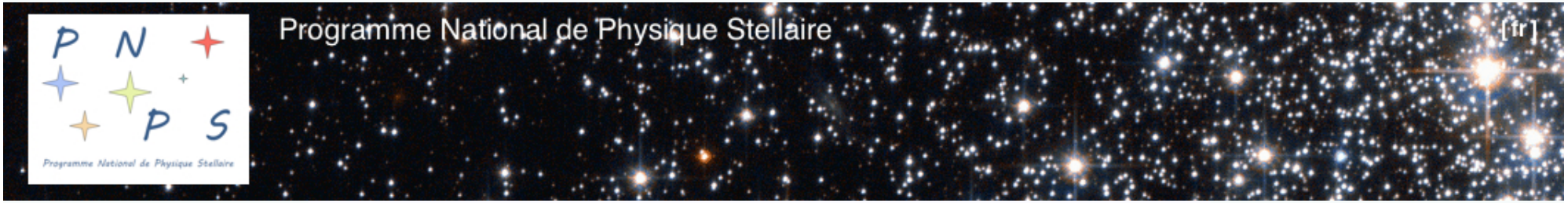


Star formation and proto-planetary disks

From filaments to star clusters
YSO and proto-planetary disk evolution

PNPS review (E. Moraux)

Colloque de prospective du PNPS – Besançon 24-27 février 2014

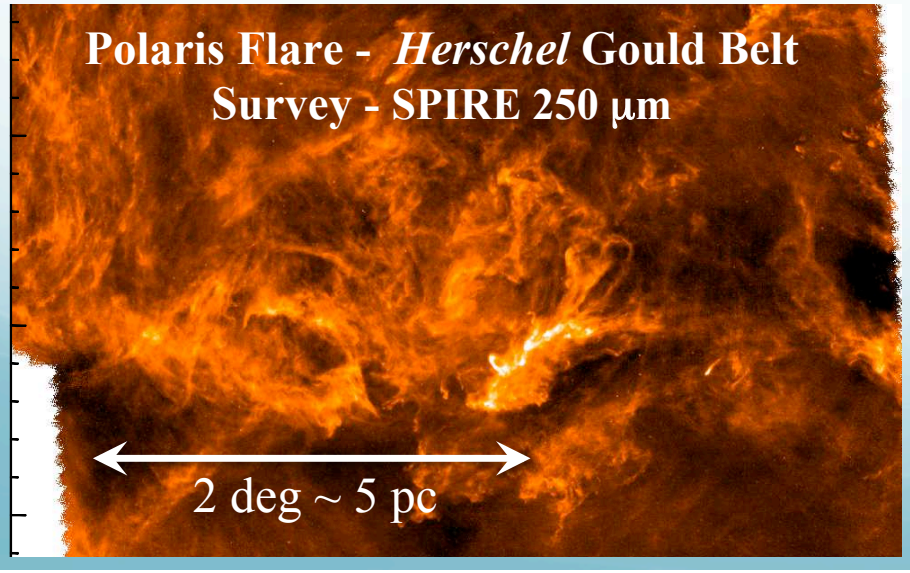
Herschel results (cf Anaëlle's talk)

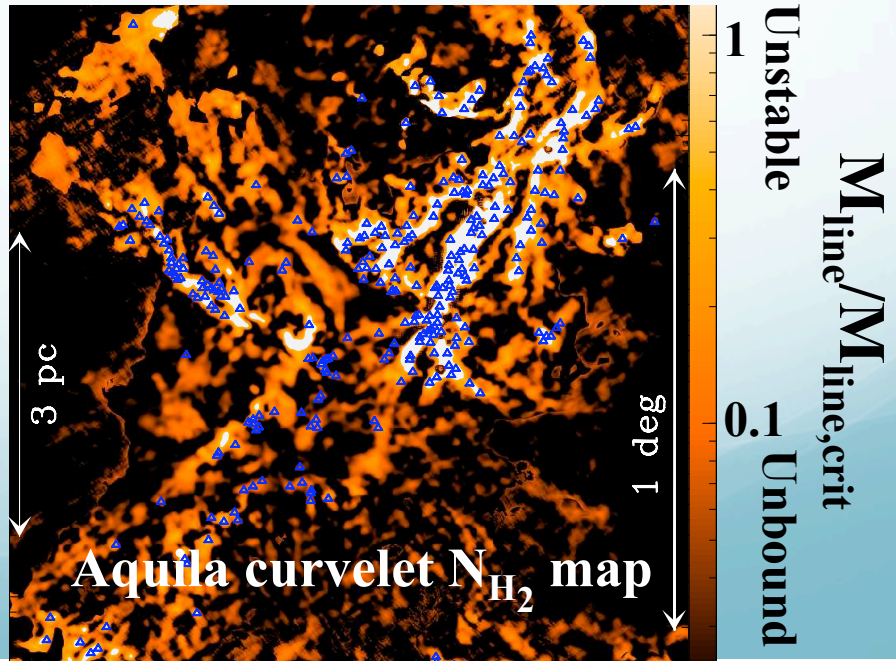
- A "universal" filamentary structure in the cold interstellar medium
  (Arzoumanian+ 2011, André+2010, Miville-Deschênes+2010)

- Filament width related to sub-sonic turbulence decay
  (Arzoumanian+ 2013, Hennebelle & André 2013)

- ~ 75 % of prestellar cores form in supercritical filaments, above a density threshold $\Sigma > 150\ M_\odot/pc^2$ ➔ $M/L > 15\ M_\odot/pc$
  (André+ 2010 ; Könyves+ 2010 ; see also PP VI chapter : astro-ph/1312.6232)

Polaris : Non-star-forming "cirrus" cloud





(cf Timea's talk)

Herschel results

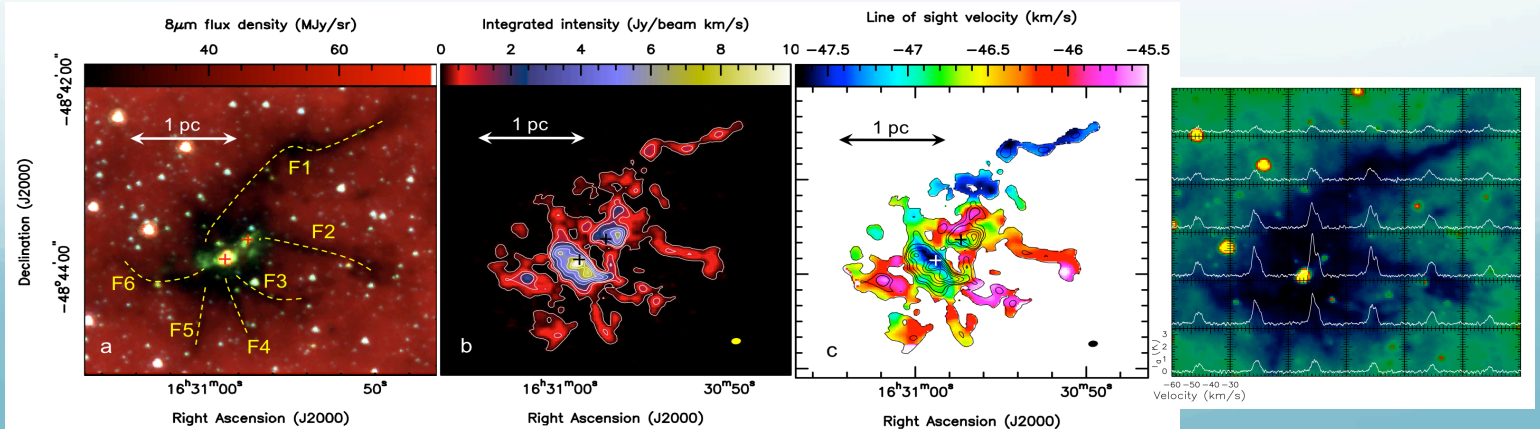
High-mass / cluster star formation:

- Dynamical networks of filaments, ridges, and hubs,
  → extreme dense core seen with ALMA (Peretto+ 2013)
- Large scale self-gravity drives evolution

(Schneider+ 2010, Hennemann+ 2012, Schneider+ 2012)

Timescales for high-mass star formation:

- Same collapsing times (higher accretion rates) (CO outflows – IRAM PdBI, Duarte-Cabral et al. 2013) than low-mass star formation
- >10 x shorter pre-stellar phase (ATLASGAL, Csengeri et al. 2014)

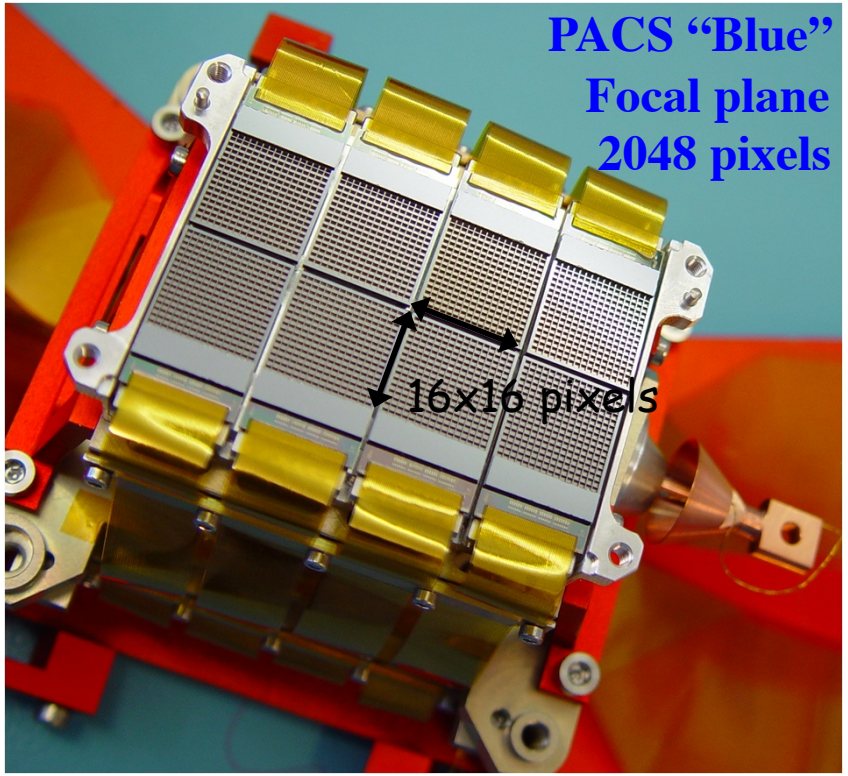


ArTéMiS : A powerful tool to study massive star-forming « ridges » beyond the nearest clouds

×3.4 higher resolution than *Herschel*/SPIRE

Up to ×10 faster than APEX/SABOCA

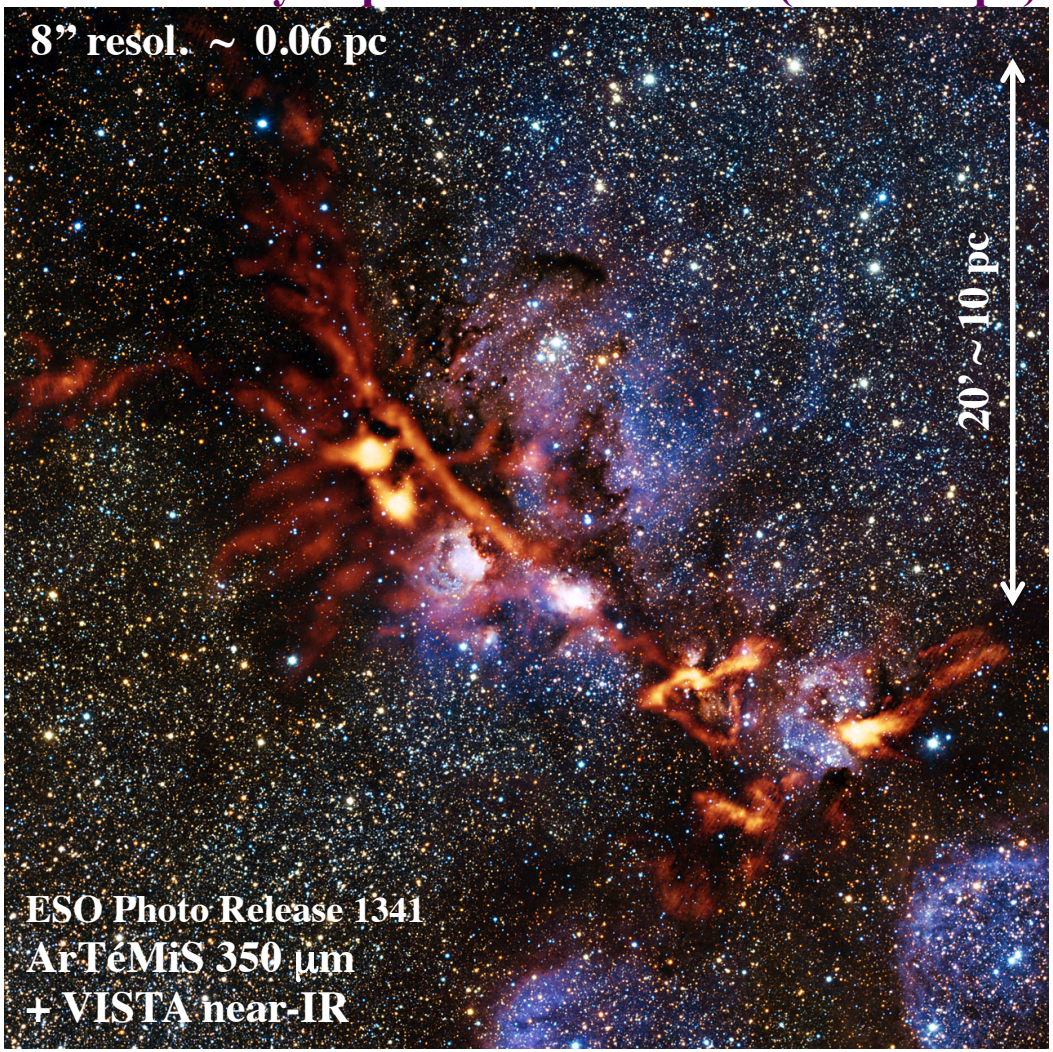
Open to ESO community starting P94



ArTéMiS : 2304 pixels @ 450 µm
2304 pixels @ 350 µm
1152 pixels @ 200 µm

PCMI

First 350 µm observations with ArTéMiS at APEX in July/Sep 2013 : NGC 6334 (d ~ 1.7 kpc)



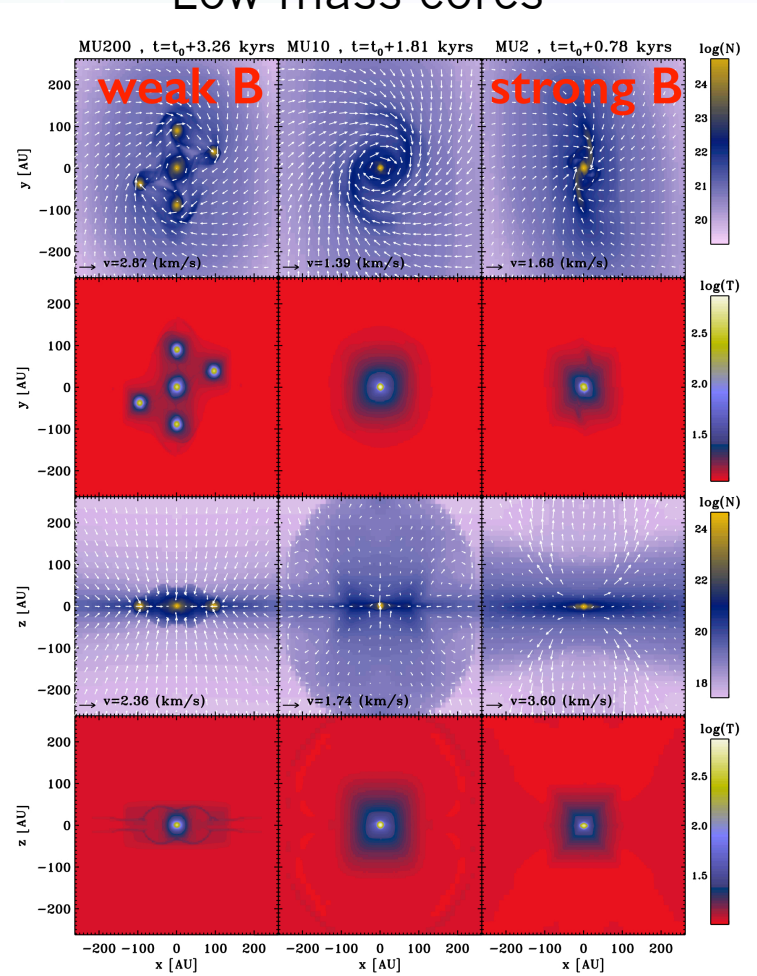
Simulations of core collapse

(Commerçon+ 2010, 2011, 2012; Hennebelle+ 2011; Hennebelle & Ciardi 2010; Joos+ 2012; Massson+ in prep.)

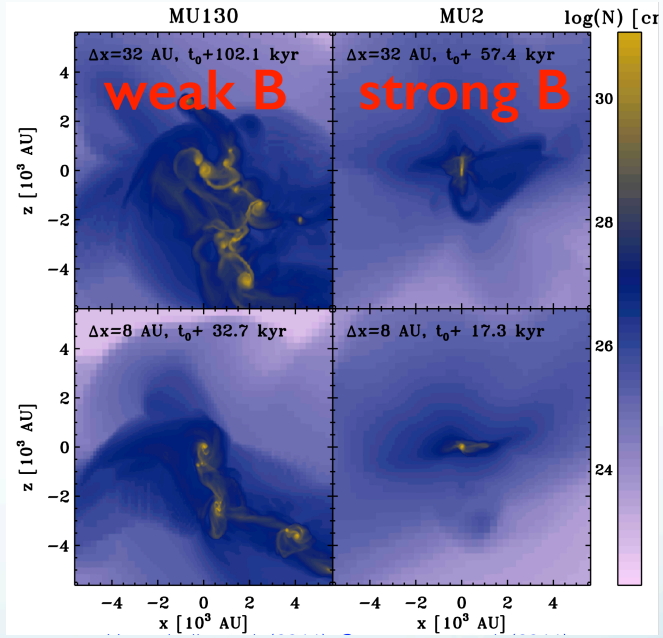
(cf Benoit's talk)

- Interplay of magnetic field and radiative transfer inhibits fragmentation

Low mass cores



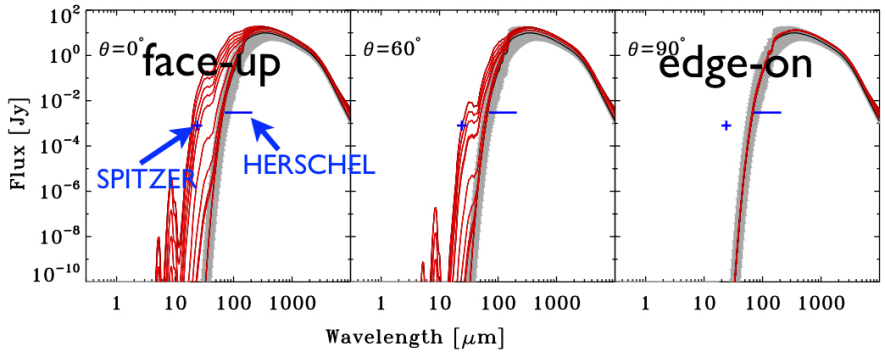
Massive cores



→ **Perspectives:**

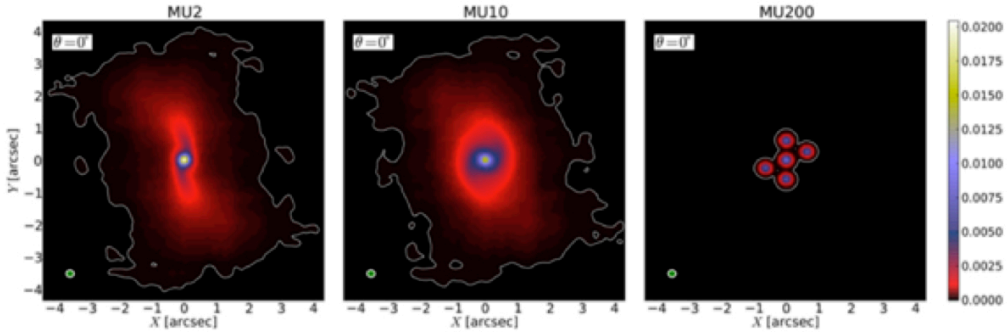
- non-ideal MHD
- multigroup radiative transfer
- second collapse, turbulence, IMF…

Synthetic observations of collapsing cores



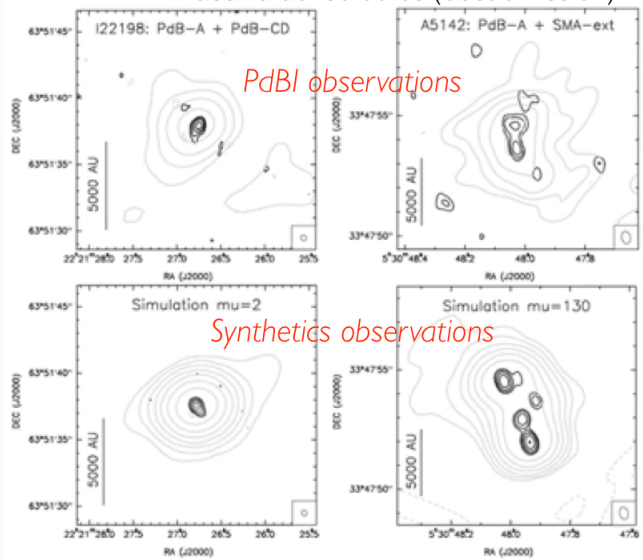
Spectral Energy Distribution of collapsing 1 Msun dense cores

Commerçon et al. (2012a)

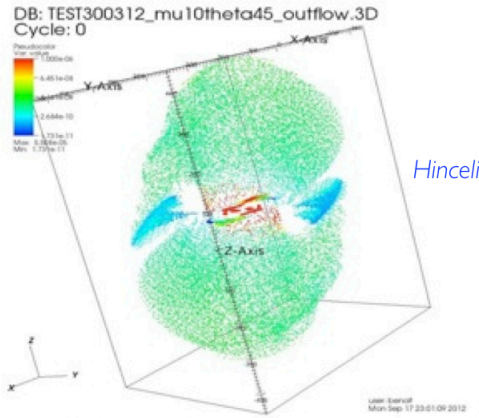


ALMA synthetic images of dust emission in Band 3 *Commerçon et al. (2012b)*

Massive dense cores (dust emission)



Palau et al. (2013)



Hincelin et al. (2013)

CO abundance in the gas phase (1 Msun)

→ **Perspectives:**

- chemistry, ANR project (cf. Sebastien's talk)
- line emission calculations
- polarization maps

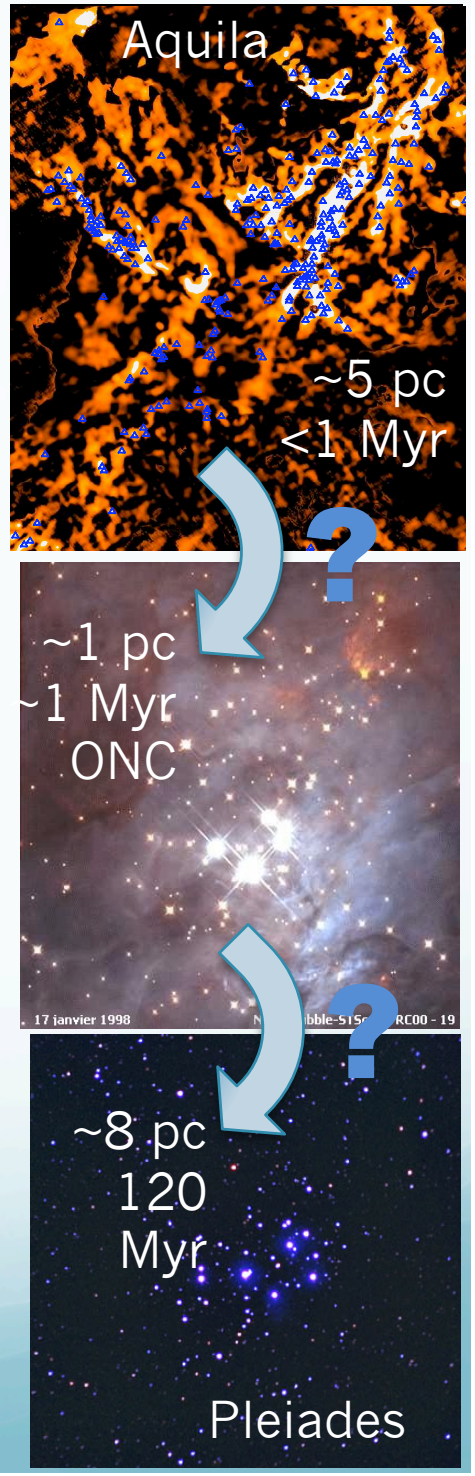
From cores to stars

- What is the impact of initial conditions on the observed properties of YSOs ?
- How to disentangle formation signatures from dynamical effects ?

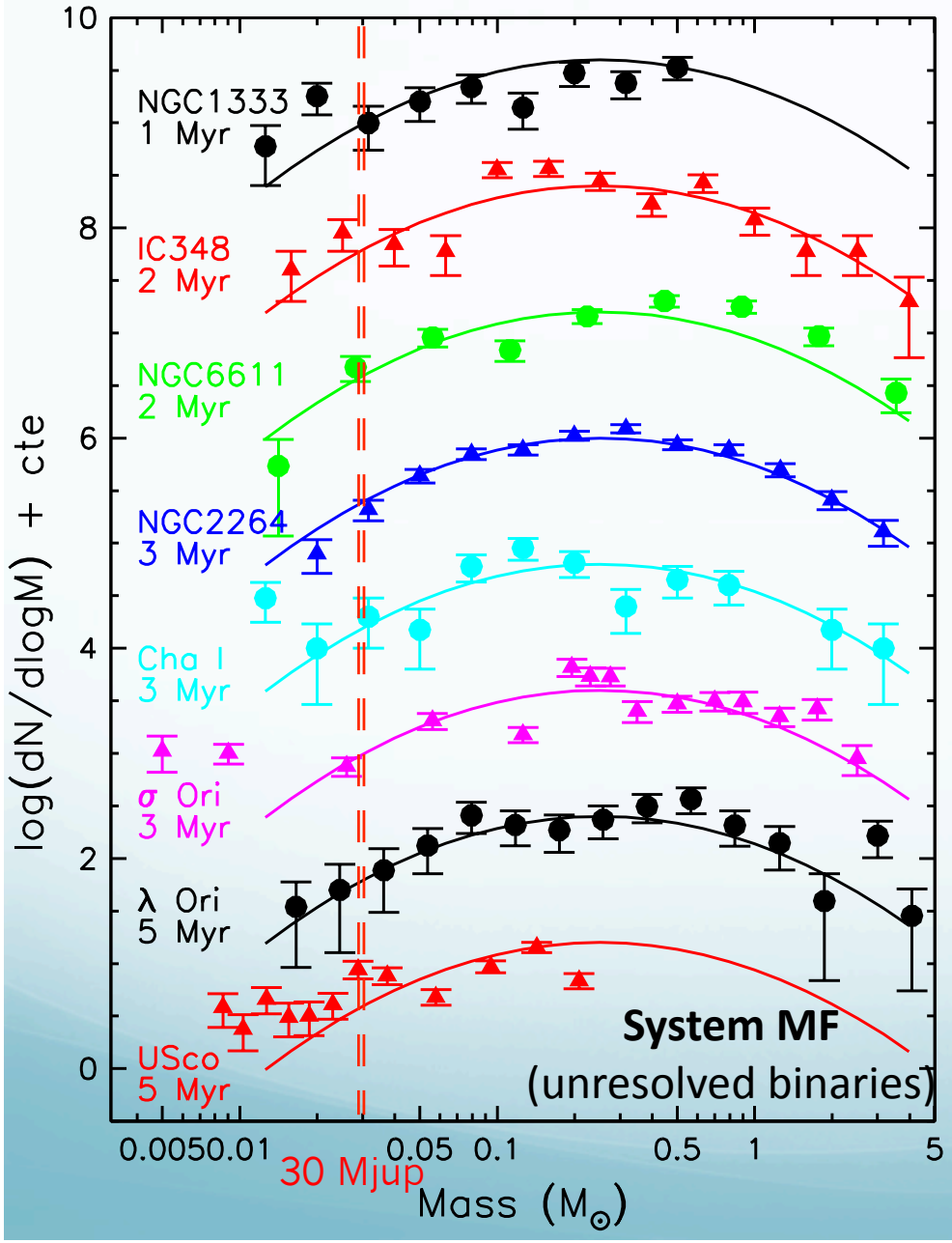
→ Characterise the statistical properties of young cluster populations **down to planetary masses** at different ages (IMF, kinematics, spatial structure, multiplicity, angular momentum...)

→ Model the early evolution of these properties: e.g. angular momentum (cf. Jerome's talk) + trace back the initial conditions using dynamical simulations

ANR-JC « DESC » (http://osug.ipag.fr/~emoraux/DESC)
ANR « Toupies » (http://ipag.osug.fr/Anr_Toupies)



SFR lower mass function



(Alves de Oliveira+ 2010, 2012, 2013 + PP VI chapter)

- **log-normal shape (M_{peak}~0.2 $M_\odot$)** (consistent with Chabrier 2005)
- **Similar MF down to 30Mjup** (consistent with open clusters)
- **Variation at lower masses ?**

→ IMF universality ?

Uncertain mass-luminosity relationship at very low masses and young ages (cf. I. Baraffe+ work on accretion effect)

Theoretical predictions of the IMF

(Hennebelle 2012; Hennebelle & Chabrier 2008, 2009, 2013; Chabrier & Hennebelle 2010, 2011)

- Theories based on core mass function, controlled by the global Mach number and the Mach number at the Jeans length of the gas *before it forms core.*

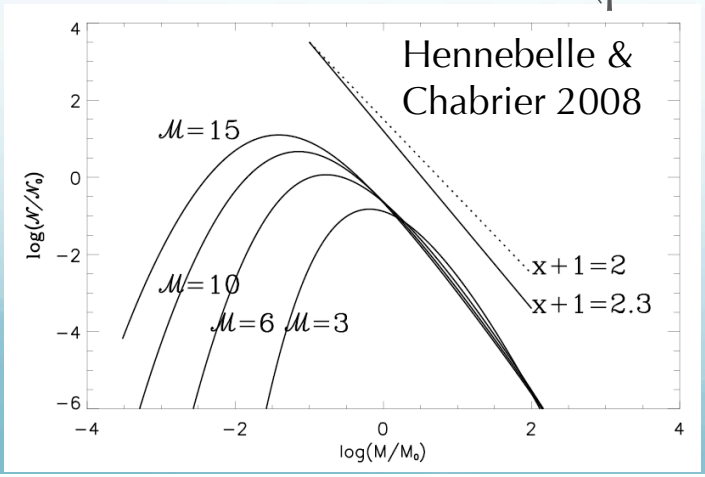
→ Power-law at high masses (>1$M_\odot$), lognormal shape below, peak ~ Jeans mass

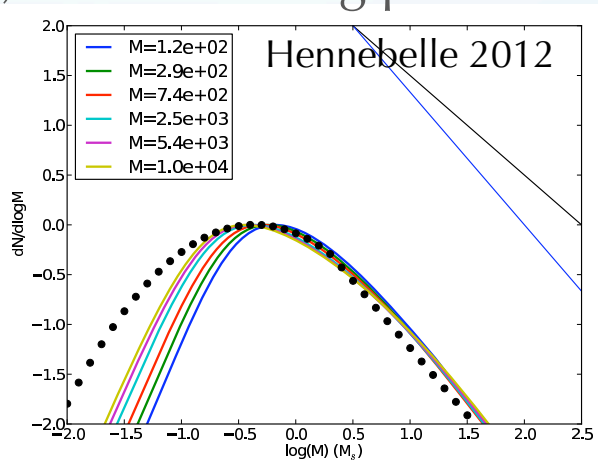
- The high mass part of the IMF appears to be **robust** because it is due to the combination of two generic processes (gravity and turbulence)

- The low mass end (the peak) is much **sensitive** to initial conditions and thermal physics (density, Mach number, temperature, …)

$$M_{peak} \approx \frac{M_{Jeans}}{1+b^2\mathcal{M}^2}$$

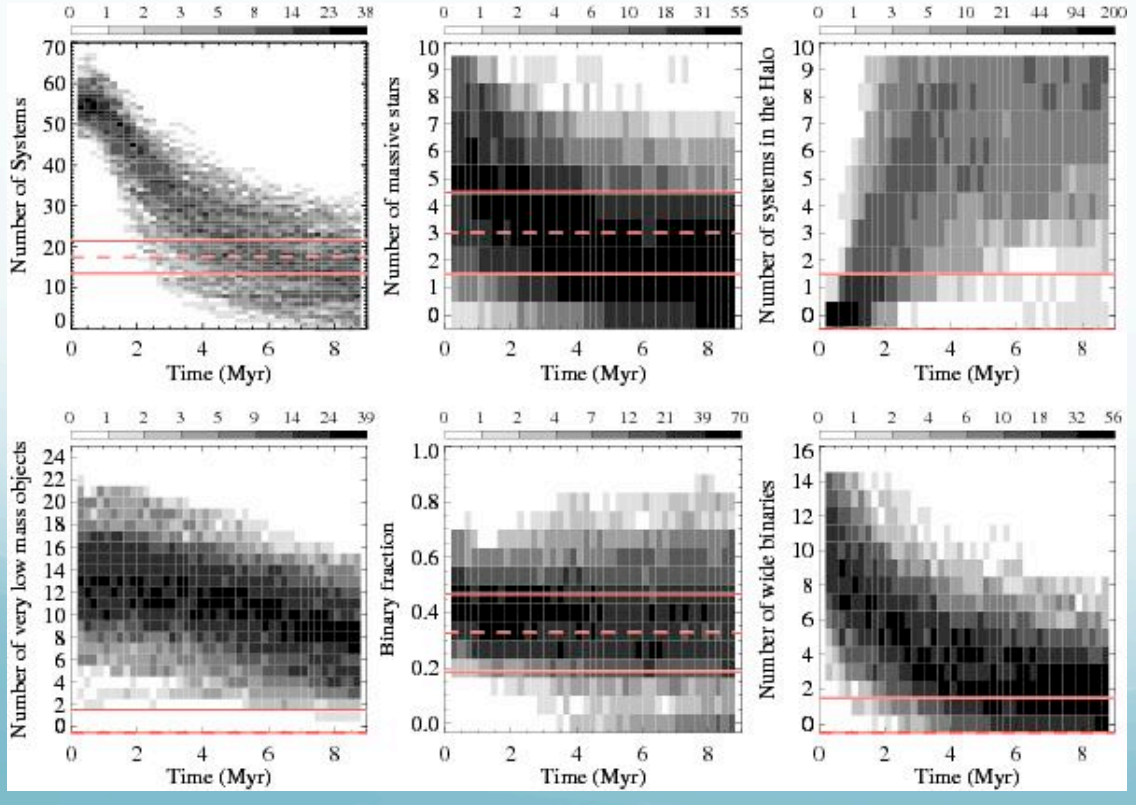
- Constancy of the IMF within clusters is difficult to explain. Self-regulation of feedback or initial conditions (possibly both…) are interesting possibilities.





Cluster early evolution (1–10 Myr)

- Example of Eta-Cha (~9Myr): deficit of VLMS and BD, mass segregation, no wide binaries → a young, yet dynamically evolved cluster ?
- NBody simulations to trace back the initial conditions
- Could the IMF be lognormal ? Probably not... (Becker+ 2013)



→ **Perspectives:**
Develop a ***hybrid hydro +Nbody code*** to link hydro simulations of cluster formation with pure N-body simulations of dynamical evolution

Clusters with GAIA

- GAIA: parallaxes + proper motions down to V~20
- GAIA-ESO-Survey with FLAMES : ~0.3 km/s down to V~19

  - 3D spatial structure + 3D kinematics
  - Relate field stars to their natal cluster → complete census
  - Internal dynamics

→ Prepare and complement GAIA (deeper and in the NIR to beat extinction): ***Large scale proper motion surveys of young clusters to reach the substellar domain*** (e.g. the DANCe project, PI H. Bouy)

→ Get ready to interpret GAIA data: *Statistical tools for* ***cluster analysis in 6D*** (position + velocity), an entire new field to explore !

From filaments to stars

Key facilities for the coming years:

- ALMA, NOEMA: dense cores
- APEX/ArTéMiS (+ CCAT in future ?) : filaments and prestellar cores
- GAIA + follow-up: young star cluster census and dynamics
- JWST/MIRI: near and mid-IR spectroscopy & imaging
- PLATO (Kepler 2): photometric variability

Towards a new generation of models:

- New generation of collapsing core models including non-ideal MHD, multi RT, chemistry → angular momentum evolution + disk formation
- Embedded cluster evolution using hybrid hydro + N-body code
- Statistical tools development for 6D analysis

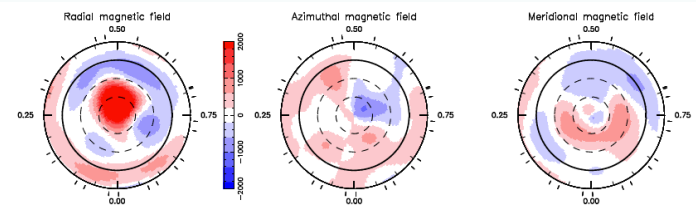
YSO and proto-planetary disk evolution

Star-disk interaction: the magnetospheric accretion process

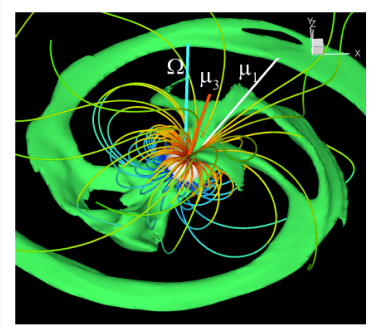
(cf Jérôme's talk)

e.g., V2129 Oph

CFHT/ESPaDOnS spectropolarimetry yields
2.1 kG octupole + 0.9 kG dipole



Donati, Bouvier, Walter et al. (2011)

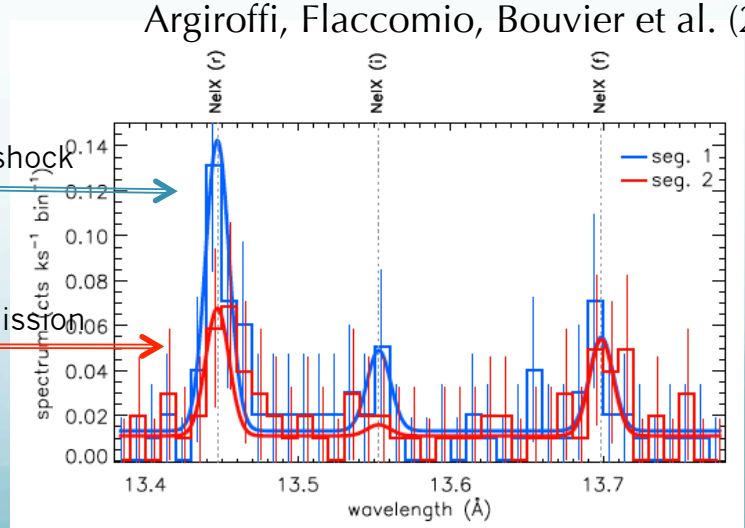


3D MHD simulations predict the accretion flow geometry

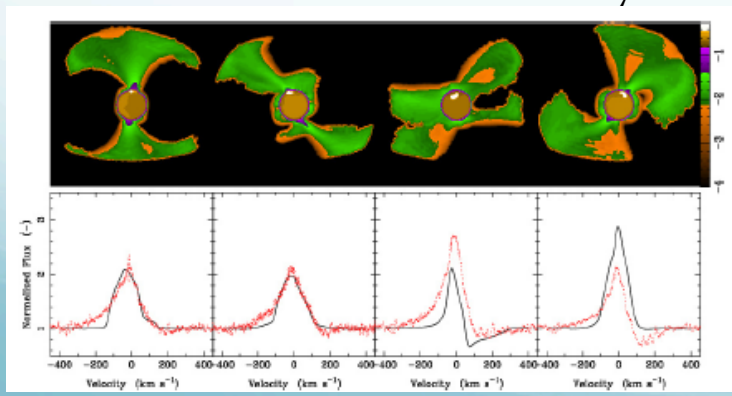
Romanova, Long, Lamb et al. (2011)

Chandra X-ray monitoring → accretion shock

Argiroffi, Flaccomio, Bouvier et al. (2011)



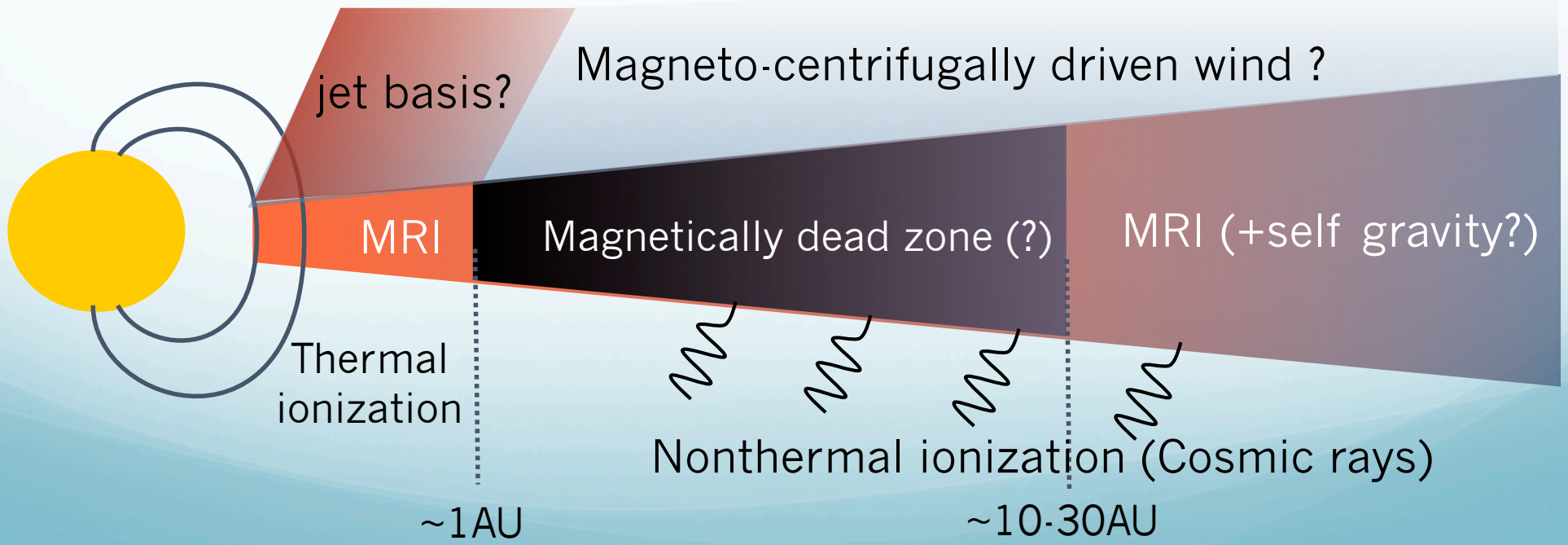
ESO/Harps line profile variability +
3D RT models → accretion dynamics



Alencar, Bouvier, Walter et al. (2012)

Accretion disk and MRI

- MRI → turbulent flows in accretion disk, the most likely mechanism to transport angular momentum
- Magnetically dead zones are the current bottleneck in transport theory
- Coexistence of the MRI and disc winds ? When discs are threaded by a mean vertical field, the MRI spontaneously evolves into discs winds → precursor of variability in jets ? (Lesur+ 2013, Fromang+ 2013)

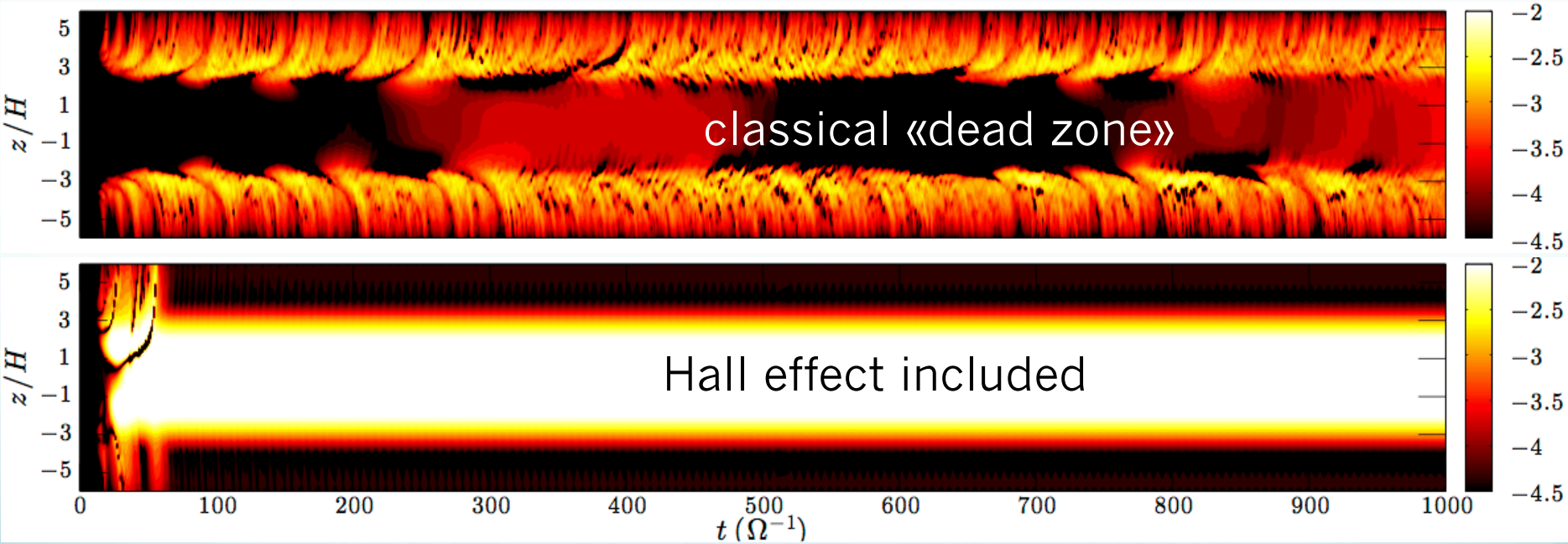


Hall effect

(Kunz & Lesur 2013, Lesur+ 2014)

- Hall effect (electron-ion drift) can revive dead zone
- Hall-dominated MRI does not lead to turbulence (dust sedimentation?)

Vertical profile of magnetic stress(=activity) as a function of time

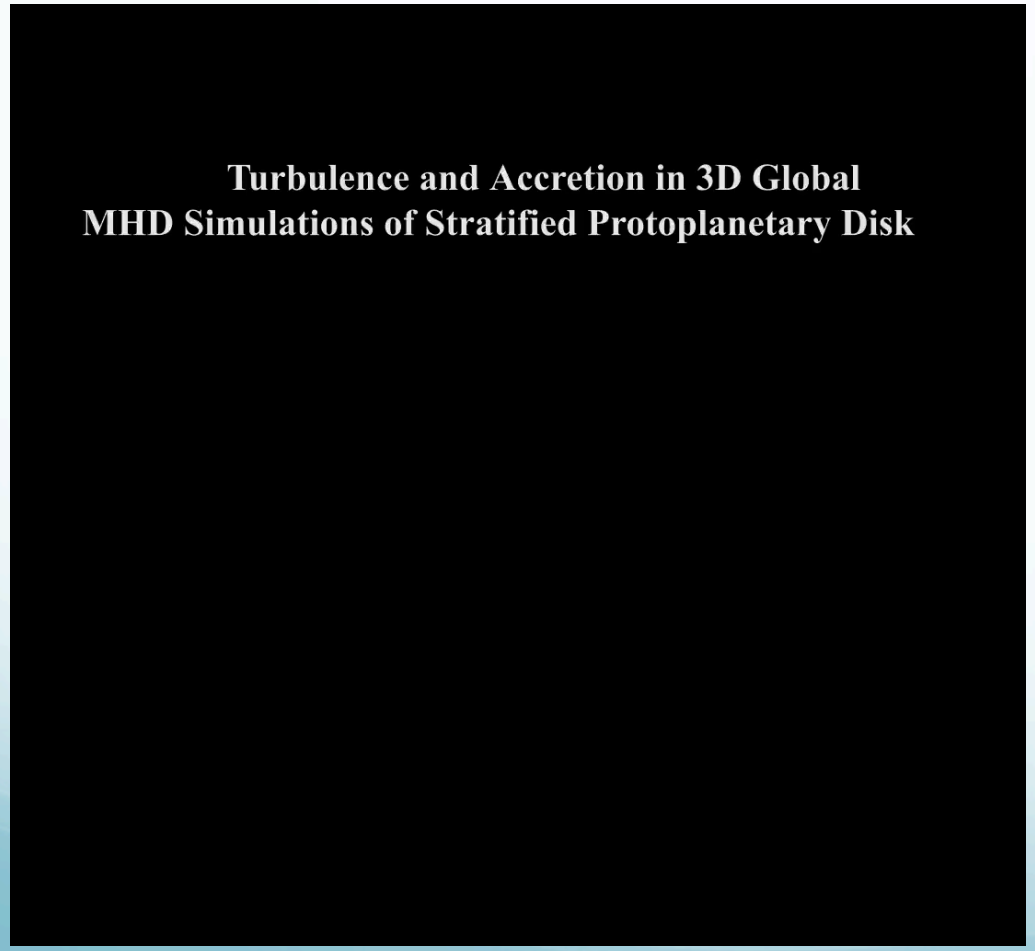


→ **Is the dead zone really magnetically dead?** Need to mix chemistry, grain dynamics and MHD models

Simulations of turbulent PP disks

(Fromang+ 2006, 2009, 2011; Flock+ 2011)

- Global simulations results are consistent with shearing boxes simulations having same resolutions, transport rate $\alpha \sim 10^{-3}$ - 10^{-2}



- But thermodynamics still too simple (T=const assumed)....

→ **Go beyond simplistic thermodynamics:** realistic equation of state with radiative transfer and chemistry

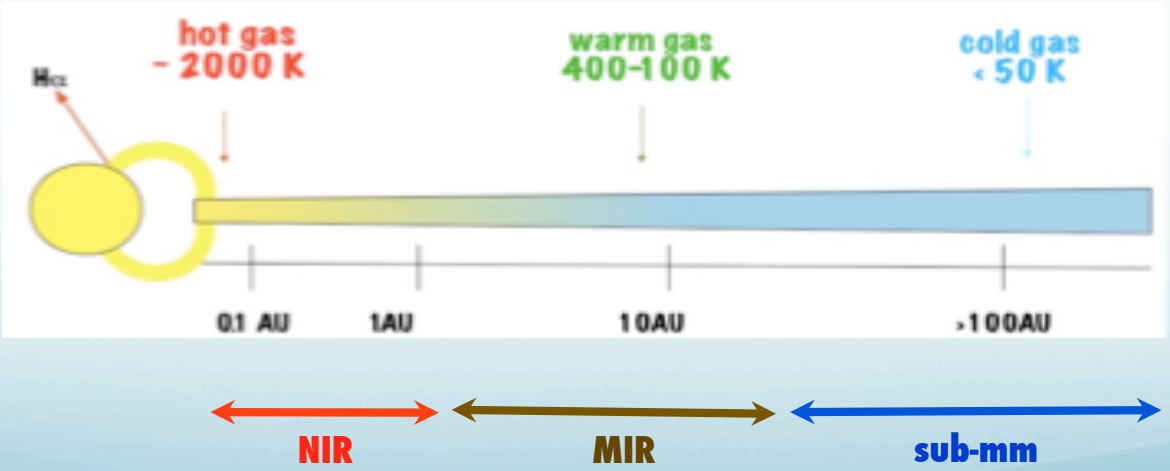
Courtesy Mario Flock

Structure of protoplanetary disks

(cf Edwige's talk)

- What is the physical and chemical structure of protoplanetary disks?
- How is this structure linked to planetary formation?
- Observations trace different disk regions

→ Multi-wavelengths multi-techniques observations



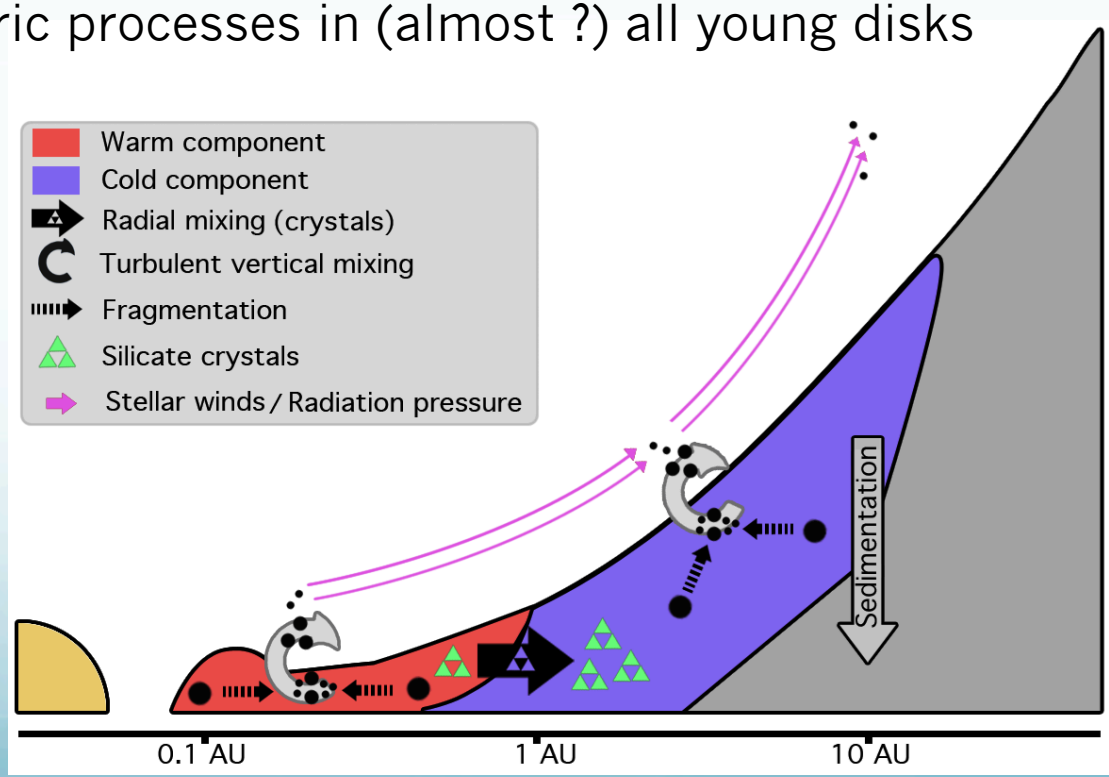
A Spitzer/IRS view of dust mineralogy

Olofsson, Augereau+ (2009; 2010)

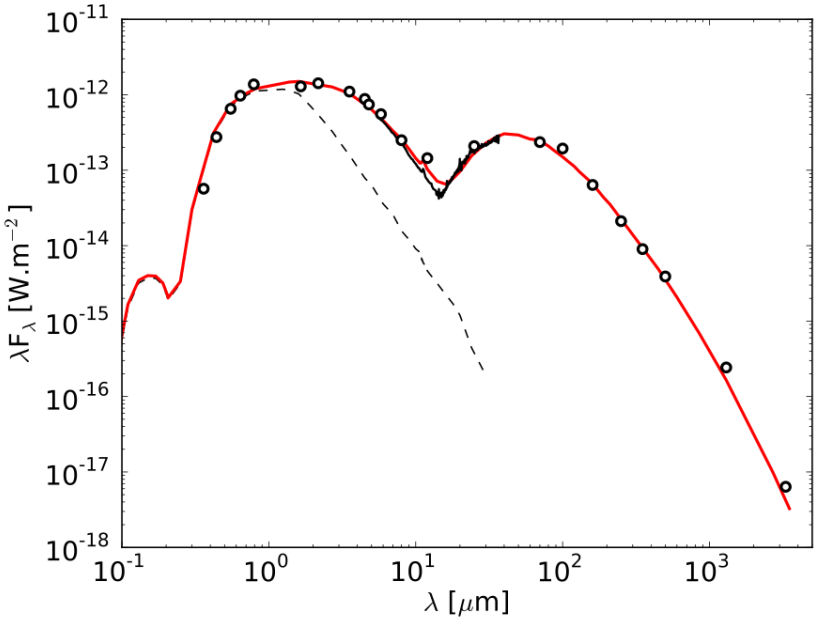
- Dust mineralogy → Constraints on crystallisation and growth of dust grains within <10 AU

- Main results:
  - Detection of crystalline grains in cold regions: radial tranpsort
  - Detection of large grains in the uppermost layers: vertical transport
  - Statistical surveys: generic processes in (almost ?) all young disks

→ The building blocks of cometary bodies and the initial conditions of planetary formation.



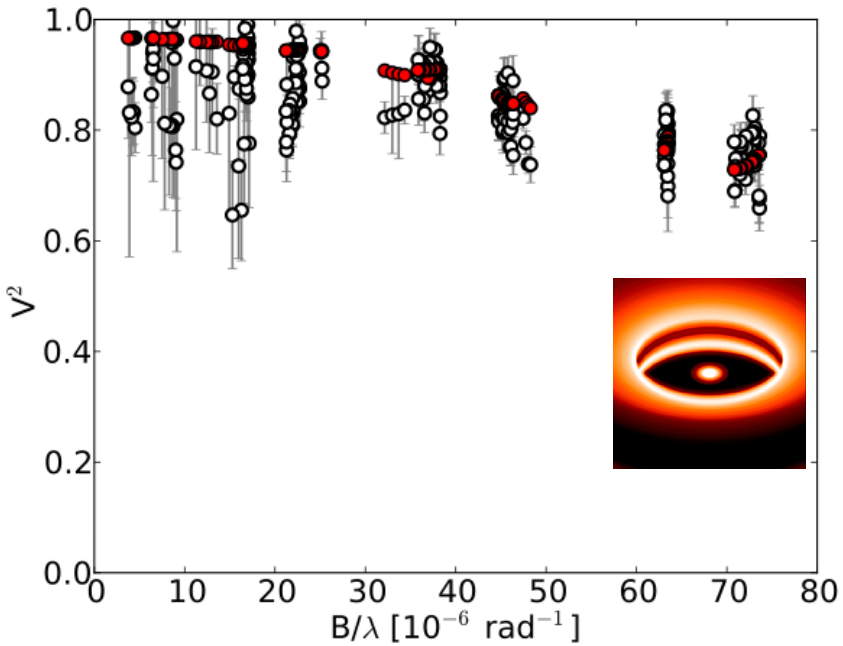
The inner edge of transition disks

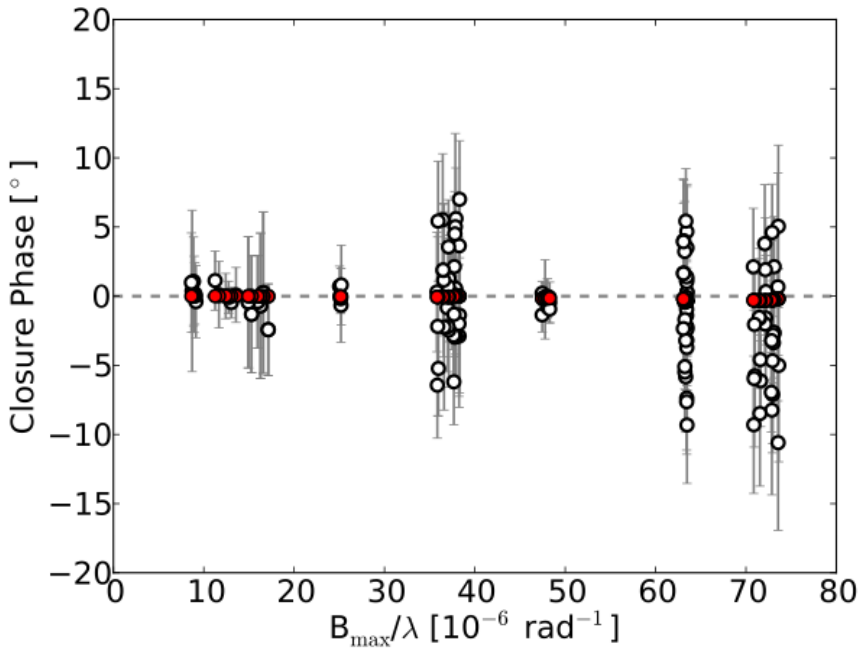


T Cha observed with PIONIER (cf JB's talk)

- Tiny inner disk : 0.07-0.13 AU
- M = 3 10^{-11} $M_\odot$
- H=0.2 AU @ 1 AU very large scale height

(Olofsson, Benisty+ 2011, 2013)





Simultaneous modeling of gas and dust

Dust Observations
SED
Images
Visibilities

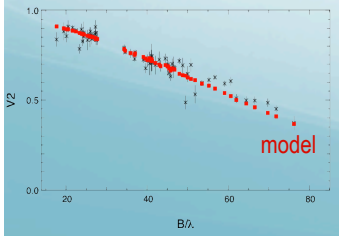
→ **MCFOST**
(Pinte et al 2006)
dust radiative transfer

Gas Observations
high-resolution IR spectra
Spitzer/Herschel spectra
IRAM/ALMA sub-mm lines

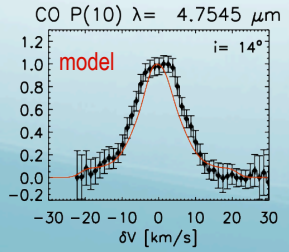
→ **ProDiMo**
(Woitke et al. 2009)
gas heating-cooling,
chemistry, line emission

⇒ **DISK STRUCTURE**
size,
gas/dust mass,
gas/dust surface density
gas/dust temperature
chemical composition

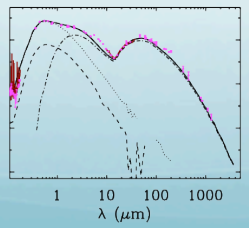
PIONIER H-band visibilities
(hot dust at R<0.2 AU)



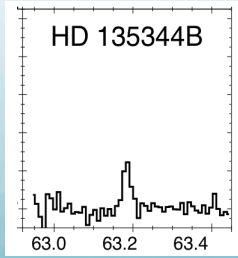
VLT/CRIRES CO 4.7μm
(warm gas 0.2<R<30 AU)



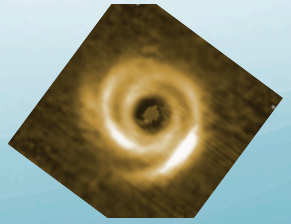
SED



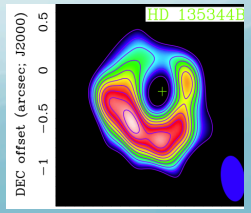
Herschel
[OI] 63 μm



NACO near-IR
(small dust R>30 AU)



SMA 830 μm
(cold dust R>45 AU)



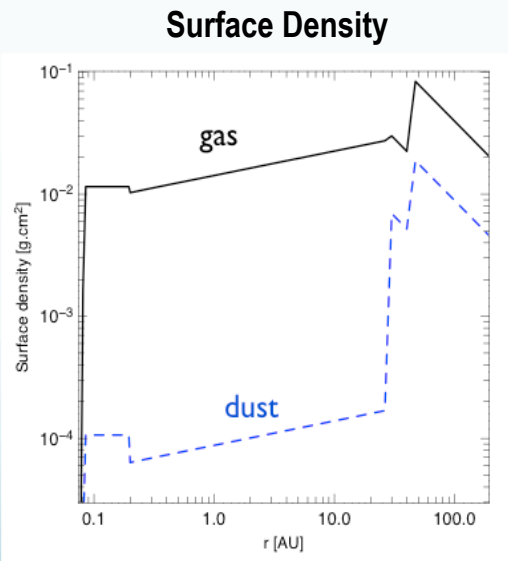
Simultaneous modeling of gas and dust

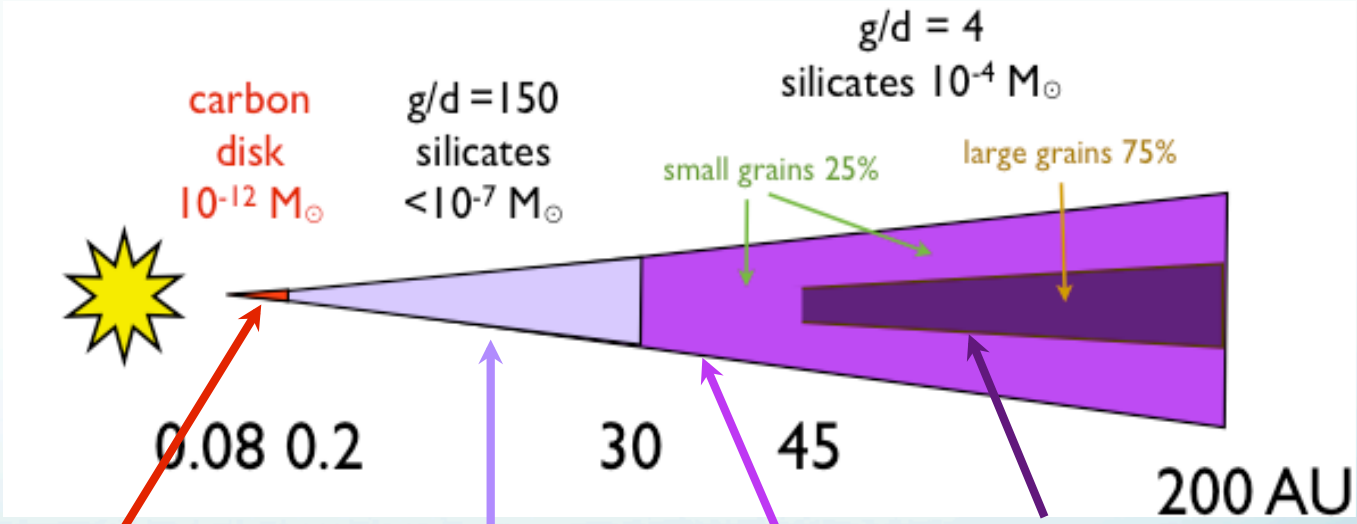
Example: Transition Disk HD 135344B

(Carmona, Pinte, Thi, Benisty, Ménard+ 2014)

FIRST TIME THAT near-IR INTERFEROMETRY AND near-IR MOLECULAR EMISSION HAVE BEEN SIMULTANEOUSLY MODELED WITH FAR-IR AND SUB-MM data

DEDUCED DISK STRUCTURE





1. Refractory grains (carbon) inside the silicate sublimation radius

2. Increasing gas surface density (consistent with planet migration)

3. No or small (few AU) gap in the gas

4. Disk have lost most of its mass, gas disk mass a few $M_{Jupiter}$

Dust evolution models

- Numerical simulations
  - Effect of a planet, dust concentration at the gap edge *(Fouchet+ 2010)*
  - Fragmentation treatment, effect on growth in various regimes *(Gonzalez+ 2013)*
  - Vortex formation from Rossby instability, dust concentration *(Crespe+ 2011)*
  - Characterization of local gas fluctuations using SPH, link with turbulence *(Arena & Gonzalez 2013)*
- Semi-analytical modelisation of grain dynamics
  - Constant grain size and migration barrier *(Laibe+ 2012)*
  - Grains growth *(Laibe+ 2014a,b)*
- Link with observations
  - Observation predictions, ALMA simulated images *(Gonzalez+2012)*

Dust evolution models

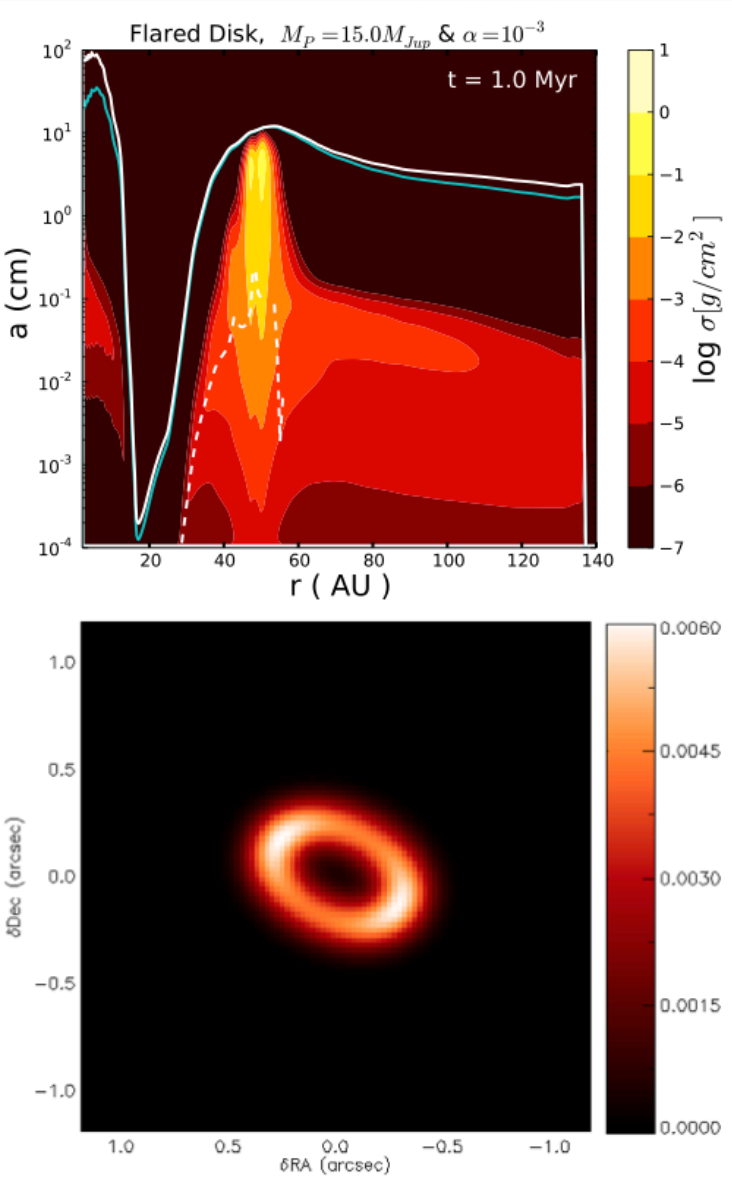
→ **Perspectives:**

- Numerical Developments
  - Global 3D disk simulations including self-consistent treatment of grain dynamics, growth and fragmentation
  - Physics improvement
  - Inner edges

- Collaboration with Geology laboratory in Lyon
  - Solid radial transport : constraints from des meteorites

- Larger involvement in observations
  - ALMA and NOEMA (sub-mm) exploitation
  - MATISSE (IR) preparation

Grain growth in transition disks



Dust coagulation-fragmentation cycles computed in the case of a disk in which a planet carved a gap.

Dust grains are trapped in a pressure bump at the edge of the gap and grow efficiently to millimeter sizes.

Simulated ALMA image, similar to observations of transition disks.

Pinilla, Benisty+ 2012, 2014
Pinilla, Birnstiel, Benisty+ 2013

YSO and PP disk evolution

Key facilities for the coming years → multi-λ observations:

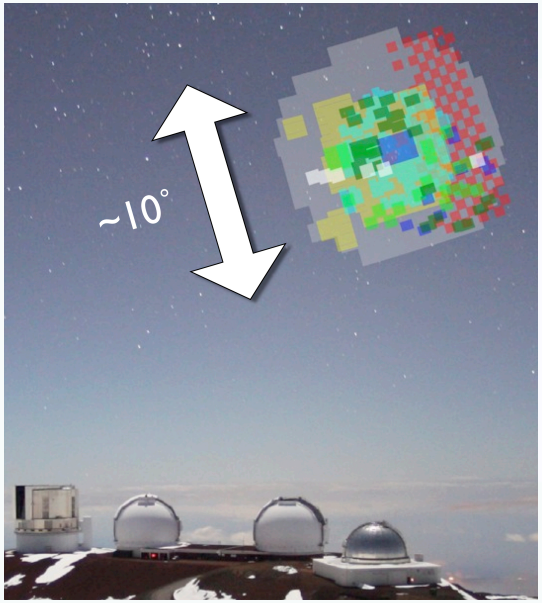
- CFHT/SPIROU: monitoring of YSO
- ALMA, NOEMA: tracing cold dust and gas
- VLT/SPHERE: high contrast direct imaging in the near-IR
- VLTI/MATISSE: interferometric imaging in the mid-IR at the milli-arcsec scale
- JWST/MIRI: spectroscopy and imaging in the near & mid-IR

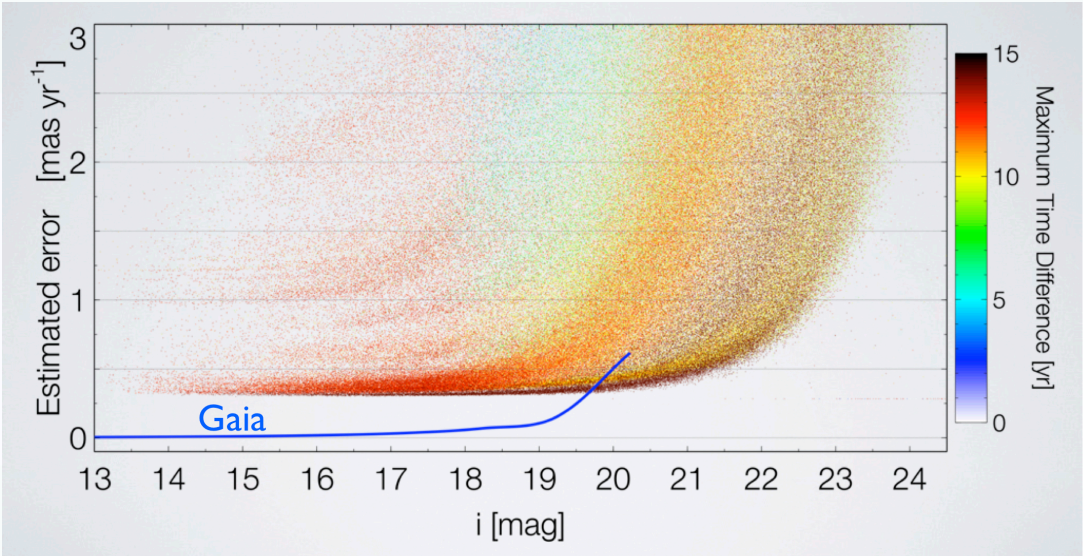
Towards a new generation of time-dependent global disk models:

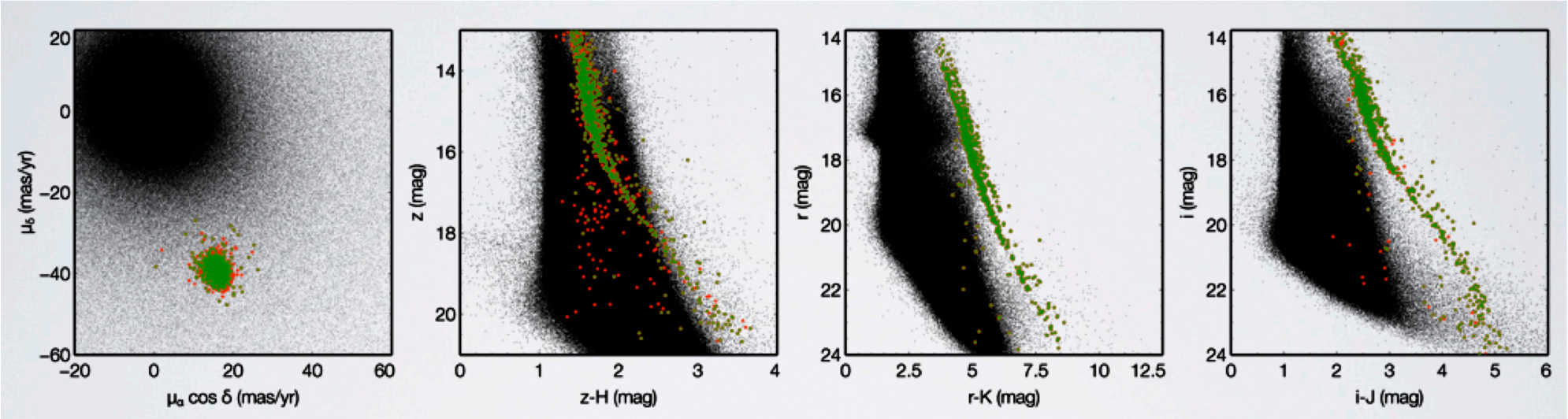
- Accretion/ejection dynamics (3D RT + MHD)
- Global disk simulations including new thermodynamics, chemistry, grain growth and dynamics, and MHD
- Simultaneous modeling of gas and dust observations

Selected results

- **IMF of SFR's down to planetary masses** (Alves de Oliveira et al. 2010, 2012, 2013)
- **Reverse dynamical evolution of eta-Cha** (Becker et al. 2013): peculiar IMF for this region ?
- **Theory of the IMF** (Maschberger et al., in prep)
- **Spatial distribution in SFR** using MST (Parker et al. 2011, 2012) and density based analysis (Joncour et al., in prep.)
- **Kinematics** (ppm) of young clusters (Bouy et al., in press)
- **Angular momentum evolution** of YSO's (Moraux et al., in press; Gallet & Bouvier, in press)


~10°


Estimated error [mas yr^{-1}]
i [mag]
Gaia
Maximum Time Difference [yr]


μ_δ (mas/yr)
μ_α cos δ (mas/yr)
z (mag)
z-H (mag)
r (mag)
r-K (mag)
i (mag)
i-J (mag)