Synthetic observations of the early stages of star formation

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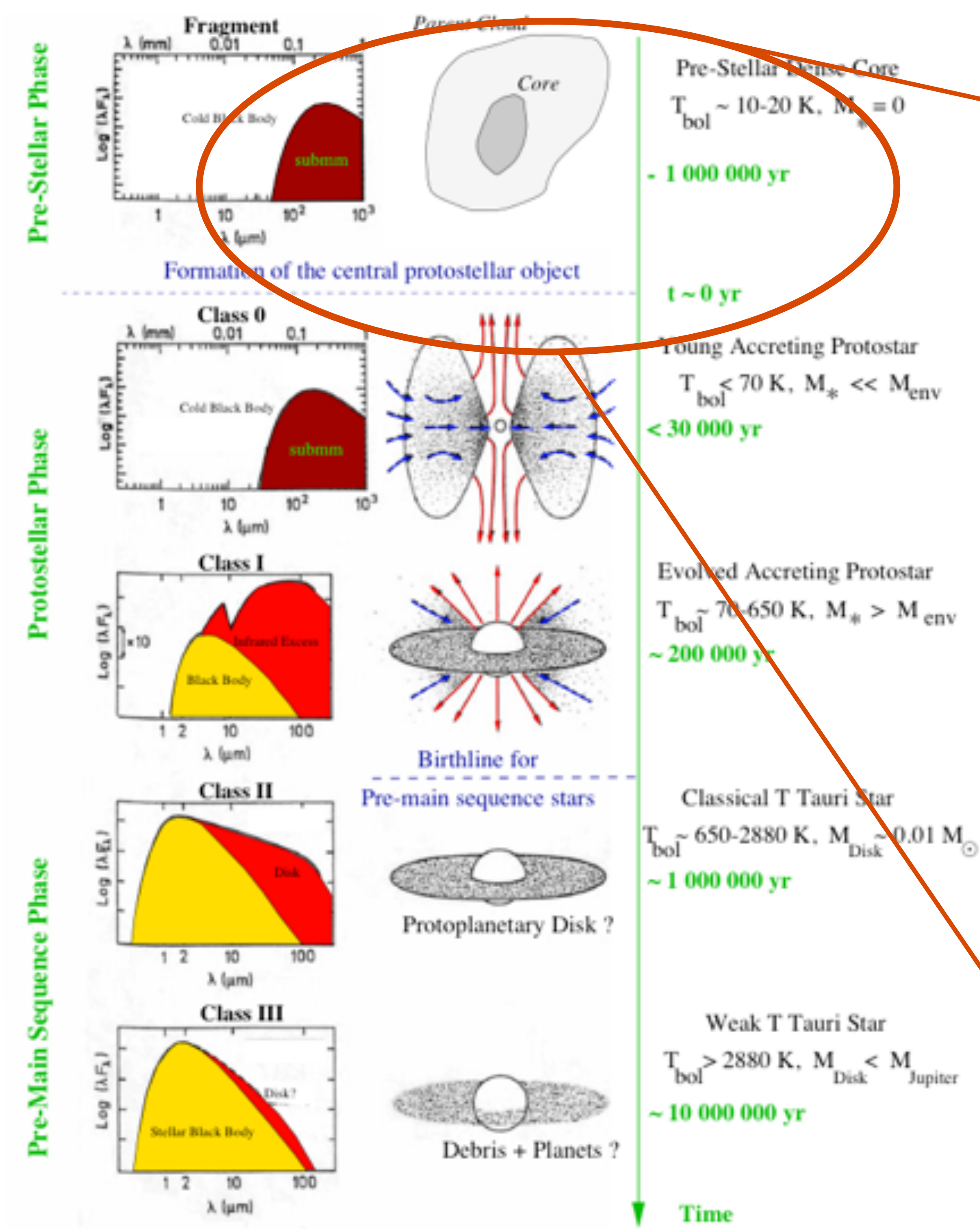
Star formation evolutionary sequence



André 2002

Prestellar dense core collapse

First collapse

Isothermal

First Larson core

Adiabatic

H_2 dissociation

Second collapse

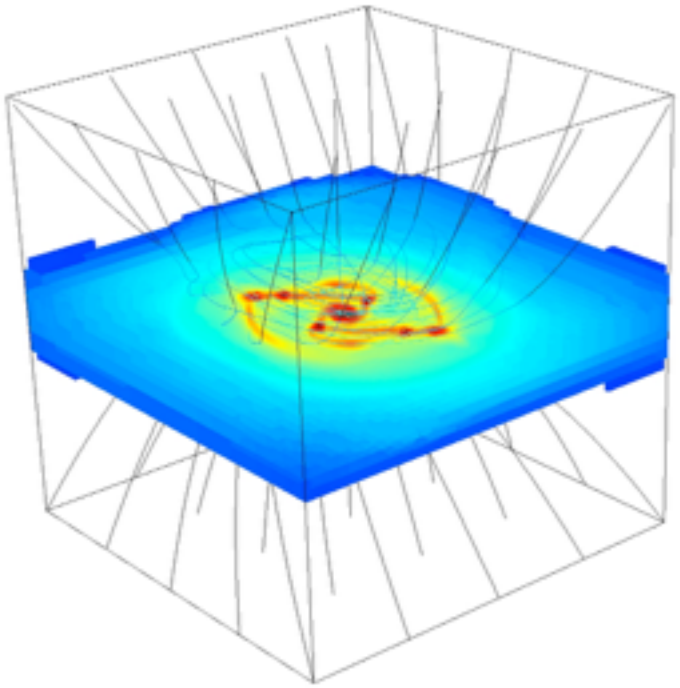
Quasi - isothermal

Second Larson core

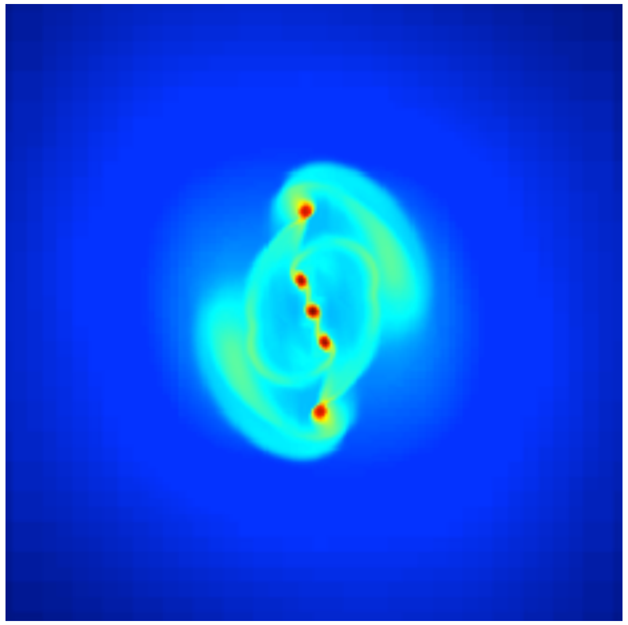
RMHD with Flux Limited Diffusion in RAMSES

✓ **RAMSES code** *(Teyssier 2002)*

- AMR code, 2nd order Godunov scheme
- Ideal MHD solver (*Fromang et al. 2006*)
- RHD solver with the Flux Limited Diffusion (*Commerçon et al. 2011b*)
- Self-gravity
- Jeans length refinement criteria (>10 pts/λ_J)



Density



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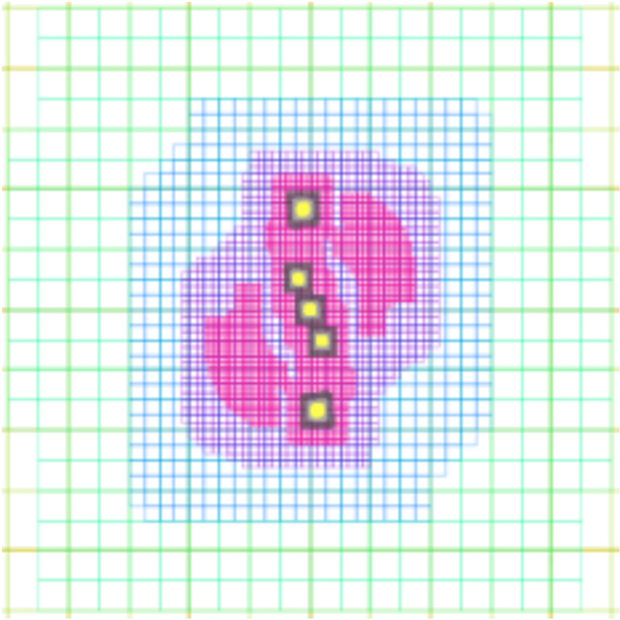
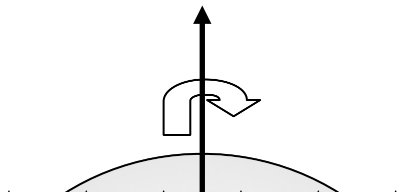


Grid

Initial conditions (numerical experiment)

1 $M_\odot$ isolated dense core: uniform density and temperature (10 K, $\alpha = E_{th}/E_{grav}$), solid body rotation ($\beta = E_{rot}/E_{grav}$), m=2 density perturbation (amplitude A=10%)
==> Small-scale fragmentation

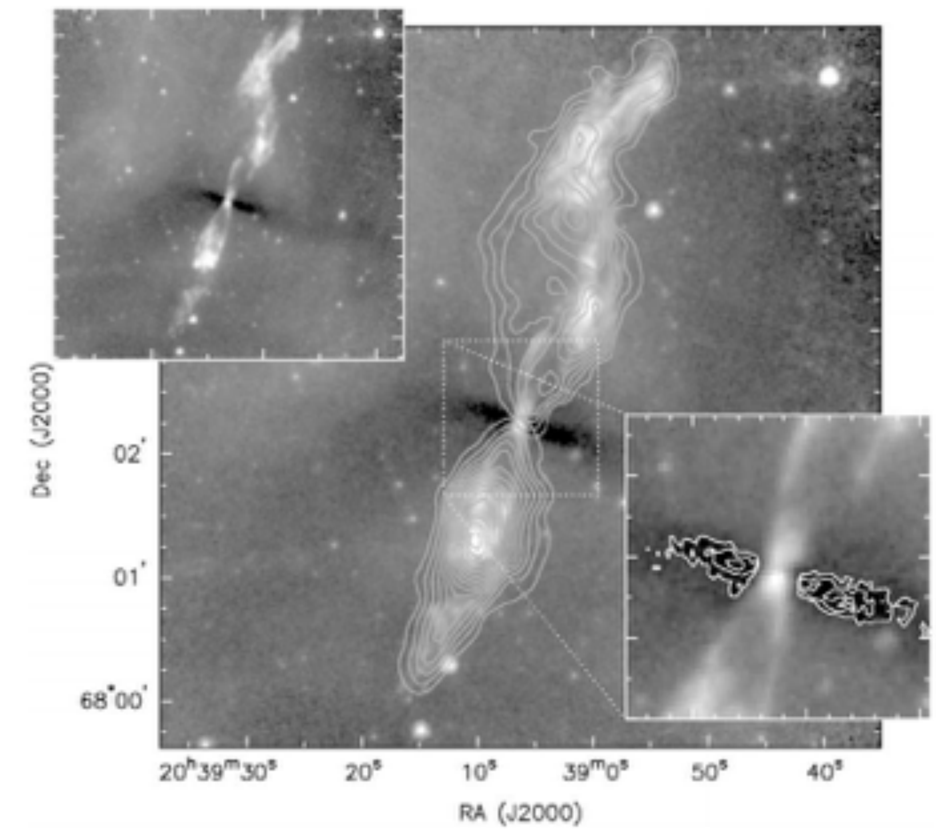
★ Radiative transfer: efficient cooling (e.g., *Attwood et al. 09*) and heating (*e.g., Krumholz et al. 09, Bate 09*).
Grey opacities from Semenov et al. 03.



★ Ideal MHD <==> flux freezing: $\varphi \propto BR^2$
Magnetic field lines are twisted and compressed:

==> **Outflow** (e.g., *Machida et al., Banerjee & Pudritz 06, Hennebelle & Fromang 08, Mellon & Li 2008*)

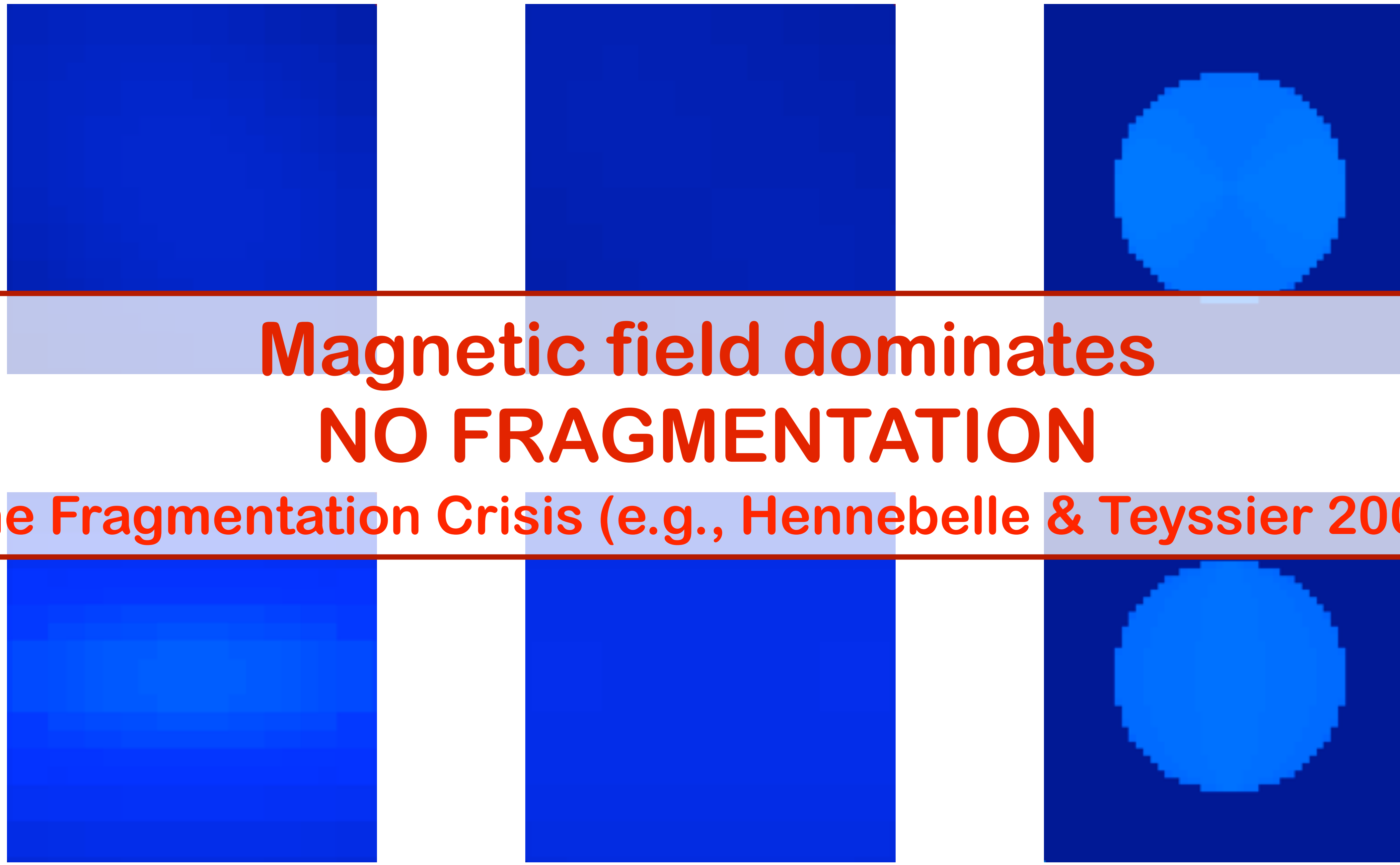
$\mu = (\varphi/M)_{crit} / (\varphi/M)$ (observations μ ~ 2-5)



Looney et al. 2007

Influence of the magnetization

	MU=5 Strong B	MU=20 Weak B	Hydro B=0



Magnetic field dominates

NO FRAGMENTATION

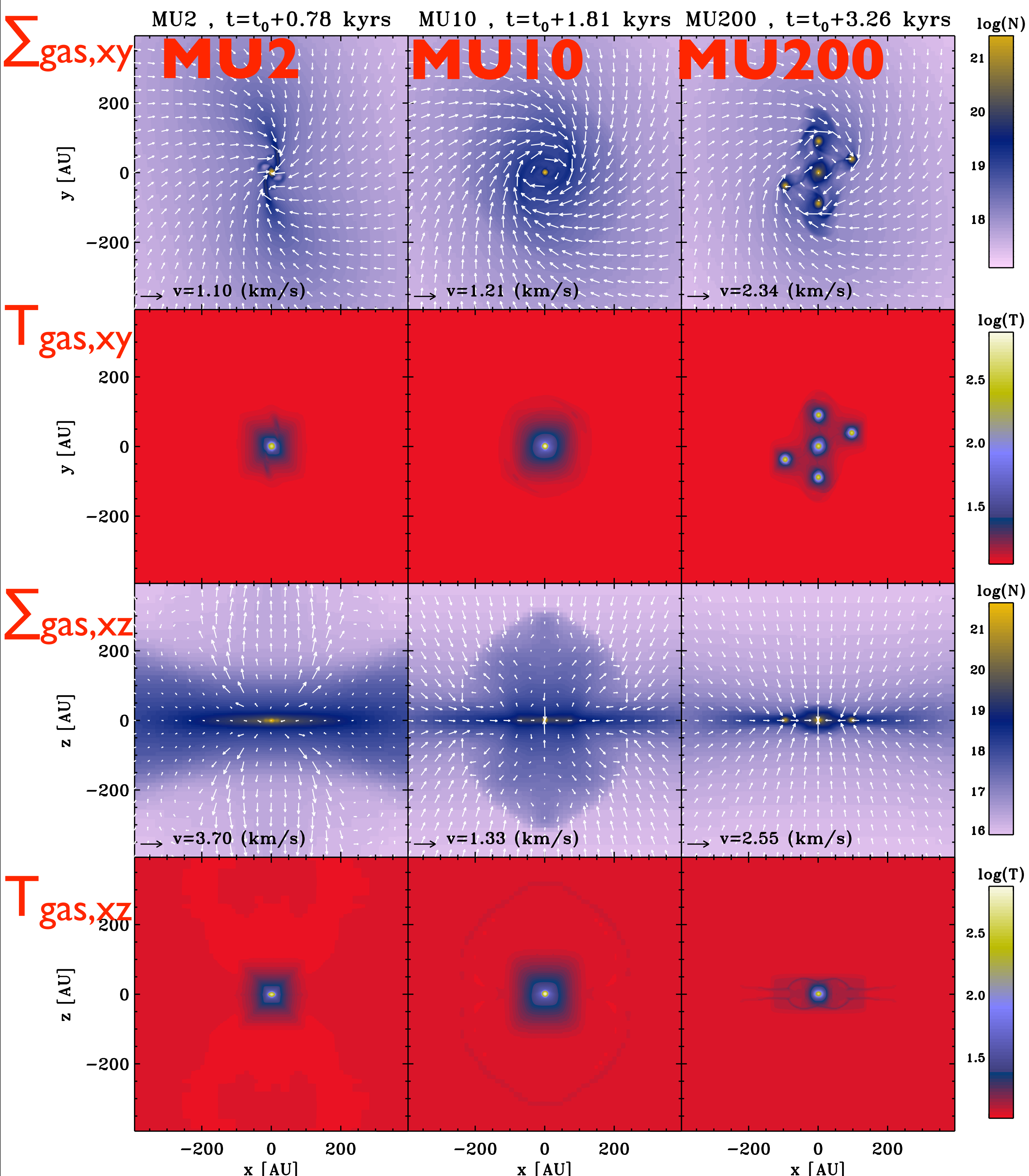
The Fragmentation Crisis (e.g., Hennebelle & Teyssier 2008)

Take Away I

- ✓ Magnetic field and radiative transfer cannot be neglected
- ✓ Strong interplay between magnetic braking and radiative feedback
- ✓ Disk can form but do not fragment

Towards synthetic observations

µµµ



- 3 representative cases
  - *MU2*: pseudo-disk + outflow
  - *MU10*: disk + pseudo-disk + outflow
  - *MU200*: disk + fragmentation

- First core lifetime:

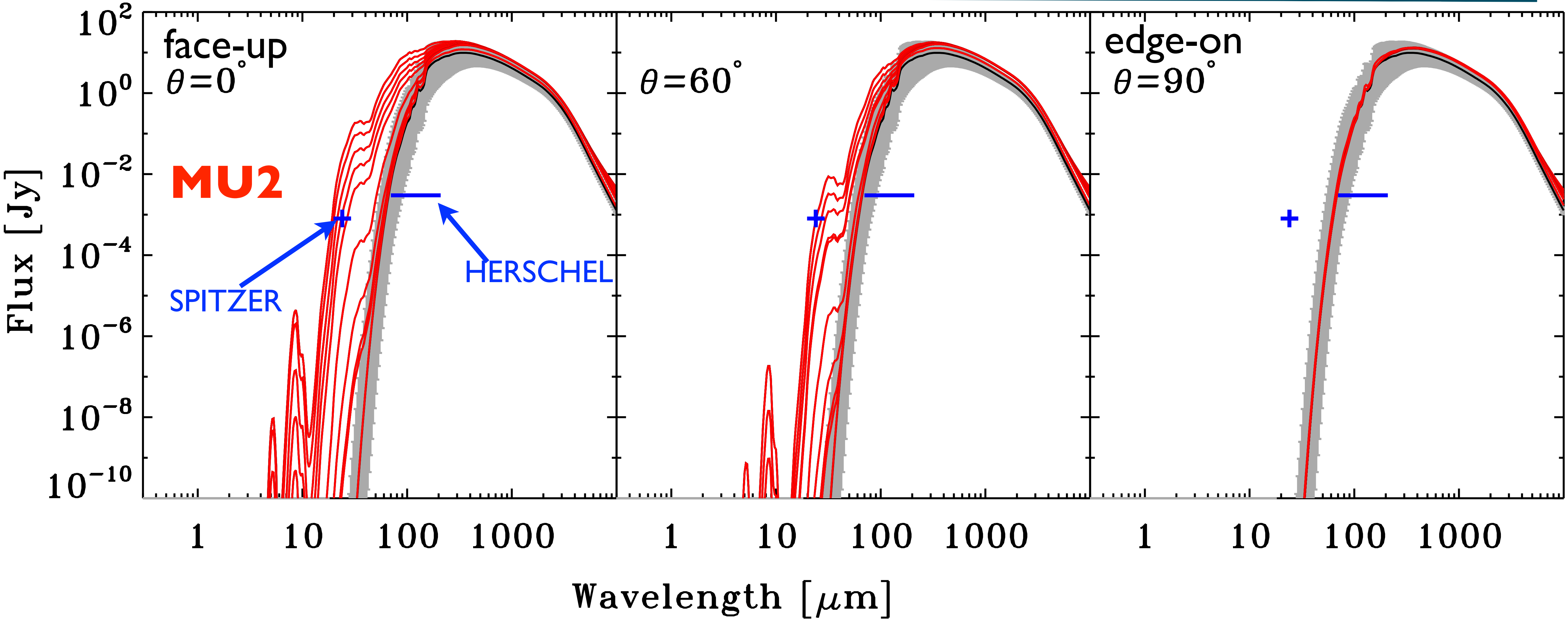
MU2	*MU10*	*MU200*
1.2 kyr	3 kyr	> 4 kyr

- Images & SED computed with the radiative transfer code **RADMC-3D**, developed by C. Dullemond (ITA Heidelberg)
- $T_{dust} = T_{gas}$ (given by the RMHD calculations)

Commerçon, Launhardt, Dullemond & Henning, A&A 2012

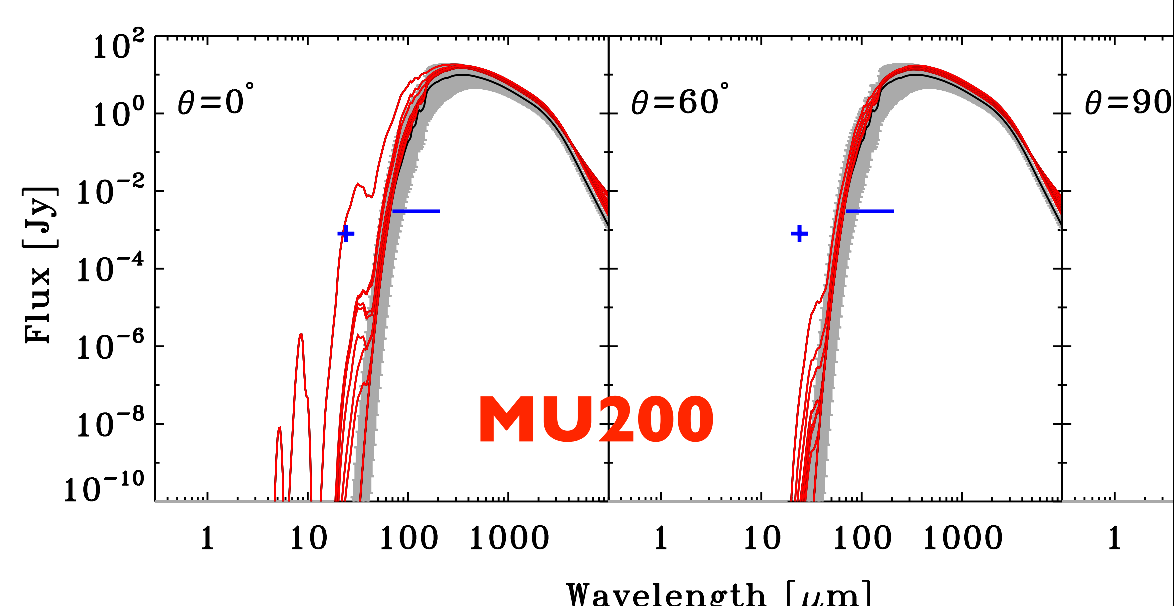
SED - Do we see a first core signature?

μμμ



- *Objects at 150 pc, 3000 AU x 3000 AU region*
- *Prestellar core = initial conditions (black line)*
- Emission in the FIR => **HERSCHEL, SPITZER**
- But similar SEDs in the MU200 model, i.e. with a disk!

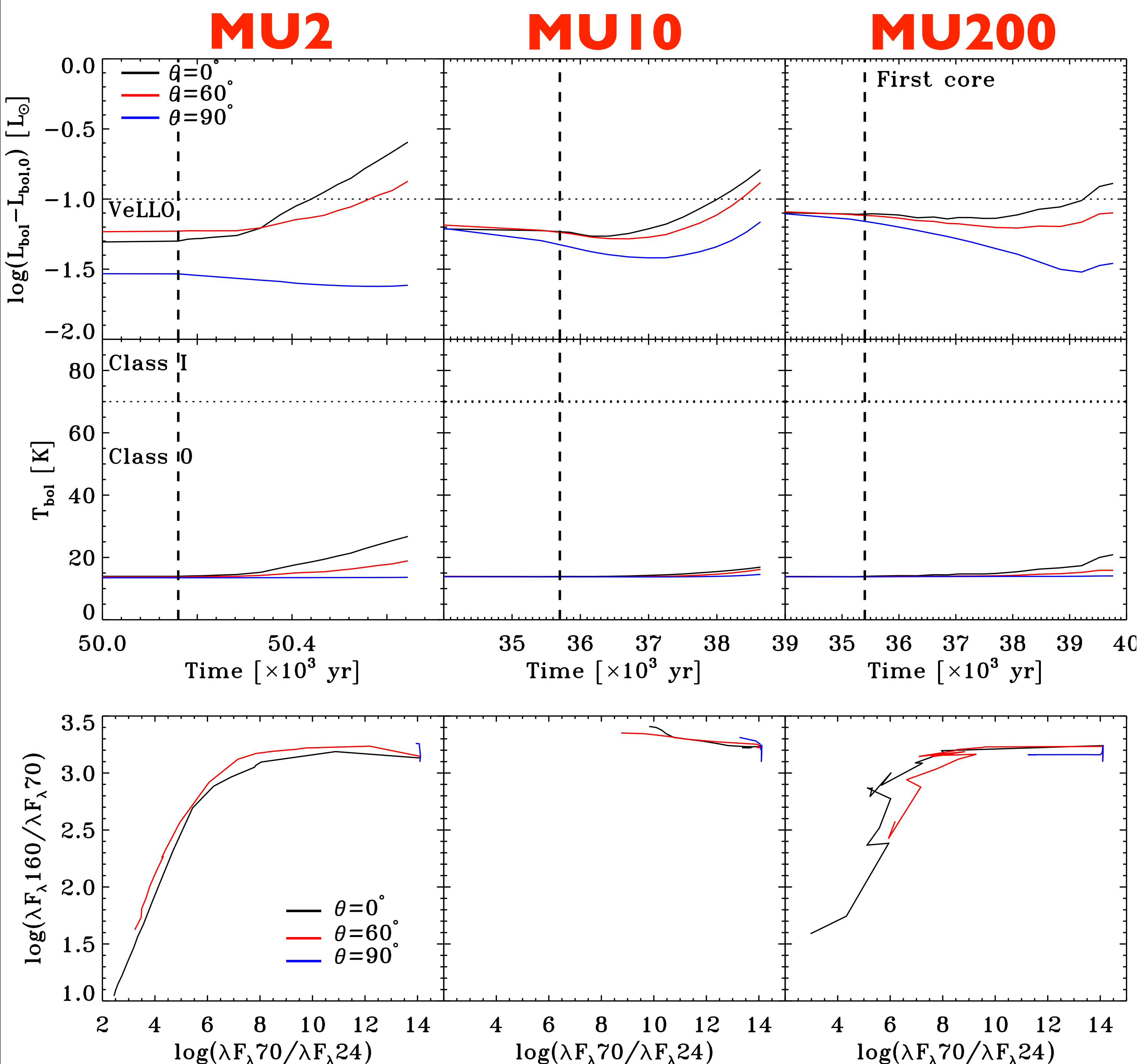
=> Issues in SED-fitting models for early Class 0?



Help to select first core candidates & to distinguish starless cores and first cores

Evolution diagrams

µµµ



FHSCs consistent with VeLLOs

Evidence of evolutionary sequence in color-color diagrams

Evolution diagrams

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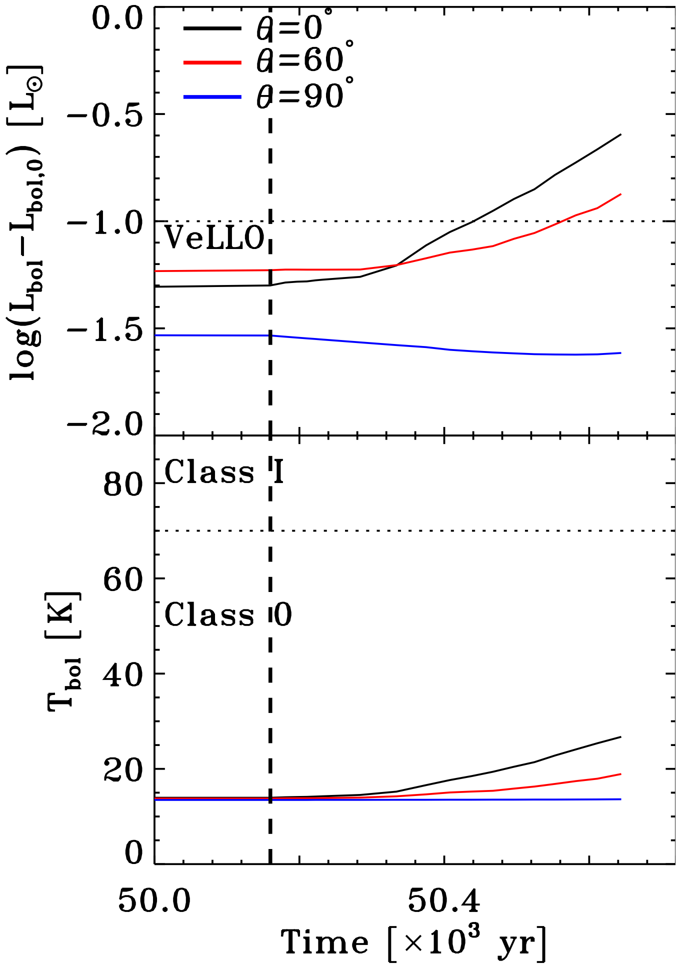
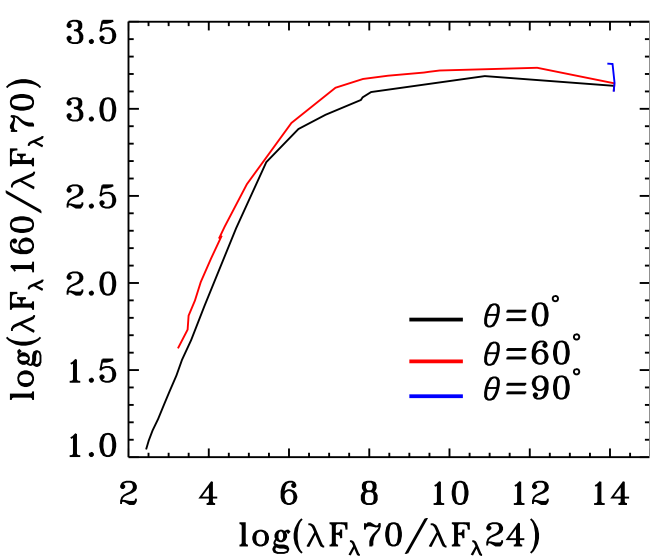
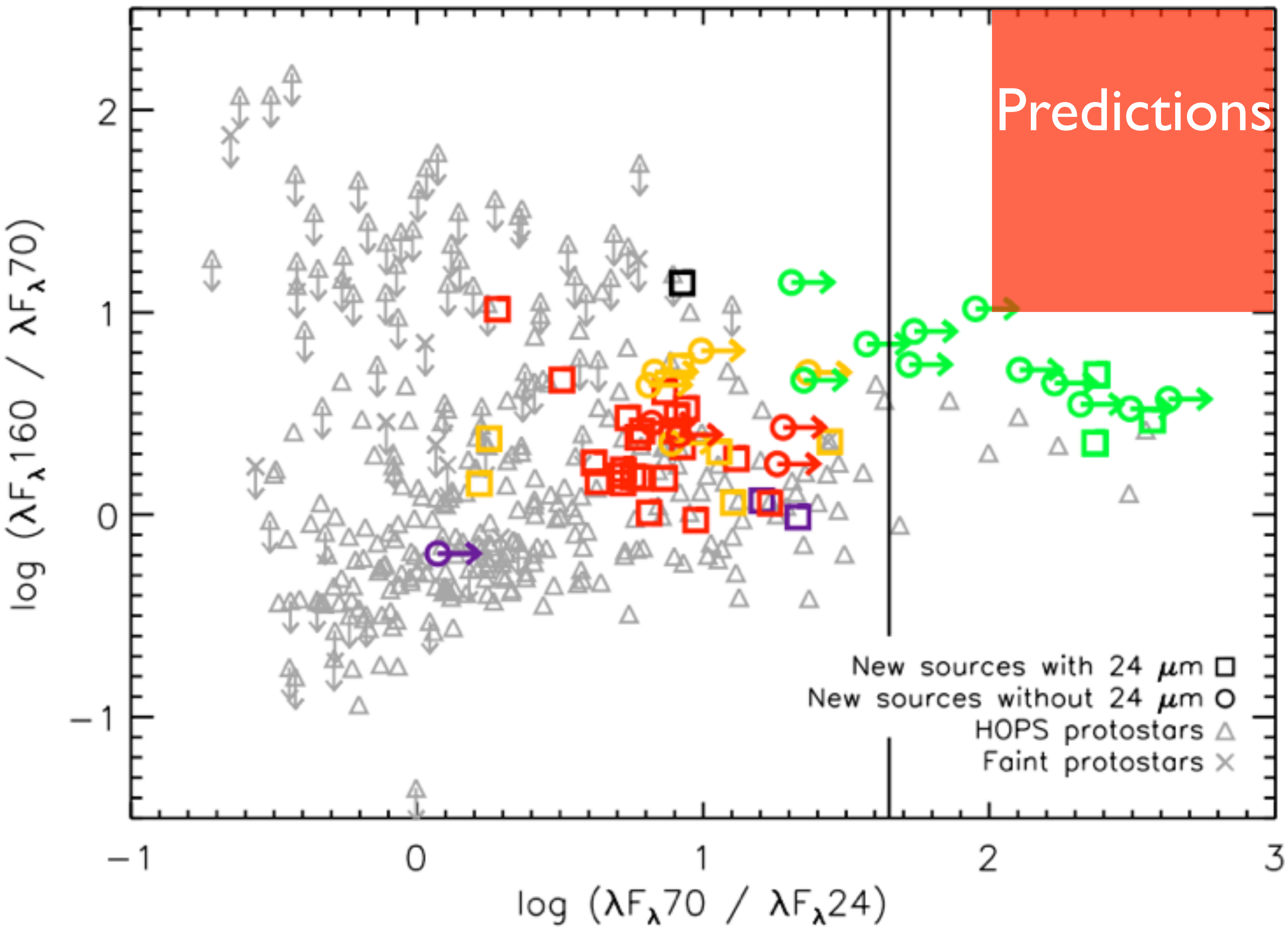
MU2







Stutz et al. 2013

ALMA predictions: which band/configuration?

μμμ

- Which frequency band/interferometer configuration combination are able to probe FHSC?

Commerçon, Levrier et al. A&A, 2012

ALMA predictions: which band/configuration?

µµµ

- Which frequency band/interferometer configuration combination are able to probe FHSC?

- IRAM **GILDAS** ALMA simulator

- Objects are virtually placed at a distance of 150 pc

- dust emission is computed over a total bandwidth of 8 GHz center around the band's central frequency

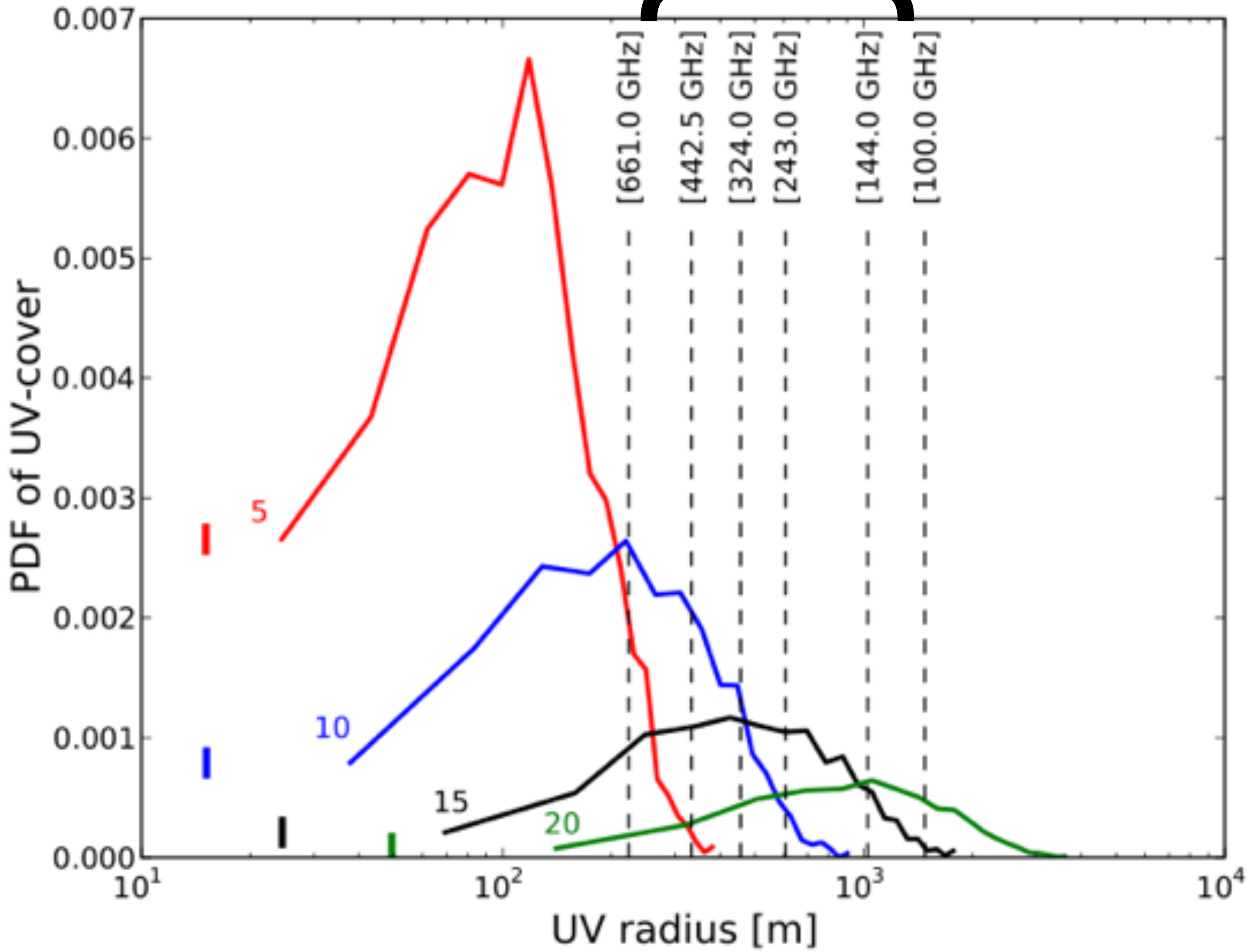
- 18 min integration time

Commerçon, Levrier et al. A&A, 2012

ALMA predictions: which band/configuration?

μμμ

10 AU @ 150 pc



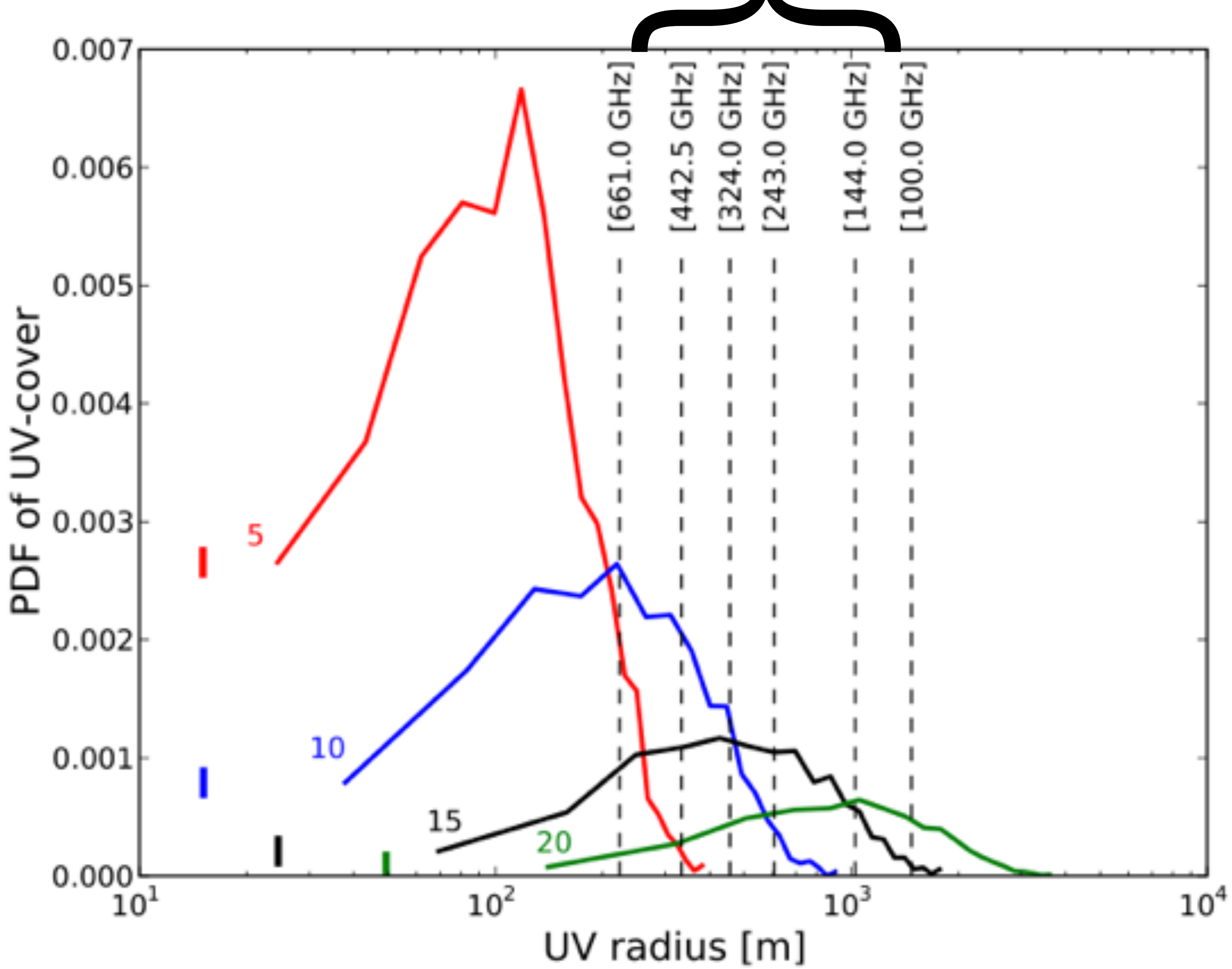
Interferometer capabilities

Commerçon, Levrier et al. A&A, 2012

ALMA predictions: which band/configuration?

µµµ

10 AU @ 150 pc

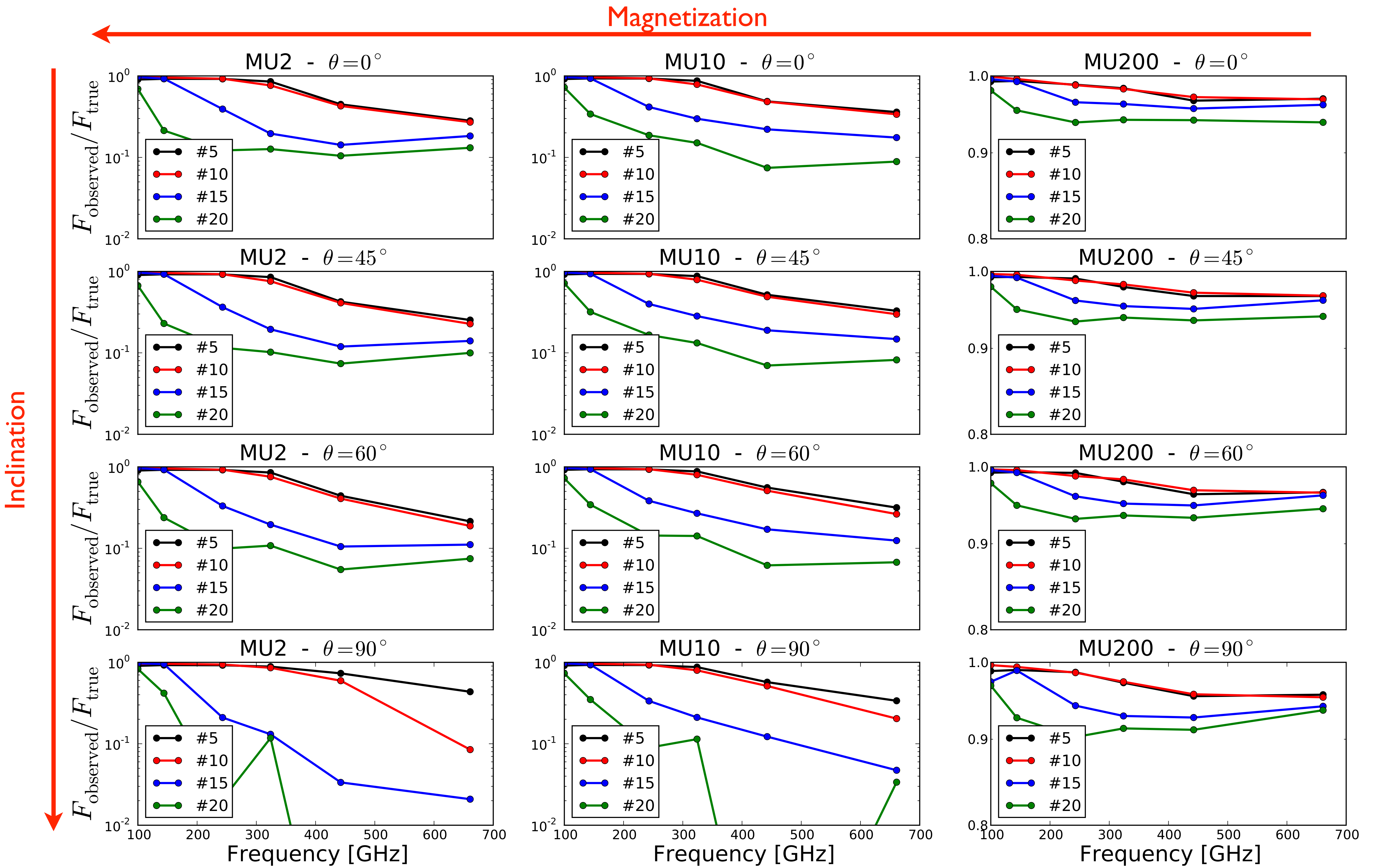


Configurations 15 & 20
better probe FHSC scales

Commerçon, Levrier et al. A&A, 2012

ALMA predictions: flux loss

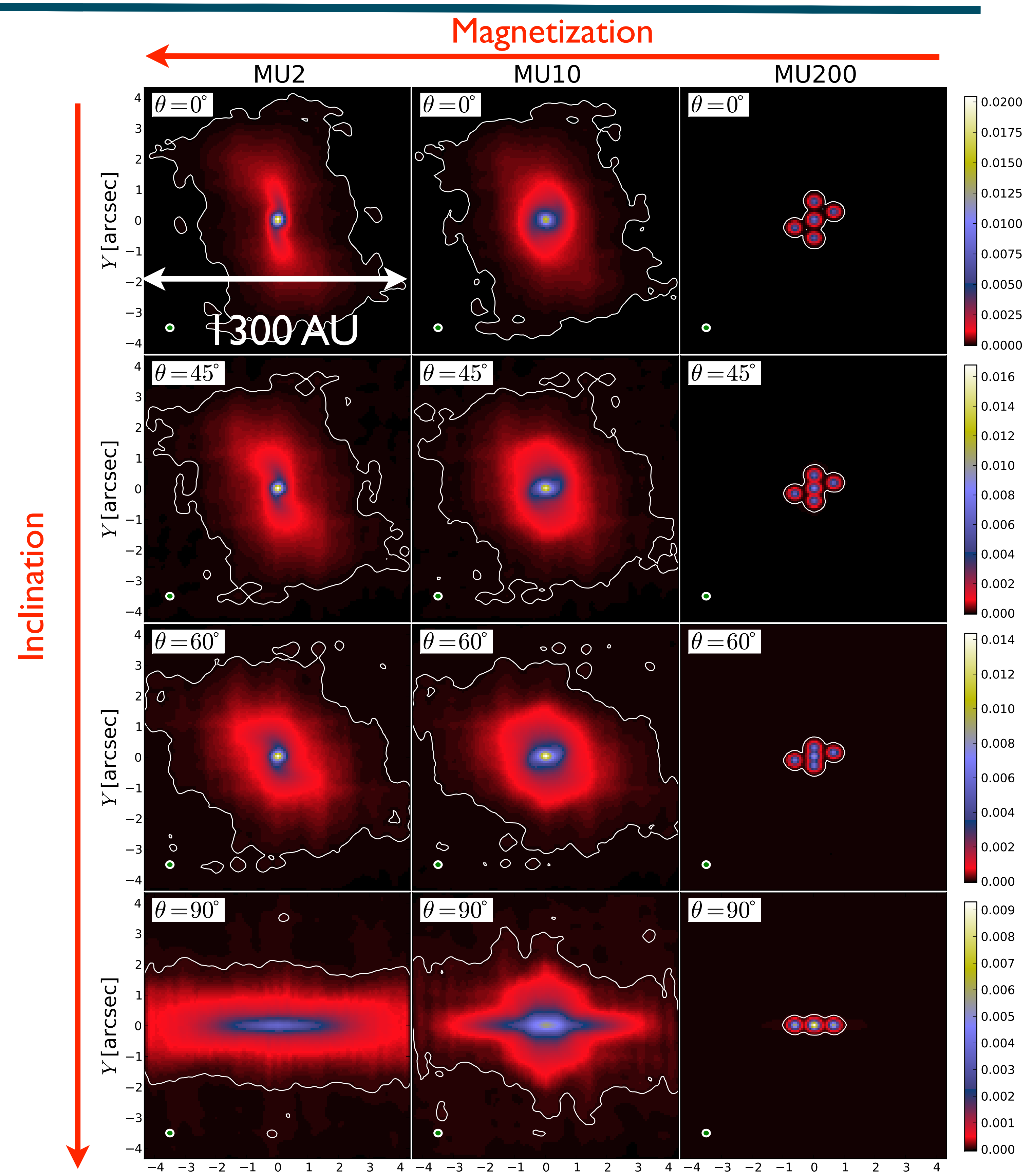
μμμ



Commerçon, Levrier et al. A&A, 2012

Synthetic ALMA dust emission maps

µµµ



ALMA Band 3 Config 20 @150 pc

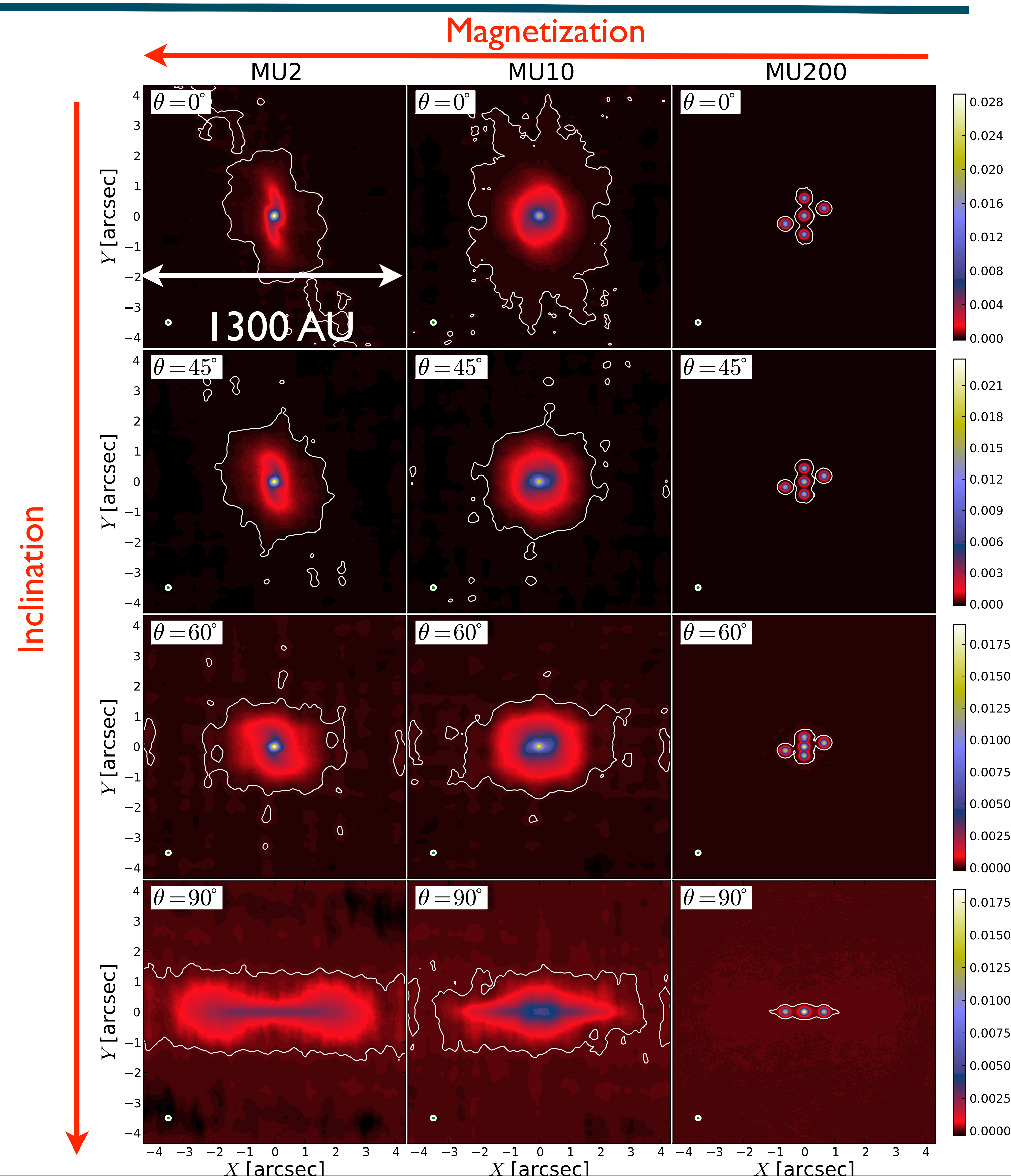
Commerçon, Levrier et al. A&A, 2012

Synthetic ALMA dust emission maps

µµµ

ALMA Band 4 Config 20 @150 pc

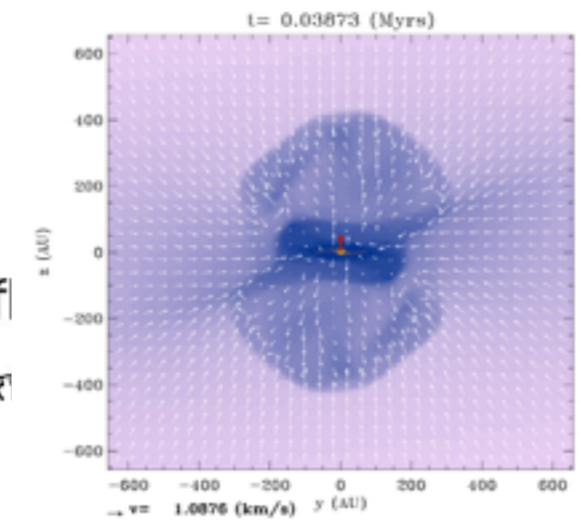
Commerçon, Levrier et al. A&A, 2012

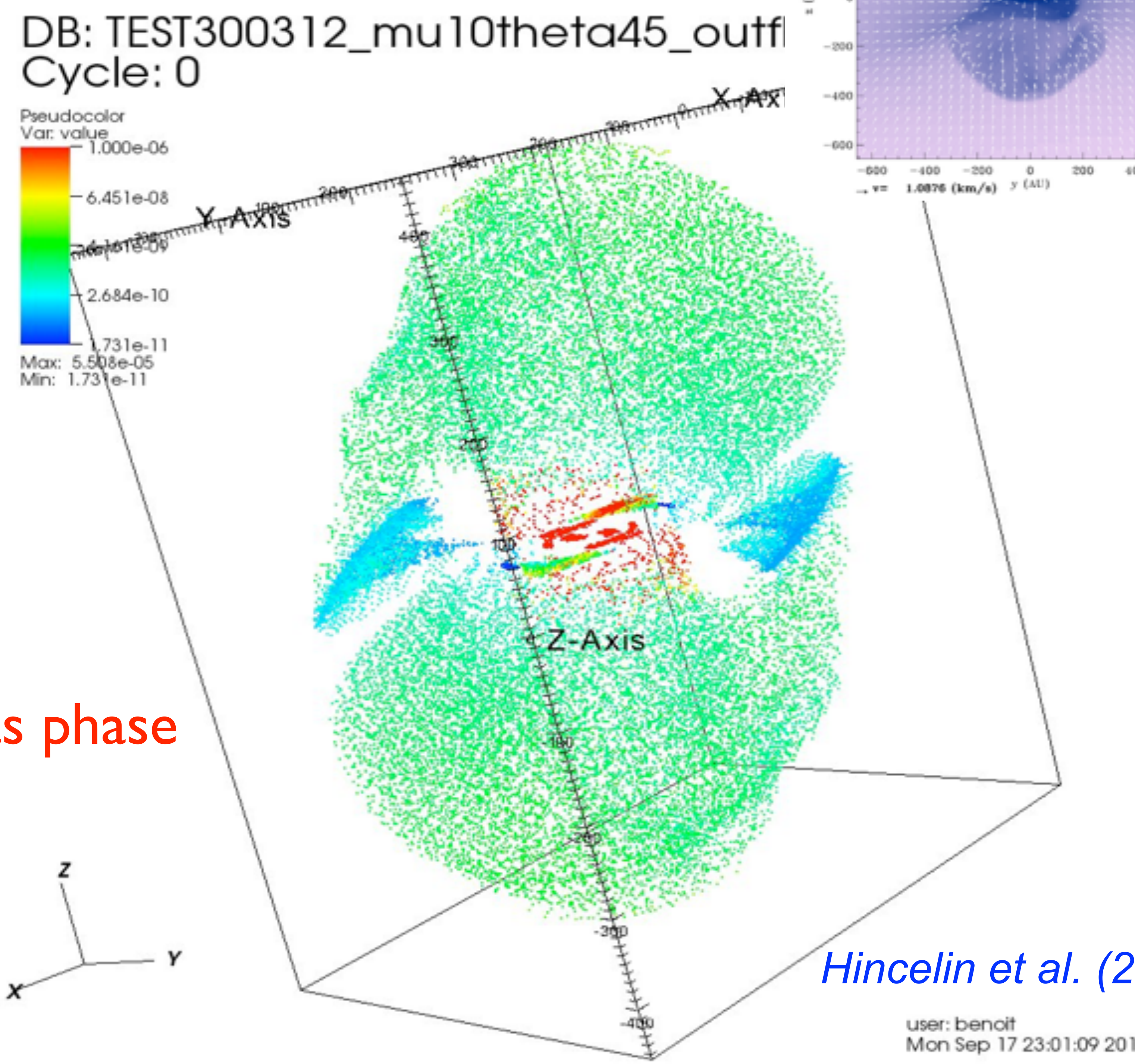


Chemical composition I (under progress)

- 10^6 tracer particles & store position, temperature & density
- Compute the chemistry using the Bordeaux **NAUTILUS** gas-grain chemistry code (655 species, >6000 reactions)
- 50 000 CPU hours for chemistry

=> Access to the 3D abundances within the collapsing dense cores



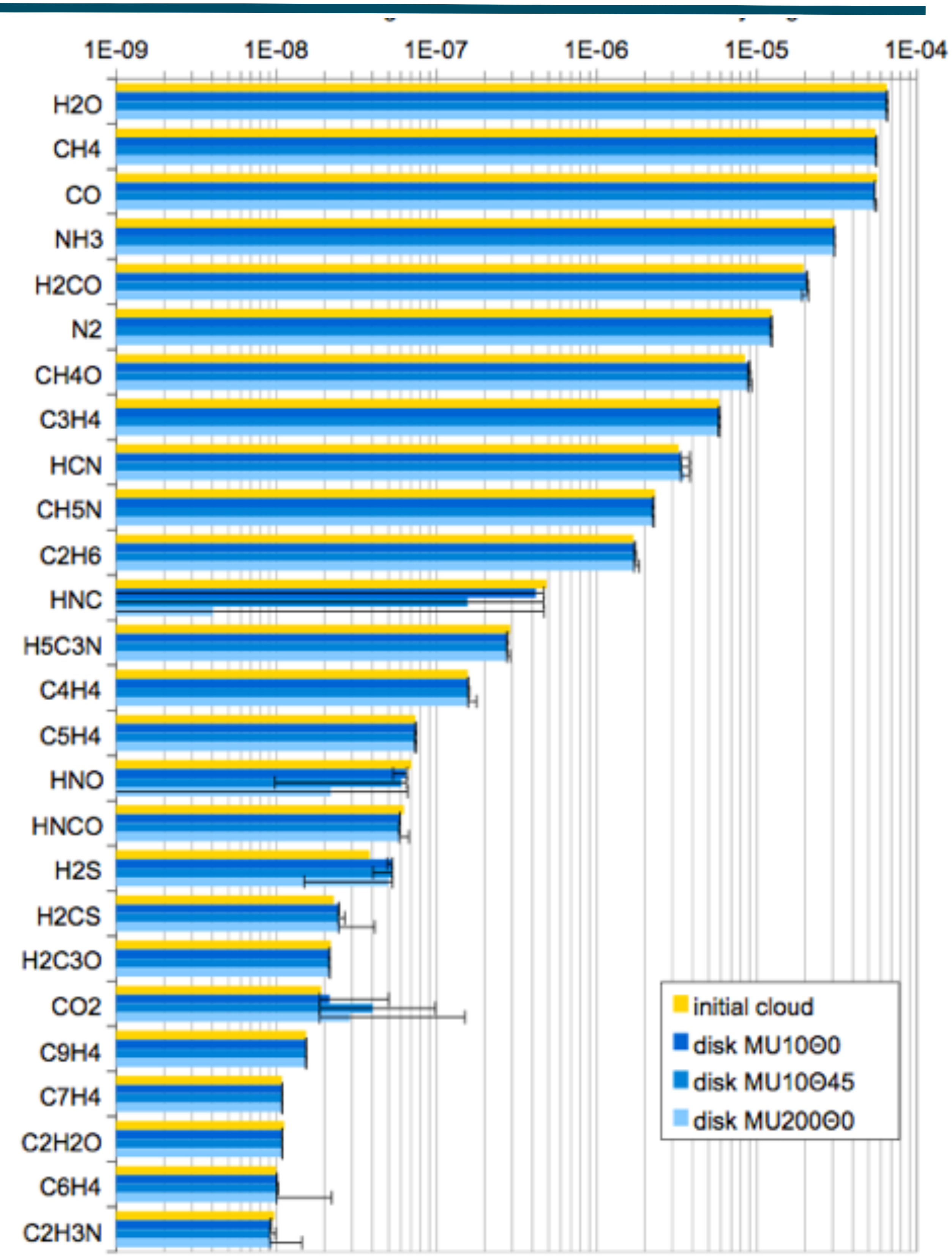


CO abundance in the gas phase

Hincelin et al. (2013)

Chemical composition I (under progress)

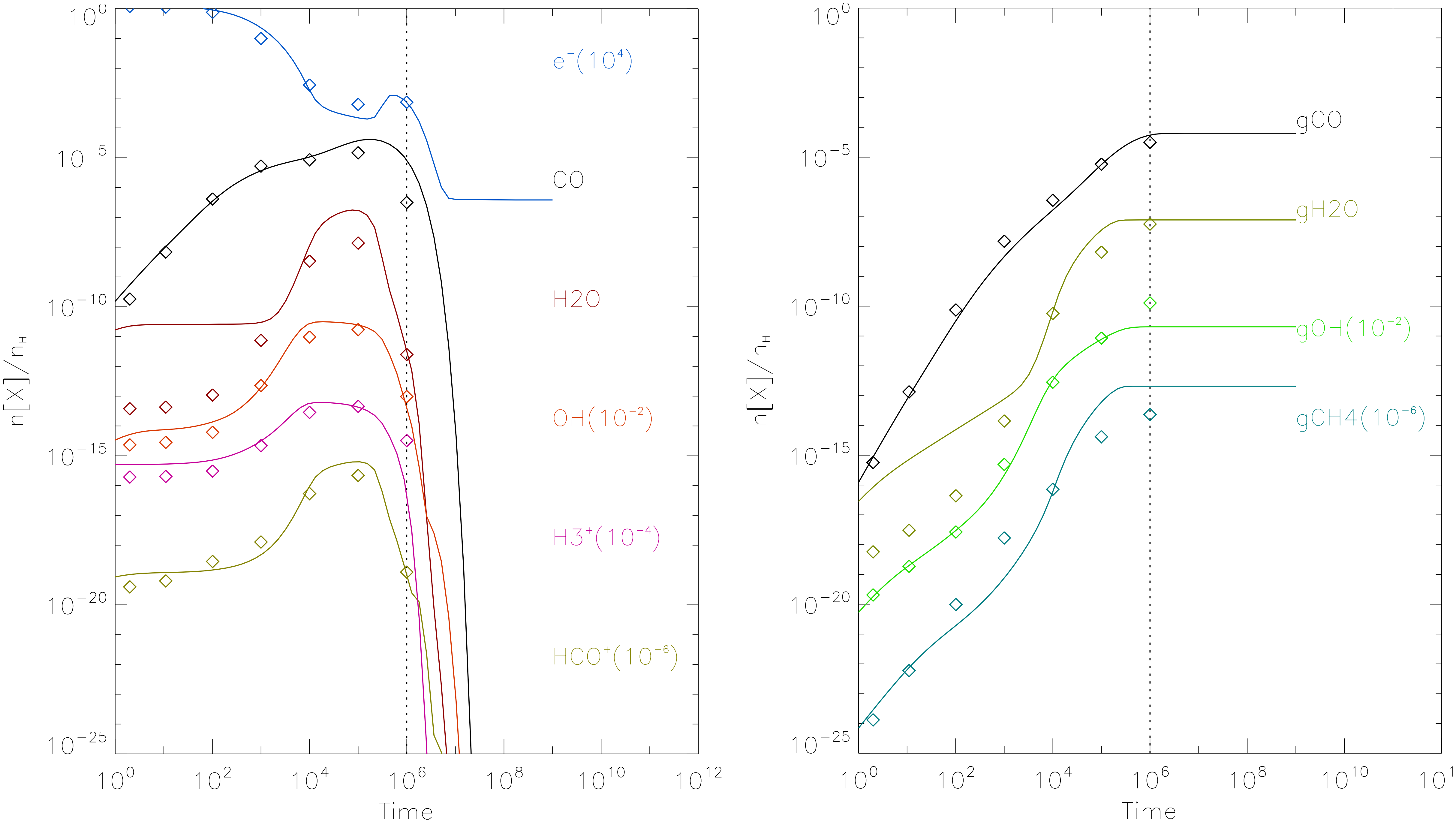
Total (gas+grain) species abundance relative to H in the disk



Hincelin et al. (2012)

Chemical composition II (under progress)

Evolution of a reduced chemical network (32 species) coupled to the dynamics.



Dzyurkevich et al., in prep.

Take Away

- ✓ First core candidates can be identified with compact emission at wavelength 20 μm< λ < 100 μm
- ✓ ALMA will give an answer to the fragmentation problem
- ✓ Need kinematics and chemical diagnostic to distinguish with later evolution stages (e.g., second core)

➡ Direct comparison between observations and 3D models

THANK YOU