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EXPOSED LONG-LIFETIME FIRST-CORES:
STAR FORMATION IN VERY LOW-MASS MOLECULAR CLOUD CORES

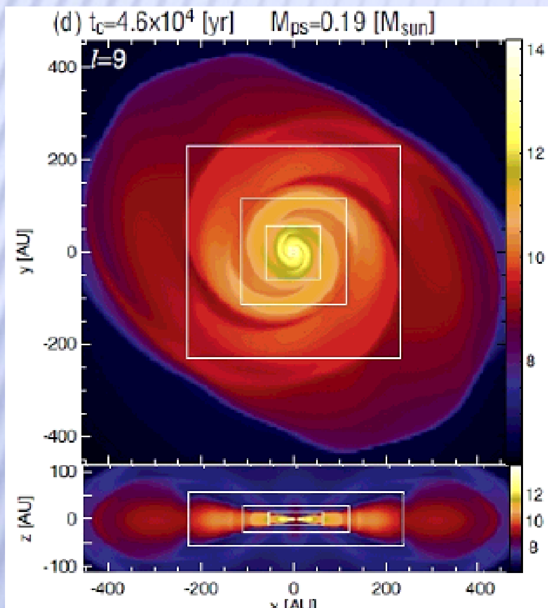
References: Tomida et al., 2010, ApJL, 714, L58
Tomida et al., 2010, ApJL, 725, L239

What is a First (Hydrostatic/Adiabatic) Core?

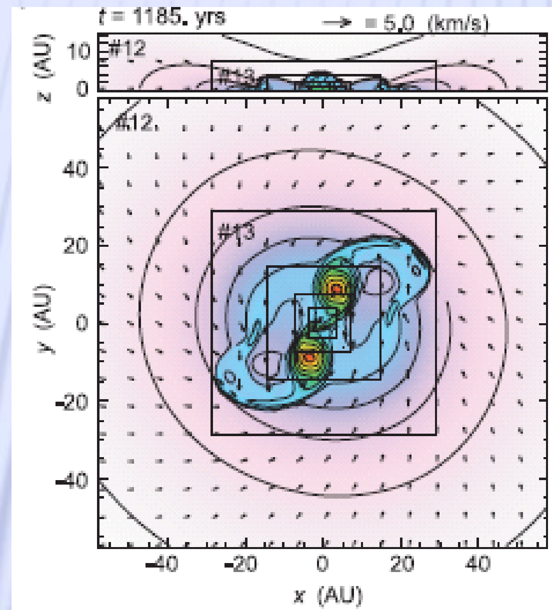
Quasi-static object forms in early phase of star formation

Second collapse when T_c ~ 2000K→shortlived ~ O(1000)yrs

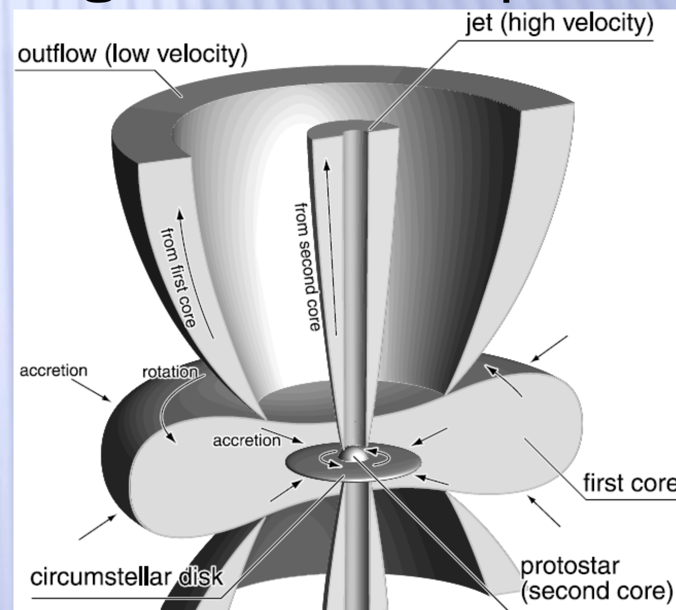
Stage of many phenomena related to ang. mom. transport.



Disk formation(Machida+)



Binary formation(Saigo+)



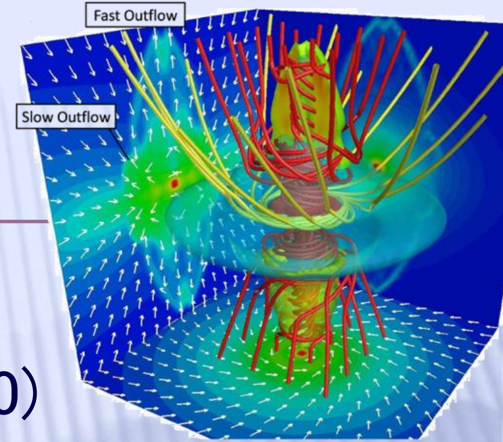
Driving molecular outflow(Machida+)

Theoretically predicted in Larson 1969, but not observed yet.

Recently, several first core candidates are reported.

→First cores are expected to be confirmed with ALMA.

First Core Properties



Prediction from RMHD simulations:

- Short lived ~ O(1,000) years=rare object (~1/1000)
- Will be observed like a compact (<100AU) dust core
- SED looks like faint(<$0.1L_{\odot}$), low-temperature blackbody
- No or very weak Near/Mid-IR component from hot protostar (observed as a "dark core" in Mid-IR, see also Commerçon's talk)
- Slow(<5km/s), loosely collimated outflow, no high-velocity jet

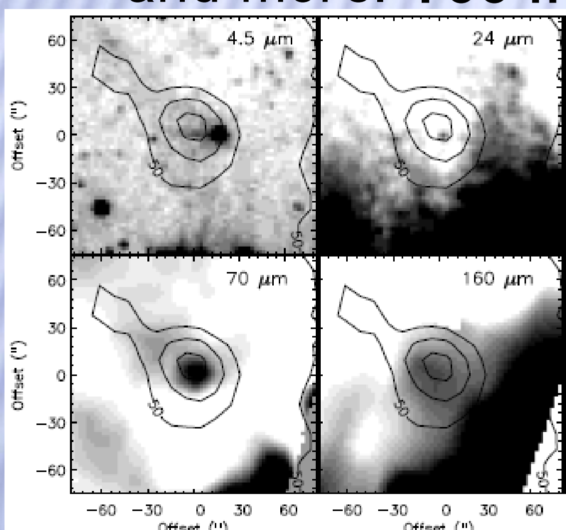
⇒A good target for ALMA, even in Early Science phase

Band	Frequency [GHz]	Angular Resolution ["]	Maximum Scale ["]	T_{bc} [mK]	Flux [mJy]
Properties of the Extended Configuration (baselines of ~36 m to ~400 m)					
3	100	1.56	10.5	7.6	0.14
6	230	0.68	4.5	11	0.20
7	345	0.45	3.0	20	0.37
9	675	0.23	1.5	175	3.2

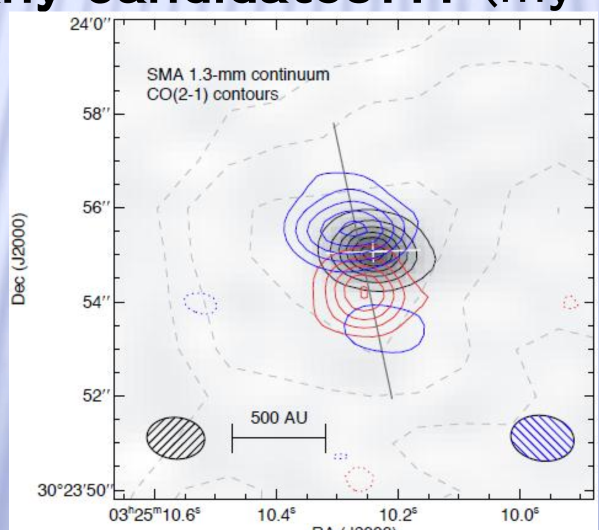
First Core Candidates

Recently, a number of first core candidates are reported:

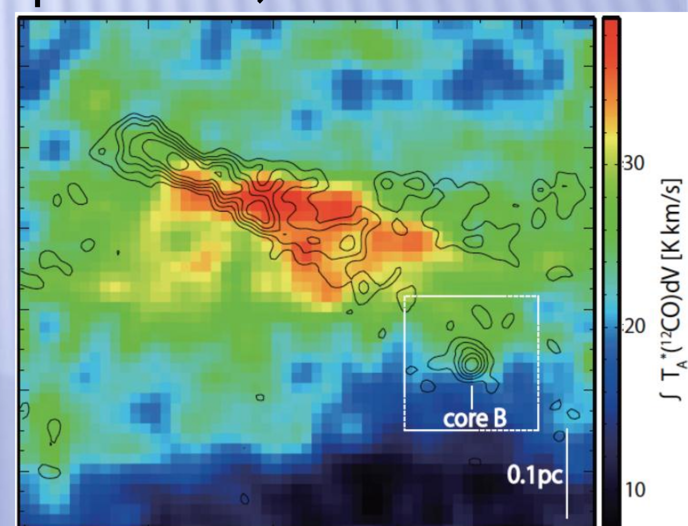
- **L1448 IRS2E**, Chen et al., 2010
- **R CrA SMM 1A**, Chen & Arce, 2010
- **Per-Bolo 58**, Enoch et al., 2010 and Dunham et al., 2011
- **L1451-mm**, Pineda et al., 2011
- **"Core B"** in Lupus-I, Kawabe et al. in prep
- **"Source A"** in rho-Oph, Kawabe et al. in prep
- …and more. **Too many candidates???** (my impression)



Enoch et al.



Pineda et al.



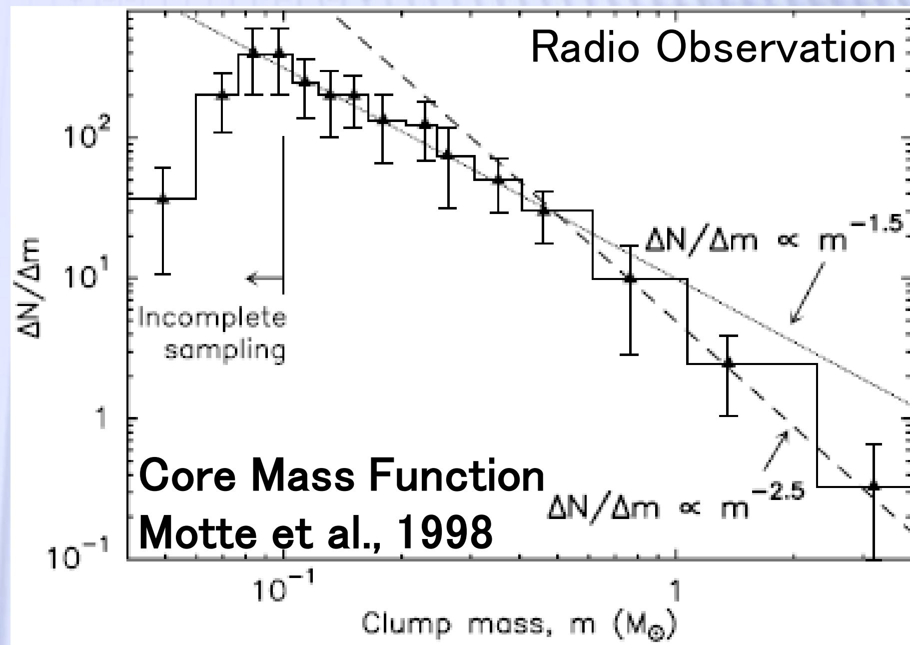
Kawabe et al.

First Cores in Low-Mass Cloud Cores

So far, formation of “typical” stars (~1Ms) has been well studied, **but…**

- Many low mass objects in CMF/IMF
- Some first core candidates seem to have fairly small masses(~0.1Ms)
- Too many first core candidates?
- (How do brown dwarves form?)

⇒Low-mass cores are interesting!



Q: **Is star formation in very low-mass (~0.1Ms) cloud cores similar to that in cores with “ordinary” masses (~1Ms) ?**

- ➢First cores in 1Ms cores evolve under short dynamical time-scale by accretion from the envelope
- ➢First cores in very low mass cores cannot reach second collapse only by accretion, and will evolve under longer time-scale(??)

- Radiation timescale in first cores is O(1000) yrs→**RHD simulations!**

Simulation Setups

3 models: 0.1Ms model and 1Ms models with and without rotation

Model	Mass($M_\odot$)	Central density($g\,cm^{-3}$)	Radius(AU)	Free-fall time(yrs)	Angular velocity(sec^{-1})
S1	1	3.2×10^{-18}	6300	3.7×10^{4}	0
R1	1	3.2×10^{-18}	6300	3.7×10^{4}	4.3×10^{-14}
R01	0.1	3.2×10^{-16}	630	3.7×10^{3}	1.4×10^{-12}

Code: 3D, nested-grids, self-gravity, FLD radiation hydrodynamics

Initial conditions: T=10K unstable Bonnor-Ebert-like sphere **without magnetic fields** (we chose non-fragmentation parameters)

Radiation Transfer: Gray, **Flux Limited Diffusion Approximation** (FLD, Levermore & Pomraning 1981, comoving frame)

EOS: ideal, γ=5/3

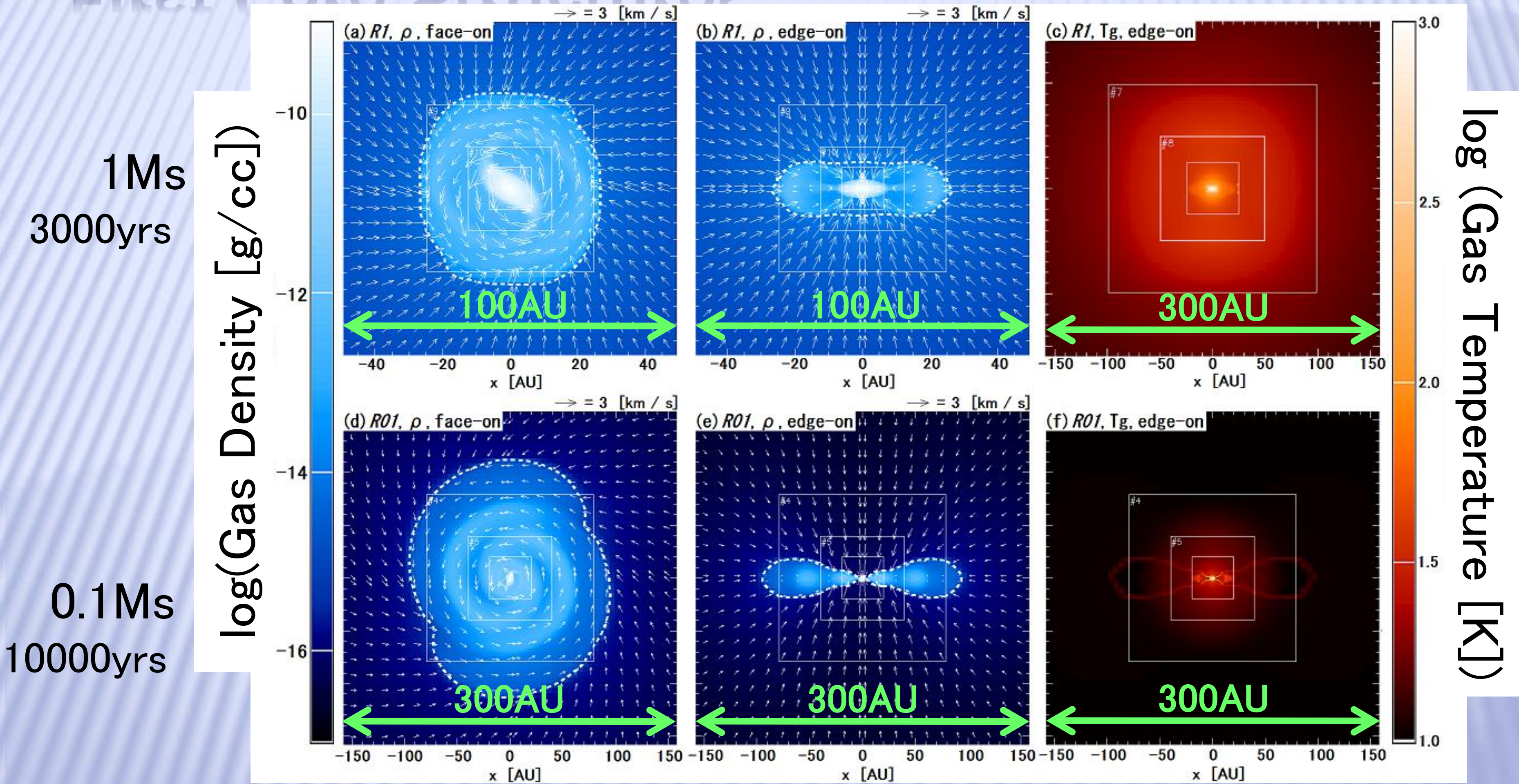
Opacity: Semenov et al., 2003 + Ferguson et al., 2005

Resolution: 64^3 x 11(R01) x14(R1, S1) levels

16 Meshes / Jeans length → 0.1AU @ First core surface

Computer: NEC SX-9 Vector Supercomputer @ NAOJ and JAXA

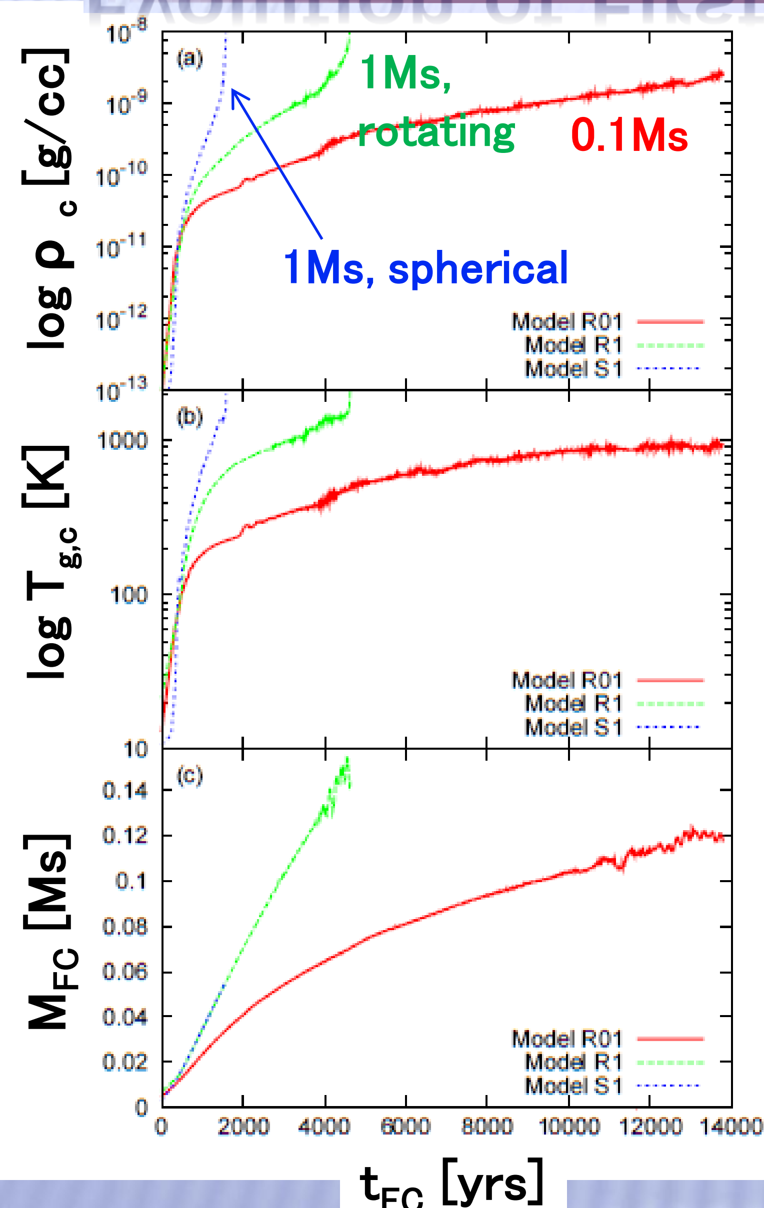
First Core Structures

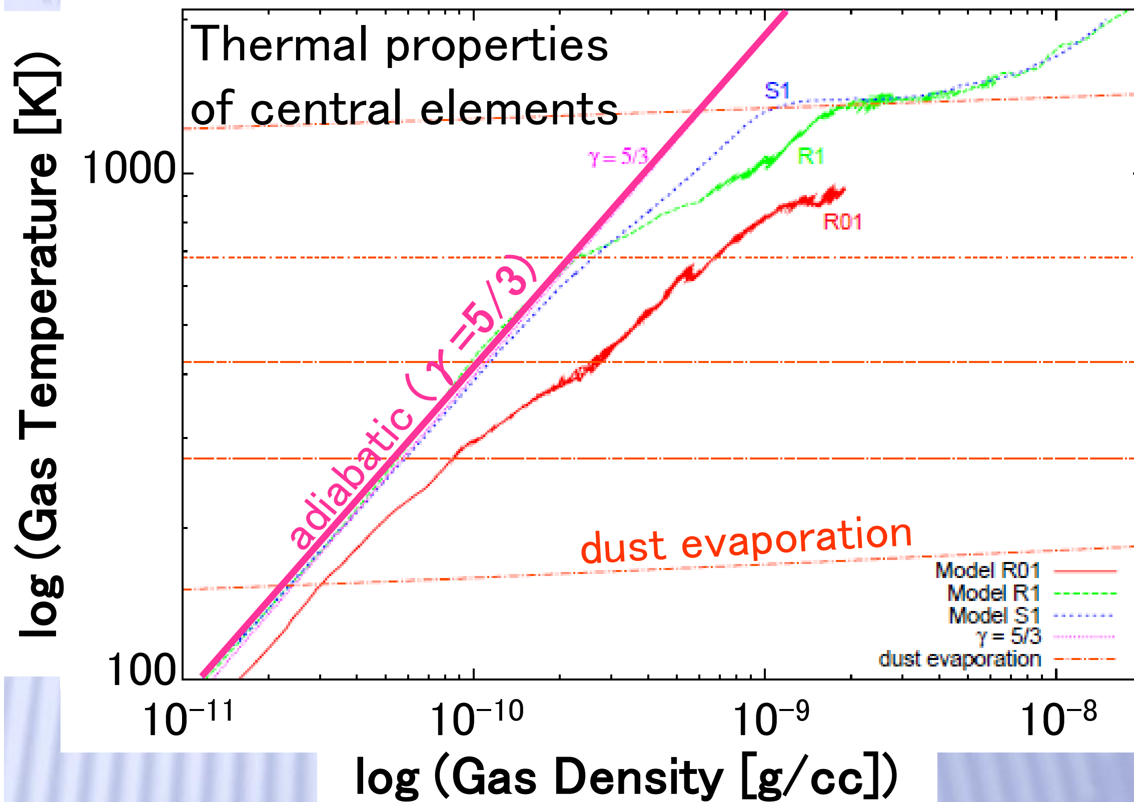


Compare at the epoch of **the same first core masses**

- larger first core disk in 0.1Ms model←Ang. mom. redistribution
- **low-density, low-temperature envelope←weak accretion + cooling**

Evolution of First ~~Adiabatic~~ Cores

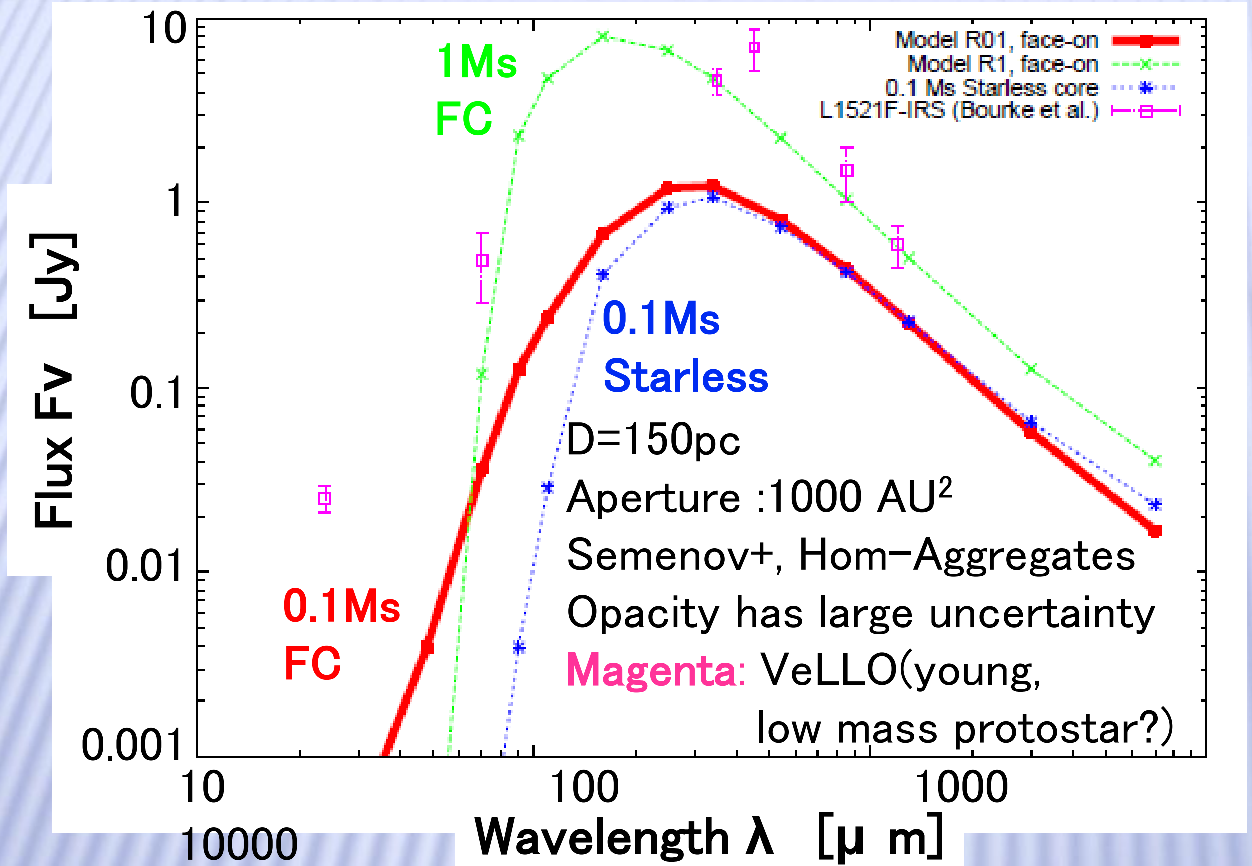


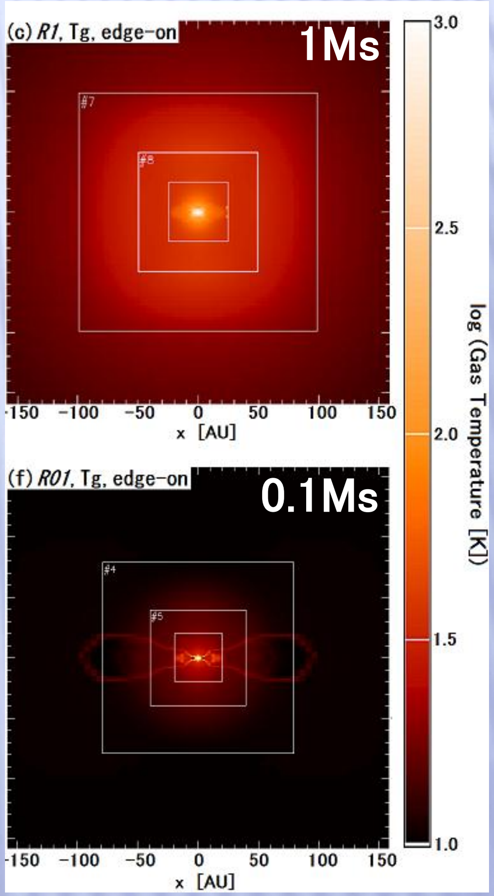


The low-mass model (R01) has…

- Qualitatively different evolution
←efficient radiation cooling
- longer lifetime, more than **13,000** yrs
(cf. t_{ff}~4,000 yrs→more common?)

Spectral Energy Distributions



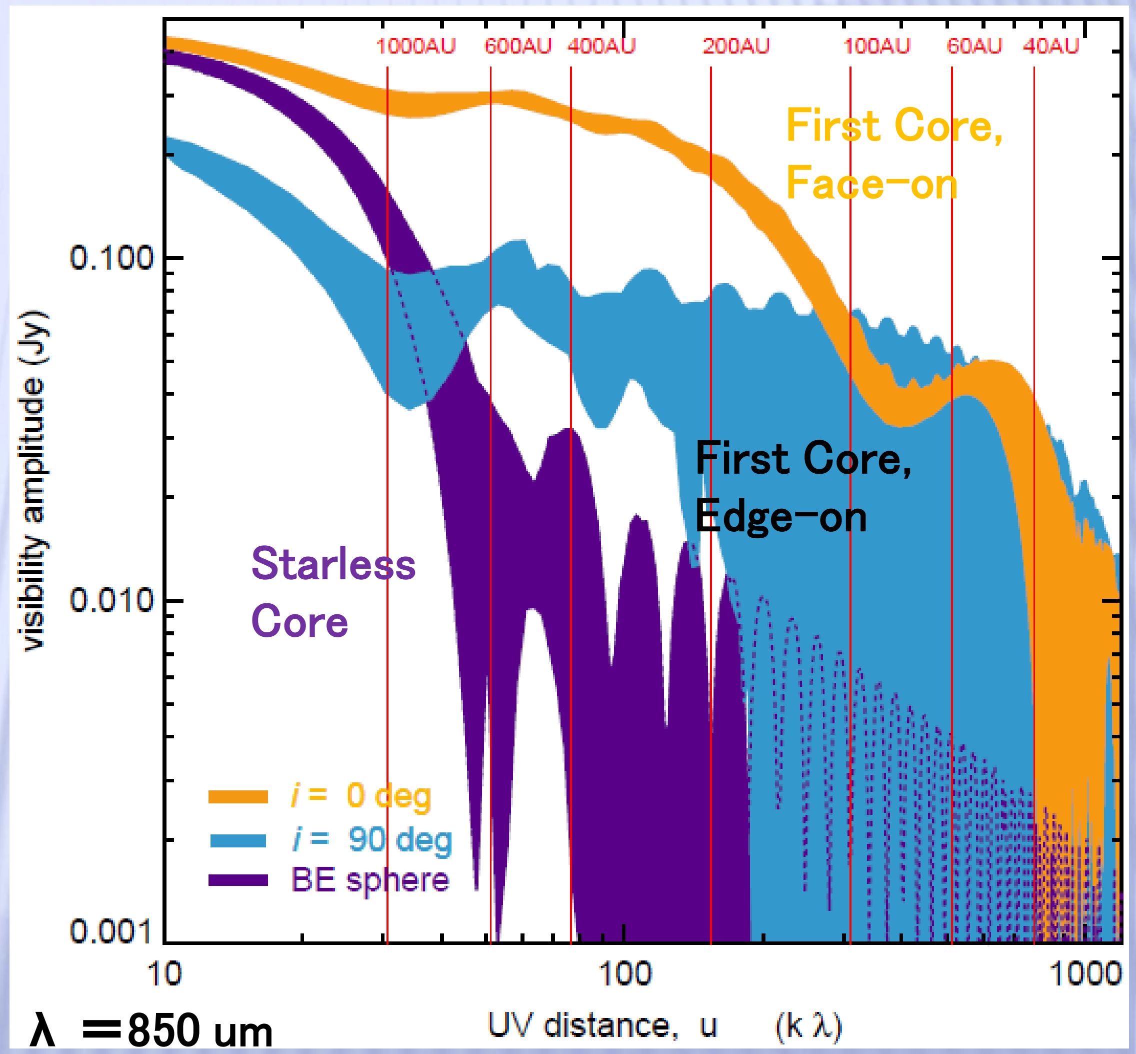


- •Radio:R01 is fainter than R1, but the difference is a factor of 2~3
- •Far IR:R1 is significantly bright← larger warm gas mass
- •Mid IR:R01 exceeds R1←hot region can be seen due to thin envelope
- •Low mass model is faint but still observable with ALMA & *Herschel*

Visibility Amplitude Distributions

First cores are faint in IR.
How can we identify them by radio observations?
→Visibility Amplitude (spatial Fourier transform of intensity distribution, obtained w/ interferometer)

First cores have flat dist. due to its fine structure.
(this is not peculiar in very low mass cases, but common in first cores)



We can ID first cores using SED & visibility amplitude. (tractable even in ALMA ES operations!)

Discussions

Such very low mass cores may not collapse so often!

If we cannot find first cores (after long survey w/ ALMA)

→Very low mass cores collapse so rarely.

⇒relation between CMF and IMF in the low mass end

- Effect of Magnetic Fields?

  Extend lifetime: Mass ejection by outflow

  Shorten lifetime: efficient angular momentum transport

  But this mechanism works even in magnetized cores.

- How do the very low mass cores become unstable?

  →external pressure, radiation, cloud–cloud collision?
- How does accretion stop?→outflow, ejection by scattering?

  ⇒Environment may affect the first core properties.

Summary

- **RHD simulations of protostellar collapse in low mass cores**
- Compared to 1Ms cases, First cores in very low mass cores
  - **evolve very slowly (>10^4 yrs) due to weak accretion**
  - different evolution under **radiative cooling**
- **Observational properties(SED, visibility)** by post processing

→Faint but still observable with ALMA and Herschel

We can expect a considerable number of first cores exist and can be observed if very low mass cores collapse with a reasonable probability because

- there are a lot of low mass cores in CMF
- their lifetime is longer than free fall time of natal cores