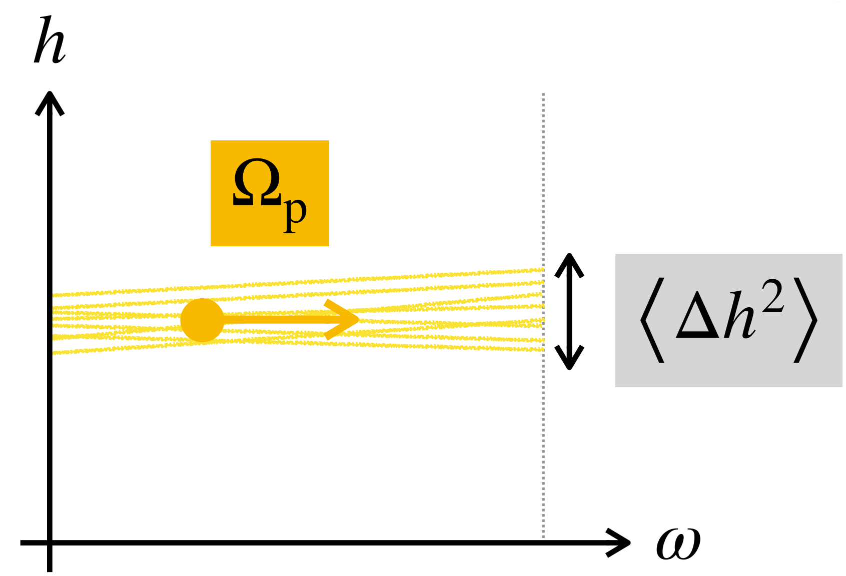




Phase-space dynamics



Background cluster



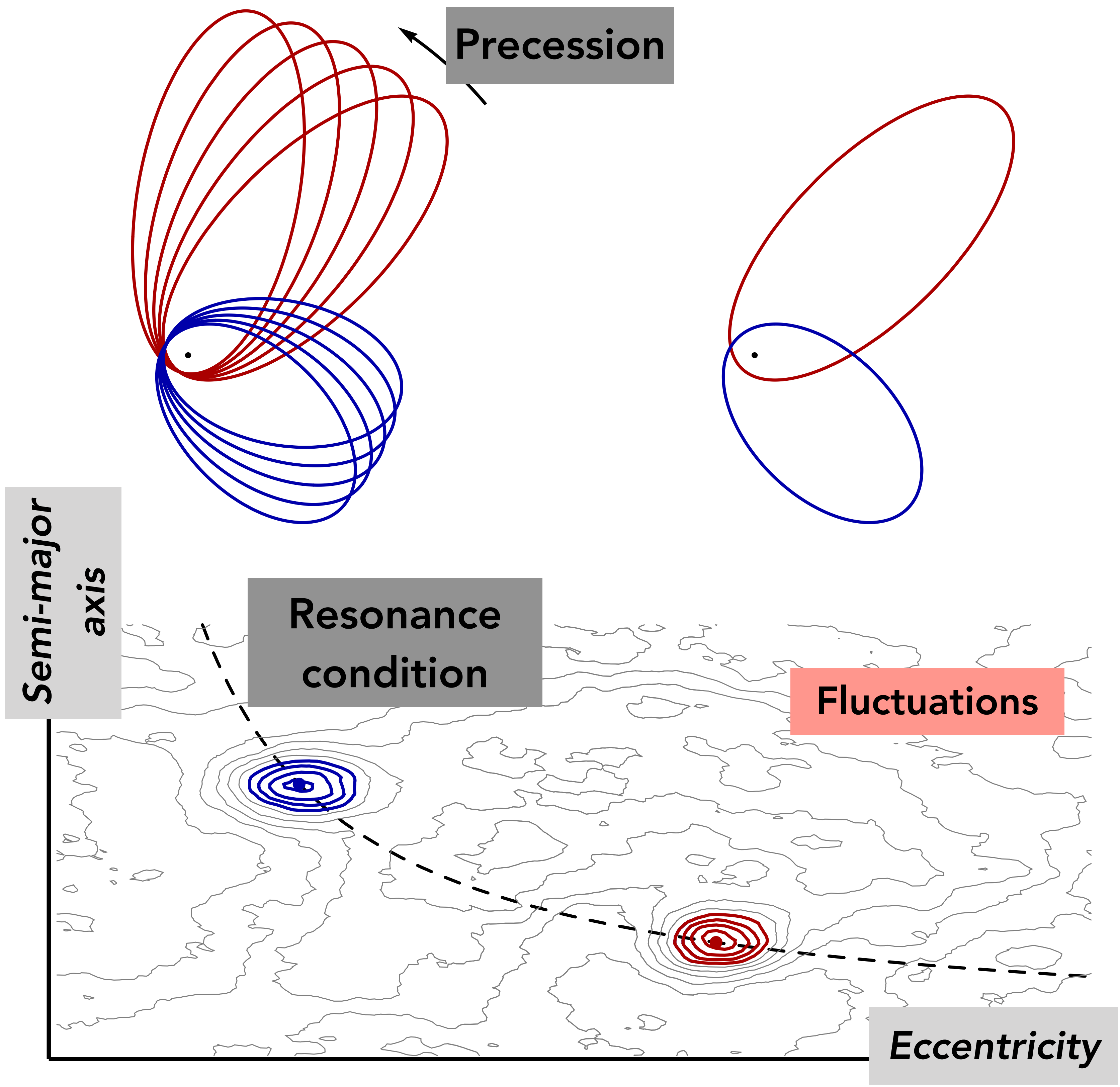
Test particle

Relaxation occurs at **resonance**

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

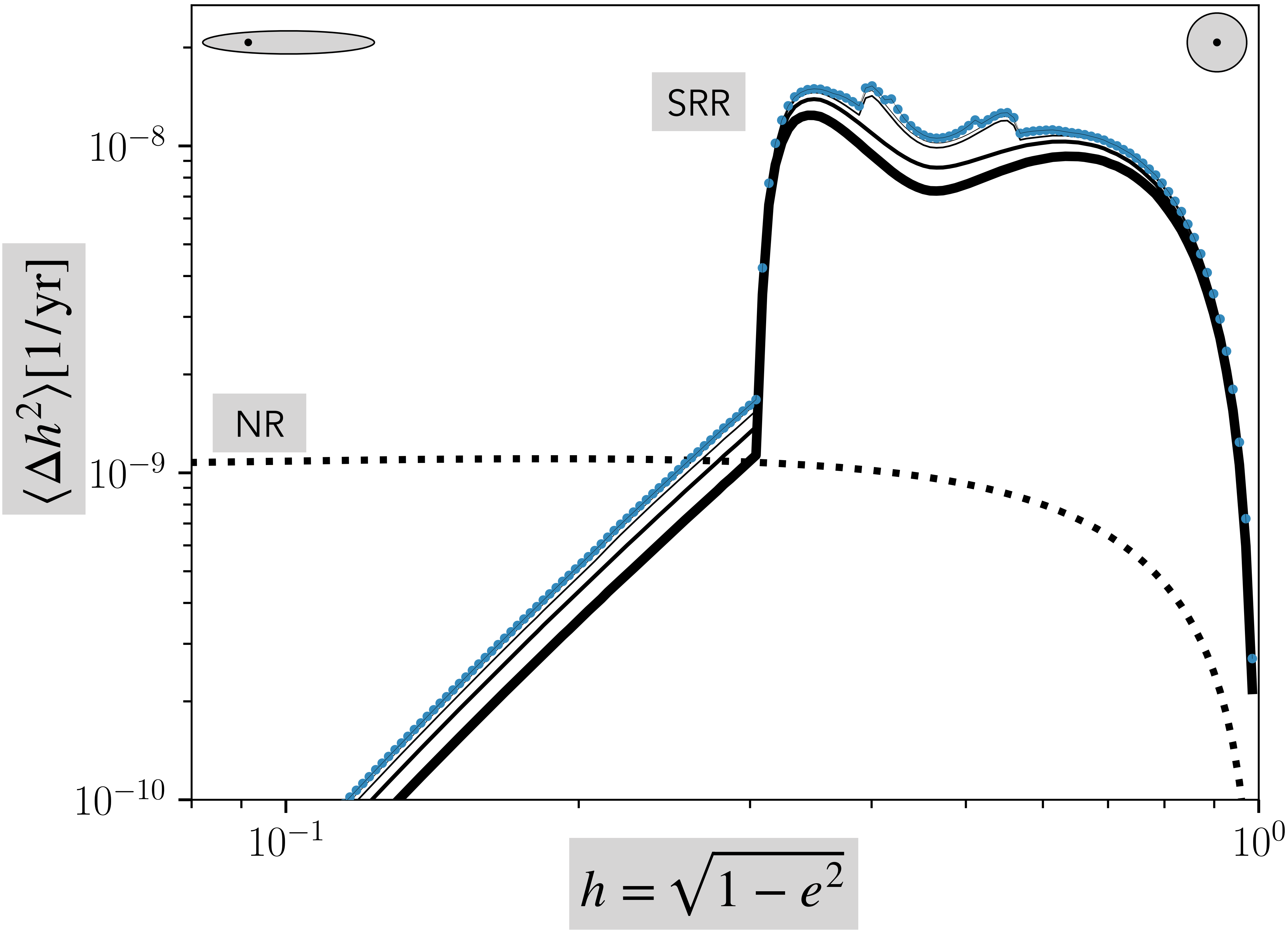
Balescu-Lenard equation

Non-local resonances

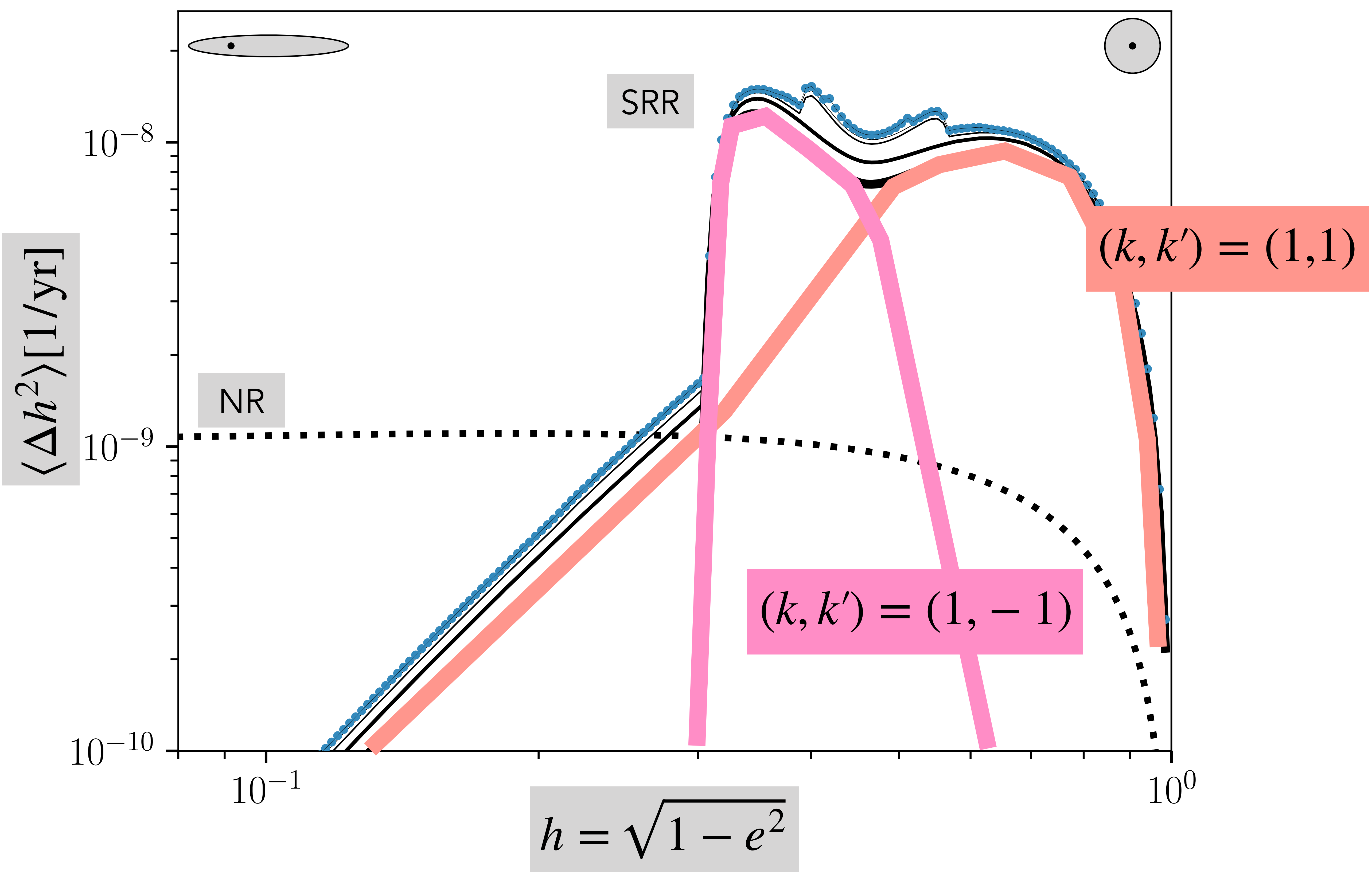


Non-local resonances
between wires

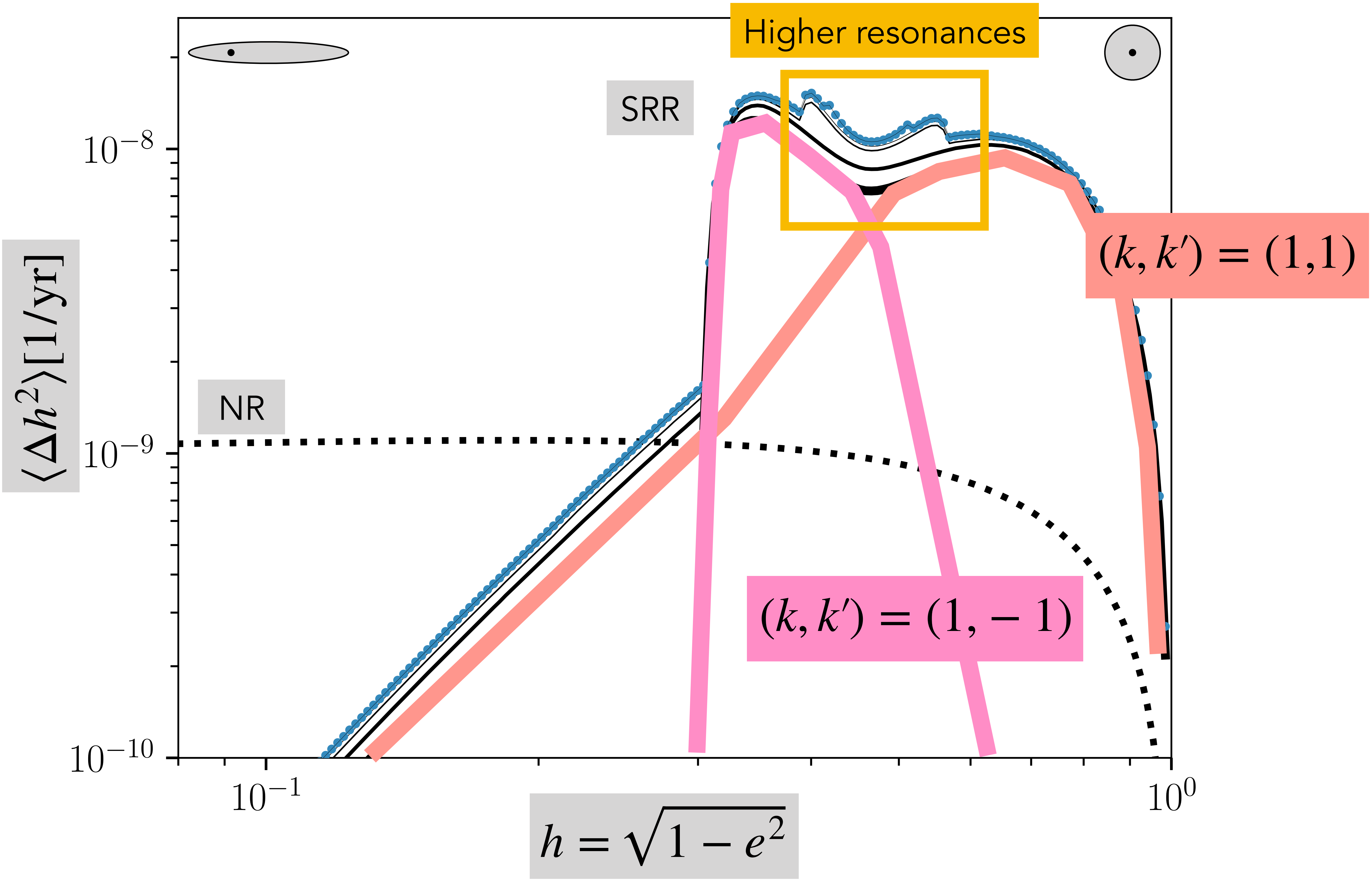
The diffusion coefficients in eccentricity



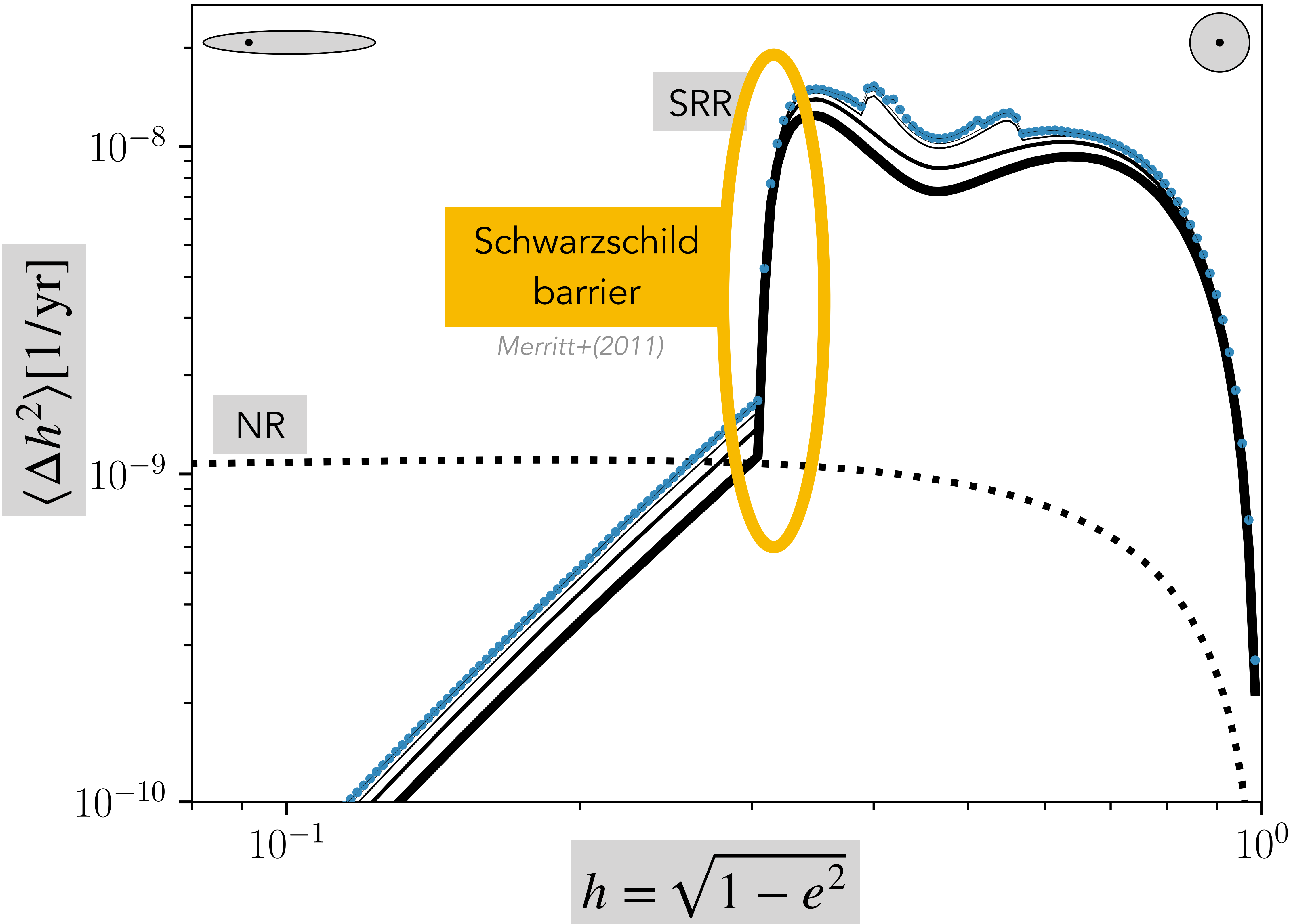
Non-local resonances $\delta_{\mathrm{D}}[k\,\Omega_{\mathrm{p}}(a,h) - k'\,\Omega_{\mathrm{p}}(a',h')]$



Non-local resonances $\delta_{\mathrm{D}}[k\,\Omega_{\mathrm{p}}(a,h) - k'\,\Omega_{\mathrm{p}}(a',h')]$



The diffusion coefficients in eccentricity

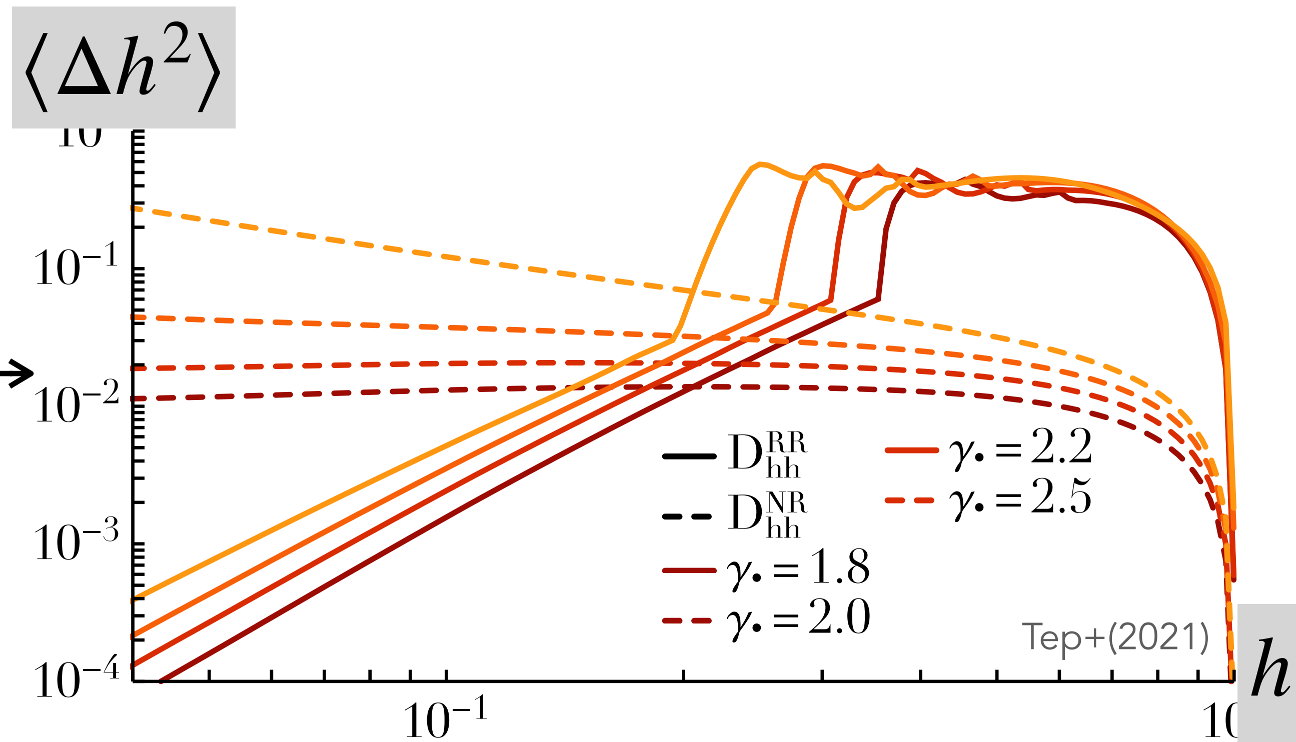


SRR around SgrA*

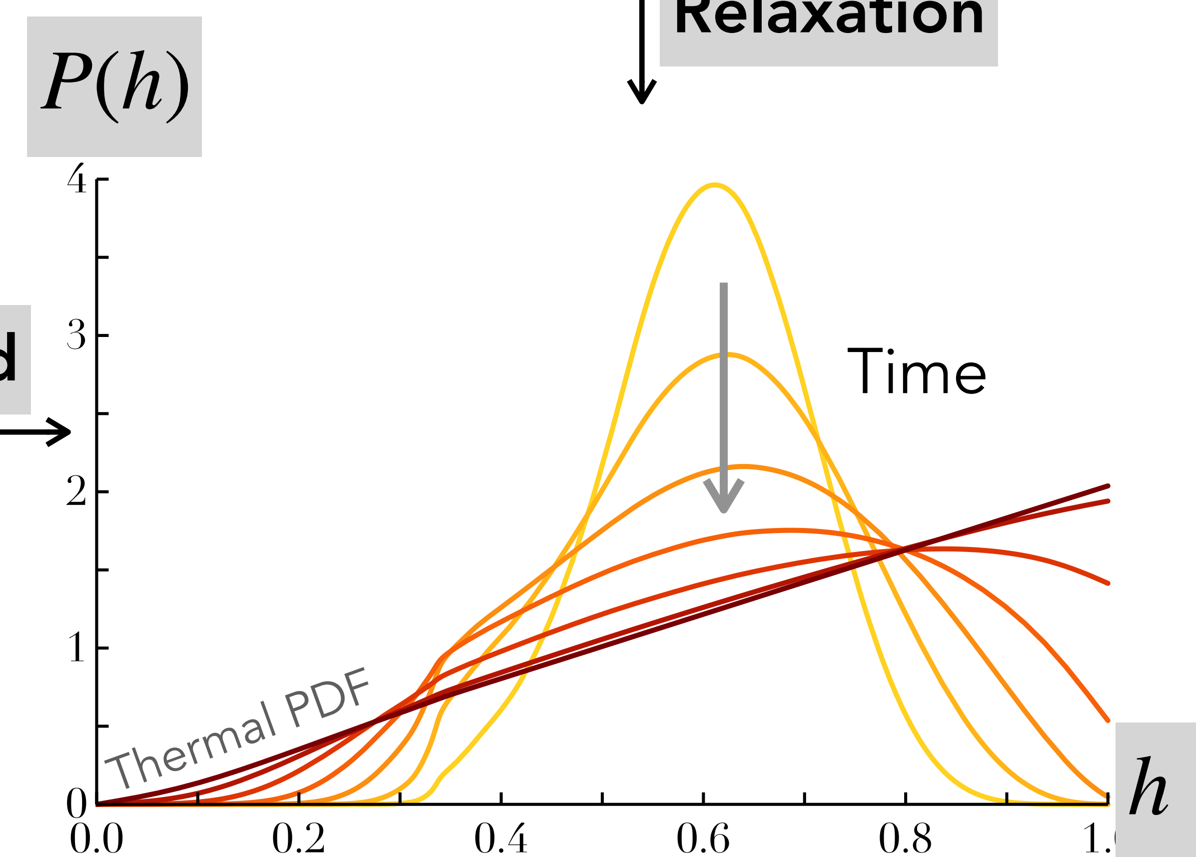
Model

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

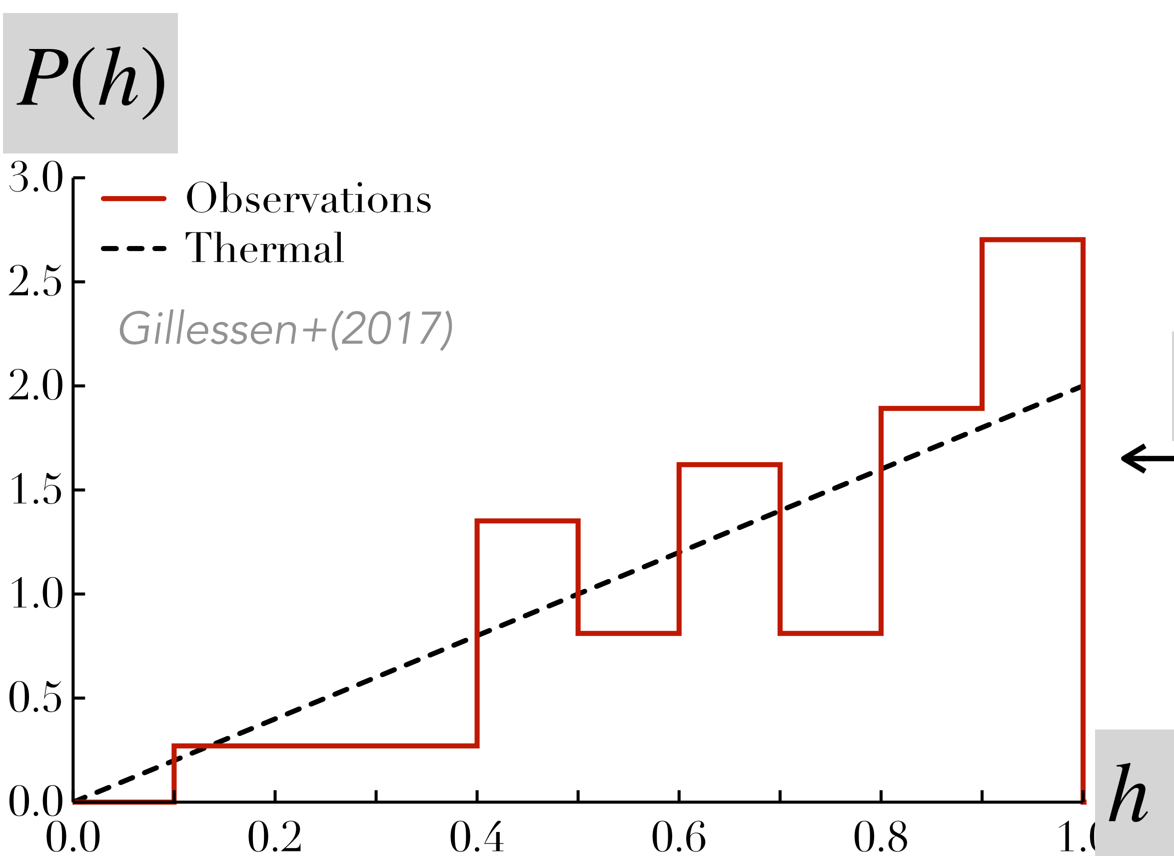
Kinetic theory



Relaxation

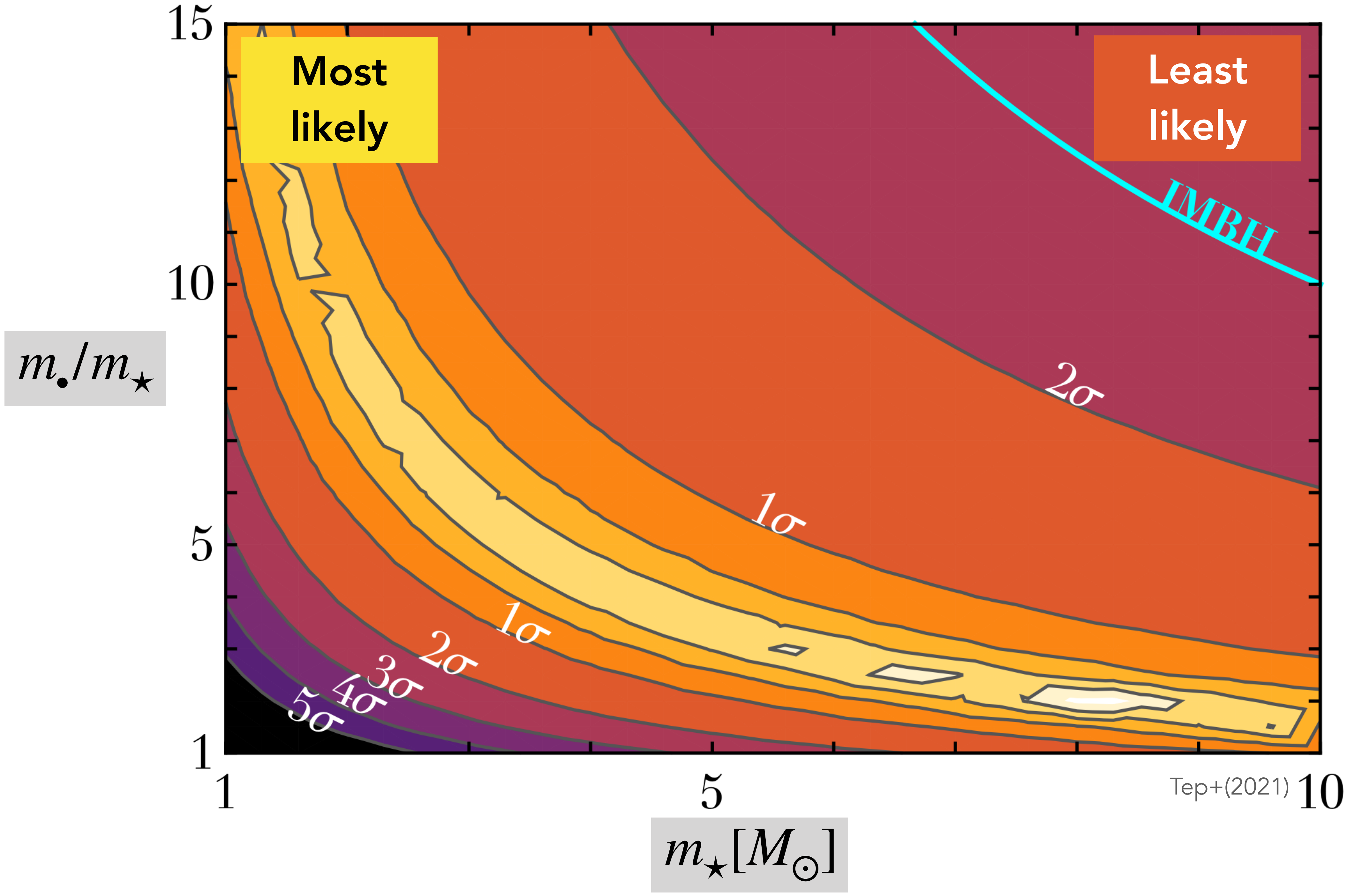


Likelihood



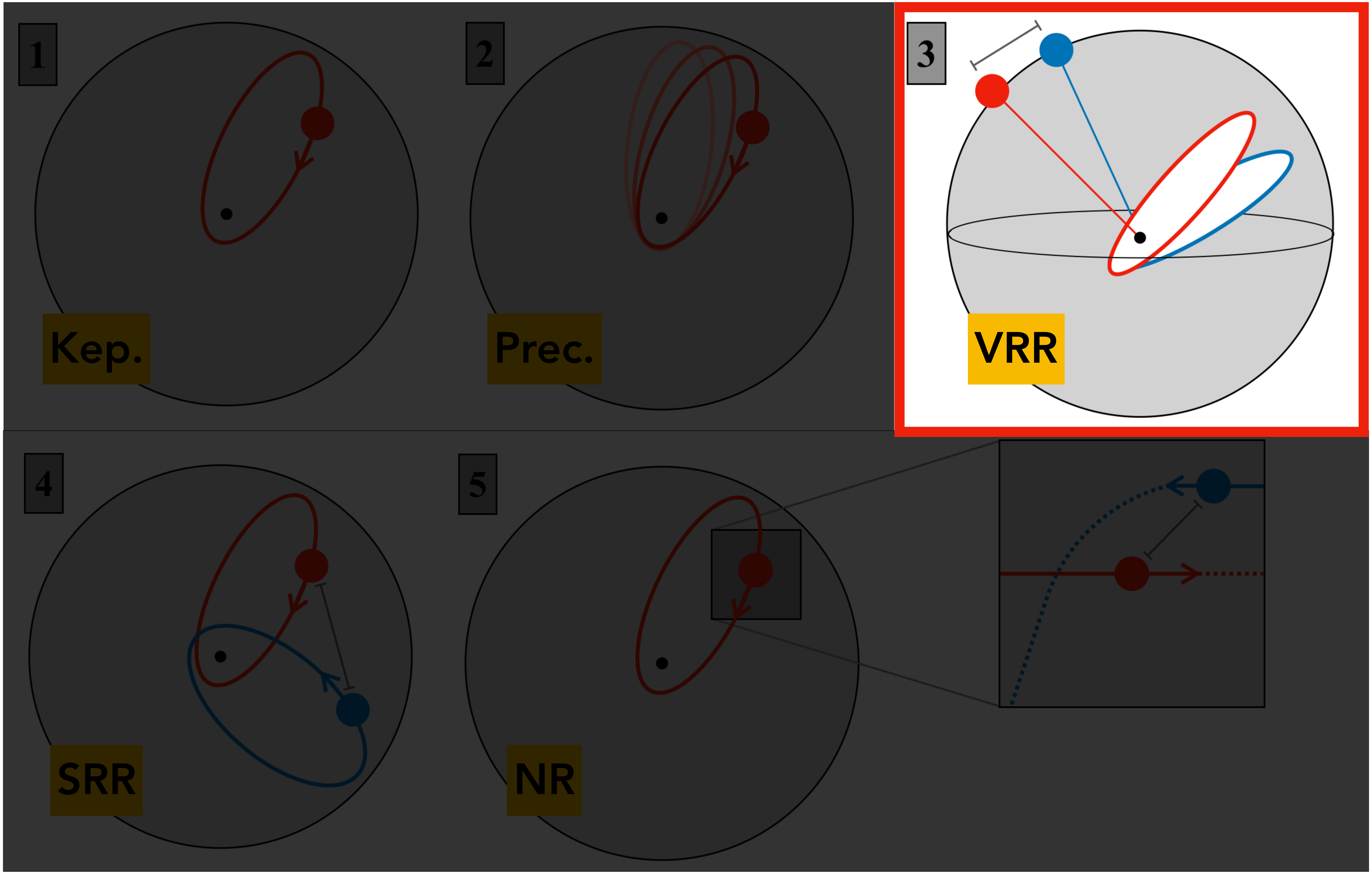
Constraining IMBHs from SRR

2-population model (stars+IMBHs)



IMBHs population hard to reconcile with the **eccentricity distribution**

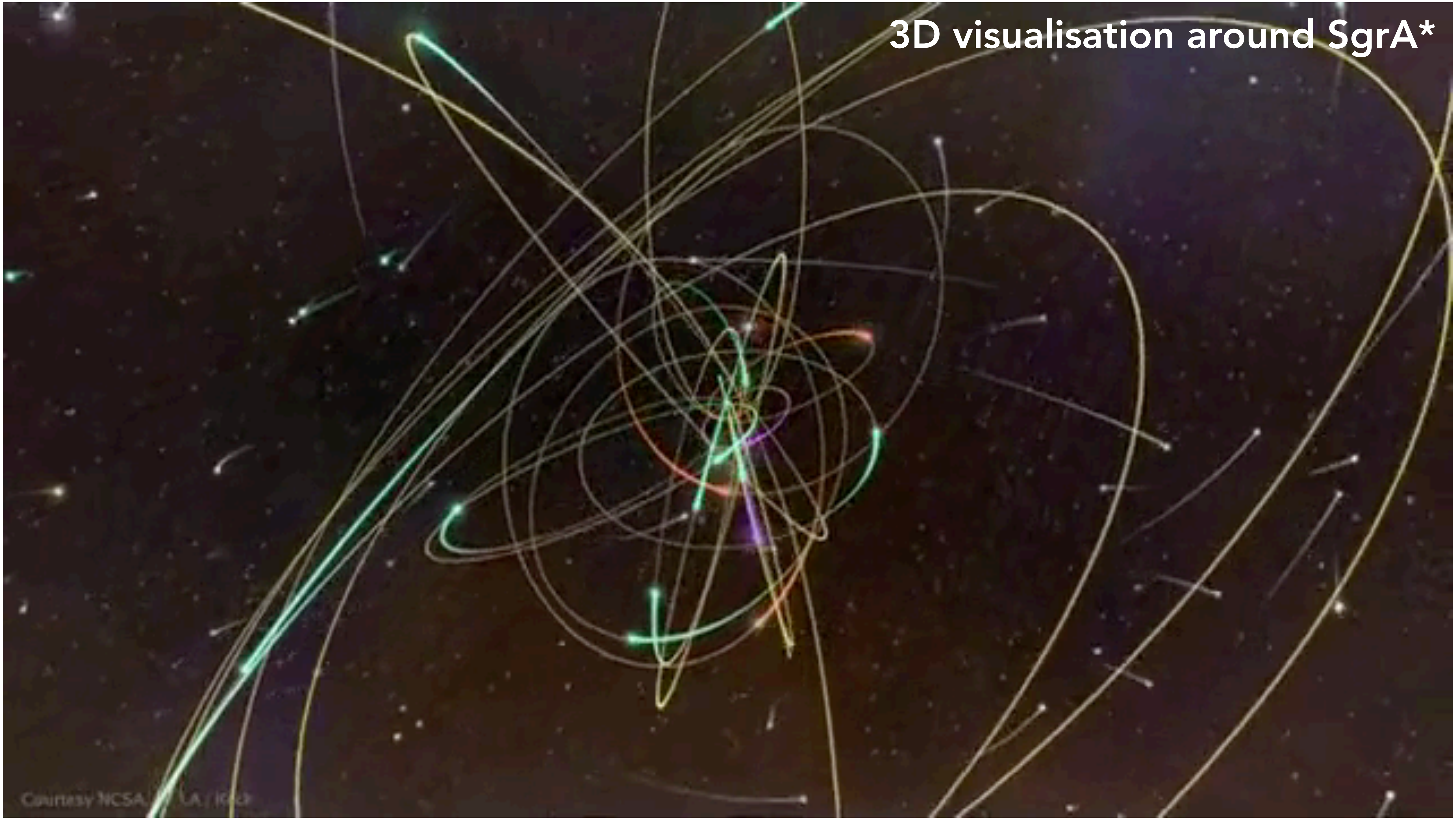
Vector Resonant Relaxation



The coherent dynamics of **orientations**

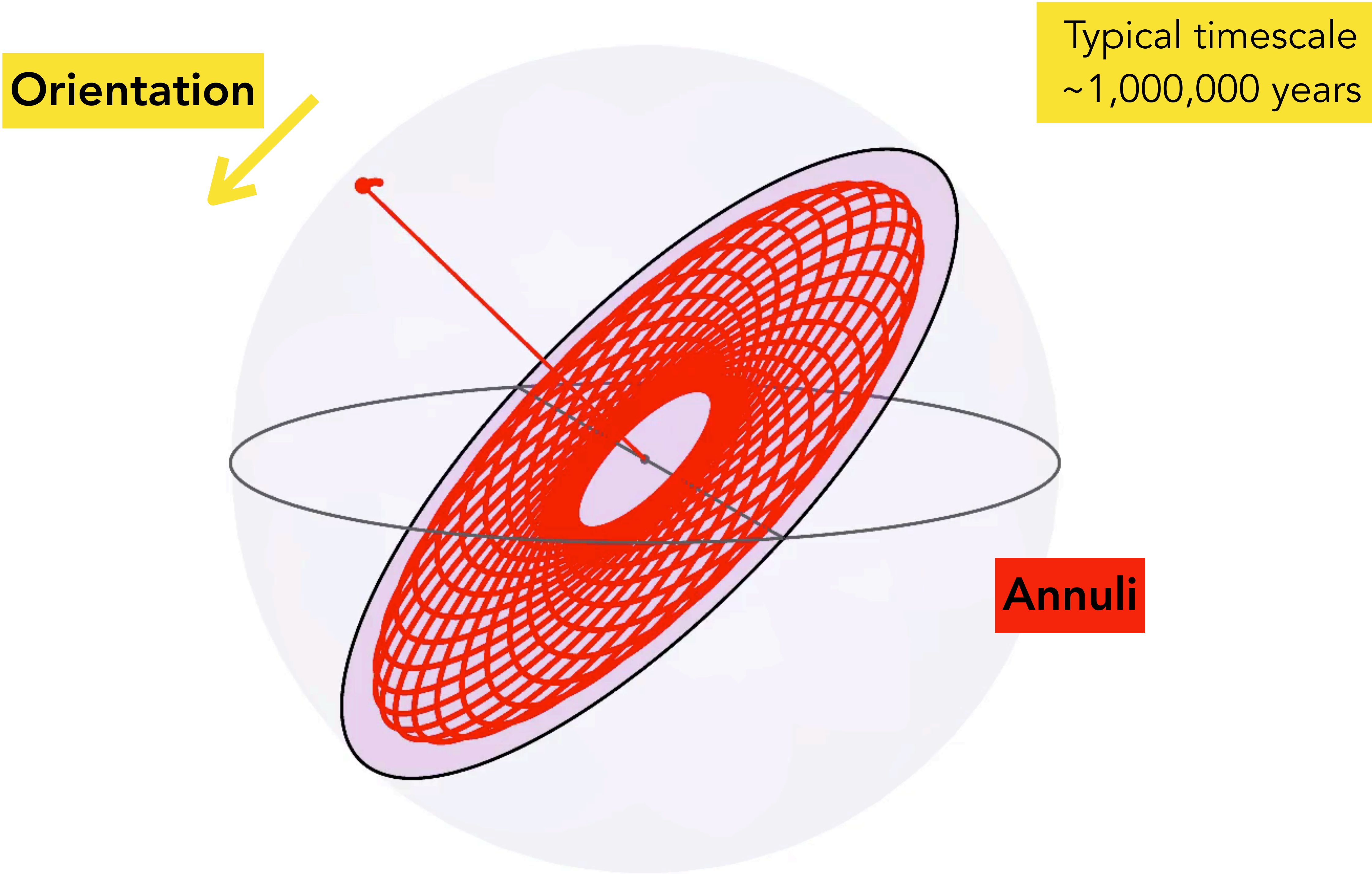
Stellar orientations

Orbits are in **all directions**



How do stars change of **orientations**?

Stellar orientations



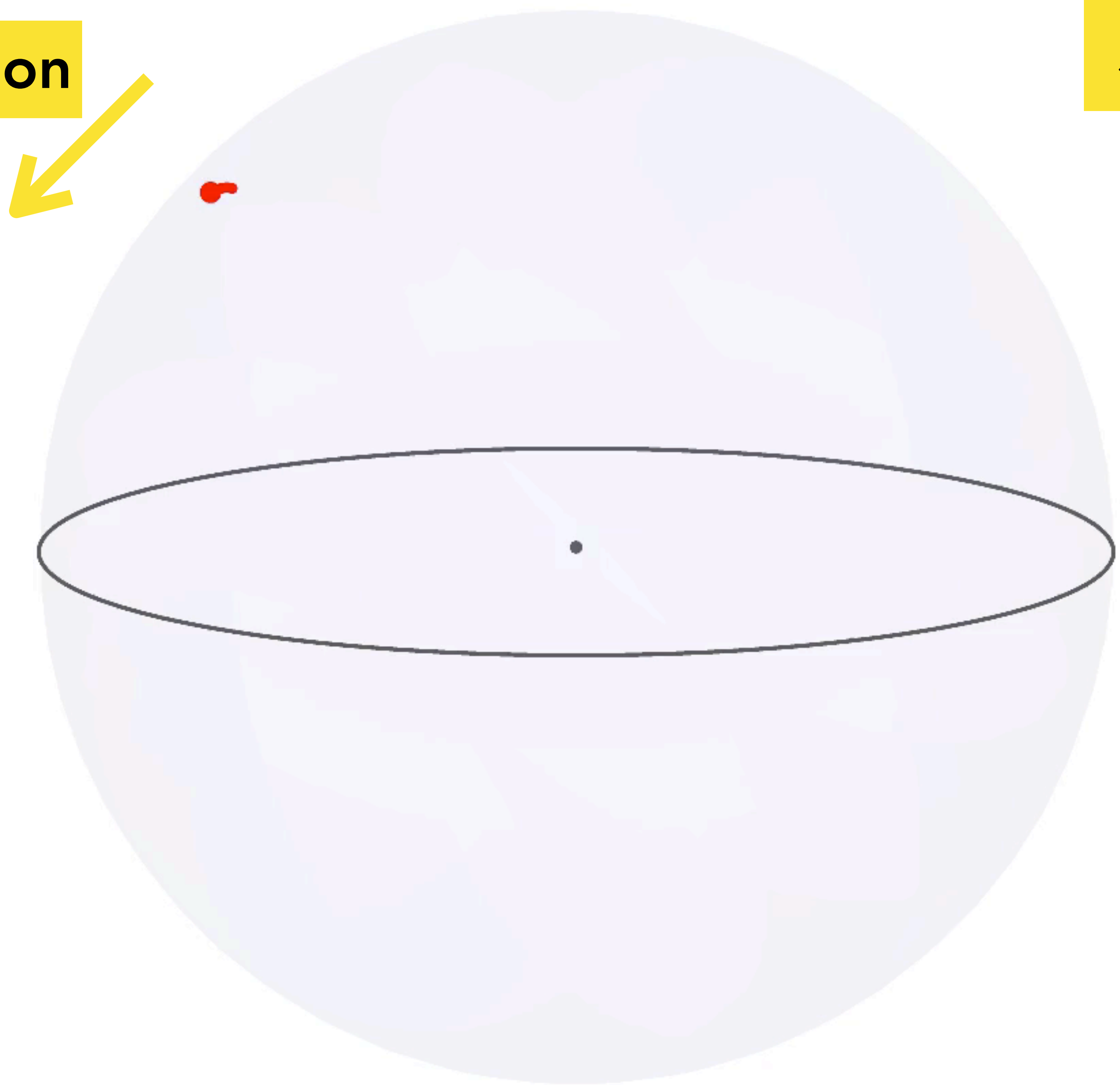
After a full precession, **ellipses** become **annuli**

Orbital orientations

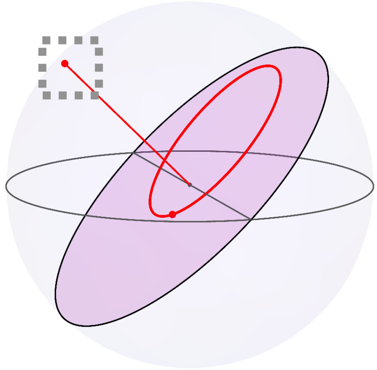
Orientation

$\hat{\mathbf{L}}$

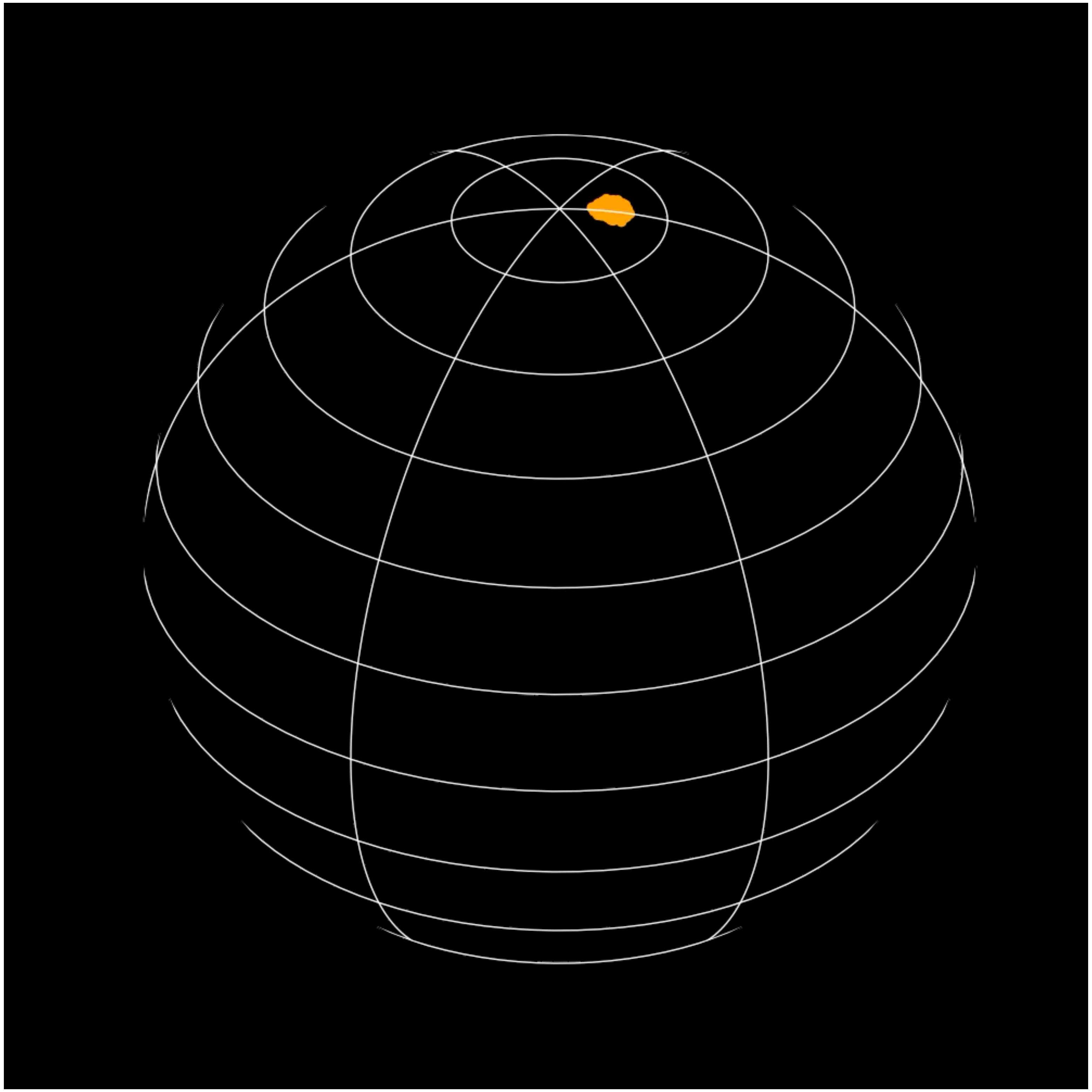
Typical timescale
~1,000,000 years



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



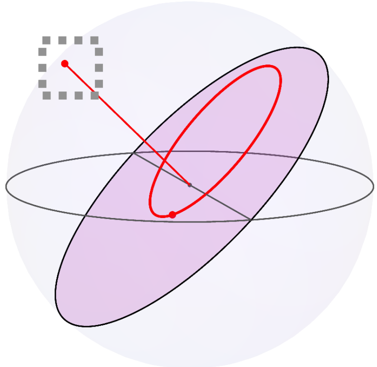
Vector Resonant Relaxation



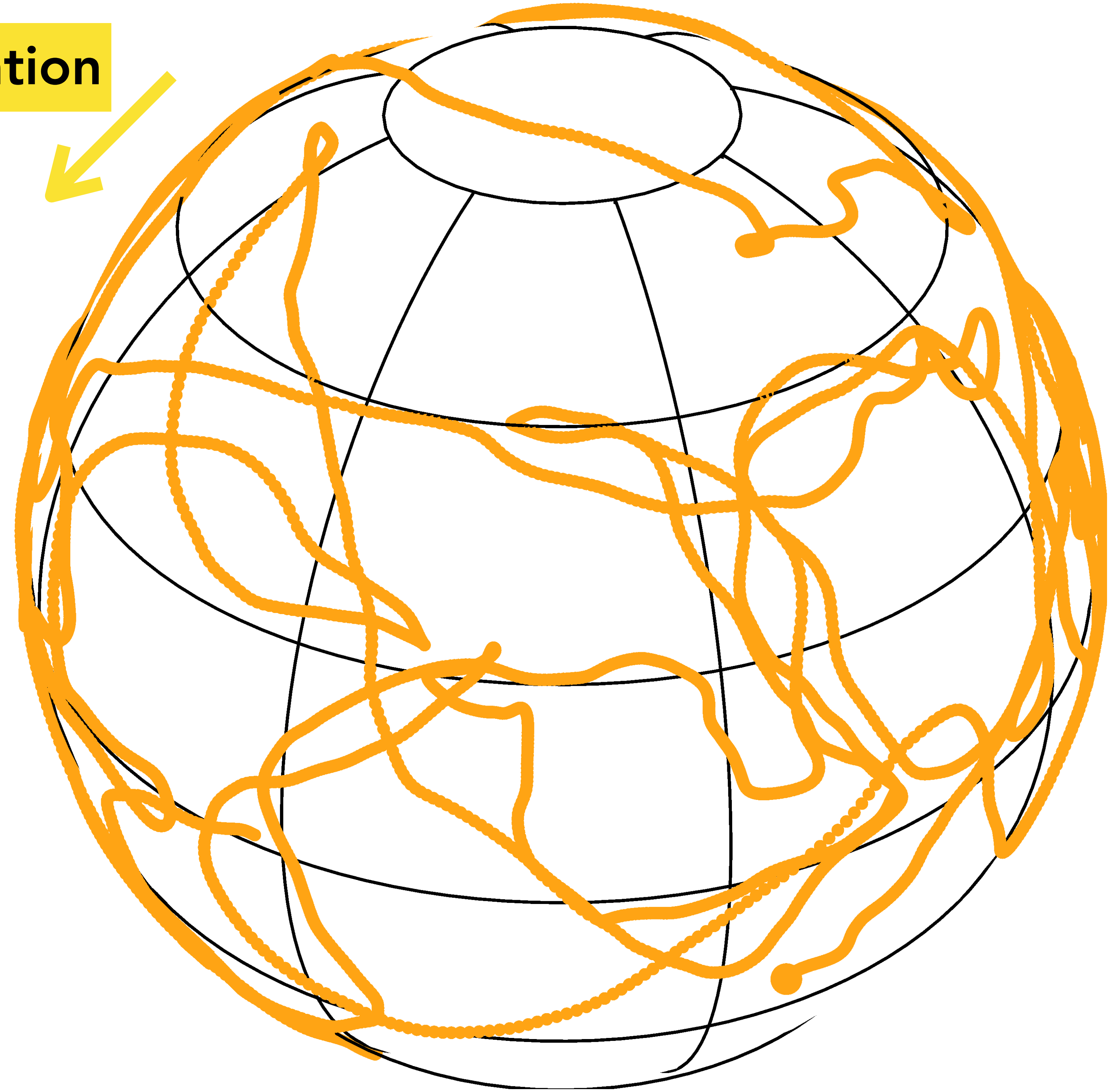
+ Motion coherent on large scales
  - **Long-range interacting system**
+ Motion smooth on short times
  - **Time-correlated noise**
+ Particles have ``preferred friends"
  - **Parametric coupling** (a, e)
+ System in statistical equilibrium
  - **Time stationarity** $(t - t')$
  - **Rotation invariance** $(\hat{\mathbf{L}} \cdot \hat{\mathbf{L}}')$

This is an intrinsically turbulent dynamics

Typical evolution of an orientation



Orientation

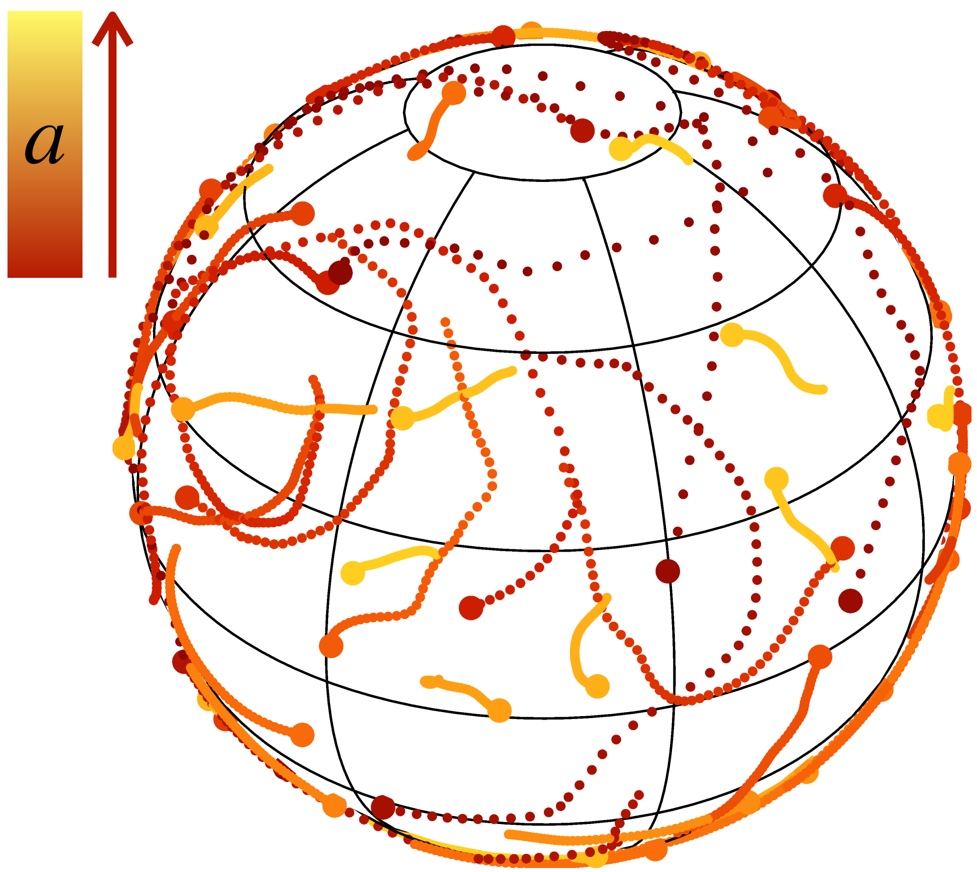


Typical timescale
~1,000,000 years

Stellar orientations follow a **correlated random walk**

Self-consistency requirement

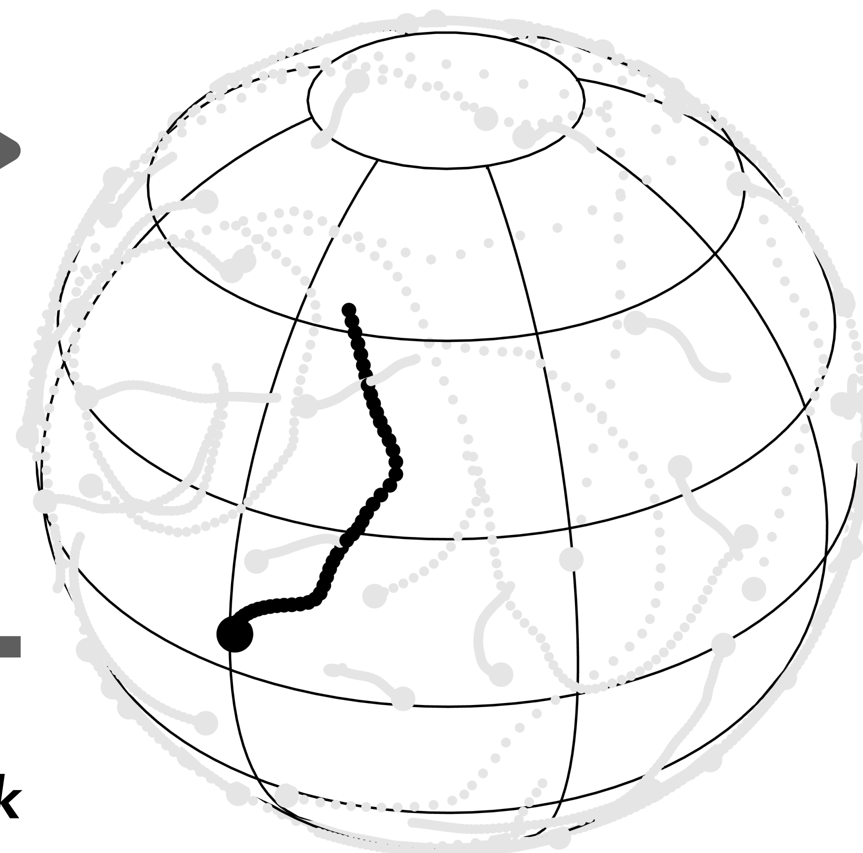
Background particles



Imposes a noisy (correlated) ***potential***

Undergoes a (correlated) ***random walk***

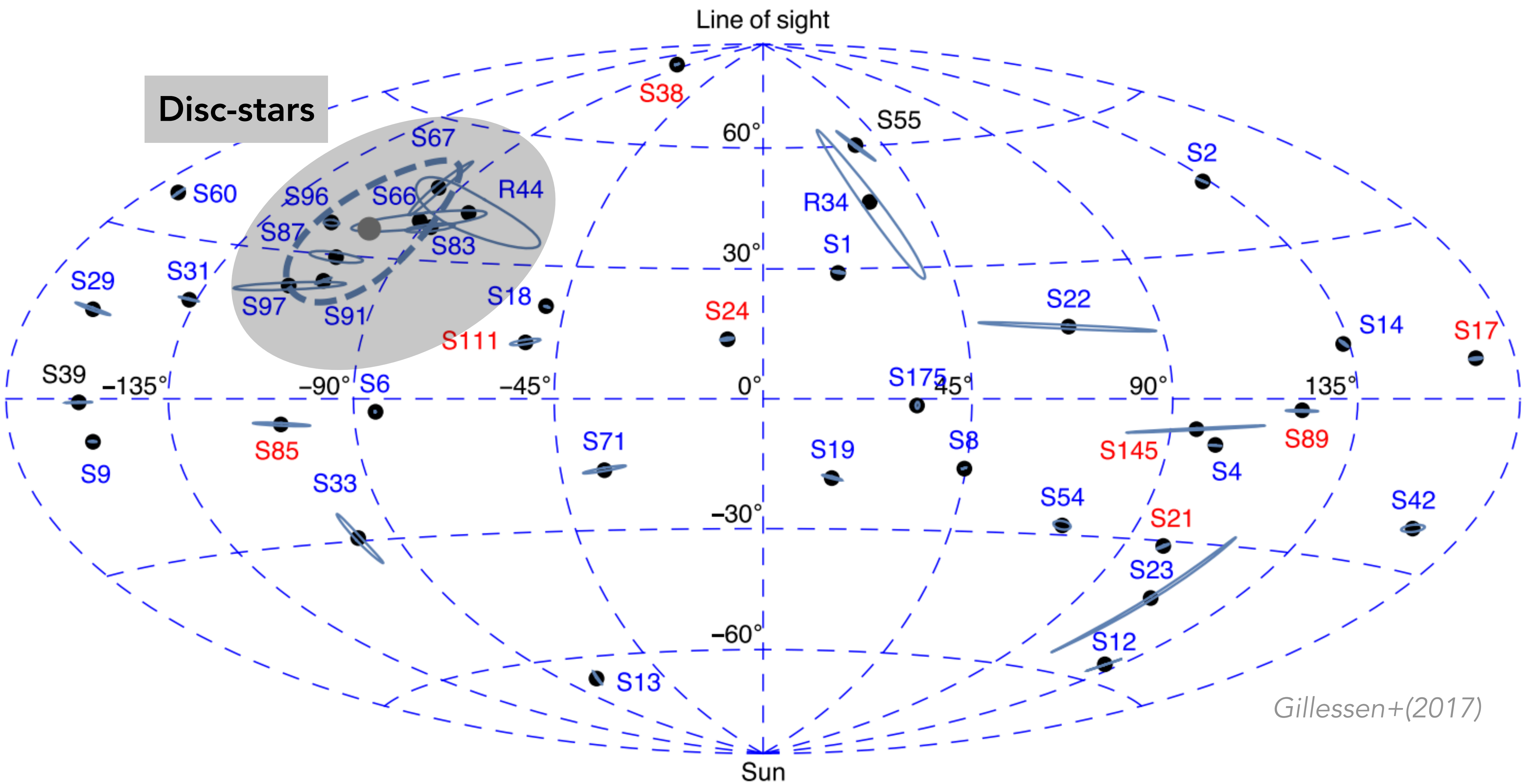
Test particle



$$\hat{C}_{\mathrm{bath}} = \left\langle \eta(\hat{\mathbf{L}}, t)\, \eta(\hat{\mathbf{L}}', t') \right\rangle$$

$$\hat{C}_{\mathrm{test}} = \left\langle \hat{\mathbf{L}}_{\mathrm{test}}(t) \cdot \hat{\mathbf{L}}_{\mathrm{test}}(0) \right\rangle$$

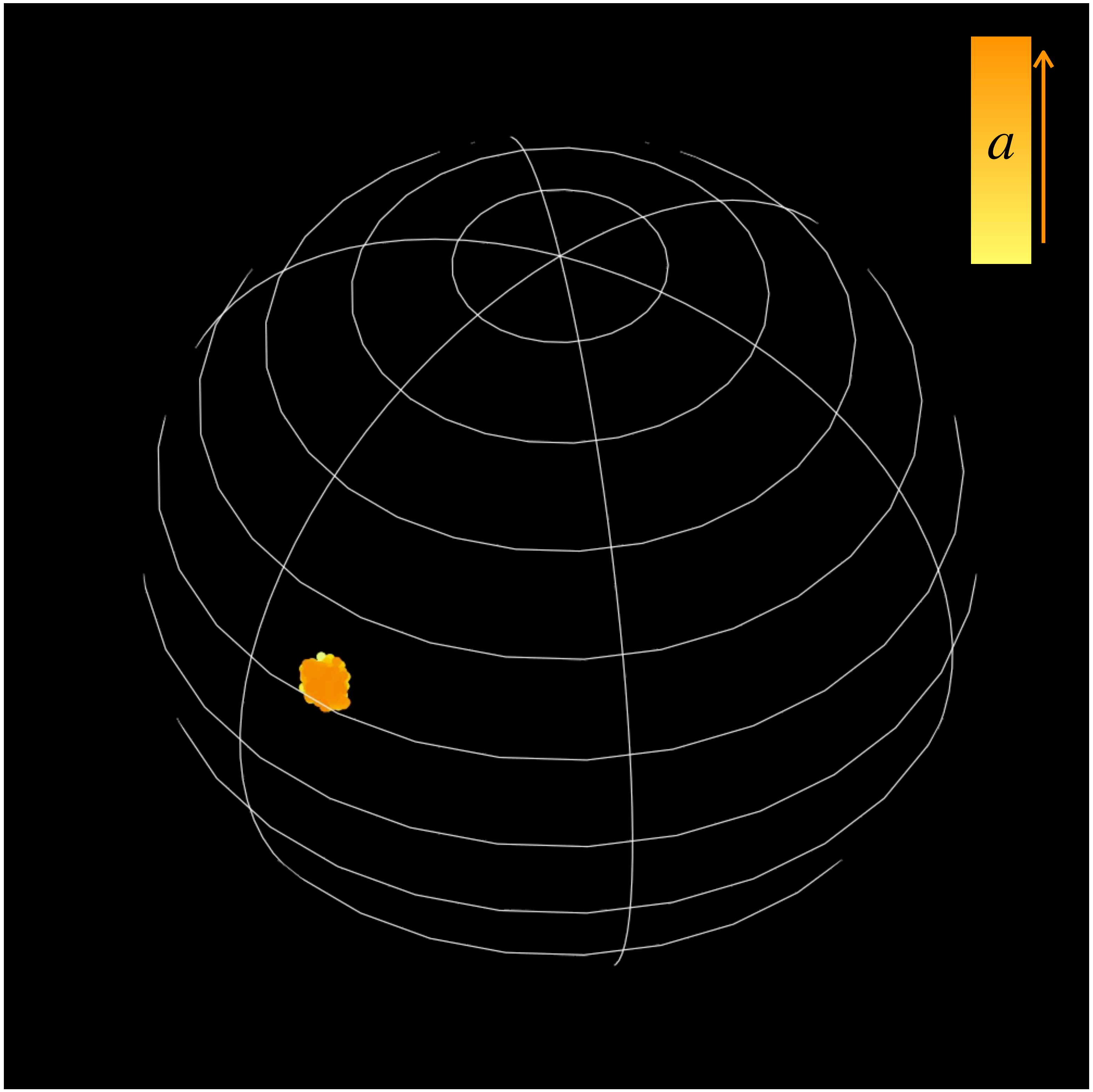
Vector Resonant Relaxation can affect the disc-stars



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

Are they **young enough**?

Vector Resonant Relaxation can randomize disc stars



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

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

+ Evolution sourced by a **shared**, **spatially-extended** and **time-correlated** noise

$$\big\langle \eta(a_i, \hat{\mathbf{L}}_i, t)\, \eta(a_j, \hat{\mathbf{L}}_j, t') \big\rangle = C(a_i, a_j, \hat{\mathbf{L}}_i \cdot \hat{\mathbf{L}}_j, t-t')$$

+ Two joint sources of **separation**

- **Parametric** separation

$$a_i \neq a_j$$

- **Angular** separation

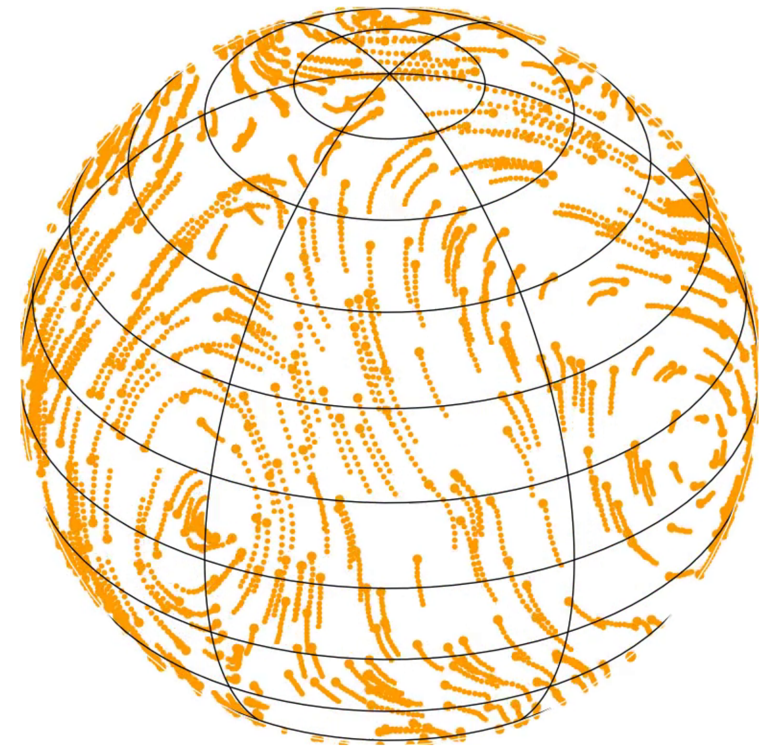
$$\hat{\mathbf{L}}_i \neq \hat{\mathbf{L}}_j$$

VRR around SgrA*

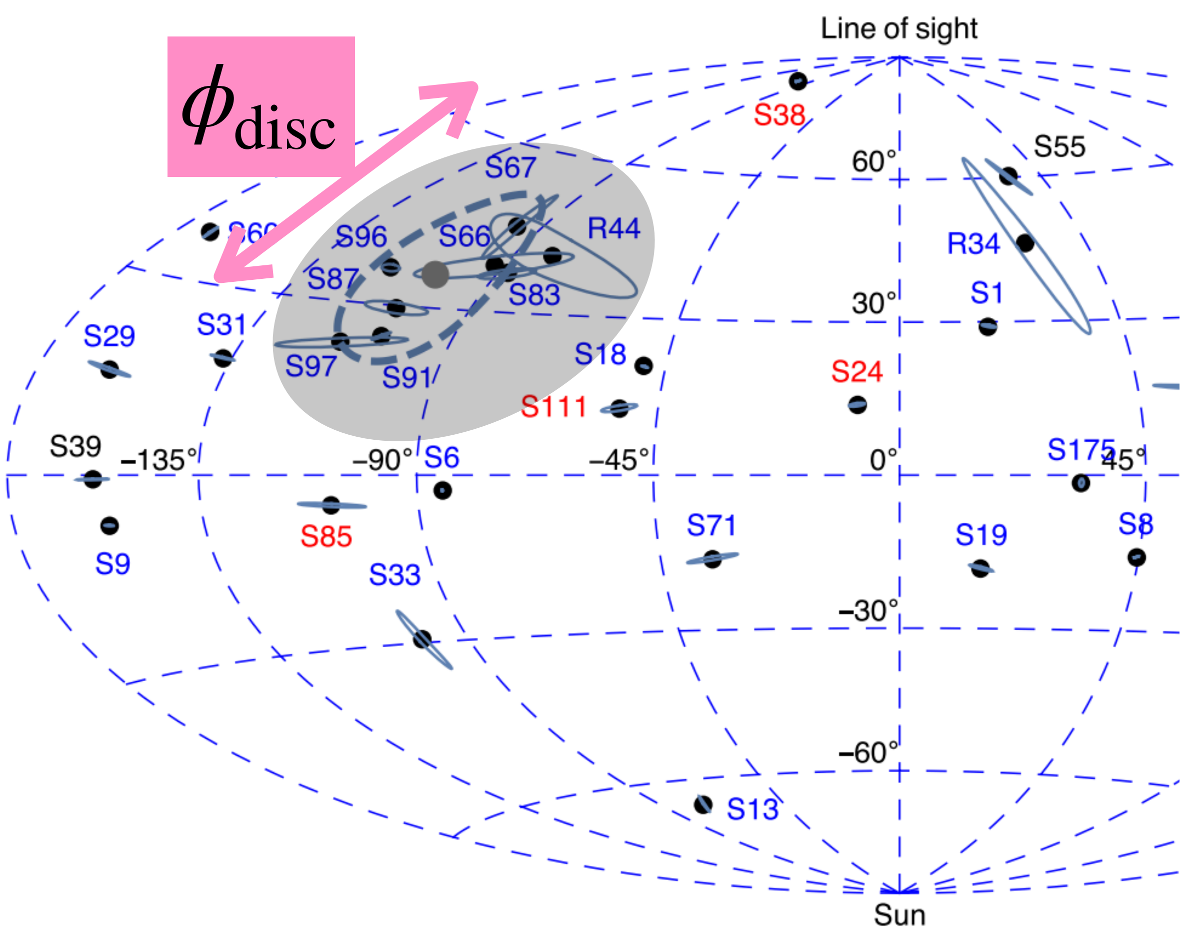
Model

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

Kinetic theory →

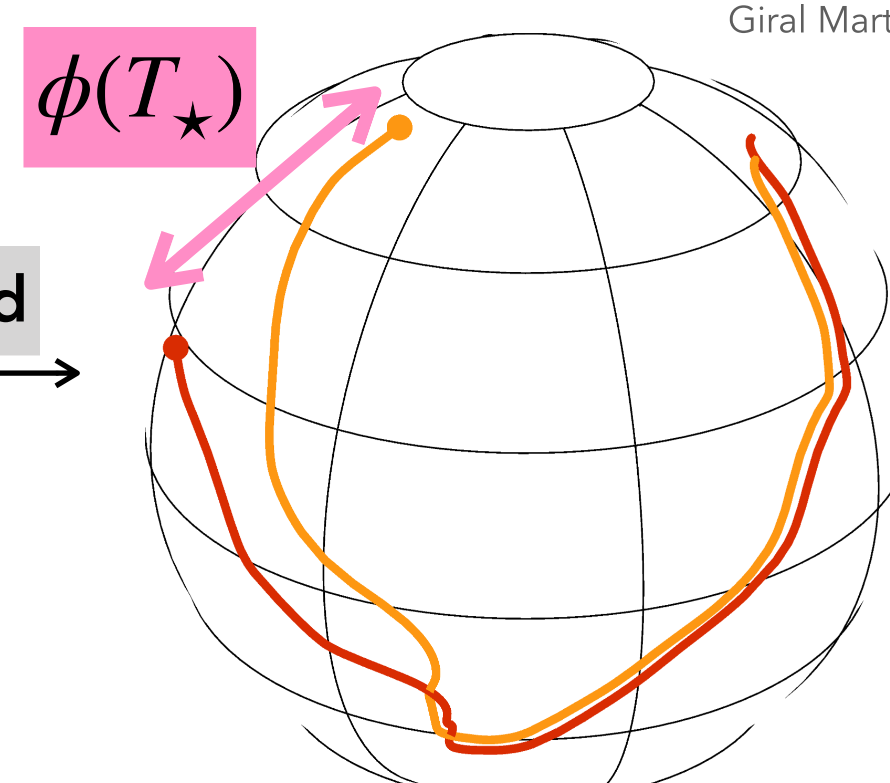


↕ **Dilution**



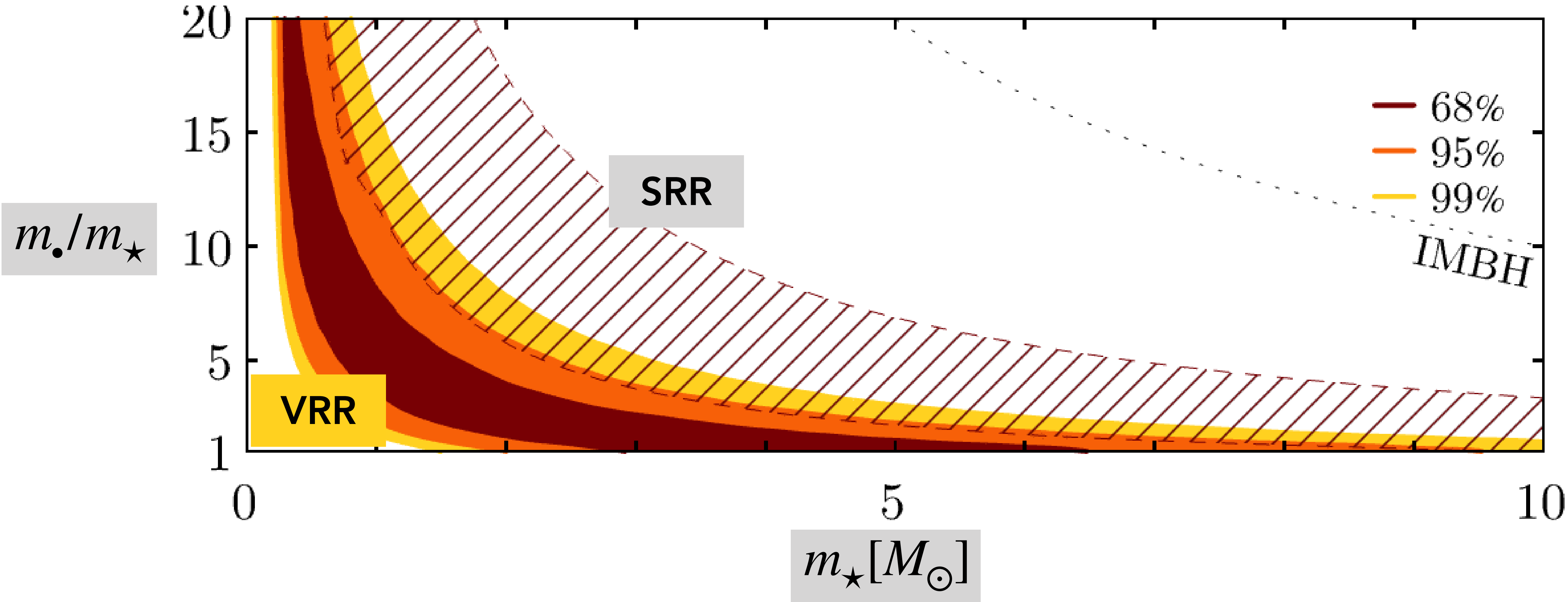
Likelihood ↔

Giral Martinez+(2020)



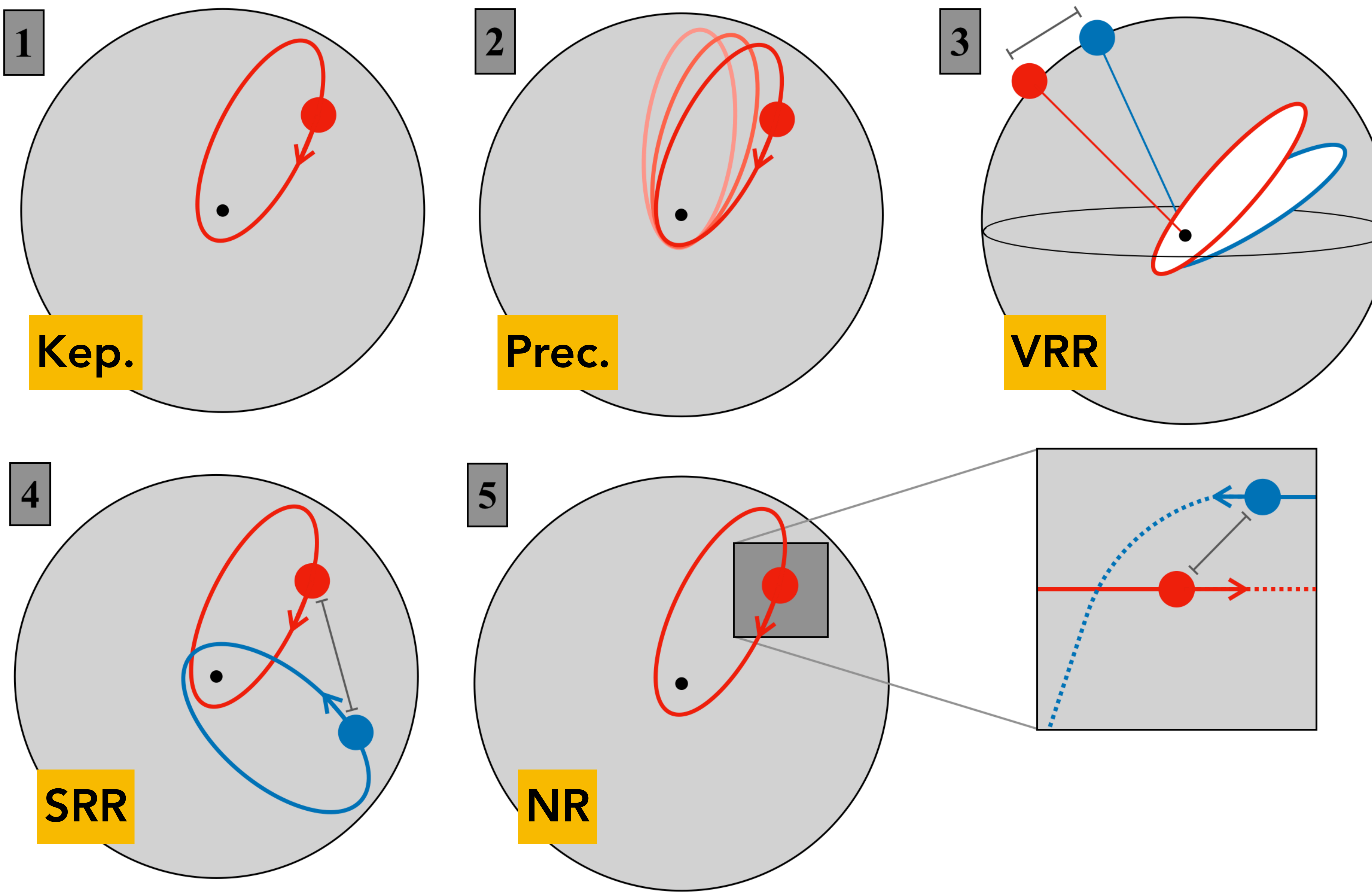
Constraining IMBHs with VRR

2-population model (stars+IMBHs)



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

A wealth of dynamical processes

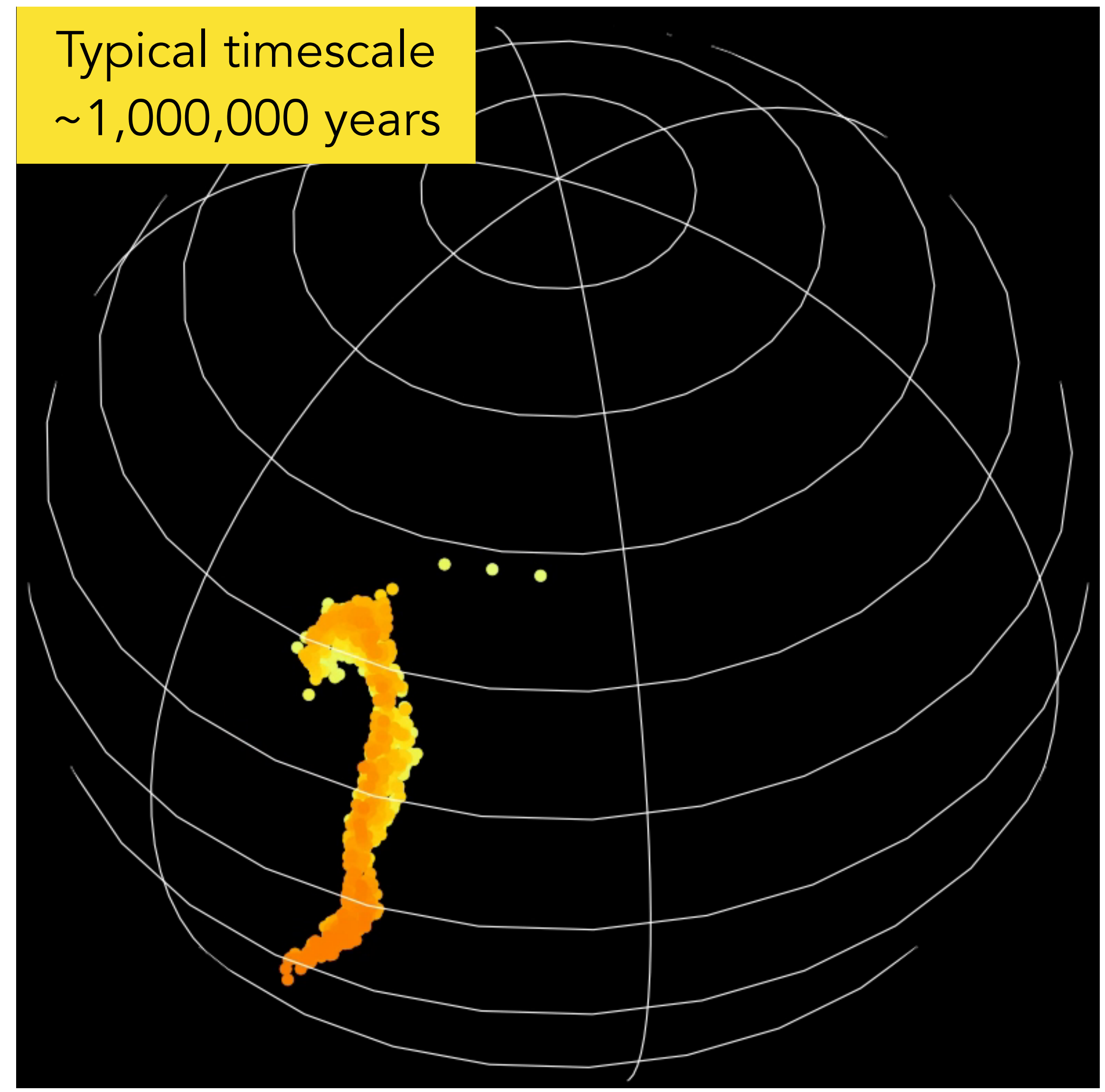


An extremely **hierarchical system**

Dynamics of galactic nuclei

Studying stellar dynamics is studying ``**ink diffusion**''

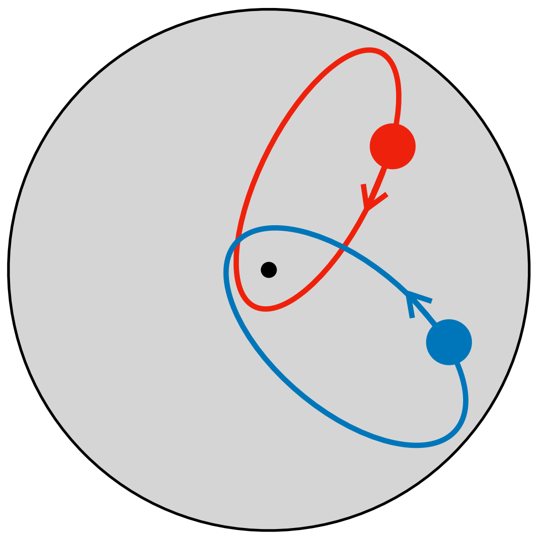
Ink in water



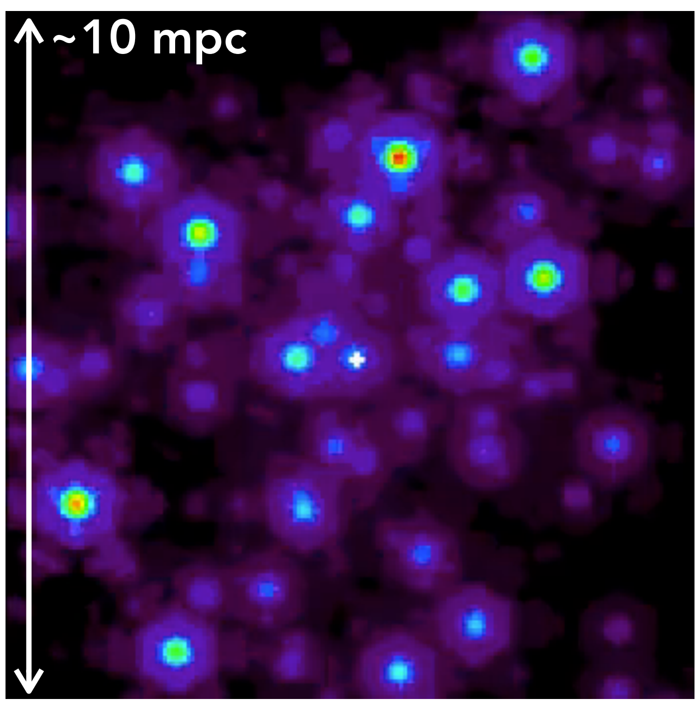
Stellar orientations

The future of galactic nuclei

New stellar orbits



TMT and ELT



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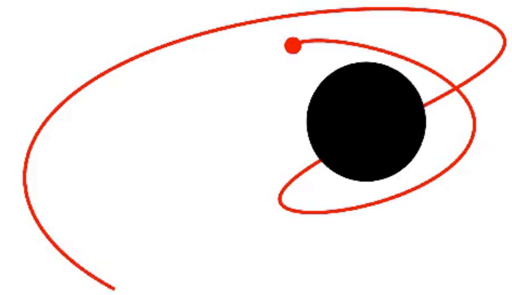
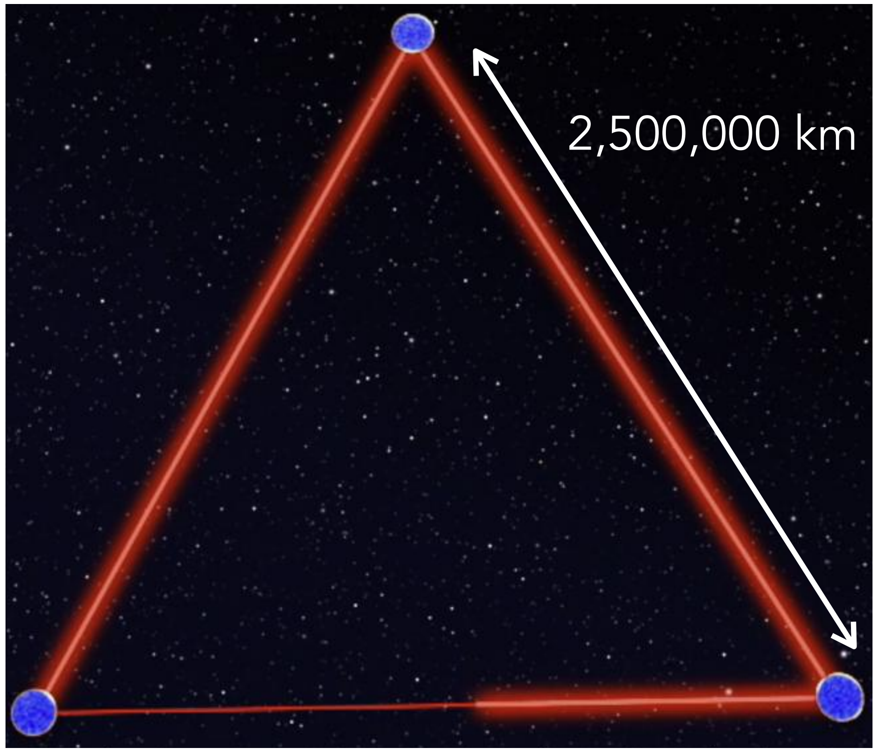
Expected observations

Infall of **compact objects**



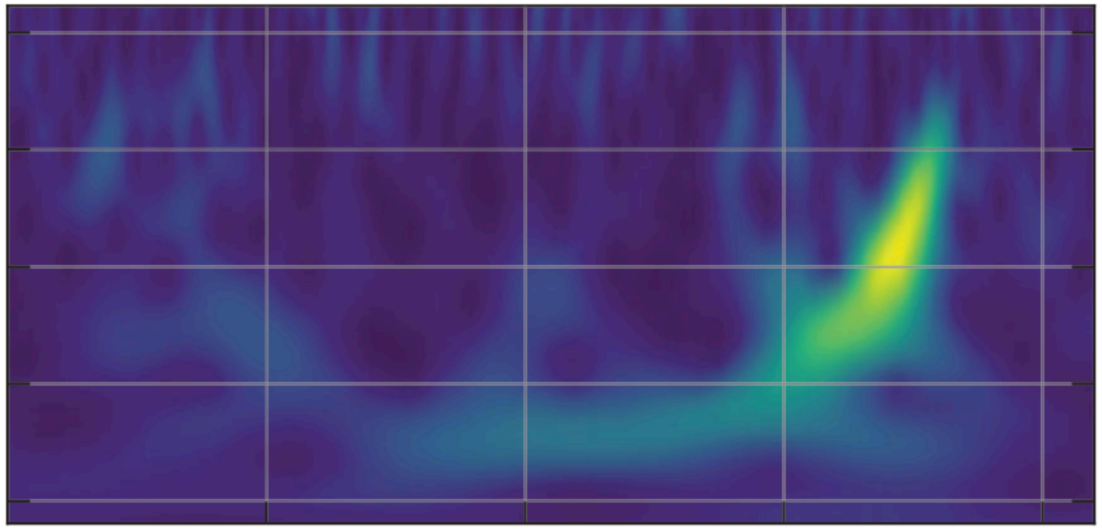
LISA spatial interferometer



Galactic nuclei are exciting

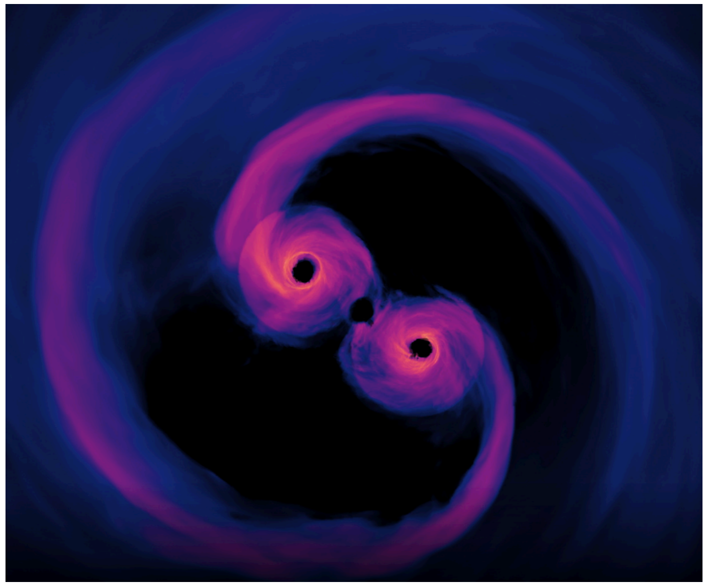
Gravitational waves

LIGO+(2015)



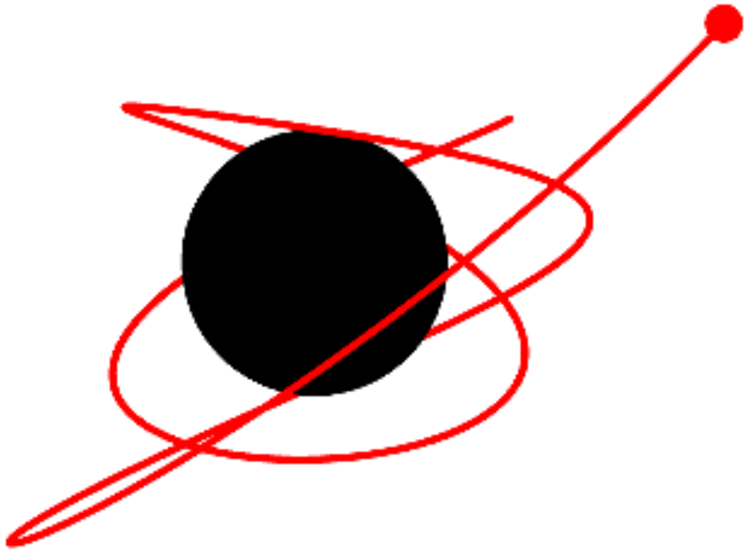
SMBH merger

Pulsar Timing Array



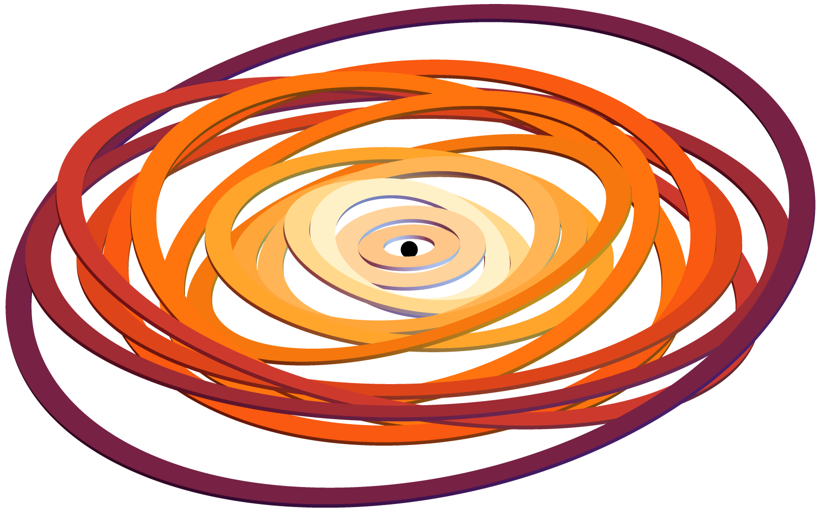
EMRIs

LISA



Discs of IMBHs

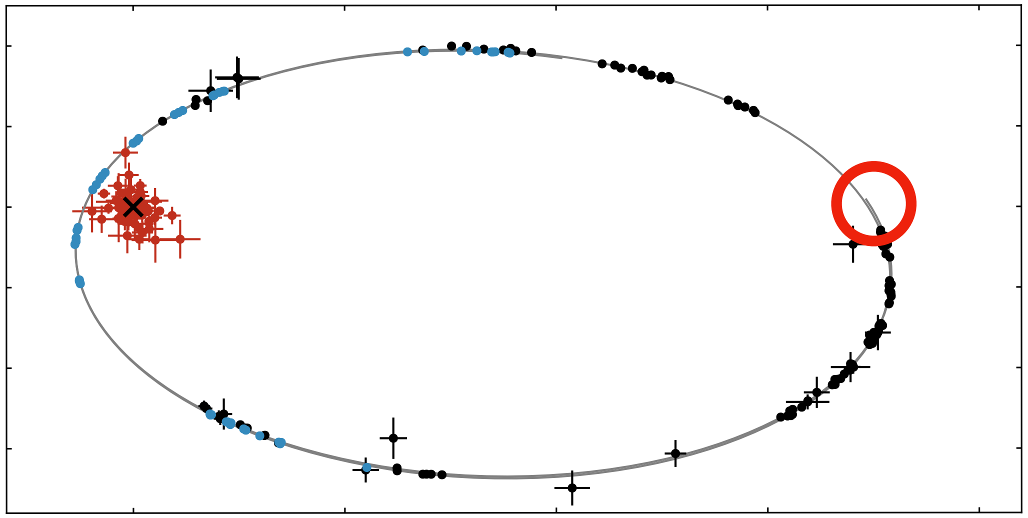
Szölgyen+(2018)



SgrA* is exciting

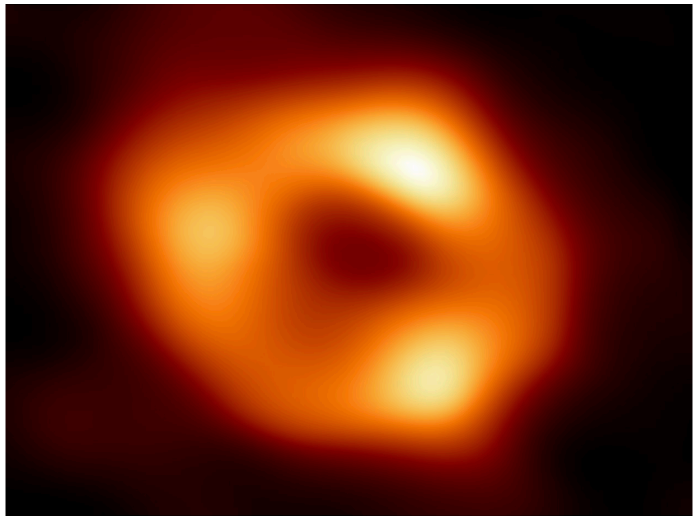
S2's **relativistic precession**

Gravity+(2020)



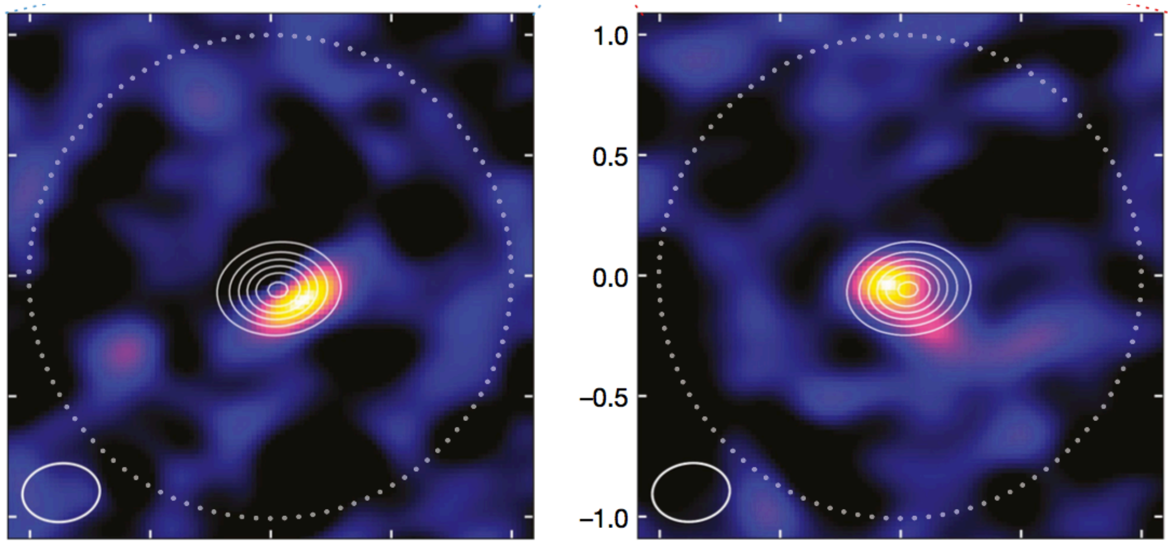
Event Horizon

EHT+(2022)



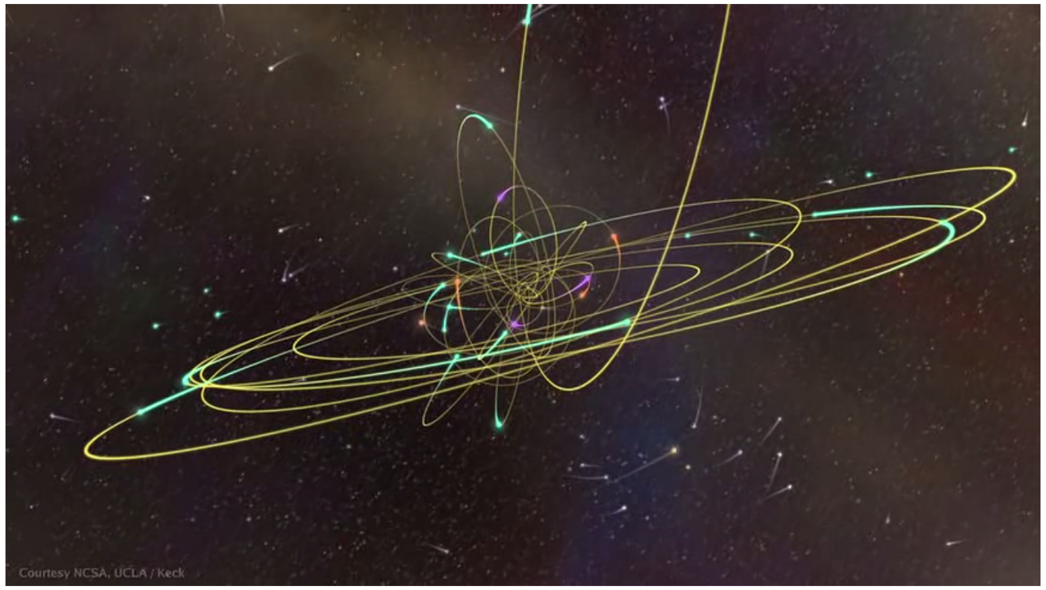
Cold **accretion** disc

Murchikova+(2019)



Clockwise **stellar disc**

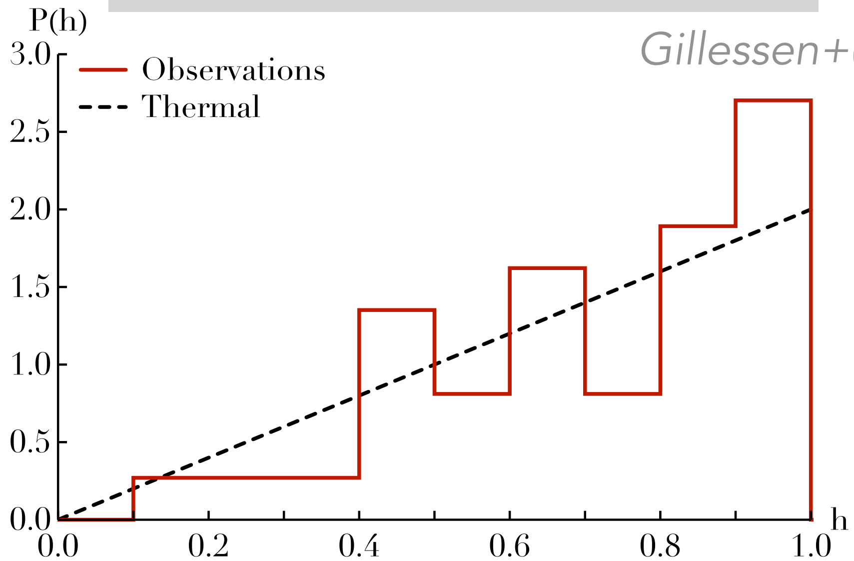
Keck



Next steps — SgrA* & Observations

SRR & Eccentricity

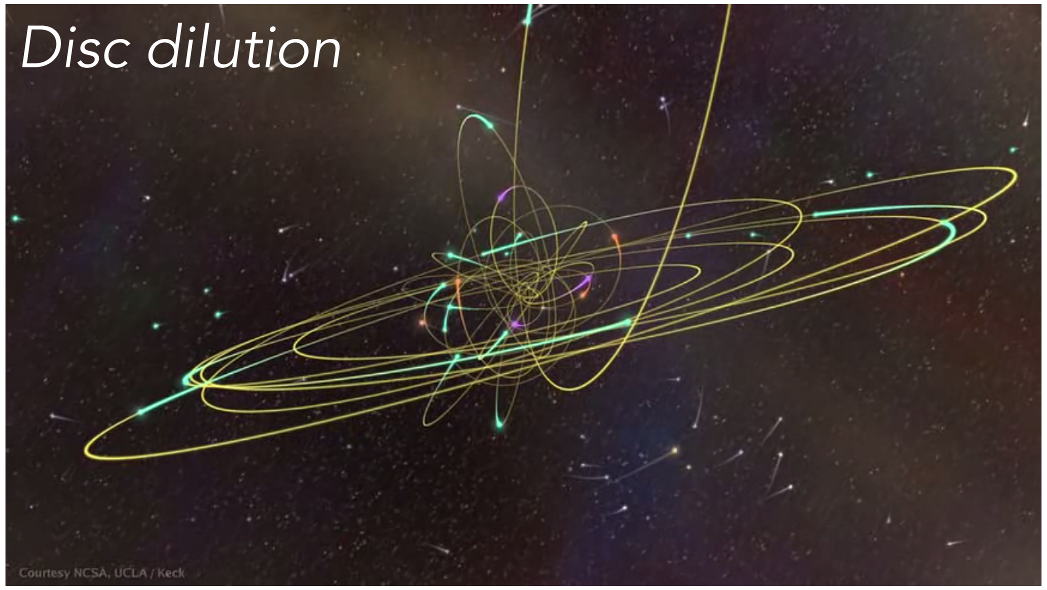
Gillessen+(2017)



Eccentricity thermalisation

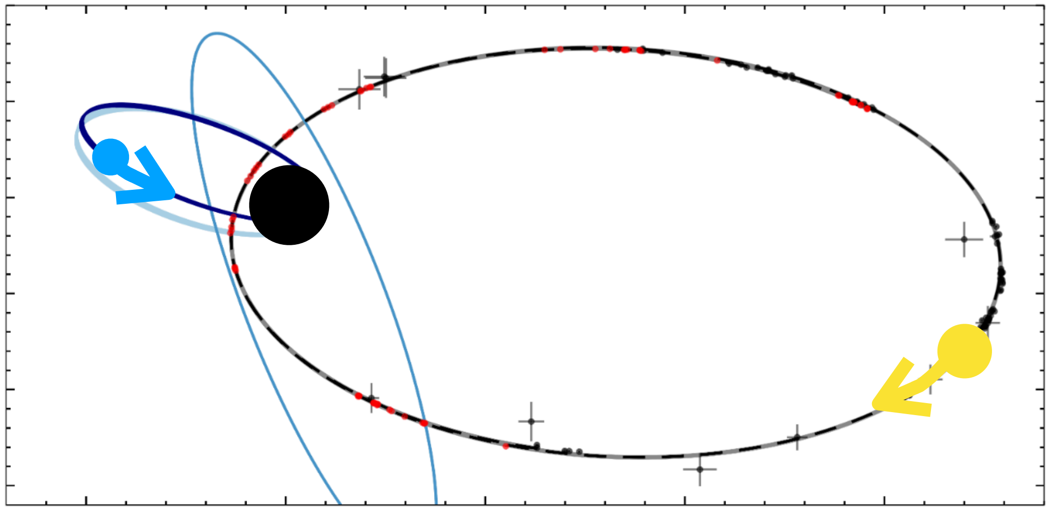
VRR & Stellar Discs

VLT, Keck



S2's kinematics

Gravity+(2023)



Local perturbations?

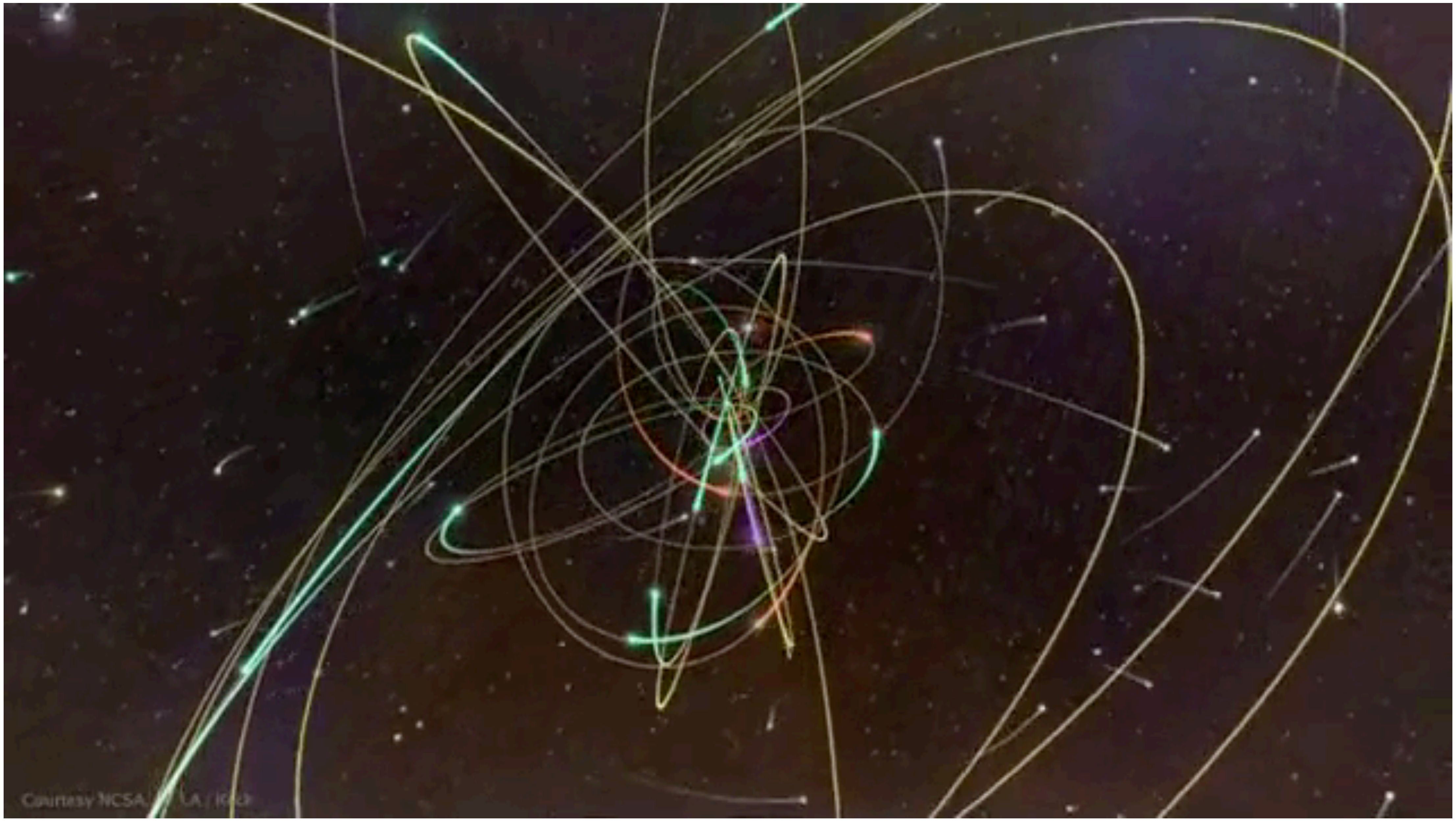
Future observations

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

Full PDF statistics

Galactic nuclei

Visualisation of **SgrA***



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Galactic nuclei, a fantastic ``astrophysical lab''

Dense (1,000,000x more than around the Sun)

Far away (10,000,000x smaller than the Moon in the sky)

Relativistic (BH 4,000,000x heavier than the Sun)

Noisy (Great source of gravitational waves)