Planet formation in the ALMA era
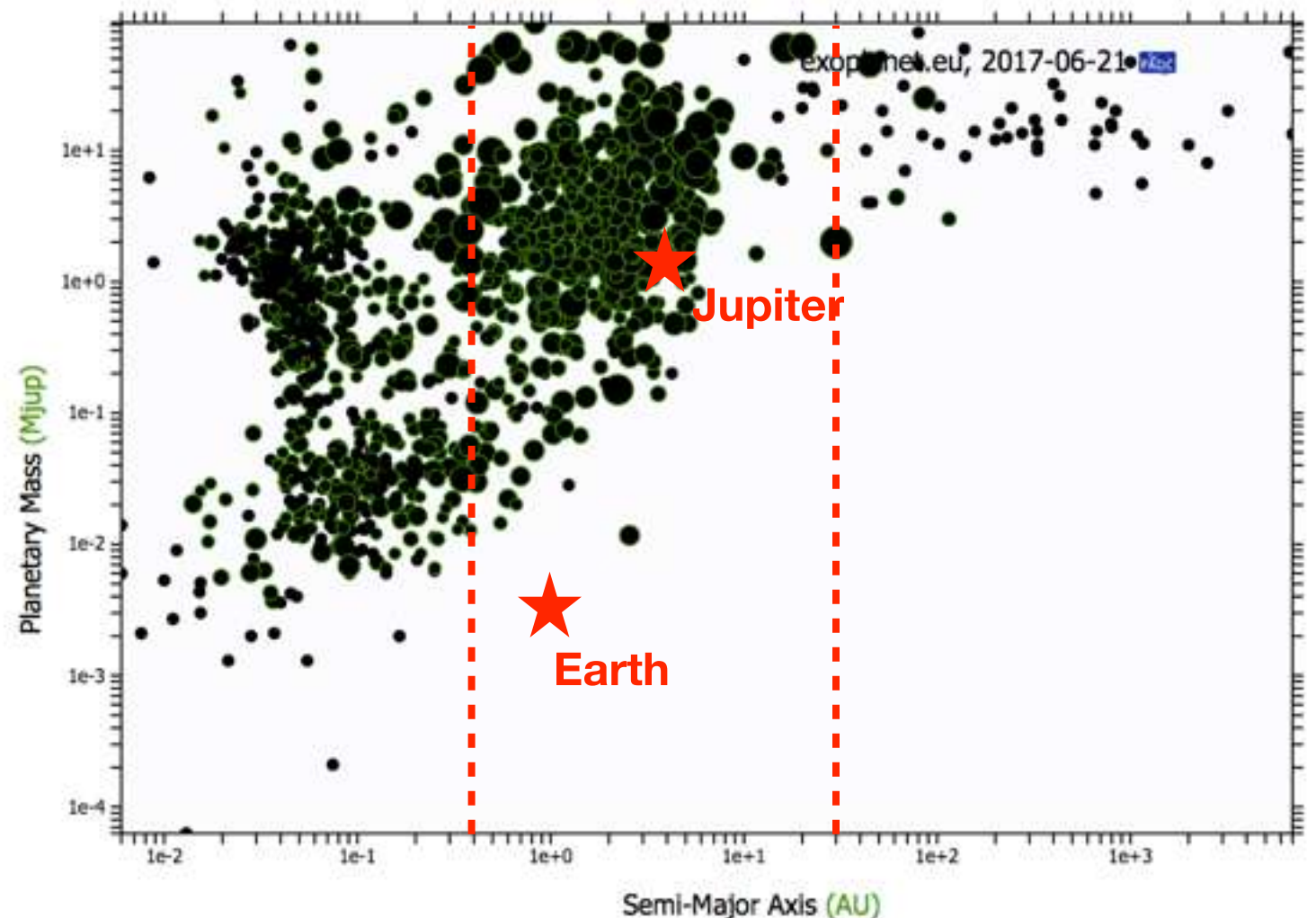
Giuseppe Lodato

A revolution in planet formation theory

- New facilities are revolutionizing our understanding of the planet formation process

  - Extra-solar planet detection campaigns (Kepler, HARPS)

>3000 planet candidates
>1000 confirmed planets

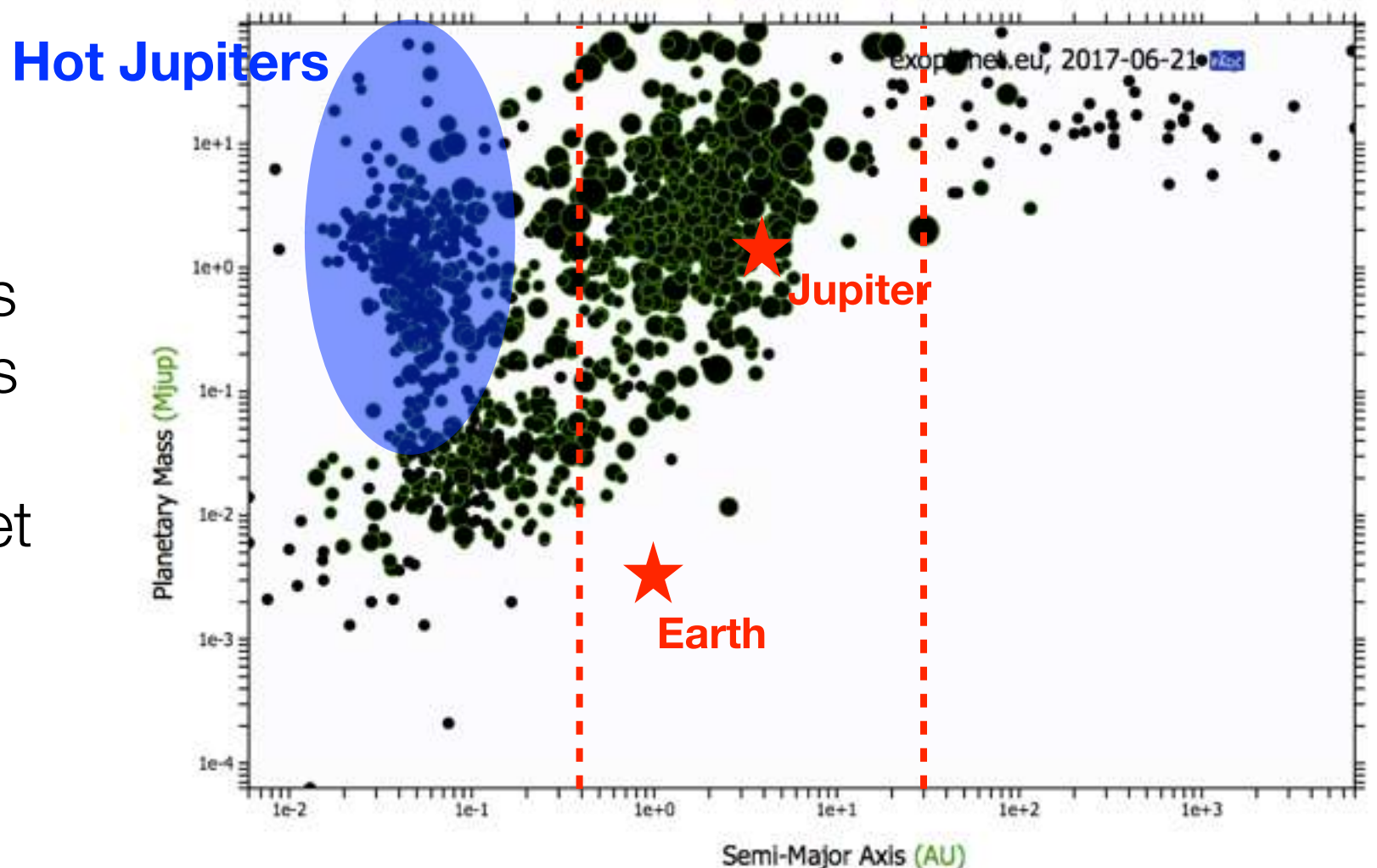From the extrasolar planet encyclopedia

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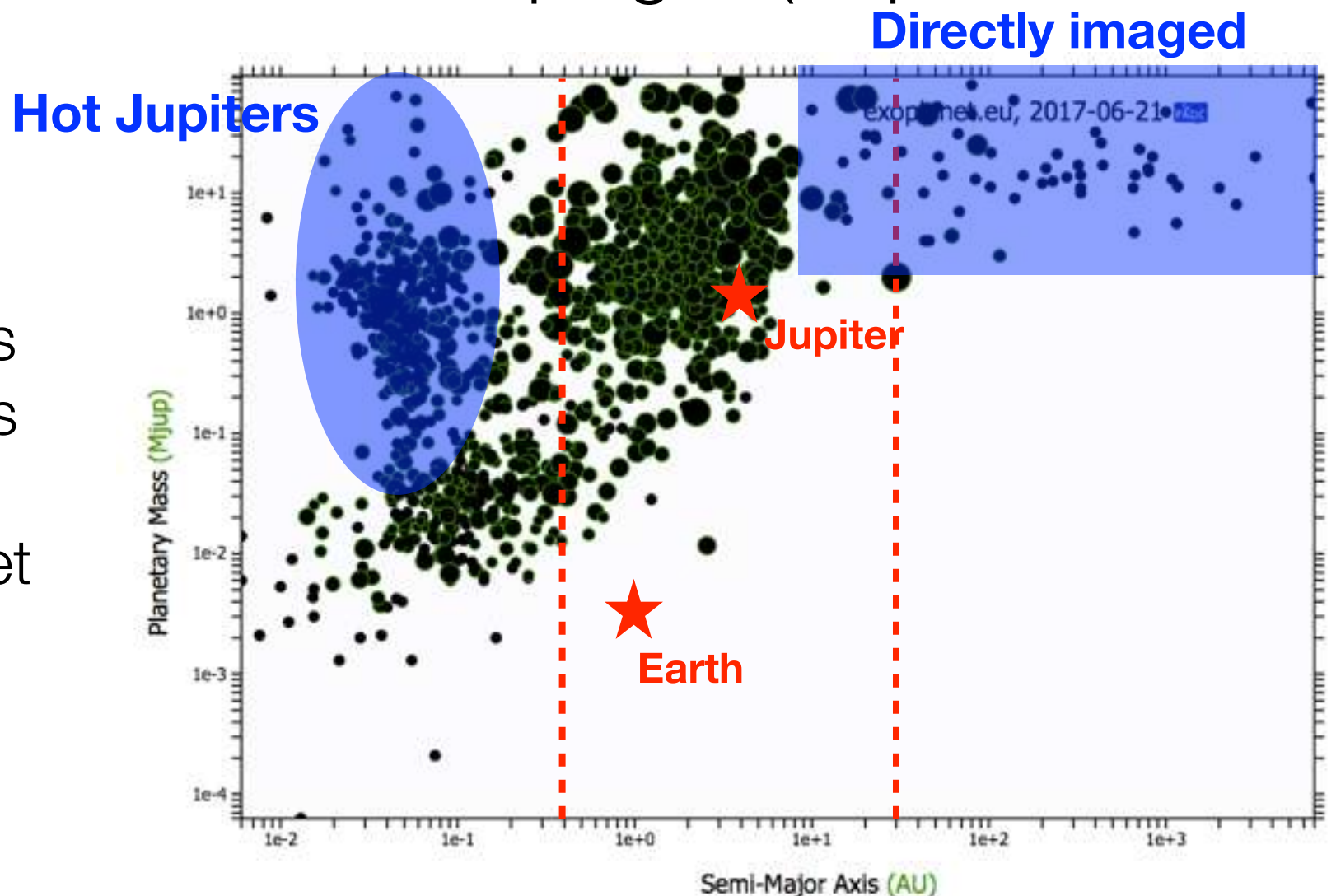
From the extrasolar planet
encyclopedia

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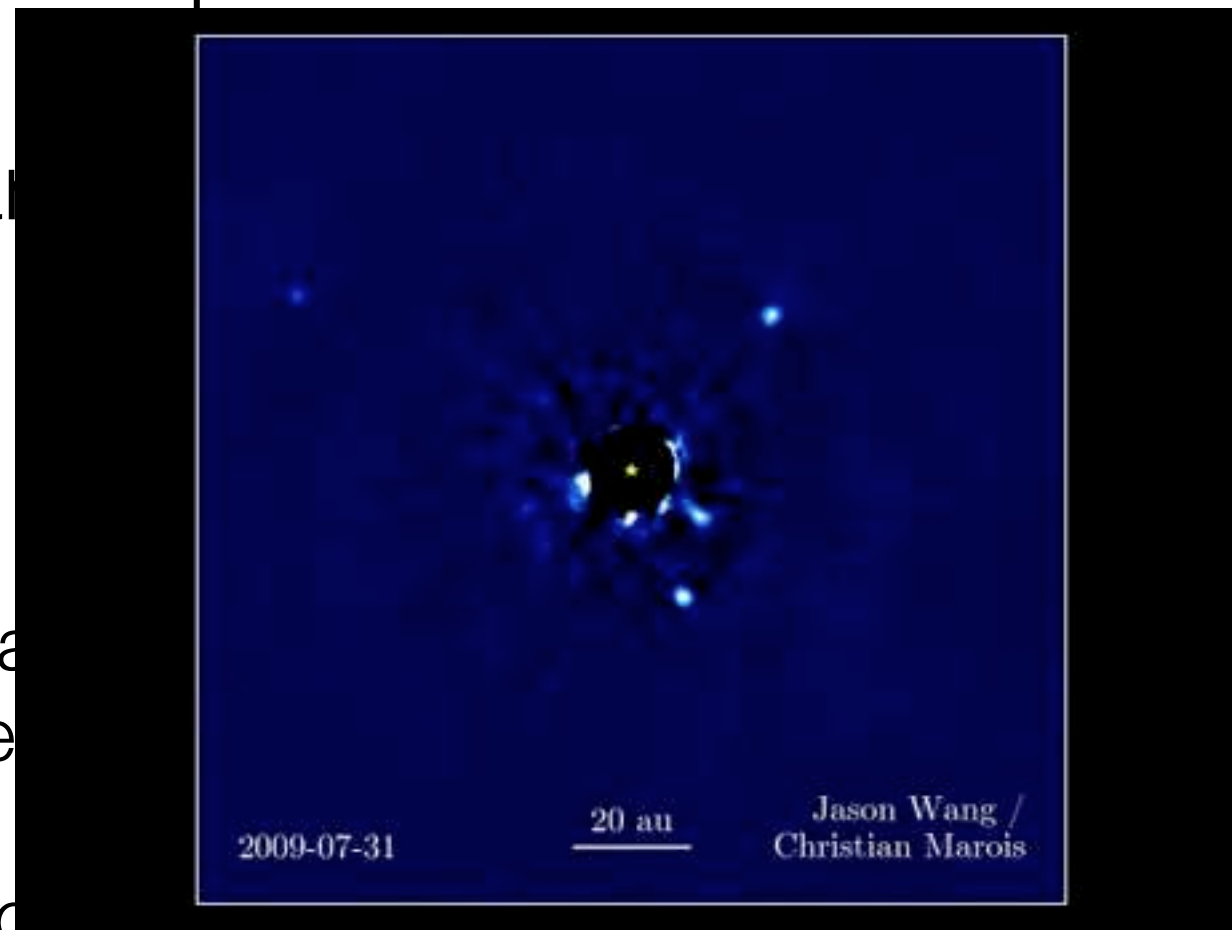
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A revolution in planet formation theory

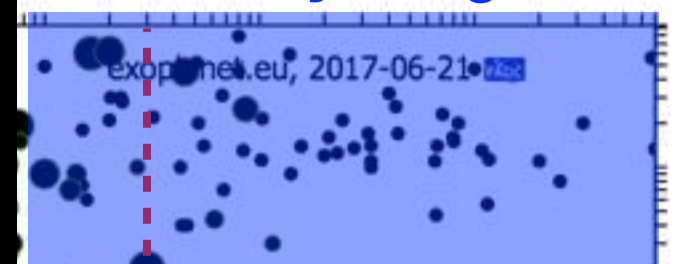- New facilities are revolutionizing our understanding of the planet formation process

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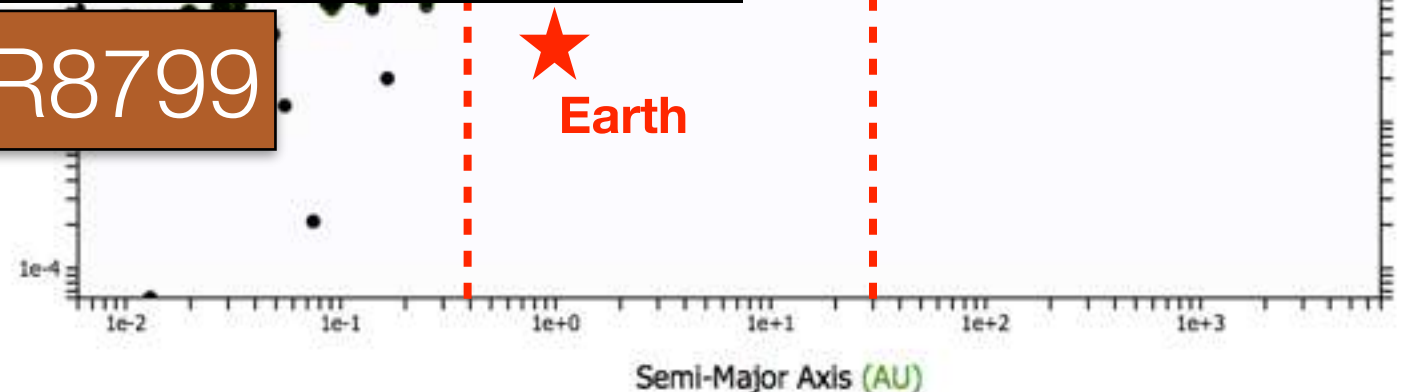>1000 confirme

From the extrasolar planet
encyclopedia

Directly imaged

exoplanet.eu, 2017-06-21

Jupiter

Earth

HR8799

20 au

2009-07-31

Jason Wang /
Christian Marois

Semi-Major Axis (AU)

A revolution in planet formation theory

- The Atacama Large Millimetre Array (ALMA), and the SPHERE instrument on VLT are redefining our ideas on protostellar discs, the site of planet formation

Protostellar discs

- Composed of gas (99%) and dust (1%)

- Gas dominated dynamics, dust dominates opacity

- mm-sized dust emit in the radio band (ALMA), micron-sized dust emits in the infrared (SPHERE)

- Different grain sizes coupled to the gas differently $\quad St = t_{\mathrm{stop}} \Omega \propto a$

- Fundamental processes in gas discs:

  - Turbulence, viscous accretion, MHD

- Fundamental processes in dust discs:

  - Vertical settling, radial migration (St~1), dust traps

Incredibly rich morphology from ALMA and SPHERE
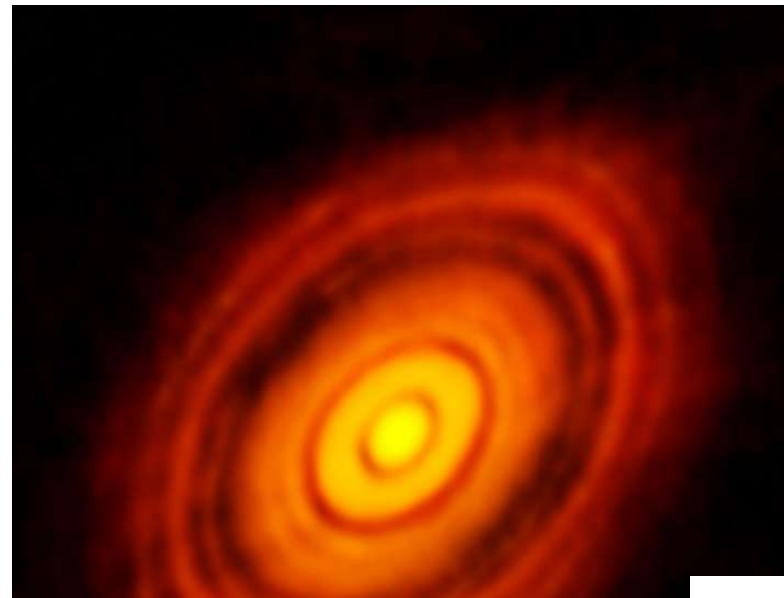
Rings
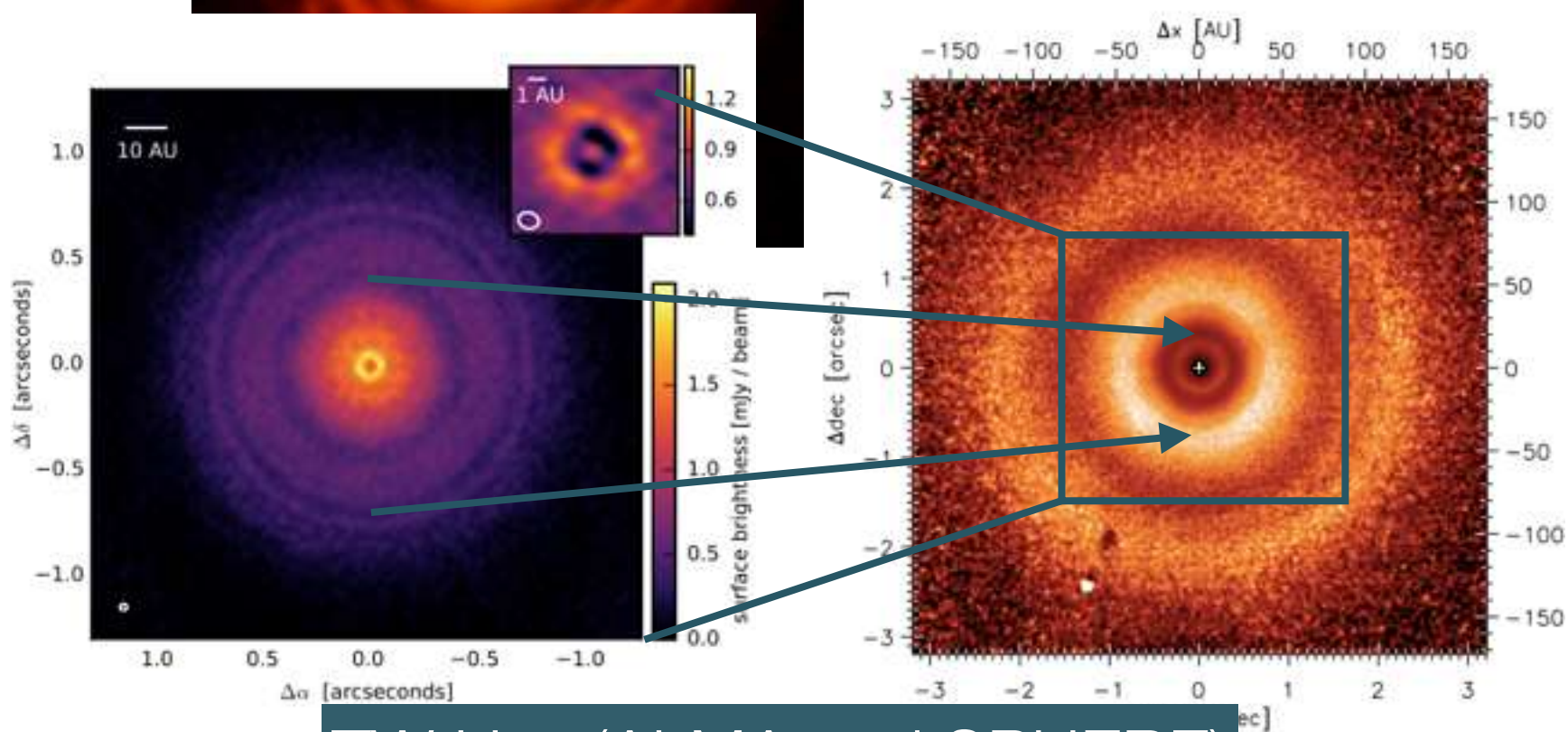
Incredibly rich morphology from ALMA and SPHERE
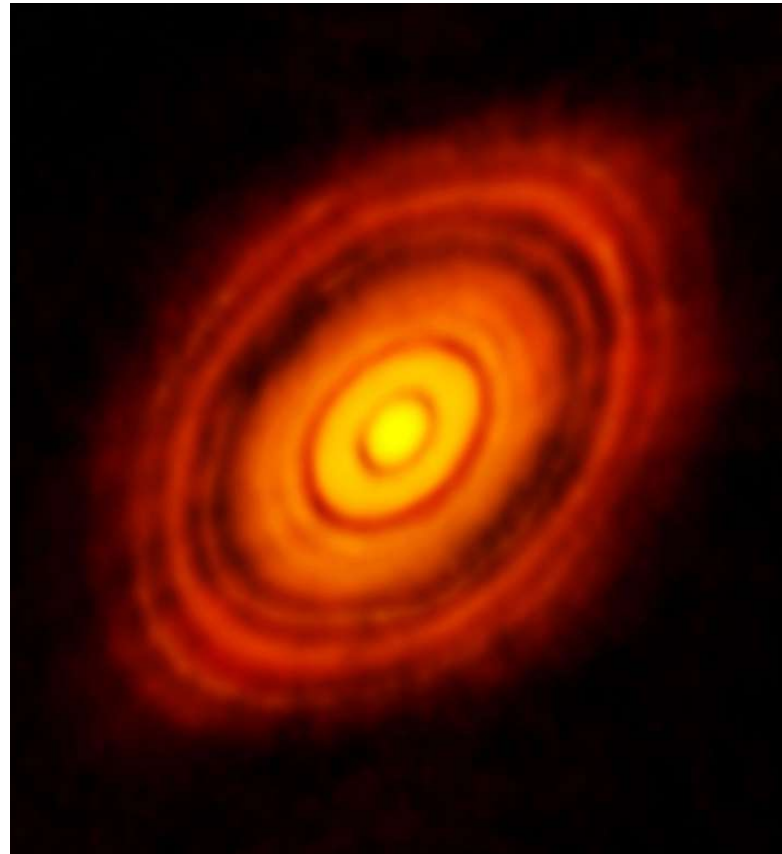
Rings

HL Tau (ALMA)

Incredibly rich morphology from ALMA and SPHERE
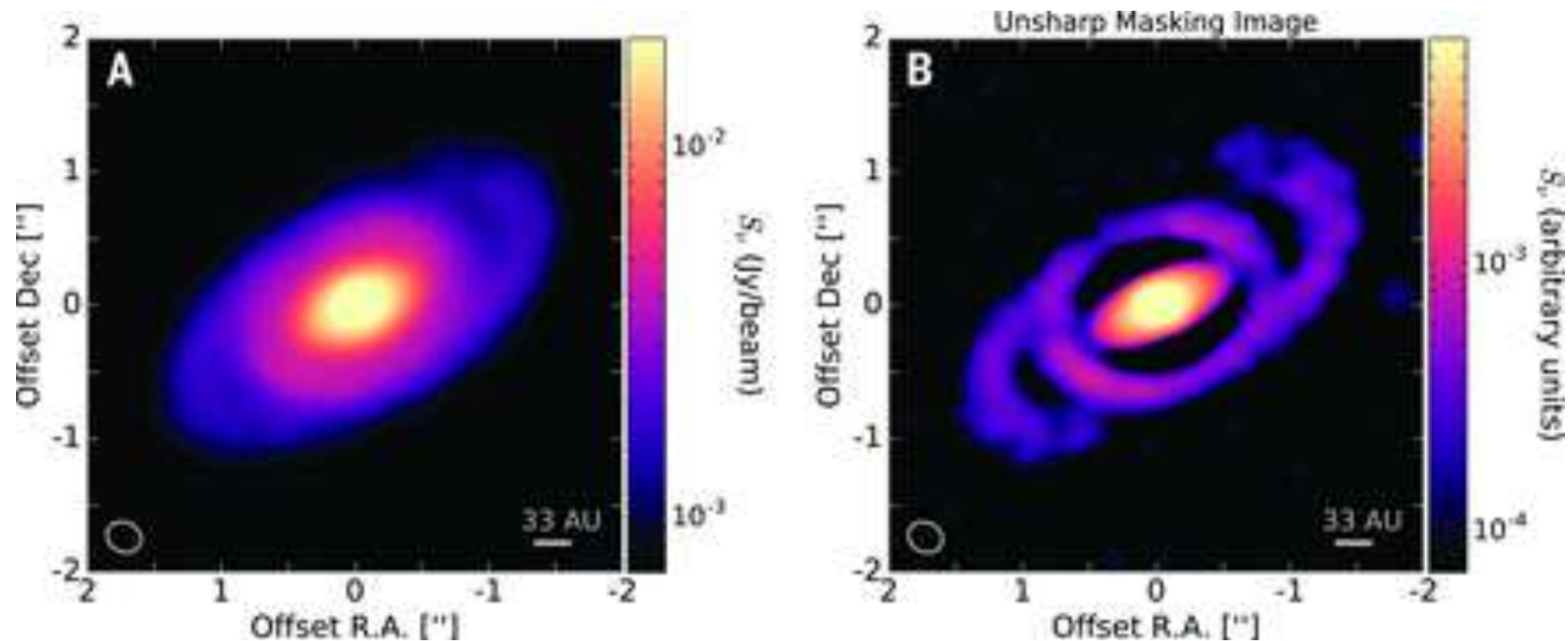
Rings

HL Tau (ALMA)

TW Hya (ALMA and SPHERE)

Incredibly rich morphology from ALMA and SPHERE

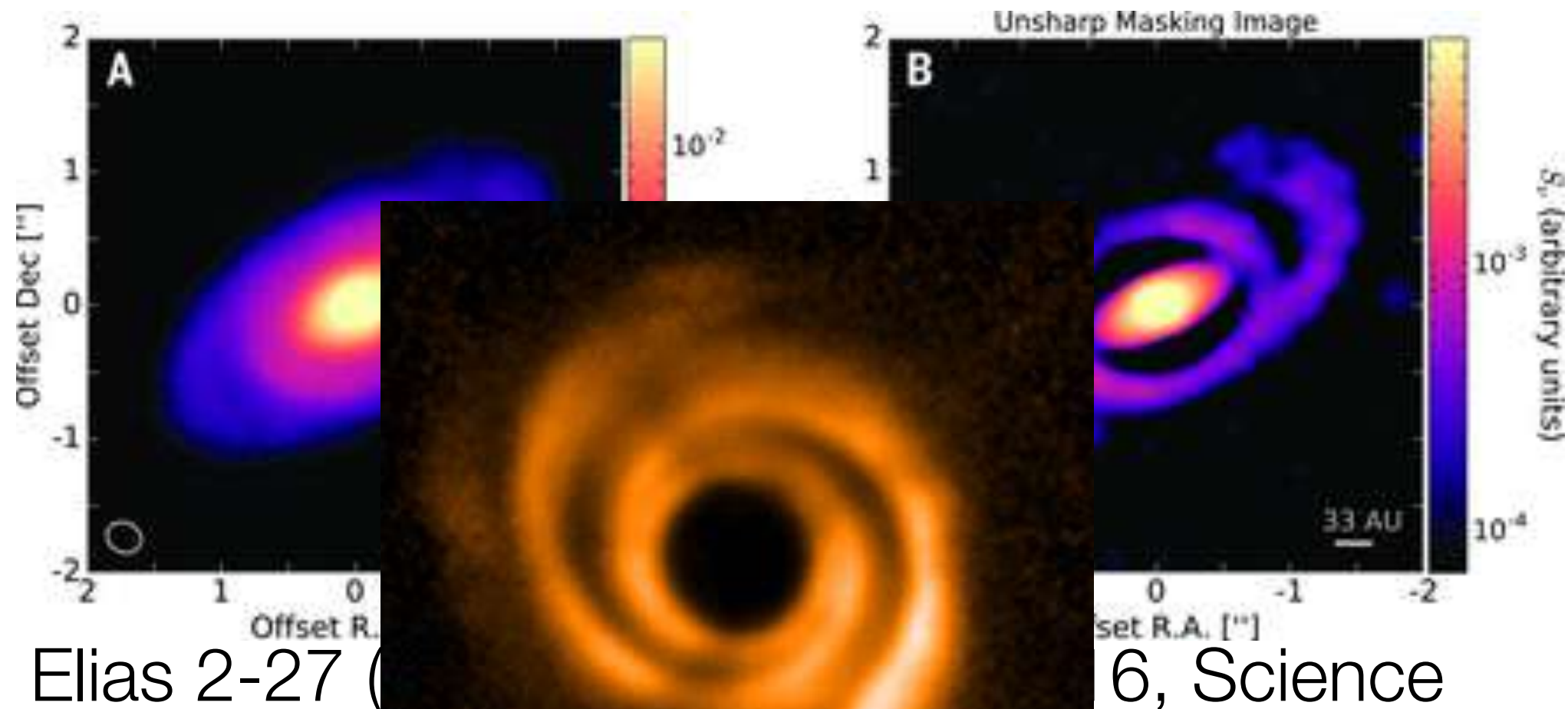Spirals

Incredibly rich morphology from ALMA and SPHERE

Spirals

Elias 2-27 (ALMA), Perez et al 2016, Science
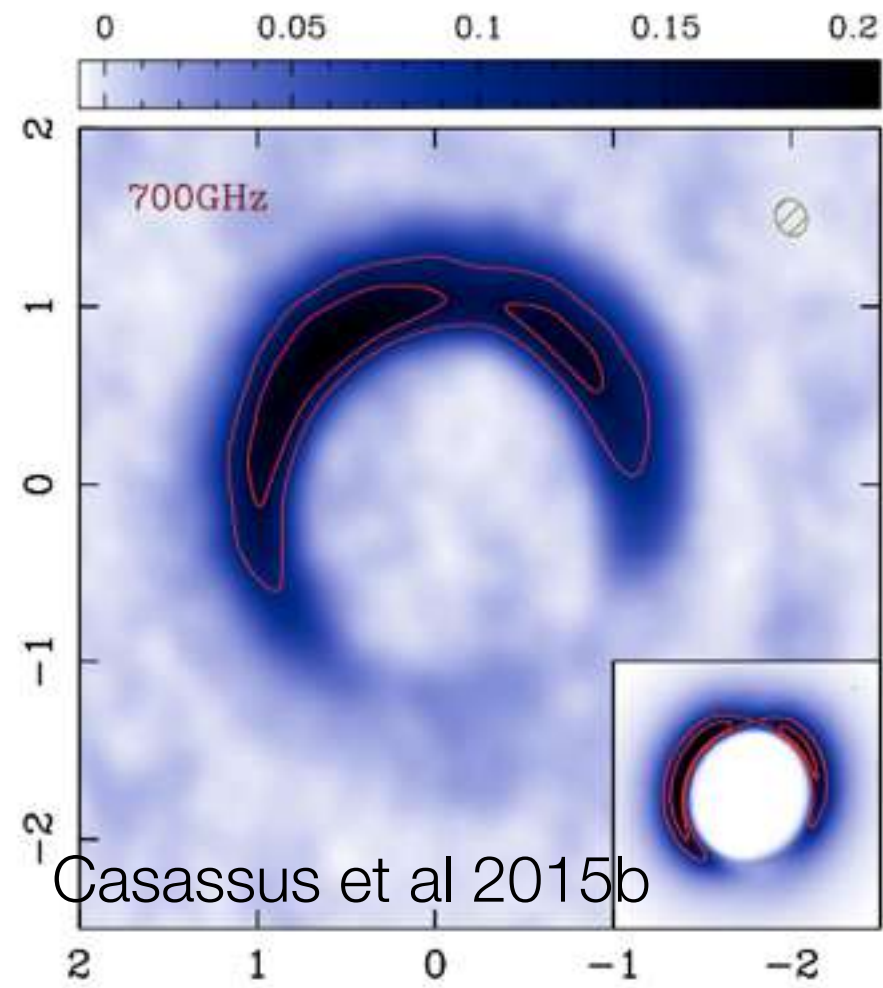
Incredibly rich morphology from ALMA and SPHERE

Spirals
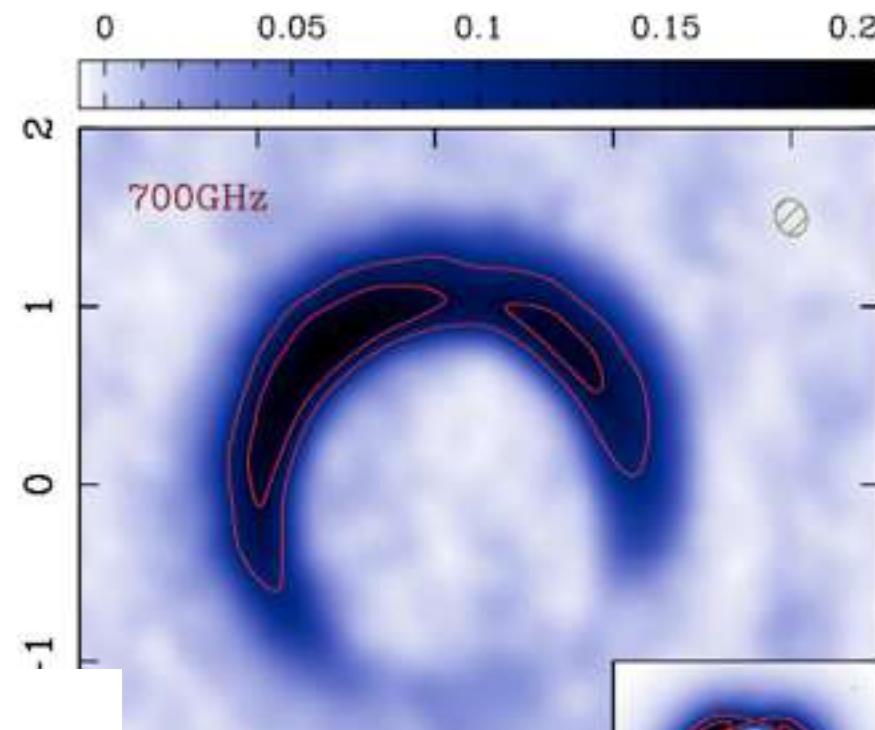

Elias 2-27 (... 6, Science

HD 135344B - SPHERE

Incredibly rich morphology from ALMA and SPHERE

Horseshoes

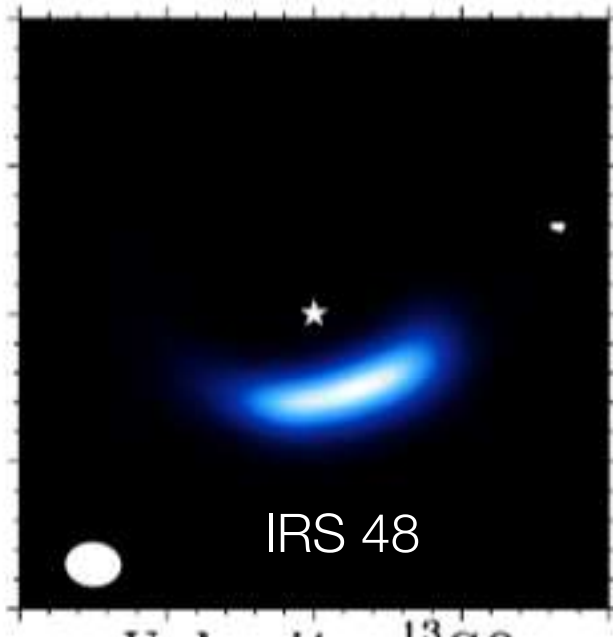# Incredibly rich morphology from ALMA and SPHERE

Horseshoes

Casassus et al 2015b

Incredibly rich morphology from ALMA and SPHERE

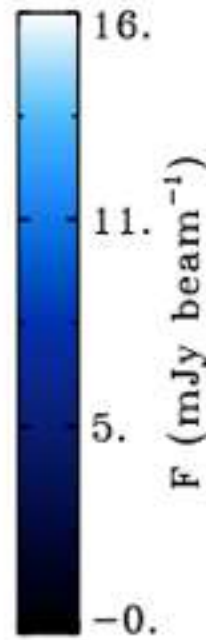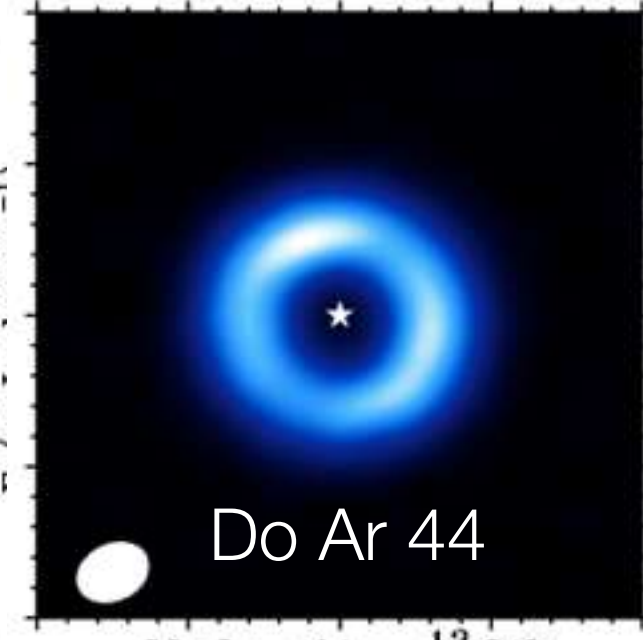## Horseshoes

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 with

  - 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, SPHERE, 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

The PHANTOM code

Includes the most advanced SPH algorithms to date:
- Full Lagrangian formulation
- Advanced switches
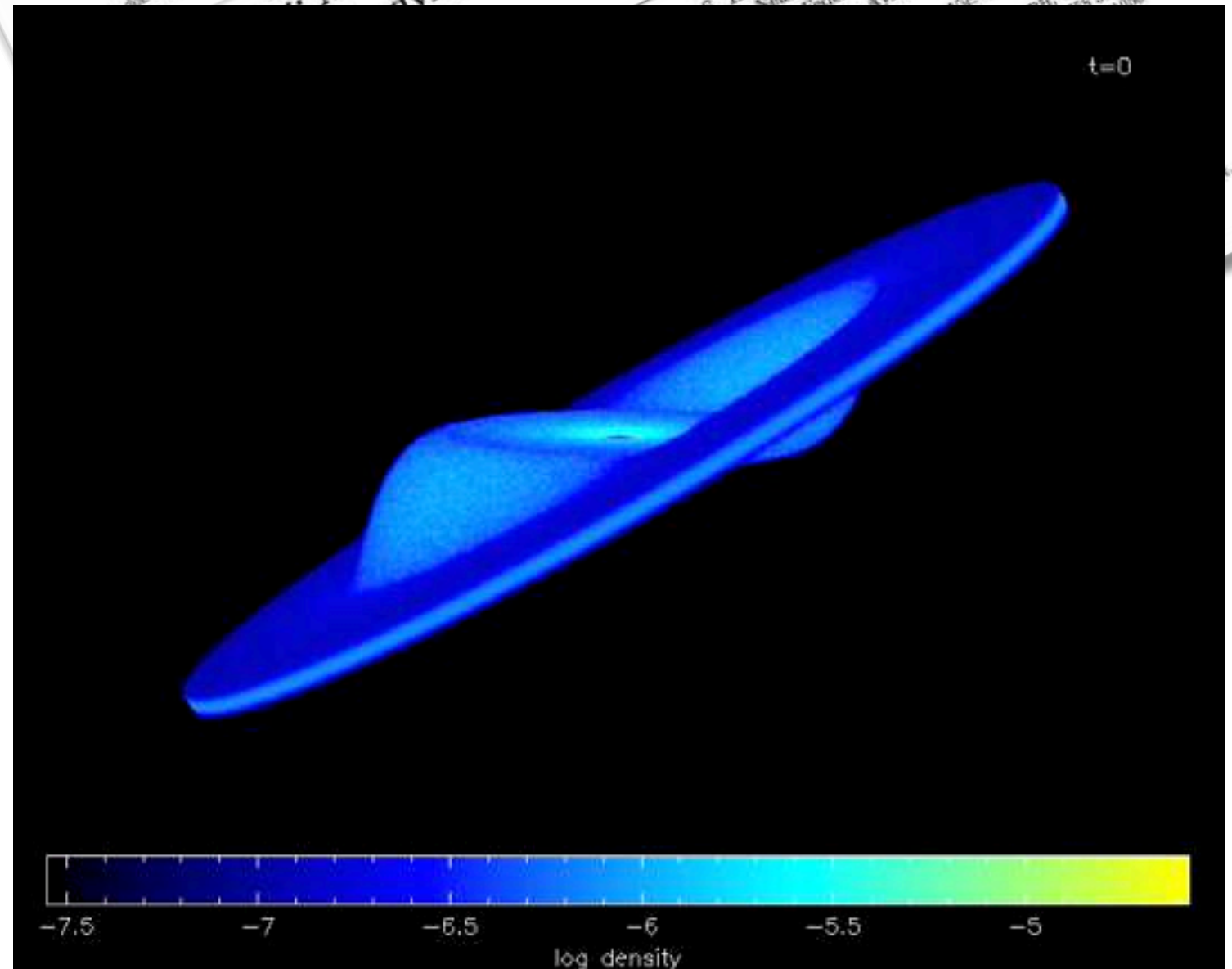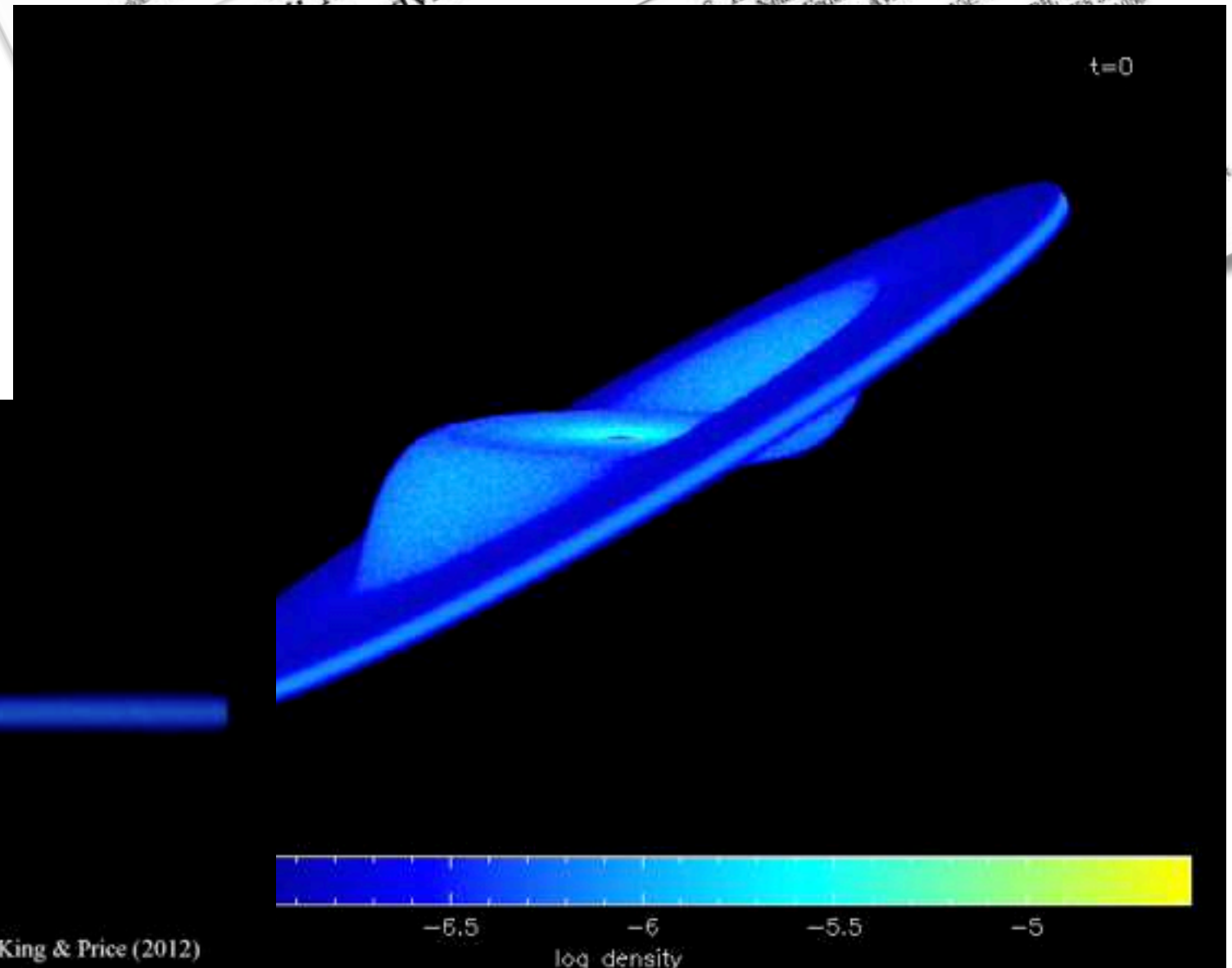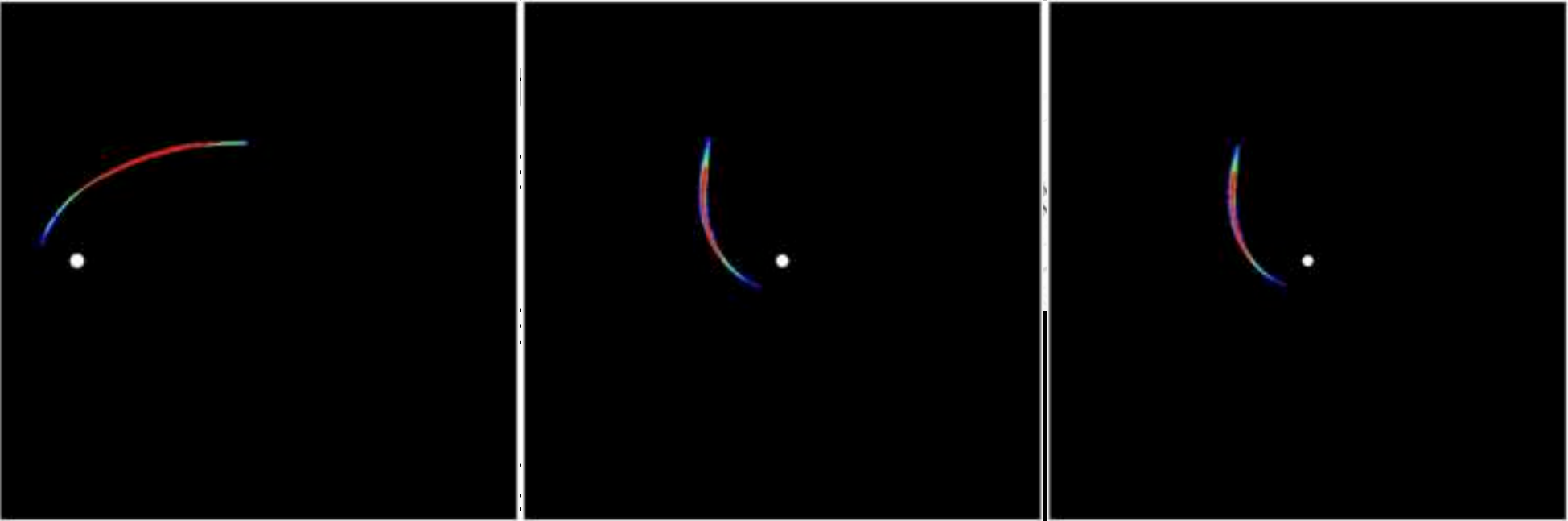- GR effects
- Gas-dust coupling
- MHD
- Self-gravity

PHANTOM: A smoothed particle hydrodynamics and magnetohydrodynamics code for astrophysics

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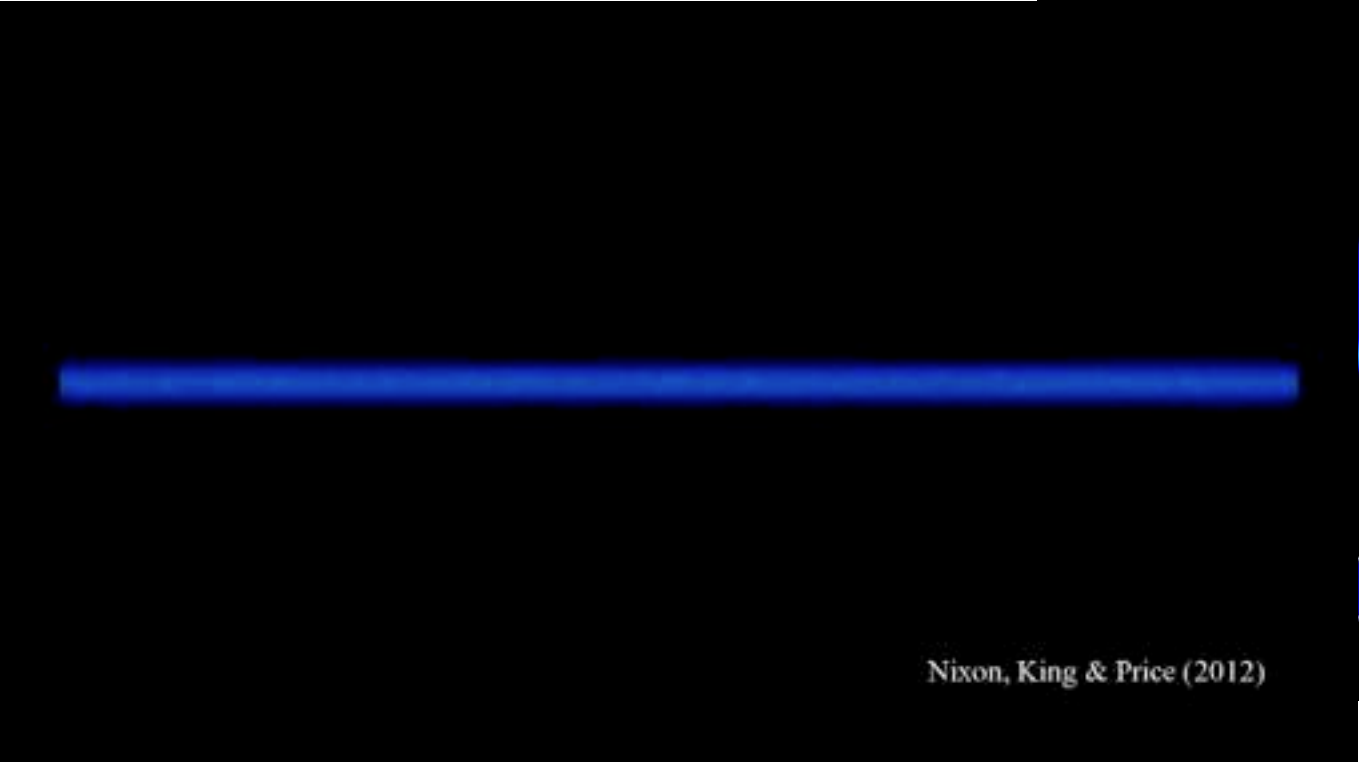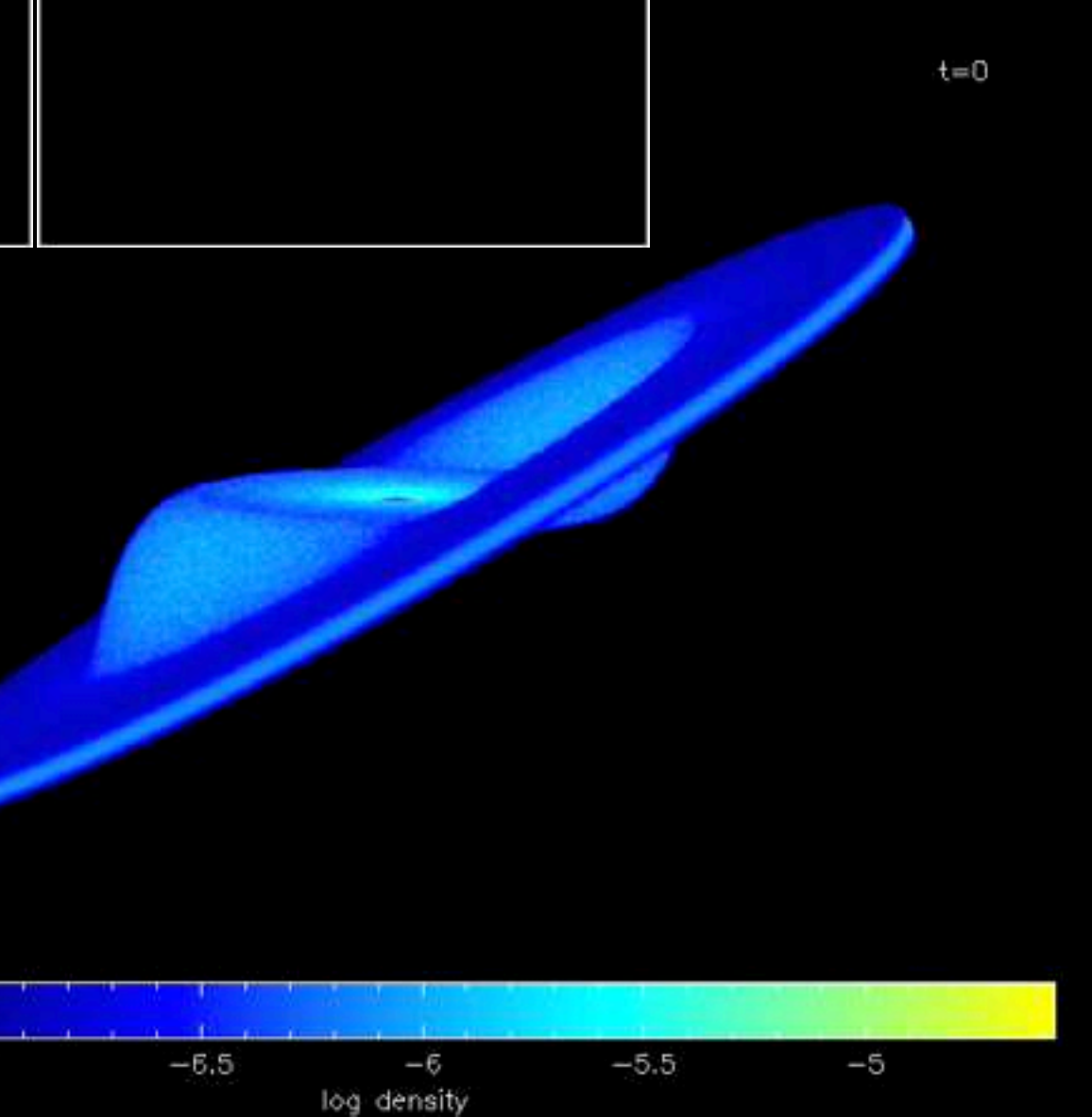- Gas-dust coupling
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Nixon, King & Price (2012)
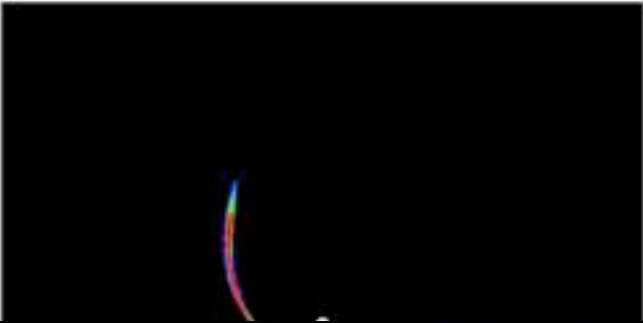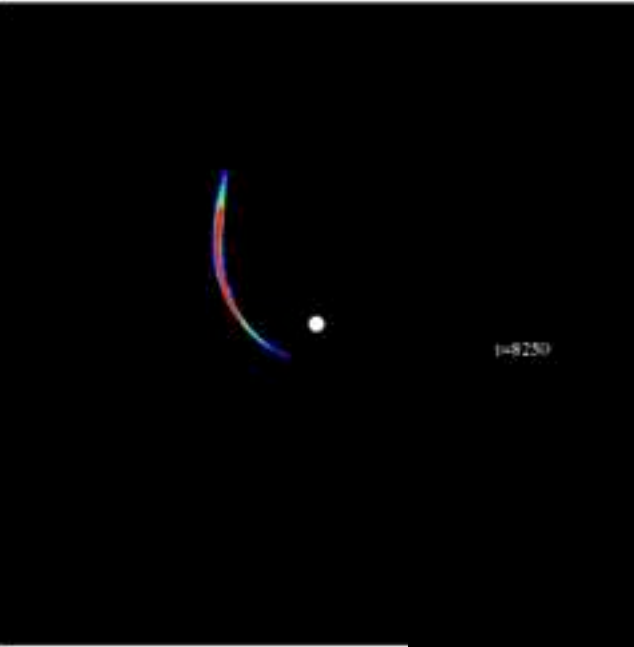
The PHANTOM code

-
-
-
-
- MHD
- Self-gravity

t=0

Nixon, King & Price (2012)

log density

−6.5   −6   −5.5   −5

The PHANTOM code

-
-
-
-
- MHD
- Self-gravity

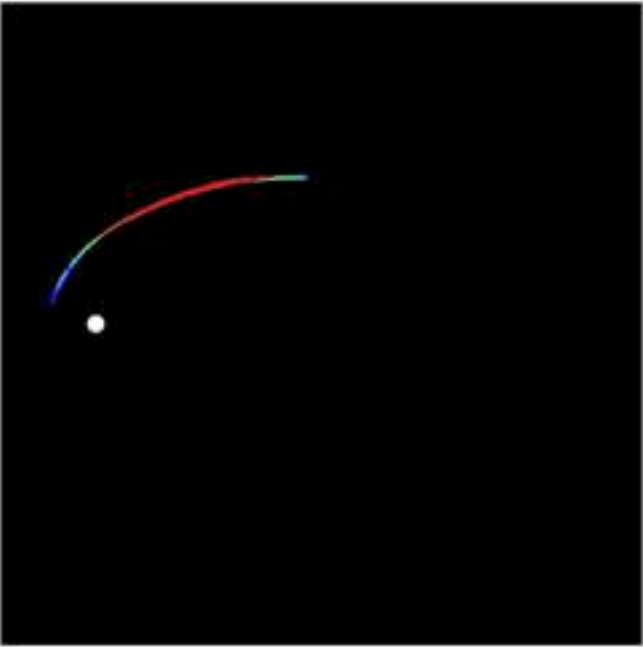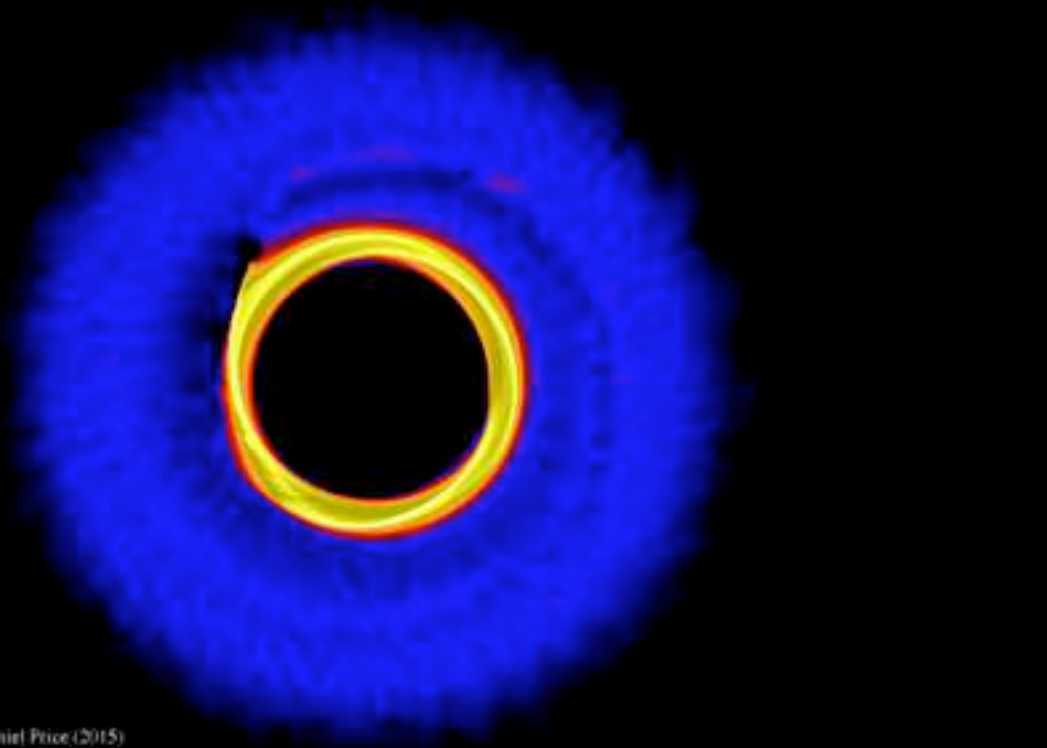Alice Ceriofi, Giuseppe Lodato & Daniel Price (2015)

Nixon, King & Price (2012)

log density

The PHANTOM code

-
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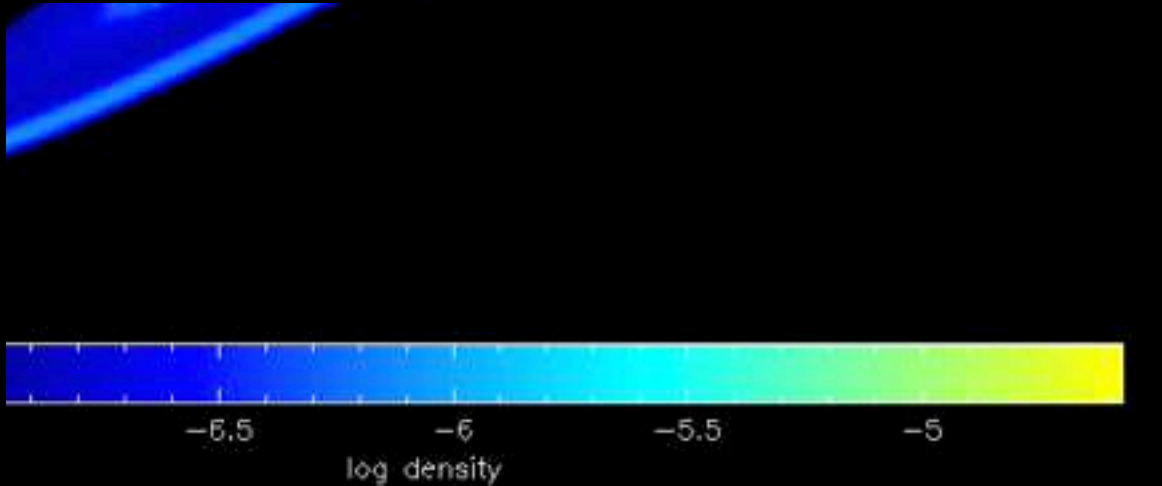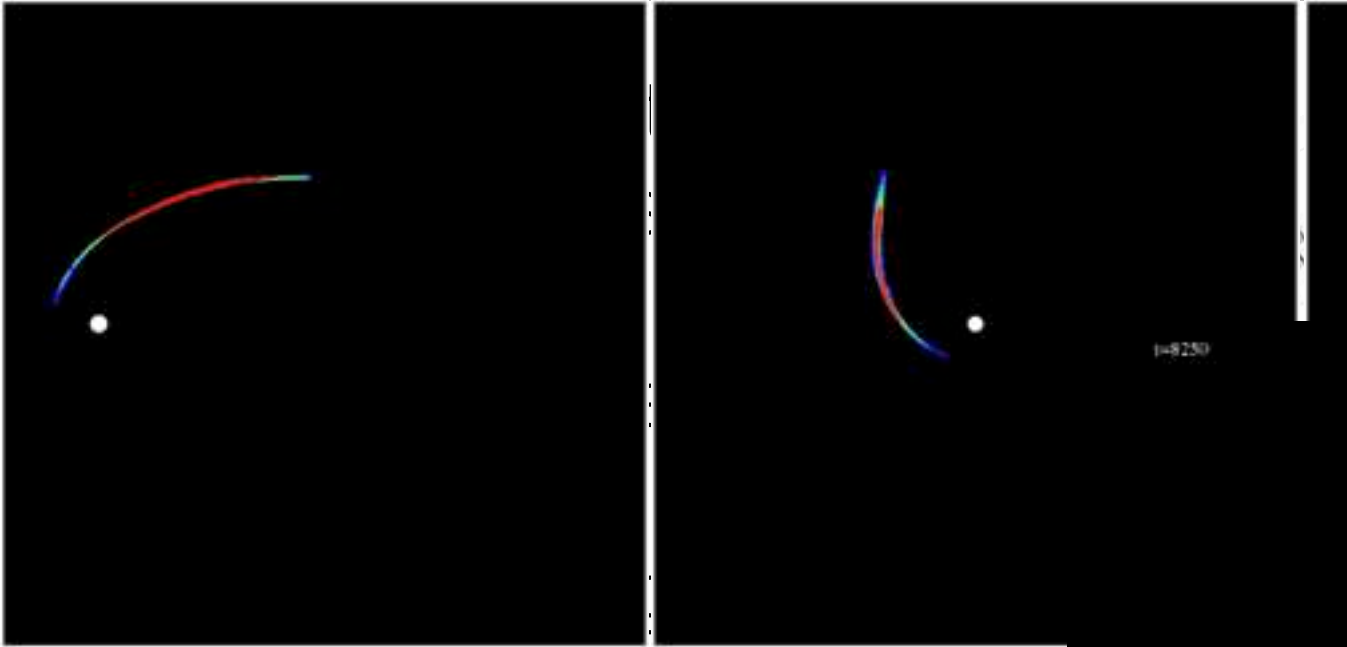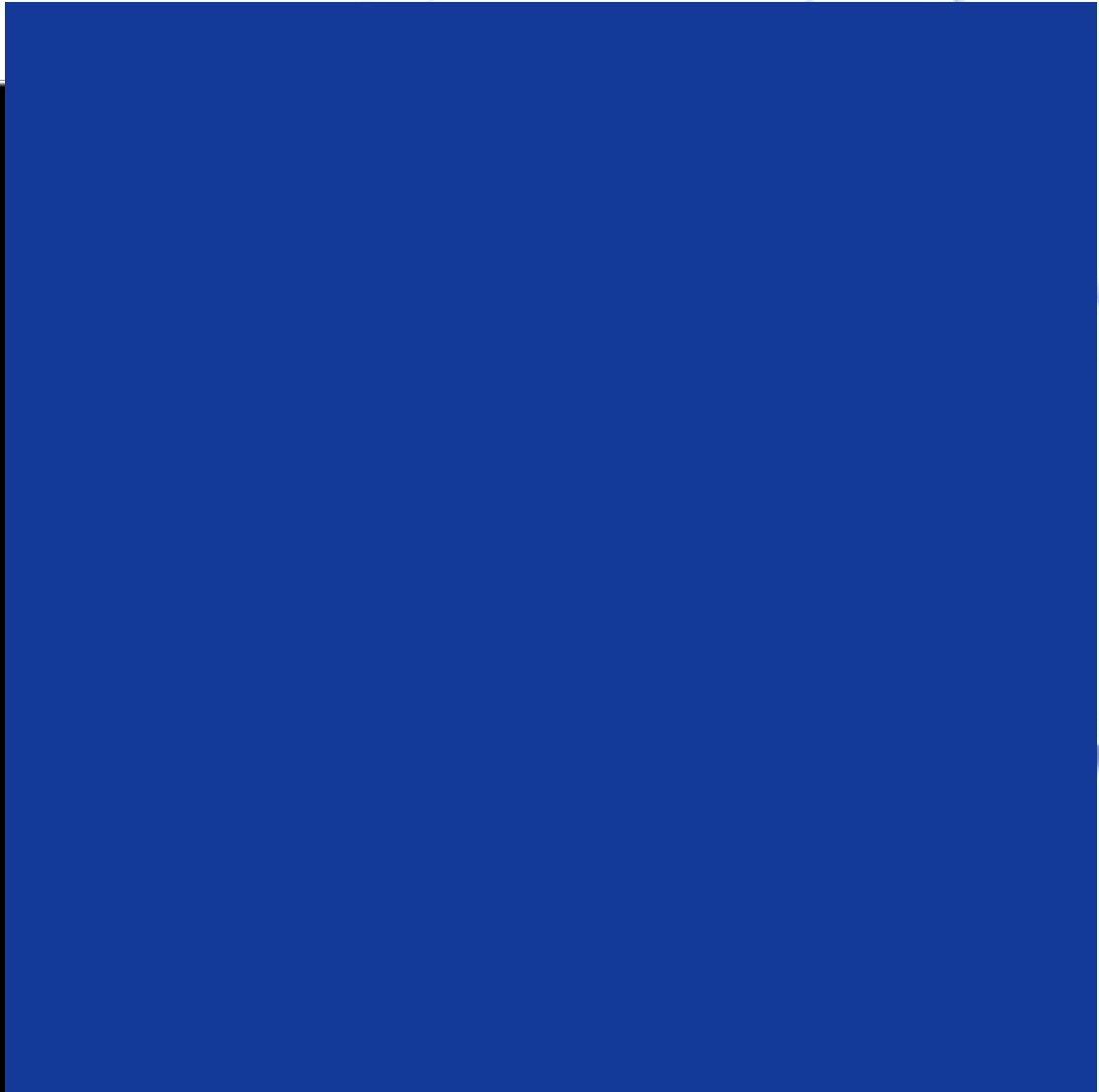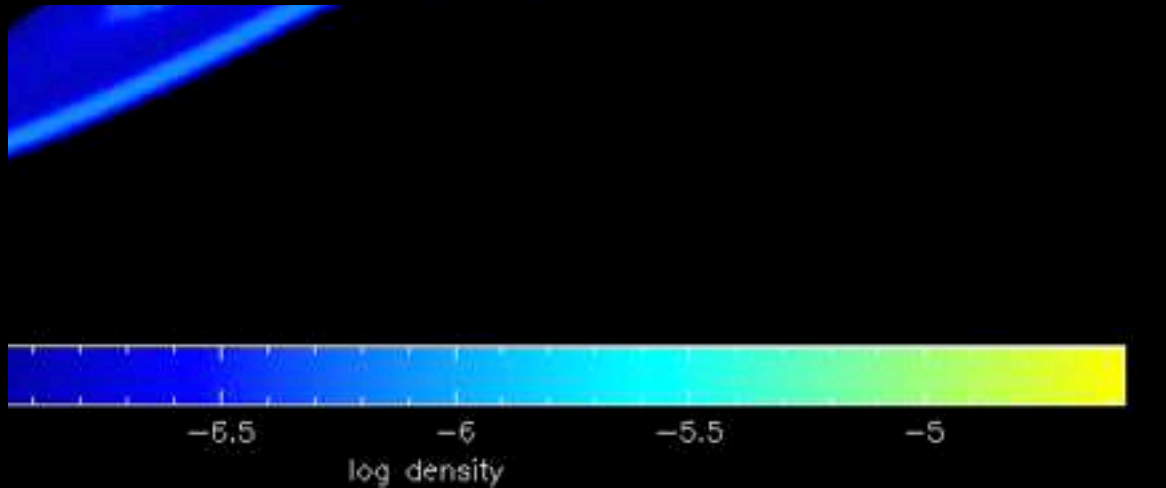- MHD
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Alice Cerioli, Giuseppe Lodato & Daniel Price (2015)

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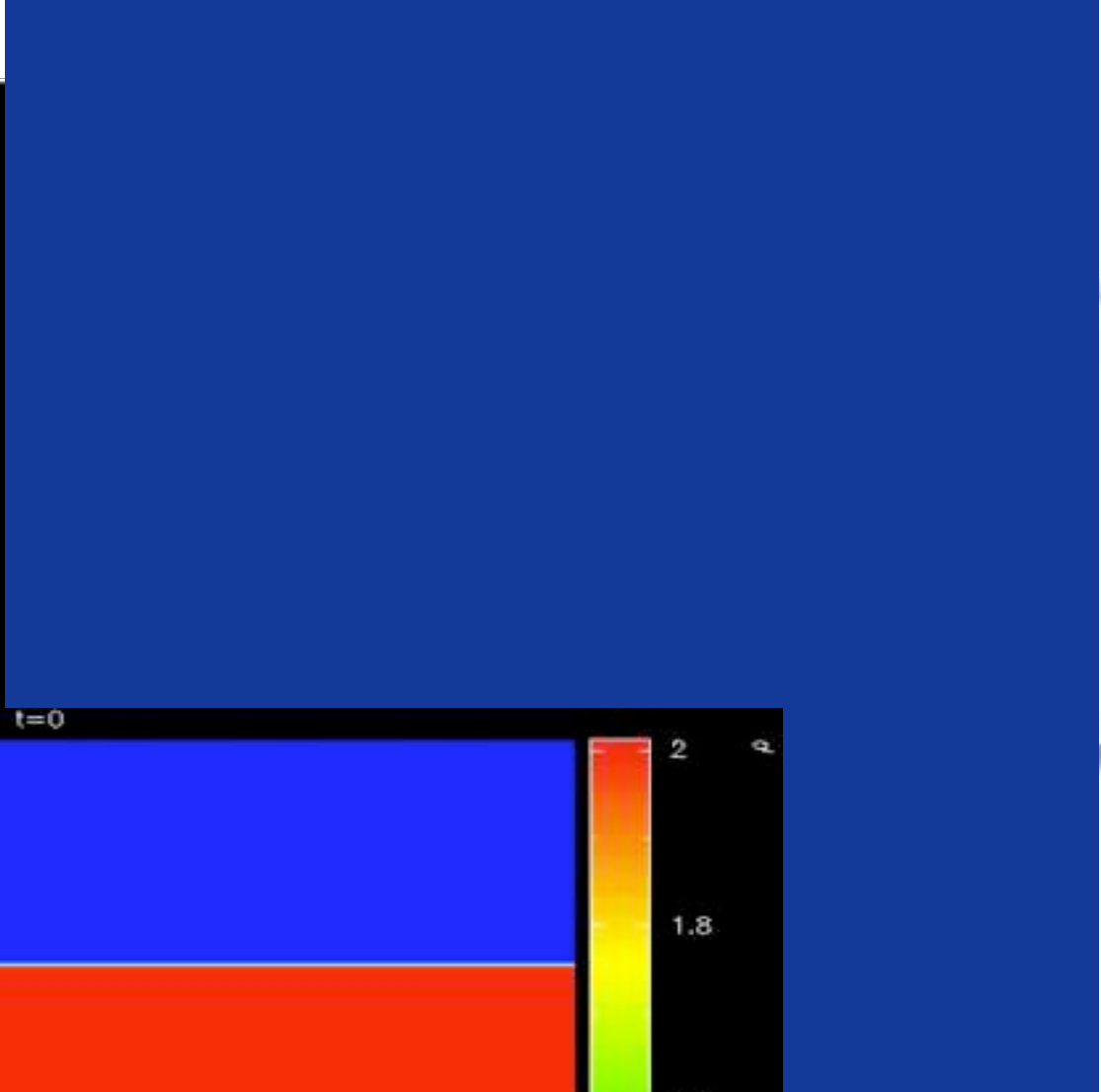
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The PHANTOM code

-
-
-
-
- MHD
- Self-gravity

The PHANTOM code

-
-
-
-
- MHD
- Self-grav

Bate, Tricco & Price (2013)

100 AU

Time: 0 yrs

log density [g/cm³]

-18 -16 -14 -12

The PHANTOM code

Bate, Tricco & Price (2013)

100 AU

Time: 0 yrs
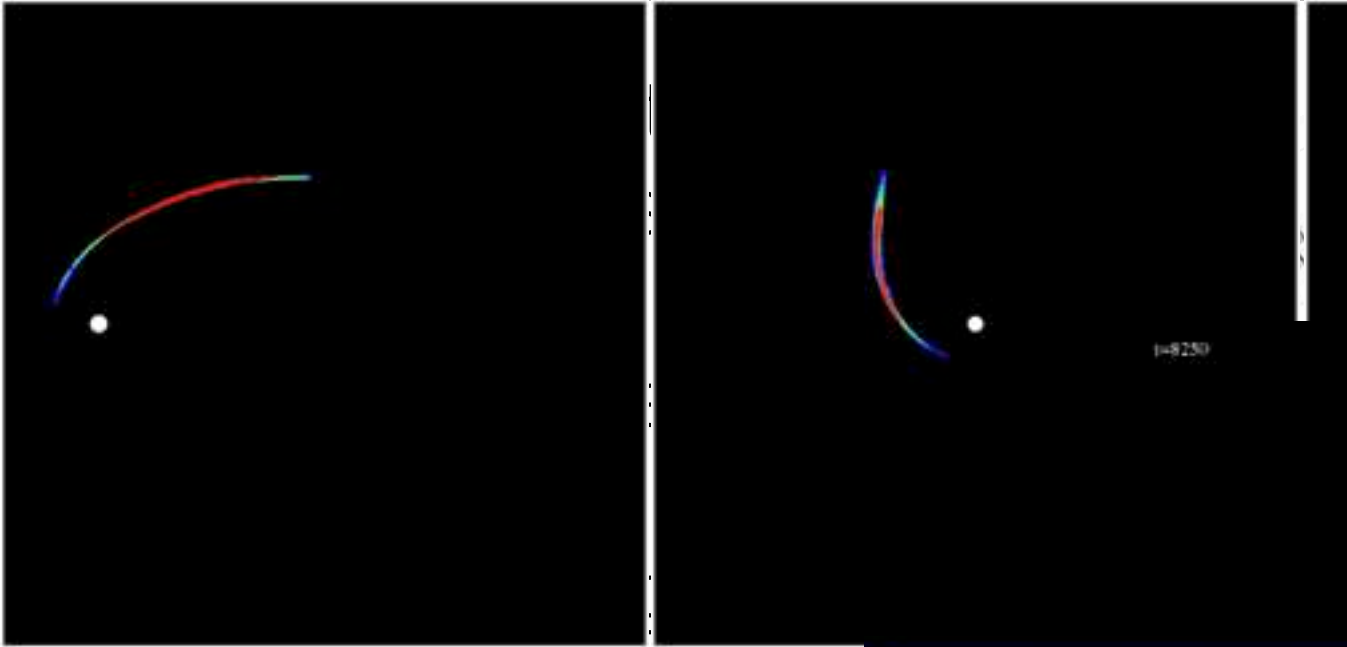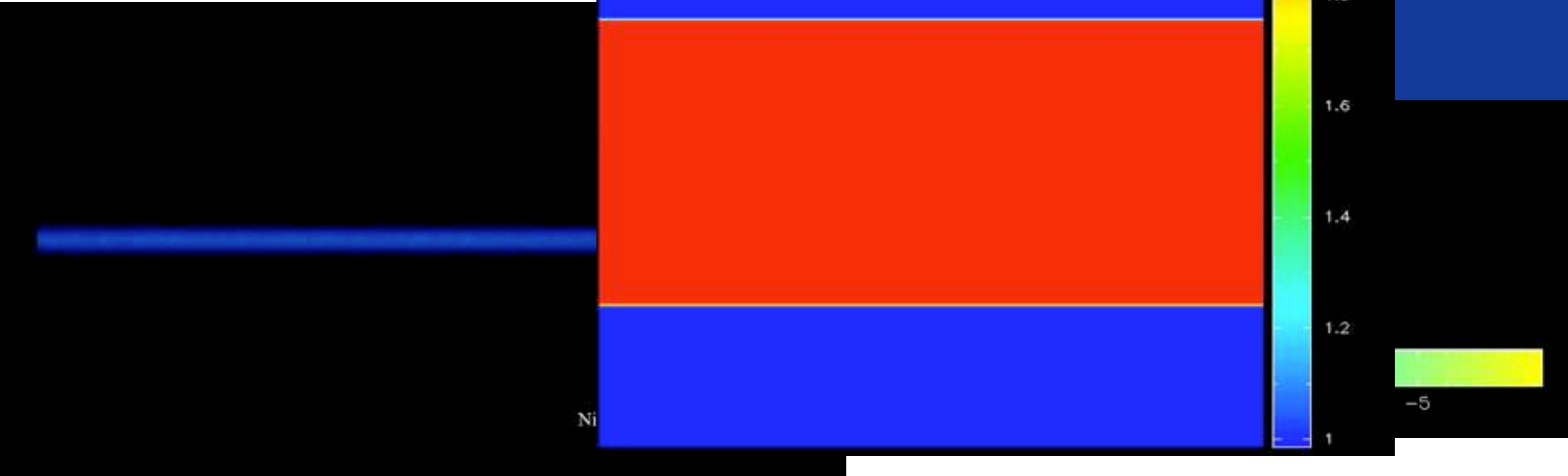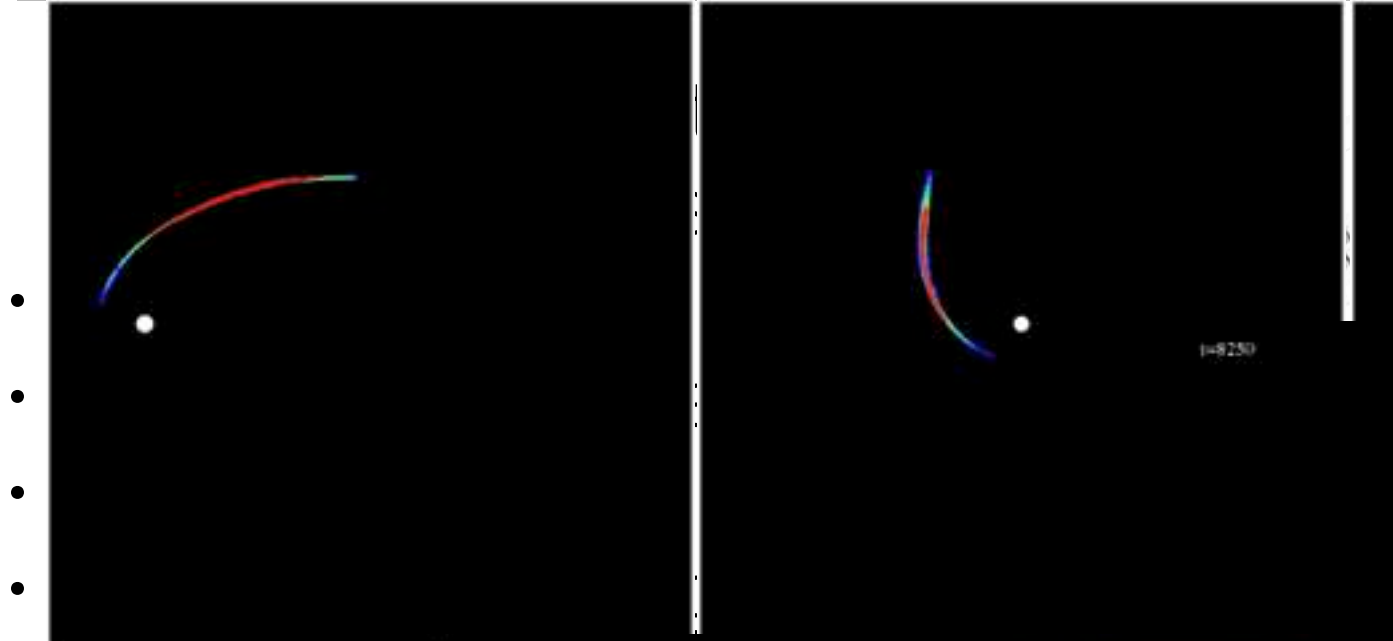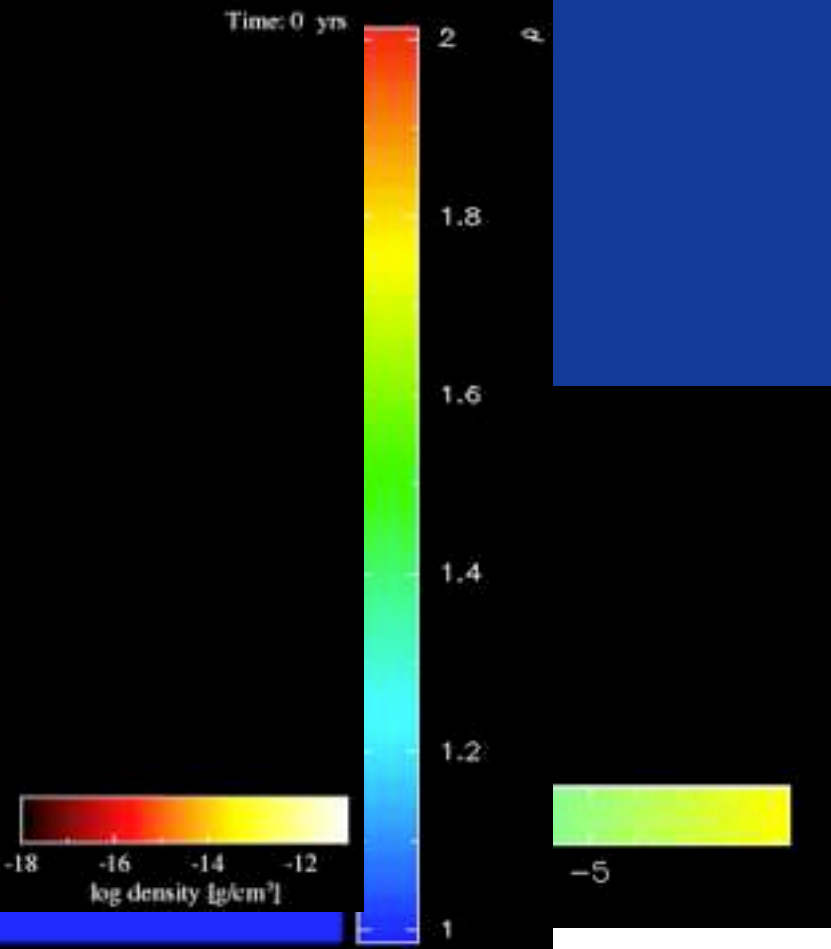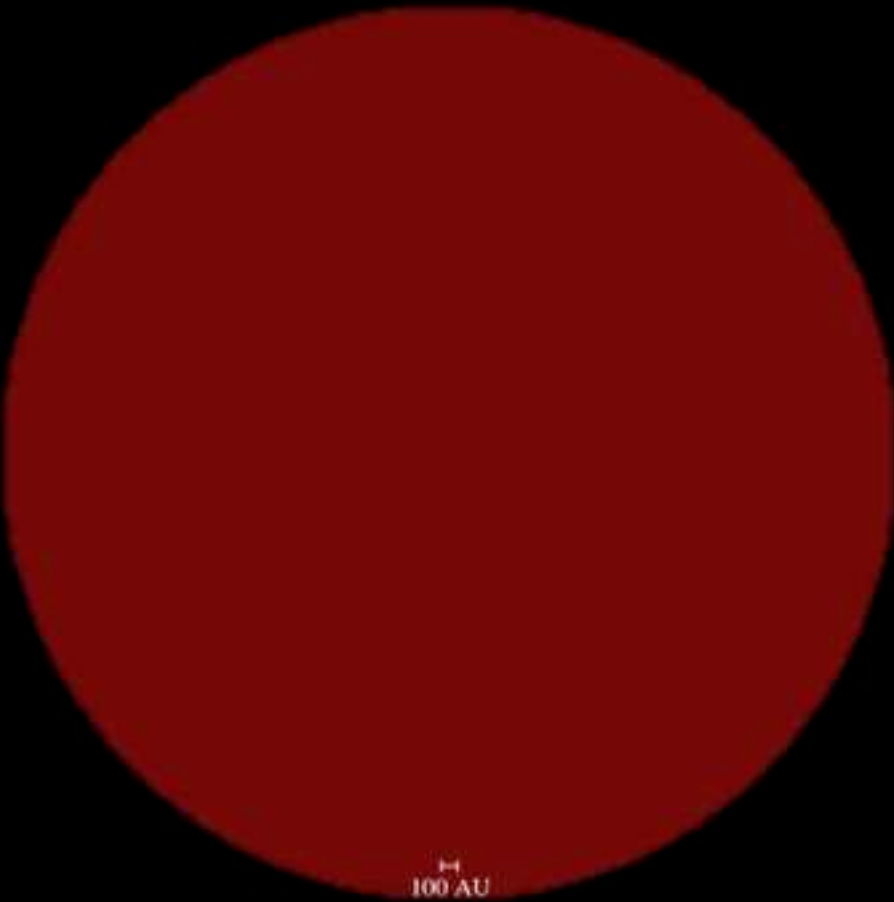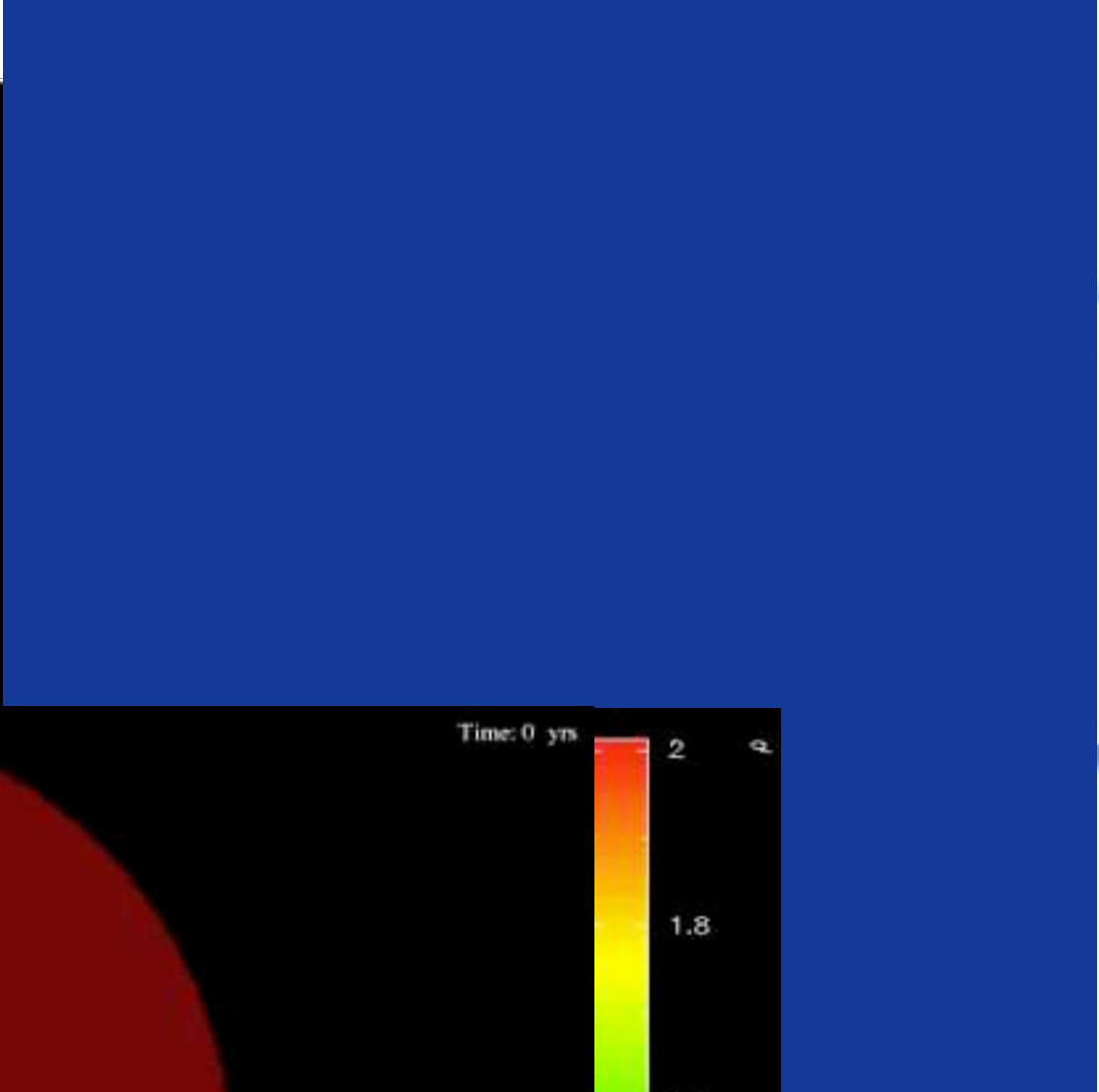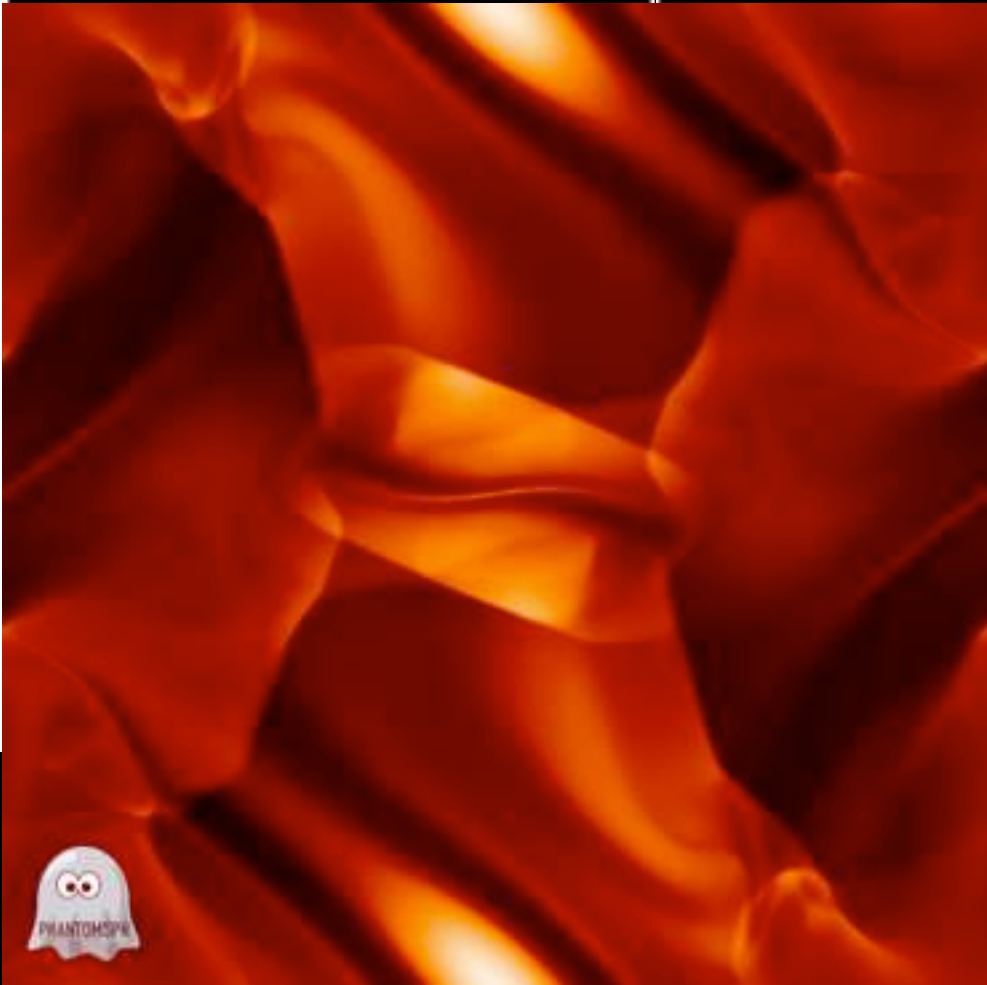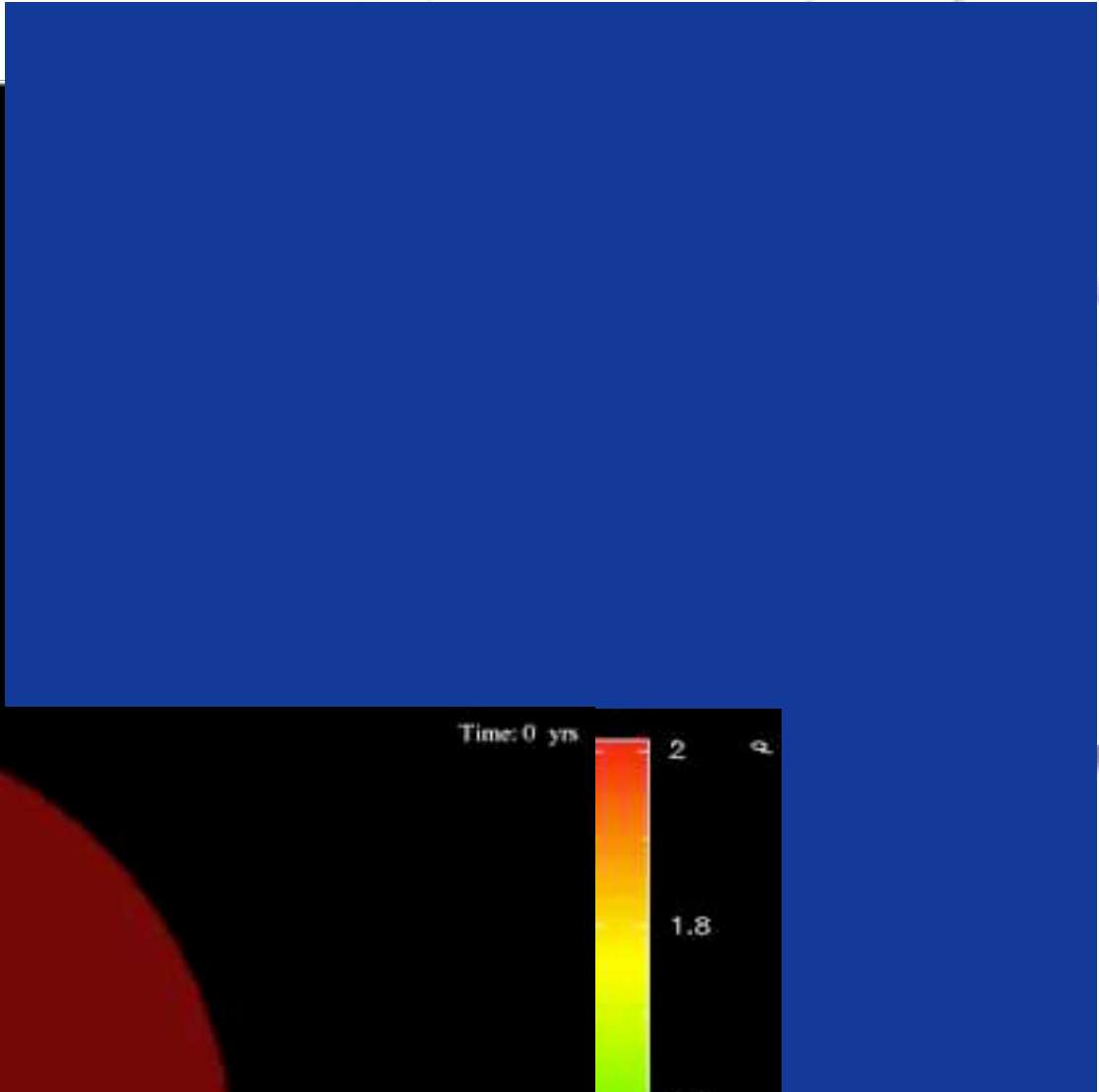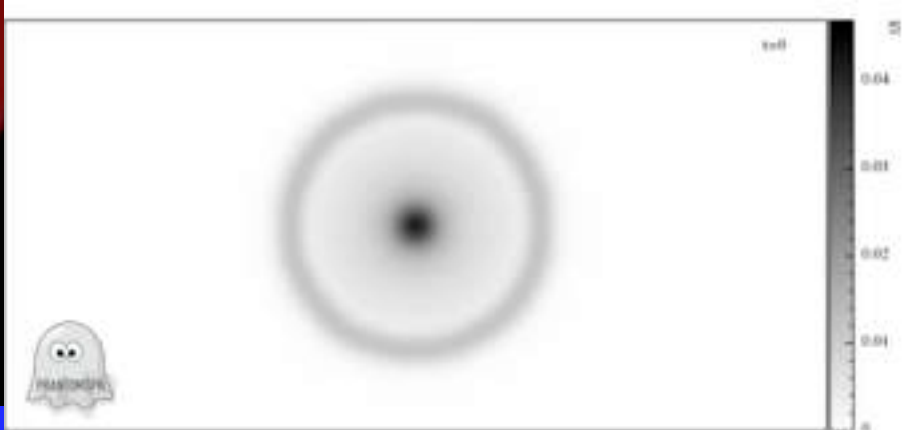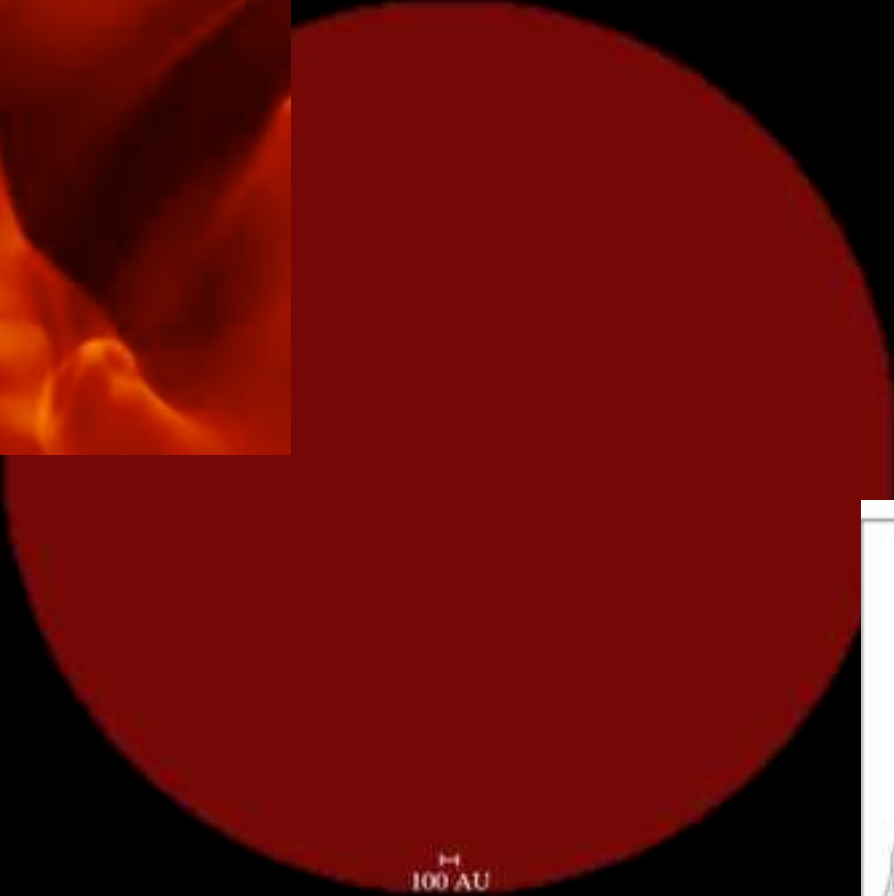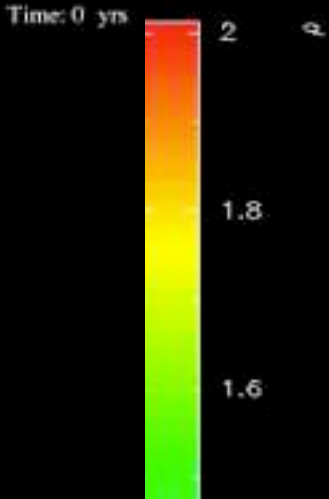
Rings and planets

- By far the most significant novelty coming from disc imaging is the widespread presence of gaps (e.g. HL Tau)

- Many mechanisms proposed to create gaps (chemistry, dead zones in the MRI, etc.)

- The most natural explanation is associated with the presence of young planets

- The gravitational torque of the planet is able to carve a gaps in the disc

Rings and planets

- By far... ad pres...

- Man... MRI, etc.)

- The ... ets

- The ...

t=0
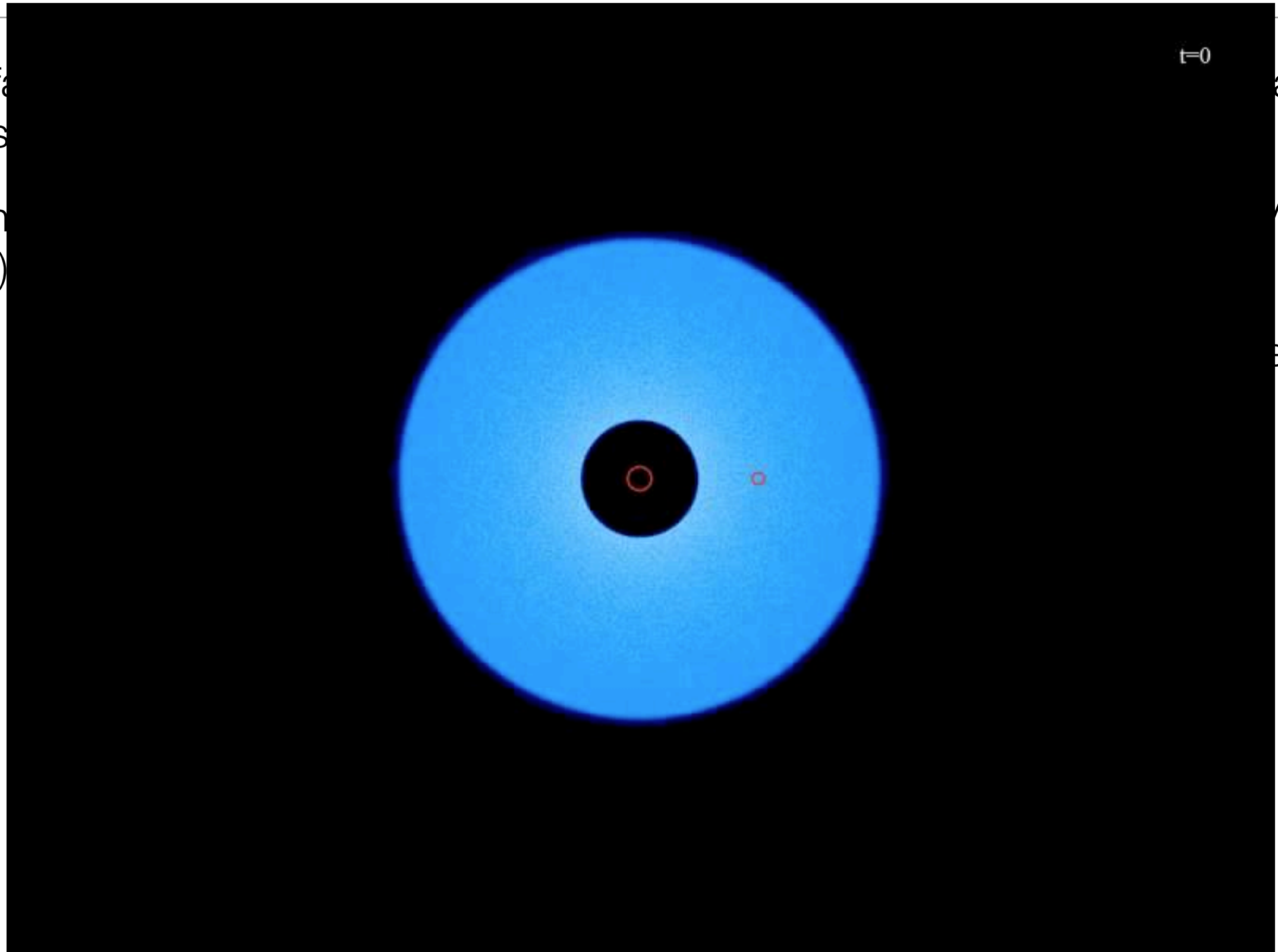
Explaining the HL Tau disc

(Dipierro et al 2015b)
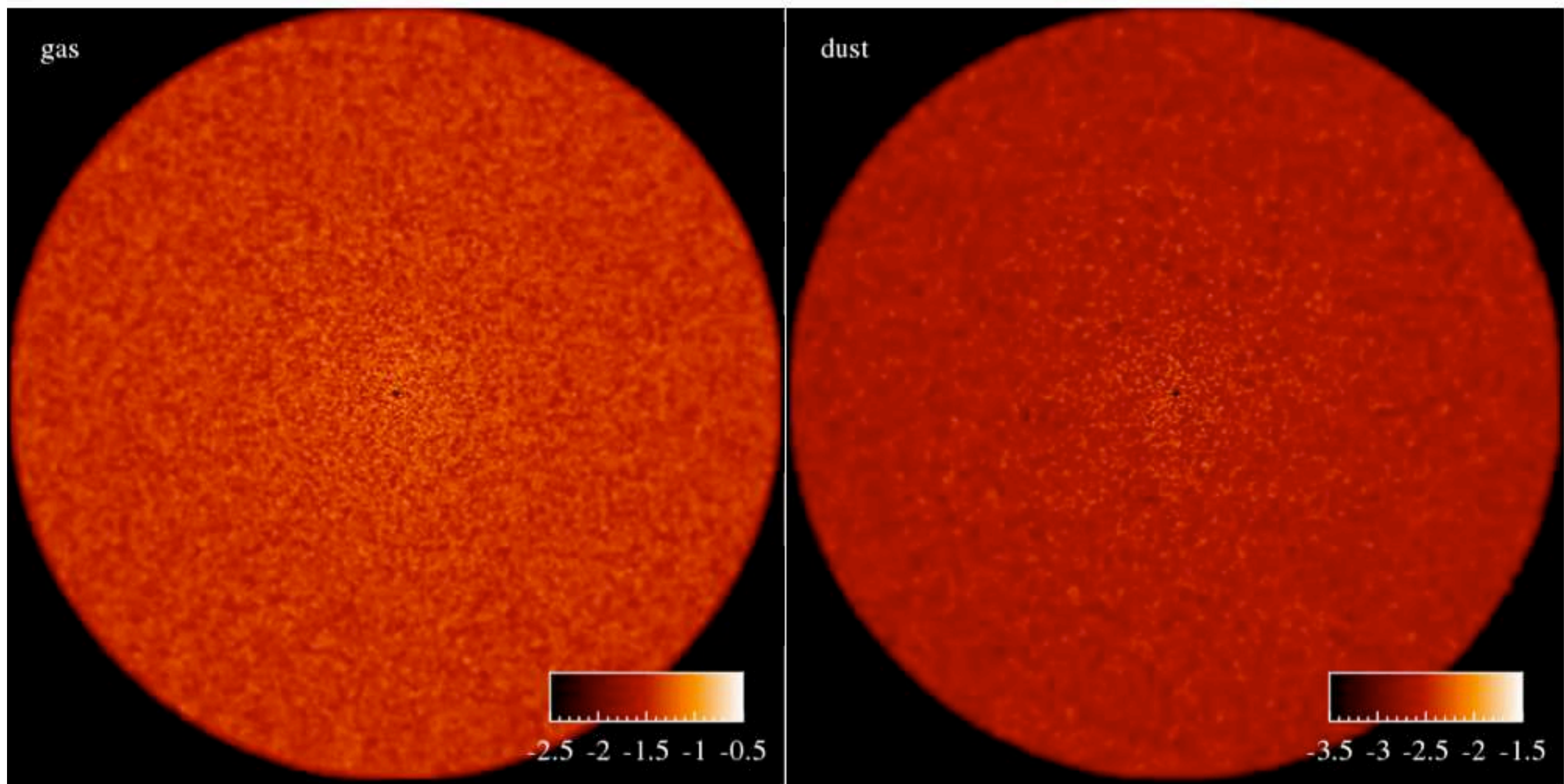
Three planets: *0.2M_Jup (@13.2au)*, *0.27M_Jup (@32.3au)*, *0.55M_Jup (@68.8au)*

Explaining the HL Tau disc
(Dipierro et al 2015b)
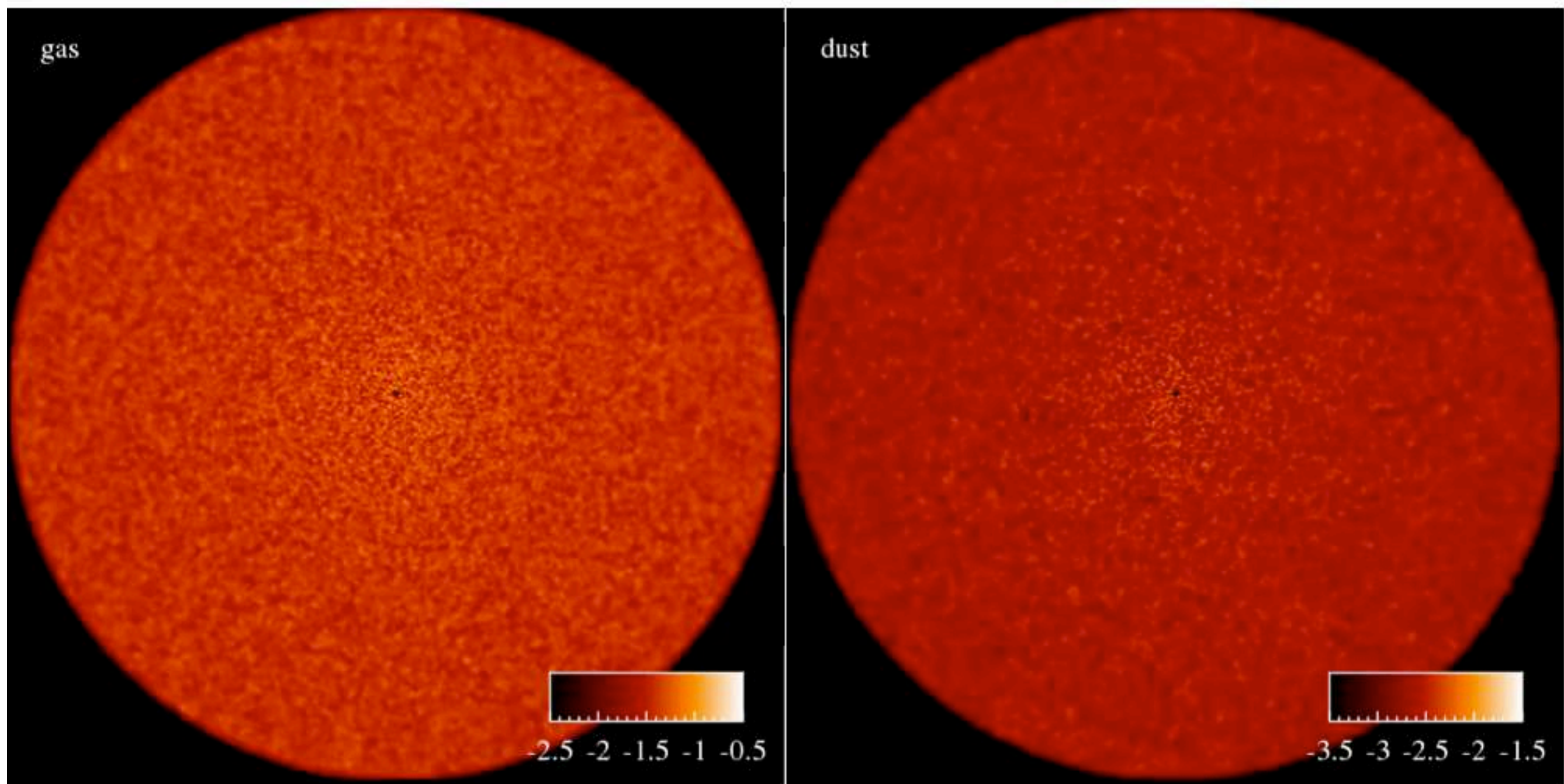
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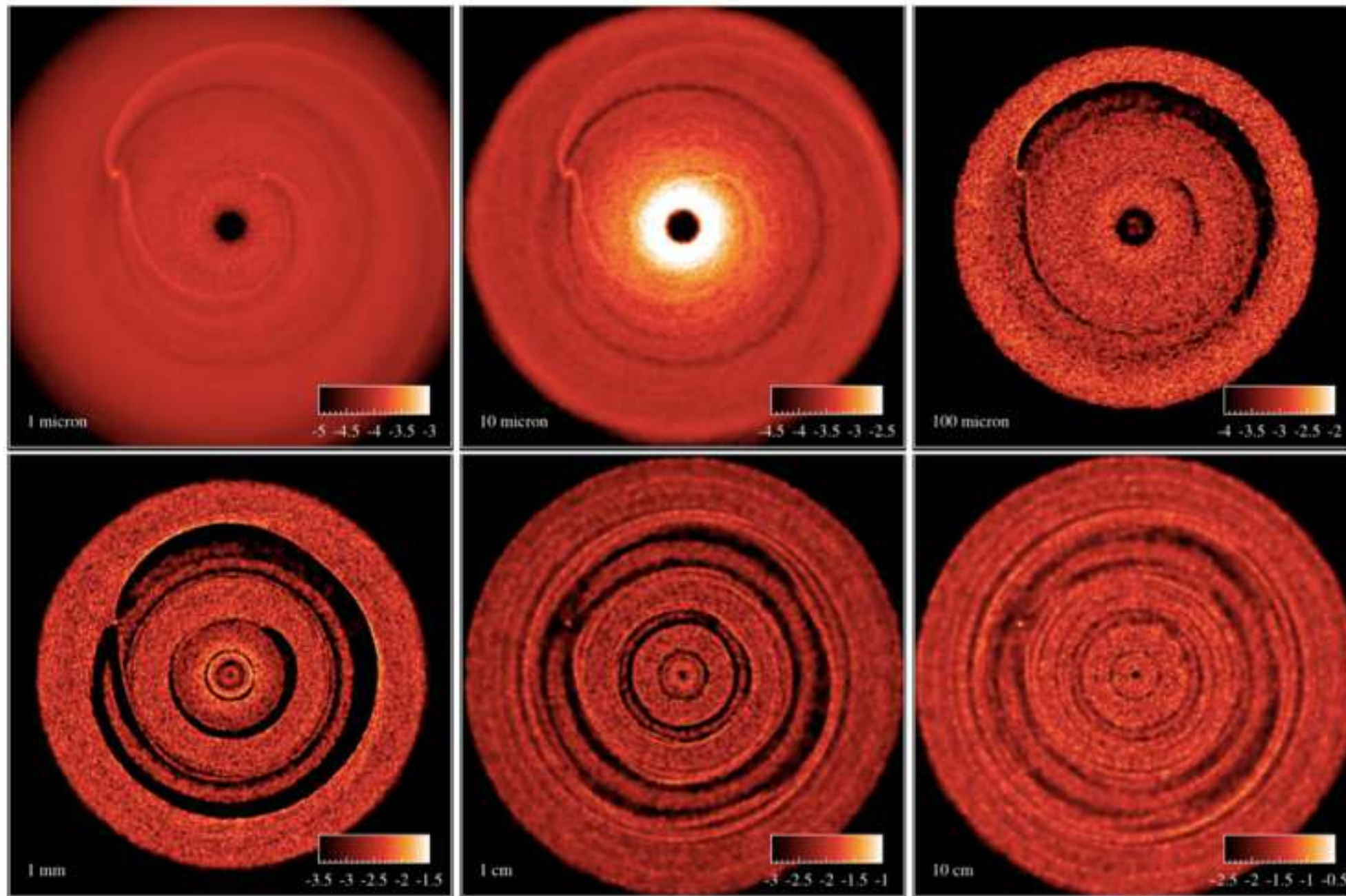
Simulate 6 different sizes, assume a dust size distribution and a
gas/dust ratio —> compute synthetic images

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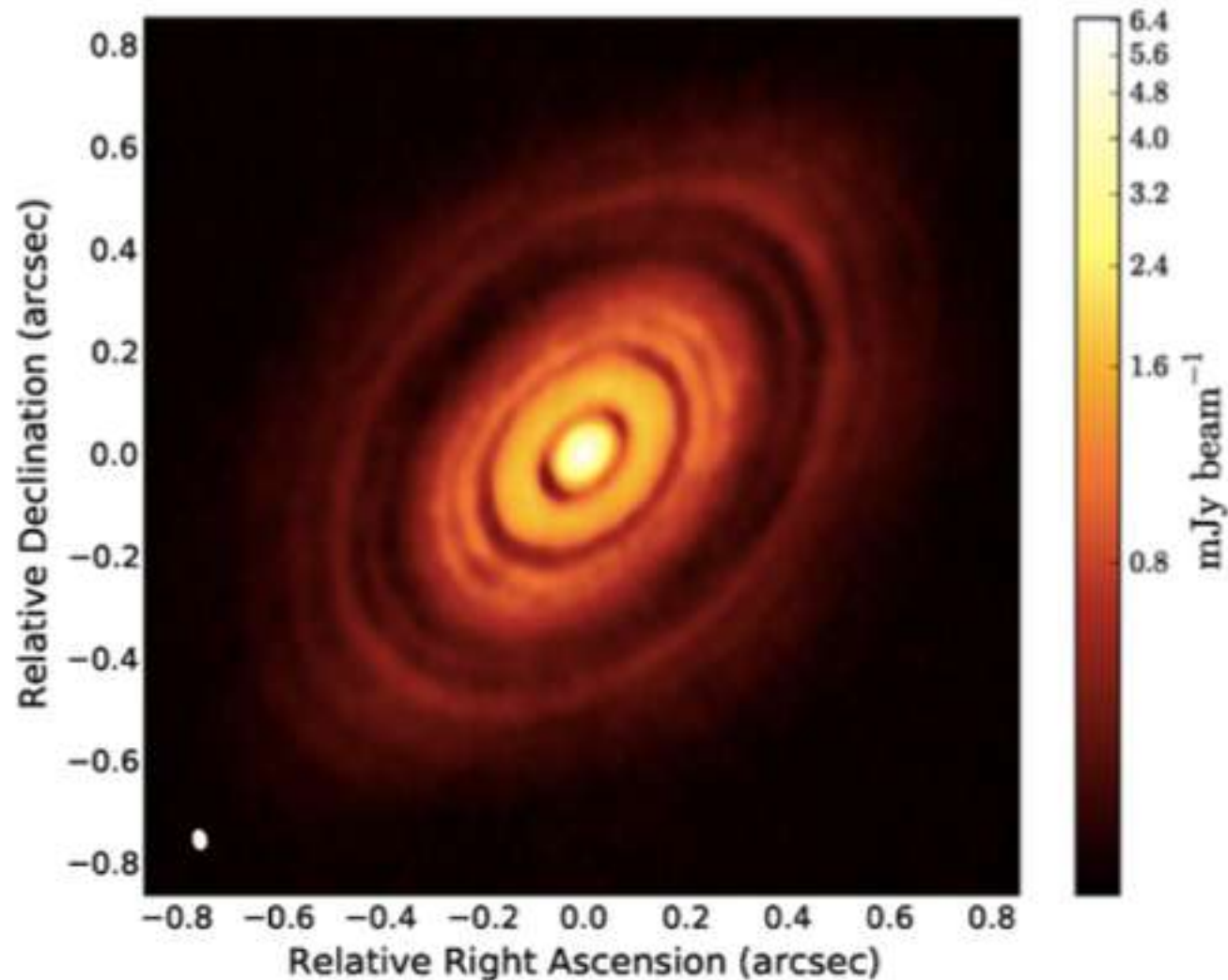
ALMA Partnership (2015)
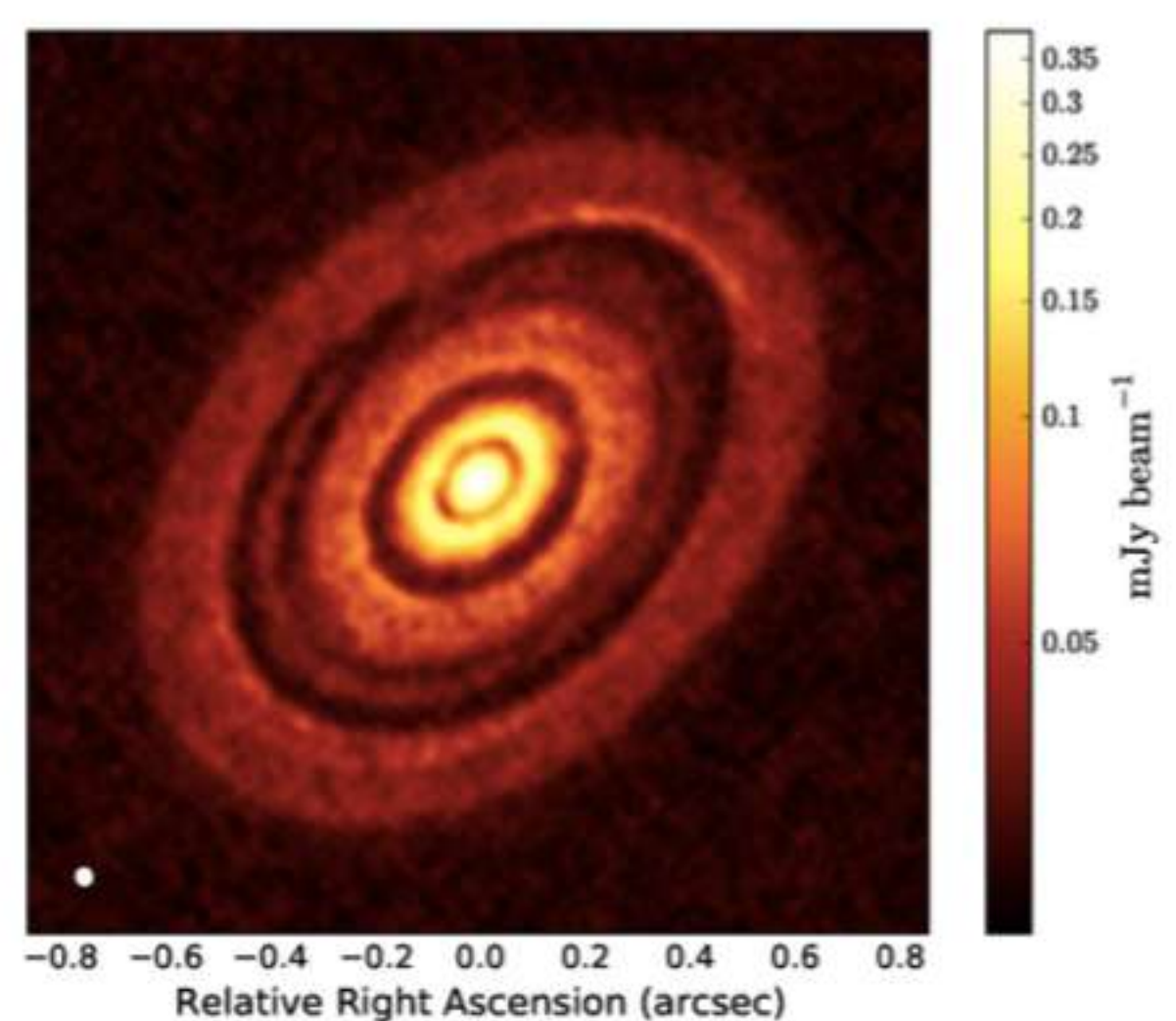
Dipierro et al (2015)

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

Other applications in the posters

Evolution of non-axisymmetric structures in protoplanetary discs

[1]**Enrico Ragusa**, [1]**Giuseppe Lodato**, [1]Giovanni Dipierro, [2]Giovanni Rosotti, [3]Jean Teyssandier, [2]Richard Booth, [6]Daniel Price, [5]Guillaume Laibe & [2]Cathie Clarke

[1]Dipartimento di Fisica, Università Degli Studi di Milano, Via Celoria, 16, Milano, I-20133, Italy
[2]Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK
[3]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
[4]DAMTP, University of Cambridge, Cambridge CB3 0WA, UK
[5]Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, UMR5574, F-69230, Saint-Genis-Laval, France
[6]Monash Centre for Astrophysics (MoCA) and School of Physics and Astronomy, Monash University, Clayton Vic 3800, Australia

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

UNIVERSITY OF CAMBRIDGE

Other applications in the posters

Evolution of non-axi... protoplanetary disc...

[1]Enrico Ragusa, [1]Giuseppe ... [2]Richard Booth, [4]Daniel Price, [5]Guillaume Laibe & ...

[1]Dipartimento di Fisica, Università Degli Studi di Milano, Via Celoria, ...
[2]Department of Physics and Astronomy, University of Leicester, Leicester, LE...
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[5]Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, UMR5574, F-69230, Saint-Genis-Laval, France
[6]Monash Centre for Astrophysics (MoCA) and School of Physics and Astronomy, Monash University, C...

Observational studies of star formation and protostellar disc dynamics

Maria Giulia Ubeira Gabellini[1,2,3], Giuseppe Lodato[1], Massimo Robberto[2,5], Leonardo Testi[3], Anna Miotello[4,6], Stefano Facchini[6], Nicola da Rio[7], Carlo Manara[8], Leonardo Ubeda[2]

Other applications in the posters

Evolution of non-axi... protoplanetary disc...

Enrico Ragusa, Giuseppe ...
Richard Booth, Daniel Price, Guillaume Laibe & ...
Dipartimento di Fisica, Università Degli Studi di Milano, Via Celoria, ...
Department of Physics and Astronomy, University of Leicester, Leicester, LE...
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Monash Centre for Astrophysics (MoCA) and School of Physics and Astronomy, Monash Uni...

Observational studi...
and protos...

Maria Giulia Ubeira Gabell...
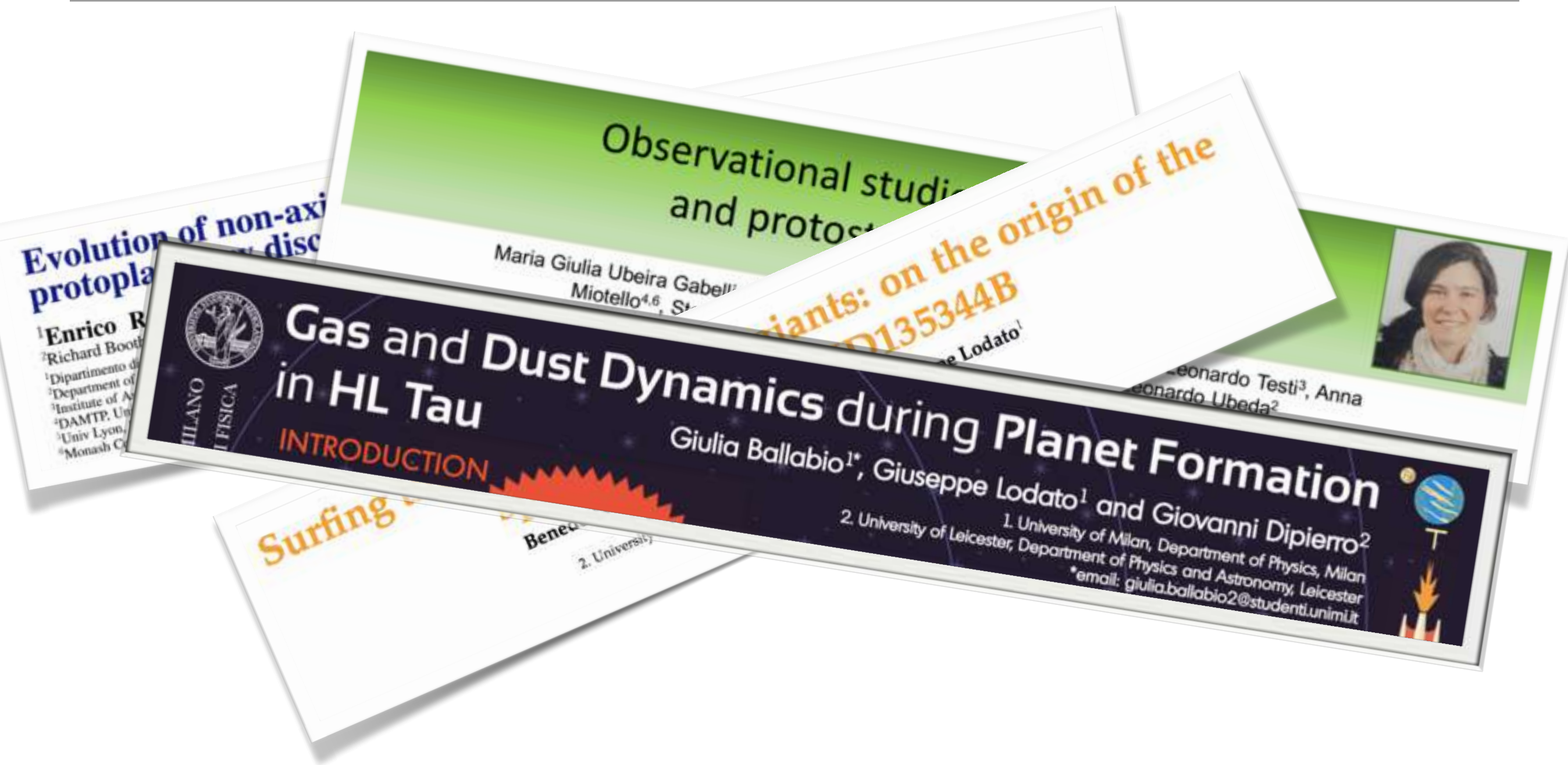Miotello[4,6], S...

...eonardo Testi[3], Anna
...eonardo Ubeda[2]

Surfing the spirals waves of giants: on the origin of the
spiral structure in HD135344B

Benedetta Veronesi[1], Giovanni Dipierro[2], Giuseppe Lodato[1]
1. University of Milan, Department of Physics, Milano
2. University of Leicester, Department of Physics and Astronomy, Leicester

Other applications in the posters

Other applications in the posters

Other applications in the posters