The Birth of Stars and Planets
- An Introduction -

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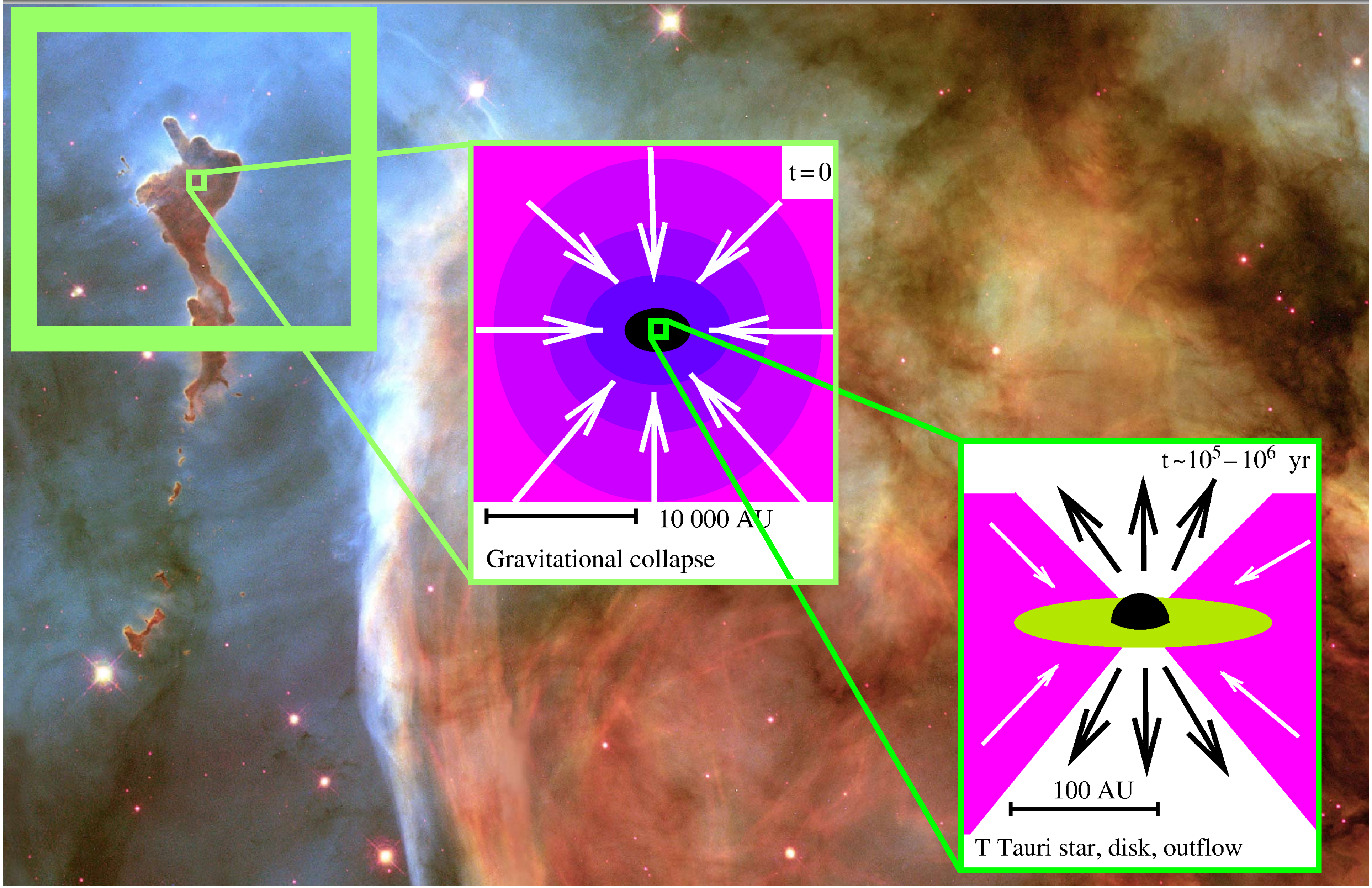
Stars are the fundamental building blocks
of the baryonic universe.

Stars provide the stable environment
needed for the formation of planetary systems
and the evolution of life.

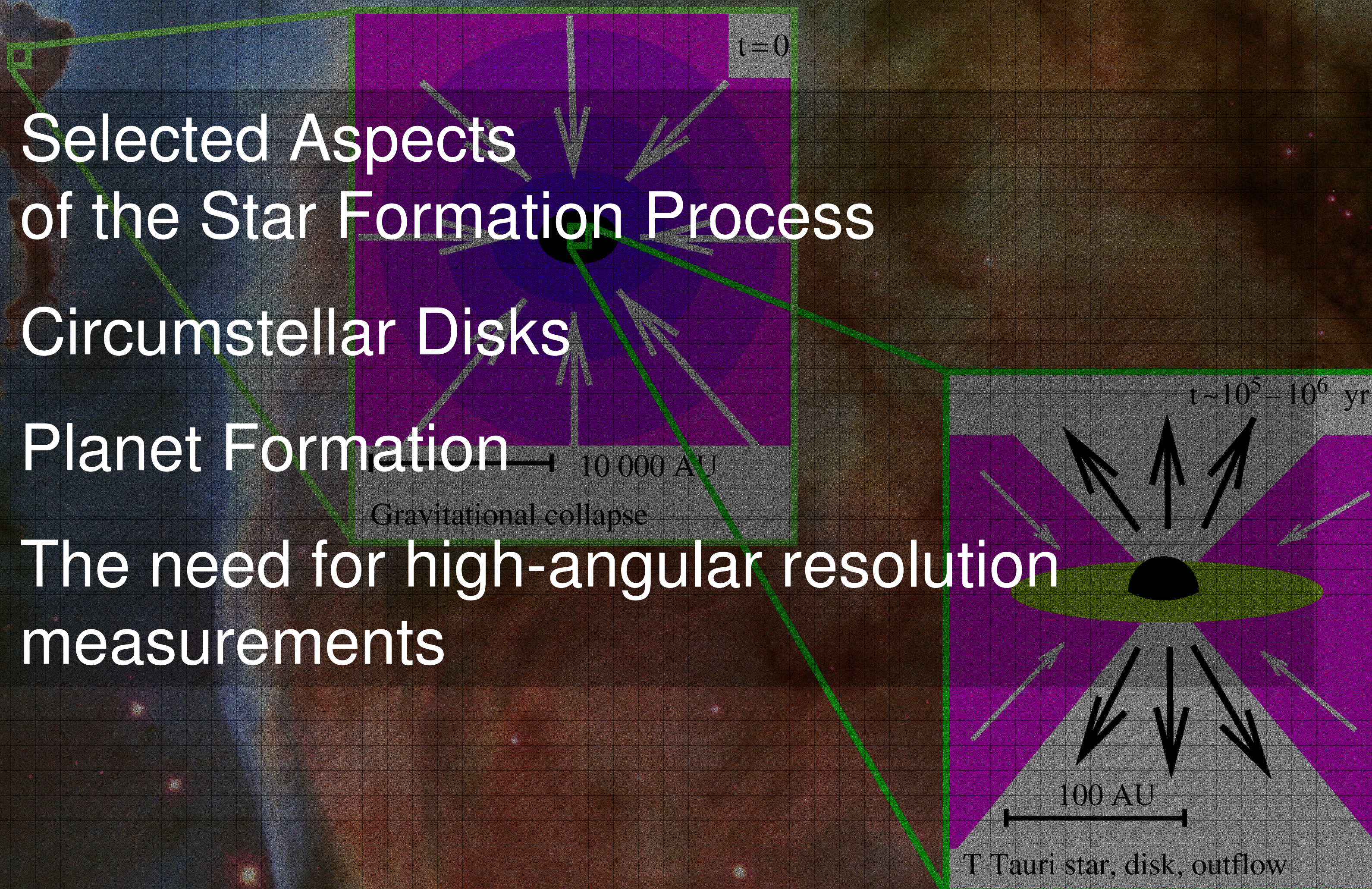
Star formation determines
the nature of galactic evolution,
how galaxies evolve chemically,
and how they convert material into
long-lived low-mass and
short-lived high-mass stars.

Clouds – Stars – Disks

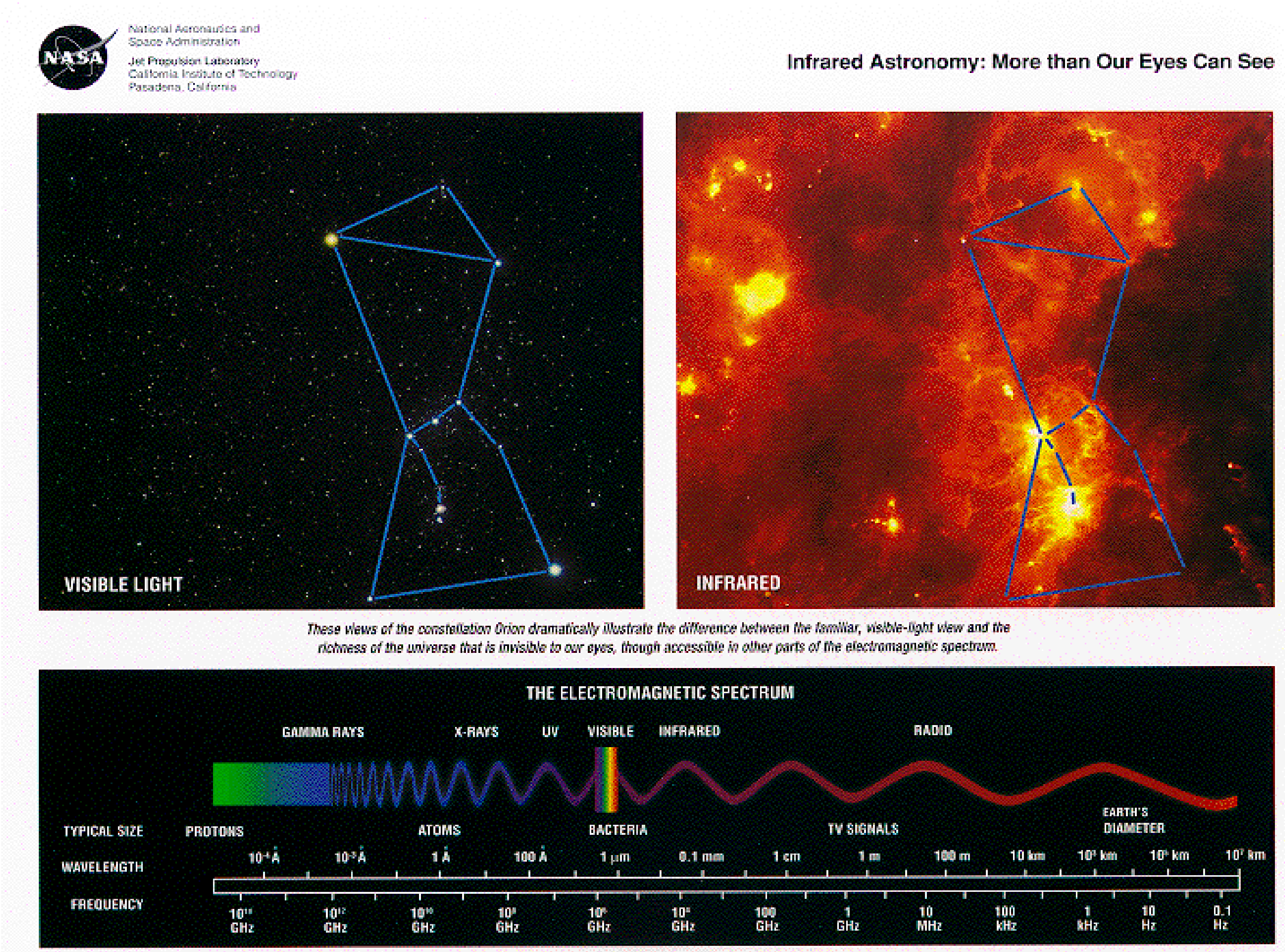


Overview

1. Selected Aspects
   of the Star Formation Process
2. Circumstellar Disks
3. Planet Formation
4. The need for high-angular resolution
   measurements



Dark Clouds?!

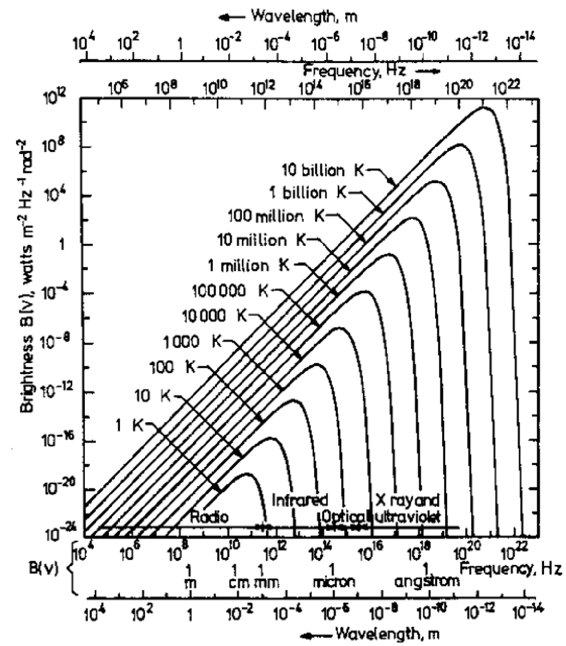


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
Infrared Astronomy: More than Our Eyes Can See
VISIBLE LIGHT
INFRARED
These views of the constellation Orion dramatically illustrate the difference between the familiar, visible-light view and the richness of the universe that is invisible to our eyes, though accessible in other parts of the electromagnetic spectrum.
THE ELECTROMAGNETIC SPECTRUM
GAMMA RAYS
X-RAYS
UV
VISIBLE
INFRARED
RADIO
TYPICAL SIZE
PROTONS
ATOMS
BACTERIA
TV SIGNALS
EARTH'S DIAMETER
WAVELENGTH
10^{-5} Å
10^{-3} Å
1 Å
100 Å
1 μm
0.1 mm
1 cm
1 m
100 m
10 km
10^{3} km
10^{5} km
10^{7} km
FREQUENCY
10^{14} GHz
10^{12} GHz
10^{10} GHz
10^{8} GHz
10^{6} GHz
10^{4} GHz
100 GHz
1 GHz
10 MHz
100 kHz
1 kHz
10 Hz
0.1 Hz

How to trace star forming regions?

$$\lambda_{max}\ [mm] \sim 2.9 / T\ [K]$$

[Wien's Law]



<u>Examples:</u>

The Sun	$T \sim 6000$ K	$\Rightarrow$	$\lambda_{max} \sim 0.5\ \mu m$	*(optical)*
Humans	$T \sim 310$ K	$\Rightarrow$	$\lambda_{max} \sim 10\ \mu m$	*(MIR)*
Molecular Clouds	**$T \sim 20$ K**	$\Rightarrow$	**$\lambda_{max} \sim 150\ \mu m$**	***(FIR/submm)***
Cosmic Backgrd.	$T \sim 2.7$ K	$\Rightarrow$	$\lambda_{max} \sim 1100\ \mu m$	*(mm)*

When do clouds collaps?

Jeans Mass: $$M_J \sim \frac{1}{\bar{\mu}^2} \sqrt{\frac{T^3}{n_H}}$$

Molecular clouds

- Low temperature (T)
- High density (n_H)
- High mean molecular weight ($\bar{\mu}$)

Jeans Mass

Jeans Mass: $$M_J \sim \frac{1}{\bar{\mu}^2}\sqrt{\frac{T^3}{n_H}}$$

- Diffuse Interstellar Cloud

  $T \sim 100K$, $\bar{\mu} \sim 1$, $n_H \sim 10\text{-}30\ cm^{-3}$

  $\mathbf{M_J > 1800\ M_{sun}}$ stable

- Molecular Cloud

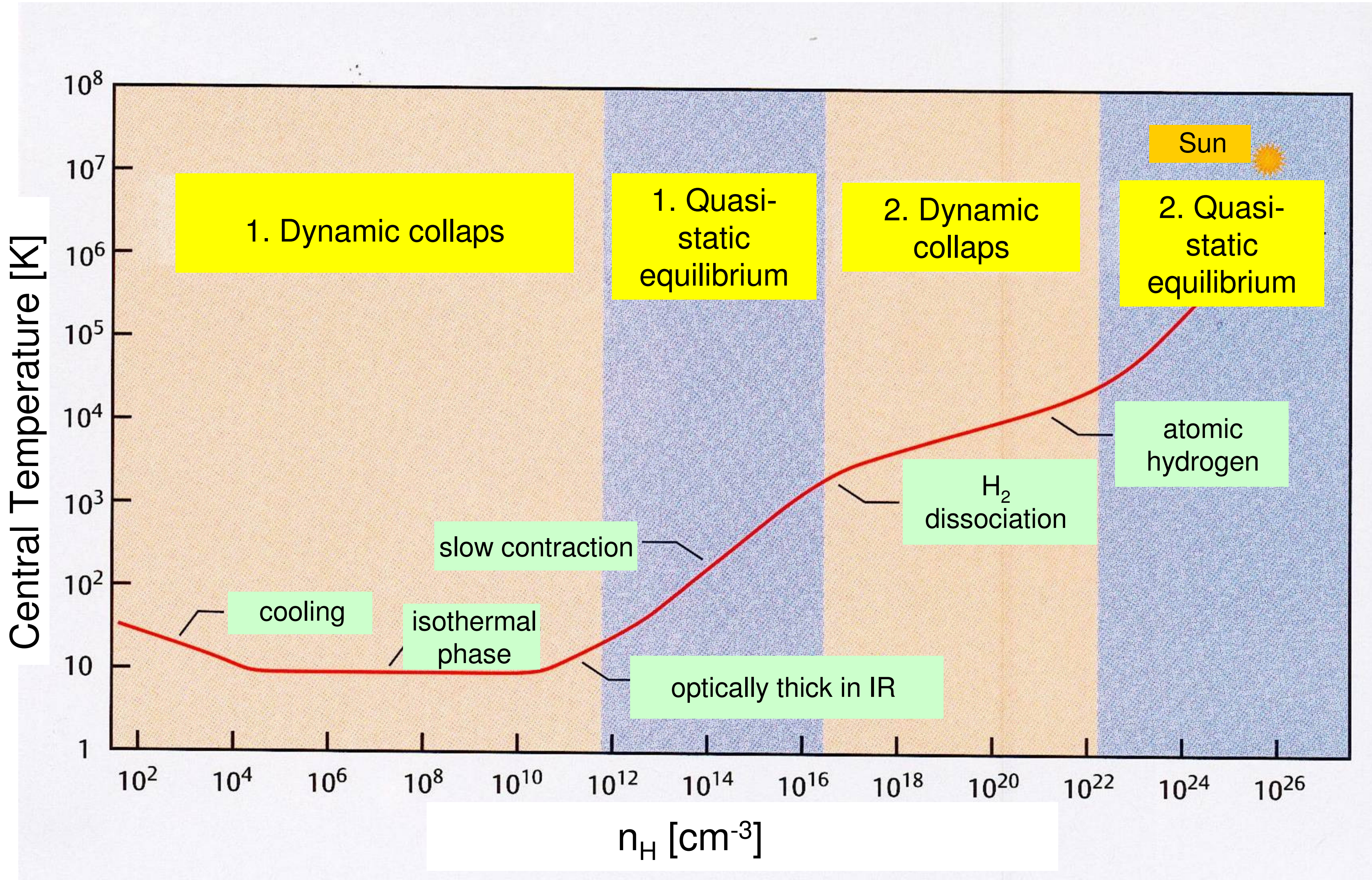
  $T \sim 20K$, $\bar{\mu} \sim 2$, $n_H = 2n_{H2} \sim 10^4\text{-}10^5\ cm^{-3}$

  $\mathbf{M_J > 180\ M_{sun}}$ unstable

Cloud properties

Cloud Type	A_V [mag]	n_H [cm^{-3}]	L [pc]	T [K]	M [M_{sun}]	Examples
Giant Molecular Clouds	1	100	50	15	10^5	Orion
Dark Cloud Complexes	5	500	10	10	10^4	Taurus-Auriga
Individual Dark Clouds	10	10^3	2	10	30	B1
Dense Cores, Bok Globules	10	10^4	0.1	10	10	TMC-1 B335

The Collapse



Timescales

1. **Dynamic Collapse** ("free fall timescale") — $10^{5\text{-}6}$ yr
   - Time a particle needs to reach the center in free fall

$$t_{dyn} \sim \sqrt{\frac{1}{\rho_0}}$$

2. **Quasistatic Phase** ("[Kelvin-Helmholtz] contraction timescale") — 10^7 yr
   - Time to release thermal energy (no nuclear fusion)
   - Virial theorem: $-\overline{E}_{pot} = 2\overline{E}_{kin}$

$$\Rightarrow t_{KH} = \frac{E_{th}}{L} = \frac{1}{2}\frac{E_{pot}}{L} \sim \frac{1}{2} G \frac{M^2}{R}\frac{1}{L}$$

3. **Nuclear Fusion** — 10^9 yr

$$t_{nuc} \sim \eta \frac{Mc^2}{L}$$

[η: efficiency: ~0.7% for H fusion]

low / intermediate mass stars

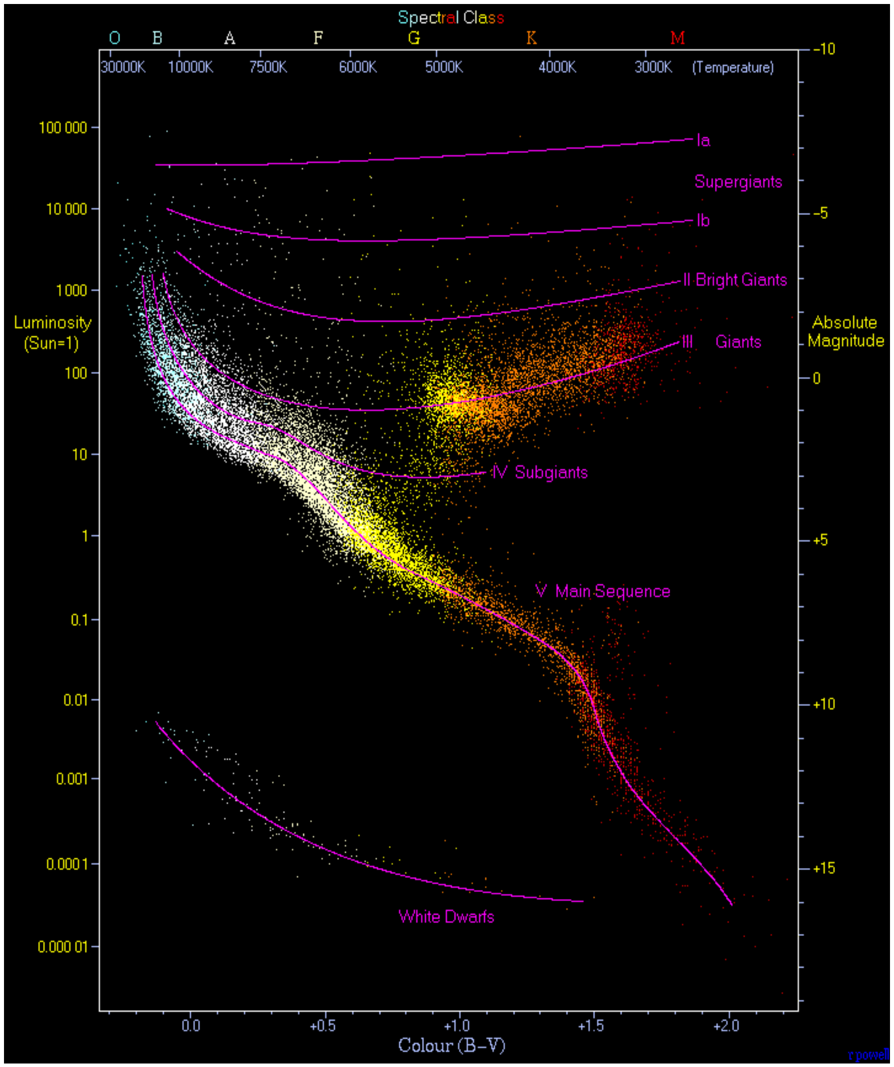
Protostar – PMS star – MS star

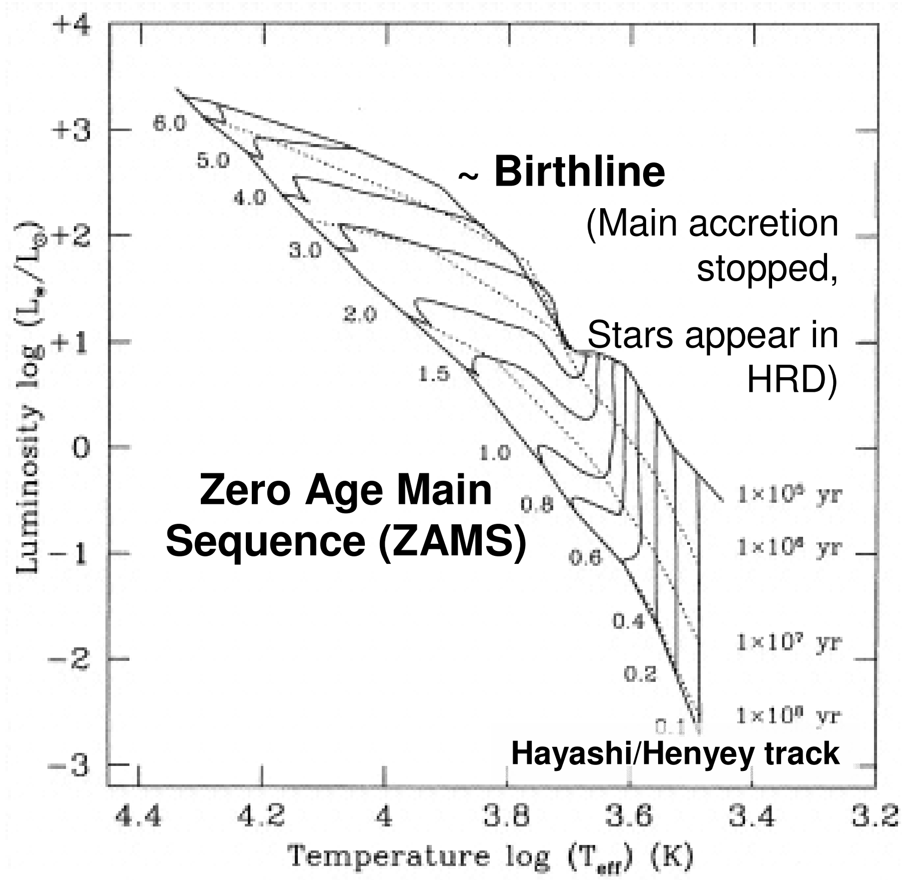
1. **Protostar**
   - Inner core optically thick in the infrared wavelength range
   - Energy / Luminosity source:
     Kinetic Energy of the infalling material
     (Accretion front)
   - *Example: Compact “mm cores” in Bok Globules*

2. **Pre-Main-Sequence Star**
   - Infall of matter almost completed
   - Energy /Luminosity souce:
     Quasi-static contraction
   - *Example: T Tauri / HAe/Be stars*

3. **Main-Sequence Star**
   - H Fusion
   - *Example: Sun*

Hertzsprung-Russel Diagram





Pre-Main-Sequence evolution = f (stellar mass)

Dotted: Isochrones

[t=0: birthline; t=$10^{8\text{-}9}$yr ~ ZAMS]

Low star formation rate

Assumptions

- *Molecular clouds are "Jeans-unstable"*
- *Collaps on free-fall timescale*

$$\Rightarrow M_{H_2} / t_{ff} \sim \text{Star formation rate (SFR)}$$

Predicted SFR : ~ few 10^2 M_{sun}/yr

Observed SFR : ~ 1...5 M_{sun}/yr

"Why are so few stars forming?"

Magnetic Fields – Ambipolar Diffusion

Interstellar magnetic fields provide support against gravity

- Magnetic field is “frozen” into the interstellar matter by the small fraction of ionized gas and dust
- As matter accumulates in the ISM (e.g., Supernova shock front), the magnetic field strength increases as the gas density increases
- After a molecular cloud accumulates sufficient mass to become self-gravitating, gravity is balanced by magnetic pressure.

$\Rightarrow$ **no collapse?**

Neutral and ionized medium decouple

$\Rightarrow$ Neutral matter collapses!

- Collisions between collapsing neutral matter and stable ionized matter

$\Rightarrow$ Decreased collapse rate
$\Rightarrow$ Typical cloud lifetime increased to several orders of magnitude longer than the free-fall time

Turbulence?

Other extreme scenario:

Weak magnetic fields

– Star formation regulated by Turbulence

- Molecular clouds are intermittent phenomena

  Cloud support on long timescales irrelevant

- Supersonic flows in the low-density ISM medium
  $\Rightarrow$ Regions of enhanced density

- Collapse criterion fullfilled only in small volumes of a cloud,
  but here on free-fall timescale

Problem: How to distinguish between both scenarios?

Magnetic field structure

Turbulence dominates

- Chaotic morphology

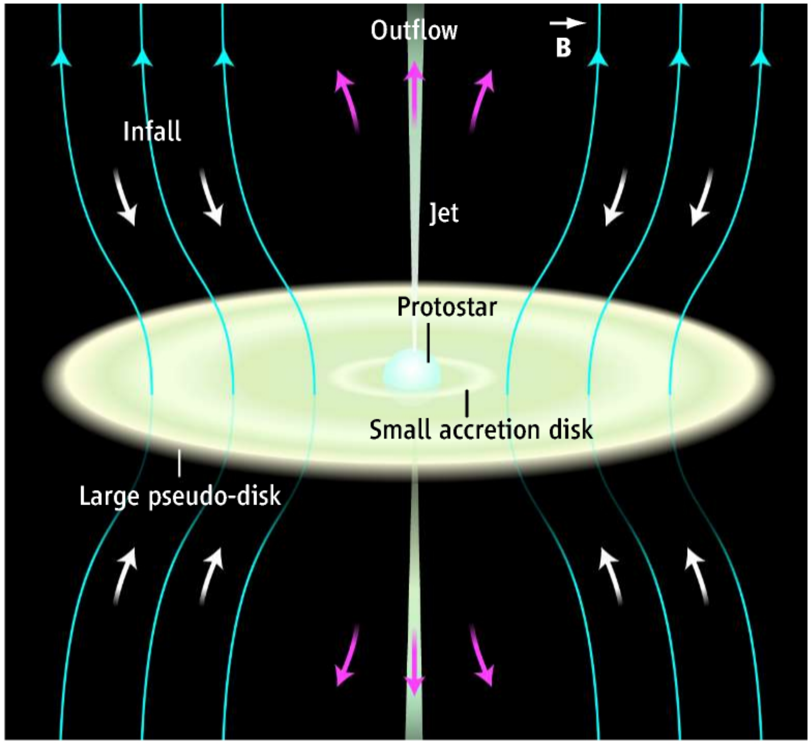
Magnetic Field dominates

- Well-ordered field lines that can be traced through polarimetric observations of the dust emission in the (sub)mm wavelength range

  Dust grains: Magnetically aligned; e.g. Davis Greenstein effect

  P perpendicular $\vec{\mathbf{B}}$

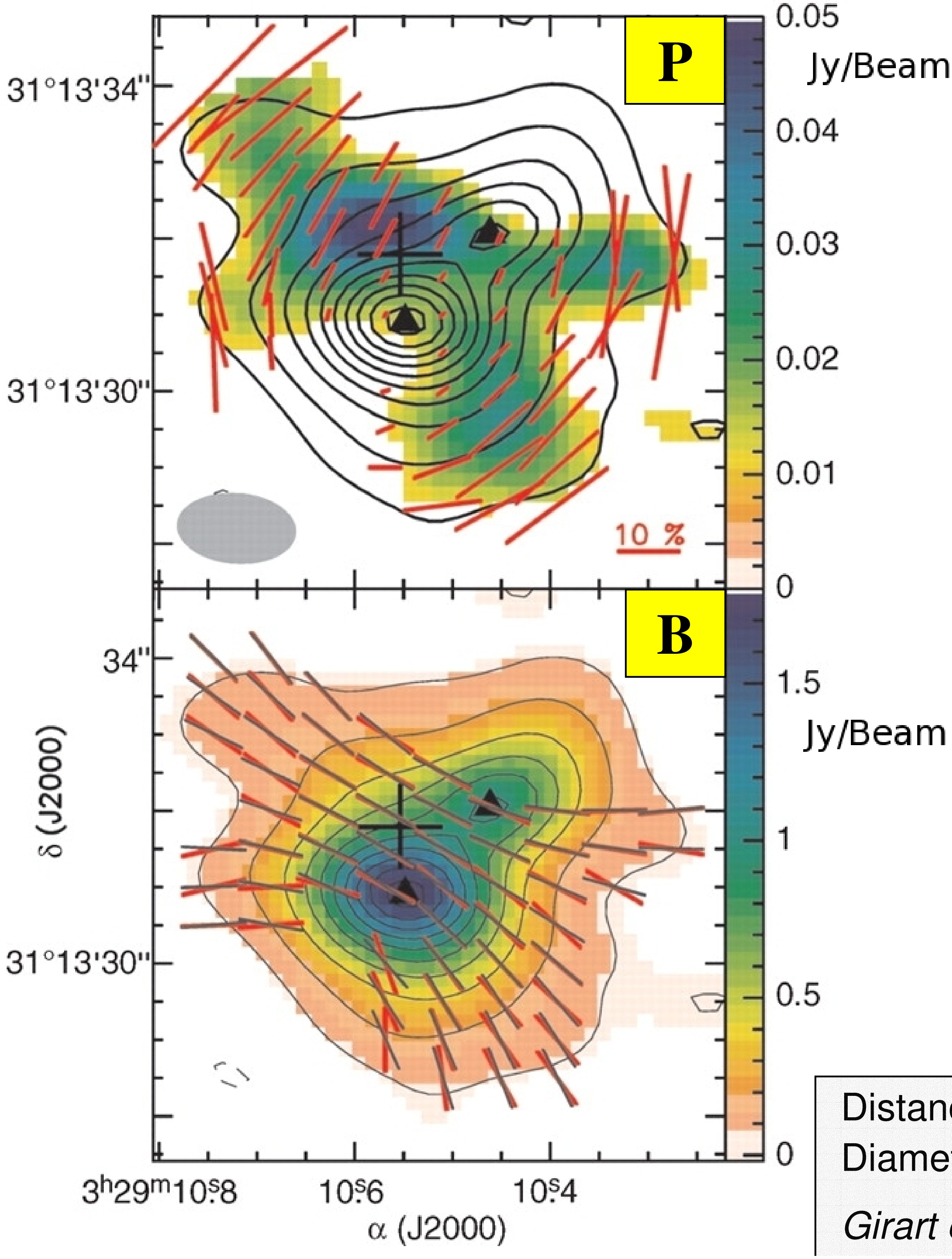
- **Neutral matter** being driven toward the core by gravity, will drag along the ions and the magnetic field



Shaped by magnetism. Schematic diagram of a collapsing molecular cloud core with a strong magnetic field (**B**) showing the characteristic hourglass shape. [Adapted from (*4*)] from Crutcher (2006)

Magnetic field: Hourglass shape

NGC 1333 IRAS 4A



- Hour glass shape of the magnetic field structure in the circumbinary envelope
- Large scale field well aligned with the minor axis
- Polarization hole
- Magnetic field strength: B ~ 5mG

Distance: 300 pc;
Diameter of displayed region ~ 2000AU

Girart et al. (2006) Science 313, 812

The Angular Momentum Problem

Angular momentum of the molecular cloud
too high to allow star formation:

No stable protostellar core smaller than
~ 3 x Solar System Size (!)

$\Rightarrow$

99.9999 % of the original angular momentum have to be "removed" during the star formation process

(to explain angular momentum of a typical star)

The Angular Momentum Problem

Proposed Solutions:

[1] Multiple Stellar Systems

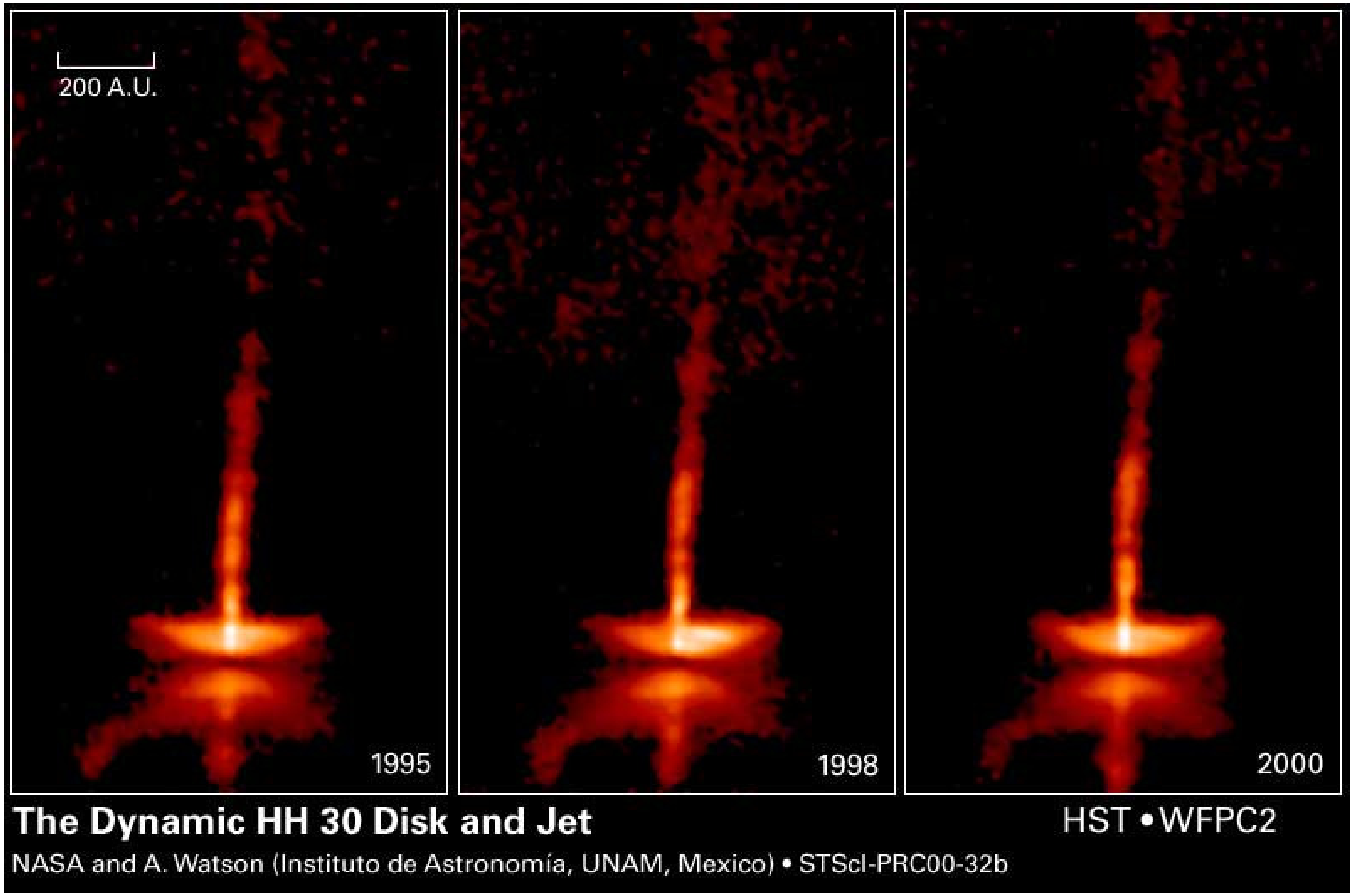
[2] Angular transport to outer disk regions

[3] Collimated, fastly rotating gas streams (Jets):

Angular momentum transfer from the disk
to a small fraction of ionized gas (plasma)

Magnetic fields in the disk accelerate the plasma:
Bipolar “fountains”

Jets and Outflows

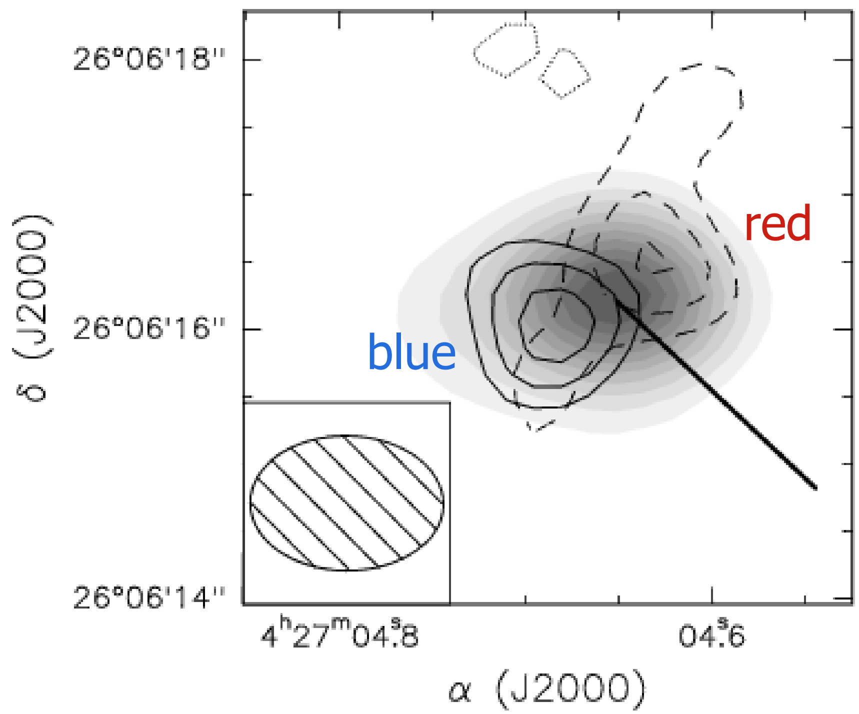


Jet velocities 100-500 km/s $\Longleftrightarrow$ Outflow velocities 10-50 km/s

Jets/Outflows are likely driven by magneto-centrifugal winds from open magnetic field lines anchored on rotating circumstellar accretion disks

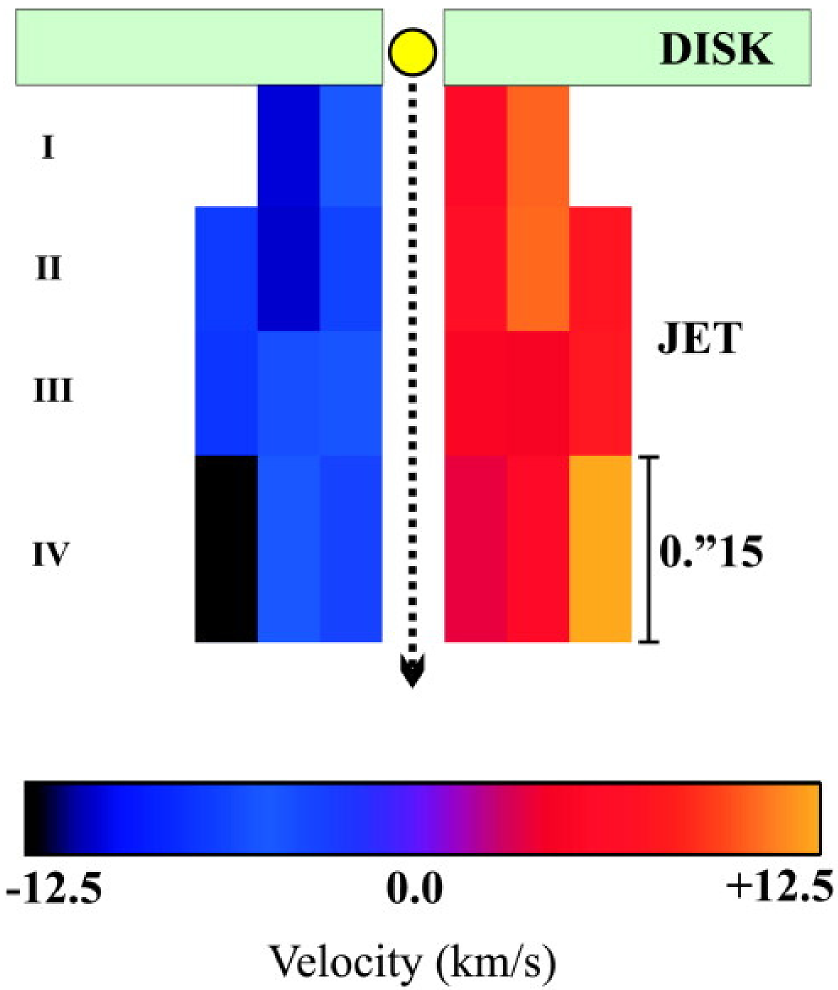
Jet rotation in DG Tau

Corotation of disk and jet



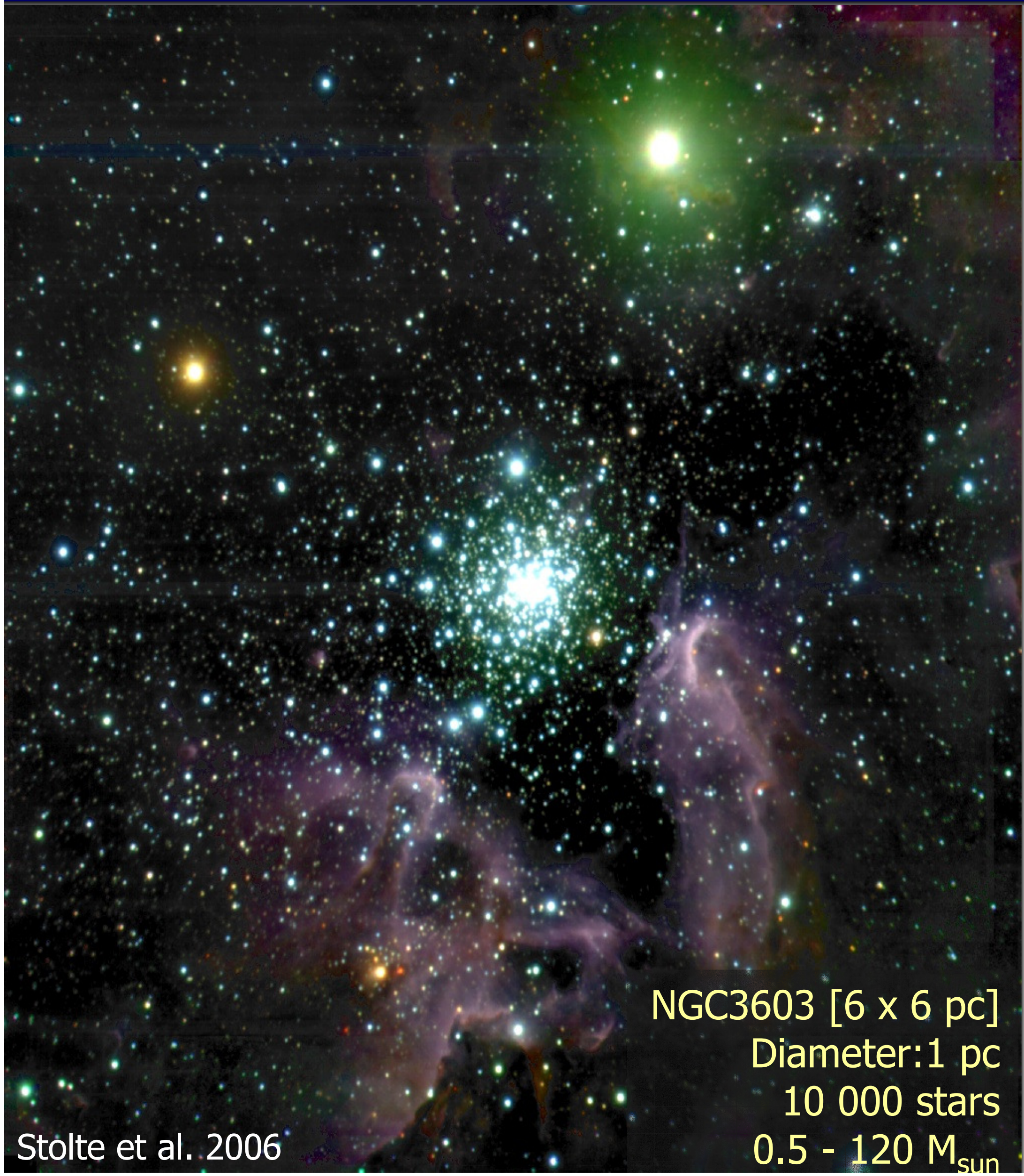
Testi et al. (2002)

Observed Radial Velocity Shift



Bacciotti et al. (2002)

Single Stars, Binaries, Multiples, … Clusters!



53% of nearby solar-type main-sequence stars are binary or multiple systems

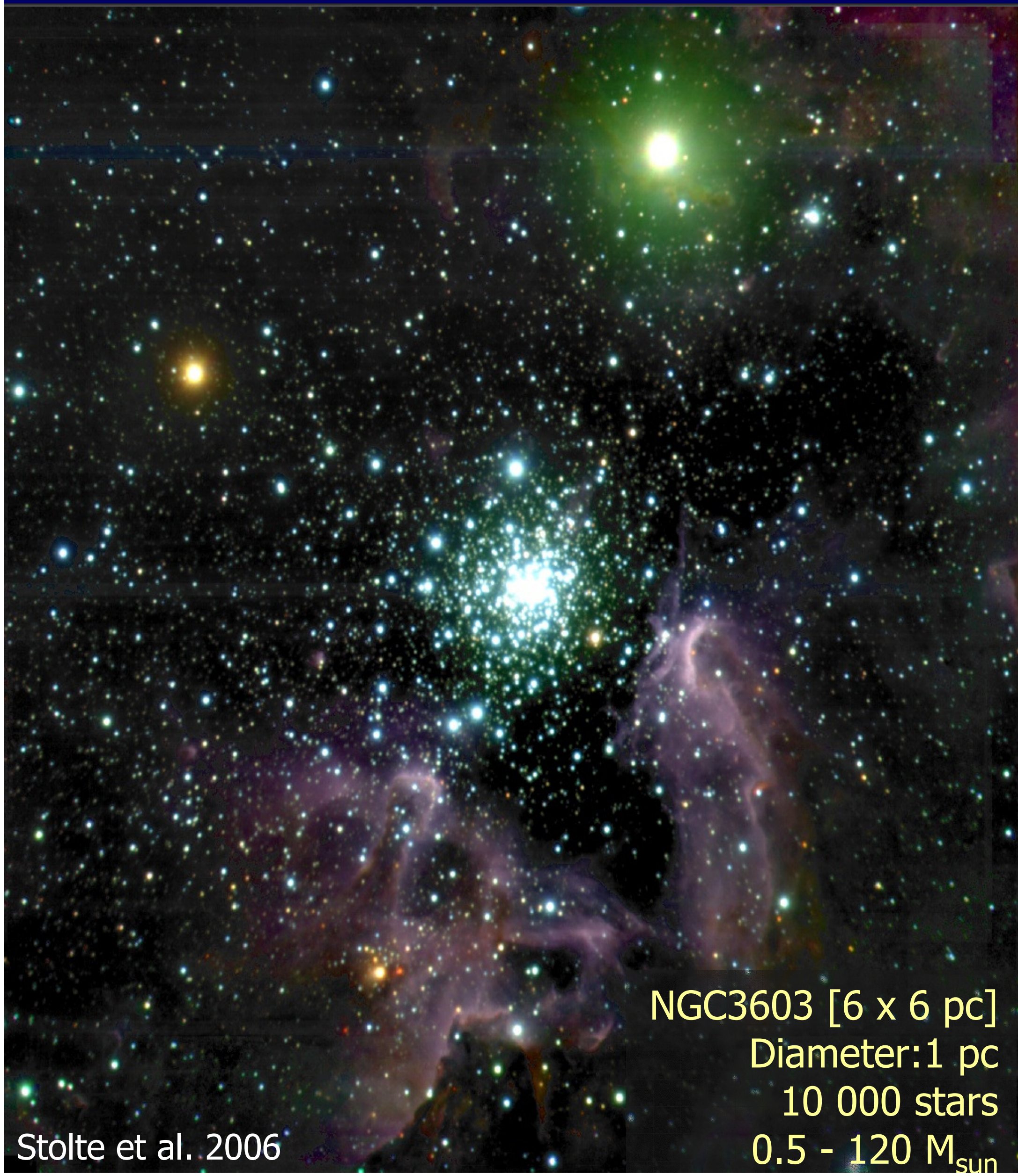
Taurus-Auriga Star Forming Region: 80-100%
(Ghez et al. 1993, Leinert et al. 1993, Reipurth & Zinnecker 1993)

Almost all stars form in clusters;
Isolated star formation is exception

Initial Mass Function
Salpeter (1955)
$dN/dM \sim M^{-2.35}$

Now, more detailed description of the IMF exist
(e.g., Kroupa 2001)

Single Stars, Binaries, Multiples, … Clusters!



Binary $\neq$ 2 individual stars

Stars in a Binary/Multiple System
- Share common history
- Influence each other

Dominating Mechanisms during Cluster Formation still under debate

What determines the IMF?

Role of Gravitational Fragmentation
vs.
Competitive Accretion?

Cloud mass distributions
vs.
Pre-stellar core mass distribution?

Massive Star Formation
($M>10M_{sun}$)

$$L \sim M^3$$

Significant energy input into the ISM during their entire lifetime (outflows, radiation, supernovae).

They produce all the heavy elements.

Form preferentially in ultra-dense proto-cluster environments

Short Contraction timescale

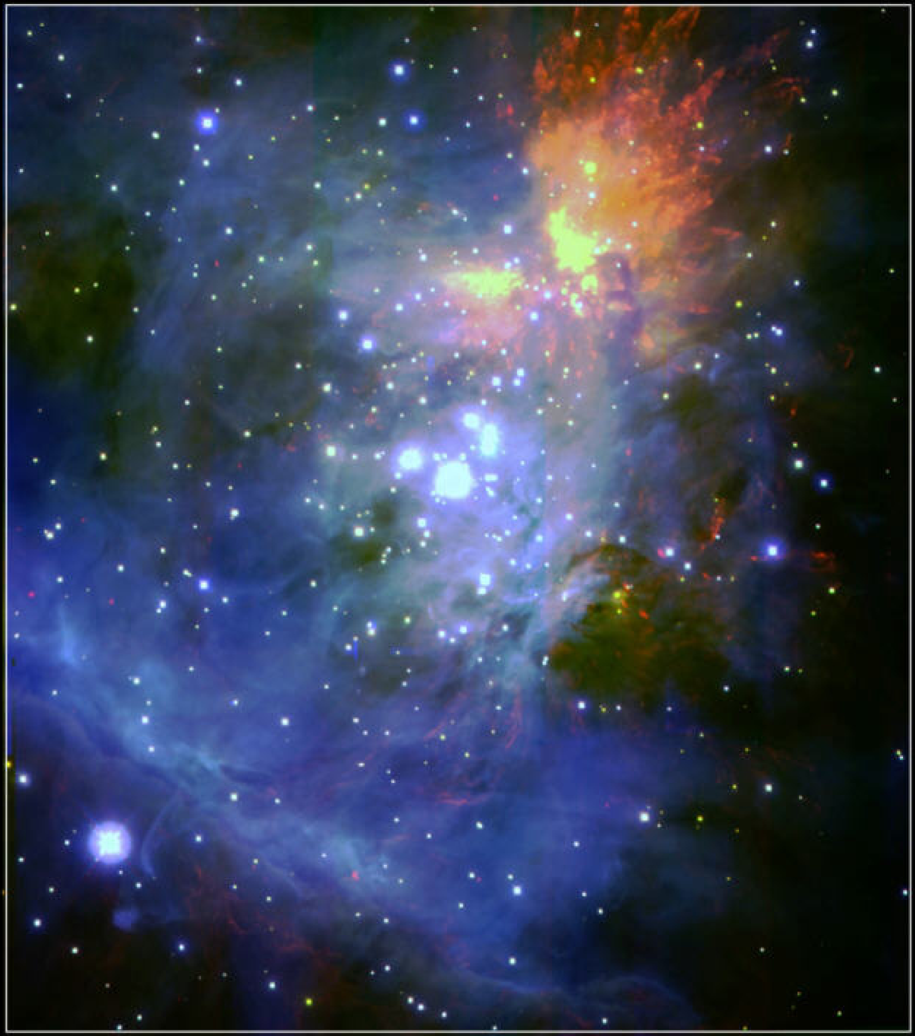
$t_{KH}=3x10^7\ yr\ (M/M_{sun})^2\ (R/R_{sun})^{-1} (L/L_{sun})$

[$60M_{sun}$, $12R_{sun}$, $10^{5.9}\ L_{sun}$: $t \sim 11000$ yr]

$\Downarrow$

Pre-main sequence evolution not observable

Relatively rare in our Galaxy: typical distances of 3-7kpc

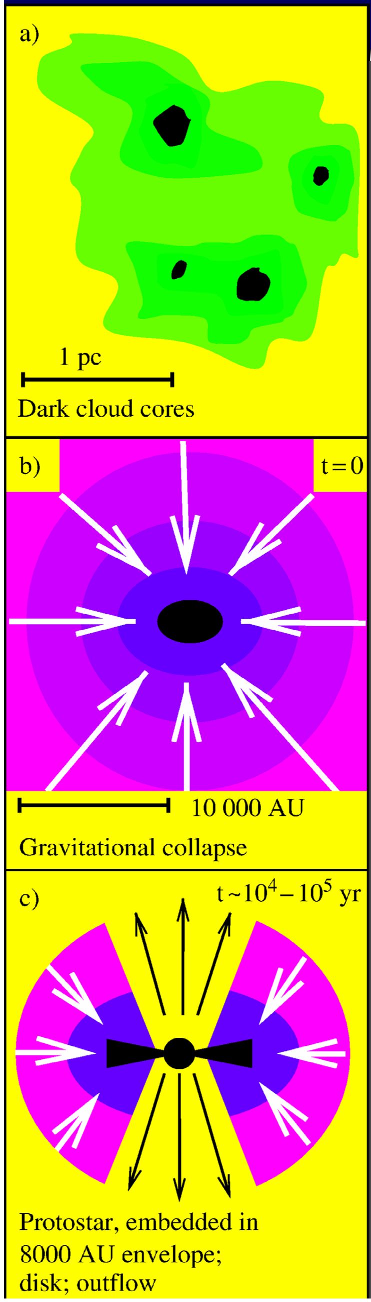


Orion Nebula
Subaru Telescope, National Astronomical Observatory of Japan
CISCO (J, K' & H_2 (v=1-0 S(1))
January 28, 1999

Interferometry and Star Formation

1. How does the accretion process onto the central star evolve with time?
2. How do large-scale (molecular) outflows and jets form?
   How do they get collimated? Where is exactly their origin?
3. Which role do magnetic fields play? Are they coupled to the disk?
   Are they important for the accretion process onto the star,
   e.g. by accretion through magnetospheric funnel flows?
4. How are the gas and dust distributed on large scales in the disk
   (radially, vertically; azimuthal structures?)?
5. Which role do stellar winds play?
6. What are the structure and geometry of the accreting protostar?
   How is the star interacting with its surrounding circumstellar disk?
7. How do disks interact with one another in young multiple stellar systems?
8. Do young massive stars have circumstellar disks?

Stars to Planets: Disks



- **Protostellar / Young circumstellar / Protoplanetary Disk**:
  - Gas / Dust disks around protostars / young stellar objects
  - typical diameter: a few 100 AU

- **Formation**:

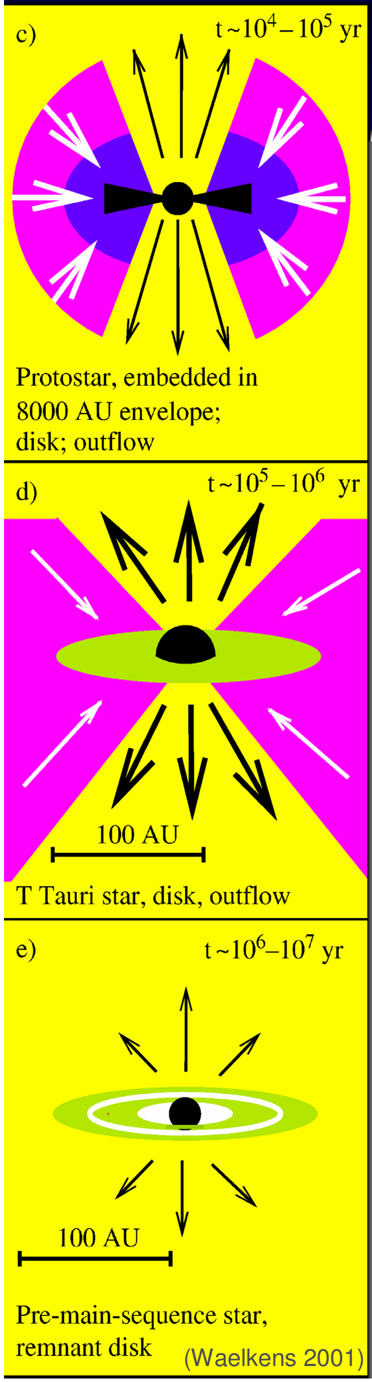
  "Byproduct" of Star formation:

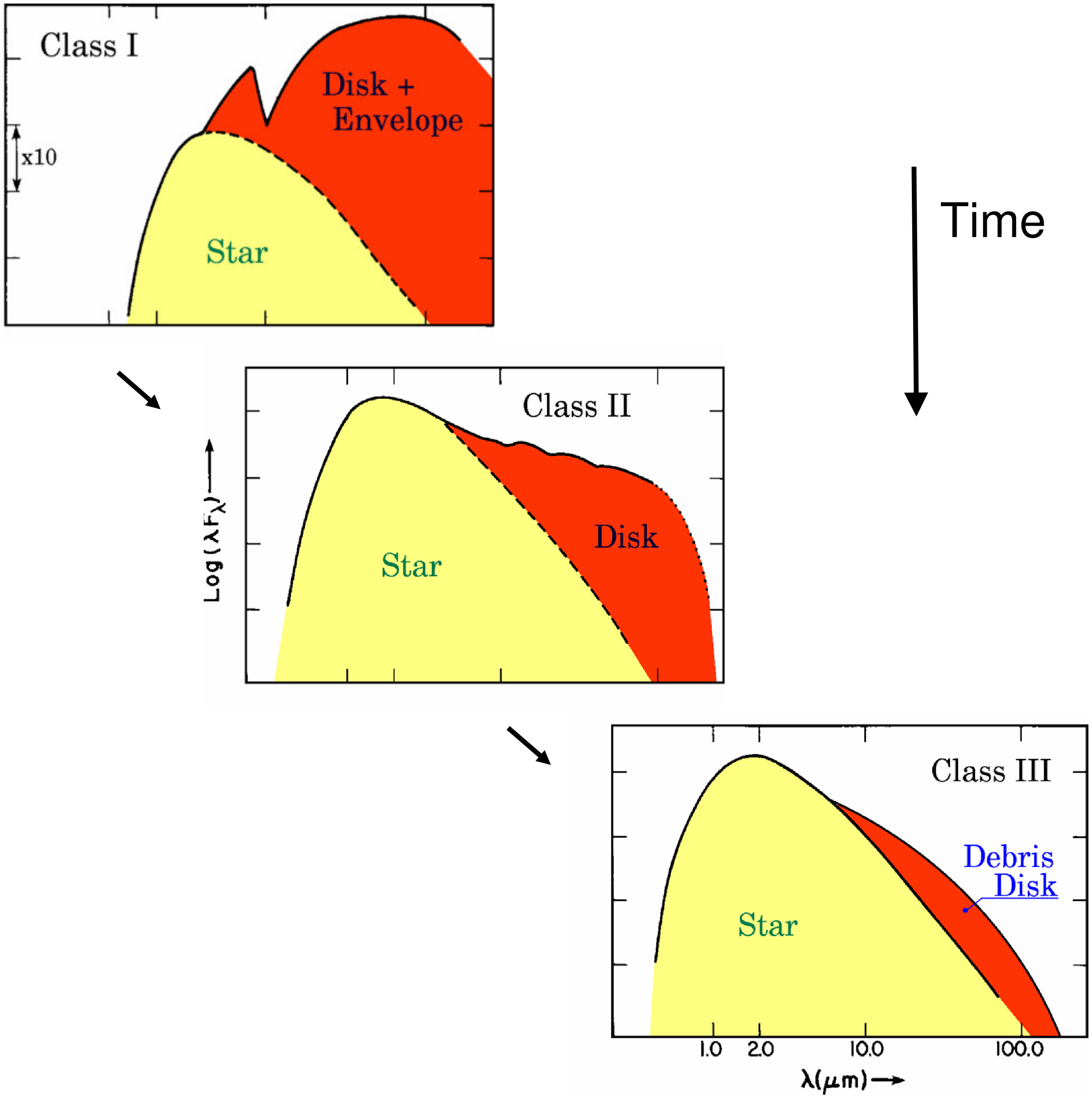
  Collapse of a rotating molecular cloud core
  (angular momentum <> 0)

  => Formation of a rotating distribution of the infalling material around the central object
  (Protostar / Pre-main-sequence Star)

- **Circumstellar Disks**
  - "Reservoir" for mass and angular momentum
  - Environment + Material for Planet Formation
  - Evolve in time (structure + composition)

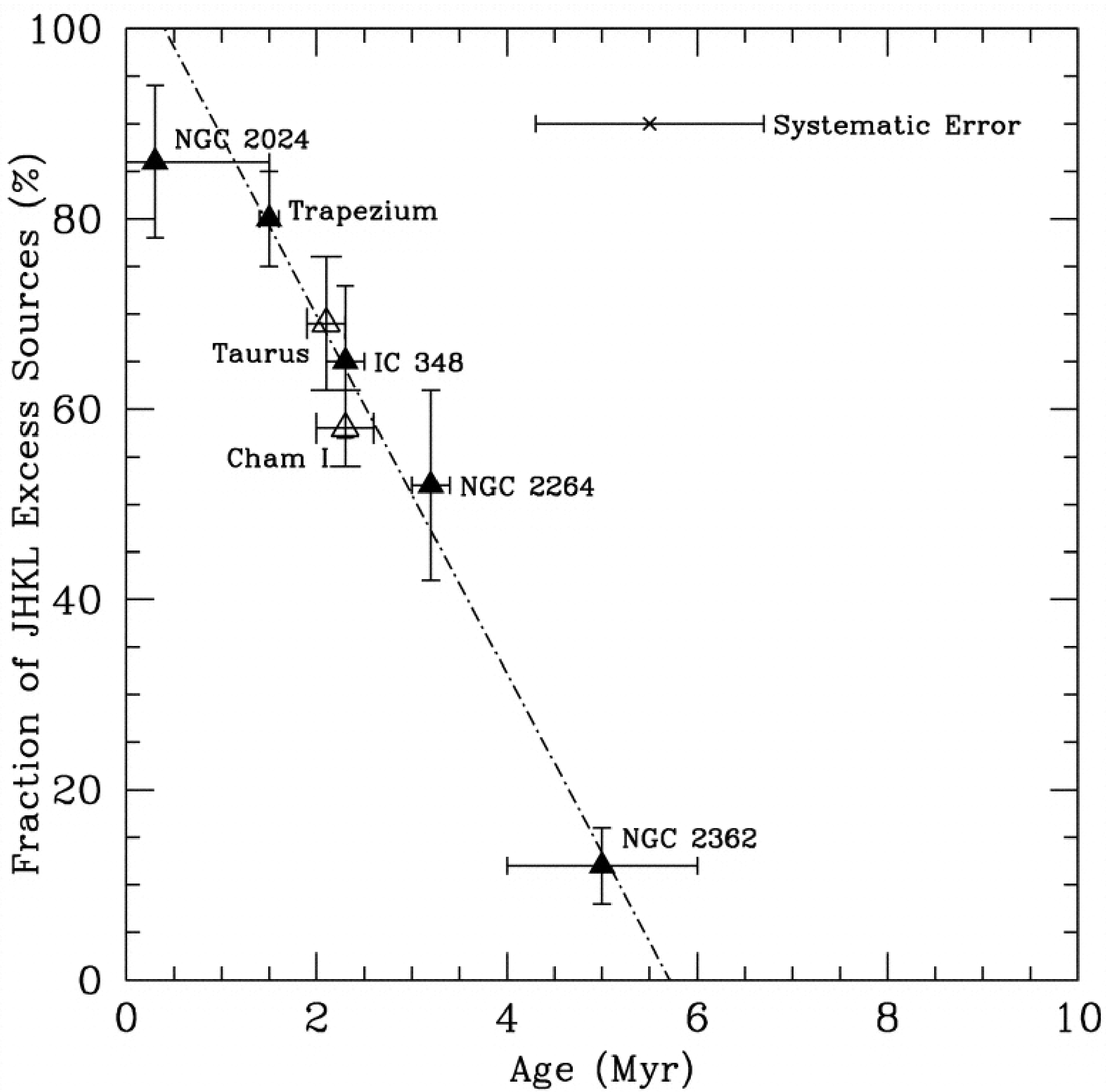
Disk Evolution

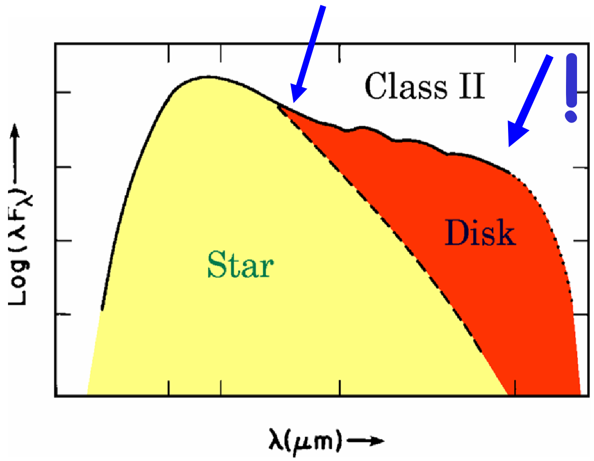




(Lada 1987)

Disk Lifetime: Inner Disk Region

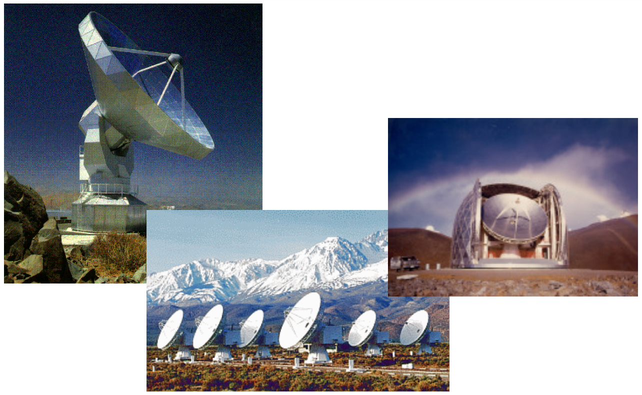




Fraction of **inner disks** traced by near-IR excess dimishes to ~0 over a few Myr

(Haisch et al. 2001)

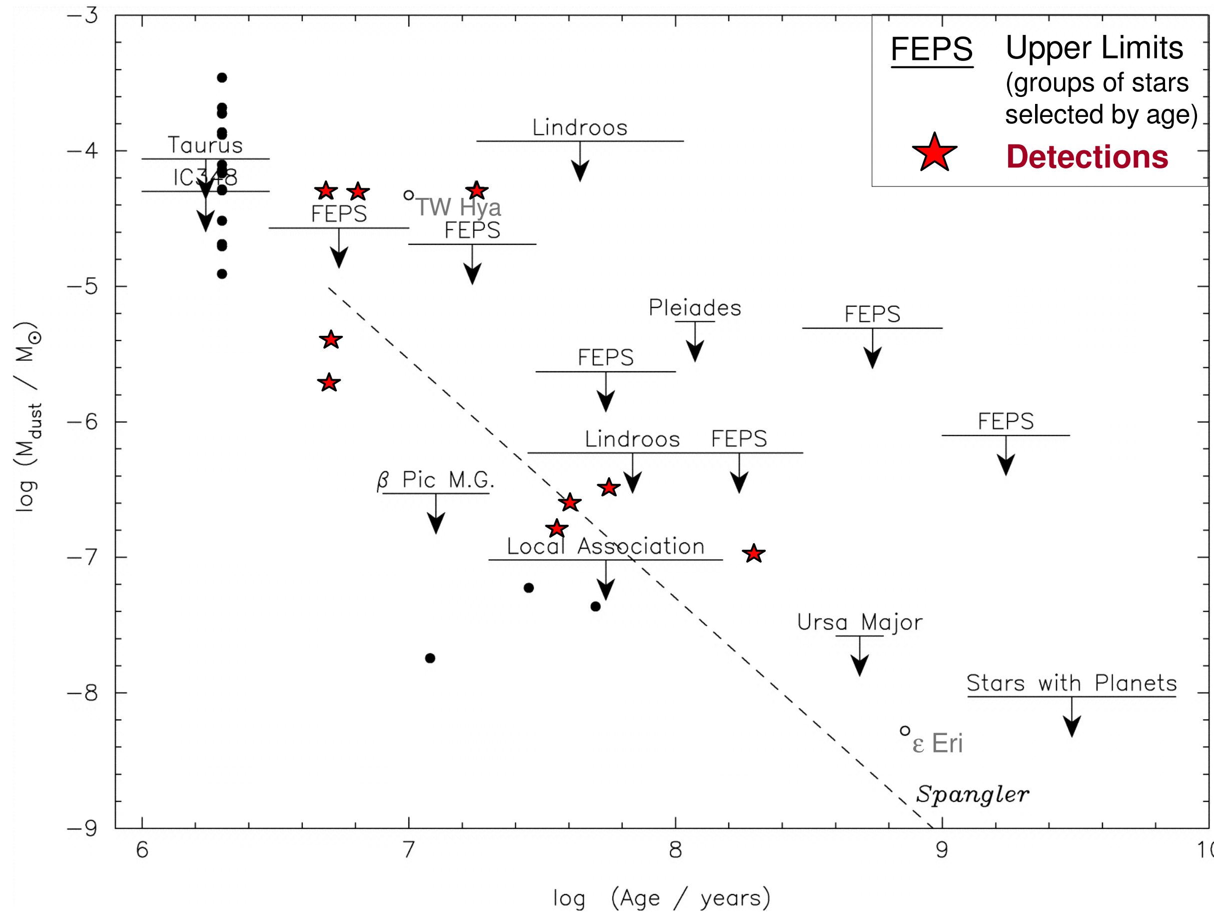
Disk Lifetime: Entire Disk



SEST, CSO, OVRO, IRAM:
trace entire disk

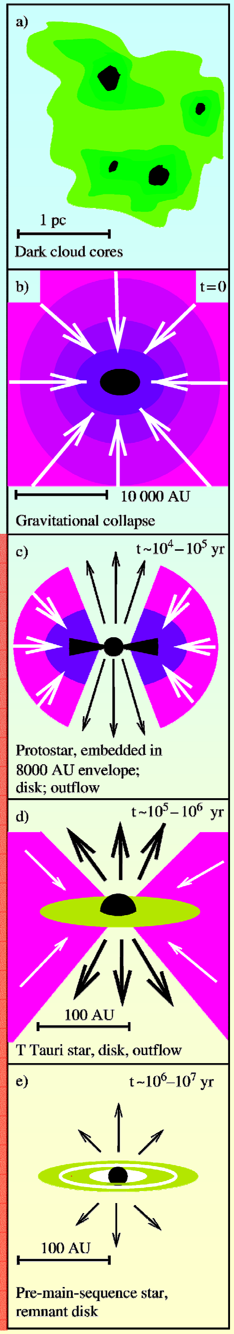
165 solar-type stars
(from FEPS legacy program):
0.5 – 2 M_{sun}; 3 Myr – 3 Gyr

- 9 new detections:
  ~10 - 200 Myr
- 1 resolved mm source



[Carpenter, Wolf, et al., 2005]
[Roccattagliata, Wolf, et al., in prep.]

Planet Formation in a Nutshell



(Waelkens 2001)

Star Formation Process → Circumstellar Disks → Planets

Core Accretion – Gas Capture

(sub)µm particles

↓

- Brownian Motion, Sedimentation, Drift
- Inelastic Collision → Coagulation

cm/dm grains

↓

- Agglomeration; Fragmentation

Planetesimales

↓

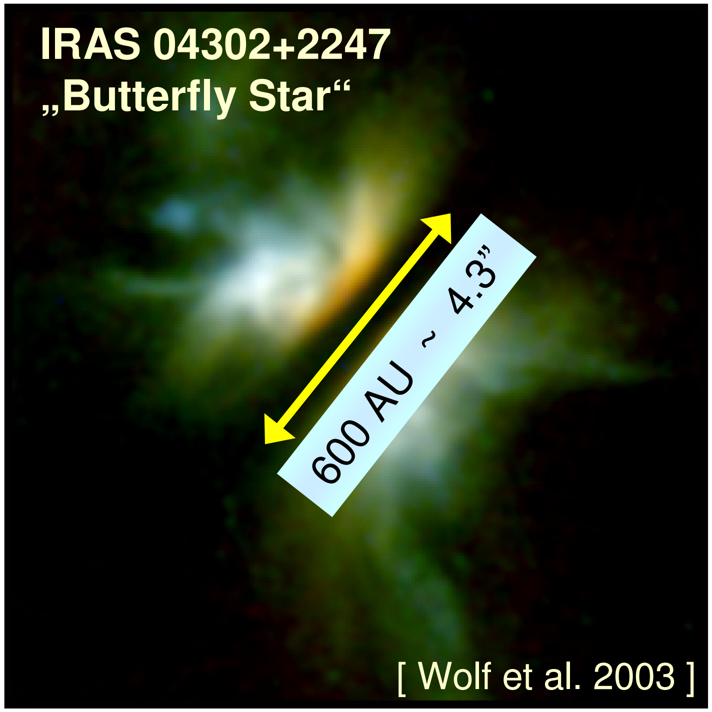
- Gravitational Interaction: Oligarchic Growth

Planets (cores)

- Gas Accretion

Alternativ: Gravitational Instability → Giant Planet

Size Scales



Solar System

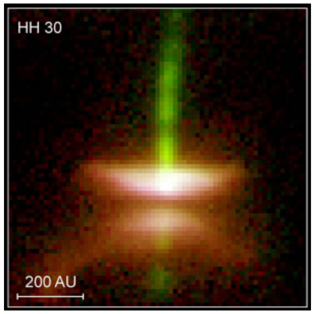
Angular diameter of the orbit of solar system planets in a distance of the Taurus star-forming region (140pc):

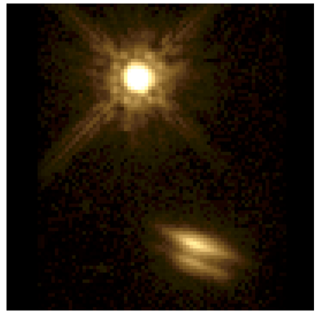
Neptune	-	0.43”
Jupiter	-	0.074”
Earth	-	0.014”

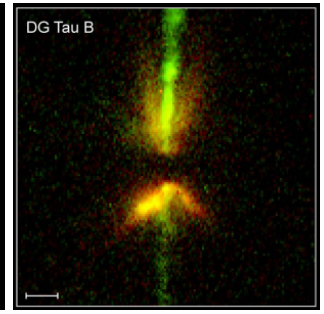
What is feasible?

AMBER / VLTI	~ few mas	[near-IR]
MIDI / VLTI	~ 10 – 20 mas	[N band]
SMA	~ 0.3” (goal: 0.1”)	[~submm]

Which disks to study?

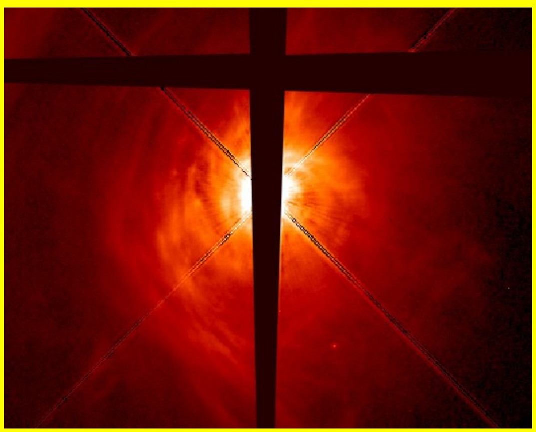




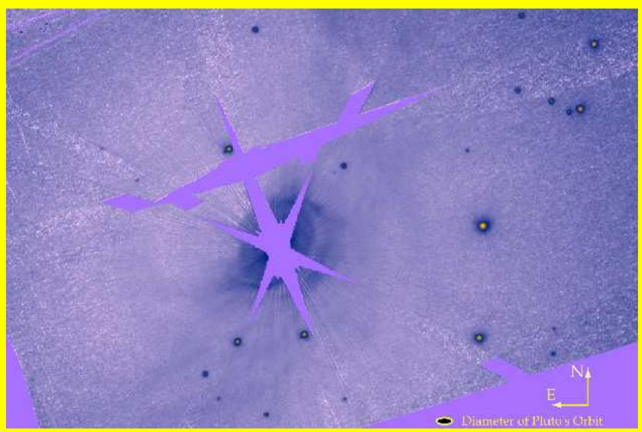


Etc. ...

Clearly identified disks, well studied, but …
Potential ”planet-building sites” hidden …



AB Aurigae



HD 100546

(Grady 2001 / 2003)

Very distant …

Preparatory studies, concentrating on face-on disks

Useful techniques:

Coronography;

Differential polarimetric imaging;

hires mm maps

=> optical, near-IR, mid-IR;

Interferometry and Planet Formation

1. How does the size distribution and chemical composition of the dust evolve?

2. How does the structure of circumstellar disks evolve (e.g., relative distribution of dust and gas)?

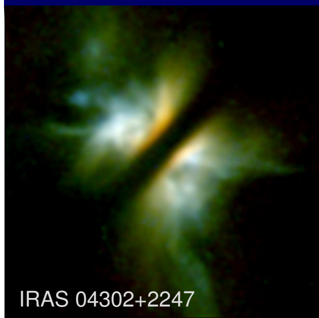
3. Do circumstellar disks show signs of the possible planet formation process or even of the existence of already formed planets (gaps; large-scale spiral structures induced by the planet; planetary accretion)?

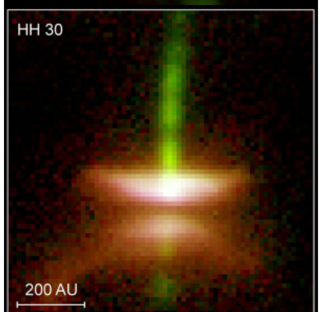
4. What are the conditions for planet formation in binary or multiple stellar systems? Which role does disk-disk interaction play?

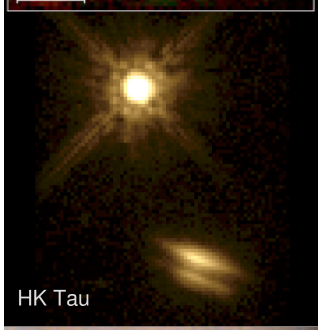
5. What is the influence of very close (sub)stellar binaries on the circumstellar disk?

6. Is planet formation possible in the environment of massive stars?

Evolution of the Disk Structure







Young circumstellar disks around T Tauri / HAe/Be stars

↓

optically thick

Debris disks

↓

optically thin

Density structure dominated by

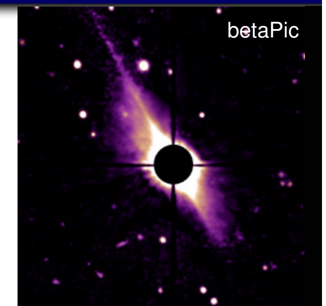
Gravitation

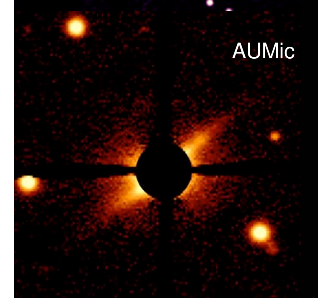
+

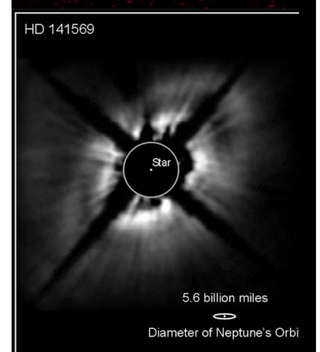
Gas dynamics

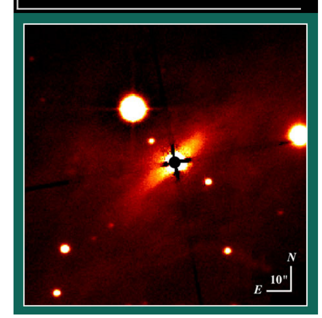
Radiation Pressure

Poynting-Robertson effect









Zodiacal Light

Etienne Leopold Trouvelot (1827-1895)

Bob Shobbrook, Siding spring, 2 hours after sunset.

Outlook

Literature: Stahler & Palla "The Formation of Stars"

(see also there for further references to the illustrations in this presentation)

Later this week:

- **Analysis of disk observations**
- **Planets in Disks**