Protoplanetary Disks

UNM Planetary Astrophysics

November 9, 2021

Guest Lecture by Dr. Dana Anderson

Image Source: Luis Calcada

Dr. Dana Anderson

LSA CHEMISTRY
UNIVERSITY OF MICHIGAN

CALIFORNIA INSTITUTE OF TECHNOLOGY
GEOLOGICAL AND PLANETARY SCIENCES
Labor Bonus et Multus

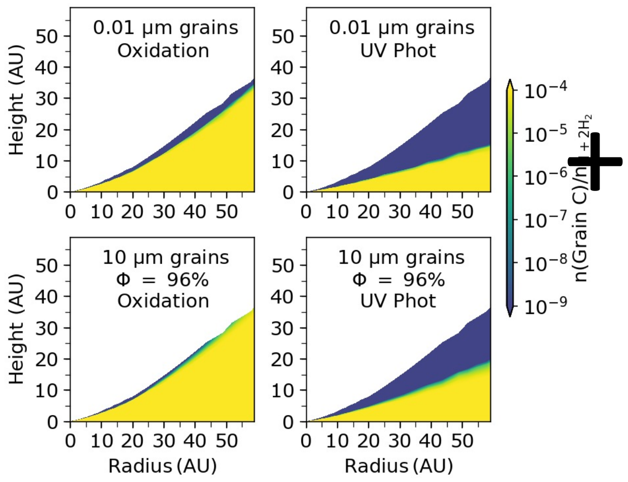
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

UNIVERSITY of VIRGINIA

VIRGINIA INITIATIVE ON COSMIC ORIGINS

I study chemistry in planet-forming "protoplanetary" disks around young stars

Using a combination of observations and computational models



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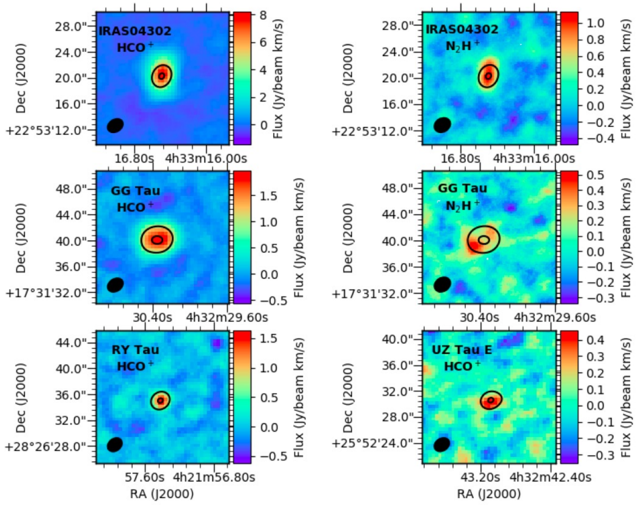


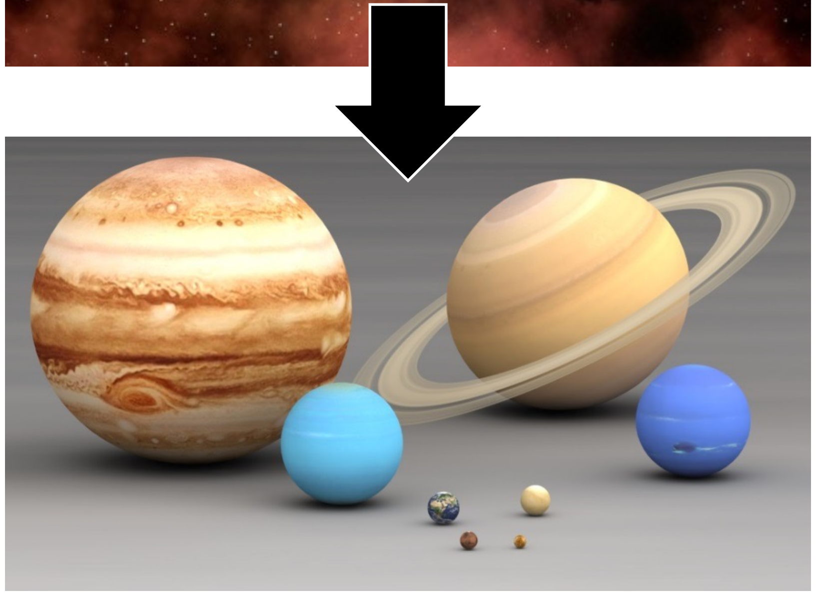


Image credits: Artist's rendition, NASA/JPL-Caltech/R. Gutermuth (Harvard-Smithsonian Center for Astrophysics); pics-about-space.com

Q1: What are protoplanetary disks?

Q2: Why do protoplanetary disks form?

Q3: How do we know protoplanetary disks exist?
(& How do we study them?)

Q4: How do protoplanetary disks relate to the planets that form from them?

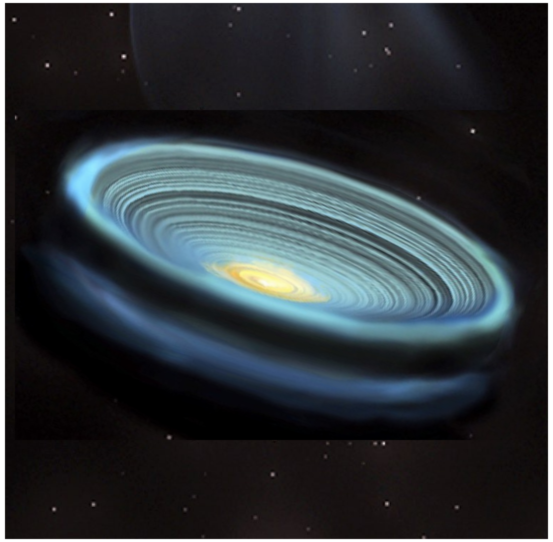
Q5: What happens to protoplanetary disks?

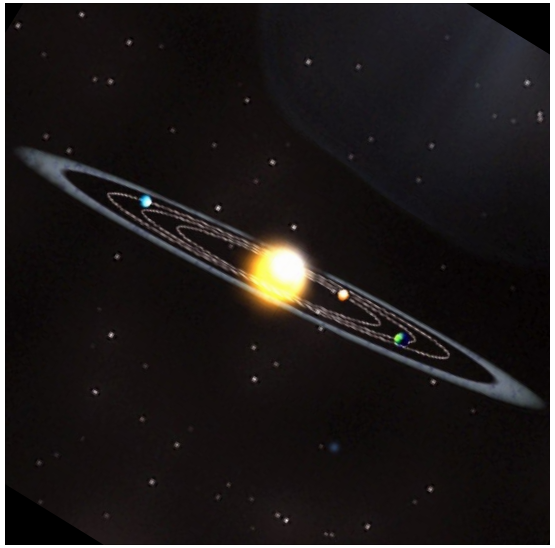
Q1: What are protoplanetary disks?

FORMING A STAR AND PLANETARY SYSTEM


~10s of Myr


~100s of kyr


~1-20 Myr


> Myr - Gyr

Slide modified from Cleeves

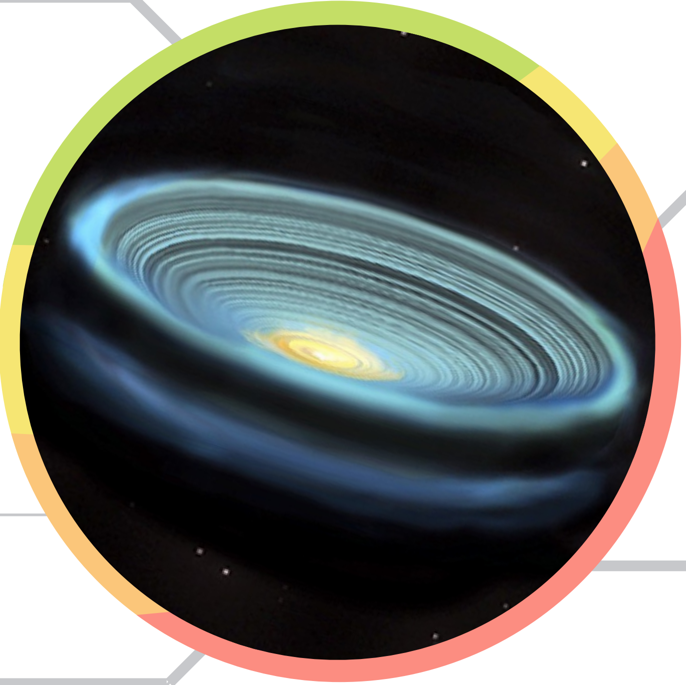
PRIMARILY MOLECULAR HYDROGEN H_2

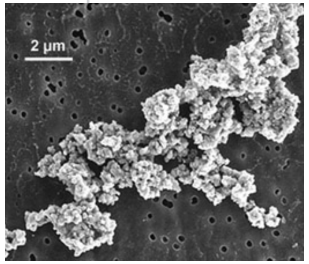
92%

HELIUM

8%

OTHER DOMINANT GASES INCLUDE CO, N_2

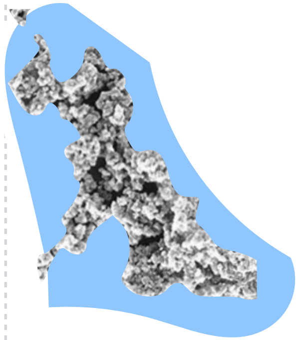




DUST

1% OF THE TOTAL MASS, INITIALLY MICRON-SIZED

ICES (H_2O, CO_2, NH_3)



T~10-100 K

n~10^6-10^{12} cm^{-3}

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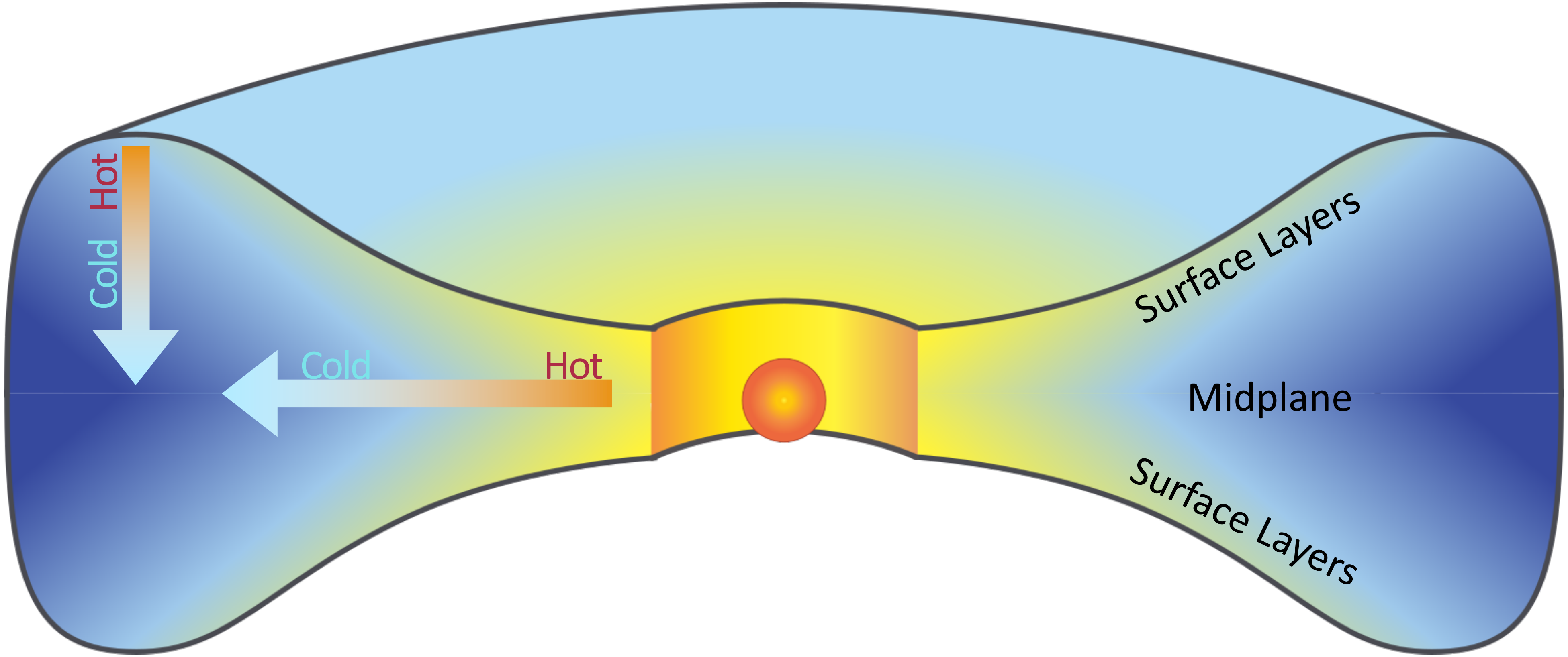
DISK GAS COMPOSITION

Gas & dust densities are higher in the disk midplane and closer to the star



Dust plays an important role in temperatures as well as radiation propagation, including shielding the disk rom stellar UV and X-rays

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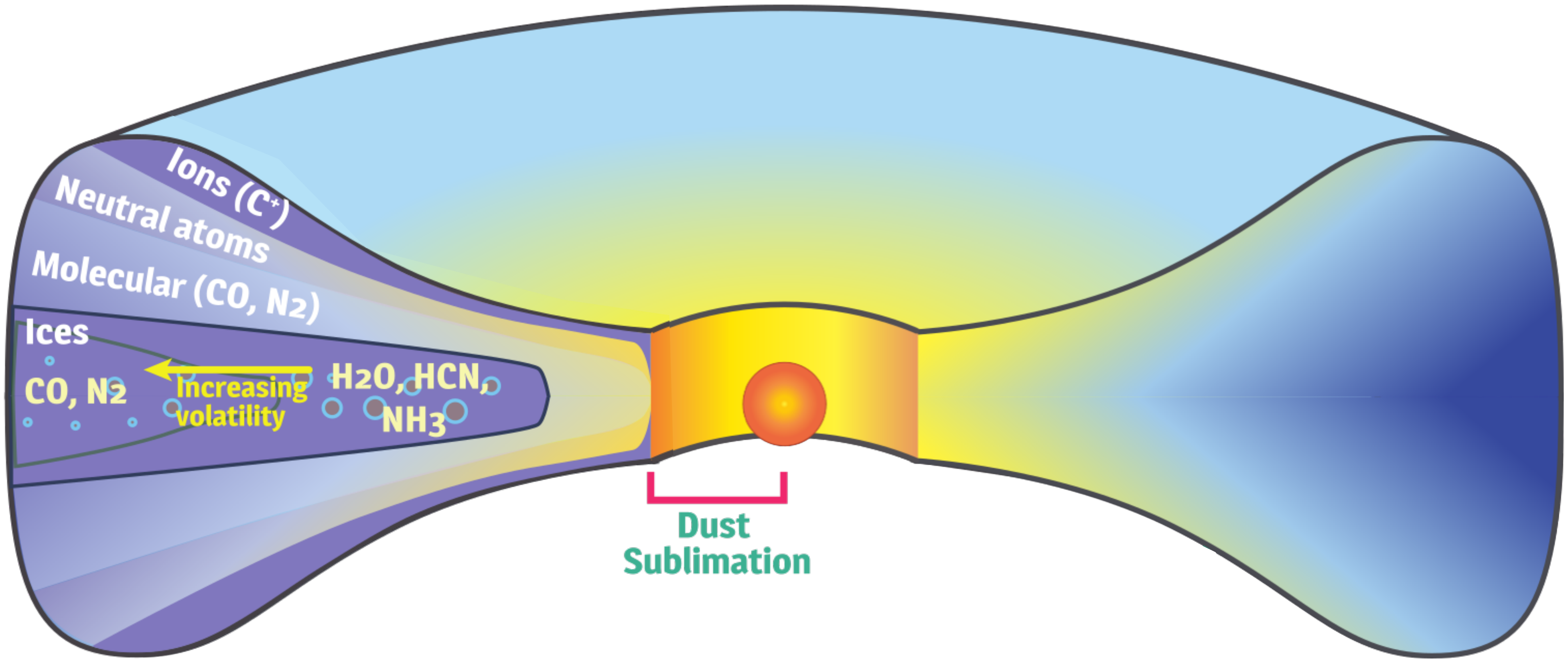
DISK GAS COMPOSITION



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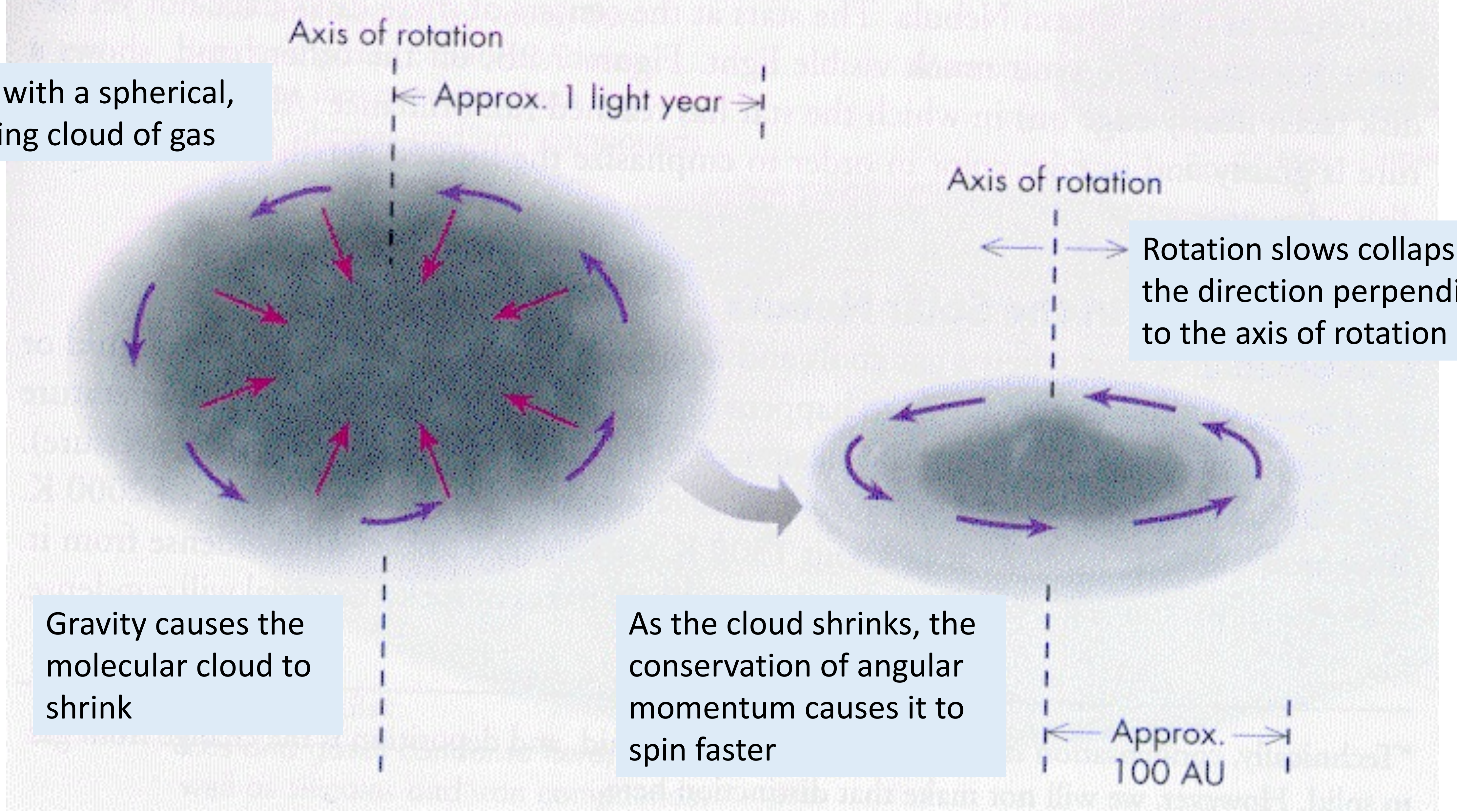
Q2: Why do protoplanetary disks form?

Interstellar Molecular Cloud **Protoplanetary Disk**



Start with a spherical, rotating cloud of gas

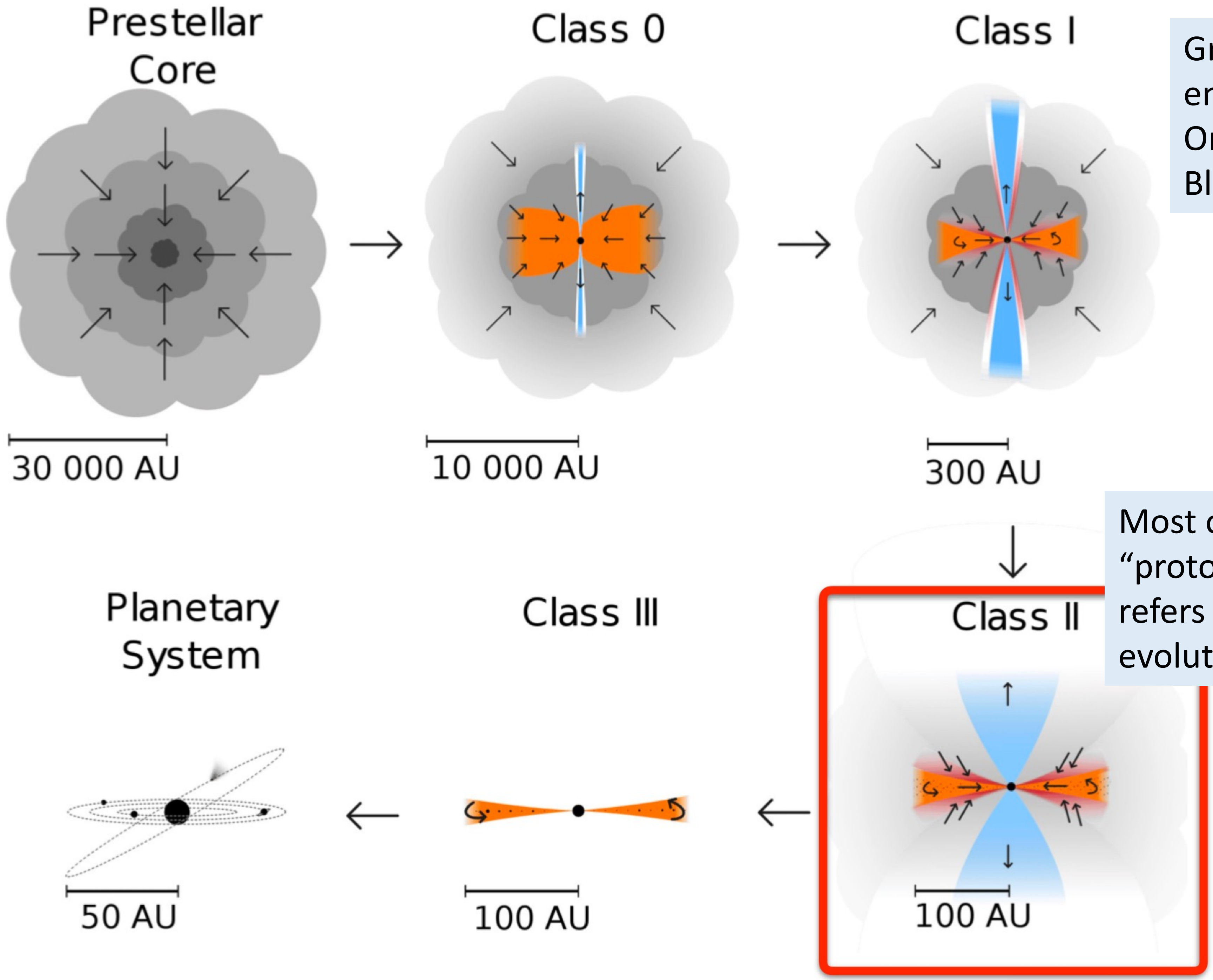
Gravity causes the molecular cloud to shrink

As the cloud shrinks, the conservation of angular momentum causes it to spin faster

Rotation slows collapse in the direction perpendicular to the axis of rotation

http://burro.case.edu/Academics/Astr221/SolarSys/Formation/starform.html

Multiple stages of disk formation and evolution



Gray = Cloud or envelope material
Orange = Disk
Blue = Outflow

Most often the term “protoplanetary disk” refers to the Class II evolutionary stage

Image credit: M. Persson

Evolution of protoplanetary disks driven by disk accretion

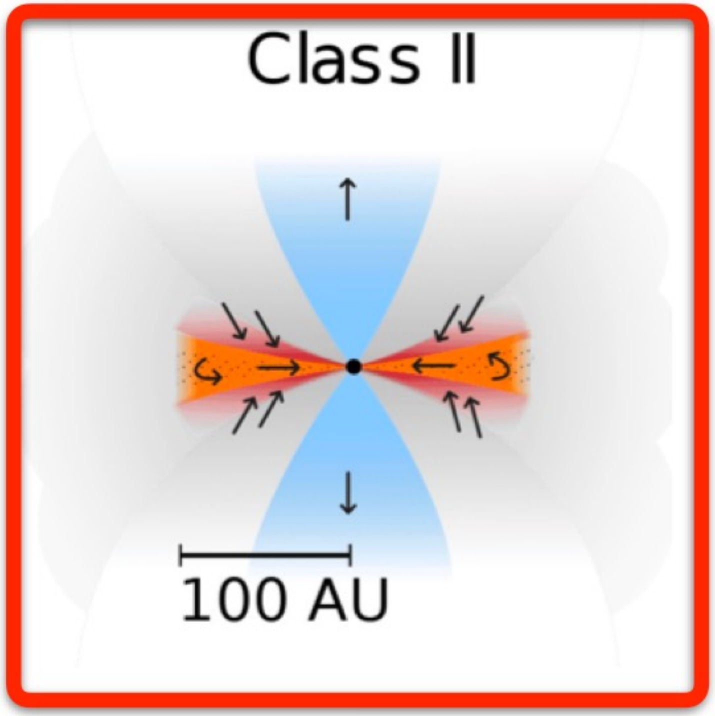


Image credit: M. Persson

In disks, there is a net transport of mass inward and angular momentum outward

What is the physical origin of angular momentum transport in disks?

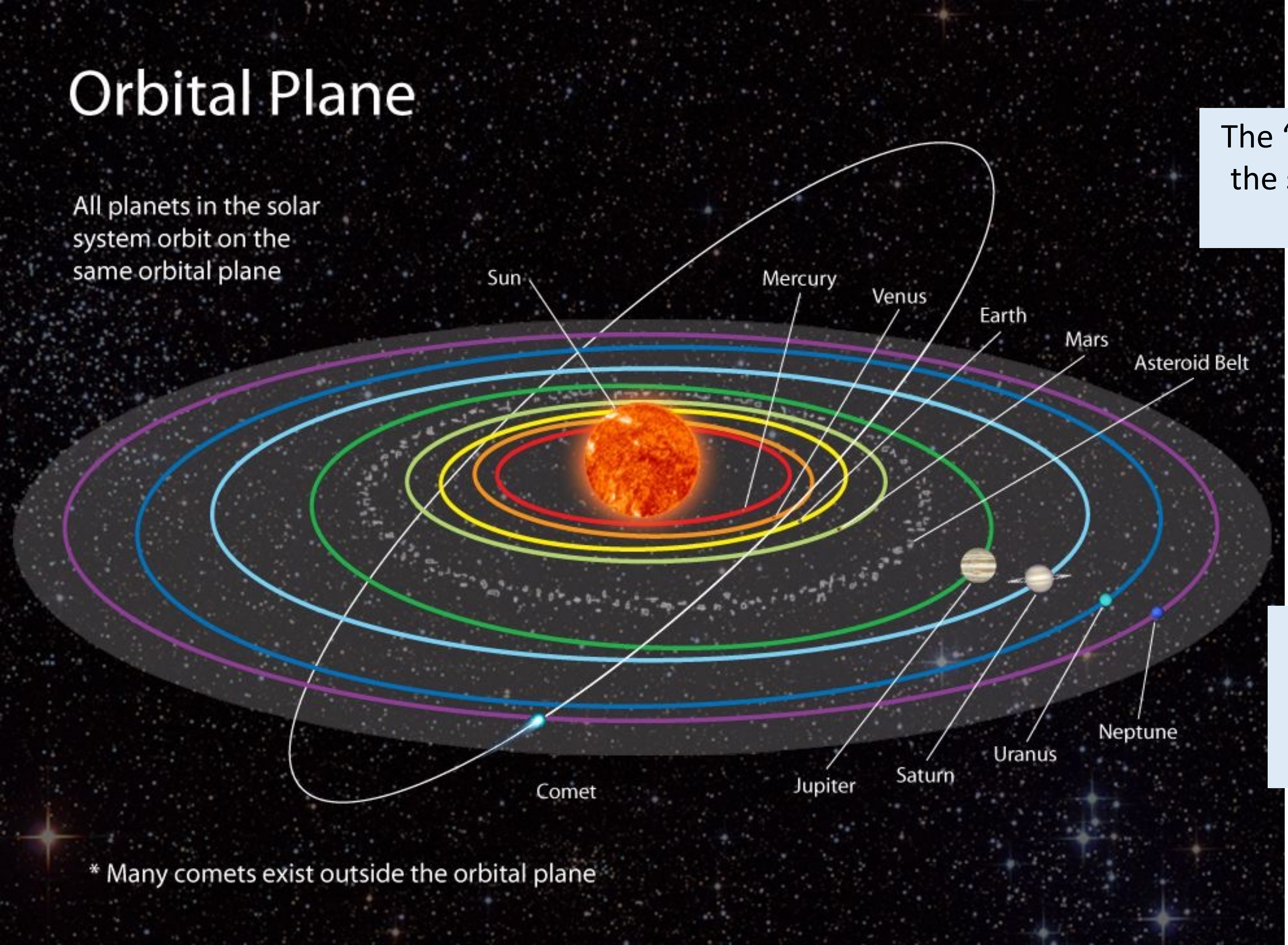
- Molecular viscosity is insufficient to cause disk evolution on the observed < 10 Myr timescales

- Instead, it is often assumed there must be macroscopic mixing of disk gas at neighboring radii, disks are "turbulent," but the physical origin of this turbulence is unclear

- Potential mechanisms of angular momentum transport in disks include:
    1) Magnetorotational instability
    2) Gravitational instability
    3) Magnetically driven outflows

- Ultimately, this is still an open question!

Q3: How do we know protoplanetary disks exist? (& How do we study them?)

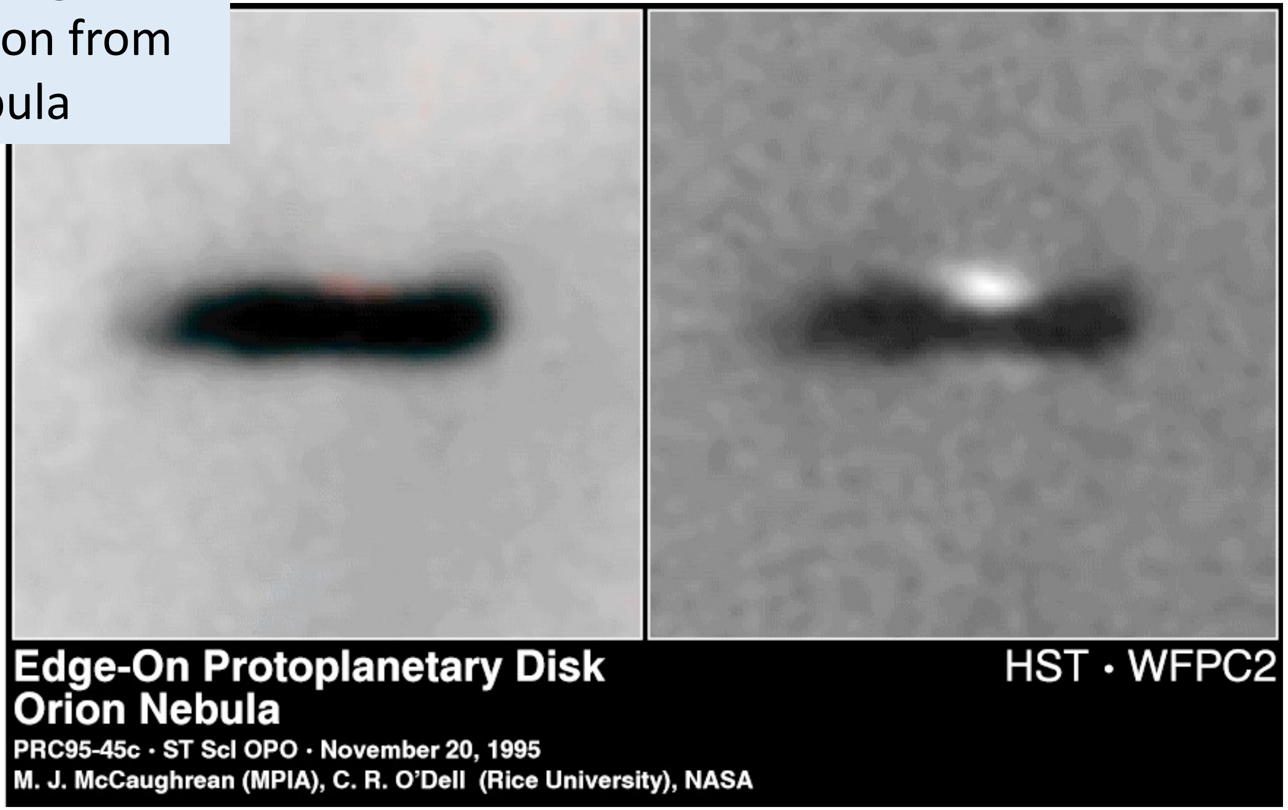


The "nebular hypothesis" for the solar system dates back to the 18th century

The protoplanetary disk that used to surround the Sun is referred to as the "solar nebula"

IMAGE:
TIM GUNTHER,
NATIONAL GEOGRAPHIC

Silhouettes of disks against background emission from the Orion Nebula

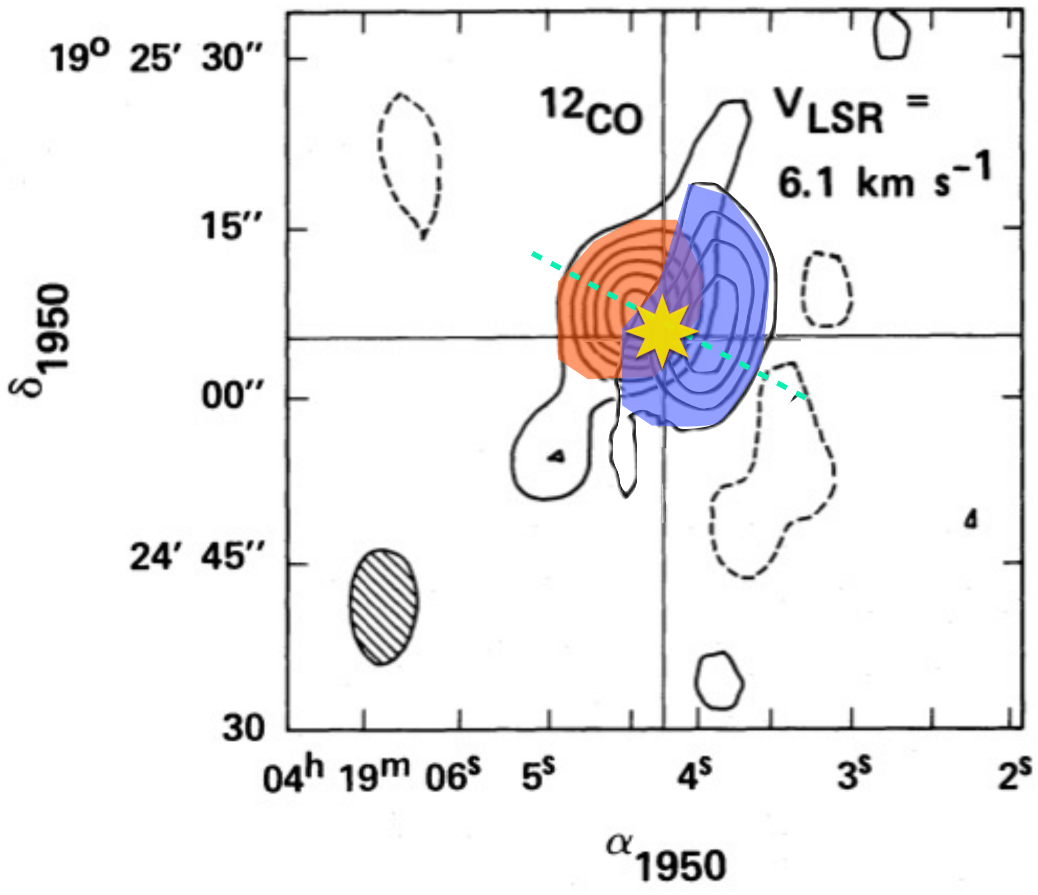


Disks in Orion

McCaughrean and O'Dell 1996

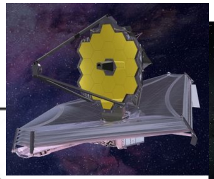
Facility: *Hubble Space Telescope*

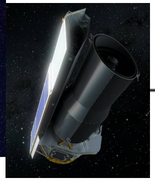
Resolved images show a rotating gas disk



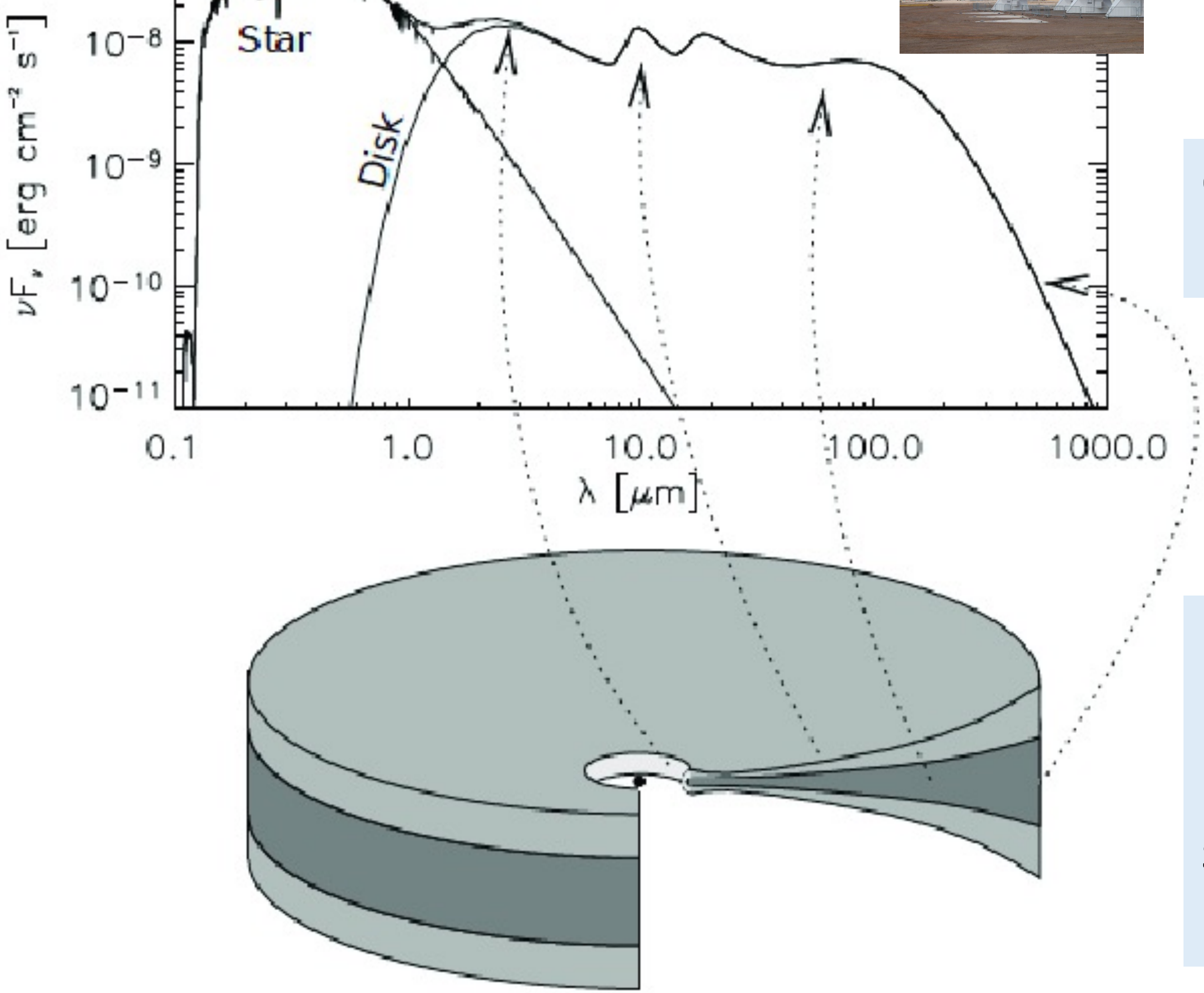
T Tau
CO 1-0
Weintraub, Zuckerman, Masson 1987

JWST & Spitzer





ALMA



Observations at different wavelengths probe different regions of the disk

[Simplified version]
IR = disk surface closer to the star
(0.1 – 10s of au)
sub-mm = larger distances and deeper
into the disk

Image credit: Mulders, thesis, University of Amsterdam, adopted from Dullemond et al. 2007

Images: NASA/Northrop Grumman; NASA/JPL-Caltech; NRAO

Molecular Species Observed in Disks

List of Molecules, Including Rare Isotopic Species, Detected in Protoplanetary Disks, with References to Representative Detections

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	
Species	Ref.	Species	Ref.	Species	Ref.	Species	Ref.	Species	Ref.
CN	10, 21	H_2O	5, 31, 19	NH_3	30	HCOOH	12	CH_3CN	24
$C^{15}N$	18	HCO^+	10, 21	H_2CO	10	c-C_3H_2	29	CH_3OH	36
CH^+	35	DCO^+	8	C_2H_2	22	CH_4	14		
OH	23, 31	$H^{13}CO^+$	37, 8	HC_3N	7				
CO	2	HCN	10, 21						
^{13}CO	32	DCN	28						
$C^{18}O$	9	$H^{13}CN$	17						
$C^{17}O$	33, 16	$HC^{15}N$	17						
H_2	34	HNC	10						
HD	3	H_2S	26						
CS	25, 4, 15	N_2H^+	27, 11						
$C^{34}S$	1	N_2D^+	20						
SO	13	C_2H	10						
CO_2	6								

McGuire (2018)

Different molecules and spectral lines also probe different regions of the disk

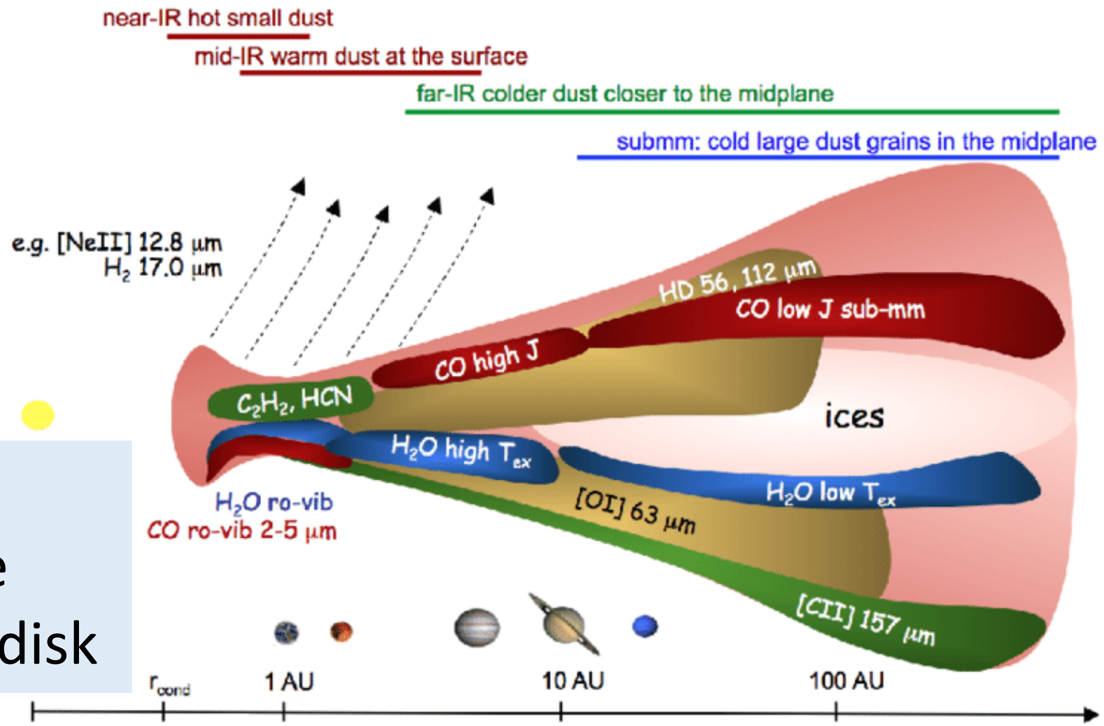
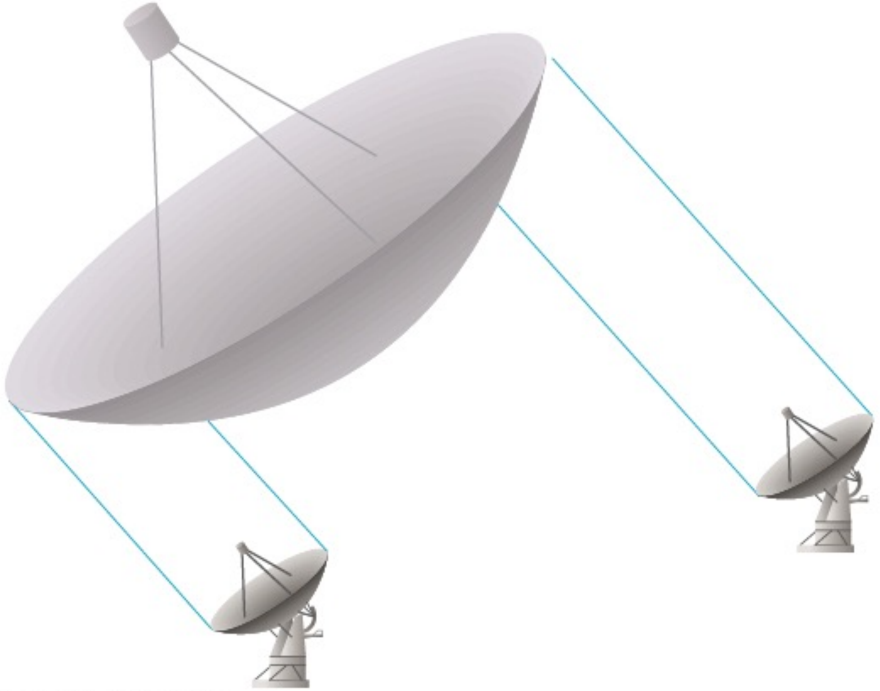


Diagram: Kamp et al. (2017)

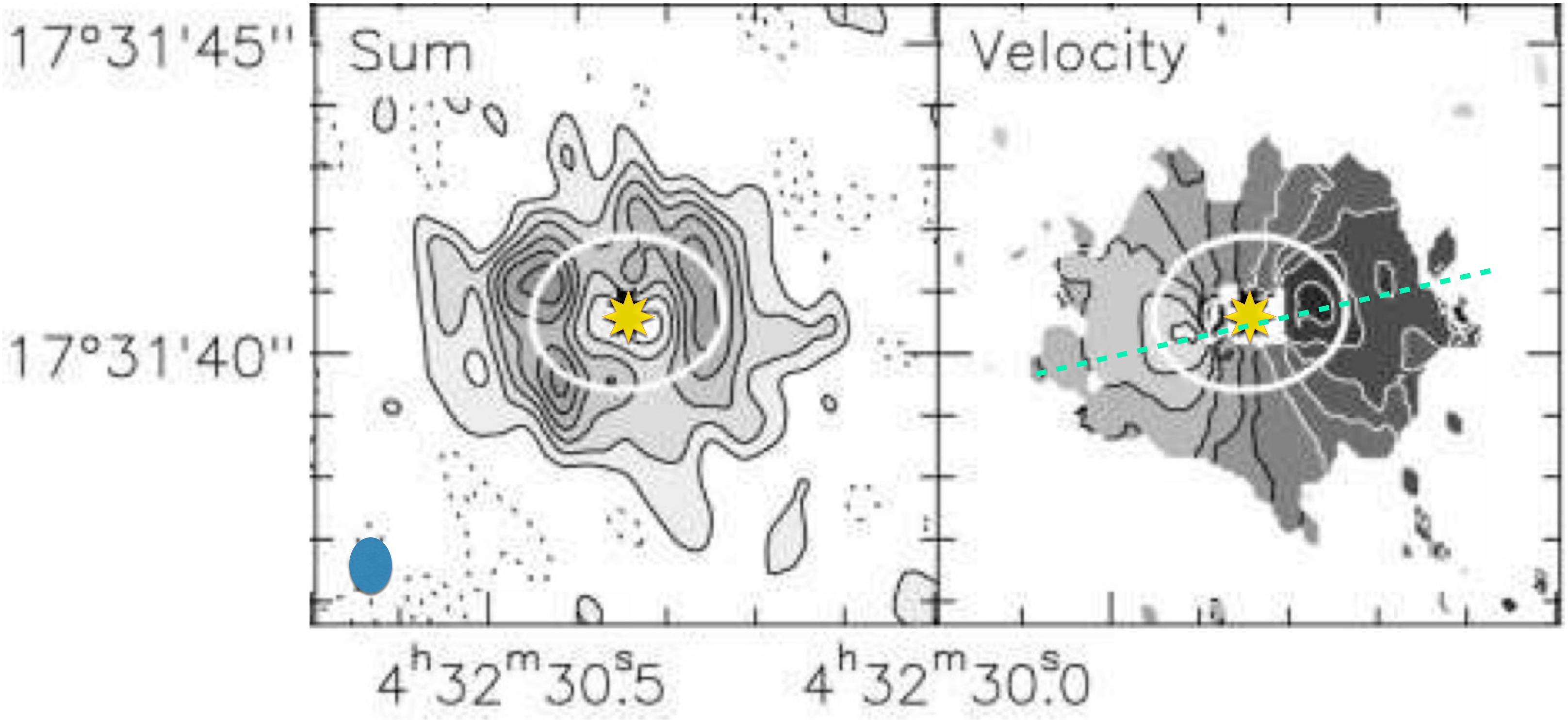
Questions?

IMAGING WITH RADIO INTERFEROMETRY

- The size scale we can resolve is proportional to the wavelength of light (1.22 λ/D).
- Hubble-like resolution at λ~mm requires 10 km-sized telescopes.
- Interferometry allows a series of smaller telescopes (an array) to act as one larger telescope.



RESOLVING PLANET FORMATION: 1999



GG Tau
^{13}CO 2-1
Guilloteau, Dutrey, and Simon 1999

Facility: Plateau de Bure Interferometer (PdBI)

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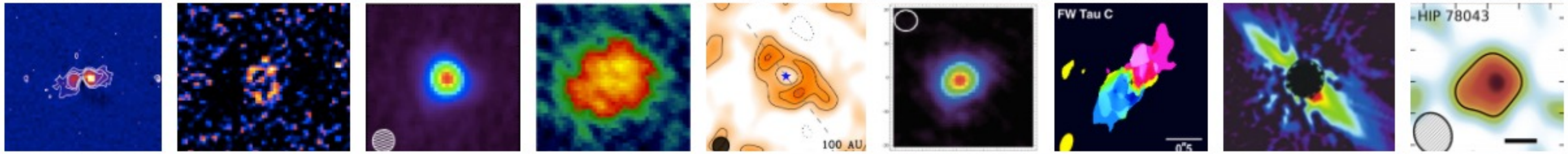
Catalog of Circumstellar Disks

Resolved Disks

Total number of disks: 253 (Pre-Main Sequence disks: 157, Debris Disks: 96)



Column visibility | Download as .csv

Object	Category	Spec Type	R band (mag)	Distance (pc)	Disk Major Axis "	Disk Diameter (AU)	Inclination (degrees)	Resolution elements across	At ref. wa (mic
2MASSI J1628137-243139	TT		17.7	140	4.3	602	86	10.8	2.1
49 Cet	Debris	A1	5.6	59	9.8	578	79	24.5	850
61 Vir	Debris	G7V	4.2	8.5	22	187	77	3.7	70
99 Her	Debris	F7+K4	4.7	15.6	15.4	240	50	2.8	70
[MR81] H alpha 17 NE	TT	M2e	16.9	150	0.38	57	20	2.9	2.2
AA Tau	TT	M0	11.8	145	2	290	59	15.4	880
AB Aur	HAe	A0e	7.1	144	18	2592	22	360	0.57
alpha CrB	Debris	A0 V	2.2	23	4	92	80	0.7	11.2
AS 205 A	TT	K0	12.8	128	0.414	53	20	13.4	1250
AS 205 B	TT	K7+M0	14	128	0.19	24	66	6.1	1250
AS 209	TT	K5	10.4	121	2.3	278	35	62.2	1250

As of today, 253 resolved disks known! Many more unresolved.

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www.circumstellardisks.org

ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY (ALMA)

Chajnantor plateau, Atacama Desert, Chile (5000 meters)

Credit: ESO/B. Tafreshi (twanight.org)

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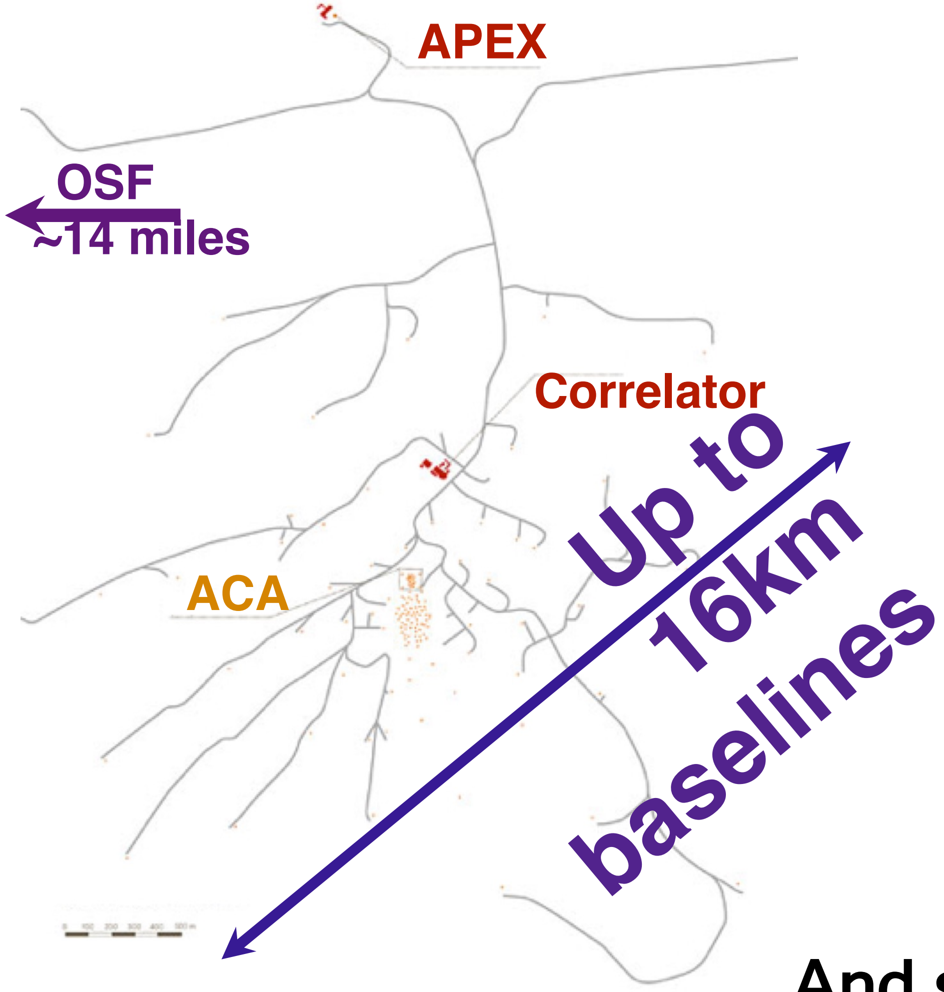
Unprecedented collecting area...



And spatial resolution!

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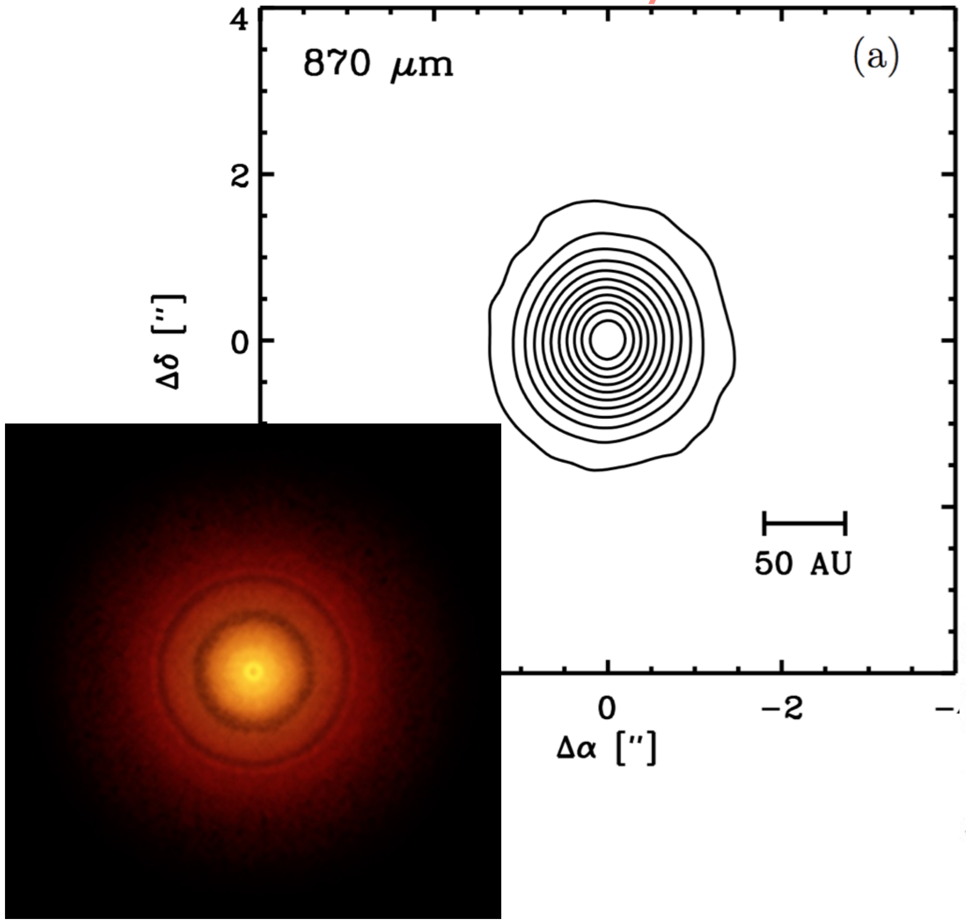
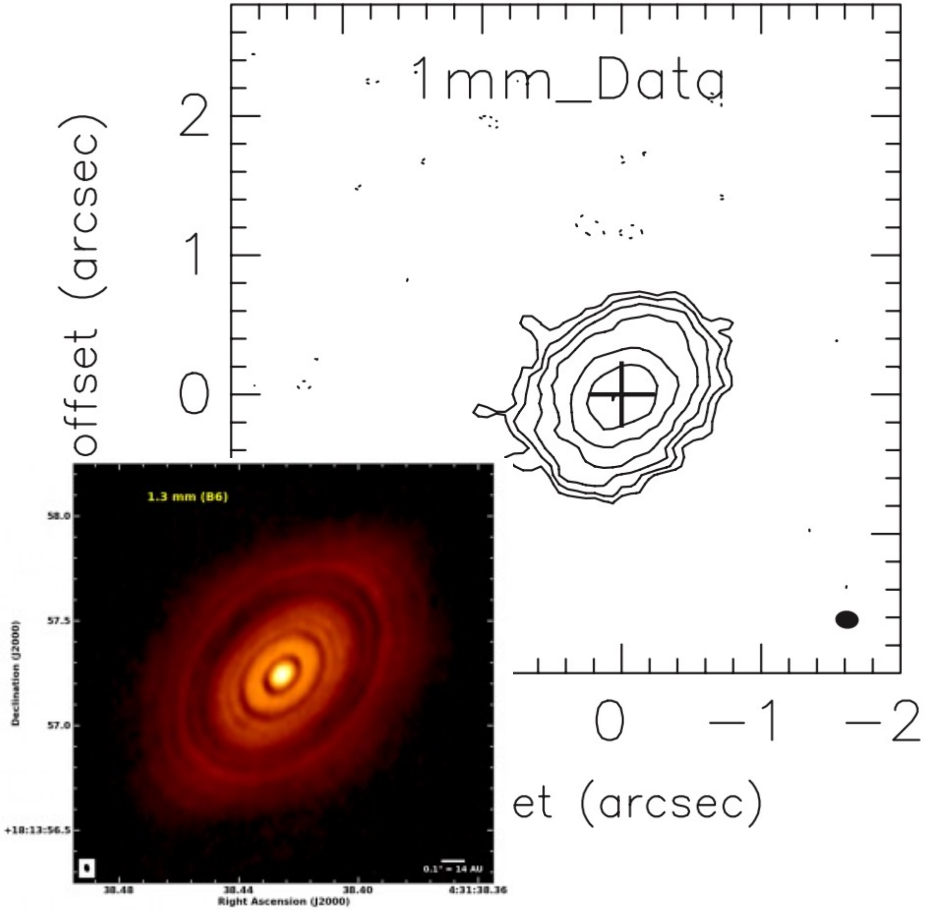
PRE-ALMA
POST-ALMA

TW Hya



HL Tau



Andrews + 2012, Kwon+ 2011
ALMA Partnership 2015, Andrews+ 2016

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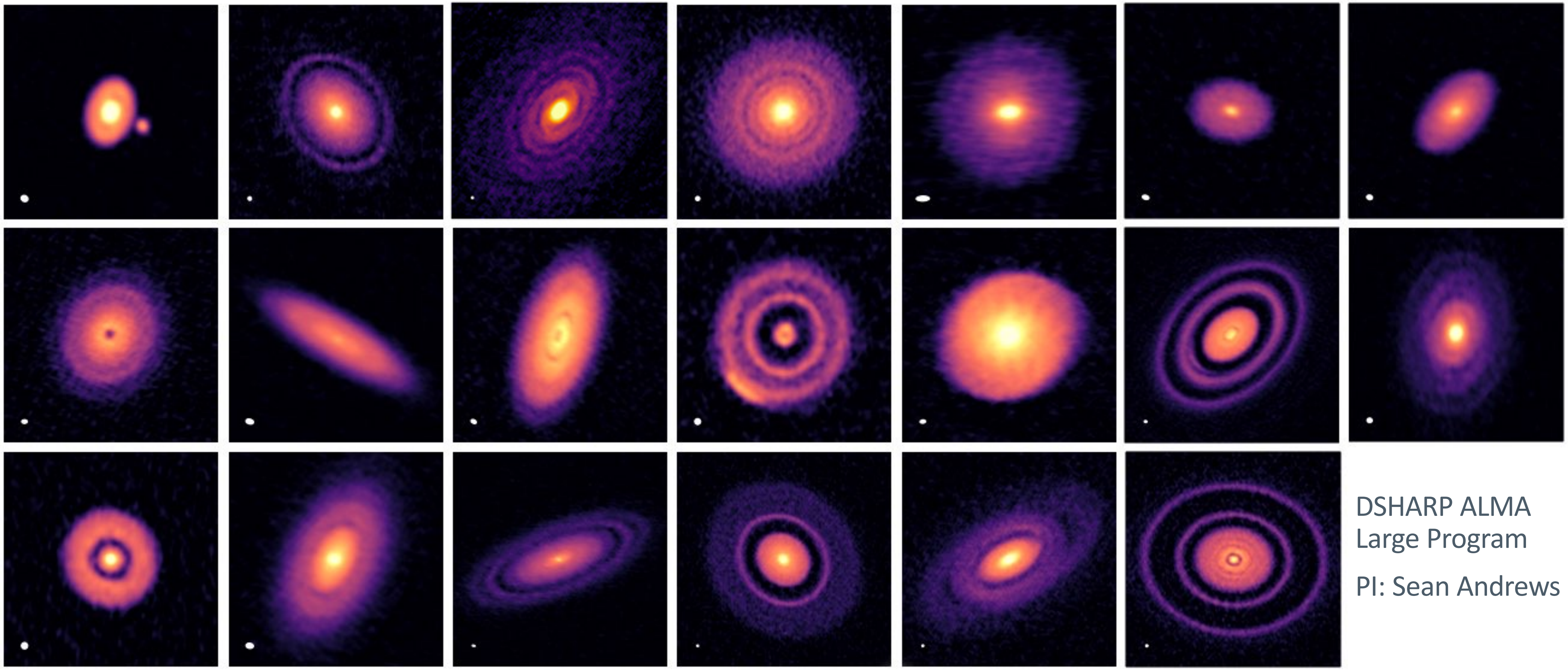
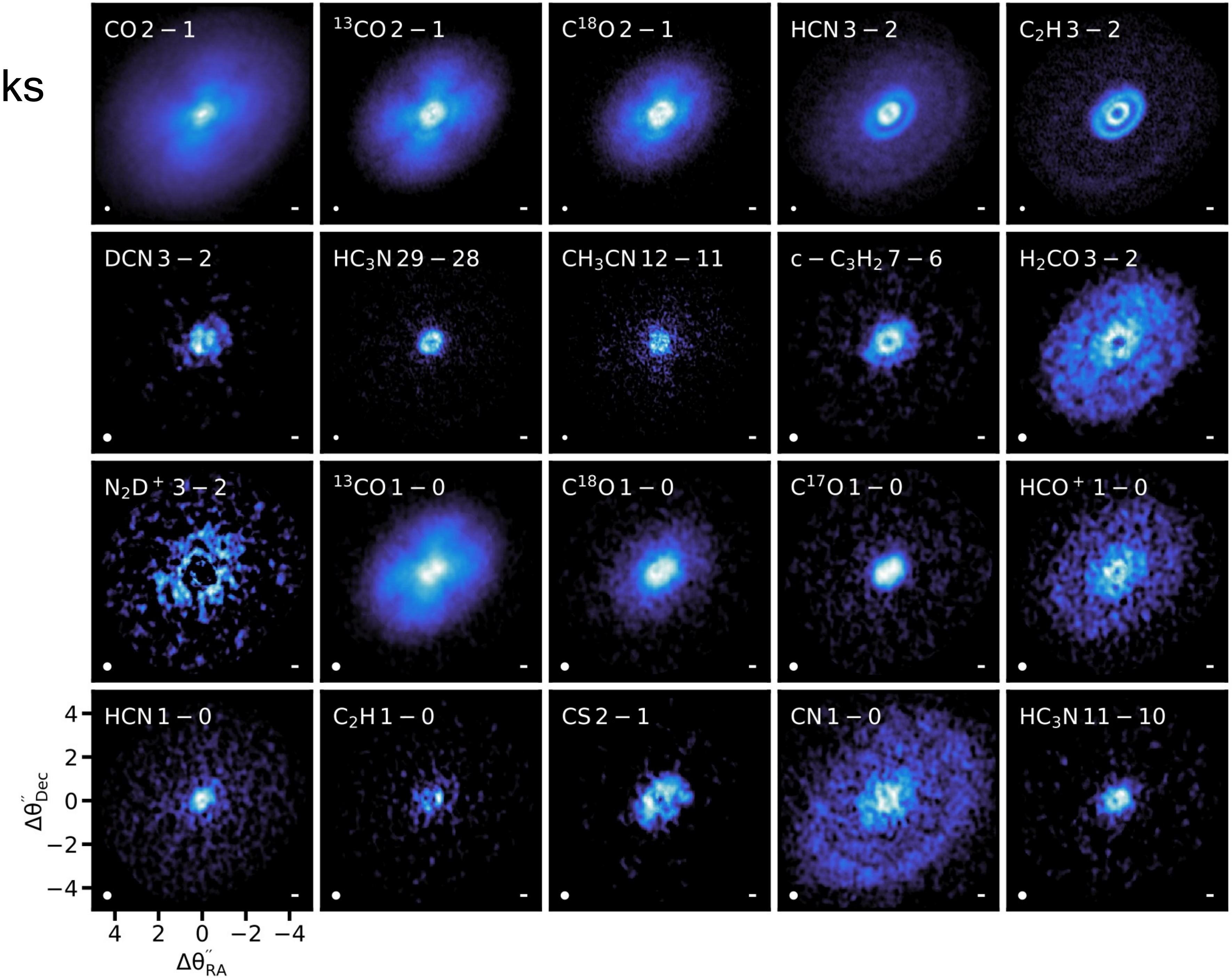
Imaging Disks with ALMA: Dust Continuum Emission



DSHARP ALMA
Large Program

PI: Sean Andrews

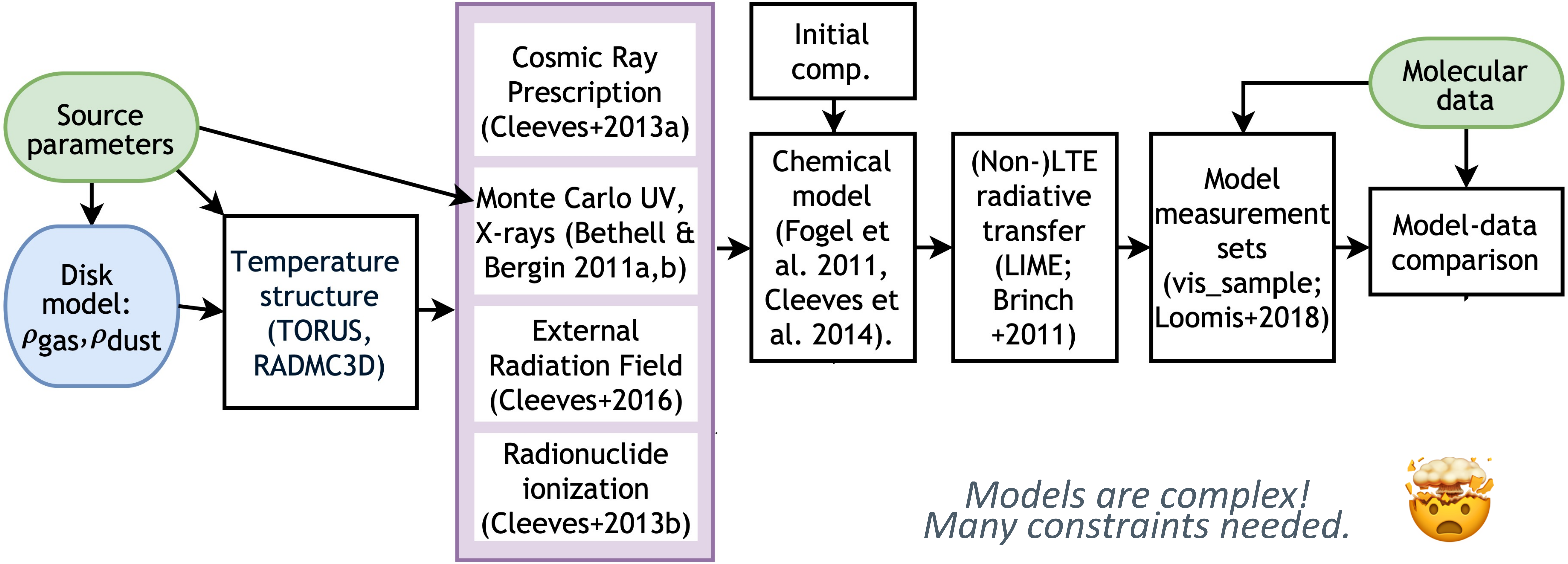
Imaging Disks with ALMA: Molecular Emission



MAPS ALMA Large Program

PI: Karin Oberg

INFERRING COMPOSITIONS: MODELING



Models are complex!
Many constraints needed.

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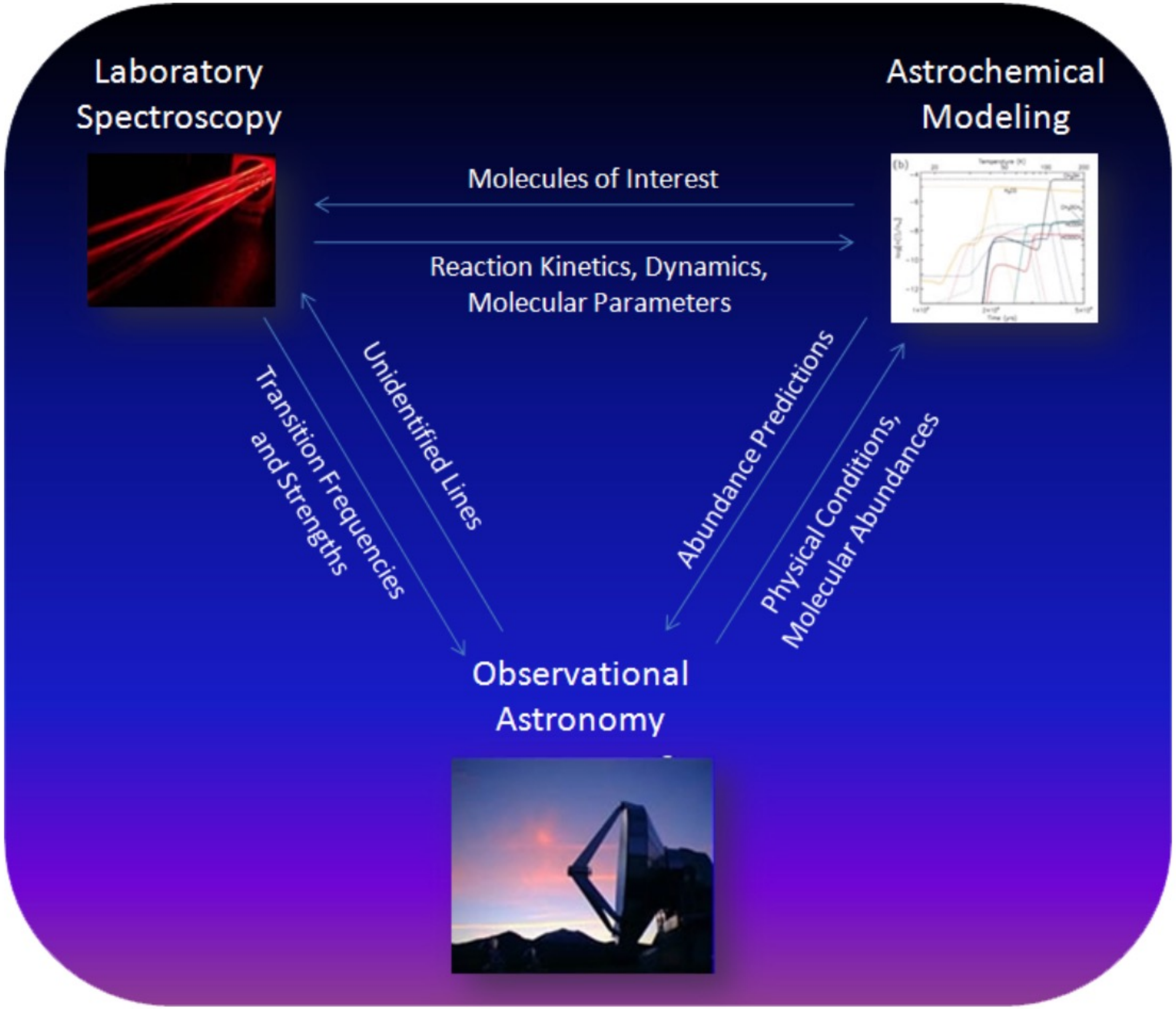
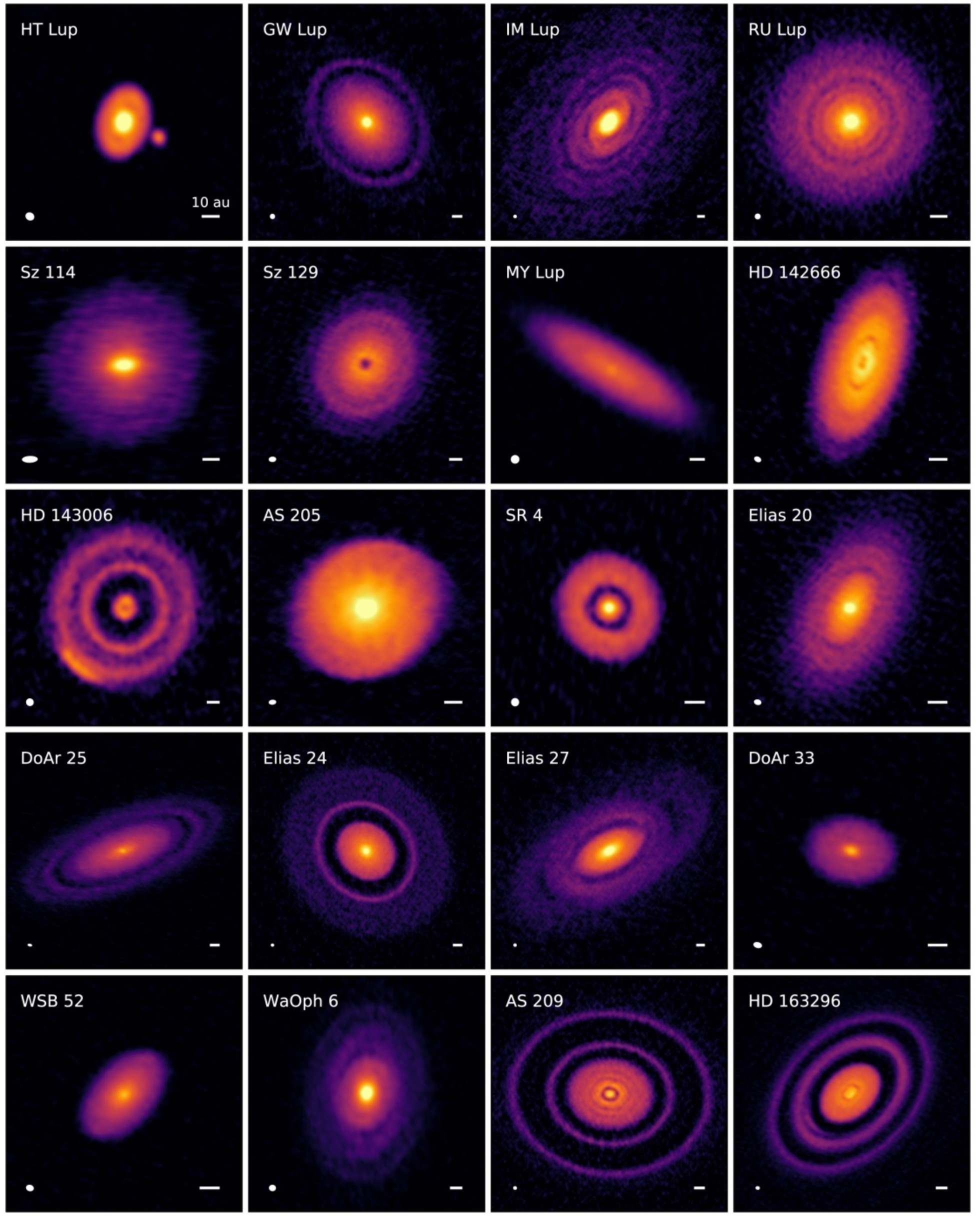
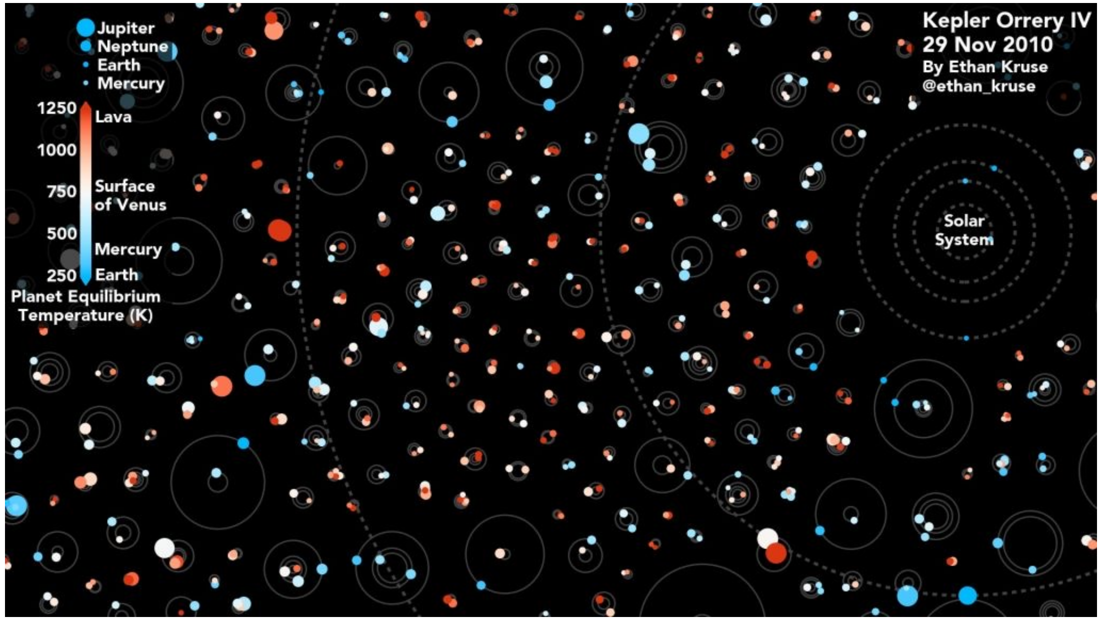


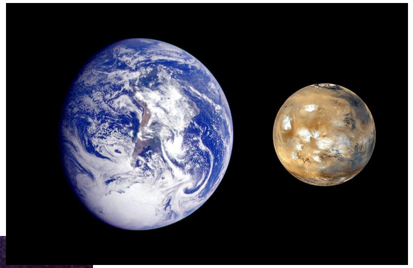
Image credit: Susanna Widicus Weaver

Q4: How do protoplanetary disks relate to the planets that form from them?

From Protoplanetary Disks to Planetary Systems





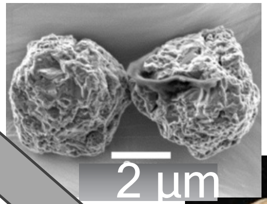


DSHARP Results: Andrews et al. 2019

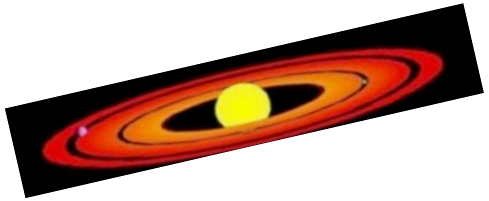
Image credits: NASA

Planet Formation in Protoplanetary Disks

Protoplanetary disk



Solids (rocky & icy materials) form dust particles, which collect and grow from pebbles to boulders to planetesimals



Over time, gases end up in the atmospheres of giant planets, accreted by the central star, or dissipate into interstellar space

Planetary system

Image credits: NASA/JPL-Caltech/L. Allen (Harvard-Smithsonian CfA); Buzzle.com; ESA/C. Carreau; McCaughrean; A. Davis, The University of Chicago; NASA; pics-about-space.com; Martin Vargic

Disk Properties Determine Planetary Outcomes

- Mass
  - Number of planets
  - Planet masses

- Composition
  - Gases → Gas giant atmospheres
  - Solids → Cores, terrestrial planets, and planetary debris

- Lifetime
  - Timescale for gas giant formation
  - Limits gas content

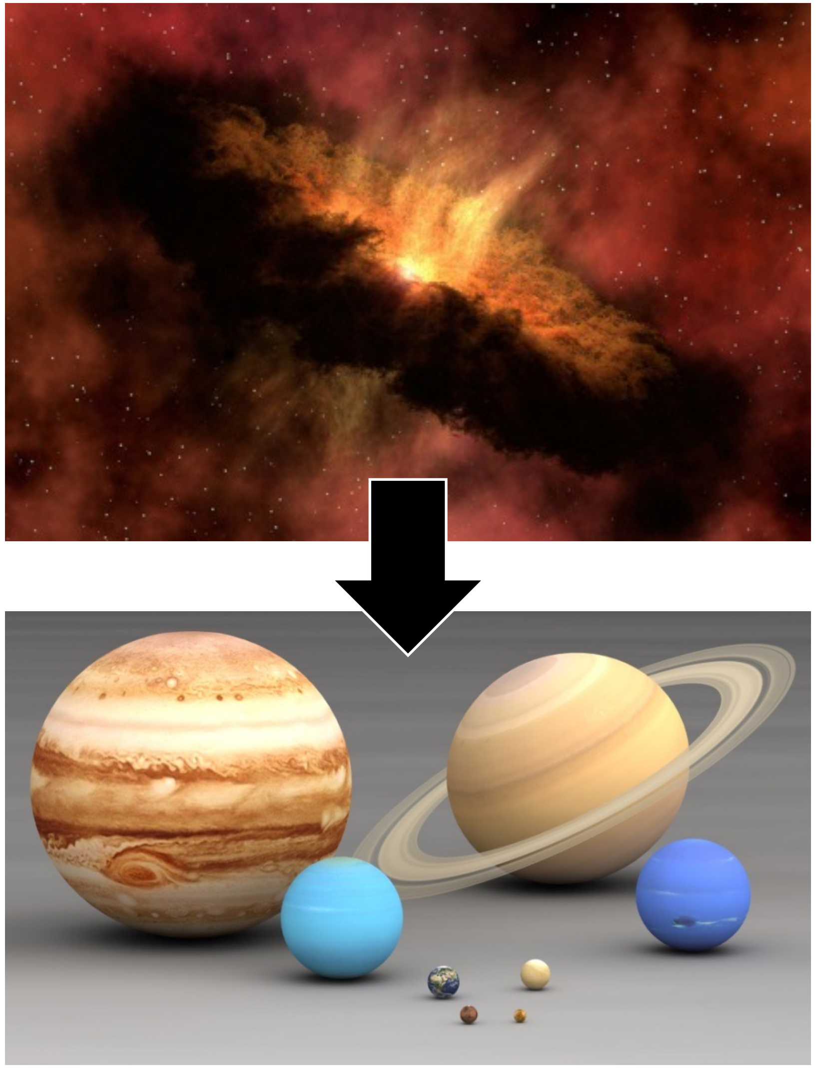


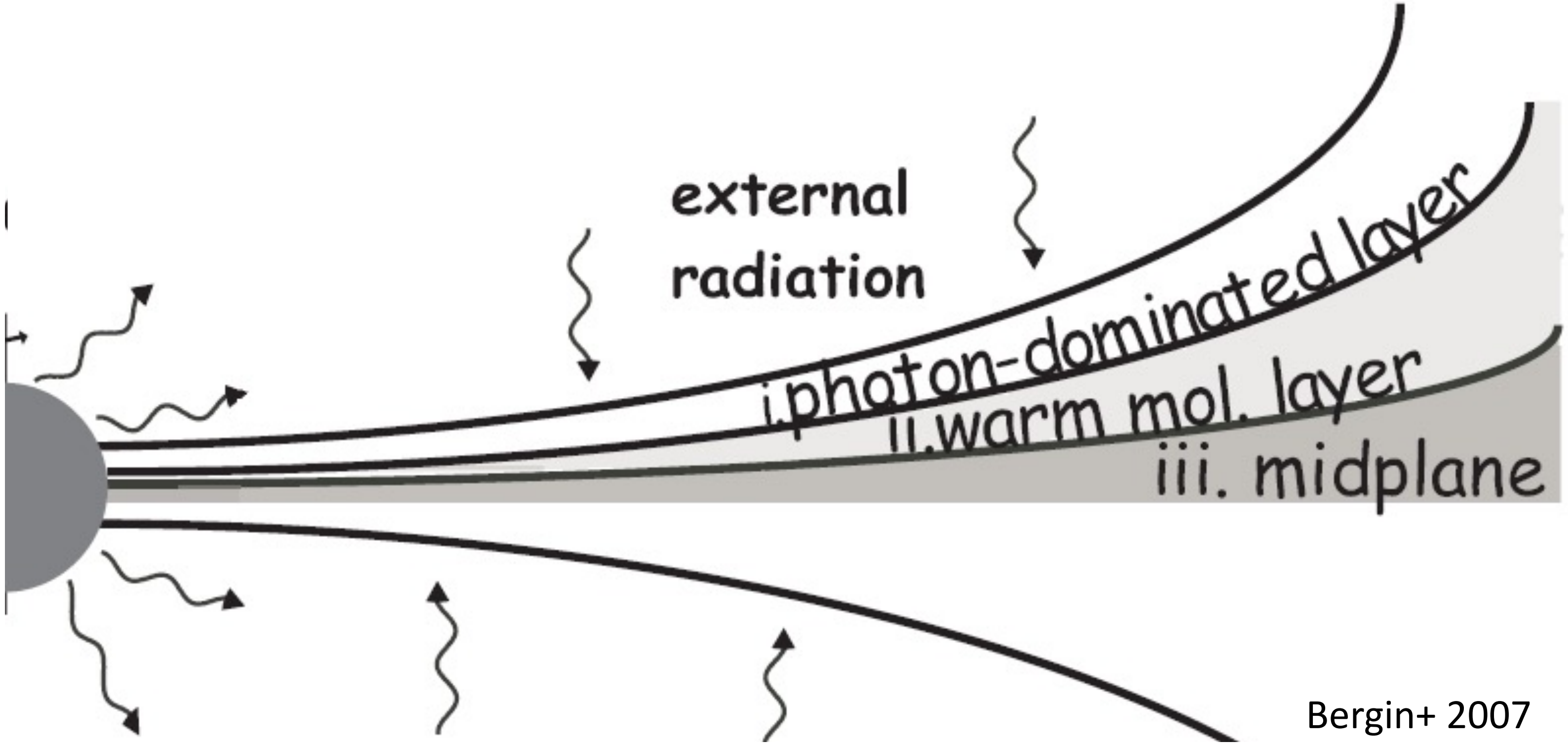
Image credits: Artist's rendition, NASA/JPL-Caltech/R. Gutermuth (Harvard-Smithsonian Center for Astrophysics); pics-about-space.com

Vertical Structure
3 Main Chemical Regions

I. Photon-dominated layer - ions, neutral atoms, small dust

II. Warm molecular layer - complex molecules, gas-grain interactions

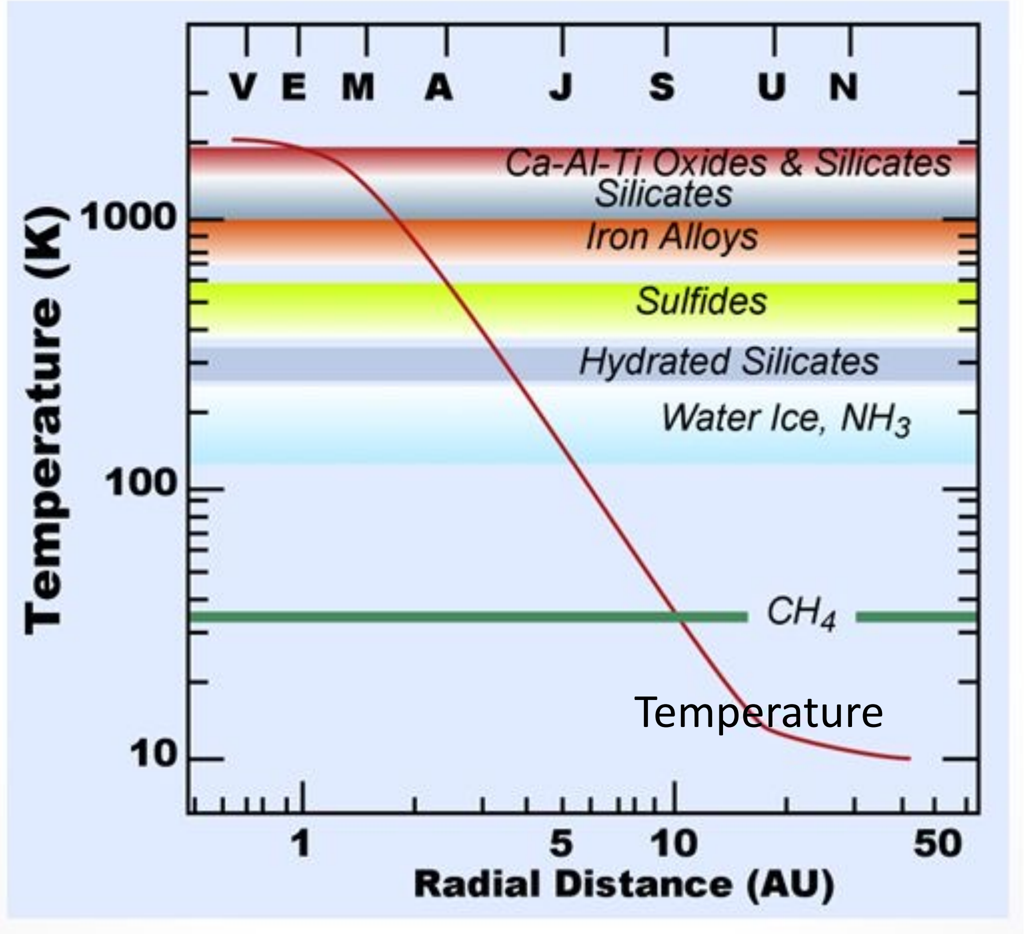
III. Cold midplane - ices coat grain surfaces

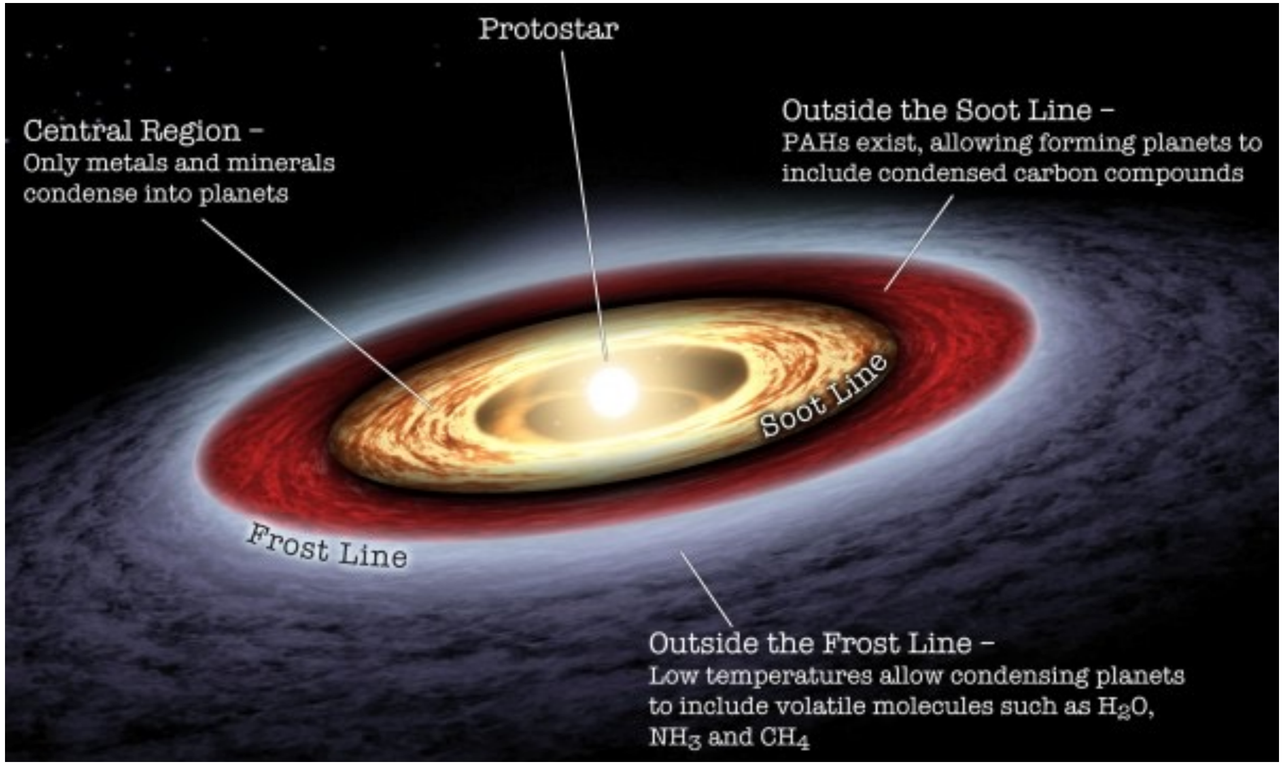


Bergin+ 2007

Radial Structure Along the Disk Midplane
Condensation Sequence & Snow lines

Snow line or frost line= distance from the central star at which a particular chemical species freezes out into ice





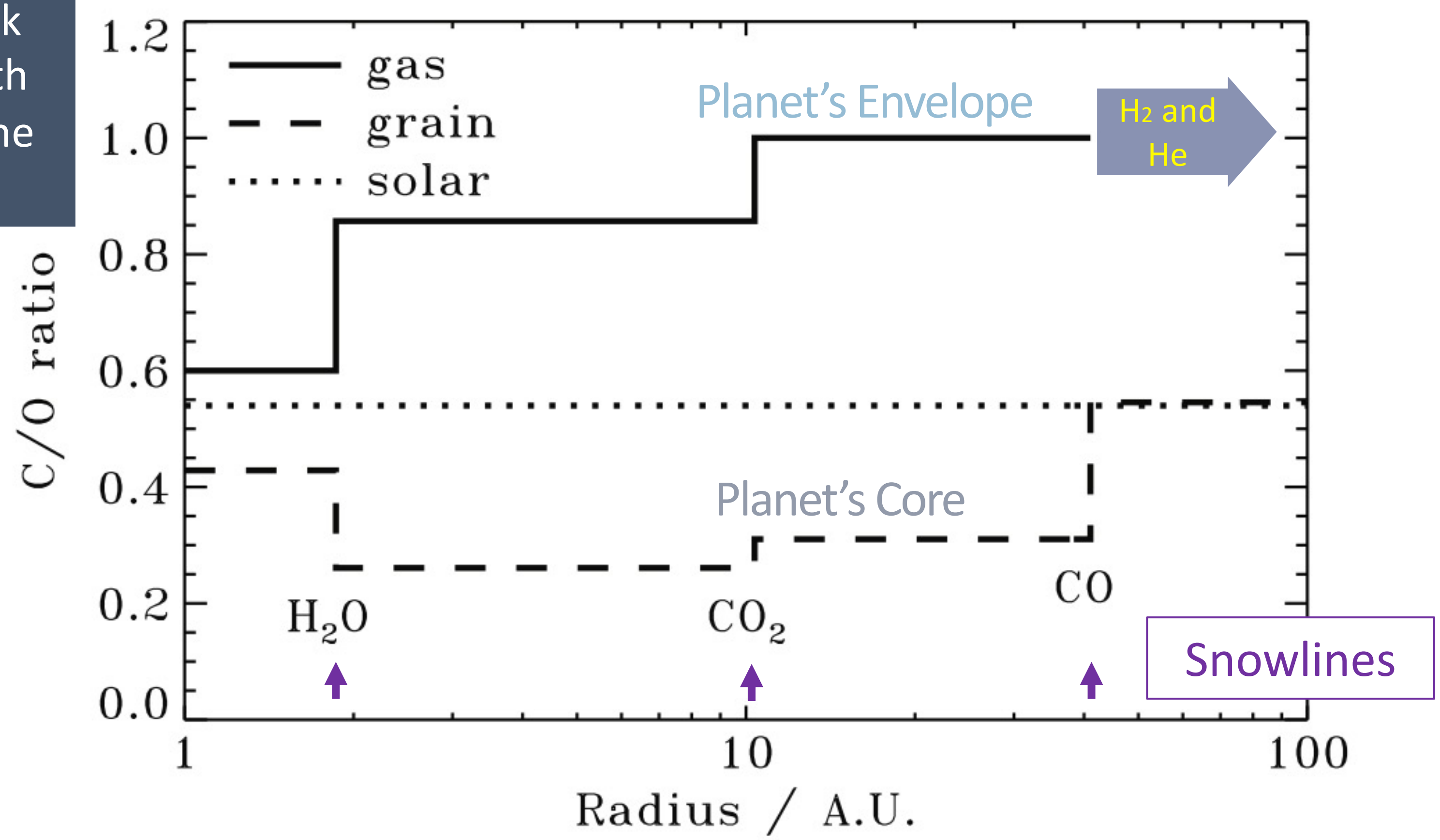
Source: Lecture by William M. White

Image credit: NASA / JPL-Caltech, InvaderXan of http://supernovacondensate.net/.

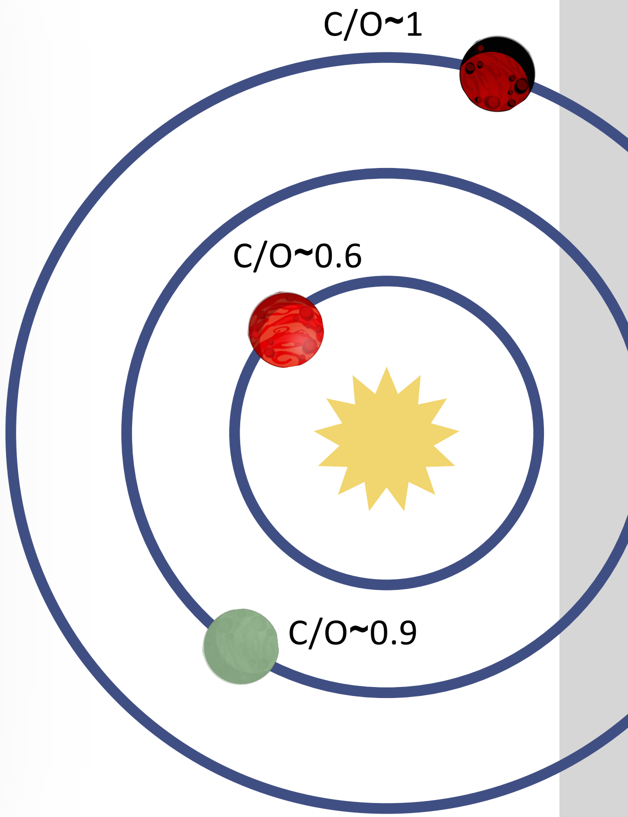
SNOW LINES AND PLANETS

Baseline expectation: freeze-out changes the chemical environment from which planets accrete

C/O ratio of disk gas changes with distance from the central star



Öberg, Murray-Clay and Bergin 2011



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Complexities in Relating Planetary Compositions to Protoplanetary Disk Locations

- Motion of disk gas and solids over time
  - Disk gas and small dust grains are turbulently mixed
  - Larger dust grains tend to settled towards the midplane and spiral inward towards the central star

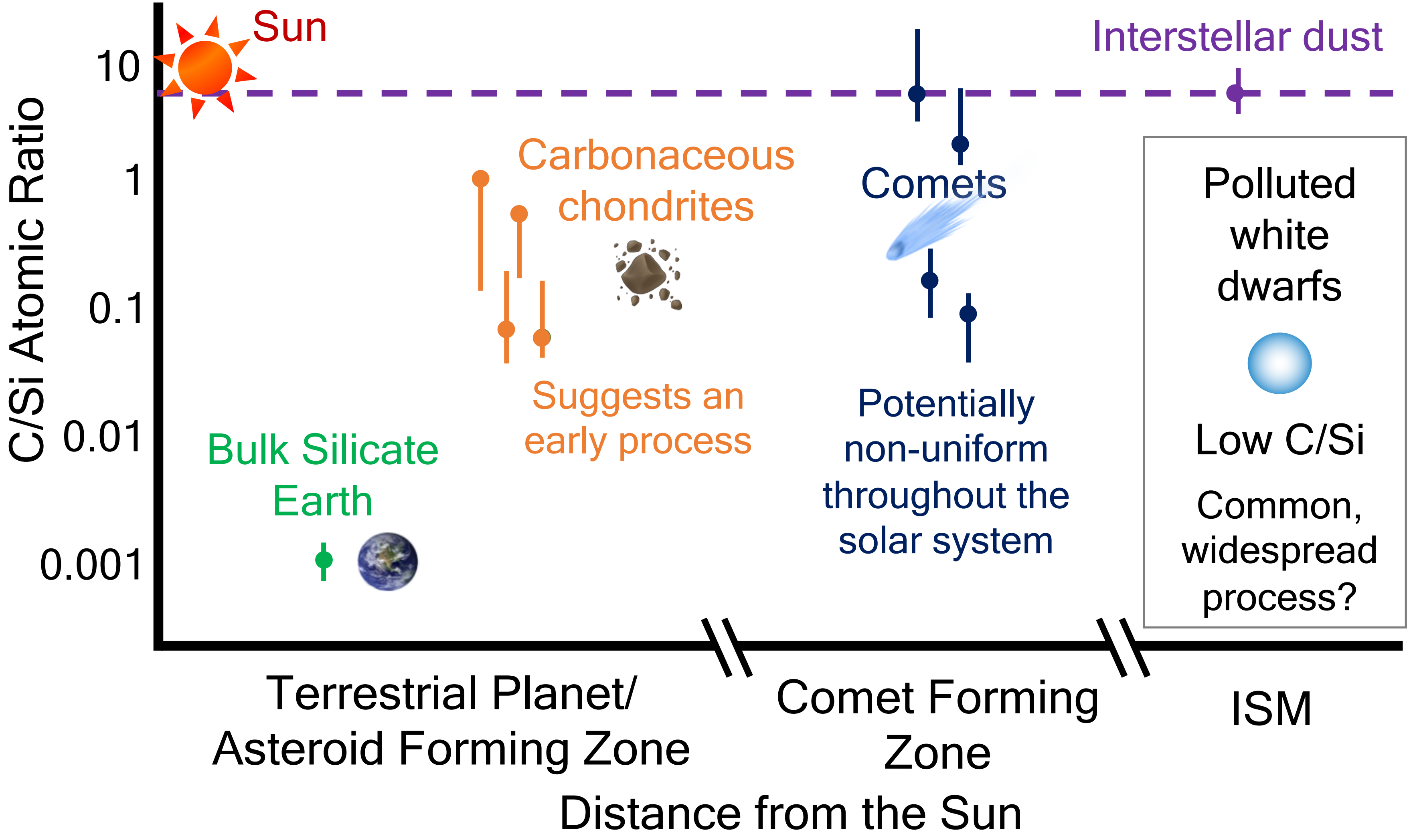
- Time dependence of chemistry & planet formation

- Alteration of planetesimal/planet compositions during assembly and later evolution

- Late delivery of materials via impactors

Reproducing Earth-like Compositions

Reproducing the Earth's composition requires a yet undetermined disk process that removes carbon from rocky solids

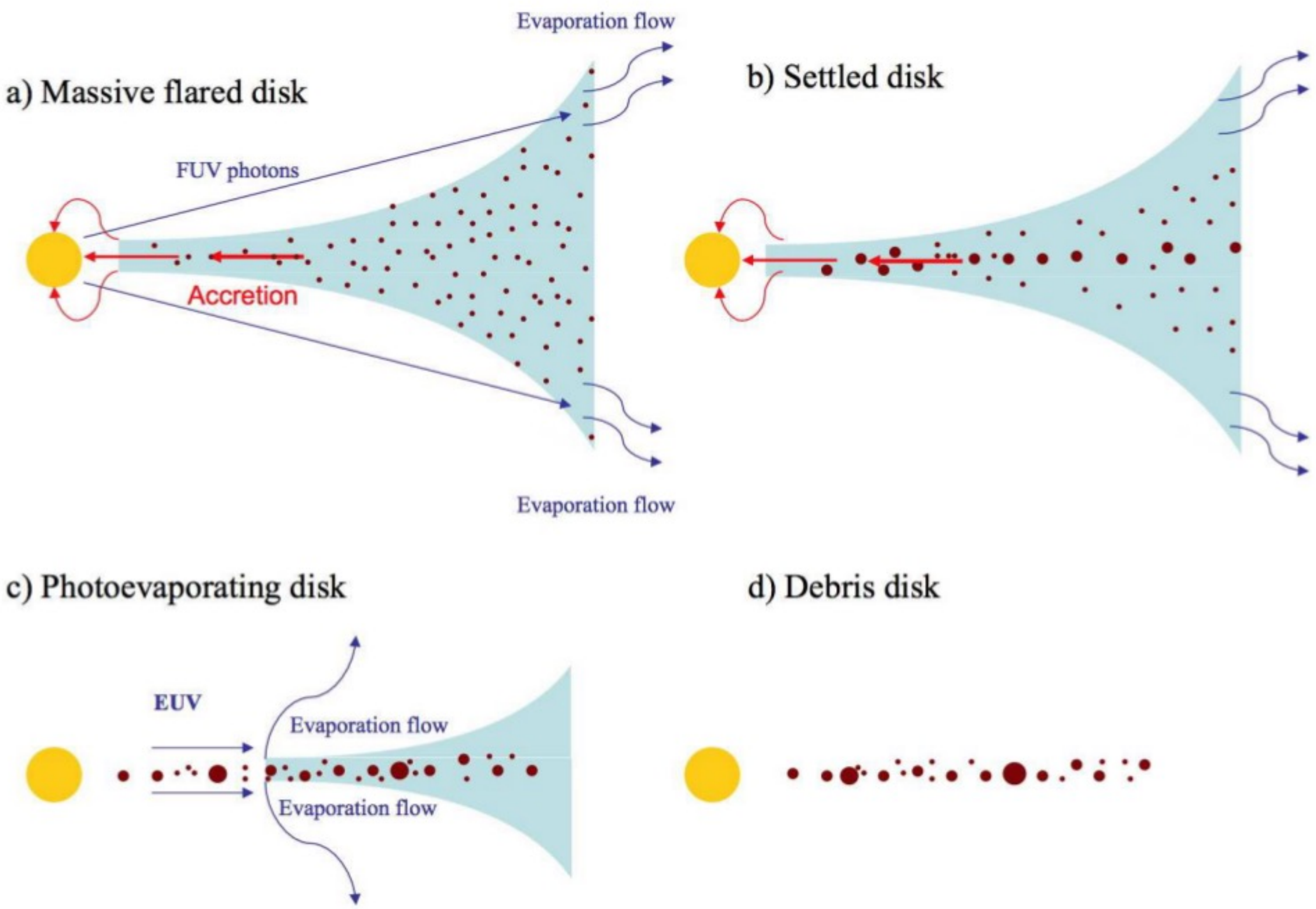


This is a current topic of my research!

Questions?

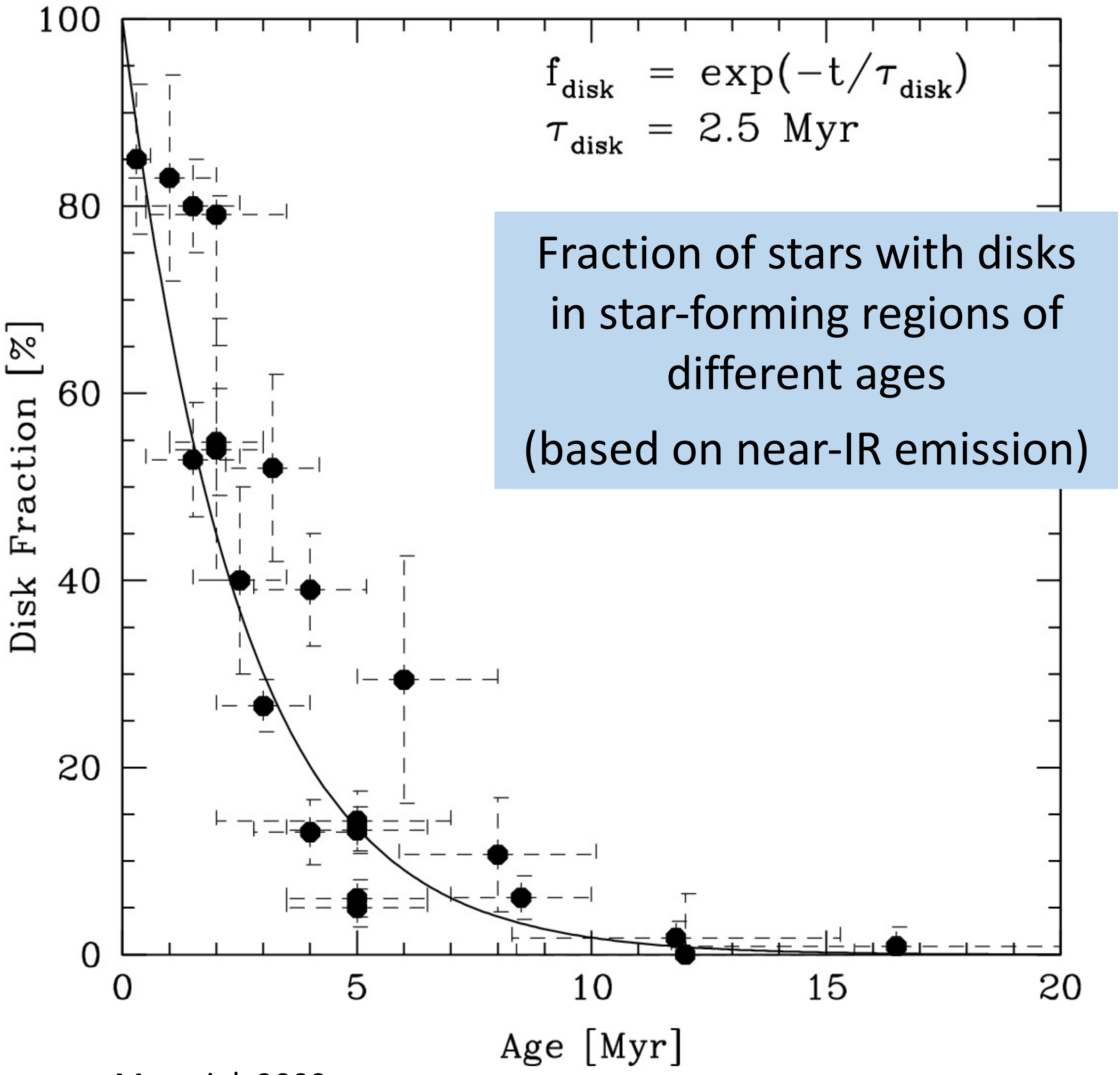
Q5: What happens to protoplanetary disks?

Gas is cleared from the disk mainly by a combination of: accretion onto the central star, accretion into gas-giant planets, and photoevaporation



Williams & Cieza 2011

Observational constraints on the lifetime of PPDs

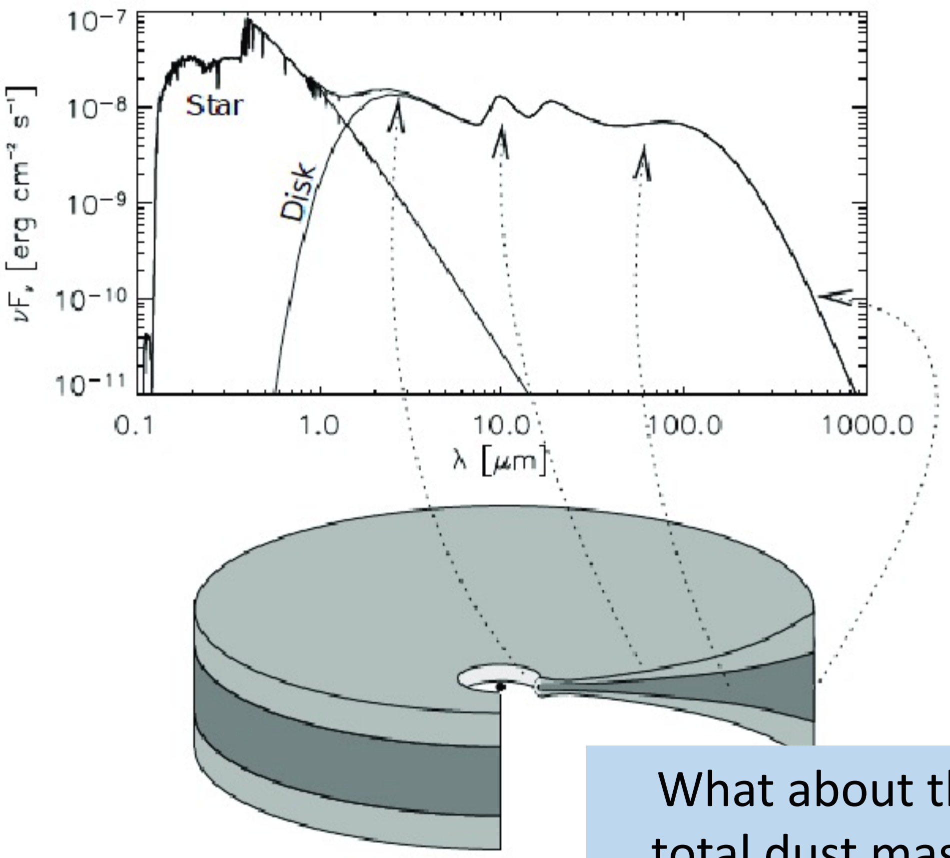


Fraction of stars with disks in star-forming regions of different ages

(based on near-IR emission)

Mamajek 2009

But recall that near-infrared observations probe dust from close to the central star

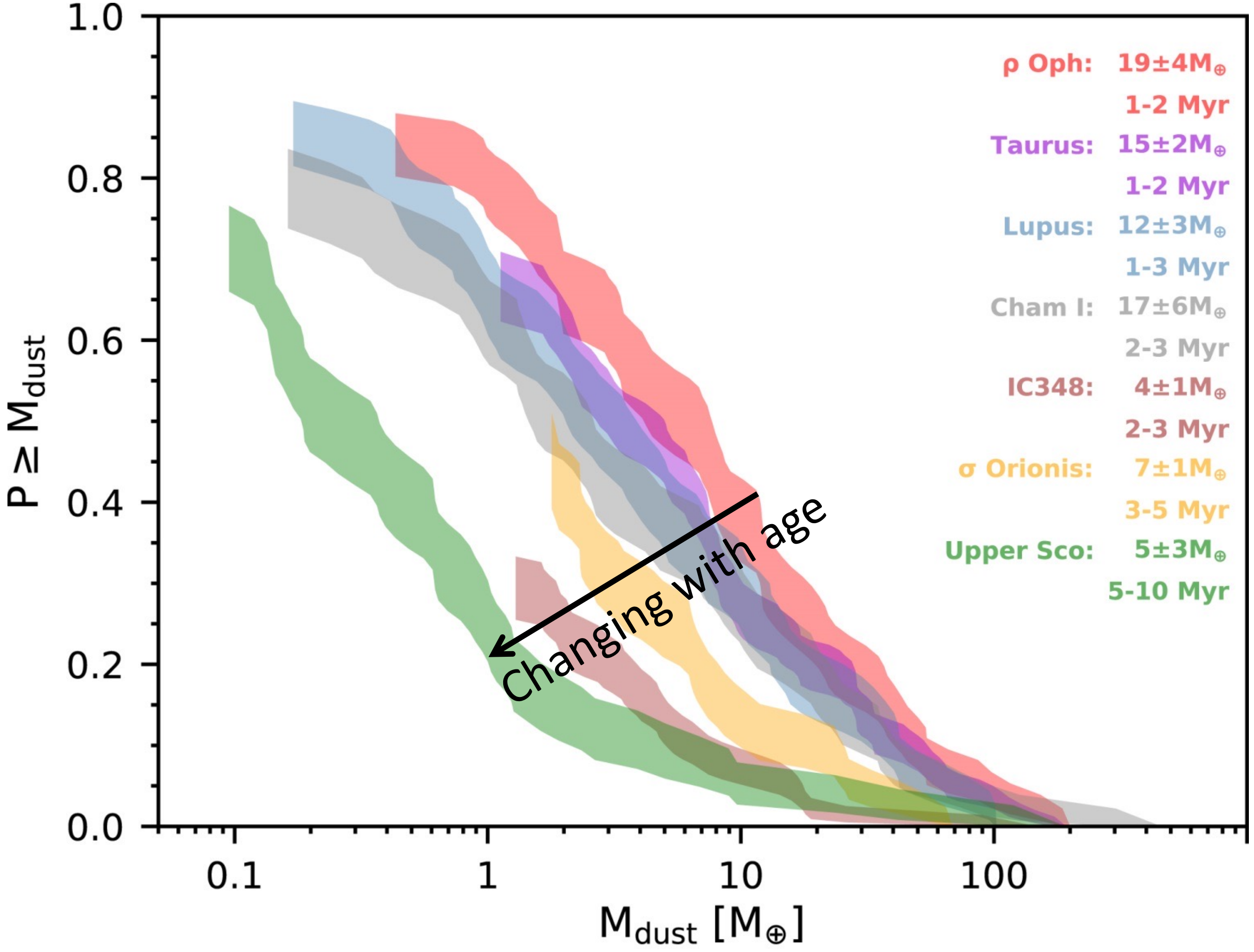


What about the total dust mass?

Image credit: Mulders, thesis, University of Amsterdam, adopted from Dullemond et al. 2007

Evolution of the Total Mass of Solids in Protoplanetary Disks

Cumulative dust mass distribution for disks in star-forming regions of different ages:



Cieza et al. (2019)

What about the total mass of gas present in these disks?

Measuring Protoplanetary Disk Gas Masses

$$M_{H_2\,gas} = M_X \times \frac{H_2}{X}$$

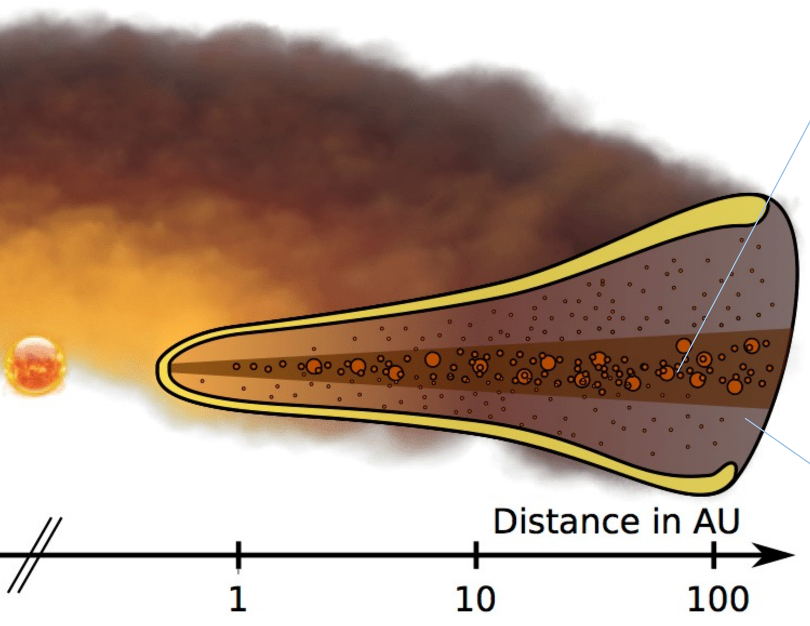


Image: http://www.til-birnstiel.de

(1) **Dust** Optically-thin (sub-)mm:

- Dust (+ice) aggregates with radii ≥cm-dm cannot be detected
- Gas-to-dust mass ratios become uncertain over time, both globally and versus distance

(2) **CO** Relatively abundant and emissive under disk conditions, but:

- CO has unknown behavior radially and temporally
- CO may be depleted by 5-100× relative to assumed values

But if we understood their chemistry, we could use additional molecular species to place further constraints on the total H_2 gas content and evolving composition of disks

HCO^+

N_2H^+

C_2H

HCN

CN

CS

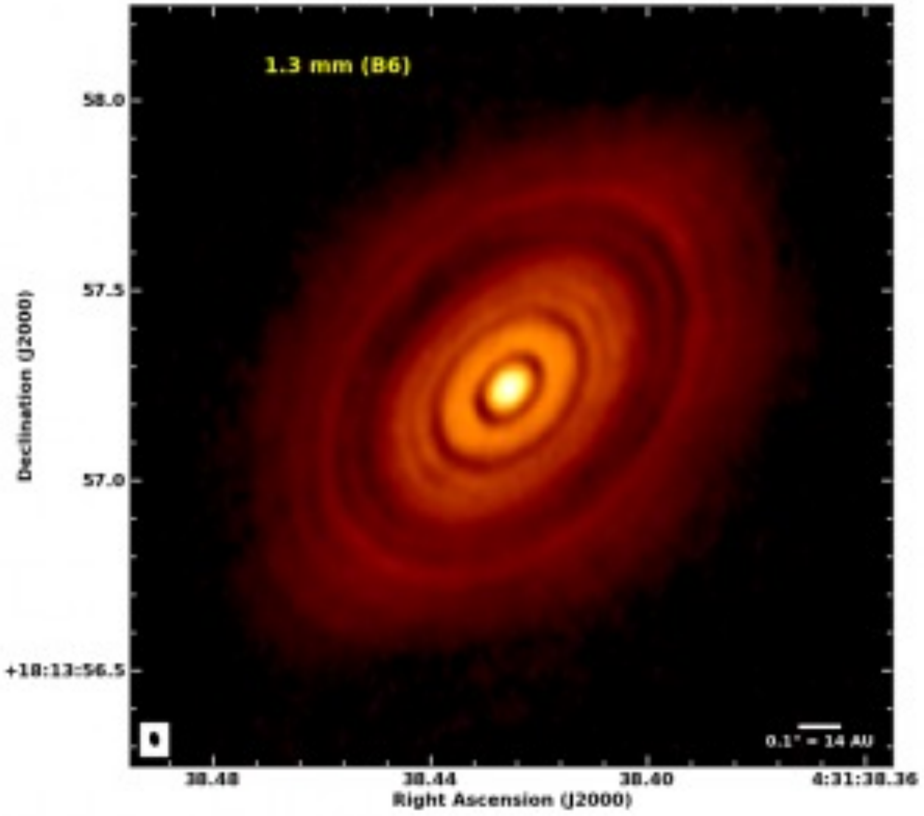
H_2CO

This is a current topic of my research!

Bonus: Hot topics in current protoplanetary disk research

When does planet formation begin?

How does this affect the evolution of the disk and formation of later planets?

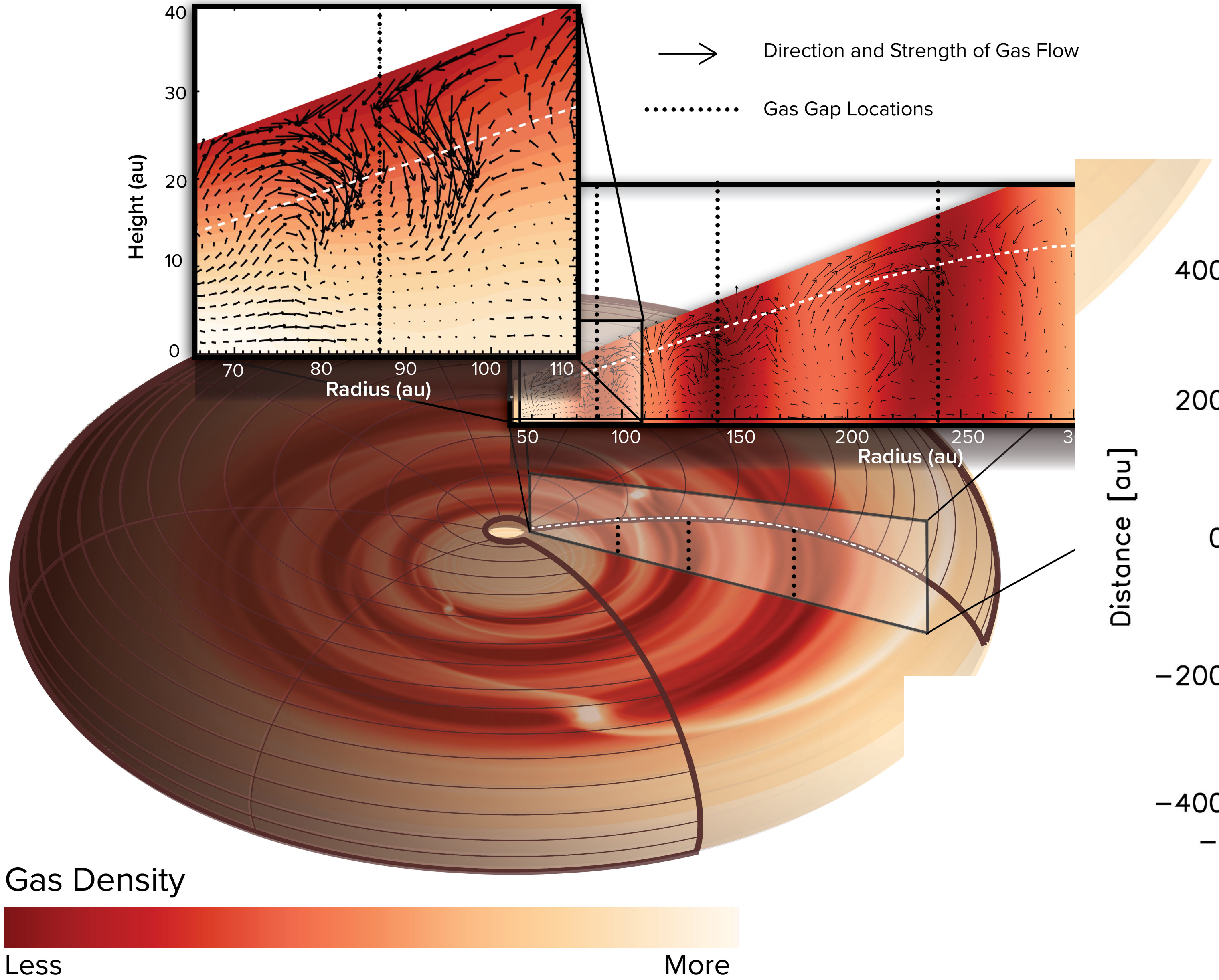


ALMA Partnership 2015

Are the substructures seen in disks caused by planets?

Detecting Protoplanets Forming in Protoplanetary Disks!

Recent observations reveal signatures of protoplanets altering the flow of gas in protoplanetary disks



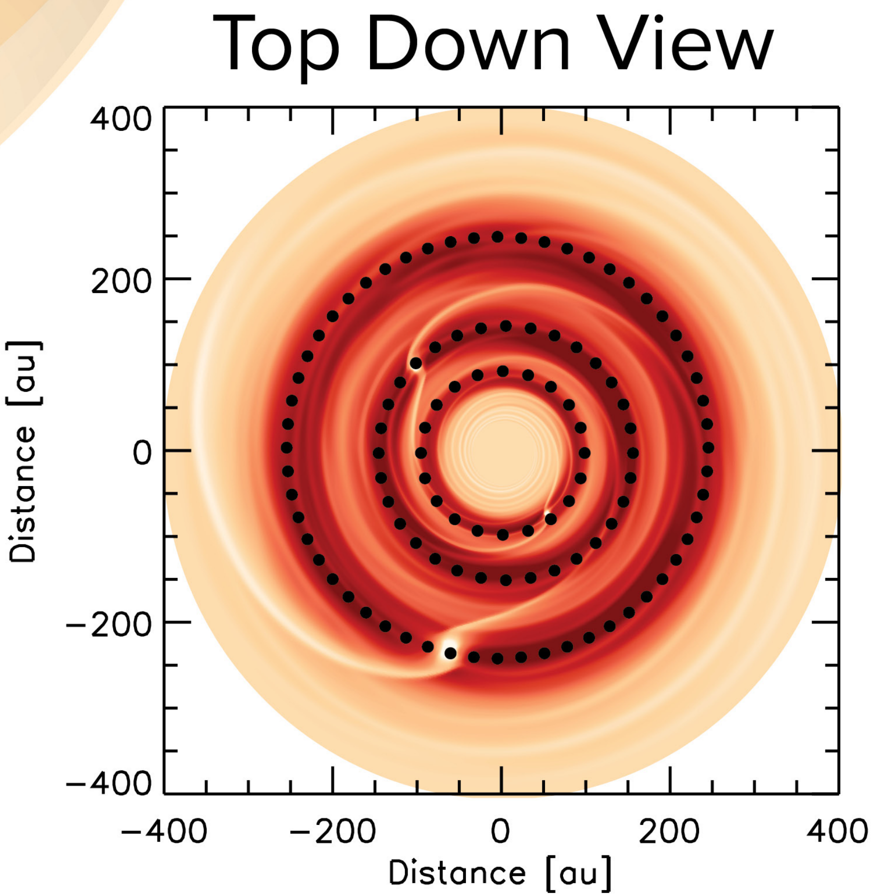
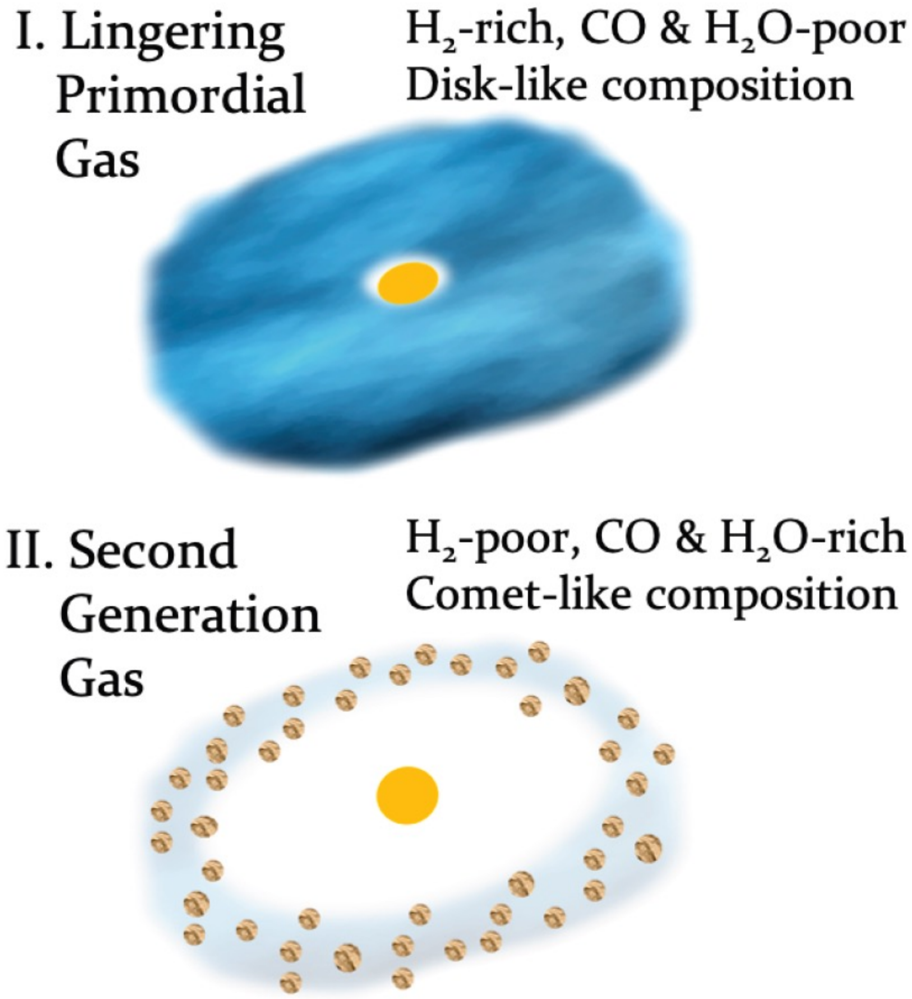


Image credits: R. Teague

When does the gas-rich lifetime of protoplanetary disks end?

Some disks around the age where gas dispersal is thought to occur (around 10 Myr) show emission from CO gas, is this leftover protoplanetary disk gas or gas released from collisions of extrasolar comets?



This is a current topic of my research!

How do protoplanetary disk compositions relate to those of interstellar clouds and solar system bodies?

How much of a disk's composition is inherited vs. reset within the disk?

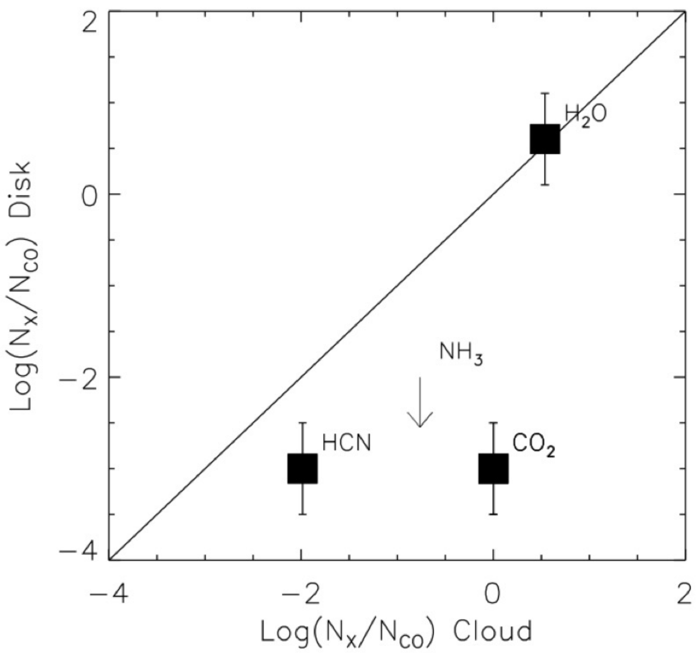


Fig. 8.— Comparison between the observed abundances of gas-phase inner disk volatiles derived from Spitzer-IRS spectra (*Salyk et al.* 2011) relative to those in ices in protostellar clouds (*Öberg et al.* 2011b; *Lahuis and van Dishoeck* 2000). Disk abundances are appropriate for the inner disk, as the Spitzer-IRS emission lines originate primarily in the few AU region.

Pontoppidan et al. (2014)

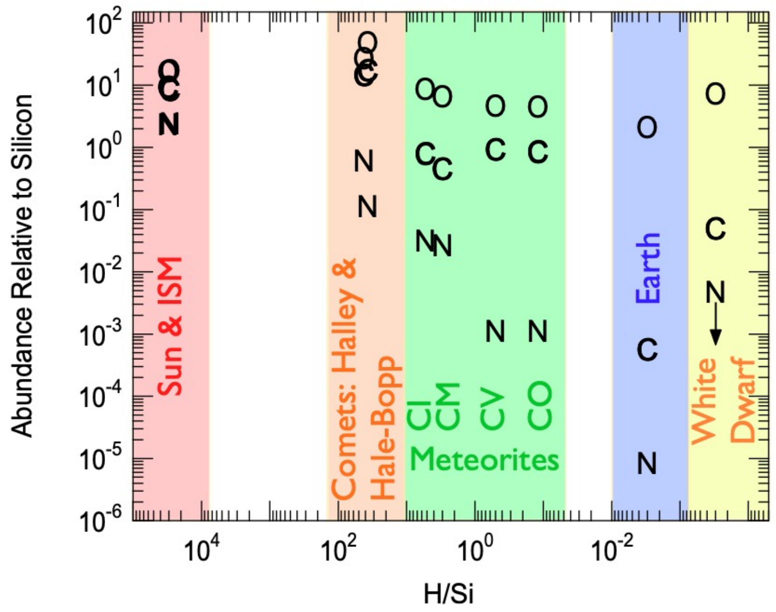


Fig. 2.— The relative CNO abundances in the solar system. The abundances are computed relative to Si, the primary refractory element in the solar system and interstellar space. The abundances are shown as a function of the H/Si ratio which separates the various bodies. The figure is taken and updated from *Lee et al.* (2010); *Geiss* (1987). The white dwarf values are for GD 40 (*Jura et al.* 2012) and are provided with an arbitrary H/Si ratio (since this is unknown).

Pontoppidan et al. (2014)

Summary

Q1: What are protoplanetary disks?

Gas & dust that encircle young stars as they form, the birthplace of planets

Q2: Why do protoplanetary disks form?

Disks are the natural outcome of the collapse of rotating molecular clouds during star formation

Q3: How do we know protoplanetary disks exist?
(& How do we study them?)

We study disks through a combination of observations, theoretical modeling, and laboratory studies

Q4: How do protoplanetary disks relate to the planets that form from them?

Disk properties determine when and where planet formation can occur and influence planet compositions

Q5: What happens to protoplanetary disks?

Disk gas is cleared from the system over time, leaving behind planets and solid debris

Want to learn more???

My contact info:

Dana Anderson
da4vn@virginia.edu

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Thanks to Ilse Cleeves for providing several of the slides!