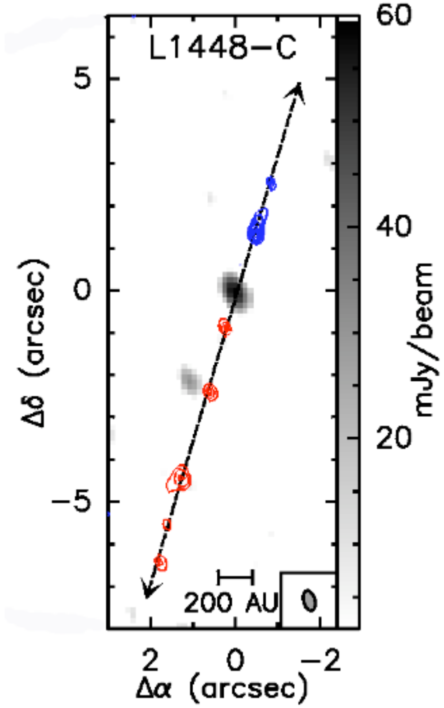
Paving the way for ALMA :

A pilot subarcsec survey of Class 0 protostars with PdBI



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with the collaboration of : P. André, P. Hennebelle, D. Stamatellos, M. Bate, A. Belloche, G. Duchêne and A. Whitworth.

Disks at the Class 0 stage : questions and results

- Questions :
  - Mechanisms of disk formation ?
  - Formation of multiple systems ?
  - Progenitors of Class I and protoplanetary disks ?

- Previous interferometric observations :
  - Surveys : Looney (2000), Jorgensen et al. (2007, 2009).
  - NGC1333-IRAS2A : Jorgensen et al. (2004, 2005, 2007), Brinch et al. (2009). No rotation : pseudo disk ?
  - Serpens-FIRS1 : Enoch et al. (2009) with CARMA.

    Massive disk ?

PdBI observations of Class 0 protostars

- A-array of Plateau de Bure Interferometer
- 1.3 mm continuum + $^{12}CO(2-1)$ emission
- Sample : 3 Taurus sources + 2 Perseus sources

  IRAM04191, L1527, L1521-F, NGC1333-IRAS2A and L1448-C
- Resolutions achieved : ~ 0.27'' - 0.56''

  ~ 40 - 80 AU for Taurus sources (140 pc)

  ~ 70 - 120 AU for Perseus sources (250 pc)
- Continuum rms noise levels : **0.12 - 1.2 mJy/beam**

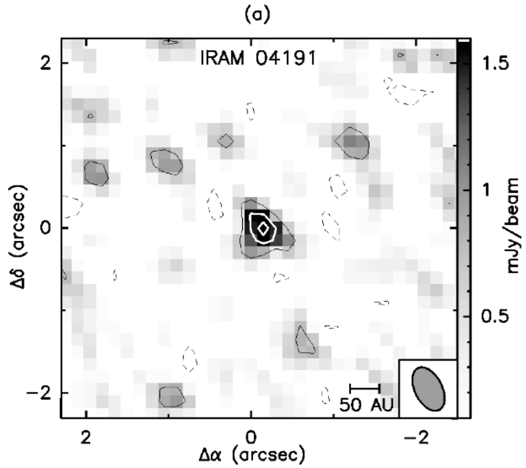
➡ Very high-resolution / good sensitivity maps

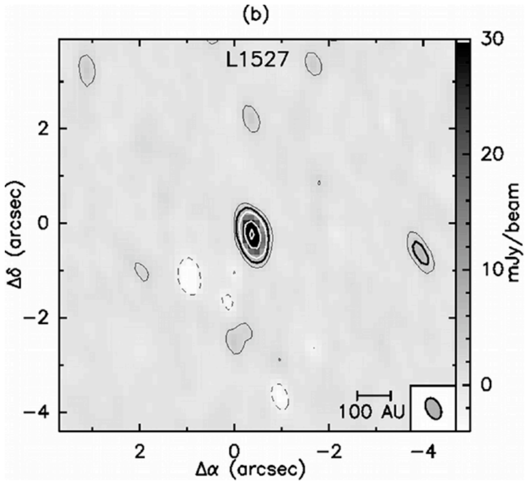
- + additional data :
  - 1.4 mm PdB-BCD arrays maps of IRAM04191, L1527 and L1448-C.
  - 2.8 mm PdB-BCD arrays for L1448-C

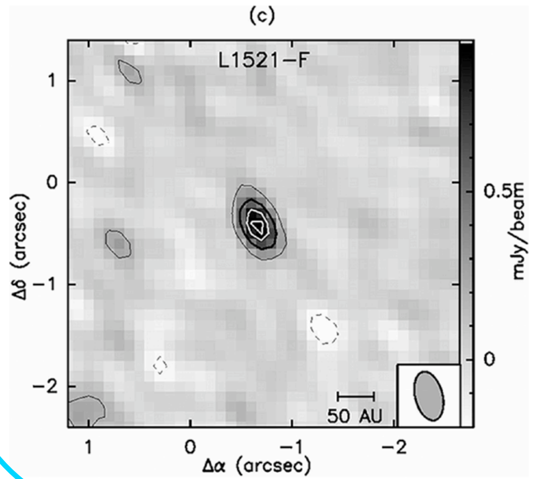
➡ High spatial dynamic range maps

PdBI 1.3 mm continuum sources properties

Taurus sources







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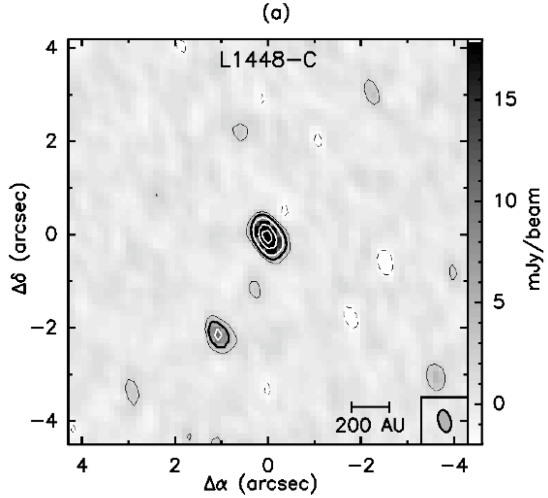
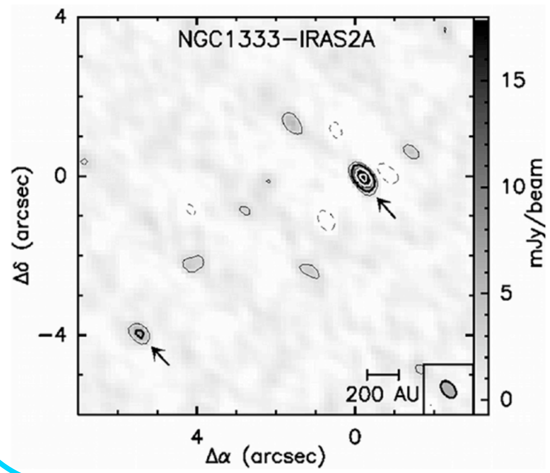
Perseus sources

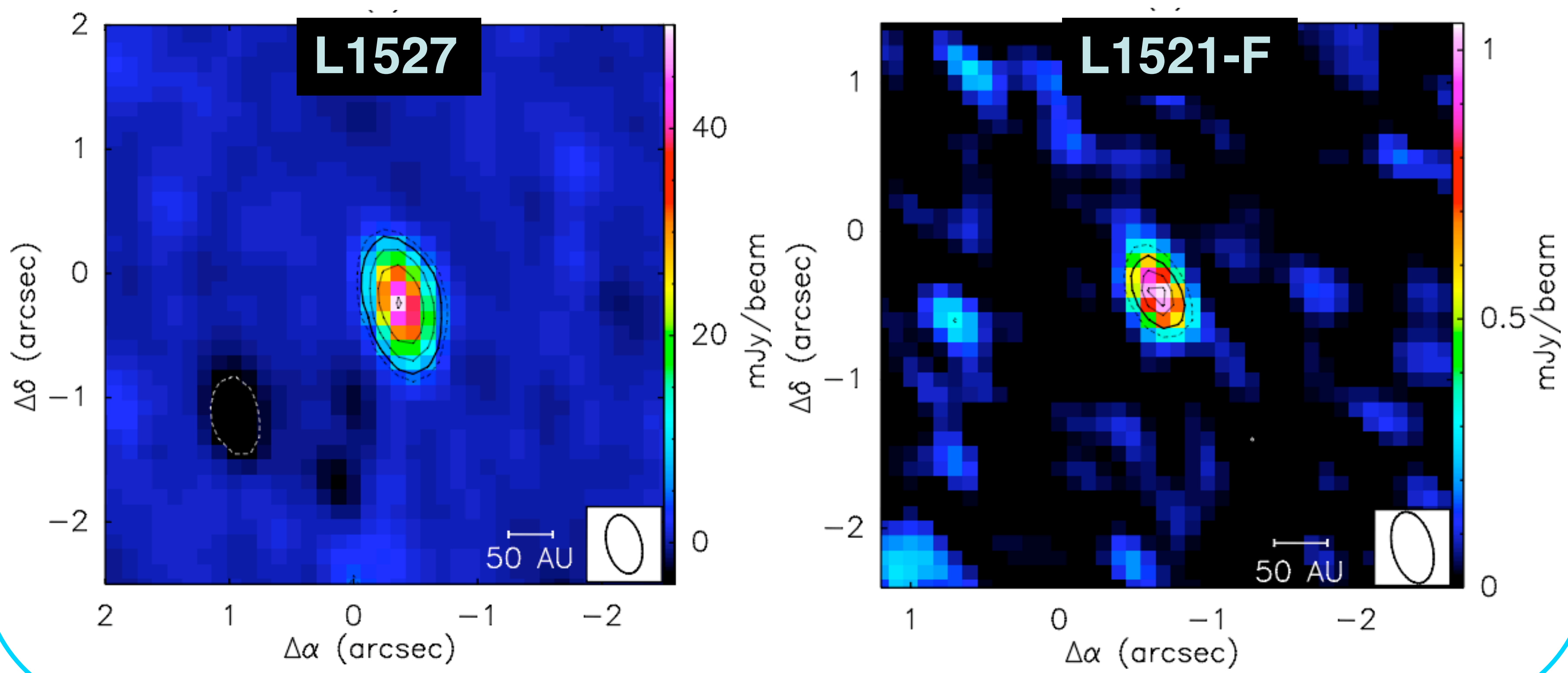




All the 5 PdBI 1.3mm continuum sources are **<u>compact sources</u>**
with typical FWHM 0.25'' - 0.9'' (fits to the PdBI visibilities)

PdBI 1.3 mm continuum maps : multiplicity

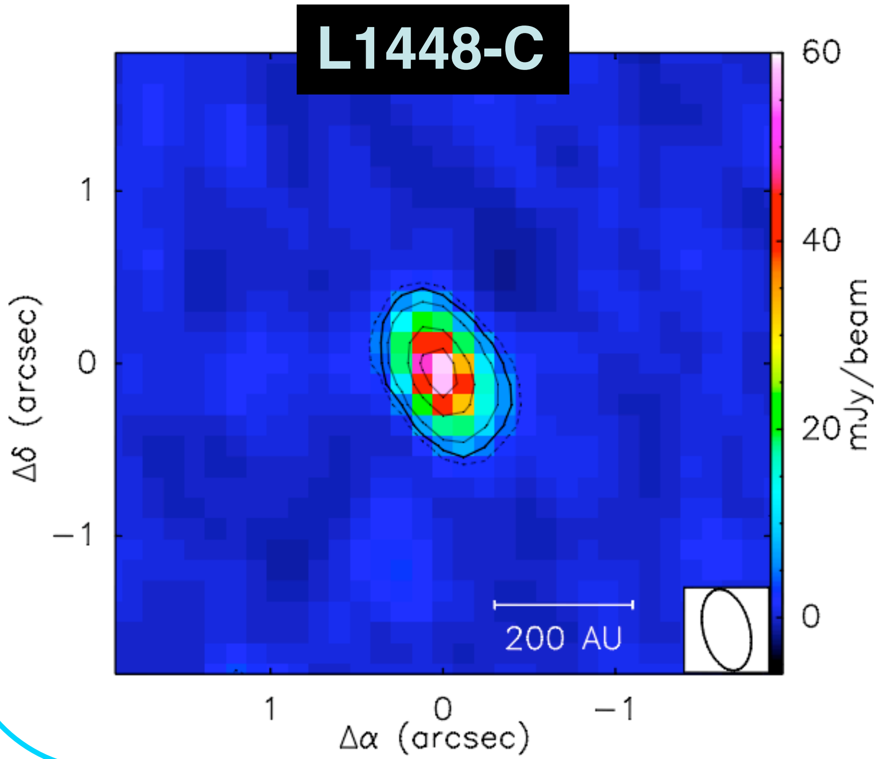
Taurus sources

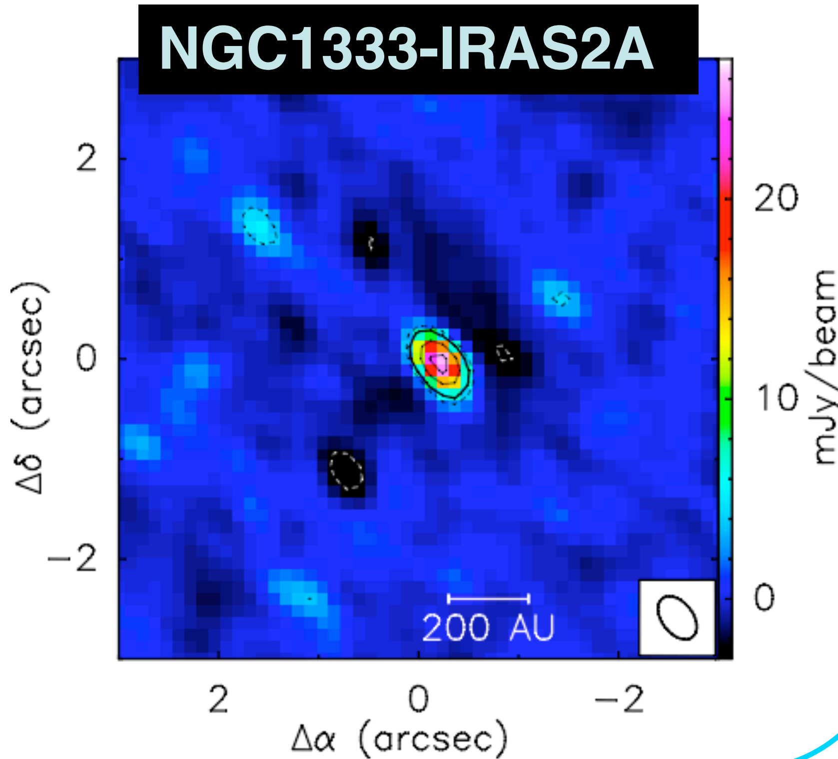


The continuum maps of IRAM 04191, L1521-F and L1527 show **single** sources.

PdBI 1.3 mm continuum maps : multiplicity

Perseus sources





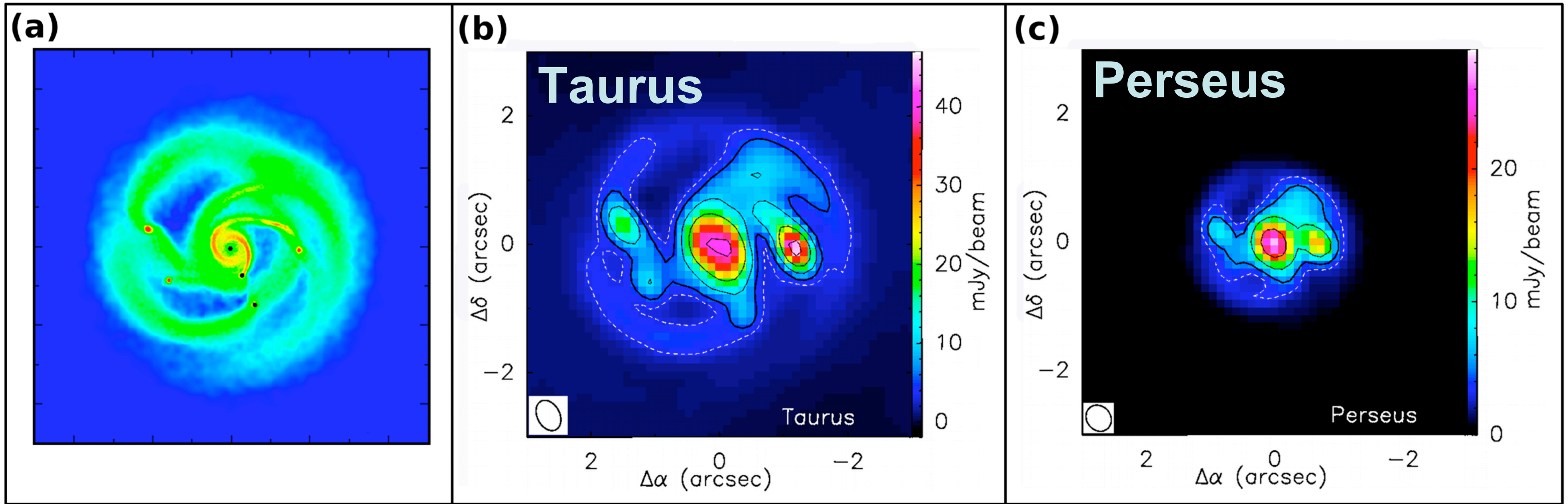
The continuum maps of NGC 1333-IRAS2A and L1448-C show **single** sources on scales 50 - 600 AU.

5 single Class 0 protostars on scales 50 - 600 AU.
+ enlarged sample with results of Looney (2000)
⇨ Class 0 BF < Class I BF at these scales ?

Comparison of the PdBI maps with hydrodynamical simulations

Comparison with numerical simulations of protostar formation :
synthetic observations of model column density maps as if observed with PdB-A.

Stamatellos & Whitworth 2009 : 0.7 M_o disk



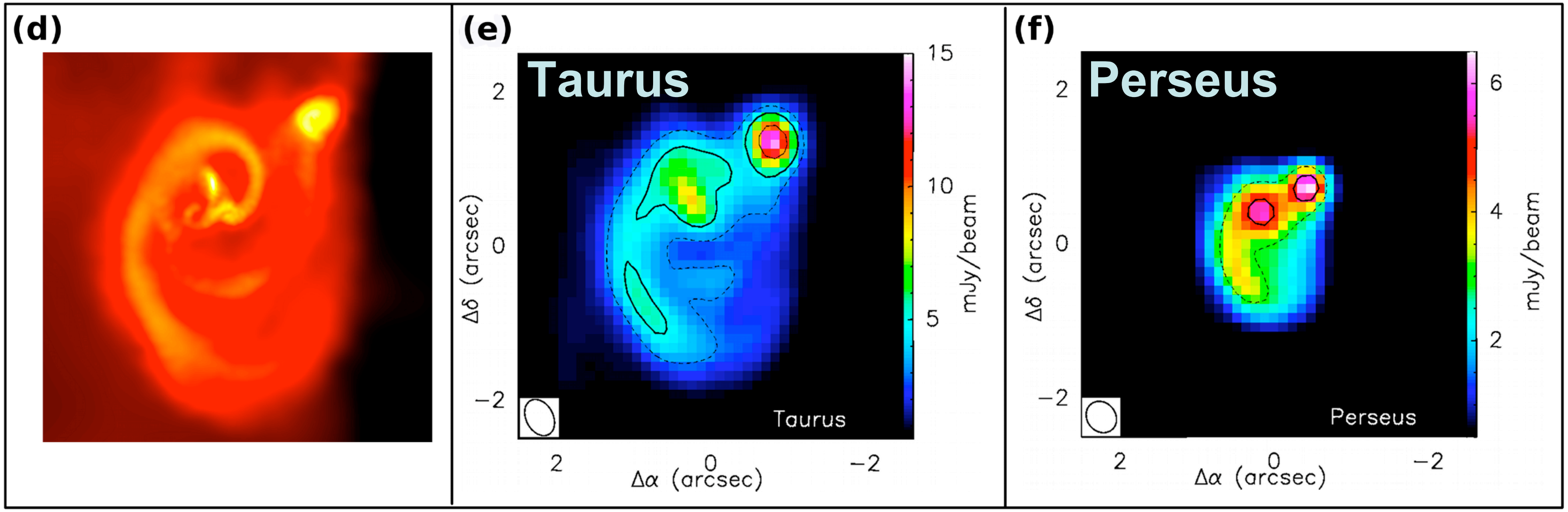
White : 3sigma level. Thick black : 5sigma level

All the 5 Class 0 protostars seen with PdB-A are **single**, **compact** sources with **typical FWHM ~ 0.25'' - 0.9''.**
Hydro simulations of Stamatellos & Whitworth (2009) produce PdB-A synthetic images with **typical FWHM ~ 1.8'' - 3.8''.**

Comparison of the PdBI maps with hydrodynamical simulations

Comparison with numerical simulations of protostar formation :
synthetic observations of model column density maps as if observed with PdB-A.

Bate 2009 : hydro simulations with radiative feedback



Dashed : 3sigma level. Thick black : 5sigma level

All the 5 Class 0 protostars seen with PdB-A are **single**, **compact** sources with **typical FWHM ~ 0.25'' - 0.9''.**
Hydro simulations of Bate (2009) produce PdB-A synthetic images with **typical FWHM ~ 1.9'' - 3.4''.**

Comparison of the PdBI maps with MHD simulations

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to our observations.

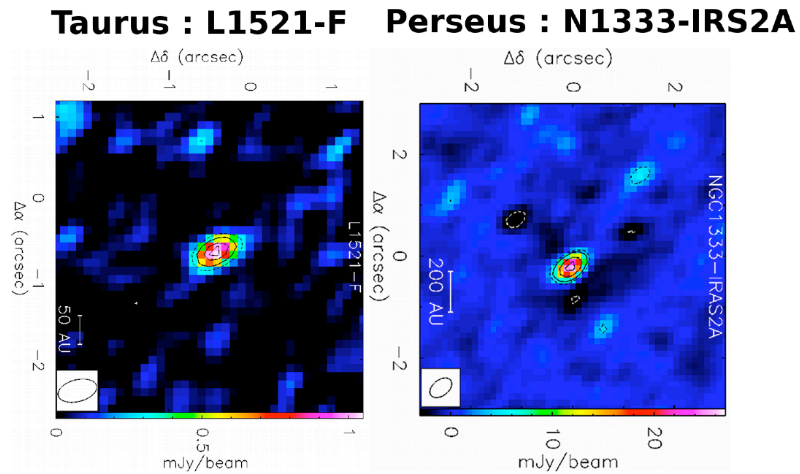
⇨ MHD simulations ?

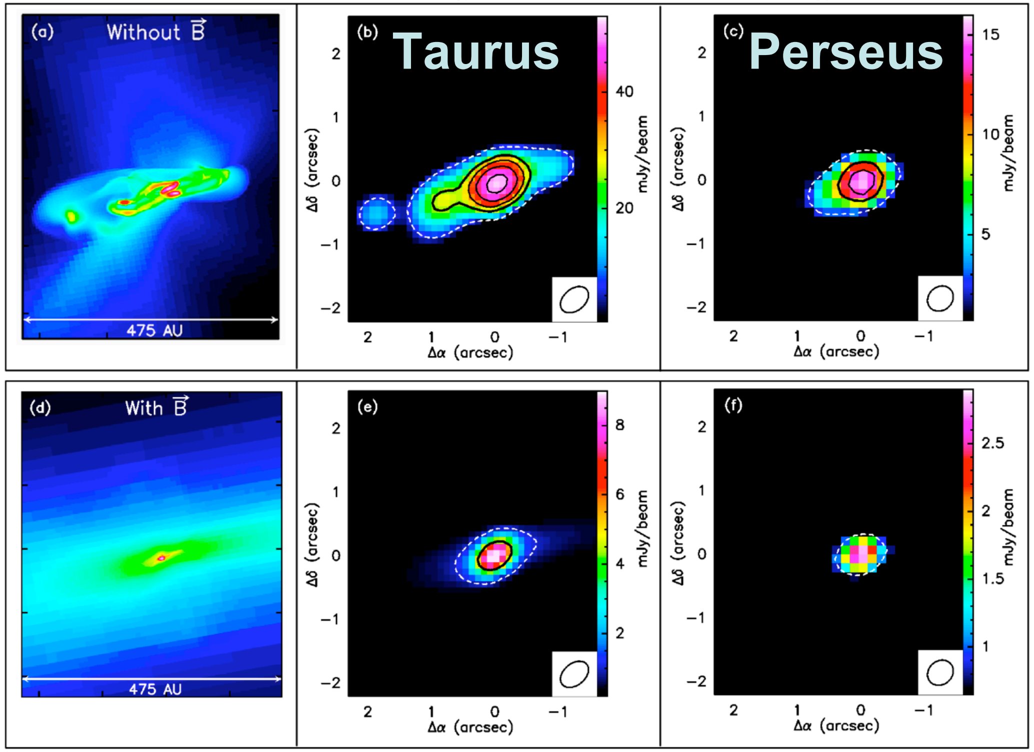
Hennebelle & Teyssier (2008) MHD simulations : produce PdB-A synthetic images with **typical FWHM ~ 0.2'' - 0.6''**

Similar to Class 0 PdB-A sources observed !

⇩

need B to produce compact, single PdB-A sources.

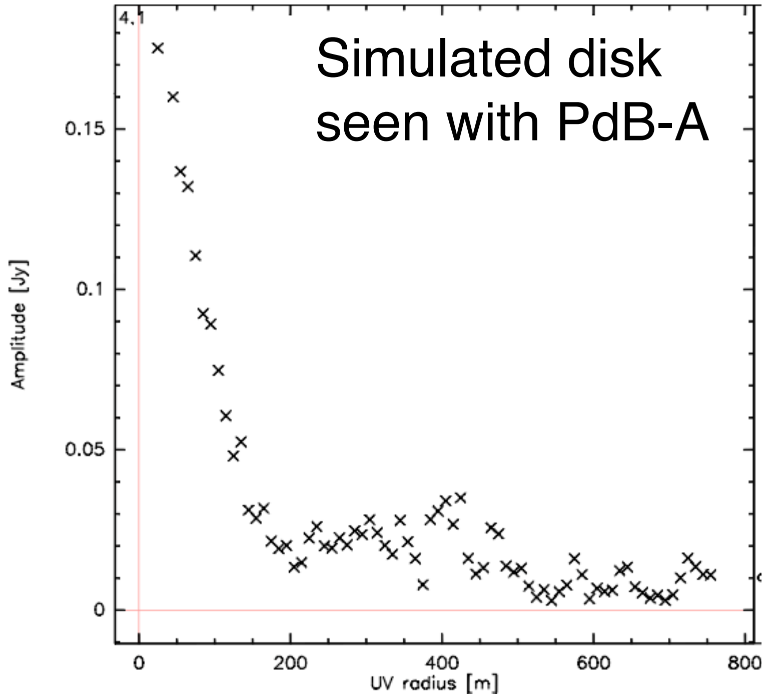


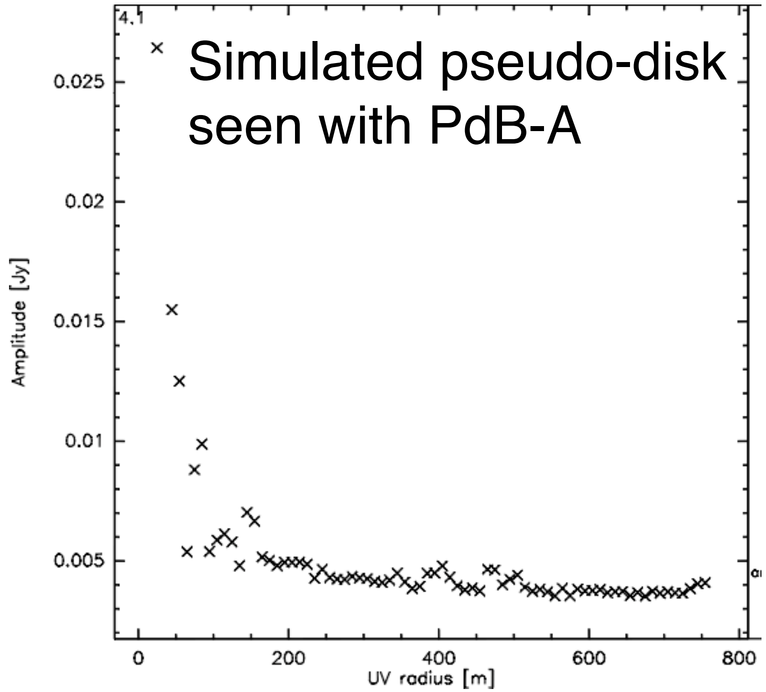


White dashed : 3sigma level. Thick black : 5sigma level

PdBI 1.3 mm maps of Class 0 protostars : disks

Continuum interferometric visibilities do not allow to distinguish disk / pseudo disk hypotheses.





One needs kinematic information to solve the question.

Essential debate : disks and pseudo-disks
have drastically different predictions as regards fragmentation
and the formation of multiple systems for instance.

Conclusions

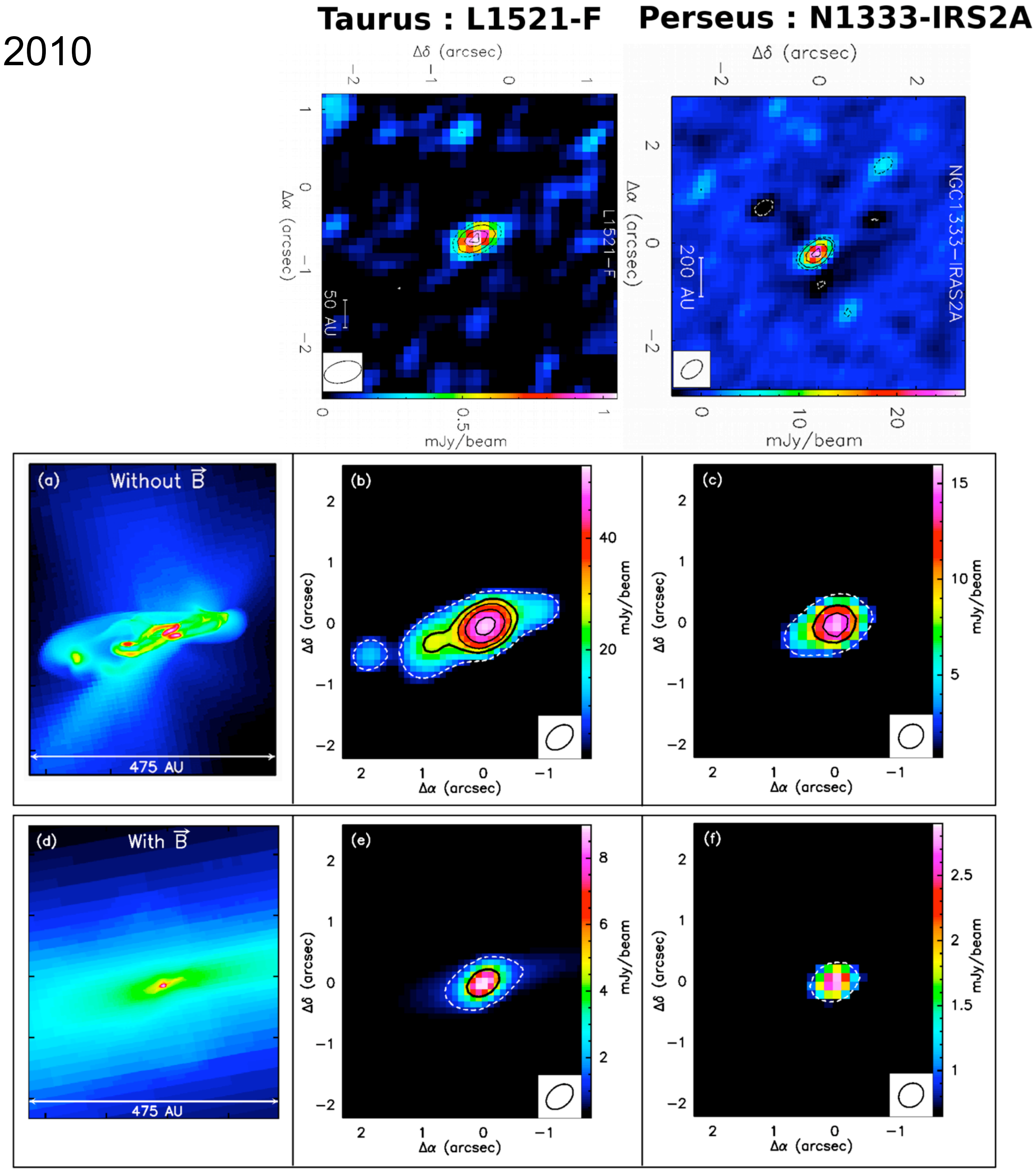
Multiplicity :

- Pilot PdBI high resolution survey of Class 0 protostars
- 5/5 single Class 0 protostars on scales 50 - 600 AU
- Suggest an increase of multiple systems frequency with separations a ~ 50 - 1000 AU with protostellar evolution (Class 0 to Class I stage). Tentative result, to confirm.
- Be careful when searching for protostellar companions : outflow features can be detected as mm/cm compact continuum sources.

Disks :

- Massive disks are not detected toward our sample
- Comparison with numerical simulations of protostellar formation : magnetized scenario favored because produce single, compact sources.
- But magnetized scenario rarely allow disks to form : pseudo disks instead.
- Without kinematic information, disks and pseudo disks signatures can not be distinguished. To investigate.

Maury et al. 2010
submitted



The case of L1448-C

L1448-C :
2dary continuum source ~ 600 AU SE.
Located along the jet axis of L1448-C.

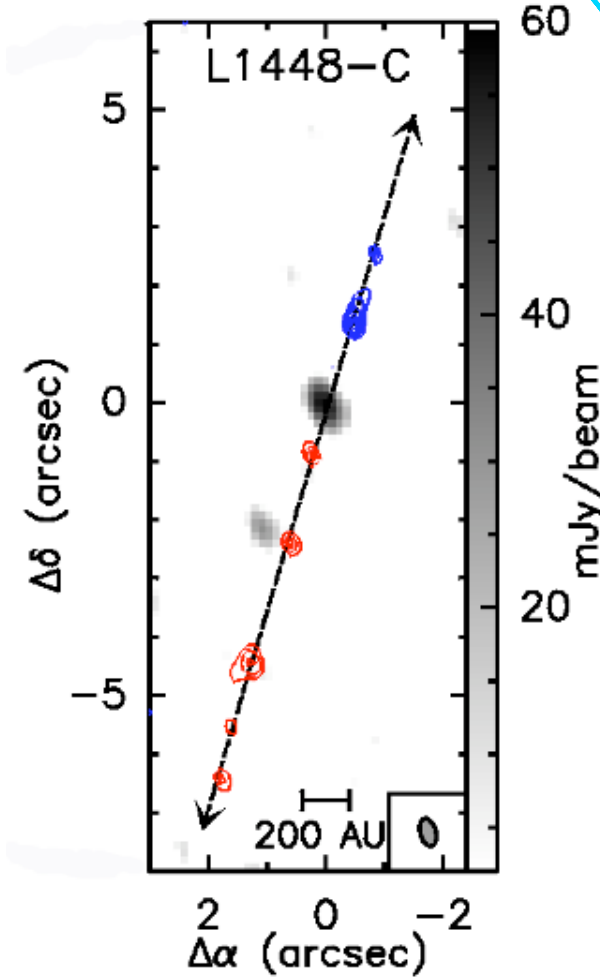
Multi-wavelength analysis :

Continuum : Spitzer, 1.3 mm, 3 mm
Line emission : SiO, CO, NH_3

2dary source is associated with :
HV bullet in our CO map + SiO peak

→ **<u>outflow feature</u>**.

Compact mm / cm continuum sources can be due to shocks : detecting secondary components in the vicinity of Class 0 protostars driving protostellar outflows do not allow to conclude the source is multiple !



Maury, André,
Hennebelle et al. (sub.)

PdBI 1.3 mm maps of Class 0 protostars : disks

Properties of the Class 0 protostars observed with PdBI :
all the 5 PdB-A sources are **compact** sources.

Taking into account interferometric filtering, sensitivities and resolutions of our observations : no massive ($M_d > 0.05\ M_o$) disk is **resolved** toward our sample on scales ~ 50 - 400 AU.

But 3 of the 5 PdB-A Class 0 sources show compact emission excess if compared to classical Class 0 enveloppe expectations : unresolved disk ?

However, our data coupled to numerical simulations suggest a magnetized scenario of protostellar collapse : massive, extended rotating supported structures are unlikely to form.
Magnetized scenario **favors pseudo-disk interpretation** of this excess emission.

But we need to fragment….

(remember…a large fraction of stars are binaries)

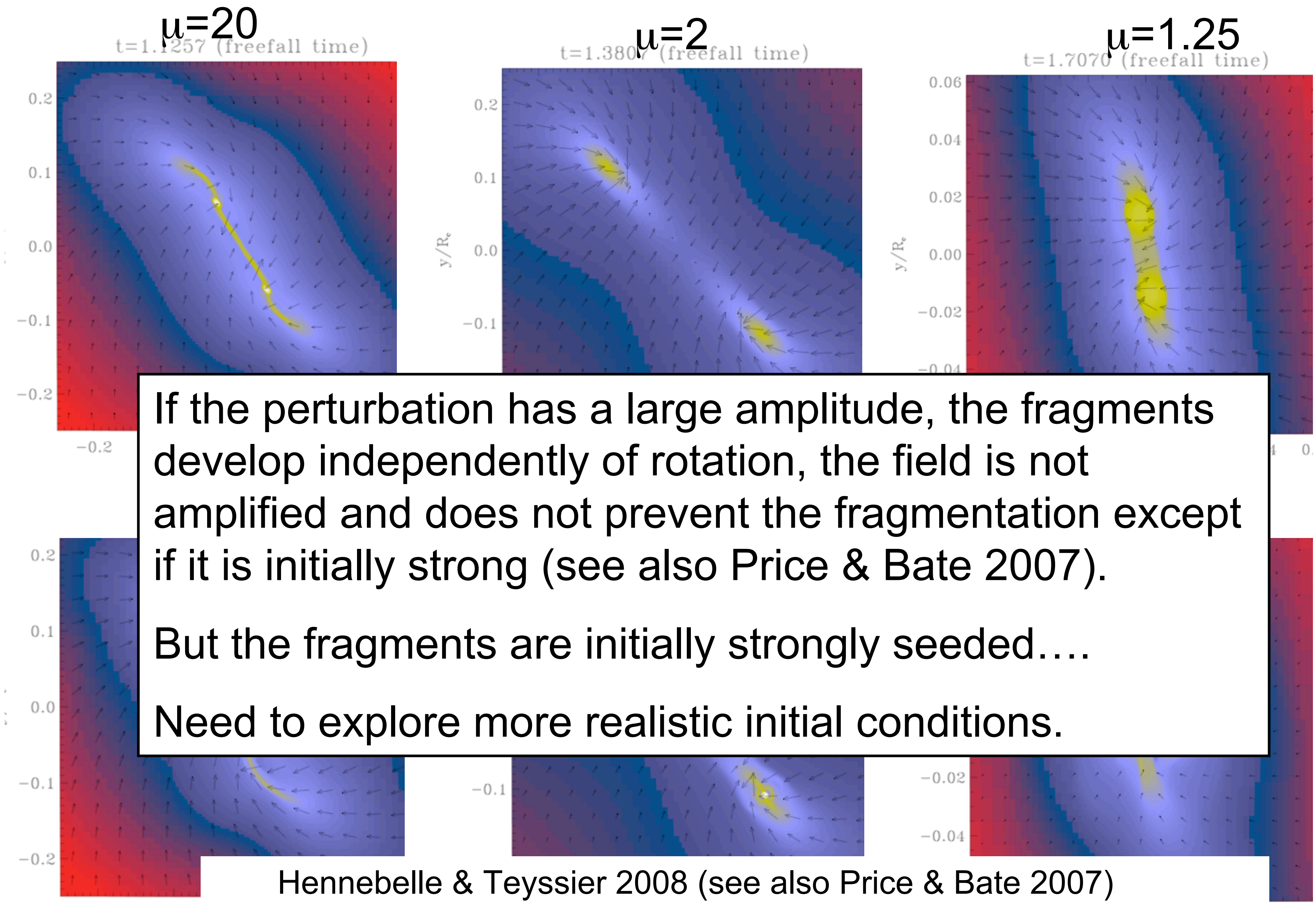
How to resolve the conumdrum ?

-Effect of larger perturbation amplitudes

-Ambipolar diffusion

-Fragmentation during the second collapse
(second collapse: H_2 dissociation at T>2000 K
dissociation energy compensate pdV work => isothermal collapse)
(Machida et al. 2007)

Let us consider an m=2 perturbation with an amplitude of 50%



If the perturbation has a large amplitude, the fragments develop independently of rotation, the field is not amplified and does not prevent the fragmentation except if it is initially strong (see also Price & Bate 2007).

But the fragments are initially strongly seeded….

Need to explore more realistic initial conditions.

Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

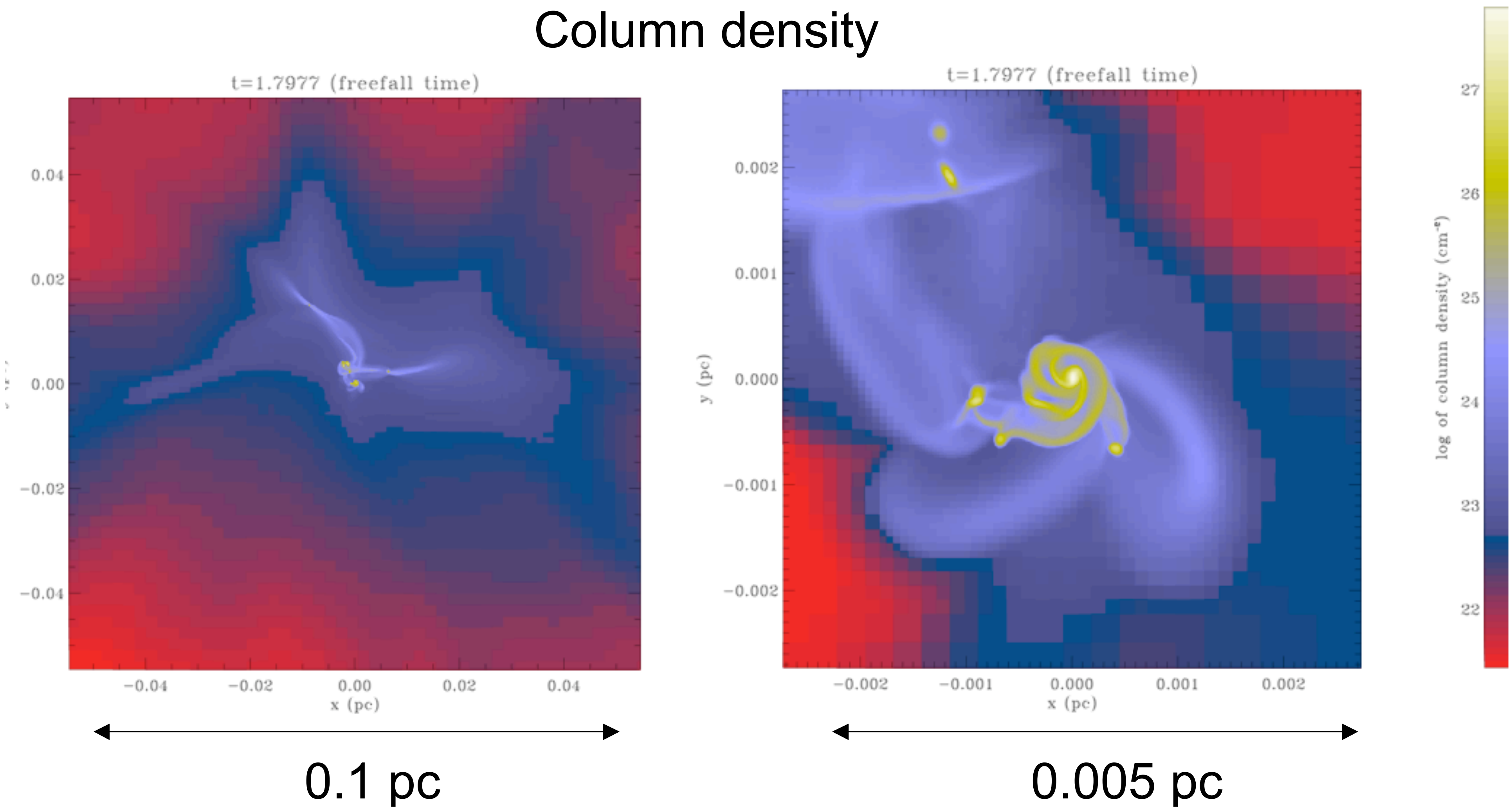
Toward less idealized/ more realistic initial conditions

Consider Bonnor-Ebert type spheres with turbulence

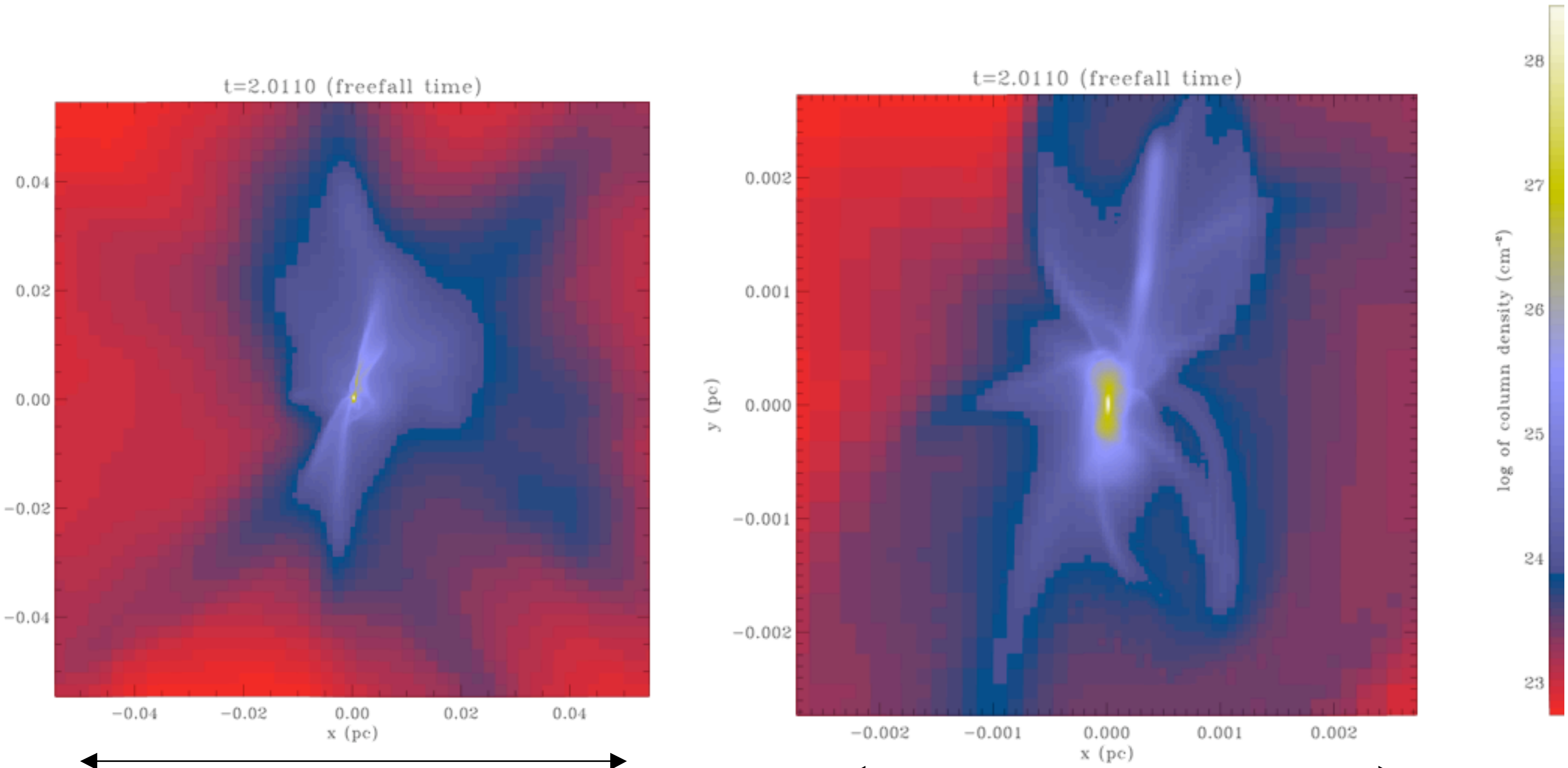
-density contrast between center and edge around 20
-turbulent field (with ramdom phases in the Fourier space) is setup initially (no forcing)

A 30 solar mass cloud
Near Virial equilibrium initially
Turbulence= gravity
No B

Column density



A 30 solar mass cloud
Near Virial equilibrium initially
Turbulence= gravity
Magnetic energy=thermal energy



0.1 pc

0.005 pc