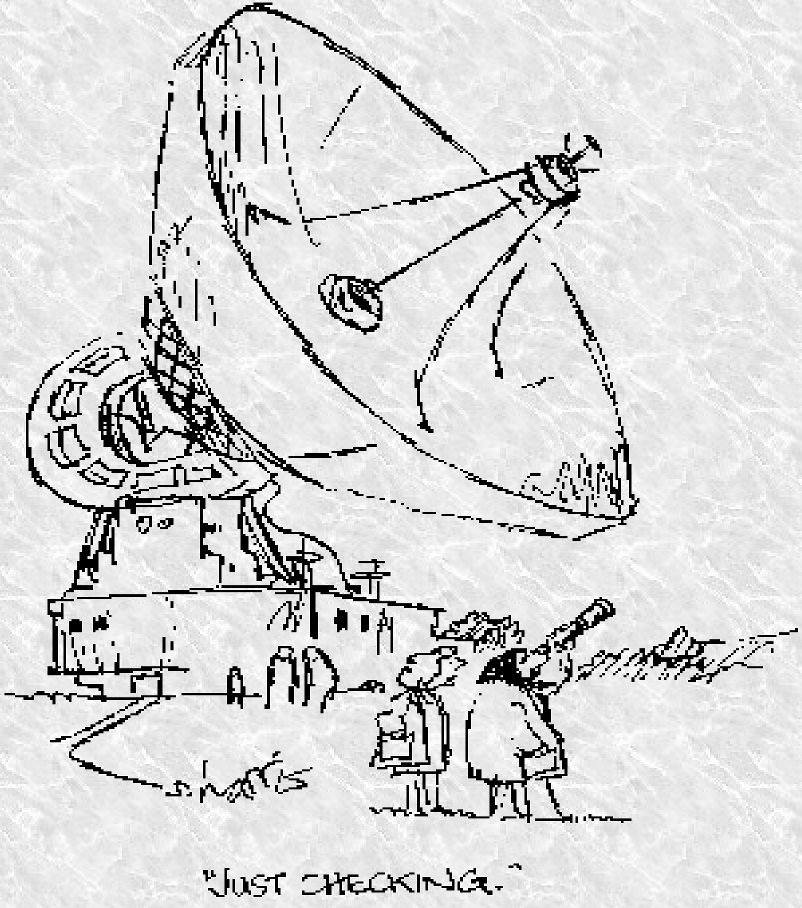
Dynamics of circumbinary discs: from supermassive black holes to protostars



Enrico Ragusa

Università degli Studi di Milano

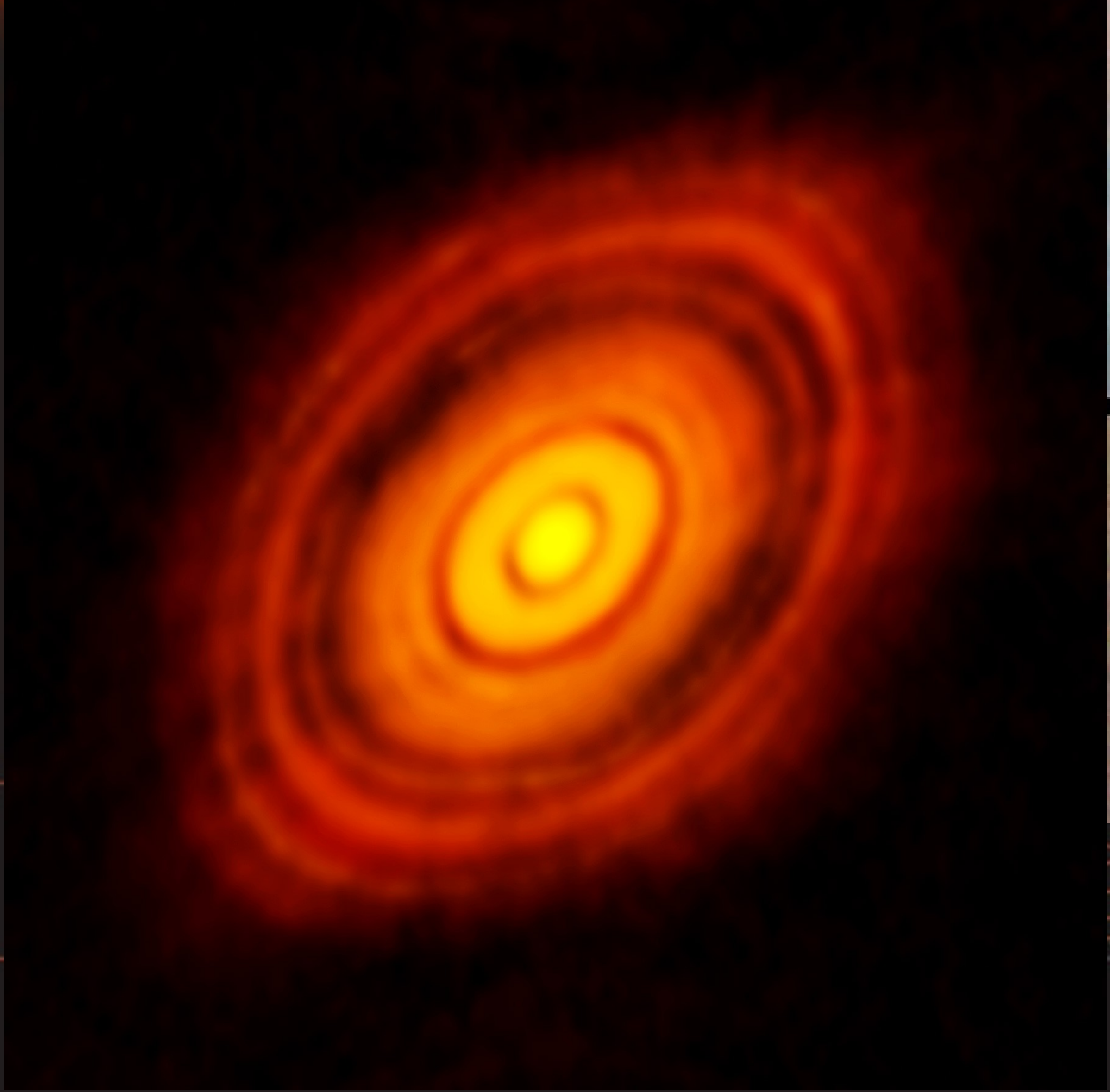
Contents

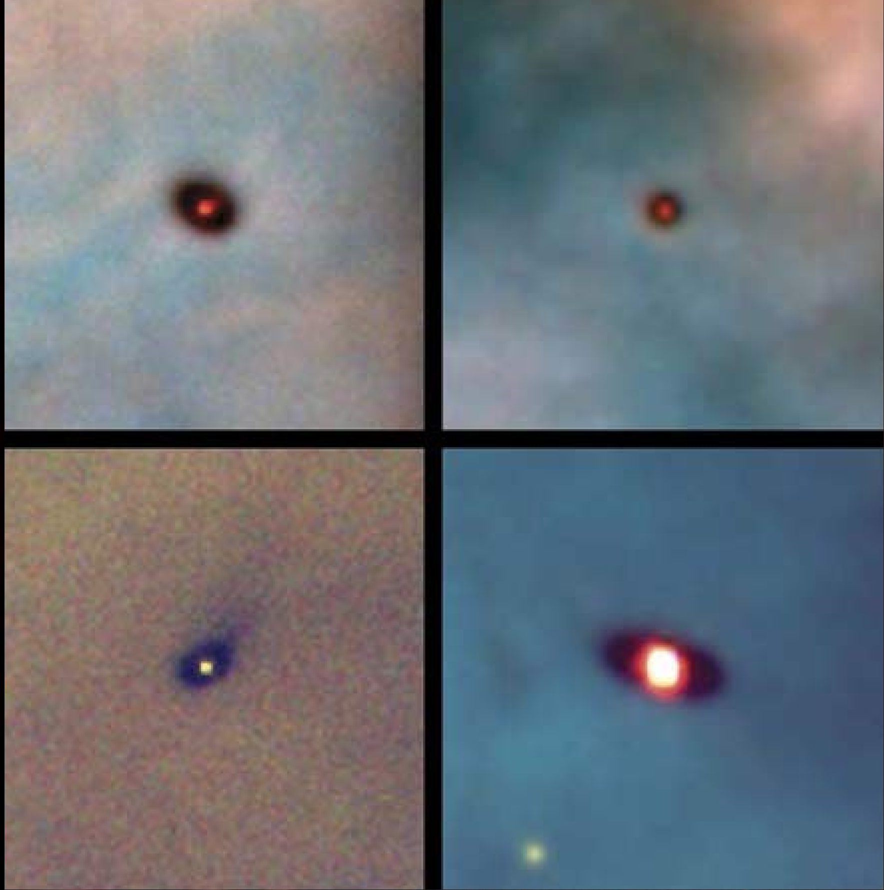
- Introduction: What are circumbinary discs?
- The problem of mass accretion in supermassive BH binaries
- The problem of asymmetries in transitional discs
- Conclusions

Introduction
Accretion disc physics

“An accretion disc is a structure formed by diffused material in orbital motion around a massive central body” (ref: Wikipedia)

- Wide mass range of the central object: Stars, WD, NS, BH, SMBH
- Angular momentum conservation --> gas forms a disc around the massive object.
- Turbulence provides a powerful mean to transport angular momentum towards larger radii and to dissipate energy, allowing accretion.
- Dynamics studied using fluid dynamics equations and modelling angular momentum transport and energy dissipation as a form of viscosity.
- Predictions: gas density distribution, temperature, luminosity...

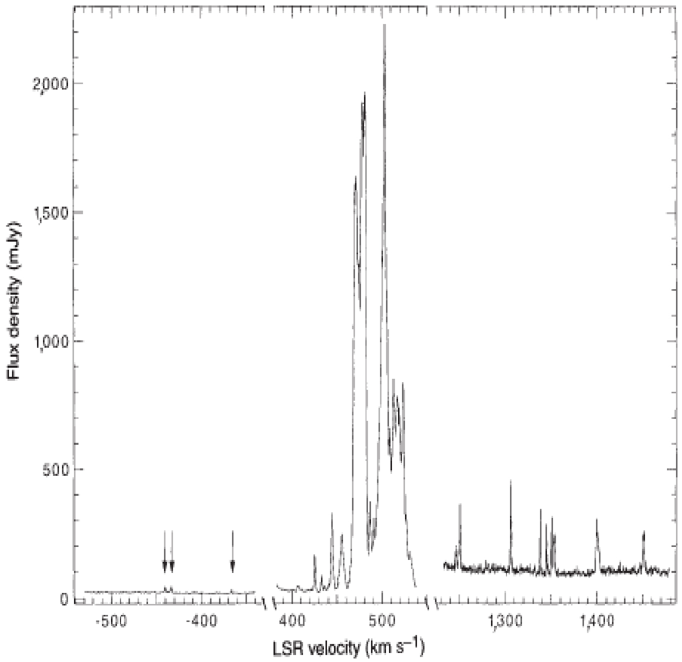


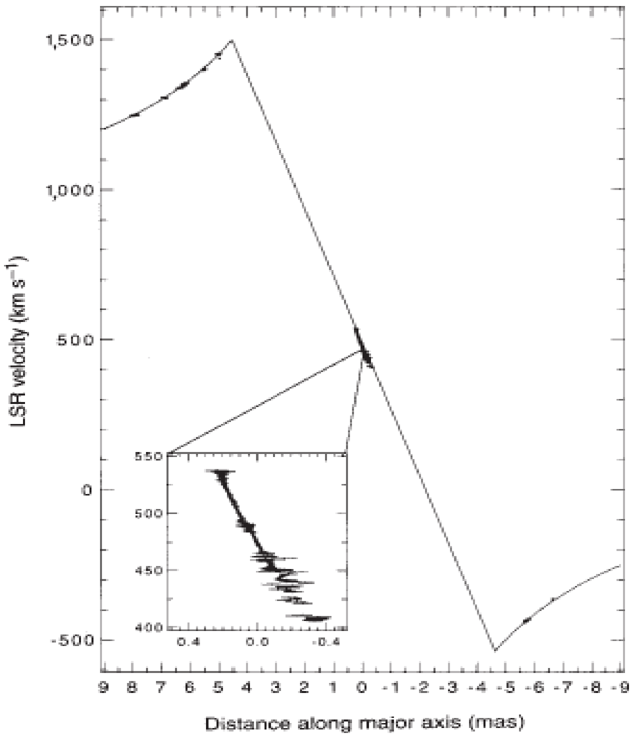


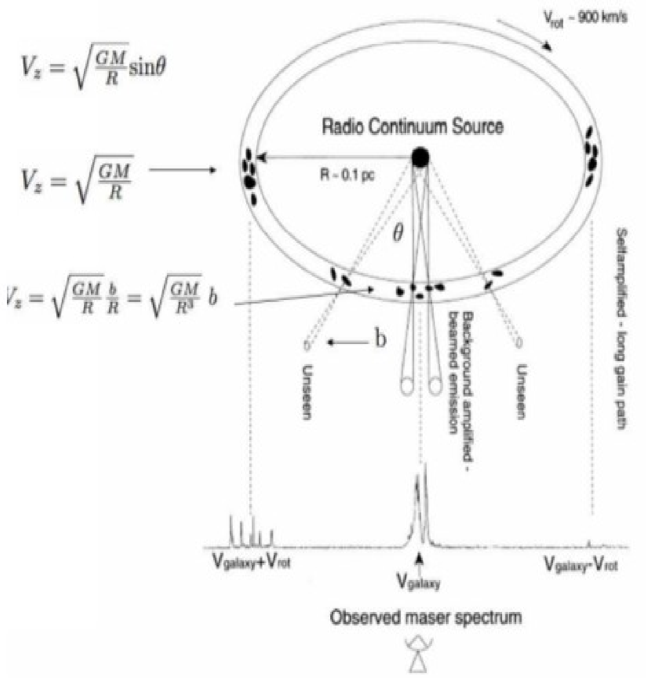

become asteroids (metal/rock) and comets
or Kuiper belt objects (ice/rock).
Not to scale

Introduction:
Accretion disc physics

- Keplerian Motion of water maser in NGC4258

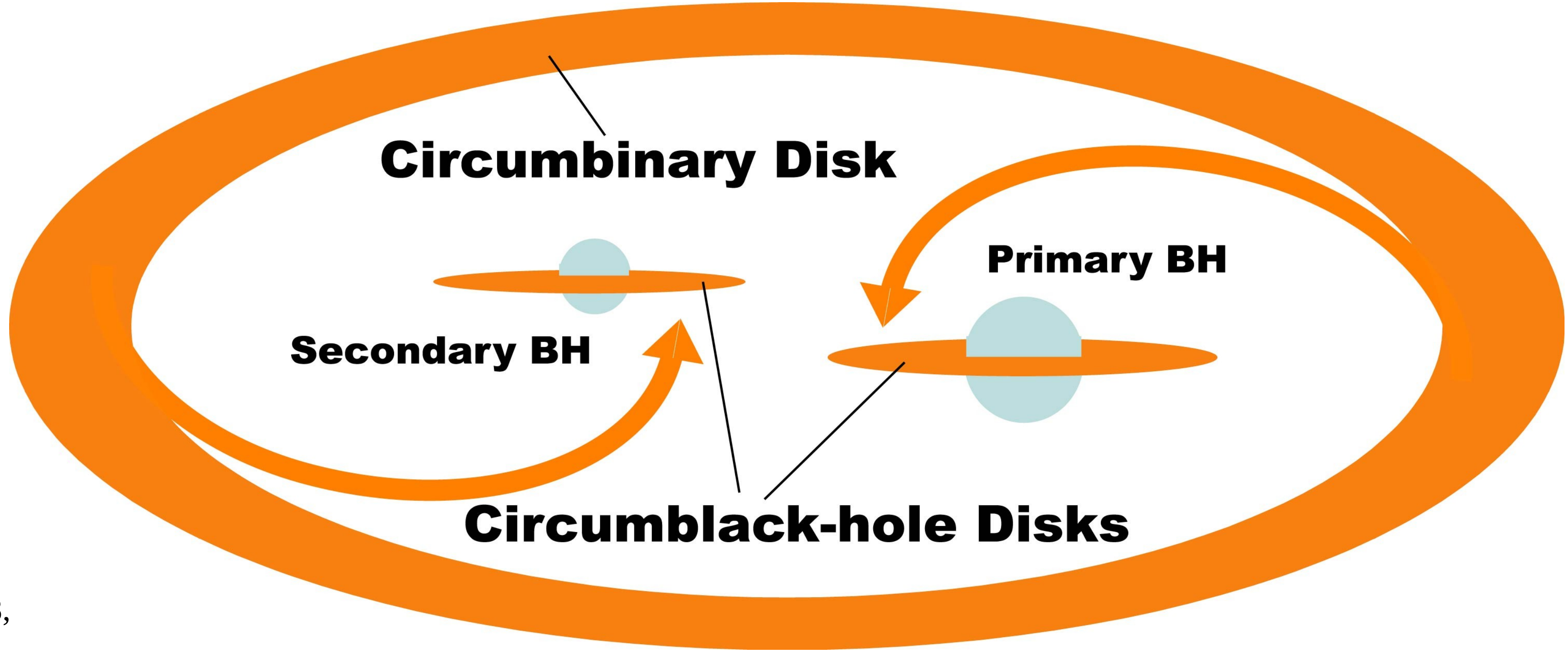






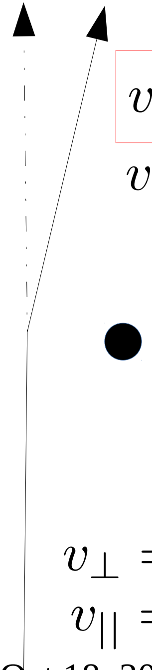
Introduction:
Circumbinary discs

- Discs surrounding binary objects



Introduction:
Circumbinary discs

- Discs surrounding binary objects
- The secondary object exerts an additional torque on the disc, **AND** viceversa:



$$\boxed{v_{||} = \Delta v - \delta v_{||}}$$

$$v_\perp = \delta v_\perp$$

$$v_\perp = 0$$

$$v_{||} = \Delta v$$

$$\delta v_\perp = \int_{-\infty}^{+\infty} \frac{F_\perp}{m} dt = \frac{2GM_{\rm sat}}{b\Delta v} \qquad b = R - a$$

$$\Delta J = -\Delta J_s = \frac{2G^2 M_{\rm sat}^2 a}{b^2 \Delta v^3} \qquad \frac{\Delta J_s}{\Delta t}(b) = \frac{dT}{dm}(b)$$

$$\Delta t = \frac{2\pi}{|\Omega_s - \omega|} \qquad dm \approx 2\pi\Sigma a db \qquad \Delta v = (\omega - \Omega_s)R$$

$$|\Omega_s - \omega| \approx \frac{\partial \omega}{\partial R}\bigg|_{R=a} \overbrace{(R-a)}^{b} + \mathcal{O}(R-a)^2 \xrightarrow{\text{Keplerian}} \frac{3}{2}\Omega_s \cdot \frac{b}{a}$$

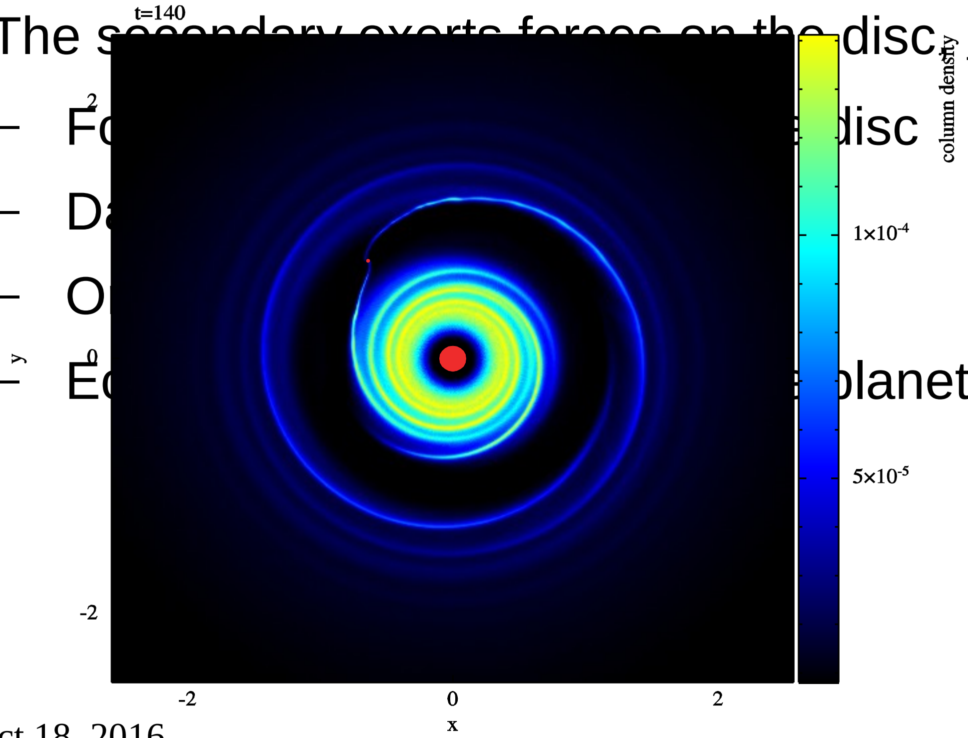
$$\boxed{\frac{dT}{dR}(R) = -\text{sgn}(R-a)\frac{8}{9}\frac{G^2 M_{\rm sat}^2 a \Sigma(R)}{\Omega_s^2 (R-a)^4}}$$

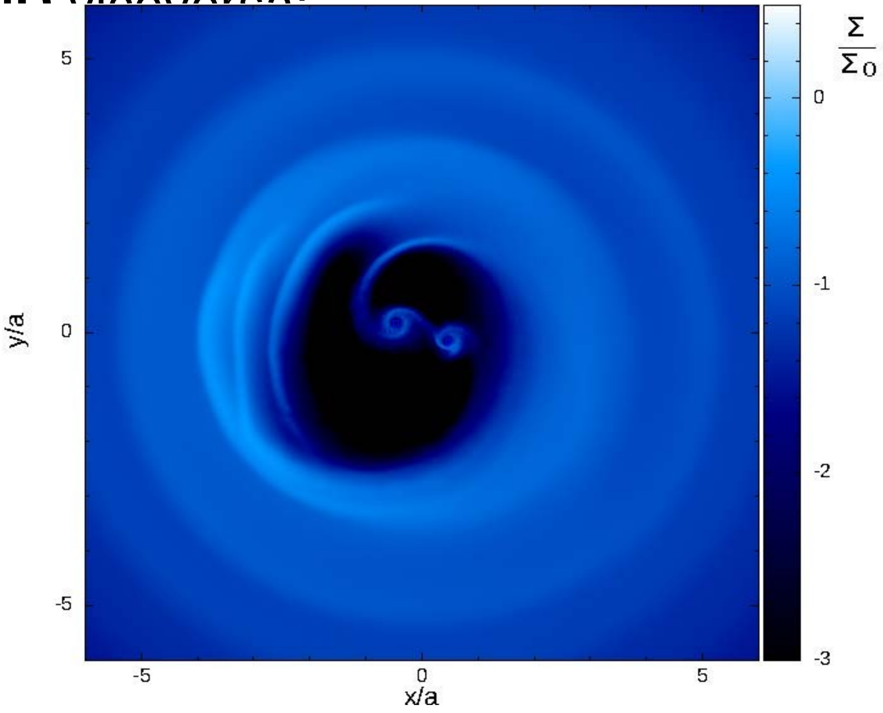
Introduction:
Circumbinary discs

- Discs surrounding binary objects
- The secondary object exerts an additional torque on the disc, **AND** viceversa:
  - Formation of a gap/cavity in the disc
  - Dam effect for accretion
  - Orbital migration of the planet
  - Eccentrity evolution (both in the planet and in the disc)

Introduction:
Circumbinary discs

- Discs surrounding binary objects
- The secondary exerts forces on the disc **AND** viceversa:
  - Fo … disc
  - D…
  - O…
  - E… planet ar…





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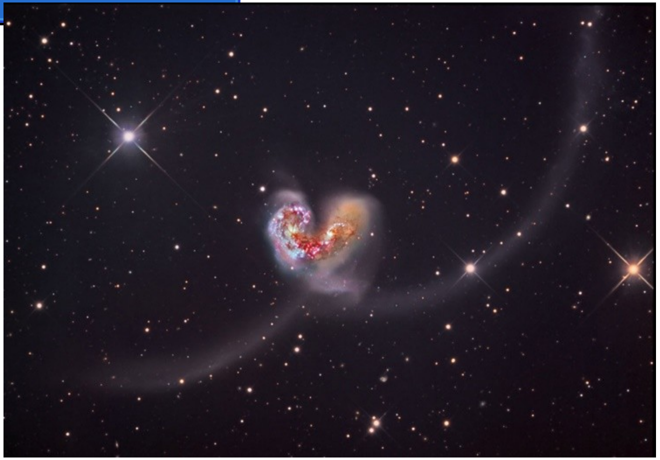
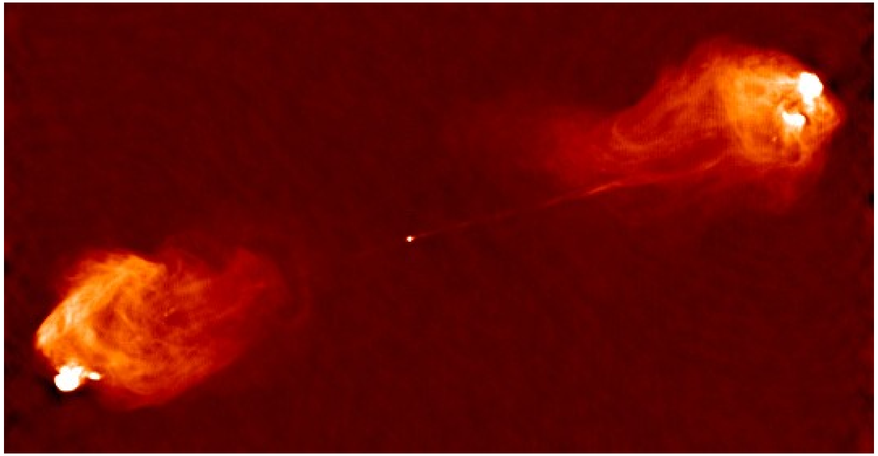
Mass accretion in SMBHBs:
Motivation

- Galaxies in the near universe formed by multiple merging of smaller structures



- Supermassive Black holes observed in the central regons of most galaxies:
  - AGN activity
  - Keplerian motion
  - M-σ relationship



Mass accretion in SMBHBs:
Motivation

- Galaxies in the near universe formed by multiple merging of smaller structures

- Supermassive Black holes observed in the central regons of most galaxies:
  - AGN activity
  - Keplerian motion
  - M-σ relationship

Coexistence of two supermassive black holes in the same galaxy

- Rapid inspiral motion driven by dynamical friction
- The surrounding gas provides a migration mechanism below parsec separations
- Final phase: emission of gravitational waves
- Merging of the two black holes

Mass accretion in SMBHBs:
Motivation

- Widely studied starting from the mid 1990s:
  - Star-planet, star-star systems

    (Artymowicz & Lubow 1996; Bate & Bonnell 1997; Gunther & Kley 2002; Ochi et al. 2005; Hanawa et al. 2010; de Val-Borro et al. 2011; Dunhill et al. 2015)
  - SMBH-SMBH systems

    (Hayasaki et al. 2007; MacFadyen & Milosavljevic 2008; Cuadra et al. 2009; Roedig et al. 2012; Shi et al. 2012; D'Orazio et al. 2013; Farris et al. 2014; Shi & Krolik 2015)
- General conclusions:
  - In contrast with previous 1D simulations, also for q=1 (strongest tidal forces) no suppression of accretion with respect to the single central object case.
  - Farris et al. (2014) and Shi & Krolik (2015), the accretion is even increased (SMBHBs).

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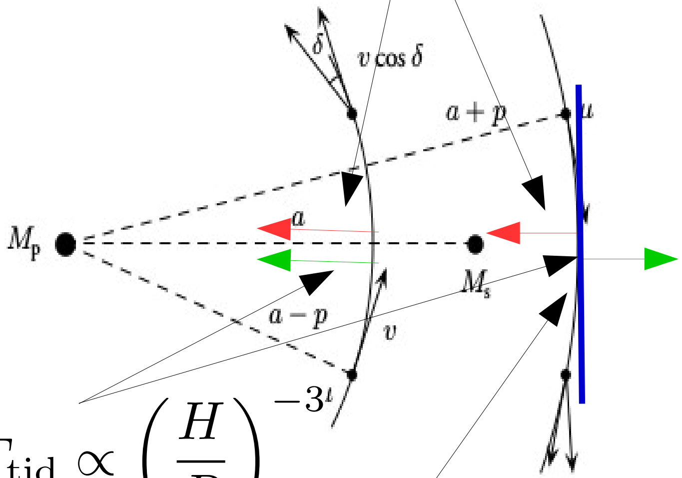
$$T_{\rm visc} \propto c_s^2\Omega^{-1} \propto H^2\Omega$$

- **BUT**:



$$T_{\rm tid} \propto \left(\frac{H}{R}\right)^{-3}$$

- Tidal Barrier?
- SMBH regime

$$\frac{H}{R} \sim 10^{-3}$$

Mass accretion in SMBHBs:
Implications

- Reduction in luminosity up to a factor 100 with respect to normal AGN activity is expected
- Guarantee that bllack holes merge on a reasonably short time scale in case of finite mass supply (Young & Clarke, 2015)
- Pileup of material at the edge of the cavity provides a stronger binary-disc interaction: faster migration rate (Rafikov 2013)?
- Spin-alignment efficiency reduced by a lower accretion rate: consequences for gravitational wave patterns and recoil velocity of the newly formed BH

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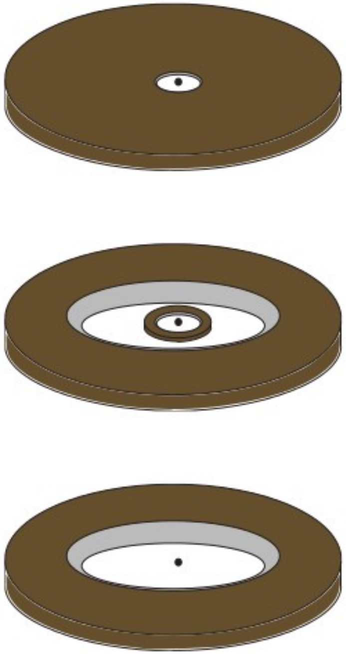
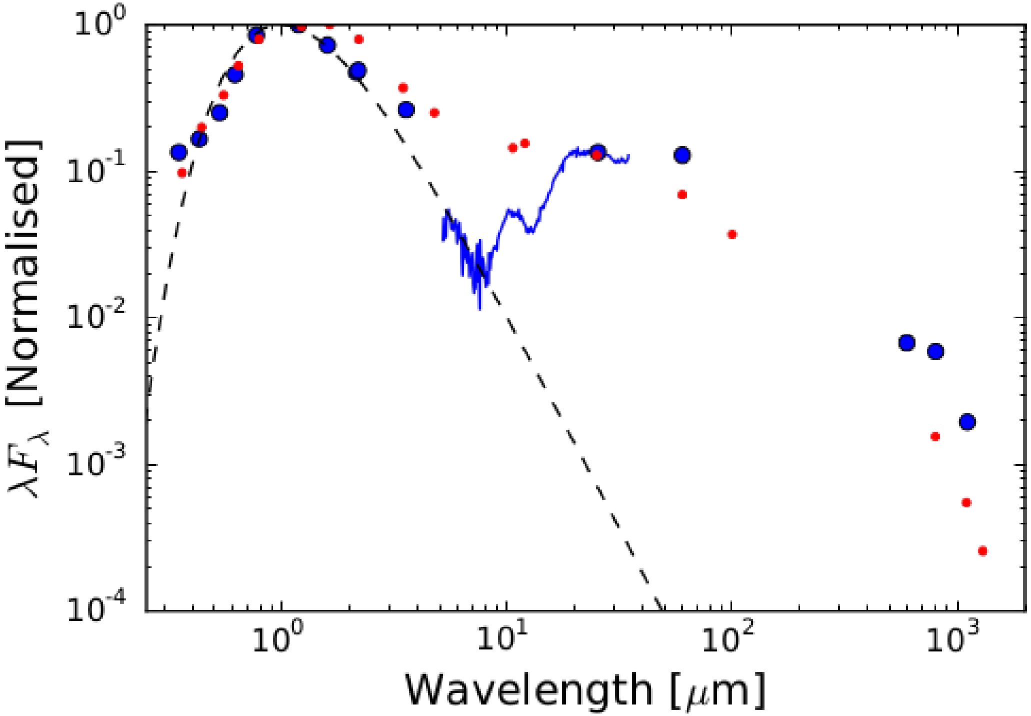
Asymmetries in transitional discs
Motivation

- Transitional discs: young stars that are dispersing their protoplanetary disc.
- They appear as discs with a cavity in the central region.





Asymmetries in transitional discs

Motivation

- Transitional discs: young stars that are dispersing their protoplanetary disc.
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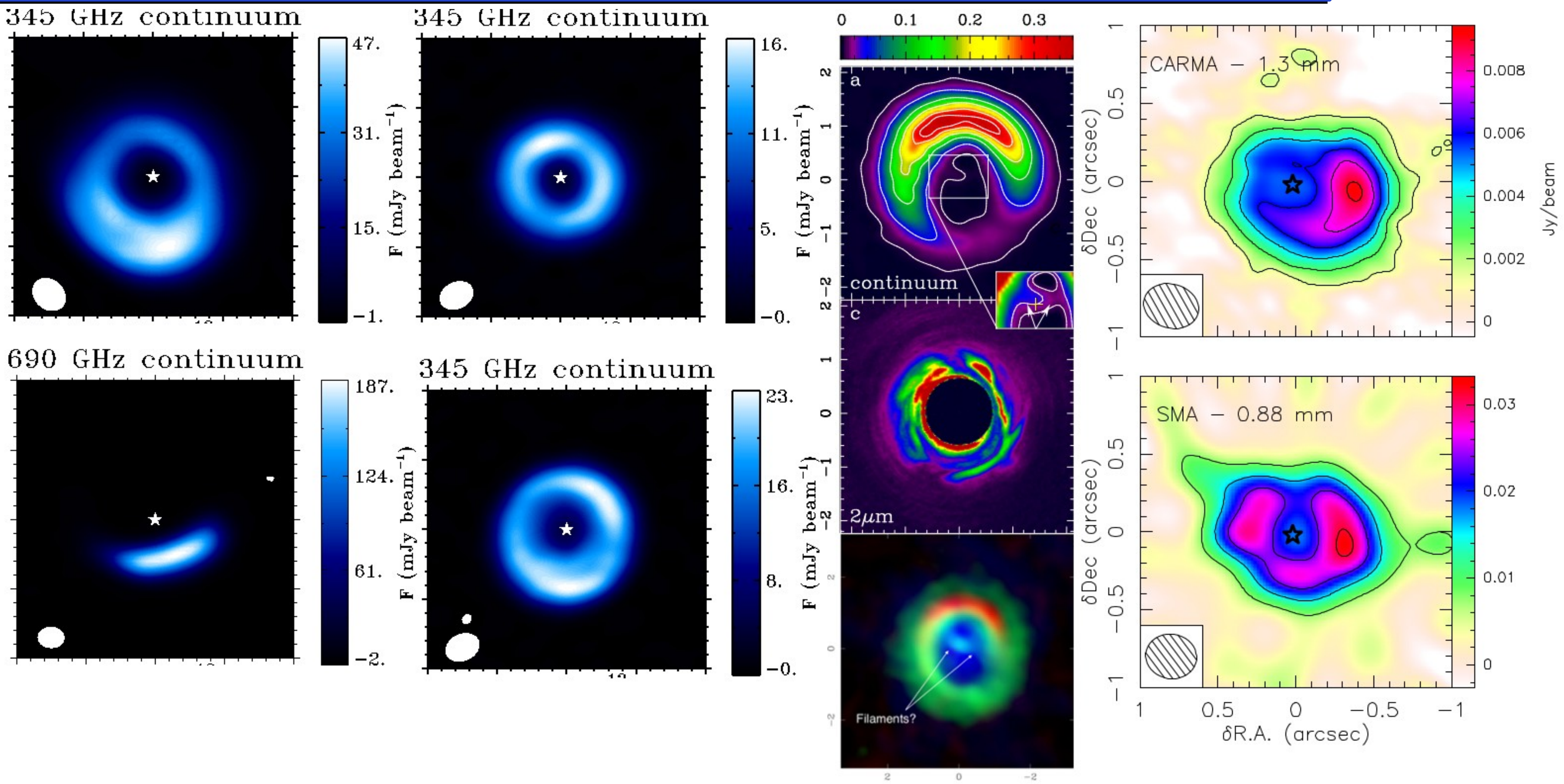
- Recent ALMA (**A**tacama **L**arge **M**illimeter **A**rray) images showed asymmetric overdense structures in transition discs.

Asymmetries in transitional discs

Motivation



Asymmetries in transitional discs

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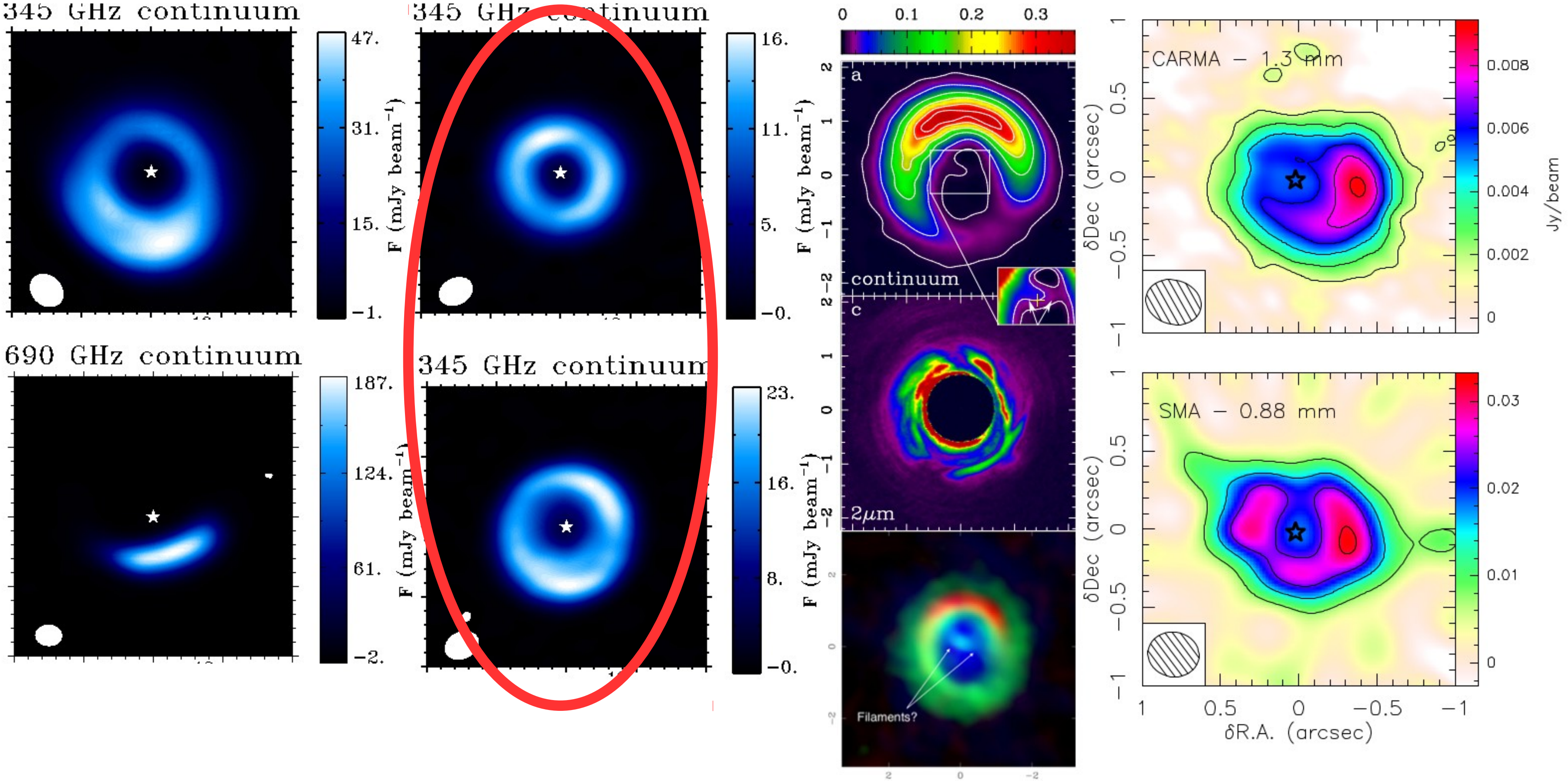
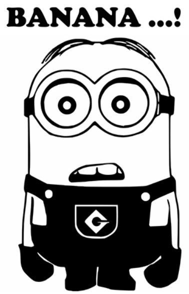
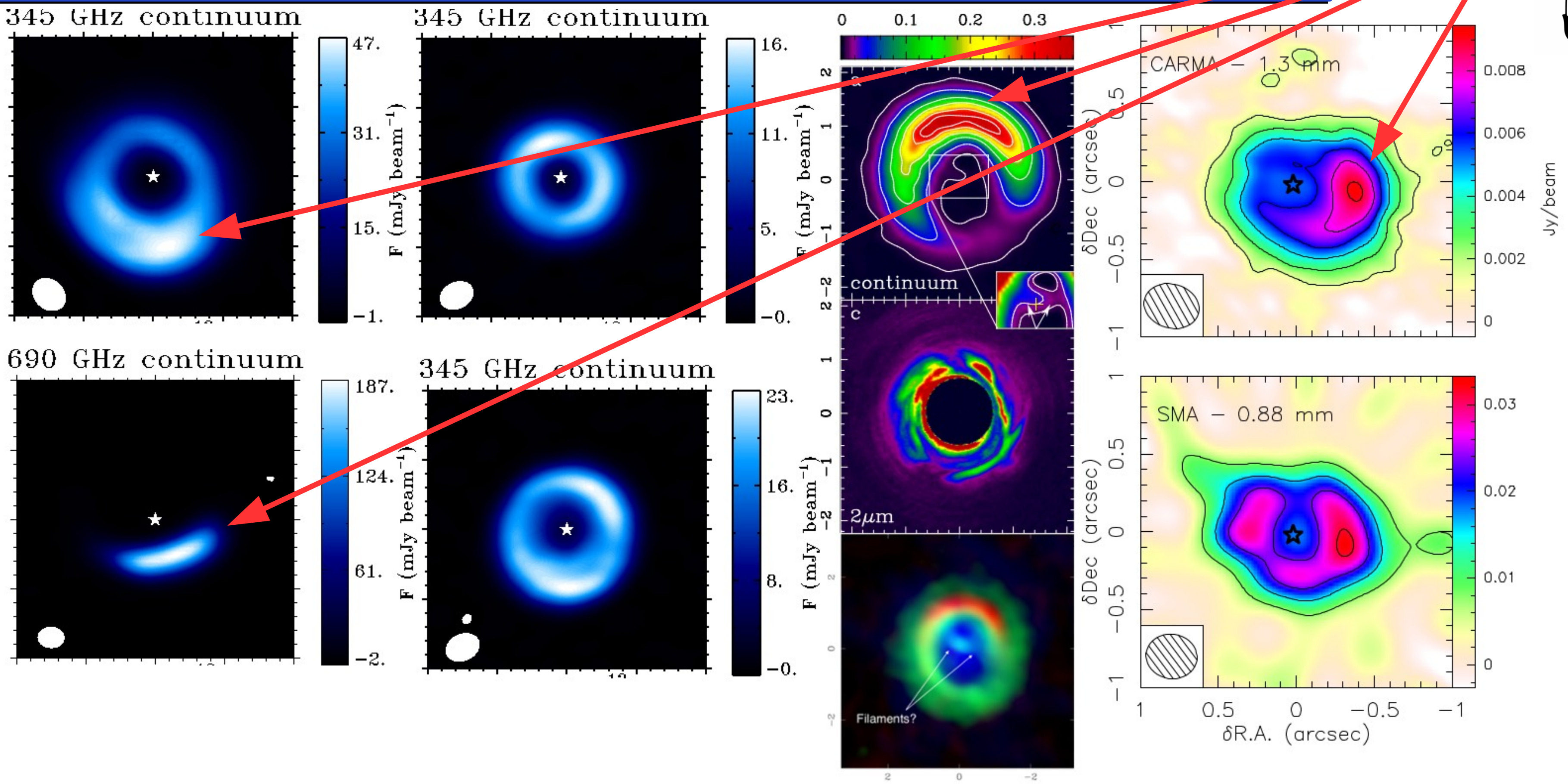


Asymmetries in transitional discs

Motivation





Asymmetries in transitional discs

Motivation

- Transitional discs: young stars that are dispersing their protoplanetary disc.
- They appear as discs with a cavity in the central region.
- Recent ALMA (**A**tacama **L**arge **M**illimeter **A**rray) images showed asymmetric overdense structures in transition discs.
- Structures explained as RWI (**R**ossby **W**ave **I**nstability), triggered in regions of low viscosity (deadzones) or by a planet. Fundamental requirement: unphysically low viscosities.
- What if a brown-dwarf instead of a planet causes the formation of the overdense lump?

Asymmetries in transition discs:
Workflow

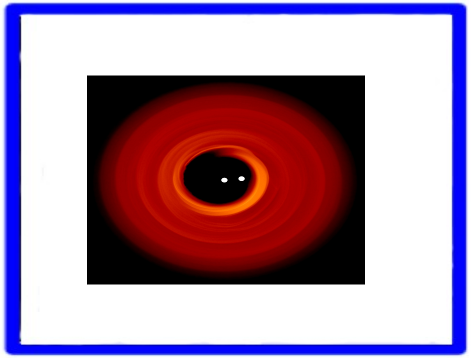
Dust model:
chemical composition,
porosity and shape

dust opacities

Thermal noise:
receivers, atmosphere

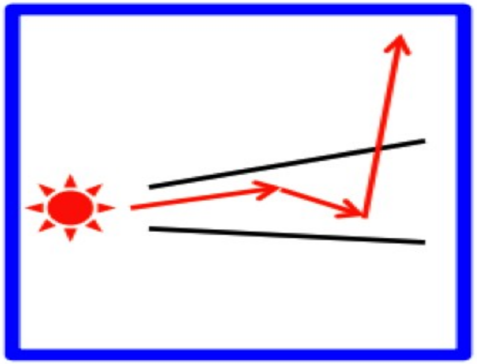
signal
corruption/convolution

Step I



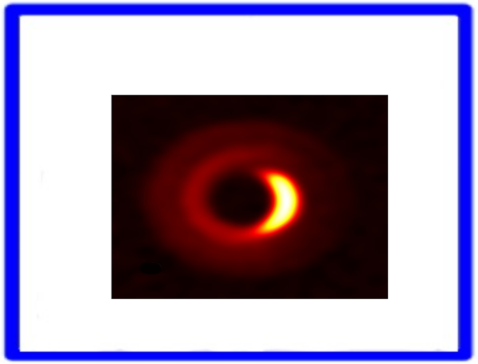
dust/gas hydrodynamics
simulations

Step II



3D RT simulations:
Full resolution images at
(sub-)mm wavelengths

Step III



ALMA simulated
observation

Asymmetries in transitional discs
Numerical simulations

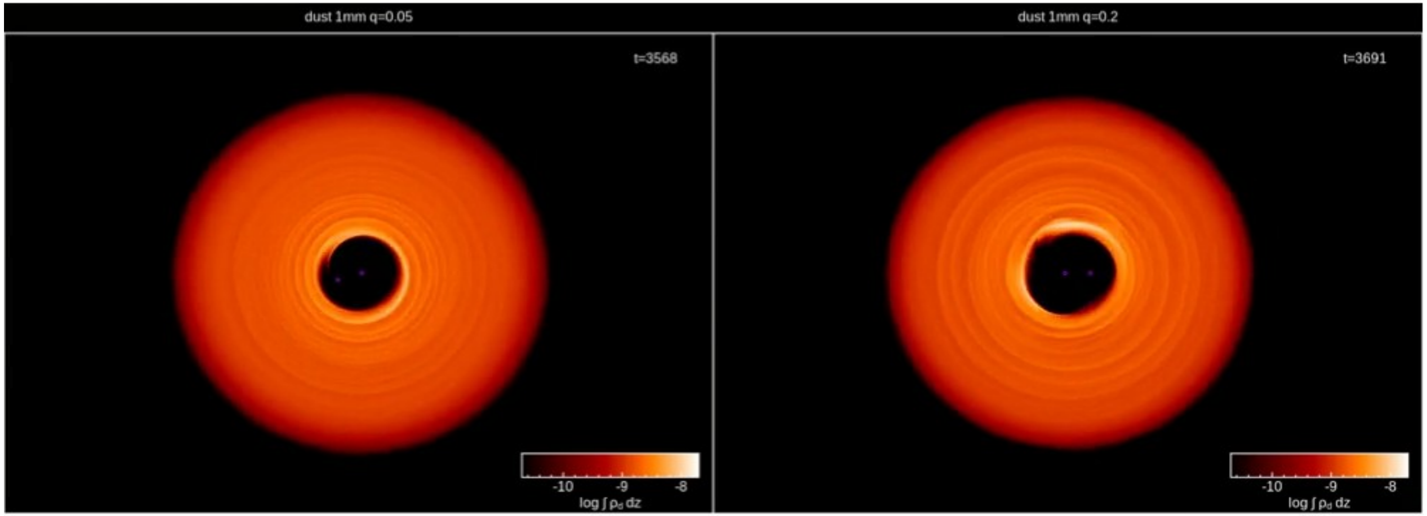
- Gas and dust numerical simulations (step 1)
- Four different mass ratios q={0.01,0.05,0.1,0.2}

Asymmetries in transitional discs
Numerical simulations

- Gas and dust numerical simulations (step 1)
- Four different mass ratios q={0.01,0.05,0.1,0.2}

q=0.05

q=0.20



Asymmetries in transitional discs
Numerical simulatic

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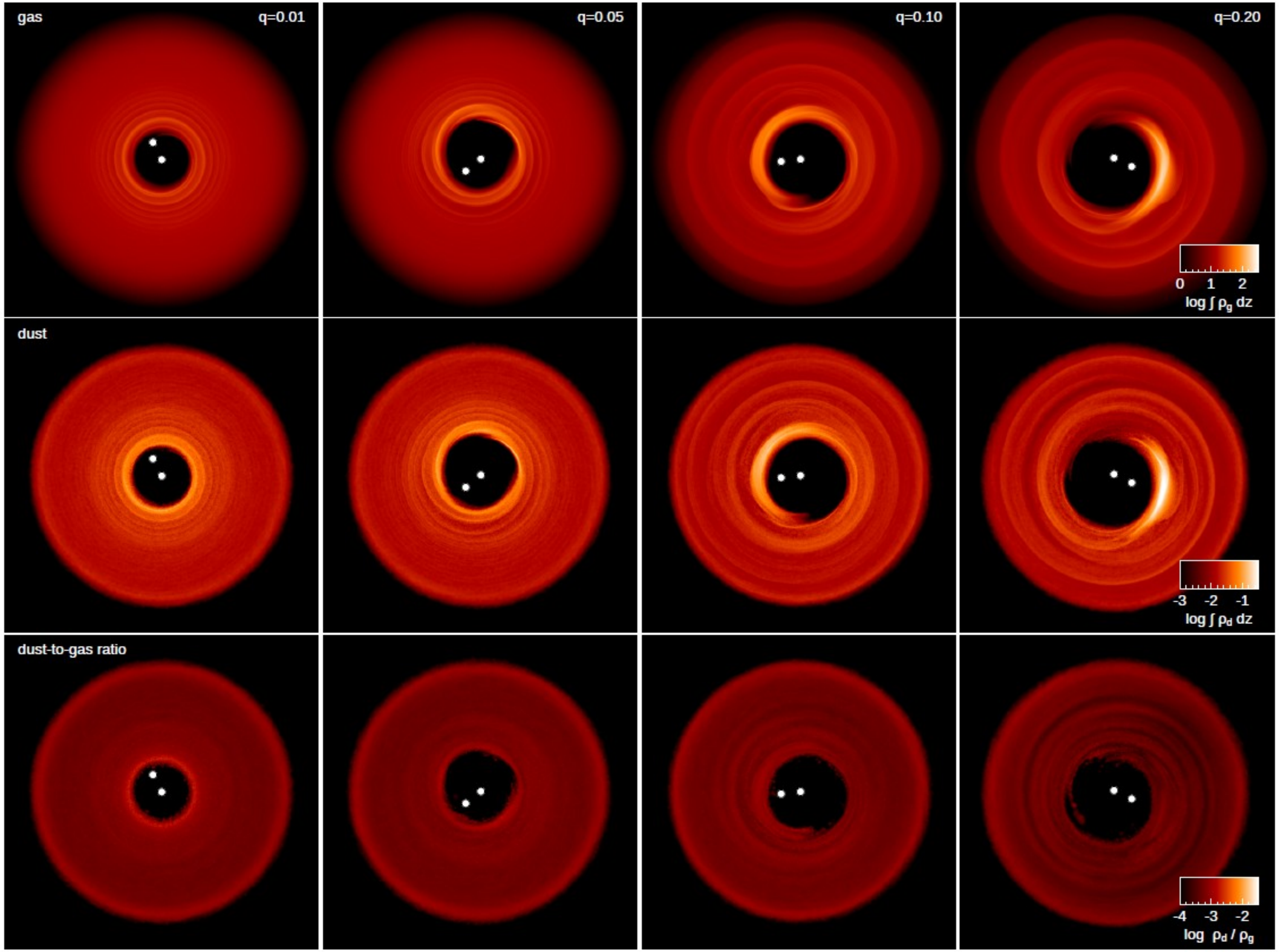


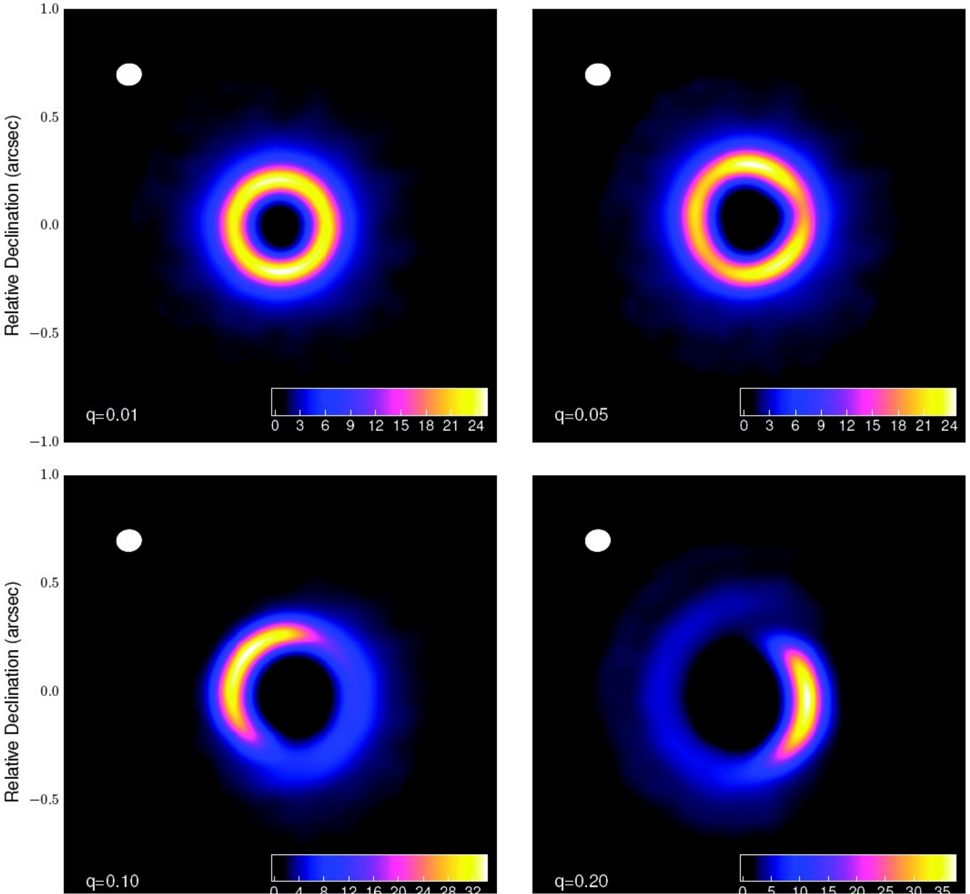
Asymmetries in transitional discs
Numerical simulations & Results

- Gas and dust numerical simulations (Step 1)
- Four different mass ratios q={0.01,0.05,0.1,0.2}
- Apply radiative transfer, to find dust temperature from star radiation (step 2)

Asymmetries in transitional discs
Numerical simulations & Results

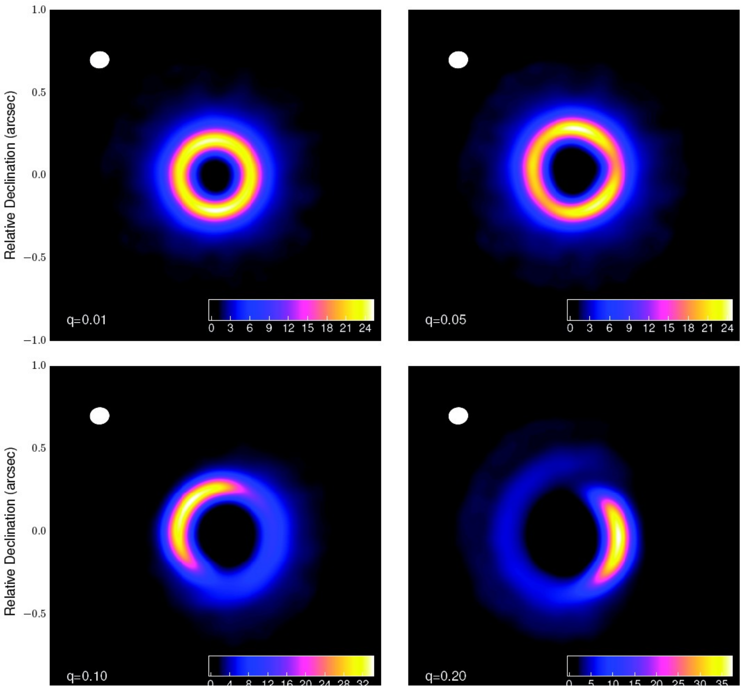
- Gas and dust numerical simulations
- Four different mass ratios q={0.01,(
- Apply radiative transfer, to find dust

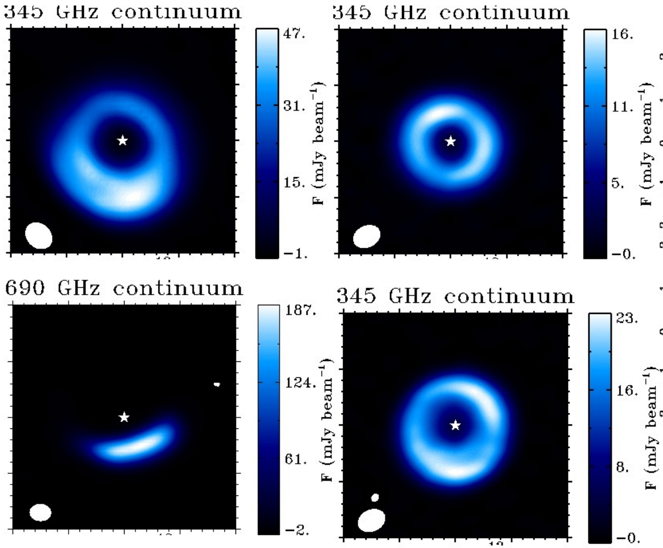
- We produce mock ALMA images starting from the output of radiative transfer (step 3)

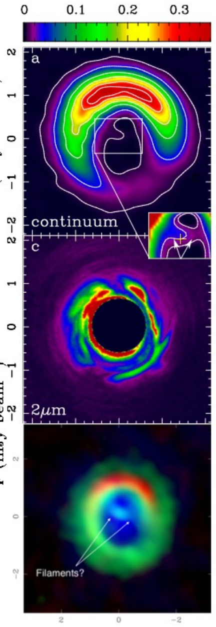


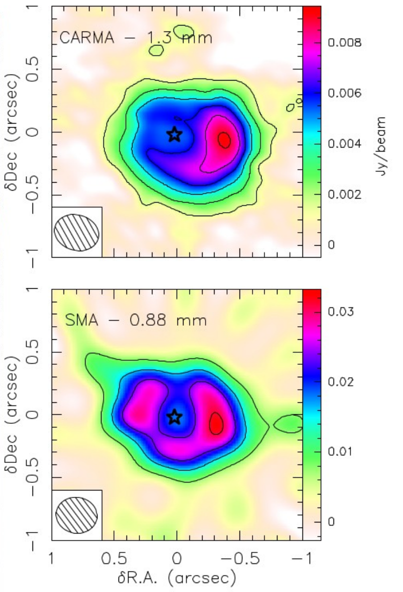
Asymmetries in transitional discs
Implications

- Similarity is quite impressive, might be the mechanism we are looking for?







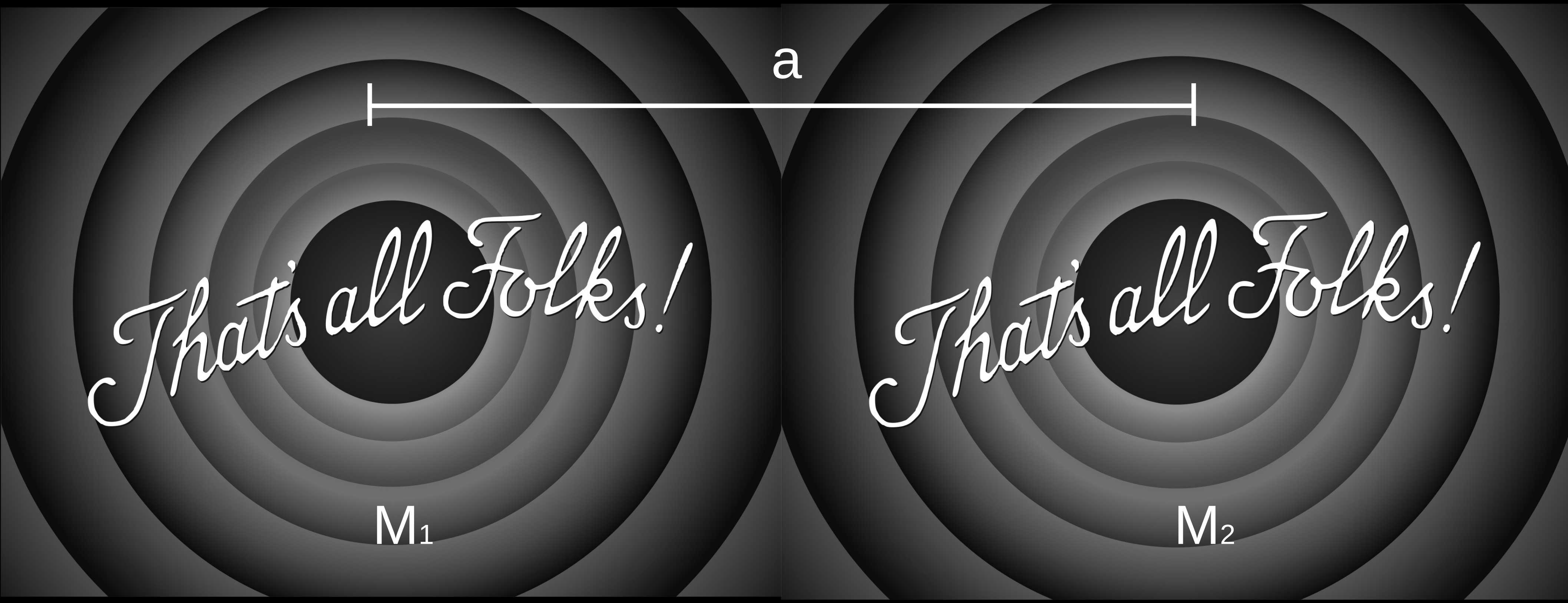


Conclusions
(& Take home messages)

- Accretion disc theory is well developed for single central objects
- The secondary object introduce an additional torque on the disc, the disc exert a back-reaction on the planet. The coupled evolution is far from trivial
- The approach to the subject can both start from observations both be more speculative in order to supply lack of them with possible observables to look for (variability, intensity, spectra...).
- Despite important progresses in the field, many aspects of dynamics of circumbinary discs still remain poorly understood.
- Numerical simulations are an important tool to investigate these systems

References (and future projects)

- E. Ragusa G. Lodato & D. J. Price MNRAS, Volume 460, Issue 2, p.1243-1253 (2016)
- E. Ragusa, G. Dipierro, G. Lodato, G. Laibe & D. J. Price (2016), in press in MNRAS
- Studying the growth of planet eccentricity due to planet-disc interaction, in collaboration with the IoA (Institute of Astronomy) in Cambridge. (since May 2016)
- Develop an analytical formalism to describe mass accretion in circumbinary discs. (Stay tuned)
- Better understanding of the development of eccentric features, and in general of the coupled disc-planet eccentricity evolution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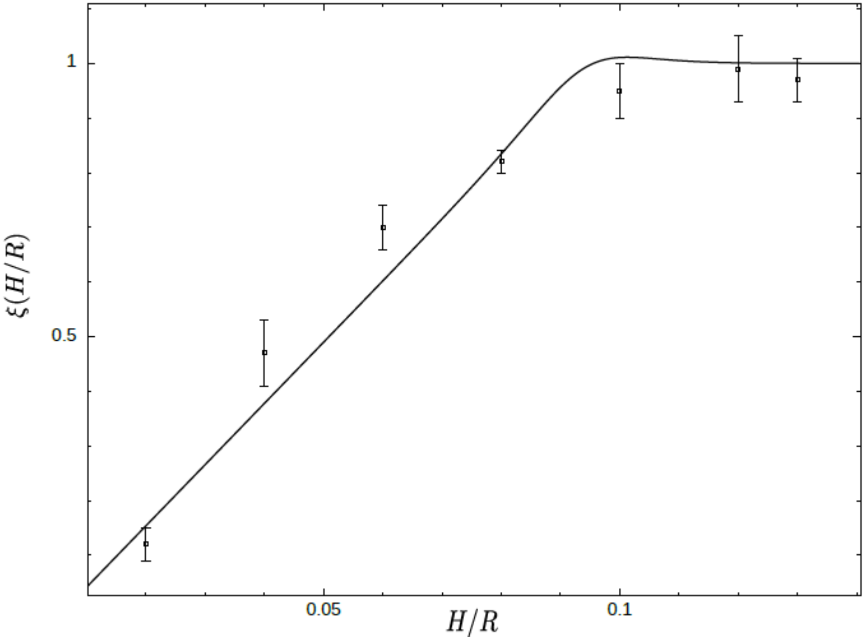
That's all Folks!
That's all Folks!
M1
M2

Mass accretion in SMBHBs:
Results

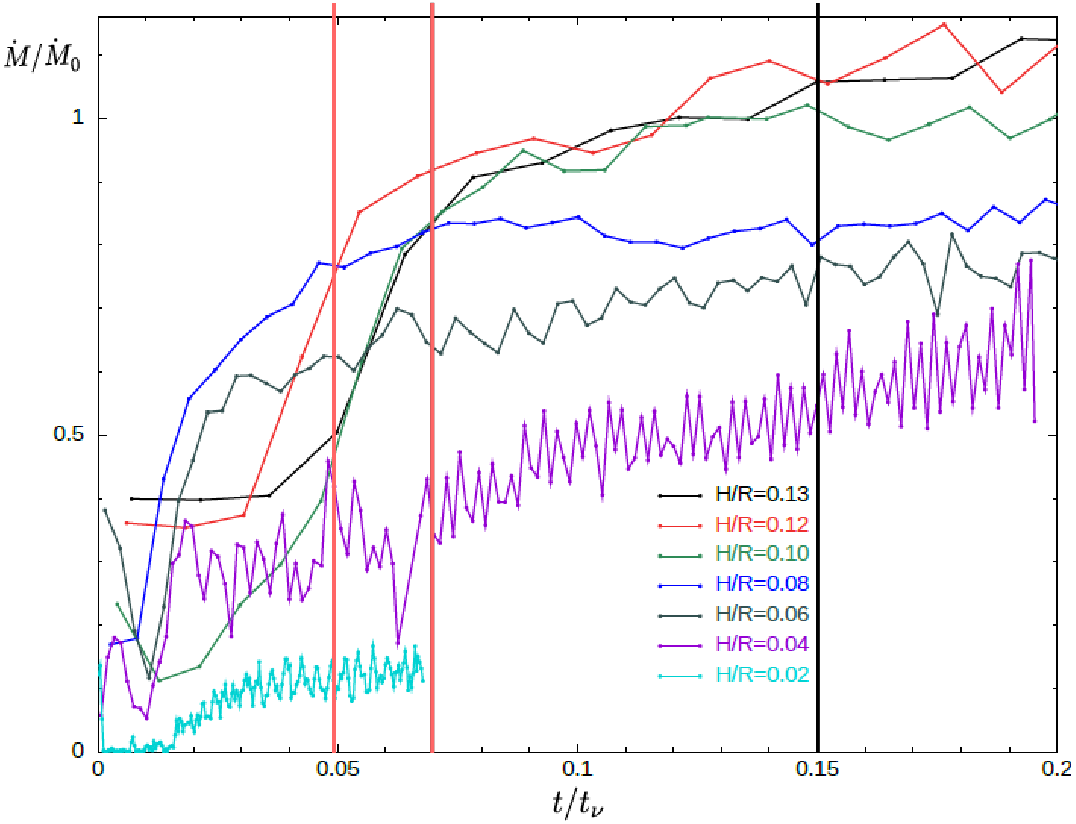


- Accretion rate for q=1, α=0.1 is given by:

$$\dot{M} = \xi(H/R)\dot{M}_0;\ \xi \propto 10\frac{H}{R}$$

- For H/R~0.1, q=1, α=0.1 is not not in agreement with results by Farris et al. (2014) and Shi & Krolik (2015) $(\dot{M}/\dot{M}_0 \sim 1.6 - 1.4)$
- Good agreement with D'Orazio et al. (2012) $\dot{M}/\dot{M}_0 \sim 1$

Accretion of gas in SMBHBs
Results



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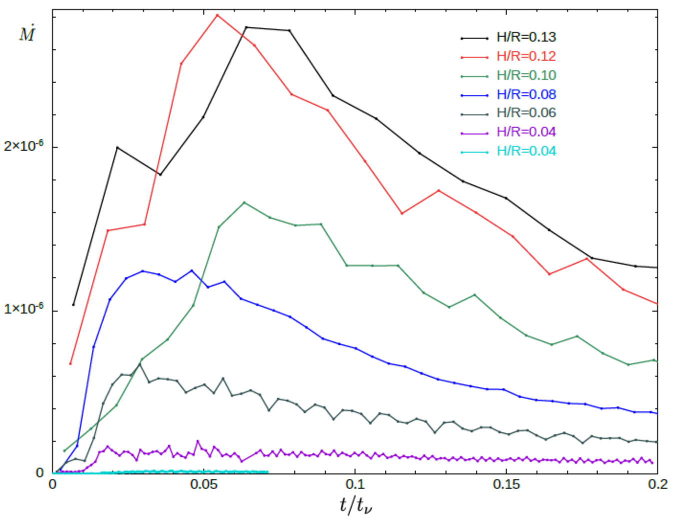
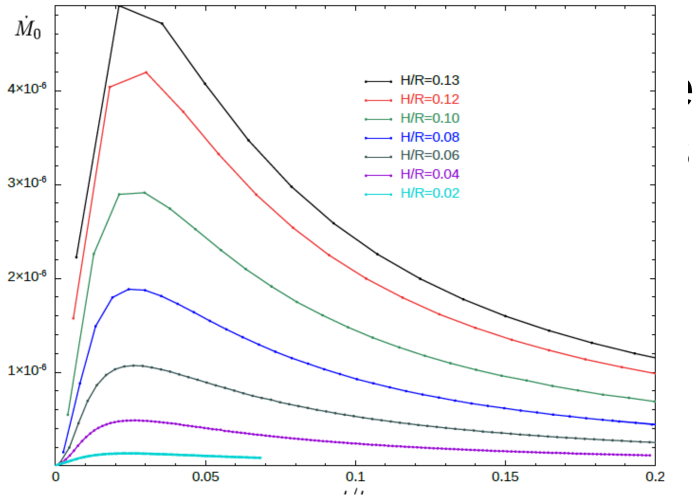
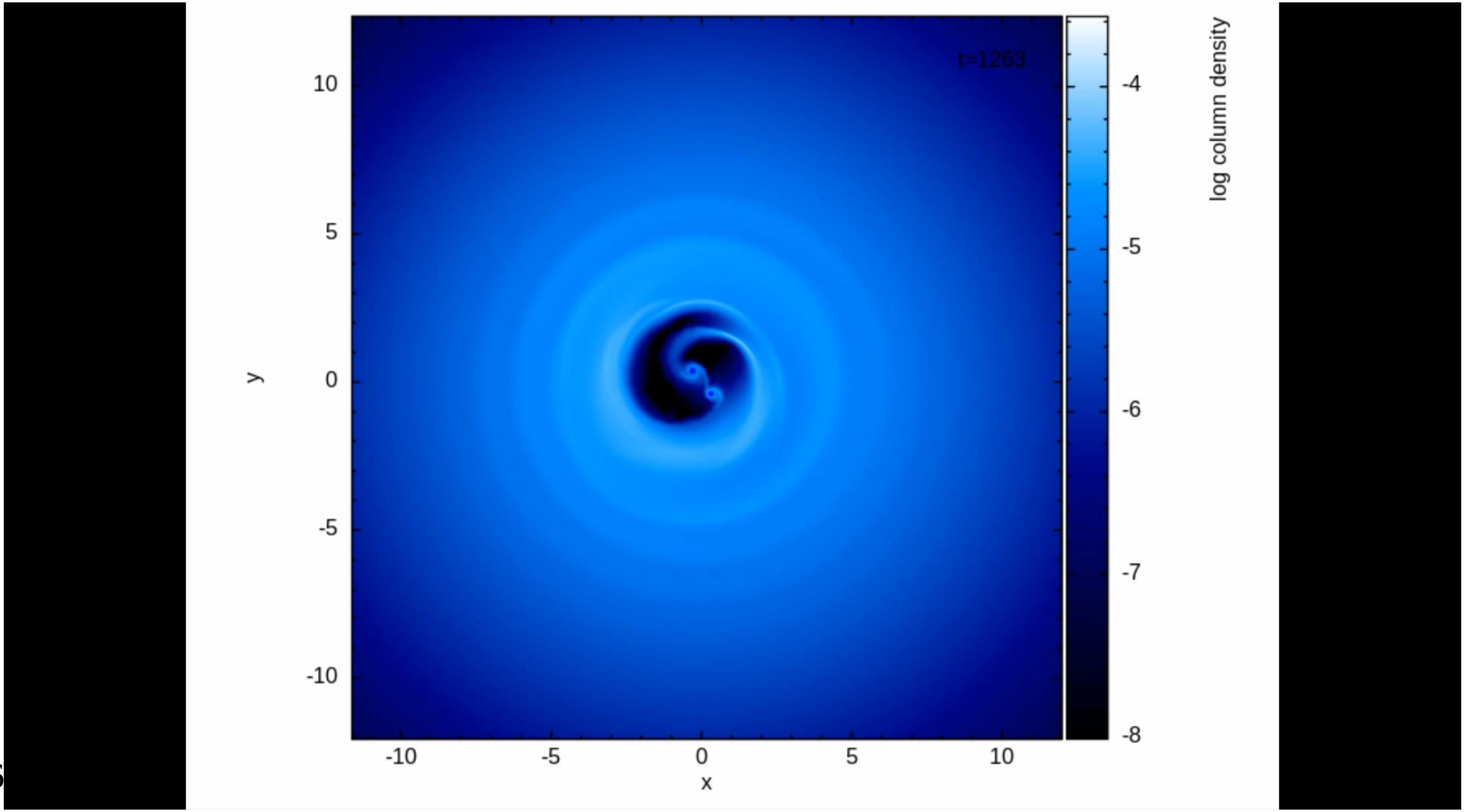




Accretion of gas in SMBHBs

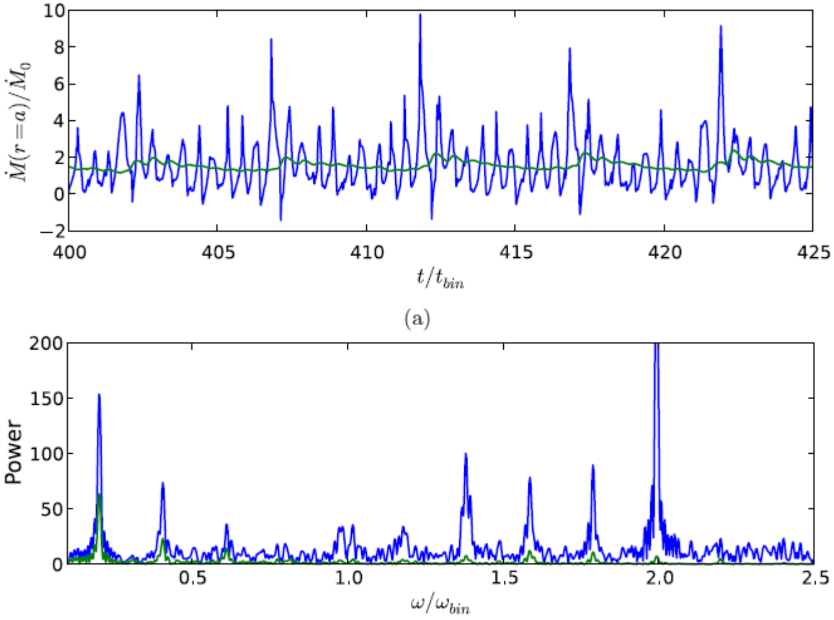
Results: Reproducing Farris et al., (2014)



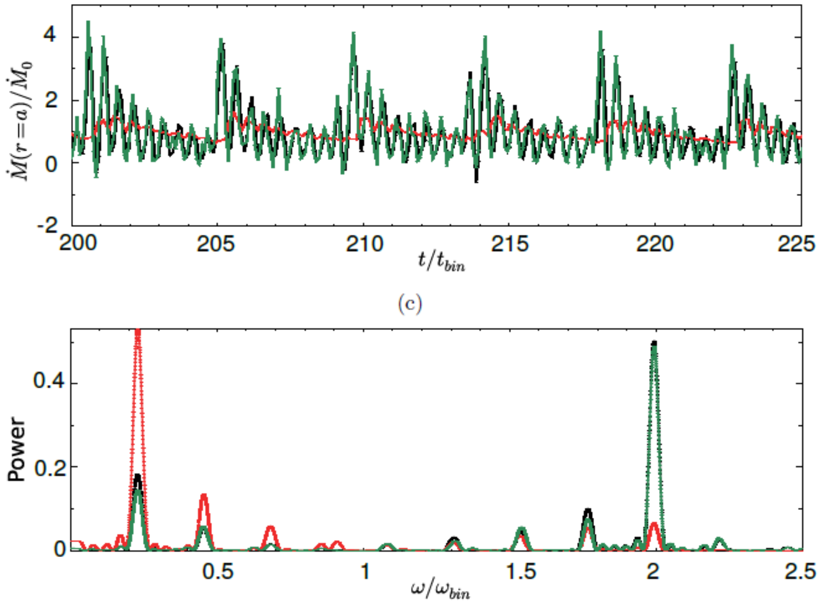
Accretion of gas in SMBHBs
Results: Reproducing Farris et al., (2014)

- Accretion (top) and periodograms (bottom) at the edge of the cavity (blue left, green right) and onto the sinks (green left, red right) vs. time

Farris et al., (2014)



Ragusa et al., (2016)



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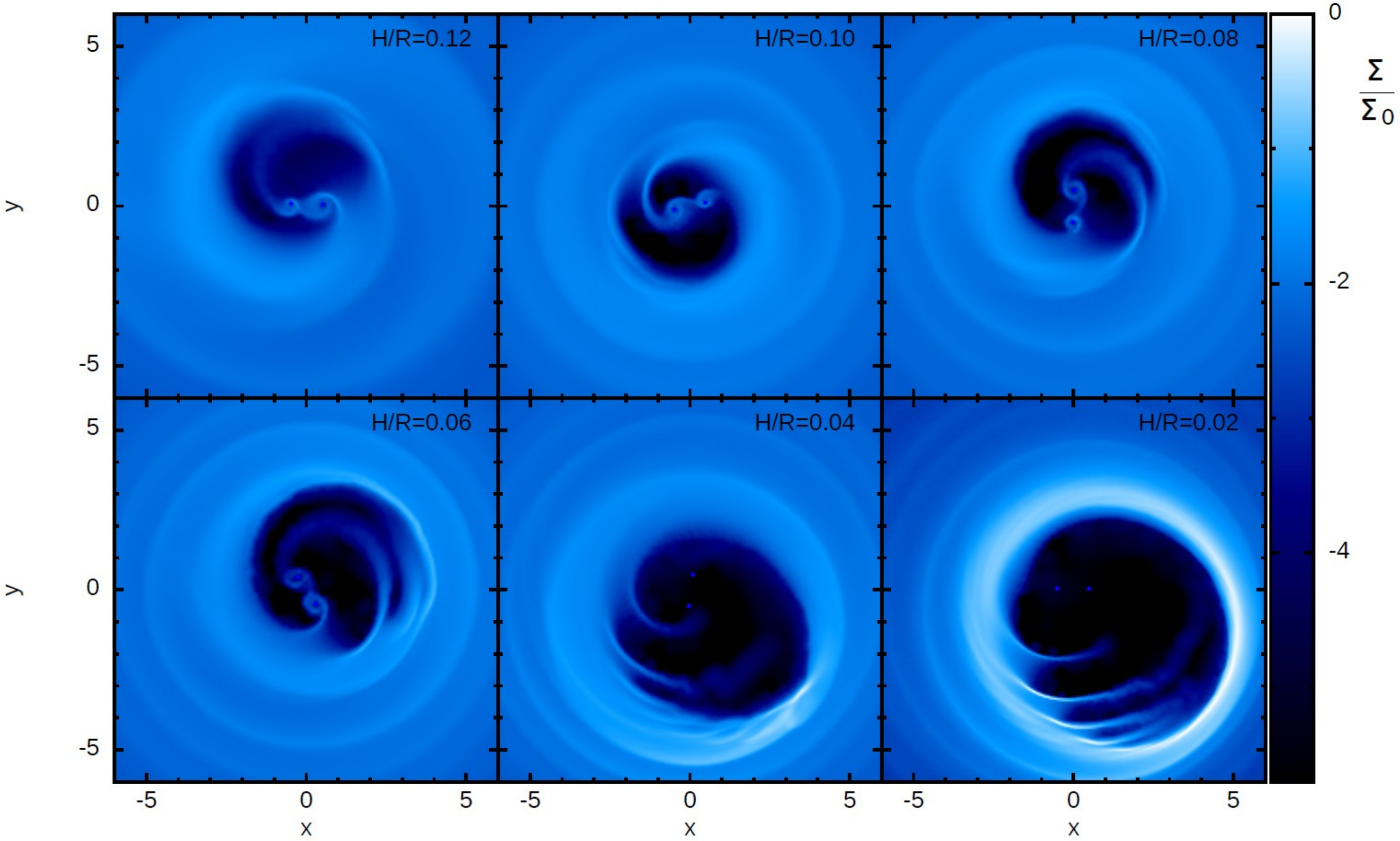
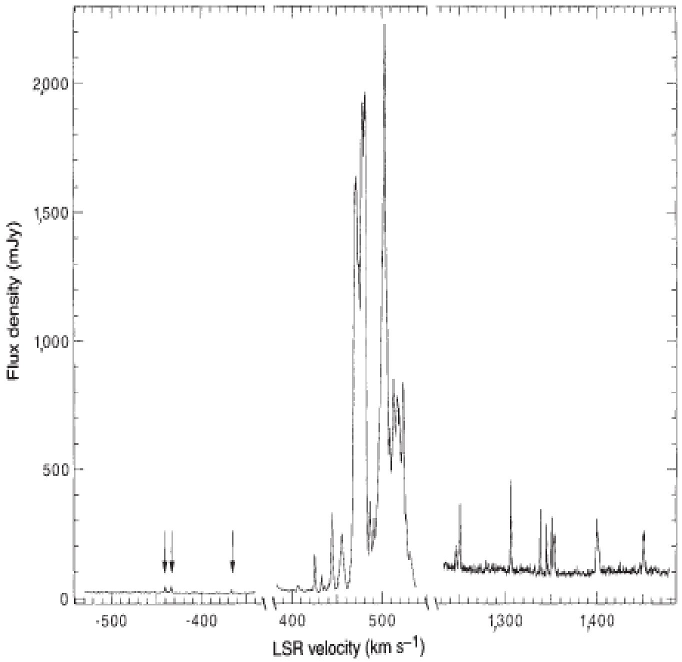
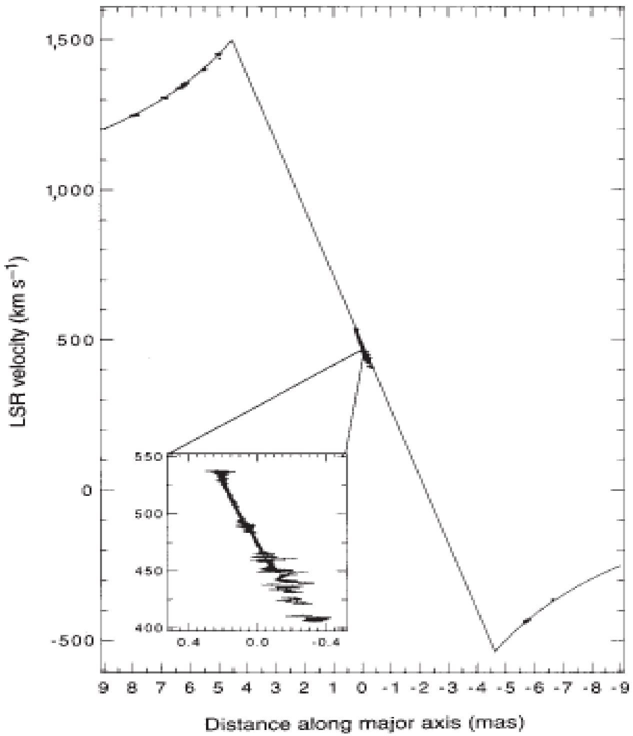
Accretion of gas in binary systems
Results

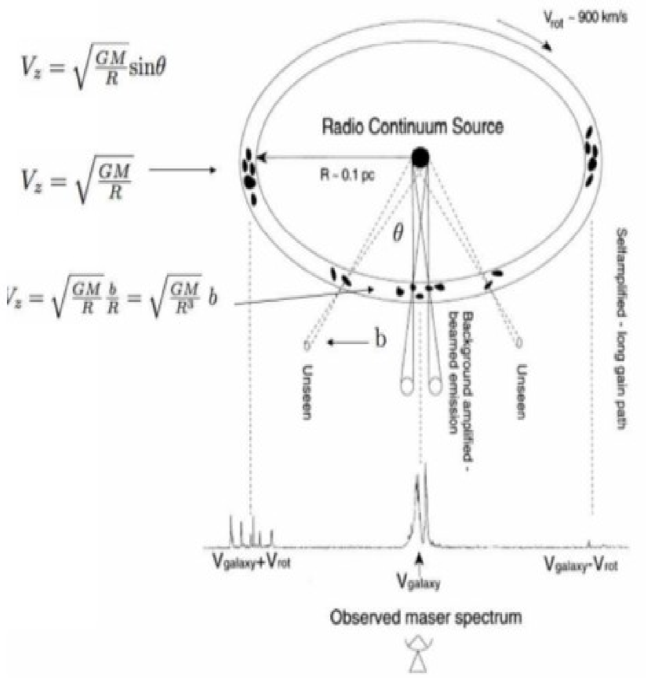


Introduction:
Accretion disc physics

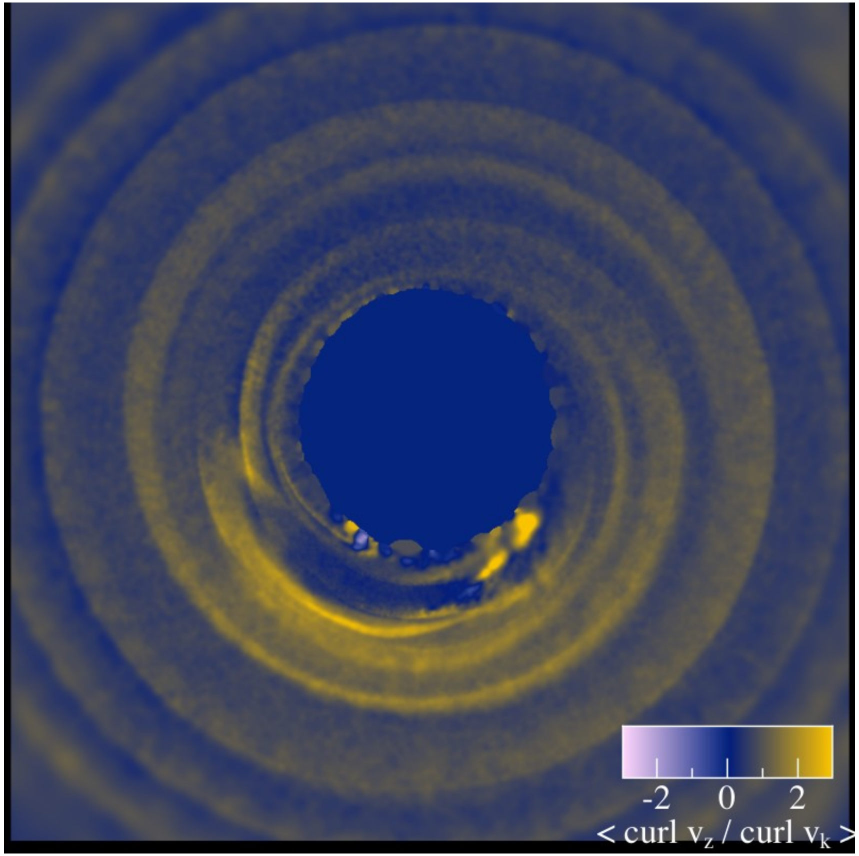
- Keplerian Motion of water maser in NGC4258







Vorticity q=0.2



$$\frac{\omega_z}{\omega_{\mathrm{K}}} = \frac{\left(\bar{\nabla} \times \bar{v}\right)_z}{\left(\bar{\nabla} \times \bar{v}_{\mathrm{K}}\right)_z}$$

$$\bar{v}_{\mathrm{K}} = \sqrt{\frac{GM_{\mathrm{tot}}}{R}}\,\hat{e}_\phi$$