Formation of Planetary Systems
I. Theory vs. Theory

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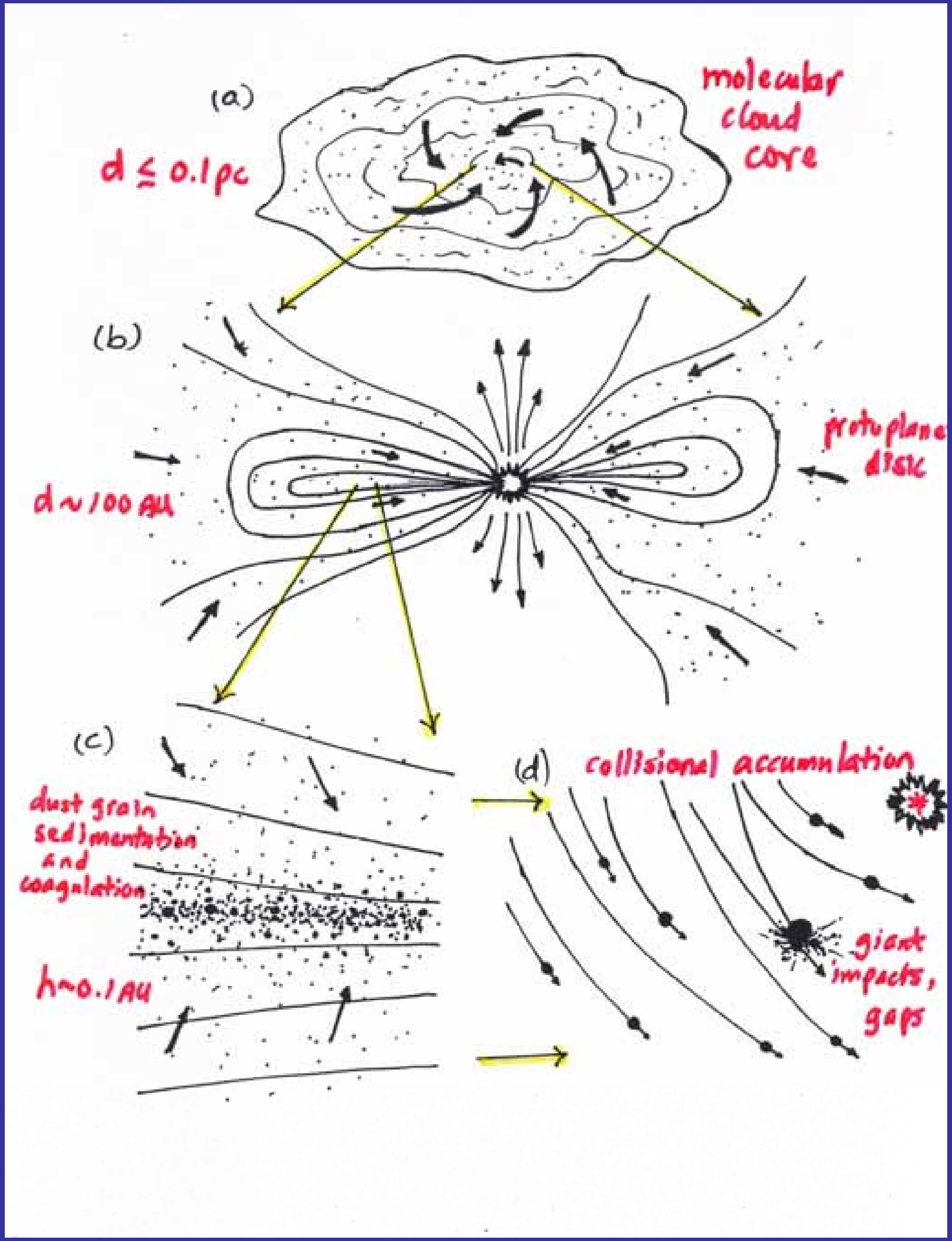
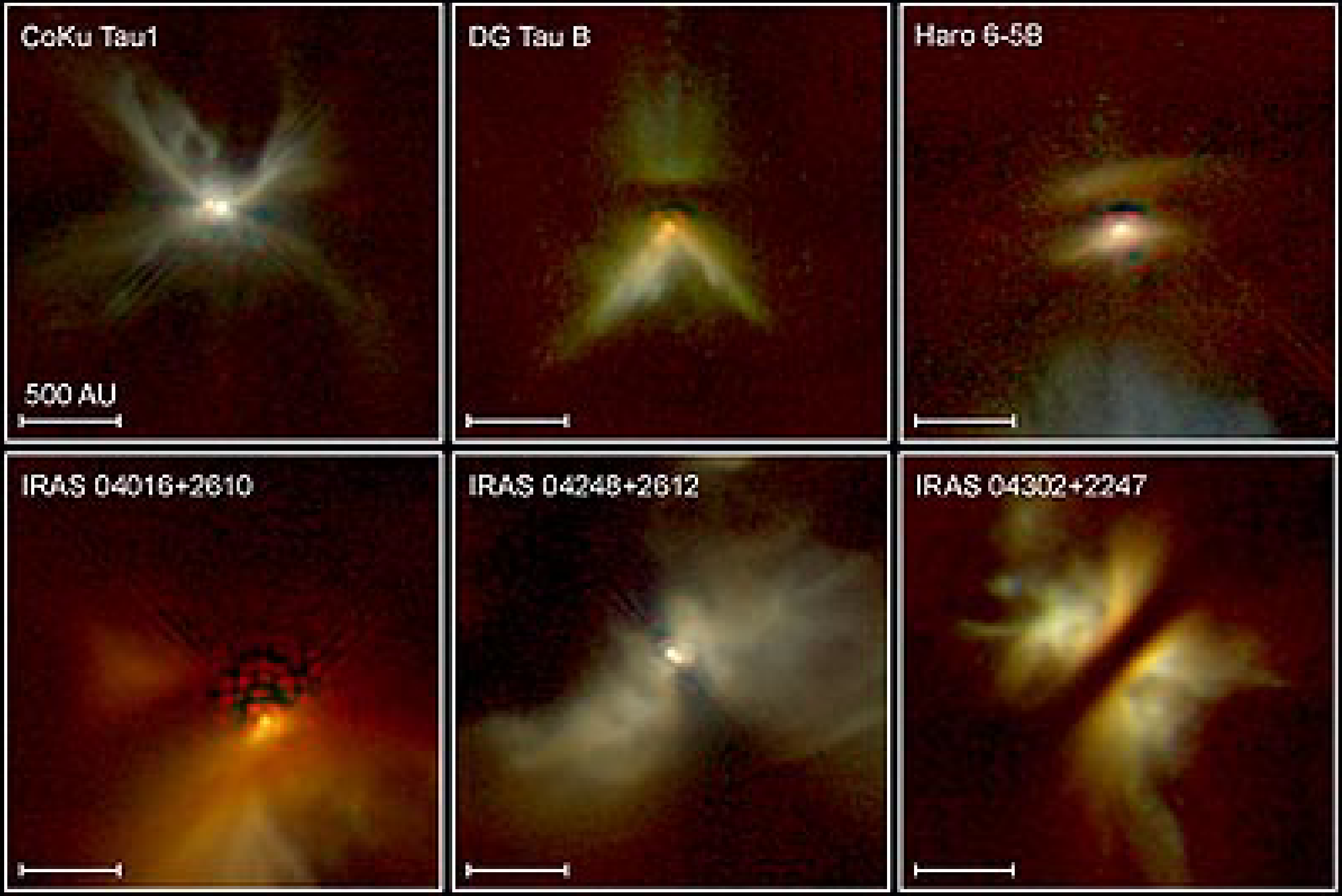
Kobe International Summer School of Planetary Sciences
“Origin of Planetary Systems”
Awaji Island, Japan
July 12, 2005


(a)
d ≤ 0.1pc
molecular cloud core
(b)
d ~ 100 AU
protoplane disk
(c)
dust grain sedimentation and coagulation
h~0.1AU
(d)
collisional accumulation
giant impacts, gaps


CoKu Tau1
DG Tau B
Haro 6-5B
500 AU
IRAS 04016+2610
IRAS 04248+2612
IRAS 04302+2247

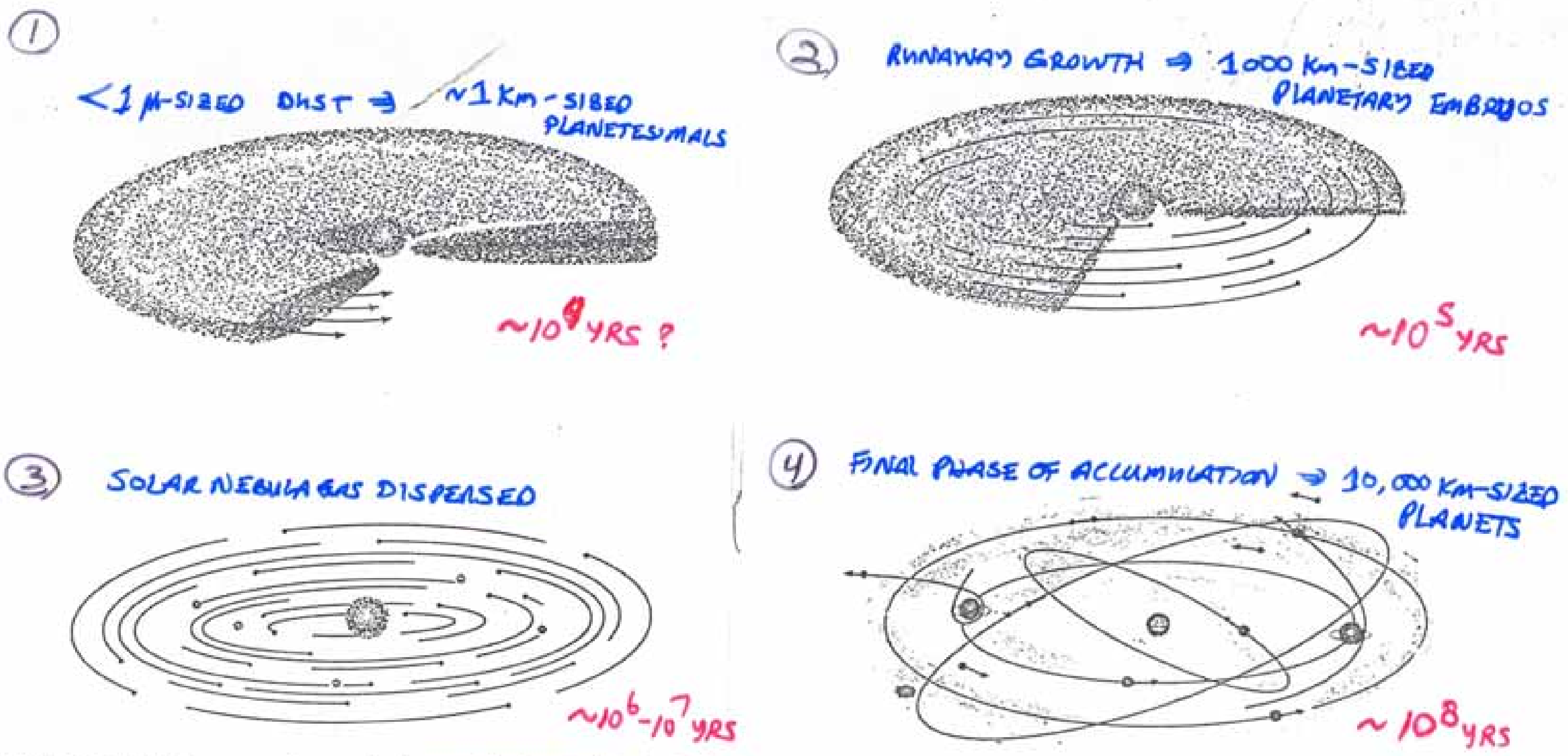
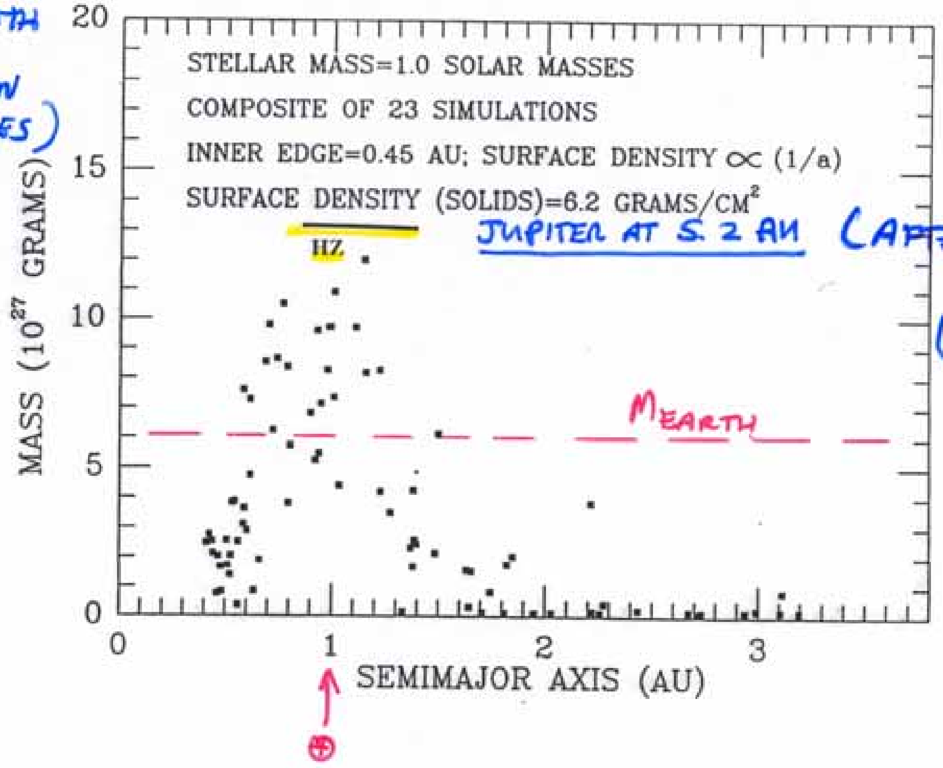


FIGURE 3.2 Possible sequence of events in the terrestrial planet region. (top left) Growth of dust grains into ~10-km-diameter "planetesimals" through nongravitational forces (sticking). (top right) Runaway growth of planetesimals, moving in nearly circular, coplanar orbits, to form ~2000-km-diameter "planetary embryos" on a 10^5-year time scale. (bottom left) Removal of gas from the inner solar system on a 10^6- to 10^7-year time scale. (bottom right) Mutual perturbation of planetary embryos into eccentric orbits and their merger to form the present planets on a 10^8-year time scale. Asteroids are relics of similar processes in the present asteroidal region that failed to complete the runaway growth stage (top right) as a consequence of either gravitational or collisional removal of most of the other bodies in that region. Jupiter's perturbations, beginning at about 5×10^6 years, were primarily responsible for this clearing of the asteroid belt.

WETHERILL (1996)

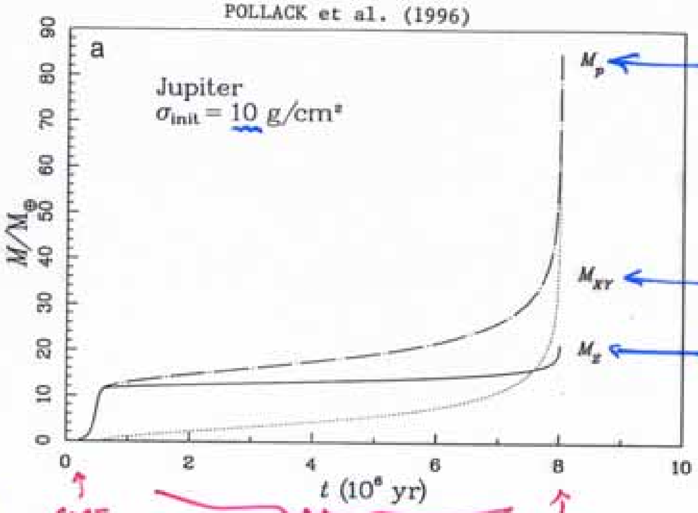
(STARTING WITH ~500 M_{moon} ~5850 BODIES)



JUPITER AT 5.2 AU (AFTER 5 MYR)

(SATURN AFTE
10 MYR

GIANT PLANET FORMATION BY CORE ACCRETION:



TOTAL MASS

GAS

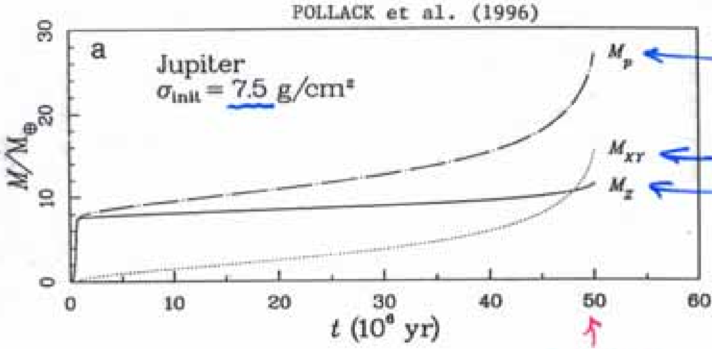
SOLIDS

(1 $M_{\rm MARS}$ SEED ASSUMED)

CORE FORMS (~1 Myr)

GAS ACCRETES (~7 Myr)

RUNAWAY ACCRETION OF GAS



TOTAL MASS

GAS

SOLIDS

50 Myr.

BUT GAS ONLY PERSISTS FOR ~1 Myr OR SO...

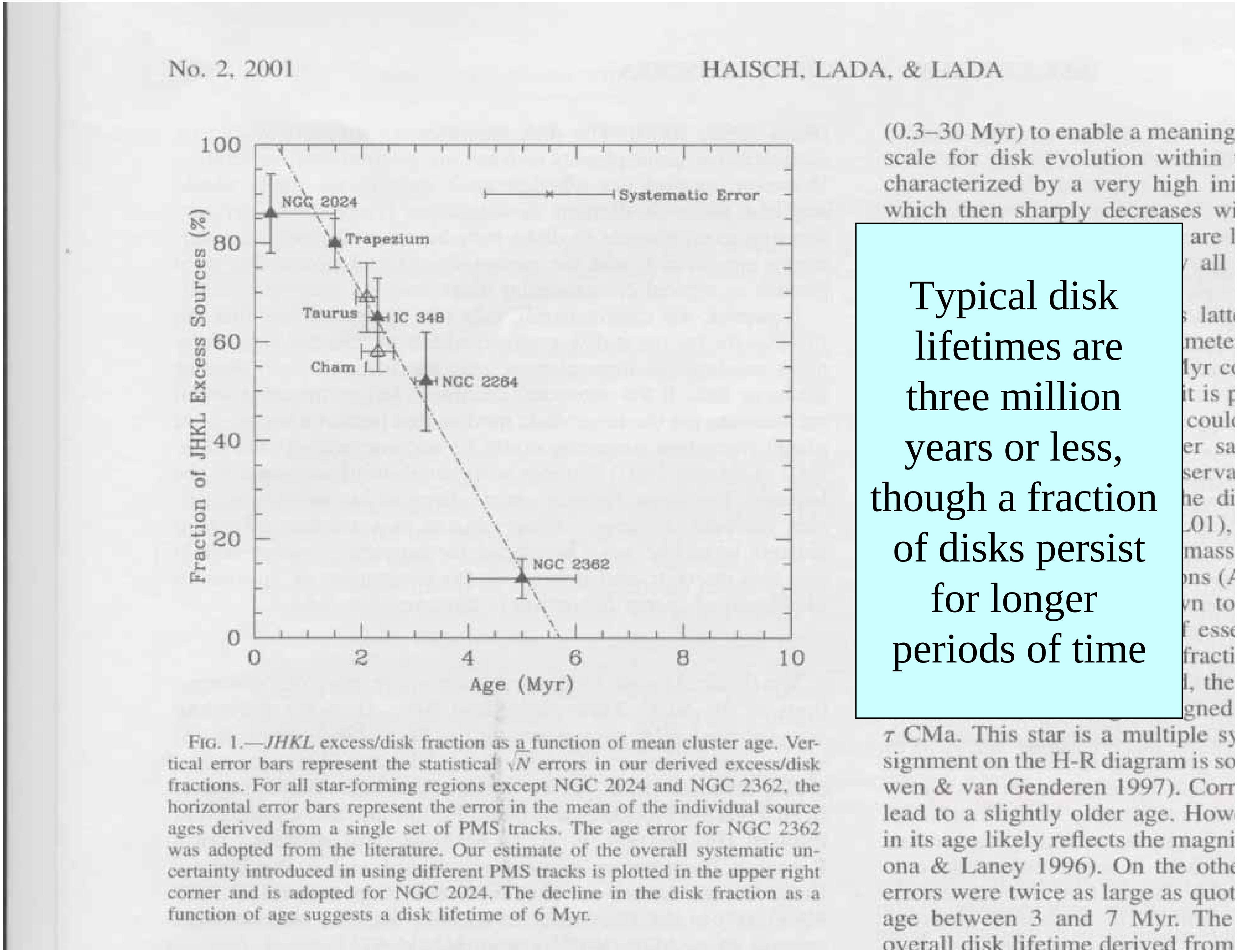
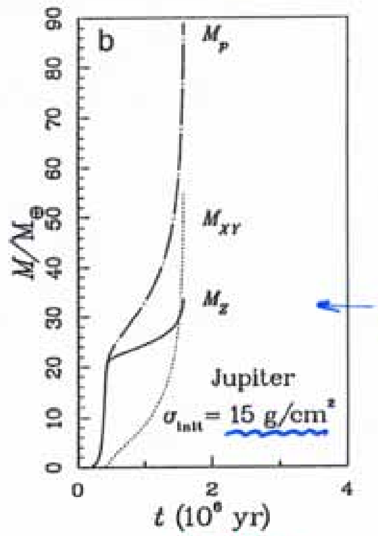


FIG. 1.—*JHKL* excess/disk fraction as a function of mean cluster age. Vertical error bars represent the statistical $\sqrt{N}$ errors in our derived excess/disk fractions. For all star-forming regions except NGC 2024 and NGC 2362, the horizontal error bars represent the error in the mean of the individual source ages derived from a single set of PMS tracks. The age error for NGC 2362 was adopted from the literature. Our estimate of the overall systematic uncertainty introduced in using different PMS tracks is plotted in the upper right corner and is adopted for NGC 2024. The decline in the disk fraction as a function of age suggests a disk lifetime of 6 Myr.

(0.3–30 Myr) to enable a meaning
scale for disk evolution within
characterized by a very high ini
which then sharply decreases wi
are l
all
s latt
mete
Myr c
it is p
coul
er sa
serva
he di
01),
mass
ns (
wn to
f esse
fracti
l, the
gned
τ CMa. This star is a multiple sy
signment on the H-R diagram is so
wen & van Genderen 1997). Corr
lead to a slightly older age. How
in its age likely reflects the magni
ona & Laney 1996). On the othe
errors were twice as large as quot
age between 3 and 7 Myr. The
overall disk lifetime derived from

Typical disk lifetimes are three million years or less, though a fraction of disks persist for longer periods of time

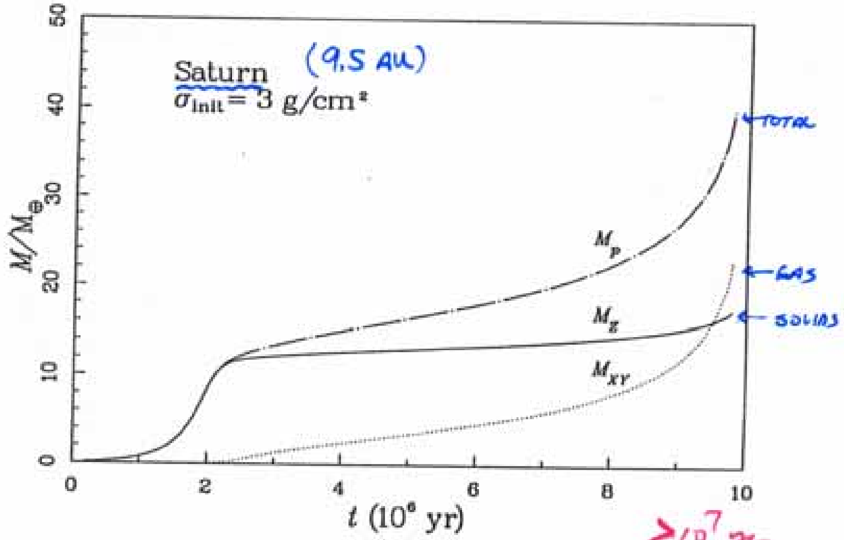
POLLACK et al (1996)



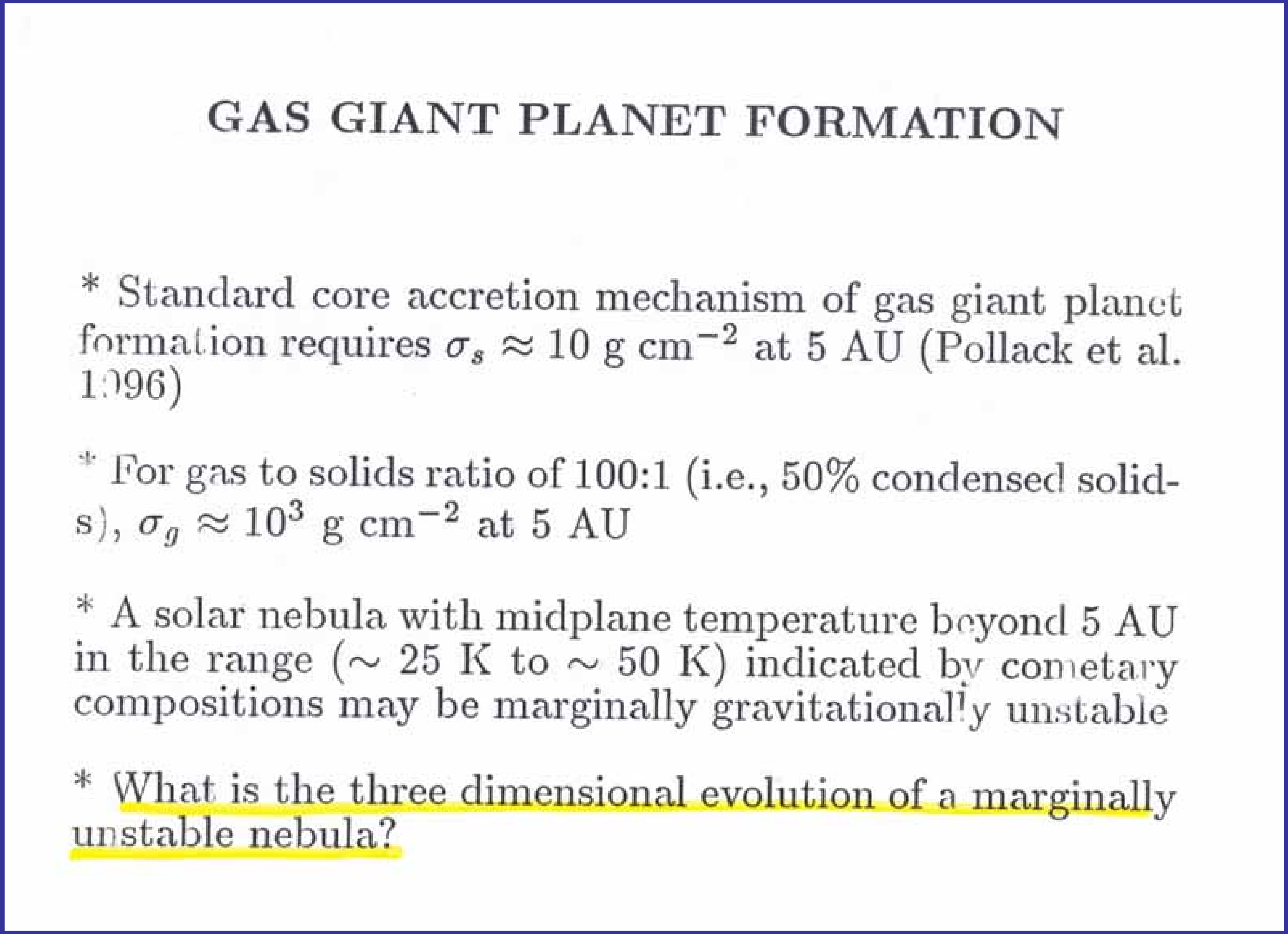
← $M_{\rm core} \gtrsim 30\, M_\oplus$

(vs. SPITZER, HD 209458)

< 2 Myr



$\gtrsim 10^7$ yr



GAS GIANT PLANET FORMATION

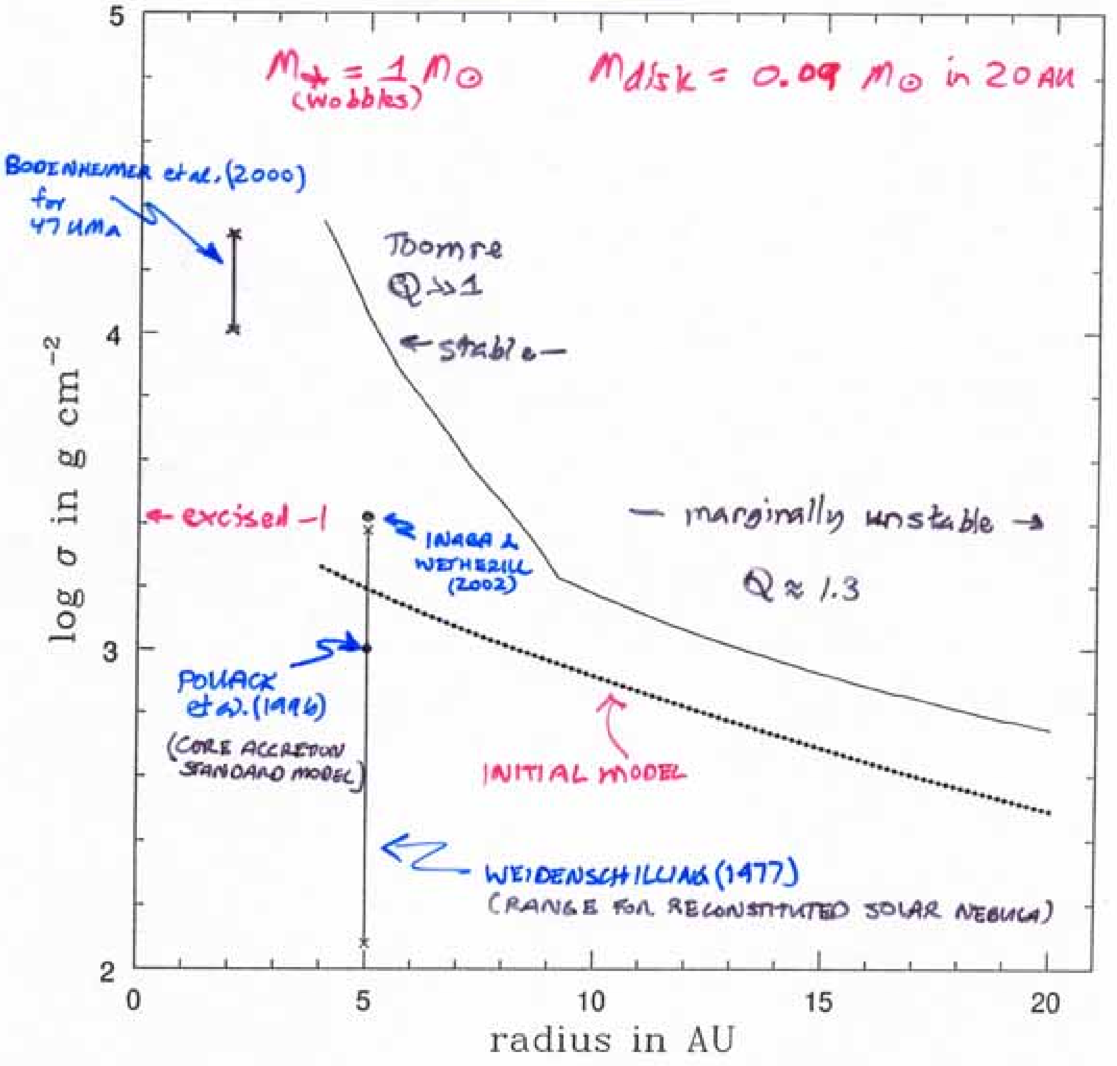
* Standard core accretion mechanism of gas giant planet formation requires $\sigma_s \approx 10$ g cm^{-2} at 5 AU (Pollack et al. 1996)

* For gas to solids ratio of 100:1 (i.e., 50% condensed solids), $\sigma_g \approx 10^3$ g cm^{-2} at 5 AU

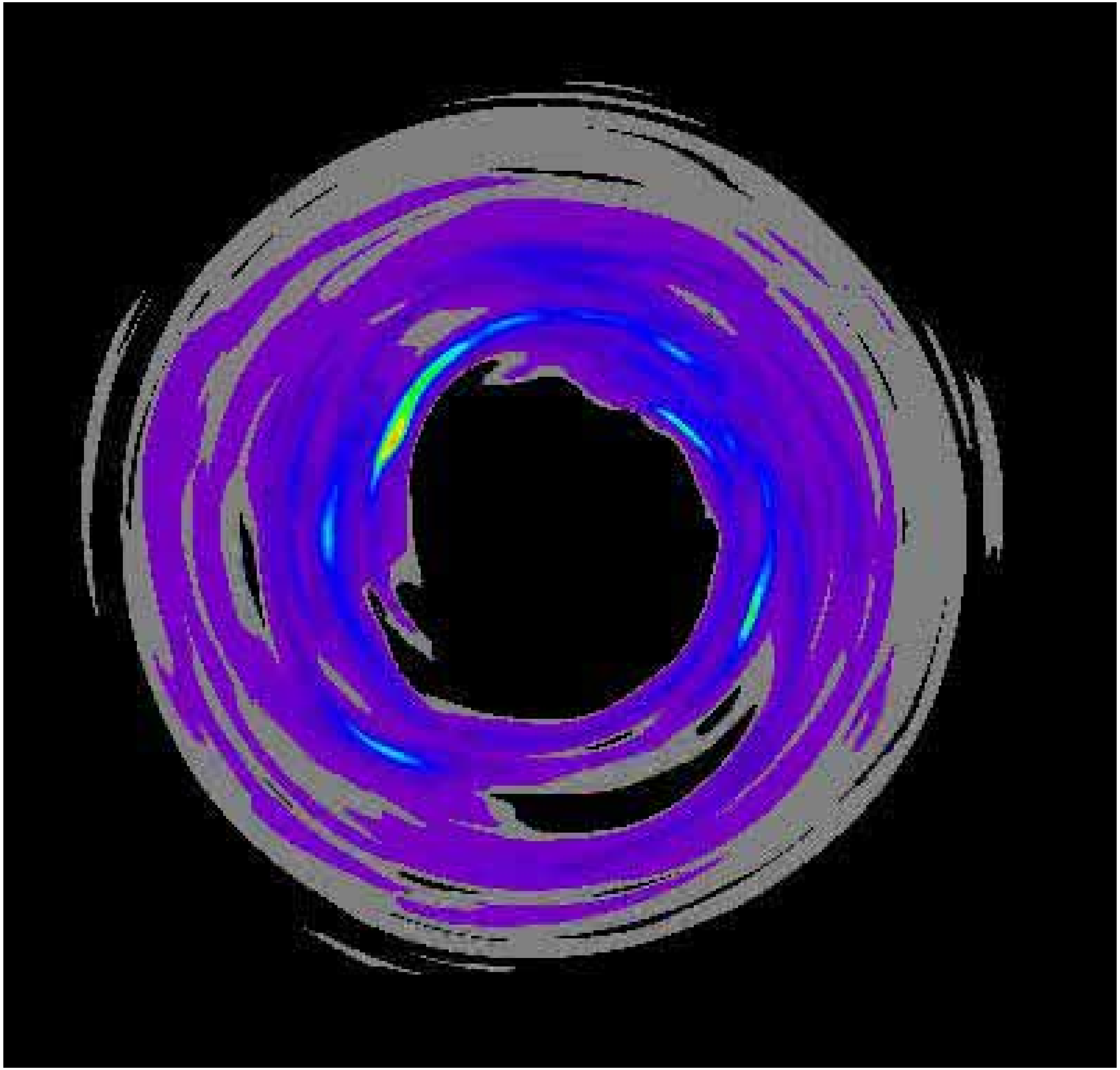
* A solar nebula with midplane temperature beyond 5 AU in the range ($\sim$ 25 K to $\sim$ 50 K) indicated by cometary compositions may be marginally gravitationally unstable

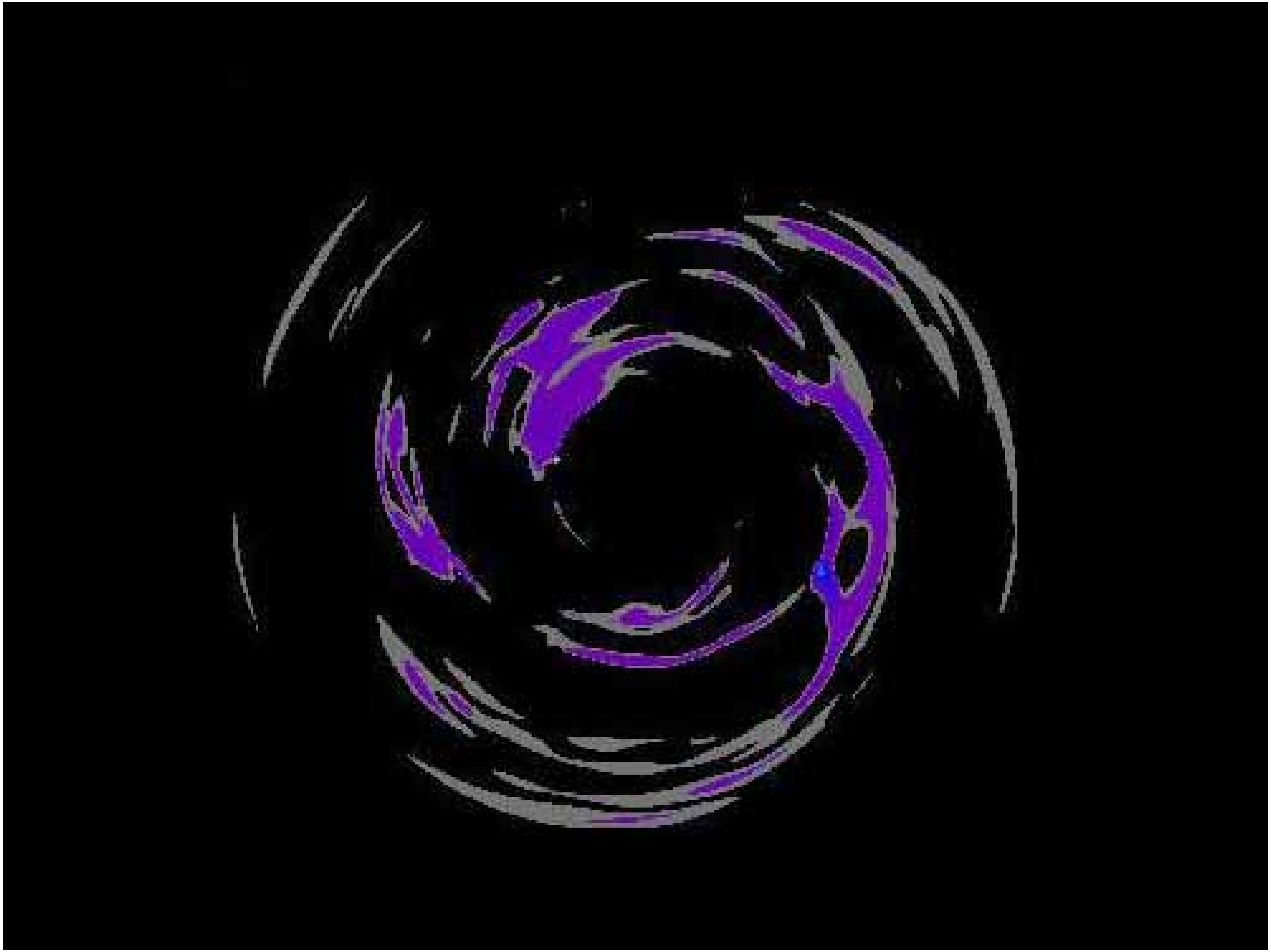
* What is the three dimensional evolution of a marginally unstable nebula?

Boss (2000)



$[\ \sigma_i \propto r^{-1} \Rightarrow r^{-3/2}\ ]$

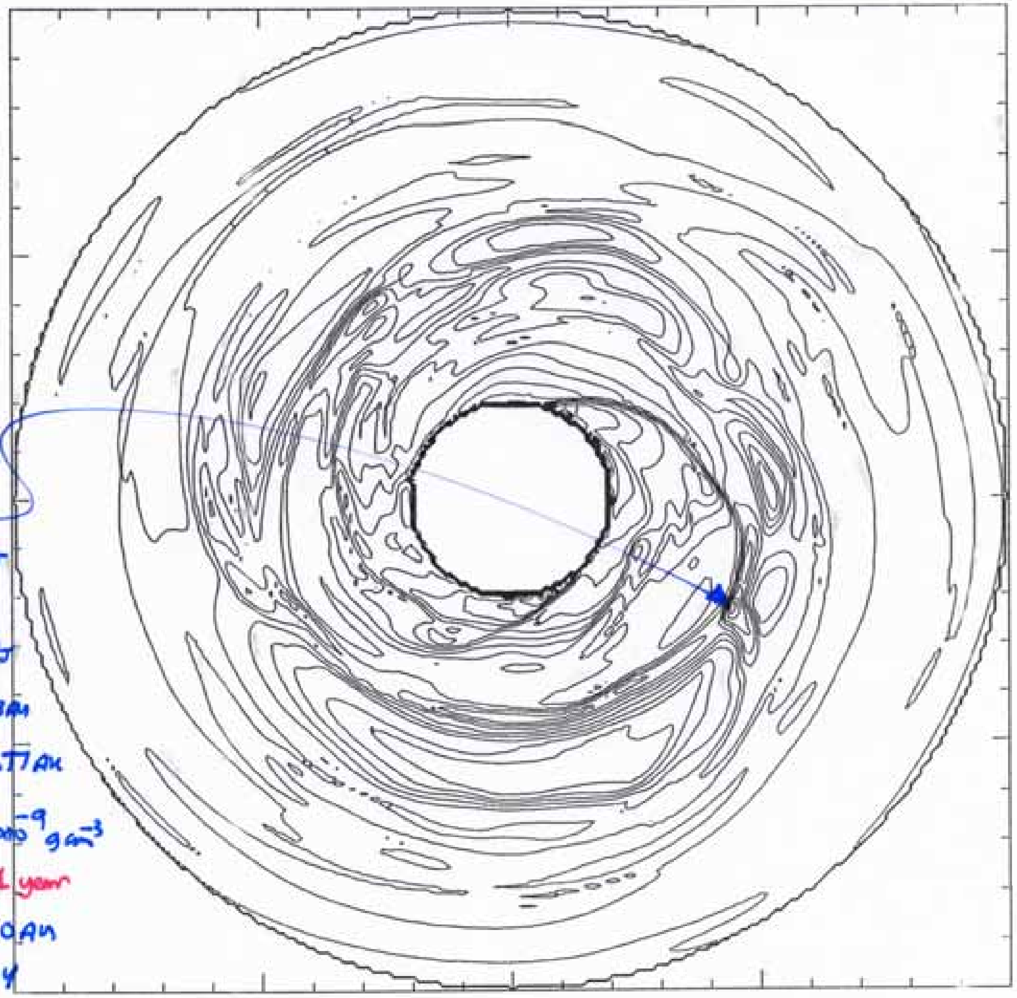




(t_i = 322 YEARS)

RADIATIVE TRANSFER + ... $Q_{i_{min}} = 1.3$ 339 YEARS

RHOMAX= −8.3 CONDIF= 0.3 R= 0.30E+15



$M \sim 1.4\, M_J$

$\langle M_{JEANS} \rangle = 0.63\, M_J$

$\langle R \rangle = 0.58$ AU

$\langle R_{TIDE} \rangle = 0.77$ AU

$\rho_{max} = 5.0 \times 10^{-9}\, g\, cm^{-3}$

$t_{ff} \sim 1$ year

$a \sim 10.0$ AU

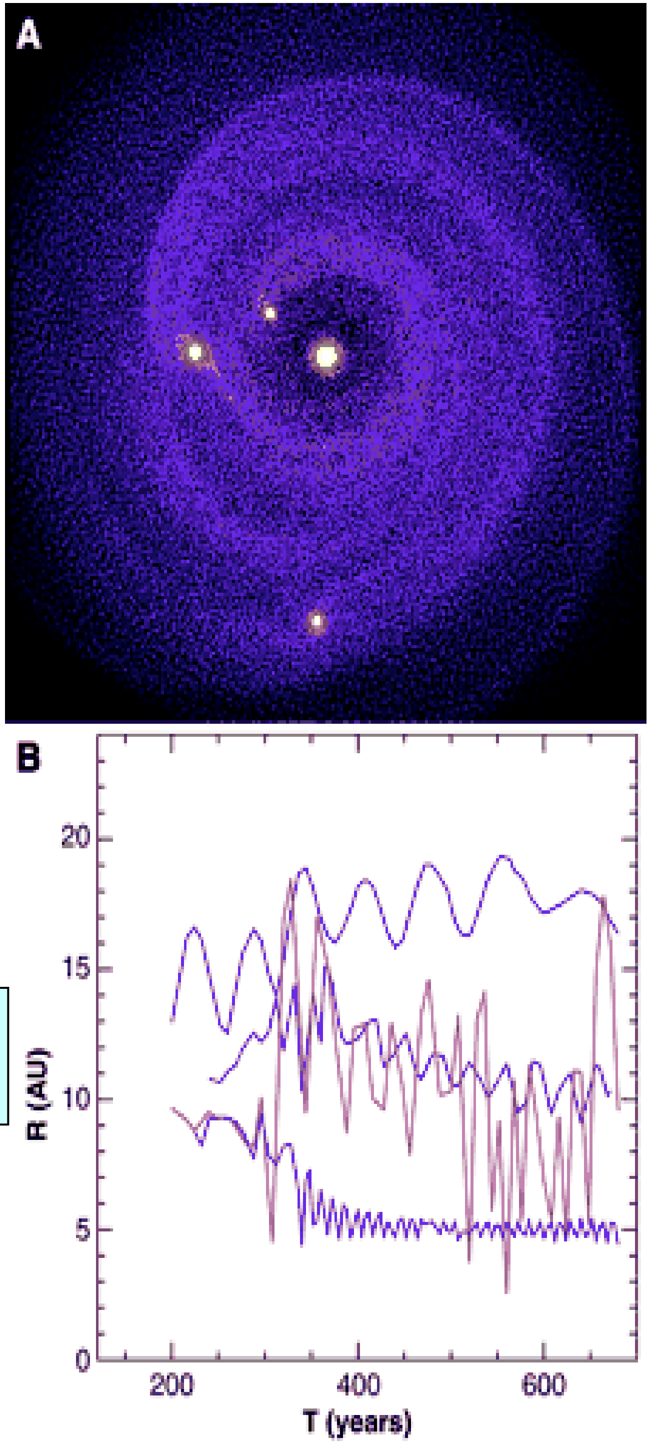
$e \sim 0.04$

$N_\phi = 512$ $N_{y_{em}} = 48$

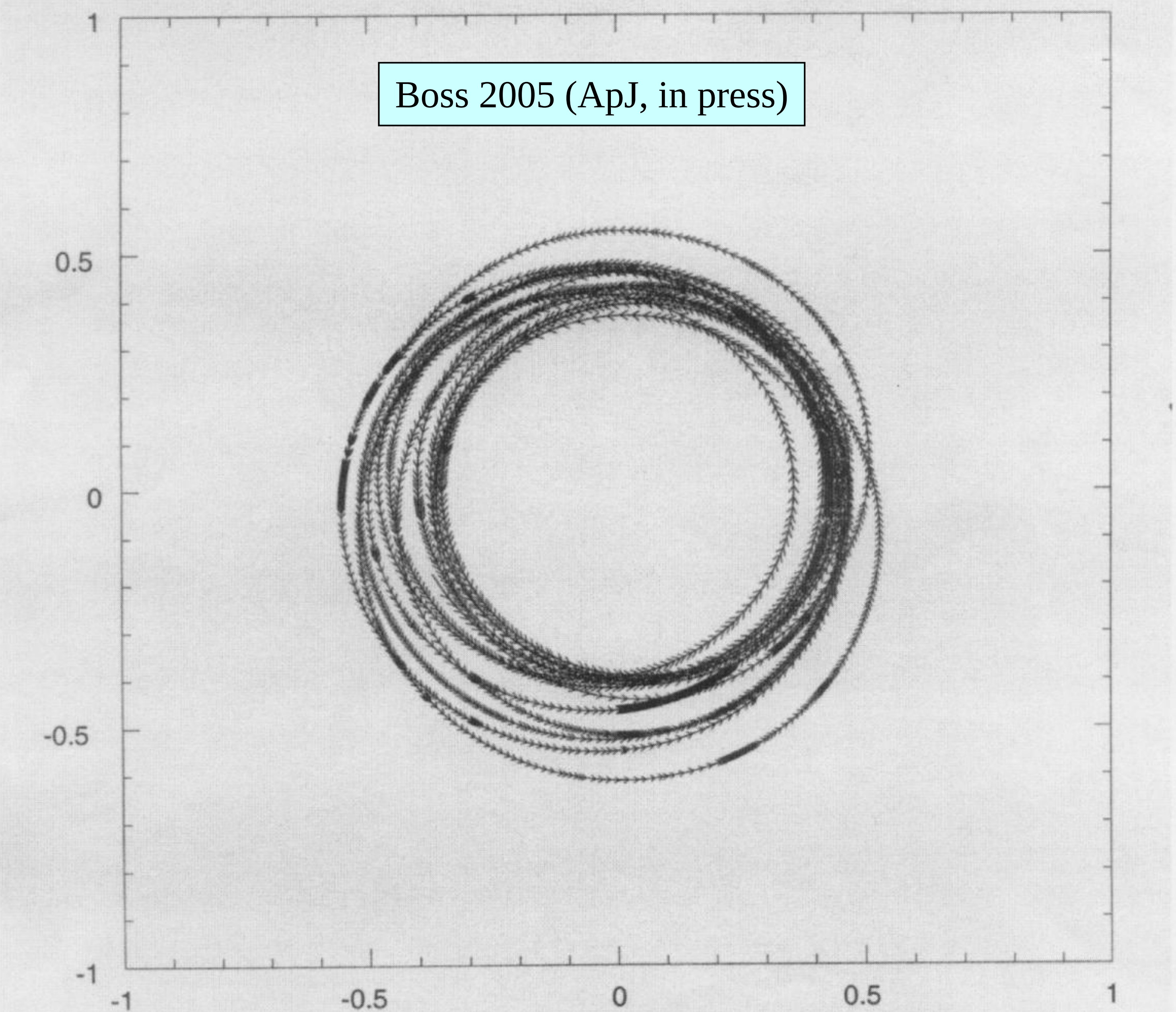
Mayer et al. 2002
disk instability
model after 800 yrs

[SPH with simple
thermodynamics]

time evolution of
clump orbits



Boss 2005 (ApJ, in press)



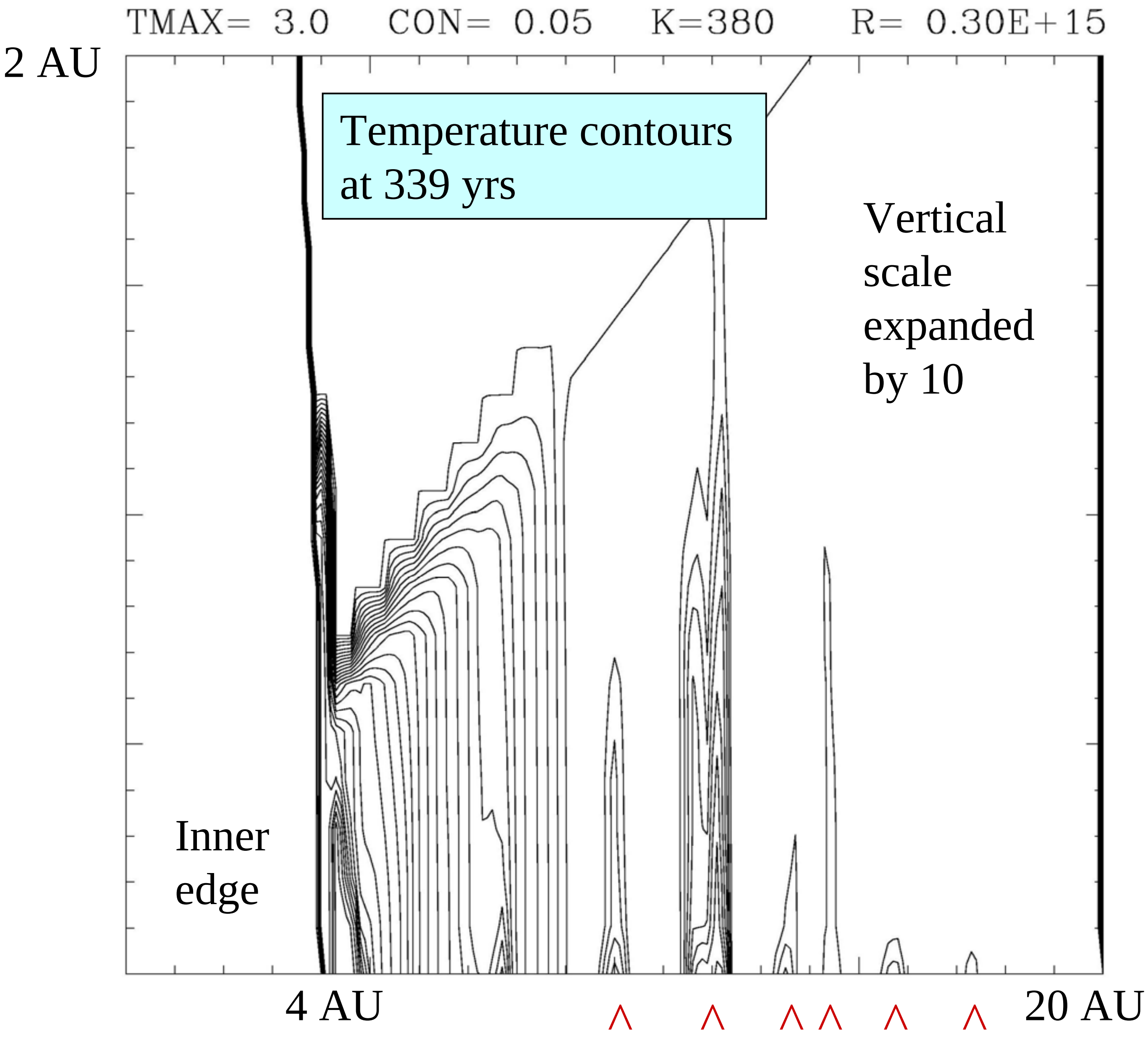
Virtual protoplanet orbits for at least 1000 years, at least 30 orbits

Disk Instability?

In order for disk instability to be able to form giant protoplanets, there must be a means of cooling the disk on the time scale of the instability, which is on the order of the orbital period.

Radiative cooling in an optically thick disk is too inefficient to cool the disk’s midplane, as its characteristic time scale is of order 30,000 yrs for the solar nebula at 10 AU.

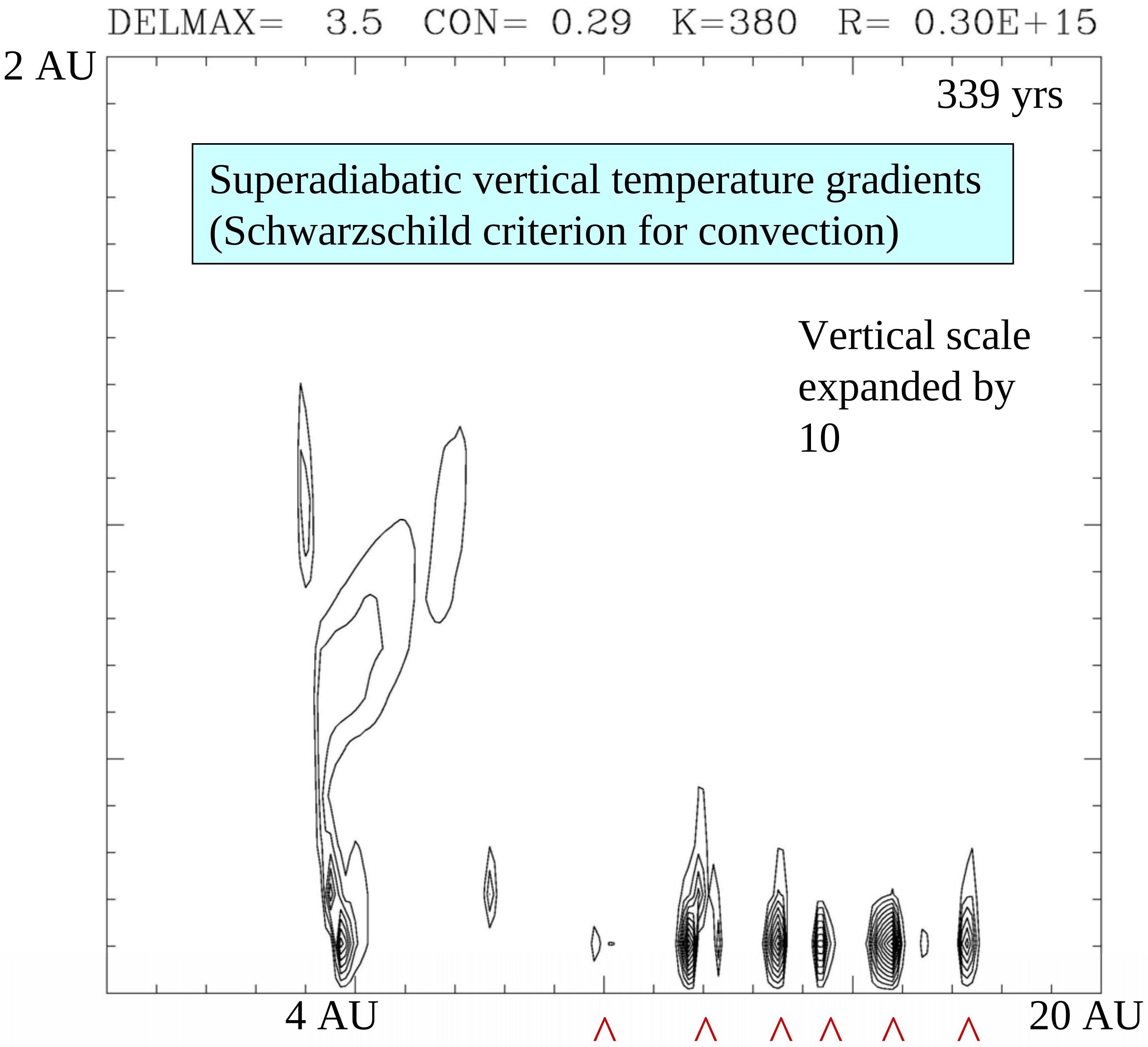
The only other possible mechanism for cooling the disk midplane is convective transport – can it do the job?



Temperature contours at 339 yrs

Vertical scale expanded by 10

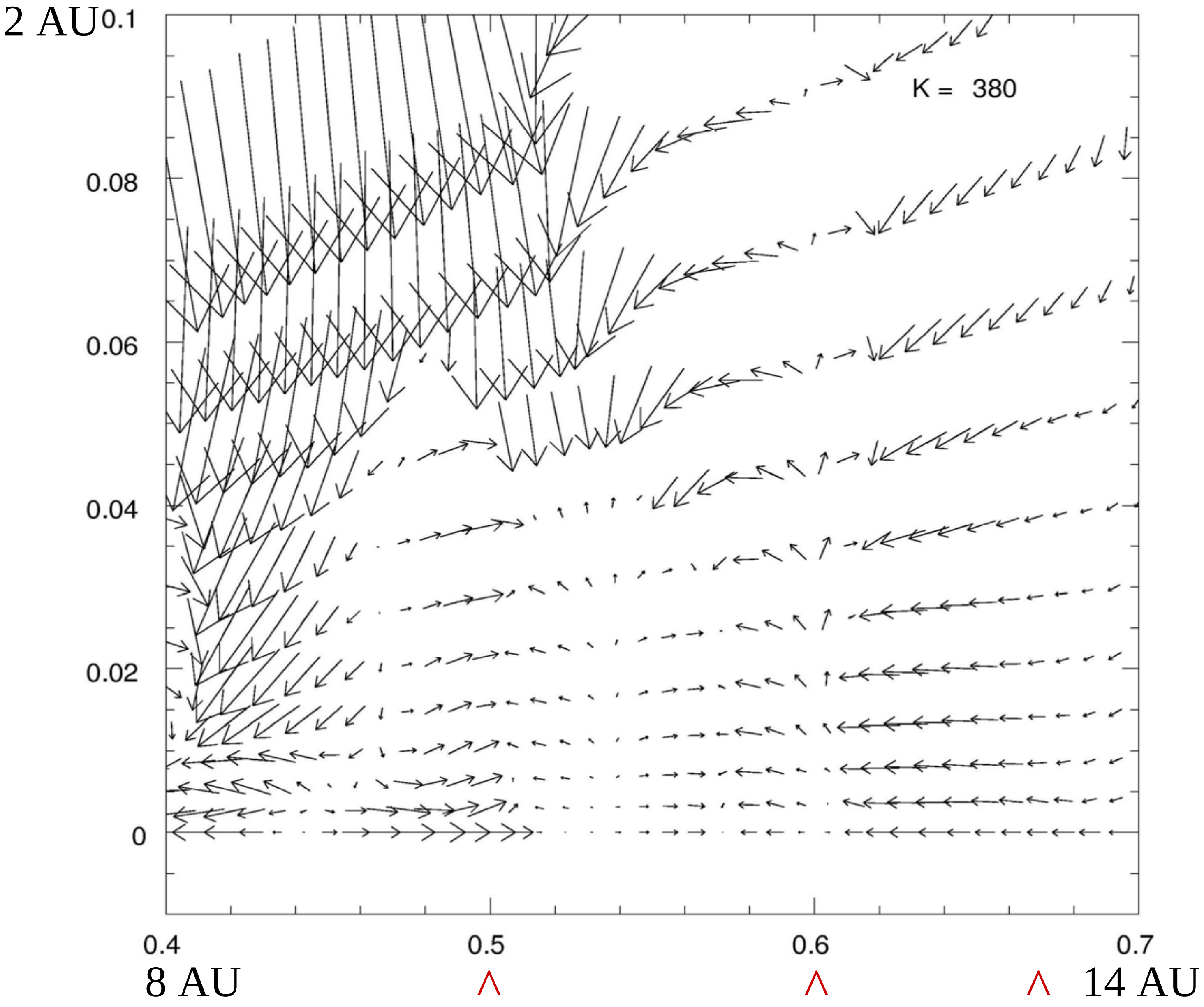
Inner edge



Superadiabatic vertical temperature gradients
(Schwarzschild criterion for convection)

Vertical scale
expanded by
10

Velocity vectors at 339 yrs



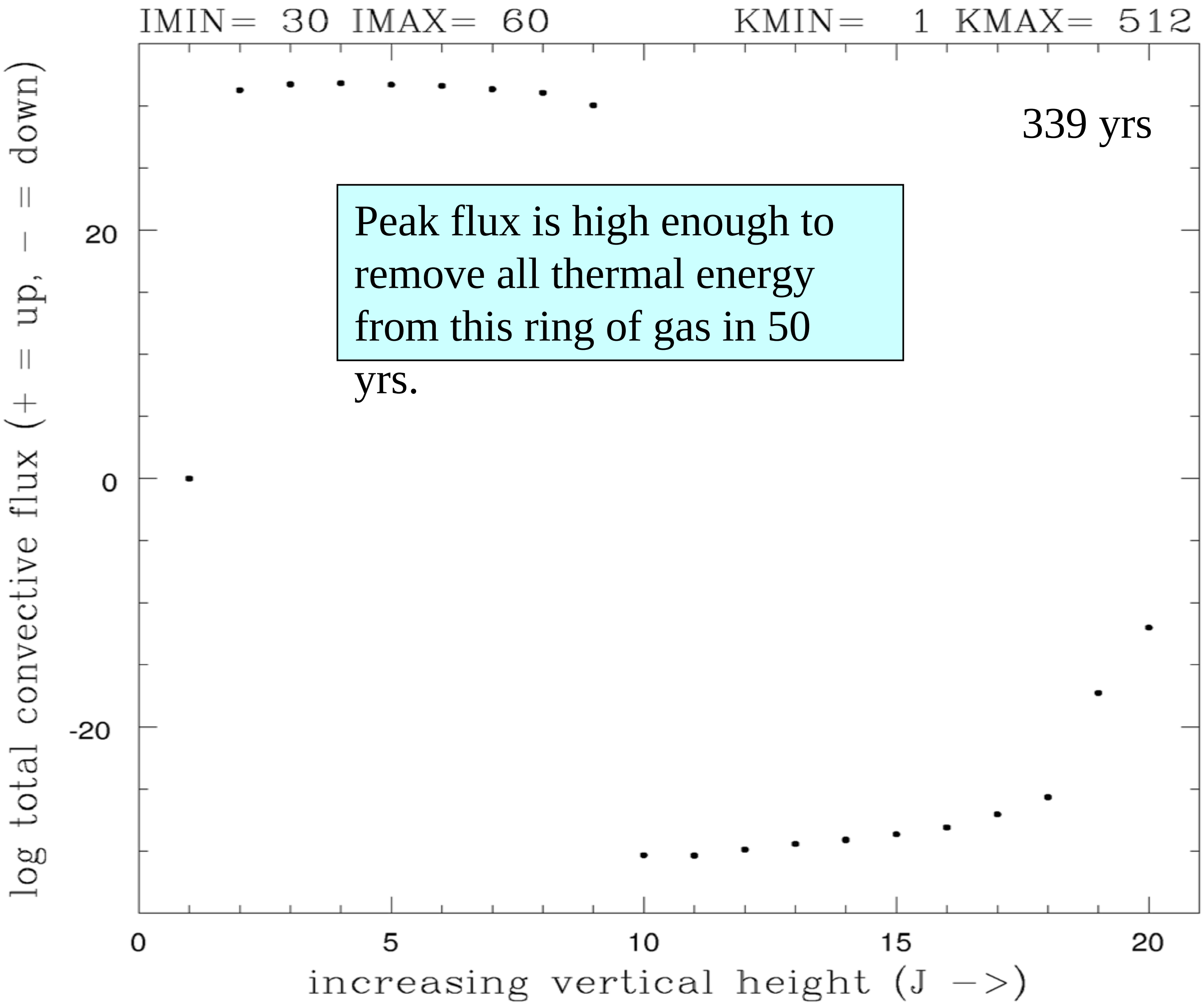
Vertical Convective Energy Flux

1. For each hydrodynamical cell, calculate the vertical thermal energy flux:

$$F_{conv} = - v_\theta A E \rho$$

where v_θ = vertical velocity, A = cell area perpendicular to the vertical velocity, E = specific internal energy of cell, and ρ = cell density.

2. Sum this flux over nearly horizontal surfaces to find the total vertical convective energy flux as a function of height in the disk.



339 yrs

Peak flux is high enough to remove all thermal energy from this ring of gas in 50 yrs.

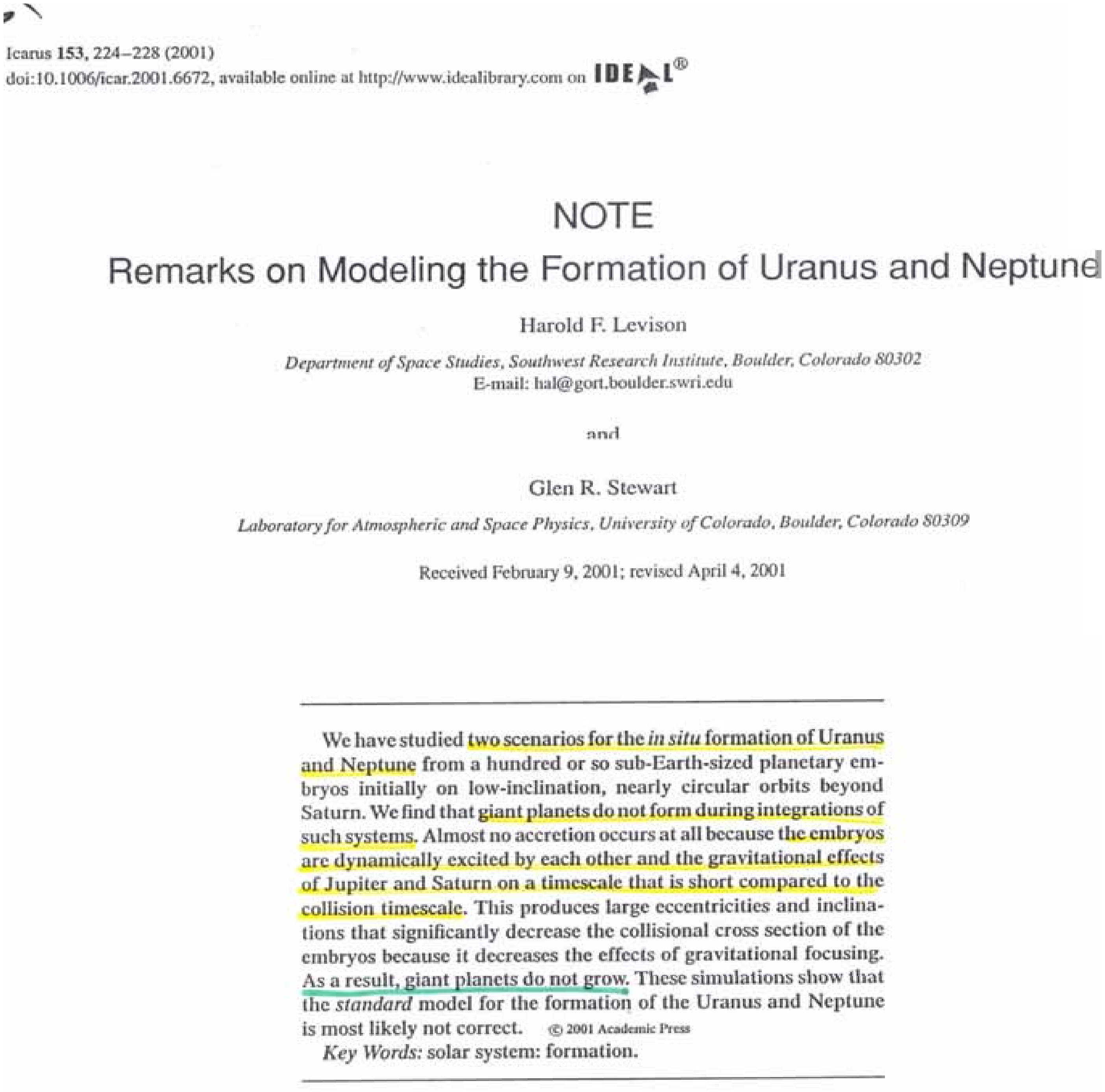
Rapid Convective Cooling? (Boss 2004)

- Radiative transfer is unable to cool disk midplanes on the dynamical time scale (a few rotational periods).
- Convective transport appears to be capable of cooling disk midplanes on the dynamical time scale.
- Evidence for convective transport includes Schwarzschild criterion for convection, convective cells seen in velocity vector fields, and calculations of the total vertical convective energy flux.
- Assuming that the surface can radiate away the disk's heat on a comparable time scale, marginally gravitationally unstable disks should be able to form giant protoplanets.

Habitable Planets per System
Chambers (2003)

[defined as terrestrial planets with masses greater that 1/3 that of Earth and Earth-like orbits]

Giant Planet System Configuration:	Giant Planet Formation Time:		
	0 Myr	3Myr	10Myr
Normal Jupiter and Saturn	1.0	0.6	0.7
Jupiter only, mass x 3	0.8	0.5	0.7
Jupiter only, eccentricity = 0.4	0.1	0.2	0.4
Jupiter & Saturn, both mass x 3	0.0	0.0	0.0
Jupiter normal, Saturn mass x 3	0.3	0.6	0.4
Jupiter & Saturn, both mass/3	0.8	0.9	0.9



Icarus **153**, 224–228 (2001)
doi:10.1006/icar.2001.6672, available online at http://www.idealibrary.com on IDEAL®

NOTE

Remarks on Modeling the Formation of Uranus and Neptune

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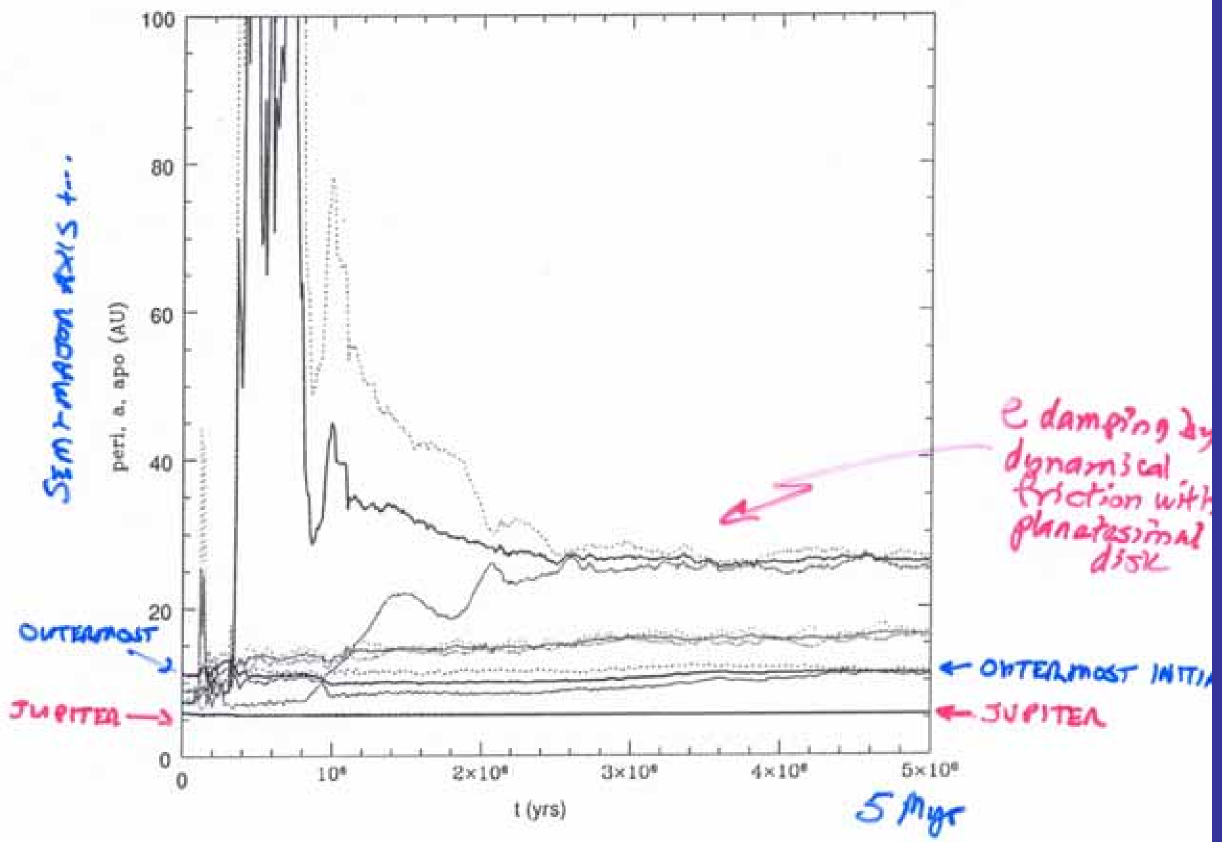
We have studied two scenarios for the *in situ* formation of Uranus and Neptune from a hundred or so sub-Earth-sized planetary embryos initially on low-inclination, nearly circular orbits beyond Saturn. We find that giant planets do not form during integrations of such systems. Almost no accretion occurs at all because the embryos are dynamically excited by each other and the gravitational effects of Jupiter and Saturn on a timescale that is short compared to the collision timescale. This produces large eccentricities and inclinations that significantly decrease the collisional cross section of the embryos because it decreases the effects of gravitational focusing. As a result, giant planets do not grow. These simulations show that the *standard* model for the formation of the Uranus and Neptune is most likely not correct.

Key Words: solar system: formation.

THOMMES, DUNCAN, & LEVISON (2002)



SEMI-MAJOR AXIS +..

OUTERMOST

JUPITER →

e damping by dynamical friction with planetesimal disk

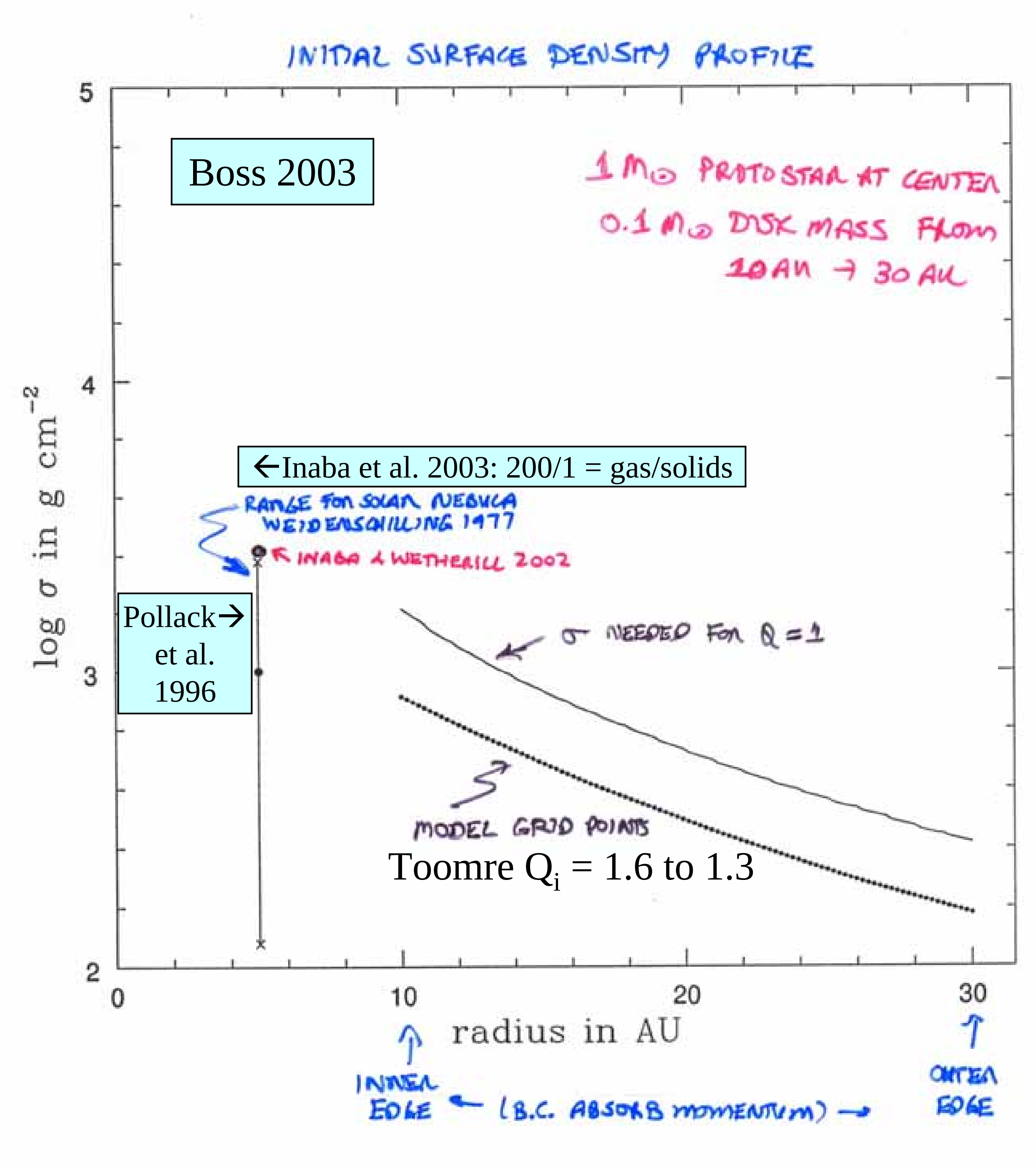
← OUTERMOST INITI

← JUPITER

5 Myr

Fig. 4.— Run 1F: Evolution of semimajor axis (bold lines), perihelion distance q (thin lines) and aphelion distance Q (dotted lines) of the four 10 $M_\oplus$ protoplanets. The protoplanet which grows to Jupiter mass (314 $M_\oplus$) over the first 10^5 years of simulation time is shown in black.

(NO INTERACTIONS WITH DISK GAS — NO TIDAL TORQUES)



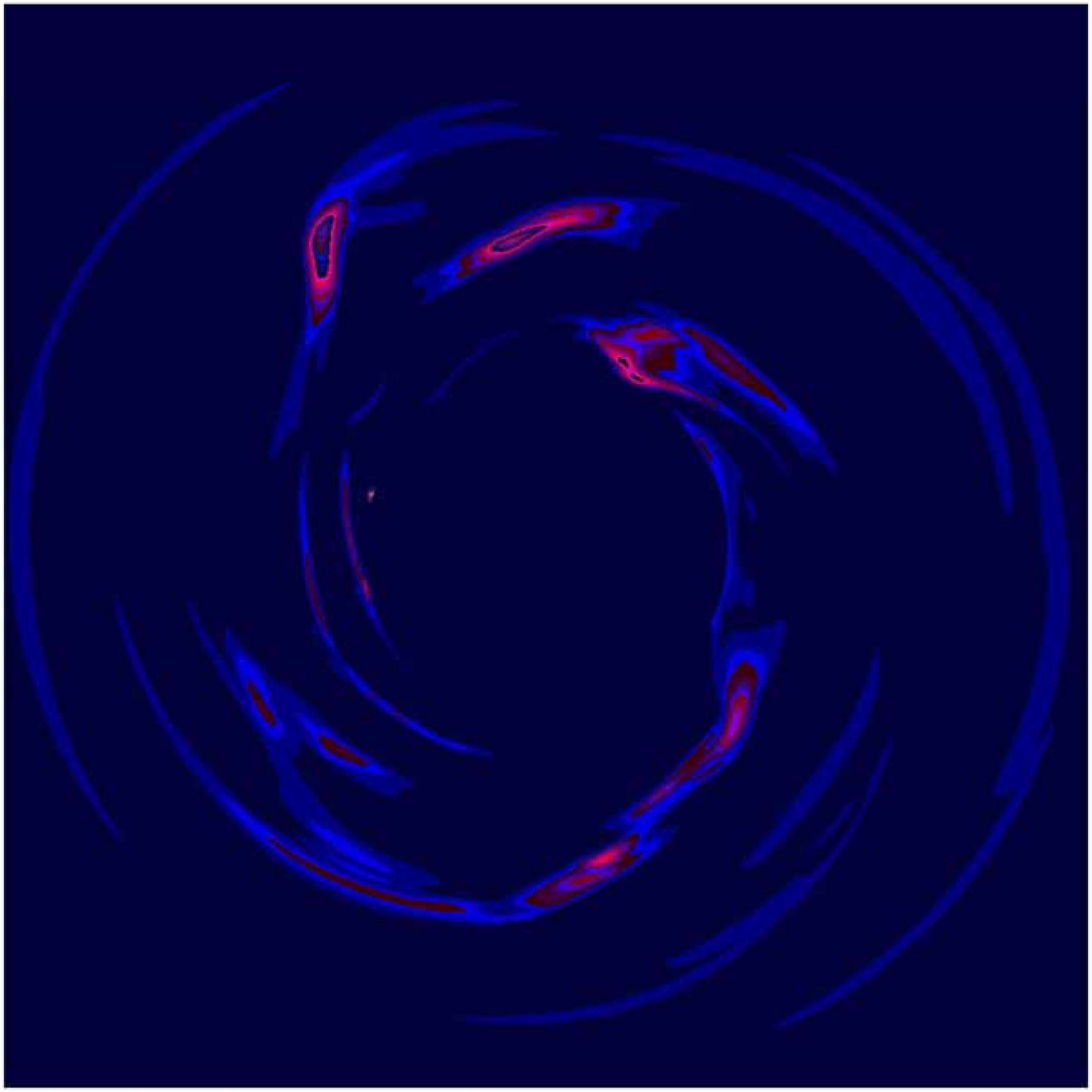
Boss 2003

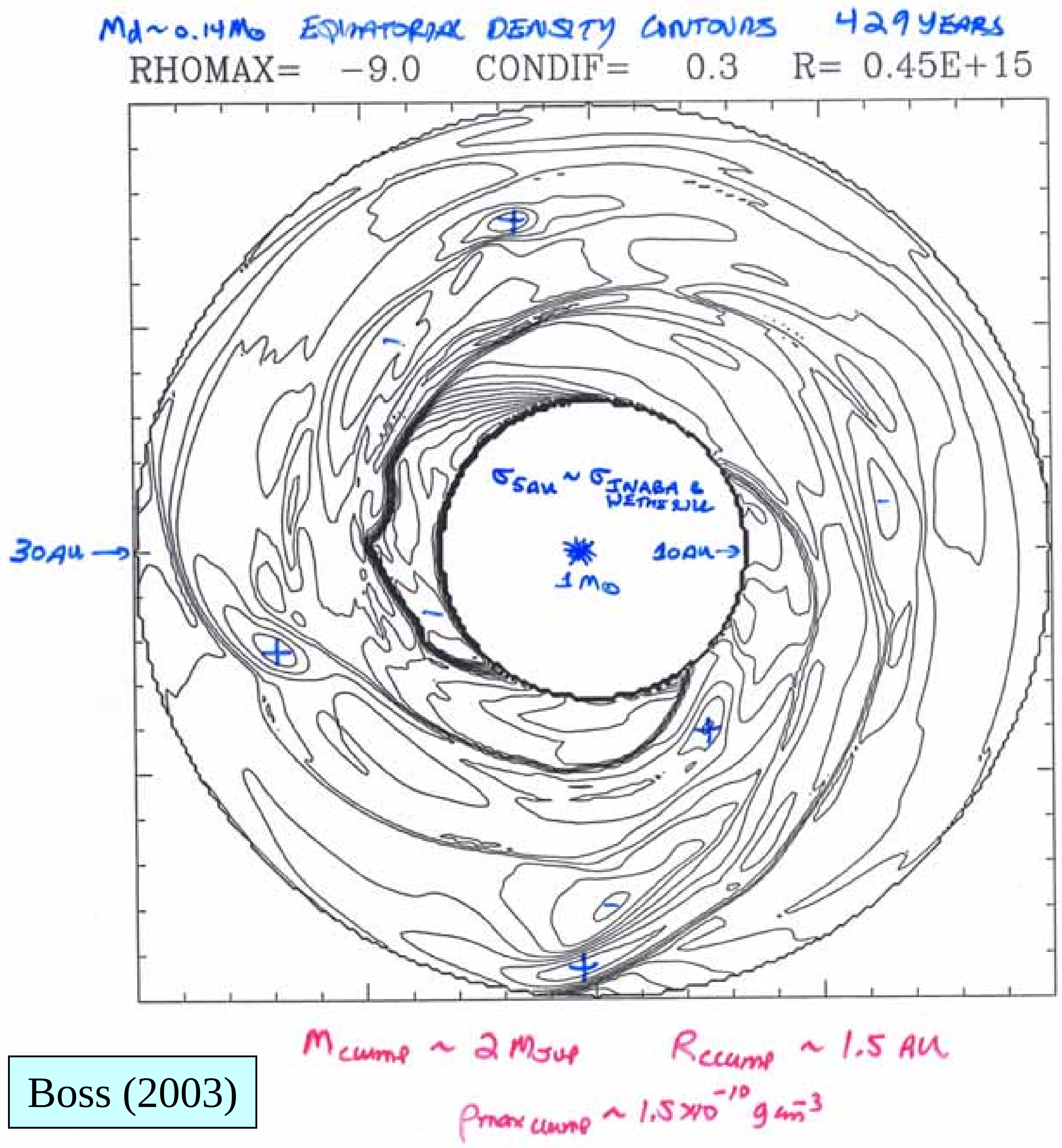
←Inaba et al. 2003: 200/1 = gas/solids

Pollack→
et al.
1996

Toomre Q_i = 1.6 to 1.3

Boss (2003) disk instability model after 429 yrs, 30 AU radius



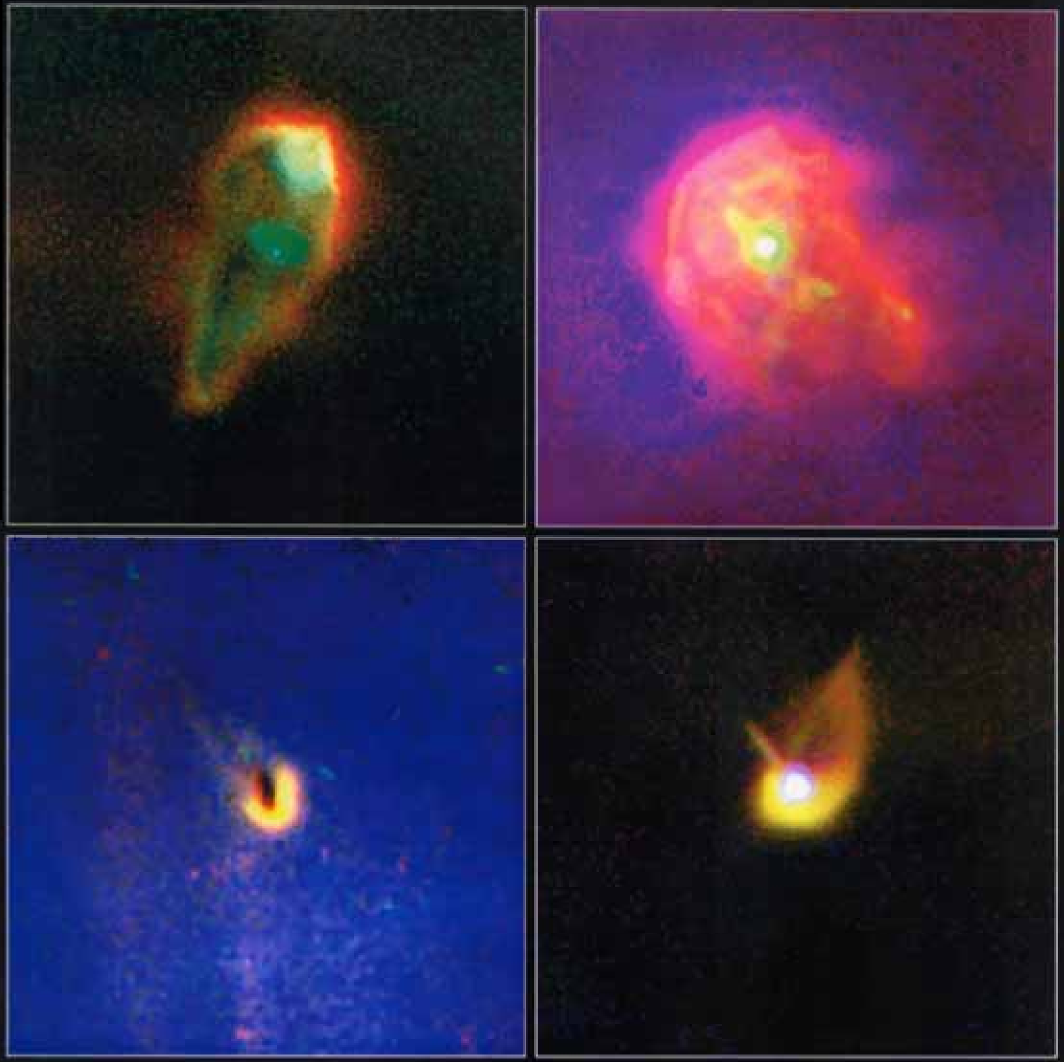

$M_d \sim 0.14 M_\odot$ EQUATORIAL DENSITY CONTOURS 429 YEARS
RHOMAX= −9.0 CONDIF= 0.3 R= 0.45E+15
30AU →
$\sigma_{5AU} \sim \sigma_{\text{INABA \& WETHERILL}}$
10AU →
$1 M_\odot$
+
−
$M_{clump} \sim 2 M_{Jup}$
$R_{clump} \sim 1.5$ AU
$\rho_{max\ clump} \sim 1.5 \times 10^{-10}$ g cm^{-3}

Boss (2003)

A new paradigm for forming the giant planets rapidly:

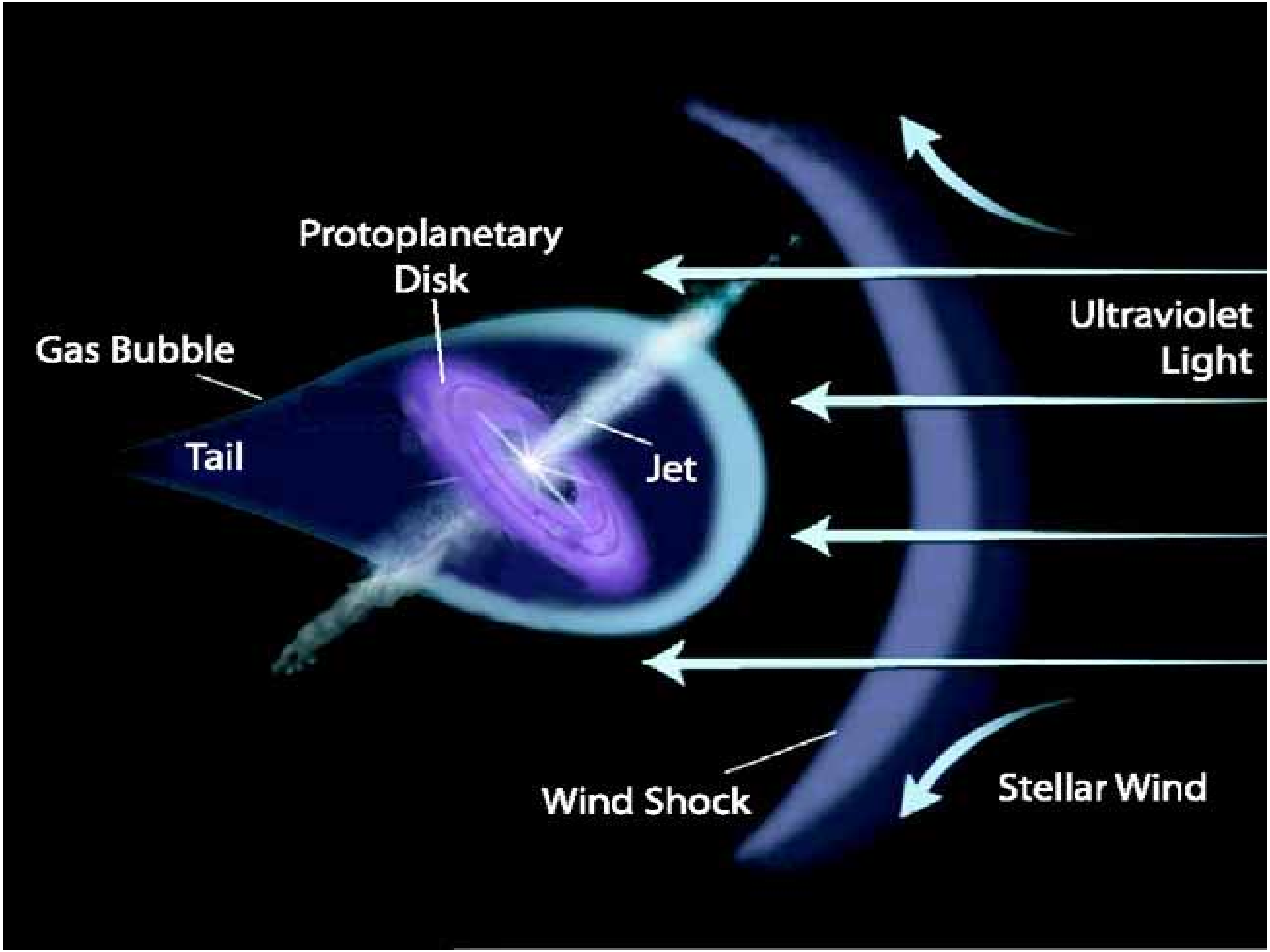
- Marginally gravitationally-unstable protoplanetary disk forms four or more giant gaseous protoplanets within about 1000 years, each with masses of about 1 to 3 Jupiter-masses
- Dust grains coagulate and sediment to centers of the protoplanets, forming solid cores on similar time scale, with core masses of no more than about 6 Earth-masses per Jupiter-mass of gas and dust (Z=0.02)
- Disk gas beyond Saturn’s orbit is removed in a million years by ultraviolet radiation from a nearby massive star (Orion, Carina, ...)

Continued…

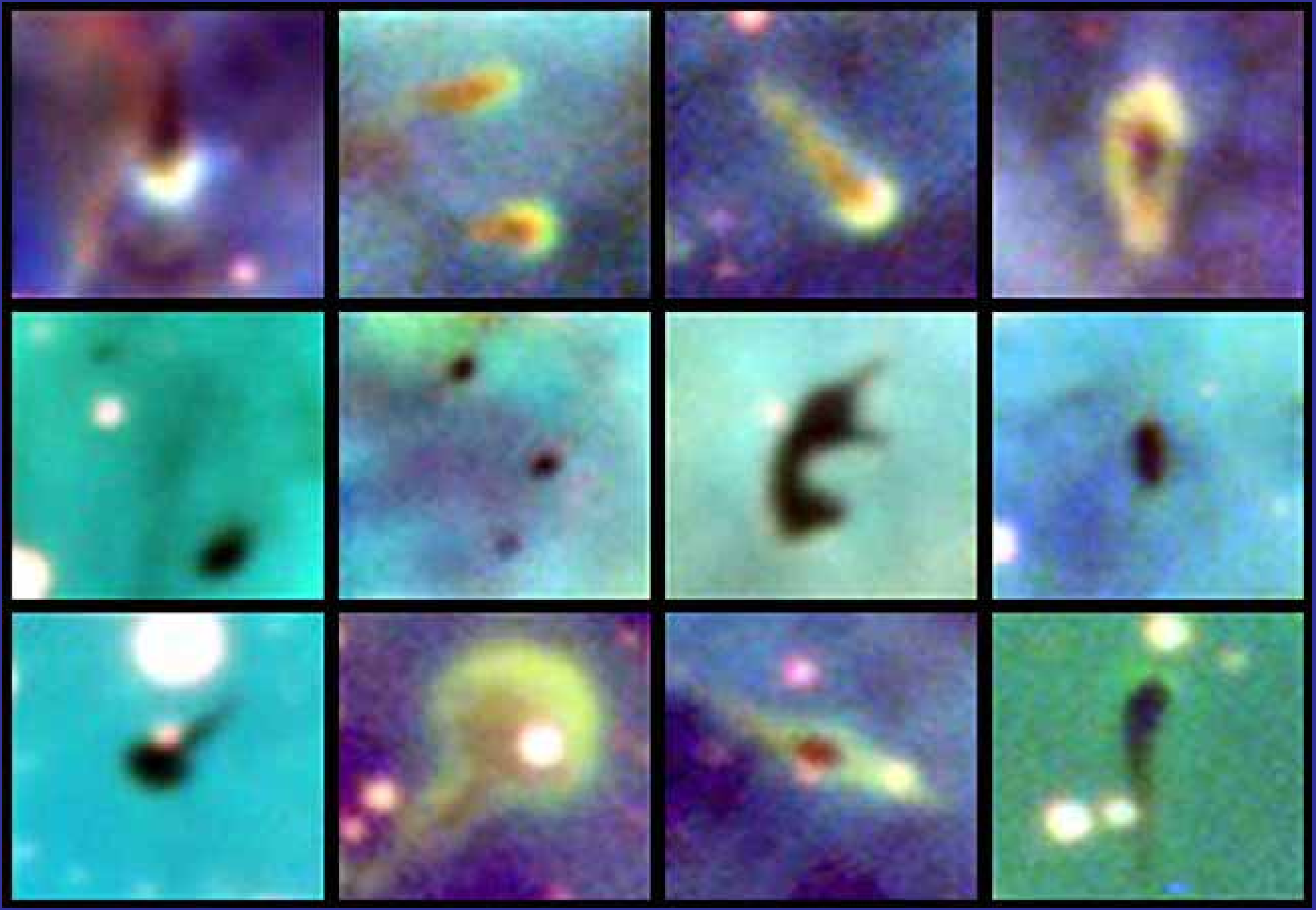


Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13

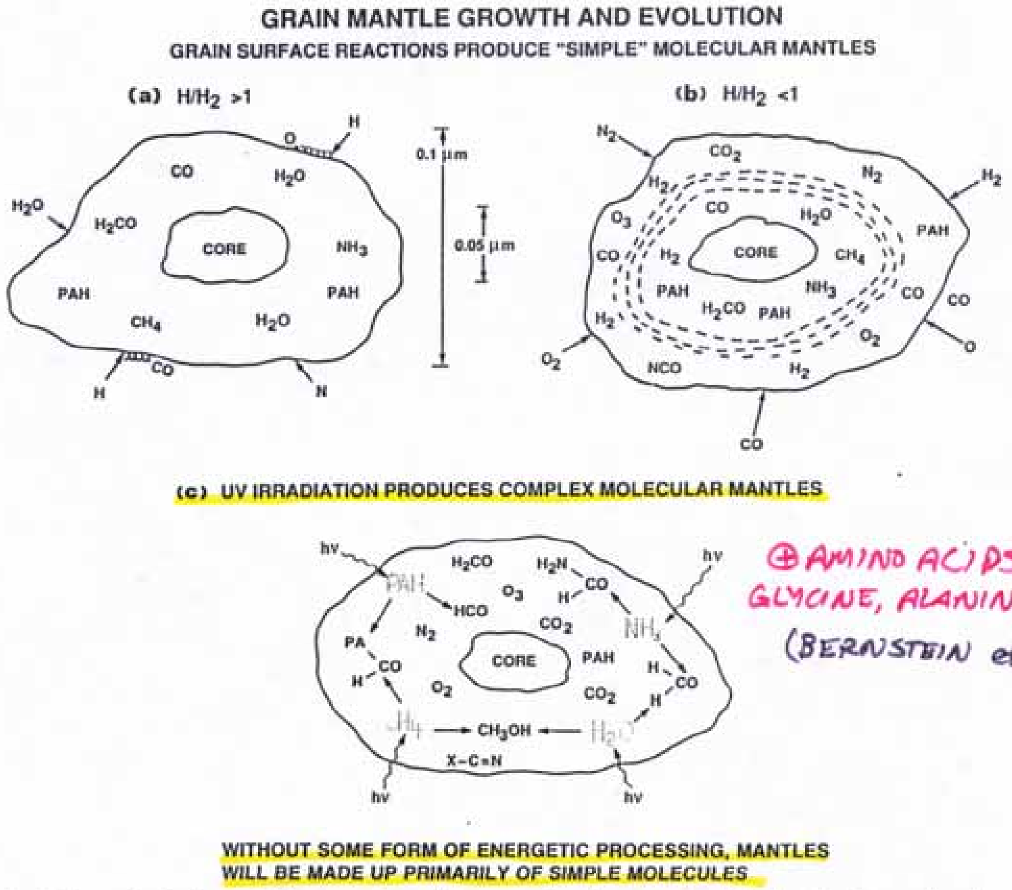

Protoplanetary
Disk
Gas Bubble
Ultraviolet
Light
Tail
Jet
Wind Shock
Stellar Wind

- Outermost protoplanets are exposed to FUV/EUV radiation, which photoevaporates most of their envelope gas in about a million years or less
- Outermost planets’ gas removal leads to roughly 15-Earth-mass solid cores with thin gas envelopes: Uranus, Neptune
- Innermost protoplanet is sheltered by disk H gas gravitationally bound to solar-mass protosun and so does not lose any gas: Jupiter
- Protoplanet at transitional gas-loss radius loses only a portion of its gas envelope: Saturn
- Terrestrial planet region largely unaffected by UV radiation



Carina Nebula protoplanetary disks

Sandford (1996) Inventory of interstellar materials available for formation of the solar system

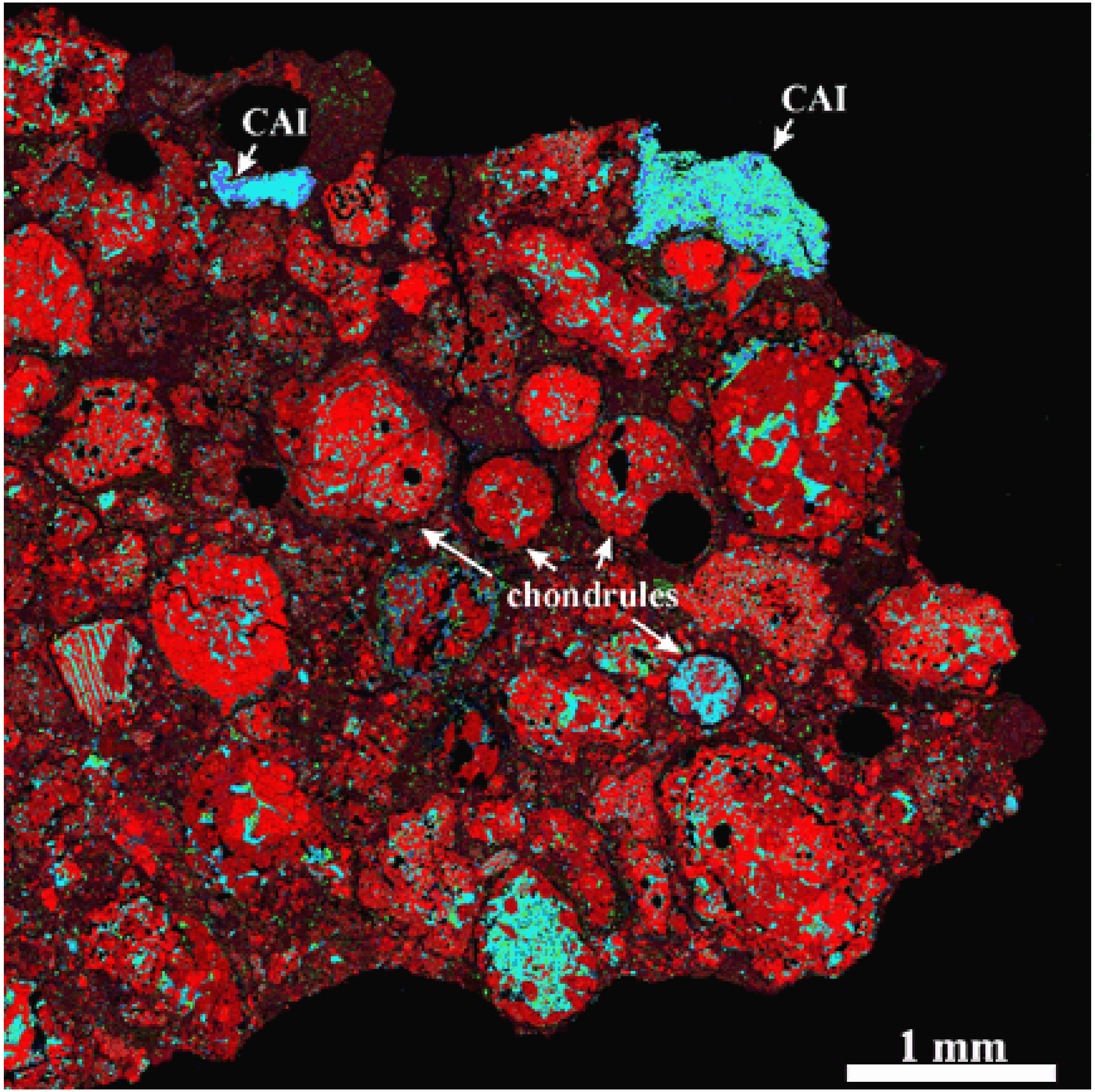


⊕ AMINO ACIDS: GLYCINE, ALANINE, SERINE,..

(BERNSTEIN et al. 2002)

FIG. 4. Schematic drawings of the types of mantles expected to be present on the dust in dense molecular clouds. (a) In regions where the local H/H_2 ratio is large, various atomic and molecular species will accrete from the gas phase. Accreted H is sufficiently mobile that it can "hop" along the surface of the grain and react with other accreted atoms and molecules. As a result, simple hydrides like CH_4, NH_3, and H_2O will dominate. (b) In contrast, low H/H_2 ratios result in the production of mantles rich in H-deficient species like CO, O_2, and N_2. (c) Irradiated and thermal processing of ice mantles creates more complex molecular species and can result in the production of more refractory "organic" mantles.

PCA 91082



(Alexander Krot, University of Hawaii)

CANONICAL SHOCK SPEED = 7 Km s^{-1}

DESCH AND CONNOLLY (2002)

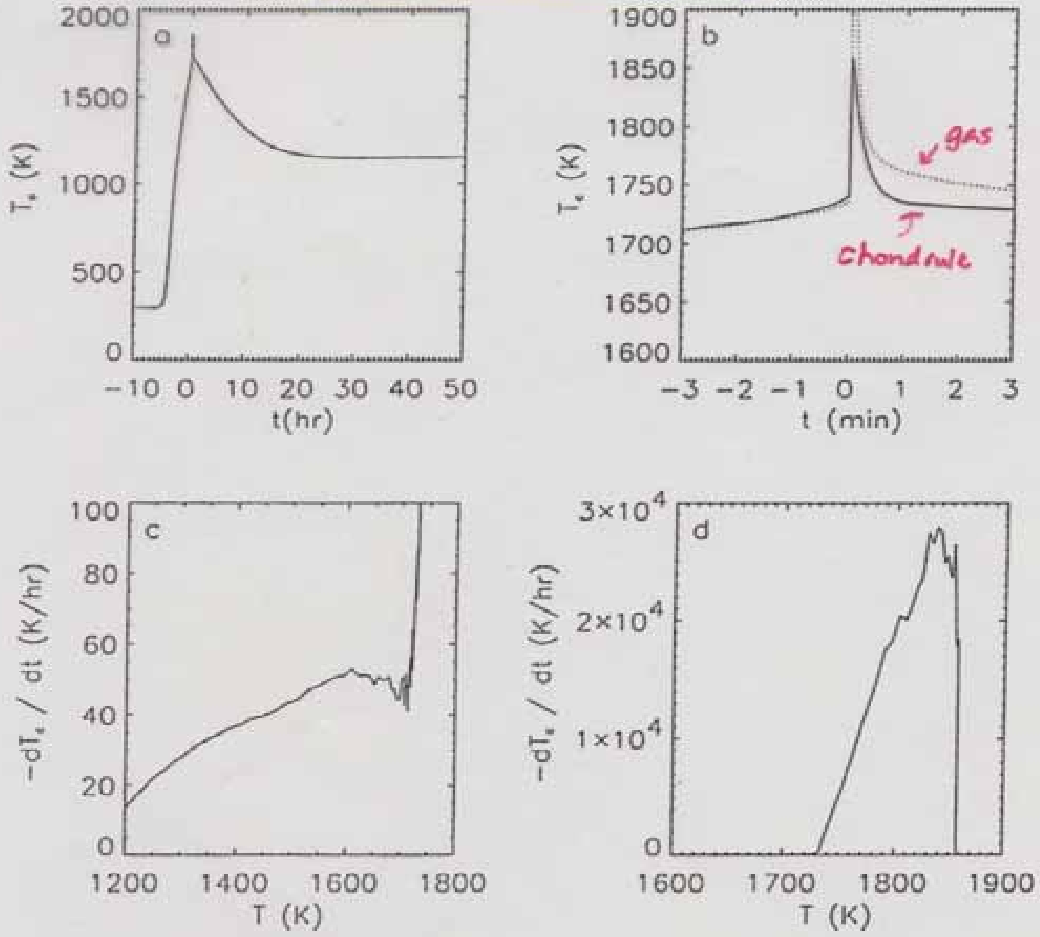
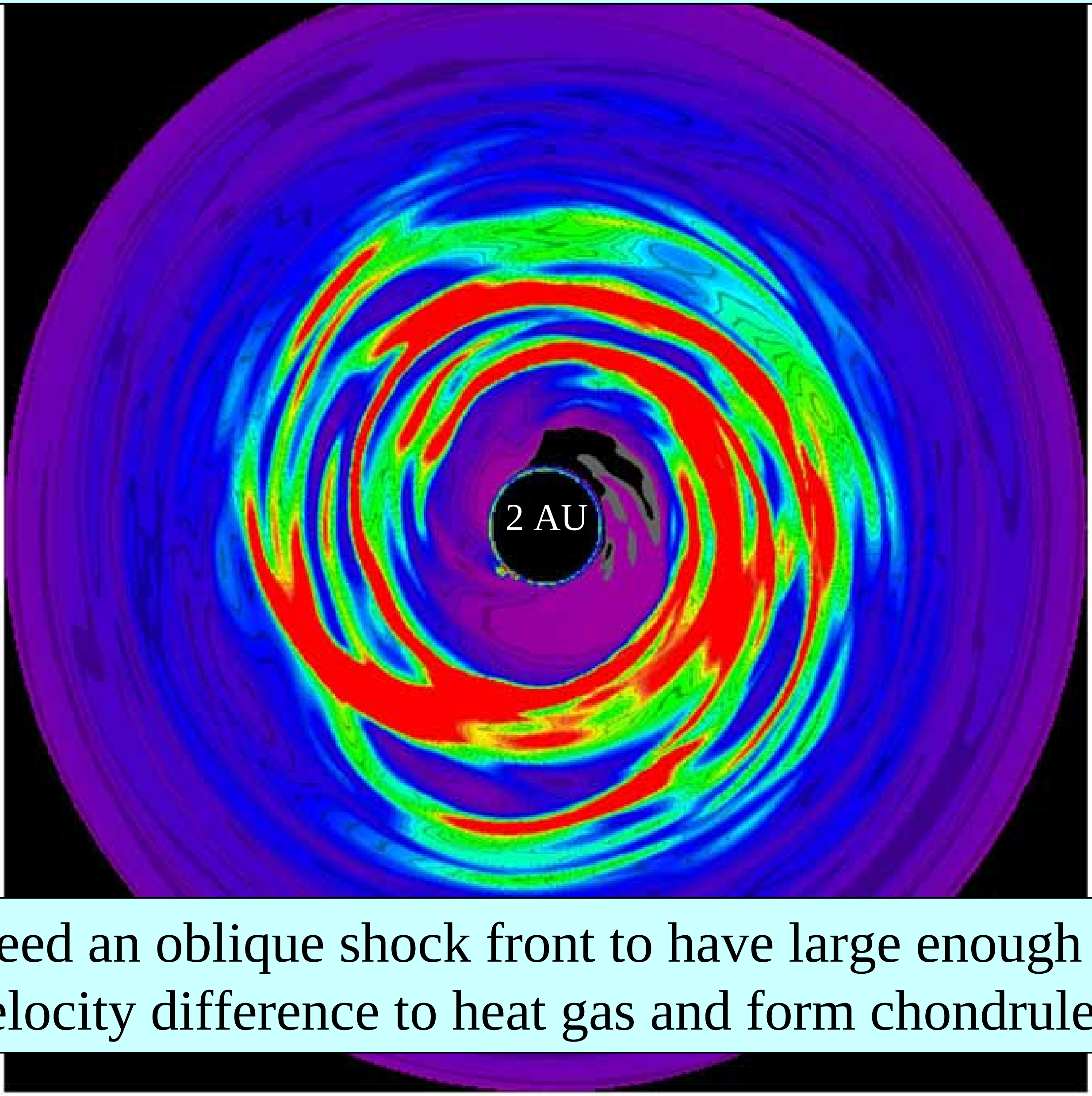


FIG. 4. Thermal history of chondrule in canonical shock. The chondrule's temperature (solid line) over the course of hours (a), and also minutes (b), where it is contrasted with the temperature of the gas (dotted line). Chondrules in the pre-shock region are heated by radiation, reaching 1000 K at 170 min before they reach the shock front. The cooling rates of the chondrules as a function of temperature are much slower through the crystallization temperatures 1400–1730 K (c) than at the higher temperatures 1730–1860 K (d), when heating is dominated by gas drag.

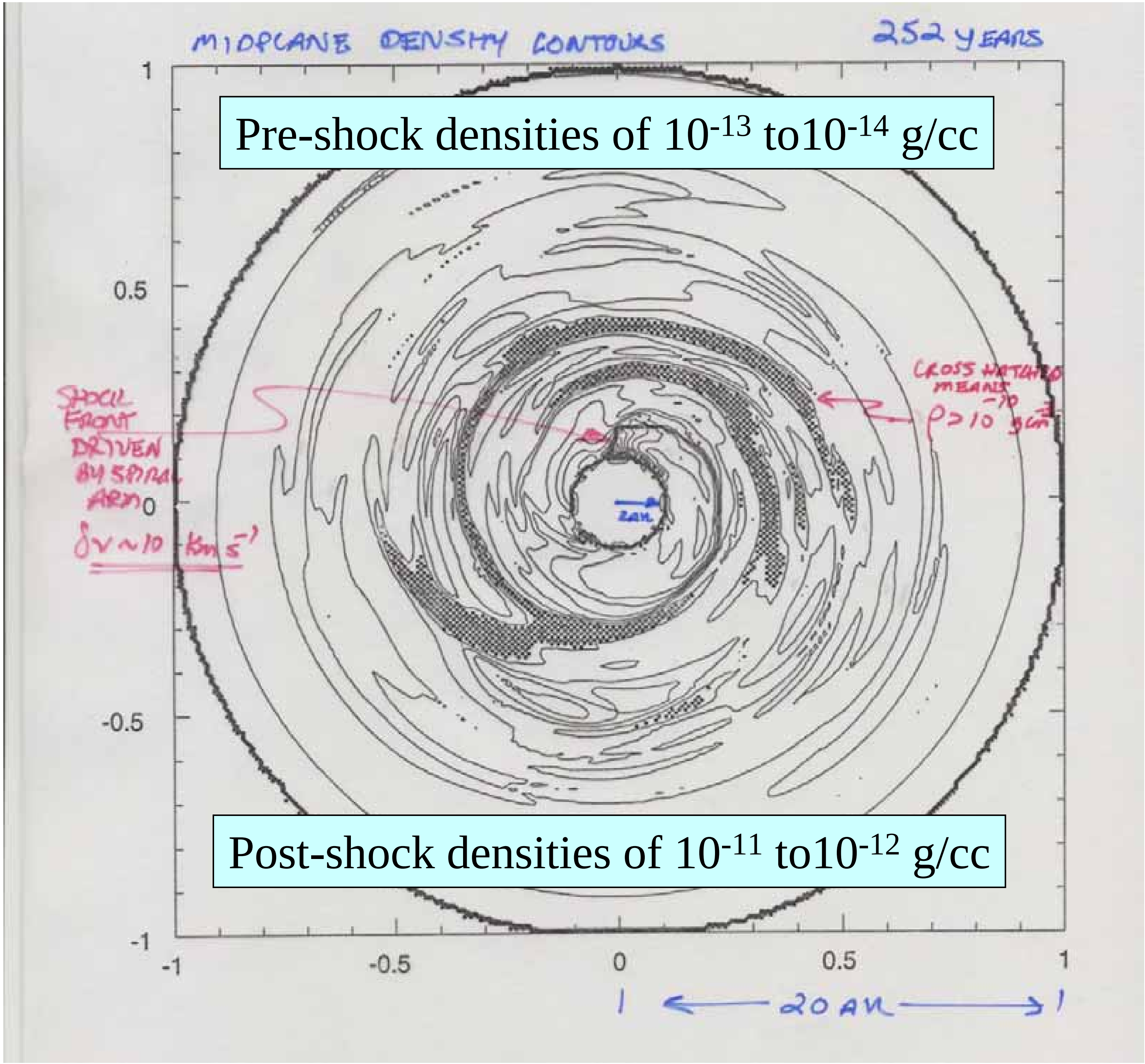
SUCCESSFULLY MATCHES: ① COOLING RATES ② TEXTURES ③ COMPOUND CHONDRULES ④ MAGNETISM

20 AU radius disk, 0.09 solar masses, radiative transfer



Need an oblique shock front to have large enough velocity difference to heat gas and form chondrules

Pre-shock densities of 10^{-13} to10^{-14} g/cc

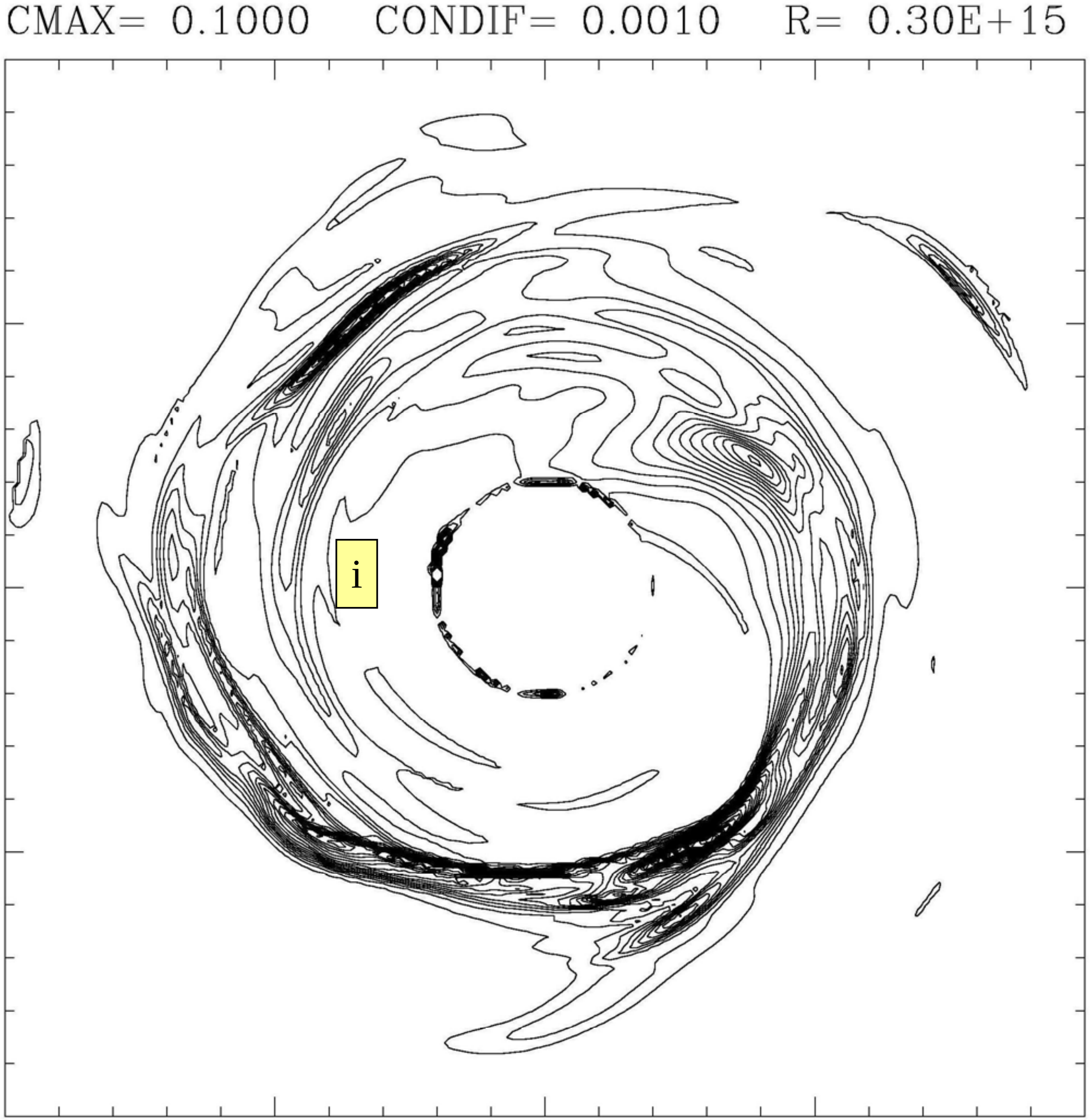


Post-shock densities of 10^{-11} to10^{-12} g/cc

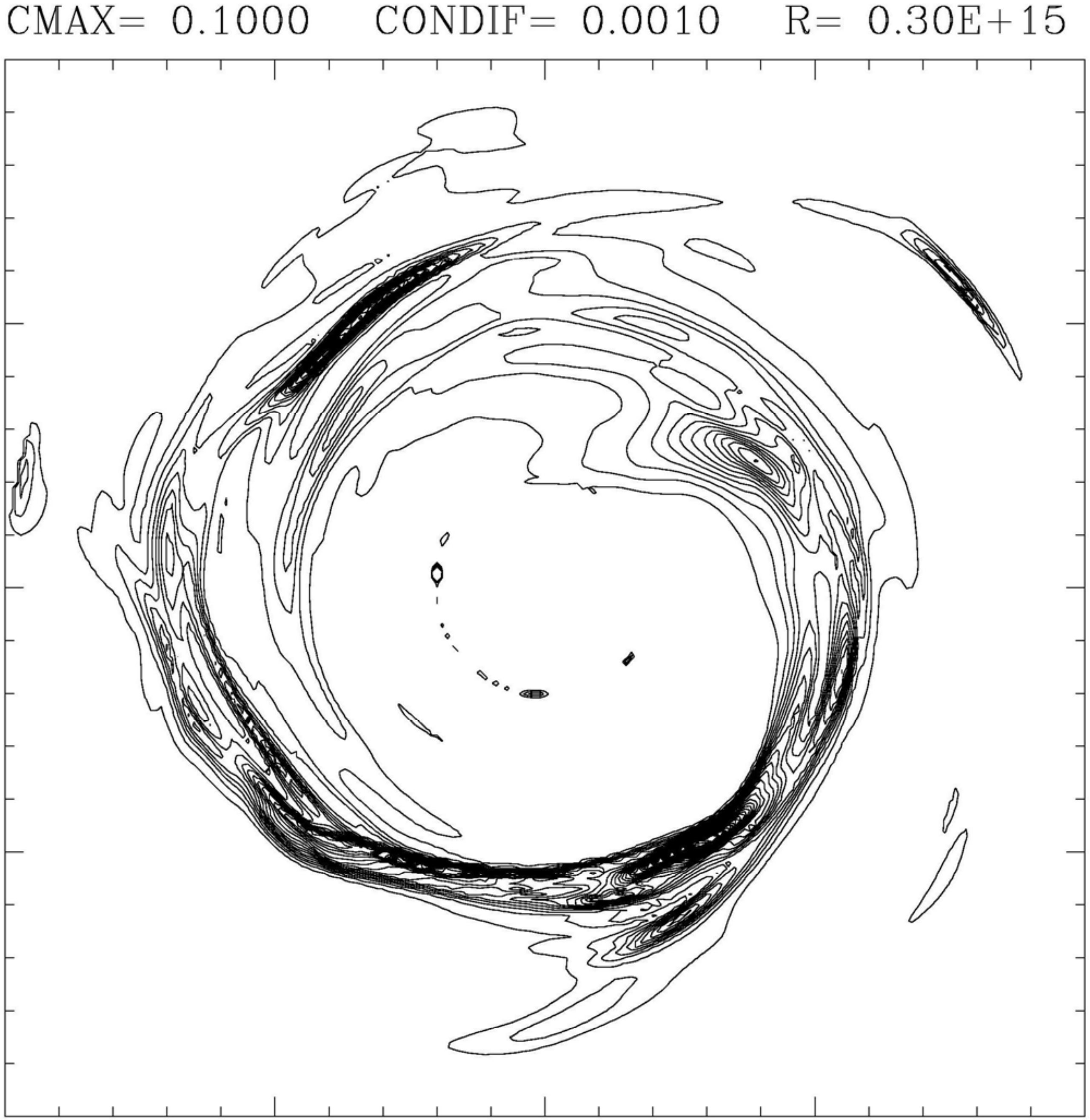
Mixing and Transport of Chondrules and CAIs in the Solar Nebula

- Assembling the chondrites appears to require the outward transport of the CAIs from the inner nebula to the asteroidal region.
- Outward transport of CAIs could be via X-wind above the disk or via gas motions within a marginally gravitationally unstable disk.
- Explaining the thermal annealing of crystalline silicates observed in comets and protoplanetary disks may require inward and outward transport over significant distances in the disk.
- Can solids in a gravitationally unstable disk be transported inward or outward through the region of maximum gravitational instability, or does this unstable region present a barrier to large-scale transport?

6 AU
$\alpha = 0.01$
757 yrs



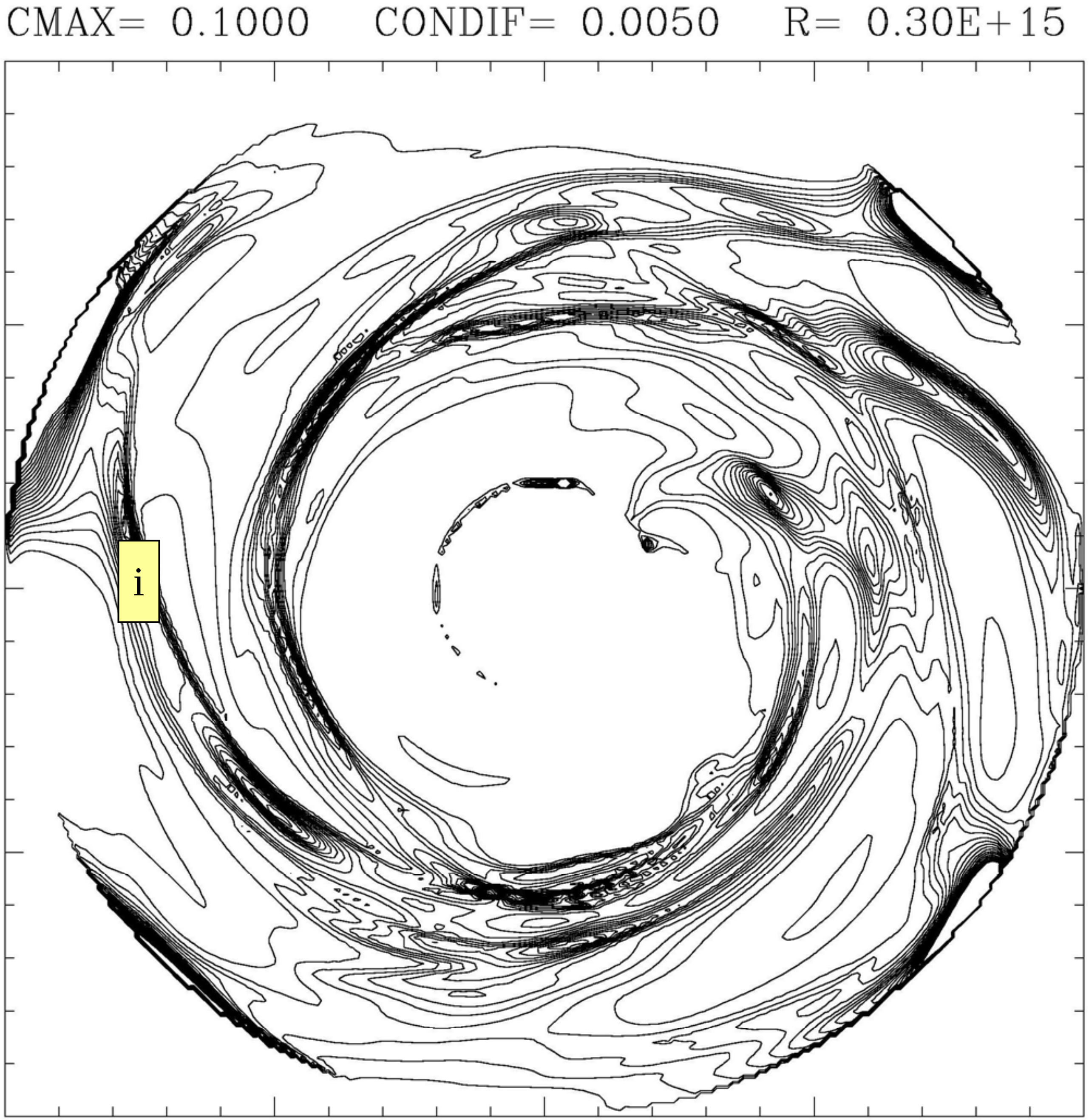
20 AU
radius
disk



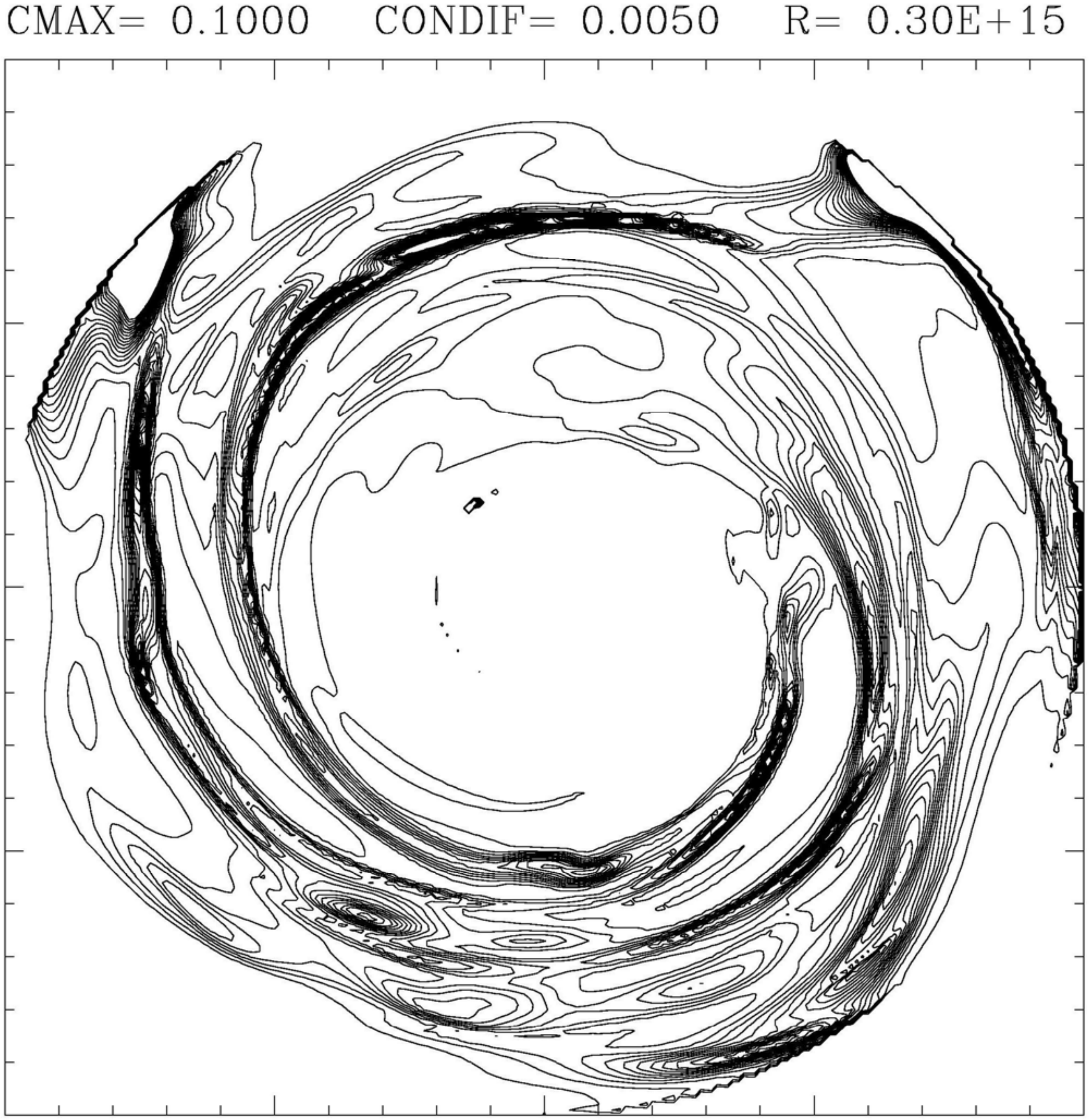
6 AU
$\alpha = 0.0001$
757 yrs

20 AU
radius
disk

15 AU
$\alpha = 0.01$
757 yrs

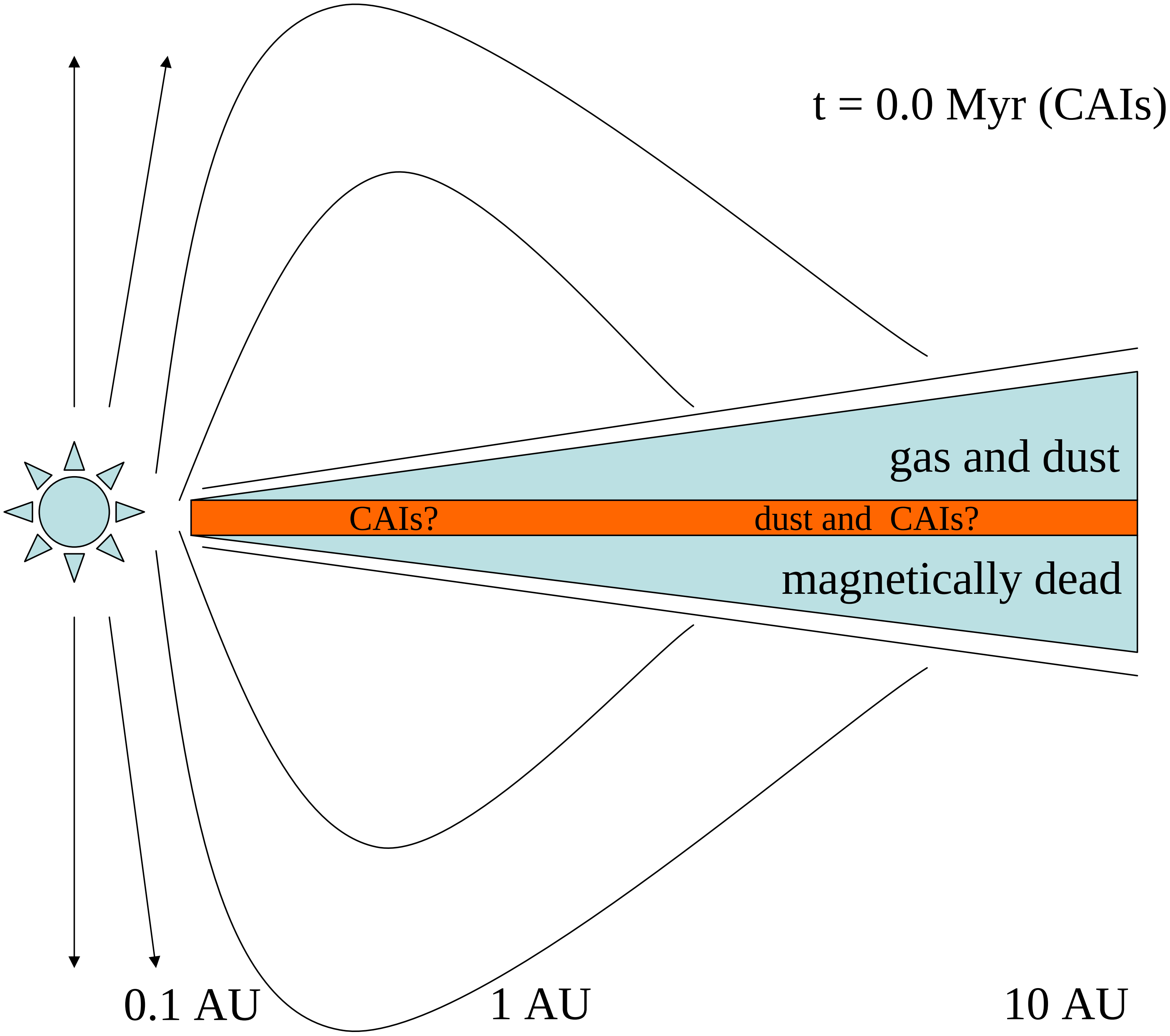


20 AU
radius
disk



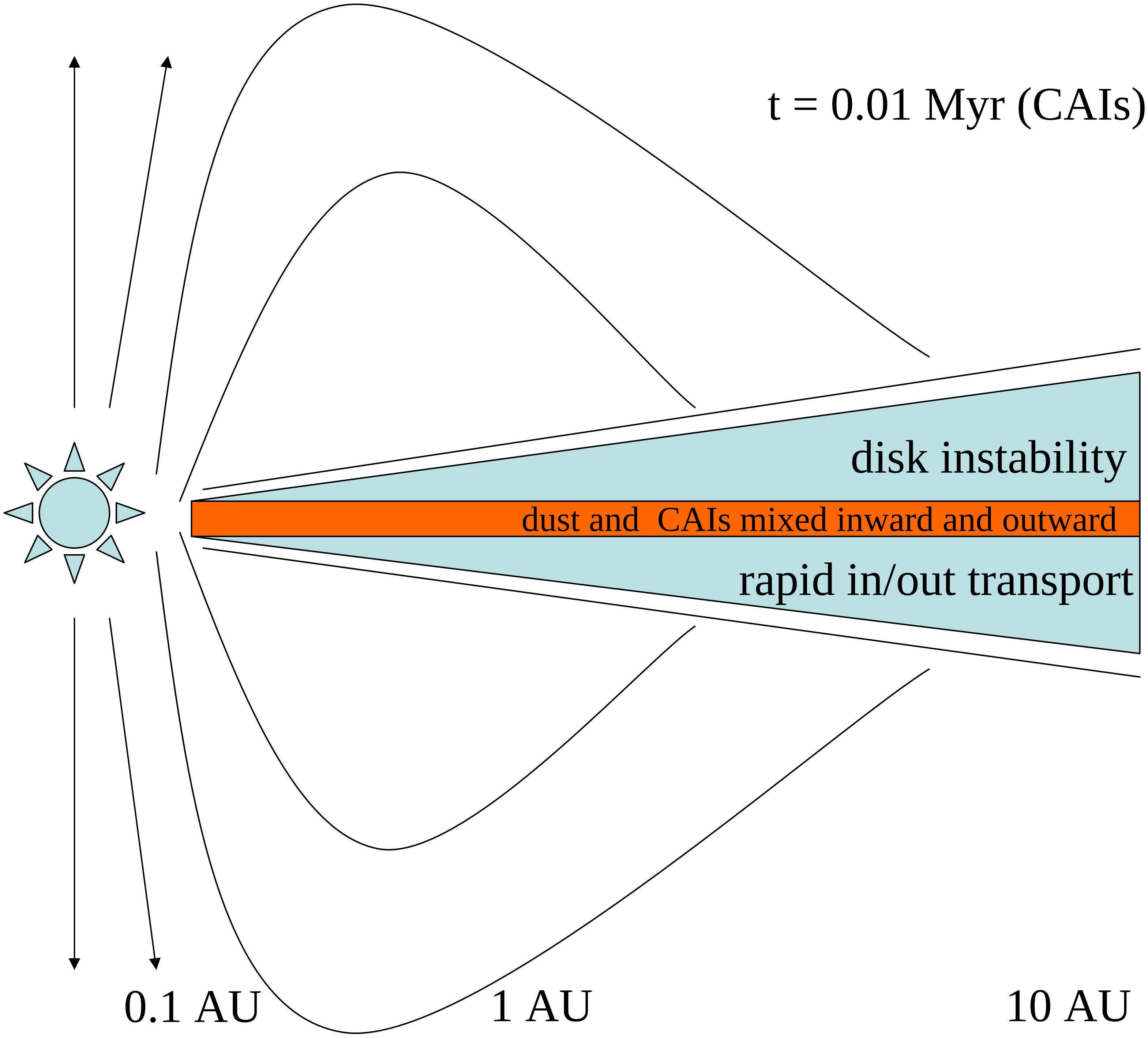
15 AU
$\alpha = 0.0001$
757 yrs

20 AU
radius
disk



t = 0.0 Myr (CAIs)

gas and dust
CAIs?
dust and CAIs?
magnetically dead
0.1 AU
1 AU
10 AU



t = 0.01 Myr (CAIs)

disk instability

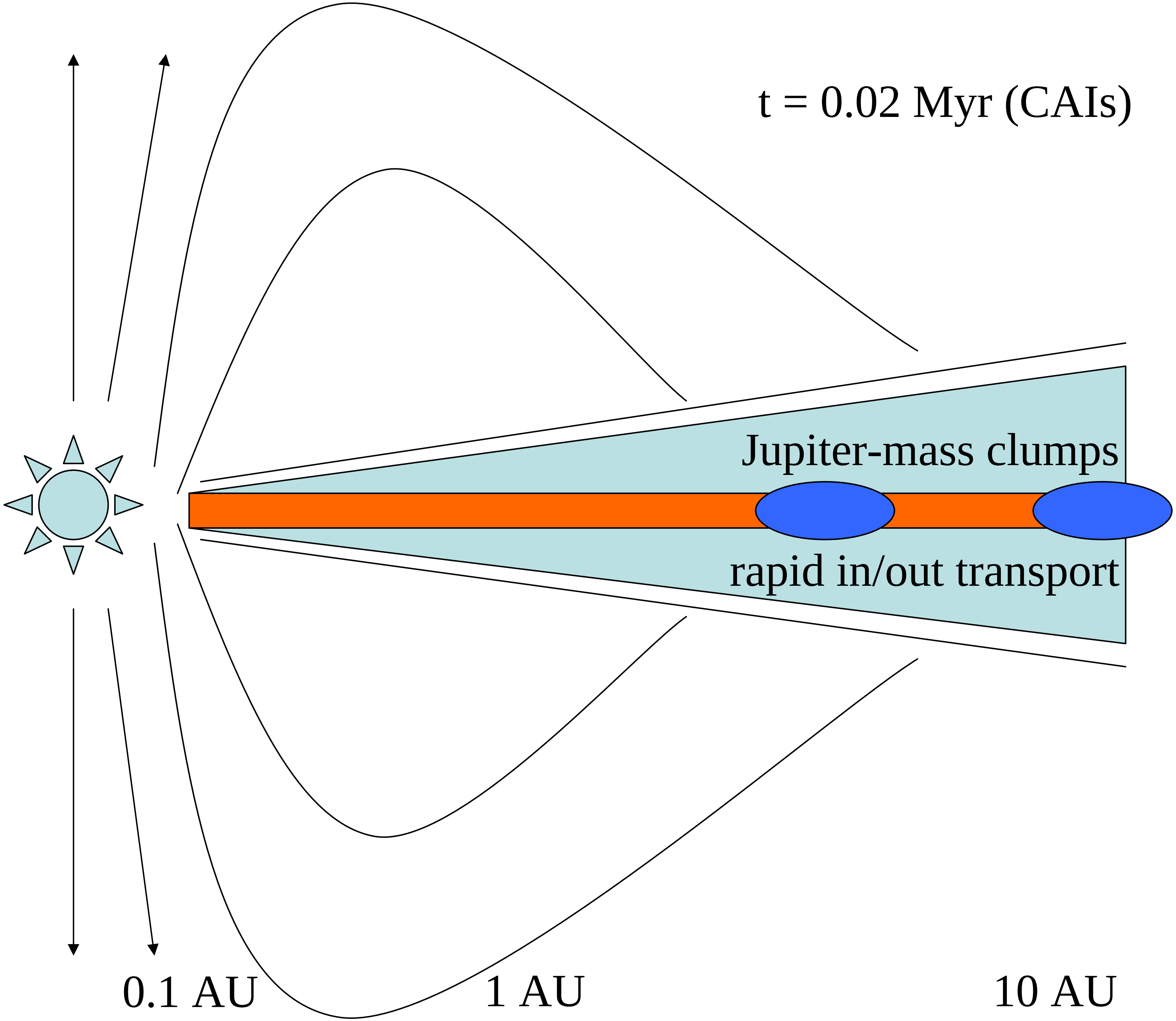
dust and CAIs mixed inward and outward

rapid in/out transport

0.1 AU

1 AU

10 AU



t = 0.02 Myr (CAIs)

Jupiter-mass clumps

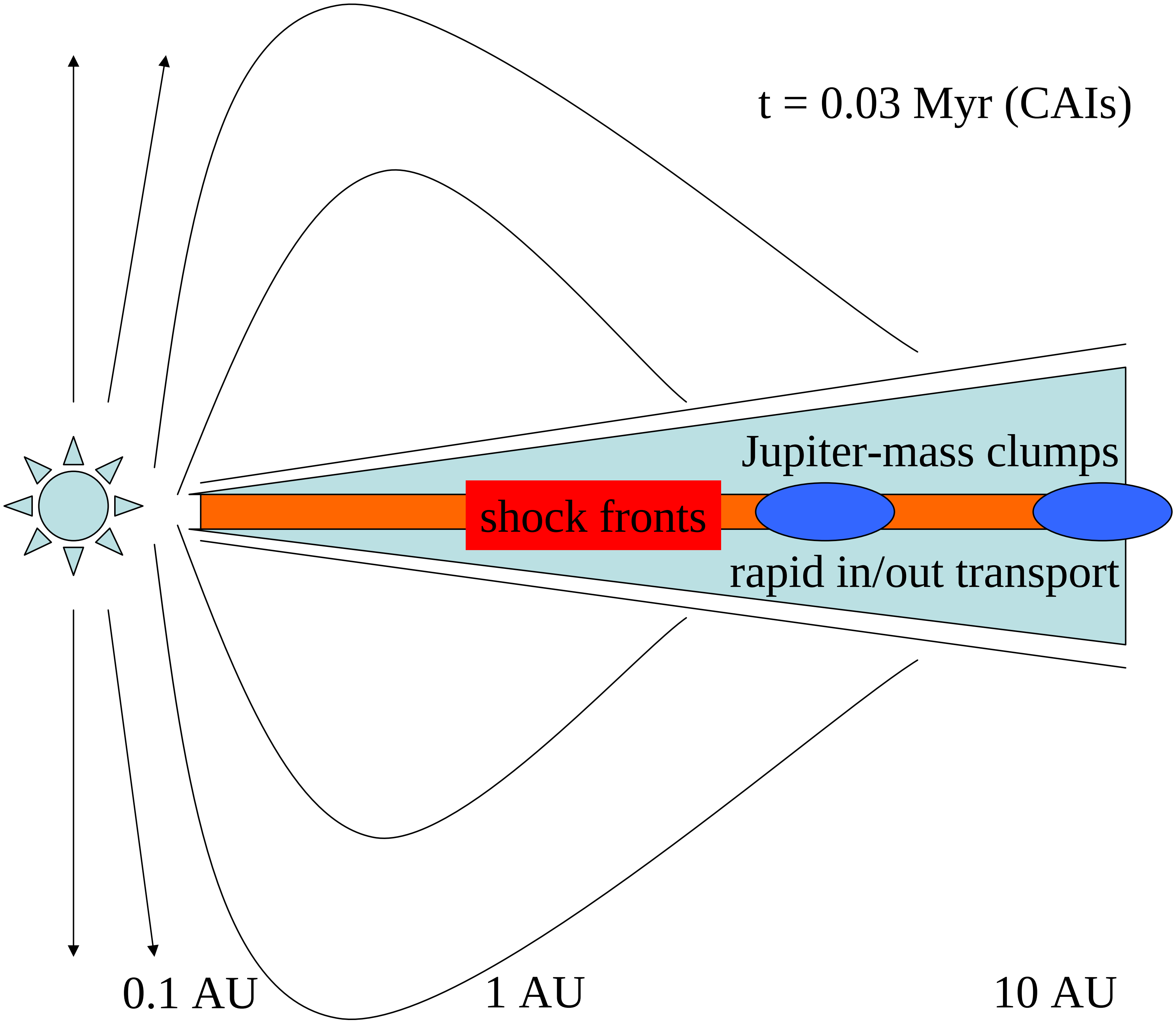
rapid in/out transport

0.1 AU

1 AU

10 AU

t = 0.03 Myr (CAIs)



Jupiter-mass clumps

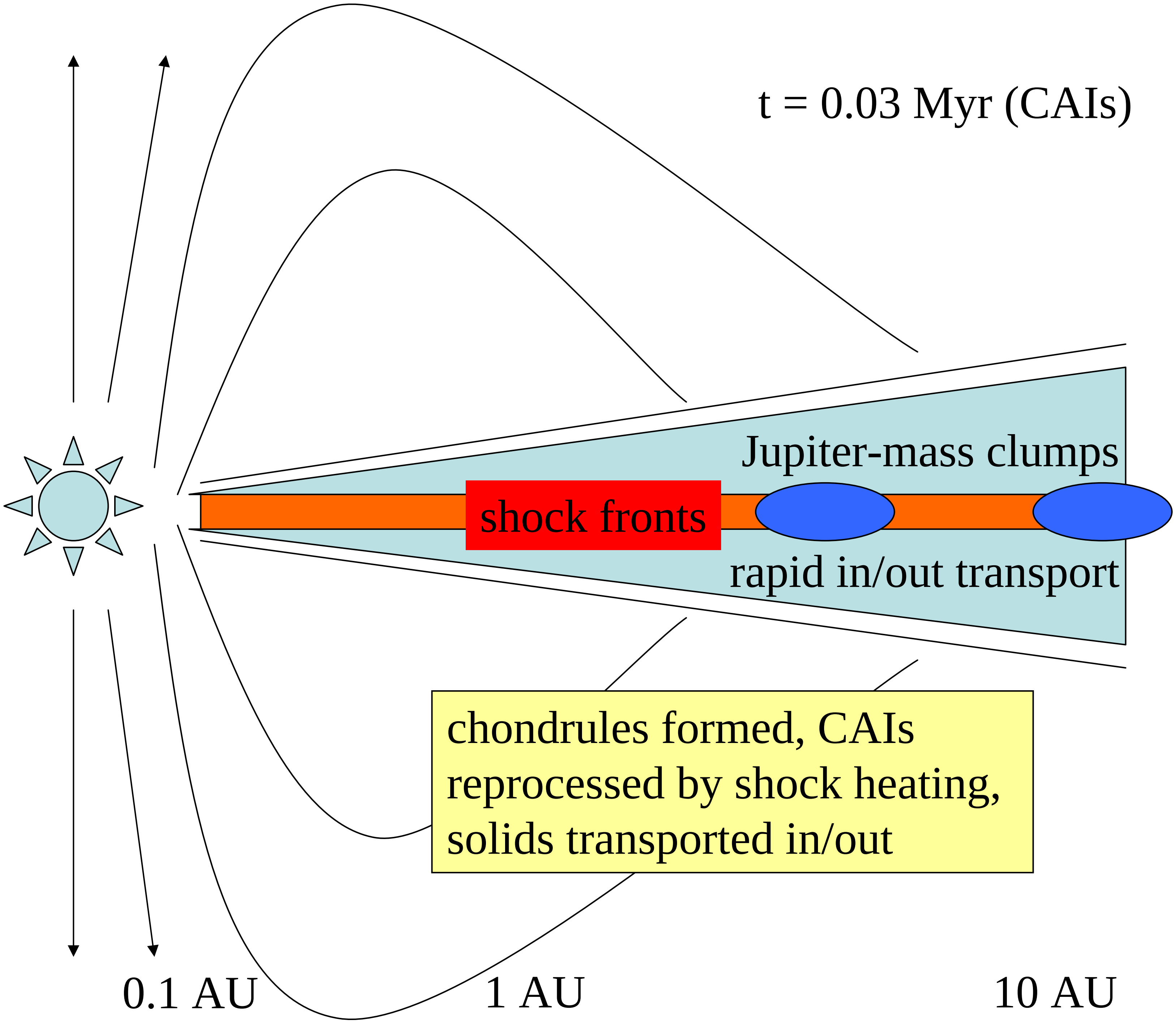
shock fronts

rapid in/out transport

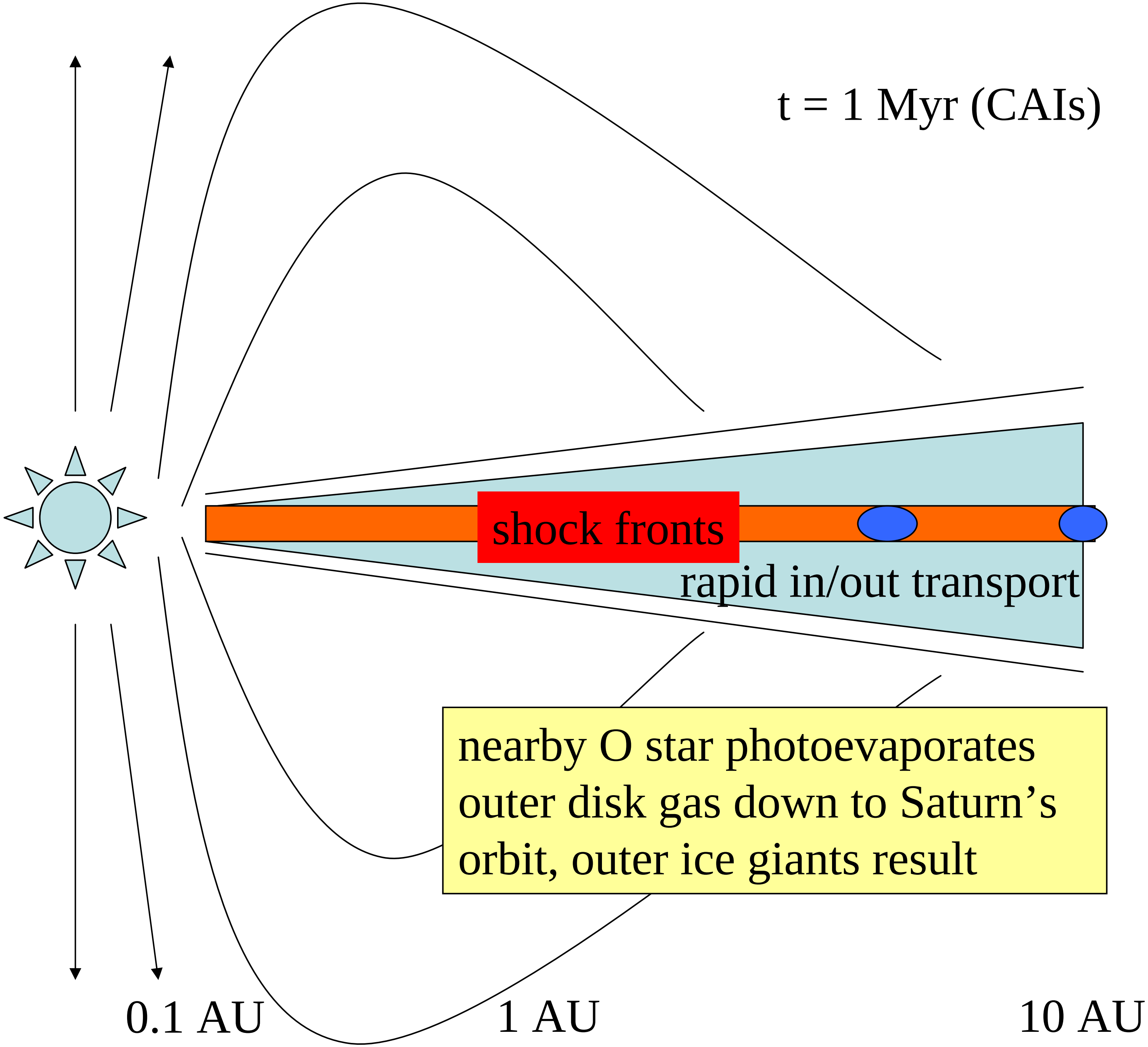
0.1 AU

1 AU

10 AU



chondrules formed, CAIs reprocessed by shock heating, solids transported in/out

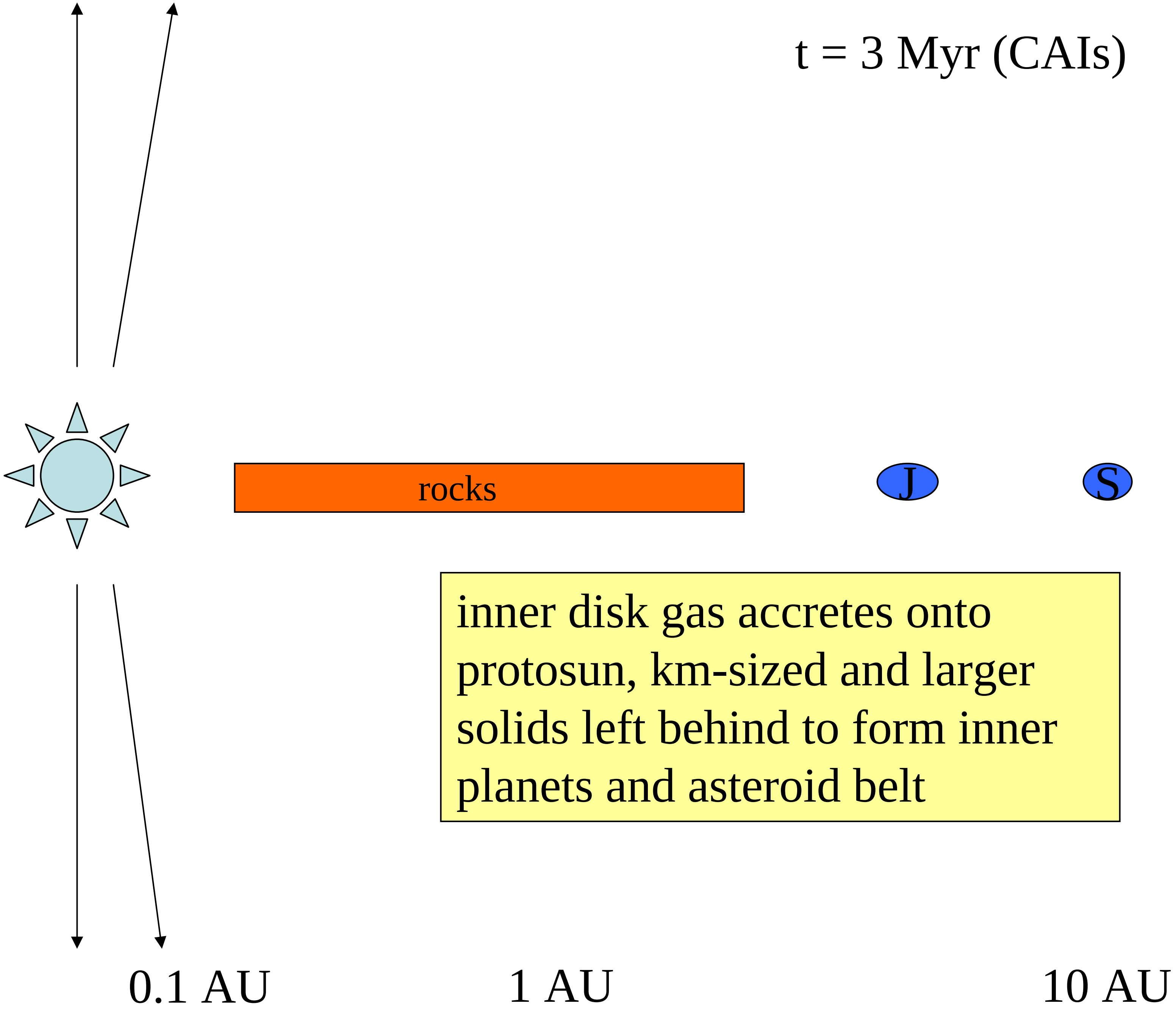


t = 1 Myr (CAIs)

shock fronts

rapid in/out transport

nearby O star photoevaporates outer disk gas down to Saturn’s orbit, outer ice giants result t = 3 Myr (CAIs)



inner disk gas accretes onto protosun, km-sized and larger solids left behind to form inner planets and asteroid belt

Formation of Planetary Systems I.: Theory vs. Theory

- Disk instability can form gas and ice giant planets in the shortest-lived protoplantary disks
- Terrestrial planet formation through collisional accumulation is permitted and even accelerated
- Implies that Solar System may have formed in a massive-star-forming region, e.g., Orion, where most stars form
- Giant planet formation leads naturally to shock fronts at 2.5 AU that are capable of forming the chondrules
- Strong UV fluxes form complex organic mantles on ice grains and icy planetesimals through photochemistry
- Headstart for prebiotic chemistry — formation of amino acids at an early phase of evolution
- Consistent with general belief that planetary systems similar to our own need not be rare — and neither need be life?