The Galactic Centre

Determination of the Mass Distribution in the Galactic Centre from Stellar Motions

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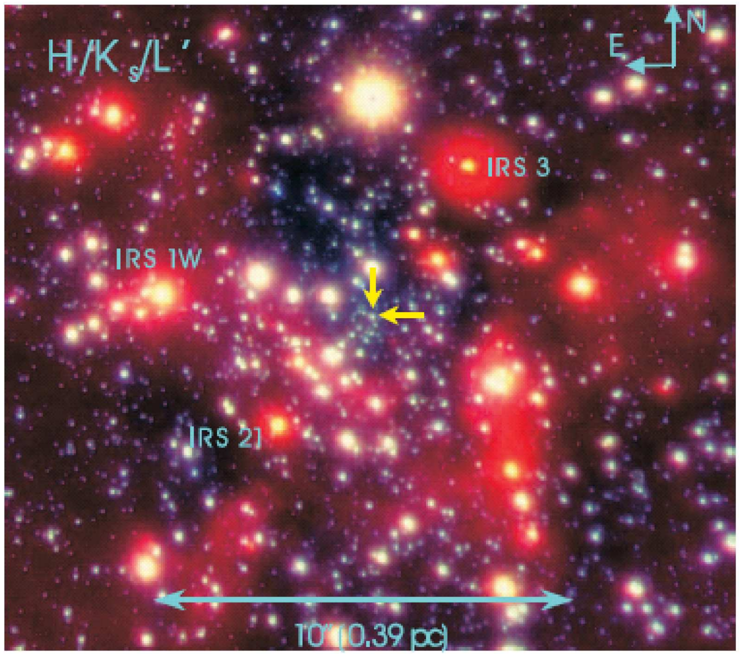
Where is the Galactic Centre?



Genzel et al. (2003)

- dynamical centre of Galaxy
- $R_0 = (7.62 \pm 0.32)$ kpc

  Eisenhauer et al. (2005)
- Celestial position: Sgr

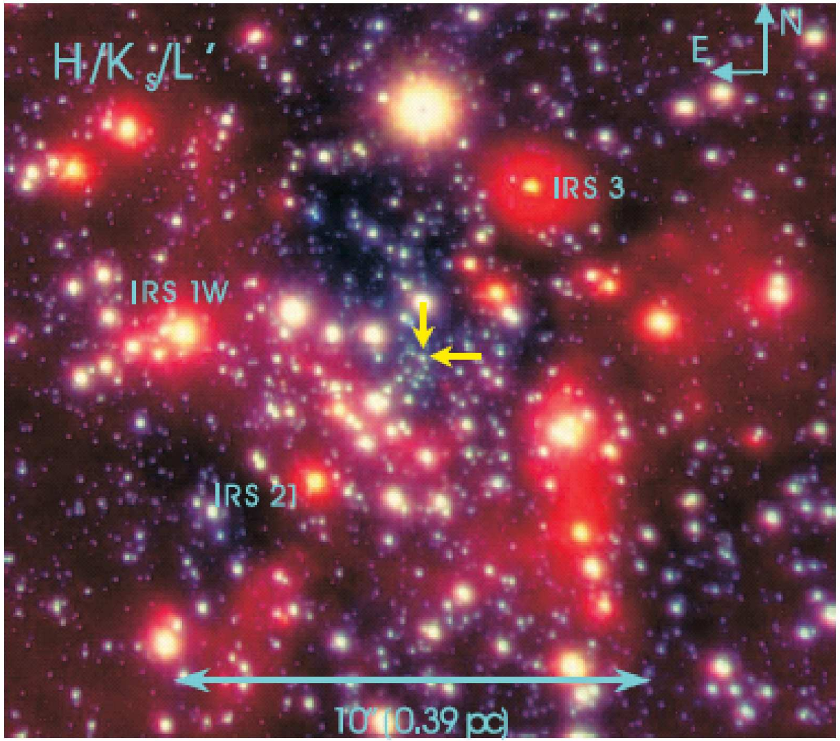
  $\alpha = 17^{\rm h}45^{\rm m}40^{\rm s}$, $\delta = -29^\circ 00' 28''$ (J2000.0)

  Reid & Brunthaler (2004)
- harbours
  - super-massive black hole
  - stellar clusters
    young and old stars
  - ISM

The Central Body: Sgr A*

- Detection in radio: Balick & Brown (1974)
- Detection in NIR: Becklin & Neugebauer (1975)
- Compact radio source
- Rejected Candidates: would have lower luminosity and density than observed
  - Stellar cluster of neutron stars and white dwarfs
  - Fermion ball
  - Boson star
- Super-massive black hole
  $M_\bullet = (3.61 \pm 0.32) \times 10^6 M_\odot$ Eisenhauer et al. (2005)

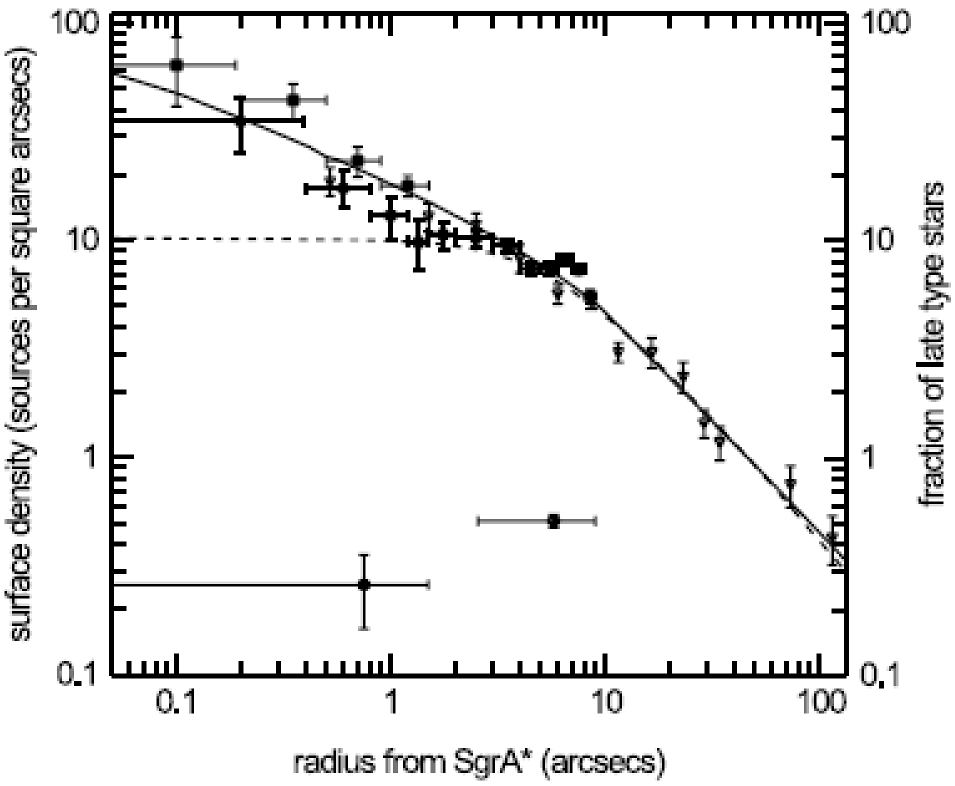
Stars and Gas in the GC



Genzel et al. (2003)

- Length scaling:
  1 " ≙ 0.037 pc
- Young stars in central 1 "
- Stellar disks of young stars inside 12 "
- Circum-nuclear ring of molecular gas, radius 45 "
- Spherical cluster of old stars in central 100 "

Cluster of Old Stars



- Old, metal-rich stars, 1-10 Gyr
- Broken power-law cusp:

$$\rho(r) \propto r^{-\alpha},\ R_{\rm br} = (6{\pm}1)''$$

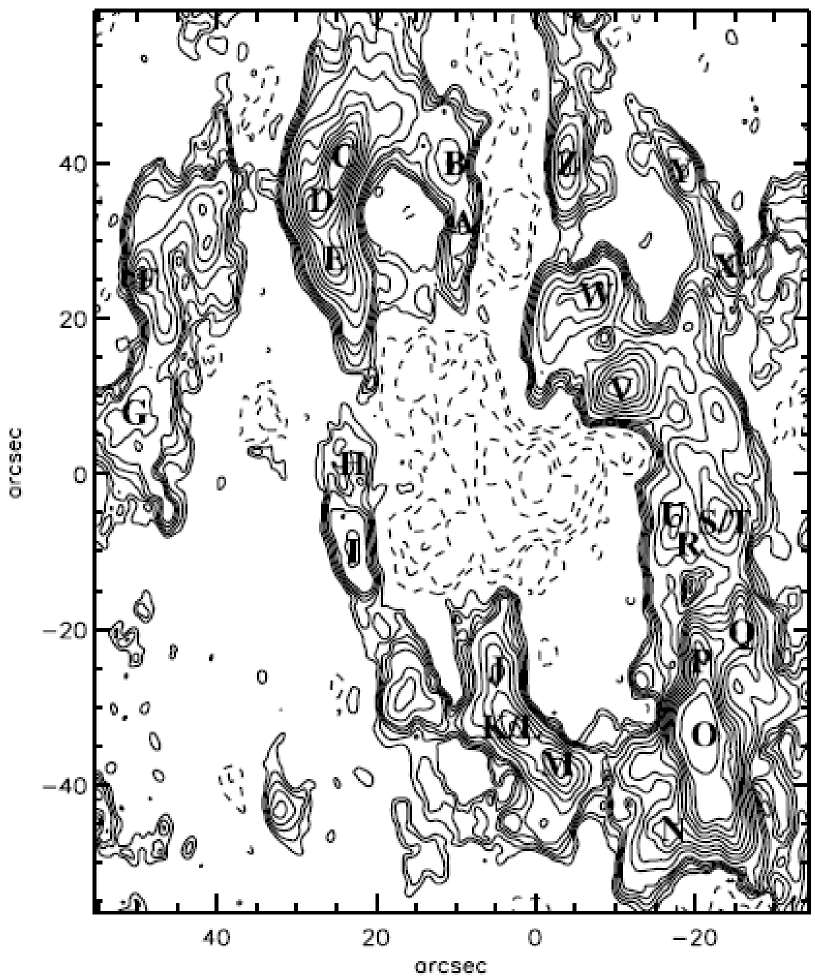
$$\alpha = \begin{cases} 1.19 \pm 0.05 & r \leq R_{\rm br} \\ 1.75 \pm 0.05 & r > R_{\rm br} \end{cases}$$

Schödel et al. (2007)

- Mass $\sim 1\ M_{\bullet}$ inside 2 pc

Genzel et al. (2003)

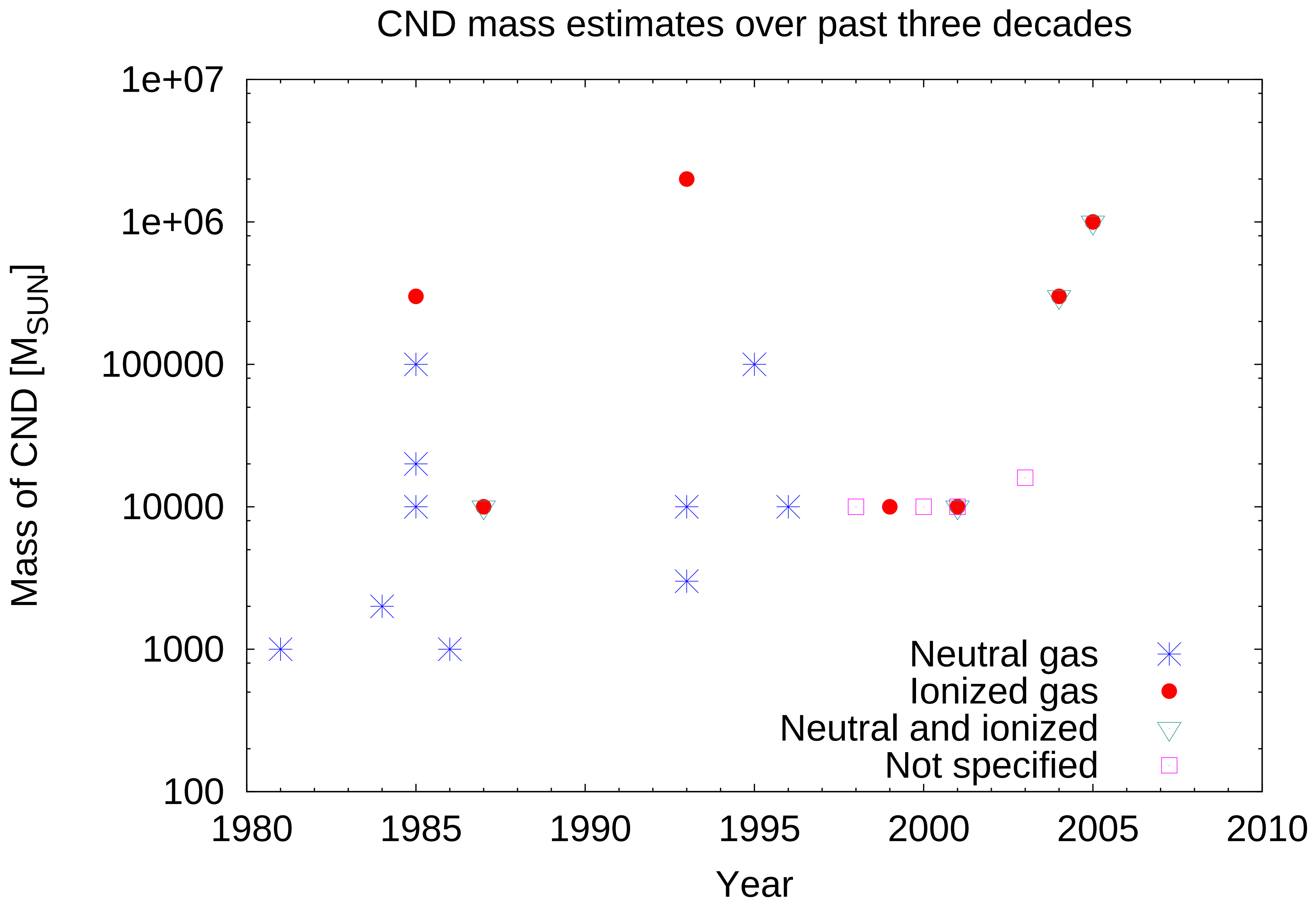
The Circum-nuclear Disk (CND)



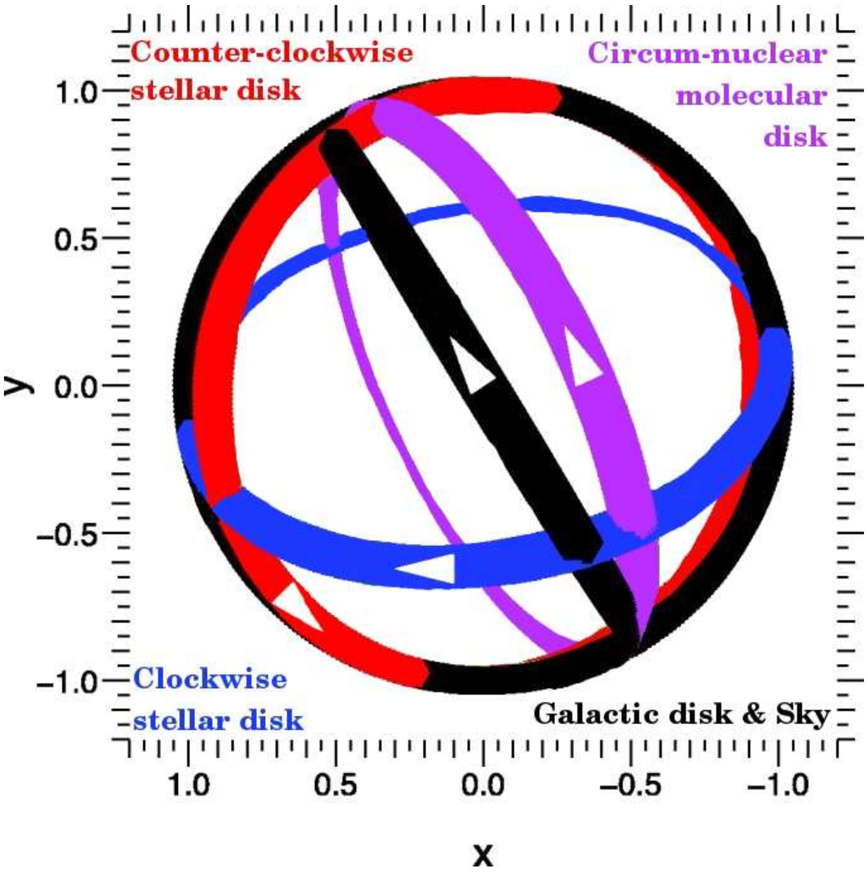
Christopher et al. (2005)

- Molecular ring:
  HCN and HCO^+, ...
- Well defined radius 1.6 pc
- Uncertain total mass:
  $M_{\rm CND} \approx 10^4 \, M_\odot$
  Genzel et al. (1985)
  $M_{\rm CND} \approx 10^6 \, M_\odot$
  Christopher et al. (2005)
- Considered as a gas source for star formation in the GC

The CND Mass


CND mass estimates over past three decades
Mass of CND [M_SUN]
1e+07
1e+06
100000
10000
1000
100
1980
1985
1990
1995
2000
2005
2010
Year
Neutral gas
Ionized gas
Neutral and ionized
Not specified

Planar Structures in the GC



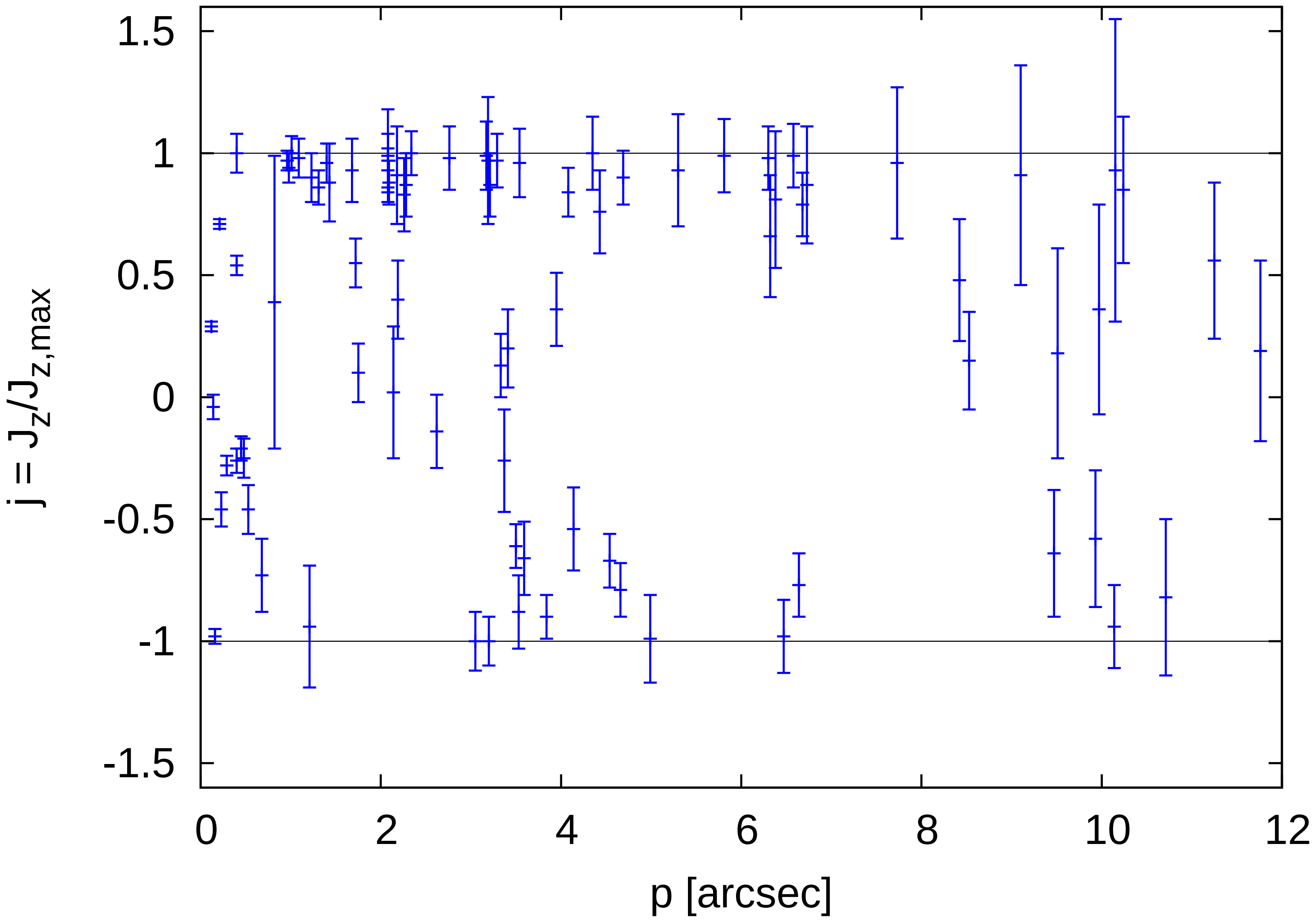
- Two coherent disks of massive O- & B-type stars $\simeq 0.1$ pc; Genzel et al. (2003), Ghez et al. (2005)
- Well defined inner (0.04 pc) and outer (0.5 pc) radii
- Geometrically thick: $h/R \sim$ 0.13

Paumard et al. (2006)

Stellar Disks in the Galactic Centre

- Young stars: (6 $\pm$ 2) Myr $\Rightarrow$ recent star formation
  Paumard et al. (2006)
- Similar disks detected in the centre of M31
  Bender et al. (2005)
- Flat mass function, mass $\sim 10^4\ M_\odot$
- Significant eccentricities for some of stellar orbits
- Clockwise disk (CWS): $e_{\rm rms} \in$ [0.2; 0.3]
  Paumard et al. (2006), Beloborodov et al. (2006)
- Counter-clockwise disk (CCWS): $e_{\rm rms} \in$ [0.6; 0.7]
- Hot topic: origin?

The Observed Angular Momentum



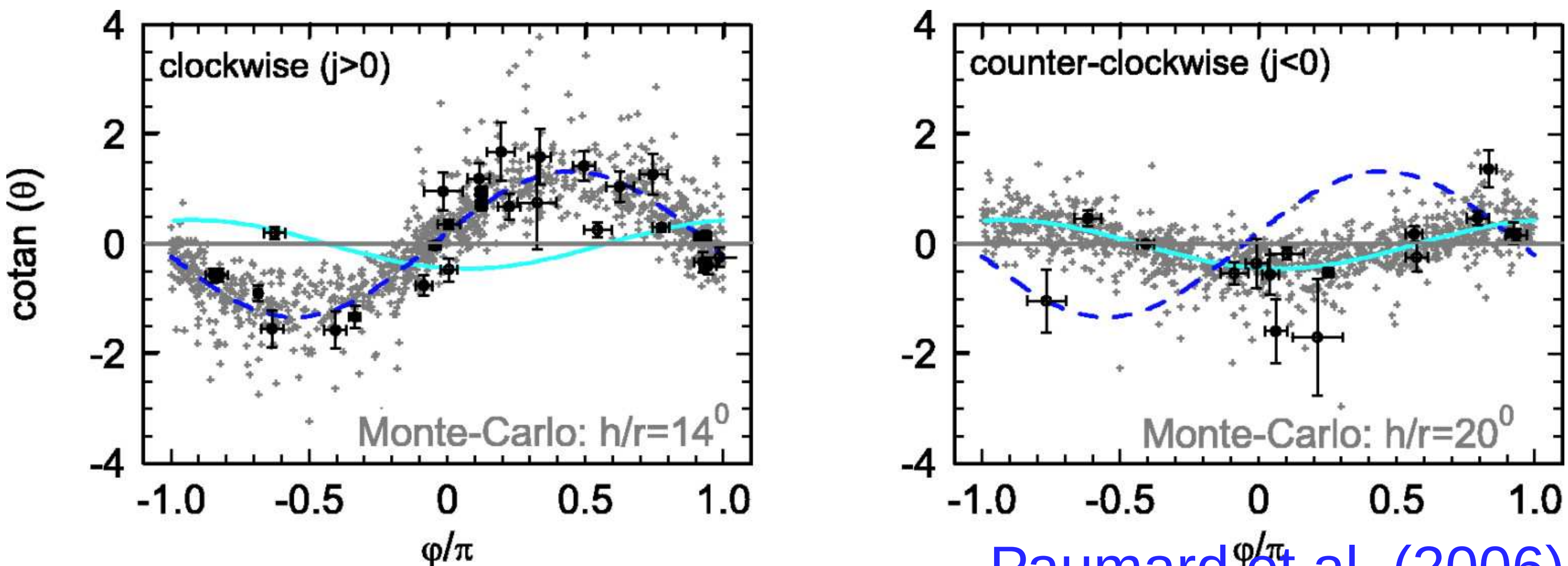
$$j = \frac{J_\mathrm{z}}{J_\mathrm{z,\ max}} = \frac{x v_y - y v_x}{\sqrt{(x^2 + y^2)(v_x^2 + v_y^2)}}$$

Genzel et al. (2003), Paumard et al. (2006)

Cosine Pattern of the Disk

- Normal vector to the disk
  $\vec{n} = (\sin i \cos \Omega, -\sin i \sin \Omega, -\cos i)$
- Velocity vector of the k-th star
  $\vec{v}_k = \|\vec{v}_k\| (\sin \theta_k \cos \phi_k, \sin \theta_k \sin \phi_k, \cos \theta_k)$

$$\vec{n} \cdot \vec{v}_k = 0 \quad \Rightarrow \quad \operatorname{cotg} \theta_k = \operatorname{tg} i \cos(\Omega + \phi_k)$$



Paumard et al. (2006)

Determination of the Mass Distribution in the Galactic Centre from Stellar Motions

Model of the GC

- System dominated by the SMBH central potential
- Two "perturbations":
  - spherical stellar cluster

$$\Phi_{\mathrm{SPHE}}(r) = \frac{4\pi G \rho_0 r_0^{\alpha}}{(\alpha-2)(\alpha-3)} r^{2-\alpha}$$

  - axi-symmetrical CND

$$\Phi_{\mathrm{CND}}(r) = -2G\lambda \sqrt{\frac{a_{\mathrm{CND}}}{R}} k \mathcal{K}(k),$$

$$k^2 = f(a_{\mathrm{CND}}, z_{\mathrm{CND}}, R, Z)$$

- CWS disk considered as a set of test particles

Thesis Aims

- Limit the mass of the CND
- Confine the spatial structure of the CWS disk

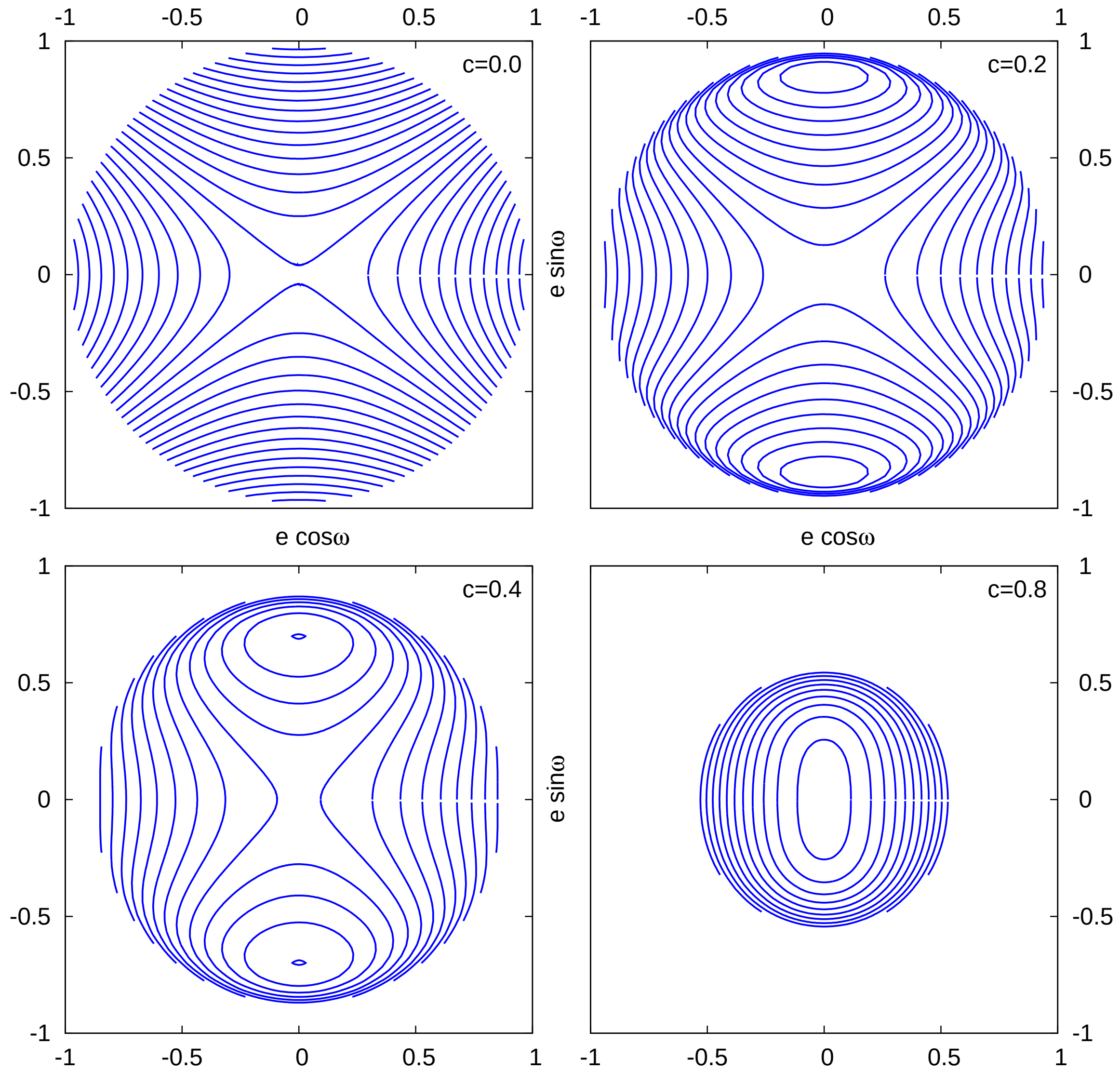
How?

- Deformation of the CWS disk
- Dependence of the deformation on the parameters of the perturbing potentials
- Compare simulation results with observations

Useful Tools and Techniques

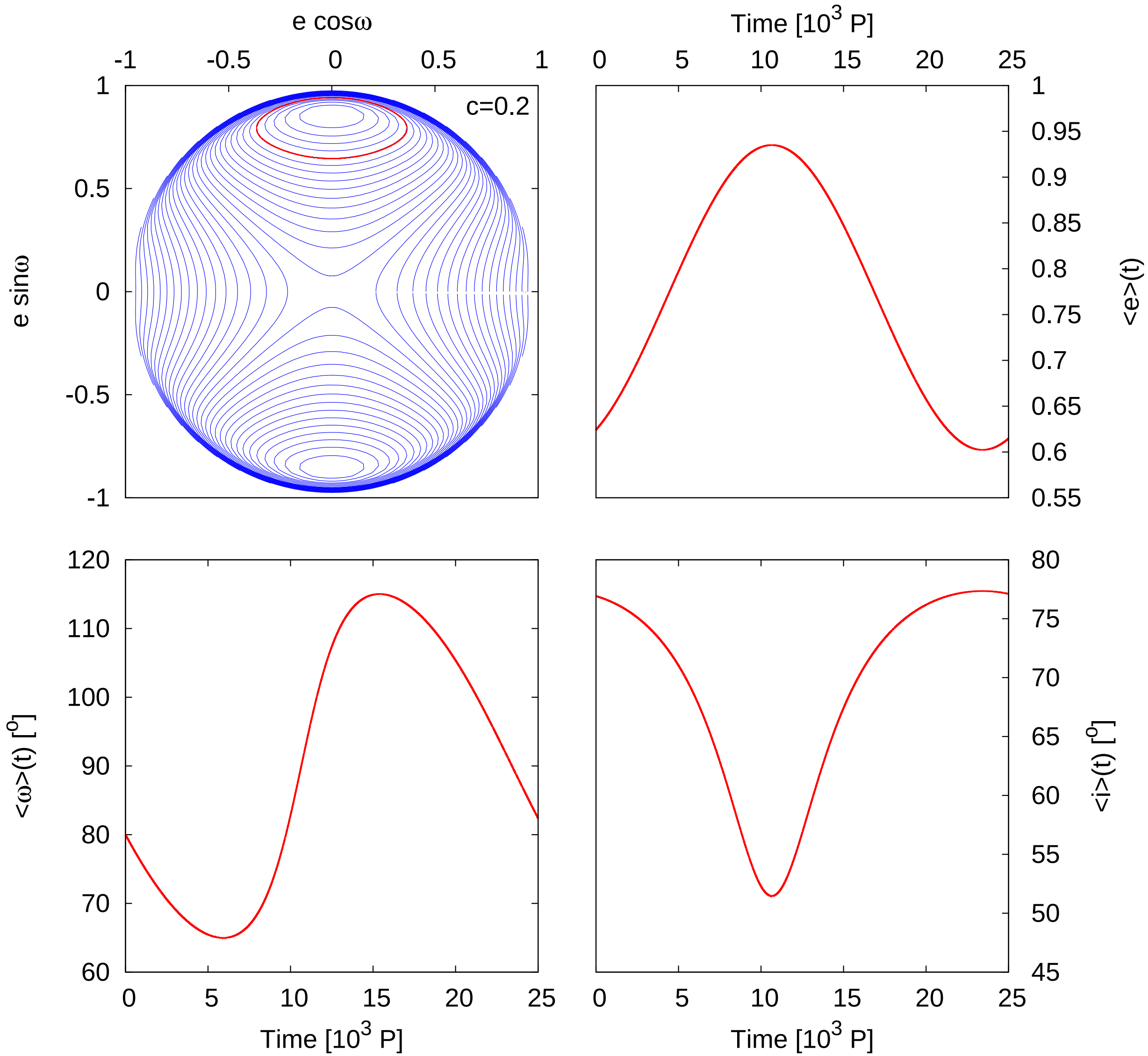
- Kozai mechanism, Kozai (1962), Lidov (1962):
  - Evolution of a hierarchical triple system; motion of an asteroid under influence of Sun and Jupiter
  - Secular evolution of the orbital elements e, i and ω
  - Hamiltonian perturbation theory & averaging technique to get rid of fast-changing variable, the mean anomaly
  - Integrals of motion: a, $c = \sqrt{1-e^2}\cos i$, $\bar{\Phi}_{\rm perturb}$
  - Convenient tool for study of motion of a test particle in the potential dominated by the central mass and perturbed by an axi-symmetrical potential and a spherical potential

The $\bar{\Phi}_{\rm perturb}$ Isocontours

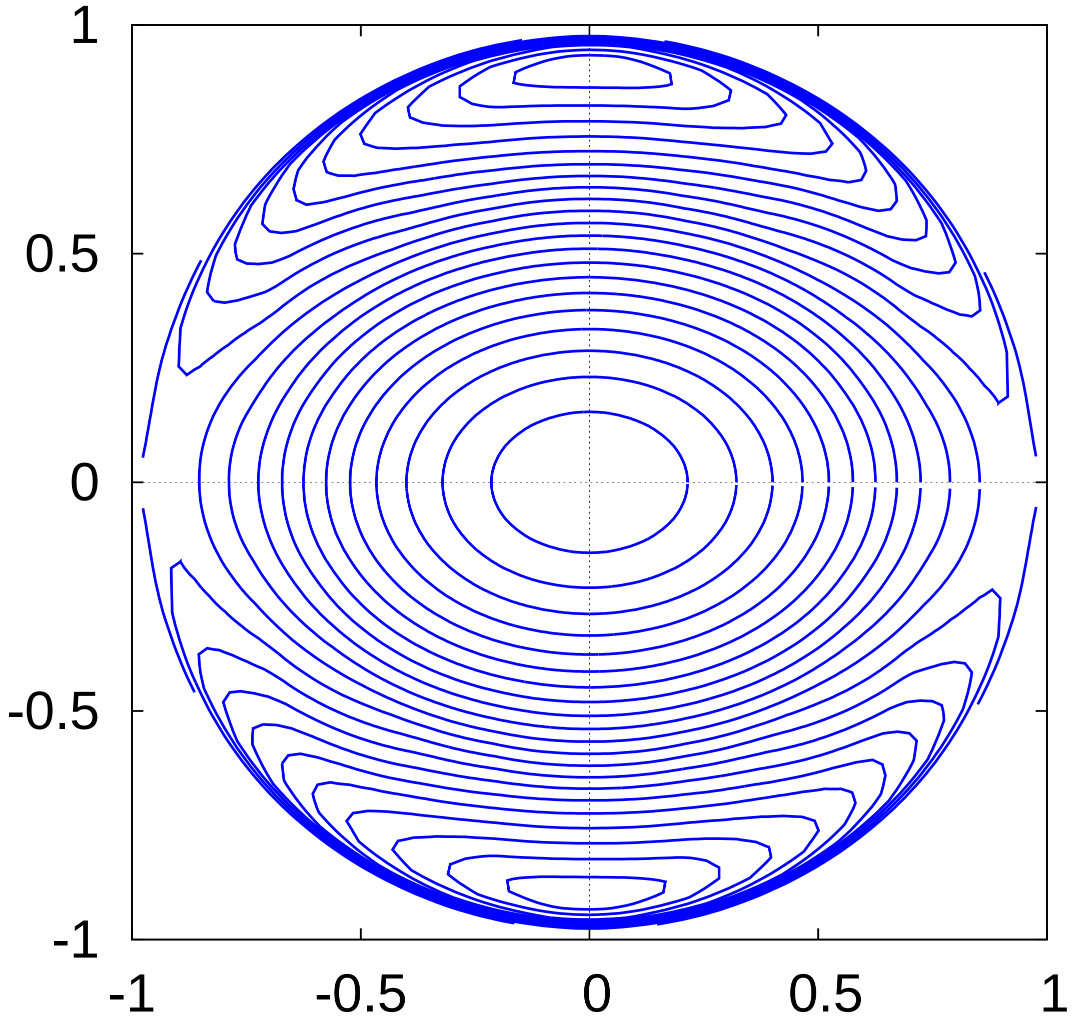


$$M_{\rm CND}/M_\bullet = 0.01,\ a_{\rm CND}/a_* = 2,\ c = 0.2$$

Secular Evolution of Orbits

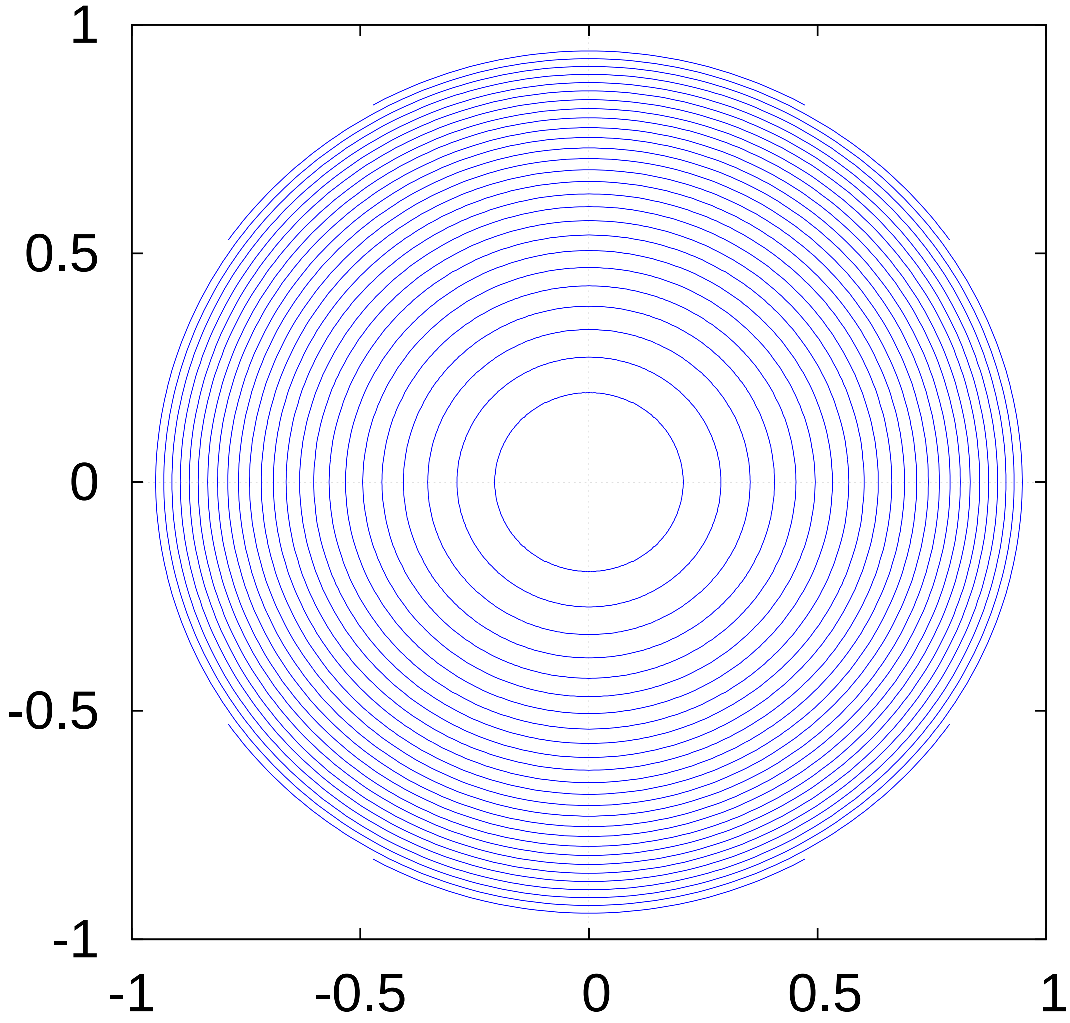


Composite Perturbation



$M_{\mathrm{CND}}/M_{\bullet} = 0.01$, $M_{\mathrm{CND}}/M_{\mathrm{SPHE}} = 0.5$, $a_{\mathrm{CND}}/a_{*} = 2$, $c = 0.2$

The GC Model



$M_{\rm CND}/M_\bullet = 0.33$, $M_{\rm CND}/M_{\rm SPHE} = 0.33$, $a_{\rm CND}/a_* = 4.5$, $c = 0.1$

The “Quadrupole Equations”

$$
\begin{aligned}
\frac{\mathrm{d}e}{\mathrm{d}\tau} &= +\frac{15}{8}\, e\sqrt{1-e^2}\,\sin^2(i)\,\sin(2\omega) \\
\frac{\mathrm{d}i}{\mathrm{d}\tau} &= -\frac{15}{8}\frac{e^2}{\sqrt{1-e^2}}\,\cos(i)\,\sin(i)\,\sin(2\omega) \\
\frac{\mathrm{d}\omega}{\mathrm{d}\tau} &= +\frac{3}{4}\frac{1}{\sqrt{1-e^2}}\left\{2(1-e^2)+5\sin^2(\omega)\left[e^2-\sin^2(i)\right]\right\}
\end{aligned}
$$

$$
\frac{\mathrm{d}\Omega}{\mathrm{d}\tau} = -\frac{3}{4}\frac{\cos(i)}{\sqrt{1-e^2}}\left[1+4e^2-5e^2\cos^2(\omega)\right]
$$

Evolution of the Orbital Elements

- Disk deformation depends more on Ω than on e, i, ω
- Quadrupole equations DO NOT describe system with a heavy spherical perturbation!
  $\Rightarrow$ alternative timescale estimate necessary

$$P_\Omega = ?$$

- $P_\Omega = f(M_{\mathrm{CND}}; M_{\mathrm{SPHE}}, \alpha_{\mathrm{SPHE}}; a_{*,0}, e_{*,0}, i_{*,0}, \omega_{*,0})$

Exploring the P_Ω Dependences

Dependence on

- $M_{\rm CND}$: $P_\Omega \propto M_{\rm CND}^{-1}$
- $a_{*,0}$: $P_\Omega \propto a_*^{-3/2}$
- $e_{*,0}$: $P_\Omega \propto \sqrt{\frac{1-e_{*,0}}{1+e_{*,0}}}$
- $i_{*,0}$: $P_\Omega \propto |\cos i_{*,0}|^{-1}$
- $M_{\rm SPHE}, \alpha_{\rm SPHE}$: no dependence has been found for mass range $M_{\rm SPHE}/M_\bullet \in [0.5; 4]$ and profiles $\alpha_{\rm SPHE} \in [1.0; 2.0]$

The P_Ω Estimate

$$\left(\frac{P_\Omega}{\mathrm{Myr}}\right) = \left(\frac{a}{\mathrm{a_{CND}}}\right)^{-3/2} \left(\frac{M_{\mathrm{CND}}}{M_\bullet}\right)^{-1} \frac{1}{|\cos i_0|} \sqrt{\frac{1-e_0}{1+e_0}}\ \ \mathrm{fn}$$

Isocontours of P_Ω

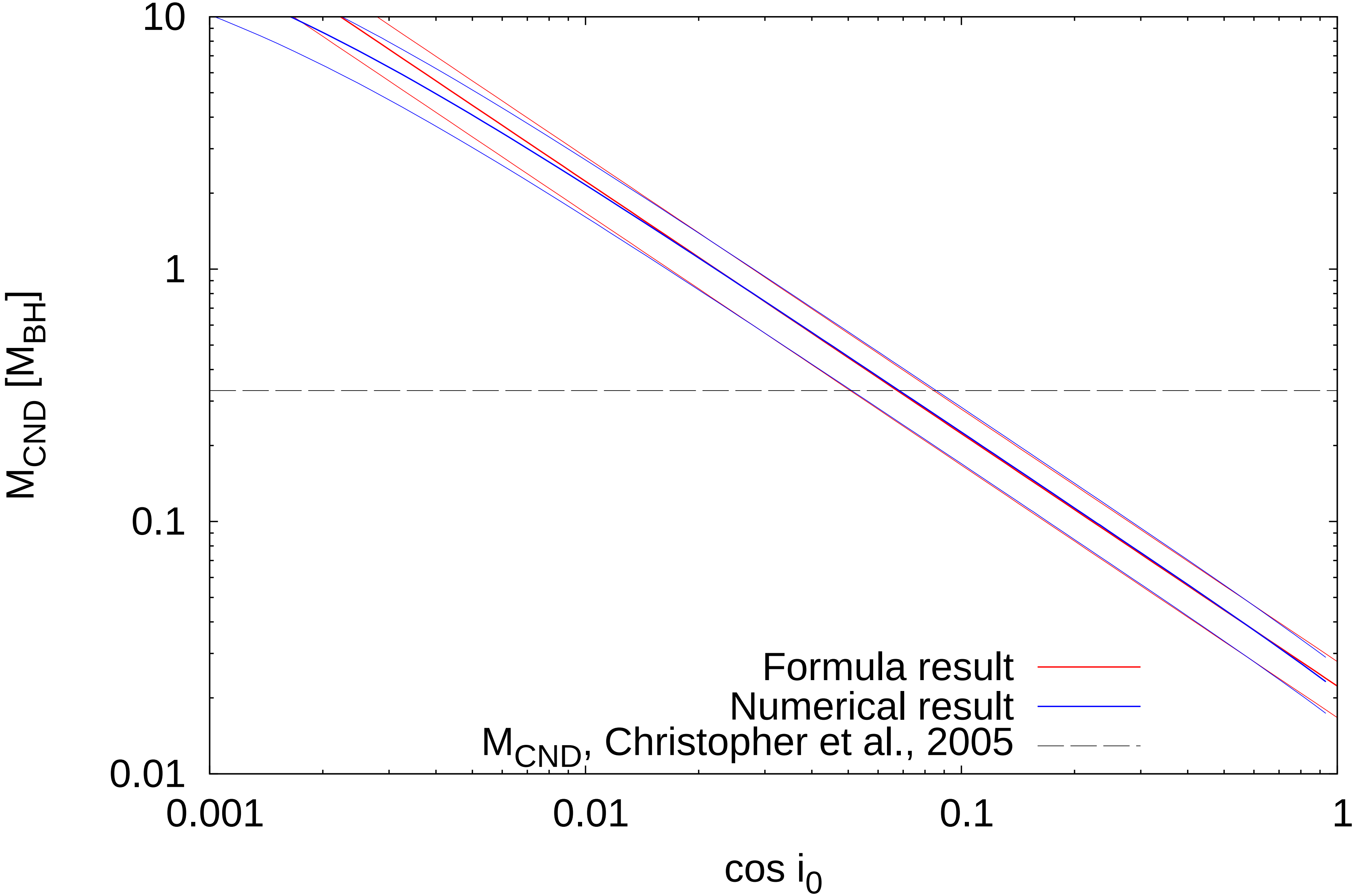


FIG: jak vypada jz(p) pro ruzne konfig

– kumulovane cetnosti

FIG: The Modelled Angular Momentu

TODO: obrazky pro par bodu podel P Omega=108 Myr, par bodu pro delsi a par bodu pro kratsi periodu.

– snapshot disku

– odpovidajici $j_z(p)$

– Aitoffova projekce $\vec{j}$ tehoz?

Conclusions

TODO: – zminit nutnost vyssich excentricit nez "pozorovanych"
– mass of CND is ...

– pocatecni rozevreni

Thank you for your attention!