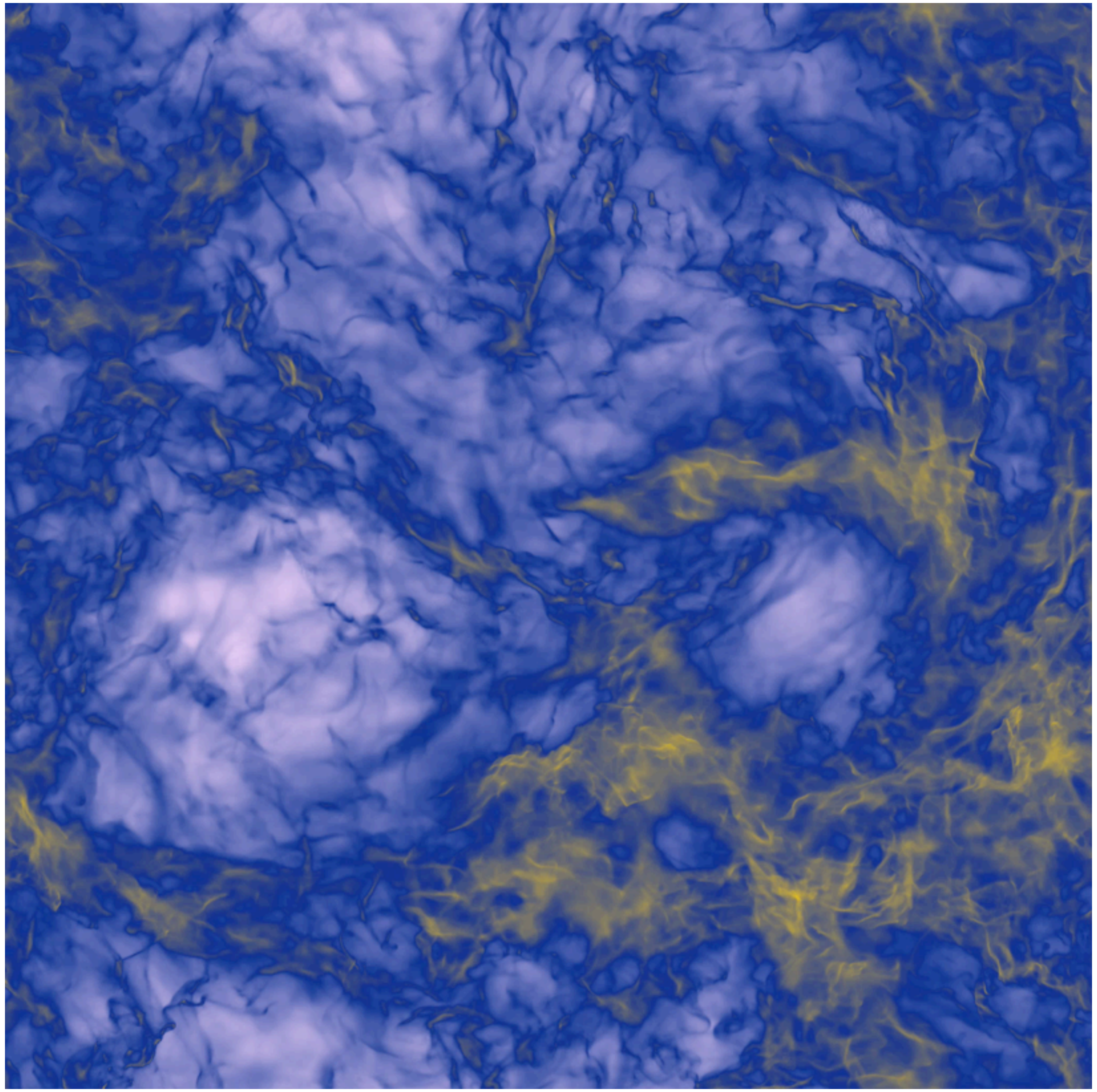
SPH methods for astrophysical fluid dynamics

Giuseppe Lodato - Università degli Studi di Milano

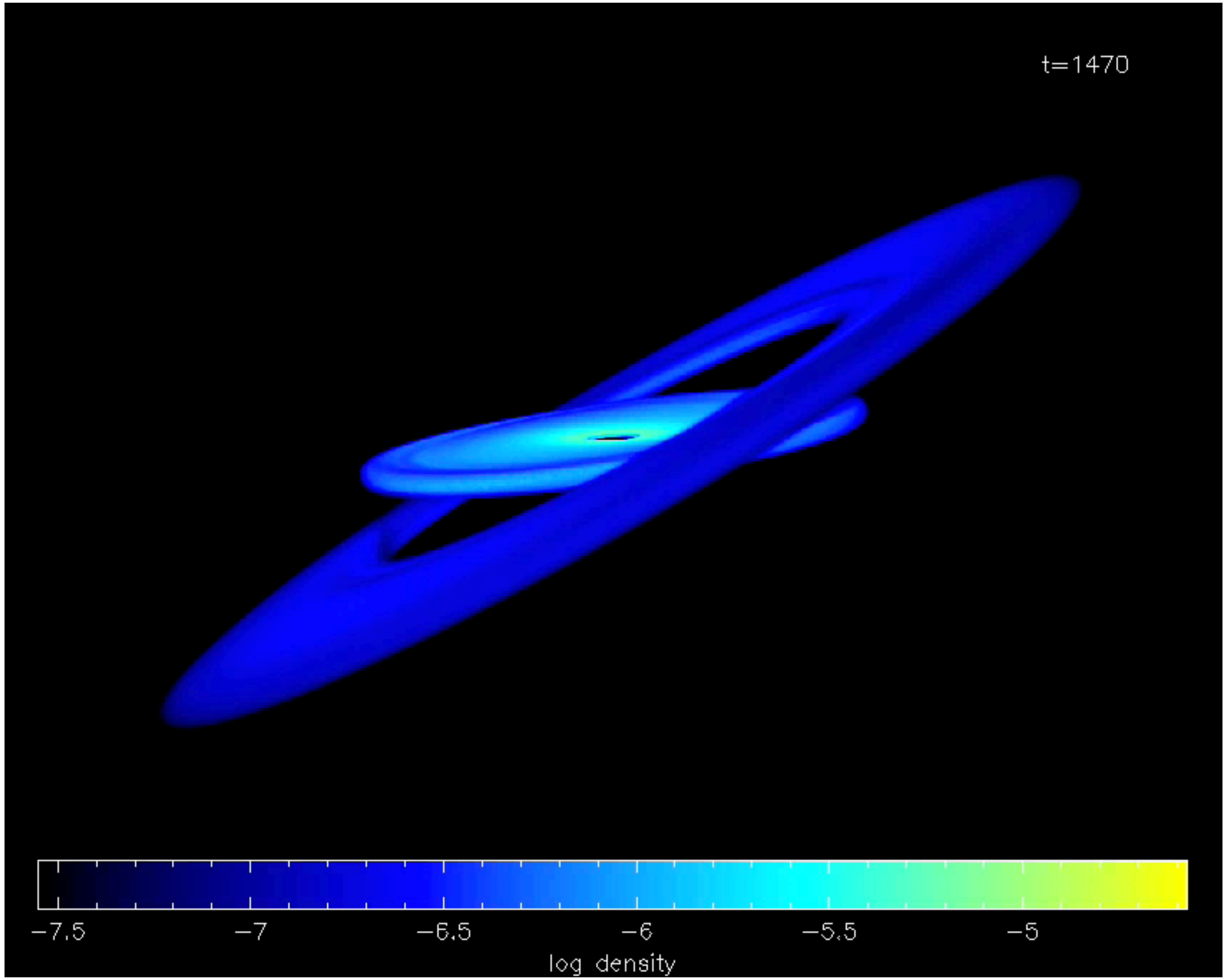
Gallery of SPH results



Supersonic turbulence in a box

(Price & Federrath 2010)

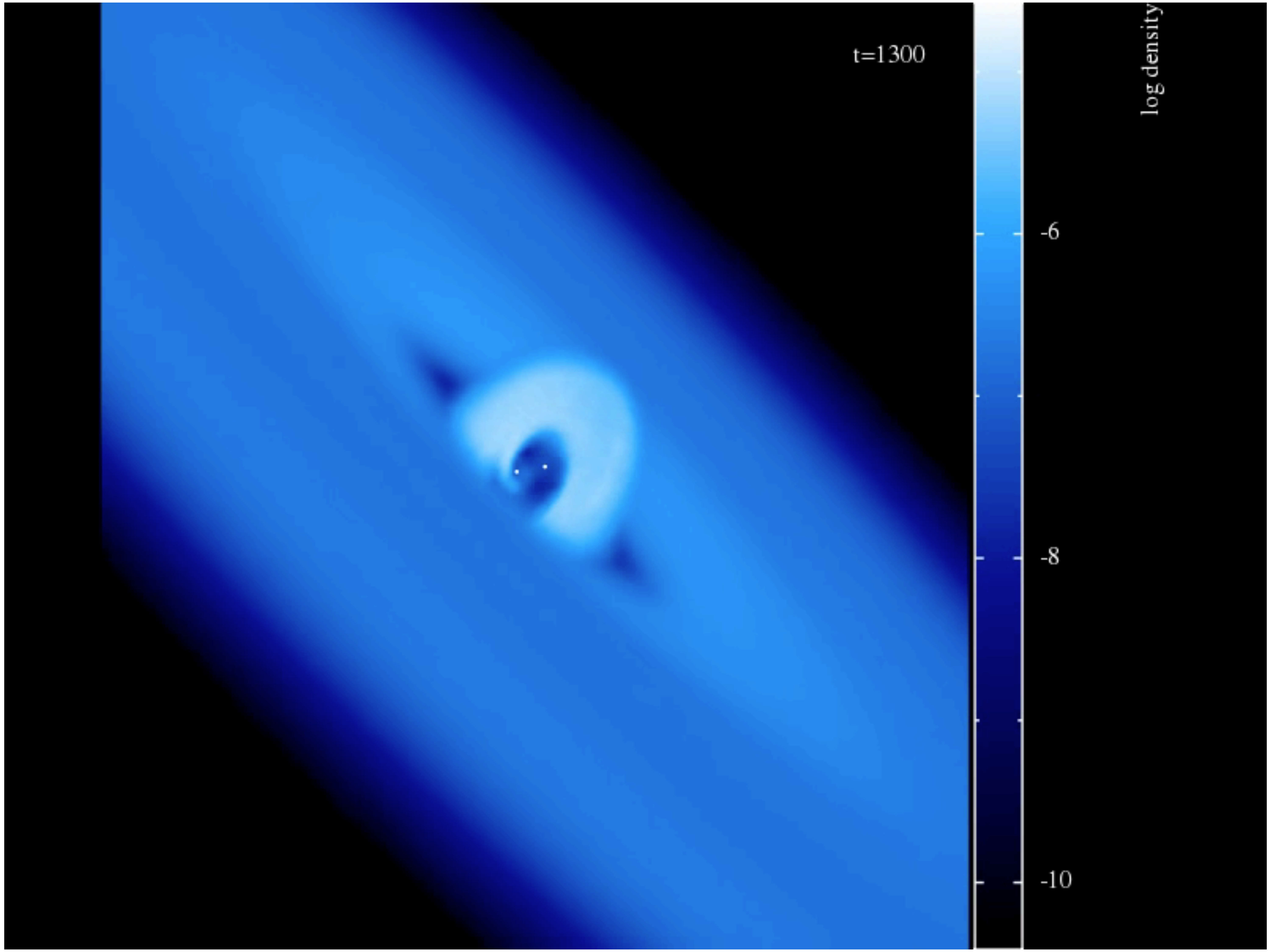
Gallery of SPH results



Disc breaks

Lodato & Price 2010

Gallery of SPH results

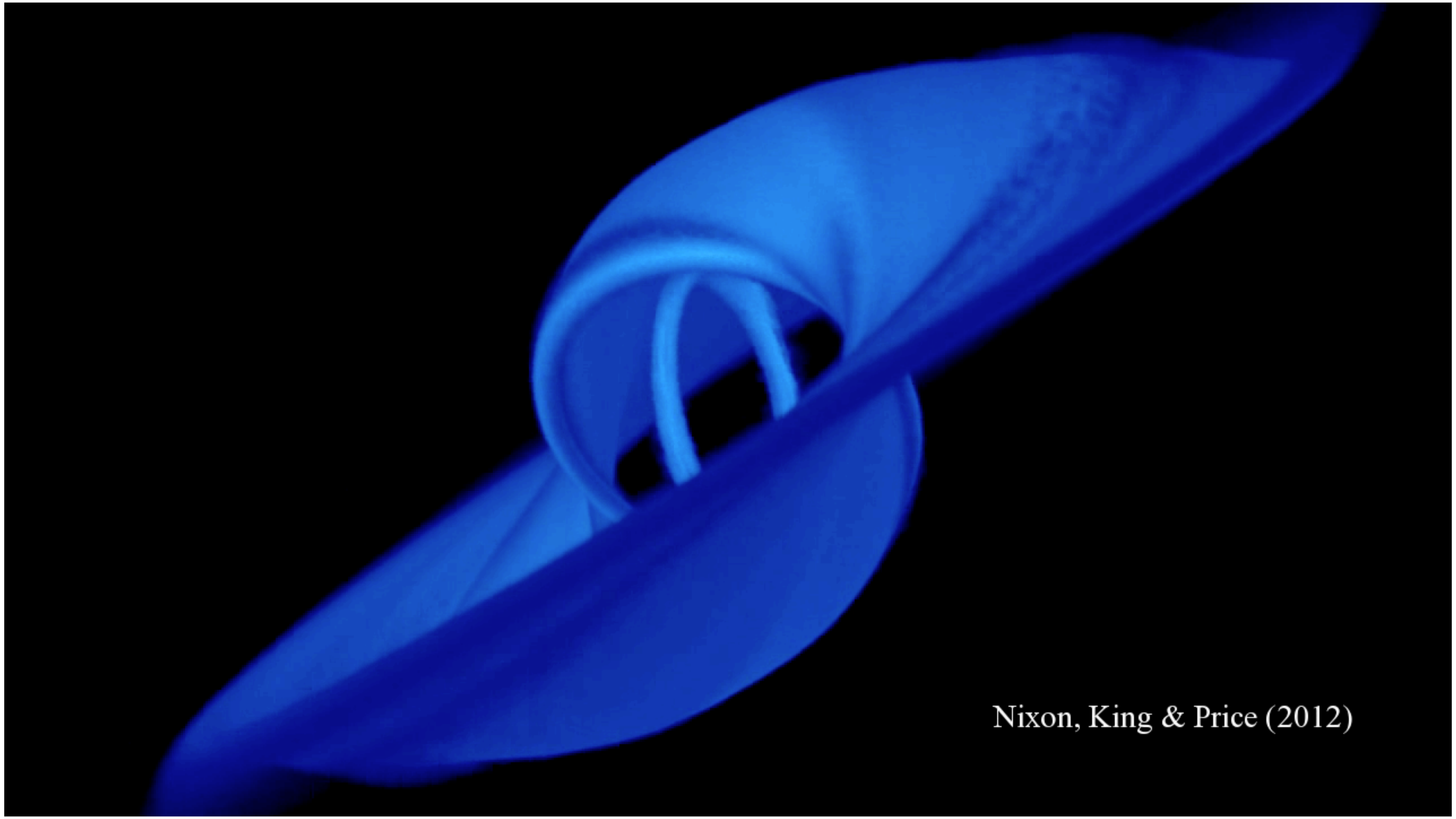


Disc breaks around binary stars

(Facchini, Lodato & Price 2013)

Gallery of SPH results

Lense-Thirring precession around spinning black holes

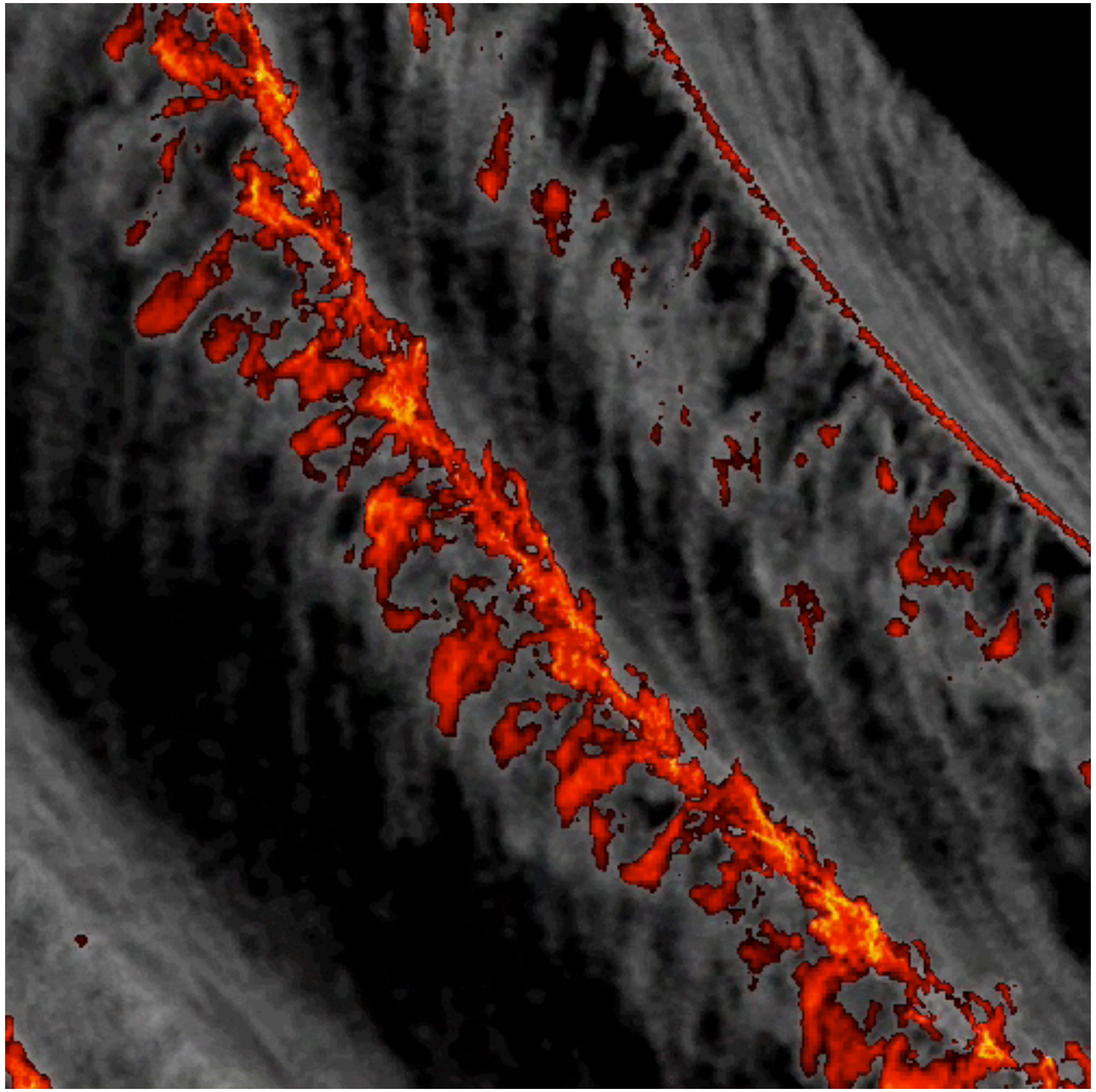


Disc breaks around black holes

(Nixon, King & Price (2012)

Gallery of SPH results

Two fluids simulations

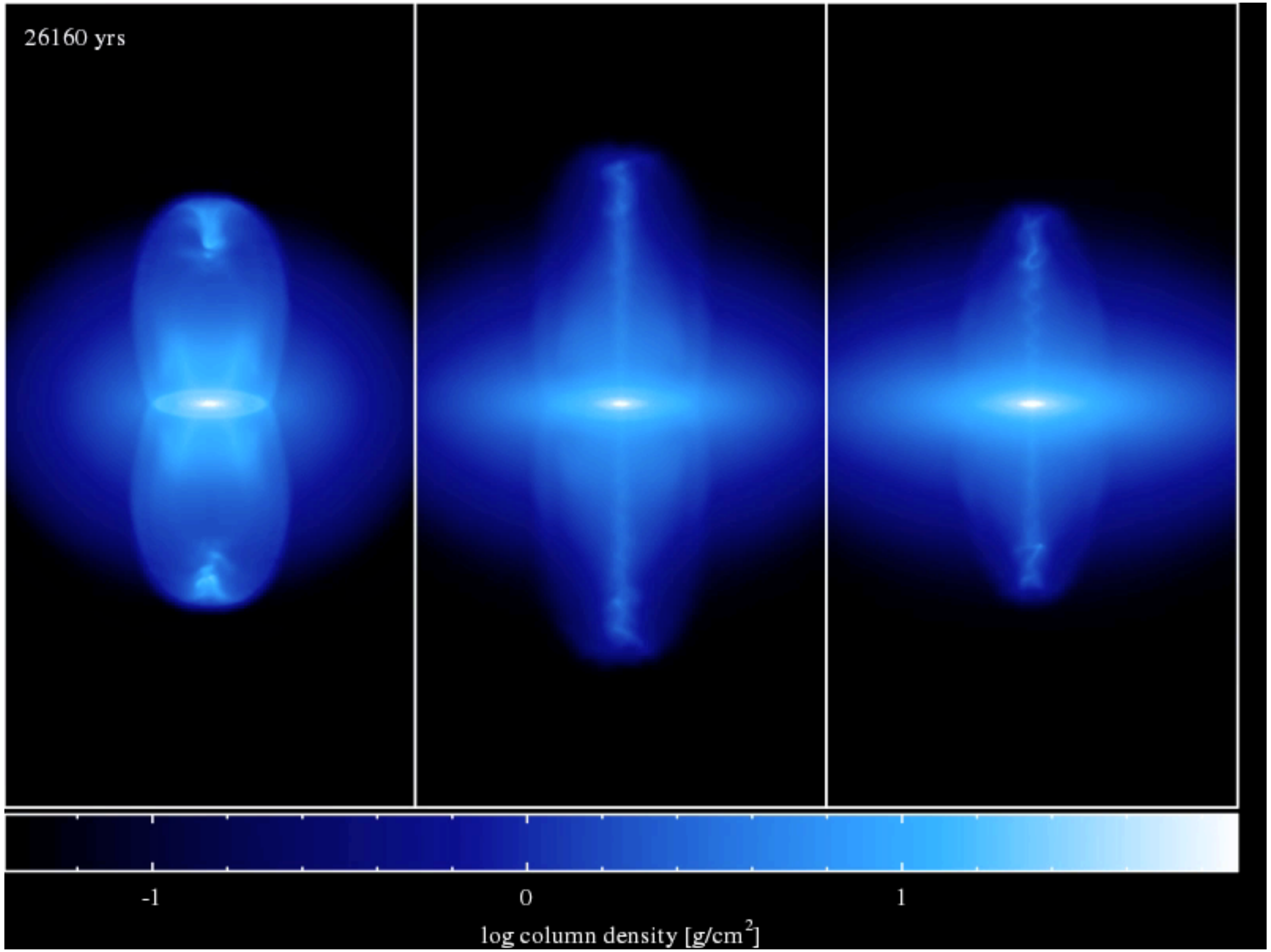


Molecular cloud formation in the galaxy

(Dobbs, Price, Pringle)

Gallery of SPH results

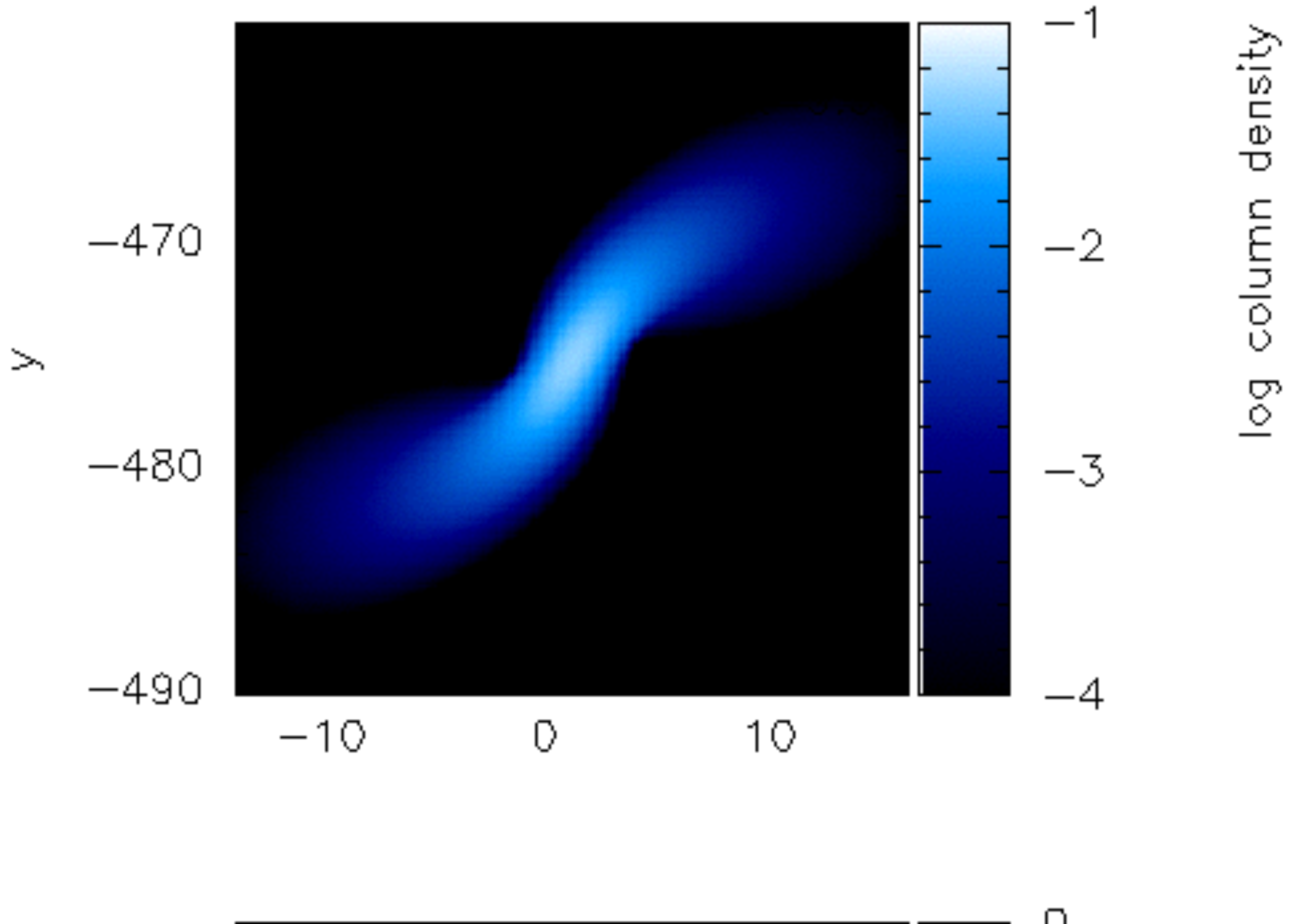
MHD included



Jet formation during star formation

(Price, Tricco, Bate, 2012)

Gallery of SPH results

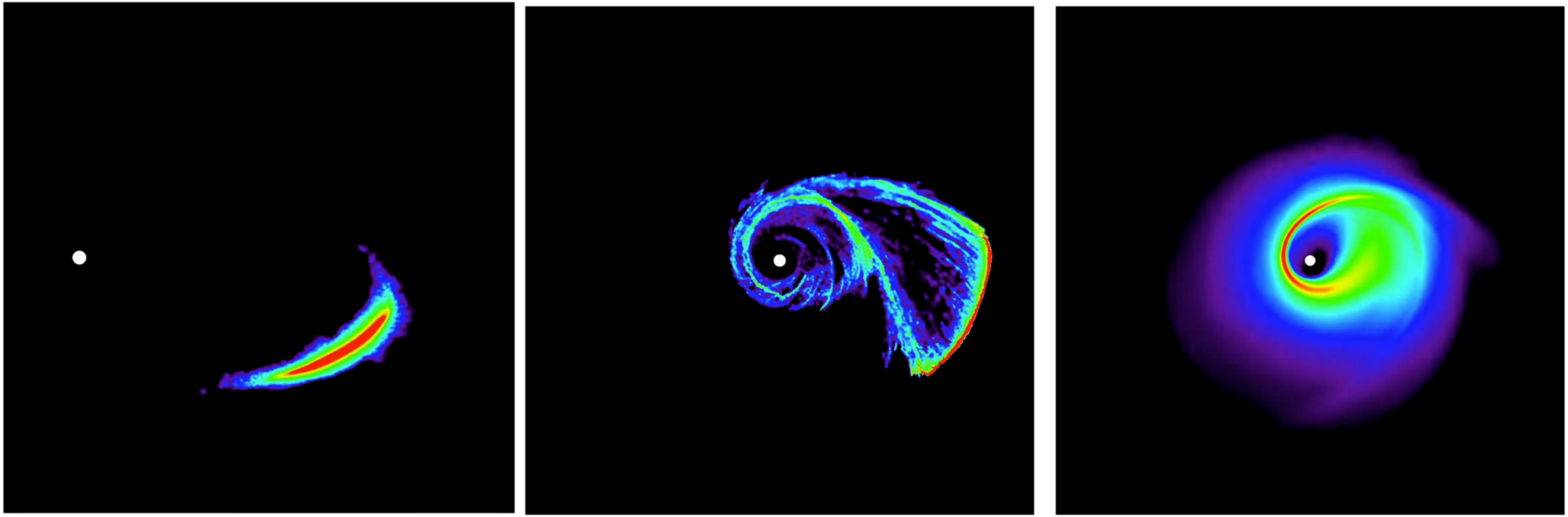


Tidal disruption of a star by a SMBH

(Lodato, King & Pringle 2009)

Gallery of SPH results

Einstein's precession in the potential

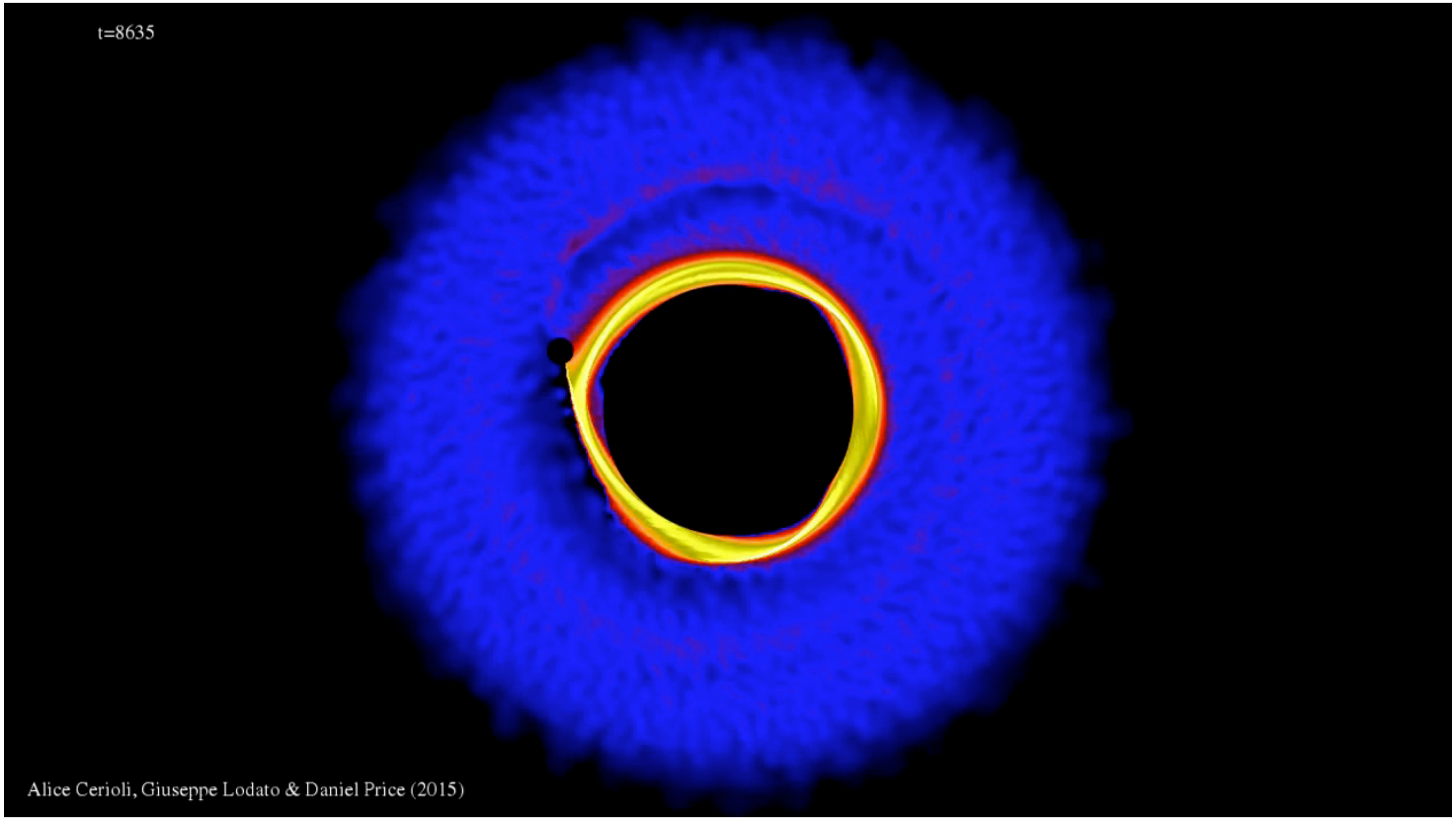


Tidal disruption of a star by a SMBH: disc formation

Bonnerot, Rossi, Lodato & Price (2016)

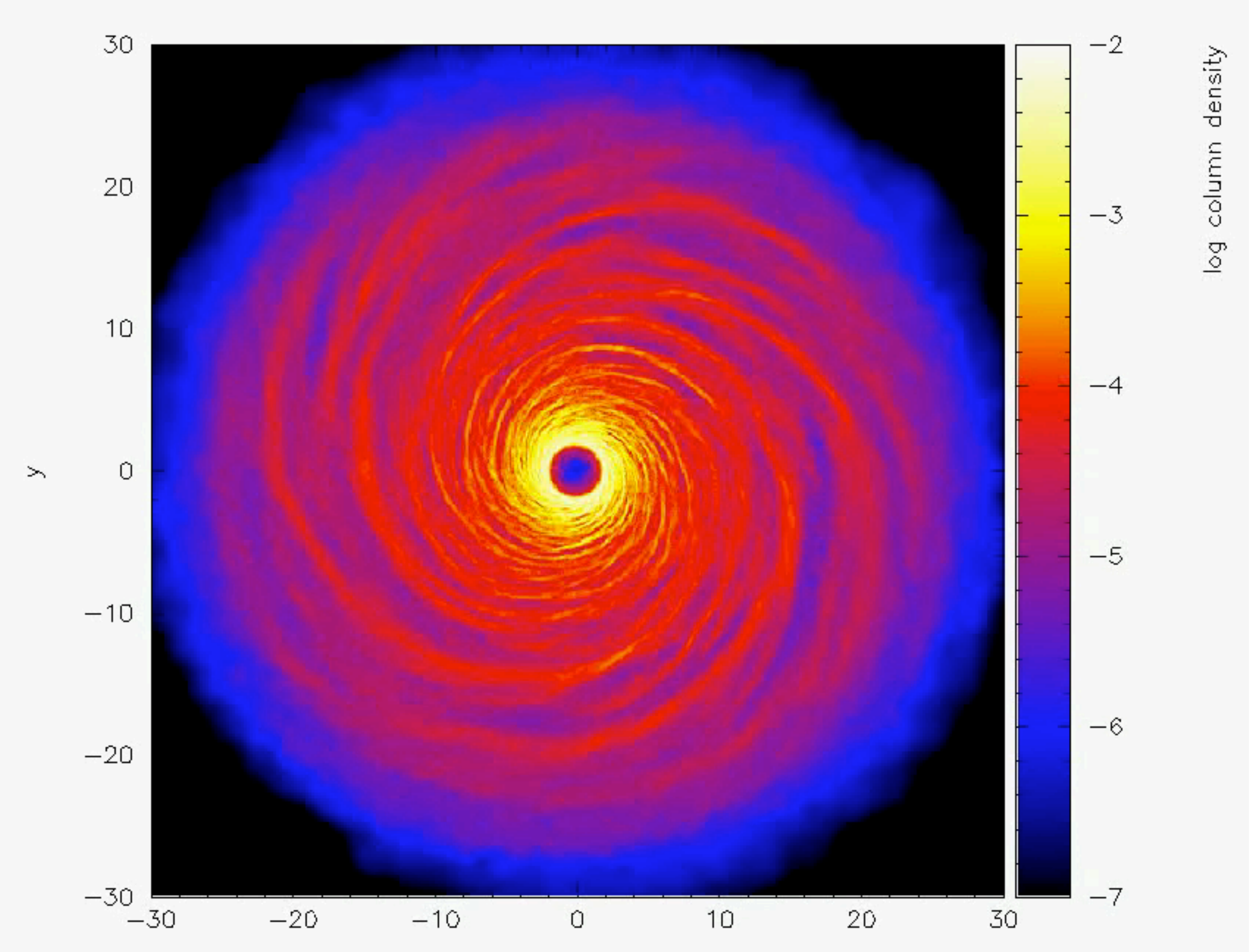
Gallery of SPH results

Gravitational wave induceddecay of the binary



Electromagnetic counterparts to gravitational waves
Cerioli, Lodato & Price (2016)

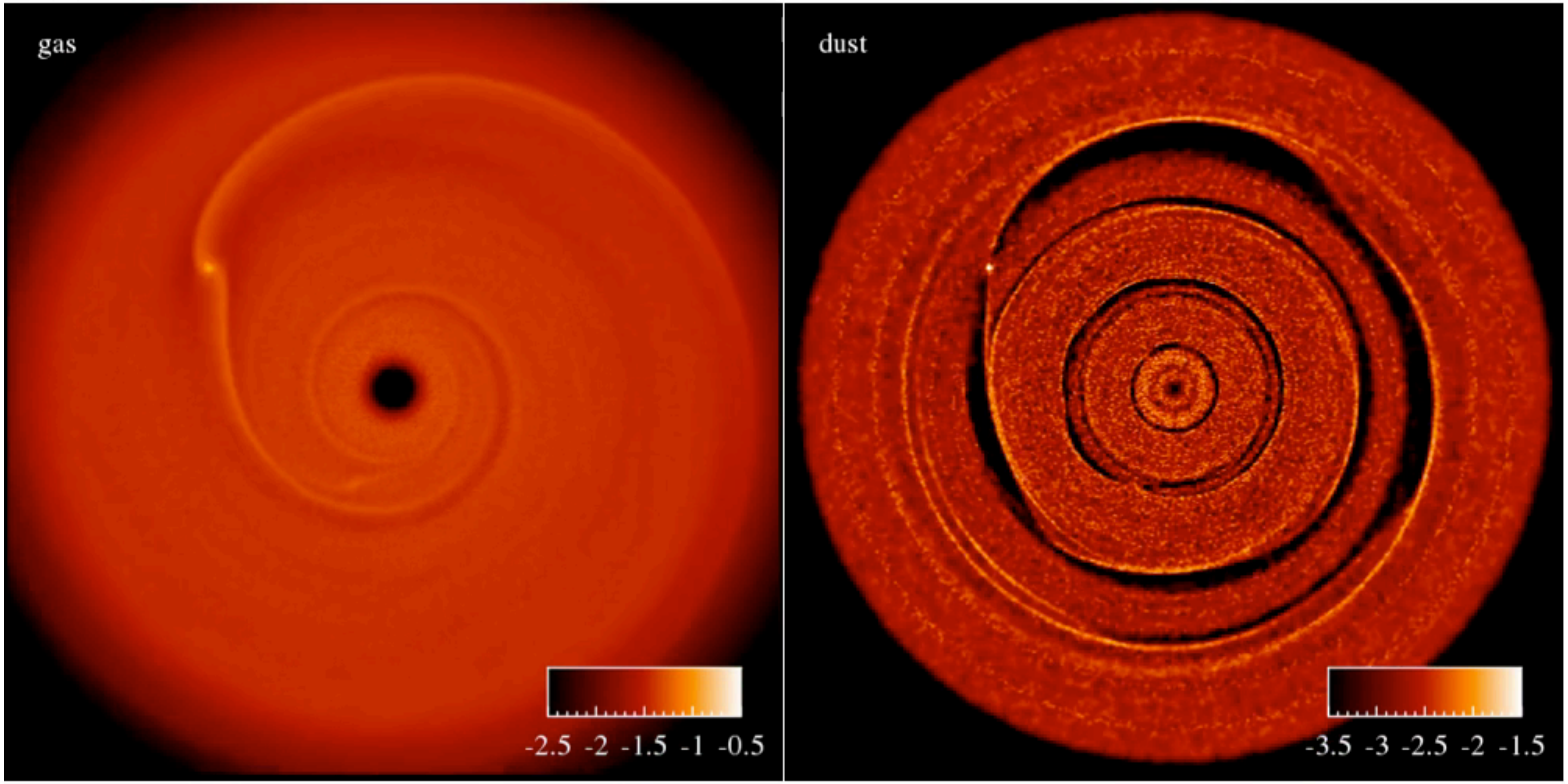
Gallery of SPH results



Self-gravitating accretion discs

Cossins, Lodato & Clarke (2009)

Gallery of SPH results



Coupled dust-gas dynamics in protostellar discs
Dipierro et al (2015)

Summary

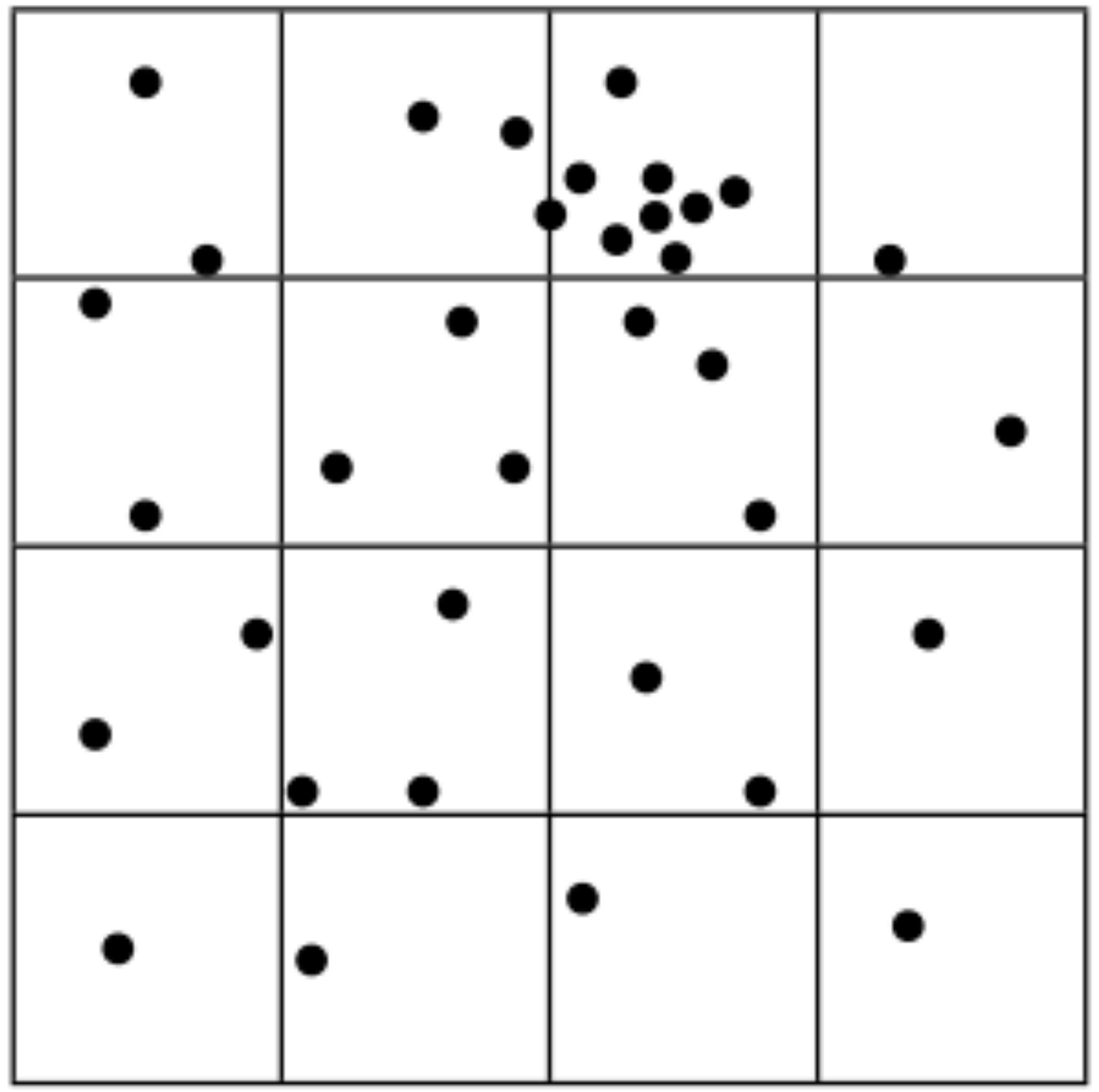
- **SPH basics**
- Advanced SPH
- A few applications to protostellar disc dynamics inthe ALMA era

Grid-based codes vs SPH

- Traditionally, numerical methods for hydrodynamics are based on **discretization on a spatial grid** -- inherently Eulerian
  - Very well developed techniques (high order, low dissipation,...) ✔
  - Easy to deal with boundary conditions ✔
  - The grid dictates a symmetry to the problem ✘
- Main idea for SPH: **discretization in mass** -- discrete fluid elements: inherently Lagrangian
  - Resolution follows density - easy to obtain large dynamical range ✔
  - Galilean invariance ✔
  - Difficult to handle shocks, difficult to include MHD, difficult to implement boundary conditions ✘

SPH basics

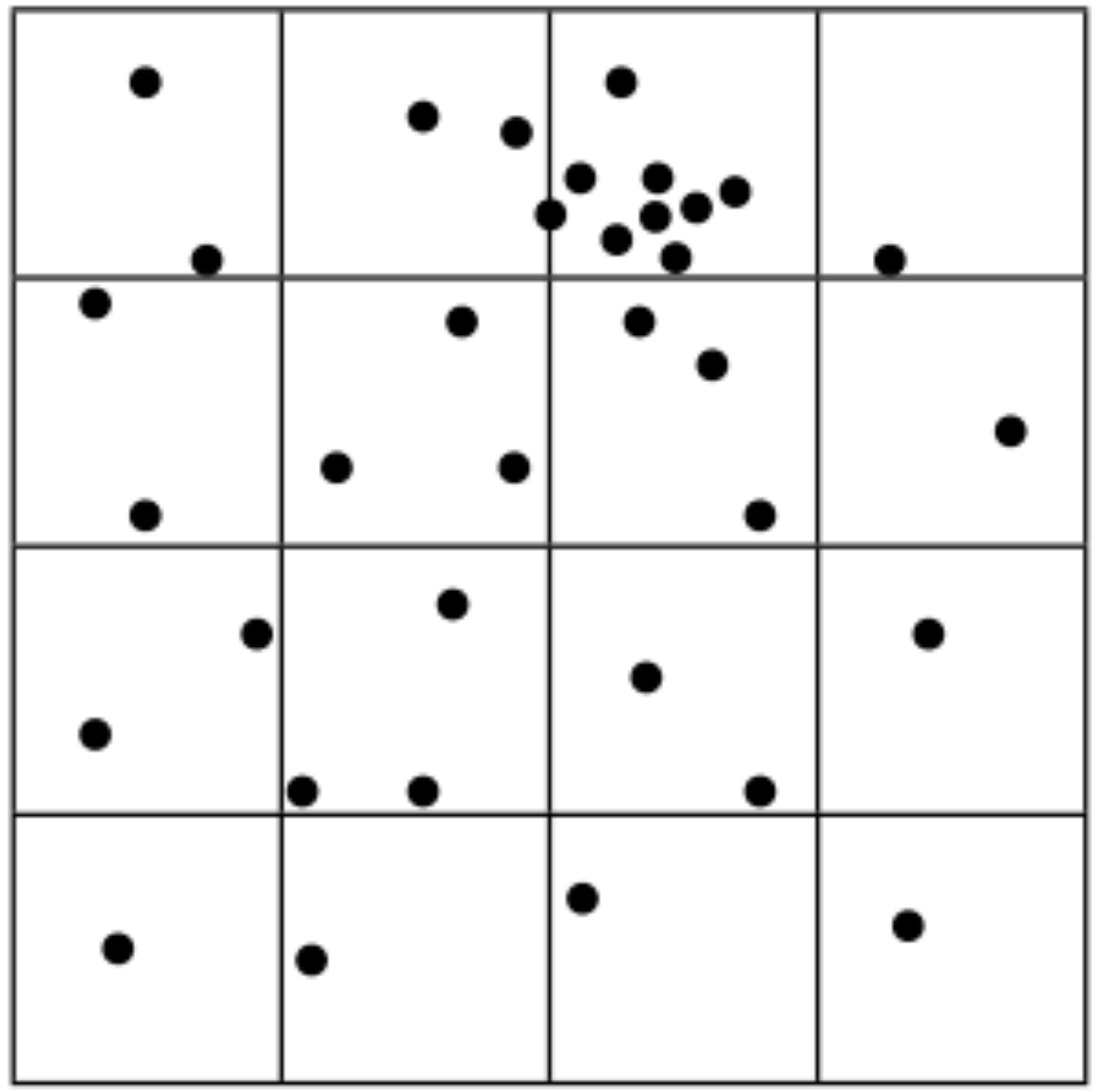
- Fundamental idea behind SPH: how to compute density from a collection of point masses

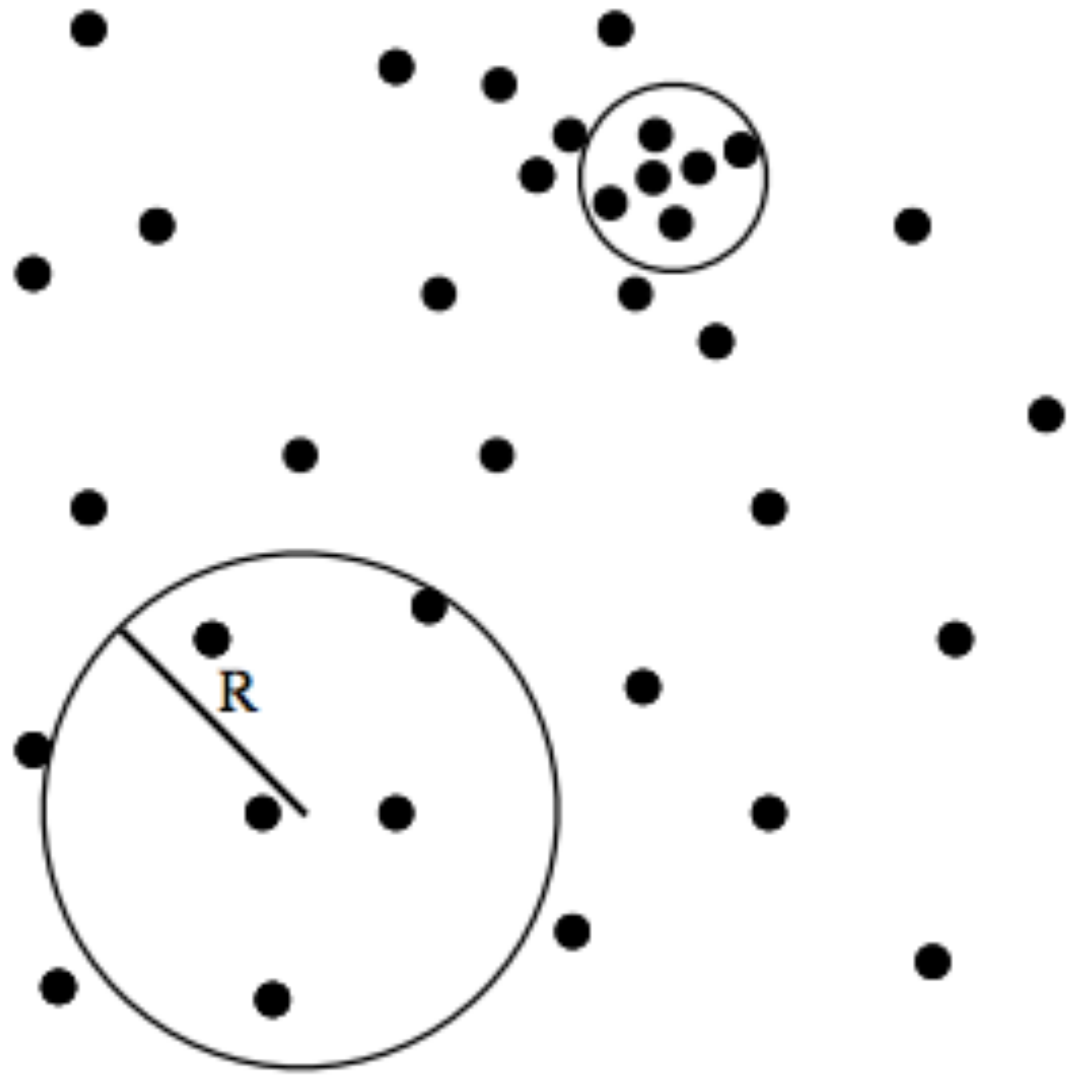


Method 1: construct a mesh around the points, then sum particles within cell and divide by cell volume

SPH basics

- Fundamental idea behind SPH: how to compute density from a collection of point masses





Method 2: construct local sample volumes, then sum particles within volume and divide by volume

SPH basics

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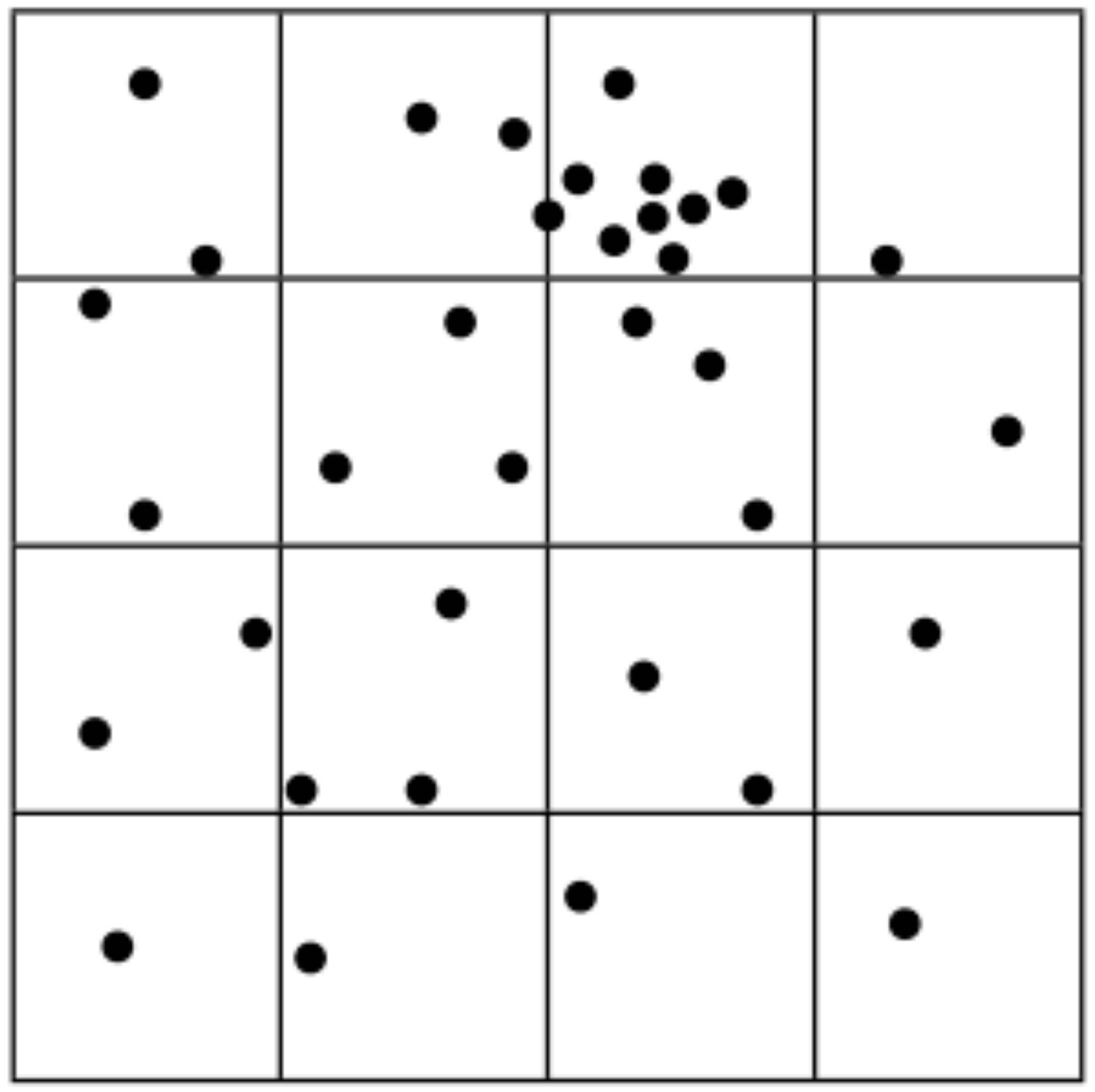
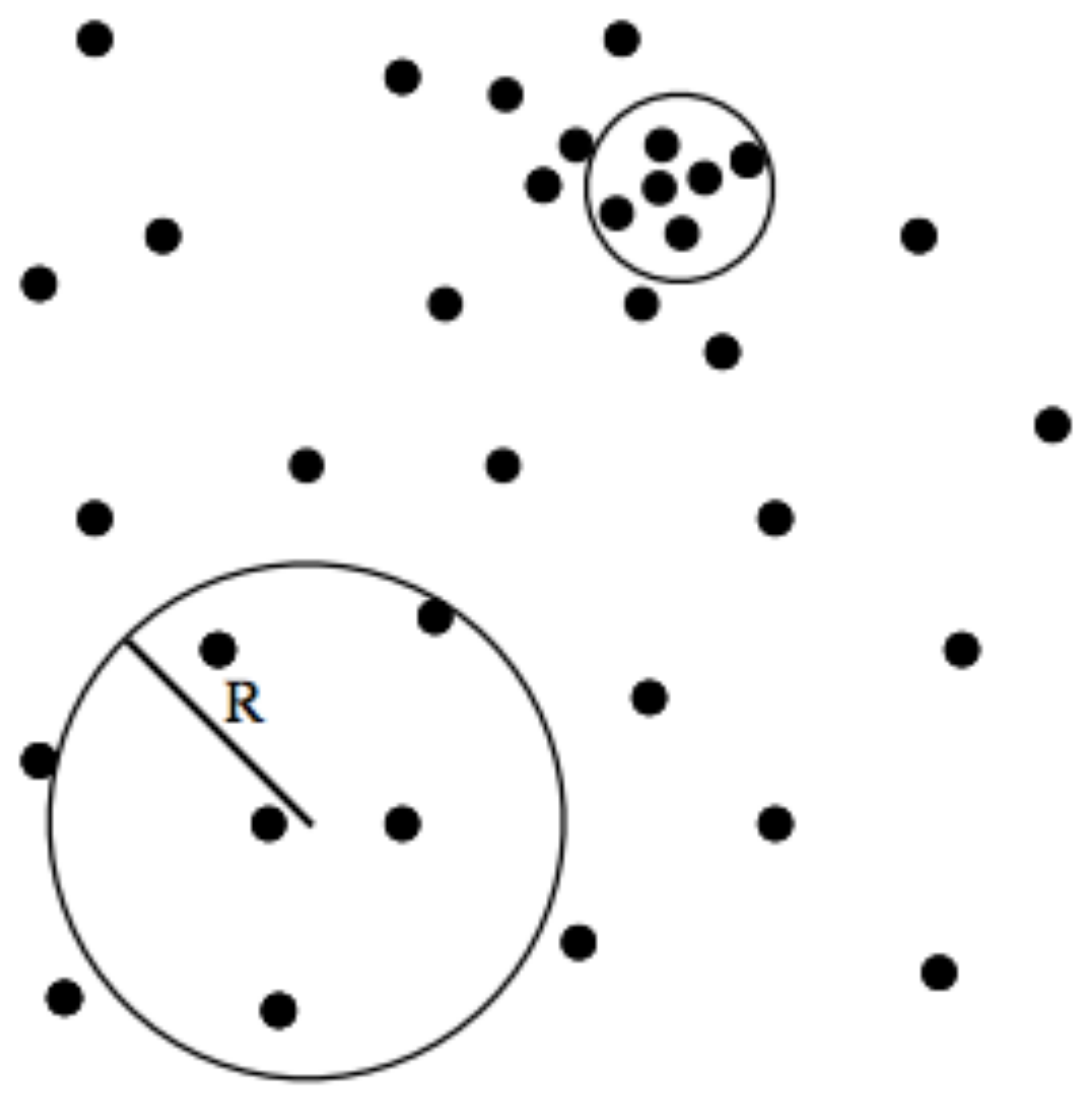
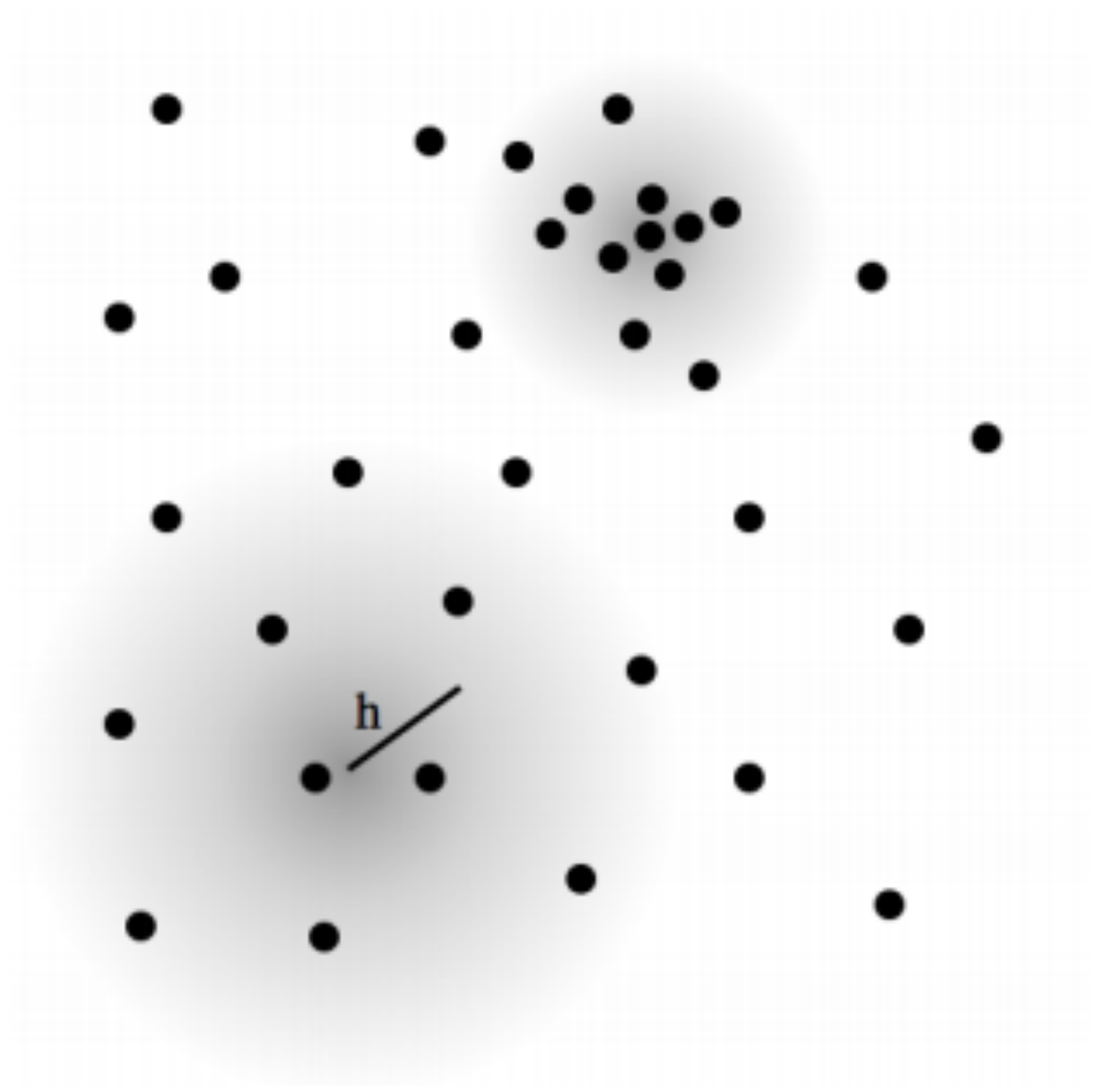






Method 3: weight contributions according to distance from sample point (SPH)

SPH basics

- Fundamental idea behind SPH: how to compute density from a collection of point masses

- Density in SPH is computed as:

$$\rho_a \approx \sum_{b=1}^{N} m_b W_{ab}$$

Smoothing kernel

Smoothing length

$$W_{ab} = W(|\mathbf{r}_a - \mathbf{r}_b|, h)$$

$$\rho h^3 = const.$$

Resolution follows density

Choice of the kernel function

- The main property of the kernel is that is should approximate a delta function: particles which are close should count more in the local evaluation of fluid properties.

- One could use a Gaussian:

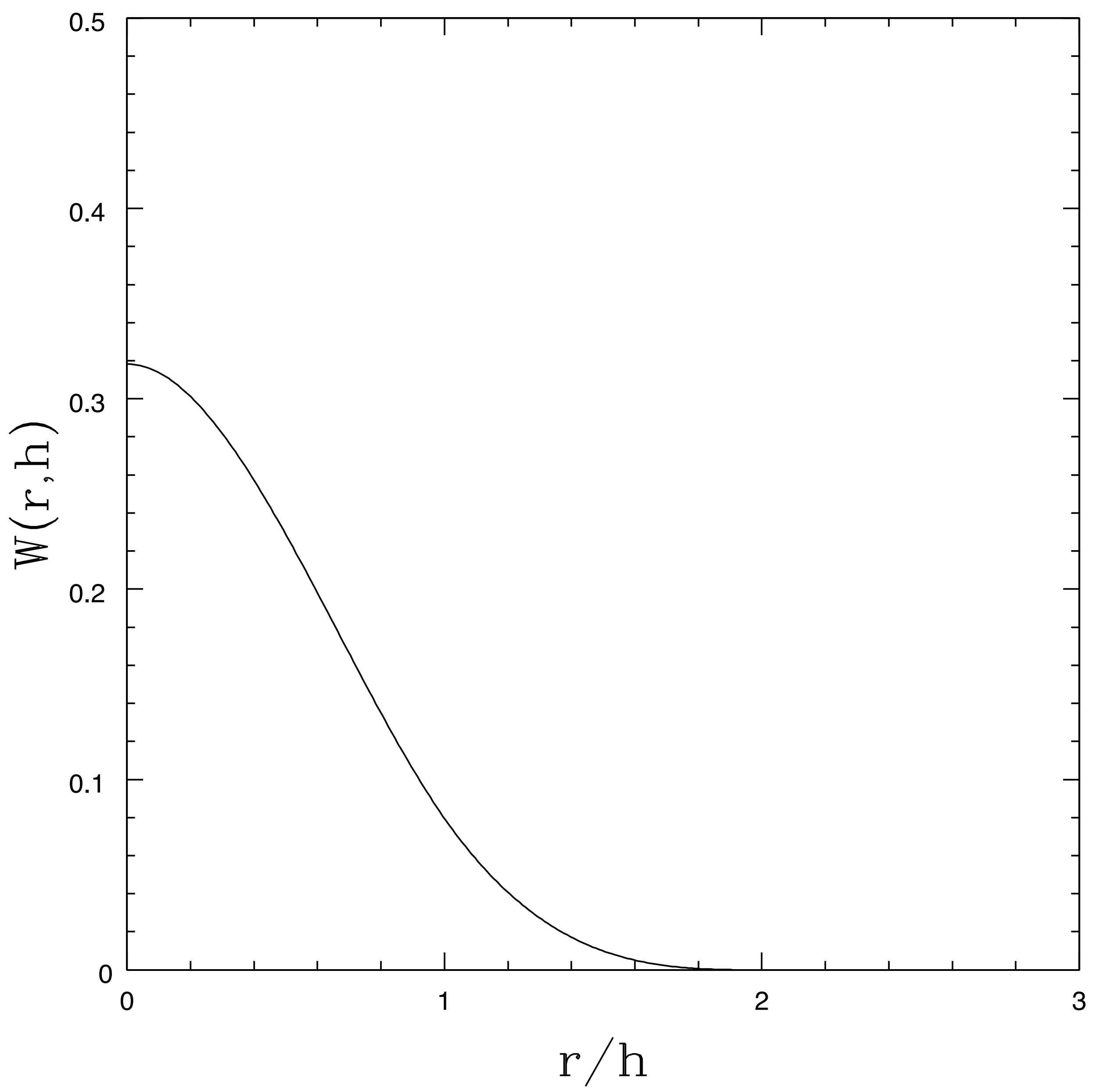
$$W(r,h) = \frac{1}{\pi^{3/2}h^3}e^{-(r/h)^2}$$

- Problem is that support is not compact. SPH summations must then extend to all particles, resulting in a total computational cost scaling with N^2:

Choice of the kernel function

- Better to use a kernel with compact support (ie. that vanishes beyond a given distance).

- Most widely used is the cubic spline kernel (find full expression in textbooks: is a cubic polynomial which vanishes for $r > 2h$)



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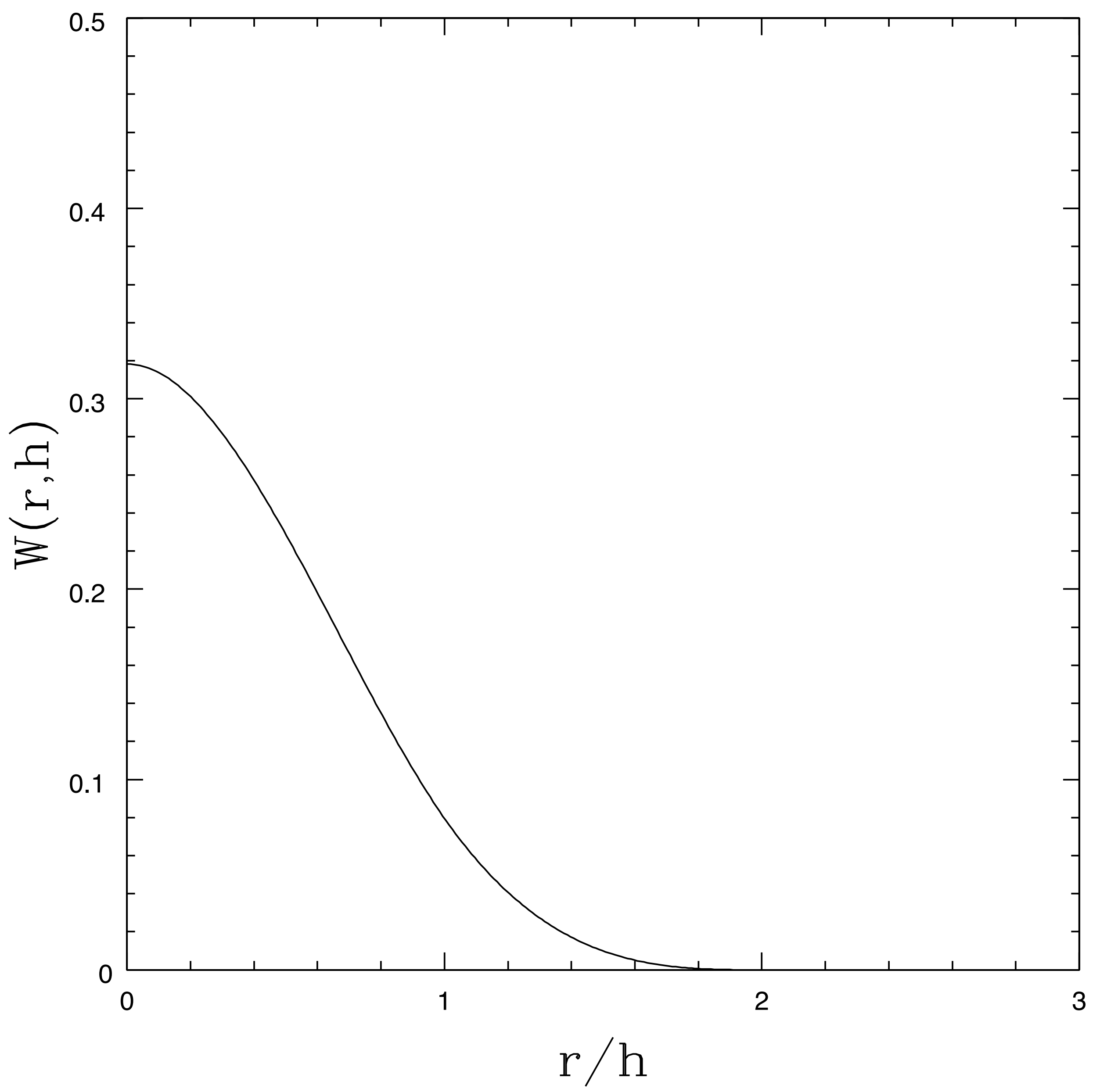

- SPH sums only involve summing over particles which lie within 2 smoothing lengths from the particle of interest. These particles are called the “**neighbours**”

- **Important to realize:** each SPH particle only feels fluid forces from its neighbours

Dynamics

- OK, we have computed density. How do we move the particles?

- Eckart (1960): Lagrangian of a continuum fluid system

$$\mathcal{L} = \int \left(\frac{1}{2}\rho v^2 - \rho u \right) \mathrm{d}V$$

- Discretize in SPH form

$$\mathcal{L} = \sum_b m_b \left(\frac{1}{2} v_b^2 - u_b \right)$$

- Equation of motion

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial \mathcal{L}}{\partial \mathbf{v}_a} \right) = \frac{\partial \mathcal{L}}{\partial \mathbf{r}_a}$$

Dynamics: note

- One could well consider a set of N bodies interacting through that Lagrangian
- Hamiltonian properties of the system preserved
- **Noether's theorem**: any symmetry in the Lagrangian determines a constant of motion
  - <u>Linear momentum exactly conserved</u> (to machine precision)
  - <u>Angular momentum exactly conserved</u> (to machine precision)
  - <u>Energy exactly conserved</u> (to machine precision, if symplectic time-integrator is used)
  - <u>Continuity exactly solved</u> (Lagrangian nature of scheme)

Basic SPH equations

$$\rho_a \approx \sum_{b=1}^{N} m_b W_{ab}$$

$$\frac{d\mathbf{v}_a}{dt} = -\sum_b m_b \left[\frac{P_a}{\Omega_a \rho_a^2} \frac{\partial W_{ab}(h_a)}{\partial \mathbf{r}_a} + \frac{P_b}{\Omega_b \rho_b^2} \frac{\partial W_{ab}(h_b)}{\partial \mathbf{r}_a} \right].$$

$$\Omega_a \equiv \left[1 - \frac{\partial h_a}{\partial \rho_a} \sum_b m_b \frac{\partial W_{ab}(h_a)}{\partial h_a} \right],$$

$$\frac{du_a}{dt} = \frac{P_a}{\Omega_a \rho_a^2} \sum_b m_b (\mathbf{v}_a - \mathbf{v}_b) \cdot \nabla_a W_{ab}(h_a).$$

Intrpretation of SPH equations based on interpolation theory

- Not needed in fact, but we go through it to clarify the nature of SPH
- Consider a fluid property A

$$A(\mathbf{r}) = \int A(\mathbf{r}')\delta(\mathbf{r} - \mathbf{r}')\mathrm{d}\mathbf{r}'$$

Intrpretation of SPH equations based on interpolation theory

- Not needed in fact, but we go through it to clarify the nature of SPH
- Consider a fluid property A

$$A(\mathbf{r}) \approx \int A(\mathbf{r}')W(|\mathbf{r} - \mathbf{r}'|, h)\mathrm{d}\mathbf{r}'$$

Intrpretation of SPH equations based on interpolation theory

- Not needed in fact, but we go through it to clarify the nature of SPH

- Consider a fluid property A

$$A(\mathbf{r}) \approx \int \frac{A(\mathbf{r}')}{\rho(\mathbf{r}')} W(|\mathbf{r} - \mathbf{r}'|, h)\rho(\mathbf{r}')\mathrm{d}\mathbf{r}'$$

- Discretize in mass

$$A(\mathbf{r}) \approx \sum_{b=1}^{N} m_b \frac{A_b}{\rho_b} W(|\mathbf{r} - \mathbf{r}_b|, h)$$

SPH interpolation

- SPH representation of unity:

$$1 \approx \sum_{b=1}^{N} \frac{m_b}{\rho_b} W_{ab}$$

- SPH representation of zero:

$$0 = \nabla 1 \approx \sum_{b=1}^{N} \frac{m_b}{\rho_b} \nabla_a W_{ab}$$

Derivatives in SPH

- SPH representation of *A(**r**)* only depends on ***r*** through the kernel. Therefore:

$$A(\mathbf{r}) \approx \sum_{b=1}^{N} m_b \frac{A_b}{\rho_b} W(|\mathbf{r} - \mathbf{r}_b|, h)$$

$$\nabla A(\mathbf{r}_a) \approx \sum_{b=1}^{N} m_b \frac{A_b}{\rho_b} \nabla_a W_{ab}$$

- Important property of SPH: the derivative is done analitically on the kernel and no approximation is done at this stage

- Immediately see that this is **NOT** a good approx for constant functions.

Derivatives in SPH

- A much better derivative estimate is obtained by the SPH representation of **∇***A* - *A***∇***1:*

$$\nabla A(\mathbf{r}_a) \approx \sum_{b=1}^{N} m_b \frac{(A_b - A_a)}{\rho_b} \nabla_a W_{ab}$$

- This form vanishes exactly for constant functions.

- Example. Compute the divergence of velocity:

$$\nabla \cdot \mathbf{v}(\mathbf{r}_a) \approx \sum_{b=1}^{N} \frac{m_b}{\rho_b} (\mathbf{v}_b - \mathbf{v}_a) \cdot \nabla_a W_{ab}$$

Momentum equation

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla P$$

- One might naively take the usual estimate for the gradient of *P* and put in the equation

$$\frac{\mathrm{d}\mathbf{v}(\mathbf{r}_a)}{\mathrm{d}t} = -\sum_{b=1}^{N} m_b \frac{(P_b - P_a)}{\rho_a \rho_b} \nabla_a W_{ab}$$

- This has the advantage of vanishing for constant pressure, but....

- Has the **BIG** disadvantage of not conserving momentum!!!

  - Force of particle *b* on *a* is equal (***and not opposite!***) to force of particle *a* on *b*!

$$\frac{d\mathbf{v}_a}{dt} = -\sum_b m_b \left[\frac{P_a}{\Omega_a \rho_a^2} \frac{\partial W_{ab}(h_a)}{\partial \mathbf{r}_a} + \frac{P_b}{\Omega_b \rho_b^2} \frac{\partial W_{ab}(h_b)}{\partial \mathbf{r}_a} \right].$$

Interpretation of SPH Euler's equation

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla P$$

$$\frac{1}{\rho}\nabla P = \nabla\left(\frac{P}{\rho}\right) + \frac{P}{\rho^2}\nabla\rho$$

$$\frac{1}{\rho}\nabla P \approx \sum_b m_b\left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2}\right)\nabla_a W_{ab}$$

$$\frac{d\mathbf{v}_a}{dt} = -\sum_b m_b\left[\frac{P_a}{\Omega_a\rho_a^2}\frac{\partial W_{ab}(h_a)}{\partial \mathbf{r}_a} + \frac{P_b}{\Omega_b\rho_b^2}\frac{\partial W_{ab}(h_b)}{\partial \mathbf{r}_a}\right].$$

Summary

- SPH basics
- **Advanced SPH**
- A few applications to protostellar disc dynamics inthe ALMA era

Advanced SPH

- Resolving shocks and discontinuities
- Adding self-gravity
- Additional physics:
  - Individual timesteps
  - Sink particles
  - MHD
  - Radiative transfer
  - General relativity

Resolving shocks and discontinuities

- The whole SPH method relies on the fact that all physical quantities are continuous and differentiable.
- This is not true at discontinuities (e.g. contact discontinuities) and shocks.
- Fluid equations can develop discontinuities even from initial conditions which are continuous
- If the SPH solution has to be continuous, such discontinuities will not appear in the solution (“the shock is not resolved”)
- How do we treat these cases?

Artificial dissipations vs Riemann solvers

- Two possible approaches:
  - Solve analitically the equations in integral form on the two sides of the discontinuity (Riemann solvers -- **Godunov** schemes). Preferred method in fluid dynamics.
  - Remove the cause of the discontinuity adding an “artificial dissipation” term to smear it out
- **Note**: in the real world there are no discontinuities --> viscosity (or physical dissipation) removes it at the microscopic scale
- Artificial dissipation is thus analogous to what happens in Nature, but on scales generally much larger

Artificial viscosity in SPH

- Both Godunov schemes and artificial viscosity can be used in both SPH and grid-based methods
- Some grid based methods use artificial viscosity (e.g. ZEUS), but most don’t.
- While Godunov schemes have a natural implementation in grid-based codes, they are more difficult to implement in SPH (but can be done)
- Most SPH codes use artificial viscosity to resolve shocks -- i.e. discontinuities in the momentum equations

Artificial viscosity in SPH

- There are various specific forms of the artificial viscosity in SPH.
- The most common is:

$$\left(\frac{\mathrm{d}\mathbf{v}(\mathbf{r}_a)}{\mathrm{d}t}\right)_{AV} = -\sum_{b=1}^{N} m_b \frac{-\alpha \bar{c}_{ab}\mu_{ab} + \beta\mu_{ab}^2}{\bar{\rho}_{ab}} \nabla_a W_{ab}$$

$$\mu_{ab} = \frac{h\mathbf{v}_{ab} \cdot \mathbf{r}_{ab}}{r_{ab}^2 + 0.01h^2}$$

- Properties:
  - Is Galilean invariant (conserves momentum and angular momentum)
  - Vanishes for rigid body rotation
  - The “β”-term is analogous to von Neumann - Rightmyer viscosity
  - Best choices for parameters are α = 1 and β = 2

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Artificial viscosity in SPH

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- Both the α and the β terms provide <u>both a **shear** and a **bulk**</u> viscosity in a <u>ratio of 5 to 3</u> (bulk viscosity = 5/3 shear viscosity)

- The α term is equivalent to a kinematic viscosity coefficient of

$$(\nu)_{ab} = \frac{1}{10}\alpha \bar{c}_{ab} h_{ab}$$

- Energy equation needs modifications in order to conserve energy

$$\frac{\mathrm{d}u_a}{\mathrm{d}t} = \frac{P_a}{\rho_a^2}\sum_b m_b(\mathbf{v}_a - \mathbf{v}_b)\cdot\nabla_a W_{ab} + \frac{1}{2}\sum_b m_b \Pi_{ab}(\mathbf{v}_a - \mathbf{v}_b)\cdot\nabla_a W_{ab}$$

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- Energy

$\frac{\mathrm{d}u}{\mathrm{d}}$ ... $_b$

SPH simulations of viscous accretion discs

Linear term in artificial viscosity equivalent to a Shakura-Sunyaev viscosity, with

$$\alpha_{\rm SS} = \frac{1}{10}\alpha\frac{\langle h\rangle}{H}$$

Note on simulating disc-like structures

- Relevant for protostellar discs, but also to disc galaxies that may form in cosmological simulations
- A disc in vertical hydrostatic balance has a thickness $H = c_s / \Omega$
- Differential rotation over a radial range ~ H, gives $\Delta v \sim \Omega H \sim c_s$
- If disc thickness not resolved, the code will think that differential rotation is a shock and will damp it strongly via artificial viscosity!!!
- <u>It is essential that $h \ll H$ for simulating any disc</u>

Problems associated with artificial viscosity

- We are actually simulating a different physical process
- Angular momentum conservation non modified, but can have significant spurious transport
- Important to limit the use of artificial viscosity to the bare minimum
- Need to use a number of “switches”:

1. Turn it off for non approaching particles (standard practice)
2. Balsara switch --> Removes significantly the shear component
3. Morris & Monaghan switch. Have individual alpha terms where for every particle alpha evolves as:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = -\frac{\alpha - \alpha_{\min}}{\tau} + S(\nabla \cdot \mathbf{v})$$

Also, recently introduced Cullen & Dehnen switch

Physical viscosity in SPH

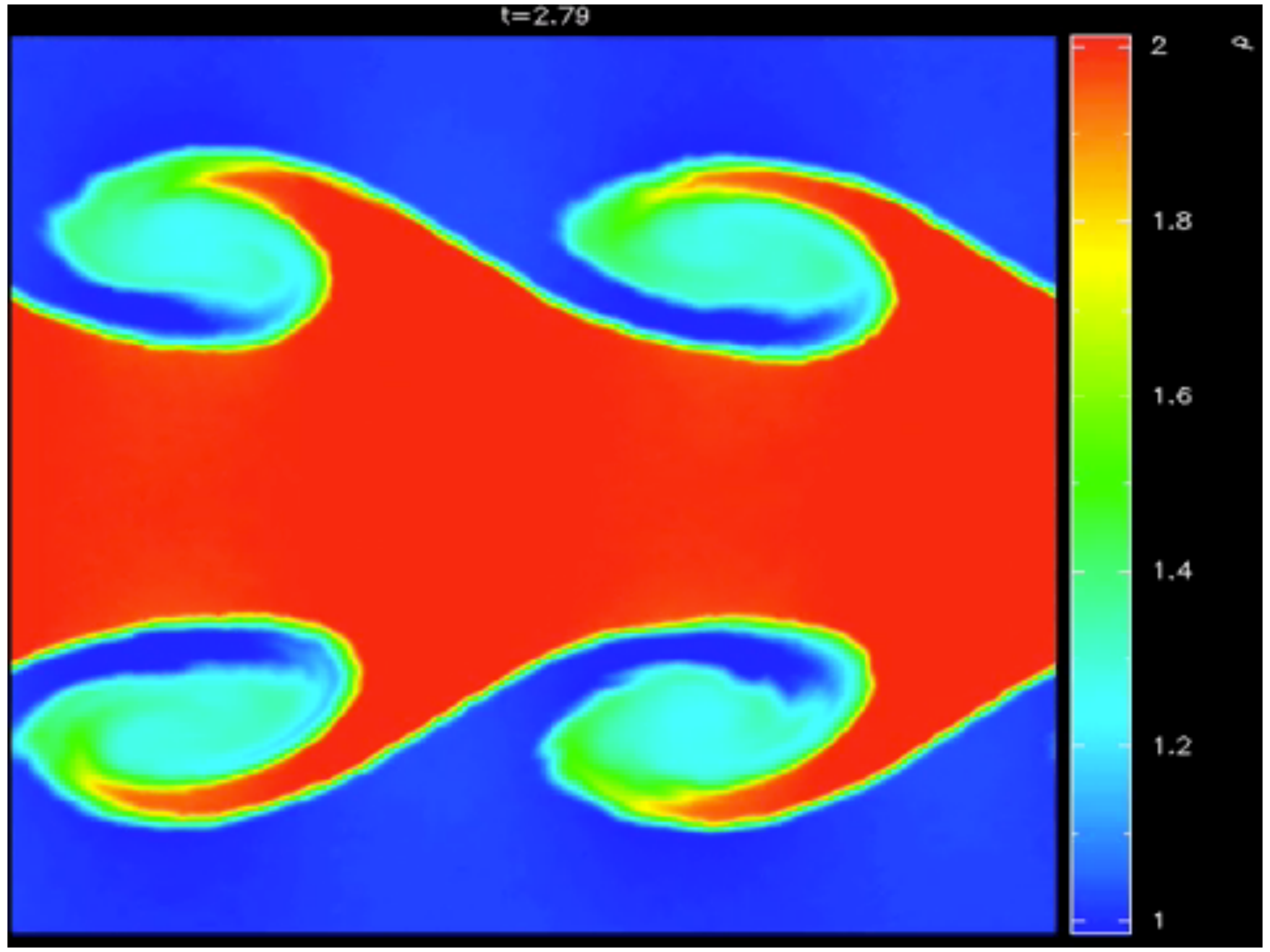
- It is also possible to implement Navier-Stokes viscosity terms in SPH

- Formulation is a bit difficult, based on either SPH estimates of second derivatives (Espanol & Revenga 2003) or computing velocity gradients (Flebbe 1993, Lodato & Price 2010)

$$\frac{\partial v_a^i}{\partial x_a^j} = \frac{1}{\rho_a \Omega_a} \sum_b m_b \left(v_b^i - v_a^i \right) \frac{\partial W_{ab}(h_a)}{\partial x_a^j}$$

Kelvin-Helmholtz instabilities in SPH

- KH instability occurs when two fluids drift past each other
- It has been claimed that SPH cannot give rise to the instability even in cases where it should (Agertz et al. 2007)
- It has been shown (Price 2008) that this is due to the fact that most codes do not include artificial thermal conductivity and hence cannot resolve discontinuities in the energy equation (the origin of the KHI)



Self-gravity in SPH

- In many cases the self-gravity of the fluid is very important
  - E.g.: collapse of a molecular cloud in star formation, dynamics of self-gravitating discs,.....
- SPH lends itself naturally to these kinds of problems due to its N-body like structure.
- Can simply use the techniques developed for years in the N-body community
- Need to remember: we are simulating a fluid, not a collection of N particles
  - Need to remove two-body interactions --> need to use **gravitational softening**

Softening vs smoothing

- Gravitational softening is a way to reduce the gravitational force on scales smaller than a typical scale, called the "softening length"
- In SPH, the natural choice is to use the smoothing length for this purpose, and the smoothing kernel to effect the softening
- Consider each particles gravitational field as due to an extended sphere with dsensity profile given by the kernel
- Not all codes do that!!!! Example: GADGET does not!
- If you don't, gravity and fluid forces are resolved differently, which might give rise to spurious behaviour (e.g. enhanced/suppressed fragmentation)

Resolving fragmentation in SPH

- Very often want to simulate processes where Jeans instability determines the structure of your system (from cosmological simulations down to star formation)
- How much resolution do you need to do that?
- Typical fragment mass is the Jeans mass

$$M_{\mathrm{J}} = \frac{\pi}{6}\frac{c_{\mathrm{s}}^3}{G^{3/2}\rho^{1/2}}$$

- <u>Zeroth order</u>: the mass of an SPH particle should be at least smaller than the Jeans mass!
- <u>First order</u>: Actually, the minimum resolvable mass is the mass contained in a smoothing kernel, which is ~ $N_{neigh} m_p$ ~ $100 m_p$ (Bate & Burkert 1997)

Tree-SPH

- Computing self-gravity directly through summation is a computationally expensive task (it scales with N^2)
- Much easier to do when self-gravity is computed using a tree code (no time to explain it here!)
- Using a tree is also a very efficient way of getting the neighbour list
- A tree code scales more mildly, as $N \log N$
- However, the use of the tree leads to a small momentum and angular momentum non-conservation
- Most SPH codes actually are Tree/SPH

Additional features

- Over the years, the "standard" SPH has been improved with a number of additions
- **Individual particle timesteps**
  - Needed because the typical evolutionary timescale in the densest regions can be orders of magnitude smaller than that in the rest of the simulation
  - While only a small number of particles are doing something, the rest is just sitting there with little evolution

Additional features

- Over the years, the “standard” SPH has been improved with a number of additions
- **Sink particles**
  - Useful to simulate accretion processes
  - For example, accretion onto a newborn star
  - Accretion onto a black hole in a large scale simulation
  - Need to be very careful with boundary conditions!

Additional features

- Over the years, the “standard” SPH has been improved with a number of additions
- **MHD**
  - This is tricky.
  - Not easy to implement the “divergence-free” nature of magnetic fields
  - Improvement have been made using Euler potential (Price)
  - Restricted to simple configurations of the field (tangled field difficult to be produced

Additional features

- Over the years, the “standard” SPH has been improved with a number of additions

- **Radiative transfer**

    - Important feature in cases where behaviour is very sensitive to thermal physics (for example, fragmentation of a gravitationally unstable disc)

    - Difficult and expensive to implement.

    - Mostly done within the diffusion approximation for optically thick cases

    - Alternative and promising (Montecarlo radiative transfer, e.g. MCFOST)

Additional features

- Over the years, the “standard” SPH has been improved with a number of additions
- **Godunov SPH:** Potentially very important (Cha & Whitworth)
- **Chemistry, multiphase SPH**
- **Gas-dust interaction** (Laibe & Price)

Good practice suggestions

1. <u>Always use variable smoothing lengths!</u>!
    - Include **“grad h” terms** to conserve energy!
2. Number of neighbours **should be large (50-100)** to avoid particle noise
3. When possible soften gravity on the same scale as fluid forces (i.e. **smoothing length = softening length**)
4. Remember to resolve Jeans mass with > 100 SPH particles
5. Use a symplectic time integrator (i.e. **leapfrog** rather than Runge-Kutta)
6. Use **artificial viscosity switches** (Morris & Monaghan, Balsara)
7. For disc simulations, always **resolve the disc thickness** with several smoothing lengths

To SPH or not to SPH?

- **Pros**
  - SPH is a solid method with **exceptionally good conservation properties** (far above any grid based code), which follow directly from its inherent **Galilean invariance**
  - Its **Lagrangian nature** makes it very good in handling problems without well defined symmetries (eccentric, warped discs, binaries)
  - Do not need to worry about boundaries (and its spurious effects!): the flow is not confined "in a box"
  - It is easy to implement and will always give an answer (careful here: possible source of problems!)
  - Advection of fluid properties natural in SPH (without losses due to the grid)

To SPH or not to SPH?

- **Cons**
  - Most SPH codes use artificial viscosity to treat shocks: leads potentially to large spurious dissipation.
  - Artificial viscosity is not inherent to SPH. **Godunov schemes** (potentially better at treating shocks) can be designed to work in SPH. Needs more investigation.
  - Not using artificial dissipation might lead to unphysical behaviour at discontinuities (i.e. Kelvin-Helmholtz case)
  - Mixing of properties very hard to implement
  - For problems with (a) *high degree of symmetry* or (b) *physical boundaries* you might be better off using a high-order grid-based code.

Summary

- SPH basics
- Advanced SPH
- **A few applications to protostellar disc dynamics inthe ALMA era**

Protostellar discs in the ALMA era

- With every new instrument, emphatic statements on the revolution it will bring
- Disc imaging across the years

Protostellar discs in the ALMA era

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TW Hya - d$\sim$50pc

2000 2016

Protostellar discs in the ALMA era

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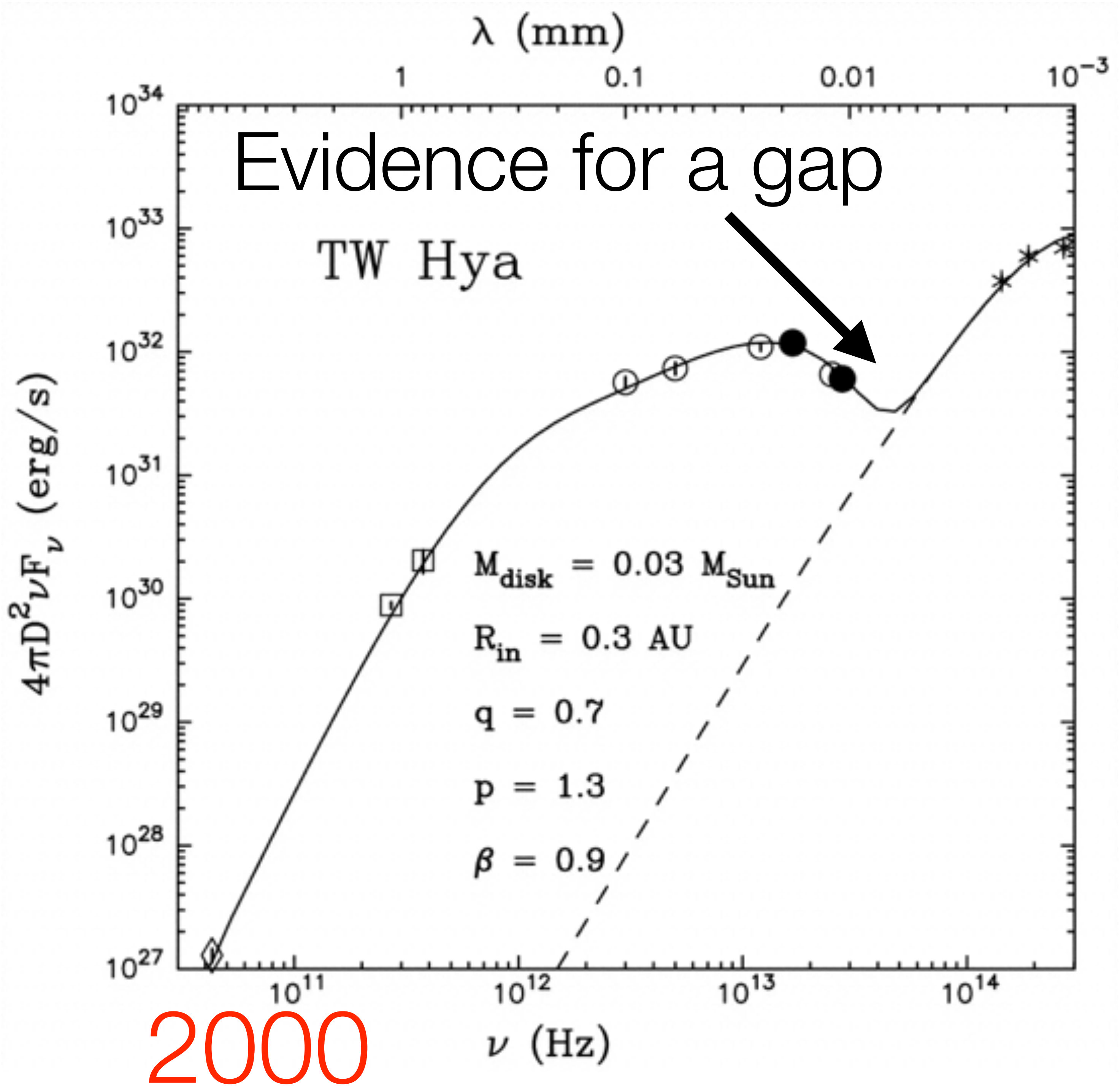
TW Hya - d∼50pc



2000

2016

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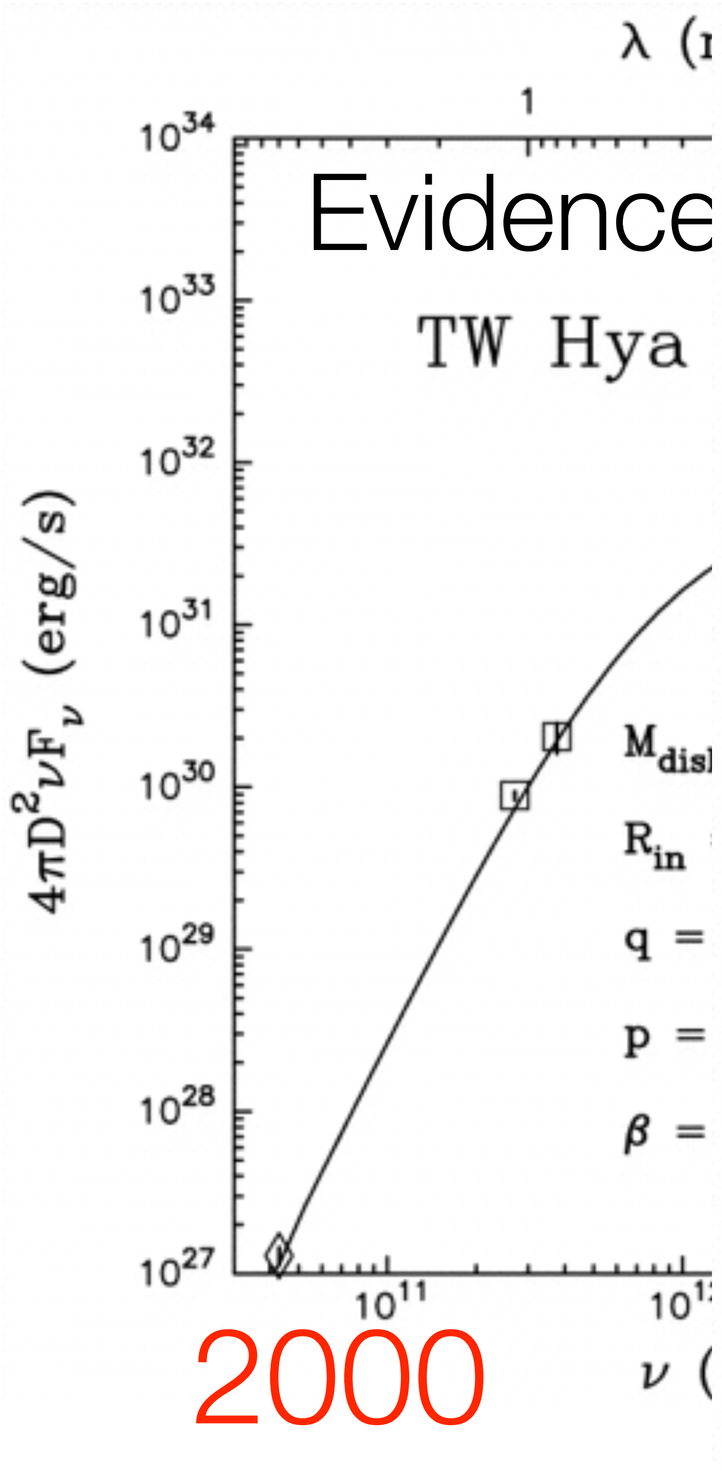
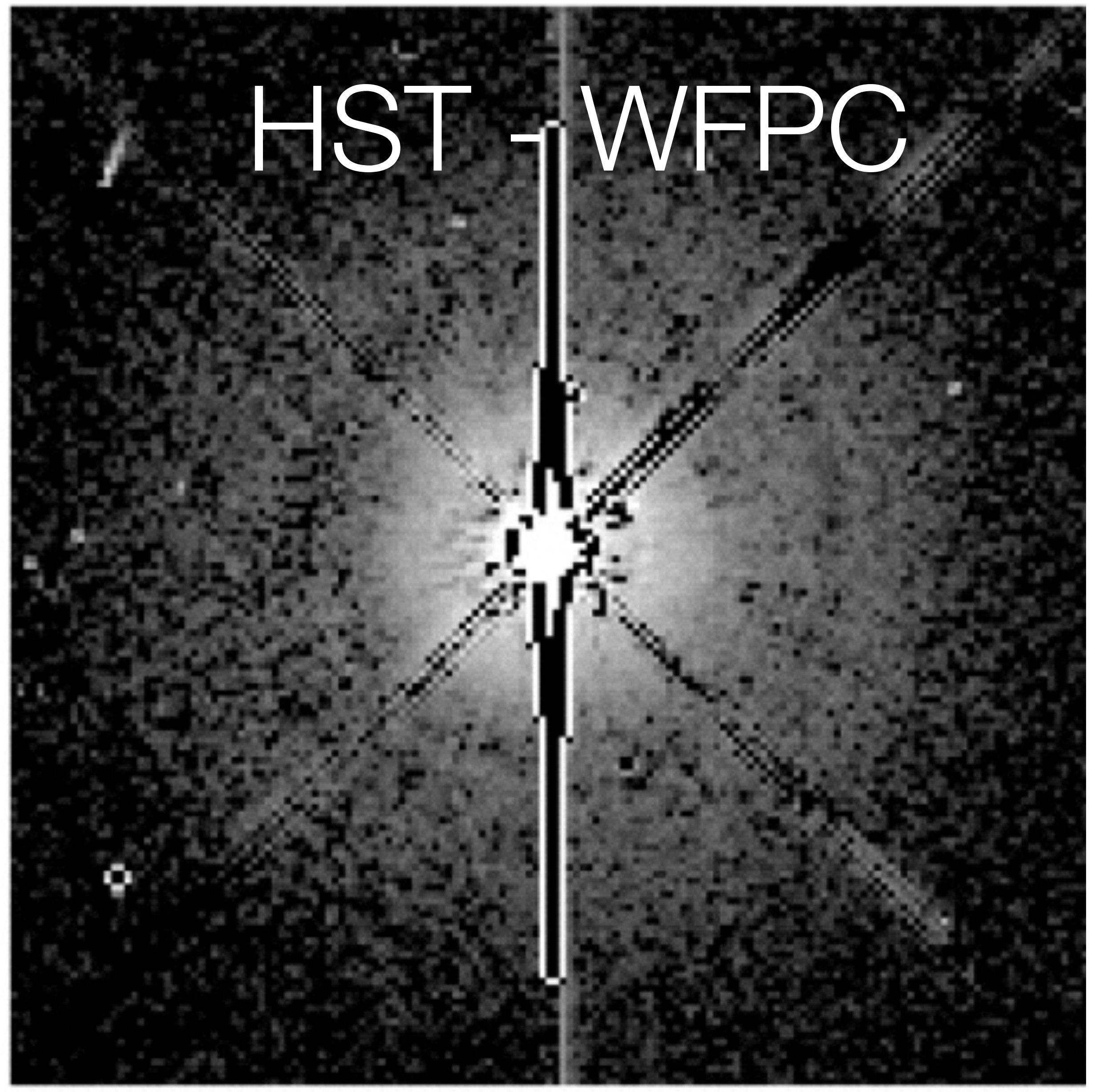
TW Hya - d∼50pc





TW Hya - PSF_a

2000

2016

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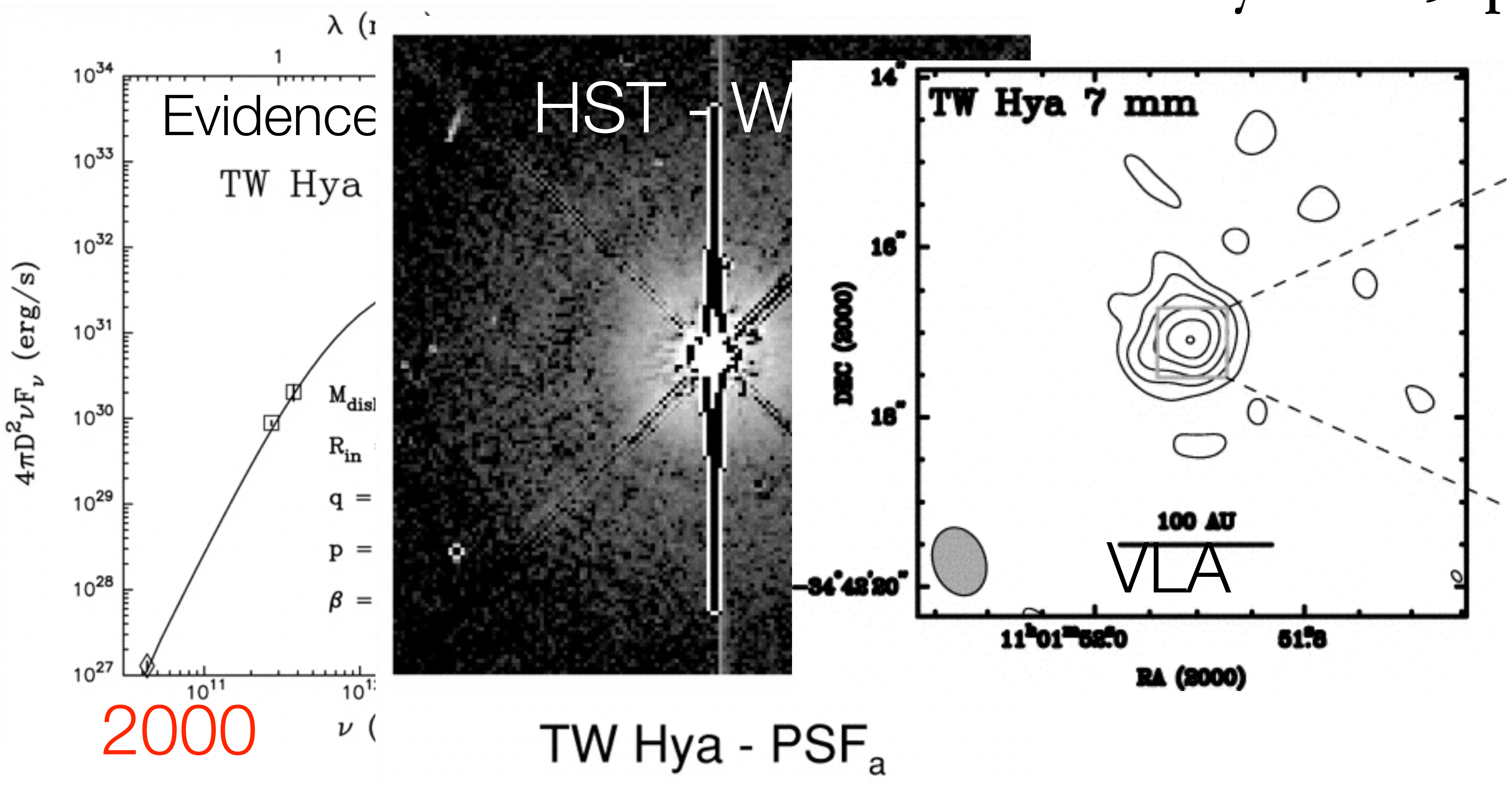
TW Hya - d∼50pc



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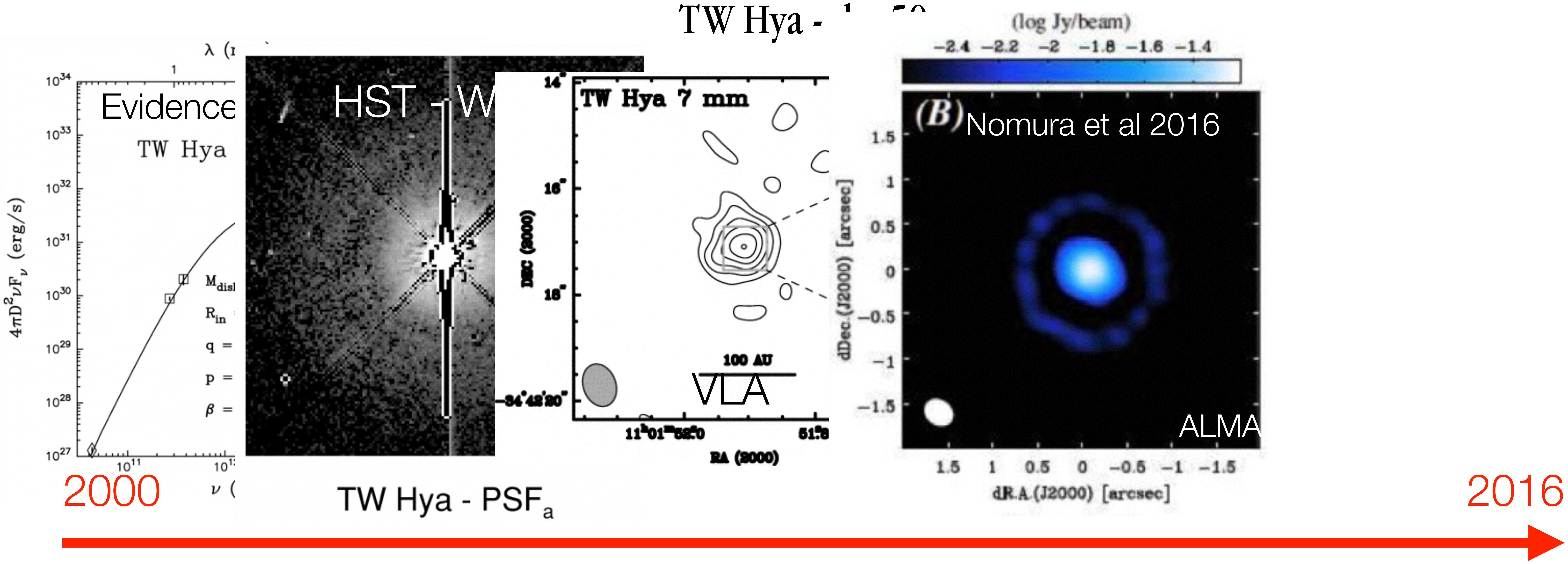

Protostellar discs in the ALMA era

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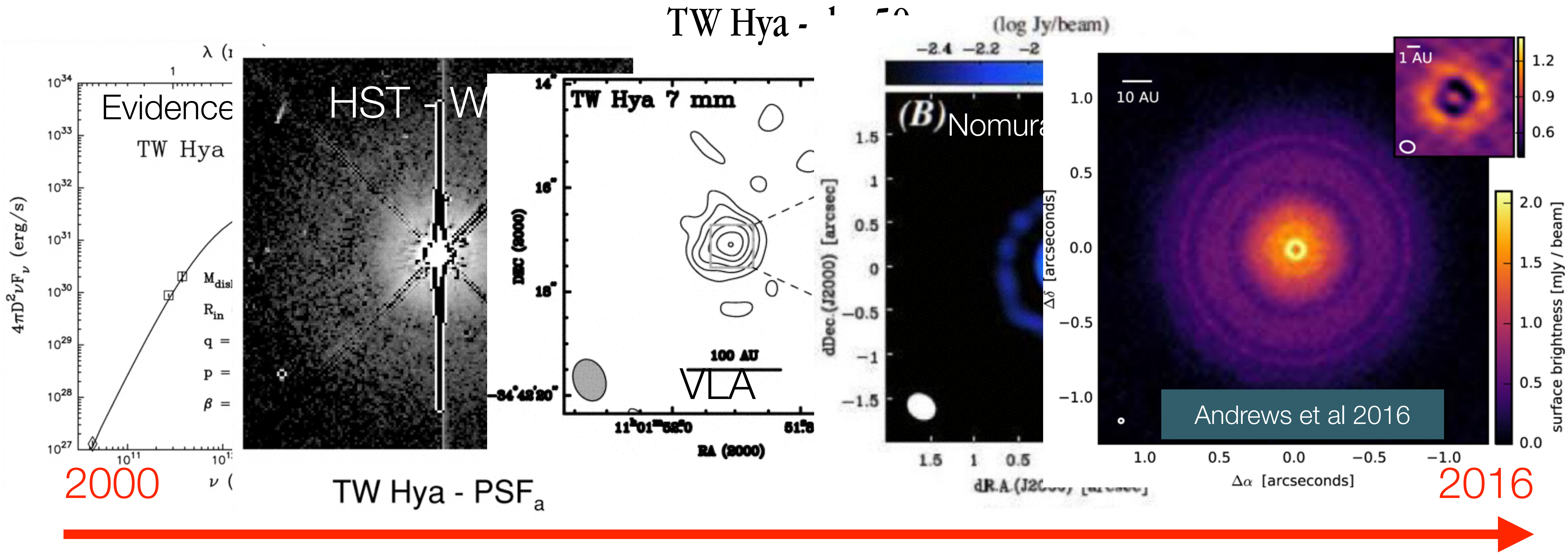

Protostellar discs in the ALMA era

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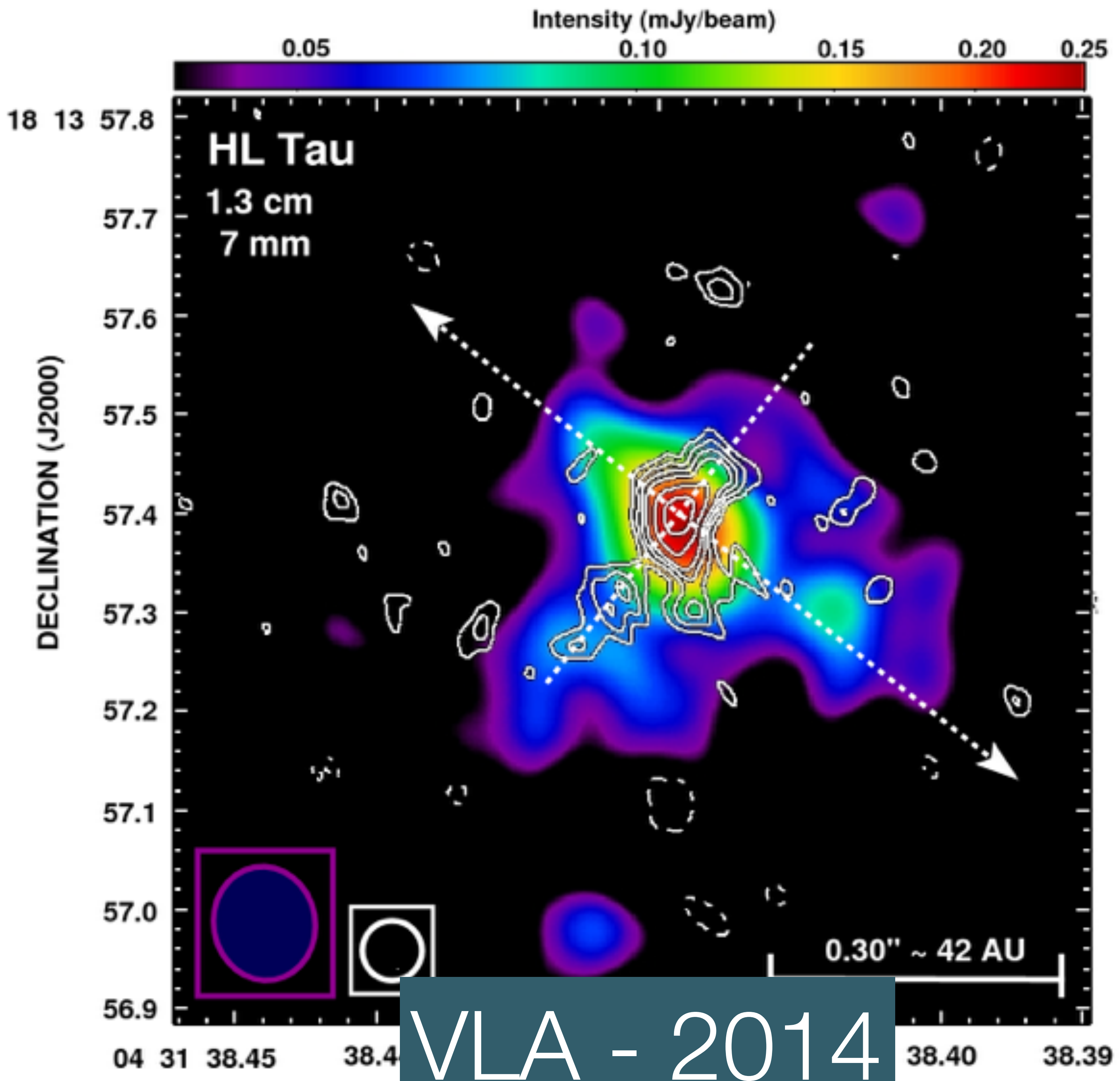
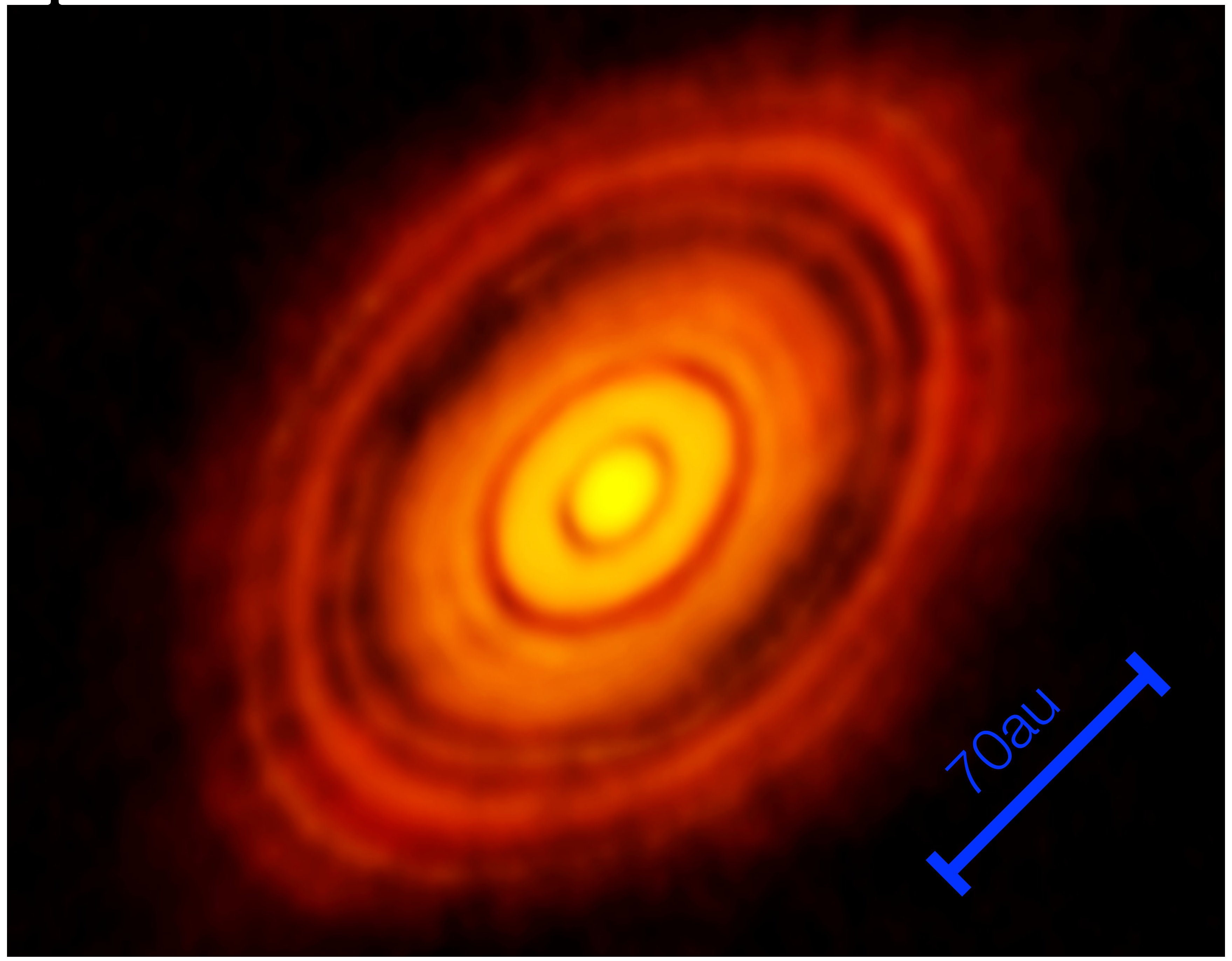
HL Tau - d~140pc



VLA - 2014



ALMA 2015

Protostellar discs in the ALMA era

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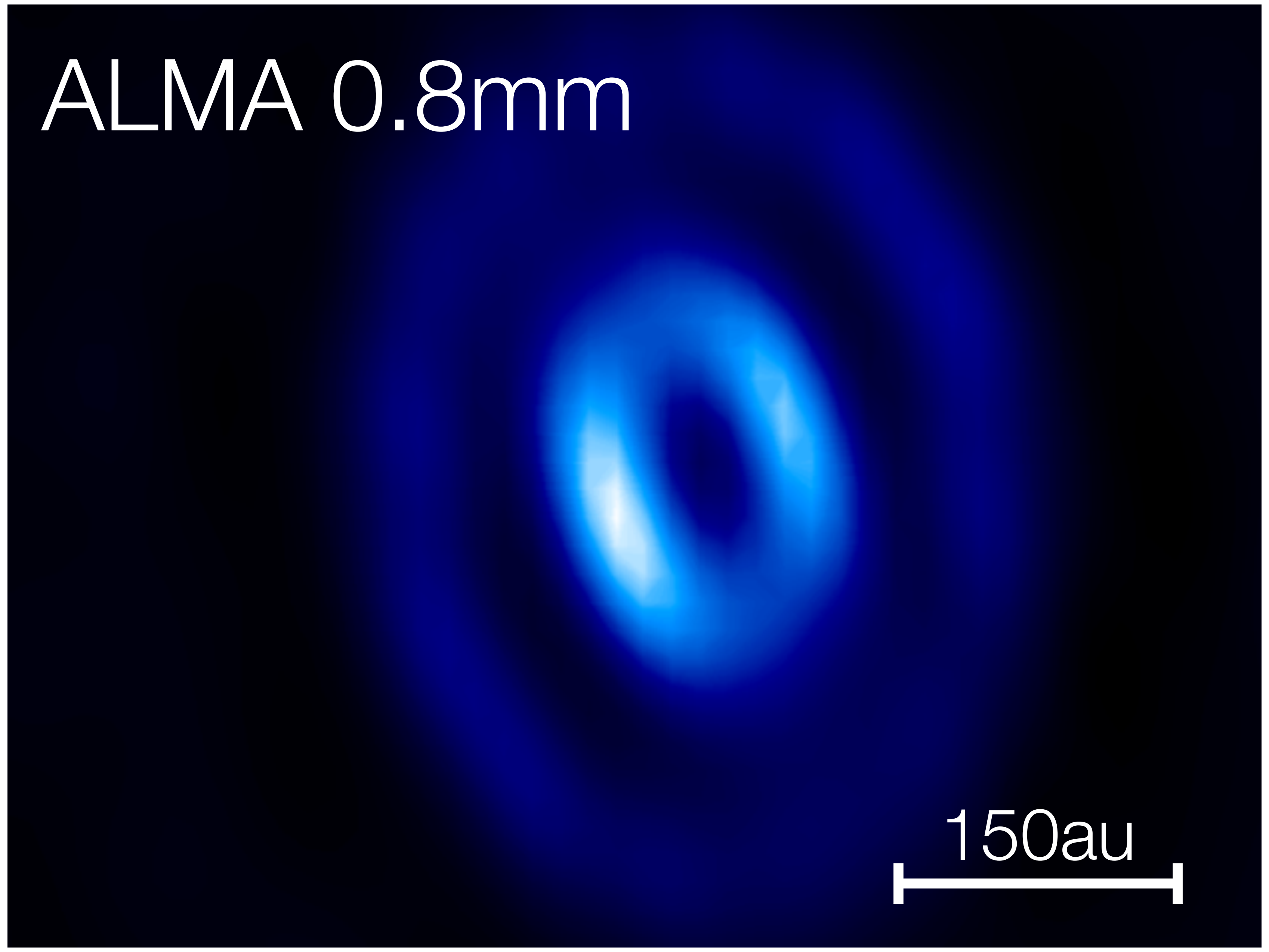
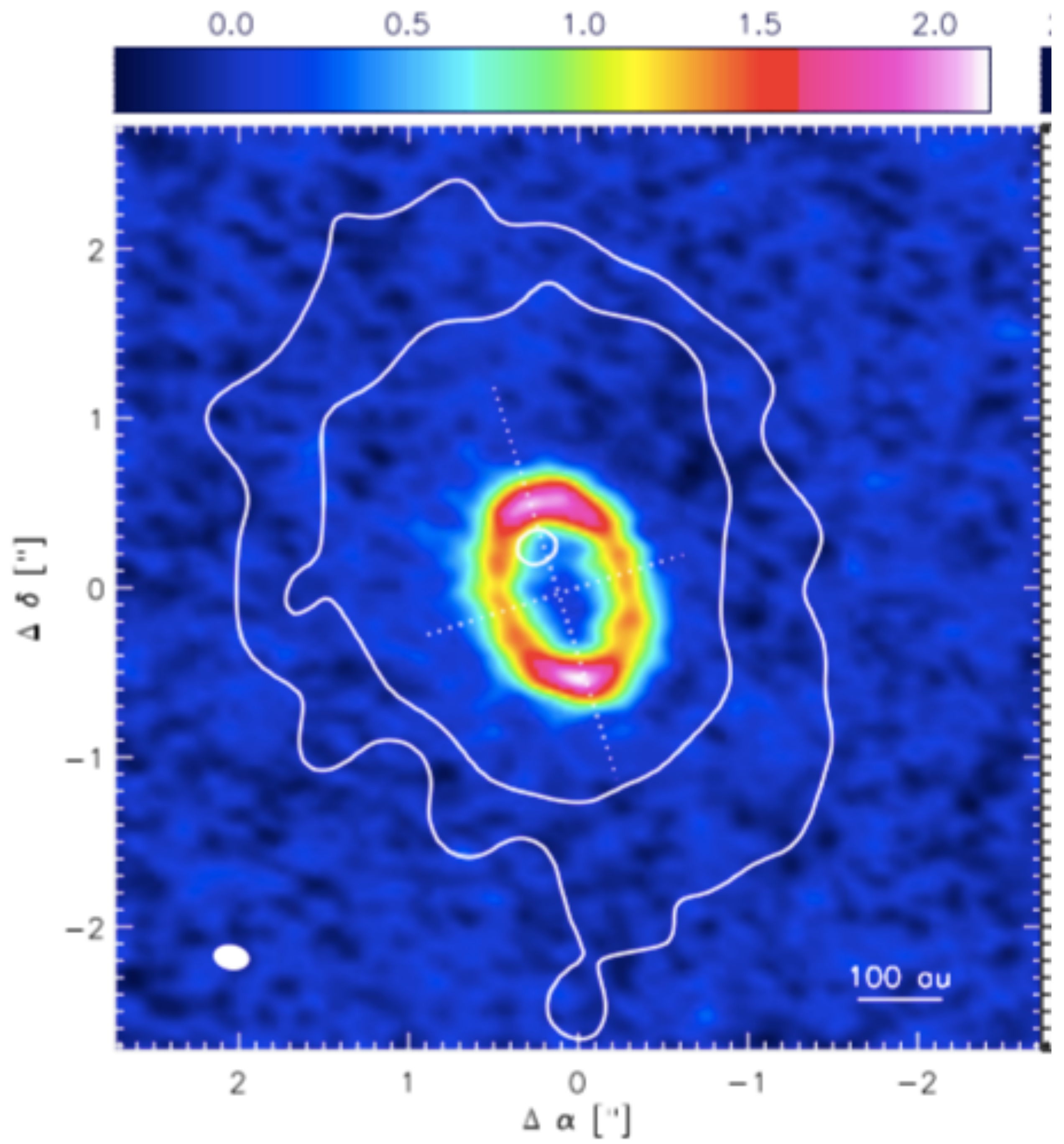
HD97048 - van der Plas in prep



Sz91 - Canovas et al 2016



Protostellar discs in the ALMA era

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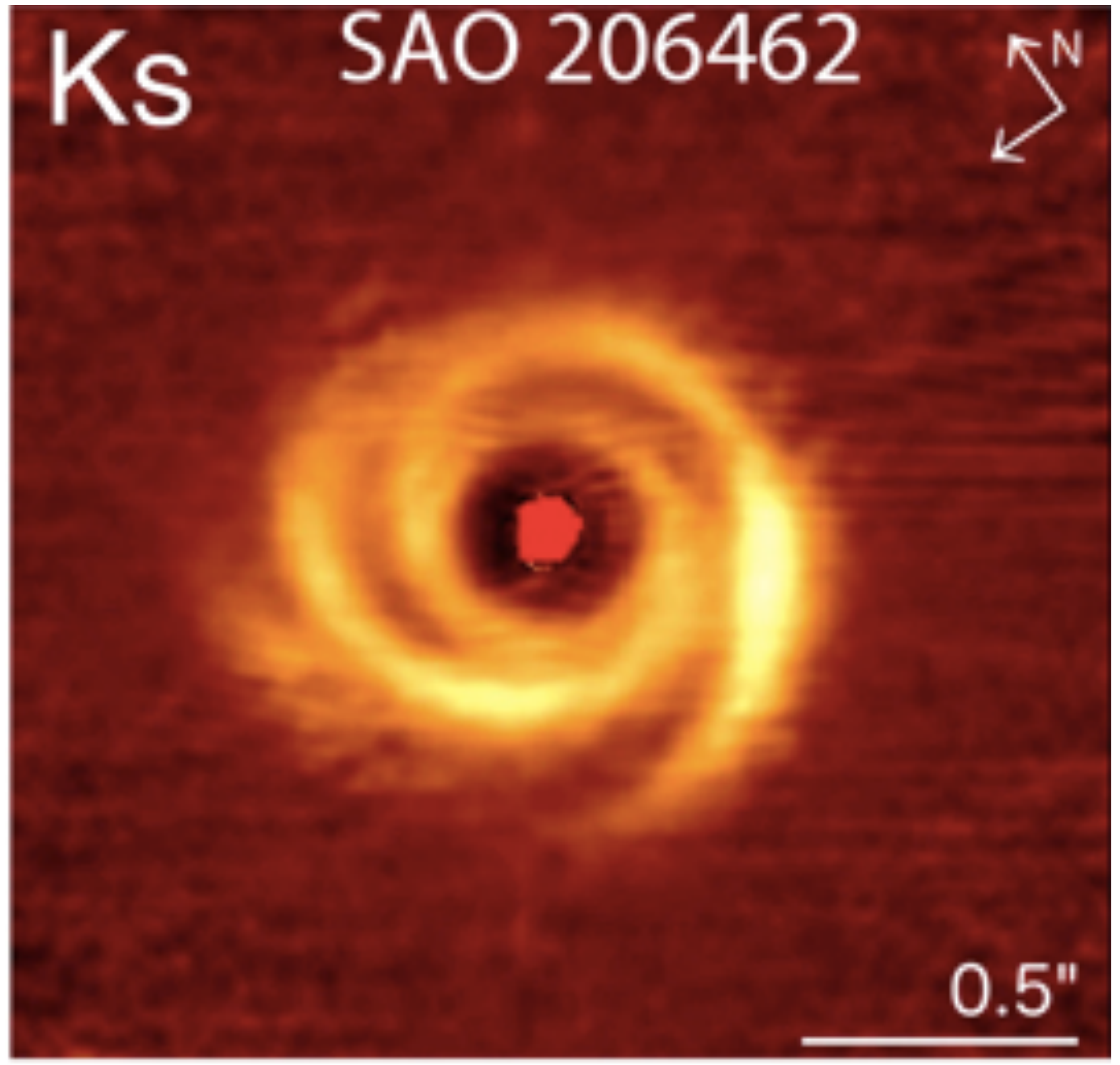
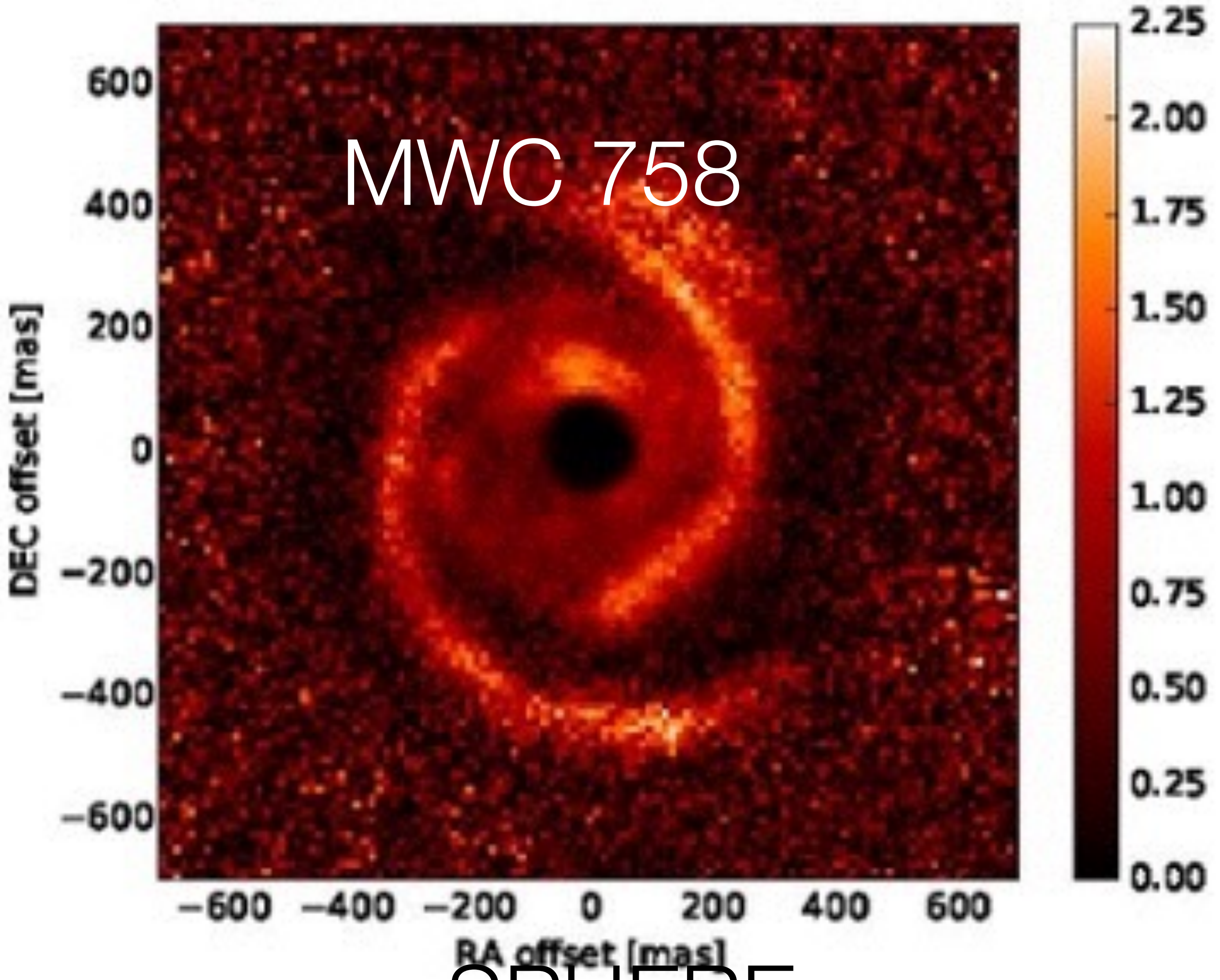
Scattered light with extreme AO (eg. SPHERE, HiCiao)

Garufi et al 2013



VLT/NACO

Benisty et al 2015



SPHERE

What should modelers do?

- For many years, disc models where 1D, axi-symmetric, power-law structures for density and temperature
- Going beyond such models is essential not only to explain observations, but also to understand dynamics
- Two component modeling (gas/dust) is crucial (CRUCIAL!)

What do we (in Milano) do?

- We start from a hydrodynamical SPH simulation using the **PHANTOM** code by D. Price
  - Two components: **gas and dust** coupled though drag
  - Several point masses: **star(s), planets**
  - **Self-gravity** (of both gas and dust)
- We use a Monte-Carlo ray tracing code to get dust temperatures from irradiation
- We compute synthetic images either in scattered light or in dust continuum assuming a given instrumental response (ALMA, HiCIAO, etc…)
- What we do NOT do (yet):
  - Chemistry: chemical network needed to get molecular species and produce gas intensity maps
  - Radiative transfer: to have temperature self-consistently during hydro simulation (almost there!)

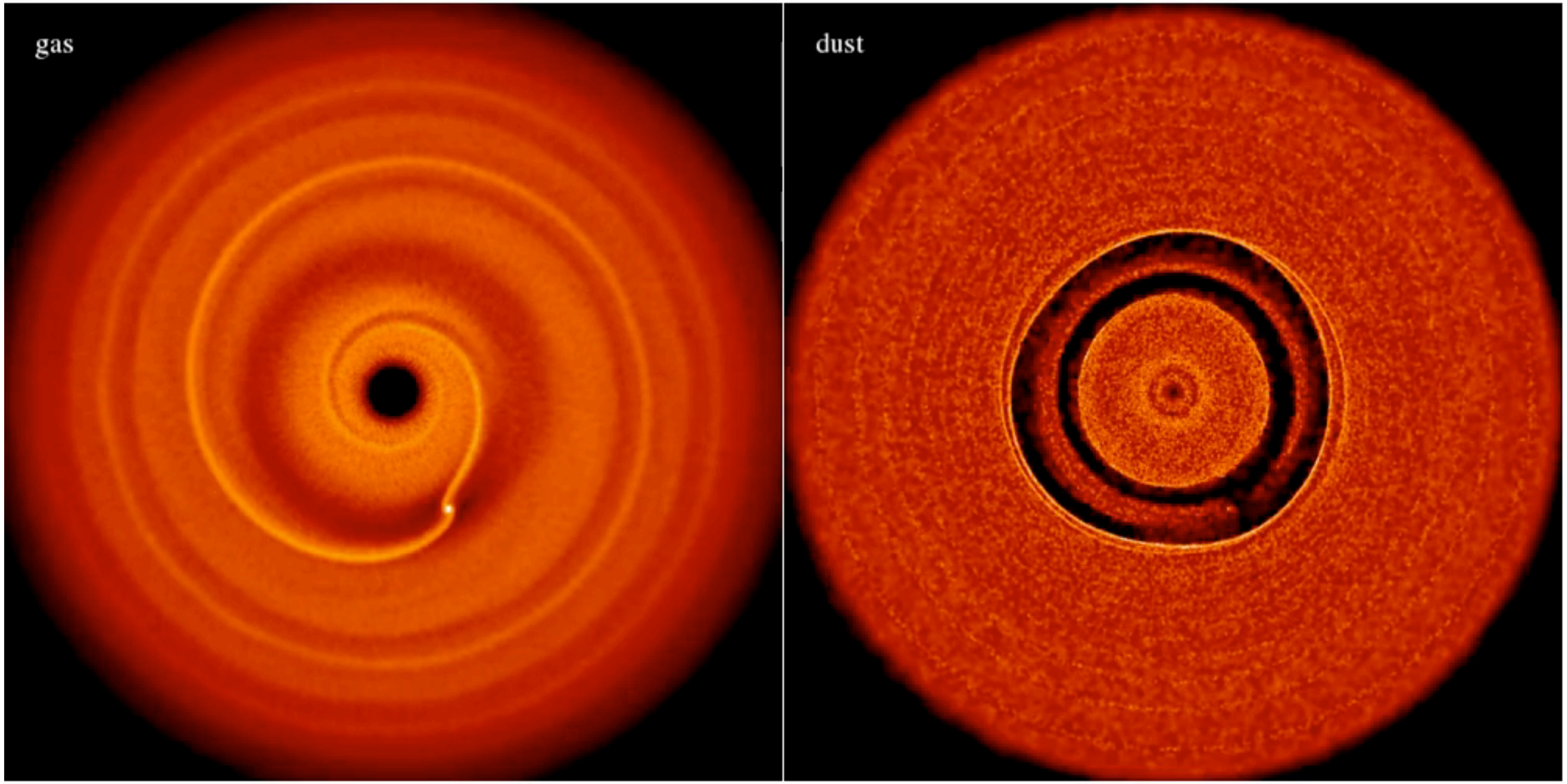
Gap opening in a dust disc

(Dipierro et al 2016)

- Several possible mechanisms, depending on planet mass and Stokes number
  - **Large planet** (satisfies gas gap opening)
    - Small dust (*St<<1*): follows the gas
    - For *St~1*: dust trapping at the gap edge (Pardekooper & Mellema 2004)
    - Dust filtration at the gap edge (Rice et al 2006)
    - This is likely to create narrow rings in dust
  - **Small planet** (does not open a gap in the gas)
    - For *St>~1*, a gap can *still* be opened in the dust
    - Here, drag *resists* rather than *assists* gap opening

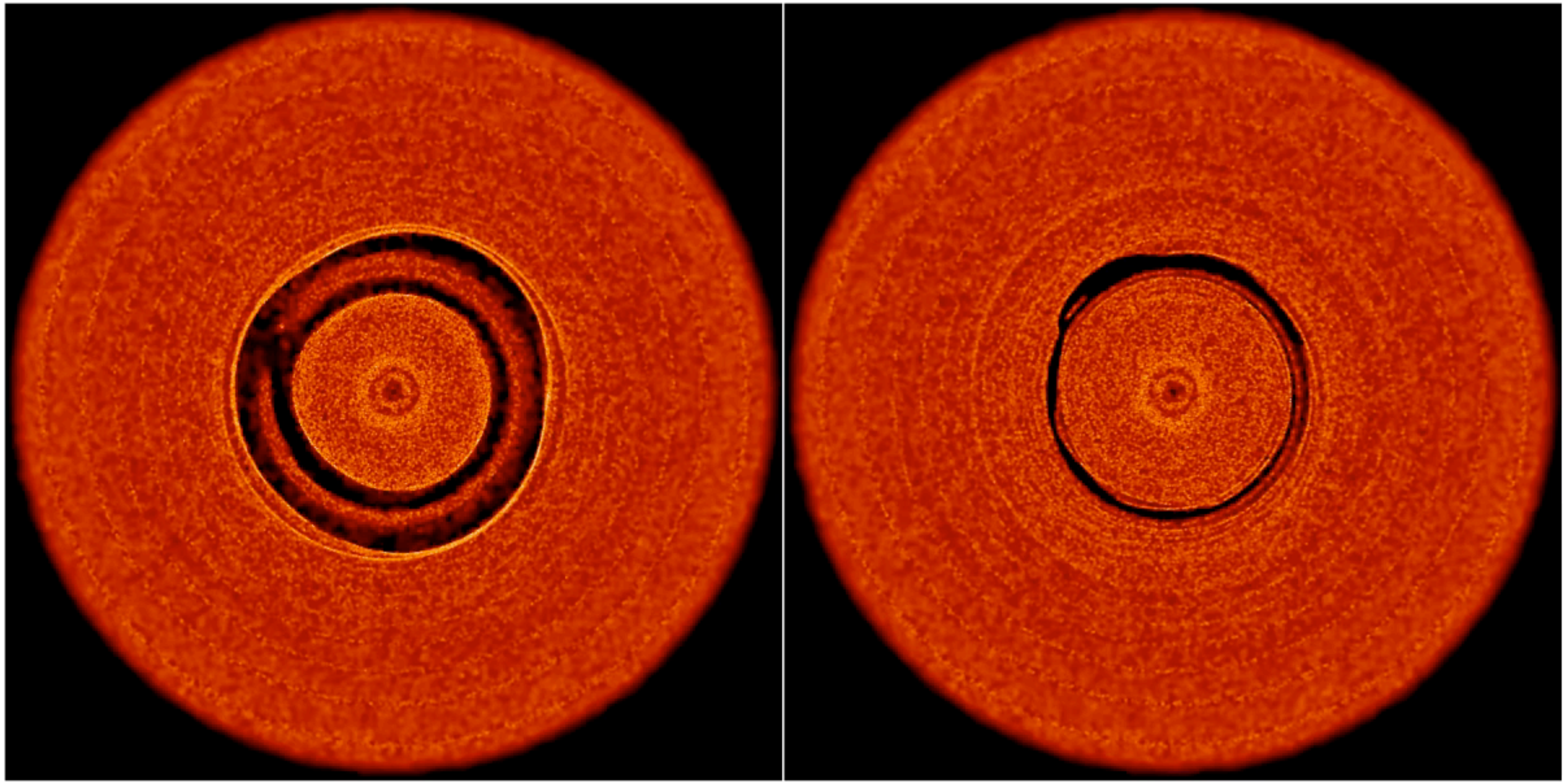
Gap opening in a dust disc

(Dipierro et al 2016)



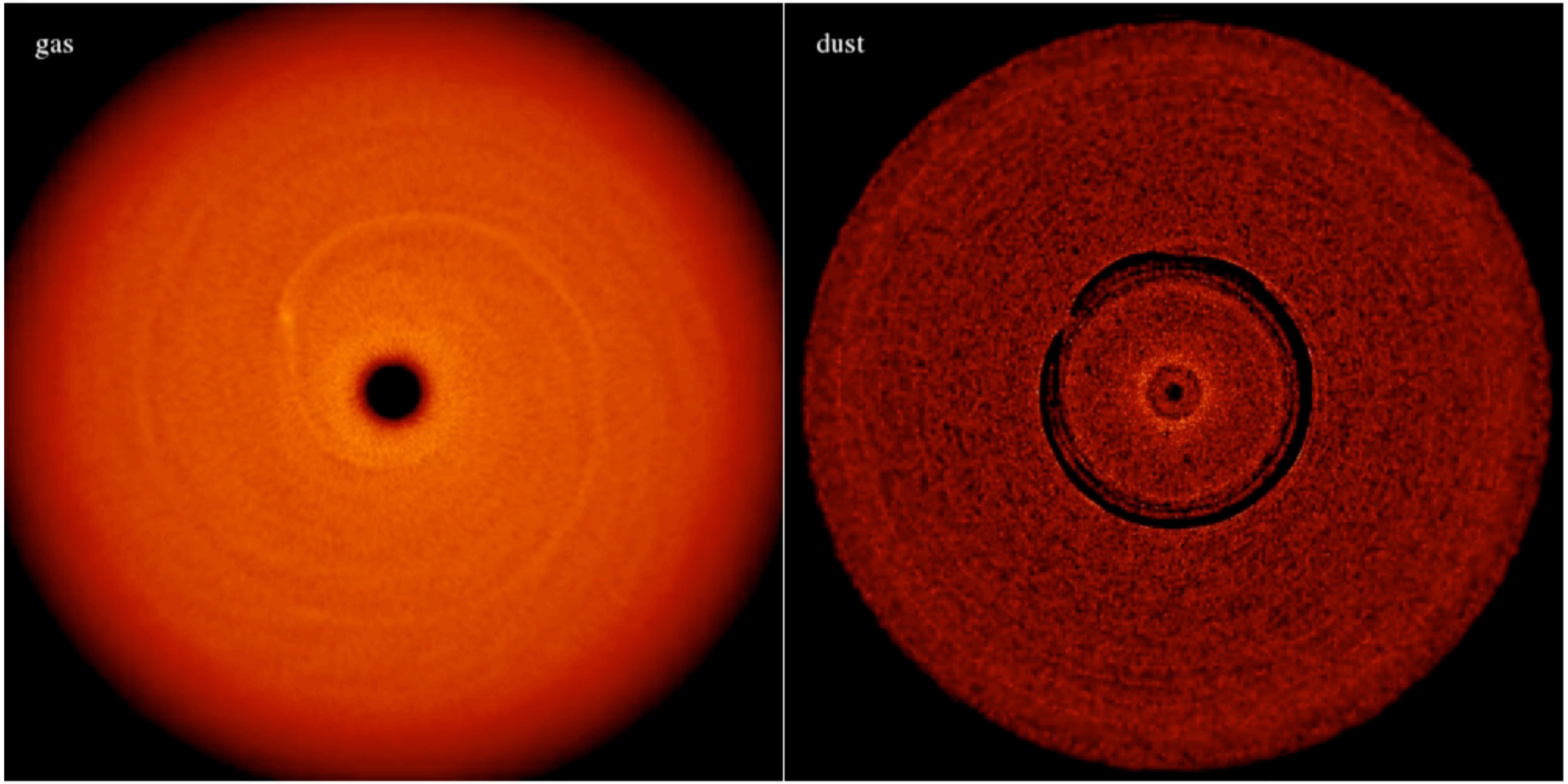
M_p=1M_{Jup} - St=10

Gap opening in a dust disc
(Dipierro et al 2016)



M_p=1M_{Jup} - St=10

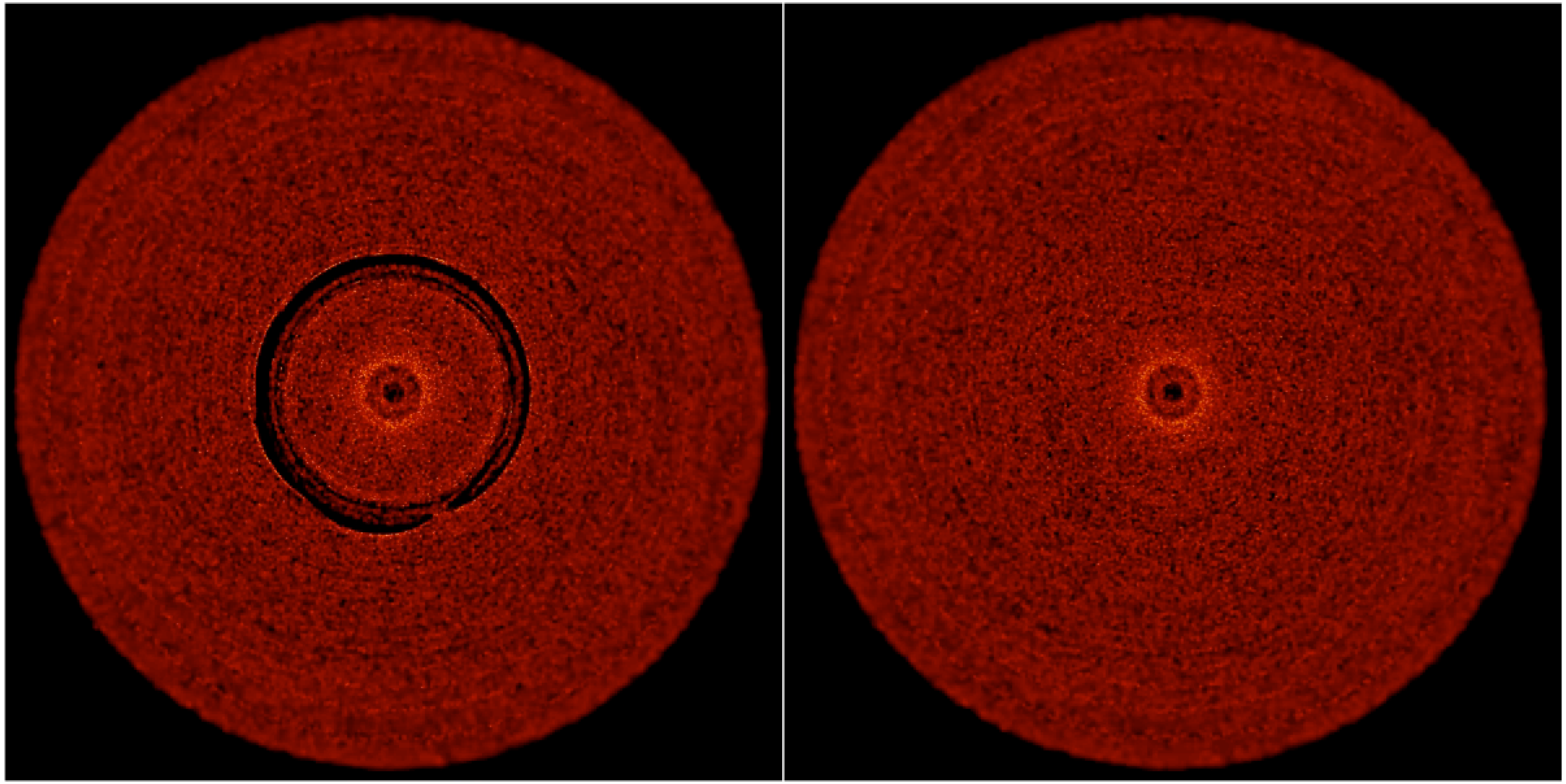
Gap opening in a dust disc
(Dipierro et al 2016)



$M_p=0.1M_{Jup}$ - $St=10$

Gap opening in a dust disc

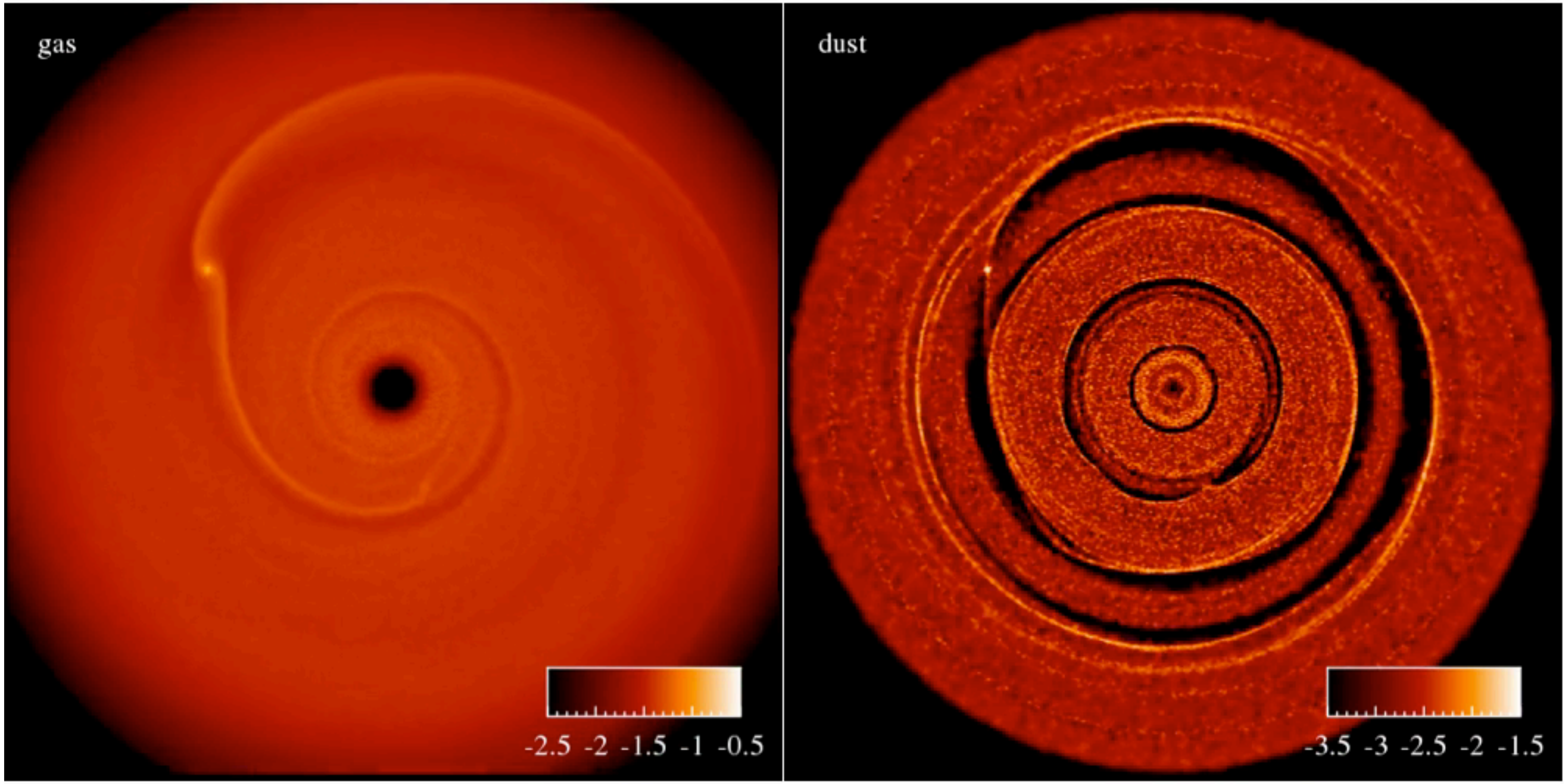
(Dipierro et al 2016)



M_p=0.1M_{Jup} - St=10

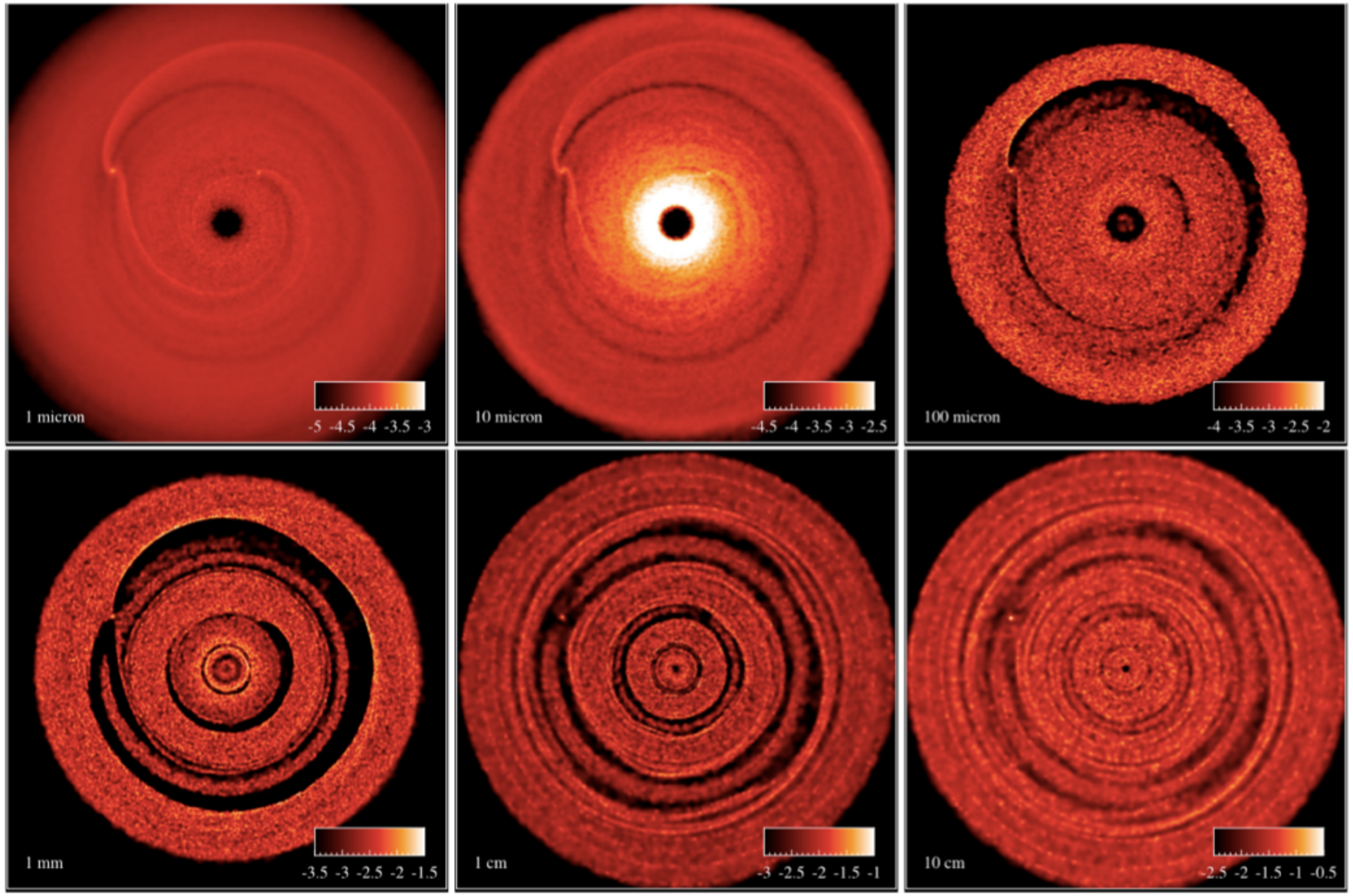
Explaining the HL Tau disc

(Dipierro et al 2015b)



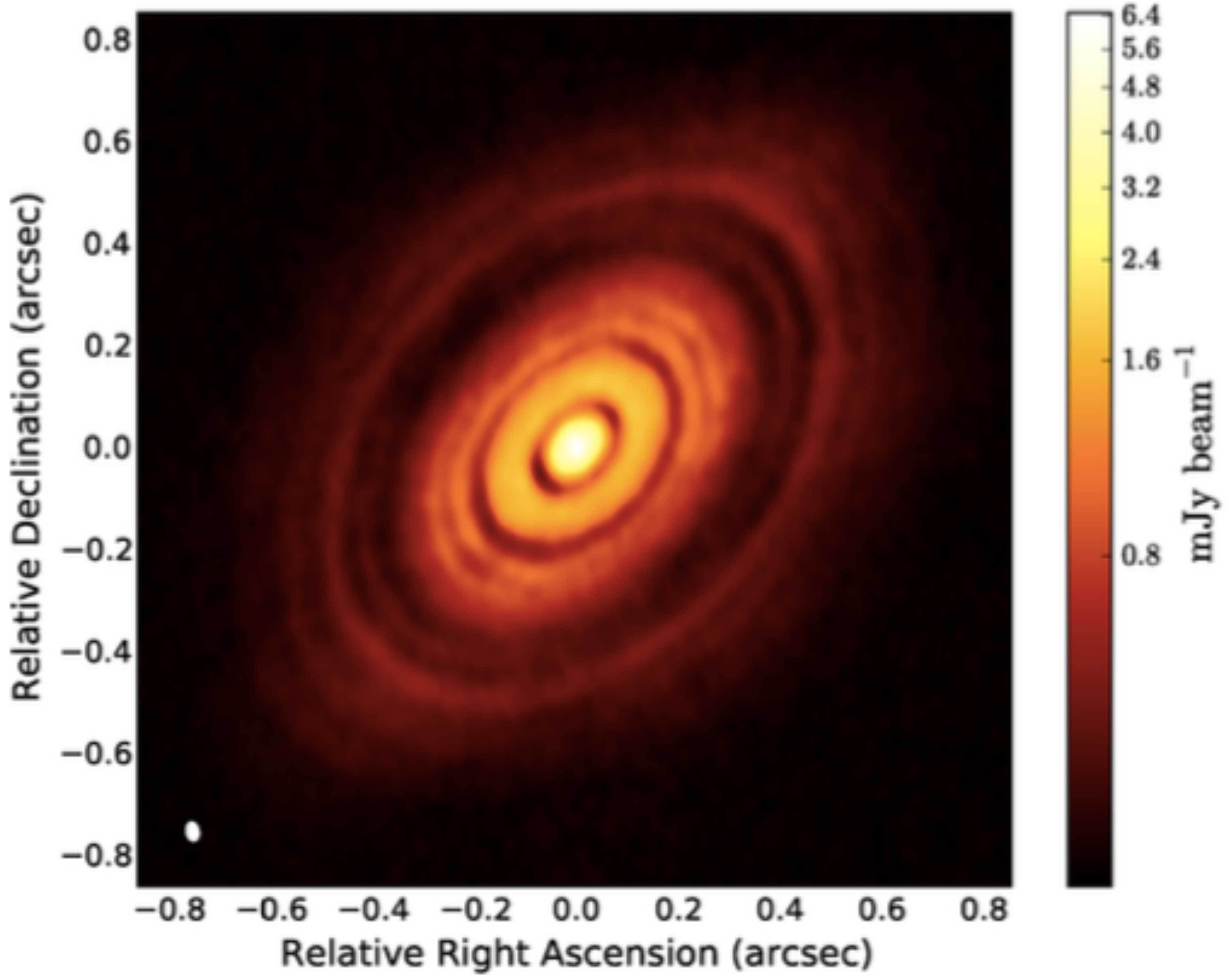
Three planets: *$0.2M_{Jup}$ (@13.2au)*, *$0.27M_{Jup}$ (@32.3au)*, *$0.55M_{Jup}$ (@68.8au)*

Explaining the HL Tau disc
(Dipierro et al 2015b)

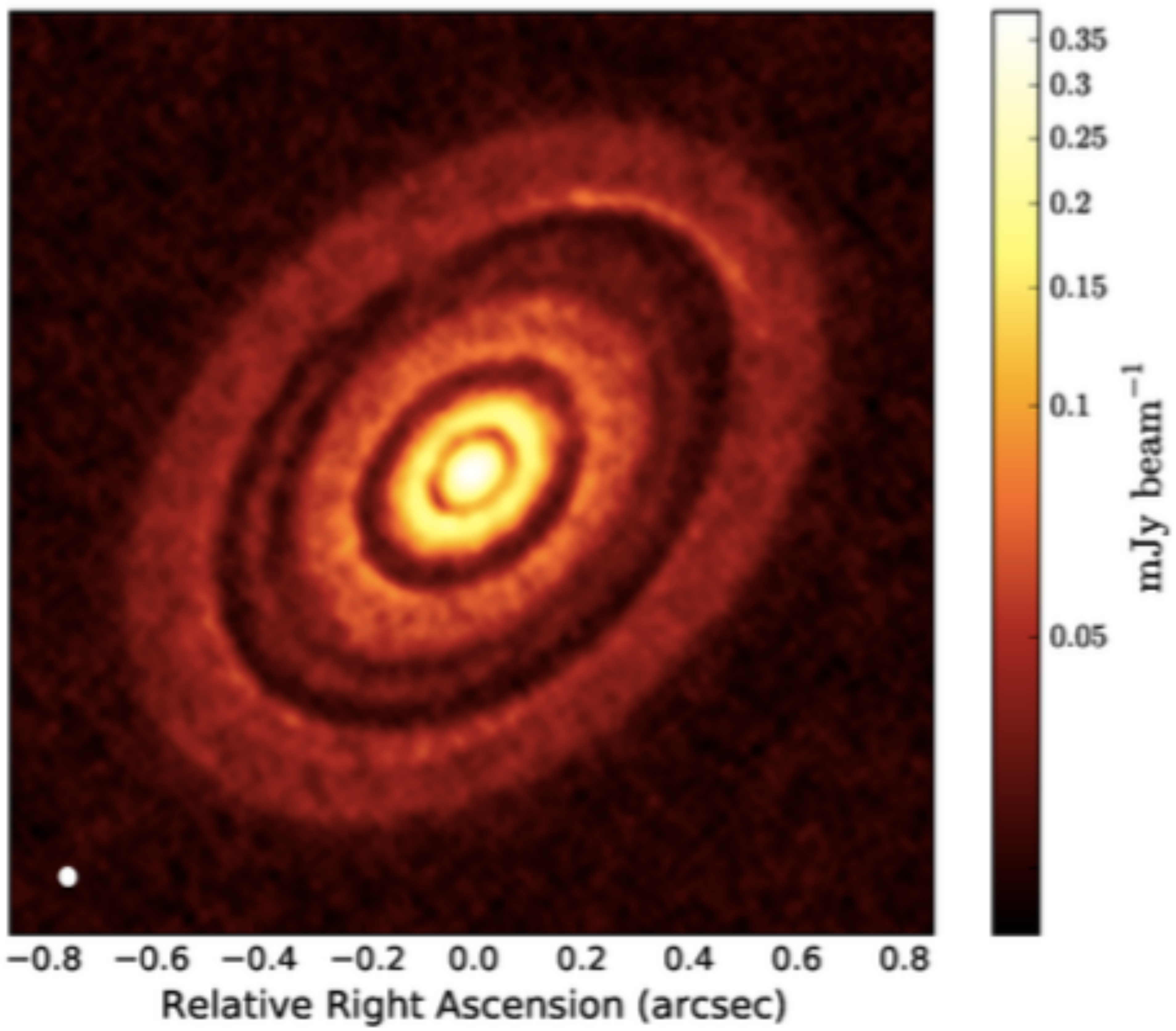


Simulate 6 different sizes, assume a dust size distribution and a gas/dust ratio —> compute synthetic images

Explaining the HL Tau disc
(Dipierro et al 2015b)



ALMA Partnership (2015)



Dipierro et al (2015)

Simulate 6 different sizes, assume a dust size distribution and a gas/dust ratio —> compute synthetic images

Ragusa et al, MNRAS in press 2016

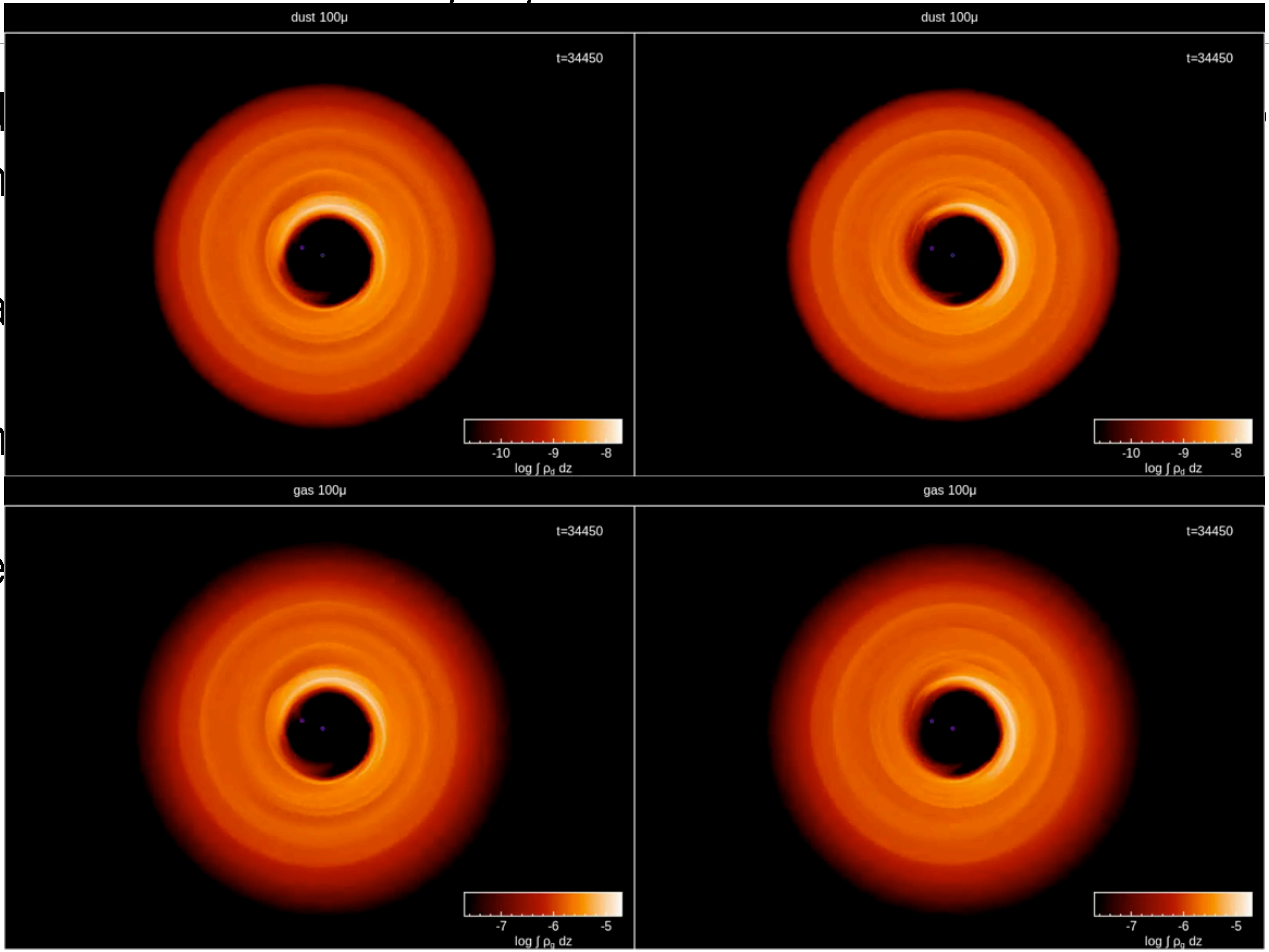
Asymmetric cavities in binary systems

- Cavity produced by a massive planet or a low mass companion prone to eccentric instability
- Require mass ratios q>~0.04 (D'Orazio et al 2016)
- Well known in the context of supemassive black hole binaries
- See Aitee et al (2013) for the protostellar case

Ragusa et al, MNRAS in press 2016

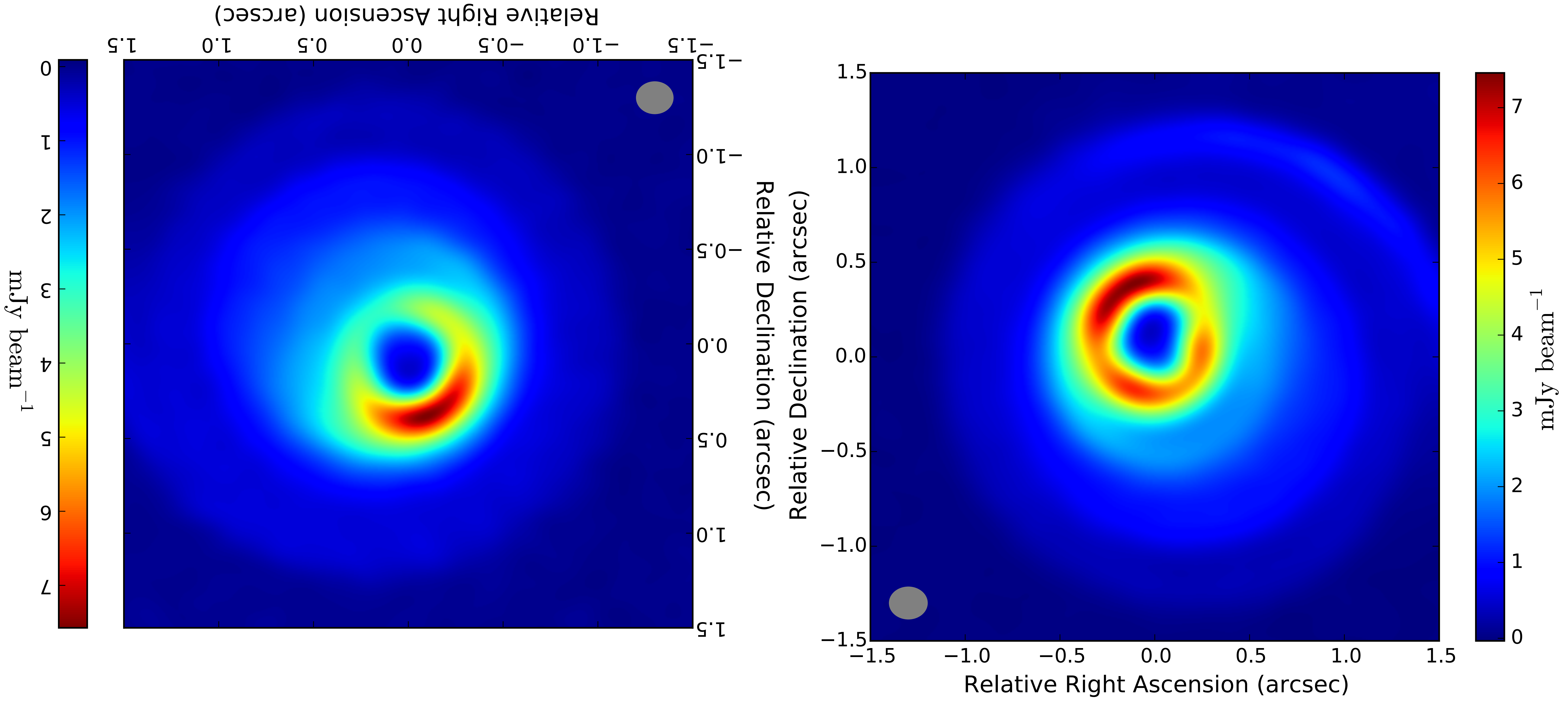
Asymmetric cavities in binary systems

- Cavity prod … prone to eccentric in
- Require ma
- Well known
- See Aitee e



Asymmetric cavities in binary systems

- How do these cavities look like through ALMA?



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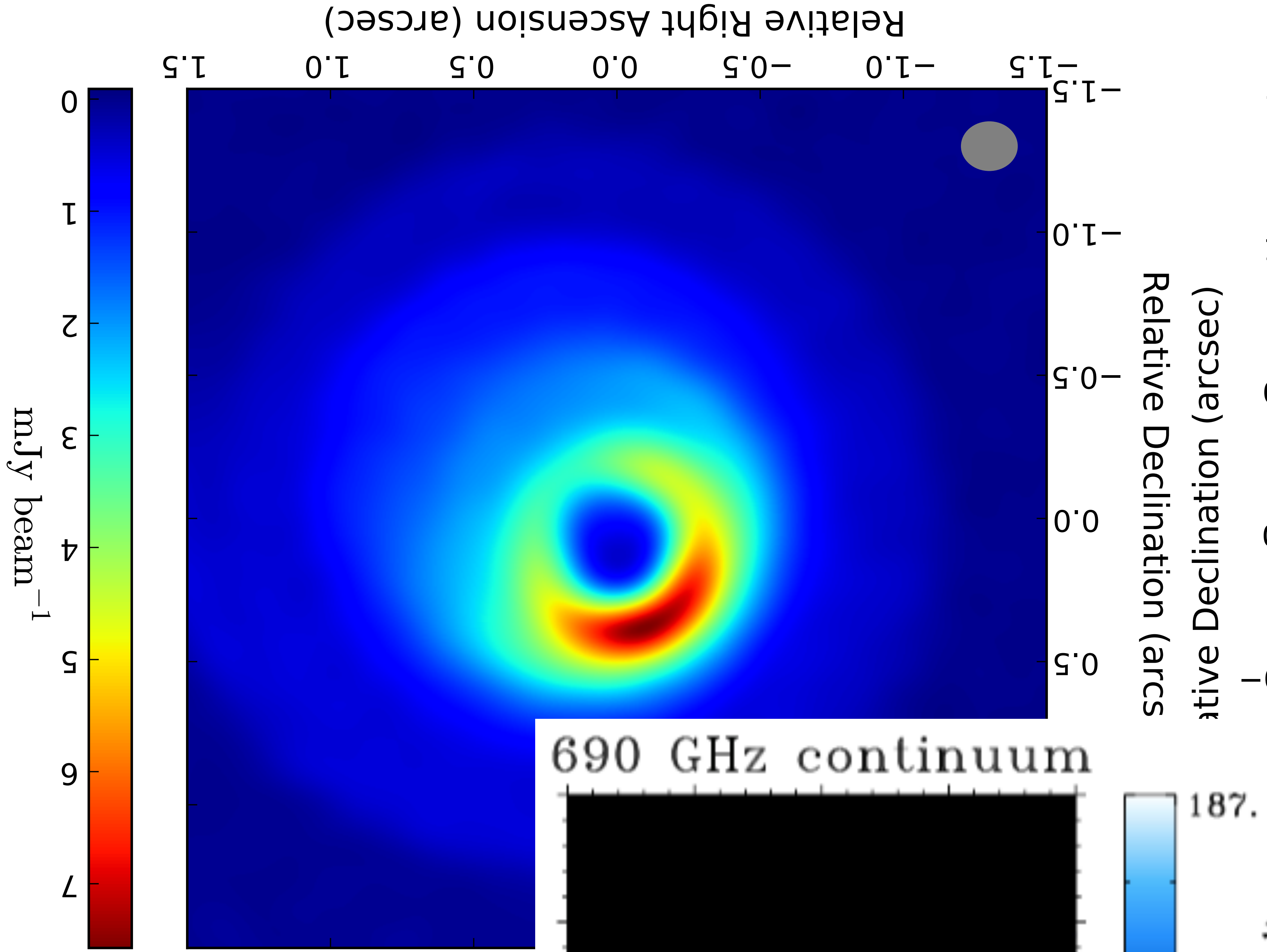

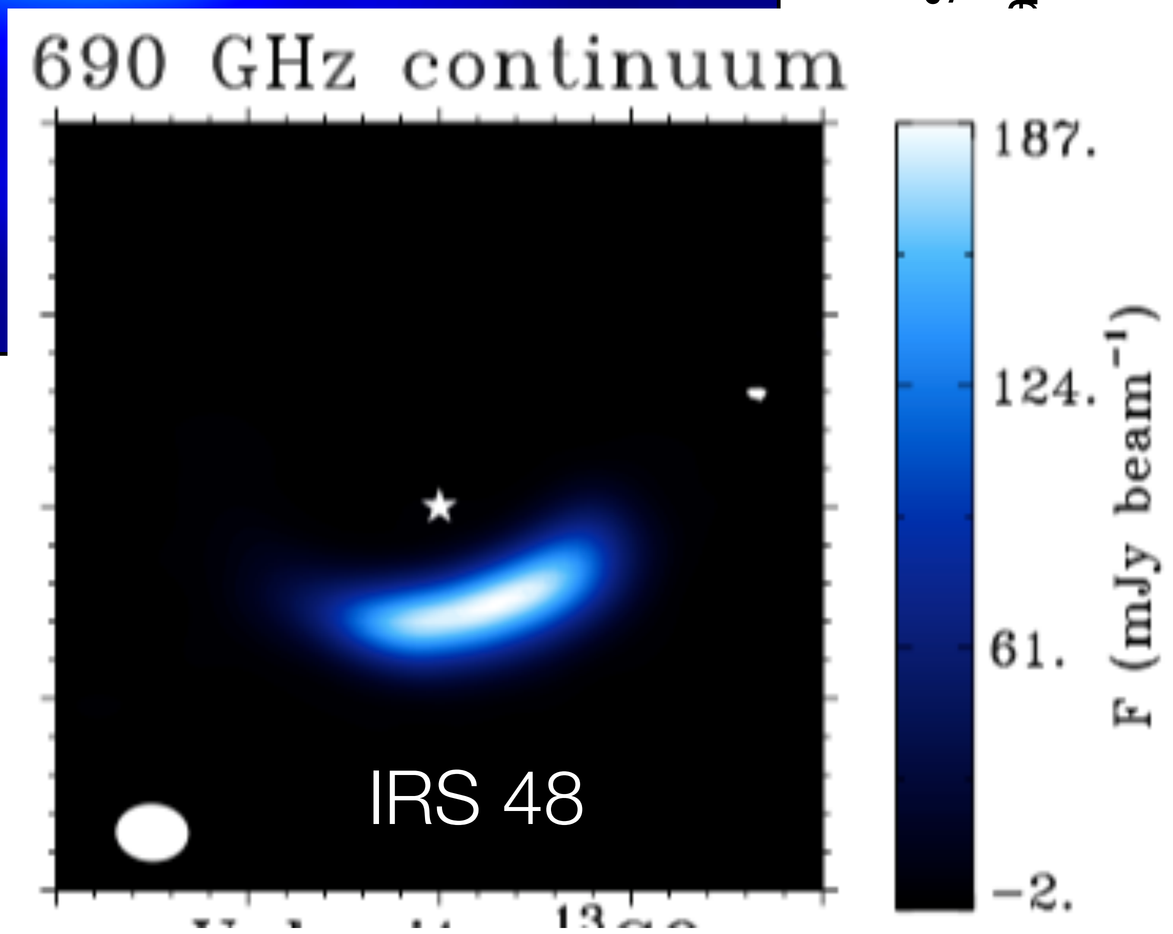

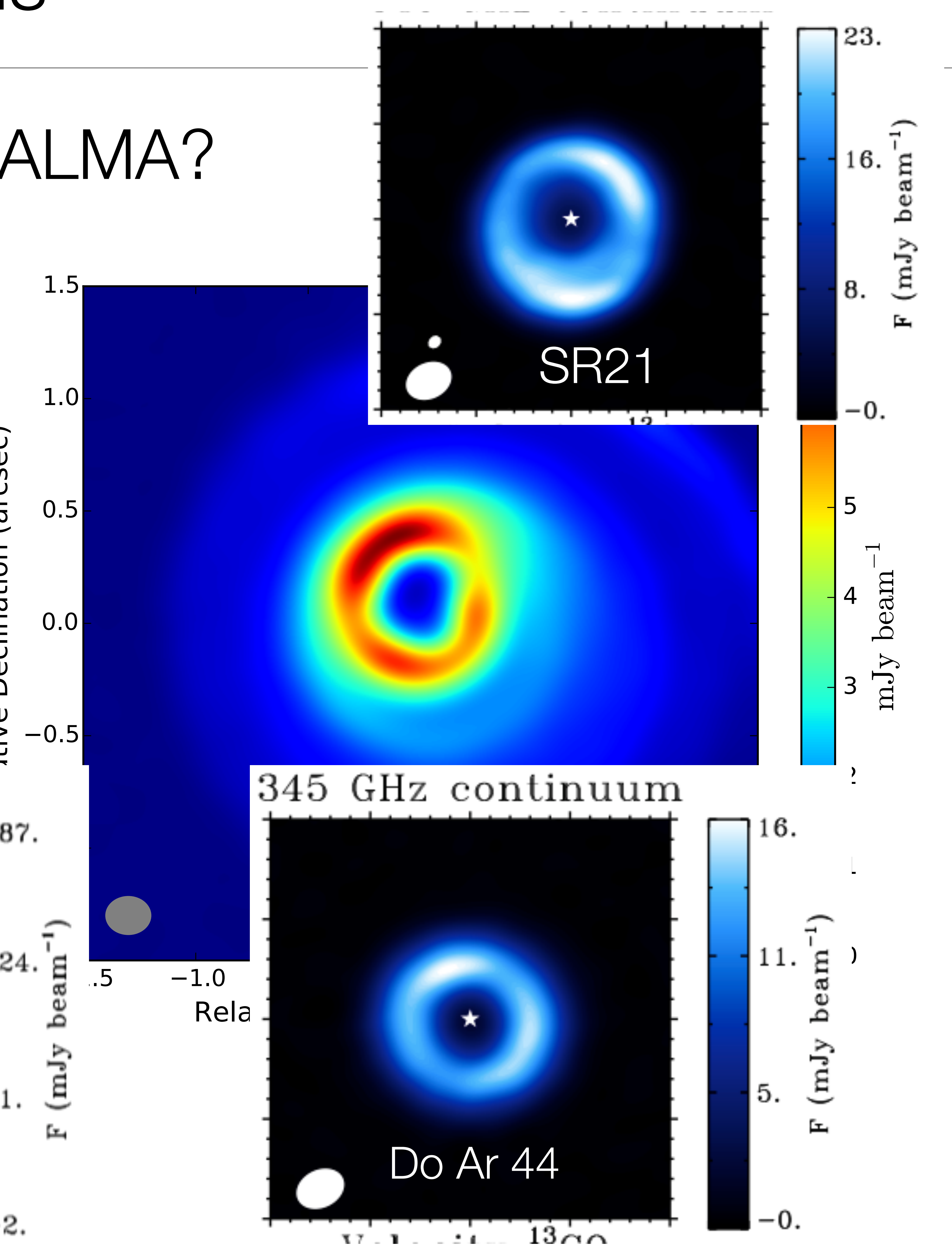

Images from van der Marel et al 2016

Conclusions

- SPH is reaching its maturity: a well founded hydro code with many physical processes included
- Whenever a detailed comparison with grid based code has been done, results appear to converge
- SPH usually does not break: very careful with validating ones solution
- Very often, bad SPH results actually come from bad SPH codes
- SPH does not mean GADGET!!!