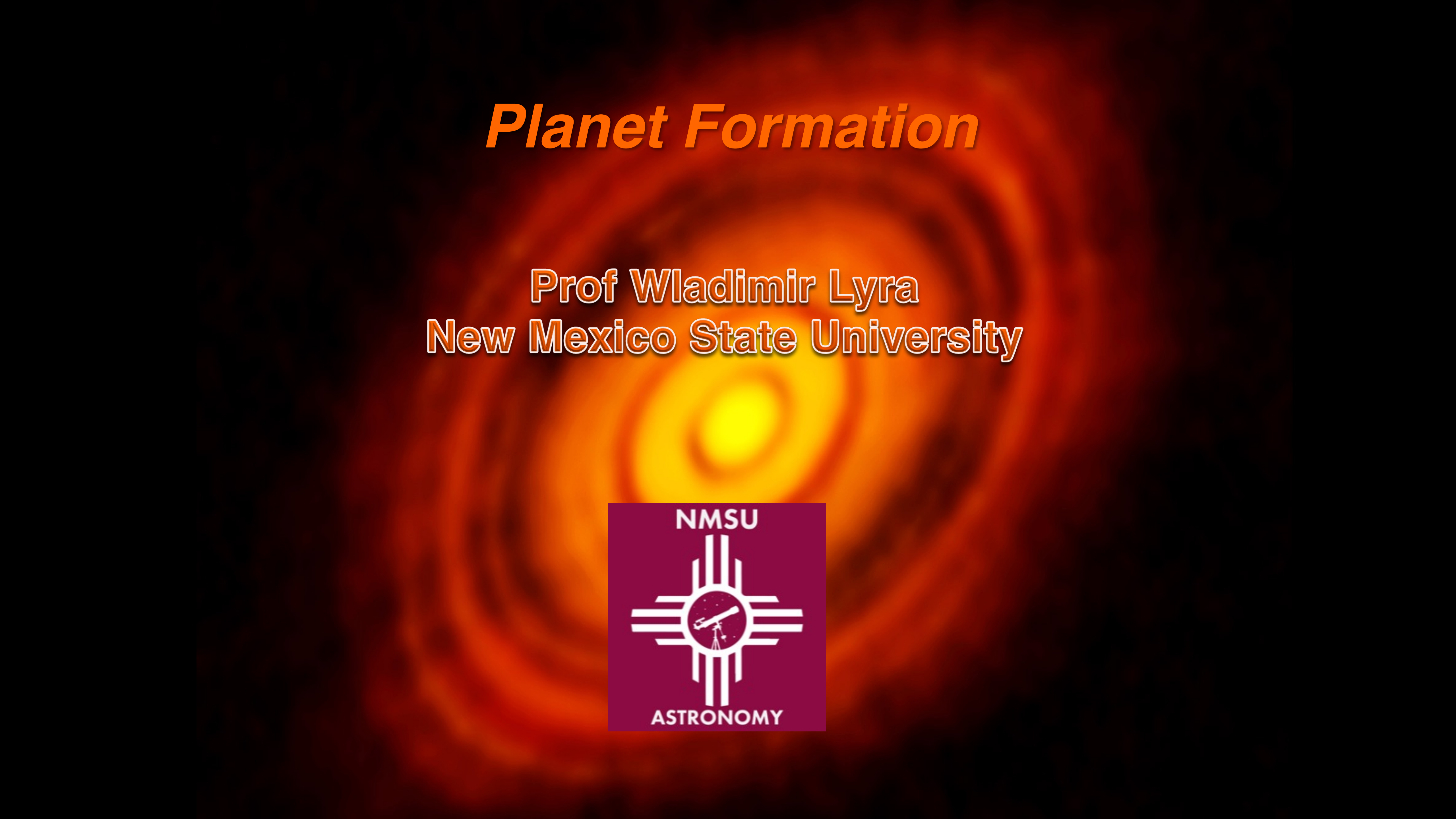
Planet Formation



Prof Wladimir Lyra
New Mexico State University

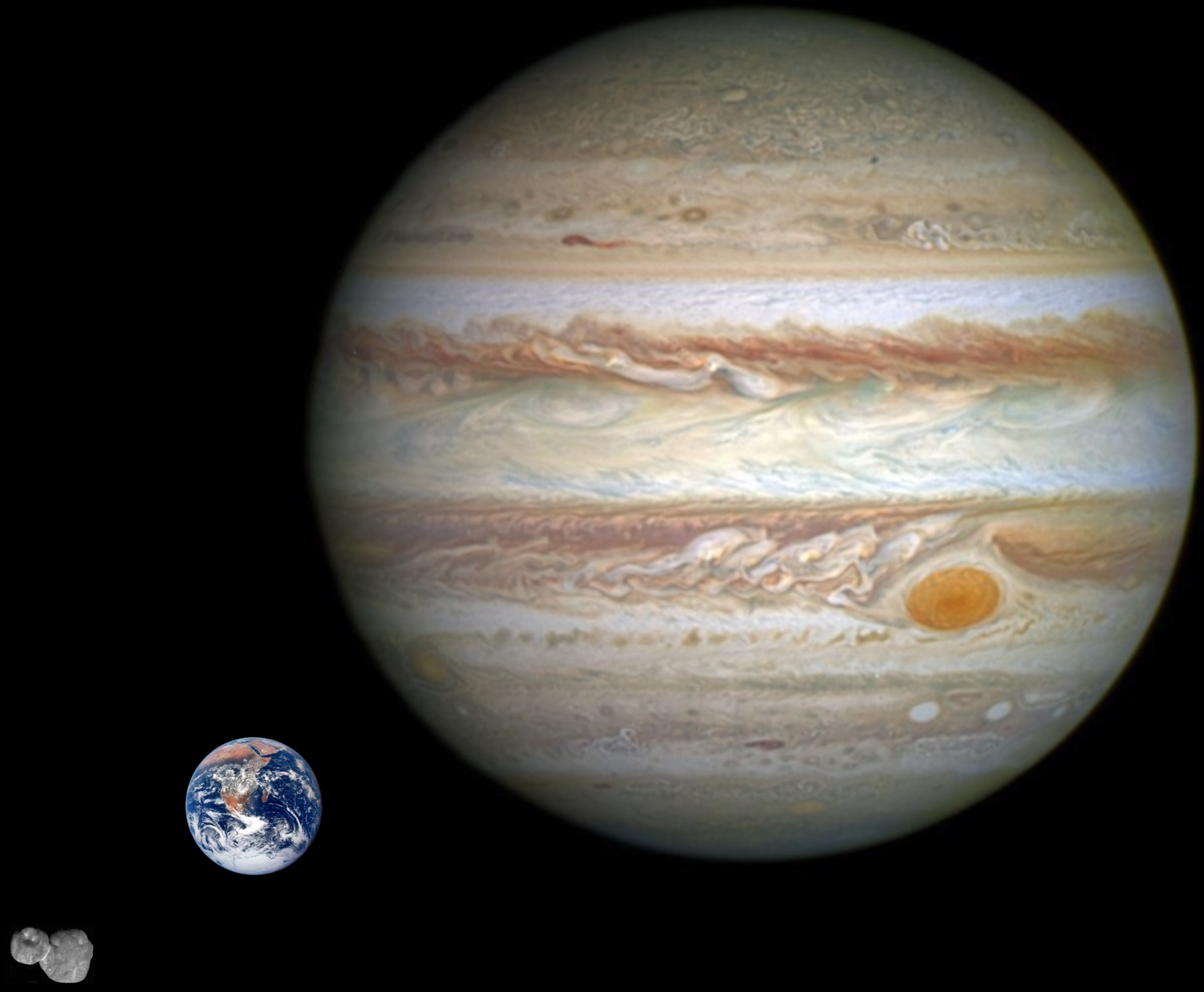
NMSU
ASTRONOMY

Quick Bio

Wladimir Lyra
Interests: Planet formation, accretion disks, hydrodynamics, computational methods.

Faculty	New Mexico State University, NM 2019 – (tenured 2022). California State University, Northridge **CA,** 2015-2019.
Visiting Faculty	Nagoya University, Nagoya, **Japan** 2015. Max-Planck Institute for Astronomy, Heidelberg **Germany** 2018, 2019.
Postdocs	Hubble Fellow @ Jet Propulsion Laboratory – Caltech, 2011-2015. American Museum of Natural History (New York **NY**), 2009-2011.
Ph.D.	Uppsala University (Uppsala, **Sweden**), 2004-2009. Nordic Institute for Theoretical Physics (Stockholm, **Sweden**). Max-Planck Institute for Astronomy (Heidelberg, **Germany**).
Research Assistant	European Southern Observatory (Garching, **Germany**, 2003). Cerro Tololo Interamerican Observatory (La Serena, **Chile**, 2003-2004). Lisbon Observatory, **Portugal** (2003). Space Telescope Science Institute (Baltimore **MD**, 2002).
B.Sc.	Federal University of Rio de Janeiro (**Brazil**), Astronomy, 1999-2003.

Planet Formation



Planet Formation - Outline of the Week

Monday

- Setting the stage: Cloud collapse, disk formation, disk structure.

Learning objective: understanding the initial conditions for planet formation.

Wednesday

- The building blocks: Planetesimal formation via Streaming Instability and Vortex Trapping.

Learning objective: understanding how dust first turns into objects that can grow by gravity.

Thursday

- Scooping up: Pebble accretion vs planetesimal accretion

Learning objective: understanding how planets grow in mass.

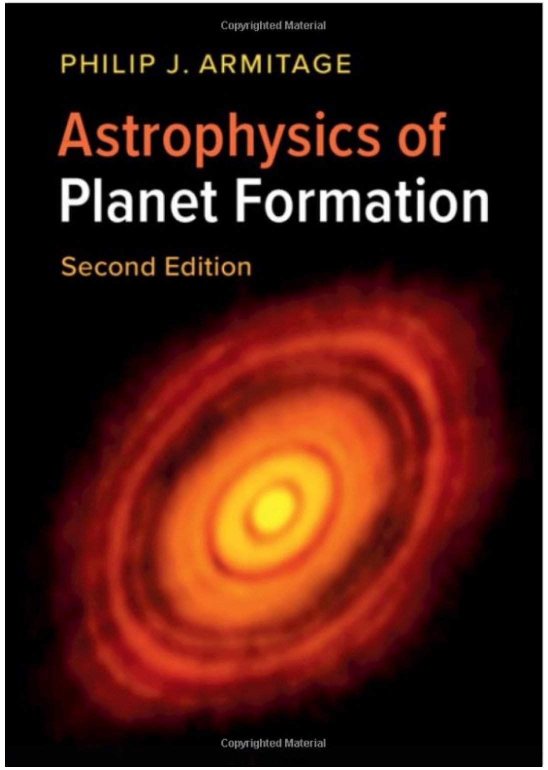
Friday

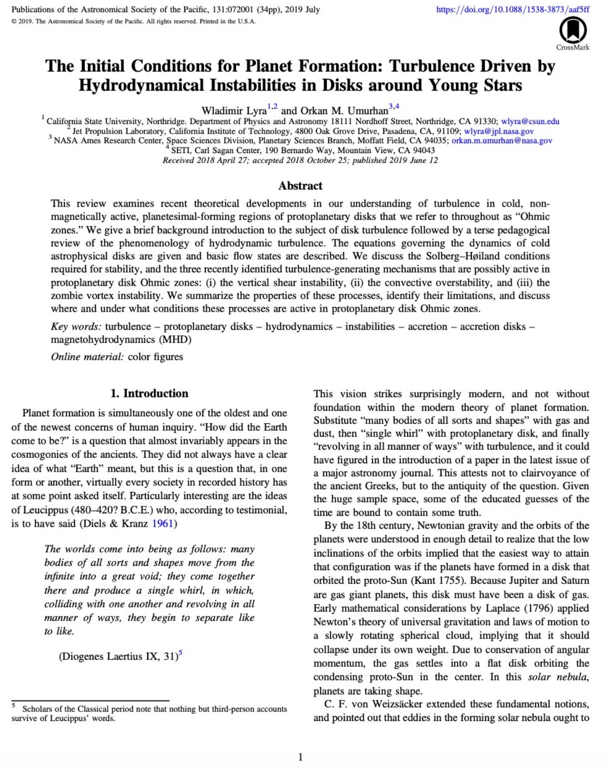
- Direct gravitational instability.

Learning objective: a competing theory to core accretion for giant planet formation.

Reading Material

- PP7 Chapter 13 - Hydro-, Magnetohydro-, and Dust-Gas Dynamics of Protoplanetary Disks, Lesur et al. 2022.
- The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars, Lyra & Umurhan 2019, PASP, 131, 1001.
- Astrophysics of Planet Formation, 2nd edition 2020, Armitage, Cambridge University Press.




Publications of the Astronomical Society of the Pacific, 131:072001 (34pp), 2019 July
https://doi.org/10.1088/1538-3873/aaf5ff

The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars

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Abstract

This review examines recent theoretical developments in our understanding of turbulence in cold, non-magnetically active, planetesimal-forming regions of protoplanetary disks that we refer to throughout as "Ohmic zones." We give a brief background introduction to the subject of disk turbulence followed by a terse pedagogical review of the phenomenology of hydrodynamic turbulence. The equations governing the dynamics of cold astrophysical disks are given and basic flow states are described. We discuss the Solberg–Høiland conditions required for stability, and the three recently identified turbulence-generating mechanisms that are possibly active in protoplanetary disk Ohmic zones: (i) the vertical shear instability, (ii) the convective overstability, and (iii) the zombie vortex instability. We summarize the properties of these processes, identify their limitations, and discuss where and under what conditions these processes are active in protoplanetary disk Ohmic zones.

Key words: turbulence – protoplanetary disks – hydrodynamics – instabilities – accretion – accretion disks – magnetohydrodynamics (MHD)

Online material: color figures

1. Introduction

Planet formation is simultaneously one of the oldest and one of the newest concerns of human inquiry. "How did the Earth come to be?" is a question that almost invariably appears in the cosmogonies of the ancients. They did not always have a clear idea of what "Earth" meant, but this is a question that, in one form or another, virtually every society in recorded history has at some point asked itself. Particularly interesting are the ideas of Leucippus (480–420? B.C.E.) who, according to testimonial, is to have said (Diels & Kranz 1961)

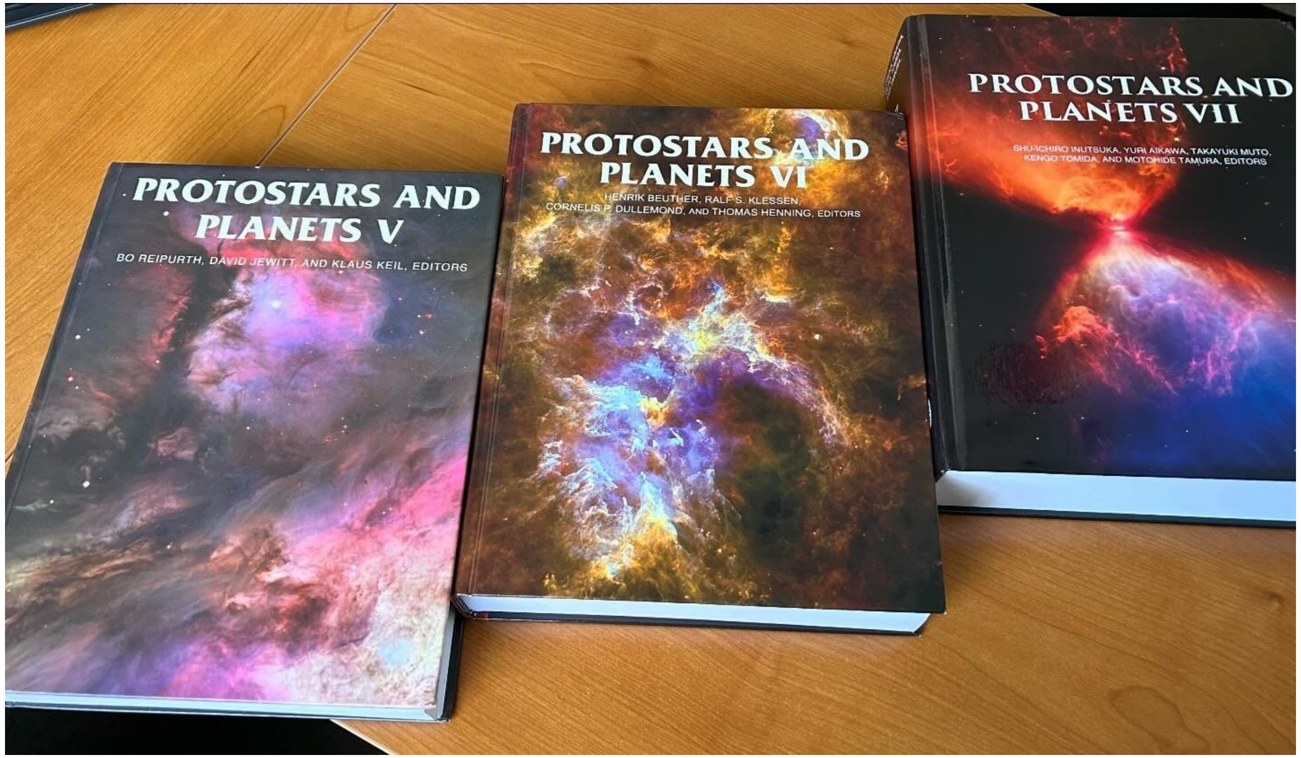
> *The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.*
>
> (Diogenes Laertius IX, 31)[5]

This vision strikes surprisingly modern, and not without foundation within the modern theory of planet formation. Substitute "many bodies of all sorts and shapes" with gas and dust, then "single whirl" with protoplanetary disk, and finally "revolving in all manner of ways" with turbulence, and it could have figured in the introduction of a paper in the latest issue of a major astronomy journal. This attests not to clairvoyance of the ancient Greeks, but to the antiquity of the question. Given the huge sample space, some of the educated guesses of the time are bound to contain some truth.

By the 18th century, Newtonian gravity and the orbits of the planets were understood in enough detail to realize that the low inclinations of the orbits implied that the easiest way to attain that configuration was if the planets have formed in a disk that orbited the proto-Sun (Kant 1755). Because Jupiter and Saturn are gas giant planets, this disk must have been a disk of gas. Early mathematical considerations by Laplace (1796) applied Newton's theory of universal gravitation and laws of motion to a slowly rotating spherical cloud, implying that it should collapse under its own weight. Due to conservation of angular momentum, the gas settles into a flat disk orbiting the condensing proto-Sun in the center. In this *solar nebula*, planets are taking shape.

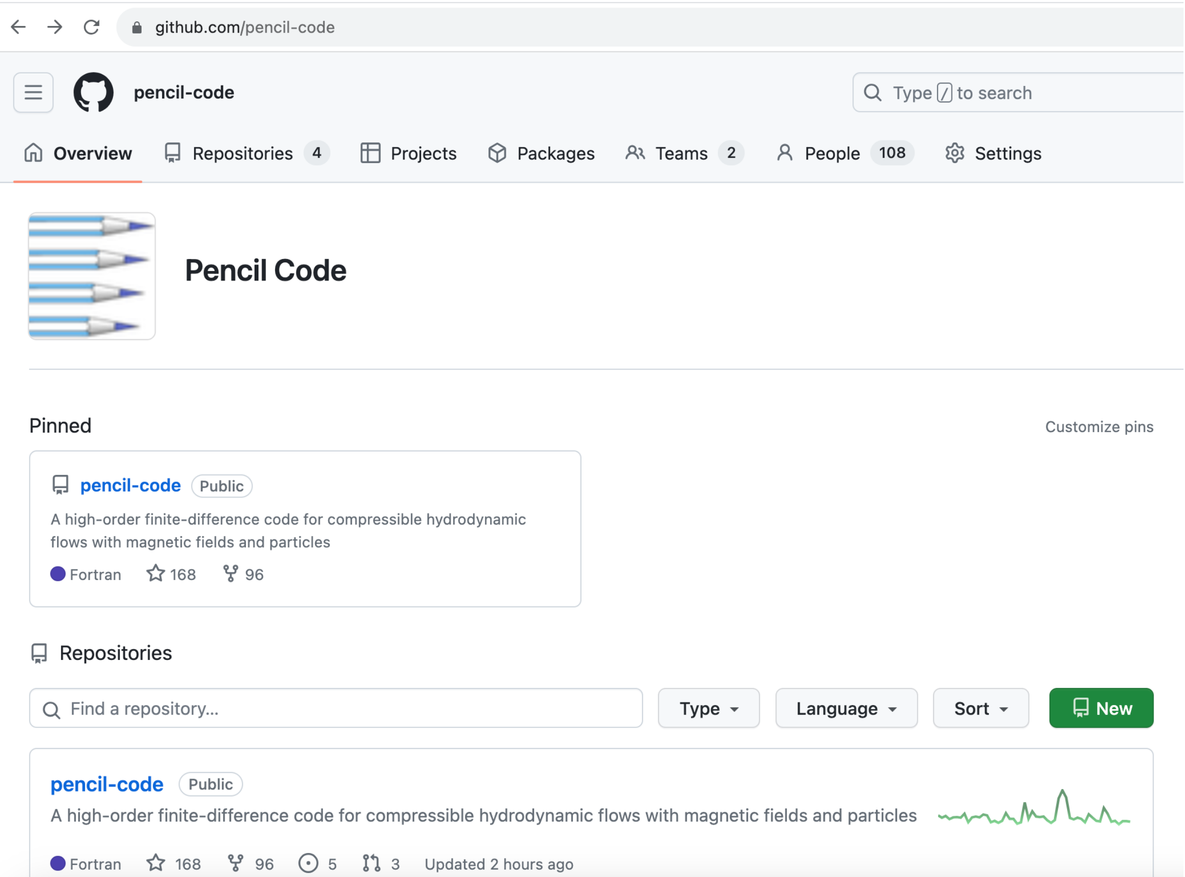
C. F. von Weizsäcker extended these fundamental notions, and pointed out that eddies in the forming solar nebula ought to

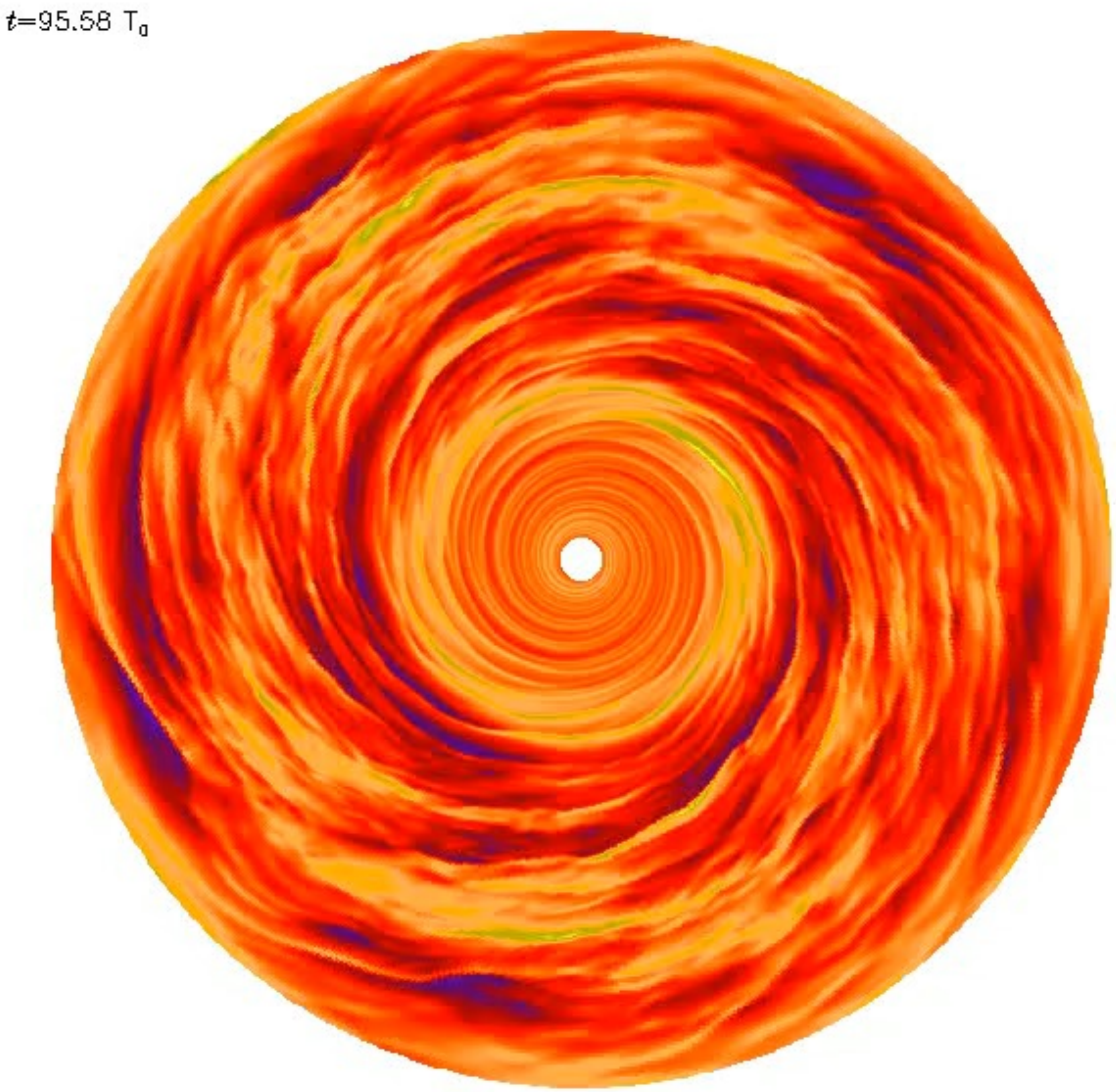
[5] Scholars of the Classical period note that nothing but third-person accounts survive of Leucippus' words.



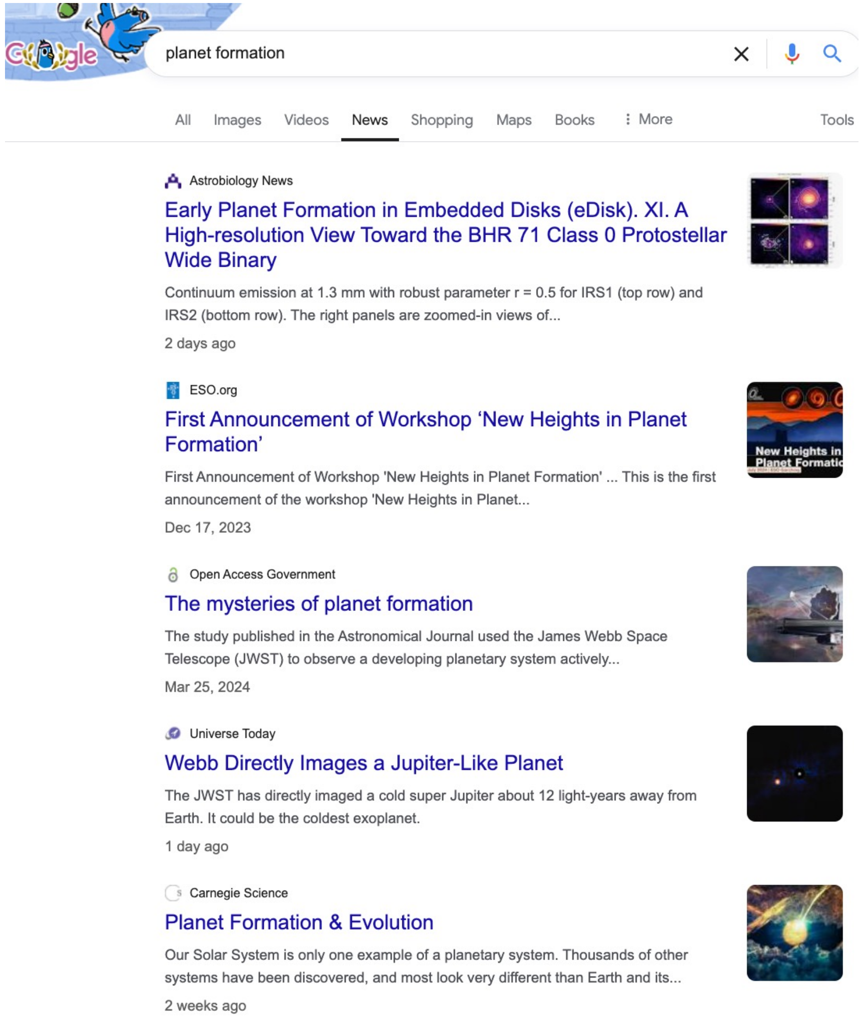
Tools

The Pencil Code





Planet Formation
is an active and evolving field of research


planet formation

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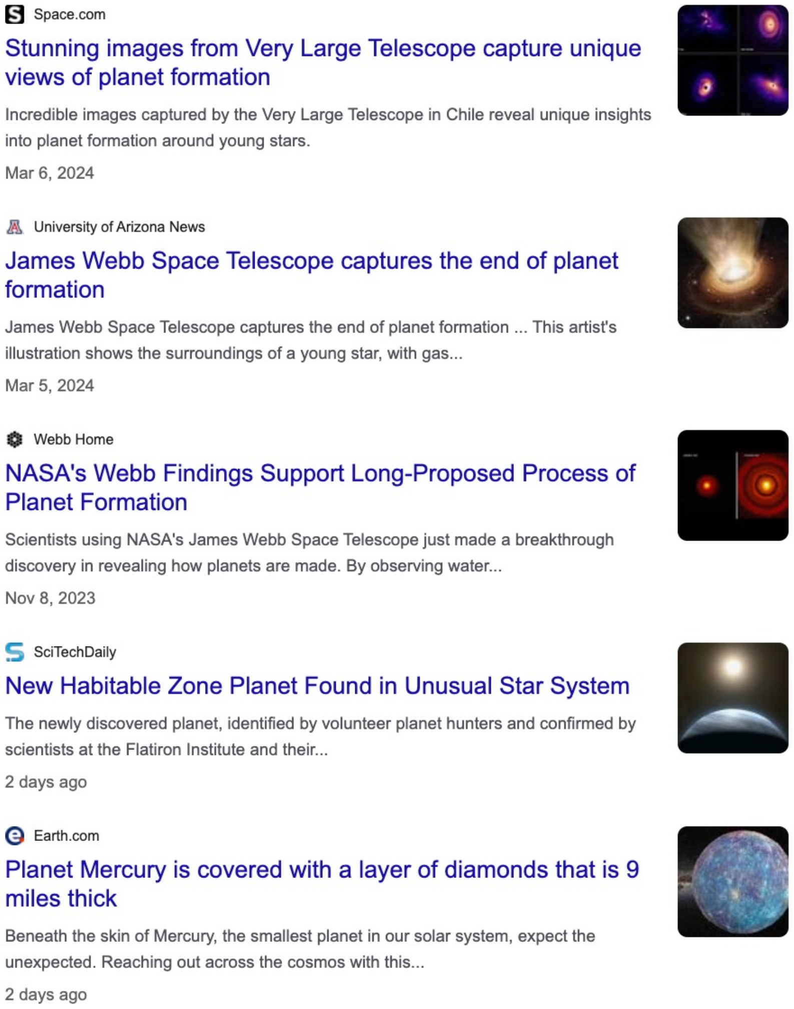
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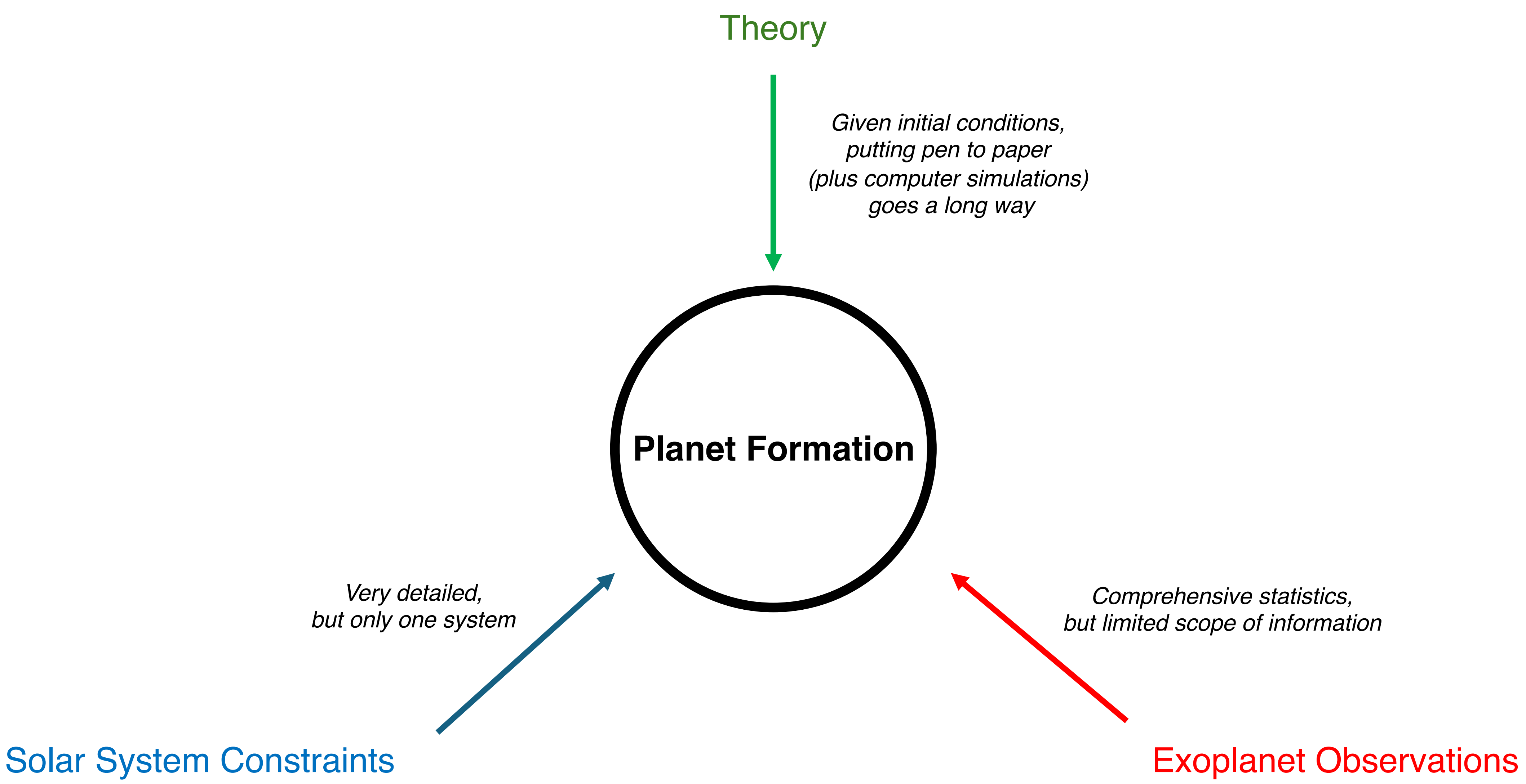
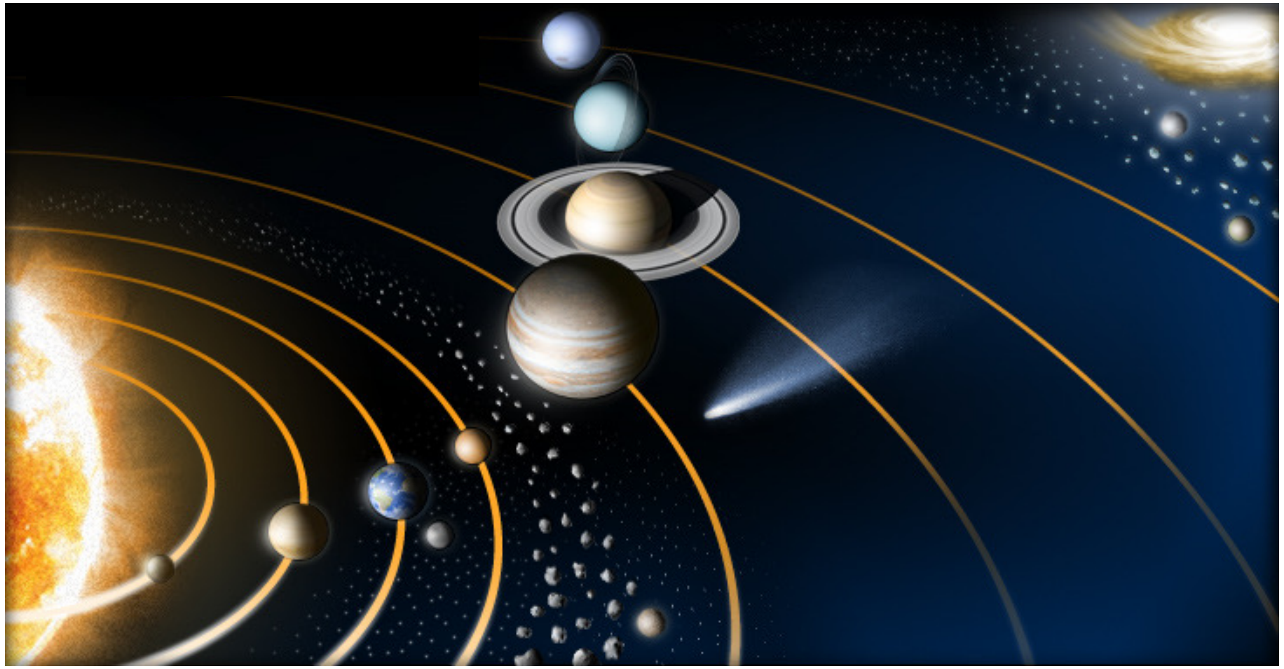
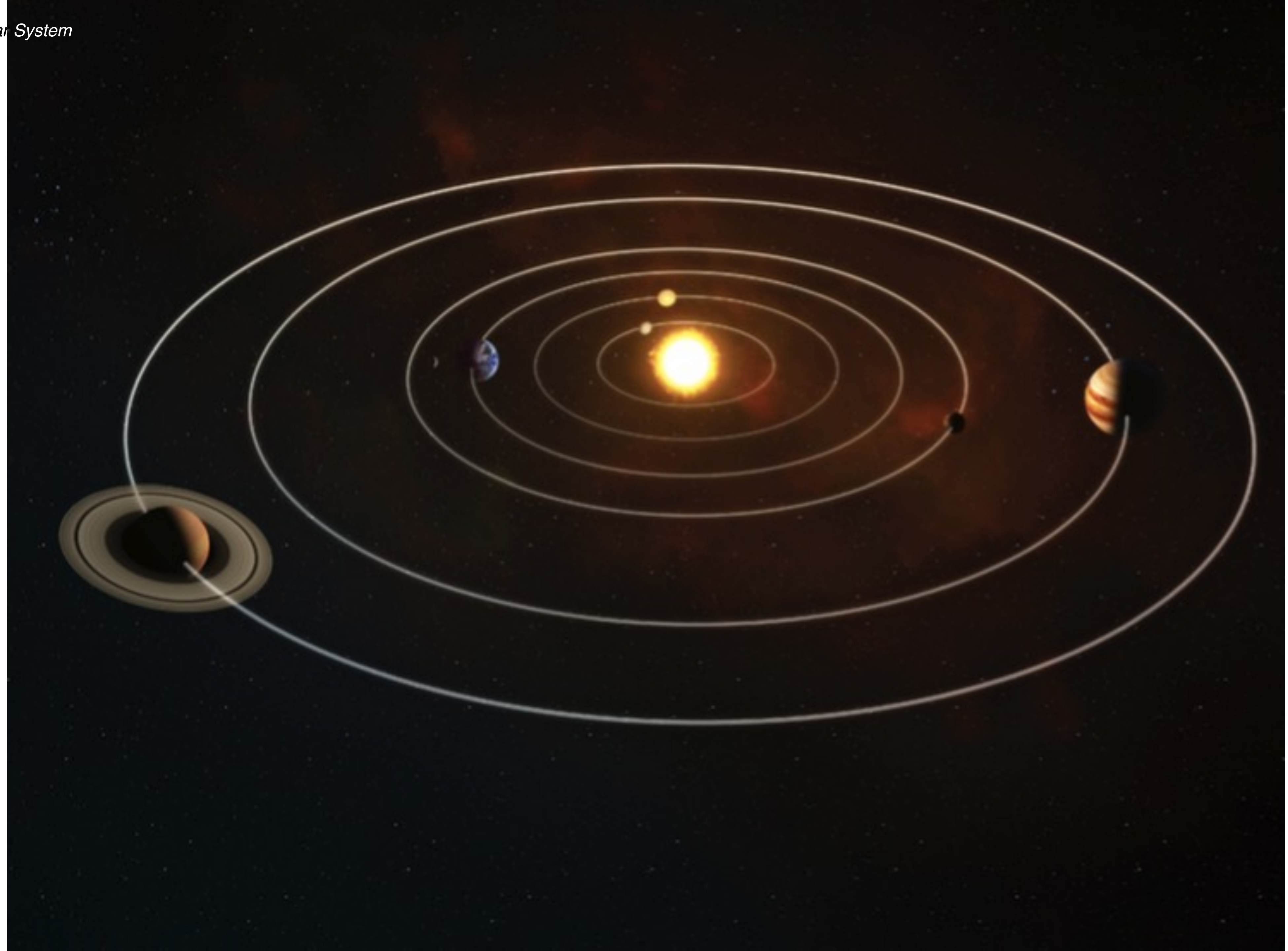

Theory
Given initial conditions, putting pen to paper (plus computer simulations) goes a long way
Planet Formation
Very detailed, but only one system
Solar System Constraints
Comprehensive statistics, but limited scope of information
Exoplanet Observations

Solar System Planets



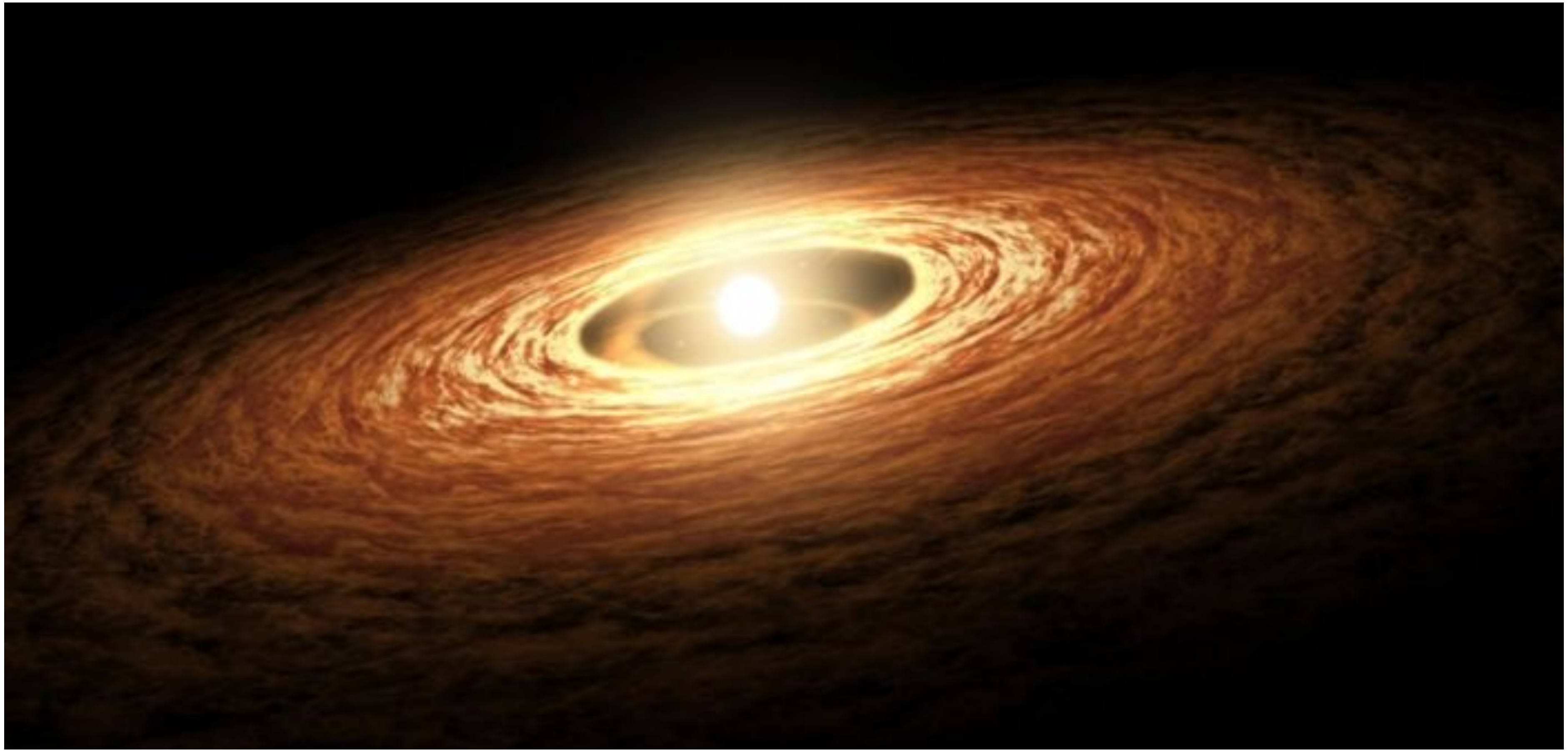
Any formation model of Solar System must explain:

- All the orbits of the planets are prograde
- All the planets have orbital planes that are roughly in the same plane (inclined by less than 6 degrees with respect to each other).
- Inner/outer planets dichotomy
  - Inner planets are **terrestrial**: dense, rocky and small,
  - Outer planets are **jovian**: gaseous/icy and large.



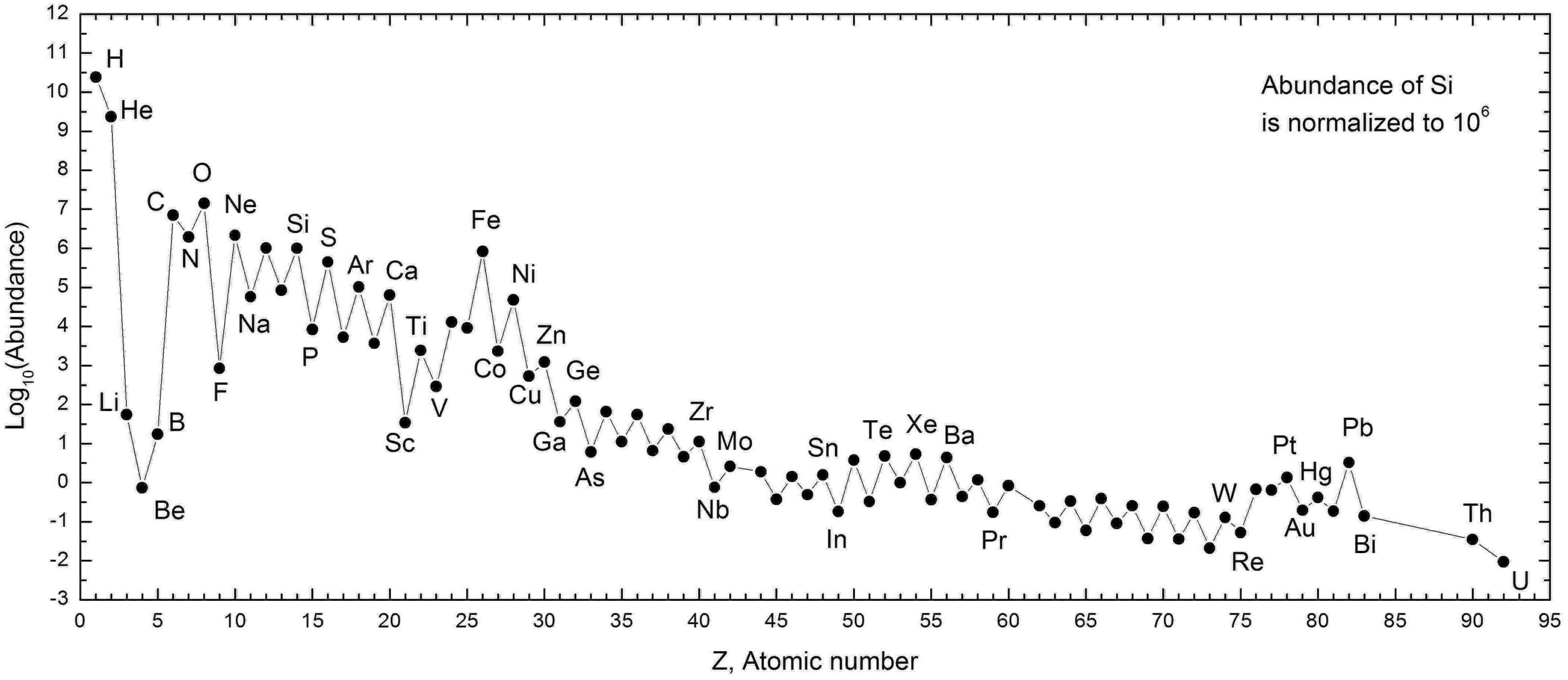
The Solar Nebula

Nebular hypothesis – planets form in disks of gas and dust
(Kant 1755, Laplace 1794)



Chemical Composition

The chemical composition of the Sun



Most abundant elements, in order:

H (71%) He (27%)

0 (1.04%) C (0.46%)

Ne (0.13%) Fe (0.11%) N (0.1%)

Si (0.06%), Mg (0.05%), S (0.04%)

Chemistry

H (71%)
He (27%)

O (1.04%)
C (0.46%)
Ne (0.13%)
Fe (0.11%)
N (0.1%)
Si (0.06%)

Volatiles

Refractory

Chemistry

H_2

He

H_2O

CH_4

Ne

NH_3

Fe, Si

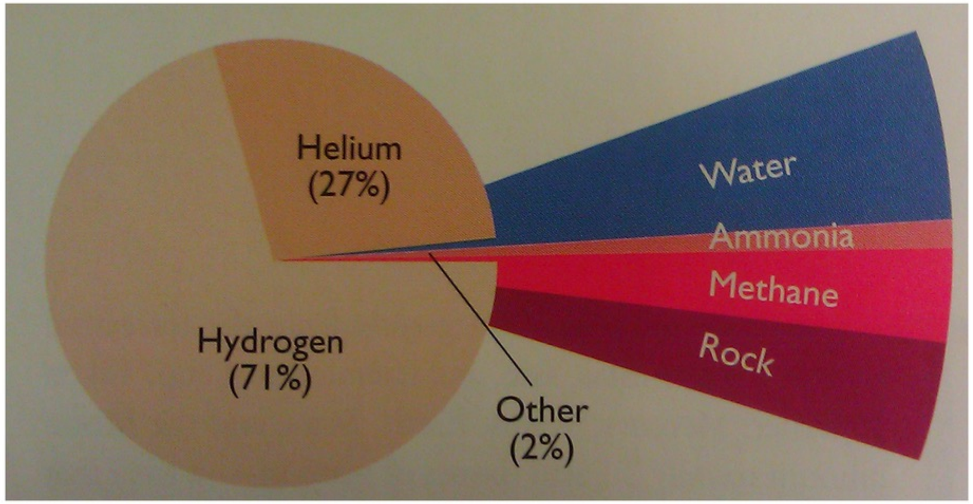
What will the chemistry of the mixture be?

H (71%)
He (27%)
0 (1.04%)
C (0.46%)
Ne (0.13%)
Fe (0.11%)
N (0.1%)
Si (0.06%)

H_2 He — Gas

H_20 - Water
CH_4 - Methane
Ne
NH_3 - Ammonia — Ices

Fe, Si – Rocks (metals and silicates) — Rock



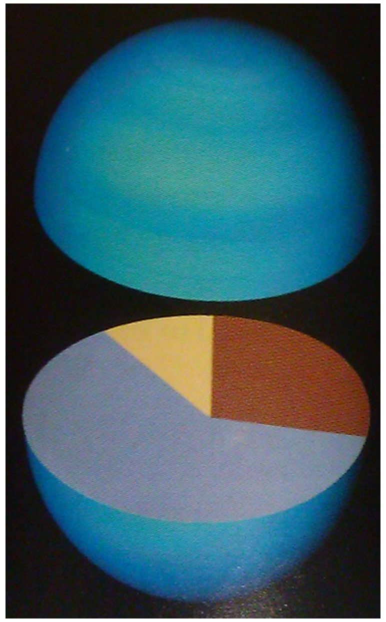
Classes of planets

Rocky Planets

Earth

Ice Giants

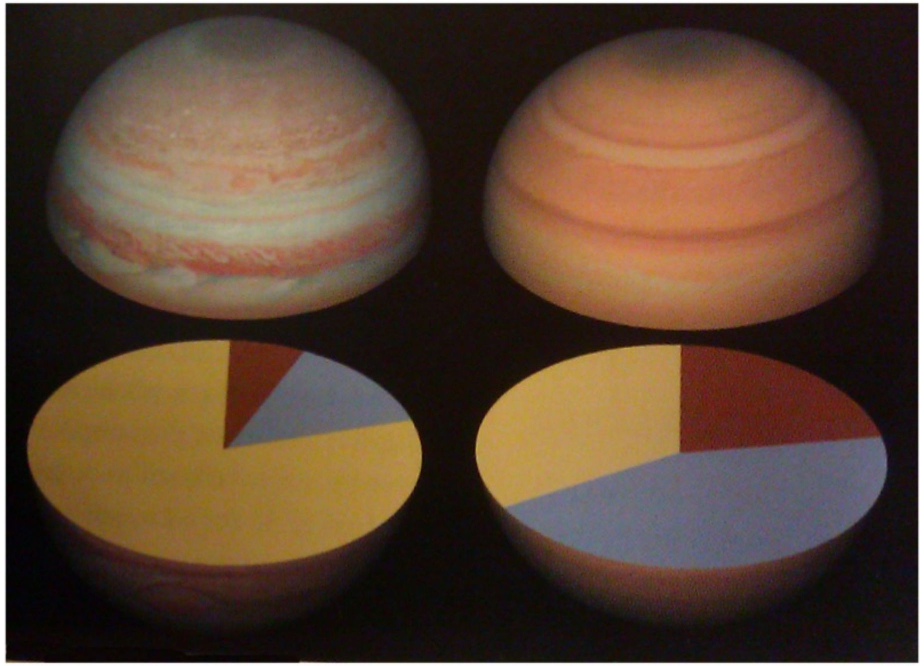
Uranus/Neptune



Gas Giants

Jupiter

Saturn

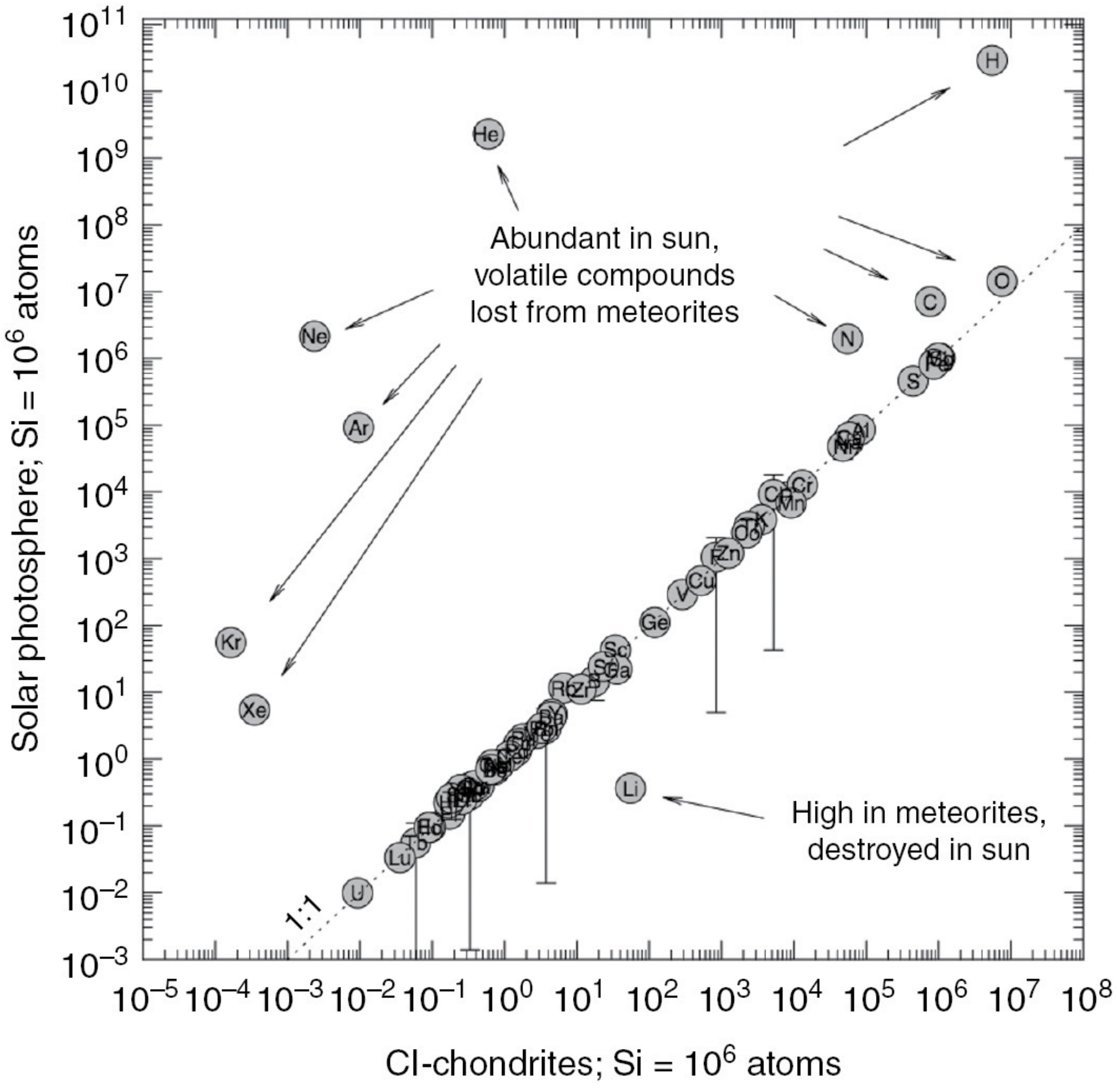


Rock

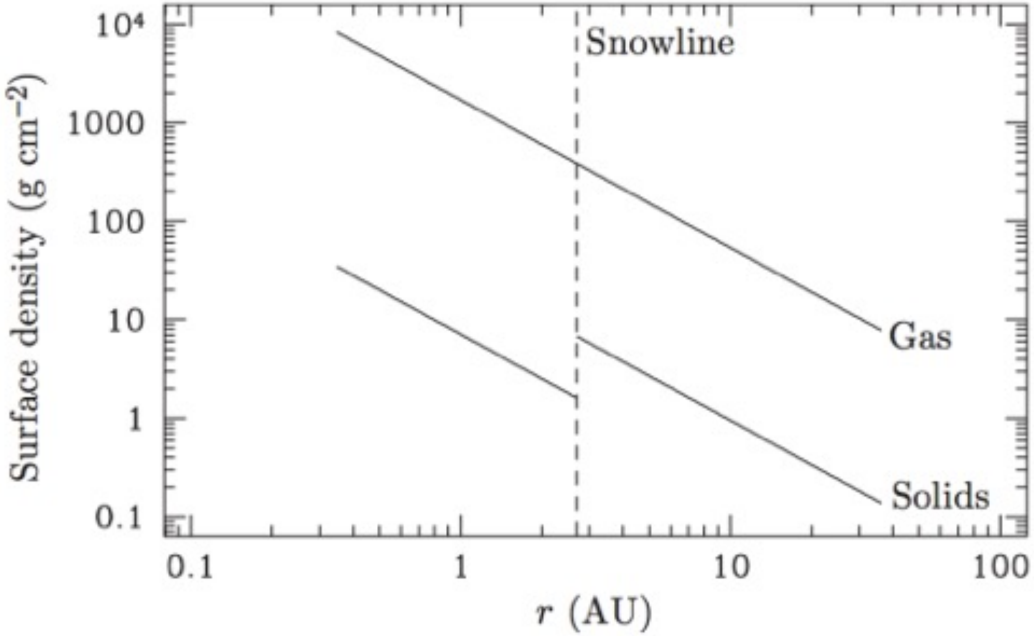
Ice

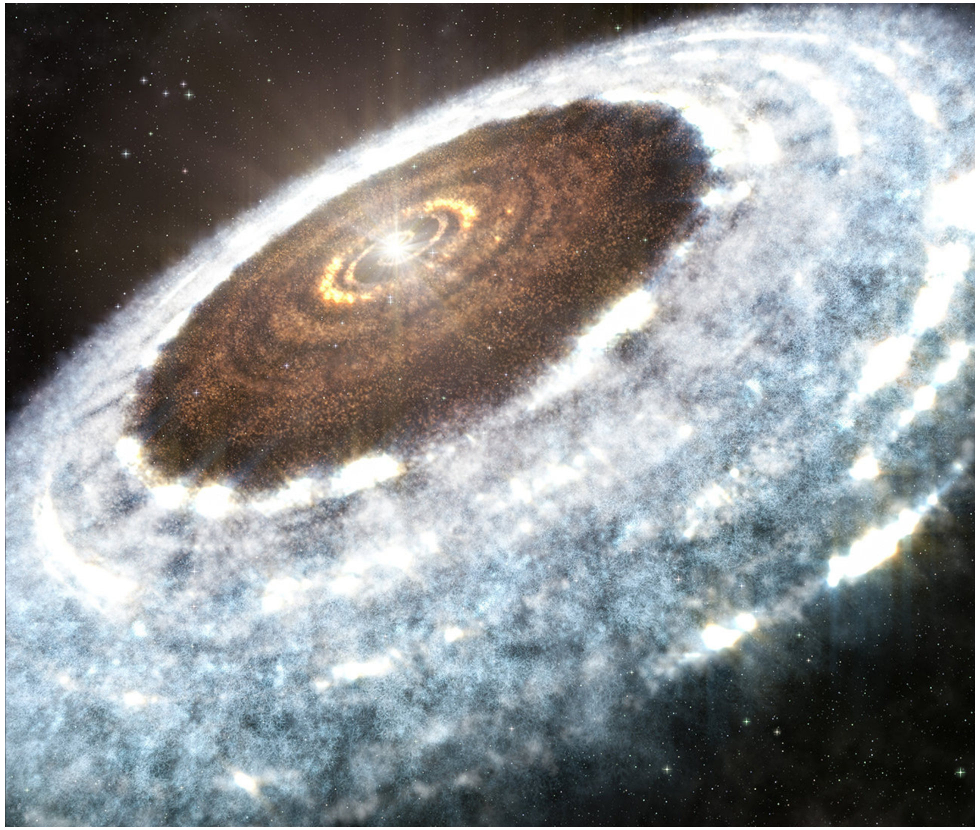
Gas

Refractories in meteorites: Solar Composition



Snowline

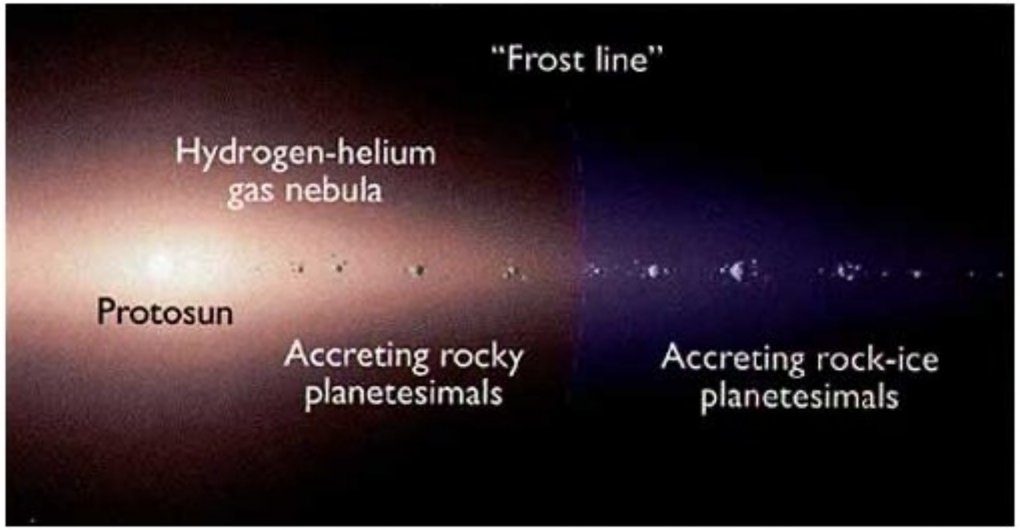

Snowline
Gas
Solids
Surface density (g cm^{-2})
10^4
1000
100
10
1
0.1
0.1
1
10
100
r (AU)



The idea, *roughly*

Inward of snowline

Rocks only
(small)



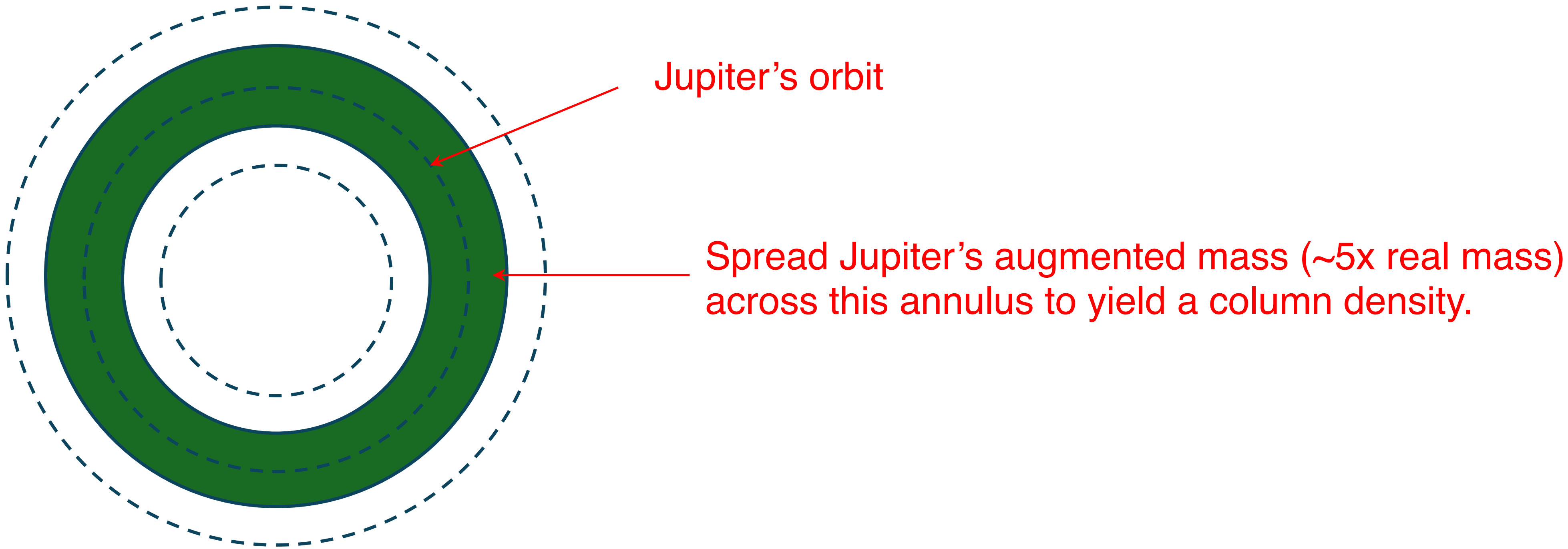
Outward of snowline

Ice comes to aid!
Growing big
icy/rocky cores.

The Minimum Mass Solar Nebula (MMSN)

How much mass was needed to form the planets?

1. Take the mass in each planet
2. Increase H/He to solar composition
3. Spread the mass into an annulus around each orbit



The Minimum Mass Solar Nebula (MMSN)

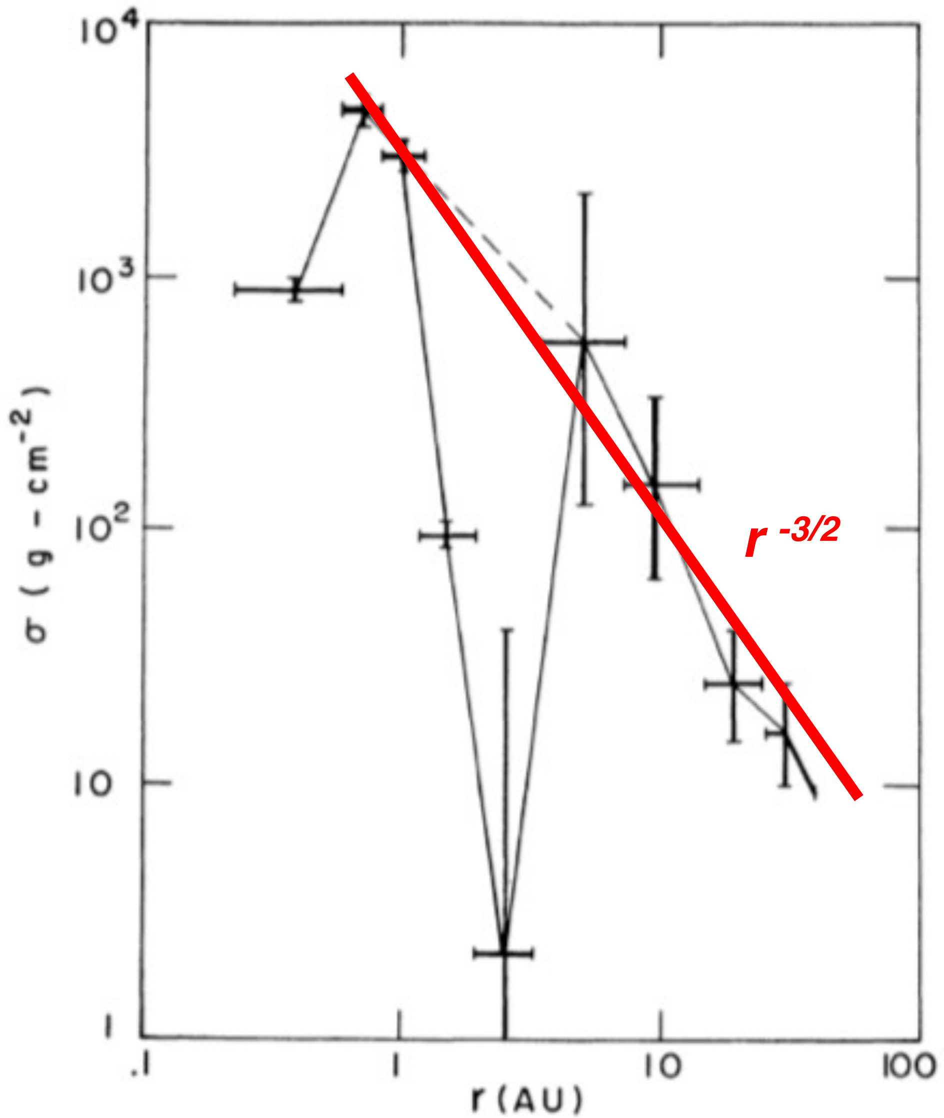
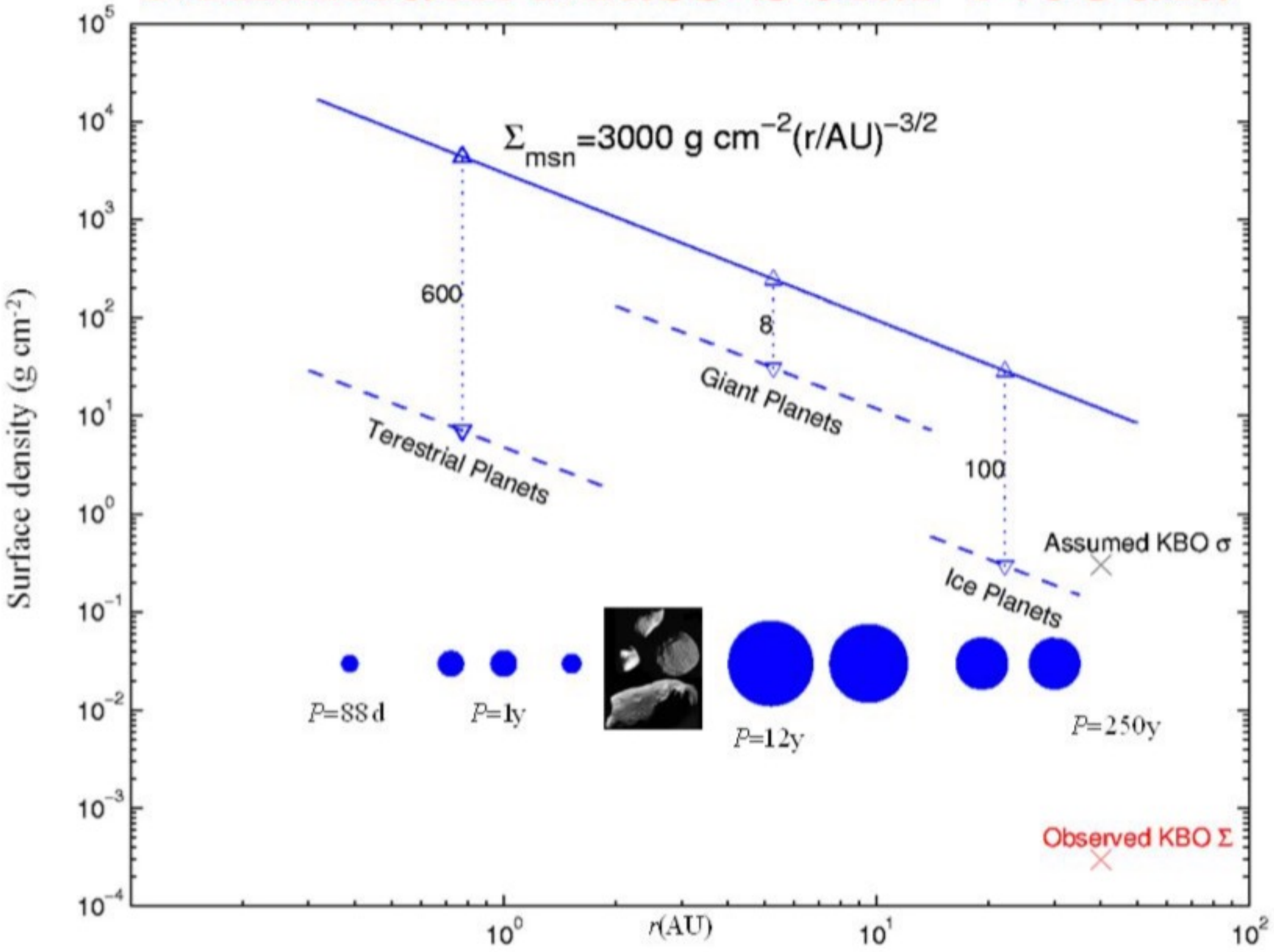


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

Minimum Mass Solar Nebula



Distribution of Disk Masses

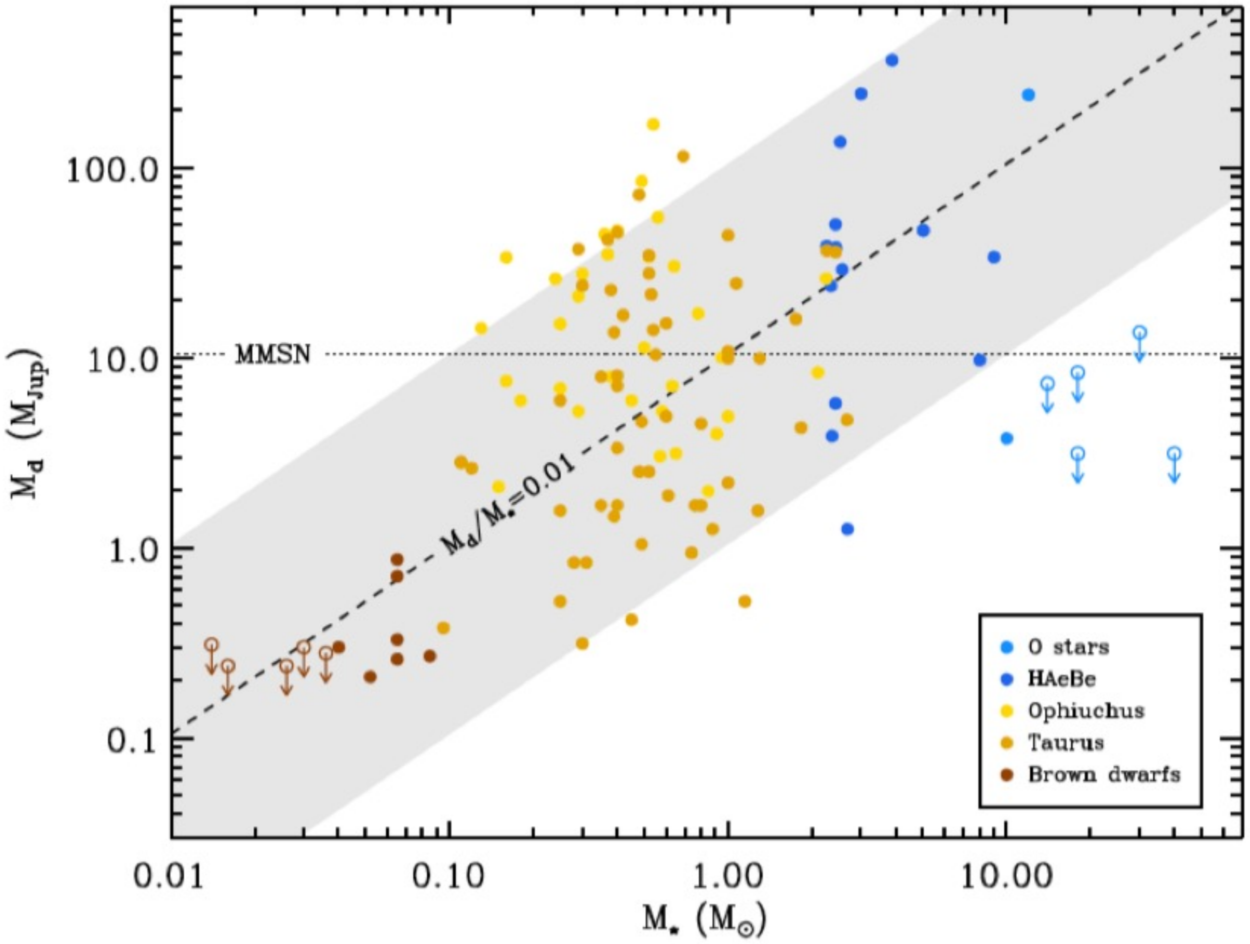
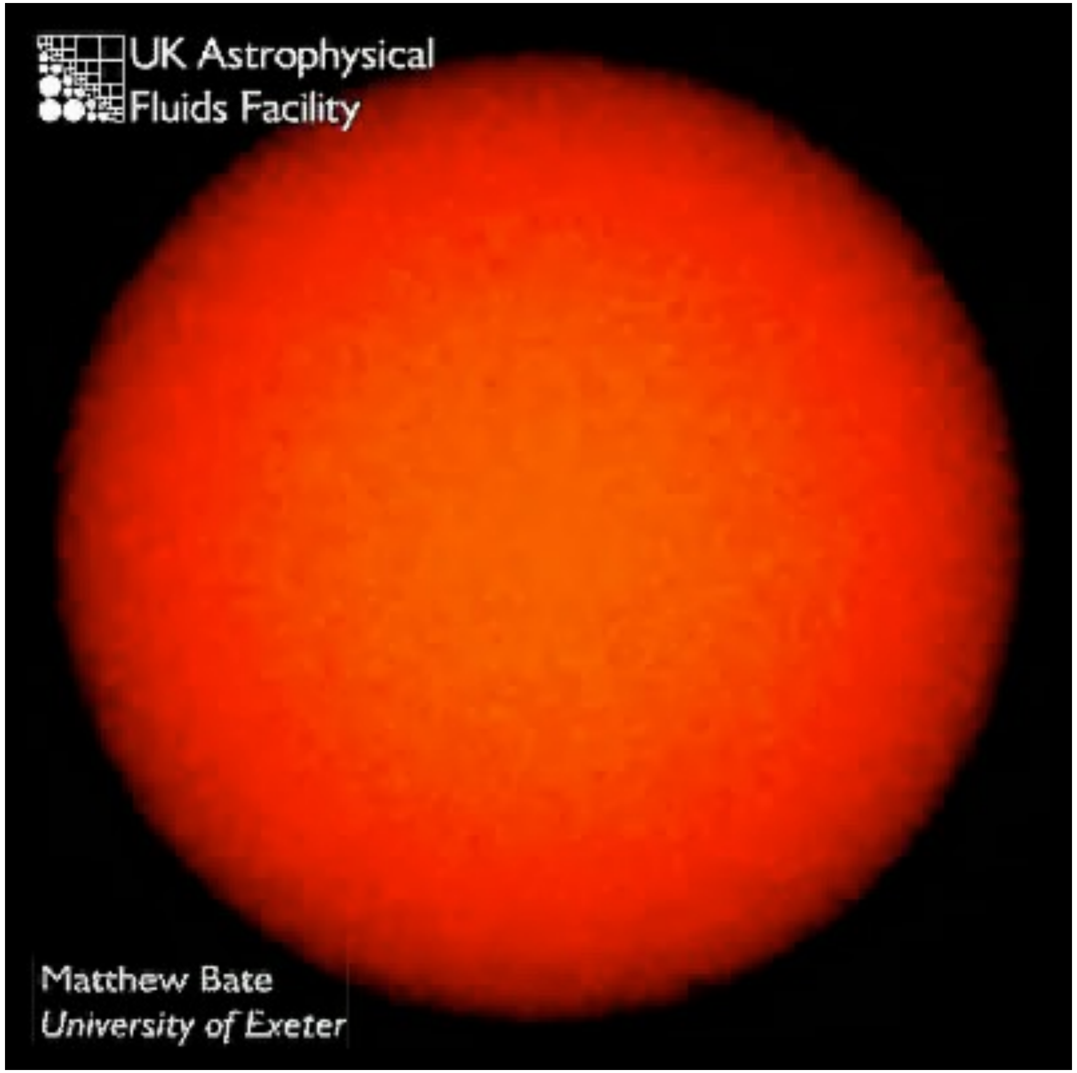


Figure 1: The disk mass as a function of the stellar mass (adopted from [51])

Square one: *Star Formation*

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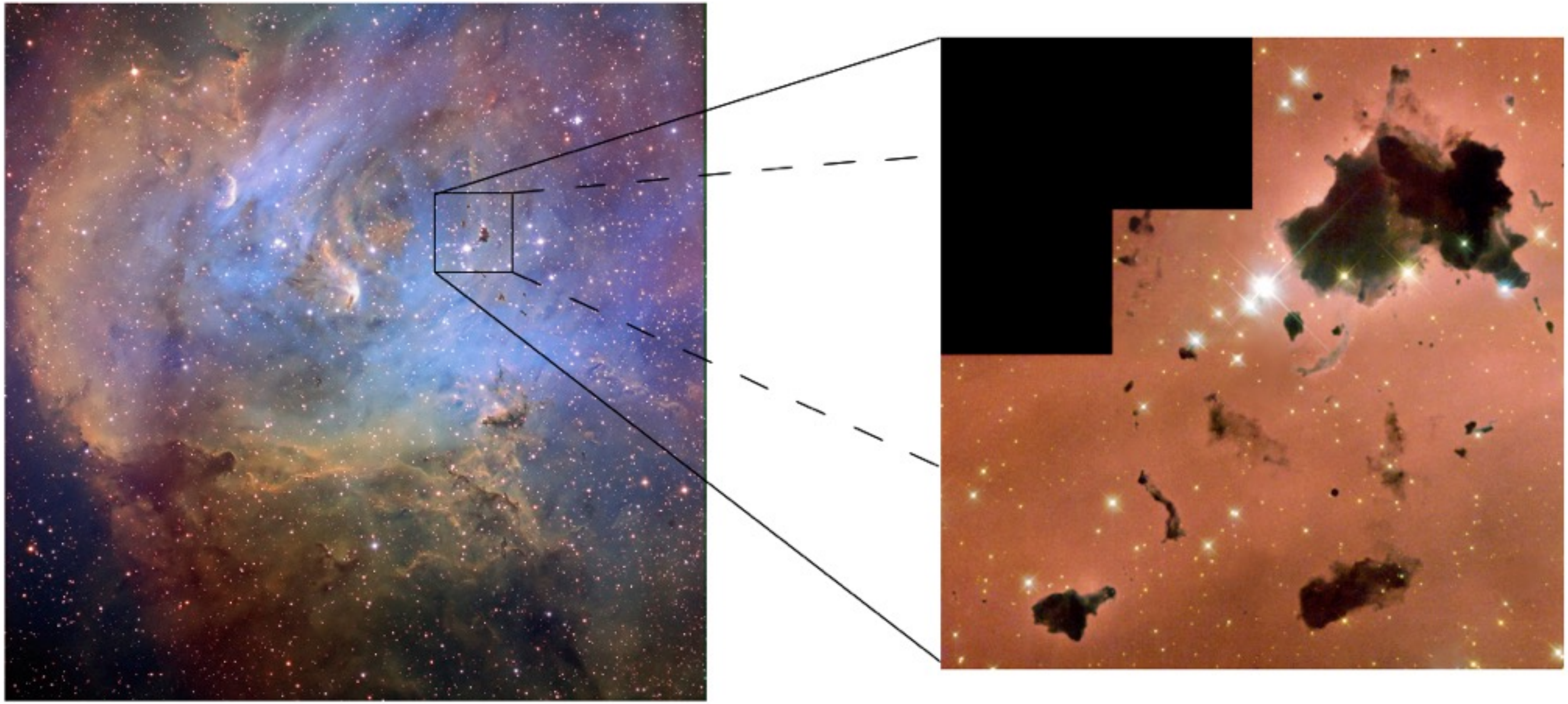
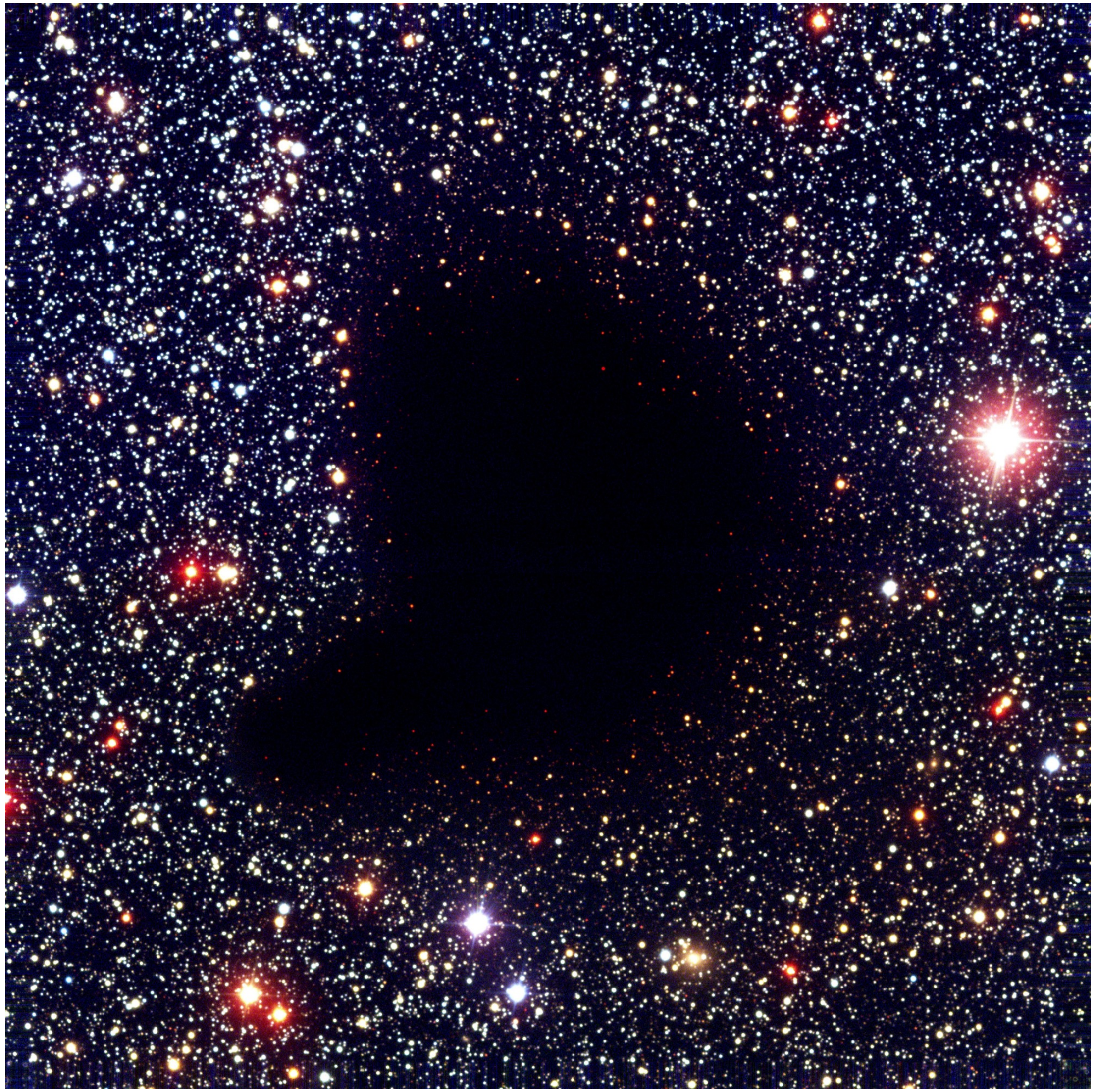
Square one: *Star Formation*



Barnard 68



Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight

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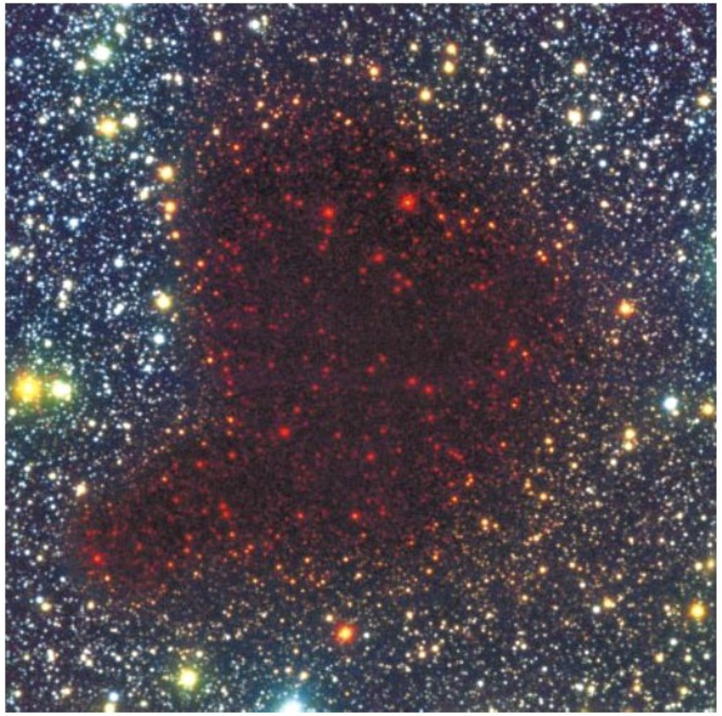
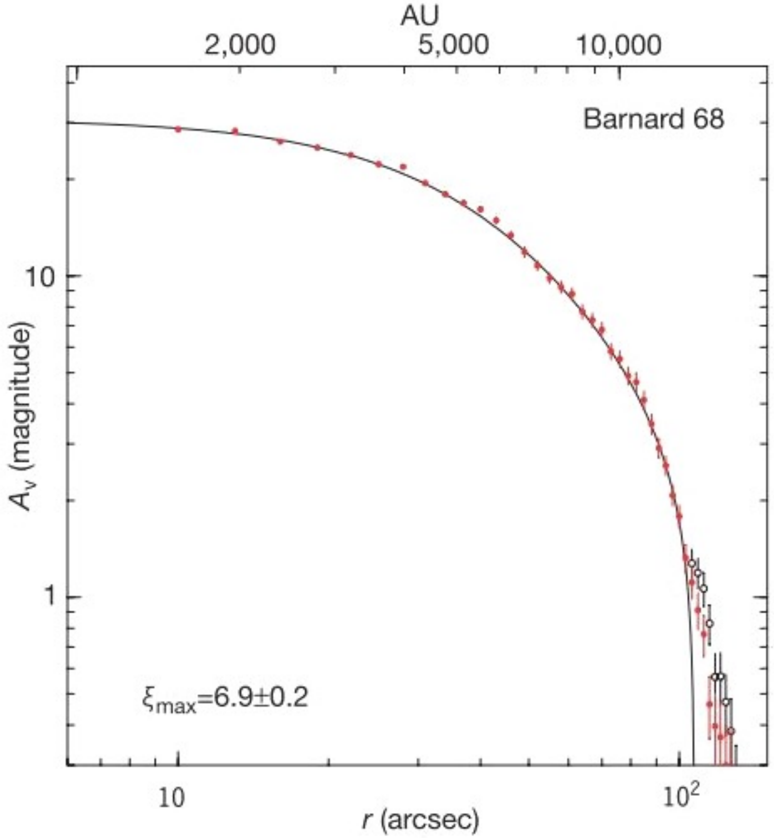
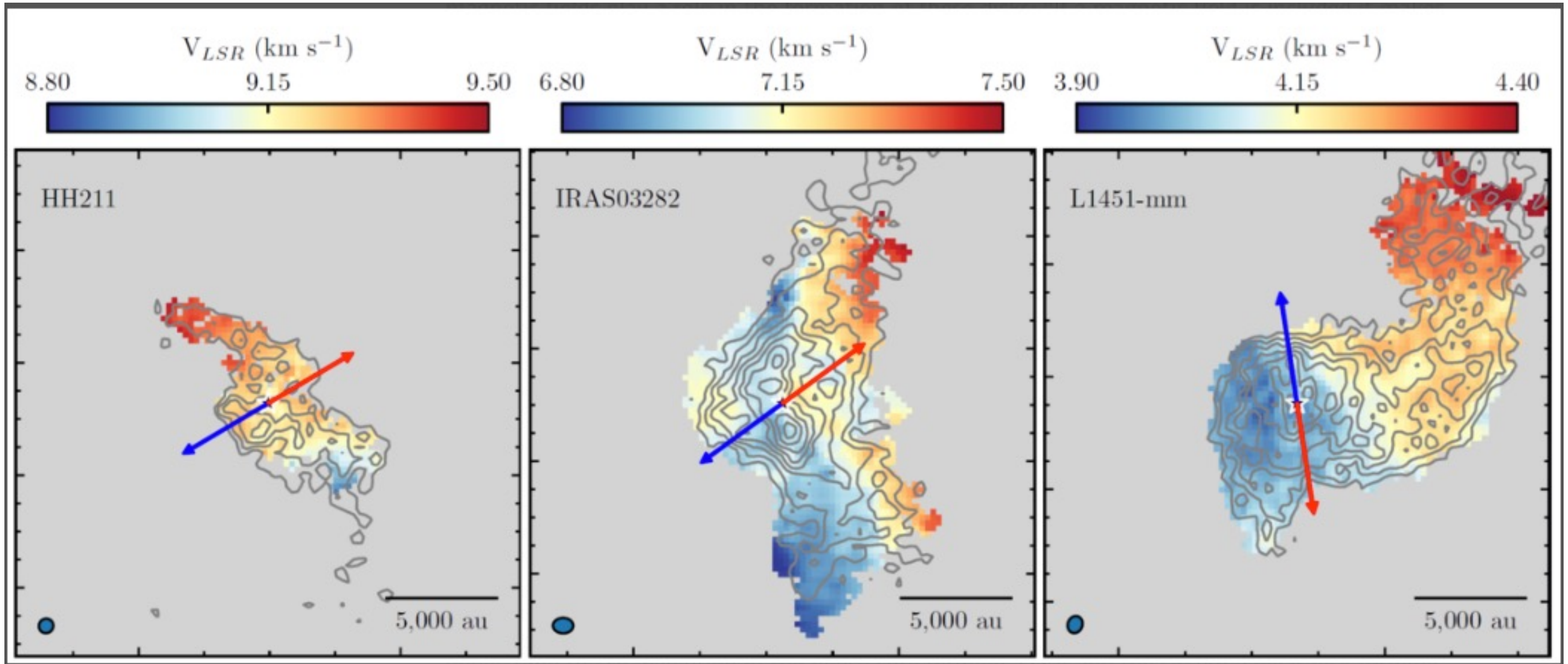




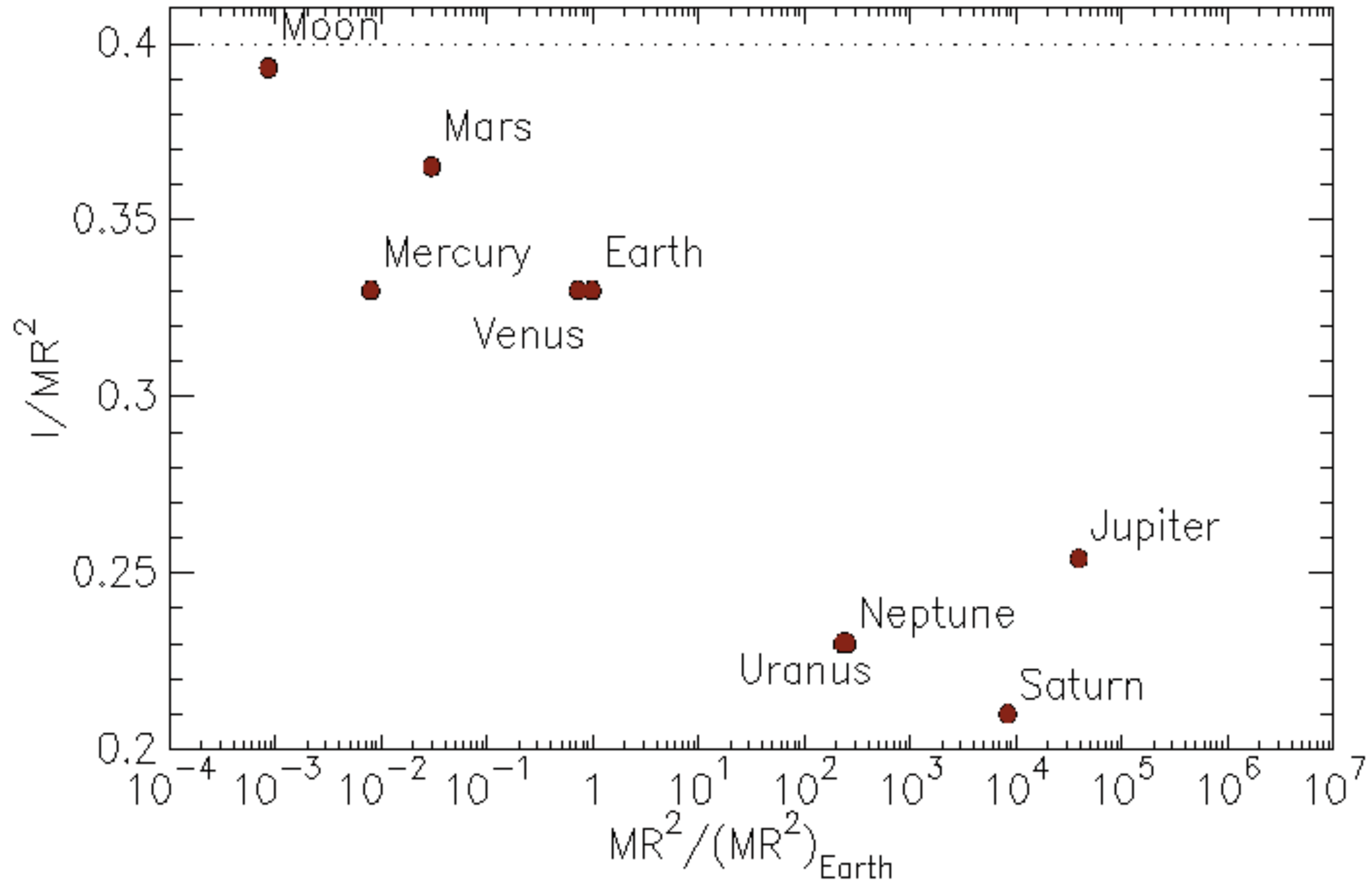
Radial Velocities – Solid body rotation



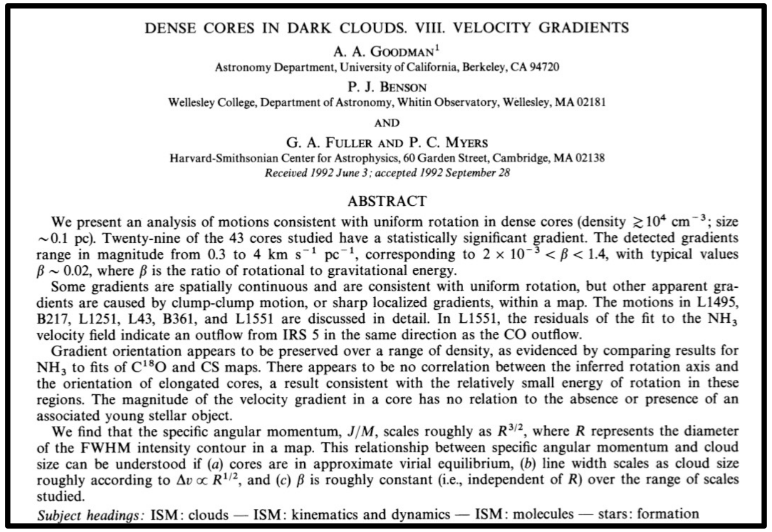
The velocity field in the three youngest proto-stellar sources in the Perseus molecular cloud. Blue denotes regions moving towards us, red denotes regions moving away from us. All systems show a systematic rotation around the axis indicated. Please note the different velocity scales indicated at the top.

(LSR=Local Standard of Rest)

Inertia moment – deviations from homogeneity ($I = 0.4\ MR^2$)



Distribution of β (rotational support)



DENSE CORES IN DARK CLOUDS. VIII. VELOCITY GRADIENTS

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Received 1992 June 3; accepted 1992 September 28

ABSTRACT

We present an analysis of motions consistent with uniform rotation in dense cores (density $\gtrsim 10^4$ cm^{-3}; size $\sim$0.1 pc). Twenty-nine of the 43 cores studied have a statistically significant gradient. The detected gradients range in magnitude from 0.3 to 4 km s^{-1} pc^{-1}, corresponding to $2 \times 10^{-3} < \beta < 1.4$, with typical values $\beta \sim 0.02$, where β is the ratio of rotational to gravitational energy.

Some gradients are spatially continuous and are consistent with uniform rotation, but other apparent gradients are caused by clump-clump motion, or sharp localized gradients, within a map. The motions in L1495, B217, L1251, L43, B361, and L1551 are discussed in detail. In L1551, the residuals of the fit to the NH_3 velocity field indicate an outflow from IRS 5 in the same direction as the CO outflow.

Gradient orientation appears to be preserved over a range of density, as evidenced by comparing results for NH_3 to fits of $C^{18}O$ and CS maps. There appears to be no correlation between the inferred rotation axis and the orientation of elongated cores, a result consistent with the relatively small energy of rotation in these regions. The magnitude of the velocity gradient in a core has no relation to the absence or presence of an associated young stellar object.

We find that the specific angular momentum, J/M, scales roughly as $R^{3/2}$, where R represents the diameter of the FWHM intensity contour in a map. This relationship between specific angular momentum and cloud size can be understood if (*a*) cores are in approximate virial equilibrium, (*b*) line width scales as cloud size roughly according to $\Delta v \propto R^{1/2}$, and (*c*) β is roughly constant (i.e., independent of R) over the range of scales studied.

Subject headings: ISM: clouds — ISM: kinematics and dynamics — ISM: molecules — stars: formation

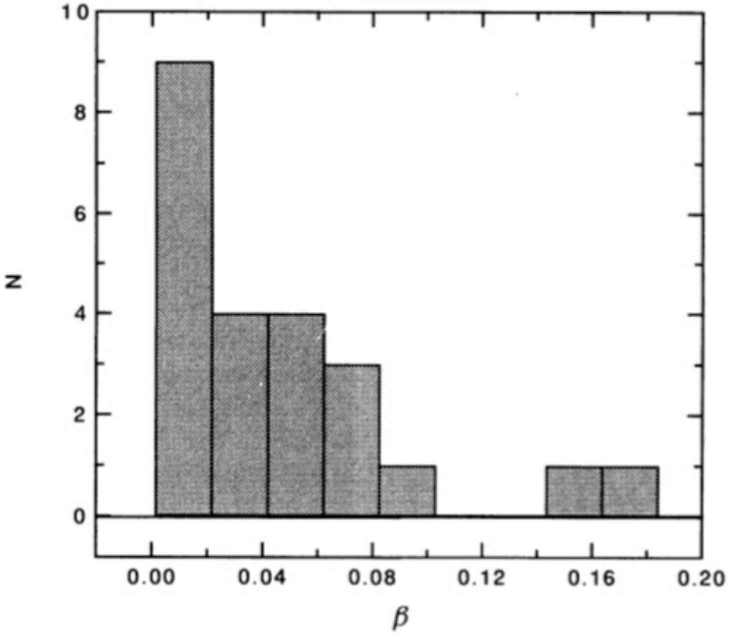
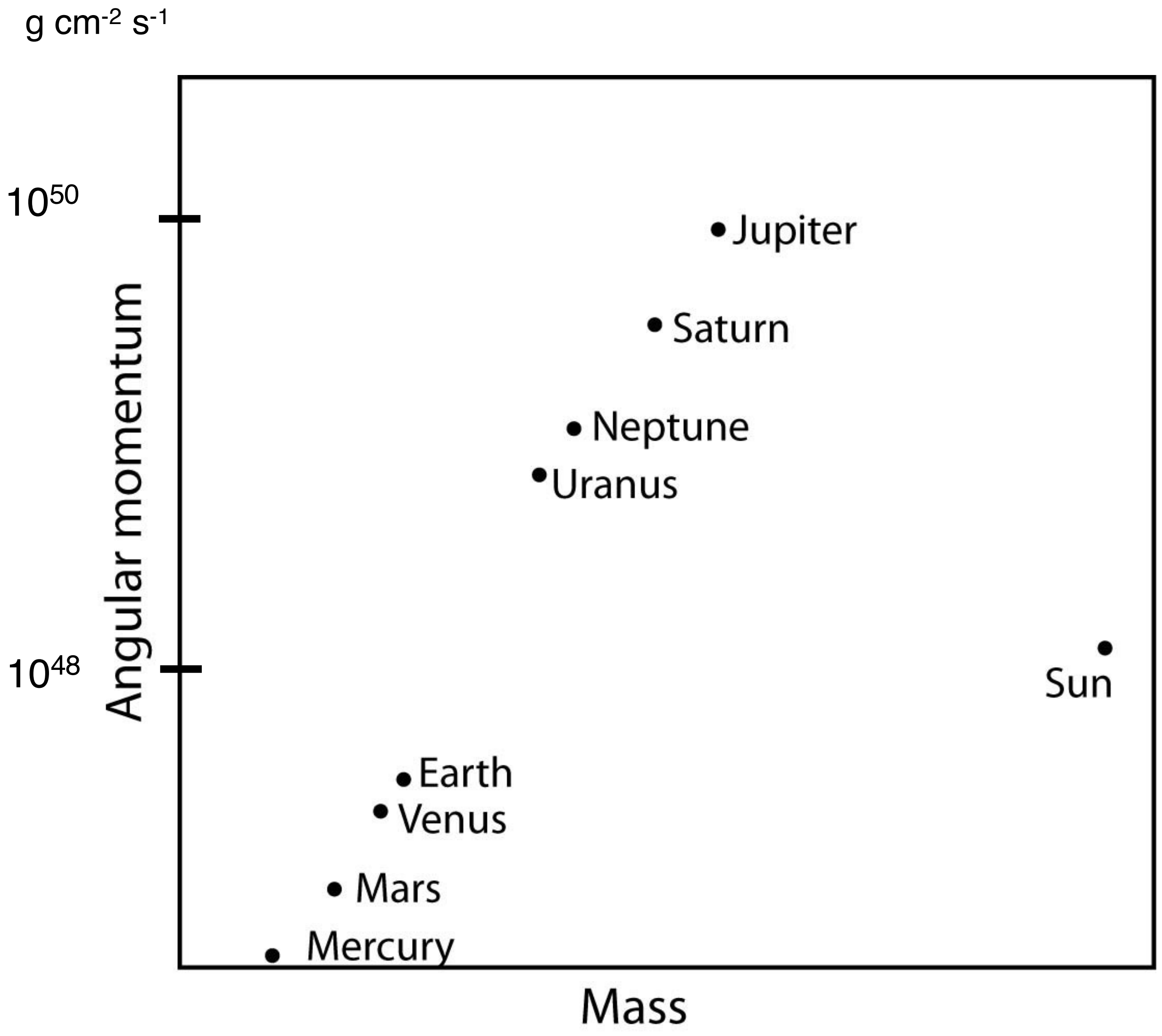


Fig. 11.—Distribution of β, shown for the 23 cores where enough information is available to calculate β *without* assuming virial equilibrium (i.e., the estimate of gravitational energy is based on the measured cloud size and a derived volume *density*, not on line width). Note that the value of $\beta = 1.4$ for L1495NW is not included in this distribution; this seemingly discrepant value is discussed in the text (§ 6.2).

β ~ 0.02 (<<1)

The Angular Momentum Problem



Angular Momentum of the Solar System:

Dominated by Jupiter's orbital angular momentum

100x larger than the ***Sun***'s spin angular momentum

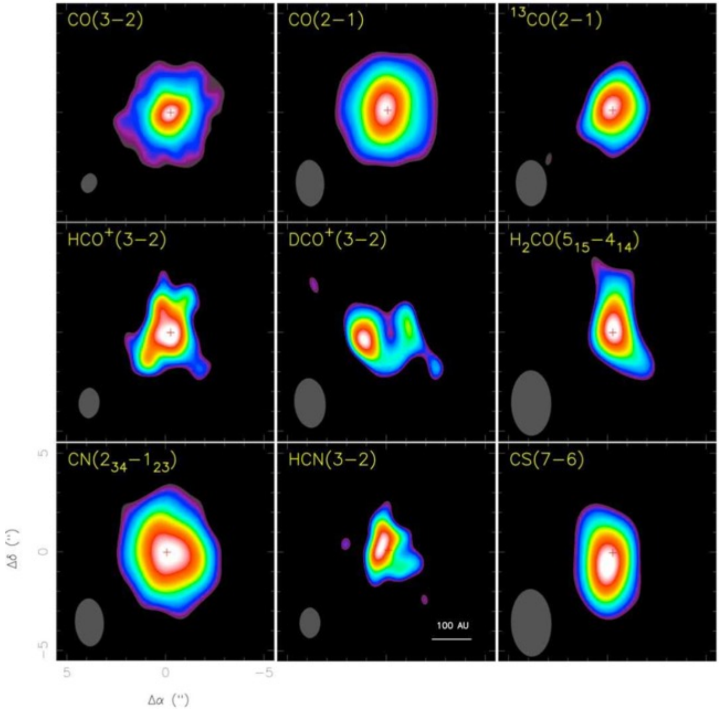
10,000x smaller than the angular momentum of a typical *molecular cloud core*.

HST view of disks in Orion

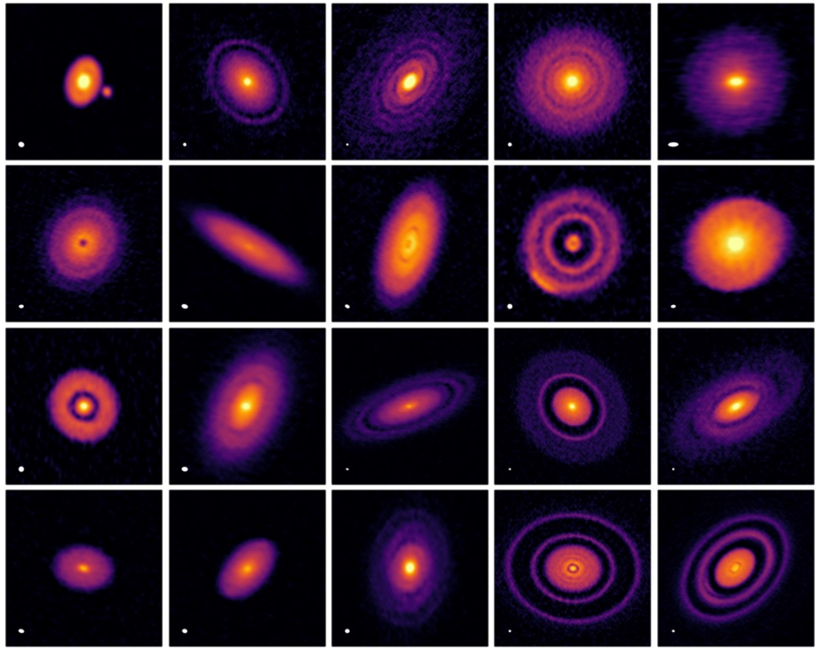
HST vs SMA vs ALMA

HST

SMA

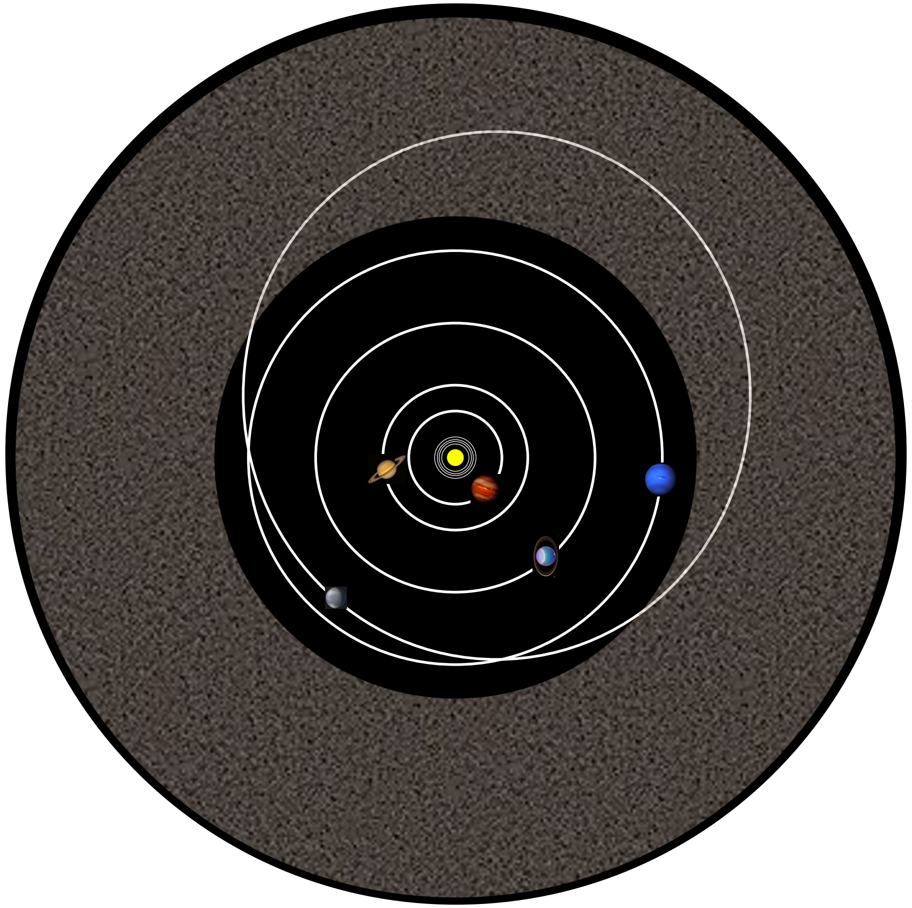


ALMA

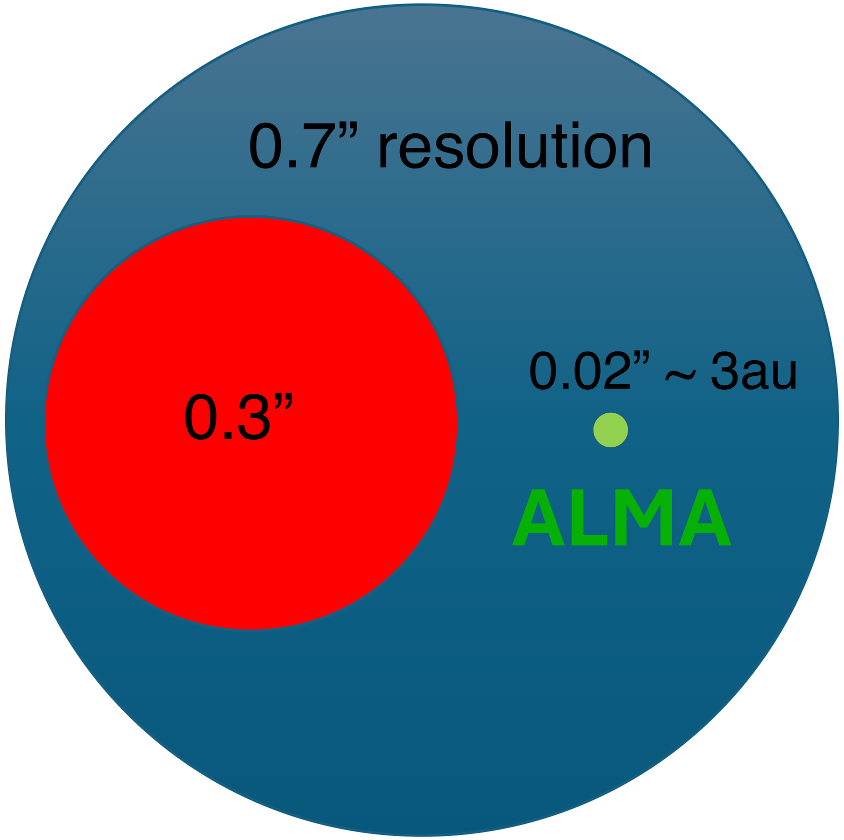


The Atacama Large (sub-)Millimeter Array (ALMA)

The ALMA Re~~v~~solution

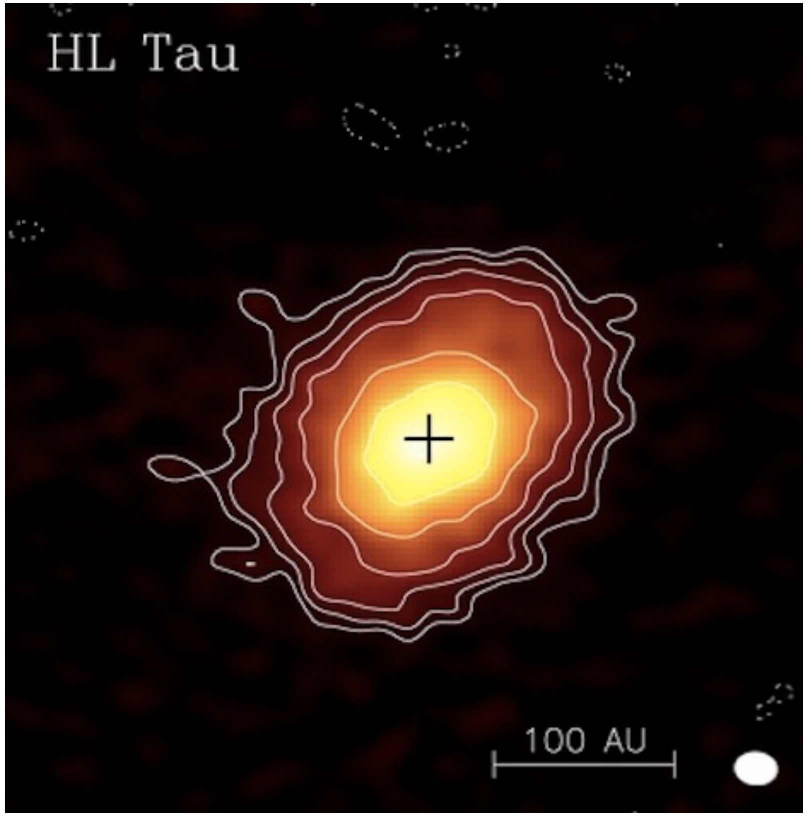


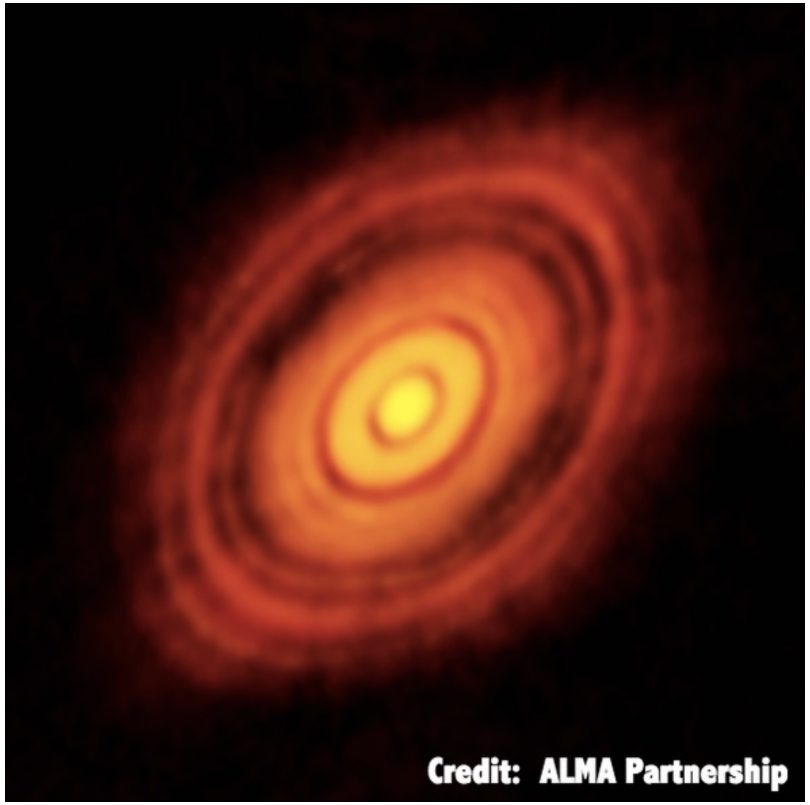
At 140 pc

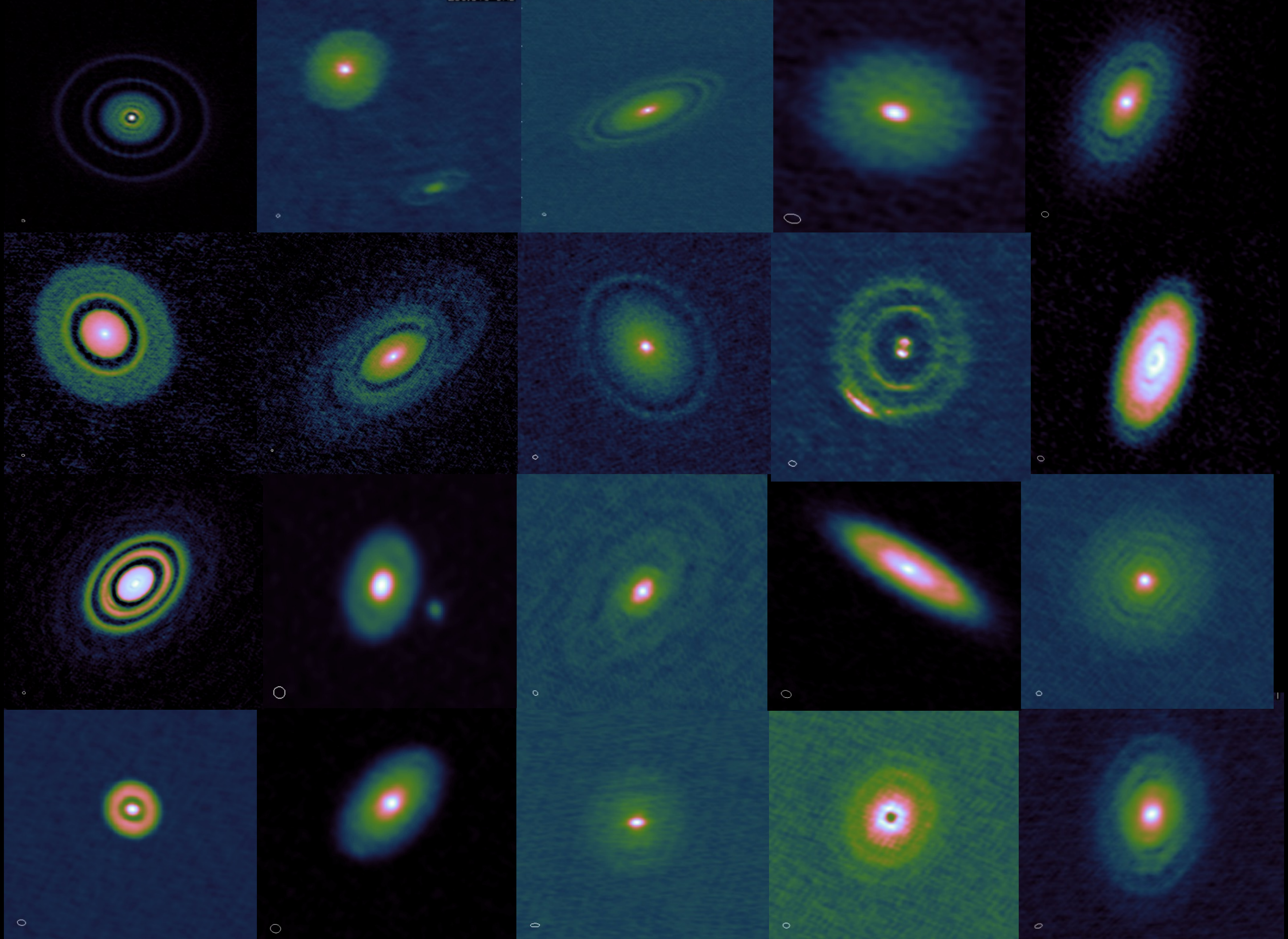


Before ALMA

ALMA







Distribution of Disk Sizes

Draft version January 16, 2020
Typeset using LaTeX **twocolumn** style in AASTeX62

The evolution of dust-disk sizes from a homogeneous analysis of 1-10 Myr-old stars

Nathanial Hendler,[1] Ilaria Pascucci,[1] Paola Pinilla,[2] Marco Tazzari,[3] John Carpenter,[4] Renu Malhotra,[1]
and Leonardo Testi[5]

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ABSTRACT

We utilize ALMA archival data to estimate the dust disk size of 152 protoplanetary disks in Lupus (1-3 Myr), Chamaeleon I (2-3 Myr), and Upper-Sco (5-11 Myr). We combine our sample with 47 disks from Tau/Aur and Oph whose dust disk radii were estimated, as here, through fitting radial profile models to visibility data. We use these 199 homogeneously derived disk sizes to identify empirical disk-disk and disk-host property relations as well as to search for evolutionary trends. In agreement with previous studies, we find that dust disk sizes and millimeter luminosities are correlated, but show for the first time that the relationship is not universal between regions. We find that disks in the 2-3 Myr-old Cha I are not smaller than disks in other regions of similar age, and confirm the Barenfeld et al. (2017) finding that the 5-10 Myr USco disks are smaller than disks belonging to younger regions. Finally, we find that the outer edge of the Solar System, as defined by the Kuiper Belt, is consistent with a population of dust disk sizes which have not experienced significant truncation.

Keywords: protoplanetary disks, stars: pre-main sequence, submillimeter: planetary systems

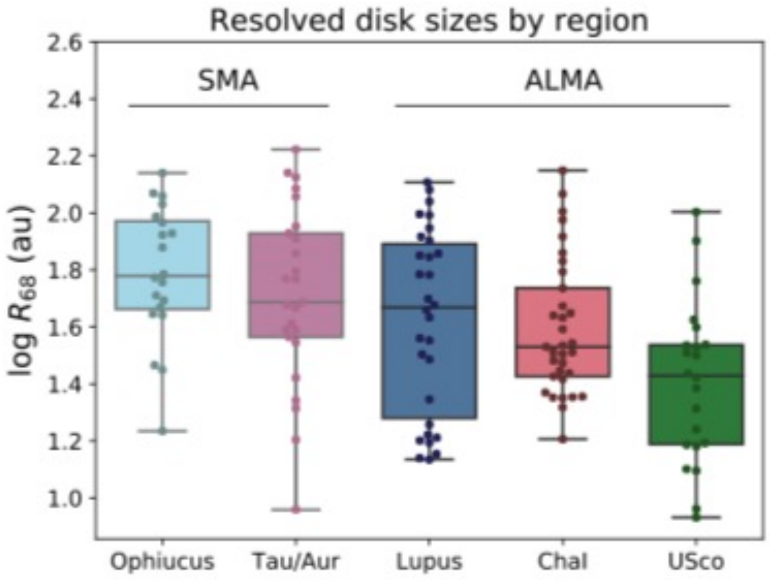
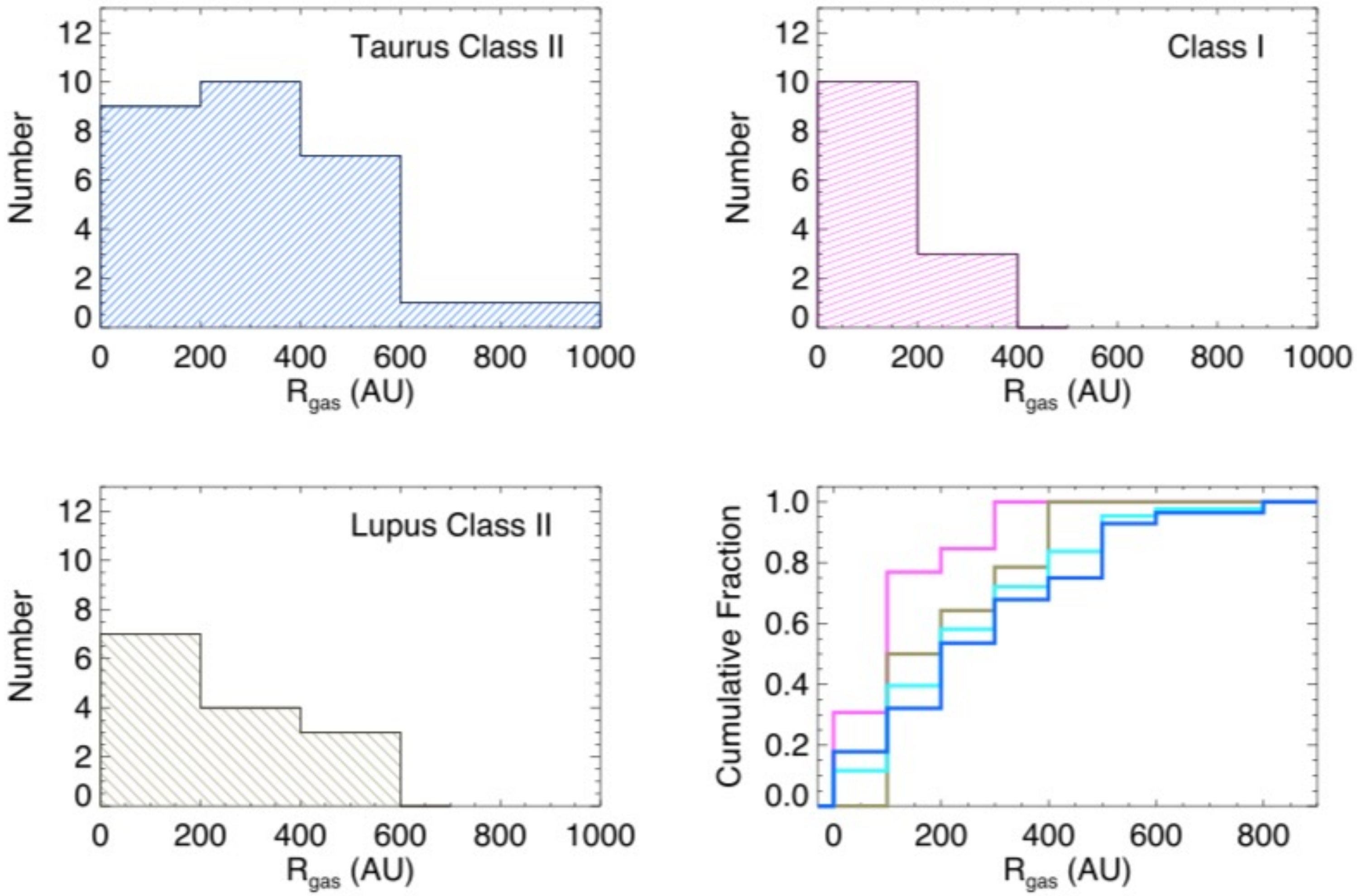


Figure 4. Swarmplots for resolved disks in different regions, ordered by age. The boxplots include a shaded region surrounding the R_{68} 25-75% quartiles, the horizontal line denotes the median disk size, while whiskers define the 0-25% and 75-100% quartiles. The regions observed with the SMA are greyed out because they are biased to the brightest millimeter disks, hence their size distributions should not be directly compared to the regions observed by ALMA.

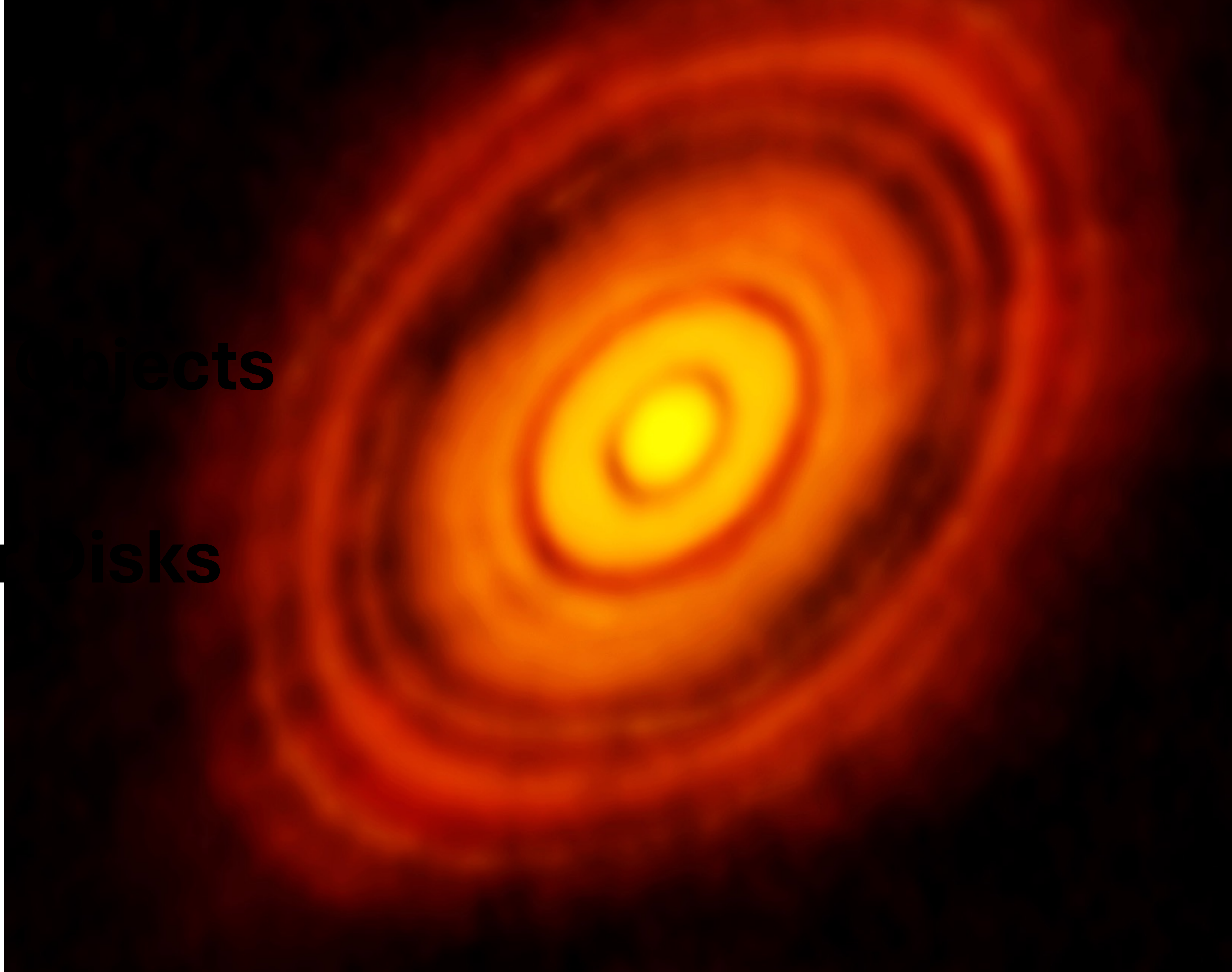
Distribution of Disk Sizes



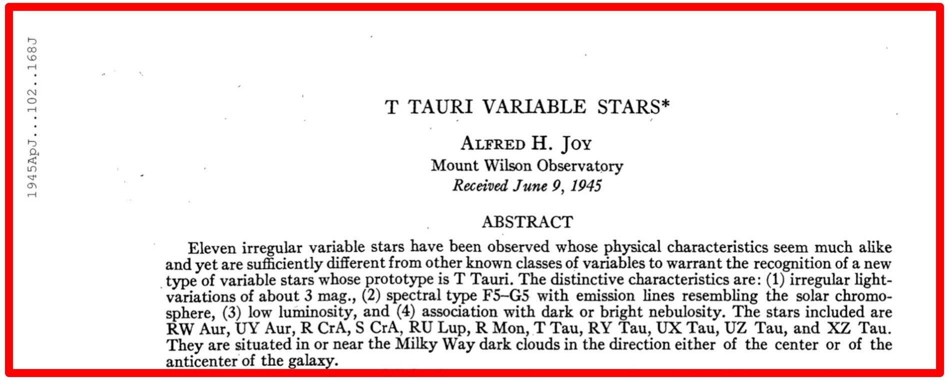
Key ideas so far

- Planets form in disks of gas and dust
  - Gas means 99% He and H
  - ”Dust” means ices and rock.
- A collapsing molecular cloud has too much angular momentum
  - A ~100au disk will form
- Disks have in average a mass ratio 0.01, although with considerable scatter.

Classes of Young Stellar Objects and Circumstellar Disks



T Tauri stars



T TAURI VARIABLE STARS*

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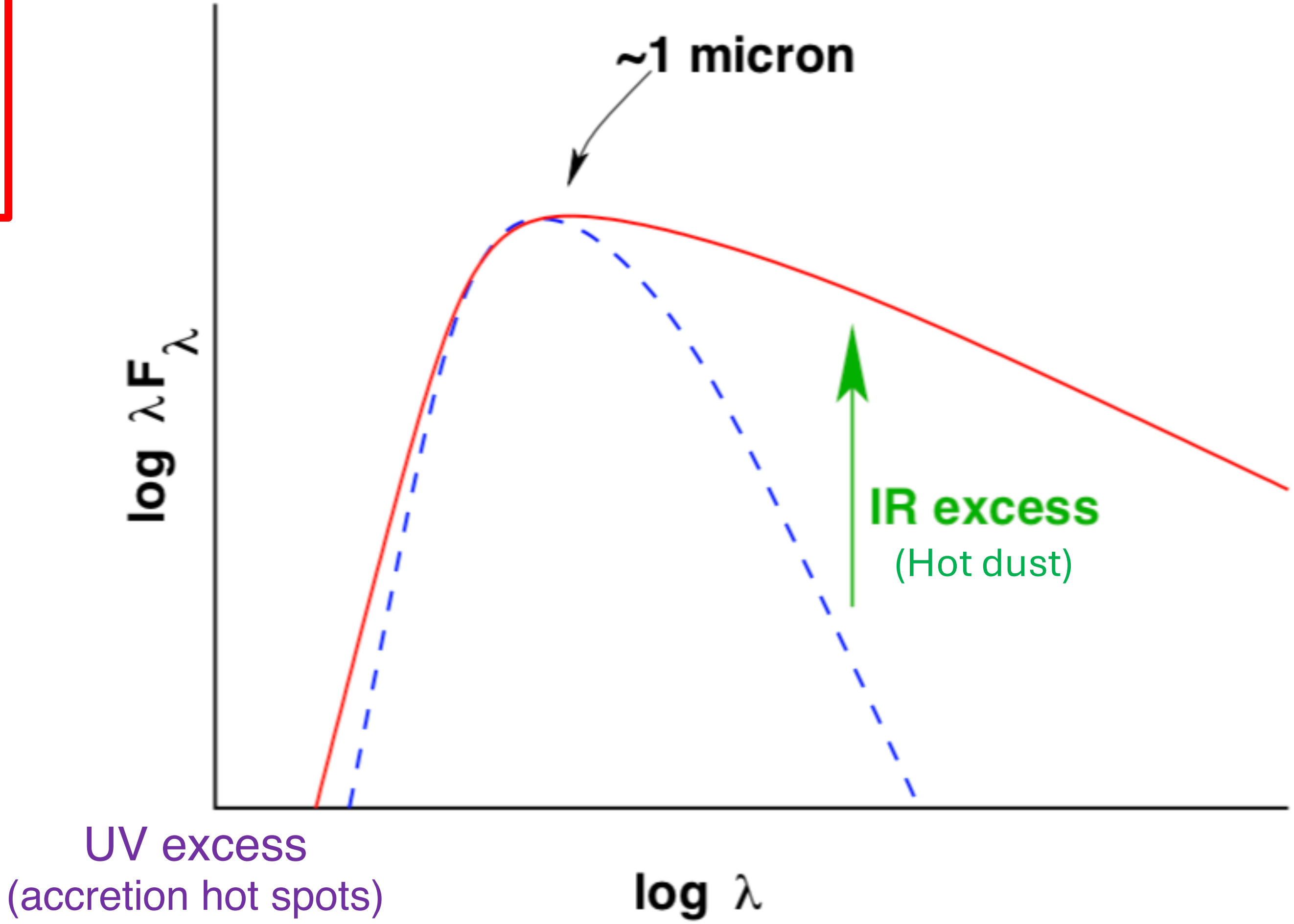
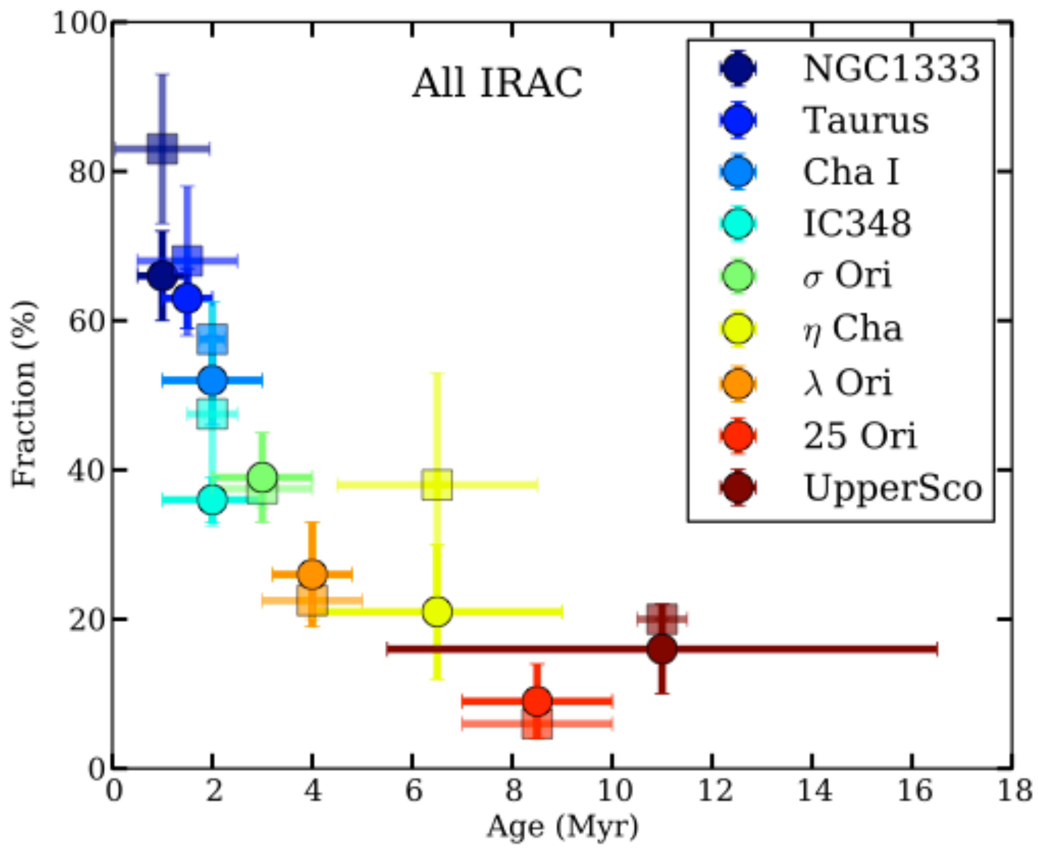
Received June 9, 1945

ABSTRACT

Eleven irregular variable stars have been observed whose physical characteristics seem much alike and yet are sufficiently different from other known classes of variables to warrant the recognition of a new type of variable stars whose prototype is T Tauri. The distinctive characteristics are: (1) irregular light-variations of about 3 mag., (2) spectral type F5–G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity. The stars included are RW Aur, UY Aur, R CrA, S CrA, RU Lup, R Mon, T Tau, RY Tau, UX Tau, UZ Tau, and XZ Tau. They are situated in or near the Milky Way dark clouds in the direction either of the center or of the anticenter of the galaxy.



Disk lifetime



(Ribas et al. 2014)

Disks dissipate within ~10Myr

A static description cannot be the full picture: **disks must evolve in time.**

α_{IR} and Infrared Excess

THE ASTROPHYSICAL JOURNAL, 420:837–862, 1994 January 10

FROM T TAURI STARS TO PROTOSTARS: CIRCUMSTELLAR MATERIAL AND YOUNG STELLAR OBJECTS IN THE ρ OPHIUCHI CLOUD

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Received 1992 November 30; accepted 1993 July 20

ABSTRACT

We present the results of a 1.3 mm continuum survey for cold circumstellar dust, conducted with the IRAM 30 m telescope on a sample of over 100 young stellar objects (YSOs) in or near the ρ Ophiuchi molecular cloud. To correlate the millimeter results with other source properties, we have used the IR classification of Wilking, Lada, & Young, but revising it critically to take into account factors such as heavy extinction. We find a sharp threshold in millimeter flux density at an infrared spectral index $\alpha_{IR}(2.2\text{–}10\ \mu m) \simeq -1.5$, which is also visible in the IRAM 30 m survey of Taurus-Auriga T Tauri stars by Beckwith and coworkers. We show that this threshold is well correlated with a disk opacity transition at $\lambda \simeq 10\ \mu m$, and can be used to set a physical boundary between Class III and Class II IR sources. At a detection sensitivity of $\sim$20–30 mJy beam^{-1} (3 σ) at 1.3 mm, less than 15% of the Class III IR sources, but as much as 60% of the Class II sources and 70%–90% of the Class I sources, are detected. Statistical studies show that the peak 1.3 mm fluxes of deeply embedded Class I sources, currently referred to as "protostars," and of "classical" T Tauri stars (Class II sources) are comparable within a factor of 2 at the angular resolution of the telescope (12″ FWHM, or a linear diameter $\sim$2000 AU). Maps of the millimeter emission are consistent with the presence of unresolved disks around Class II sources and of resolved, extended envelopes around Class I sources. Therefore, the difference between Class I and Class II YSOs lies mainly in the *spatial distribution* of their circumstellar dust. Converting the integrated millimeter fluxes derived from our maps into masses, we find that (1) $\sim$30% of the Class II sources have masses larger than the "minimum-mass solar nebula" ($\sim$0.01 $M_\odot$); (2) the envelopes of Class I sources contain more circumstellar material than Class II disks, consistent with Class I sources being younger than Class II sources; but (3) their total circumstellar masses are not large ($\lesssim$0.1 $M_\odot$). This suggests that the central object has already accumulated most of its final stellar mass at the Class I stage. In contrast, a very strong 1.3 mm emission is found toward two deeply embedded outflow sources (IRAS 16293 and VLA 1623) which remain undetected shortward of 25 μm. These latter sources belong to a new class of YSOs ("Class 0") introduced by André, Ward-Thompson, & Barsony, which are surrounded by significantly larger amounts of circumstellar material ($\sim$0.5 $M_\odot$ or more), still to be accreted by the central protostellar core. Class 0 YSOs appear to be significantly younger, and therefore at an earlier protostar stage, than Class I sources.

Subject headings: circumstellar matter — dust, extinction — ISM: individual (ρ Ophiuchi) — radio continuum: stars — stars: pre–main-sequence

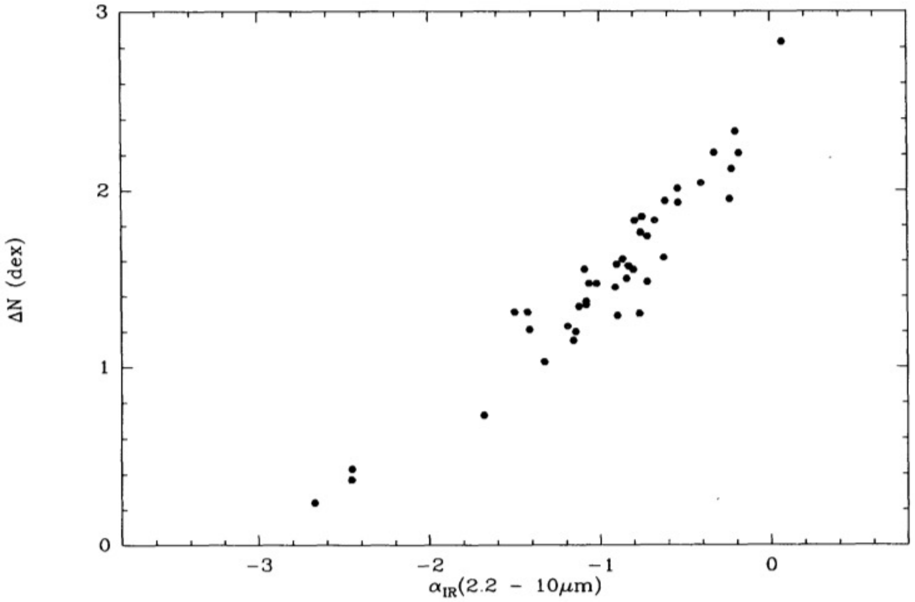
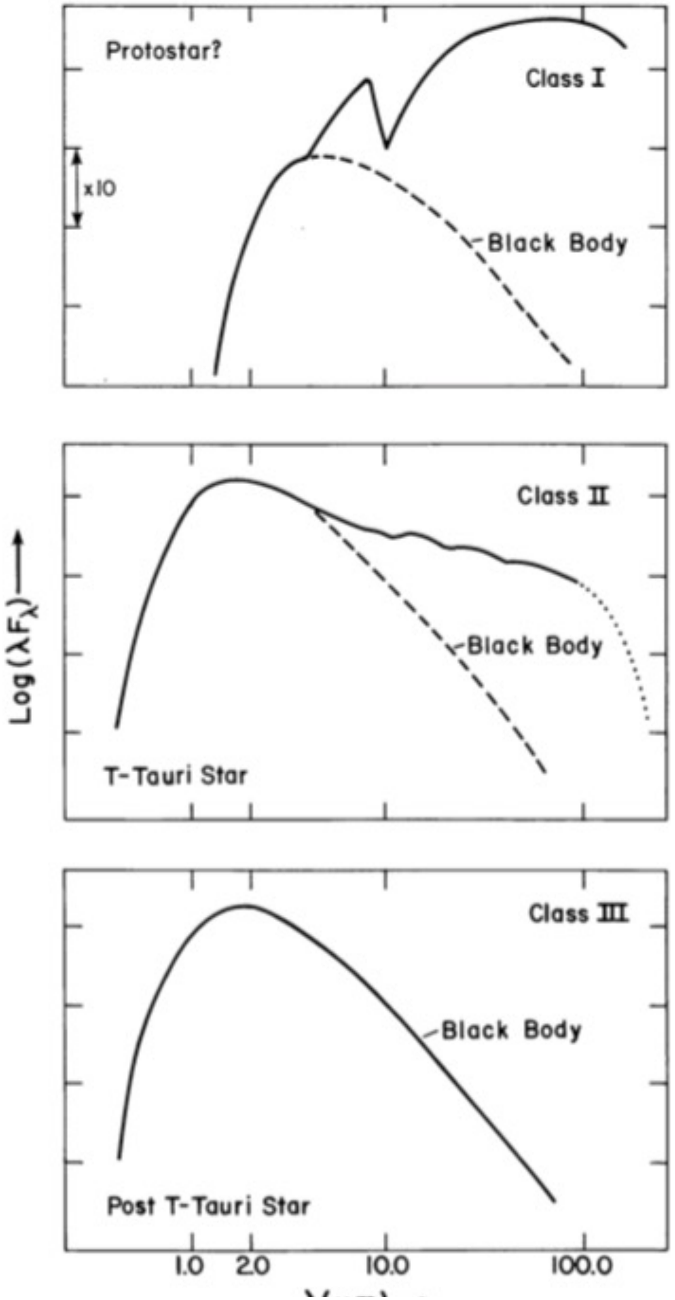


FIG. 2.—Plot of the 10 μm IR excess ΔN vs. the near-IR spectral index α_{IR} measured between 2.2 and 10 μm, for the T Tauri stars of Taurus-Auriga. The good correlation suggests that α_{IR} may be used as an indicator of the 10 μm excess for highly extinguished stars where it is difficult to measure directly by comparison with the photosphere. $\Delta N \sim 1$ marks the boundary between optically thin and optically thick disk emission at 10 μm (cf. Skrutskie et al. 1990).

Classification of T-Tauri stars



STAR FORMATION: FROM OB ASSOCIATIONS TO PROTOSTARS

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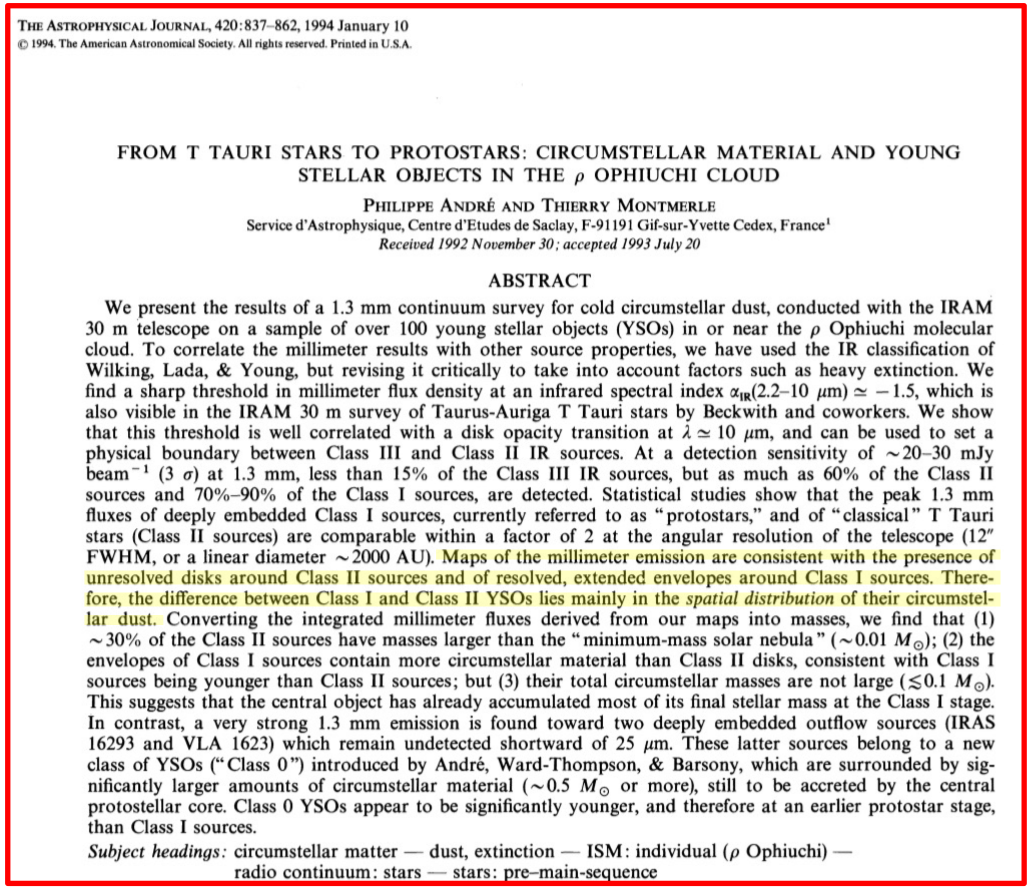
4.2. An Evolutionary Sequence?

Does the more or less continous variation in the spectral shapes of embedded infrared sources represent a sequence of evolution for protostars and young stellar objects? Most class II and III objects are associated with visible stars, mostly T Tauri stars and PMS stars. On the other hand, most class I objects are invisible and heavily obscured. Consequently their nature is difficult to ascertain. They could be protostars, or very deeply embedded T Tauri-PMS stars or some intermediate type of object. However, it is unlikely that they are merely more heavily reddened versions of T Tauri stars because examples of such stars exist in the Ophiuchi cluster and their energy distributions are typically flat or decreasing at long wavelengths (similar to optically visible T Tauri stars but unlike class I objects), but are considerably steeper at shorter wavelengths than the visible T Tauri stars. It is possible that class I objects are protostars, although many are the driving sources of molecular outflows a circumstance that has been interpreted to indicate that such objects are in a post-protostar phase of very early stellar evolution (Wynn-Williams 1982; Lada 1985). Recent theoretical models which predict the emergent energy distributions of low mass protostars strongly suggest that class I objects are indeed objects in the process of building up mass by the accretion of infalling circumstellar matter (Adams and Shu 1985, Shu, Lizano and Adams, this conference). In any event it appears evident and it is reasonable to assume that class I objects are in a much younger stage of development than class II sources. Since class III sources are stars with very little near in circumstellar dust it also seems reasonable to assume that they are the most removed in time from the events of stellar formation and the most evolved of the infrared sources.

T-Tauri classes as an evolutionary sequence



THE ASTROPHYSICAL JOURNAL, 420:837–862, 1994 January 10

FROM T TAURI STARS TO PROTOSTARS: CIRCUMSTELLAR MATERIAL AND YOUNG STELLAR OBJECTS IN THE ρ OPHIUCHI CLOUD

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Received 1992 November 30; accepted 1993 July 20

ABSTRACT

We present the results of a 1.3 mm continuum survey for cold circumstellar dust, conducted with the IRAM 30 m telescope on a sample of over 100 young stellar objects (YSOs) in or near the ρ Ophiuchi molecular cloud. To correlate the millimeter results with other source properties, we have used the IR classification of Wilking, Lada, & Young, but revising it critically to take into account factors such as heavy extinction. We find a sharp threshold in millimeter flux density at an infrared spectral index $\alpha_{IR}(2.2\text{–}10\ \mu m) \simeq -1.5$, which is also visible in the IRAM 30 m survey of Taurus-Auriga T Tauri stars by Beckwith and coworkers. We show that this threshold is well correlated with a disk opacity transition at $\lambda \simeq 10\ \mu m$, and can be used to set a physical boundary between Class III and Class II IR sources. At a detection sensitivity of $\sim$20–30 mJy beam^{-1} (3 σ) at 1.3 mm, less than 15% of the Class III IR sources, but as much as 60% of the Class II sources and 70%–90% of the Class I sources, are detected. Statistical studies show that the peak 1.3 mm fluxes of deeply embedded Class I sources, currently referred to as "protostars," and of "classical" T Tauri stars (Class II sources) are comparable within a factor of 2 at the angular resolution of the telescope (12″ FWHM, or a linear diameter $\sim$2000 AU). Maps of the millimeter emission are consistent with the presence of unresolved disks around Class II sources and of resolved, extended envelopes around Class I sources. Therefore, the difference between Class I and Class II YSOs lies mainly in the *spatial distribution* of their circumstellar dust. Converting the integrated millimeter fluxes derived from our maps into masses, we find that (1) $\sim$30% of the Class II sources have masses larger than the "minimum-mass solar nebula" ($\sim$0.01 $M_\odot$); (2) the envelopes of Class I sources contain more circumstellar material than Class II disks, consistent with Class I sources being younger than Class II sources; but (3) their total circumstellar masses are not large ($\lesssim$0.1 $M_\odot$). This suggests that the central object has already accumulated most of its final stellar mass at the Class I stage. In contrast, a very strong 1.3 mm emission is found toward two deeply embedded outflow sources (IRAS 16293 and VLA 1623) which remain undetected shortward of 25 μm. These latter sources belong to a new class of YSOs ("Class 0") introduced by André, Ward-Thompson, & Barsony, which are surrounded by significantly larger amounts of circumstellar material ($\sim$0.5 $M_\odot$ or more), still to be accreted by the central protostellar core. Class 0 YSOs appear to be significantly younger, and therefore at an earlier protostar stage, than Class I sources.

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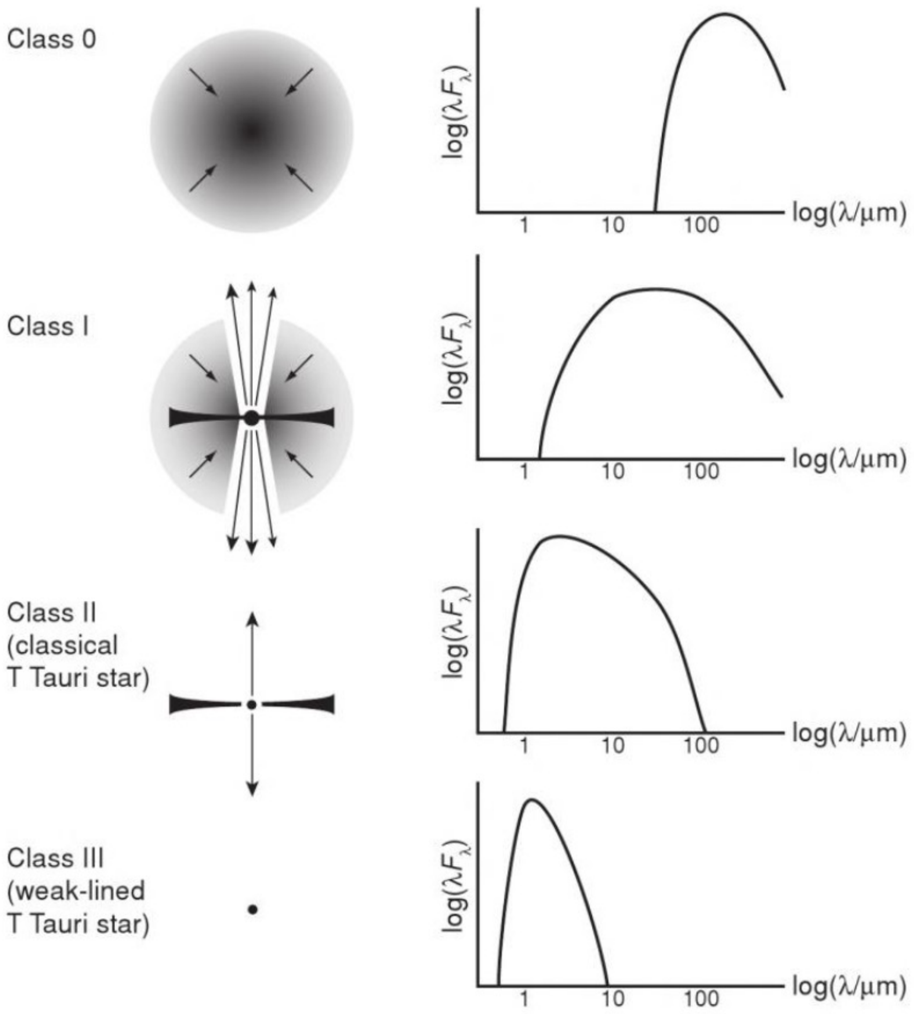


T-Tauri classes as an evolutionary sequence

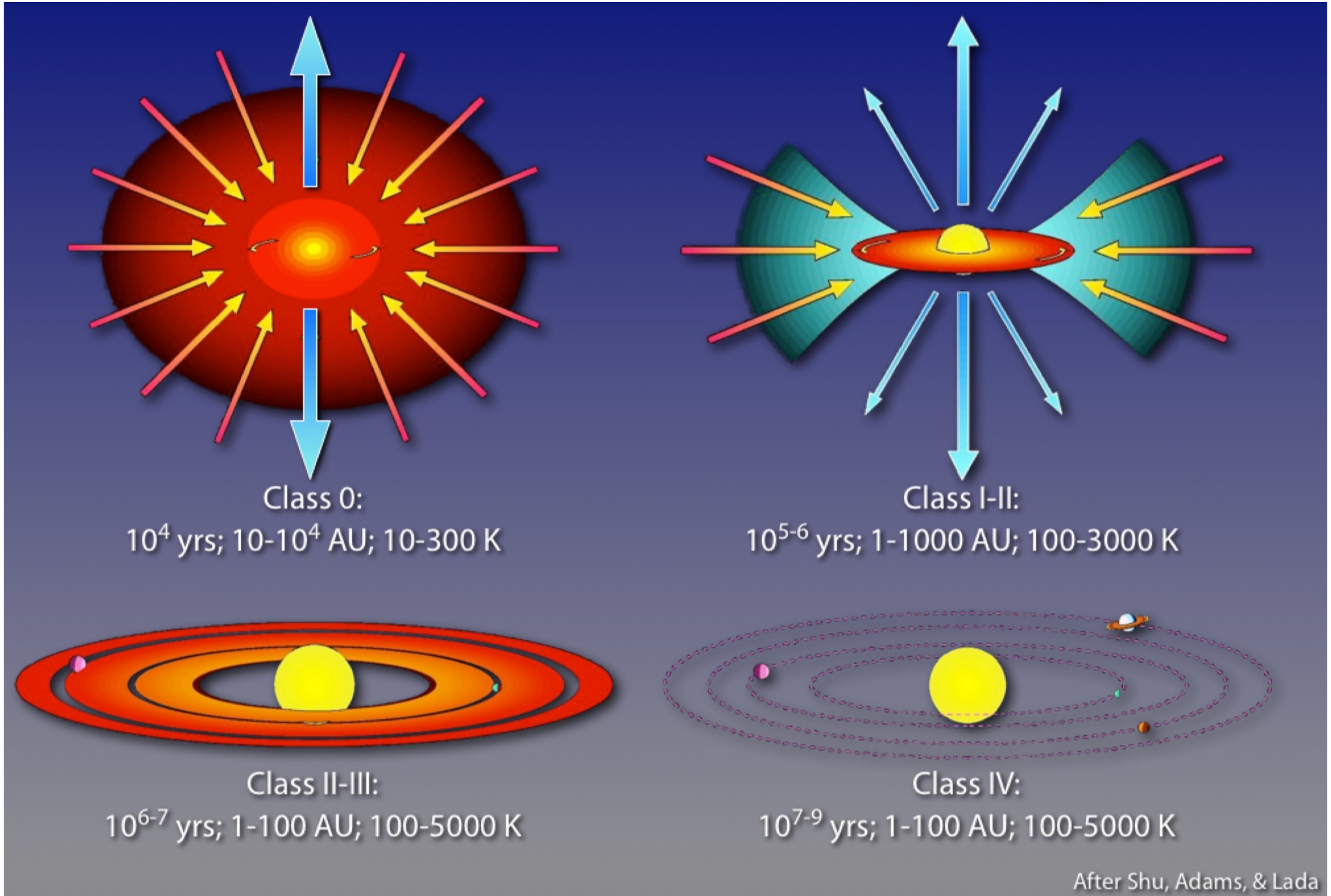


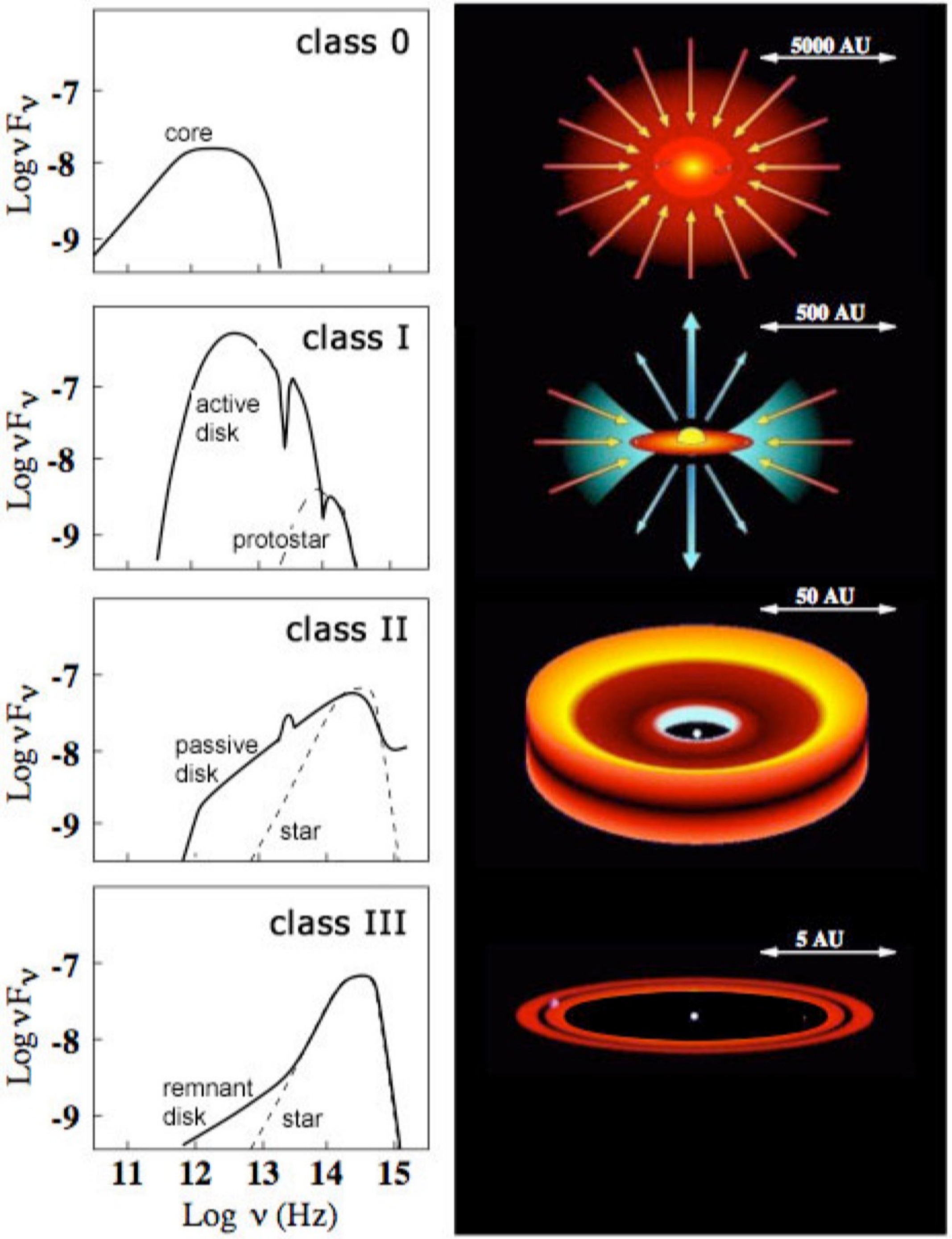
Table 1 Classification of young stellar objects

Class	SED slope	Physical properties	Observational characteristics
0	–	$M_{\rm env} > M_{\rm star} > M_{\rm disk}$	No optical or near-IR emission
I	$\alpha_{\rm IR} > 0.3$	$M_{\rm star} > M_{\rm env} \sim M_{\rm disk}$	Generally optically obscured
FS	$-0.3 < \alpha_{\rm IR} < 0.3$		Intermediate between Class I and II
II	$-1.6 < \alpha_{\rm IR} < -0.3$	$M_{\rm disk}/M_{\rm star} \sim 1\%,\ M_{\rm env} \sim 0$	Accreting disk; strong Hα and UV
III	$\alpha_{\rm IR} < -1.6$	$M_{\rm disk}/M_{\rm star} \ll 1\%,\ M_{\rm env} \sim 0$	Passive disk; no or very weak accretion

- IR-based classification: Lada & Wilking (1984)
- Class I-II-III
- Spectral slope between 2 and 25 μm

$$\alpha_{\rm IR} = \frac{d \log \nu F_\nu}{d \log \nu} = \frac{d \log \lambda F_\lambda}{d \log \lambda}$$

- Flat spectrum; Class 0
- CTTS / WTTS EW(Hα) ~ 10 Å



Evolution summary (Spitzer Core to Disk Legacy)

The Astrophysical Journal Supplement Series, 181:321–350, 2009 April doi:10.1088/0067-0049/181/2/321

THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

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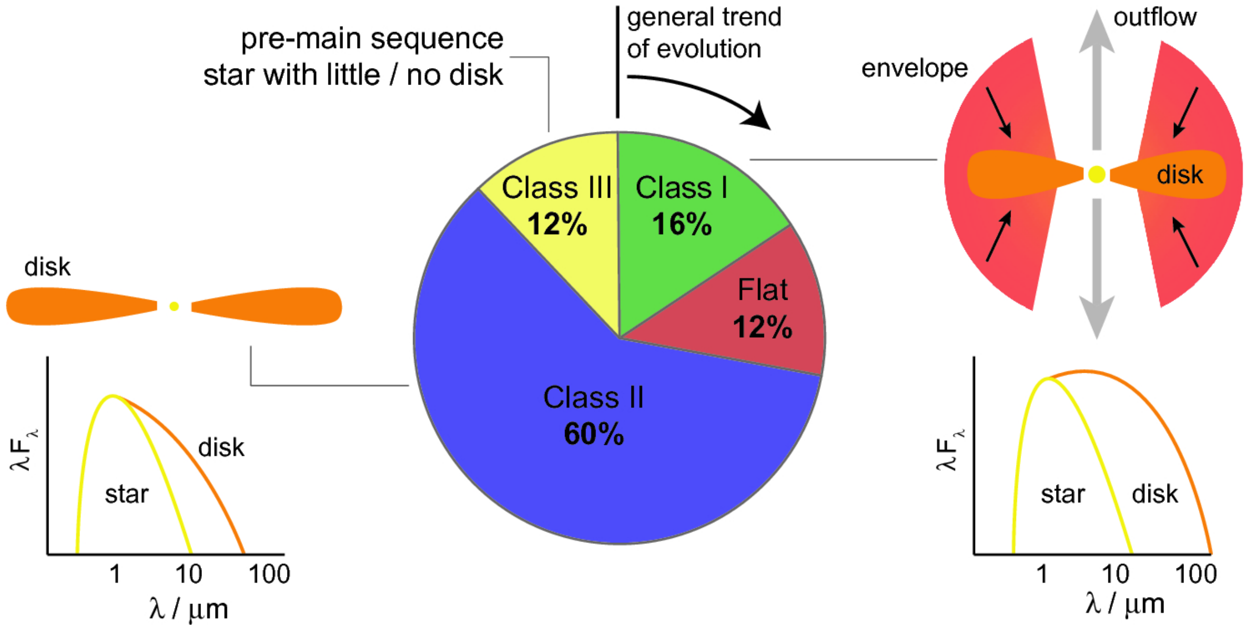
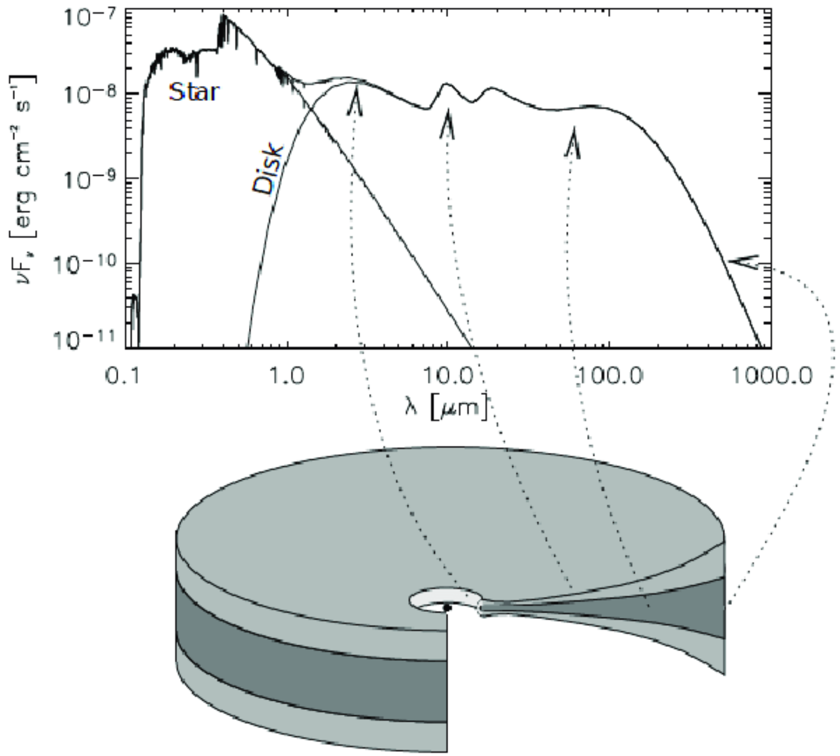
Received 2008 August 2; accepted 2008 November 3; published 2009 March 11



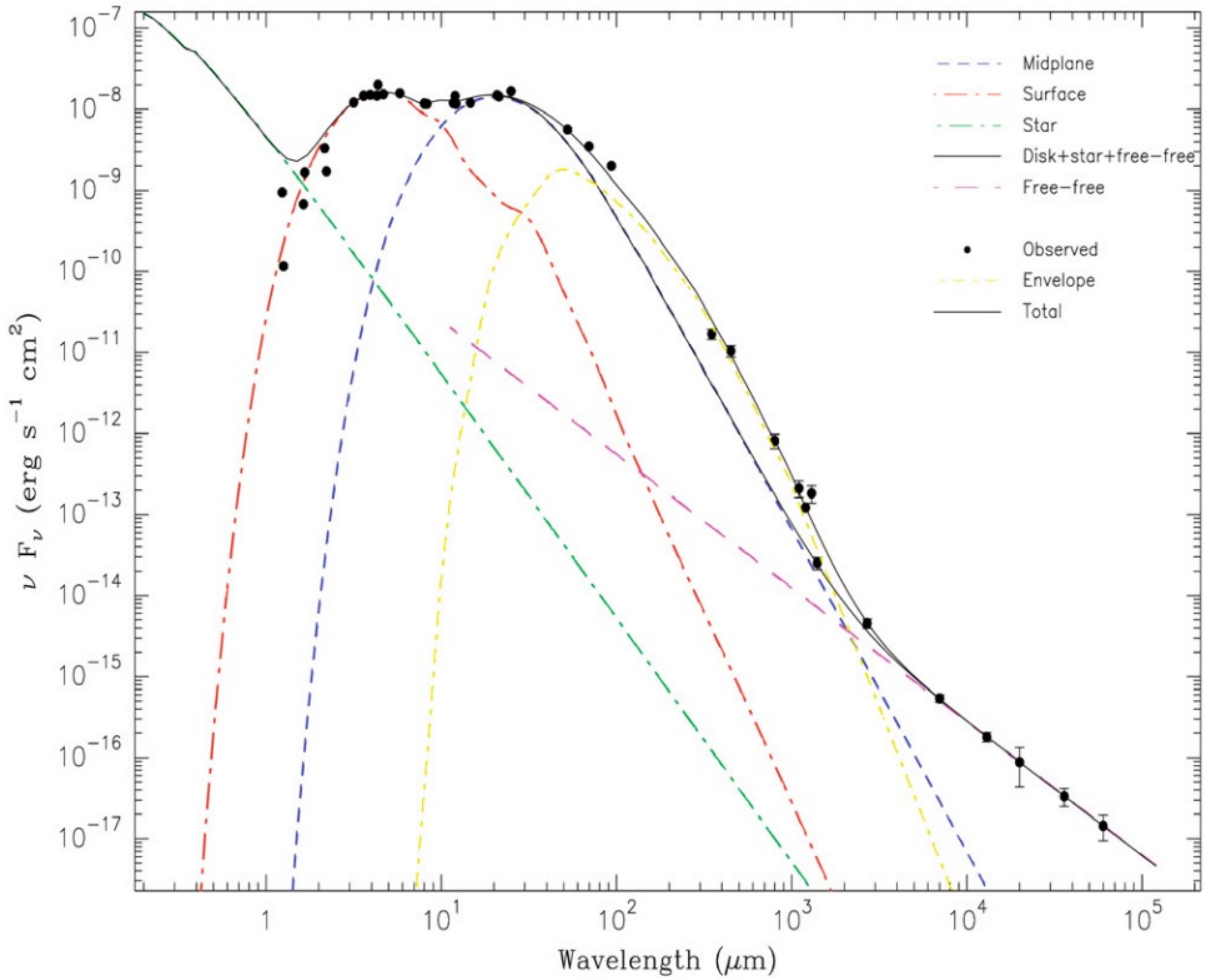
Class II is the (main) epoch of planet formation

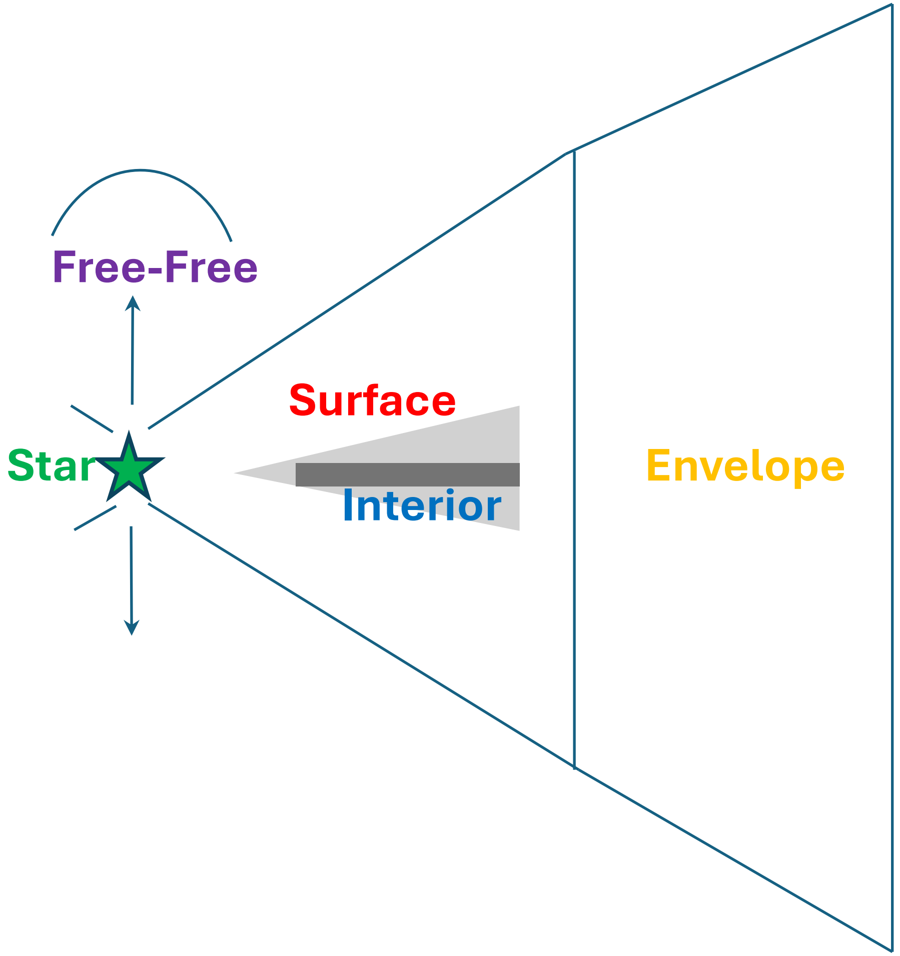
Disks are optically thick in infrared and optically thin in millimeter



To witness planet formation we must observe in millimeter

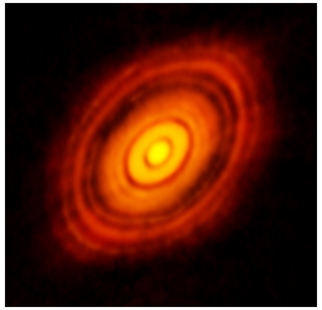
SED fitting for R Mon

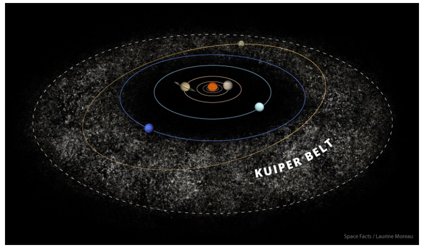




New Developments since the 1980s and 1990s

- Observations of Protoplanetary Disks
  (initial conditions)





- Discovery of the Kuiper Belt
  (frozen leftovers of formations)
- Discovery of extrasolar planets
  (confirm earlier ideas but also points to diversity of outcomes)
- Formulation of the models of
  - *Core Accretion*
  - *Streaming Instability*
  - *Pebble Accretion*
  - *Vortex Trapping*