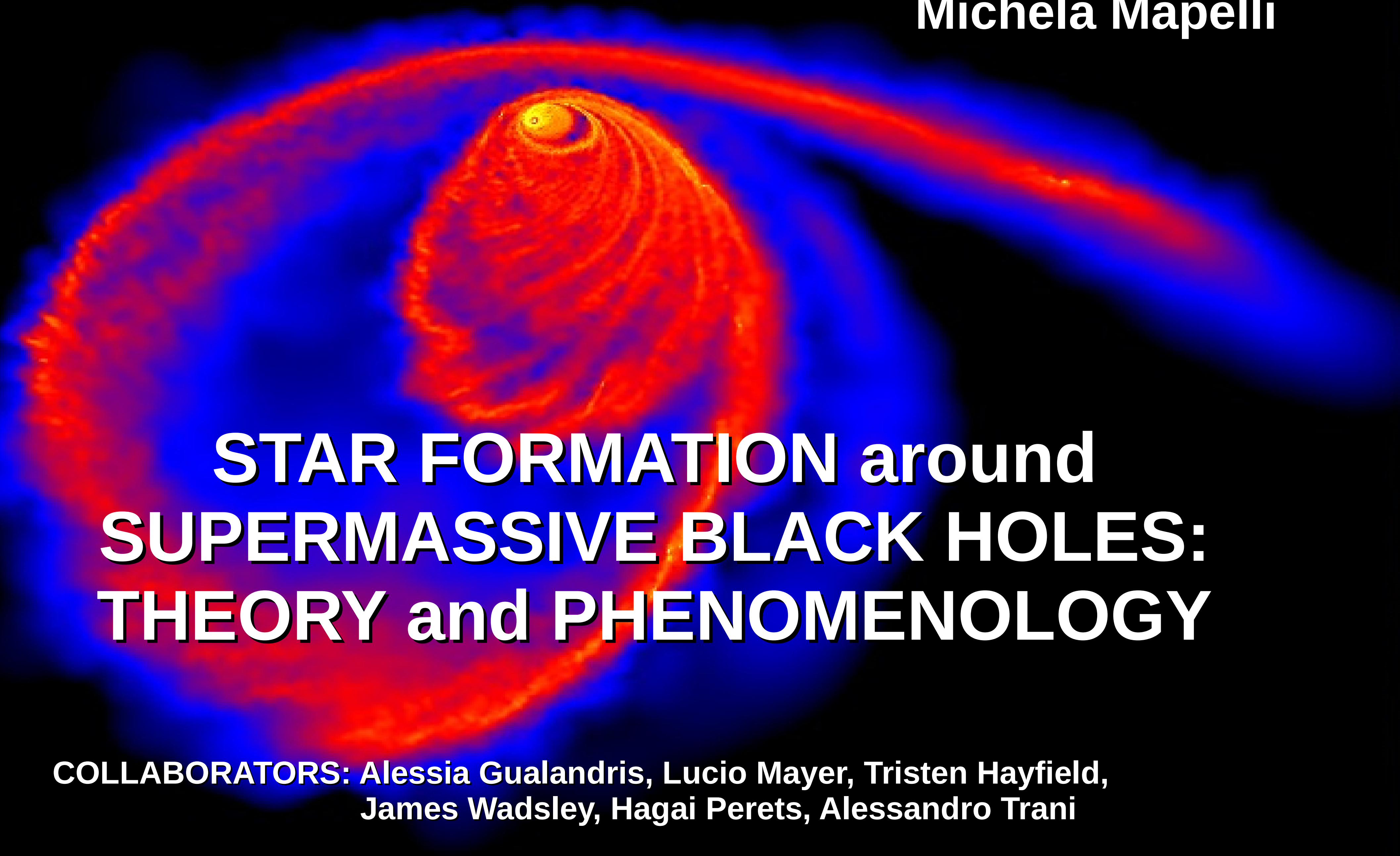
Michela Mapelli



STAR FORMATION around SUPERMASSIVE BLACK HOLES: THEORY and PHENOMENOLOGY

COLLABORATORS: Alessia Gualandris, Lucio Mayer, Tristen Hayfield, James Wadsley, Hagai Perets, Alessandro Trani

Binational Heraeus Summer School Series, September 2 2014

OUTLINE

1. What do we observe in the Galactic centre?

2. What is puzzling about the Galactic centre?

3. Simulating star formation in the Galactic centre

4. The secular evolution of the Galactic centre

5. Gravitational waves from a galactic centre

1. What do we observe in the Galactic centre?

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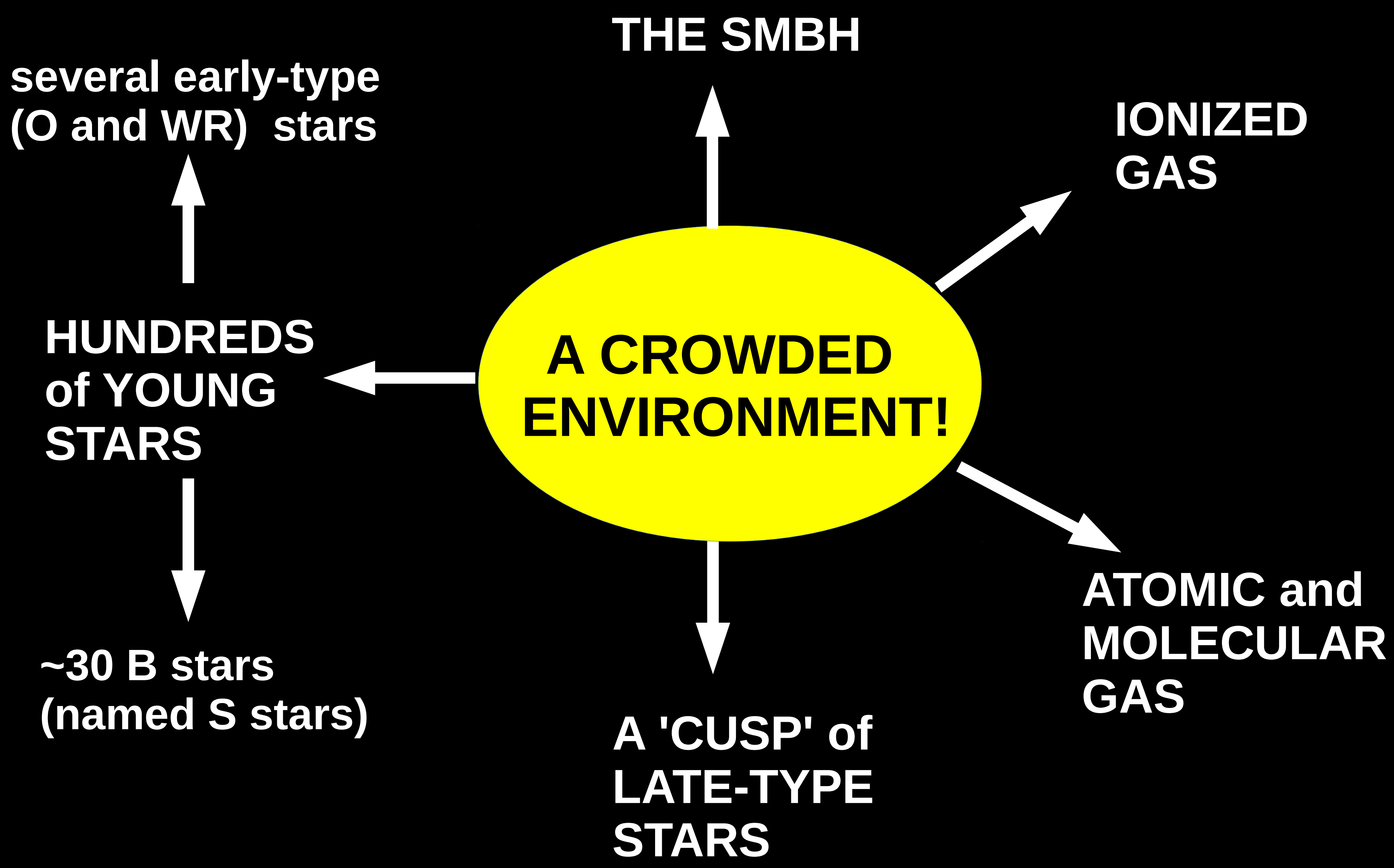


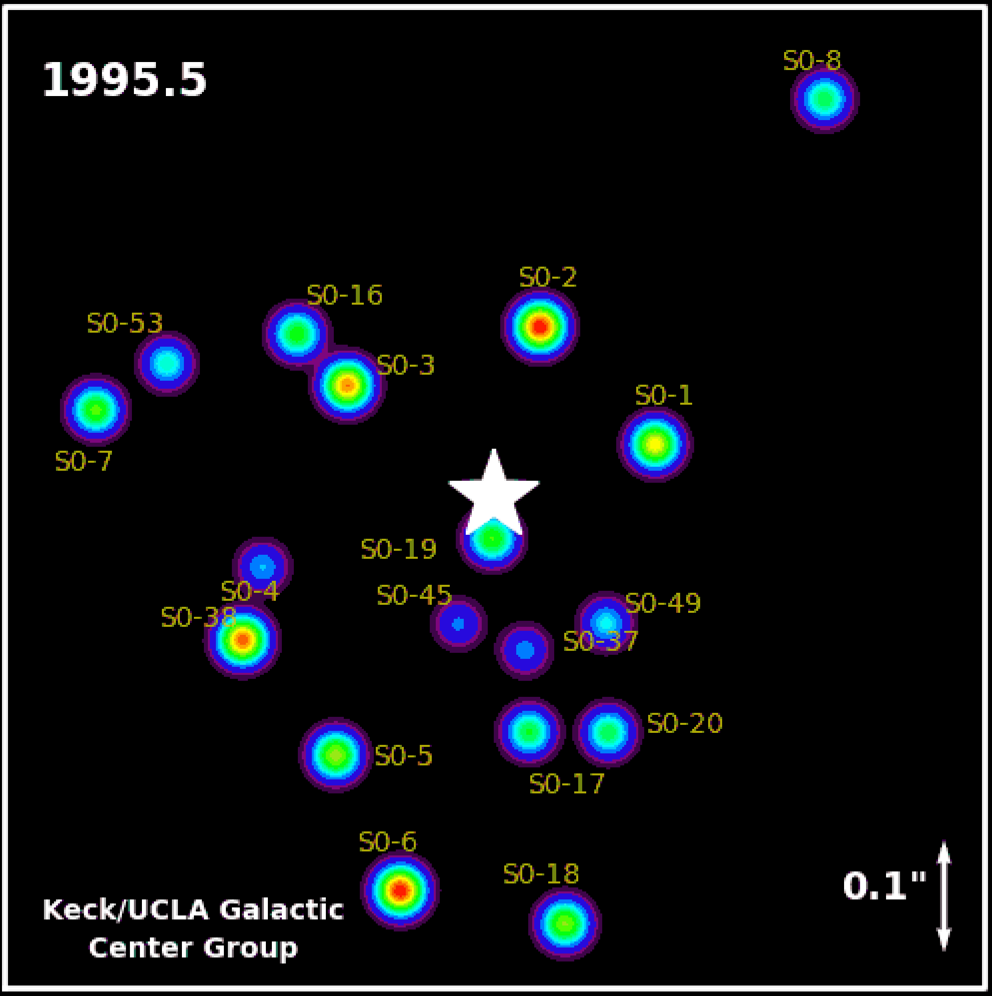
1. What do we observe in the Galactic centre?

- The closest supermassive black hole (SMBH) candidate ~ 8 kpc

-The only SMBH candidate for which we can exclude almost every other nature

thanks to S02 star's orbit
→ measured mass of
$4x10^6$ Msun in <1000 AU

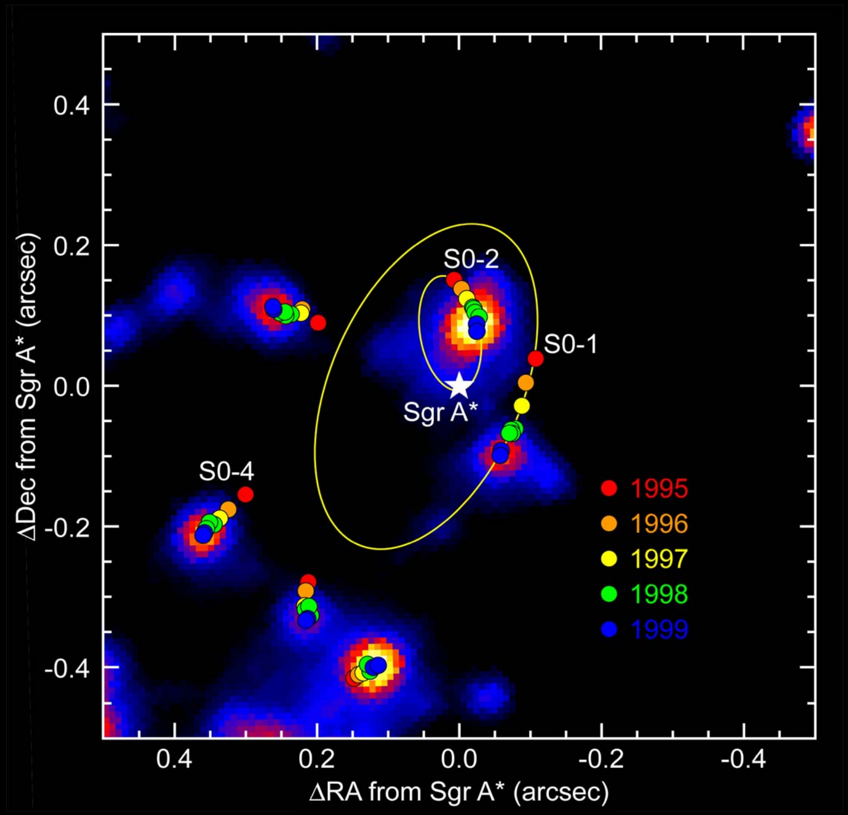
-A unique laboratory to study the extreme physical processes that occur in the vicinity of a SMBH



Credits: prof. Andrea Ghez

1. What do we observe in the Galactic centre?

HOW CAN WE PRESENT SMBH MASS MEASUREMENT TO STUDENTS?



easy for circular orbits..

circular uniform motion:

$$v = \frac{2\,\pi r}{T}$$

from Newton's laws:

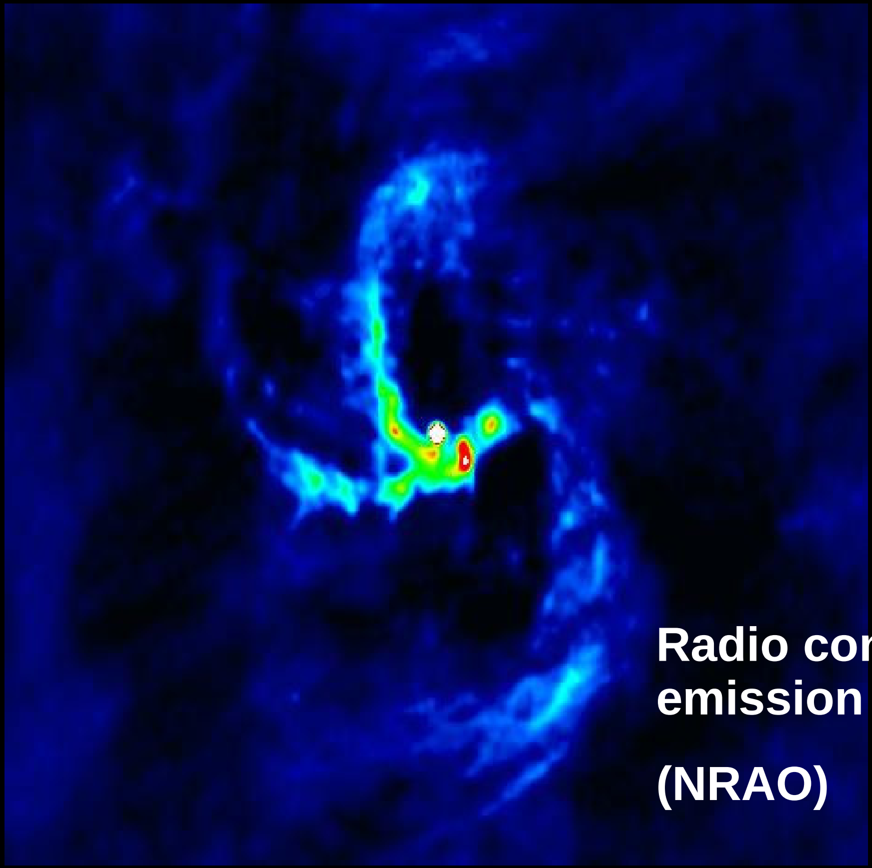
$$\frac{G\,m\,M}{R^2} = \frac{m\,v^2}{R} \longrightarrow M = \frac{4\,\pi^2\,R^3}{G\,T^2}$$

$$M = 4 \times 10^6 M_\odot \left(\frac{r}{1000\,AU}\right)^3 \left(\frac{16\,yr}{T}\right)^2$$

1. What do we observe in the Galactic centre?

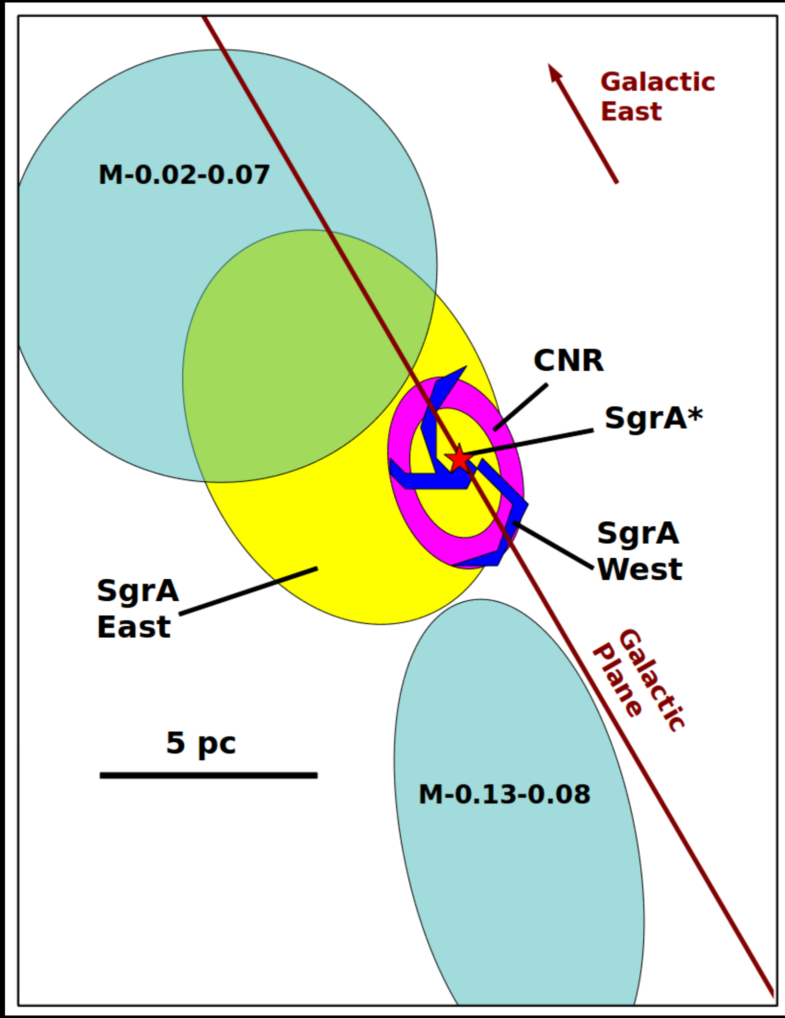
IONIZED GAS

- SgrA West or the Minispiral



Radio continuum emission at 3.6 cm

(NRAO)



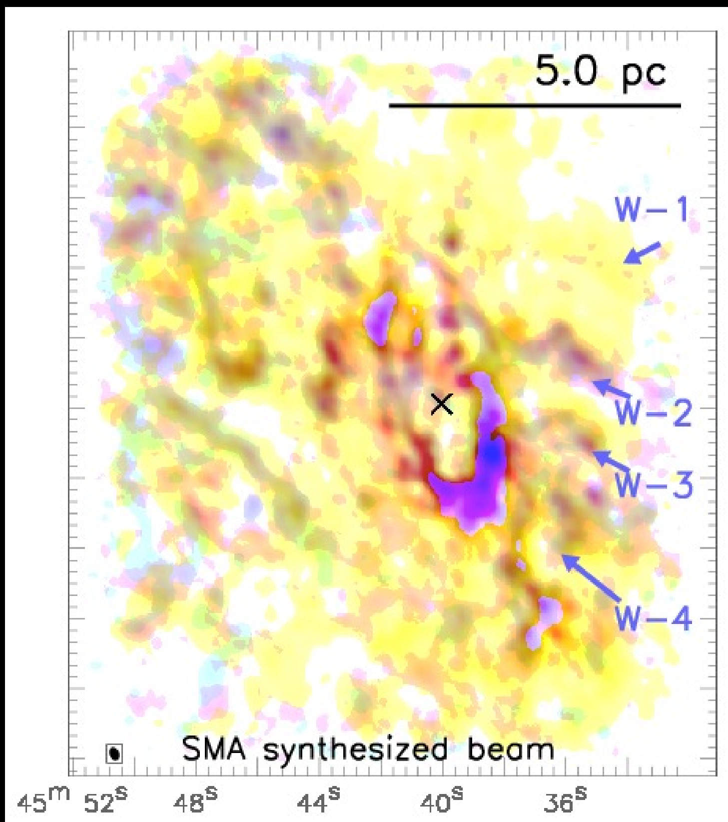
MM & Gualandris 2014

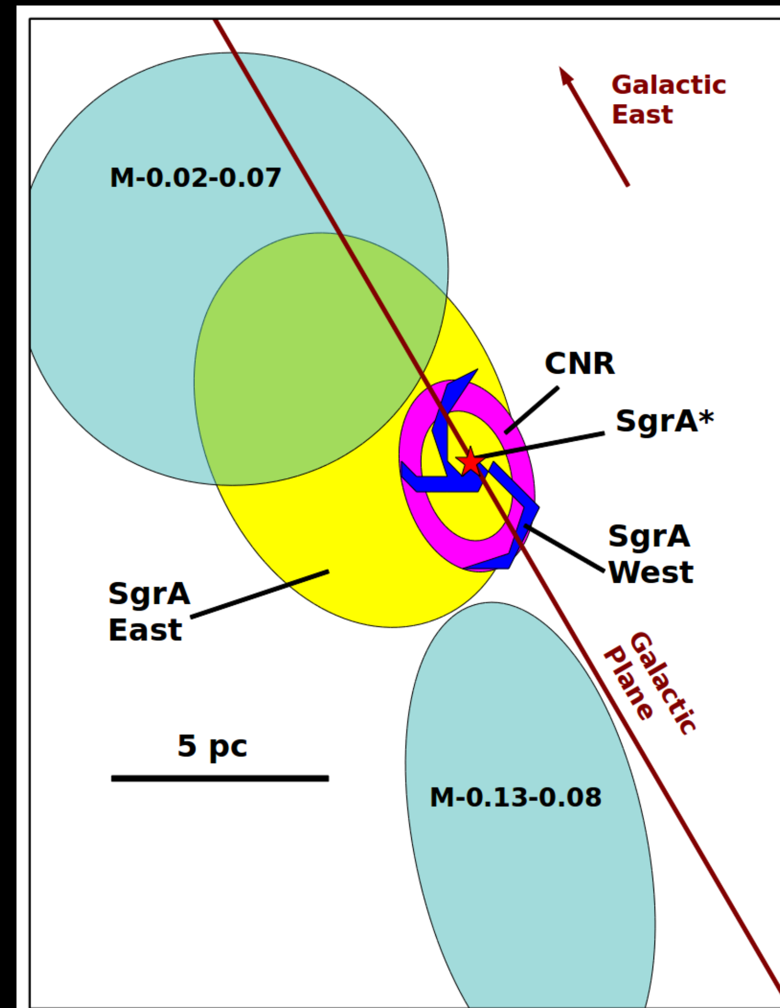
- SgrA East: a SN shell?

1. What do we observe in the Galactic centre?

MOLECULAR GAS

- The circumnuclear ring





CO 3-2, HCN from Sub-Millimeter Array

CS 7-6 from Green Bank Telescope

Courtesy of H. Baobab Liu

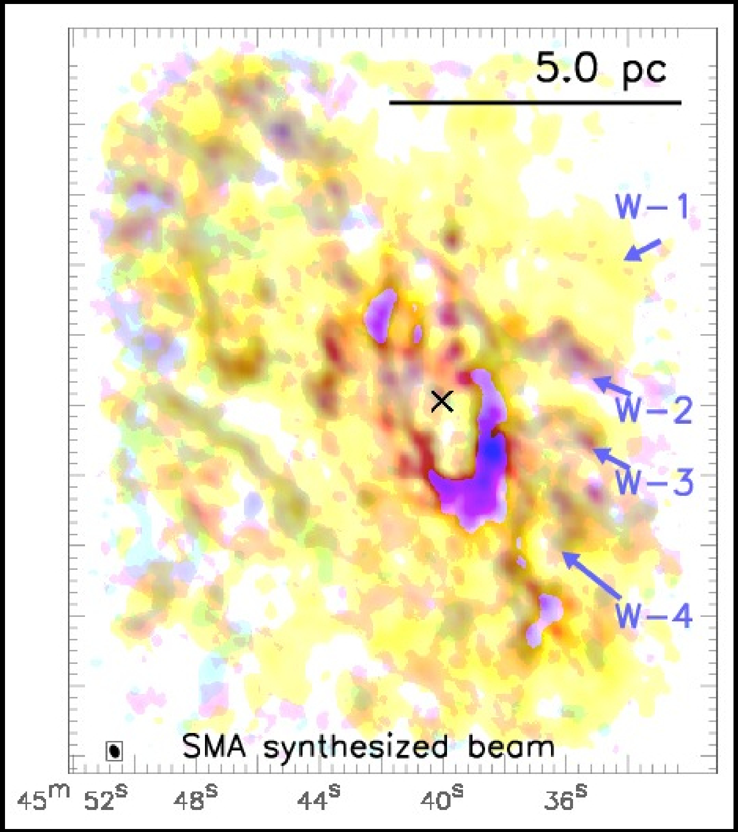
From Liu et al. 2012

MM & Gualandris 2014

1. What do we observe in the Galactic centre?

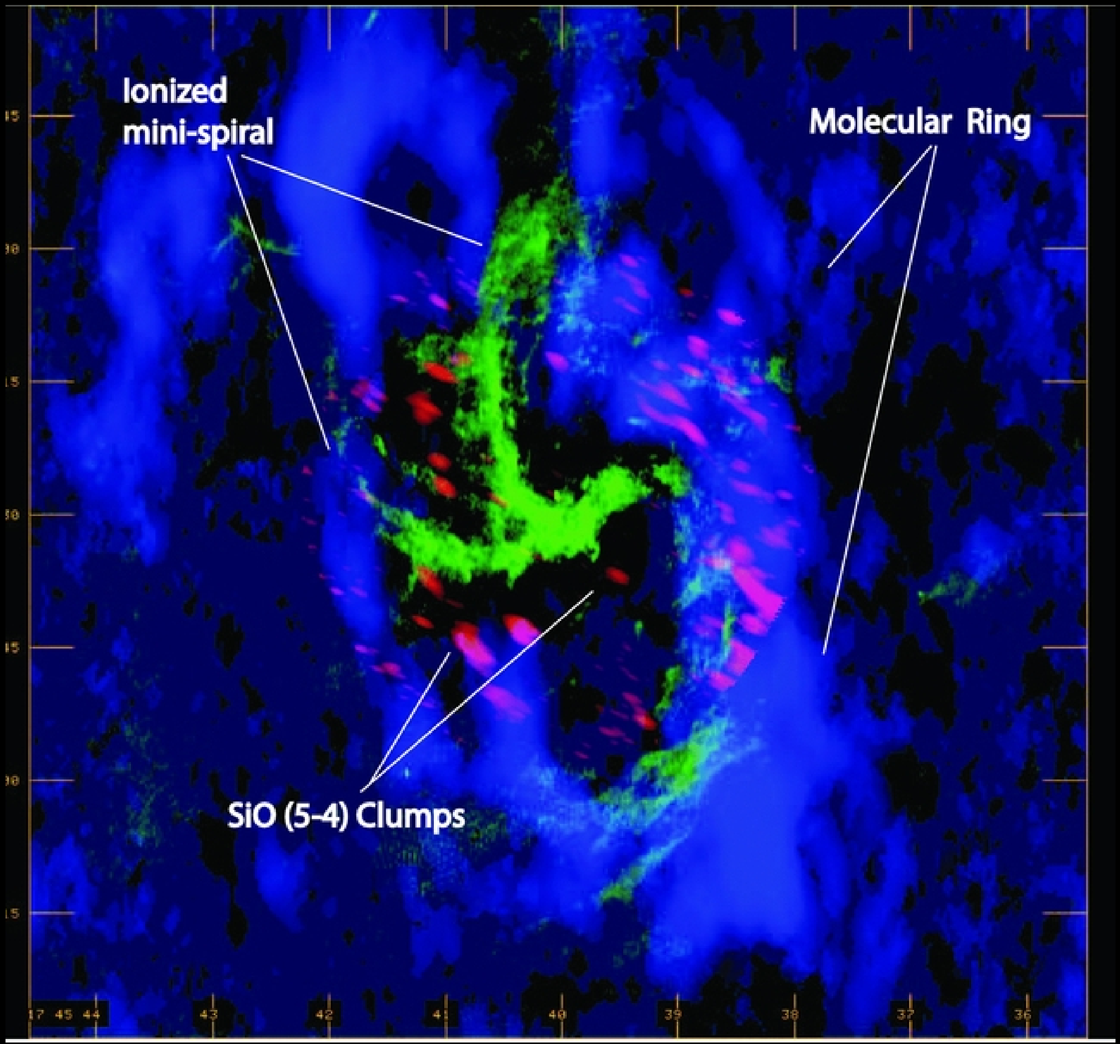
MOLECULAR GAS

- The circumnuclear ring



Courtesy of H. Baobab Liu

From Liu et al. 2012



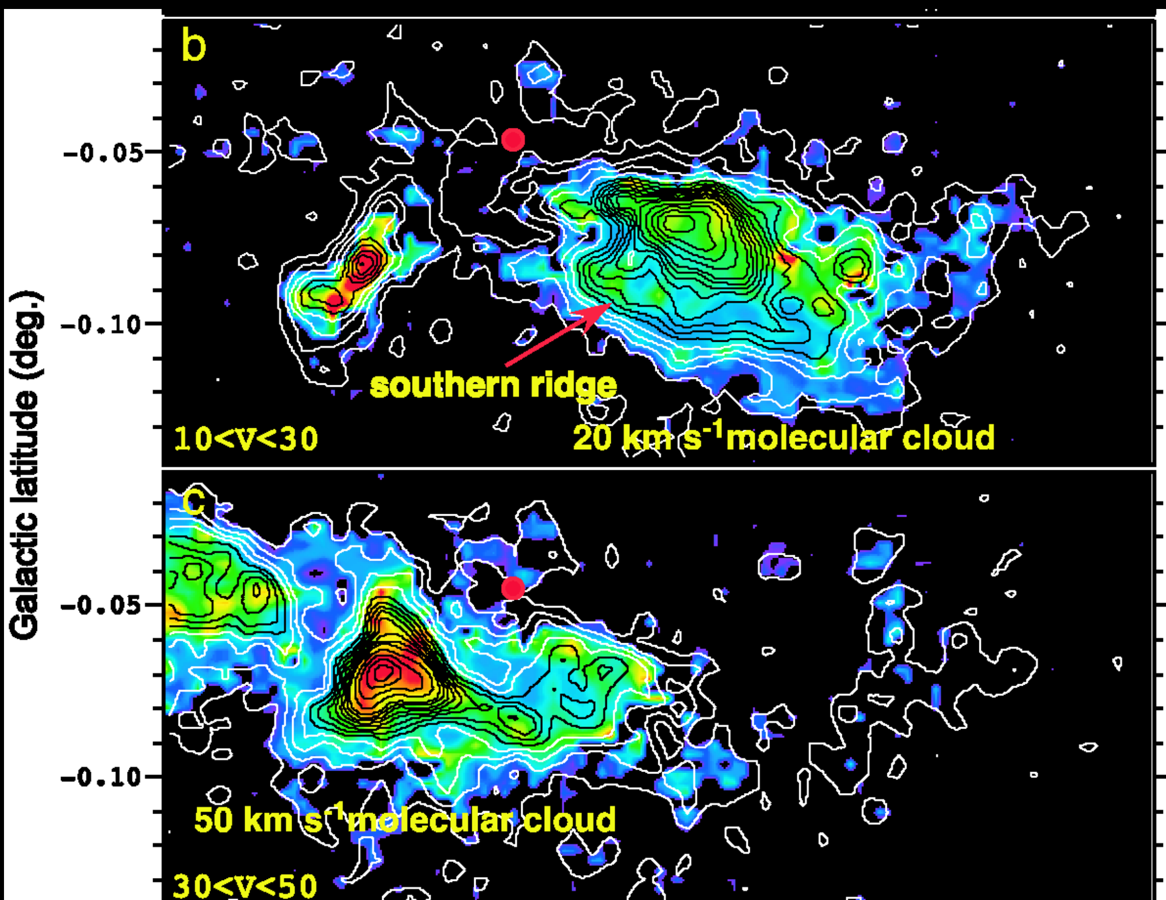
Yusef-Zadeh et al. 2013 ,ALMA Cycle0

- The young star outflows

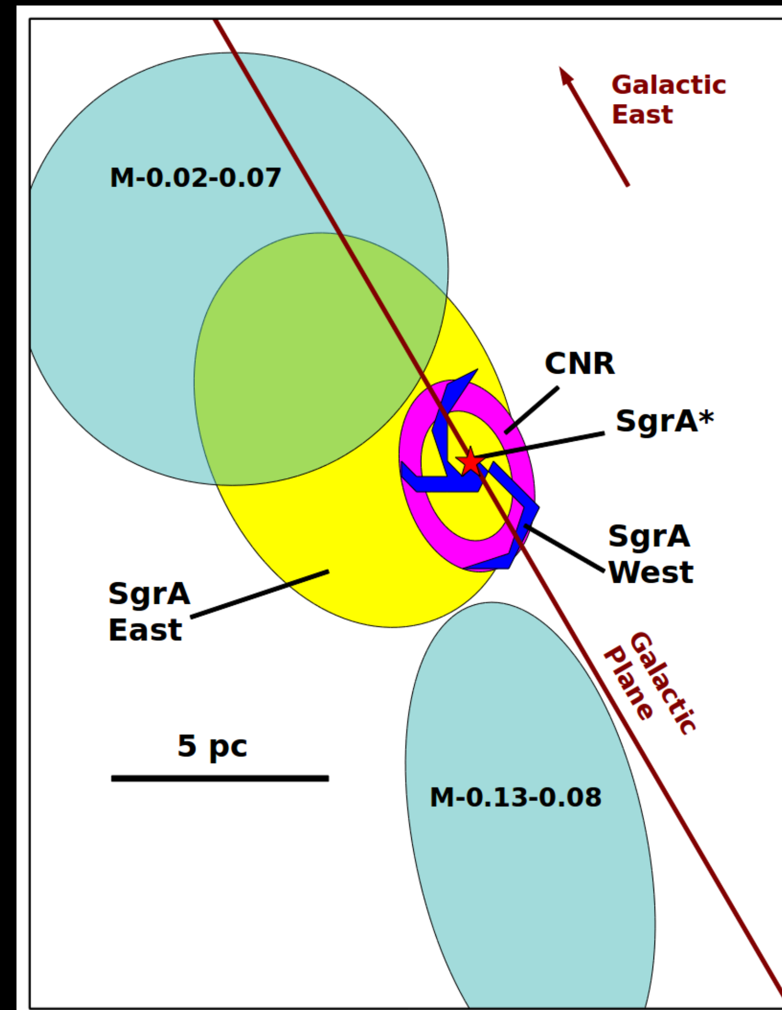
1. What do we observe in the Galactic centre?

MOLECULAR GAS

- The circumnuclear ring
- The young star outflows
- The two giant molecular clouds



Tsuboi et al. 2011

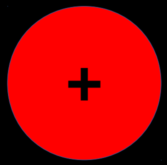


MM & Gualandris 2014

1. What do we observe in the Galactic centre?

For the students:
Which difference between ionized atomic and molecular gas?

IONIZED: mostly ionized hydrogen H+ (just a proton)

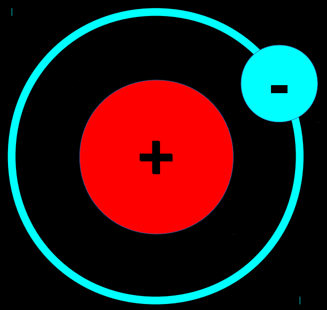


In the Universe T> 10^3 K, n<1 cm^-3
Sound speed > 100 km/s

Density of ATMOSPHERE
we breath ~10^20 cm^-3

In the GC we observe it in radio continuum
as free-free emission: electrons scattering off the protons
without recombining

ATOMIC:mostly neutral hydrogen H

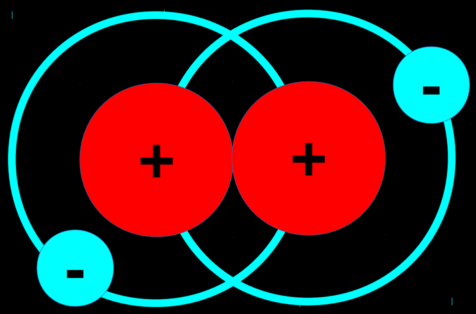


In the Universe 10^2 K< T < 10^4 K,
0.1 cm^-3<n<10 cm^-3
Sound speed ~10 km/s
In the GC we observe it in radio as free-free,
free-bound emission → more difficult

1. What do we observe in the Galactic centre?

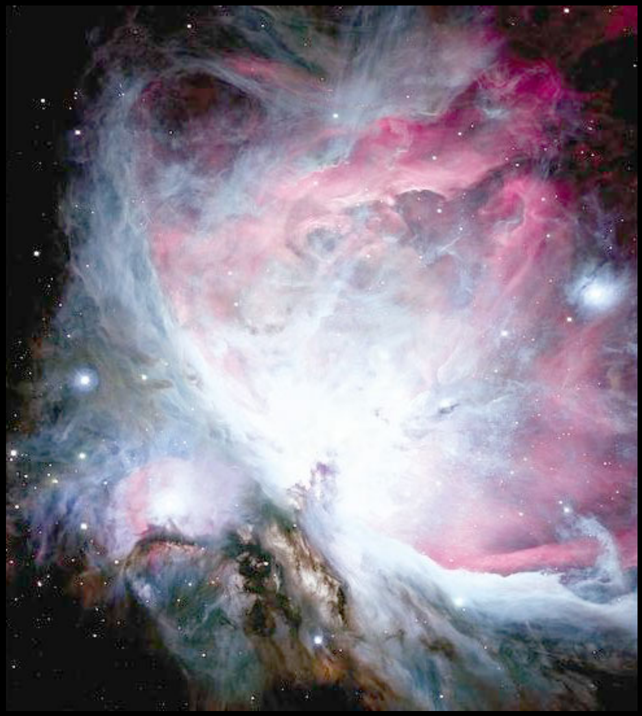
For the students:
Which difference between ionized atomic and molecular gas?

MOLECULAR: mainly Hydrogen molecules H2

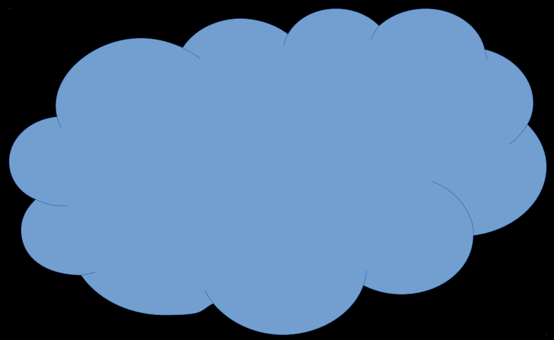


In the Universe 10 K<T<100 K,
10 cm^-3<n<1e6 cm^-3
Sound speed ~1 km/s

Transition of molecular hydrogen are too faint
→ we need to observe lines from other molecules
More intense but much more more rare
e.g. HCN, CO, CS



VERY IMPORTANT FOR THIS TALK BECAUSE FORMS DENSE CLOUDS (MOLECULAR CLOUDS) WHERE STARS FORM!



1. What do we observe in the Galactic centre?

OLD STARS: Spherical cusp with

$$\rho_* = 2.8 \pm 1.3 \times 10^6 \, M_\odot \mathrm{pc}^{-3} \left(\frac{R}{6\,\mathrm{arcsec}} \right)^{-\alpha}$$

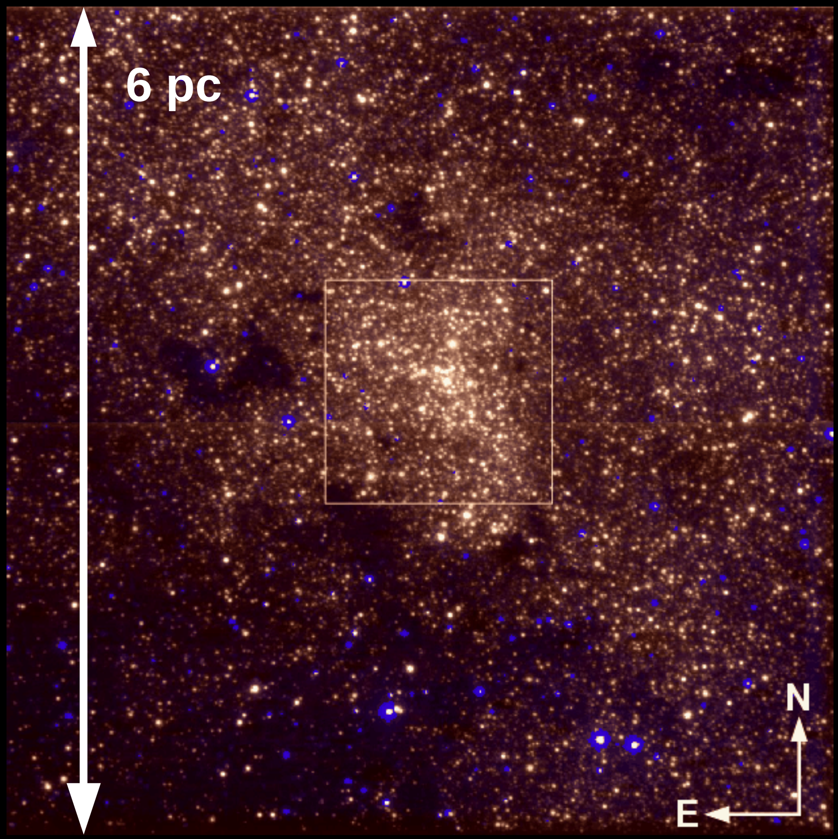
$$\alpha = 1.75 \qquad \text{if } R \geq 6\,\mathrm{arcsec}$$

$$\alpha = 1.2 \qquad \text{if } R < 6\,\mathrm{arcsec}$$

6 arcsec = 0.24 pc

The cusp extends out to ~2-3 pc

Is embedded into the bulge
and in particular into a
flattened 'nuclear bulge'



ISAAC @ VLT imaging observations at 2.09 mm and in the J-band

Schoedel et al. 2007

YOUNG STARS

S-stars:

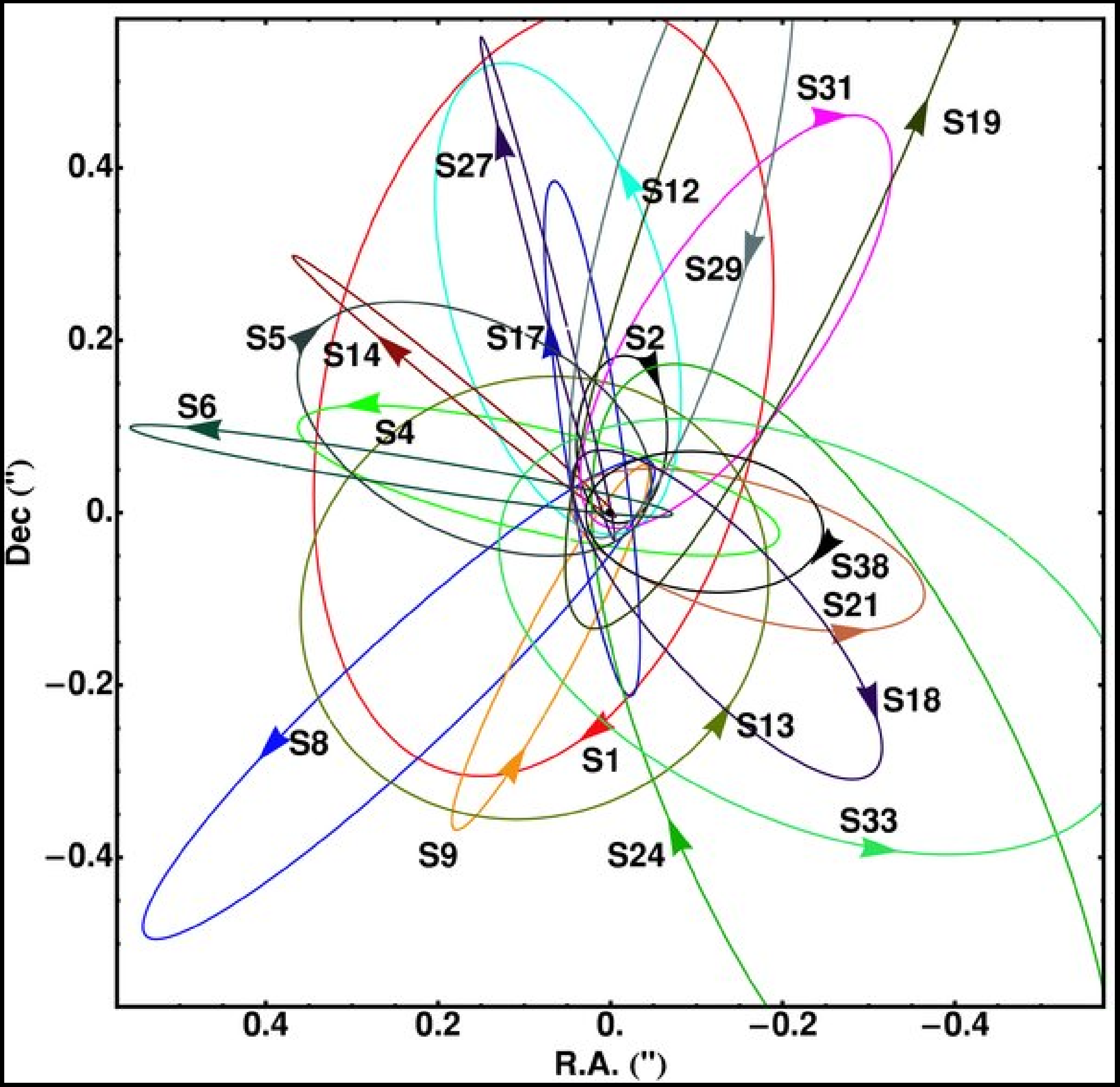
~30 stars closest to the SMBH

- B-type stars

- randomly oriented orbits with semi-major axis< 0.04 pc (~8200AU~ 1 arcsec)

- eccentricity distribution f(e) $\propto$2e

- age 20 – 100 Myr



Gillessen et al. 2009

1. What do we observe in the Galactic centre?

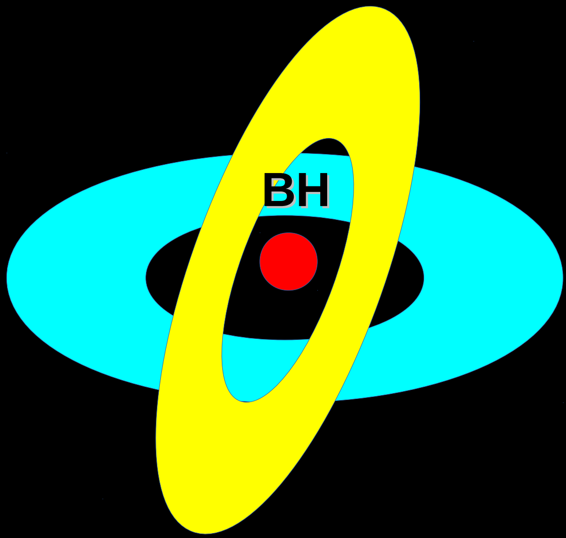
YOUNG STARS

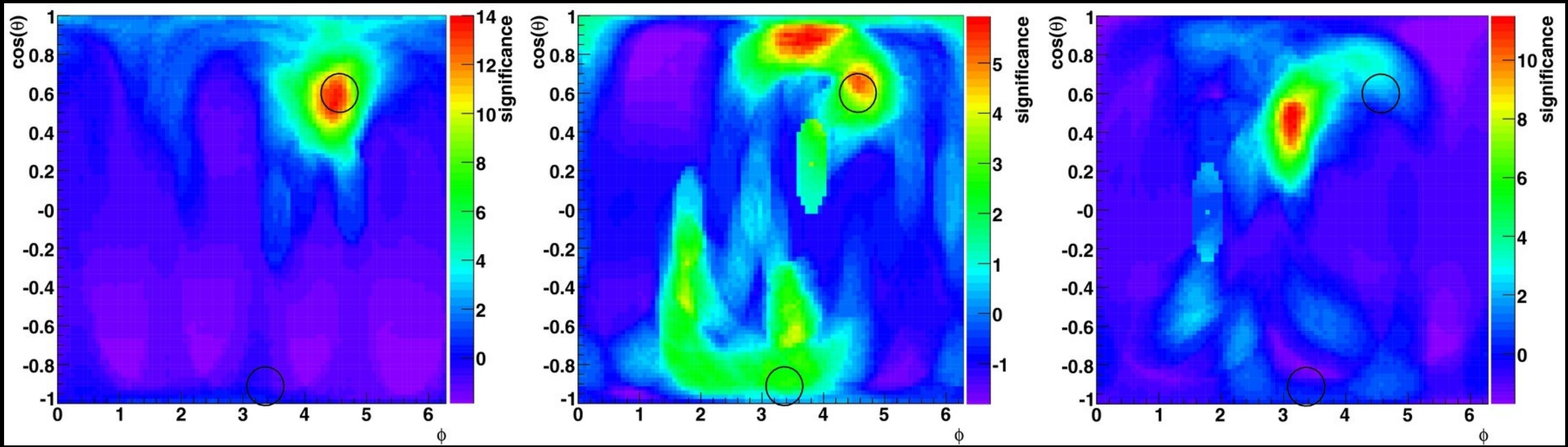
The other early-type stars in the central pc:

O and WR stars, age~ 2-6 Myr

One or two discs?

- Counter-CW disc
- CW disc: a~0.04-0.4 pc, e~0.3, warped and tilted





Paumard et al. 2006; Bartko et al. 2009; Lu et al. 2009

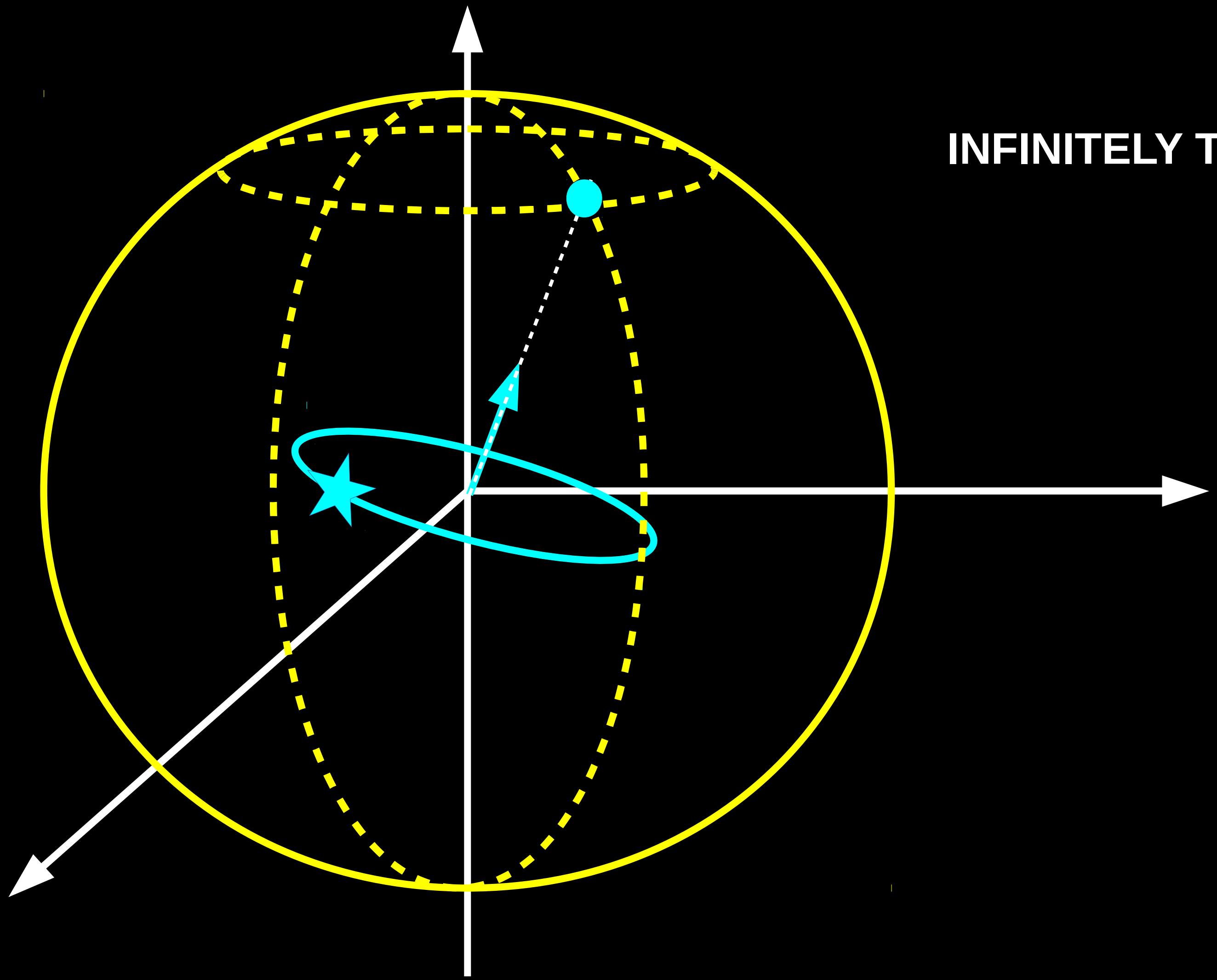
But...

1. What do we observe in the Galactic centre?

HOW CAN WE PRESENT THIS KIND OF PLOTS TO STUDENTS?

1) Refresh what angular momentum is …

2) Do a sketch (or a 3-D model with paper and pencils)



INFINITELY THIN DISC

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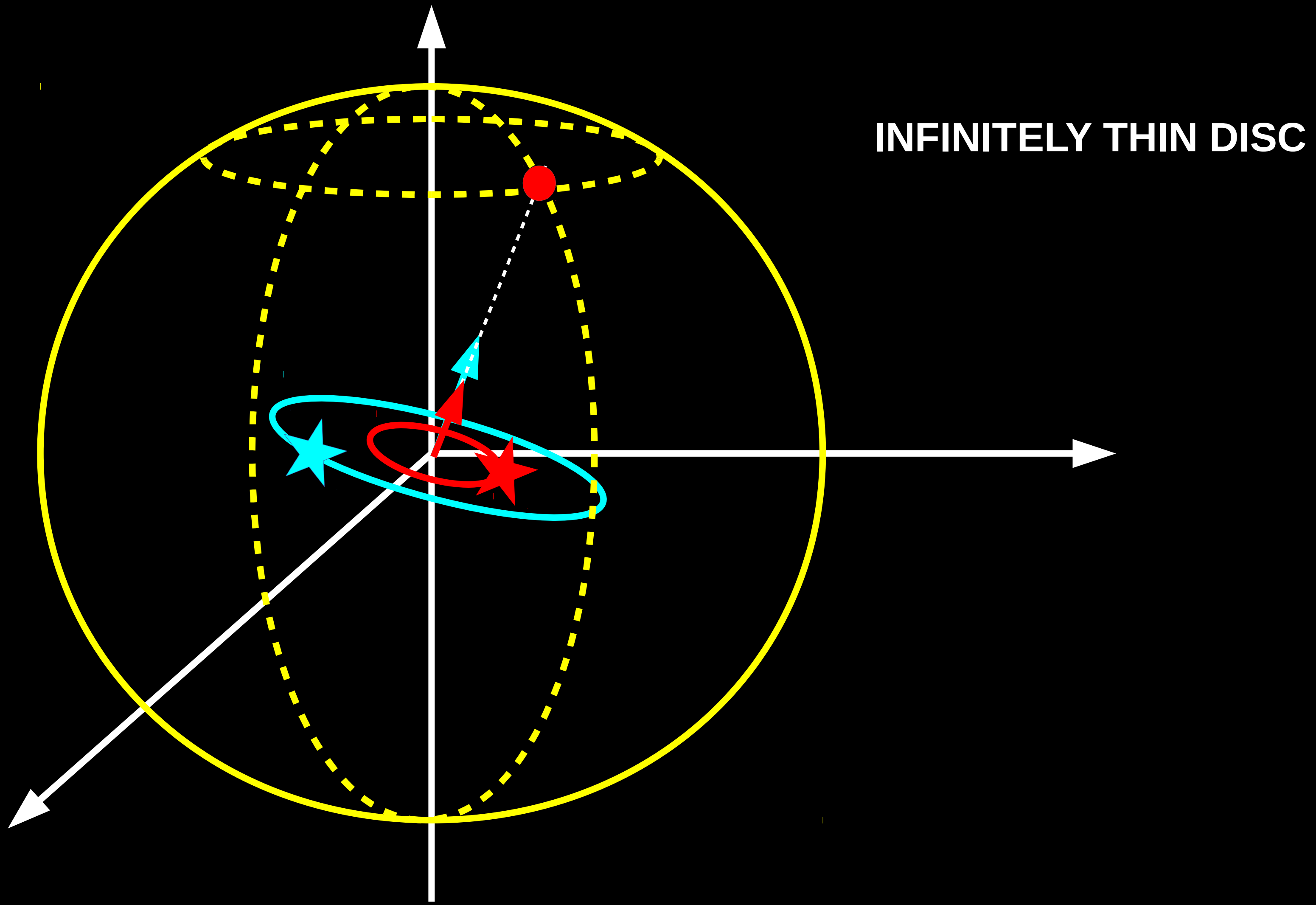

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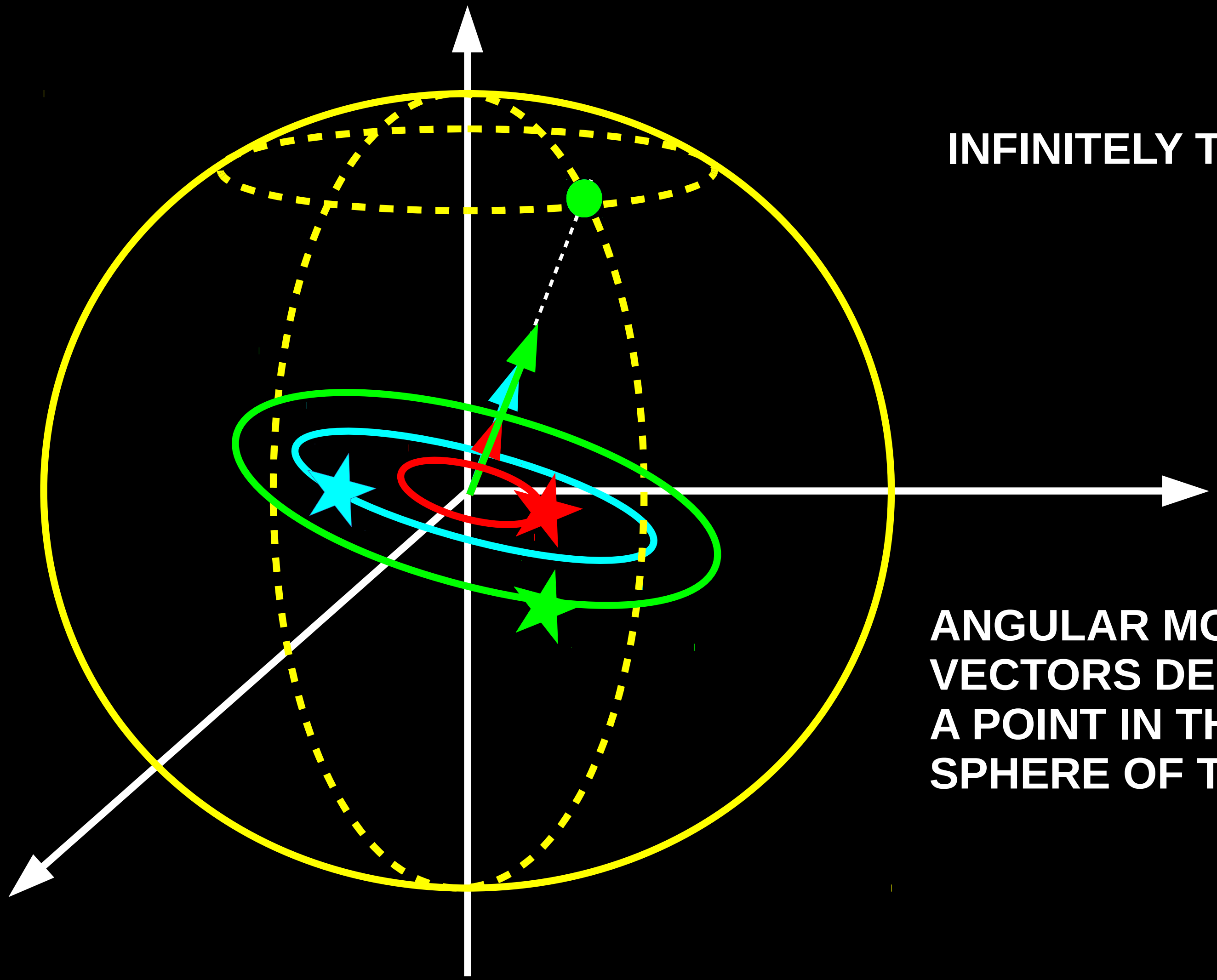

INFINITELY THIN DISC

ANGULAR MOMENTA VECTORS DEFINE A POINT IN THE SPHERE OF THE SKY!

1. What do we observe in the Galactic centre?

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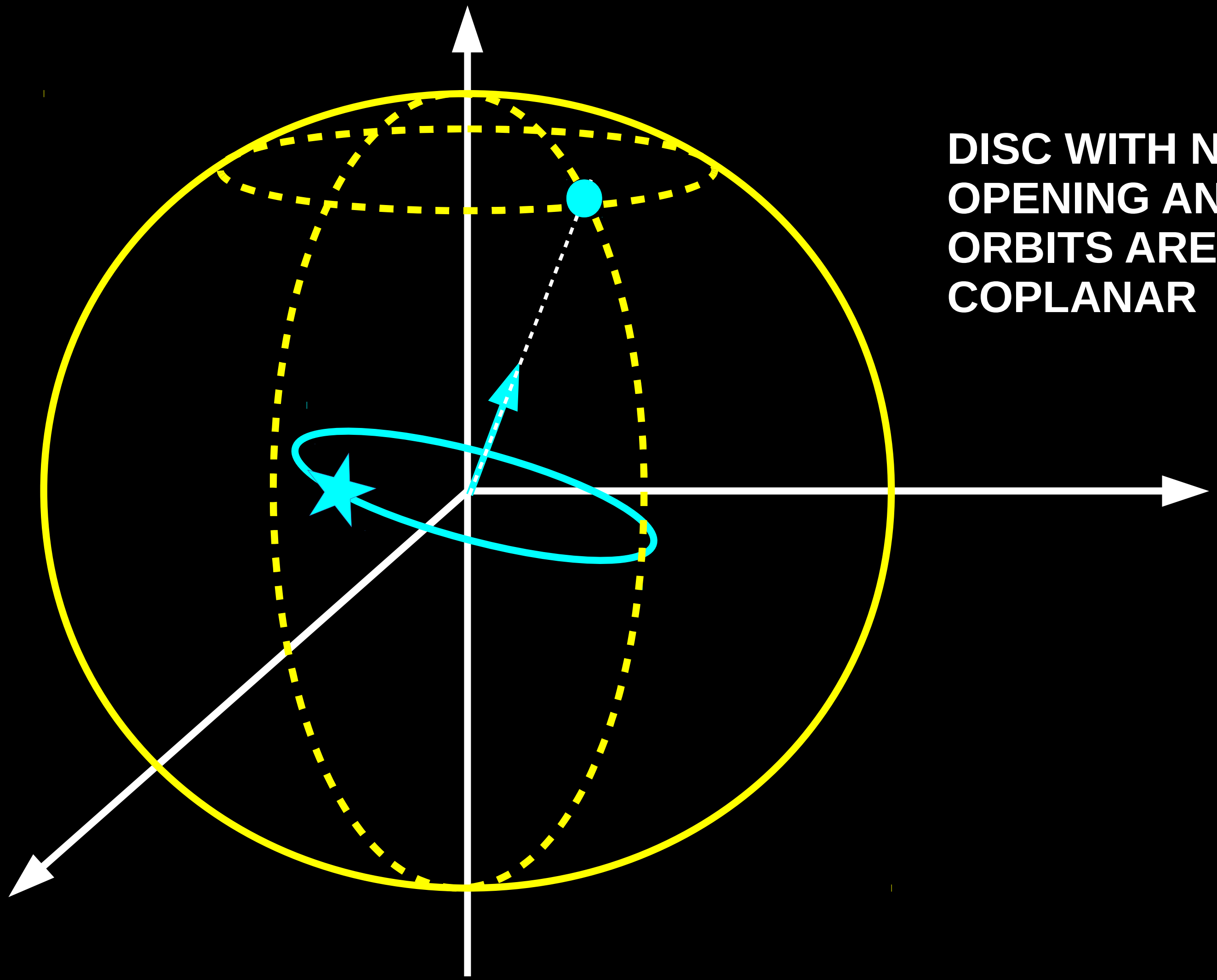

DISC WITH NON-ZERO OPENING ANGLE = ORBITS ARE NOT PERFECTLY COPLANAR

1. What do we observe in the Galactic centre?

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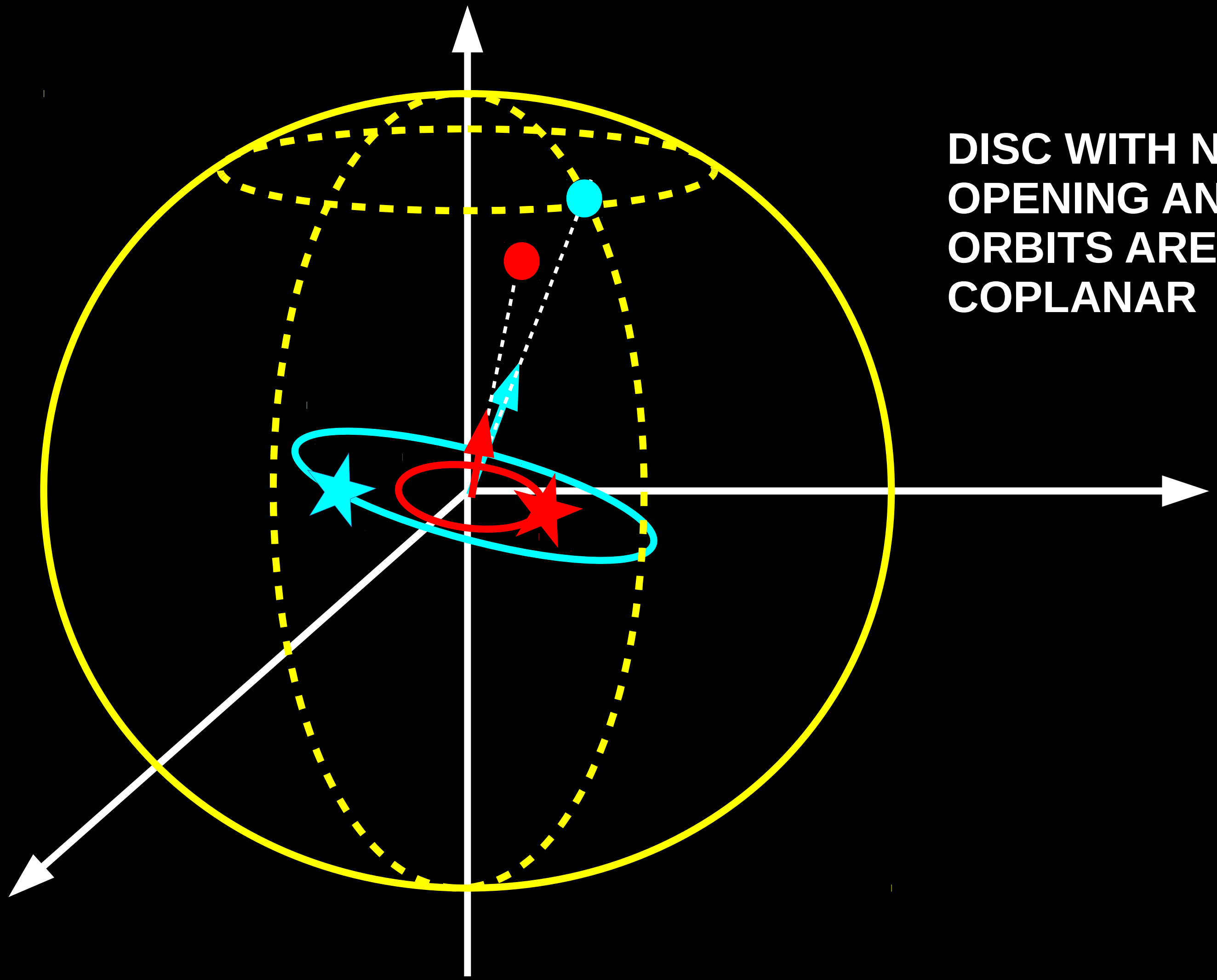

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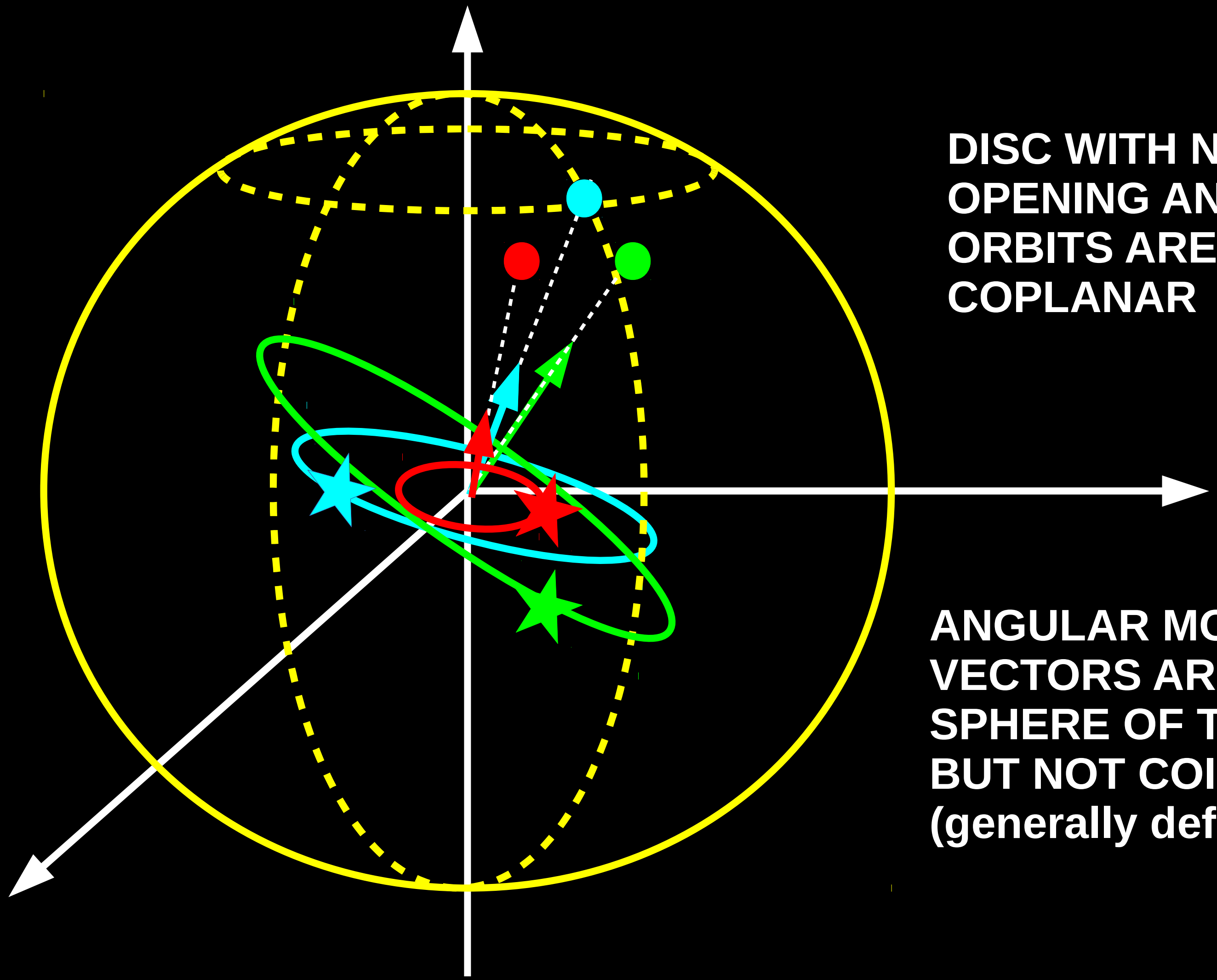

DISC WITH NON-ZERO OPENING ANGLE = ORBITS ARE NOT PERFECTLY COPLANAR

ANGULAR MOMENTA VECTORS ARE CLOSE IN THE SPHERE OF THE SKY, BUT NOT COINCIDENT (generally define a circle)

1. What do we observe in the Galactic centre?

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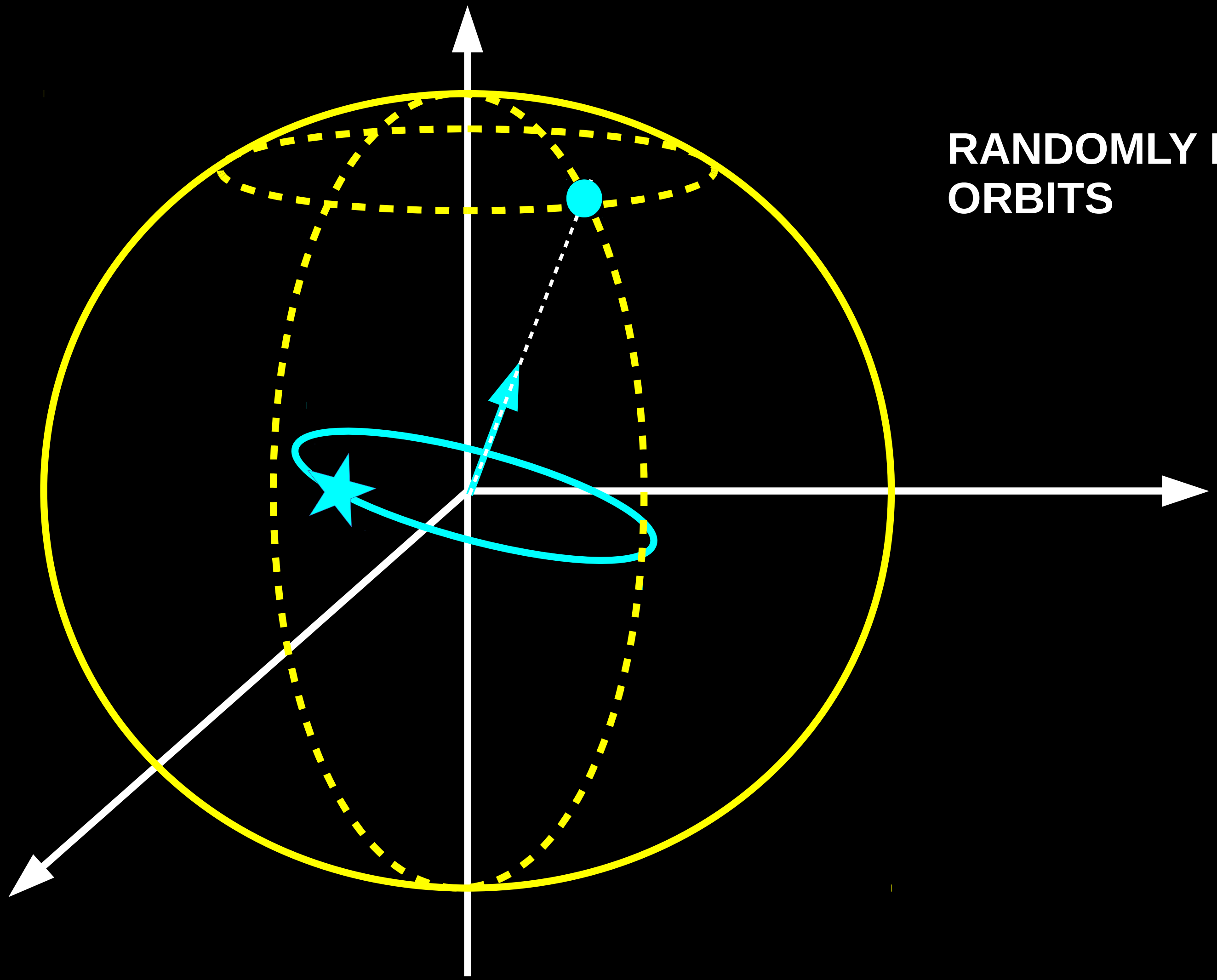

RANDOMLY DISTRIBUTED ORBITS

1. What do we observe in the Galactic centre?

HOW CAN WE PRESENT THIS KIND OF PLOTS TO STUDENTS?

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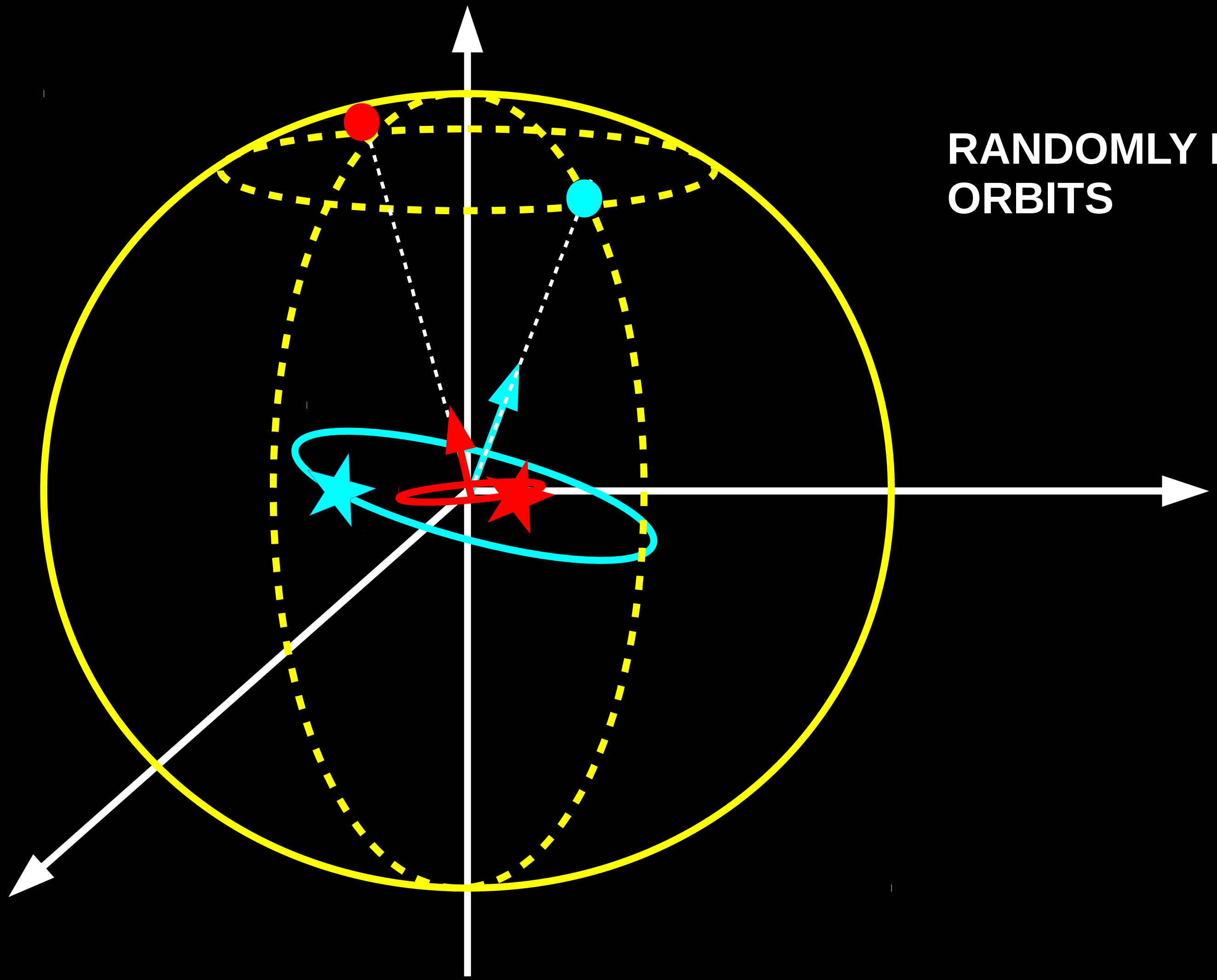

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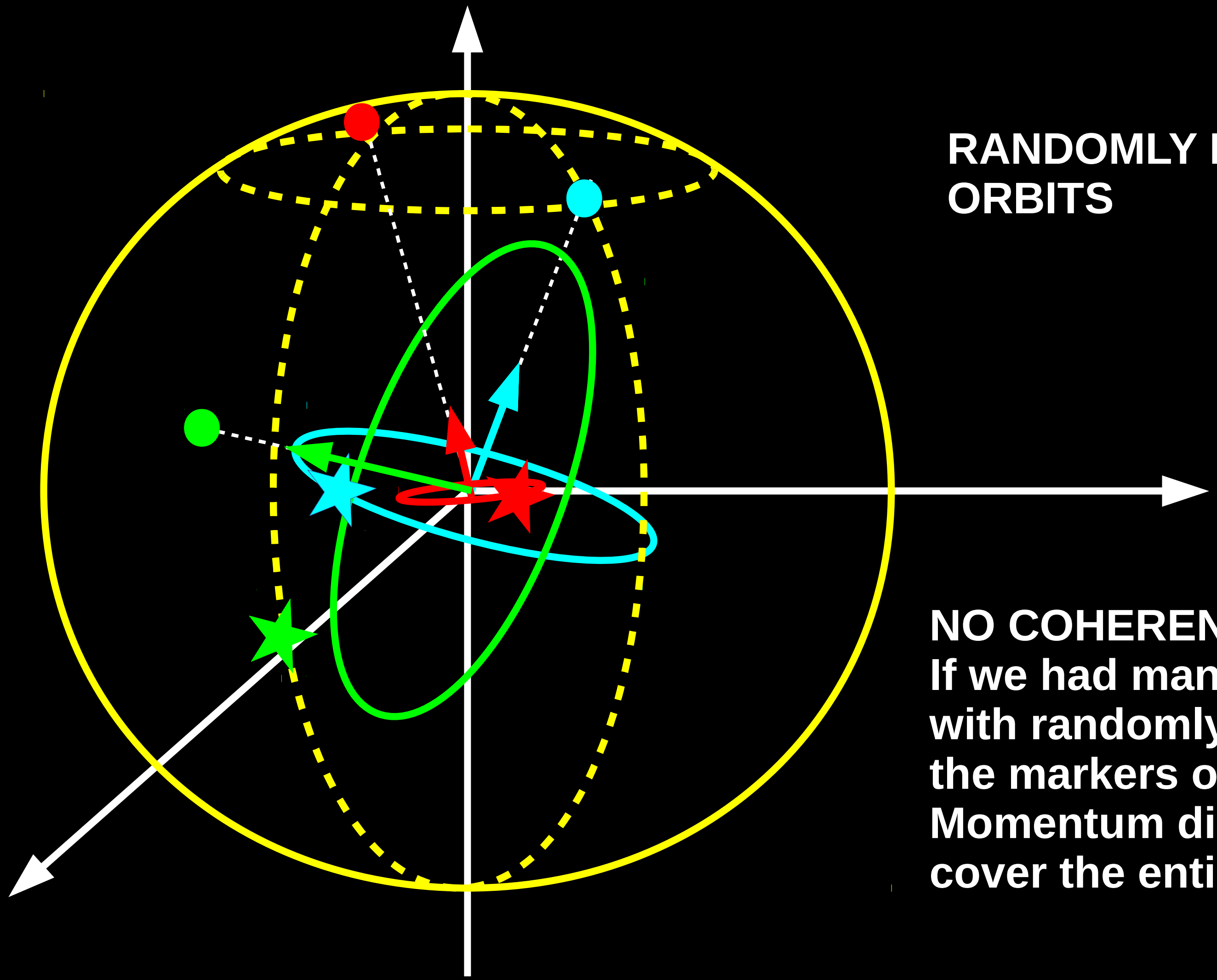


RANDOMLY DISTRIBUTED ORBITS

NO COHERENCE LEFT
If we had many stars
with randomly oriented orbits,
the markers of angular
Momentum directions would
cover the entire sphere

1. What do we observe in the Galactic centre?

YOUNG STARS

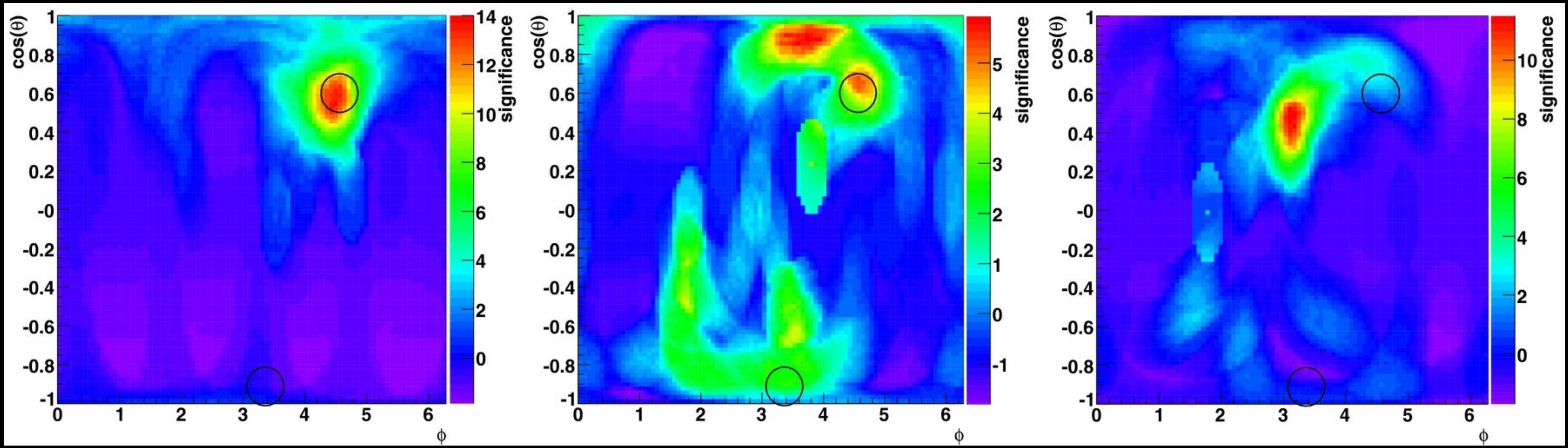
The other early-type stars in the central pc:

O and WR stars, age~ 2-6 Myr

One or two discs?

– Counter-CW disc

– CW disc: a~0.04-0.4 pc, e~0.3, warped and tilted



Paumard et al. 2006; Bartko et al. 2009; Lu et al. 2009

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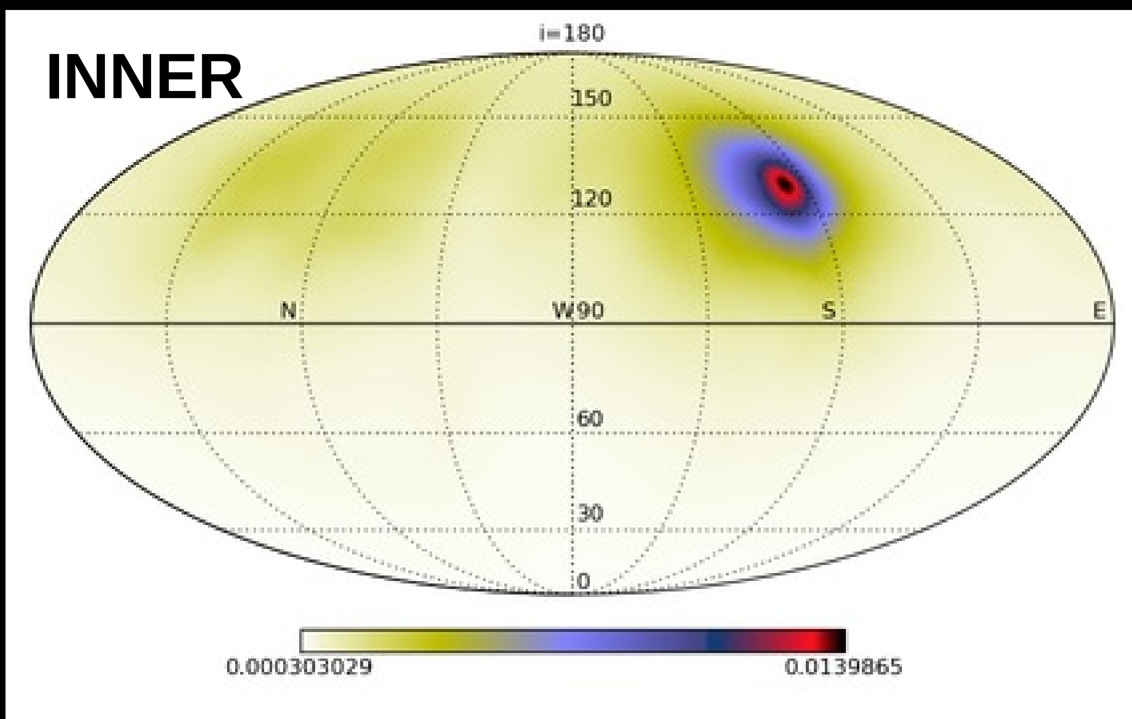
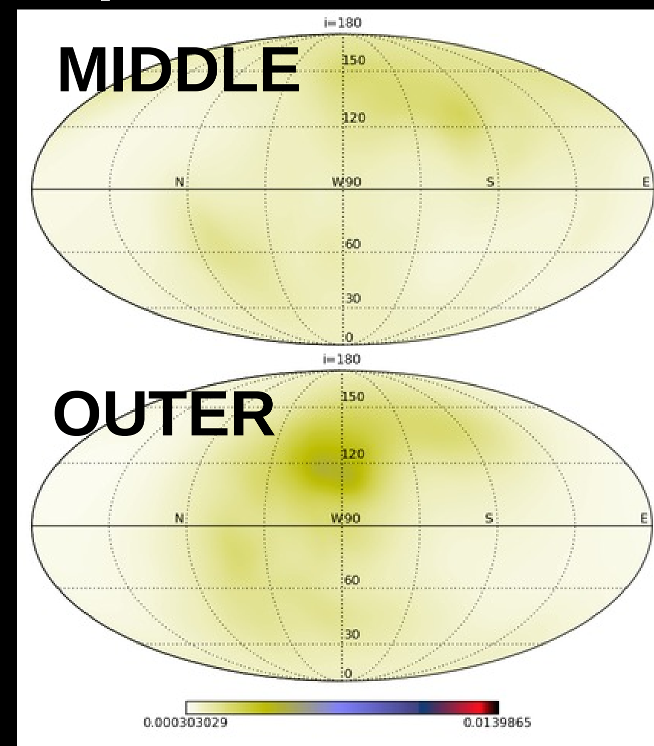
0.1 pc





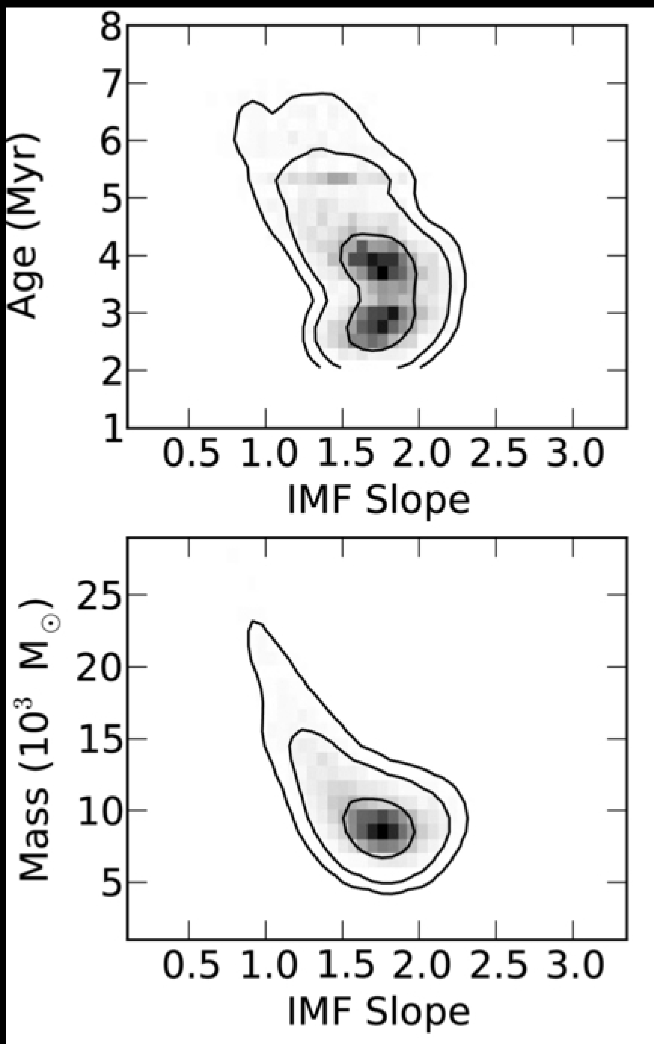
→ Only 20% ET stars in the CW disc

Yelda et al. 2014

YOUNG STARS

The other early-type stars in the central pc:

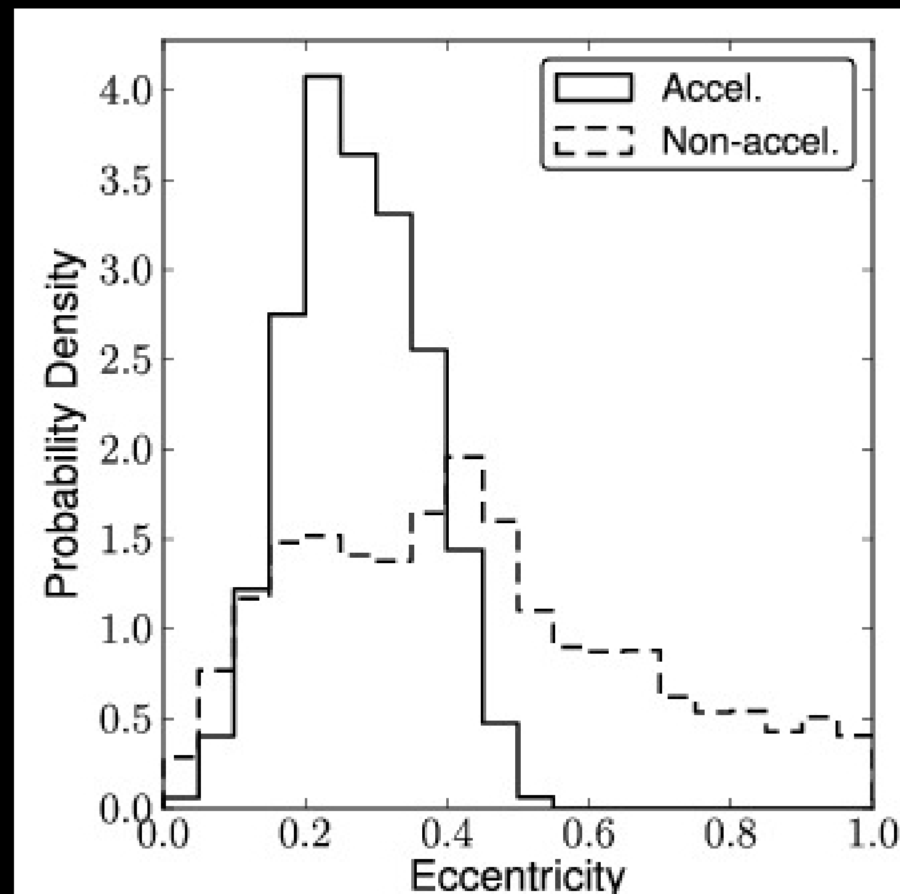
Mass – Age



Do et al. 2013; Lu et al. 2013

Eccentricity

0.3 if only reliable members considered



Yelda et al. 2014

2. What is puzzling about the Galactic centre?

2. What is puzzling about the Galactic centre?

The young stars should not be there!

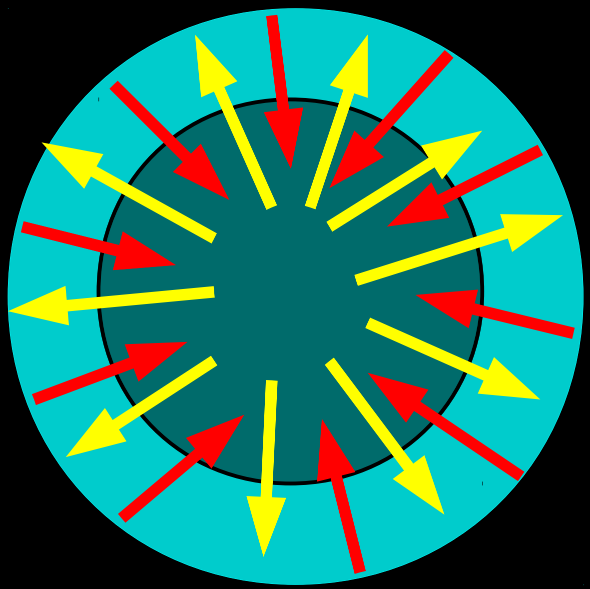
WHY?

1. What do we observe in the Galactic centre?

For the students: Quick note about star formation

MOLECULAR CLOUDS are REGIONS of STAR FORMATION

Basic concept of star formation is consequence of Newton's law:
Stars form when gravitational pull is stronger than pressure force so that gas collapses



Pressure makes gas expand in a time: $$t_s = \frac{r}{c_s}$$

Gravity makes gas collapse in a time: $$t_{\rm ff} = \frac{1}{\sqrt{G\,\rho}}$$

The two are equal if $$r = \frac{c_s}{\sqrt{G\,\rho}}$$

$$r \sim 0.1\,\mathrm{pc}\left(\frac{c_s}{1\ \mathrm{km\ s^{-1}}}\right)\left(\frac{10^6\,\mathrm{cm^{-3}}}{n}\right)^{1/2}$$

Ionized and atomic gas have too large sound speed and too small density to allow gas to collapse on small (sub-parsec) scales → no stars form

Molecular gas has sufficiently small sound speed and large density to allow gas to collapse on small (sub-parsec) scales → stars can form

For the students: Quick note about star formation

BOTTOM LINE IS:
WE NEED COOL AND DENSE MOLECULAR CLOUDS FOR STAR FORMATION TO OCCUR

CAVEAT: in this very simplified picture we did not mention cooling..but radiative cooling might be too much for school girls and boys...
The real thing would require also:

$$t_{\mathrm{cooling}} \leq t_{\mathrm{ff}} \leq t_s$$

2. What is puzzling about the Galactic centre?

The young stars should not be there!

A molecular cloud is disrupted by the tidal field exerted by the SMBH if its density is lower than the Roche density

$$n_{\rm RL} \sim 10^7\,{\rm cm}^{-3}\,\left(\frac{m_{\rm BH}}{3\times 10^6\,M_\odot}\right)\,\left(\frac{\rm pc}{r}\right)^3$$

Typical cloud density < 10^6 cm^{-3}

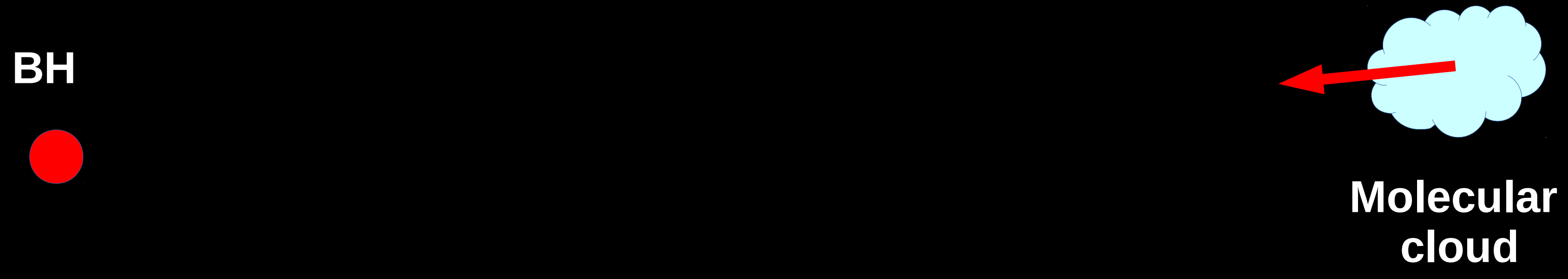
→ **The stars cannot form in 'normal conditions' if the cloud is disrupted (Phinney 1989).**

2. What is puzzling about the Galactic centre?

For the students: Quick note about tidal disruption

Again...we need good ol' Newton

We generally assume gravitational forces between point-like objects
Ok if they are sufficiently distant



2. What is puzzling about the Galactic centre?

For the students: Quick note about tidal disruption

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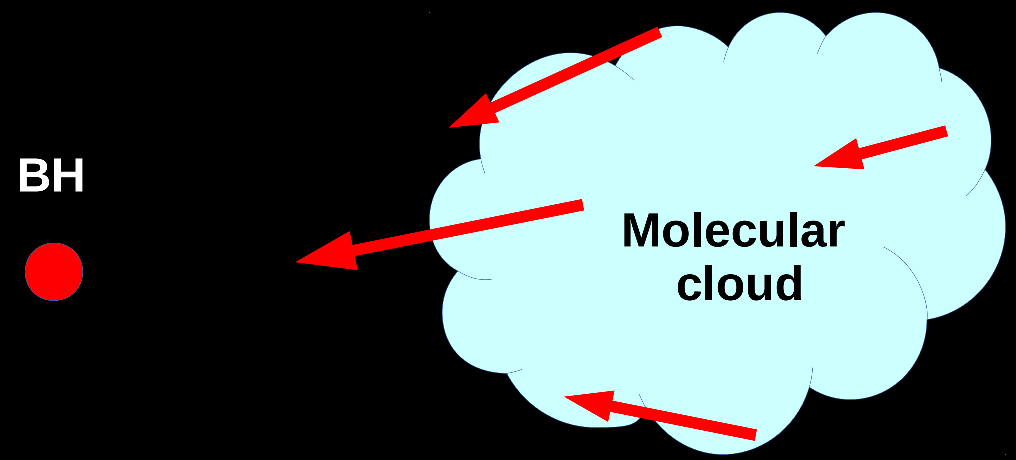
We generally assume gravitational forces between point-like objects
If two bodies approach 'too much' gravitational forces start acting differently on different parts of body surfaces

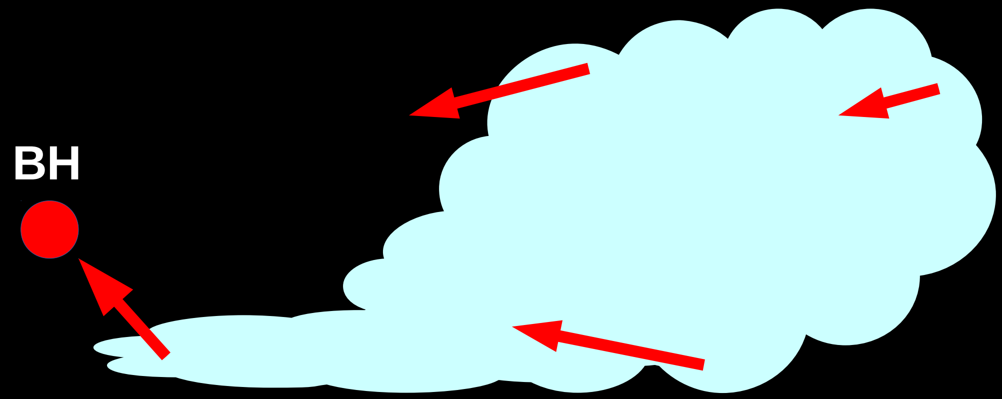


2. What is puzzling about the Galactic centre?

For the students: Quick note about tidal disruption

Again...we need good ol' Newton

We generally assume gravitational forces between point-like objects
If two bodies approach 'too much' gravitational forces start acting differently on different parts of body surfaces
Till the most extended body is teared apart from gravitational forces:
It is TIDALLY DISRUPTED



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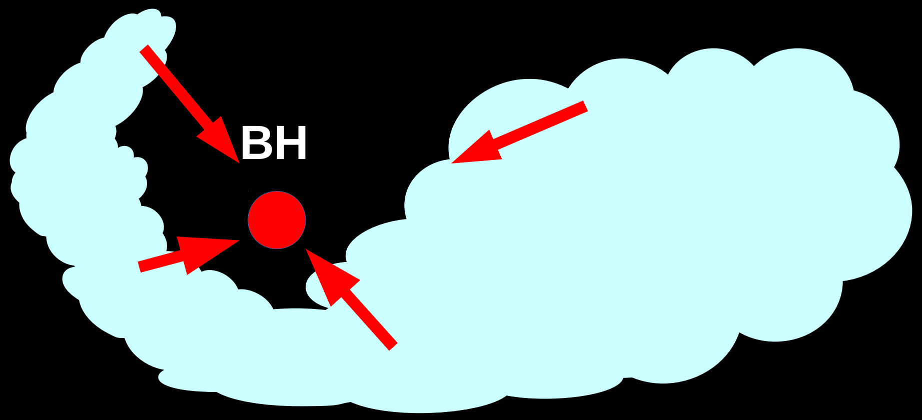


If the molecular cloud had non-zero ANGULAR MOMENTUM, the ang. mom. Is conserved during disruption → the molecular cloud end in a disc

2. What is puzzling about the Galactic centre?

For the students: Quick note about tidal disruption

Again...we need good ol' Newton

Tidal force important if $$F_{\rm grav} < F_{\rm tid}$$

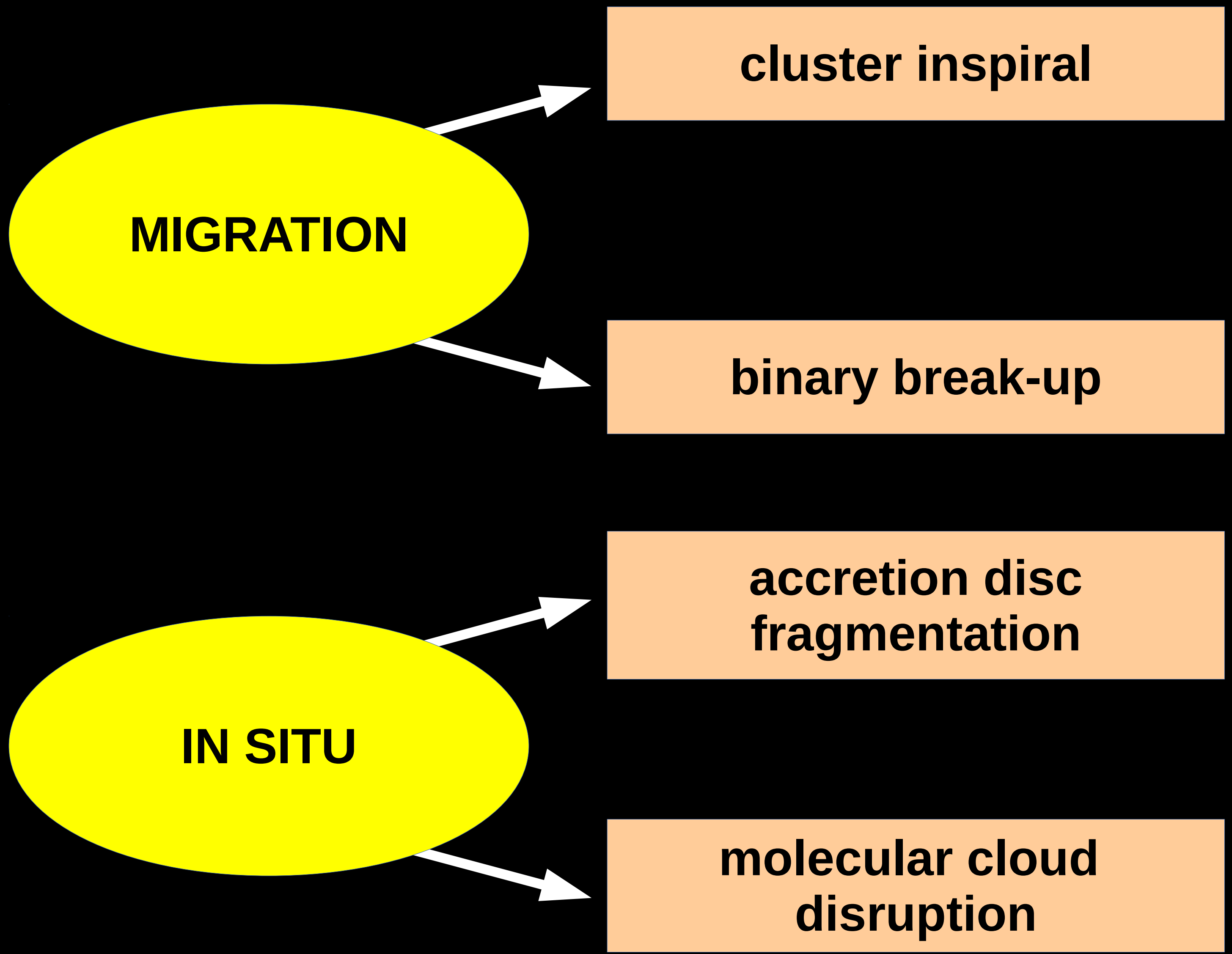
$$\frac{G\,M_{\rm cloud}}{R_{\rm cloud}^2} < 2\,\frac{G\,m_{\rm BH}\,M_{\rm cloud}\,R_{\rm cloud}}{r^3}$$

roughly assuming $$M_{\rm cloud} \sim \rho_{\rm cloud}\,\frac{4\,\pi}{3}\,R_{\rm cloud}^3$$

We find

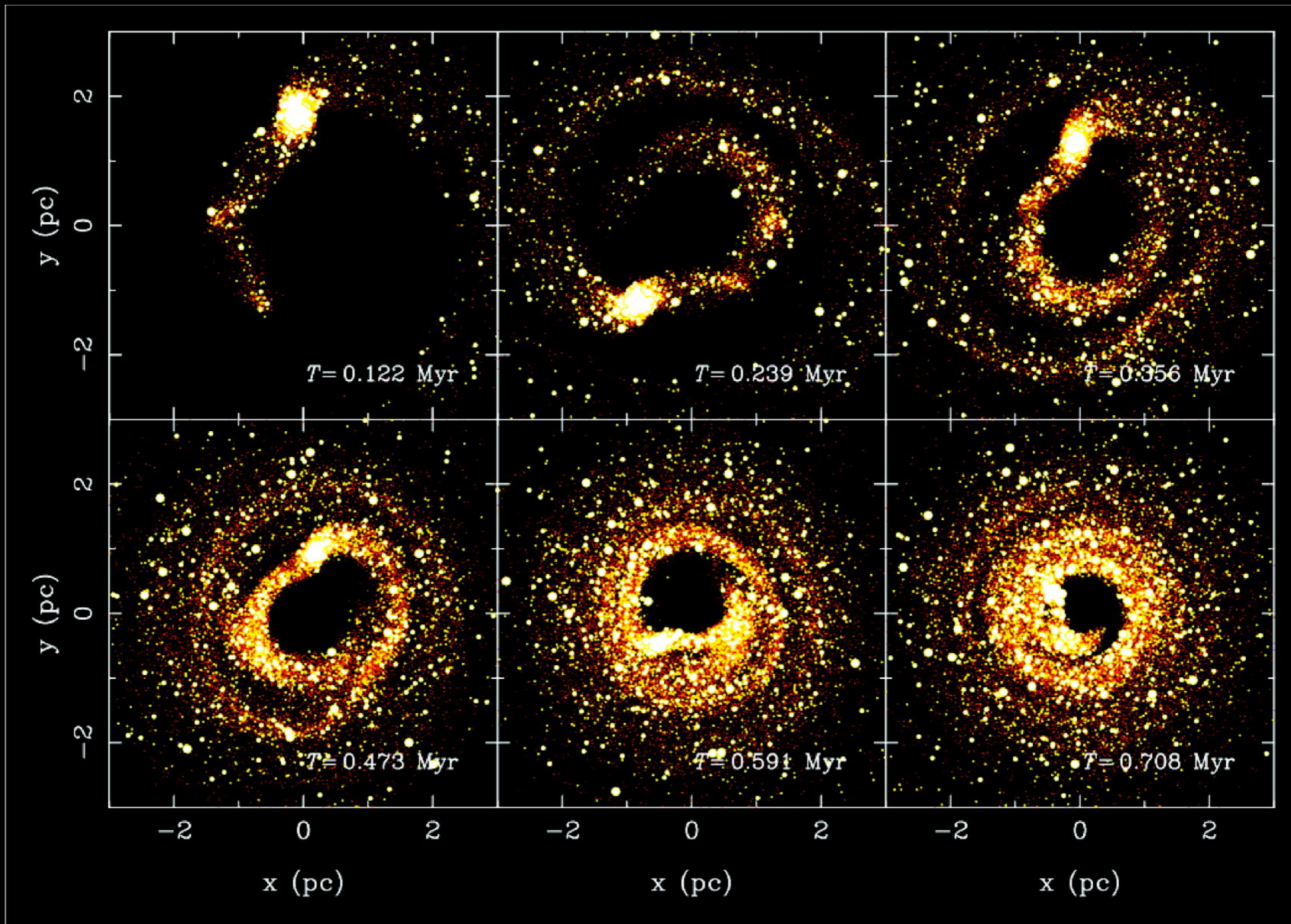
$$\rho_{\rm cloud} < \frac{m_{\rm BH}}{2\,r^3} \sim 10^{-16}\ {\rm g\ cm}^{-3}\left(\frac{m_{\rm BH}}{3\times10^6 M_\odot}\right)\left(\frac{1\ {\rm pc}}{r}\right)^3$$

Scenarios to explain the formation of the ET stars



Cluster inspiral:

A star cluster spirals toward the SMBH and is disrupted

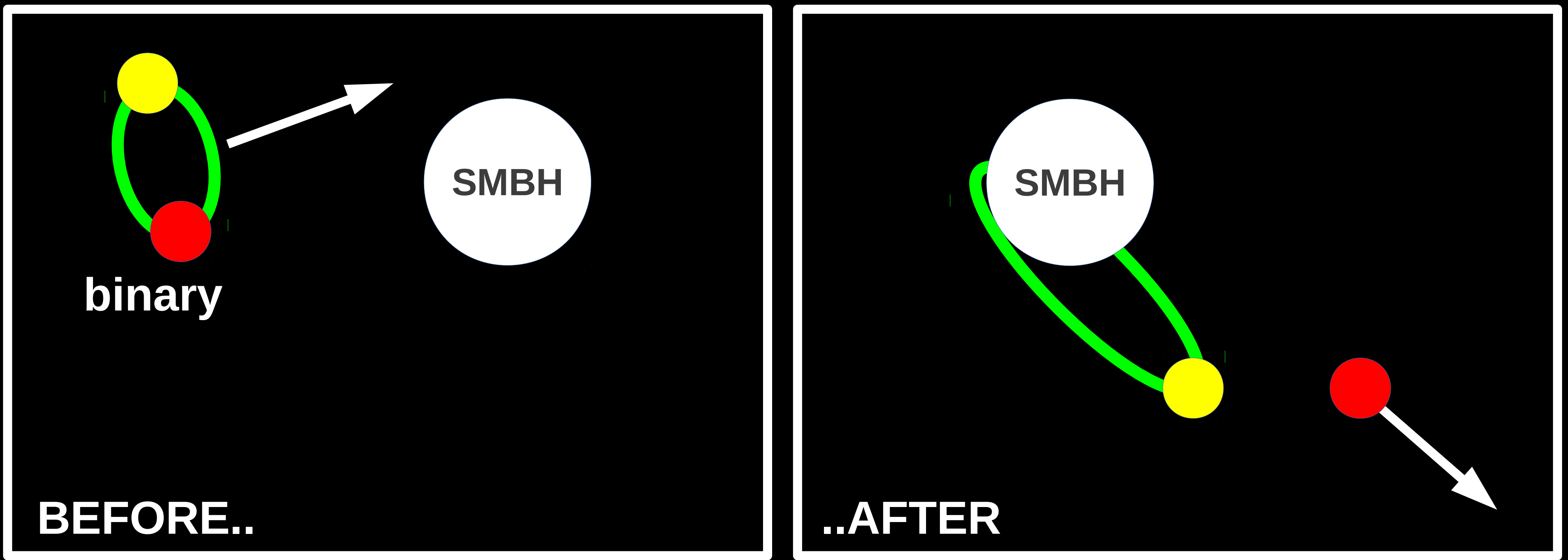


Fujii et al. 2008

Binary break-up:

Several binaries are captured and disrupted by the SMBH

Note for students: binaries are simply Kepler binaries!

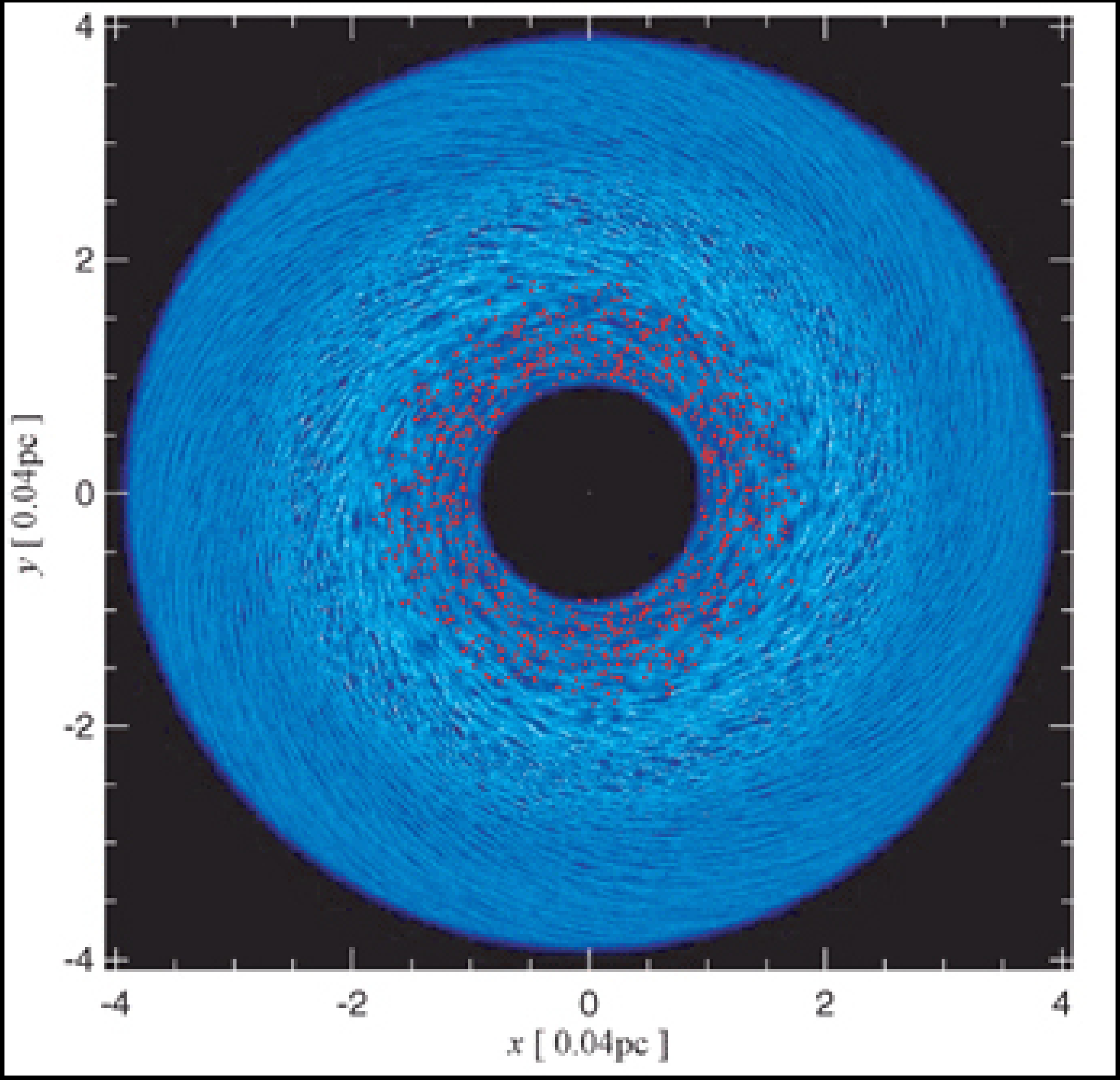


$$a_c \sim 0.6 \left(\frac{m_{\rm BH}}{M_{\rm bin}}\right)^{1/3} r_{\rm tid} \qquad e_c \sim 1 - \frac{r_{\rm tid}}{a_c} \sim 0.97$$

Hills 1991, Perets et al. 2007, Perets & Gualandris 2010

Accretion disc fragmentation:

If the SMBH accretion disc becomes unstable to fragmentation it can form stars



What fragmentation means?
Collapse of gas clumps to form stars

What accretion disc means?
A disc of gas which feeds the BH (see Luca Zampieri's Exercises after this talk)

Nayakshin et al. 2007

For students asking smart questions

BUT.. discs are very different from 'spherical clouds'

Does the rule that $t_{\text{ff}} \leq t_s$

holds even if we have a ROTATING disc?

We have one more ingredient here: rotation

→ rotation increases velocity of gas so that even cool and dense gas might move too fast for gravity to win

→ we can find a new criterion as

$$\boxed{t_{\text{ff}}^2 \leq T\, t_s}$$

Orbital period

angular frequency

$$\boxed{Q = \frac{t_{\text{ff}}^2}{T\, t_s} = \frac{1}{G\,\rho}\,\frac{\Omega}{2\,\pi}\,\frac{c_s}{h}}$$

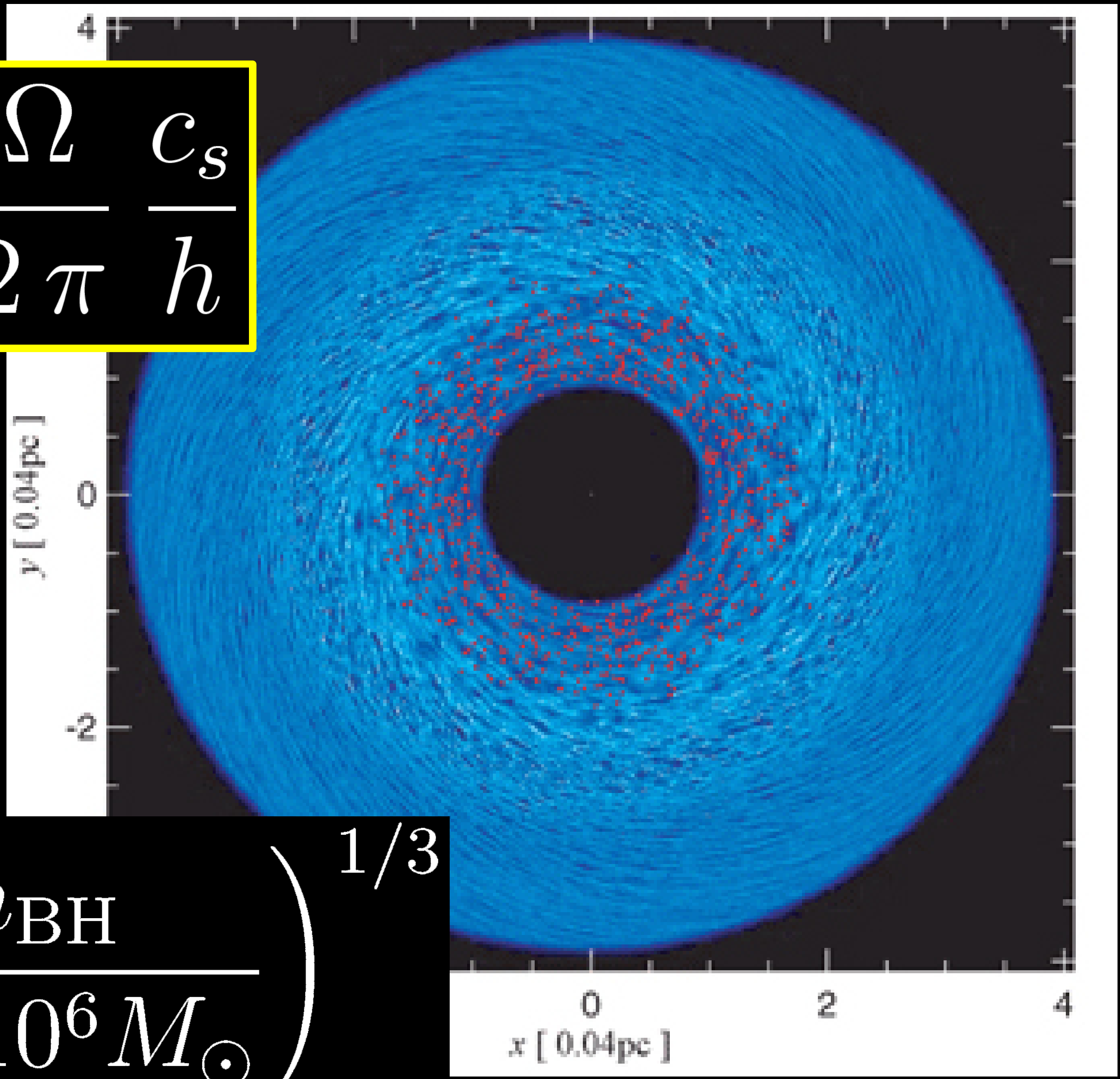
disc scale height

Called Q Toomre parameter (Toomre 1971)

Accretion disc fragmentation:

If the SMBH accretion disc becomes unstable to fragmentation it can form stars

$$\boxed{Q = \frac{t_{\rm ff}^2}{T\,t_s} = \frac{1}{G\,\rho}\,\frac{\Omega}{2\,\pi}\,\frac{c_s}{h}}$$

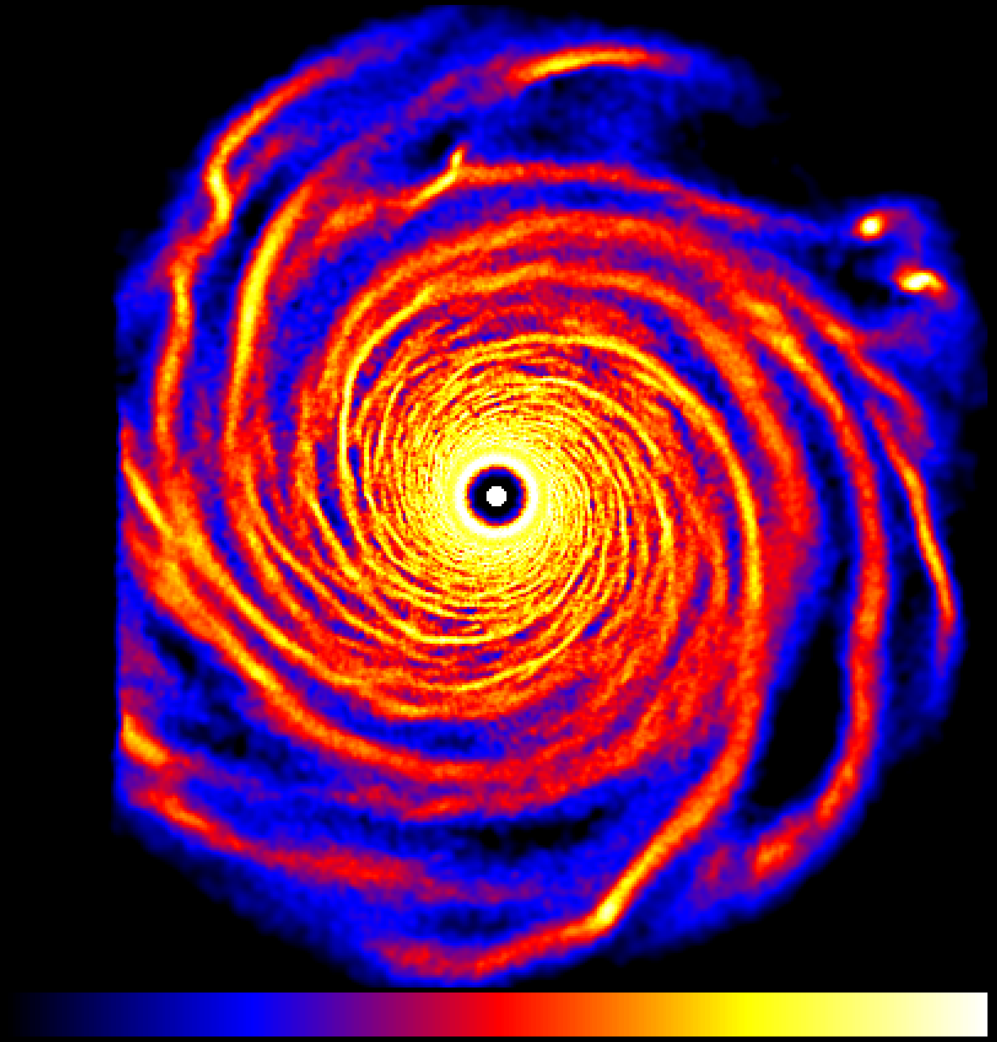


$$r_{\rm Q=1} \sim 1.2\,{\rm pc}\left(\frac{m_{\rm BH}}{3\times10^6 M_\odot}\right)^{1/3}$$

Nayakshin et al. 2007

Accretion disc fragmentation:

If the SMBH accretion disc becomes unstable to fragmentation it can form stars



Credits: Prof. Ken Rice

2. What is puzzling about the Galactic centre?

Molecular cloud disruption:

A molecular cloud is disrupted by the SMBH, but

(i) the residual angular momentum,
(ii) the shocks that take place in gas streams

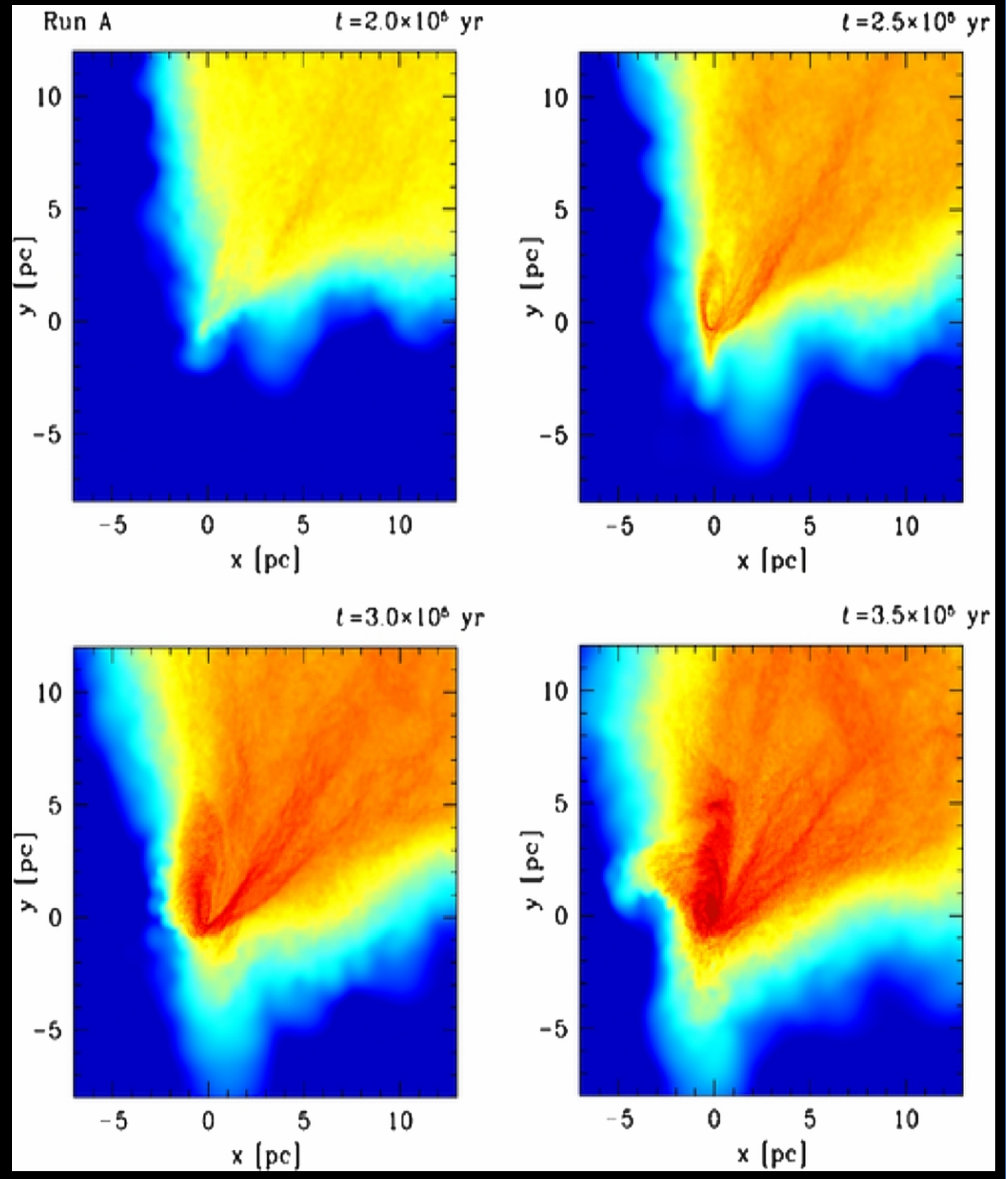
might lead to the formation of a DENSE DISC, denser than Roche density

(i) residual angular momentum

→ **Formation of a rotating disc**

(ii) shocks induce fast cooling

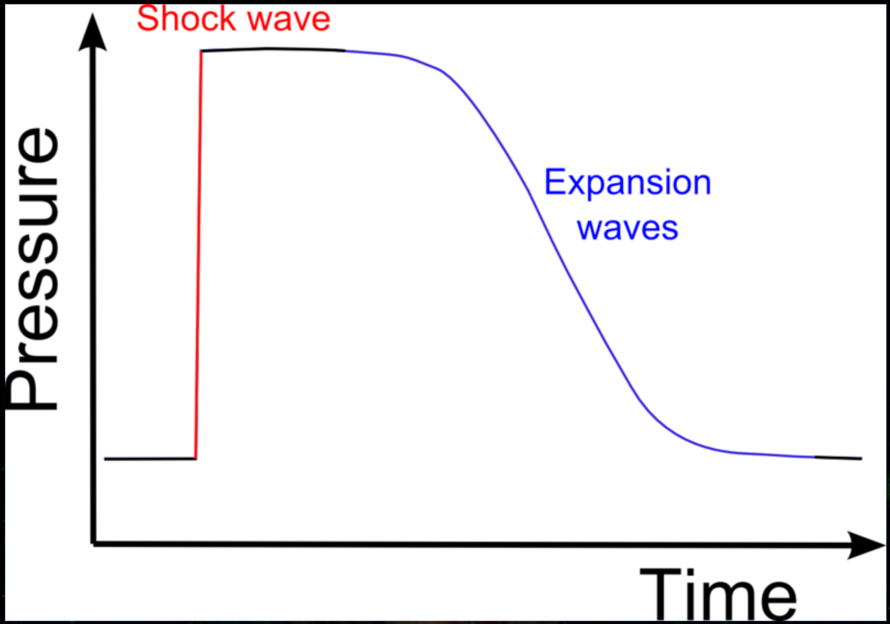
→ **Density increases**



Bonnell & Rice 2008; MM et al. 2008; Hobbs & Nayakshin 2009; Alig et al. 2011; MM et al. 2012; Alig et al. 2013; Lucas et al. 2013

2. What is puzzling about the Galactic centre?

For the students: Quick note about shocks and SF



Shock := a discontinuity in the properties of the fluid (pressure, density, temperature, velocity..)

Measured by Mach number:
ratio between actual velocity and sound speed in the fluid

Shock compresses the fluid

↓

density increases dramatically in the 'bow' front

↓

higher density means better conditions for star formation!

3. Simulating star formation in the Galactic centre

3. Simulating star formation in the Galactic centre

* A turbulent molecular cloud
R~15 pc
M~10^5 M⊙

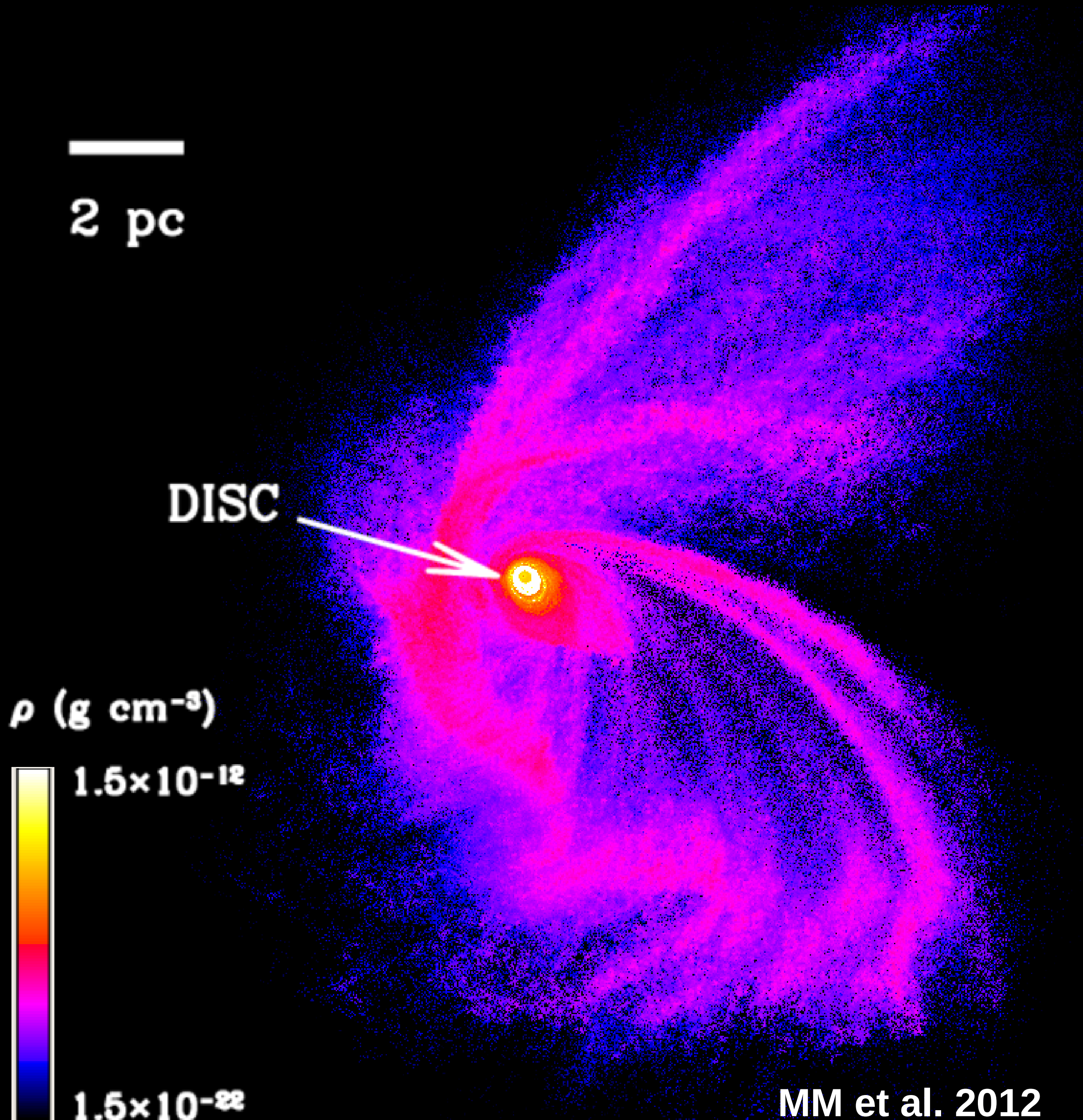
* At 25 pc from the GC

* impact parameter 0.01 pc and marginally bound

* a SMBH sink particle

* integration with OSPH (Read et al. 2010)

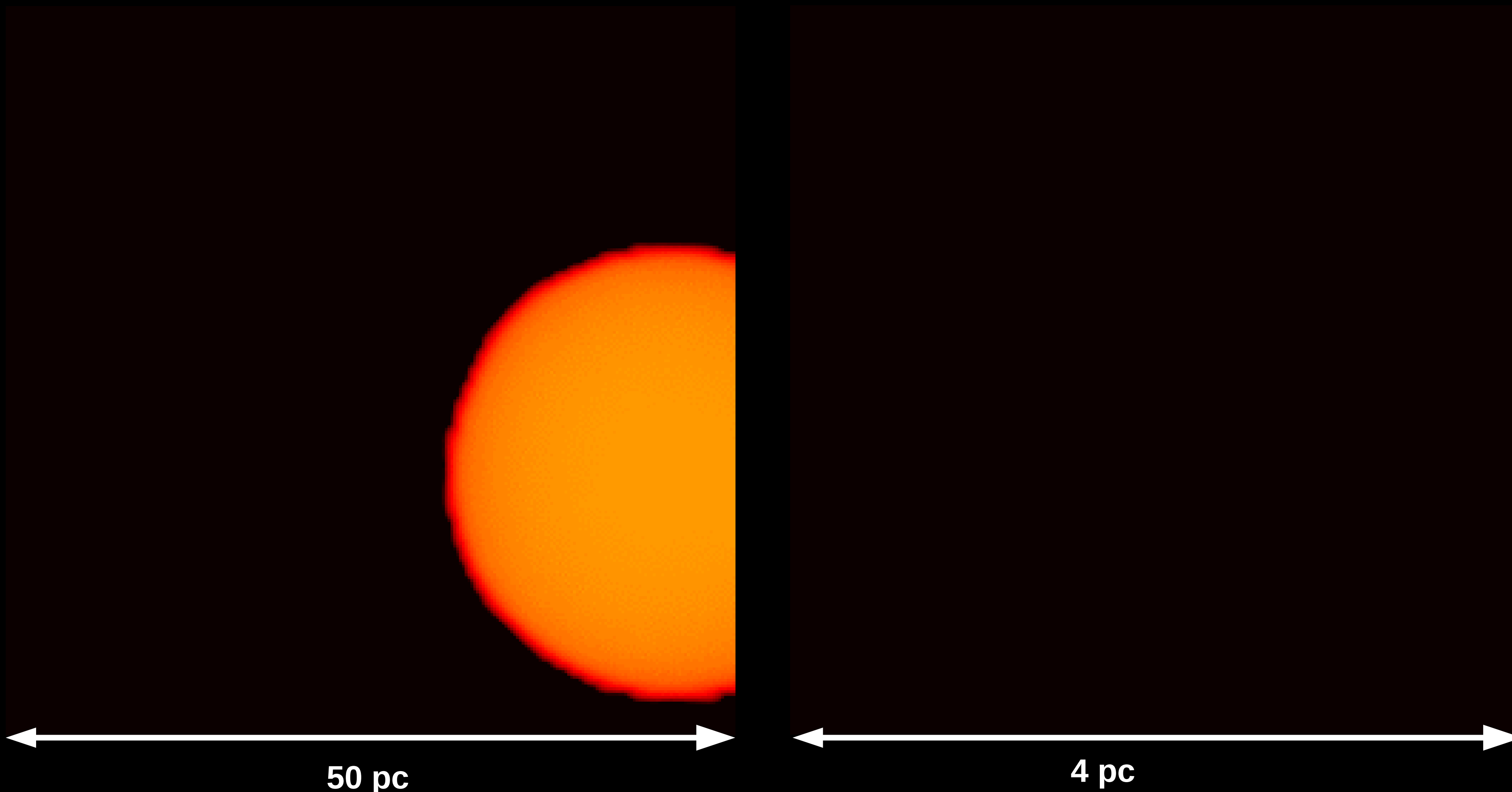
* cooling + Planck & Ross. opacities (Boley 2009, 2010)



MM et al. 2012

3. Simulating star formation in the Galactic centre

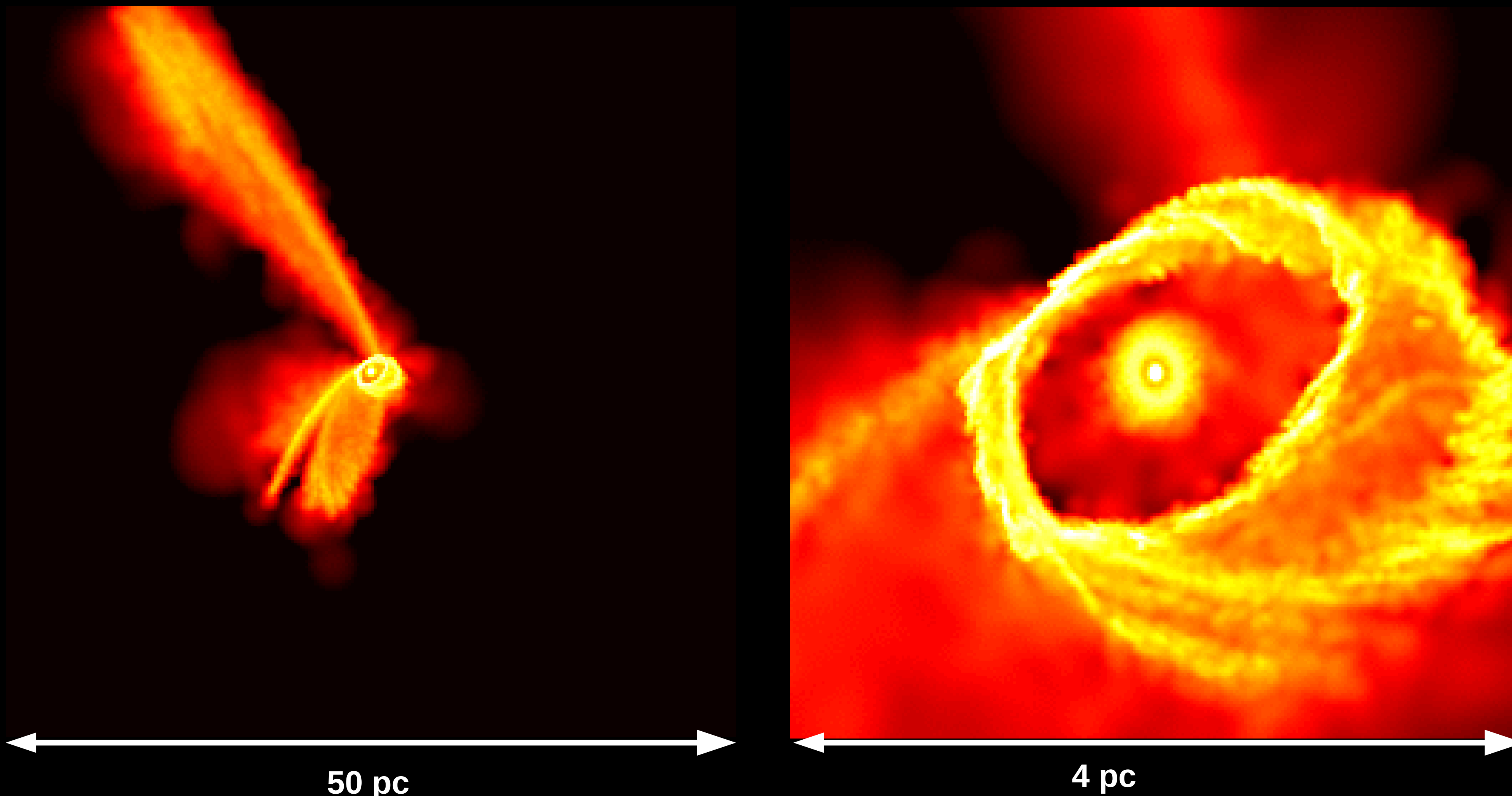
Movie from t=0 to t=0.63 Myr



MM et al. In preparation

3. Simulating star formation in the Galactic centre

Movie from t=0 to t=0.63 Myr



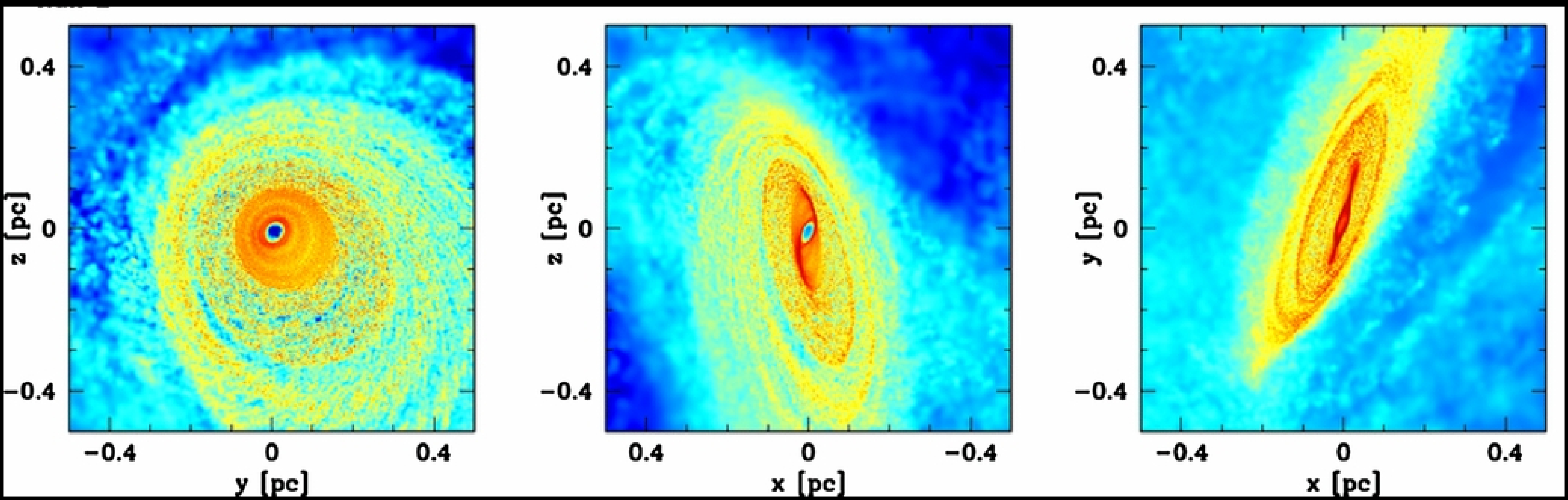
MM et al. In preparation

Formation of a gas disc

with $r_{out} \sim 0.5$ pc $r_{int} \sim 0.1$ pc

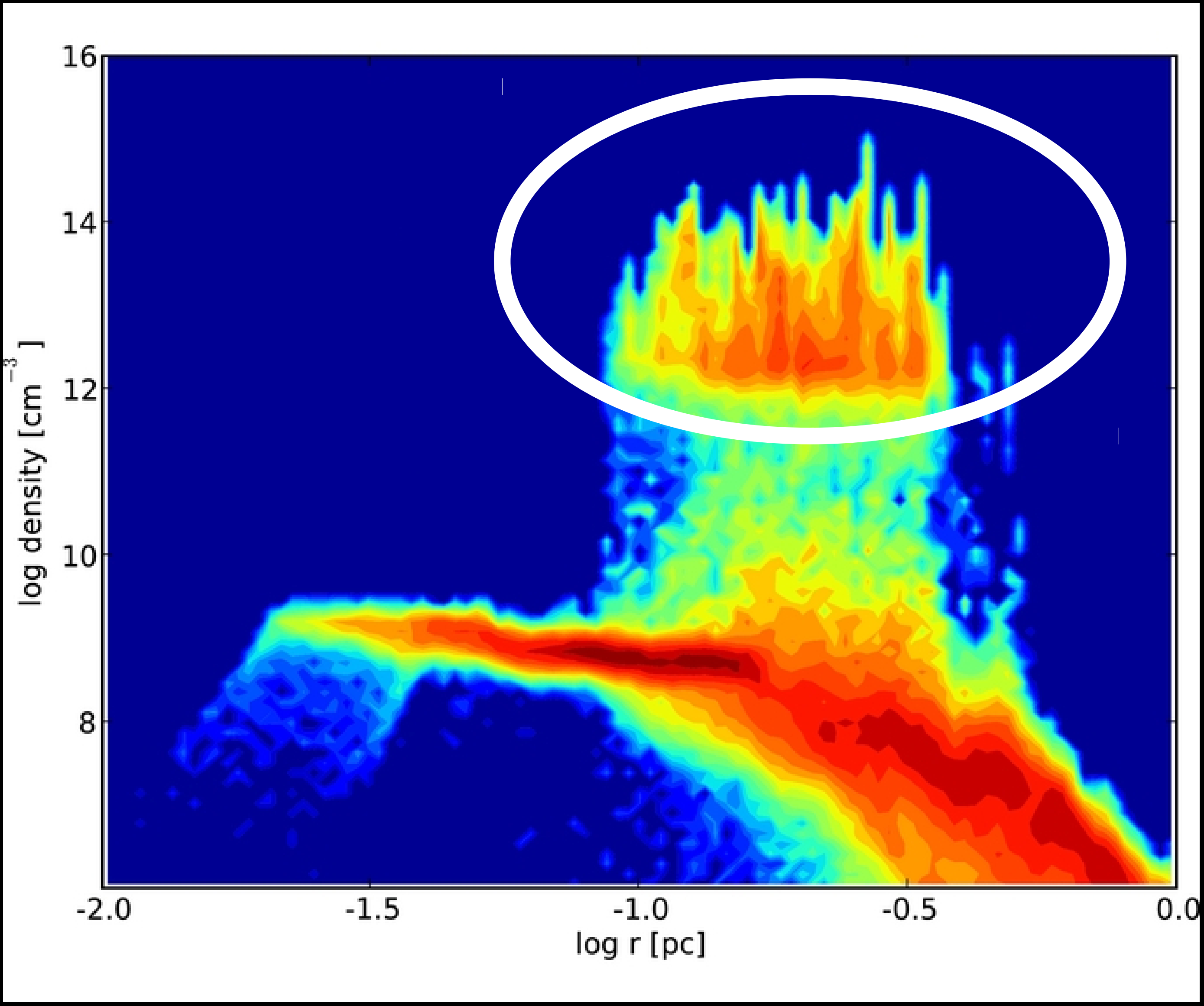
$H \sim 0.1$-0.05 pc $n \sim 10^{9-10}$ cm^{-3}

We follow the beginning of gas fragmentation



MM et al. 2012

We call 'protostars' the gas clumps with n>32 and density $\rho > \rho_{th} = 2 \times 10^{12}$ cm^{-3} within a radius r = 2.2×10^{-3} (T_{MC}/500 K)$^{1/2}$ pc CHOSEN WITH A TRIAL AND ERROR APPROACH

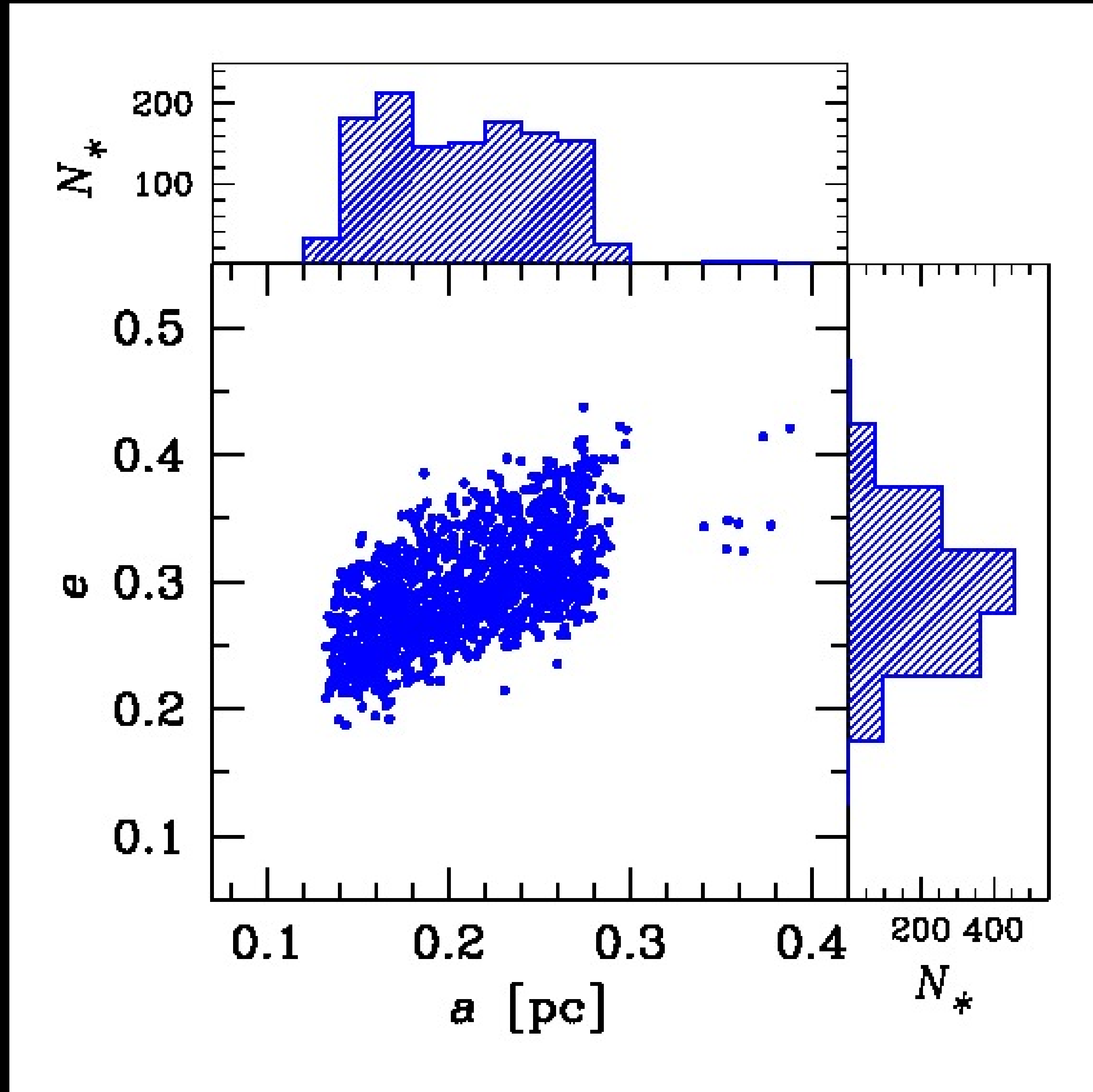


MM et al. 2012

ORBITAL PROPERTIES
of >32 particle clumps (proto-stars):

– Av. eccentricity~ 0.3 in agreement with observations (Yelda et al. 2014)

– Semi-major axis~ 0.1 – 0.4 pc in agreement with old observations (Bartko et al. 2009; Lu et al. 2009), not with new observations (Yelda et al. 2014)



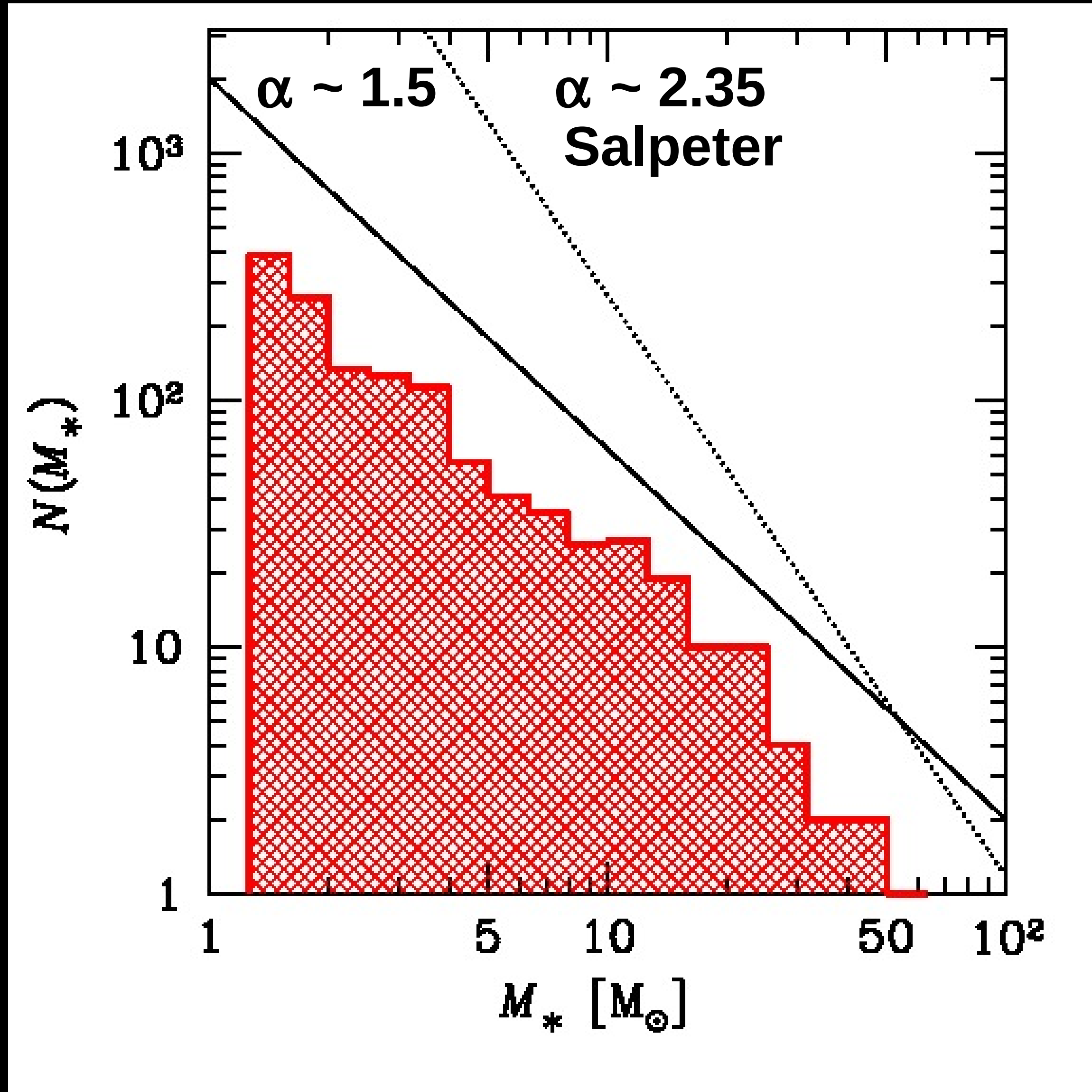
MM et al. 2012

MASS FUNCTION of PROTOSTELLAR CLUMPS:

Best fitting slope
α ~ 1.5 +/- 0.1

Best fitting OBSERVED slope
α ~ 1.7 +/- 0.2

(Lu et al. 2013; while Paumard et al. 2006; Bartko et al. 2009; Eisenhauer et al. 2009 indicated α ~0.5)



MM et al. 2012

MODEL COMPARISON

Scenario	Star distribution	Eccentricity	Age
Cluster inspiral	disc	depends on cluster orbit	> 6 Myr
Binary break-up	random	>0.9	depends on stellar population
Accretion disc	disc	~ 0	1 – 6 Myr
Molecular cloud disruption	disc	~ 0.3 (depends on cloud orbit)	1 – 6 Myr

MODEL COMPARISON

Scenario	Star distribution	Eccentricity	Age

NONE of the PROPOSED SCENARIOS is ABLE to EXPLAIN the observed young stellar population in the Galactic centre,

in particular

– the S-stars

– the CW disc (20% of ET stars)

– the ET stars that do not belong to the CW disc (80%)

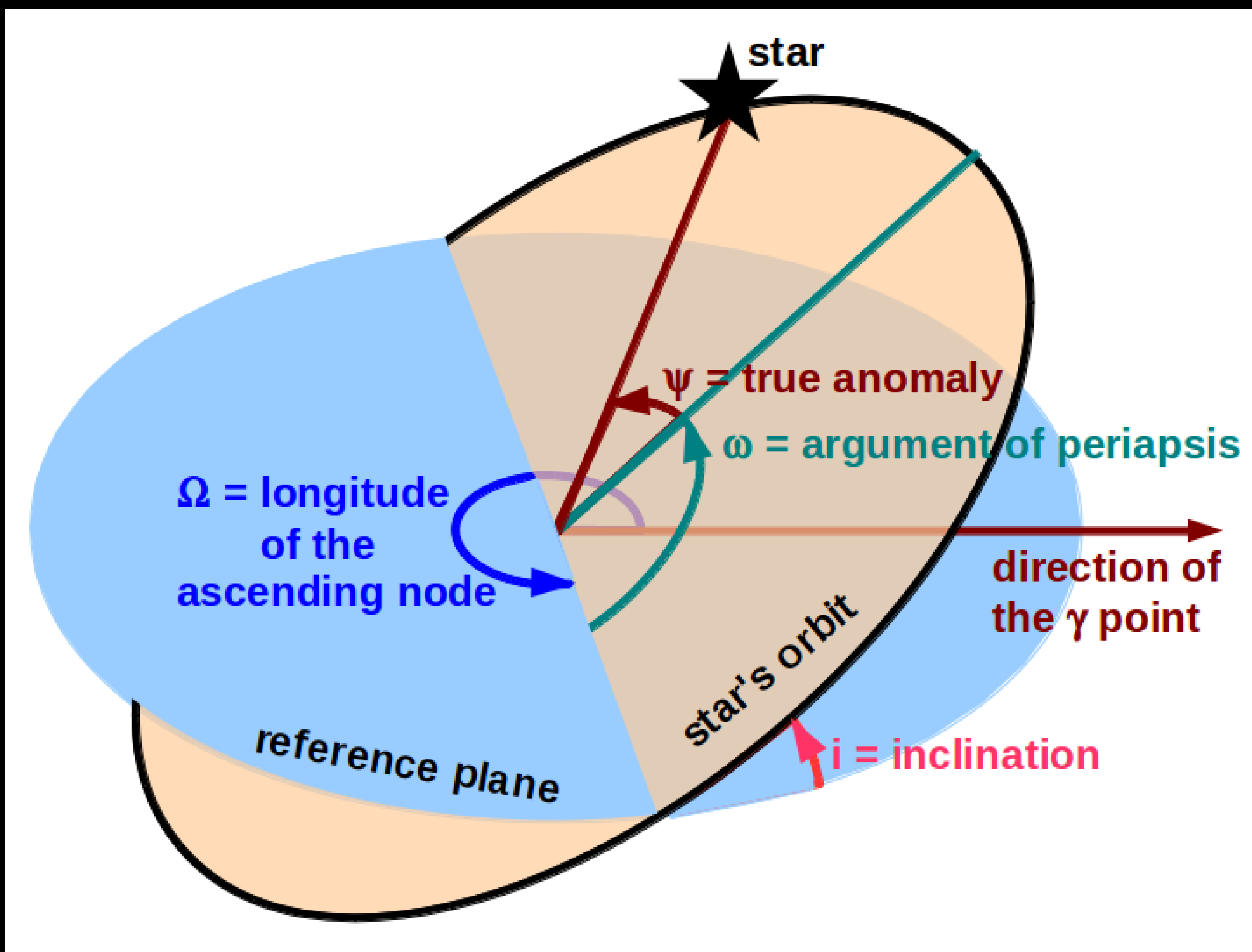
BUT THE STARS EVOLVE VIA DYNAMICAL PROCESSES

4. The secular evolution of the Galactic centre

NEWTONIAN PRECESSION(s)

A star orbiting the SMBH can be described as in Keplerian motion around the SMBH plus an EXTERNAL POTENTIAL (= the old stellar cusp, the other young stars, the CNR)

The external induces PRECESSION



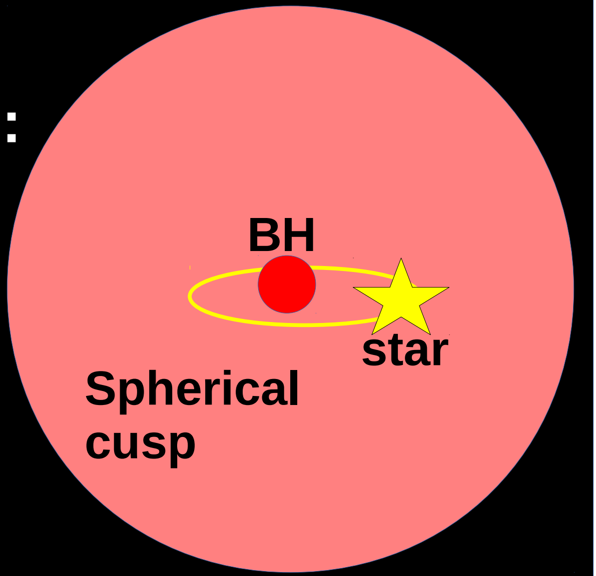
Precession can affect:

- argument of periapsis
- longitude of asc. node
- inclination
- eccentricity

Depending on the structure of the external potential

4. The secular evolution of the Galactic centre

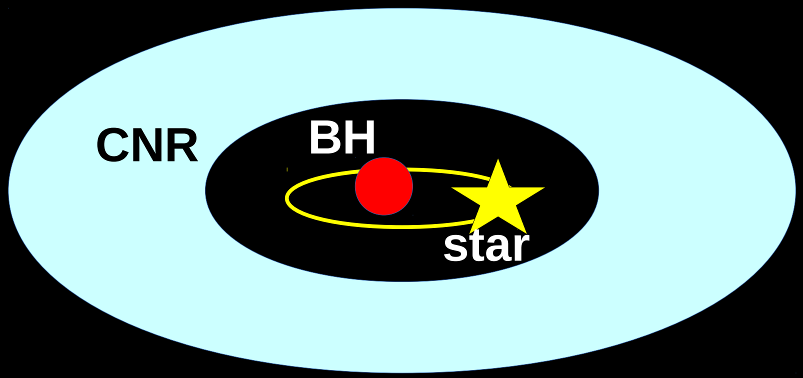
- SPHERICAL POTENTIAL (e.g. OLD STELLAR CUSP):



Timescale

$$T_{\rm cusp} = \frac{m_{\rm BH}}{M_{\rm cusp}}\,T_{\rm orb}\,f(e)$$

Only argument of pericentre



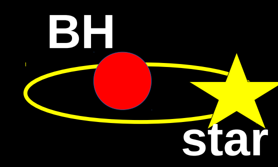
- AXISYMMETRIC POTENTIAL
(e.g. CNR = circumnuclear ring)

Timescale

$$T_{\rm K} = \frac{m_{\rm BH}}{M_{\rm DISC}}\,\frac{R_{\rm DISC}^3}{a^{3/2}\sqrt{G\,m_{\rm BH}}}$$

- if i~0 only longitude of ascending node
- if i>>0 also inclination and eccentricity are affected

RELATIVISTIC PRECESSION:
precession of orbits in general relativity



Caused by the SMBH mass, even if there are no external potentials
Three types (Schwarzschild prec. + 2 precession effects that depend on spin)

Schwarzschild precession (lowest order correction to Newton):

$$T_{\rm RP} = 1.3 \times 10^3 {\rm yr}\,(1-e^2)\,\left(\frac{a}{10^{-3}{\rm pc}}\right)^{5/2}\,\left(\frac{4\times 10^6 M_\odot}{m_{\rm BH}}\right)^{3/2}$$

- affects only argument of pericentre
- efficient for very small semi-major axis
- more efficient for high eccentricity
- more efficient for large BH mass

4. The secular evolution of the Galactic centre

- relativistic precession
Important only if a<<0.1 pc

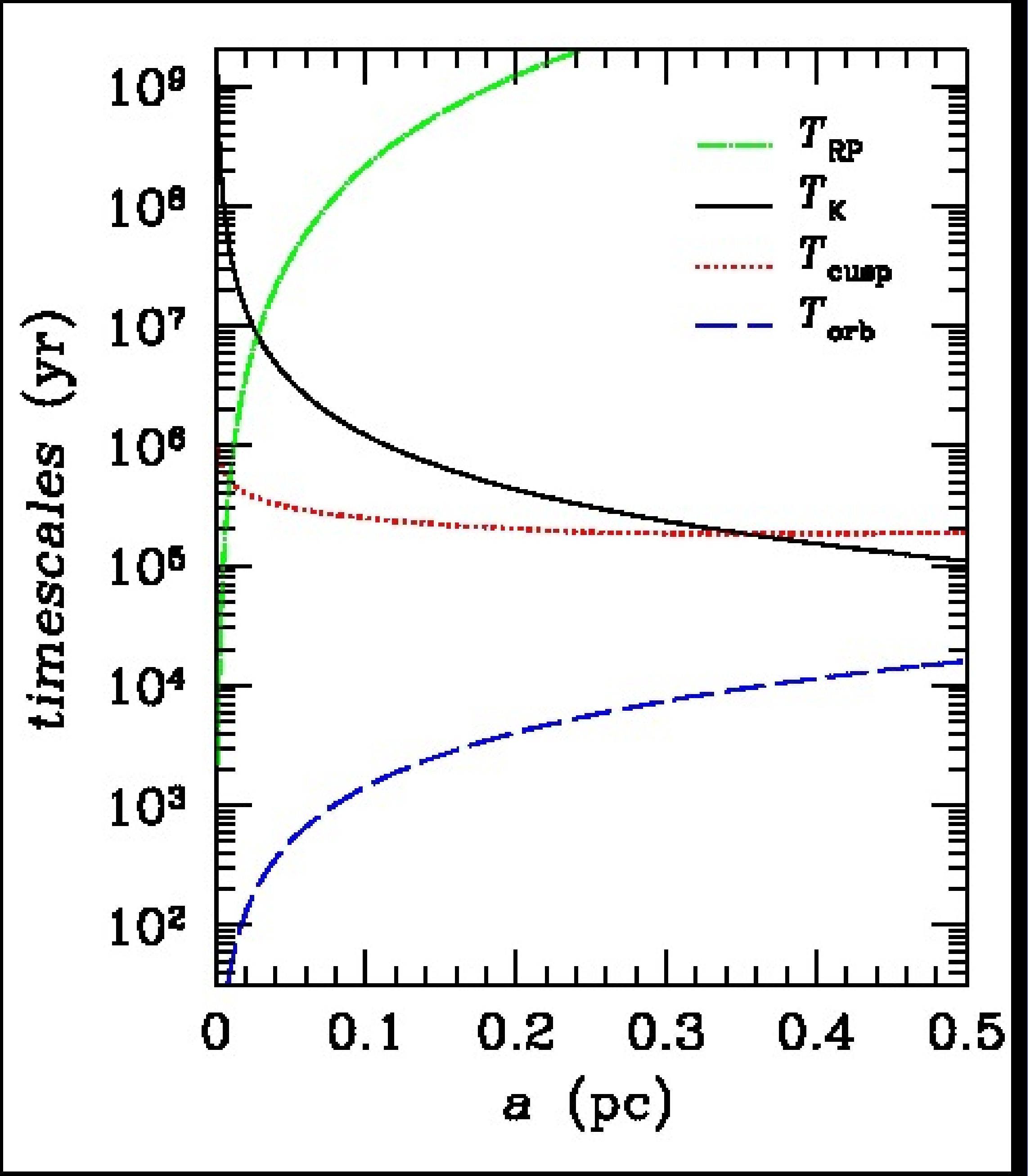
- cusp important at <0.3 pc

- CNR important at >0.3

↓

IF SPHERICAL POTENTIAL DOMINATES over AXISYMMETRIC (T_{cusp}<<T_K),

then only precession of argument of pericentre and of longitude of asc. node are not damped



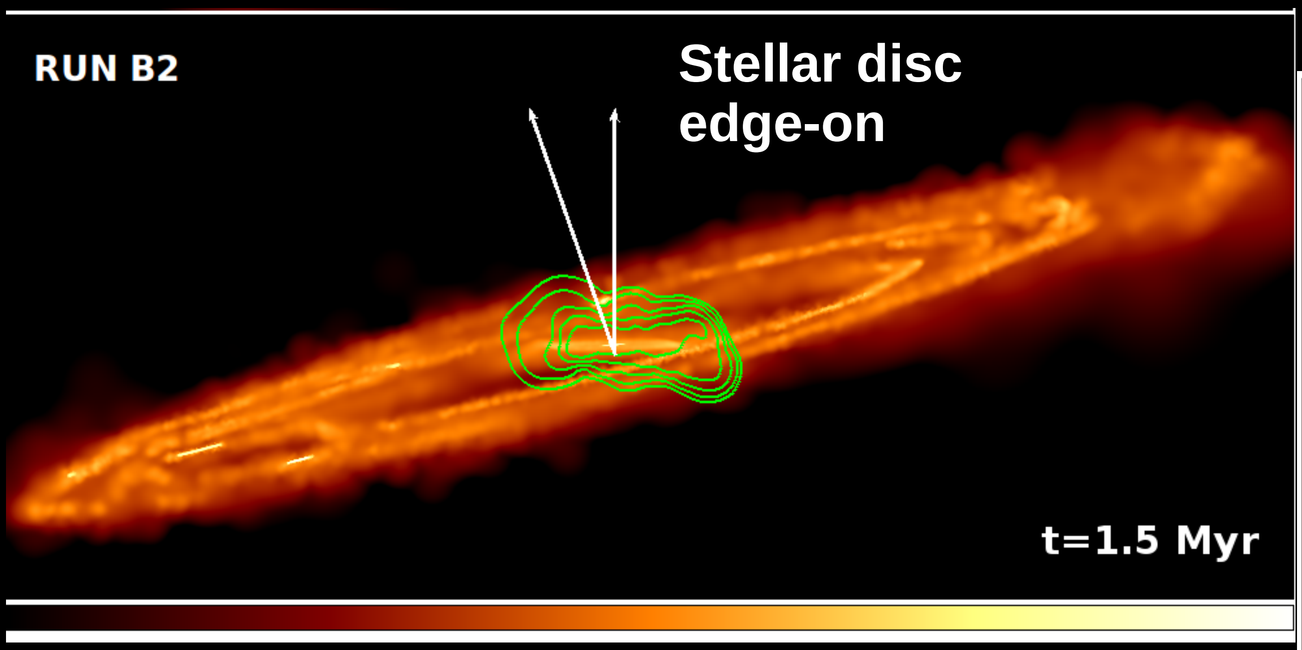
MM, Gualandris & Hayfield 2013

EXAMPLE 1: a stellar disc precesses because of
- a spherical cusp (not shown in image)
- a circumnuclear ring (made of different annuli, slightly inclined with respect to stellar disc)

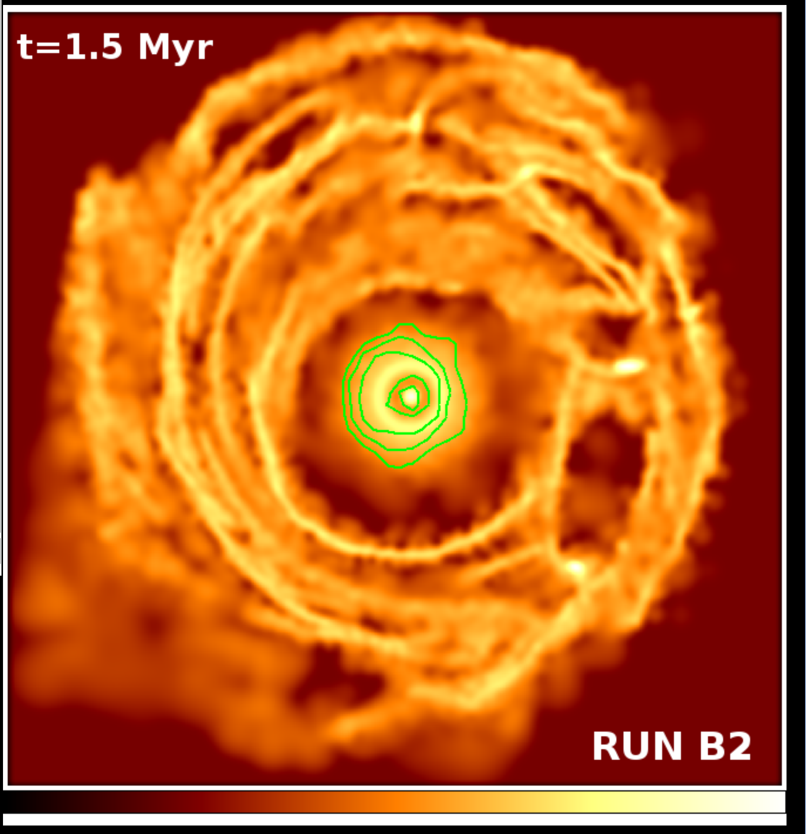
in an N-body/SPH simulation (MM et al. 2013)

NEWTONIAN PRECESSION

Stellar disc edge-on

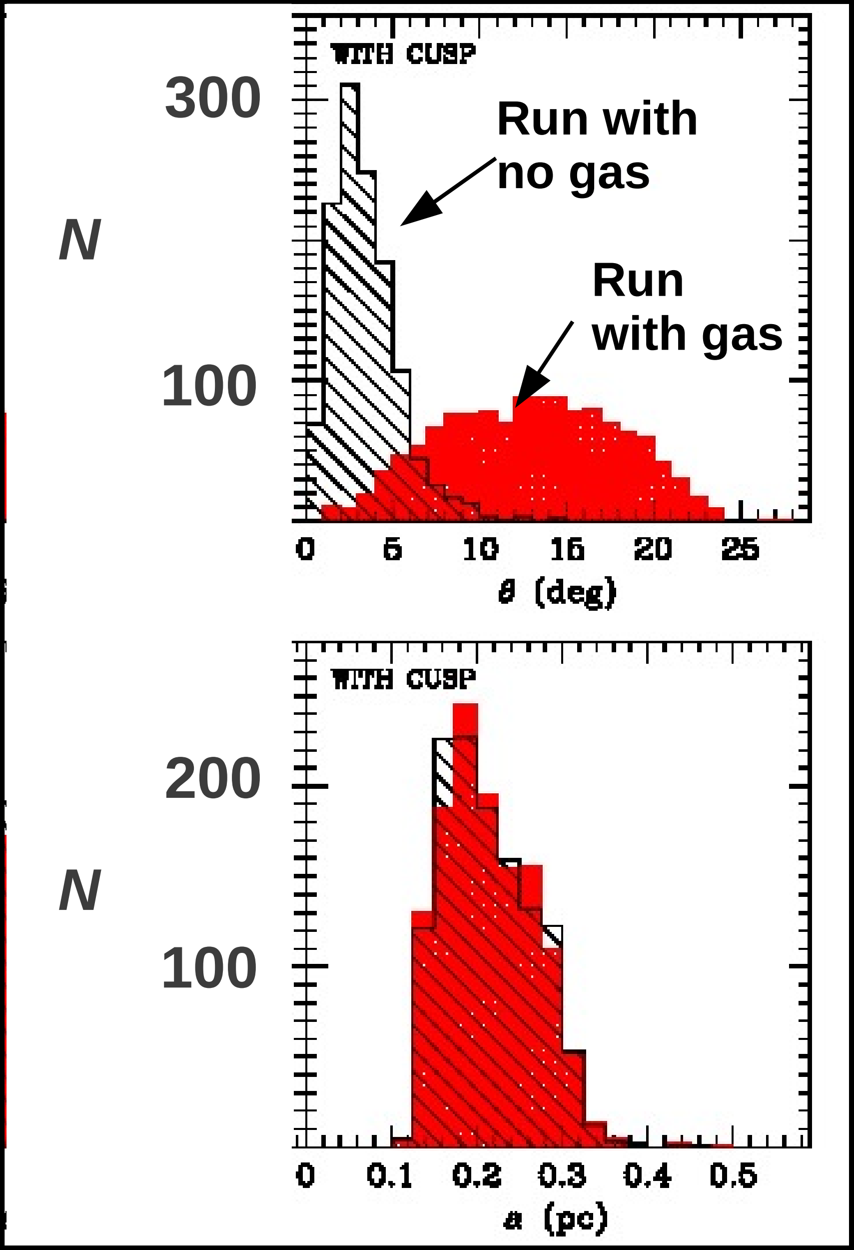


Stellar disc face-on



Green contours: stars
Colour-coded map: density of gas in CNR

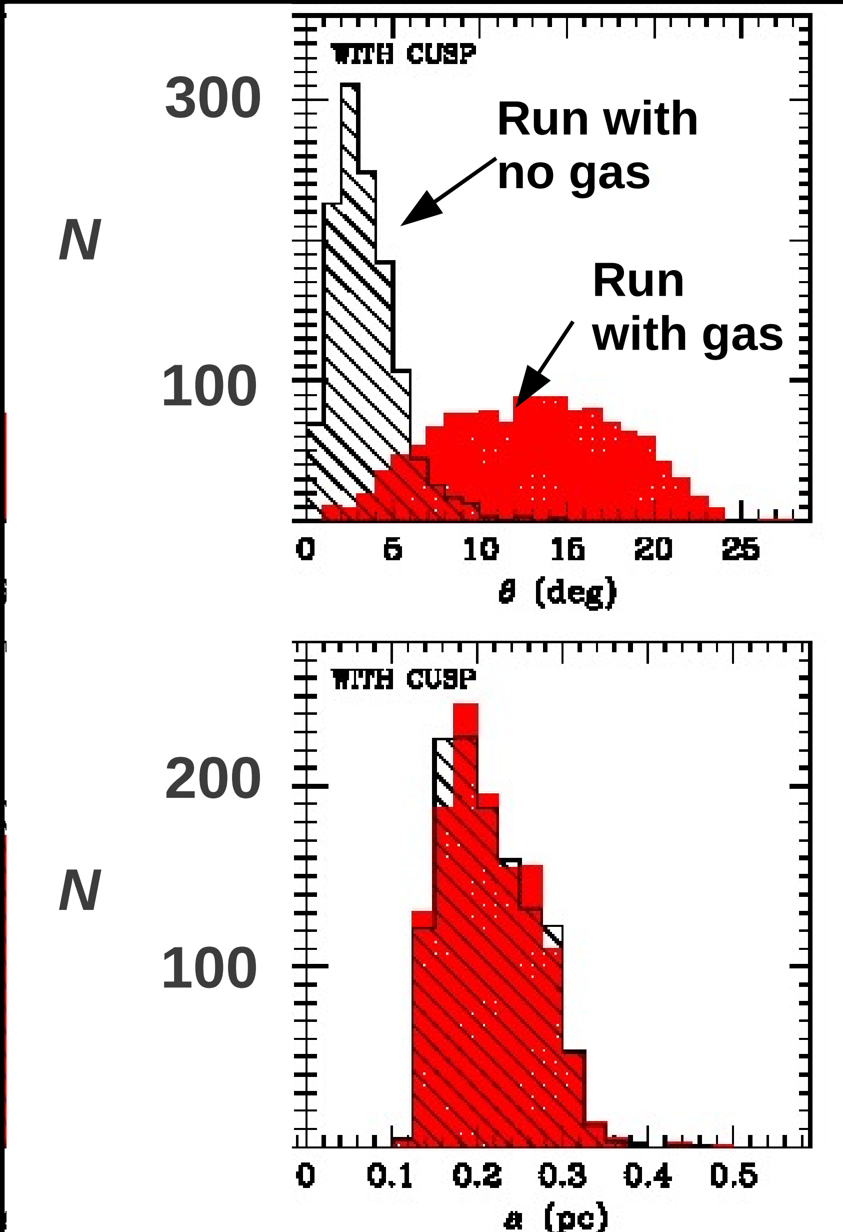
since *i* != 0, a differential change of Ω induces a broadening of the inclination distribution!



semi-major axis does not change since energy is conserved

MM, Gualandris & Hayfield 2013

since i != 0, a differential change of Ω induces a broadening of the inclination distribution!



– Gas and stellar disc are slightly INCLINED (i~ 5 – 20 deg)

– Spherical cusp damps all but the precession of Ω

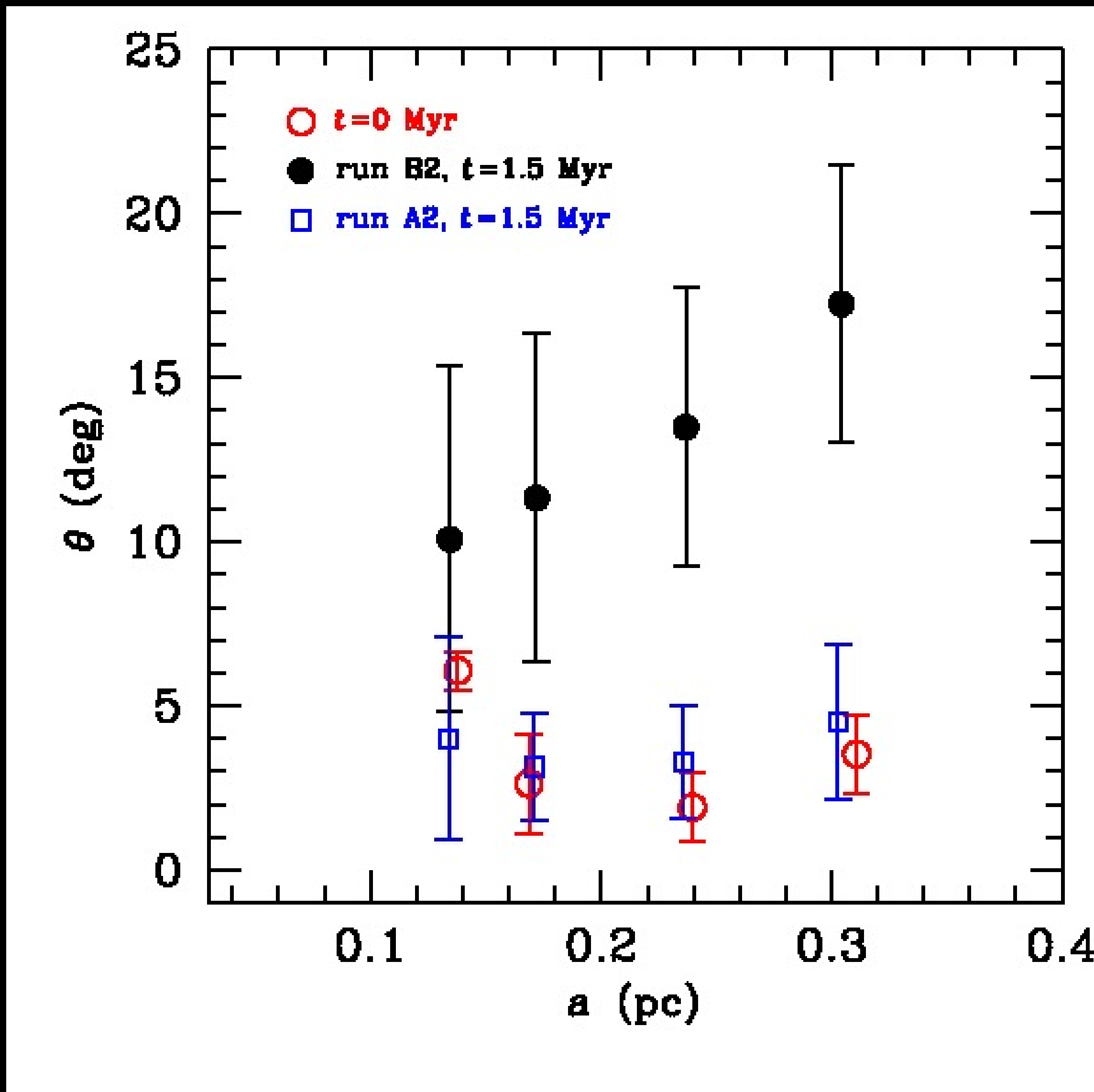
– Since $T_K \sim a^{-3/2}$ precession is faster for larger a

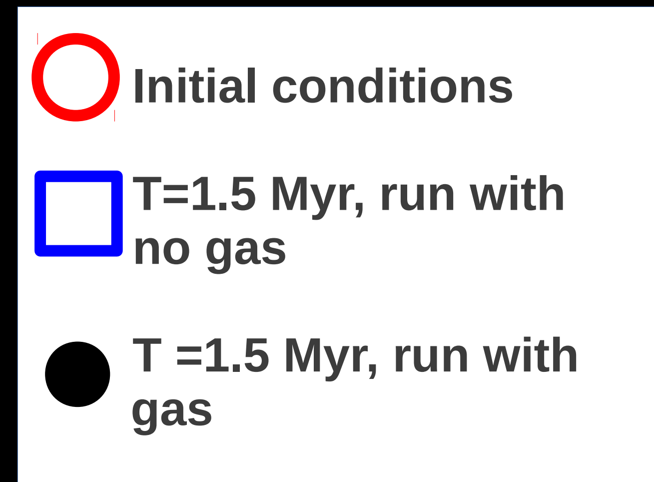
Ω changes more rapidly at the outskirts

since i != 0
a differential change of Ω induces a broadening of the inclination distribution!

MM, Gualandris & Hayfield 2013

since *i* != 0, a differential change of Ω induces a broadening of the inclination distribution!





CHANGE OF INCLINATION DEPENDS ON SMA → GENUINE PRECESSION

THE DISC IS ABOUT TO BE DISMEMBERED

MM, Gualandris & Hayfield 2013

EXAMPLE 2: RELATIVISTIC PRECESSION of S2

RELATIVISTIC PRECESSION (RP) VERSUS NEWTONIAN PRECESSION (NP)

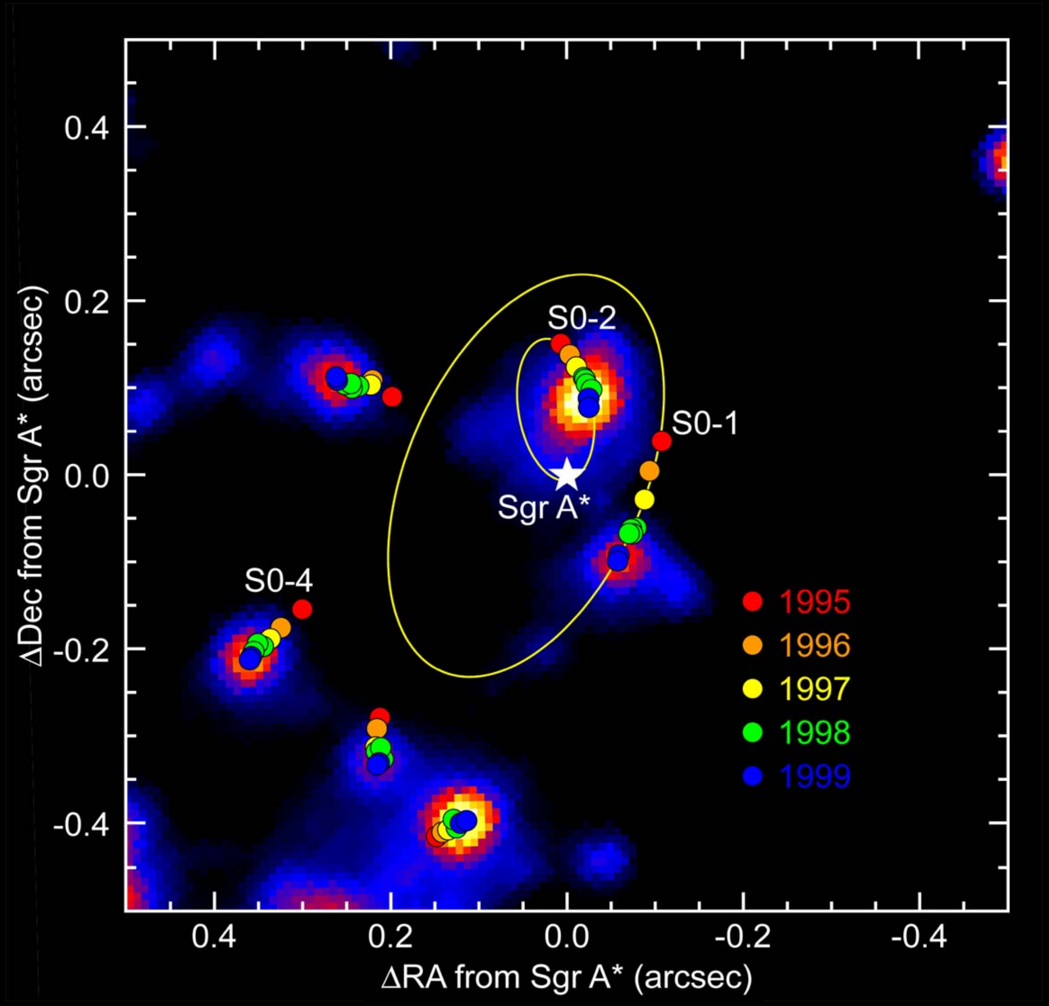
Can we measure the relativistic precession of S2?

S2 suffers from RP and spherical cusp NP both affect only pericentre!!

Period ~ 16 yr
Eccentricity = 0.883

Semi-major axis = 0.12”
~0.0048pc
~1000 AU

→ Pericentre ~ 0.00056 pc
~ 15 light hours
~ 4 x distance Neptune-Sun



EXAMPLE 2: RELATIVISTIC PRECESSION of S2

RELATIVISTIC PRECESSION (RP) VERSUS NEWTONIAN PRECESSION (NP)

Can we measure the relativistic precession of S2?

S2 suffers from RP and spherical cusp NP both affect only pericentre!!

Change in angle per orbit

$$\Delta\theta \sim \frac{a\,(1+e)\,\Delta\omega}{D}$$

Change in angle per orbit due to RP

$$\Delta\theta \sim 0.83\ \mathrm{mas}\left(\frac{0.117}{1-e}\right)\left(\frac{m_{\rm BH}}{4.3\times10^6 M_\odot}\right)\left(\frac{8.28\ \mathrm{kpc}}{D}\right)$$

Change in angle per orbit due to NP

$$\Delta\theta \sim\ -0.69\ \mathrm{mas}\left(\frac{10^3 M_{\rm cusp}(<a)}{m_{\rm BH}}\right)$$

If M*(a)>10^-3 mBH ~1000 Msun RP and NP are comparable → difficult but not impossible to disentangle (GRAVITY @ VLT will go to astrometric accuracy ~ 10 μas, Gualandris, Gillessen & Merritt 2010; Angelil & Saha 2010)

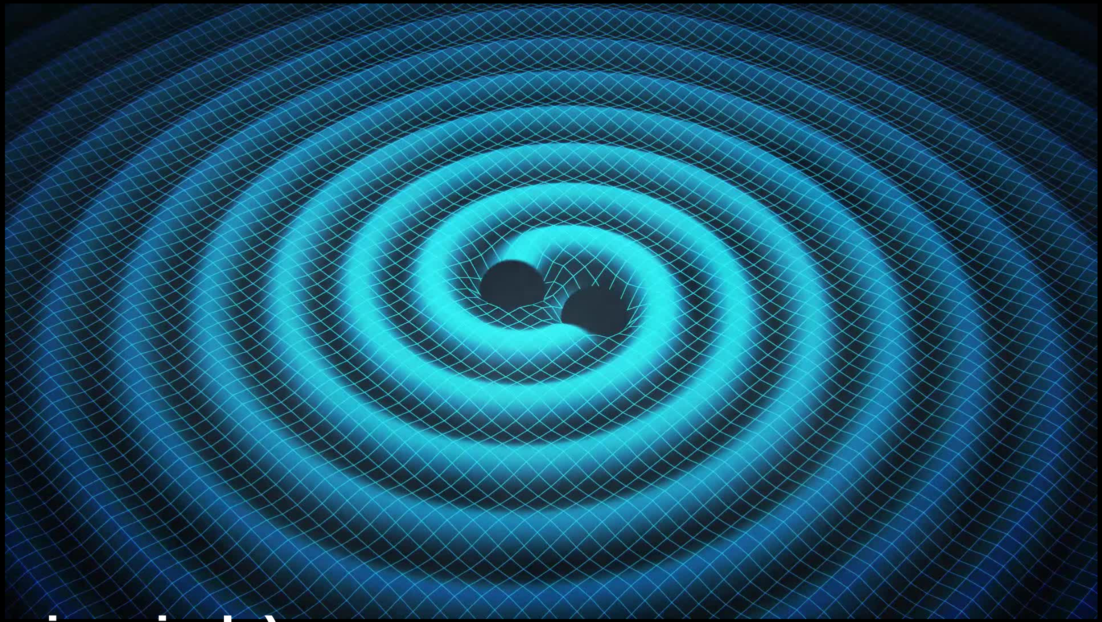
5. Gravitational waves from a galactic centre

5. Gravitational waves from a galactic centre

HOW CAN WE PRESENT GRAVITATIONAL WAVES to students?

Masses in general relativity deform the space-time

An ASYMMETRIC MOVING MASS generates ripples in the curvature of space-time that propagate as waves



Very close or merging compact object binaries are sources of GWs

MERGERS of stellar-mass BHs with SMBH are sources of GWs

called EMRIs (extreme mass-ratio inspirals), given the high mass ratio between SMBH and stellar BH

FREQUENCY: GW frequency before merger ~ 2 x Newtonian orbital freq.

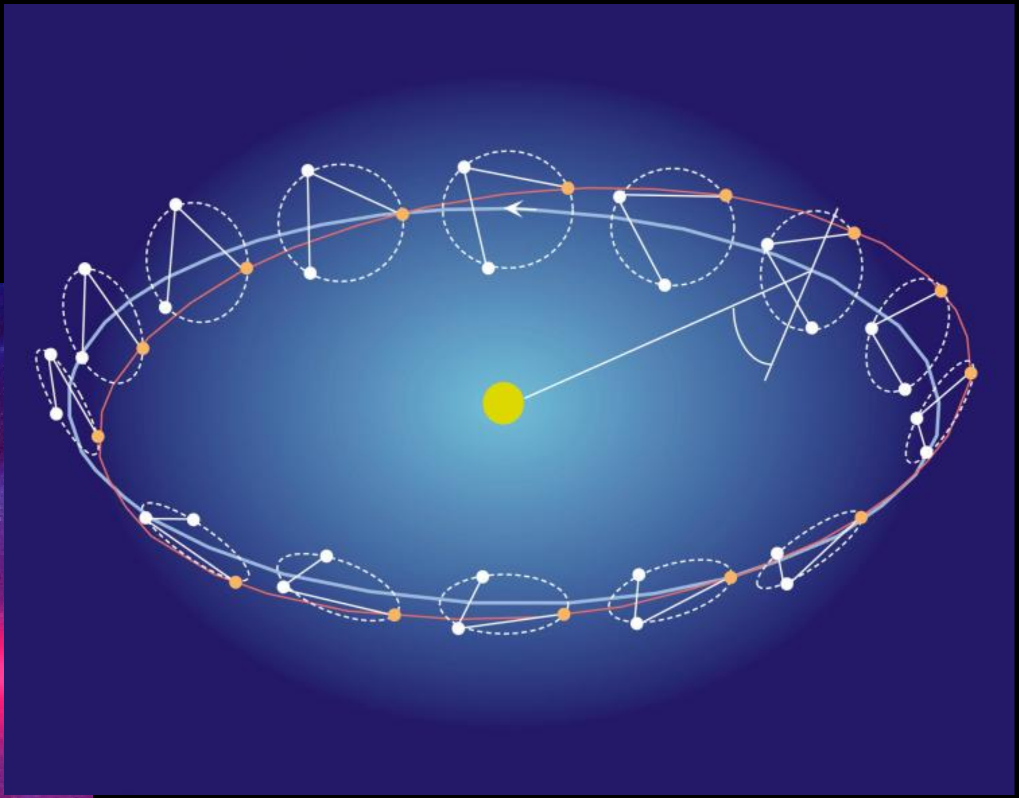
$$\nu_{\rm GW} = 2\,\nu_{\rm orb} \sim 10^{-6}{\rm Hz}\,\left(\frac{m_{\rm BH}}{10^6\,M_\odot}\right)^{1/2}\,\left(\frac{10^{-4}{\rm pc}}{a}\right)^{3/2}$$

5. Gravitational waves from a galactic centre

HOW CAN WE PRESENT GRAVITATIONAL WAVES to students?

EMRI frequencies (~10^-6 Hz) will be observed only by SPACE-BORNE GRAVITATIONAL WAVE OBSERVATORIES

E-LISA (>2030)

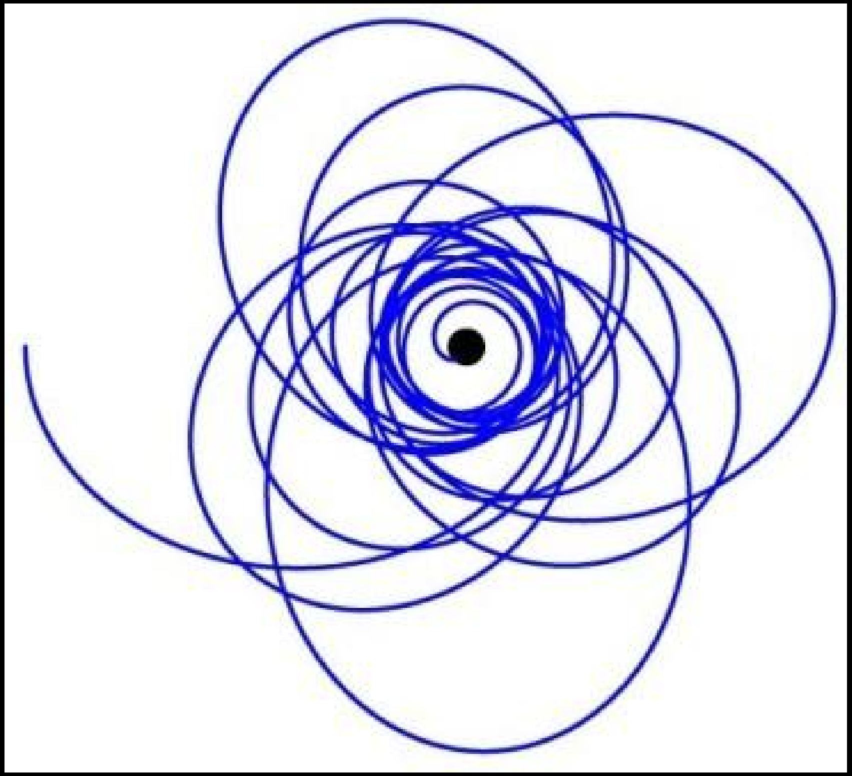


5. Gravitational waves from a galactic centre

HOW CAN WE PRESENT GRAVITATIONAL WAVES to students?

It can be shown that GW emission induces

(1) orbital decay:
The orbit loses energy and reduces semi-major axis (INSPIRAL) till merger occurs



(2) circularization:
gravitational wave emission reduces eccentricity

This occurs on a timescale

$$T_{\rm GW} \sim 6 \times 10^{12}{\rm yr}\,(1-e^2)^{7/2}\left(\frac{a}{1\ {\rm mpc}}\right)^4 \left(\frac{3\times 10^6 M_\odot}{m_{\rm BH}}\right)^2 \left(\frac{10\,M_\odot}{m_{\rm bh}}\right)$$

Peters (1964)

5. Gravitational waves from a galactic centre

Can we estimate the RATE of EMRIs in a galactic centre?

– VERY DIFFICULT TASK!!! –

WHY?

EMRIs depend on interplay between

(1) **RELATIVISTIC PRECESSION (RP)**

(2) **GRAVITATIONAL WAVE DECAY TIMESCALE (GW)**

(3) **RESONANT RELAXATION (RR)**

5. Gravitational waves from a galactic centre

(1) RELATIVISTIC PRECESSION (RP) TIMESCALE

$$T_{\mathrm{RP}} = 1.3 \times 10^3 \mathrm{yr}\, (1 - e^2) \left(\frac{a}{10^{-3}\mathrm{pc}}\right)^{5/2} \left(\frac{4 \times 10^6 M_\odot}{m_{\mathrm{BH}}}\right)^{3/2}$$

(2) GW DECAY TIMESCALE

$$T_{\mathrm{GW}} \sim 6 \times 10^{12} \mathrm{yr}\, (1 - e^2)^{7/2} \left(\frac{a}{1\ \mathrm{mpc}}\right)^4 \left(\frac{3 \times 10^6 M_\odot}{m_{\mathrm{BH}}}\right)^2 \left(\frac{10\, M_\odot}{m_{\mathrm{bh}}}\right)$$

(3) RESONANT RELAXATION (RR) TIMESCALE

$$T_{\mathrm{RR}} \sim 10^4 \mathrm{yr} \left(\frac{a}{1\ \mathrm{mpc}}\right)^{3/2} \left(\frac{m_{\mathrm{BH}}}{3 \times 10^6 M_\odot}\right)^{1/2} \left(\frac{10\, M_\odot}{m_{\mathrm{bh}}}\right) \left(\frac{10^3}{N_*}\right)^{1/2}$$

????

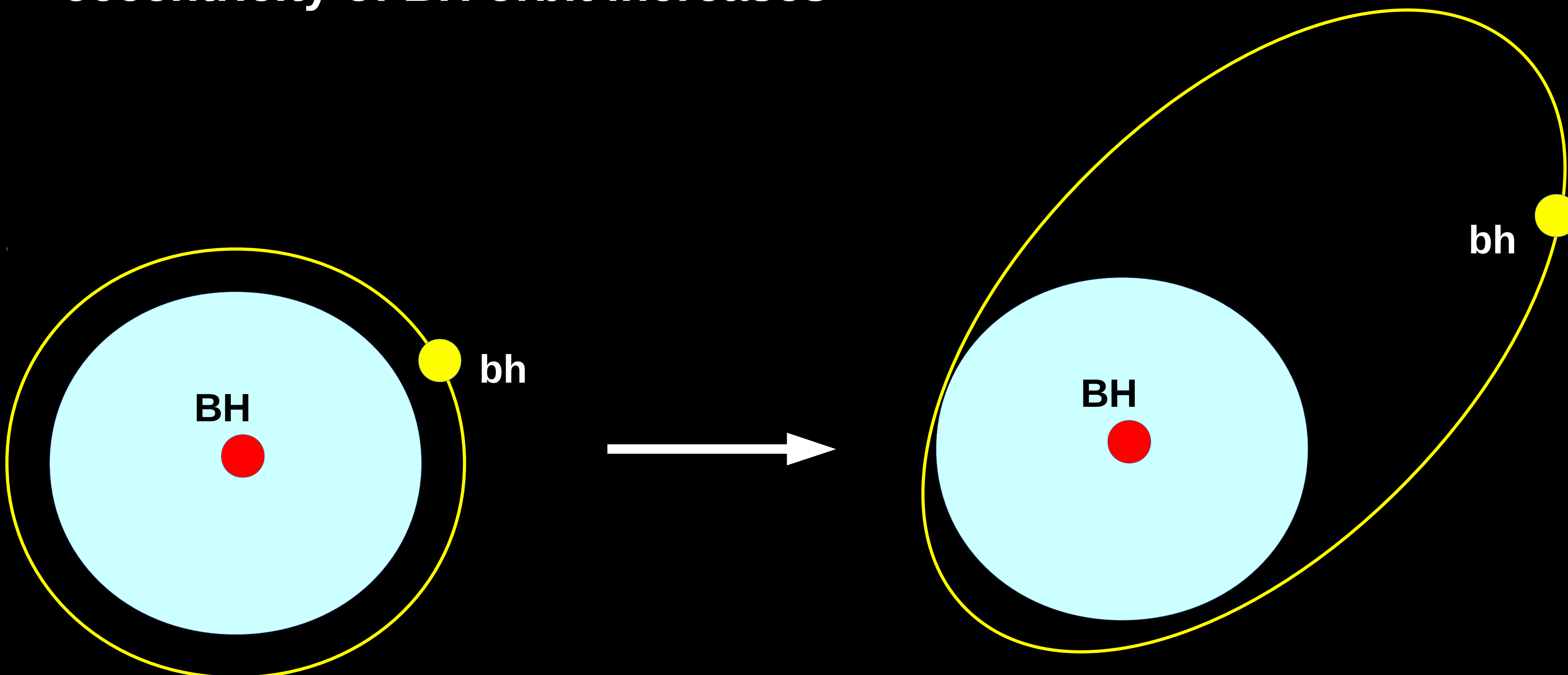
5. Gravitational waves from a galactic centre

RESONANT RELAXATION

Stars orbiting between the SMBH and the stellar BH exert TORQUES

such torques REDUCE ANGULAR MOMENTUM, not energy

→ eccentricity of BH orbit increases

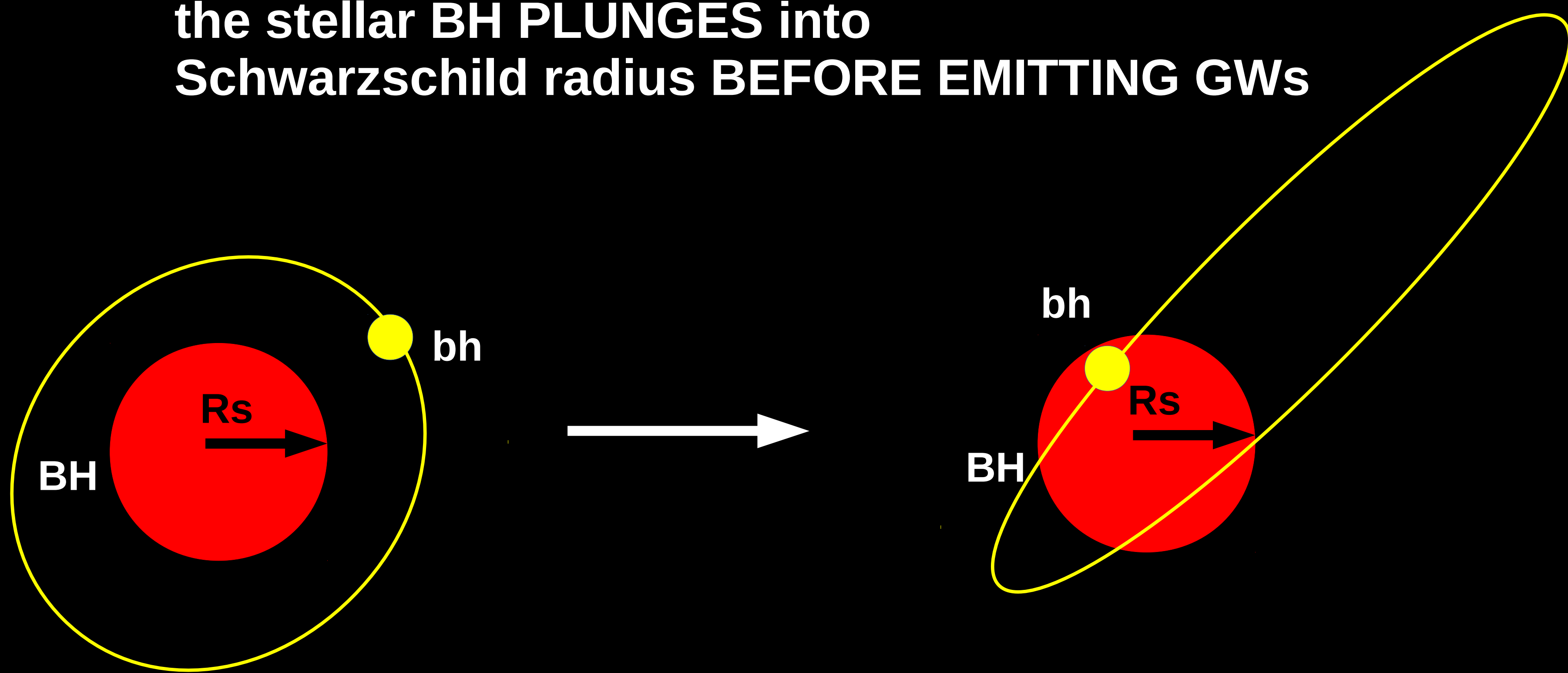


5. Gravitational waves from a galactic centre

WHICH INTERPLAY BETWEEN RP, GW DECAY and RR?

1) RR tends to increase eccentricity of stellar BH orbit

→ **If RR more efficient than GW decay the stellar BH PLUNGES into Schwarzschild radius BEFORE EMITTING GWs**

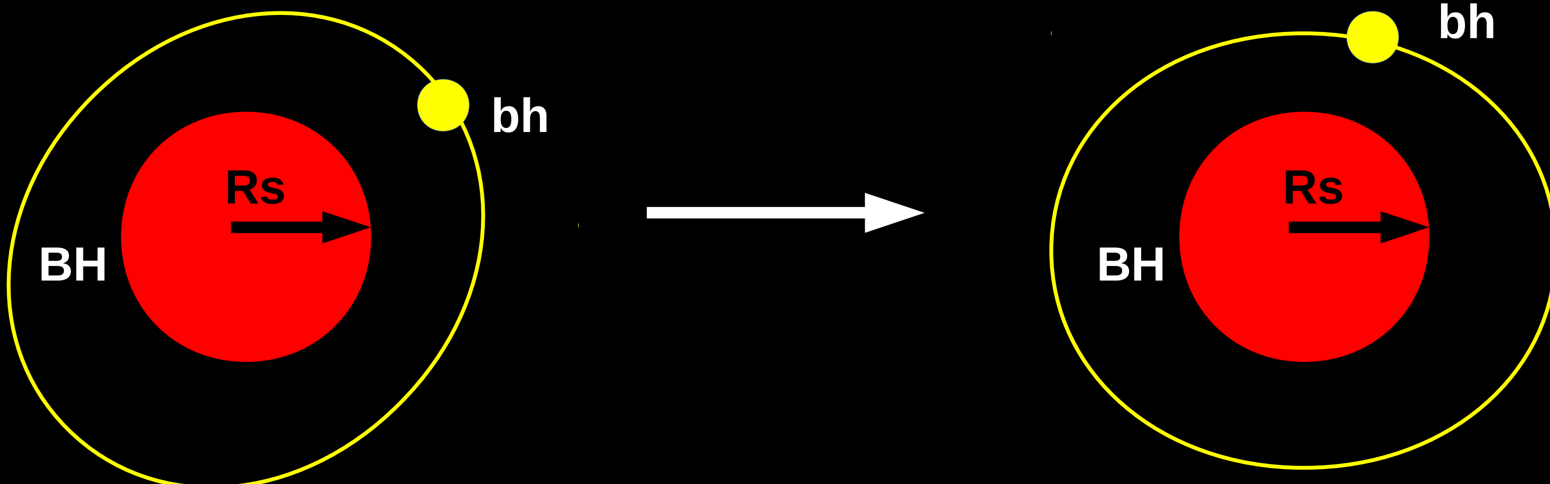


→ **WE HAVE NO EMRI, because no GW**

WHICH INTERPLAY BETWEEN RP, GW DECAY and RR?

2) RP tends to change the pericentre of the BH orbit

→ If RP more efficient than RR
the fast change of BH pericentre
nullify the effect of RR torques
and BH orbit remains ~ the same



→ The shielding effect of RP on RR is called
Schwarzschild barrier (Merrit+ 2011): RP keeps
orbits stable against plunge

5. Gravitational waves from a galactic centre

WHICH INTERPLAY BETWEEN RP, GW DECAY and RR?

In summary,

(1) If $T_{GW} < \min(T_{RR}, T_{RP})$

GW emission is efficient and leads to an EMRI

(2) If $T_{RR} < \min(T_{RP}, T_{GW})$

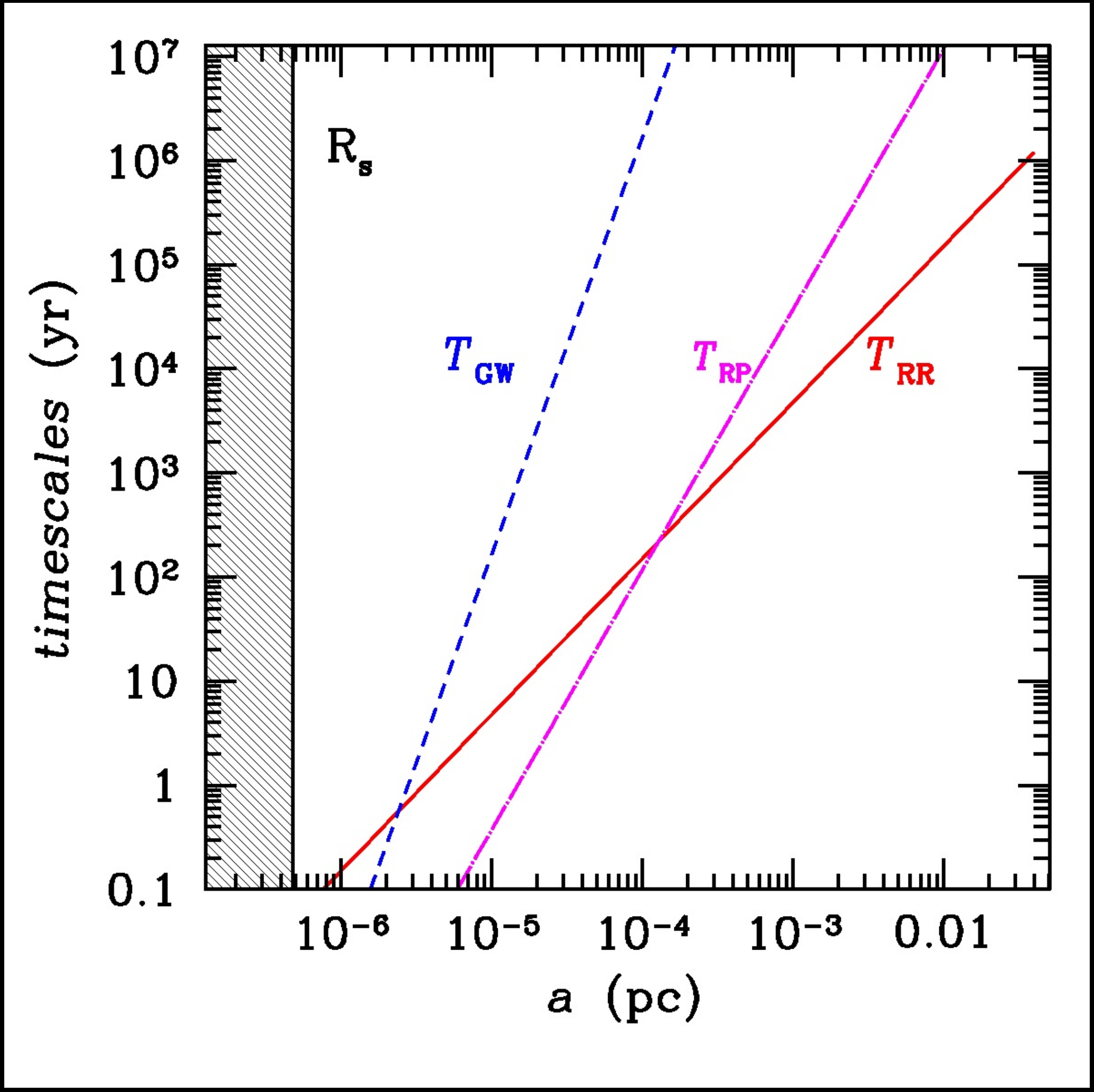
RR increases the eccentricity till the BH PLUNGES into the Schwarzschild radius of the SMBH, WITHOUT EMRI

(3) If $T_{RP} < \min(T_{RR}, T_{GW})$

RP prevents RR from plunging the BH into the Schwarzschild radius, but the BH is 'stuck' in its orbit and cannot merge
Another perturbation is needed to produce an EMRI or a plunge!

5. Gravitational waves from a galactic centre

WHICH INTERPLAY BETWEEN RP, GW DECAY and RR?



ecc = 0.8
m_{BH}= 10^7 M⊙
m_{bh}=10 M⊙

RR seems to dominate down to a=10^-4 pc BUT VERY DIFFICULT TO MAKE REALISTIC PREDICTIONS!!

CONCLUSIONS for science:

– The Galactic centre is a unique laboratory to study Star formation under extreme conditions

– It is a crowded environment: the SMBH, the (ionized and molecular) gas, the old stars, the early-type stars (S-stars and CW disc included)

– Many scenarios proposed to explain star formation: migration (binary break-up and cluster inspiral) and in situ (accretion disc fragmentation, molecular cloud disruption)

– Molecular cloud disruption reproduces many features of CW disc (eccentricity, mass function, ages) BUT DOES NOT EXPLAIN EVERYTHING

– Secular dynamical evolution of stars might explain the remaining issues, but more studies are needed!!!

– Gravitational waves in a galactic centre are a challenging field

CONCLUSIONS for teaching:

– The study of Galactic centre is in continuous expansion:
The students can put their hands on a hot research topic!

– It is a fascinating topic, and relatively easy to explain

– It involves a lot of physics, from black holes and general relativity to star formation

– High-school students can do useful exercise

* derive the mass of a BH by applying Newton!
* understand the importance of angular momentum
* understand the mechanism of star formation in different regimes
* play with timescales

– Simulations, movies, cartoons are extremely important for learning (you 'touch' astrophysics with your eyes)

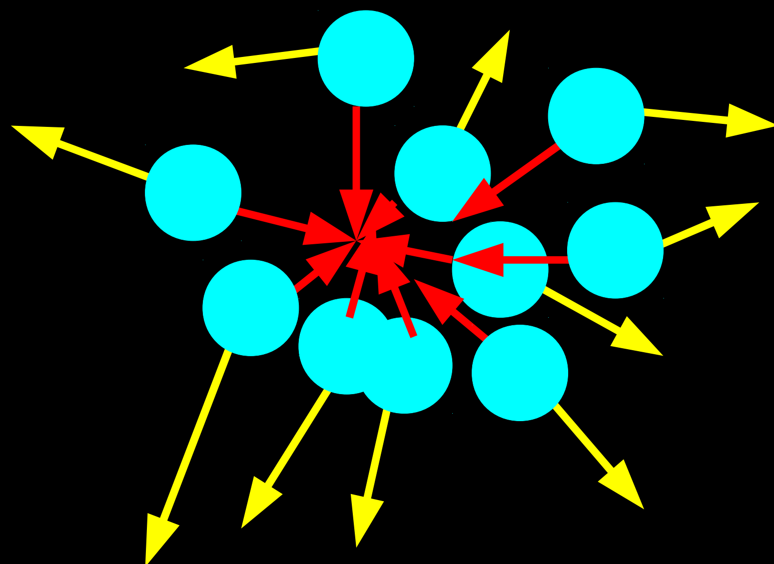

THANKS

1. What do we observe in the Galactic centre?

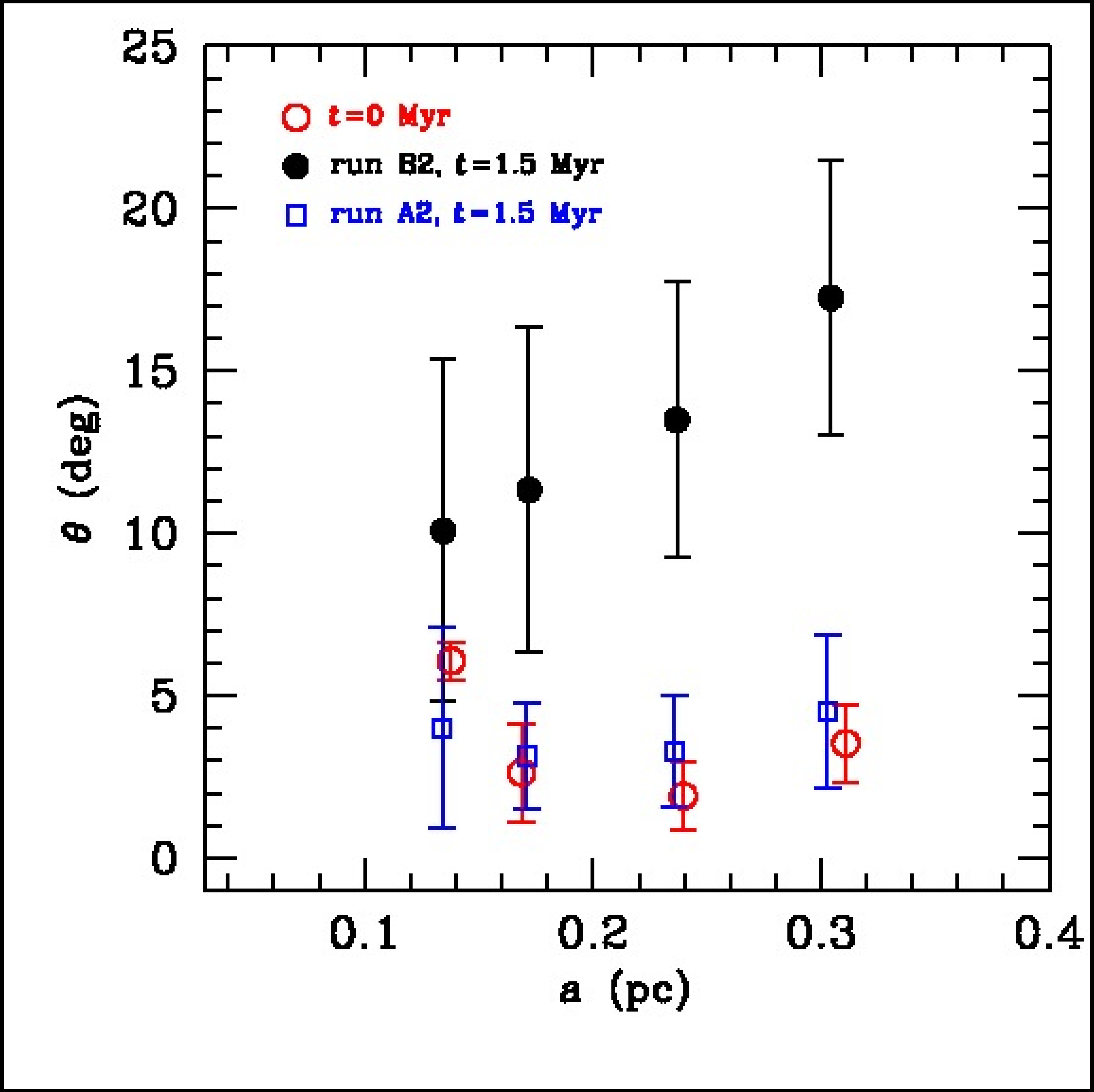
For the students: Quick note about star formation

MOLECULAR CLOUDS are REGIONS of STAR FORMATION

Basic concept of star formation is consequence of Newton's law:
Stars form when gravitational pull is stronger than pressure force



WHICH IS THE IMPORTANCE OF INCLINATION CHANGE FOR THE COMPARISON WITH OBSERVATIONS?



THE DISC IS ABOUT TO BE DISMEMBERED

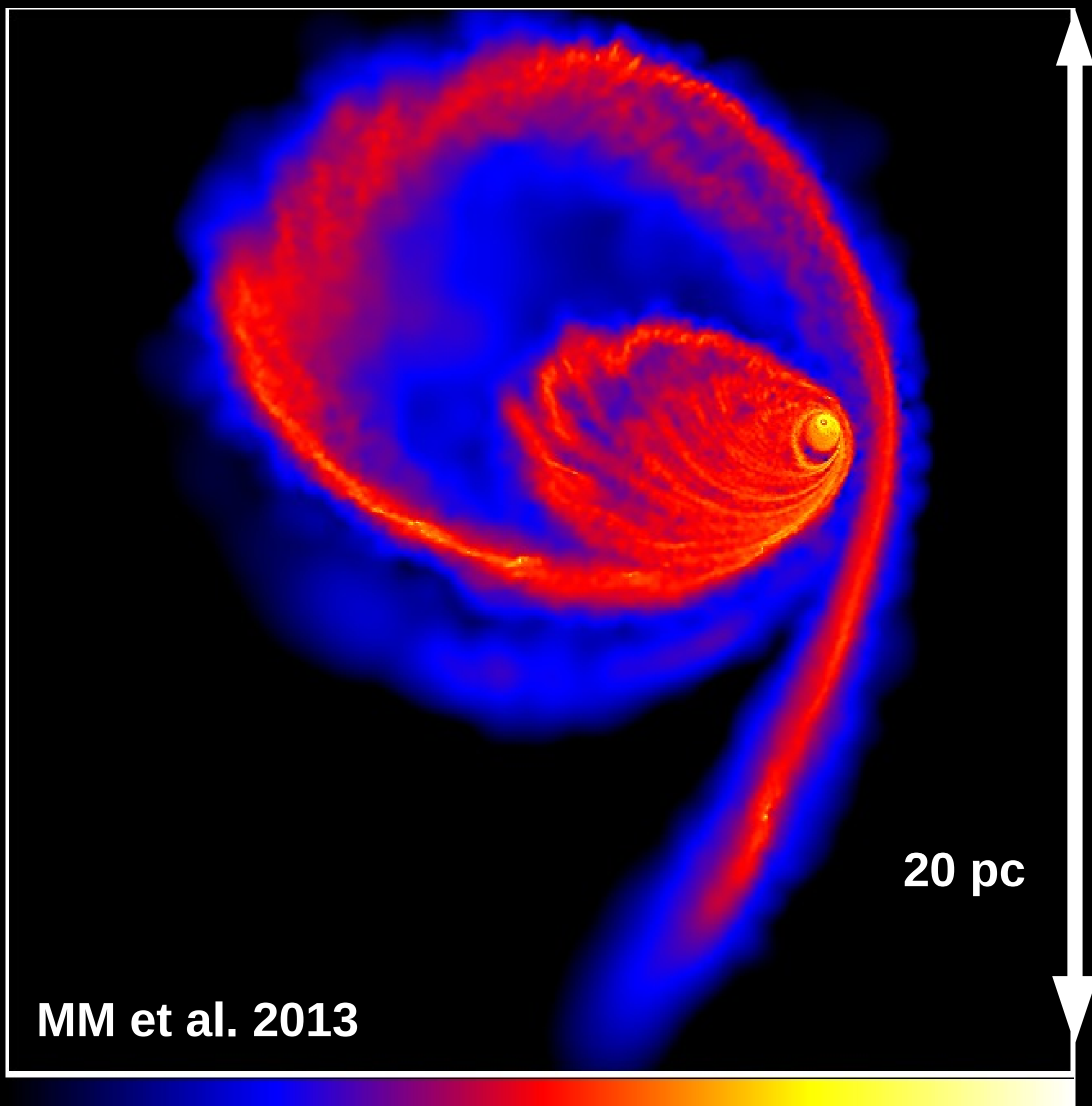
CAN THIS EXPLAIN THE OUTLIERS?

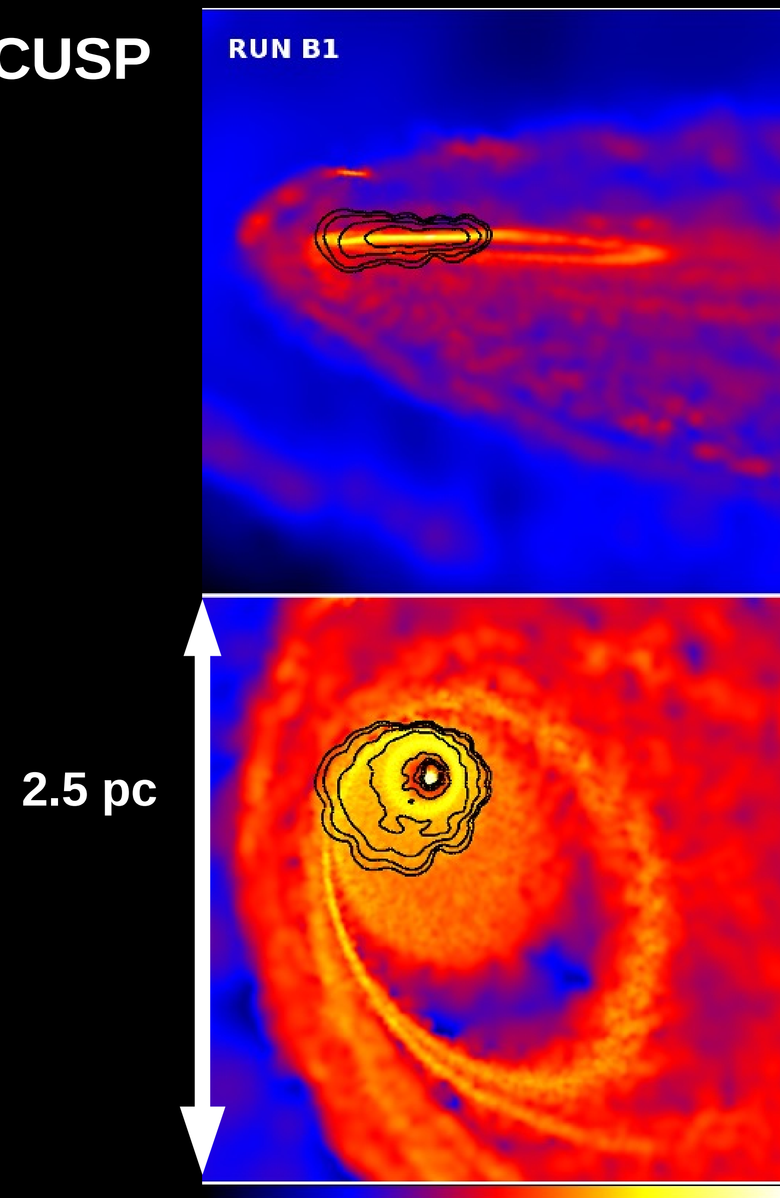
IT IS VERY PROMISING!

MM, Gualandris & Hayfield 2013

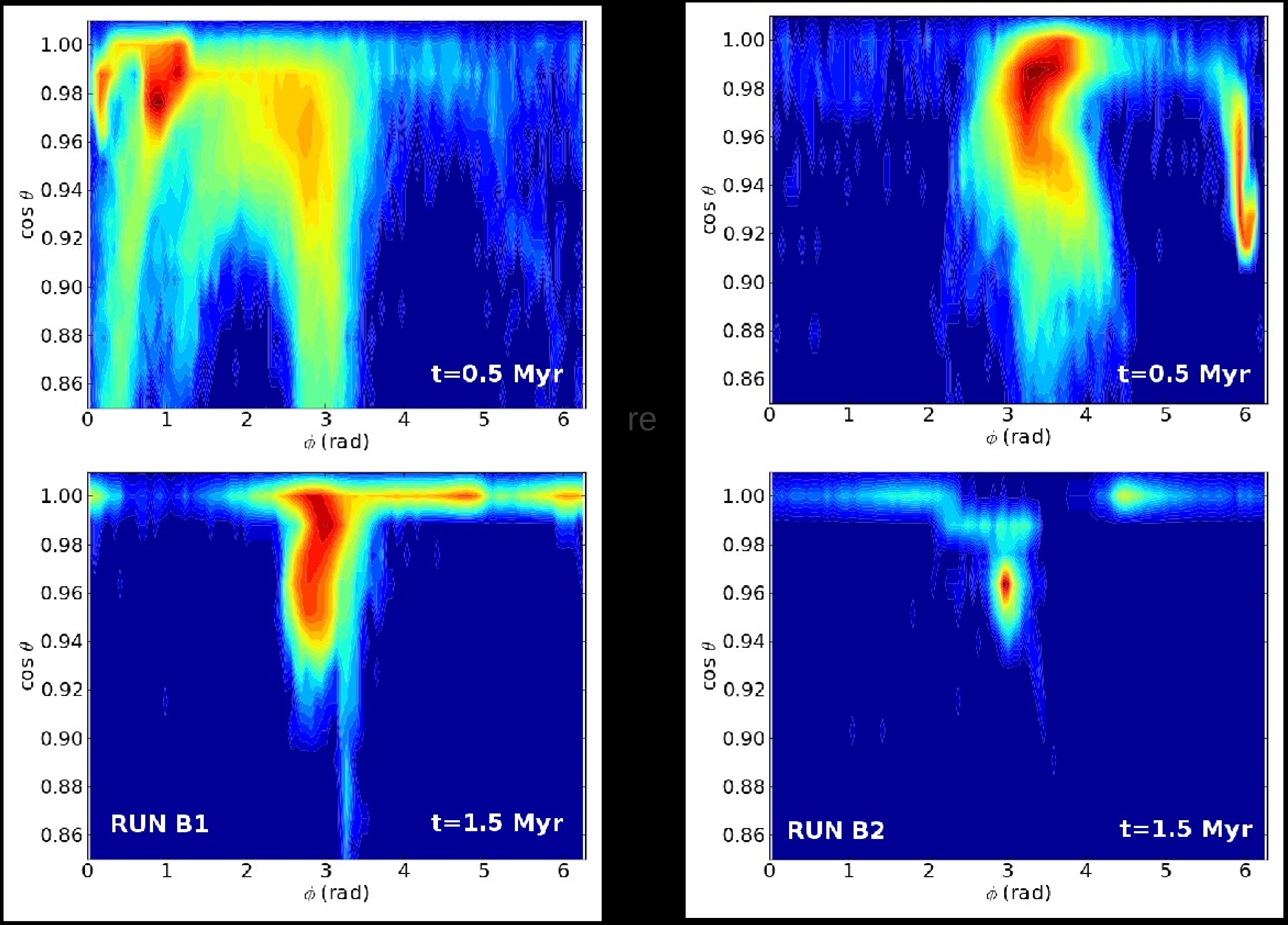
We simulate the infall of a second molecular cloud and study the precession exerted onto the stellar disc

WITHOUT (run B1) the SPHERICAL CUSP





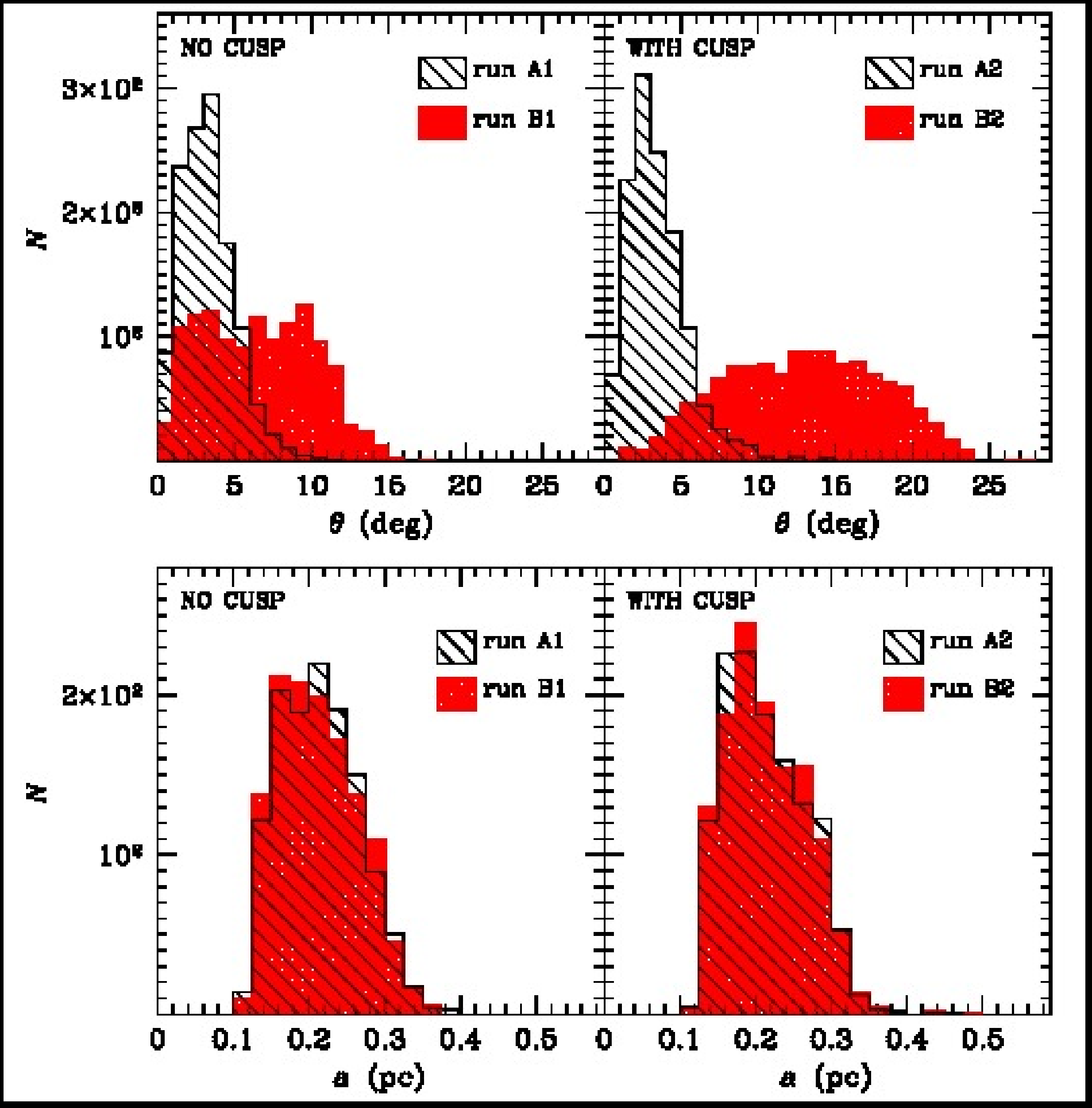
Angular momentum direction of gas particles versus stellar disc



re

MM et al. 2013

since *i* != 0, a differential change of Ω induces a broadening of the inclination distribution!



Run A1: no gas, no cusp

Run A2: no gas, with cusp

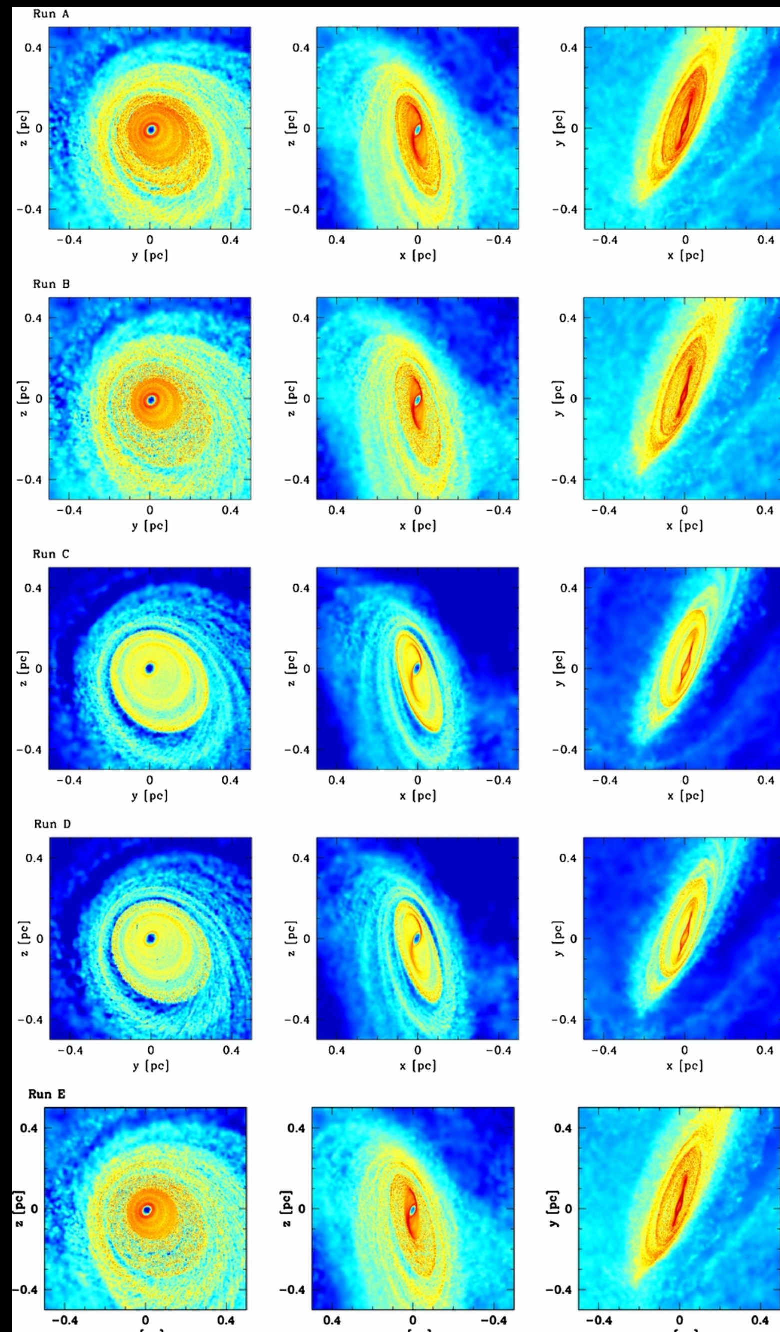
Run B1: with gas, no cusp

Run B2: with gas and cusp

MM et al. 2013

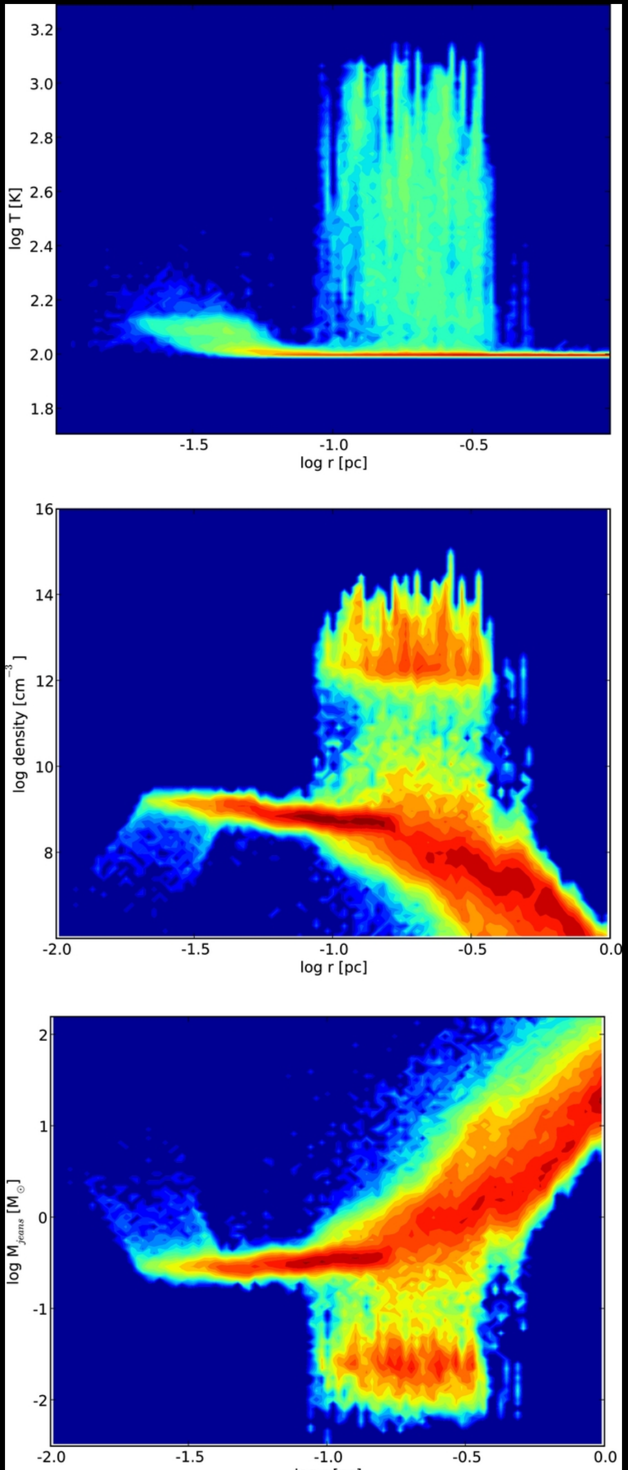
3. Simulating star formation in the Galactic centre

*** Gas disc**
with $r_{out} \sim 0.5$ pc
$r_{int} \sim 0.1$ pc
$H \sim 0.1\text{-}0.05$ pc
$n \sim 10^{9\text{-}10}$ cm^{-3}



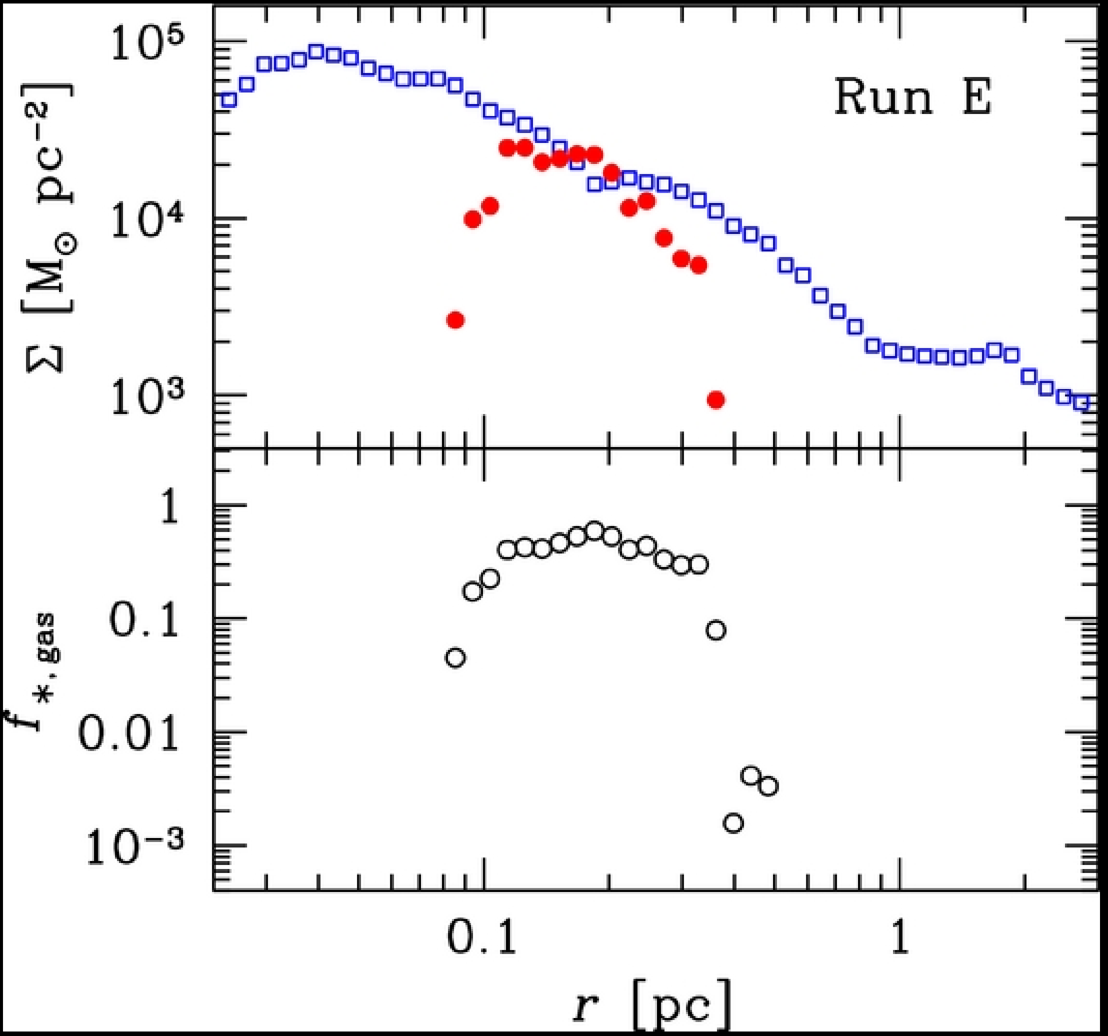
MM et al. 2012

3. Simulating star formation in the Galactic centre



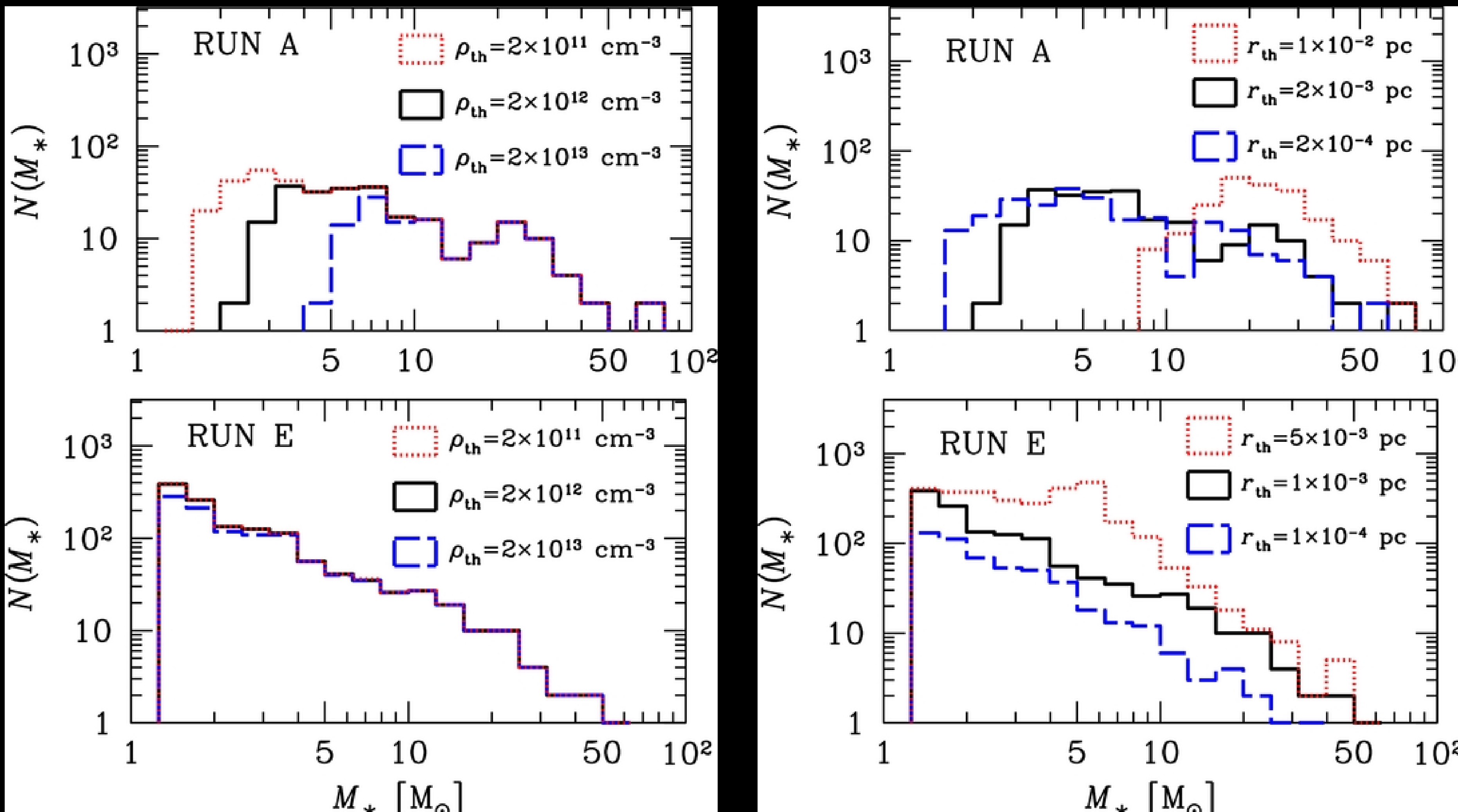
MM et al. 2012

How much gas is converted into stars?



MM et al. 2012

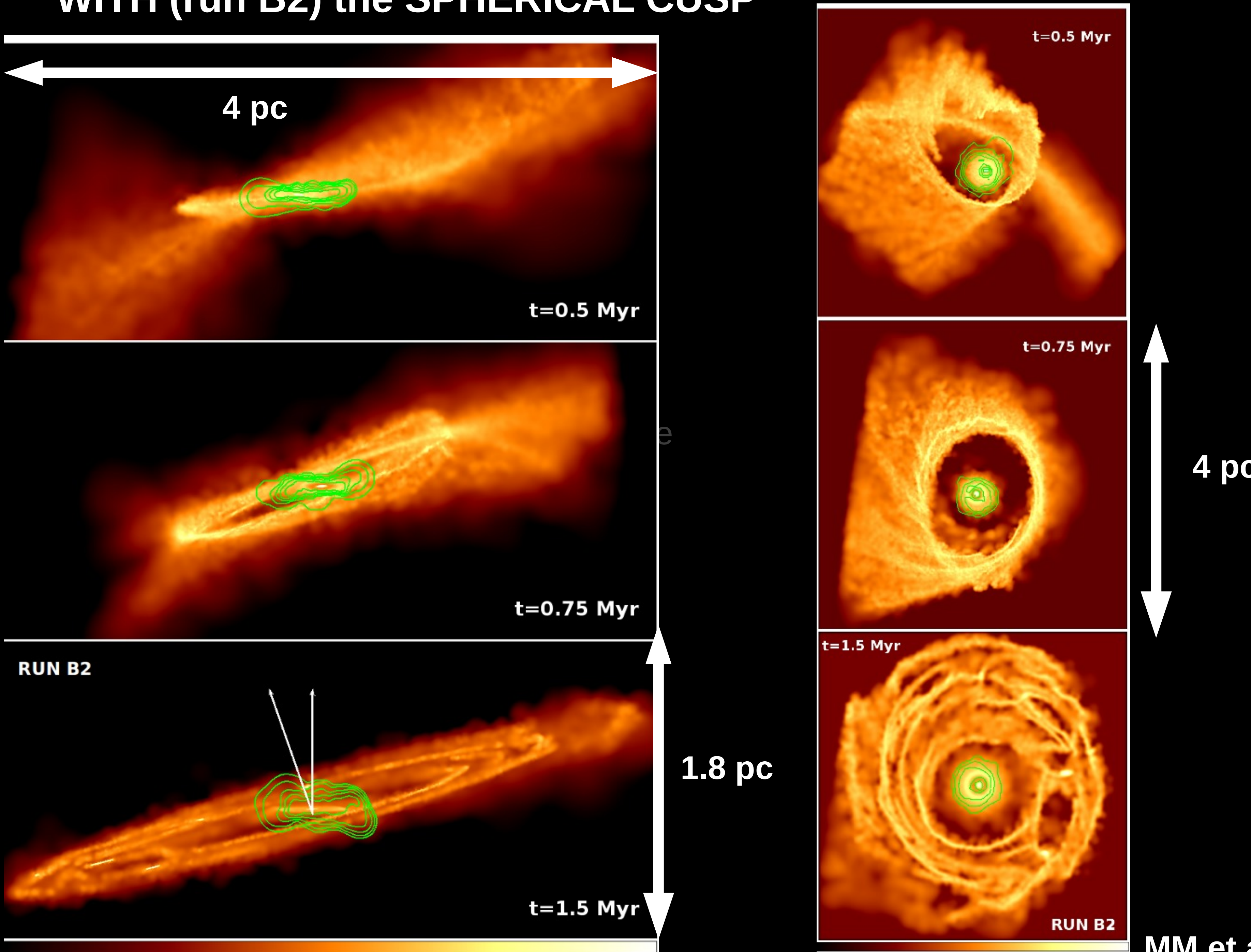
How much the clump mass function depends on the assumption (critical density and radius)



MM et al. 2012

4. The secular evolution of the Galactic centre

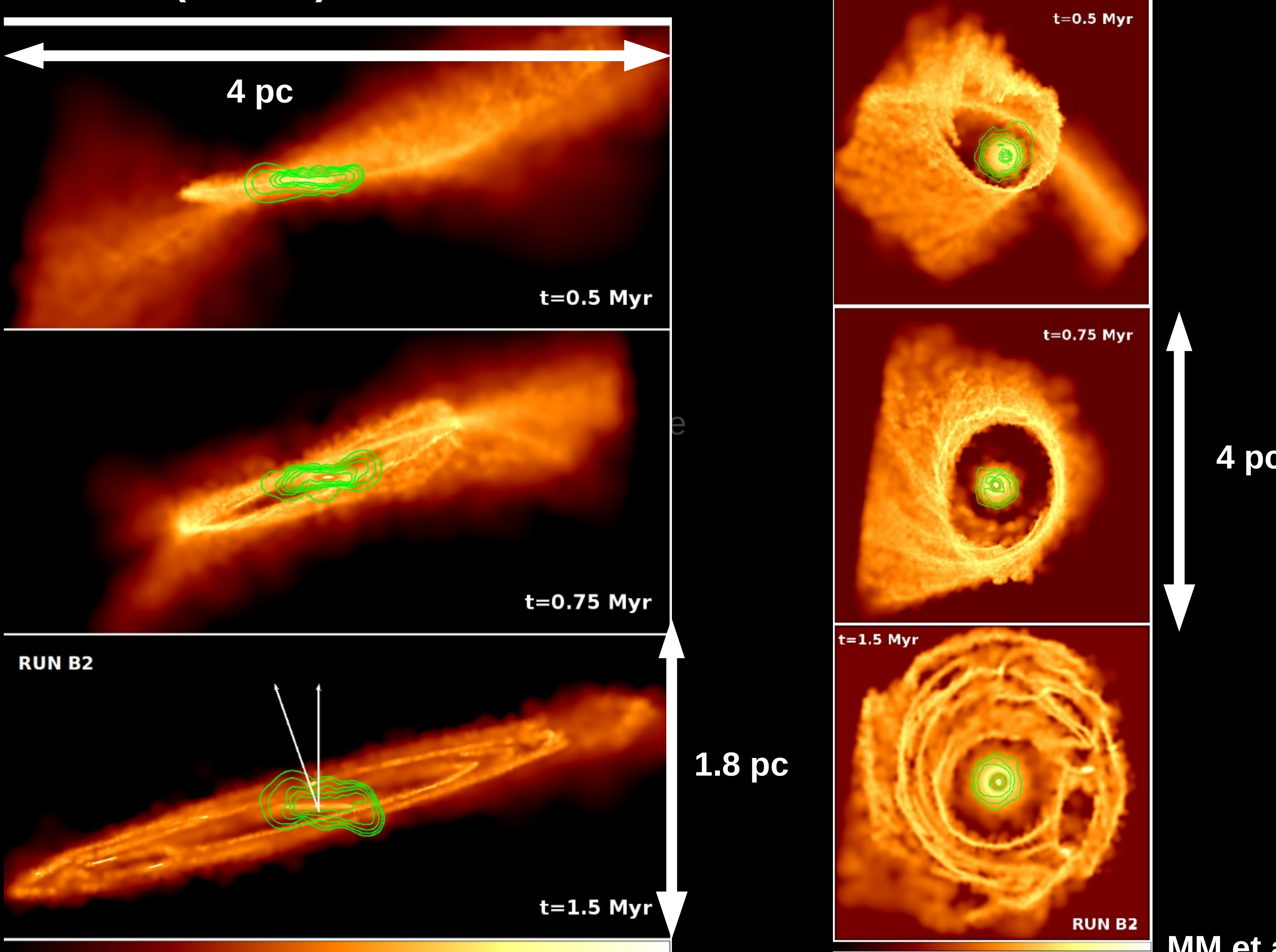
WITH (run B2) the SPHERICAL CUSP



MM et al. 2013

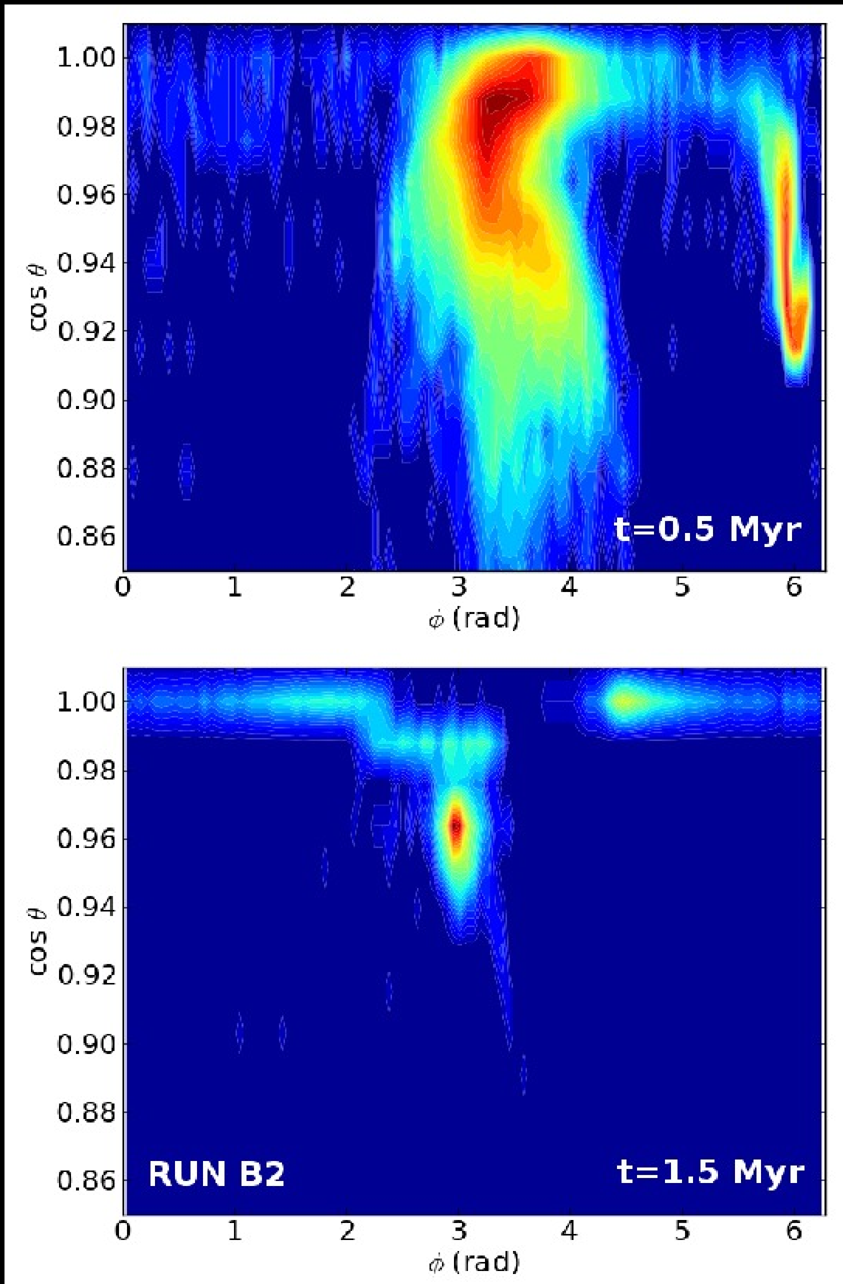
4. The secular evolution of the Galactic centre

WITH (run B2) the SPHERICAL CUSP



MM et al. 2013

Angular momentum direction of gas particles versus stellar disc



– Gas and stellar disc are slightly INCLINED (i~ 5 – 20 deg)

– Spherical cusp damps all but the precession of Ω

– Since $T_K \sim a^{-3/2}$ re
precession is faster for larger *a*

→ Ω changes more rapidly at the outskirts

→ since *i* != 0
a differential change of Ω induces a broadening of the inclination distribution!

MM, Gualandris & Hayfield 2013