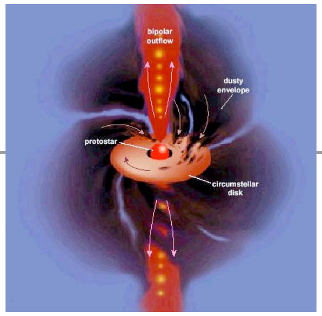
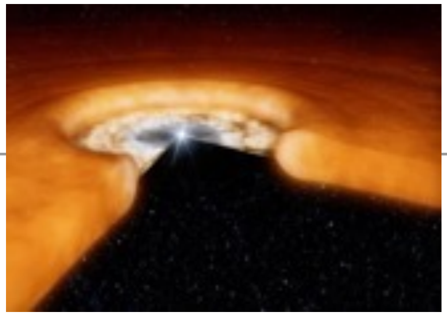
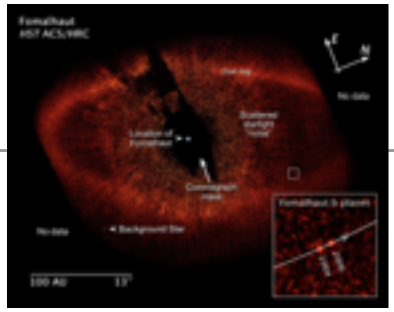
Csillagkeletkezés

A csillagközi anyagtól a bolygókig

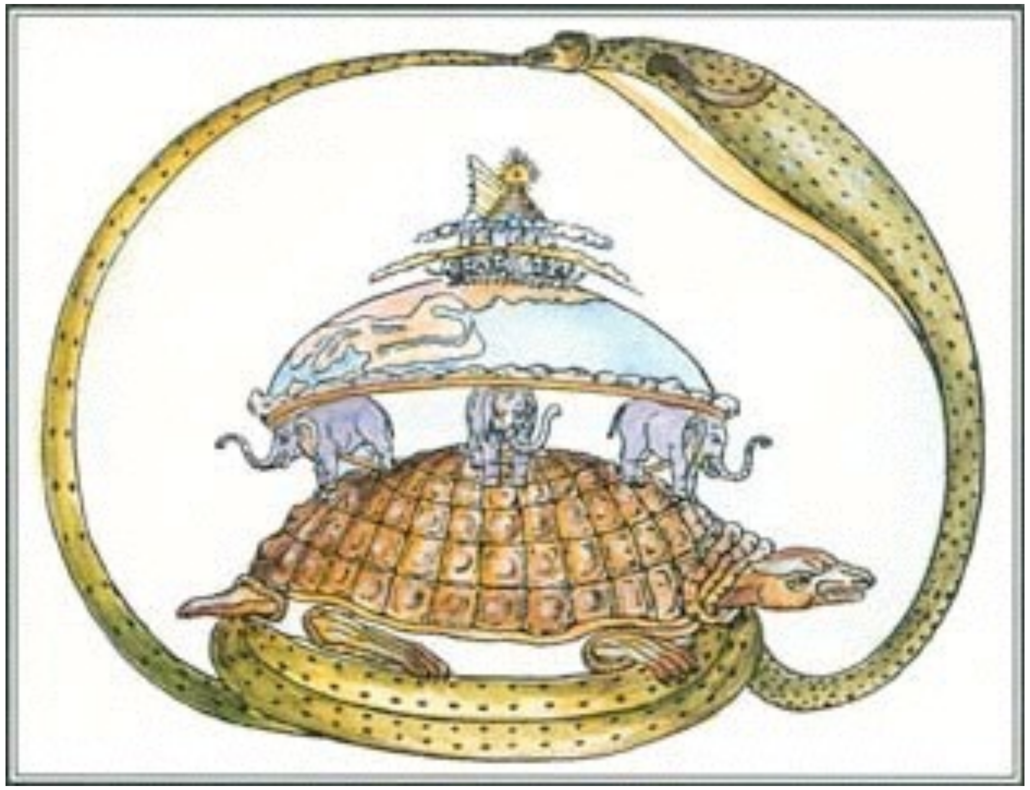


Ábrahám Péter
MTA Csillagászati és Földtudományi Kutatóközpont
Konkoly-Thege Miklós Csillagászati Intézet

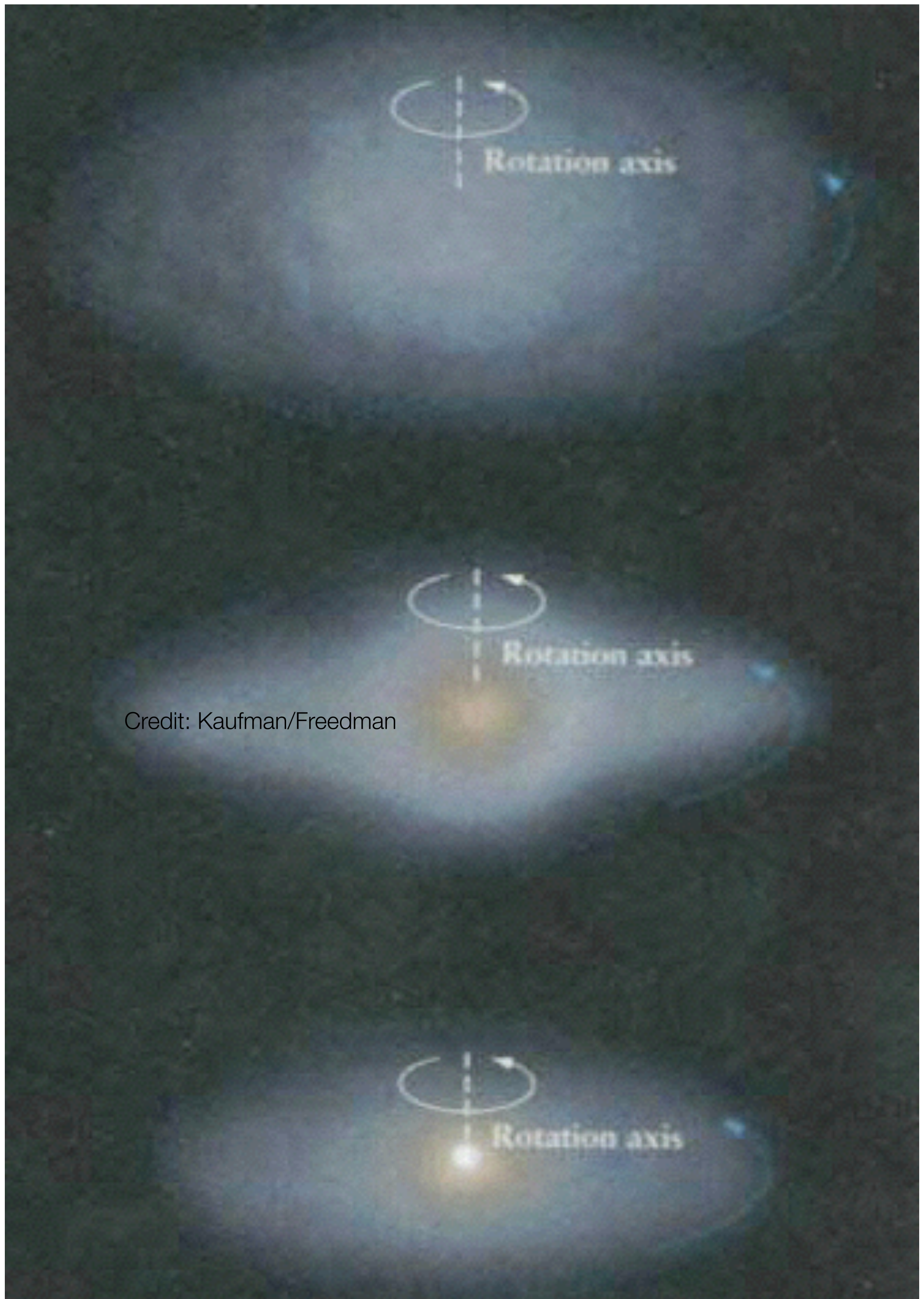
ELTE, 2016 október 4.

Minden civilizáció (egyik) alapkérdése…

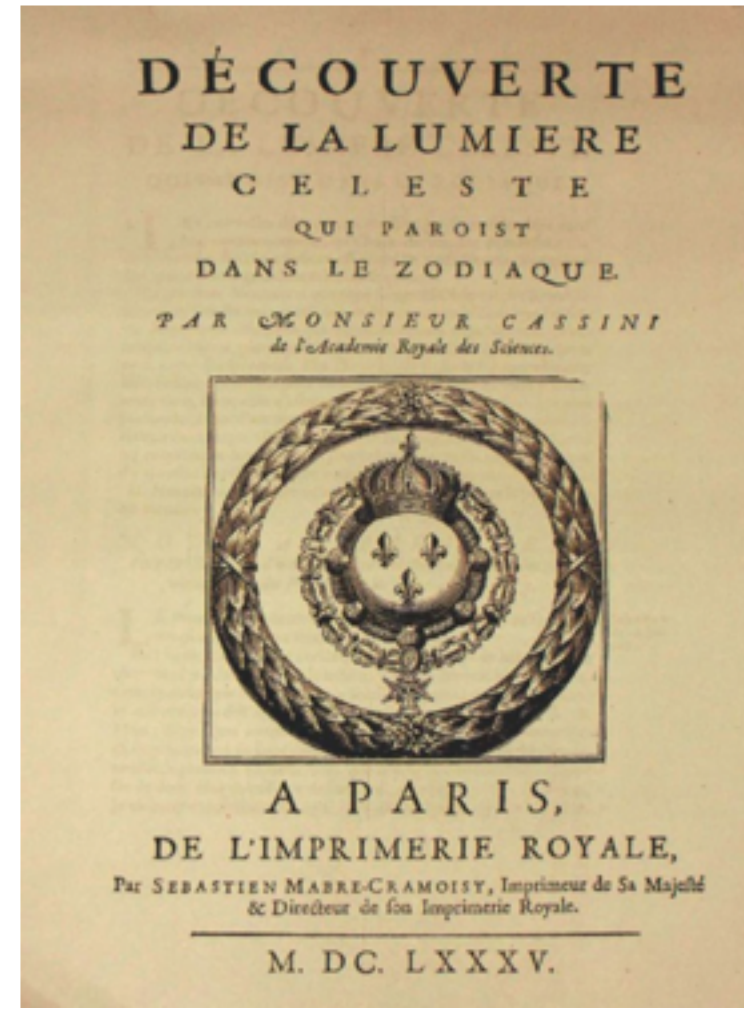


Norse representation of the World Tree. Yggdrasil carved on an ancient rune stone.

Tudományos megközelítés: XVII-XVIII. sz.



Az állatövi fény jelenségének helyes értelmezése (Cassini, 1683)



A Naprendszer keletkezésének Kant-Laplace elmélete (XVIII. sz.)

Young, circumstellar discs

A brief history:

- The "Solar nebular hypothesis"

1734: ***Emanuel Swedenborg:*** Nebular Hypothesis "***Urnebel***"

1755: ***Immanuel Kant:*** Rotating Cloud "***Urwolke***"
"Allgemeine Naturgeschichte und Theorie des Himmels"

1796: ***Pierre-Simon Laplace:*** Rotating Gasball w/ Gravitation
But: Planets have 99% of angular momentum in solar system

⇒ ***Angular momentum problem!***

time passes...

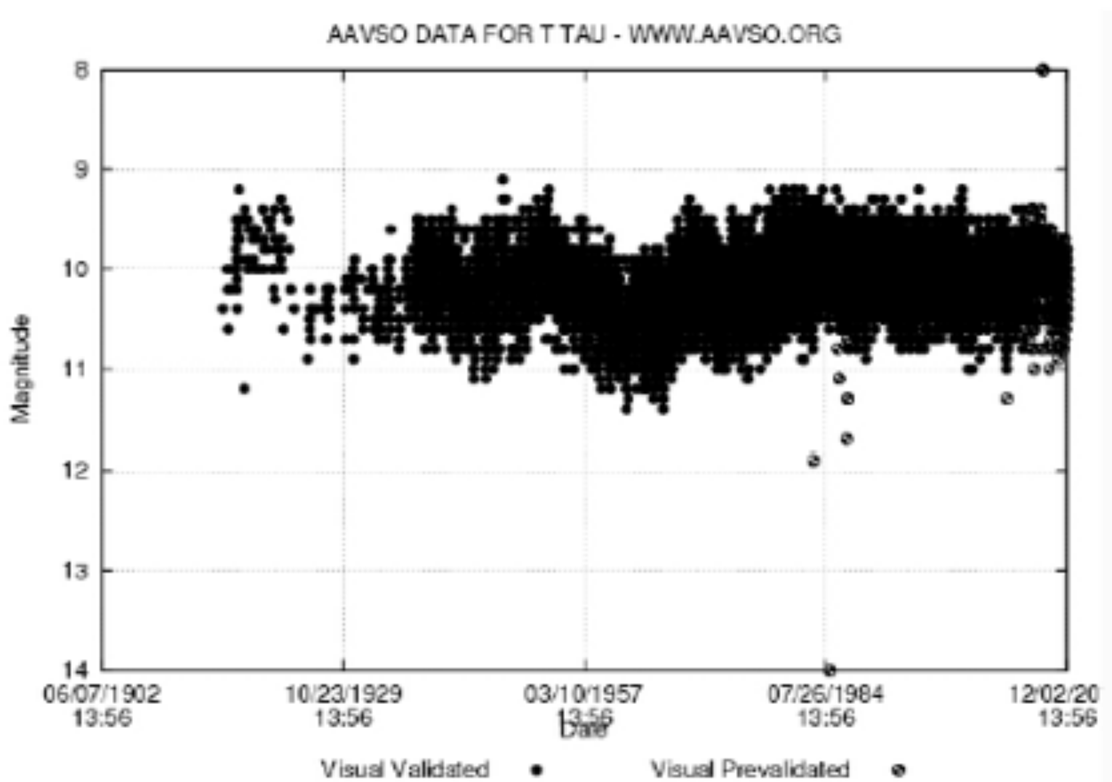
1972: ***Victor Safronov:*** Solar Nebula-Disc-Model

⇒ *First full explanation of the formation of the Sun & Planets*
The solution: ***Disc solves the angular momentum problem!***

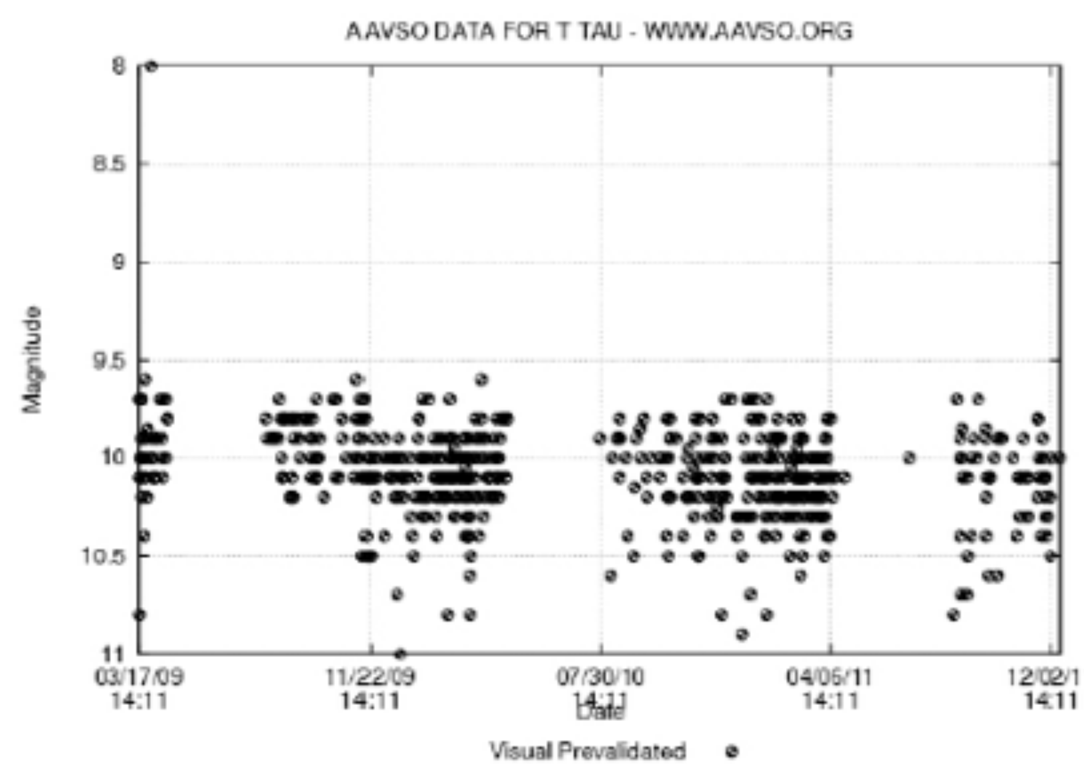
1974: ***Lynden-Bell & Pringle:*** Calculation of full disc model

Indirect evidence for circumstellar gas + dust discs

T Tauri 100 year lightcurve



T Tauri 3 year lightcurve

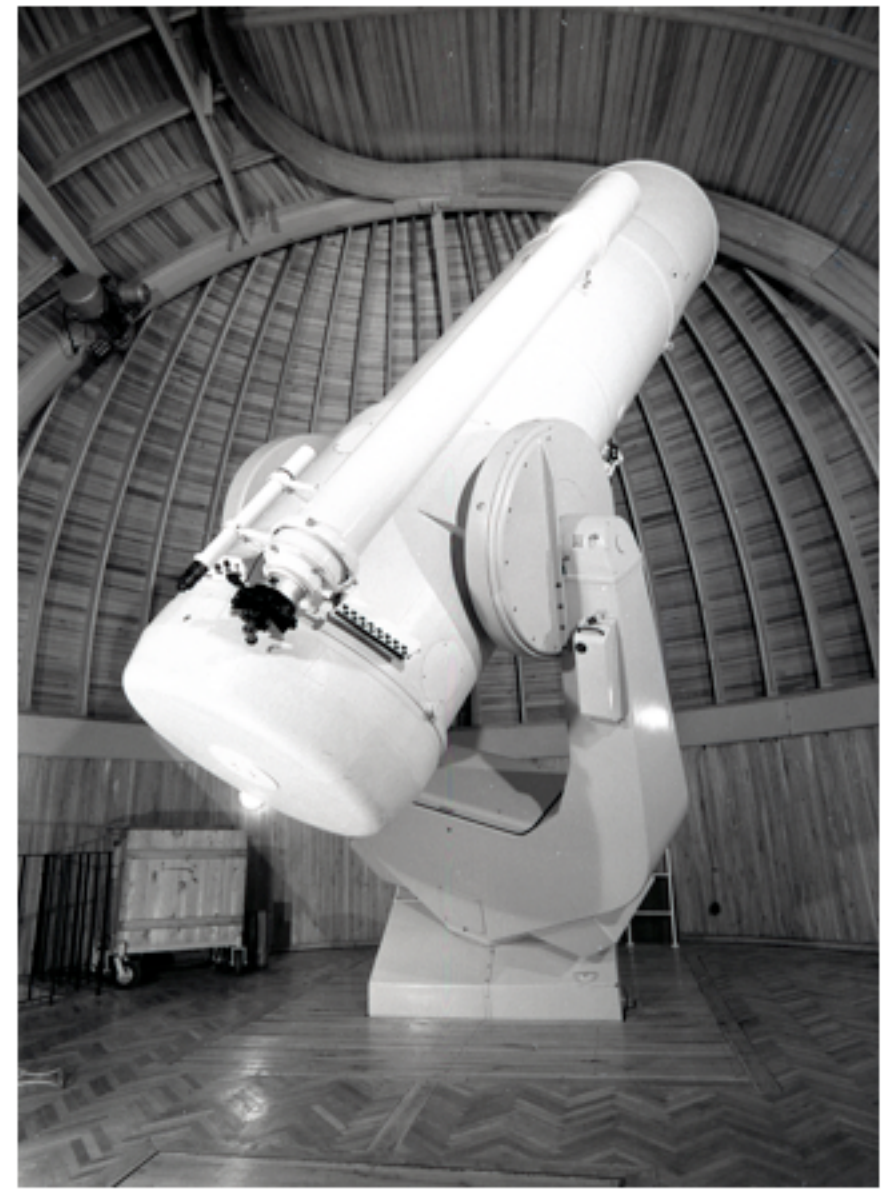


T Tauri stars were discovered as a new class of variable sources. Early on, it was suggested that they might be young stars harbouring circumstellar discs, from which planets might form.

Discovery & definition: Joy 1945, Herbig 1962
Identification as PMS stars: Ambartsumian 1947, 1952

Közvetett bizonyítékok a csillagkörüli korongok létezésére: a perdület megmaradása, infravörös többletsugárzás, “fényelnyelés érv”, a Naprendszer szerkezete stb.

Egy kis történelem: hazai előzmények

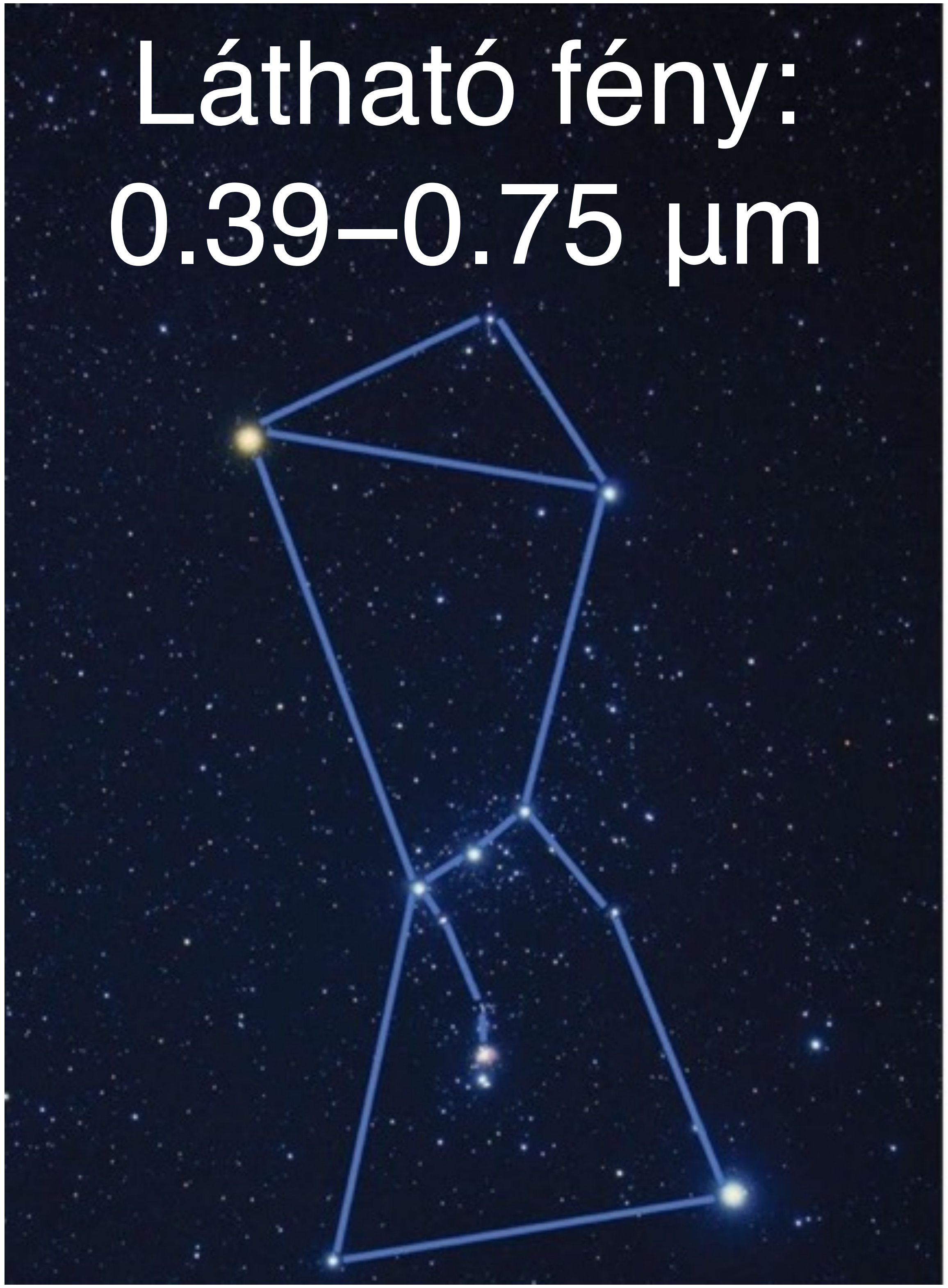


1962. Schmidt teleszkóp: üstökösök, fiatal csillagok, csillagközi por

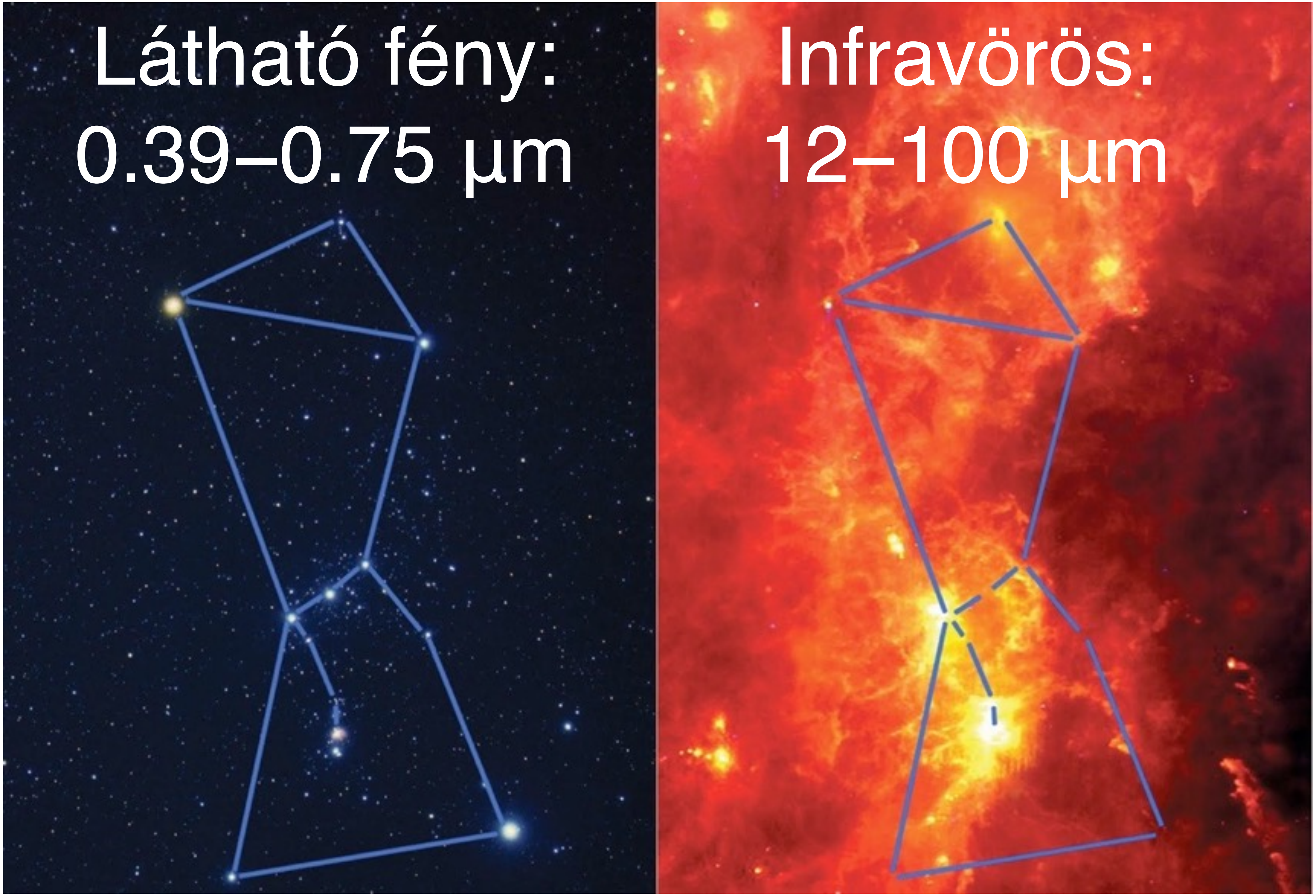
Egy kis történelem...

IRAS 1983

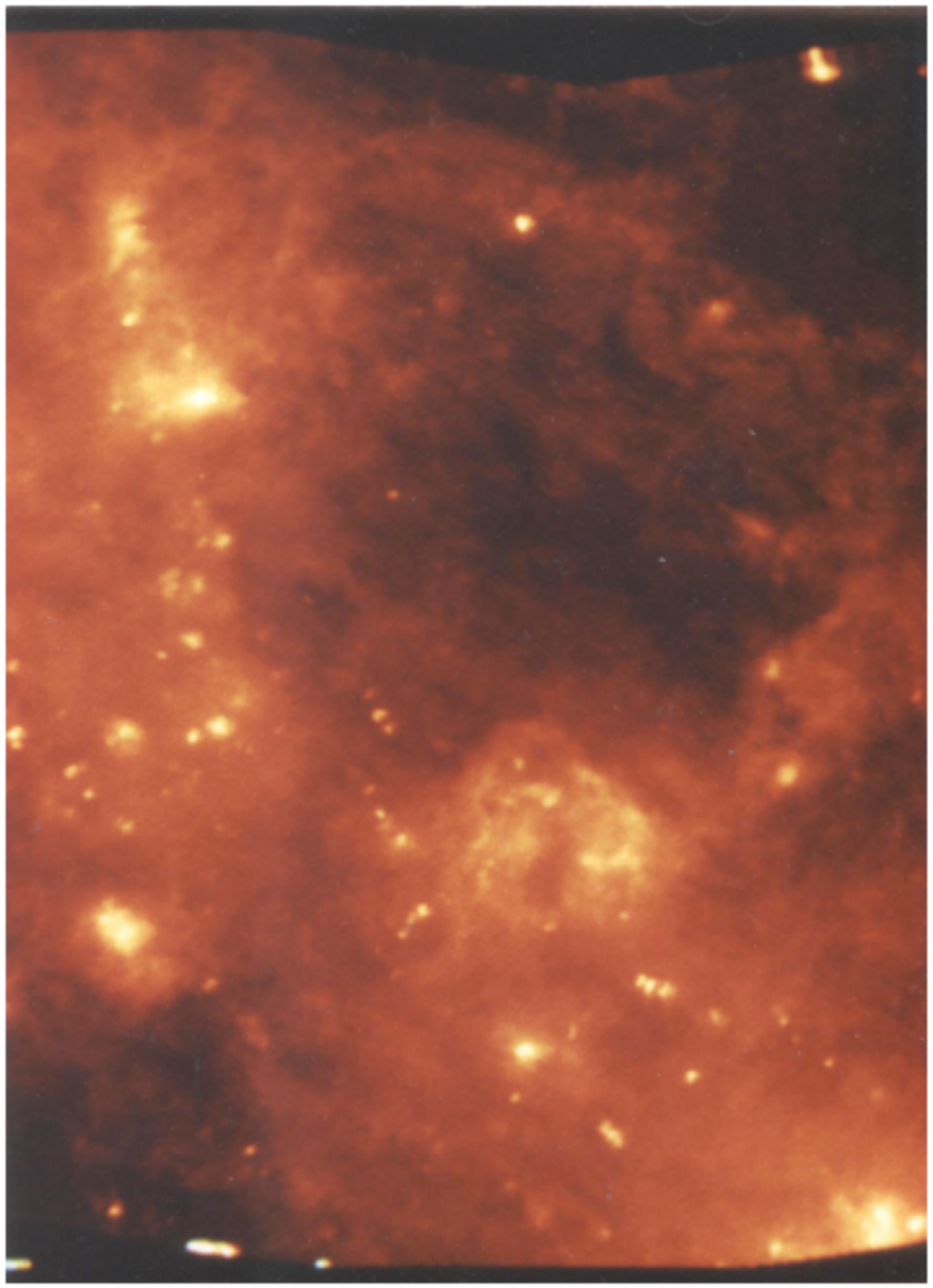
Az univerzum infravörösben

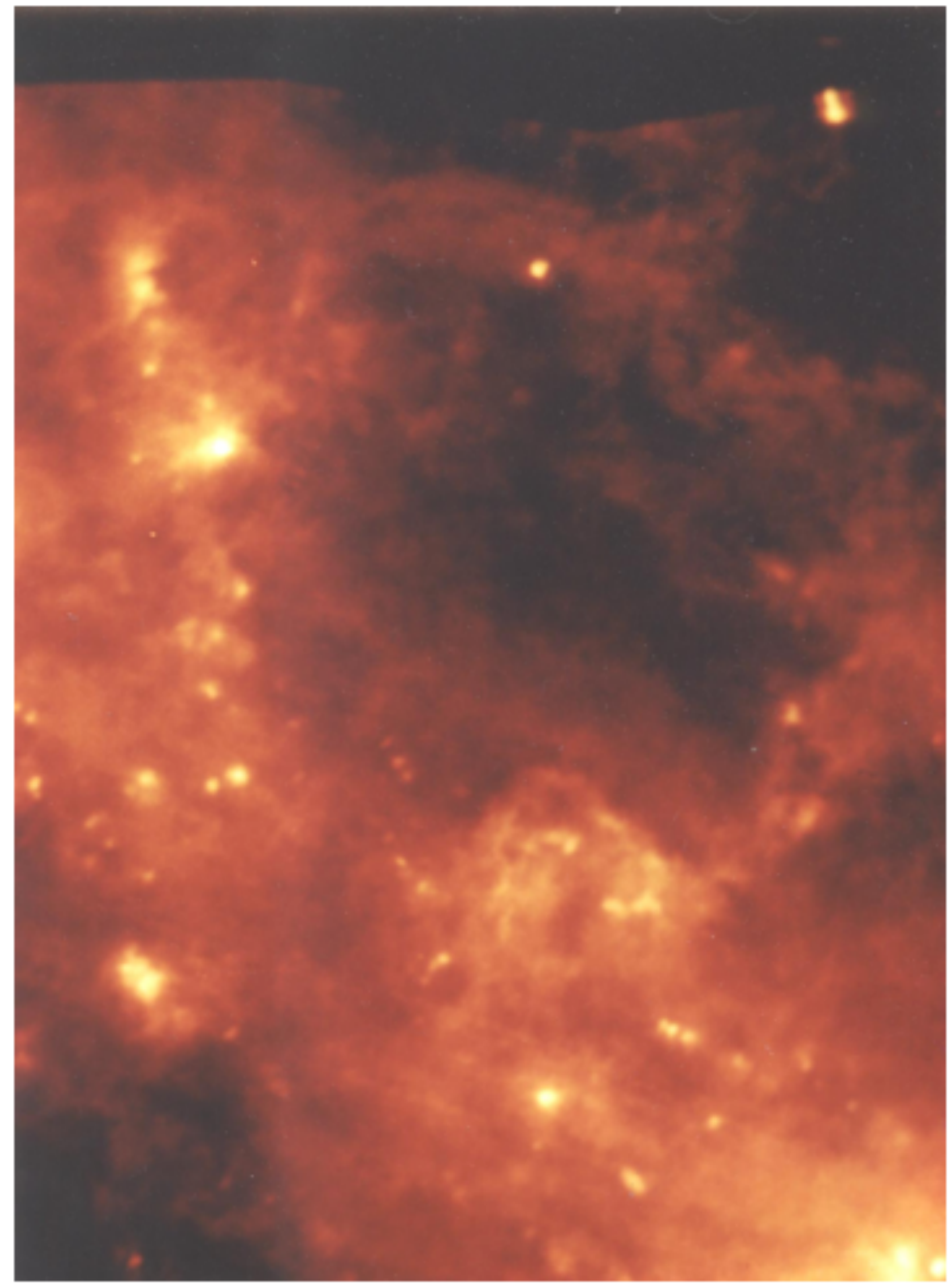


Az univerzum infravörösben



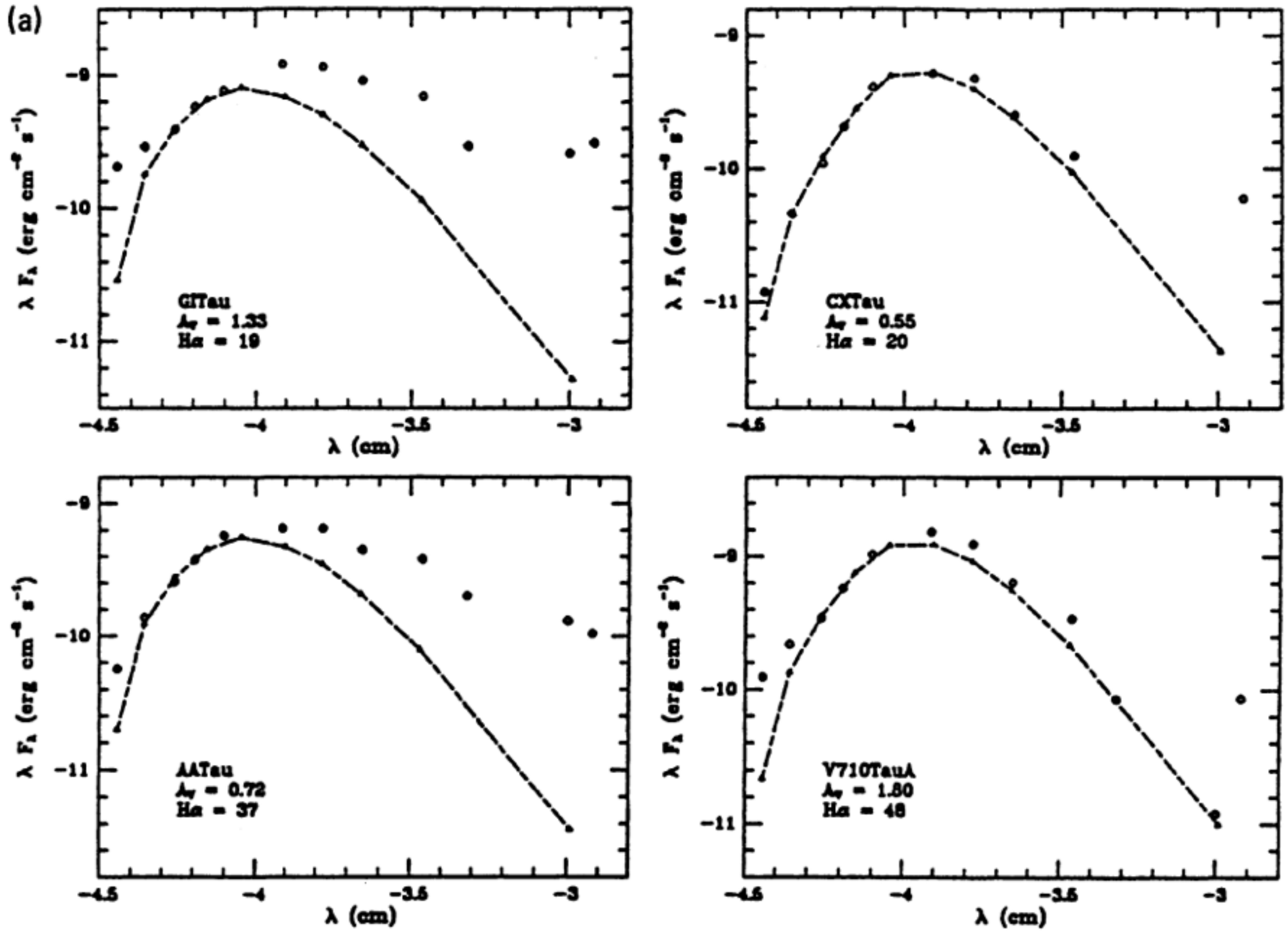
Cepheus Buborék





Kun, M., Balázs, L.G. & Tóth, I. 1987

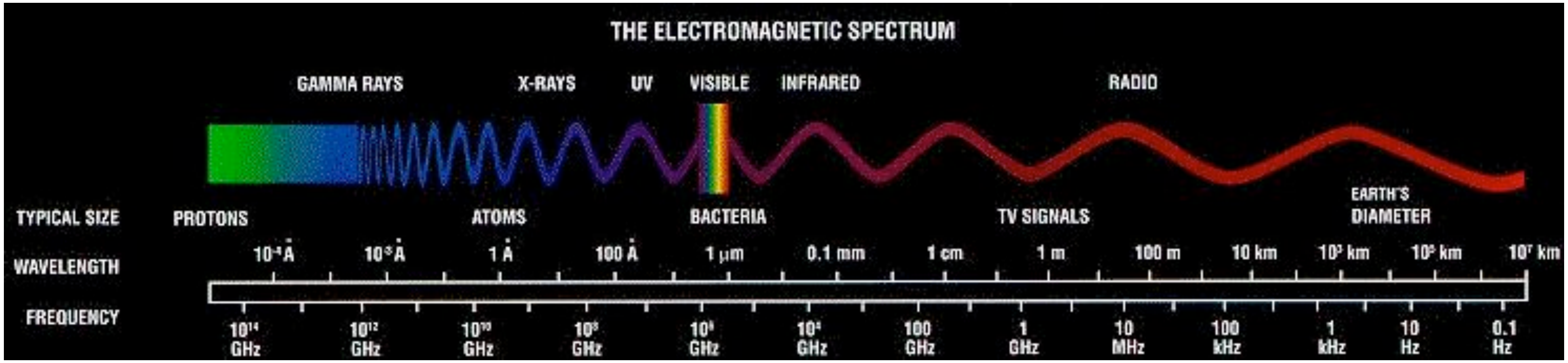
Egy kis történelem...

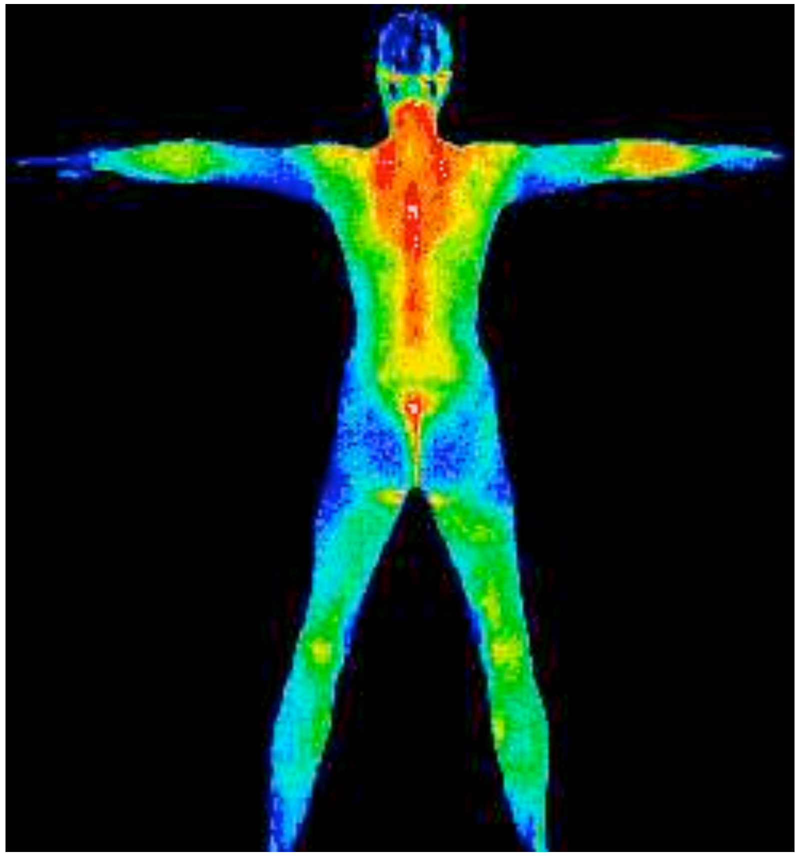


Strom et al. 1989

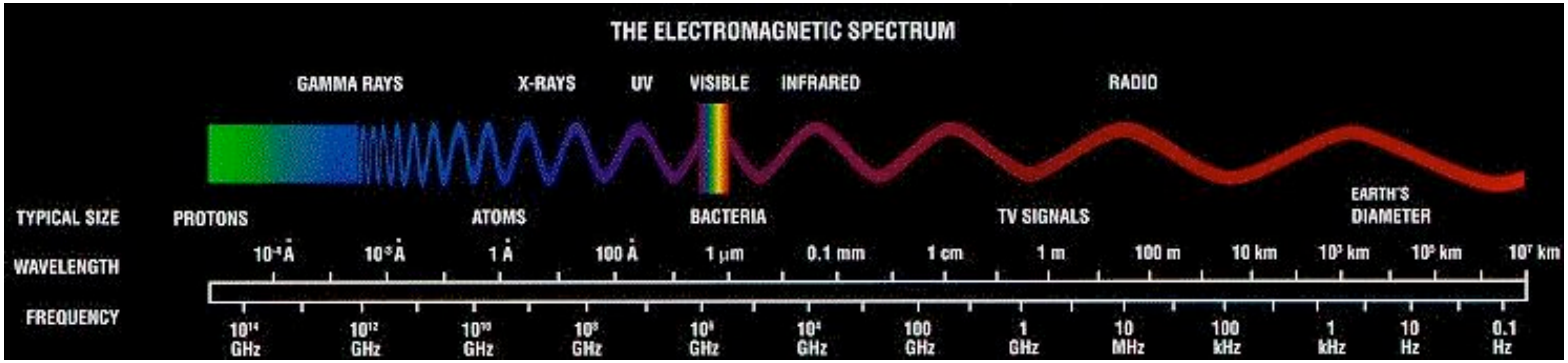
Sir William Herschel (1800)

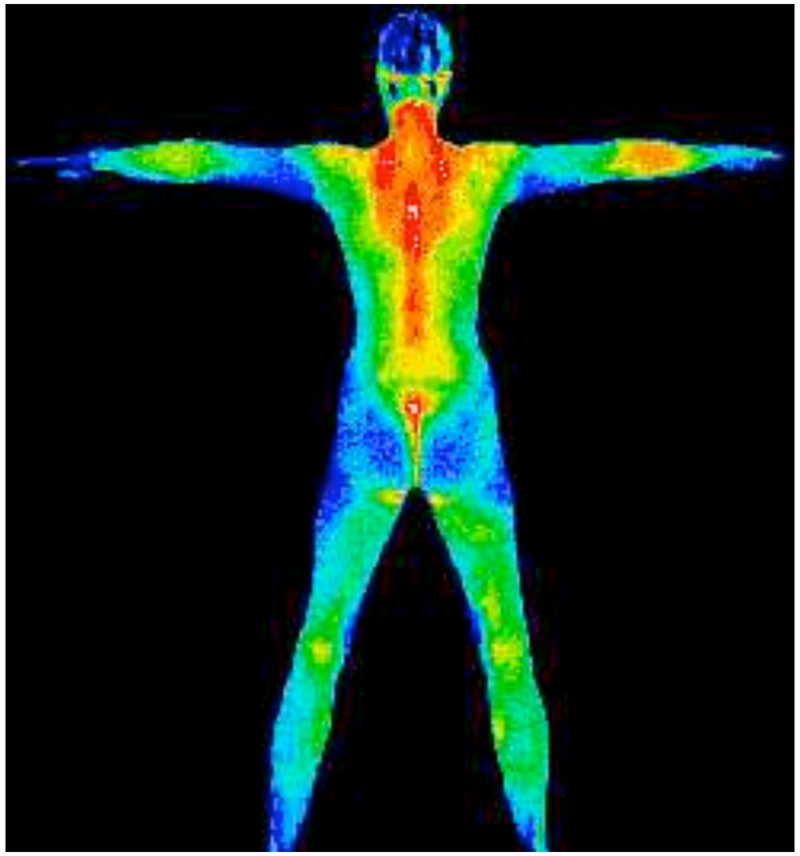
A világ infravörösben...

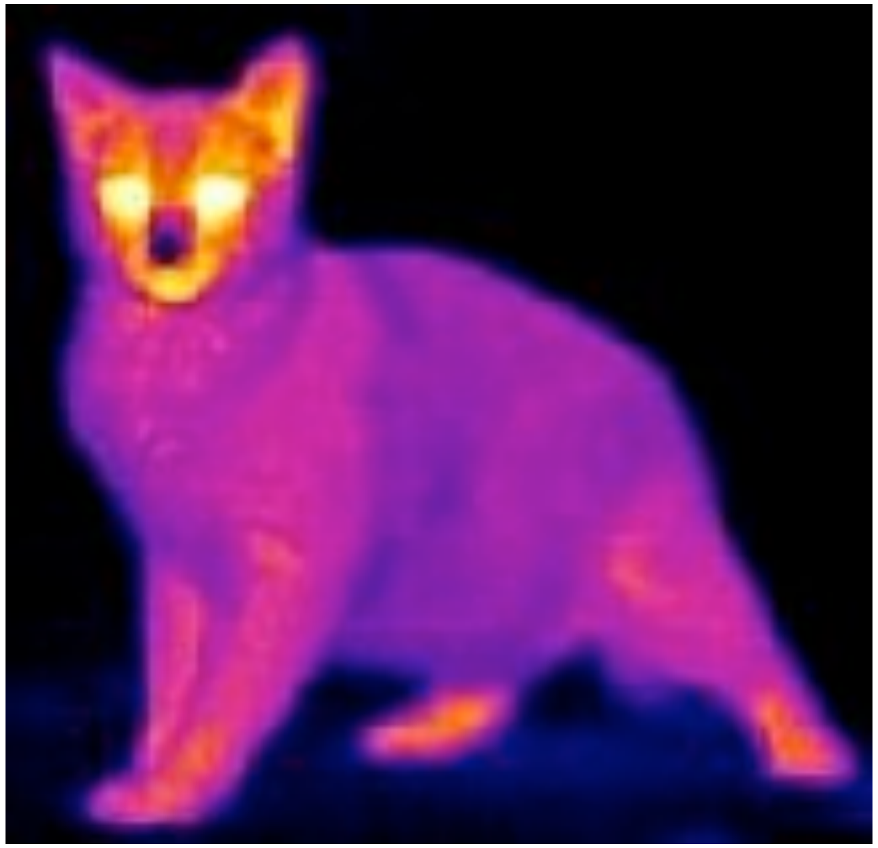




A világ infravörösben...







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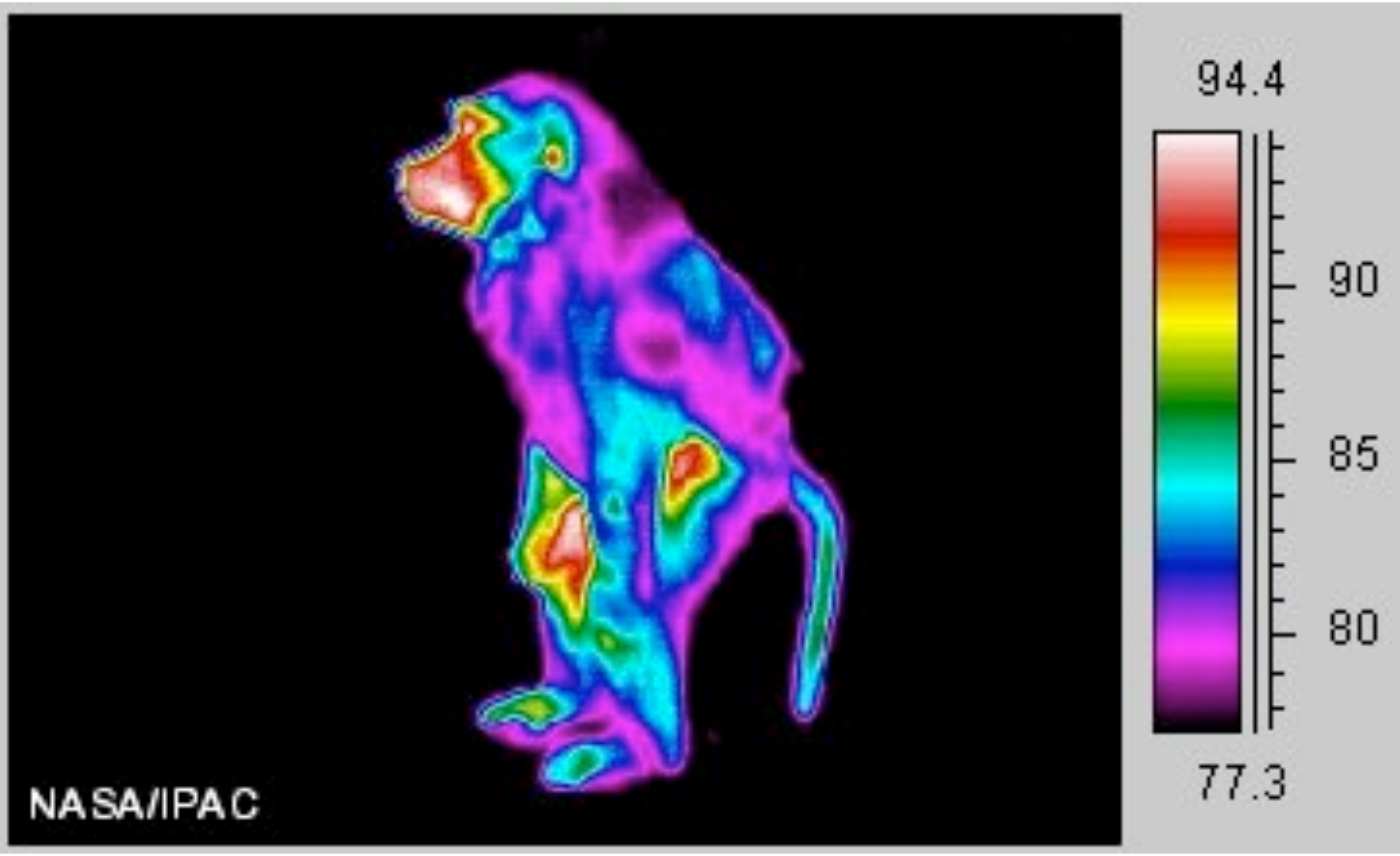
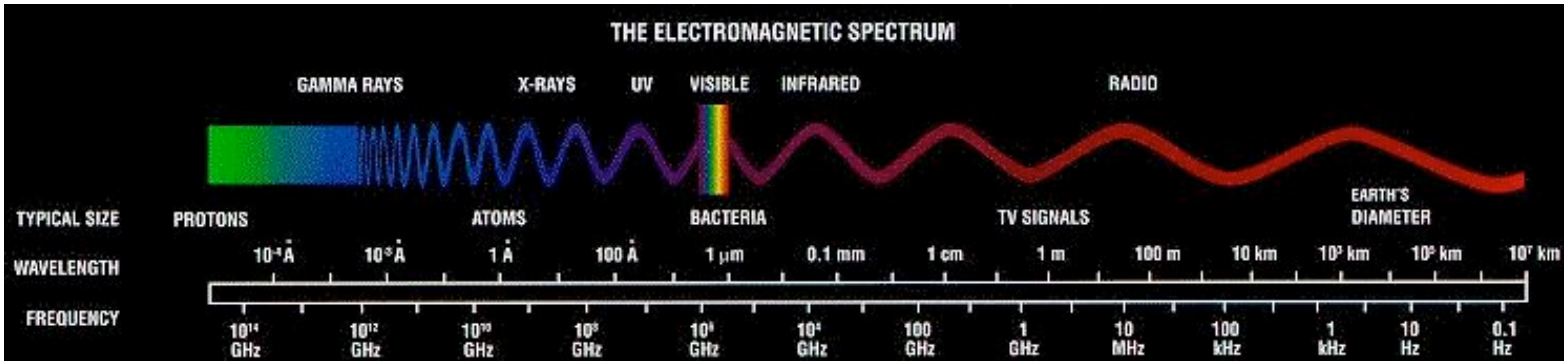
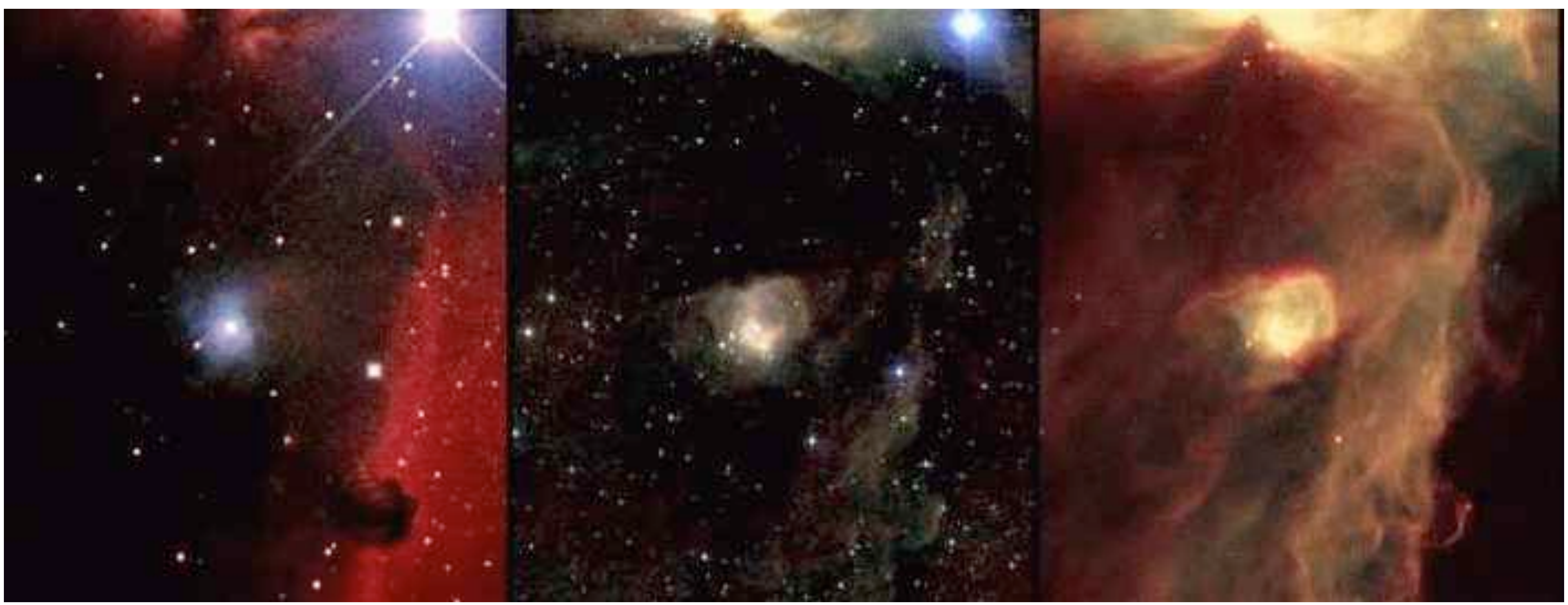


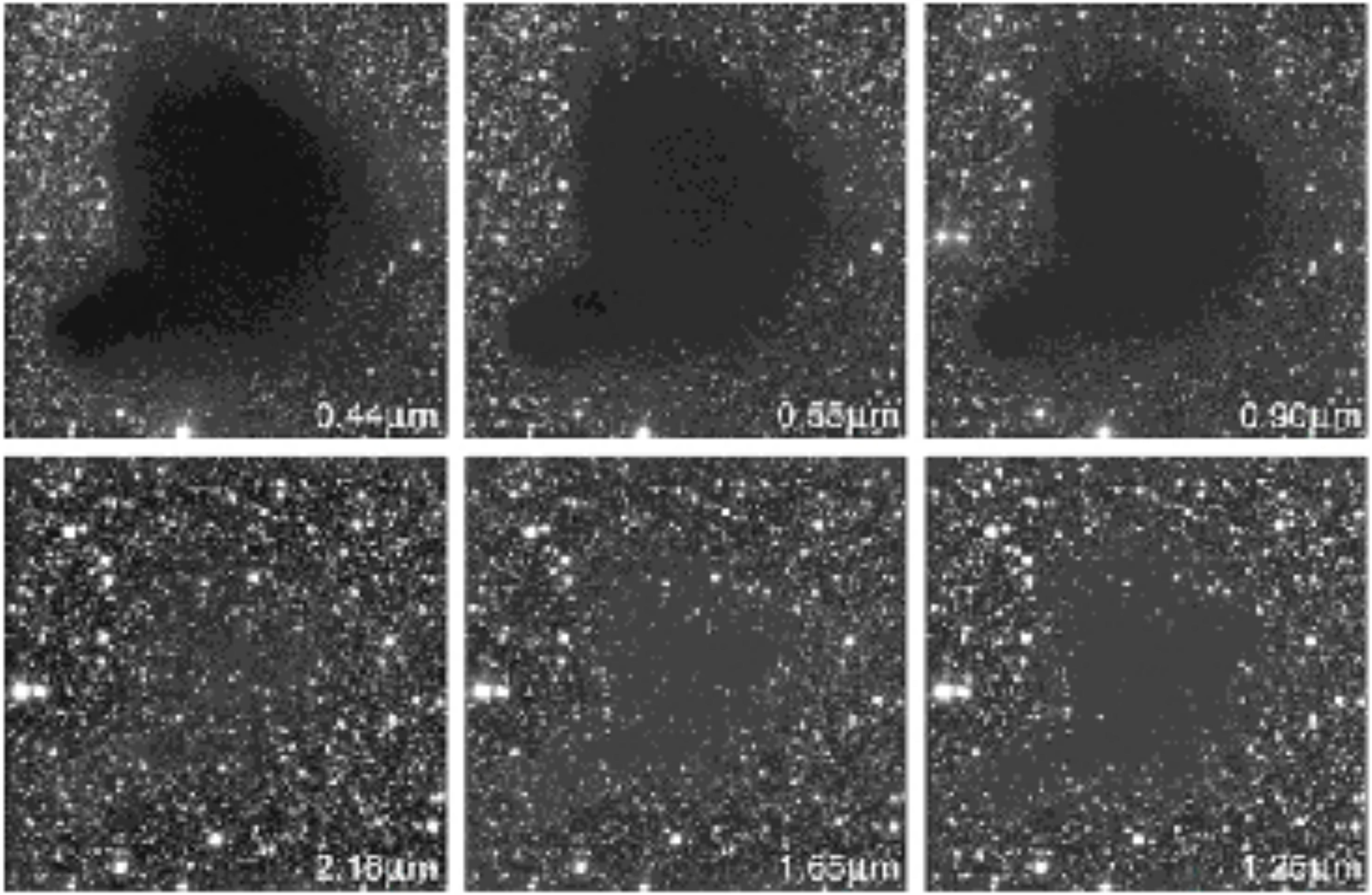
A világ infravörösben...

A világ infravörösben...

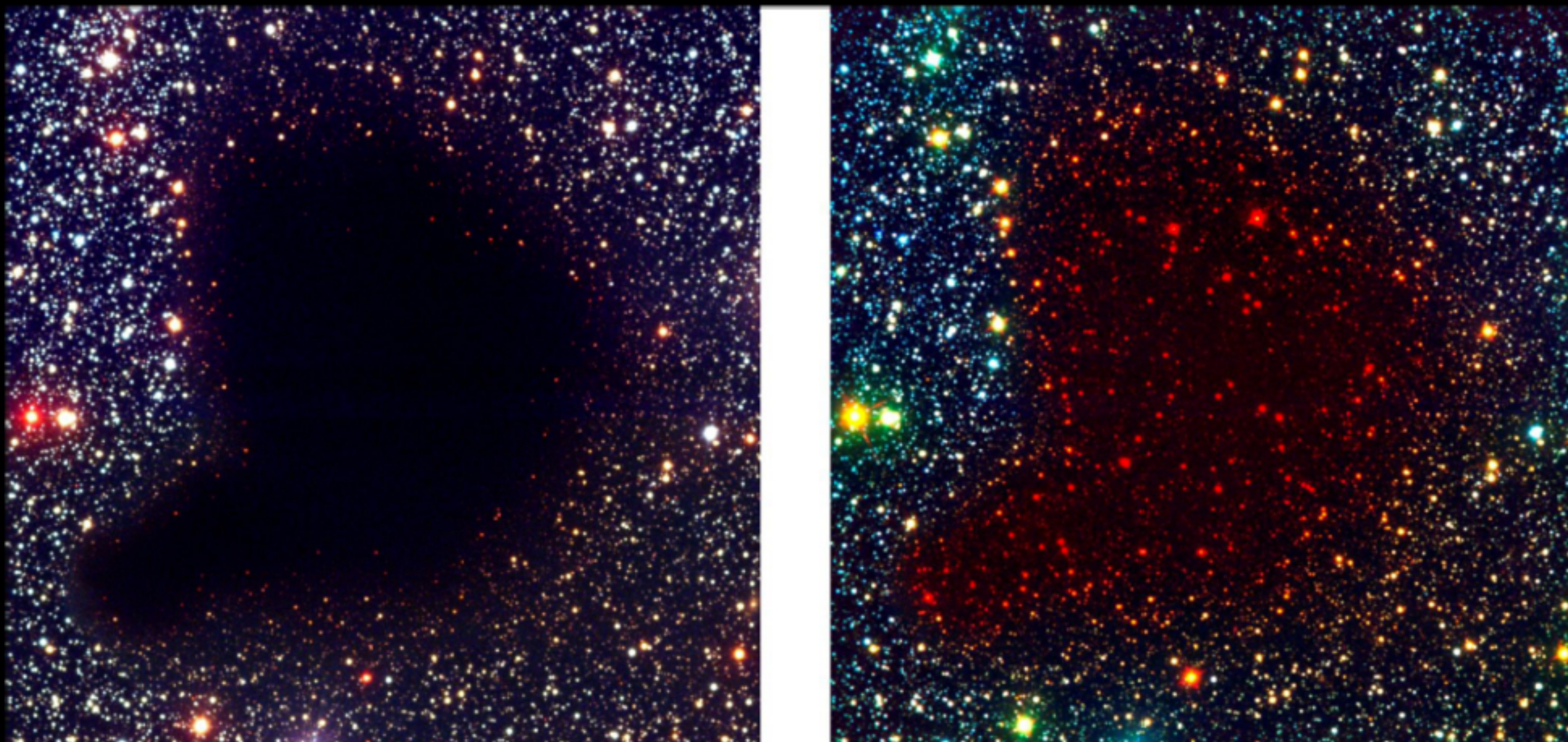




A Barnard 68 sötét globula



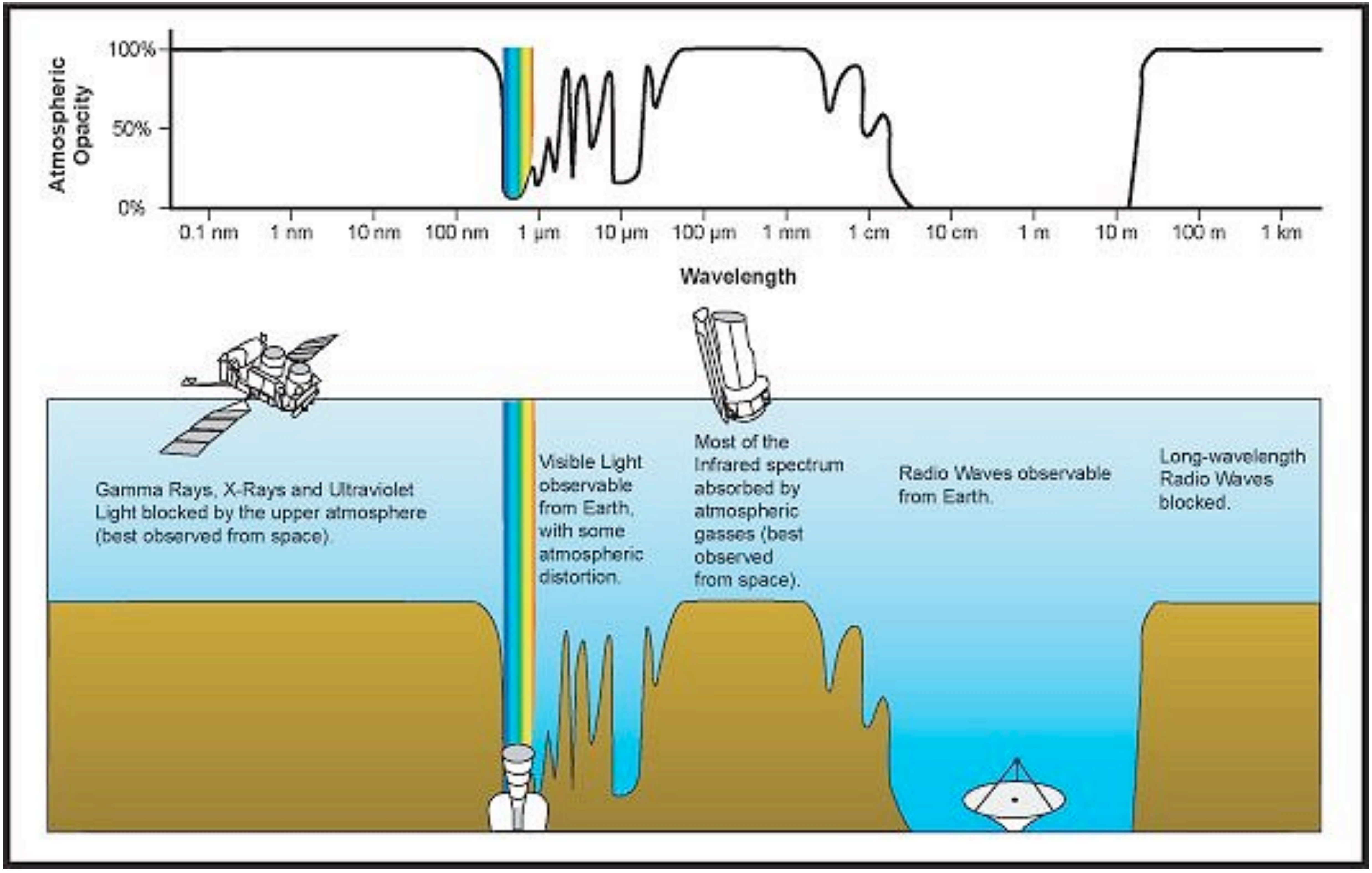
Optical | Infrared



Extinction map agrees with submm emission map

Alves et al. 2001

Légköri áteresztés

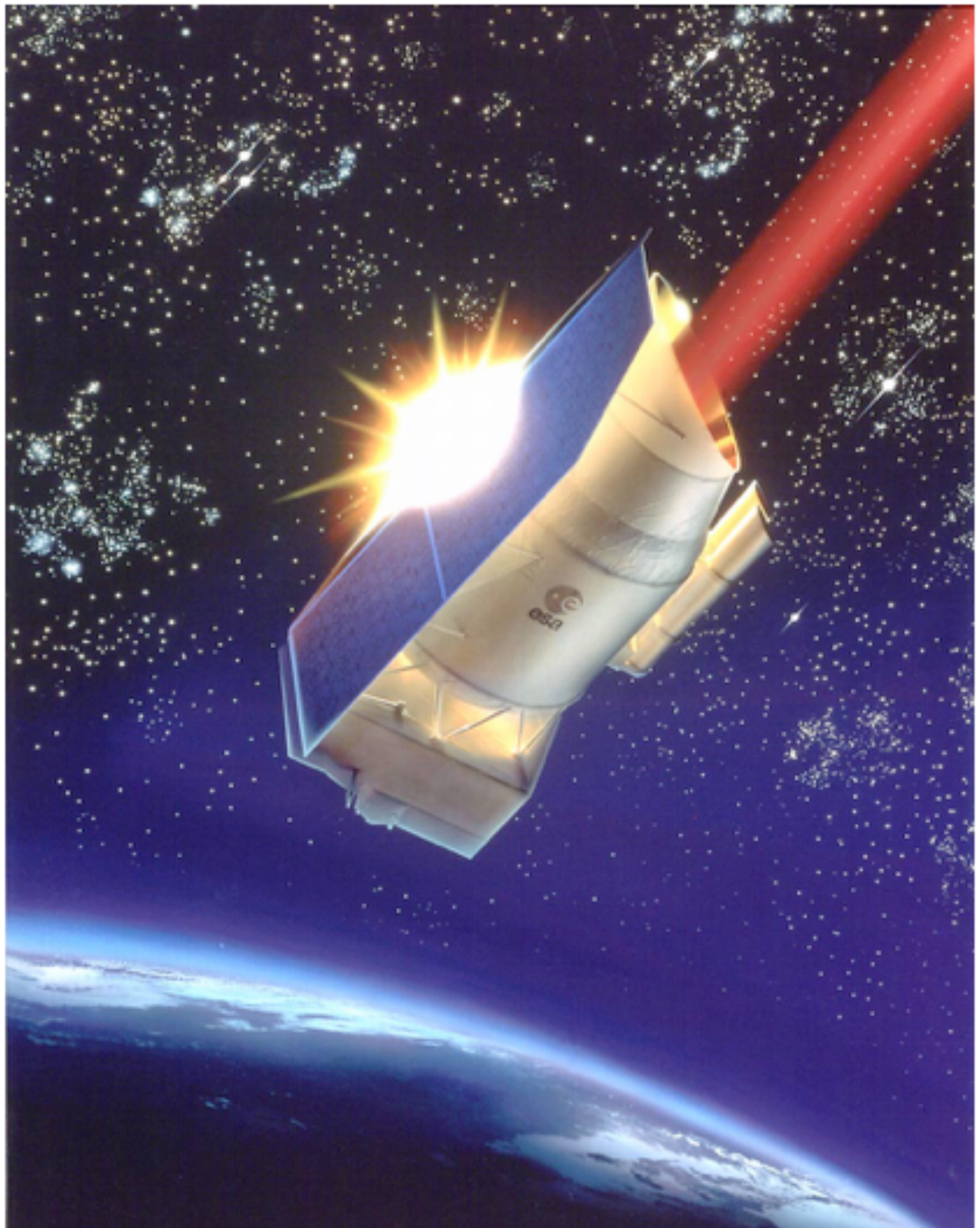


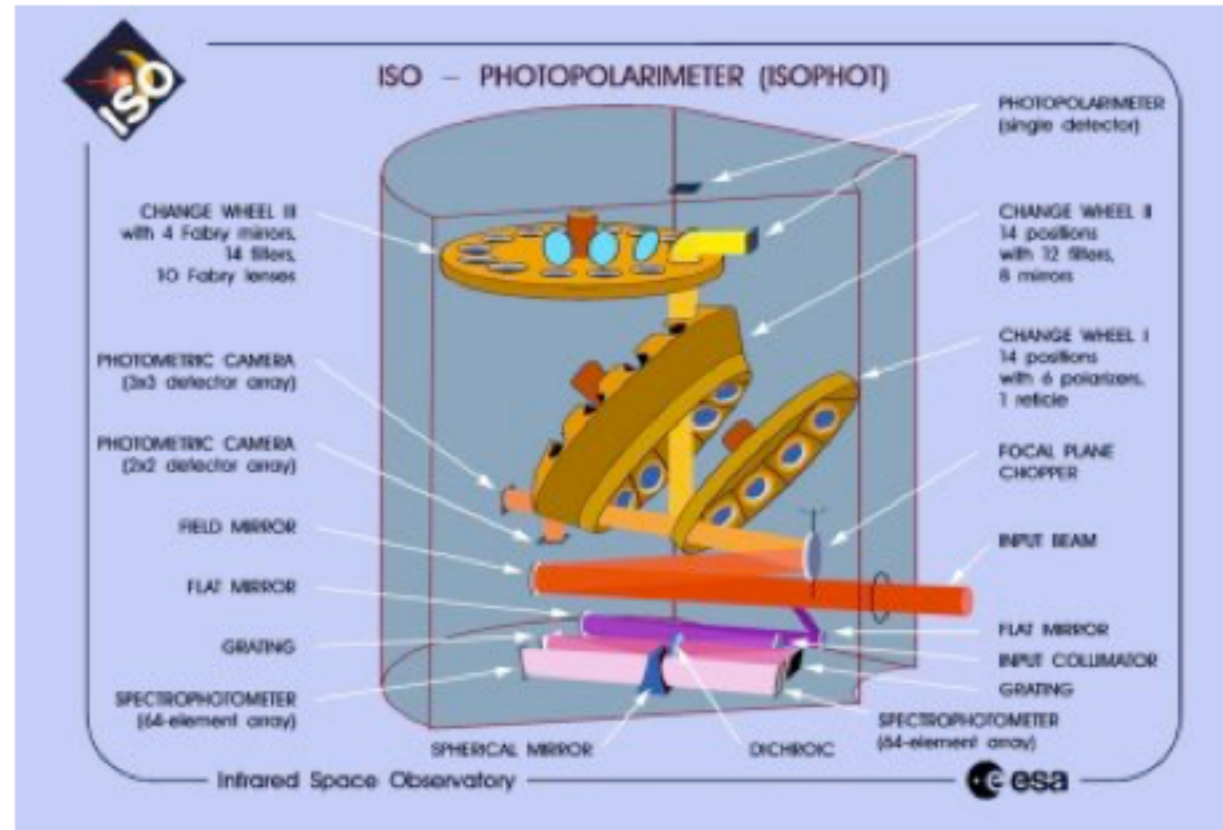
Az infravörös műszerek

Mauna Kea (4200 m)

Infrared Space Observatory

Infrared Space Observatory





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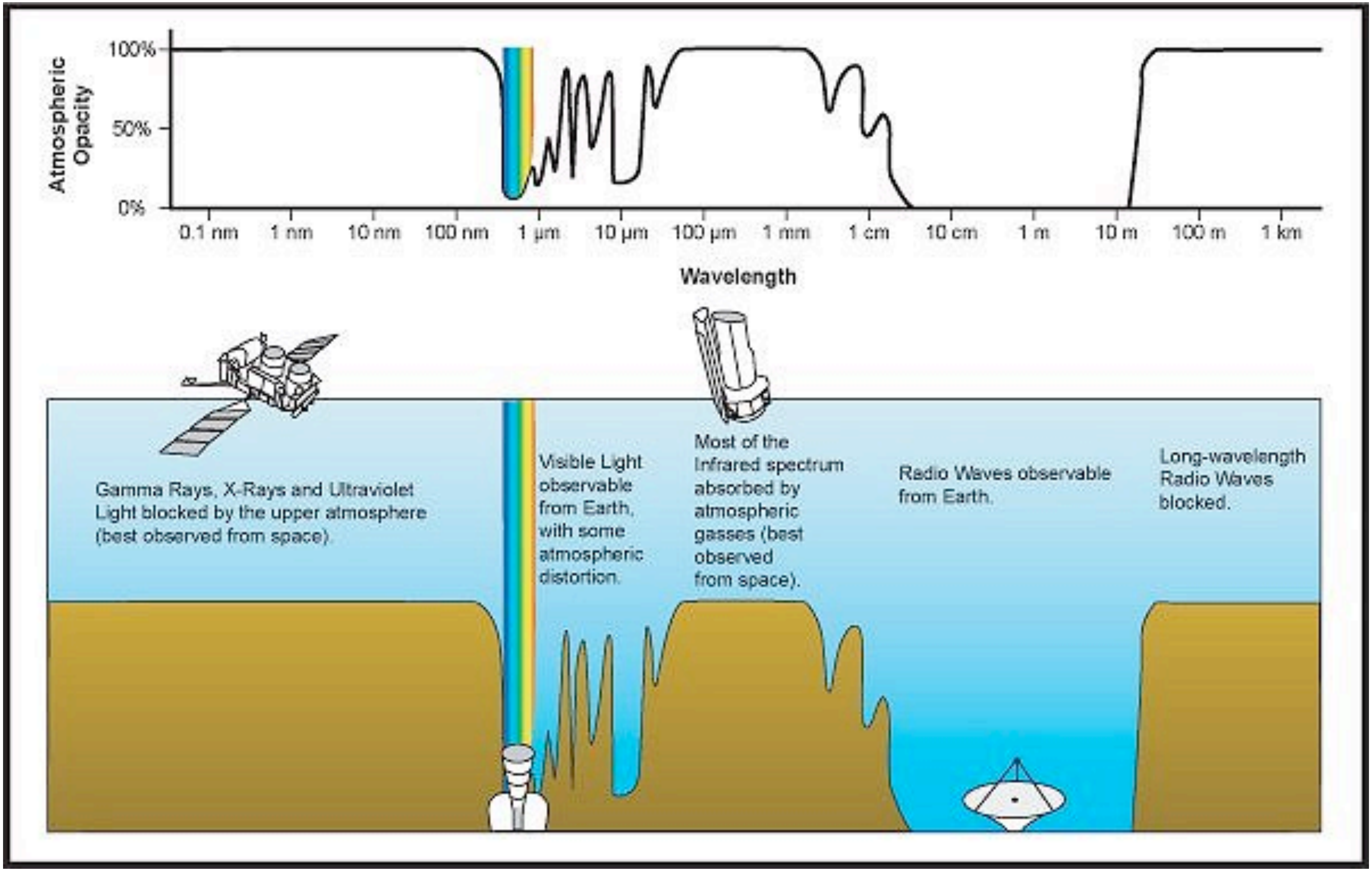
Légköri áteresztés

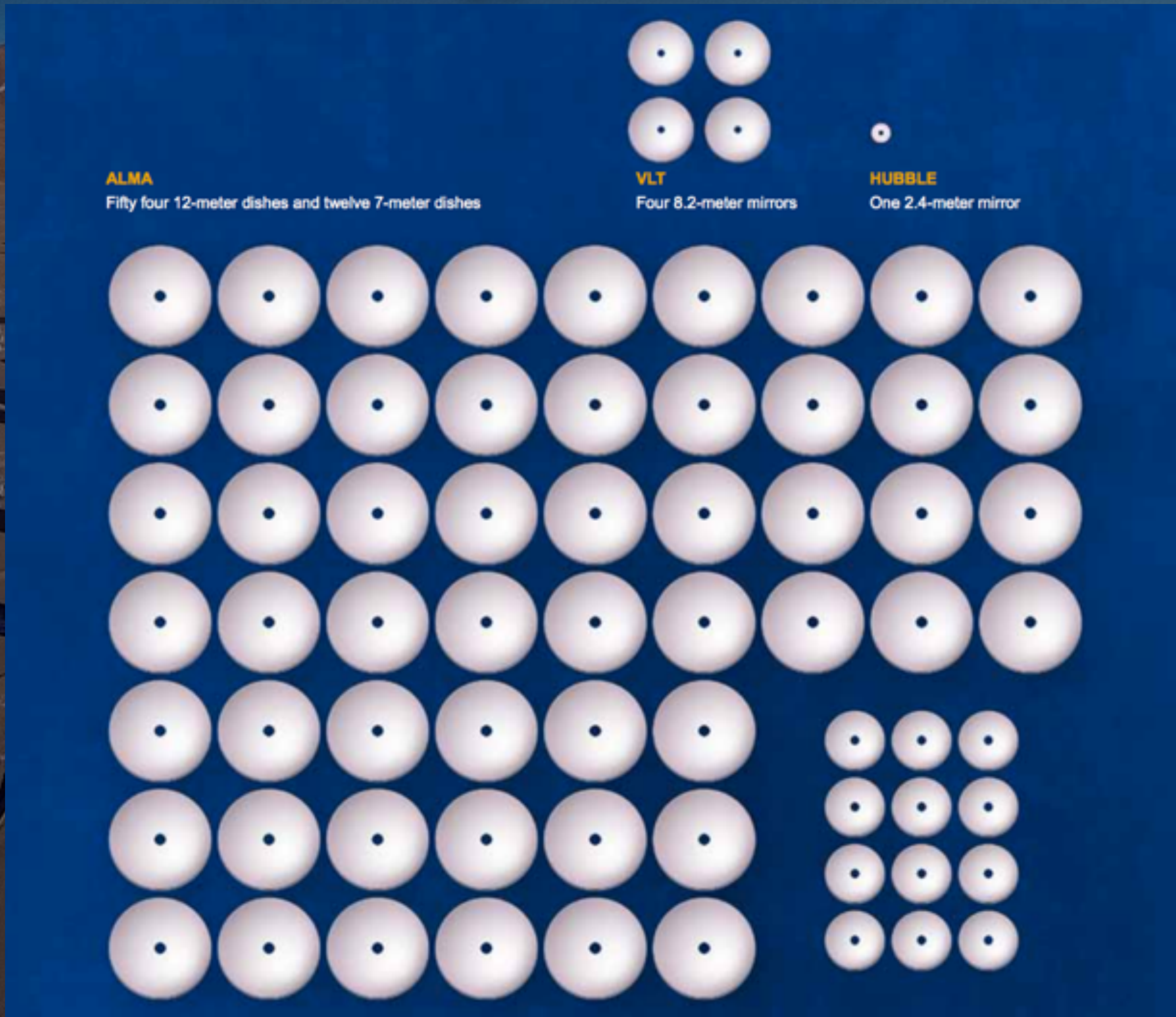


ALMA

Atacama Large Millimeter/submillimeter Array

ALMA

- 54 darab 12 méteres és 12 darab 7 méteres antenna
- Teljes fénygyűjtő felület: 6600 négyzetméter



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- 0.4−3.1 milliméteres hullámhosszú sugárzást mér

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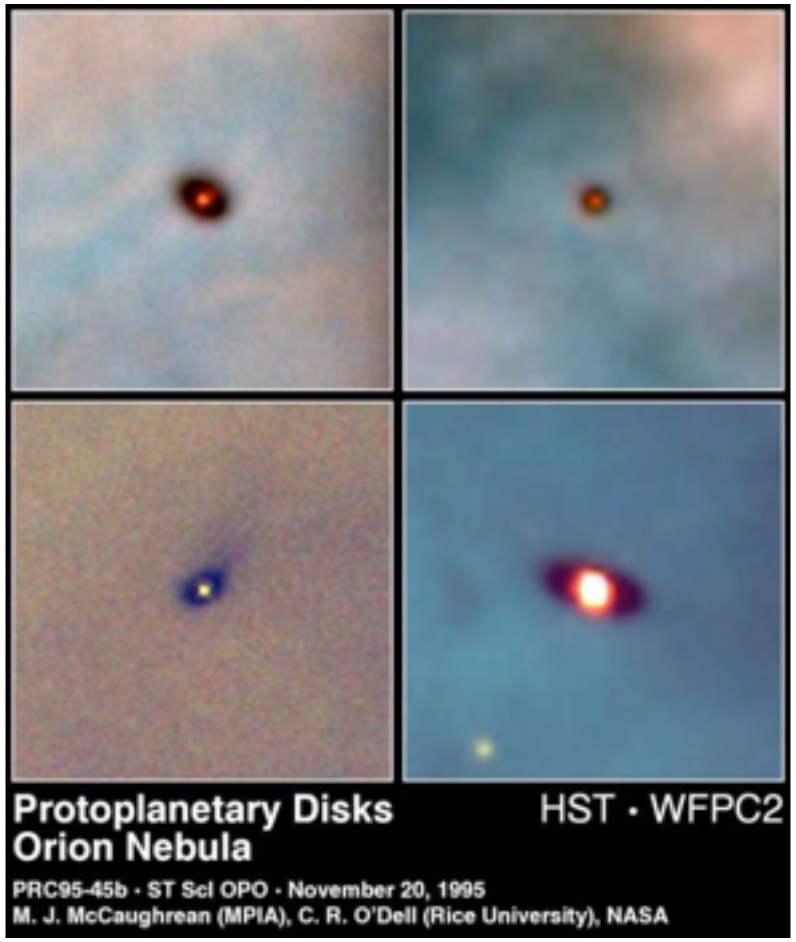
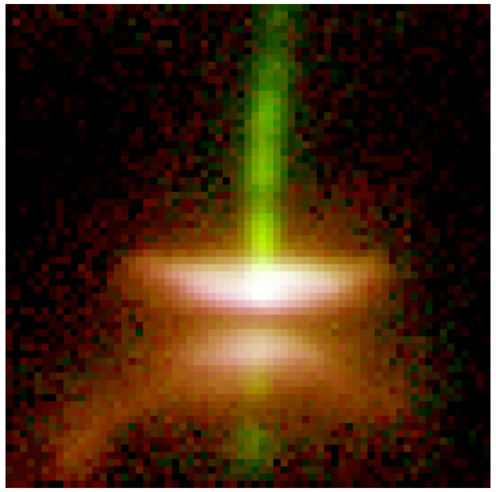
- 0.4−3.1 milliméteres hullámhosszú sugárzást mér
- Antennák felülete tökéletes parabola (< 20 μm)
- Térbeli felbontás: 0.006″ (golflabda 1500 km-ről)

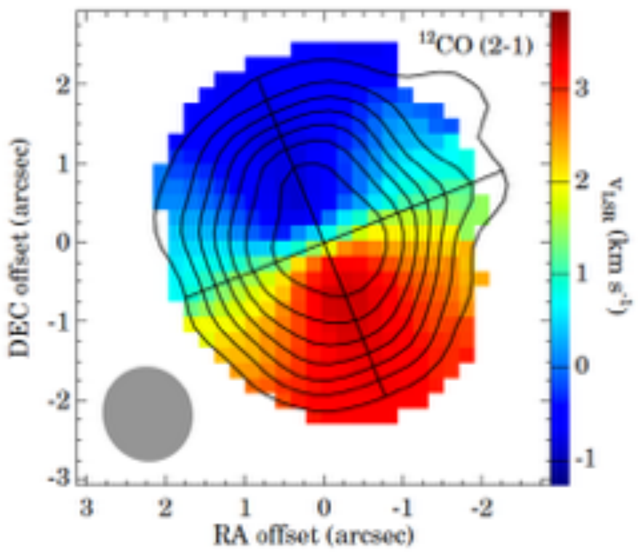
A csillagkörüli korongok megfigyelése

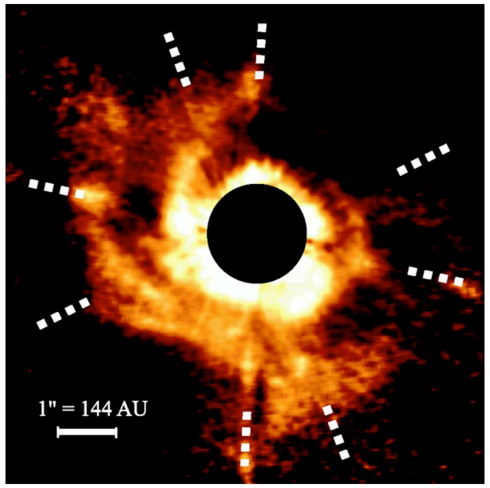
- Hatalmas technikai kihívás (szögmásodpercnél jobb térbeli felbontás; infravörös technológia)
- Megfigyelése módszerek: sziluett képek, szórt fény, infravörös hőtérképek, molekulavonalak





Burrows et al. (1996)





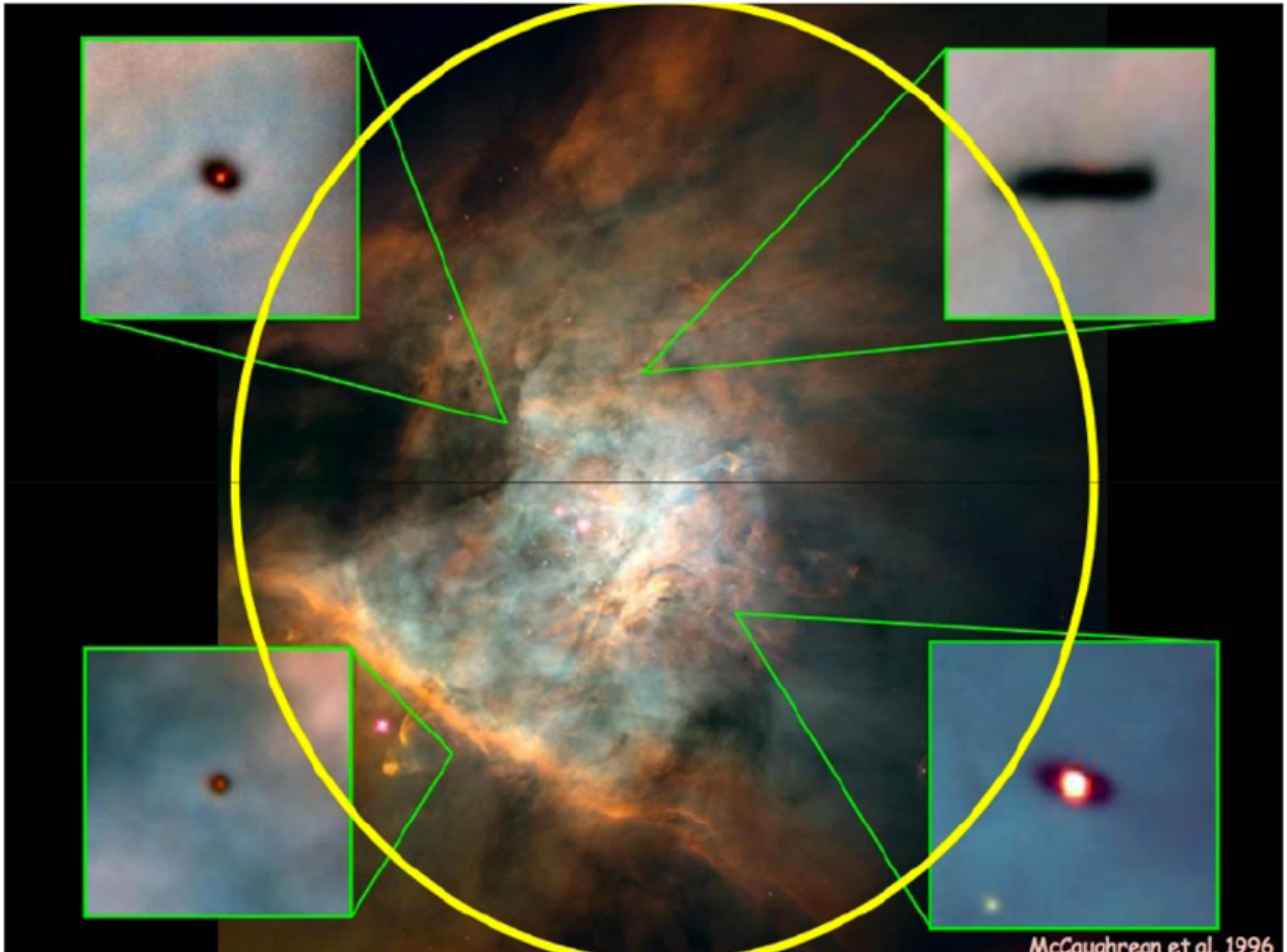
Fukagawa et al. (2004)

Typical sizes

Linear Size	Angular	size
	Taurus 140 pc	Orion 450 pc
5 AU Inner disk	0.04"	0.01"
100 AU Outer disk	0.7"	0.2"
1000 AU YSO envelope	7"	2"
10000 AU=0.05 pc Cloud core	74"	23"

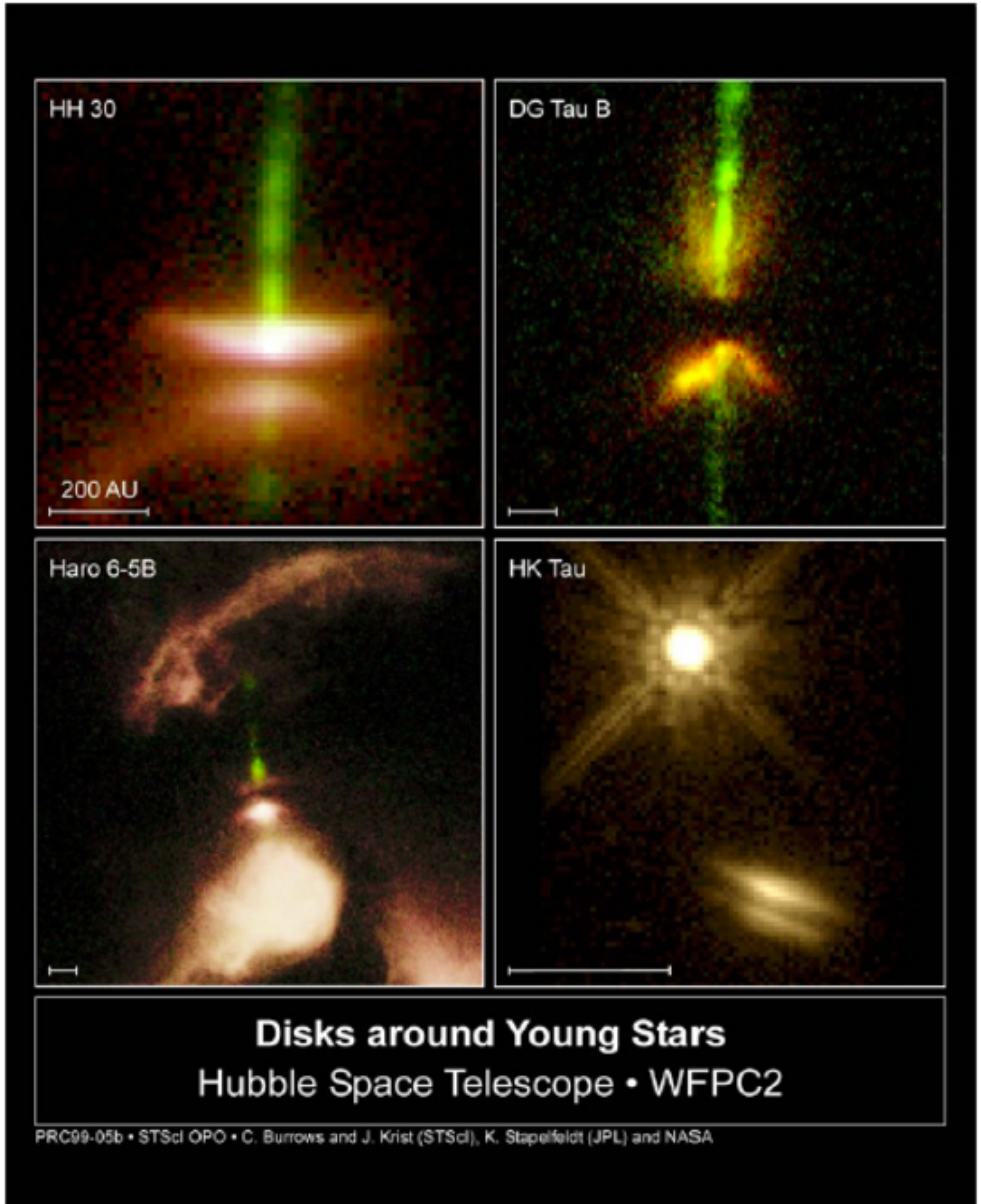
Direct detection of young, circumstellar discs

in shadowed light… *"silhouette discs"*



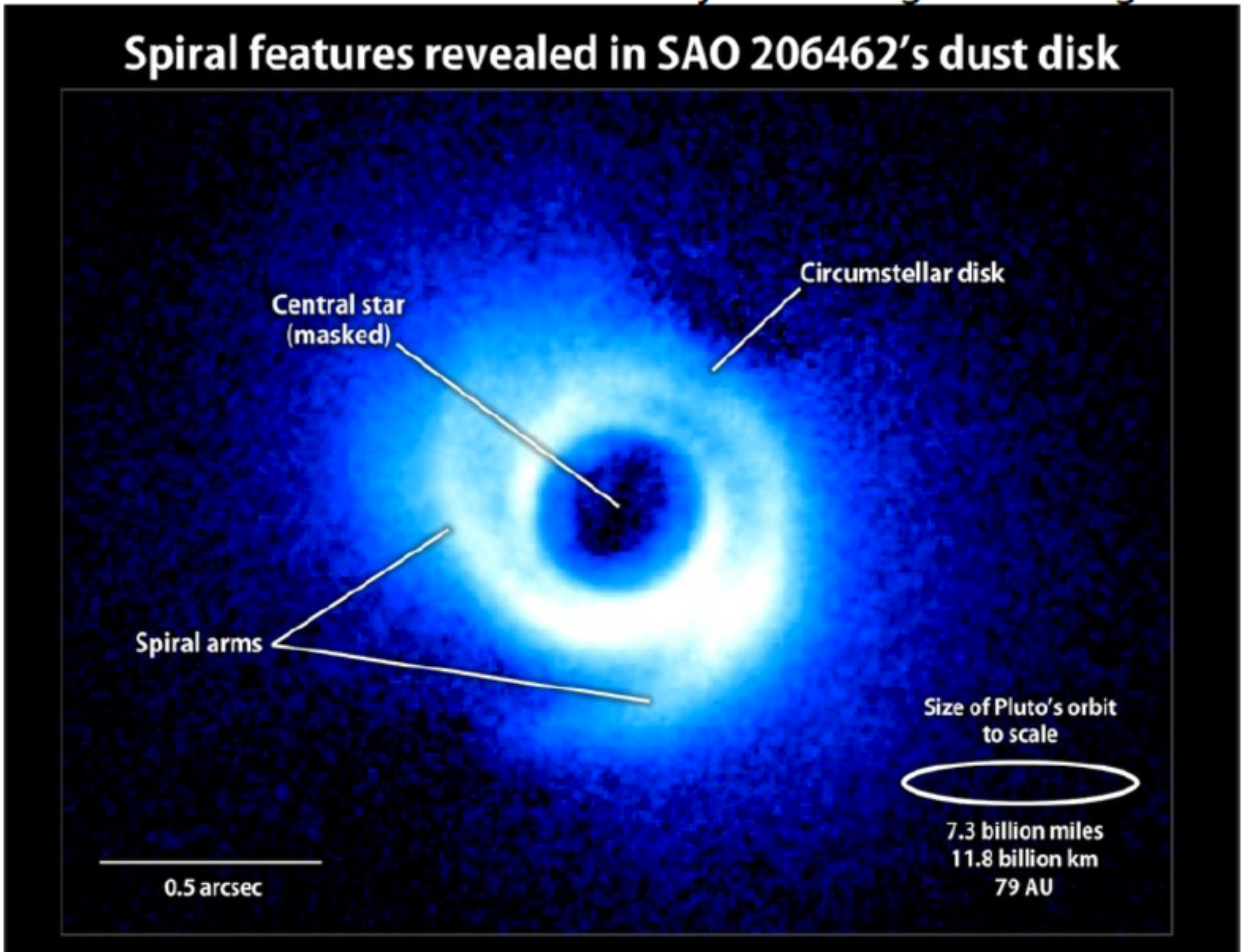
slide courtesy Sebastian Wolf

Direct detection of young, circumstellar discs



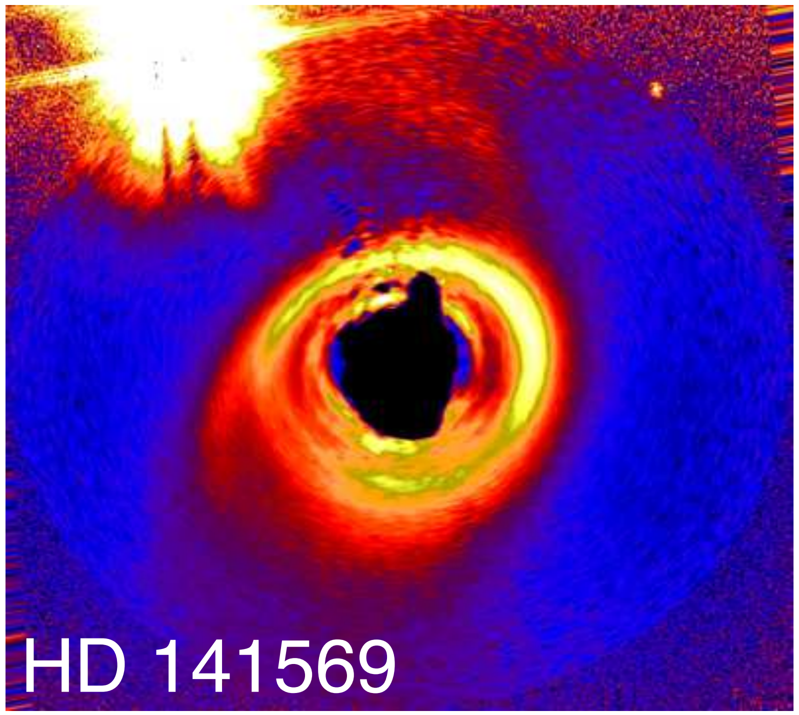
Direct detection of young, circumstellar discs

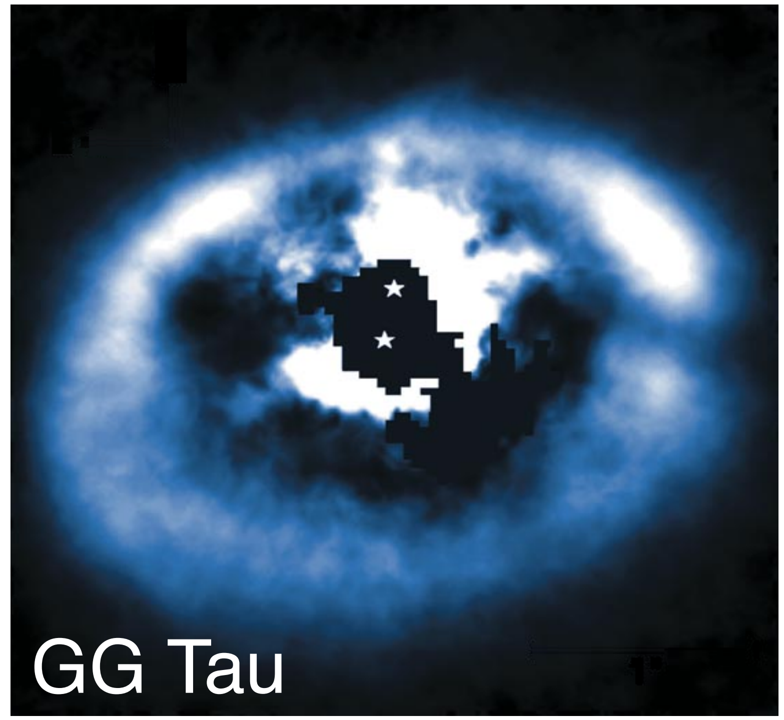
Disc radiation can be observed directly with long-wavelength imaging.

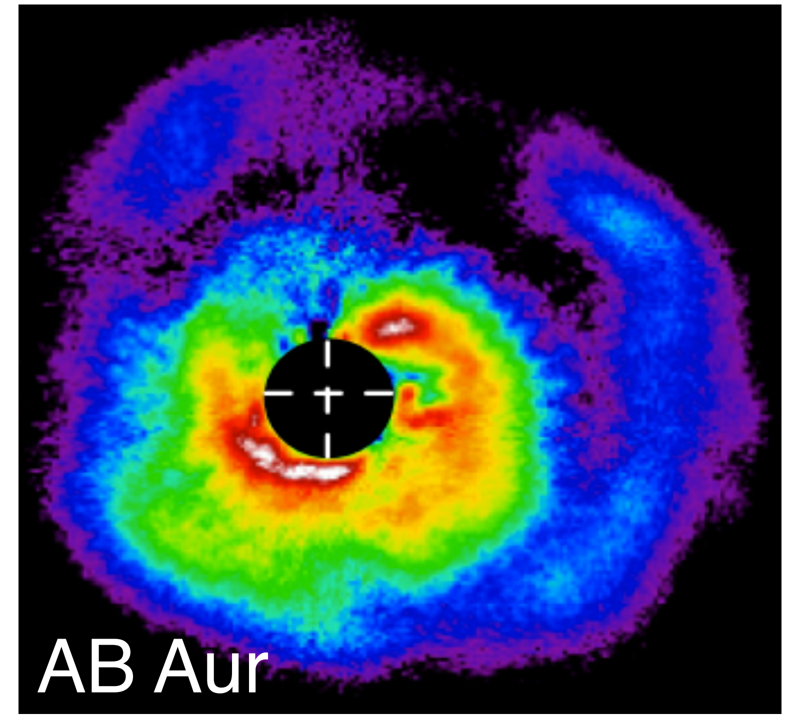


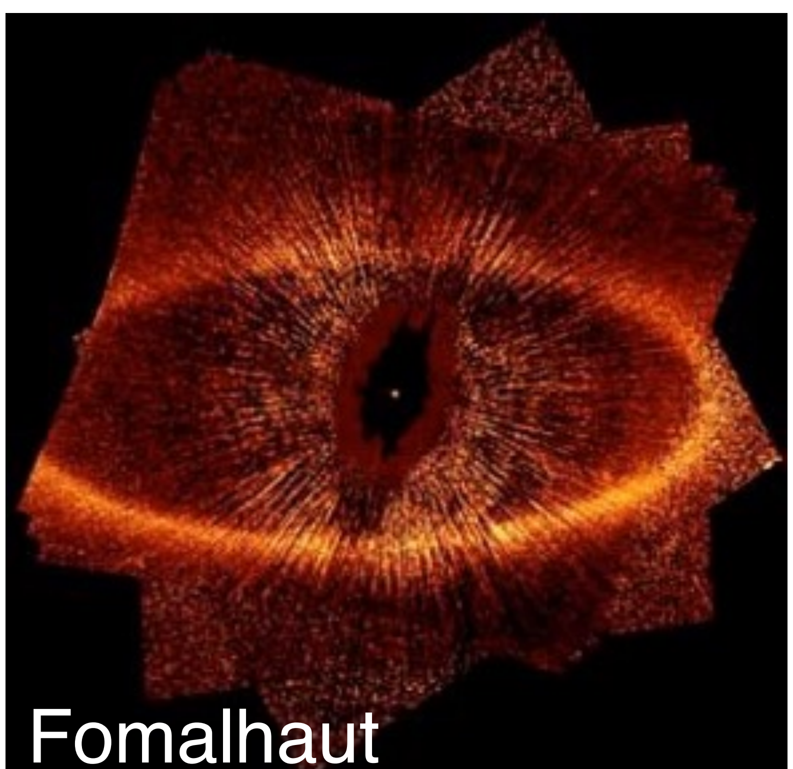
Csillagkörüli korongok

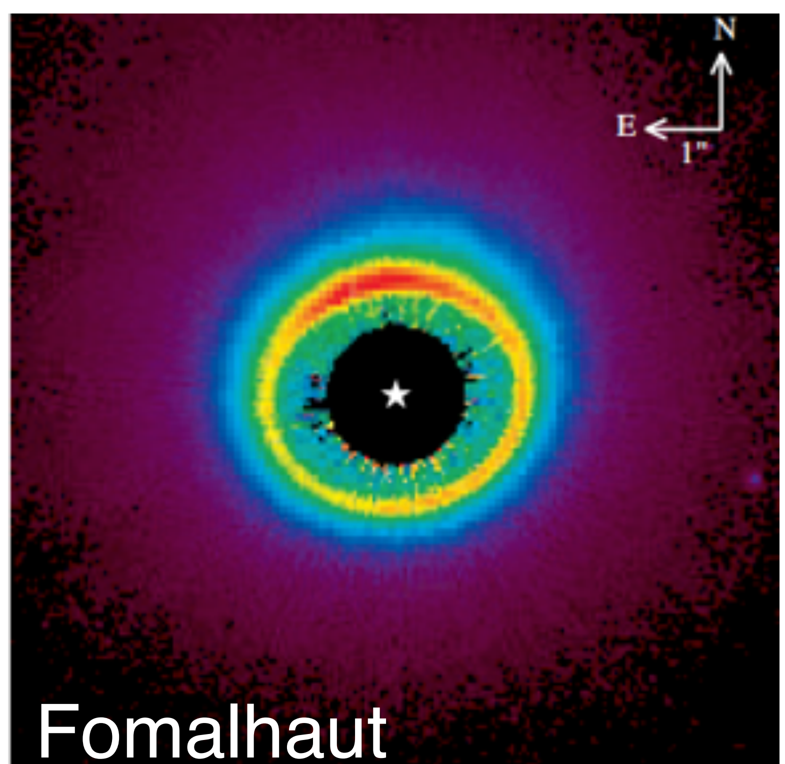
Ahogyan a csillagászok látják:

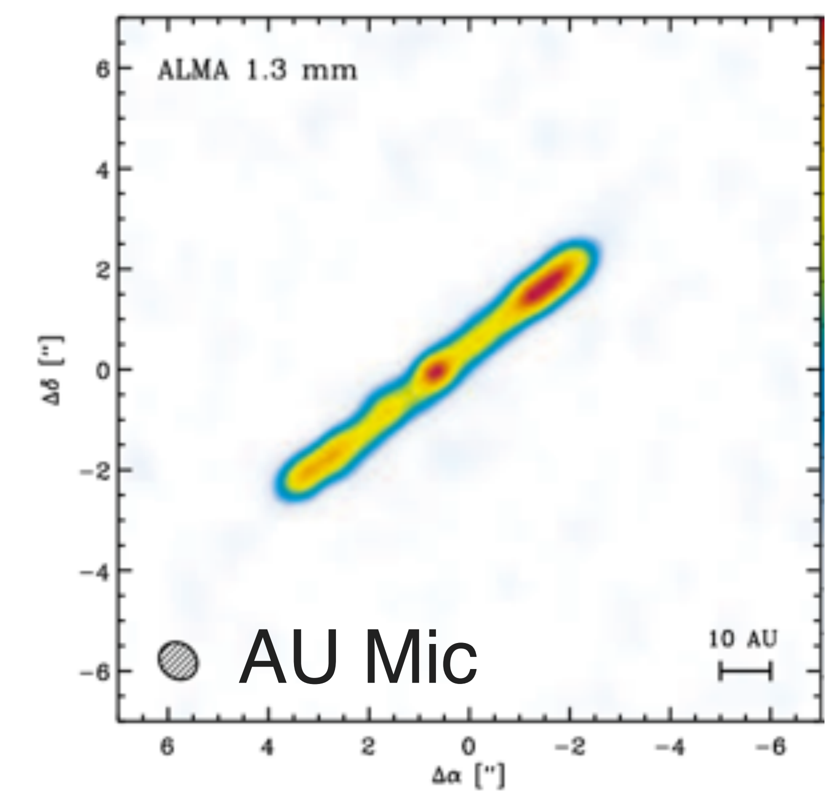




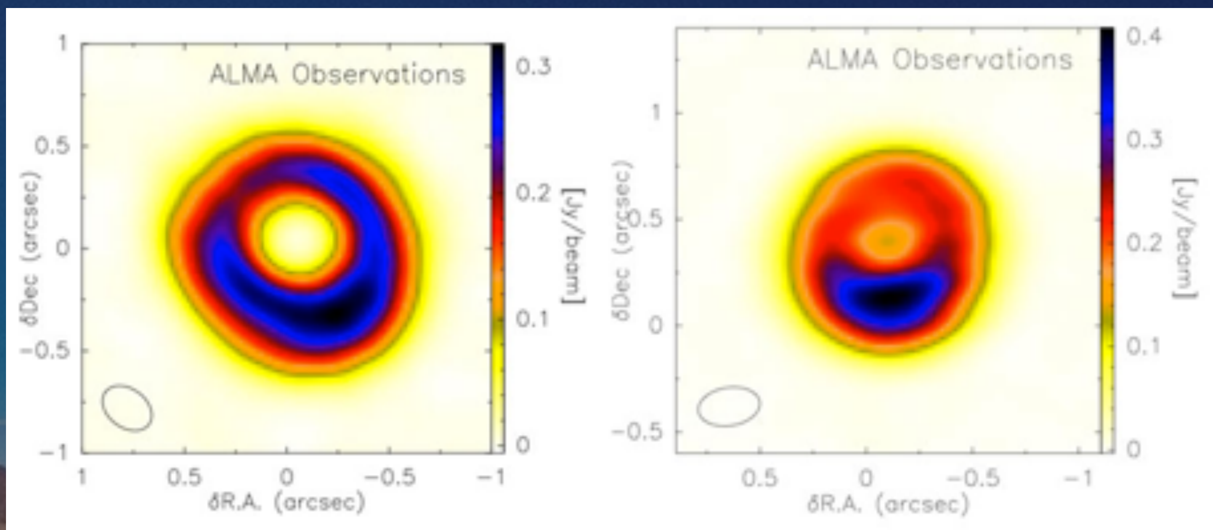


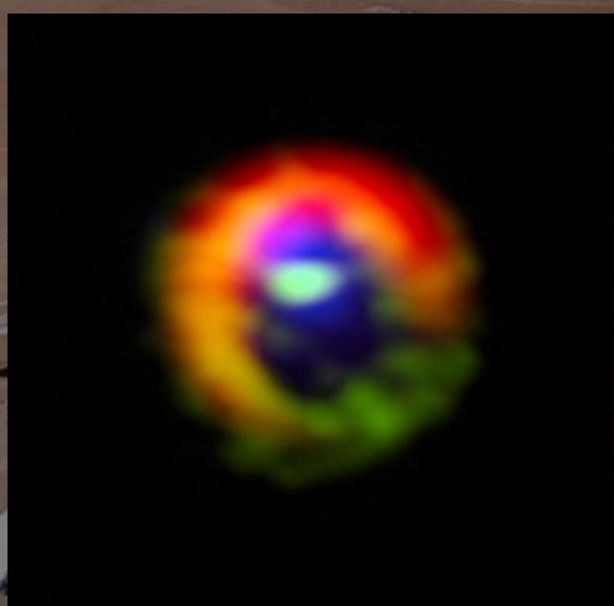






Korong-kutatás ALMA-val





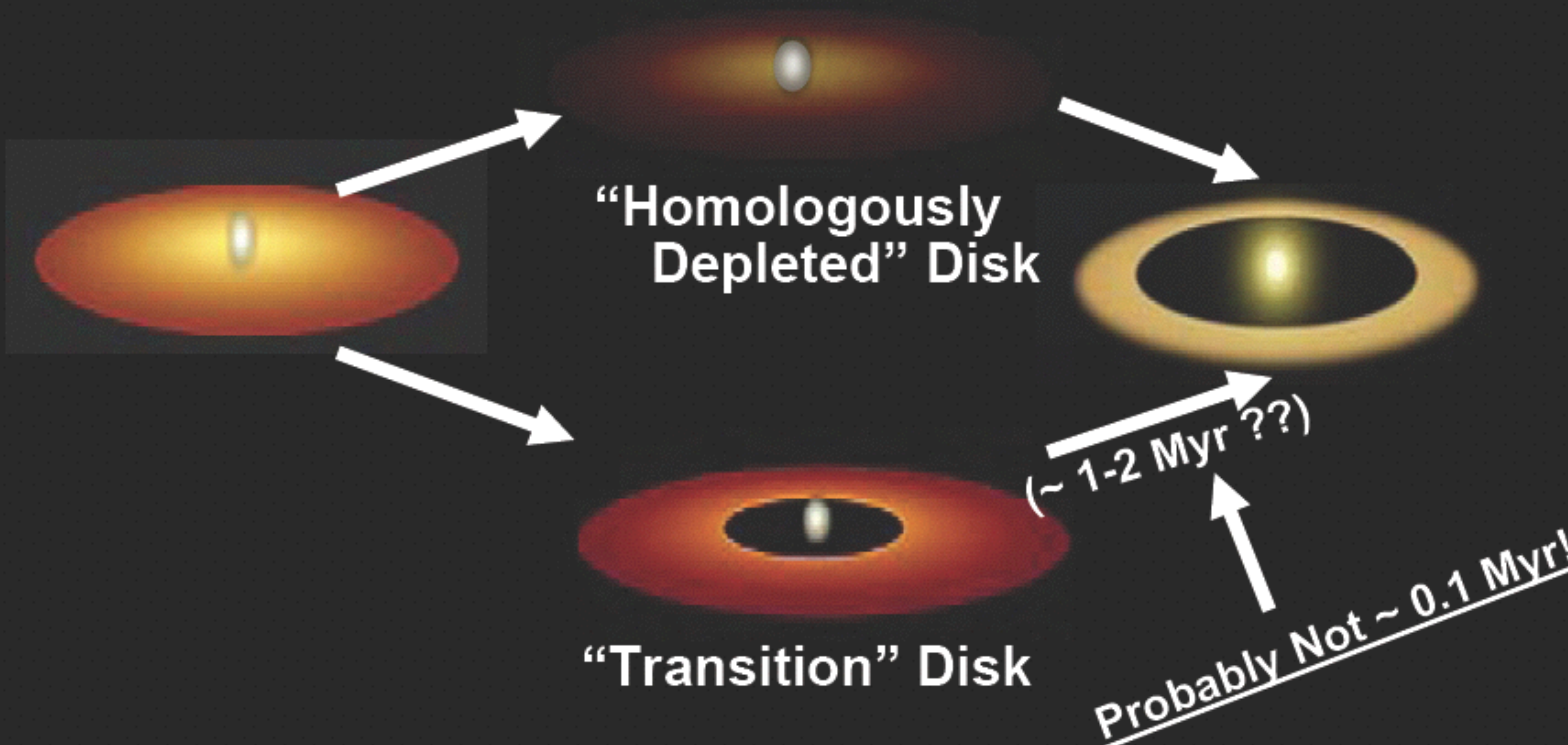
A korongok részletes szerkezete

Mi az aszimmetriák oka?

Bolygók, örvények a korongban?

Circumstellar Disk Evolution

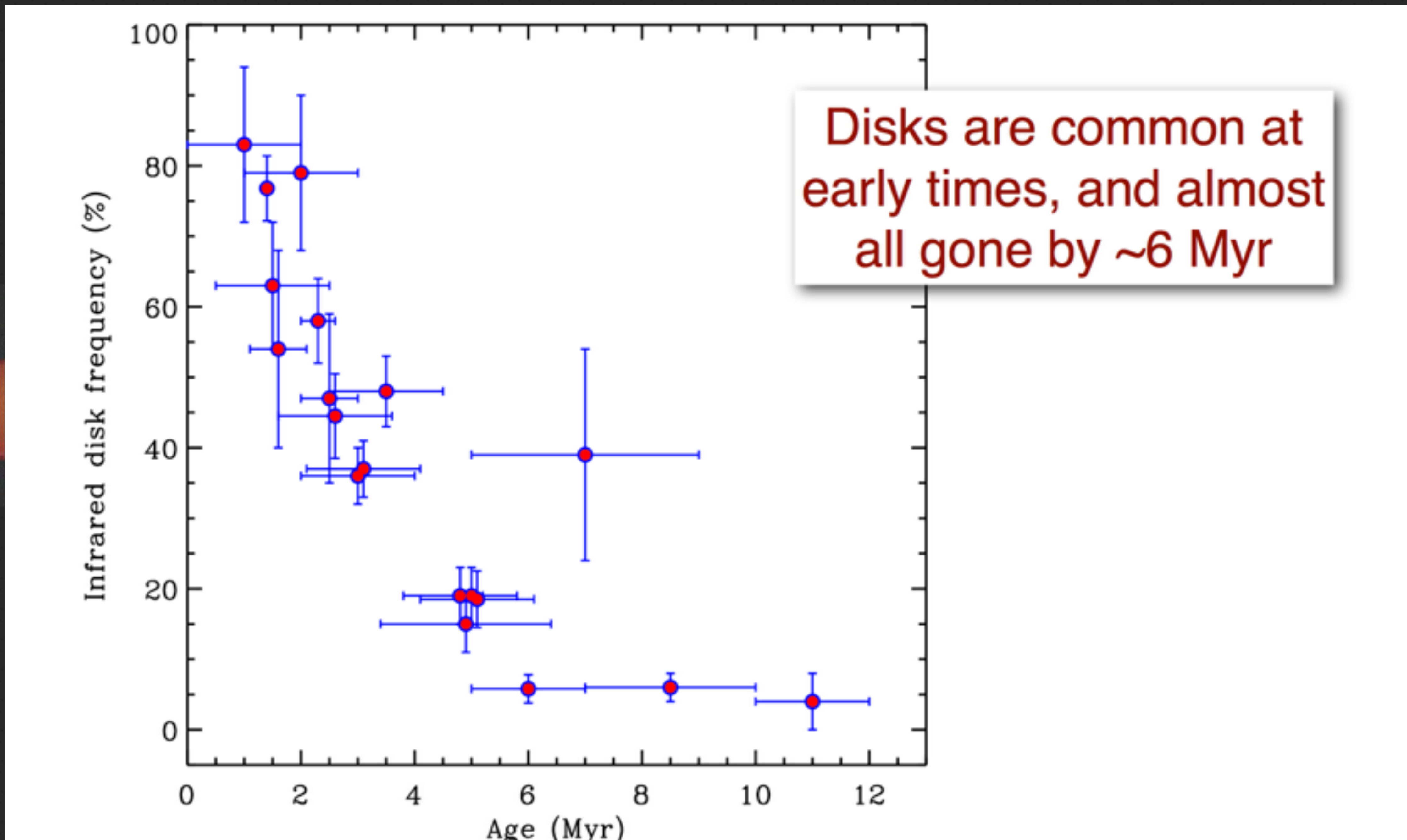
- **Primordial Disk**
- **'Evolved' Primordial Disk**
- **Debris Disk**



Currie & Lada et al. 2008, ApJ submitted

Circumstellar Disk Evolution

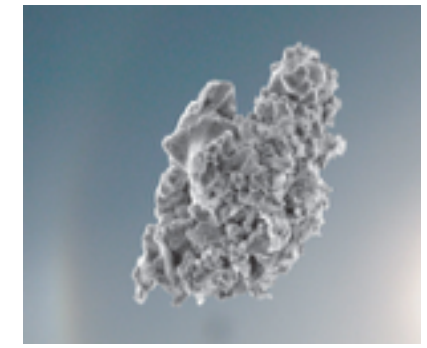
•



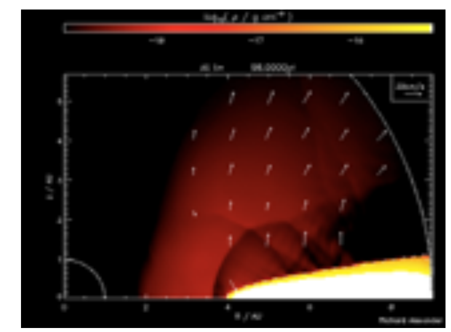
Currie & Lada et al. 2008, ApJ submitted

Fizikai folyamatok, amelyek erodálják a korongot

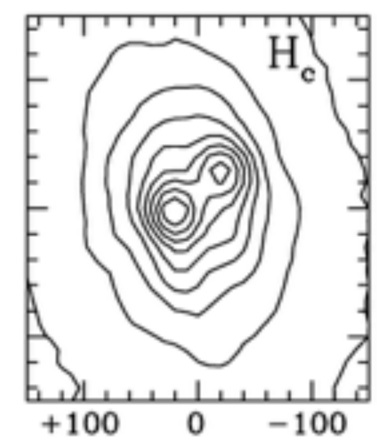
- A porszemcsék növekedése és leülepedése a korong középsíkjába



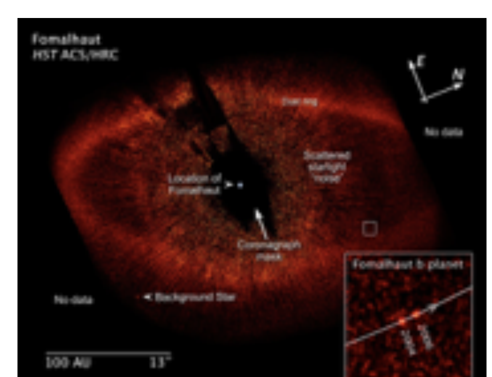
- A korong gáztartalmának elpárolgás a csillag ultraibolya sugárzásának hatására



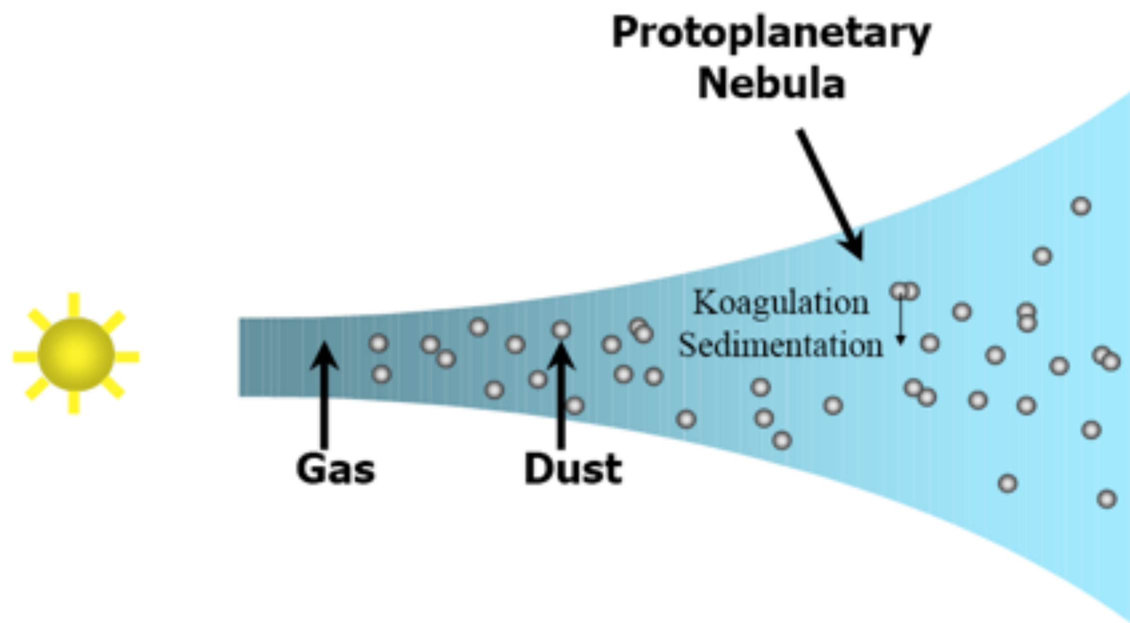
- Közeli kísérő gravitációs perturbációja

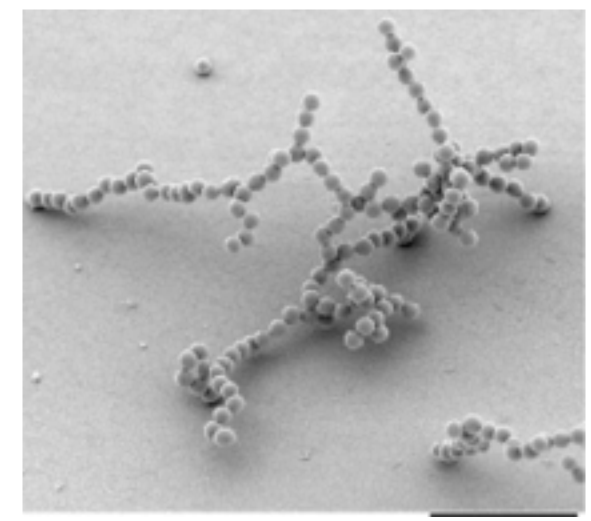


- Bolygókeletkezés



A porszemcsék növekedése





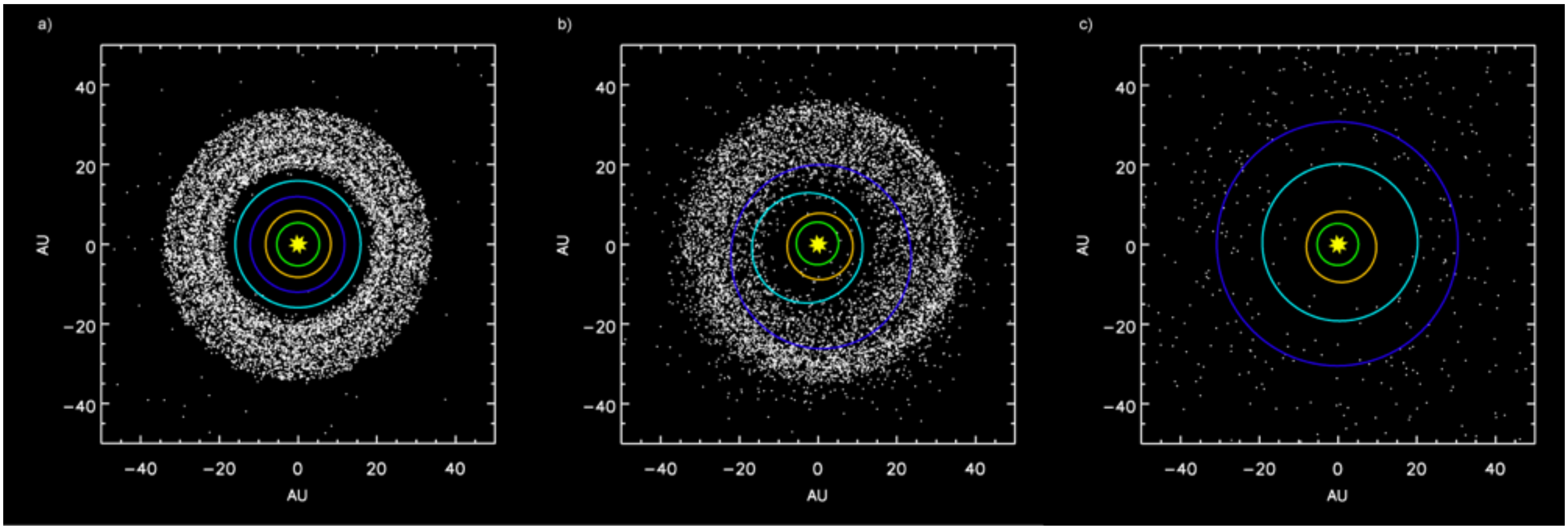
- a porszemcsék leülepednek a korong középsíkjába
- az ütközések összetapadáshoz és a méret növekedéséhez vezetnek
- a por gyakorlatilag lecsatolódik a gázról, elkezd függetlenül mozogni. Mivel a gáz valamivel a kepleri sebesség alatt kering, ez közegellenállást jelent a porszemcsék számára
- Valahogy meg kell mentenünk az 1 m-es sziklákat, ha bolygókat akarunk...

A bolygók keletkezése

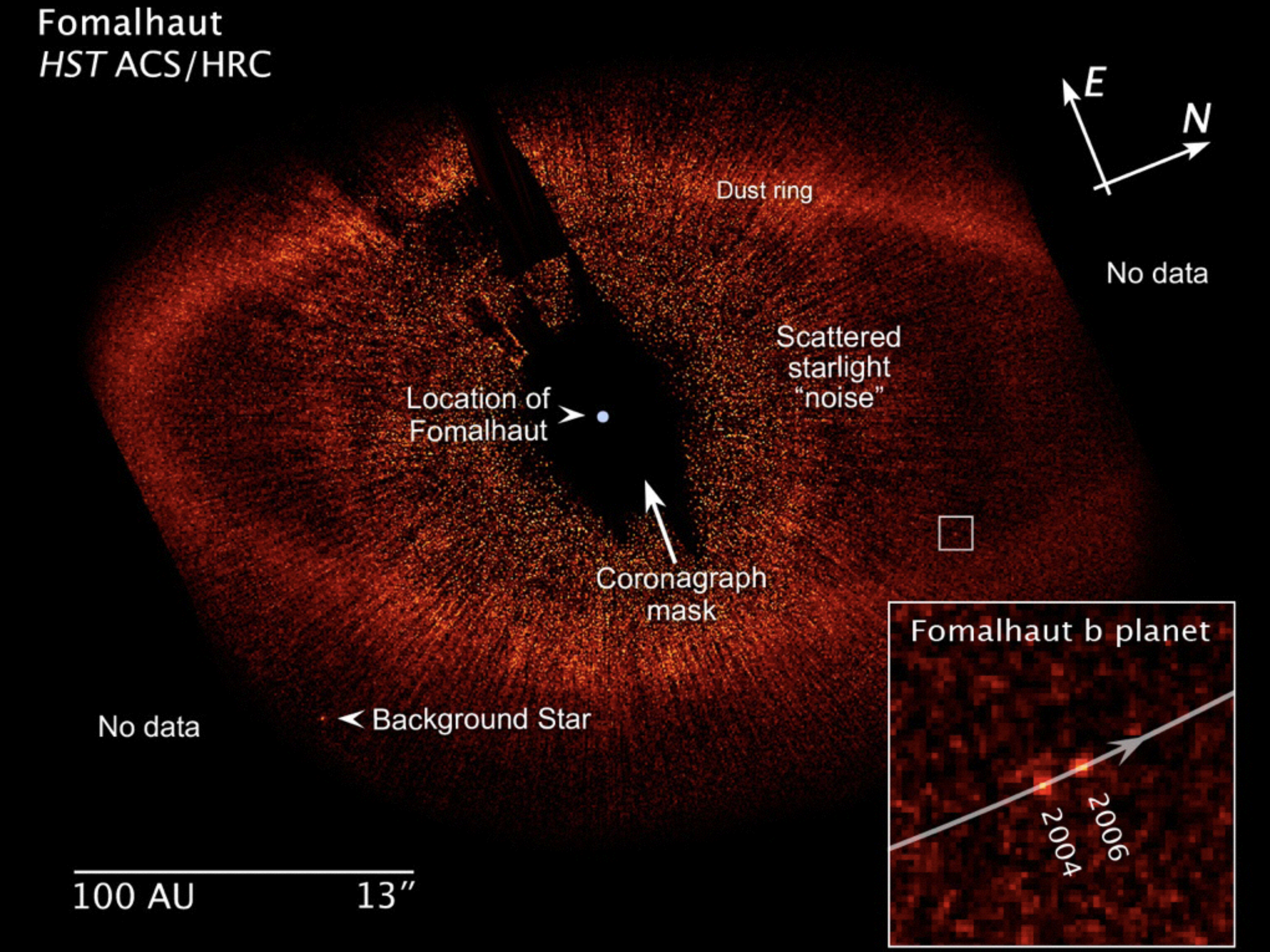
1. pornövekedés és ülepedés. Kilométeres testek létrejötte.
2. gravitációs hatáskeresztmetszet
3. “megszaladási fázis”: a legnagyobb bolygócsírák növekednek leggyorsabban
4. oligarcha fázis
5. a protobolygóktól a bolygókig (kaotikus növekedési fázis)
6. A gázburok akkretálása
7. Időskála: néhány millió év!

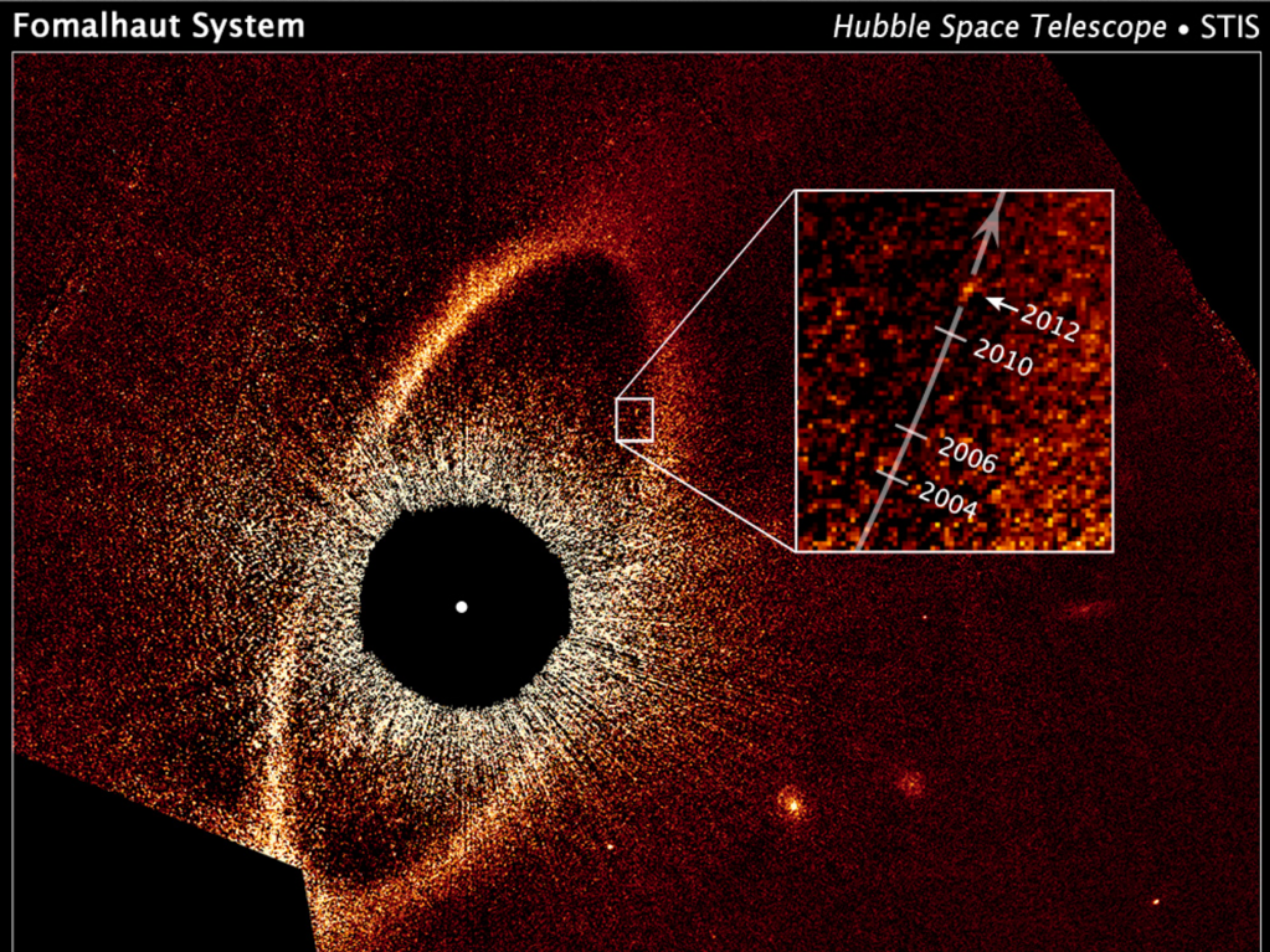
   A korong fizikai paraméterei (sűrűség- és hőmérsékletprofil, kémiai összetétel, a jégvonal helye, fejlődési időskálák) megadják a bolygókeletkezés kezdőfeltételeit, és közvetlenül megszabják, milyen bolygórendszer fog keletkezni.

Bolygómigráció a korai Naprendszerben



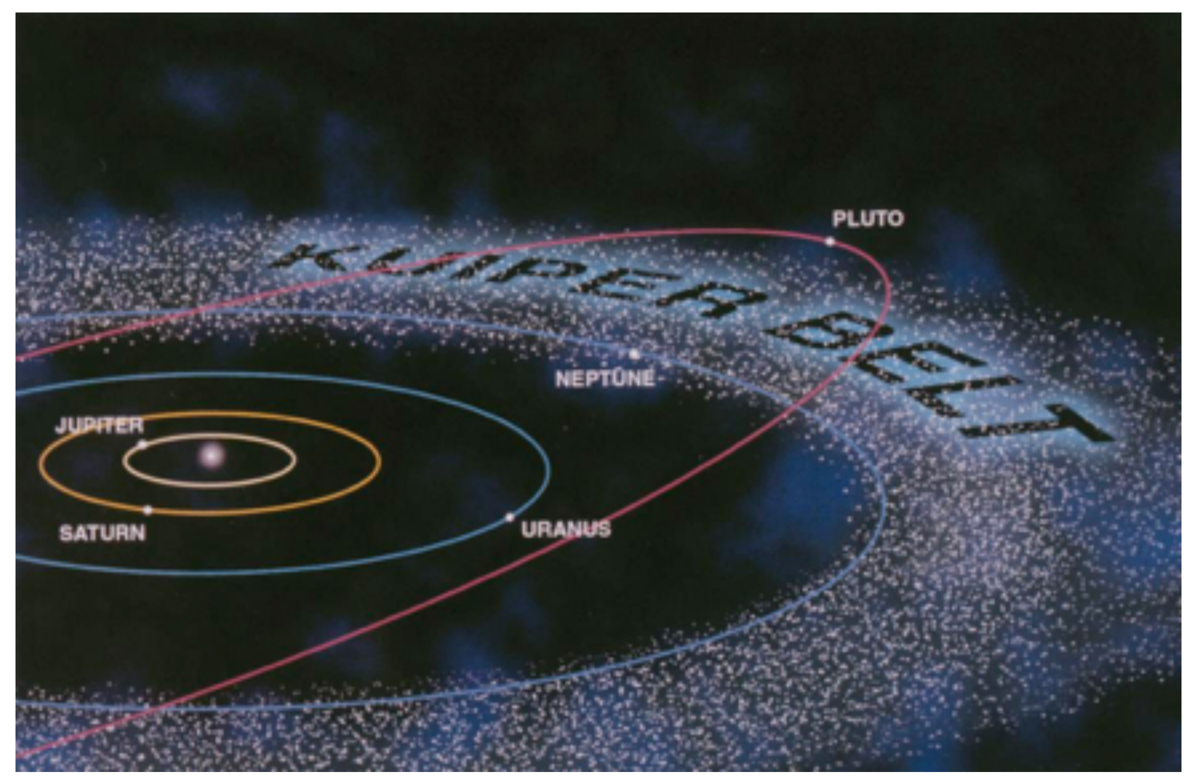
Credit: Gomes et al.

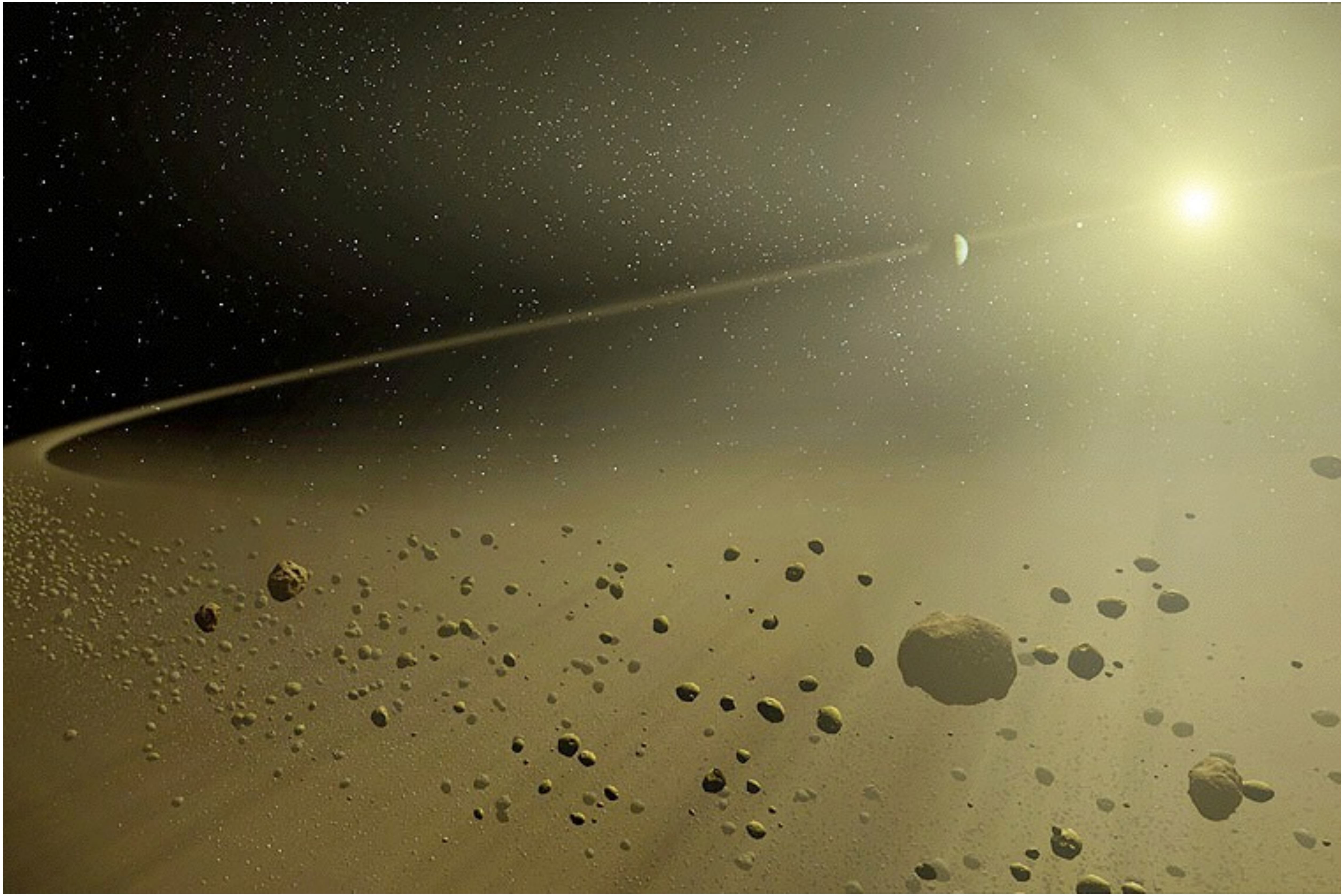

Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2004
2006
No data
Background Star
100 AU
13″


Fomalhaut System
Hubble Space Telescope • STIS
2012
2010
2006
2004

Bolygócsíra gyűrűk a Naprendszerben

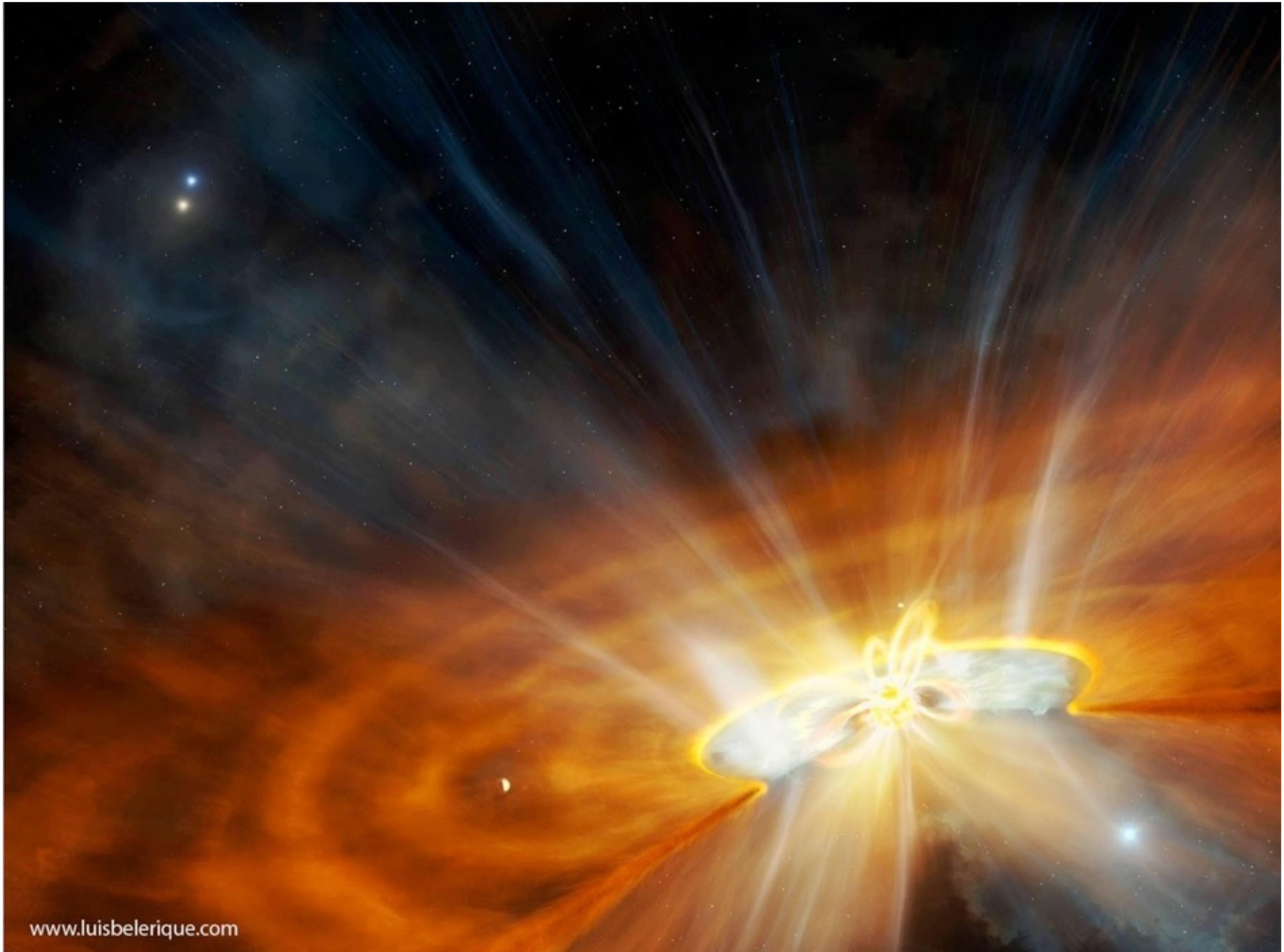
- a Naprendszerben két planetezimál gyűrű található: a kisbolygóöv és a külső Kuiper-öv
- a kisbolygók ütközései friss port hoznak létre, amelynek szórt fénye és infravörös sugárzása megfigyelhető (állatövi fény)
- Trans-Neptunian Objects program a Herschel Space Observatory-val





‘Star formation spans densities from 10^4 cm^{-3} to 10^{24} cm^{-3}, involves all the known forces of nature, with observational diagnostics across the entire spectrum, and requires experimental access to relevant primitive materials that has no parallel in any other branch of astrophysics’

Shu et al. 1993


www.luisbelerique.com

- Average properties of cores from which sun-like stars form (Chap. 2)

  - **$n \sim 10^5$ cm^{-3}**
  - **$T \sim 10$-30 K**
  - **$R \sim 10^{17}$ cm**
  - **$M \sim 1\ M_{sun}$ (inside $n > 3 \times 10^4$ cm^{-3})**
  - **$B \sim 20$-30 μG**
  - **$\Omega \sim 3 \times 10^{-14}$ rad s^{-1}**
    - **One turn every 7×10^6 yr**

- Average properties of T Tauri stars, the precursors of sun-like stars
  - **n~10^{23} cm^{-3} (mostly H^+ and e)**
  - **T~10^6 K**
  - **R~10^{11} cm**
  - **M~1 M_{sun}**
  - **B~1 kG (probably dynamo generated)**
  - **Ω~10^{-5} rad s^{-1}**
    - **>factor 10 below break-up**

The problems

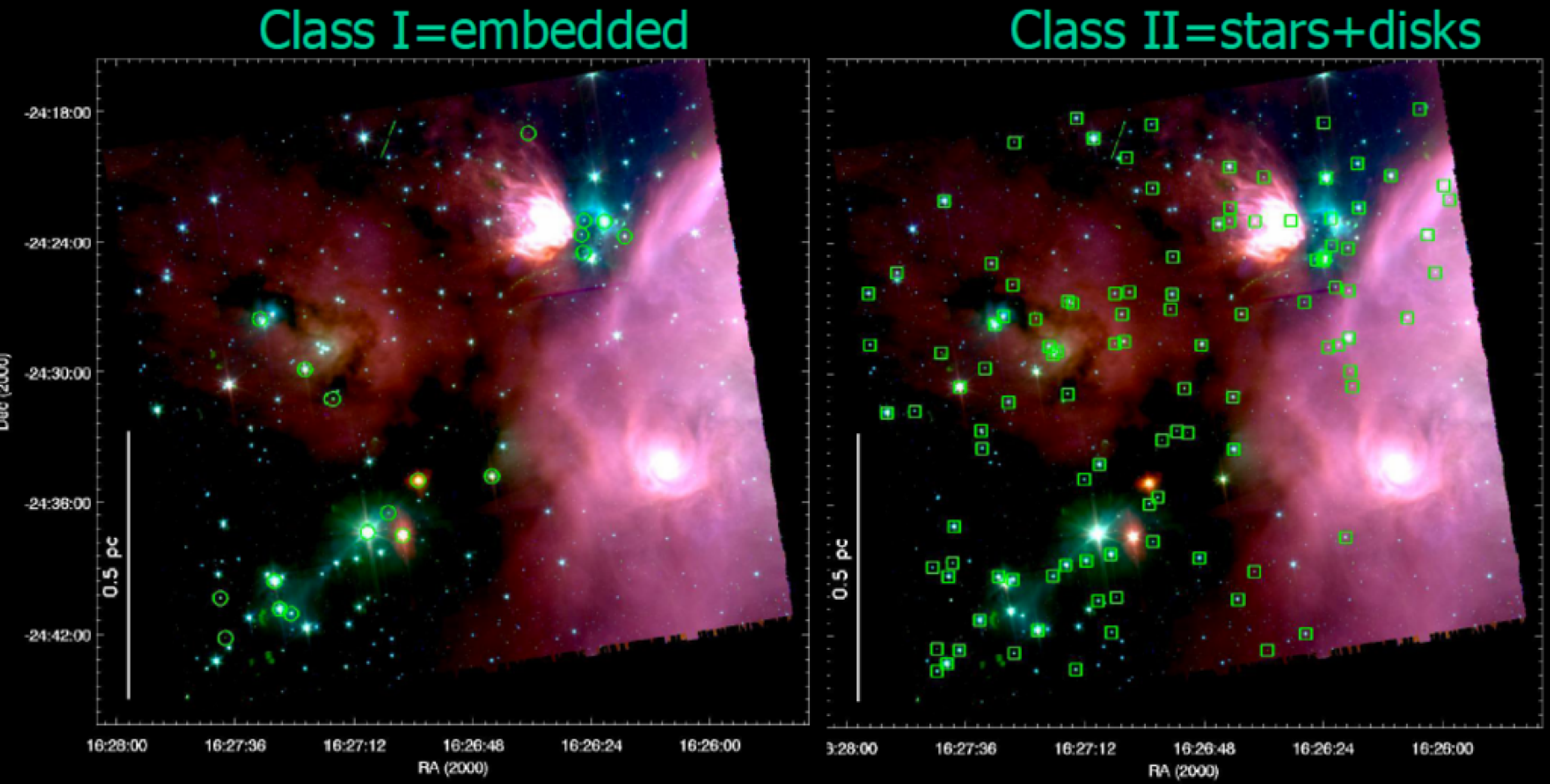
- Collapse by a factor of 10^{18} in n and 10^6 in R →
- ***Angular momentum problem***
  - ΩR^2=**const** → Ω increases by factor of 10^{12}
  - ***Not*** observed!
- ***Magnetic flux problem***
  - BR^2=**const** (field freezing) → B increases by factor of 10^{12}
  - ***Not*** observed!
- ***Dynamical problem***
  - Very difficult to follow many orders of magnitude with numerical techniques →semi-analytical models as tests

Észak-Amerika köd

Ophiuchus


SPITZER
SPACE TELESCOPE
NASA/JPL-Caltech www.spitzer.caltech.edu

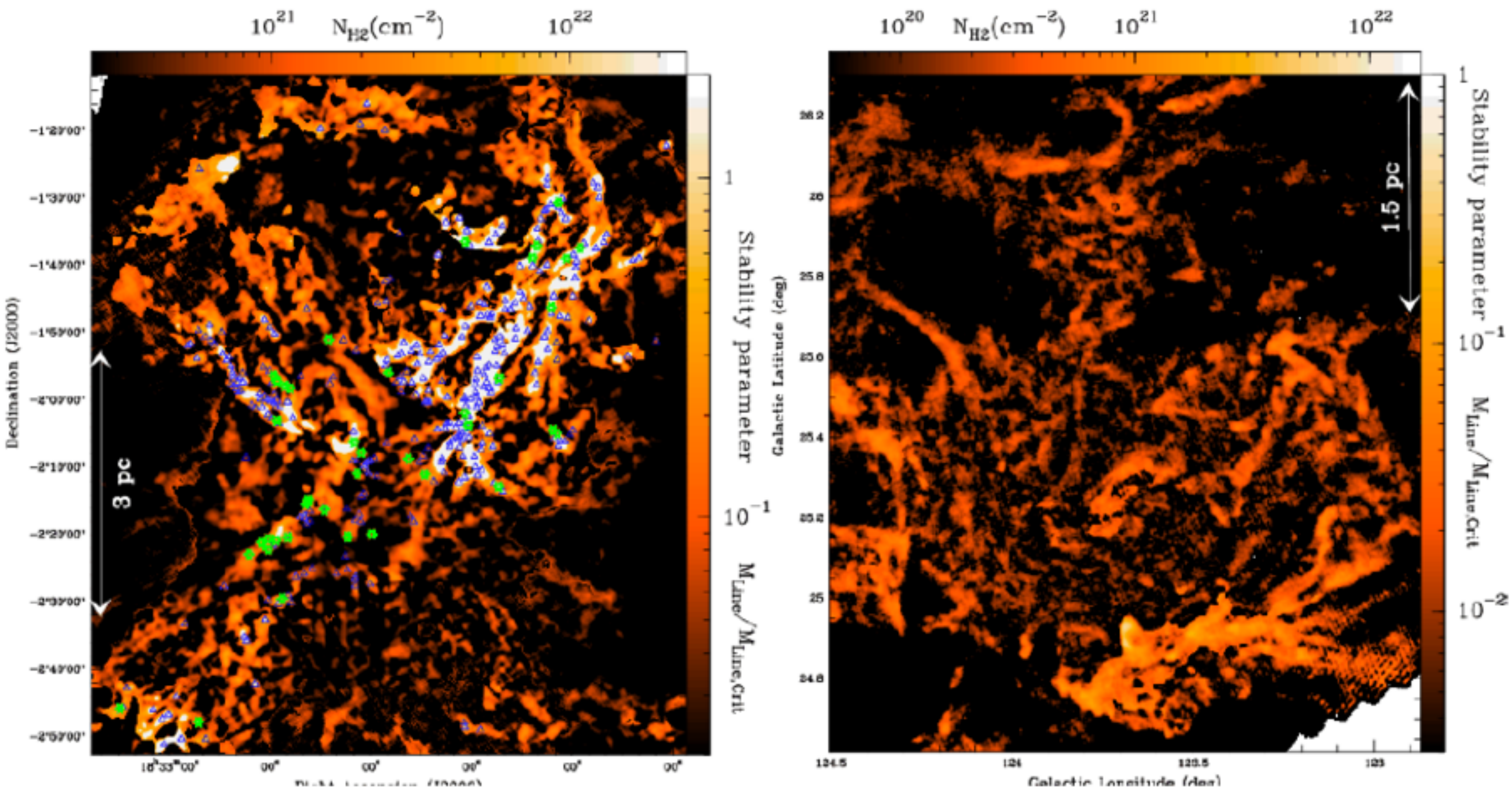
Spatial distributions Oph



Note that Class II sources (young stars + disk) much more distributed throughout cloud

Allen et al. 2007

Star formation along dense filaments in Serpens/Aquila



André et al. 2010, Herschel

- Stars forms at high (column)densities
- Similar filamentary structure in non-starforming clouds

Overall star formation rates

Low-mass star forming regions

	Cha II	Lupus	Perseus	Serpens	Ophiuchus
SFR (M_{sun}/Myr)	6.5	24	96	59	73
SFR/Area (M_{sun}/Myr-pc^2)	0.65	0.83	1.3	3.4	2.3
$\frac{M_*}{M_{cl}+M_*}$	0.021	0.040	0.028	0.041	0.046

Evans et al. 2009

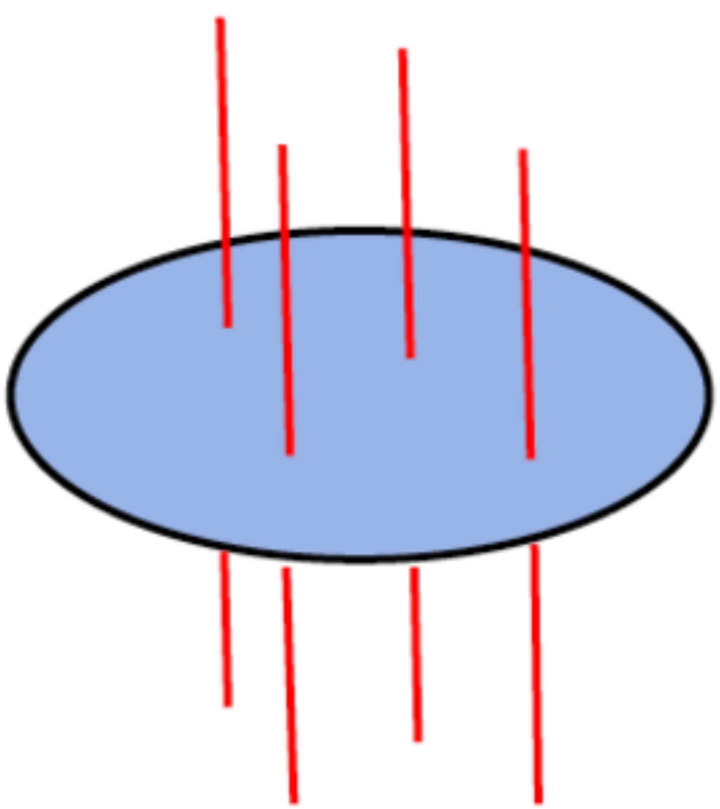
SFR assumes $\langle M_* \rangle = 0.5\ M_{sun}$; $t_{SF} = 2$ Myr

2.3 Cloud and core formation

- Gravity, turbulence, magnetic fields all play a role in making filaments
- Densest filaments fragment into star-forming cores via gravitational instability

Concept 1

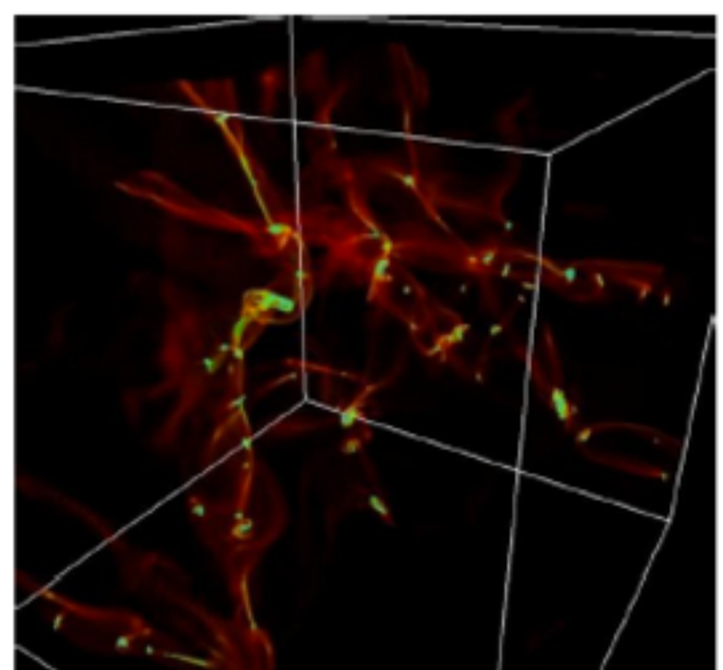
magnetically supported sheet



Shu, Mouschovias, …

Concept 2

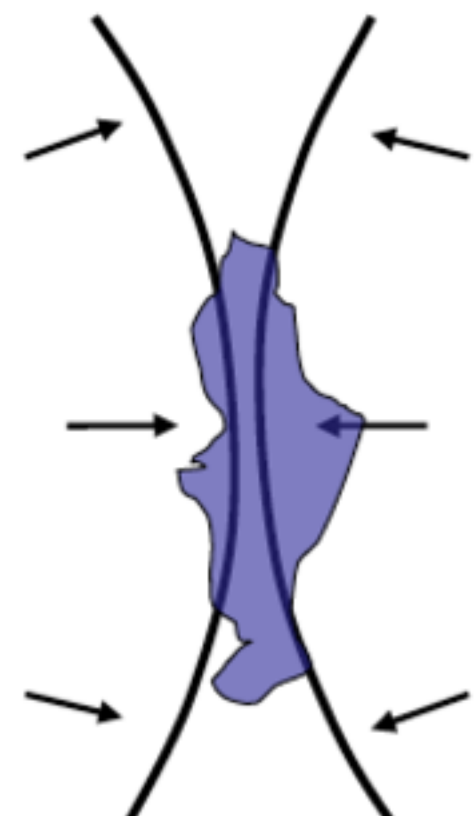
turbulent fragmentation



snapshot from P. Padoan, Klessen

Concept 3

cloud formation & thermal fragmentation



Hartmann et al. , Heitsch

Two paradigms for star formation
a. Slow quasi-static evolution

- Core gradually becomes more centrally condensed
- Evolution likely dominated by magnetic fields: ambipolar diffusion (see Sect. 2.11)
  - Clouds may form by accumulation of matter along flux tubes by instabilities
- Gradual dissipation of low-level turbulence
- Predicts lifetimes $t_{AD} \sim 10\ t_{ff}$

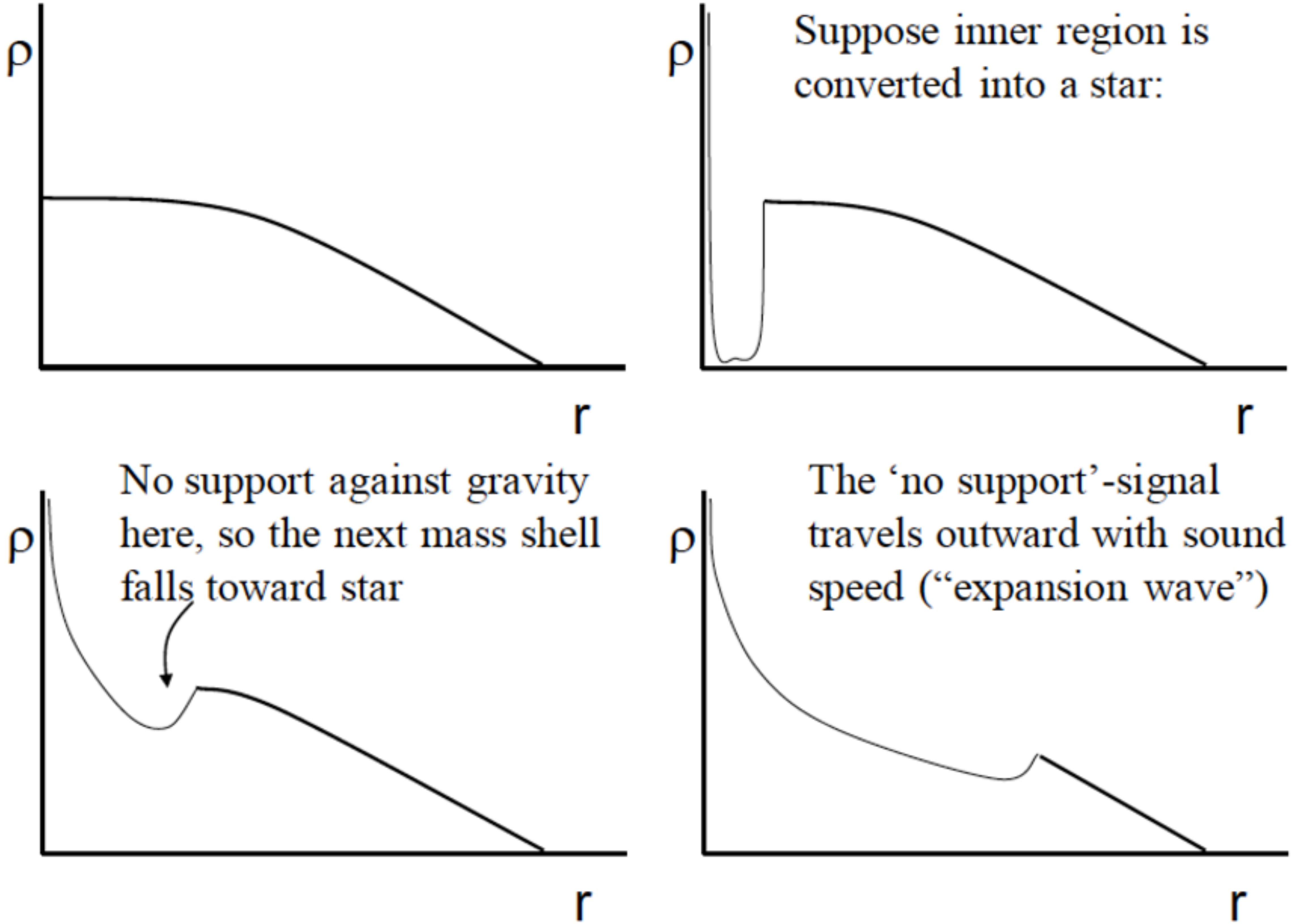
Shu et al. 1987
Mouschovias 1991

b. Fast gravo-turbulent fragmentation

- Molecular clouds are intermittent phenomena in ISM dominated by compressible turbulence
- Turbulent flows form density enhancements that may or may not be self-gravitating
  - Magnetic fields play minor role
  - Turbulence decays on a freefall timescale
- Star formation takes place rapidly on a cloud crossing time

Ballesteros-Paredos et al. 2003
MacLow & Klessen 2004

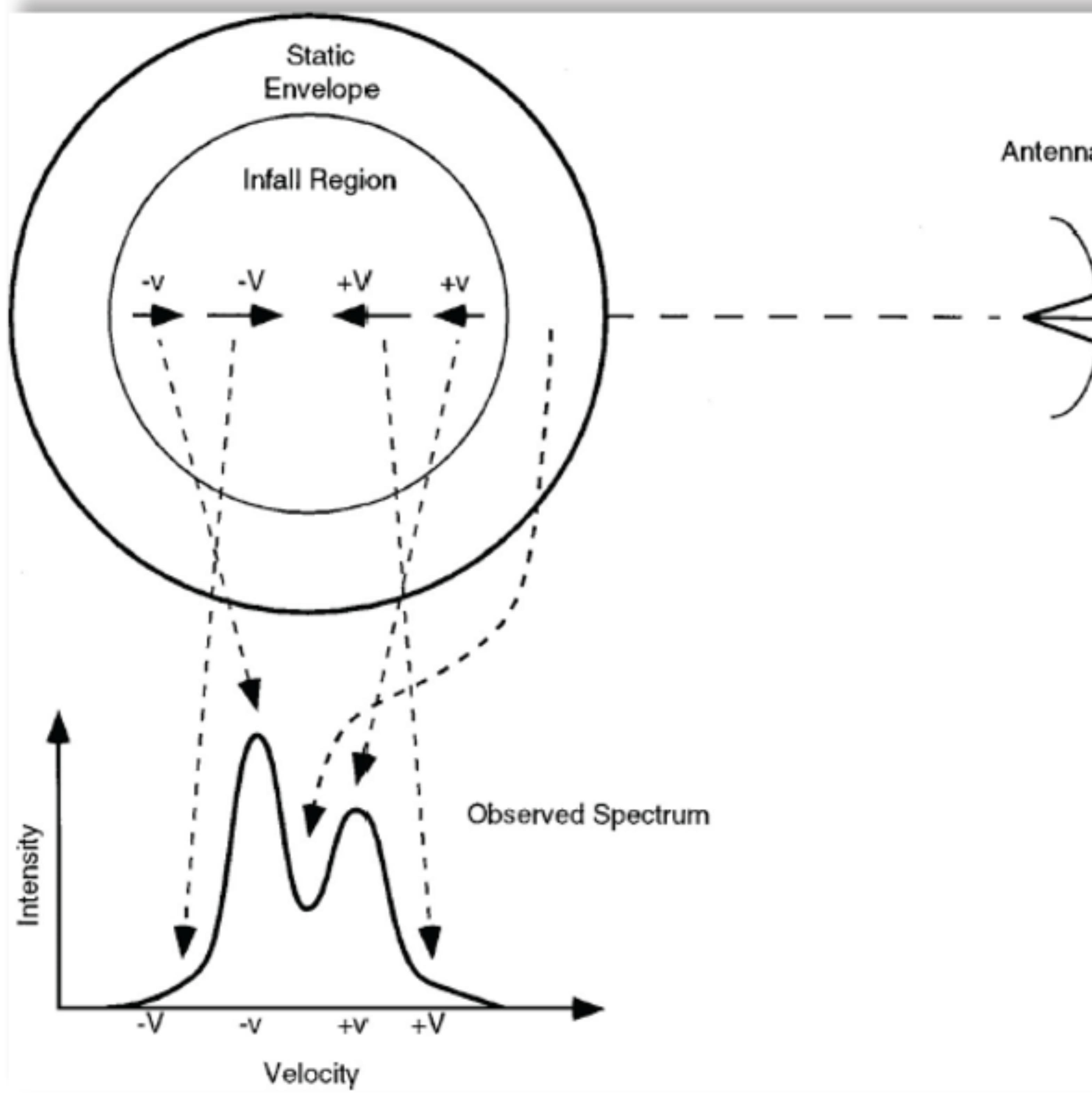
Inside-out collapse of metastable sphere



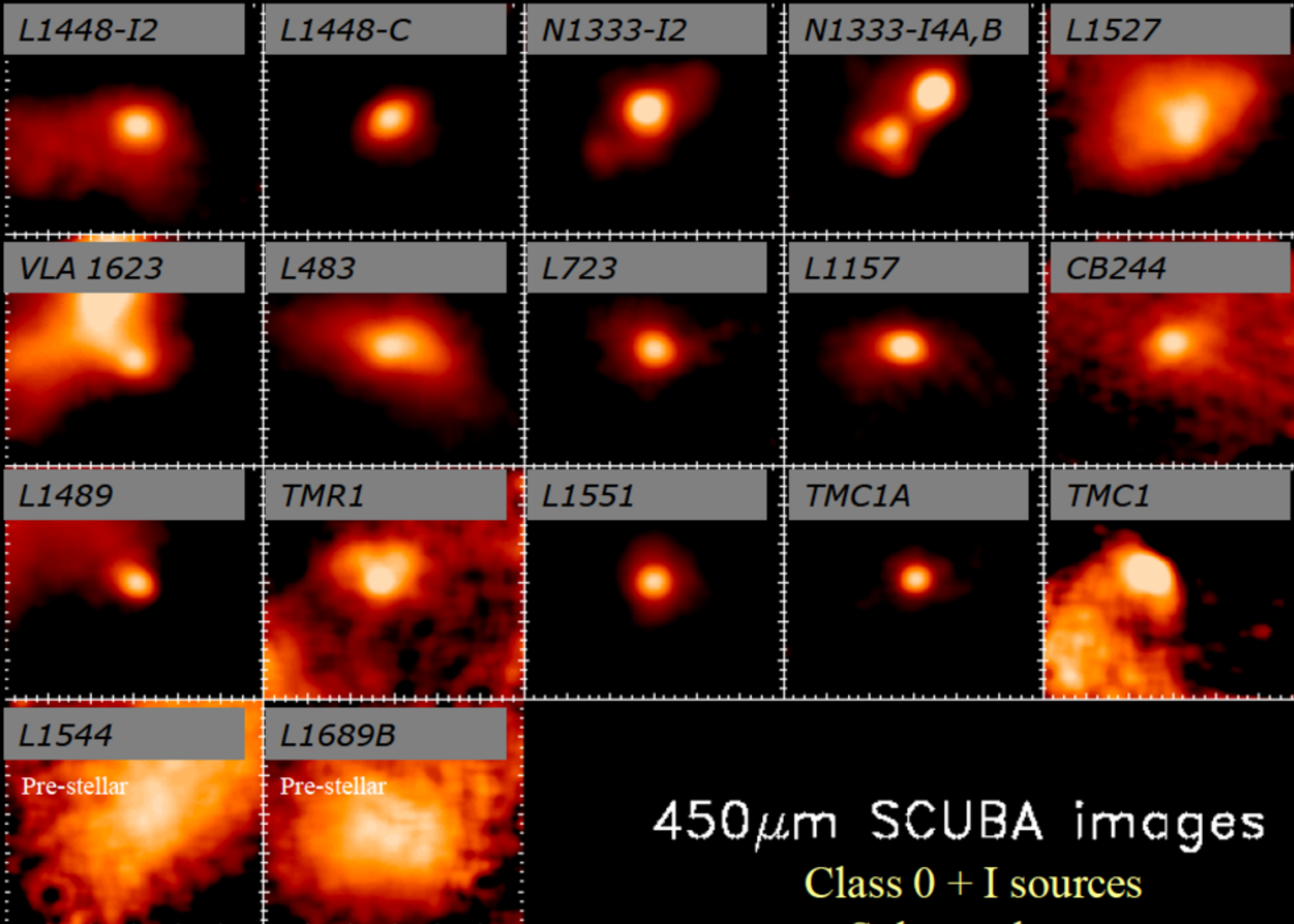
(warning: strongly exaggerated features)

The origin of various parts of the line profile for a cloud undergoing inside-out collapse

The static envelope outside r_{inf} produces the central self-absorption dip, the blue peak comes from the back of the cloud, and the red peak from the front of the cloud. The faster collapse near the center produces line wings, but these are usually confused by outflow wings.



Evans 1999, ARA&A



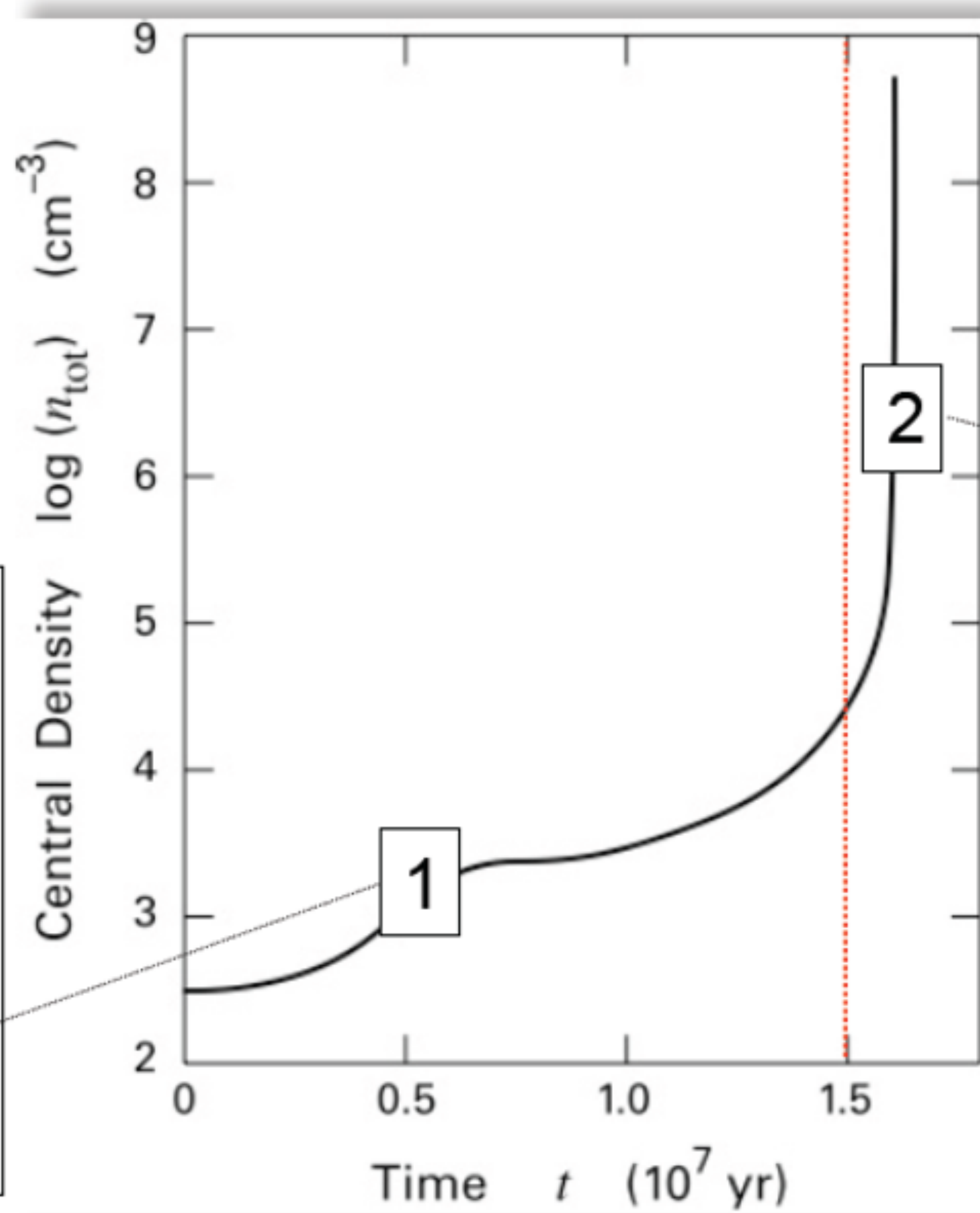
450μm SCUBA images

Class 0 + I sources

Submm data

Note emission much more concentrated than in pre-stellar cores

Early growth and collapse



In a magnetized cloud undergoing contraction, the density gradually increases via ambipolar diffusion until the central Σ / B has surpassed the critical value.

The contracting deep interior effectively separates from the more slowly evolving outer portion of the cloud.

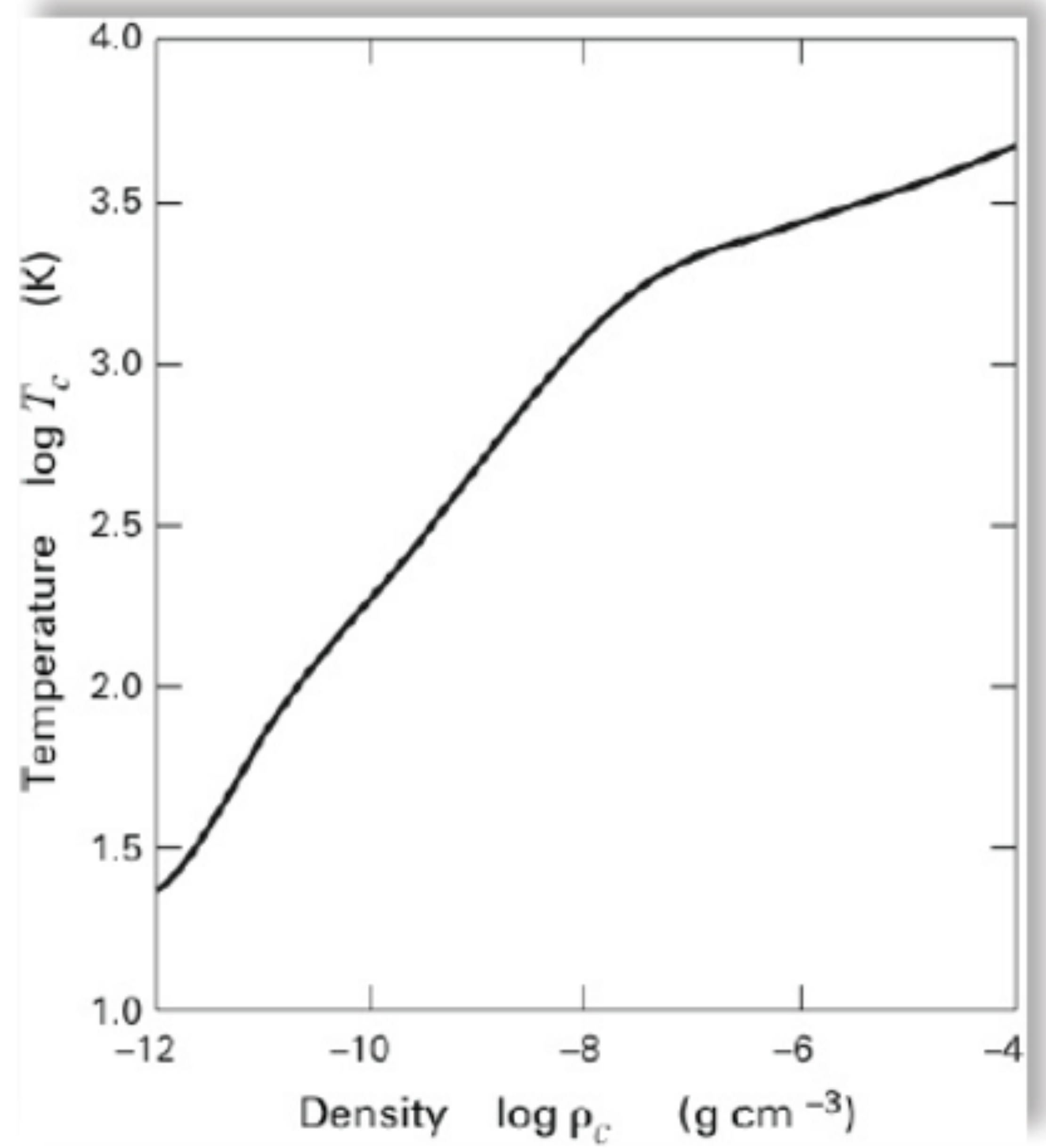
The structure that arises from the contraction is not yet a *protostar* but a temporary configuration known as the first core. To describe its growth and rapid demise, let's neglect (for now) the important element of rotation and magnetic support.

•The isothermal approximation breaks down! As its density climbs, the central lump becomes opaque to its own cooling radiation, and further compression causes its internal temperature to rise steadily.

•The enhanced pressure decelerates material drifting inward, which gently settles onto the hydrostatic structure.

•The settling gas radiates, removing energy from the outer skin and further enhancing compression.

•The core eventually stops expanding and begins to shrink.



$M \sim 5\times10^{-2}\, M_\odot$, $R \sim 5$ AU

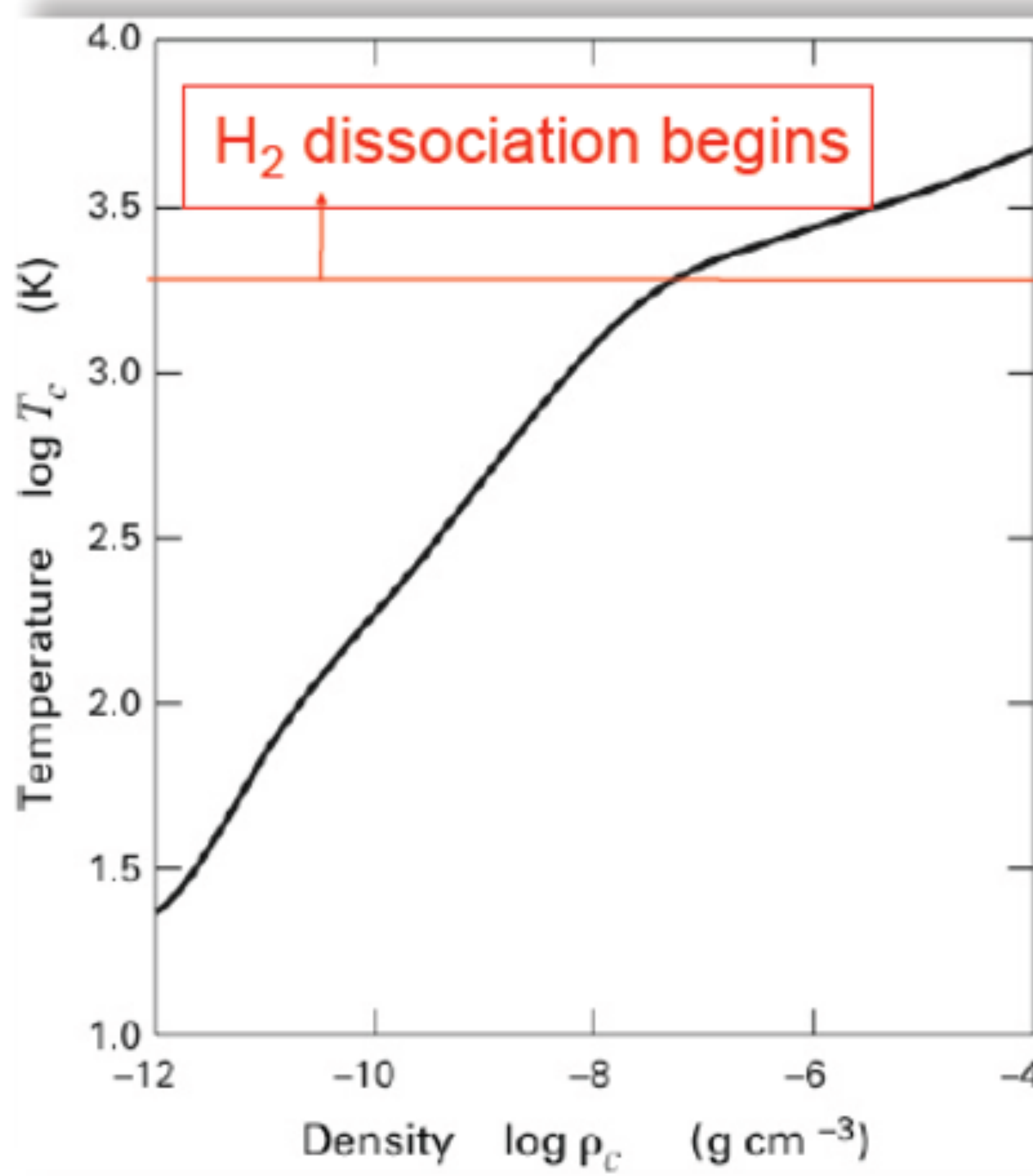
$\rightarrow \rho \sim 10^{-10}$ g cm^{-3}

With the addition of mass and shrinking of the radius, T soon surpasses 2000 K and collisional dissociation of H_2 begins ➔ T starts to level off:

- the number of H_2 molecules in the core is $XM/2m_H$ ($X = 0.70$);
- the thermal energy per molecule is $3k_BT/X = 0.74$ eV (< 4.48 eV) @ T=2000 K .

↓

During the transition epoch, even a modest rise in the fraction of dissociated hydrogen absorbs most of the compressional work of gravity, without a large increase in temperature.



As the density of the first core keeps climbing (whereas the T rise is damped by the dissociation process), the region containing atomic H spreads outwards from the center and increase the mass until the entire configuration becomes unstable and collapses: recall the isothermal Bonnor-Ebert sphere becomes unstable when the center to edge density ratio is ~14. This marks the end of the first core.

The collapse of the partially dissociated gas takes the central region to much higher density and temperature ➔ collisional ionization of the hydrogen.

The true protostar is born.

With a radius of several $R_\odot$, a protostar of 0.1 $M_\odot$ has $T > 10^5$ K and density $\sim 10^{-2}$ g cm^{-3}.

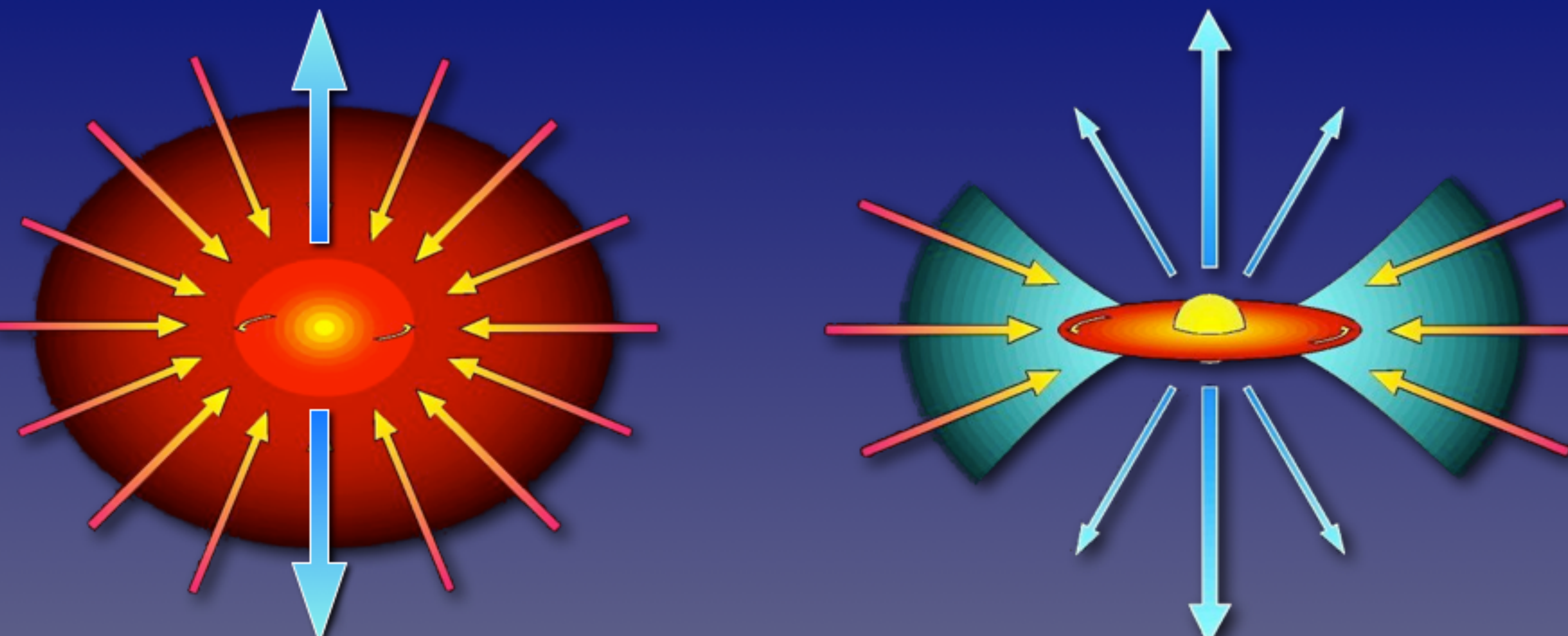
The gas approaching the protostellar surface now travels at free-fall velocities >> local sound speed. The steady rise in the protostellar mass gradually inflates this supersonic infall region and the cloud collapse proceeds inside-out ➔ main accretion phase.

Accretion Luminosity

$$L_{acc} \equiv \frac{GM_*\dot{M}}{R_*} = 61\, L_{sun} \left(\frac{\dot{M}}{10^{-5}\, M_{sun}\ \mathrm{yr}^{-1}} \right) \left(\frac{M_*}{1 M_{sun}} \right) \left(\frac{R_*}{5 R_{sun}} \right)^{-1}$$

This is the energy per unit time released by infalling gas that converts *all* its kinetic energy into radiation as it lands on the stellar surface. Throughout the main accretion phase, L_{acc} is very nearly equal to L_{rad}, the average luminosity escaping.

The isolated star formation paradigm



Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K

Class I-II:
10^{5-6} yrs; 1-1000 AU; 100-3000 K

Pre-main sequence evolution depends on the stellar mass

- T Tauri stars are solar-type, low-mass stars

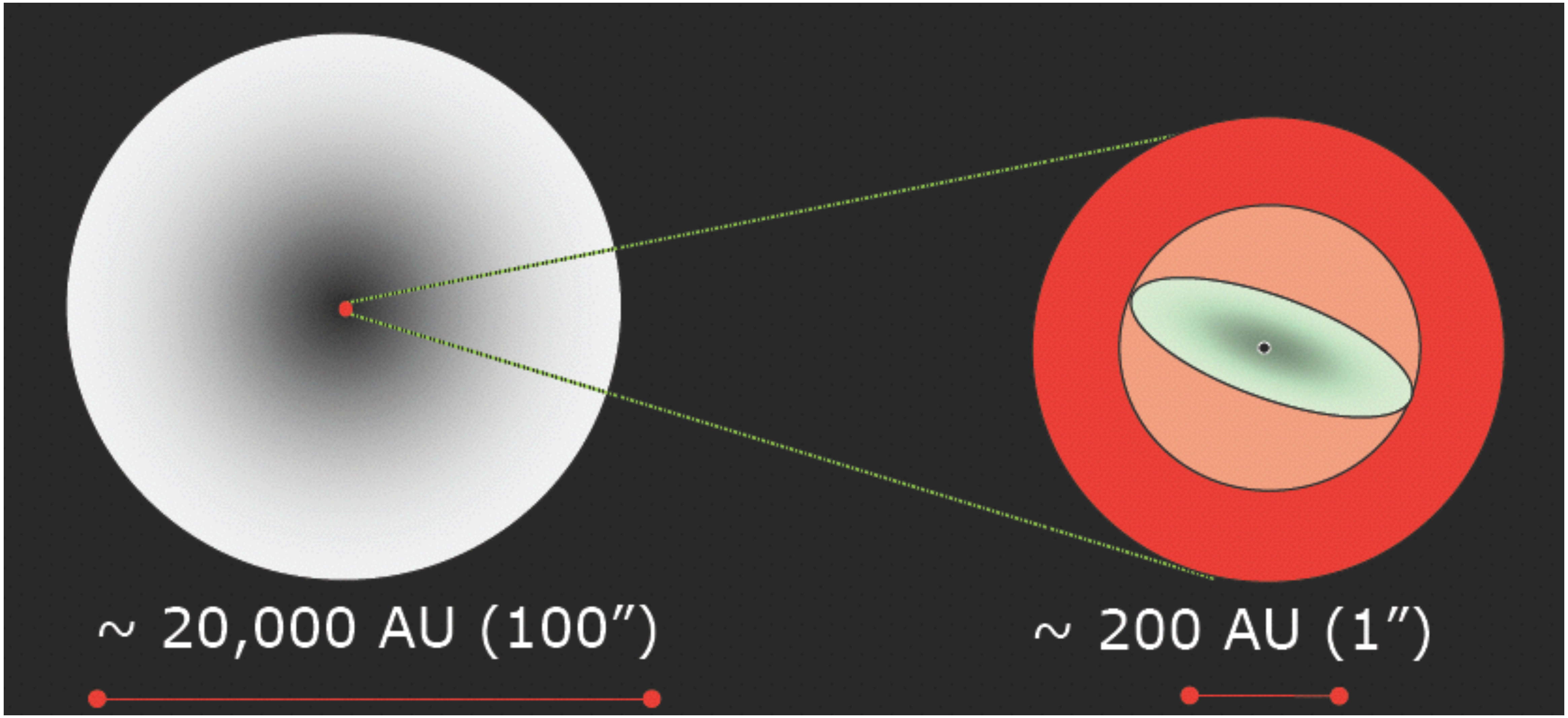
  0.5-1 < M(T Tauri) < 2-3 Msun

- Herbig Ae/Be stars are their higher-mass counterparts *(Herbig 1960)*

  2-3 < M(HAeBe) < 8 Msun (maybe much more...)

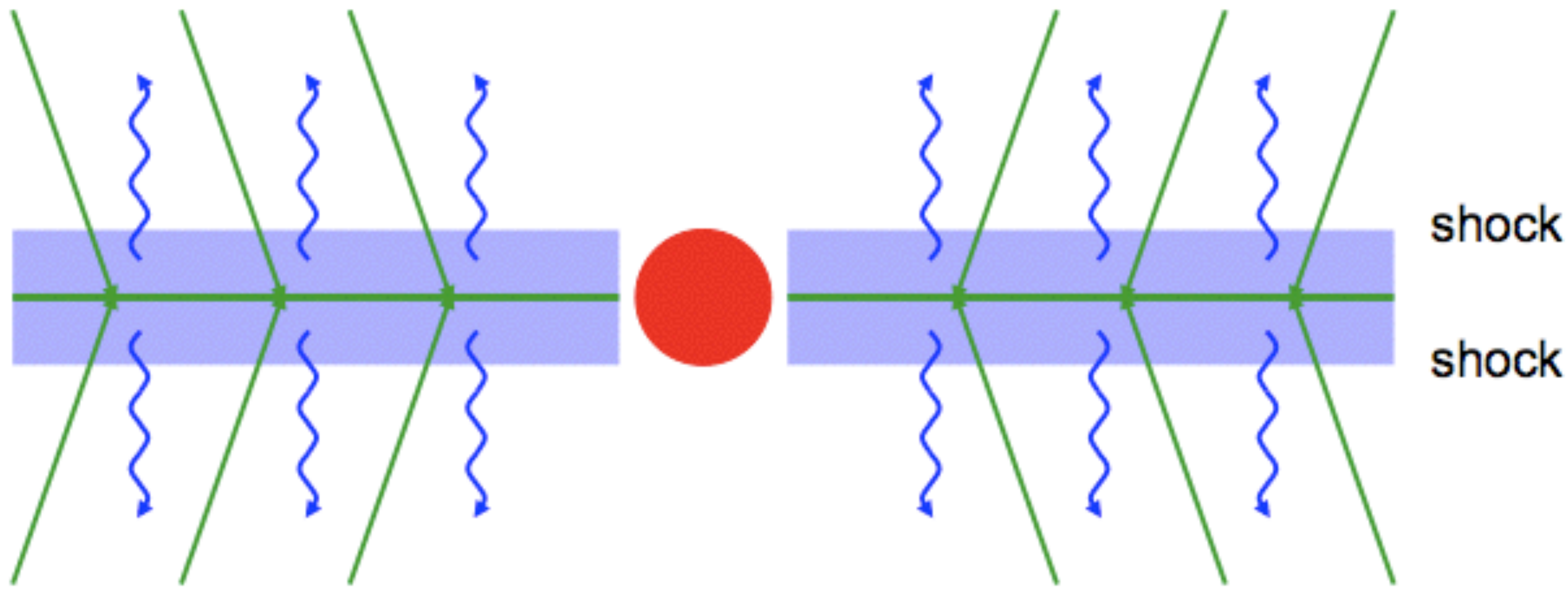
As in T Tau, HAeBe also show disc emission.

Many, but not all, HAeBe are associated with molecular clouds
or young clusters.



Jorgense (2008)

A csillagkörüli korong keletkezése



- Infalling matter collides with matter from the other side
- Forms a shock
- Free-fall kinetic energy is converted into heat

$$\frac{kT}{\mu m_p} \approx \tfrac{1}{2} v_{\mathrm{ff}}^2 = \frac{GM_*}{r}$$

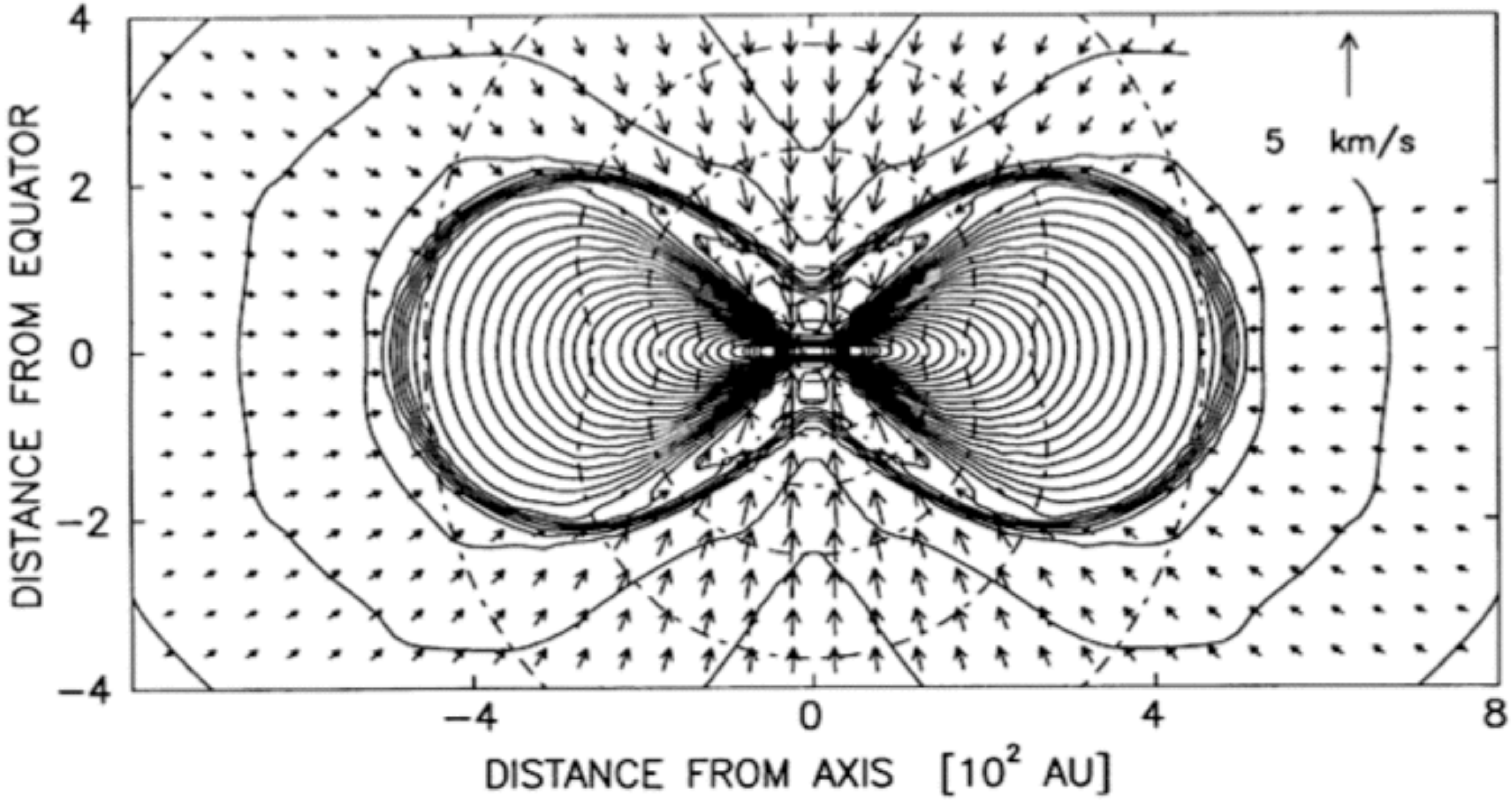
At 10 AU from $1M_\odot$ star:

$$T \approx 25000\,K$$

- Heat is radiated away, matter cools, sediments to midplane
- Disk is formed

A csillagkörüli korong keletkezése

3-D Radiation-Hydro simulations of disk formation



Yorke, Bodenheimer & Laughlin 1993

Kepleri forgás

Disk material is almost (!) 100% supported against gravity by its rotation. Gas pressure plays only a minor role. Therefore it is a good approximation to say that the tangential velocity of the gas in the disk is:

$$v_\phi \cong \Omega_K r = \sqrt{\frac{GM_*}{r}}$$

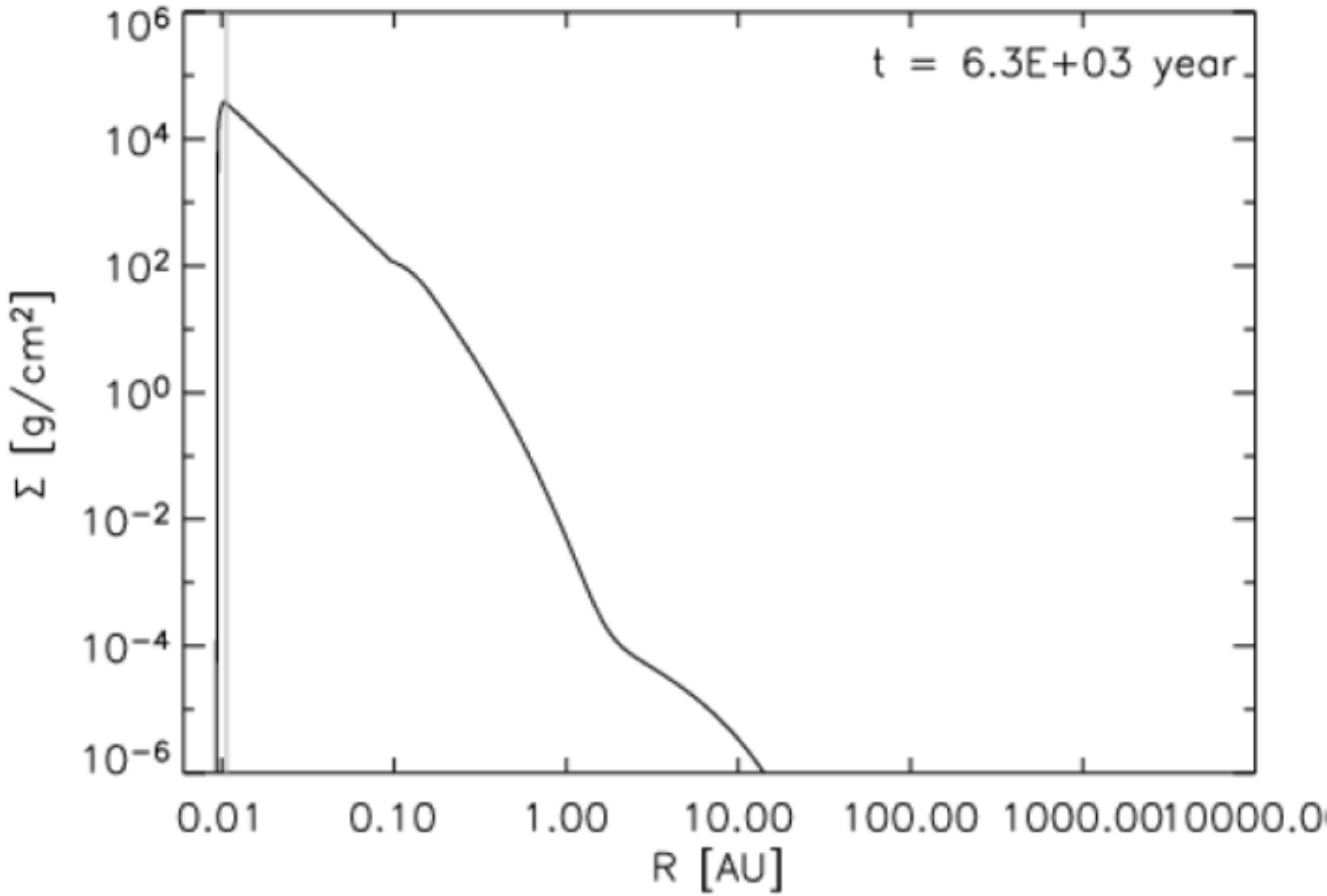
$$\Omega_K \equiv \sqrt{\frac{GM_*}{r^3}}$$

Kepler frequency

A perdületmegmaradás problémája

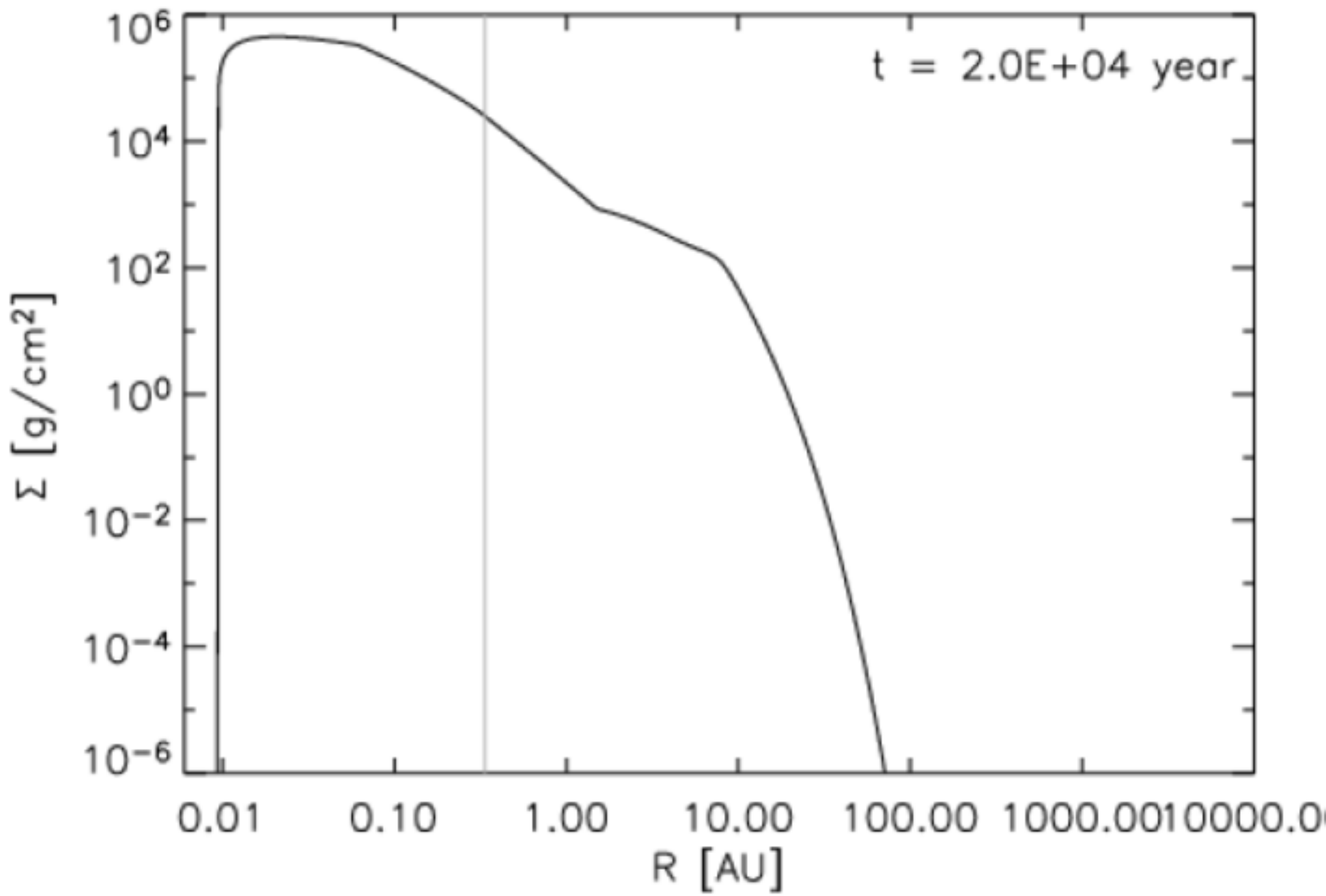
- Angular momentum of 1 $M_\odot$ in 10 AU disk:
  3×10^{53} cm²/s
- Angular momentum of 1 $M_\odot$ in 1 $R_\odot$ star:
  $<< 6 \times 10^{51}$ cm²/s (=breakup-rotation-speed)
- Original angular momentum of disk = 50x higher than maximum allowed for a star
- Angular momentum is strictly conserved!
- Two possible solutions:
  – Torque against external medium (via magnetic fields?)
  – Very outer disk absorbs all angular momentum by moving outward, while rest moves inward.
    Need *friction through viscosity!*

Formation & viscous spreading of disk

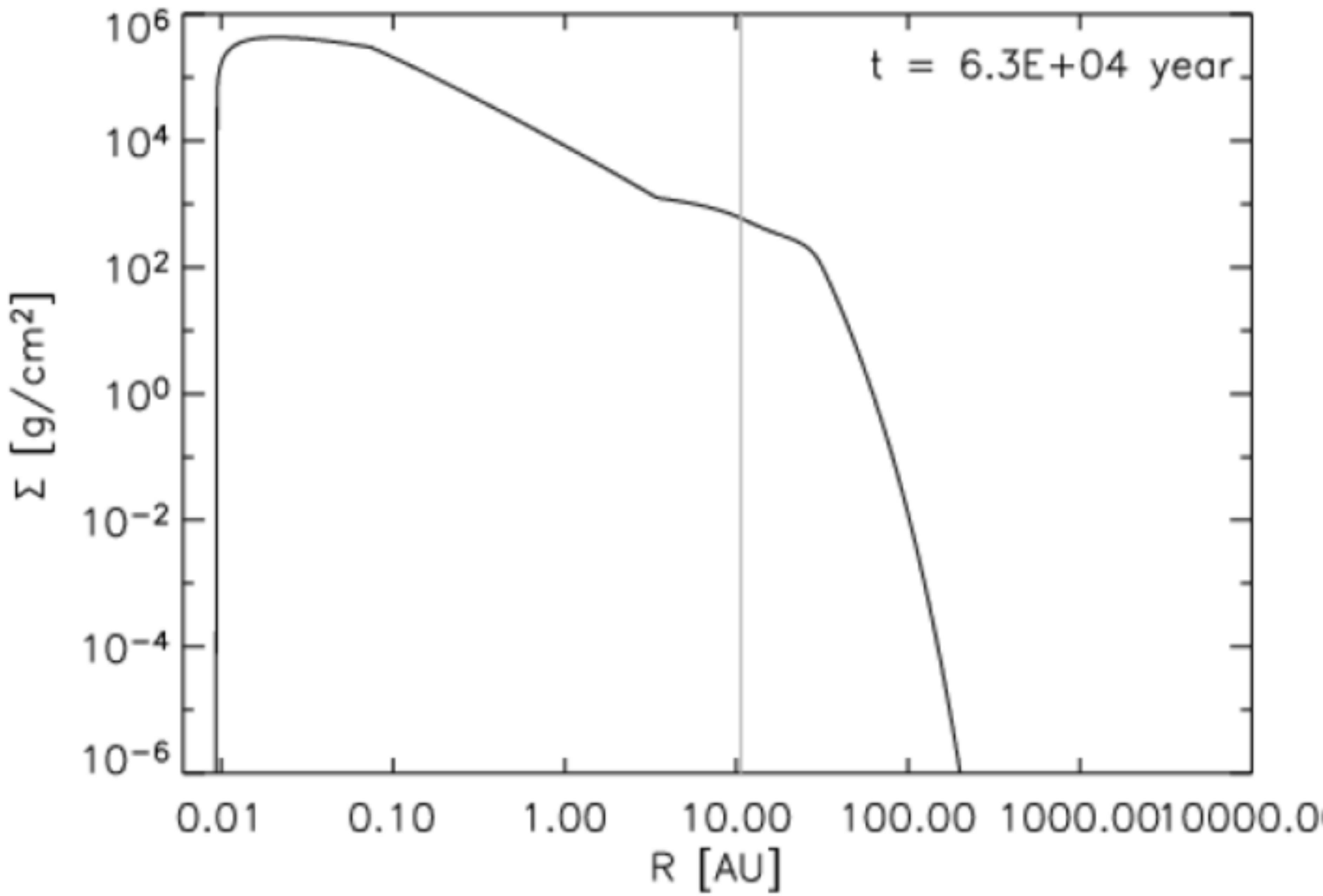


CD

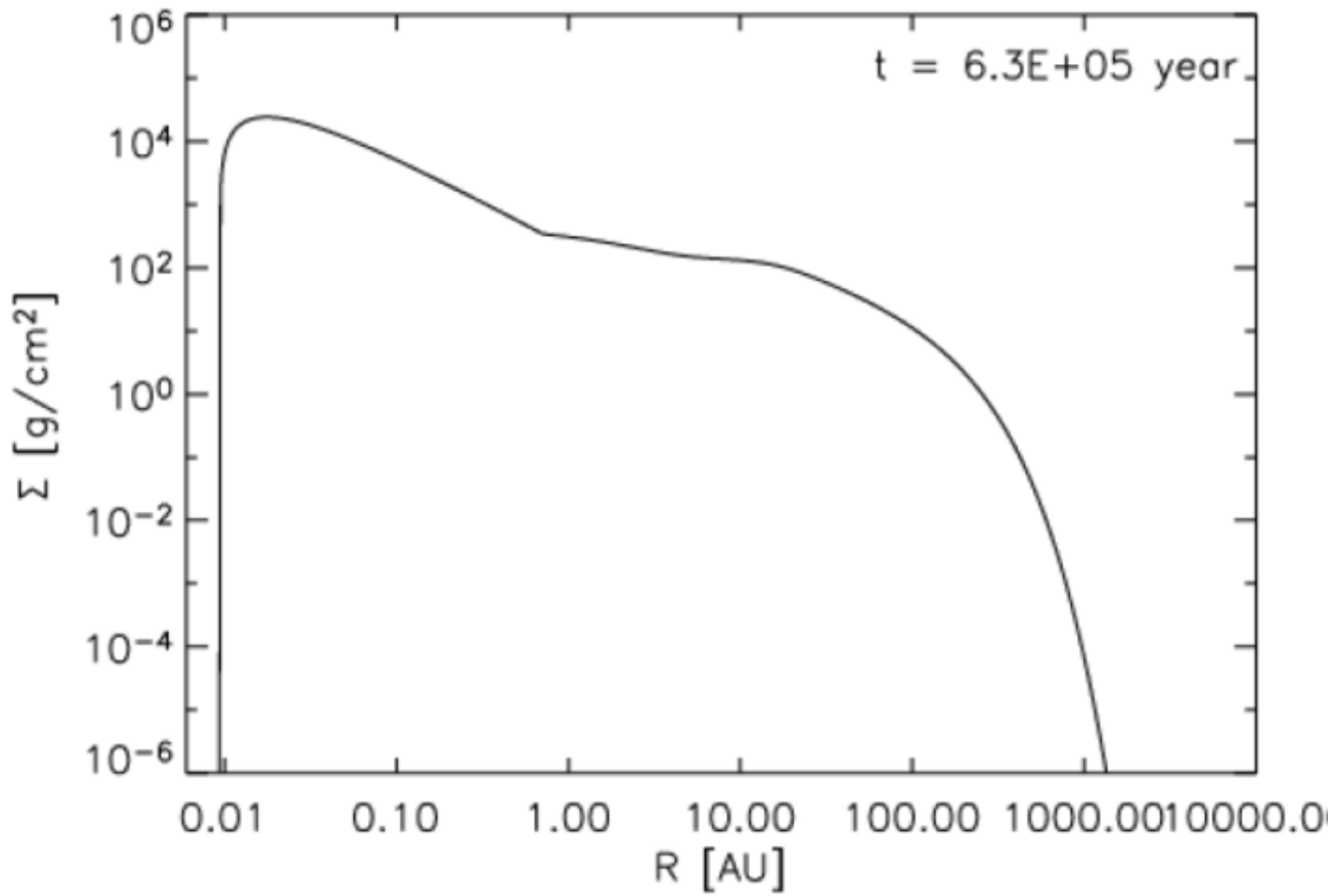
Formation & viscous spreading of disk



Formation & viscous spreading of disk

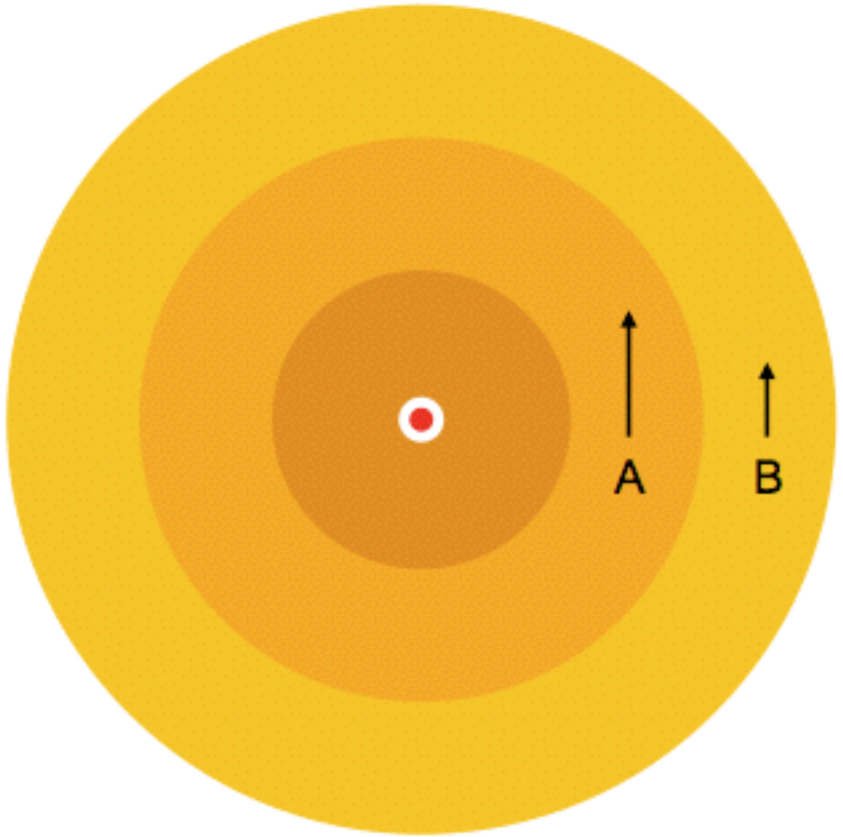


Formation & viscous spreading of disk



Kifelé irányuló perdület-transzfer

Ring A moves faster than ring B. Friction between the two will try to slow down A and speed up B. This means: angular momentum is transferred from A to B.



Specific angular momentum for a Keplerian disk:

$$l = r v_\phi = r^2 \Omega_K = \sqrt{G M_* r}$$

So if ring A looses angular momentum, but is forced to remain on a Kepler orbit, it must move inward! Ring B moves outward, unless it, too, has friction (with a ring C, which has friction with D, etc.).

Turbulens viszkozitás

Problem with turbulence as origin of viscosity in disks is: most stability analyses of disks show that the Keplerian rotation stabilizes the disk: *no turbulence!*

Debate has reopened recently:

- Non-linear instabilities
- Baroclynic instability? (Klahr et al.)

But most people believe that turbulence in disks can have only one origin: *Magneto-rotational instability (MRI)*

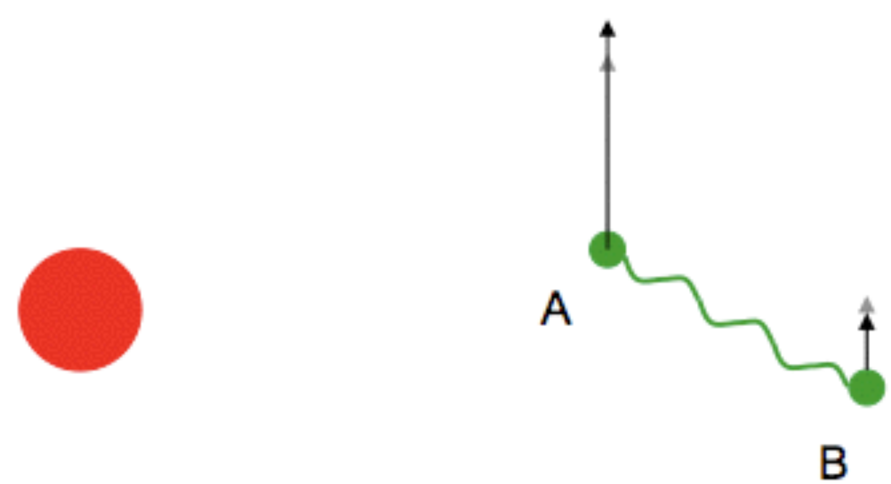
Magneto-rotational instability (MRI)

(Also often called Balbus-Hawley instability)

Highly simplified pictographic explanation:

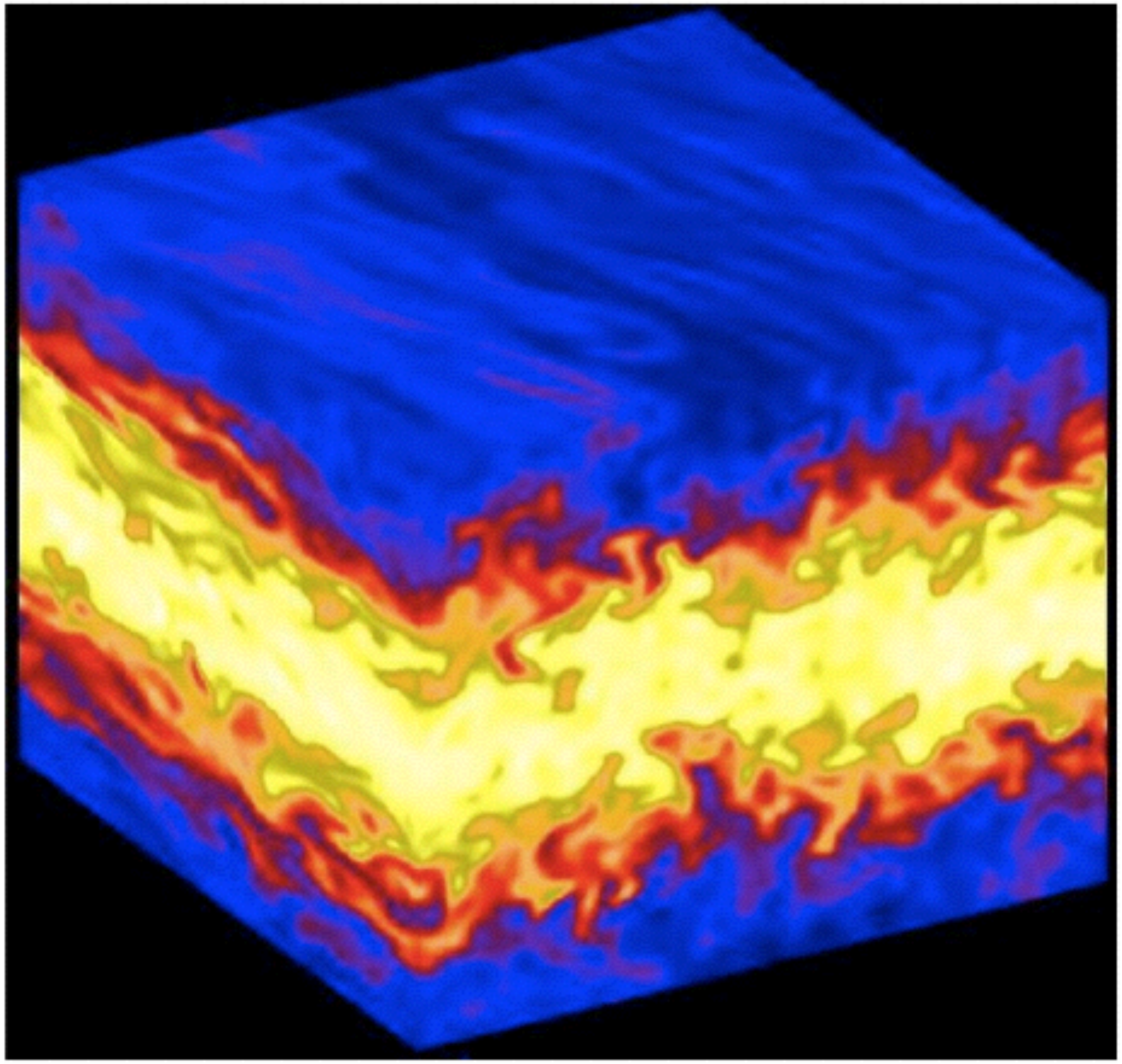
If a (weak) pull exists between two gas-parcels A and B on adjacent orbits, the effect is that A moves inward and B moves outward: a pull causes them to move apart!

The lower orbit of A causes an increase in its velocity, while B decelerates. This enhances their velocity difference! This is positive feedback: an instability.



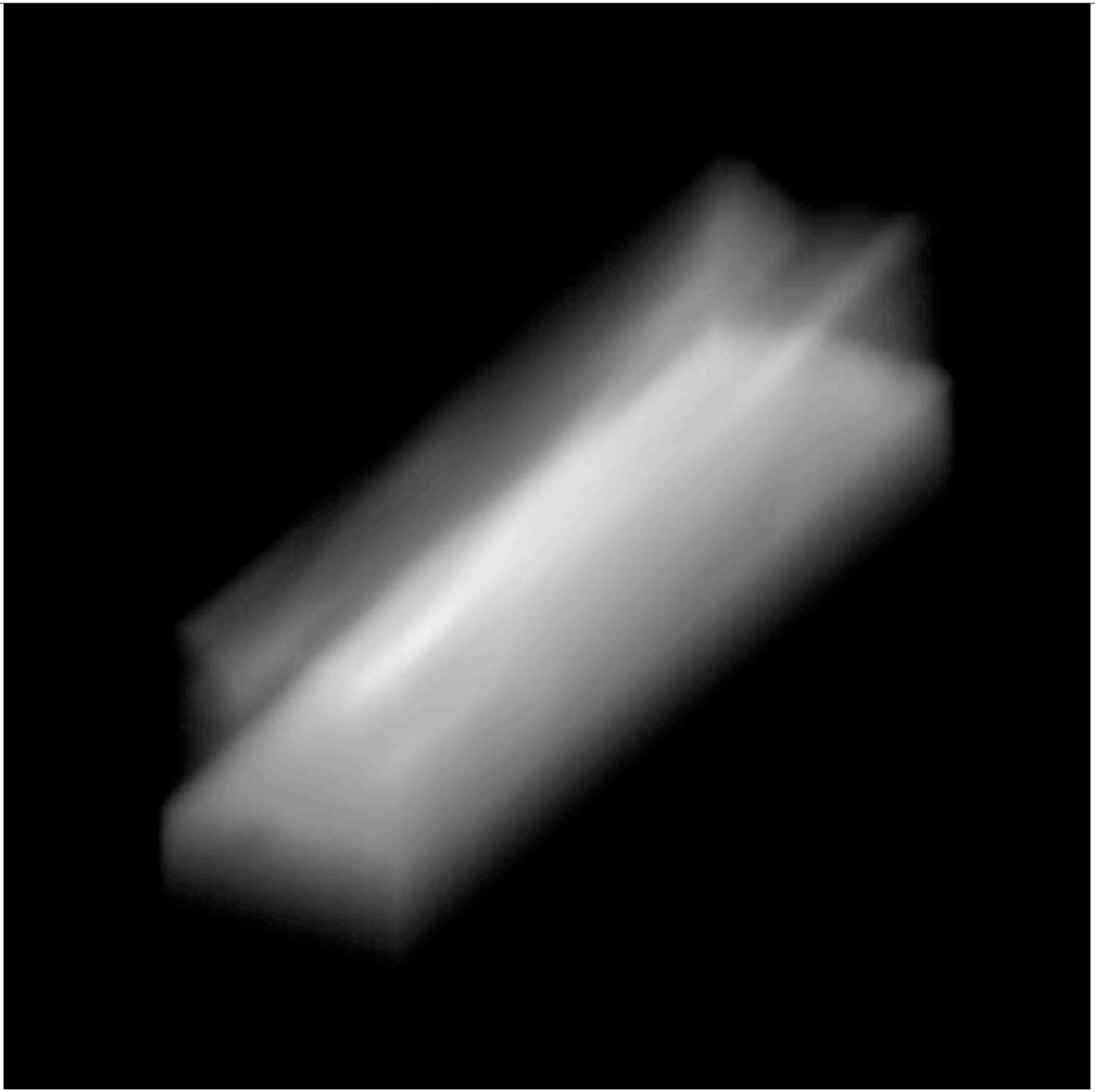
<u>Causes turbulence in the disk</u>

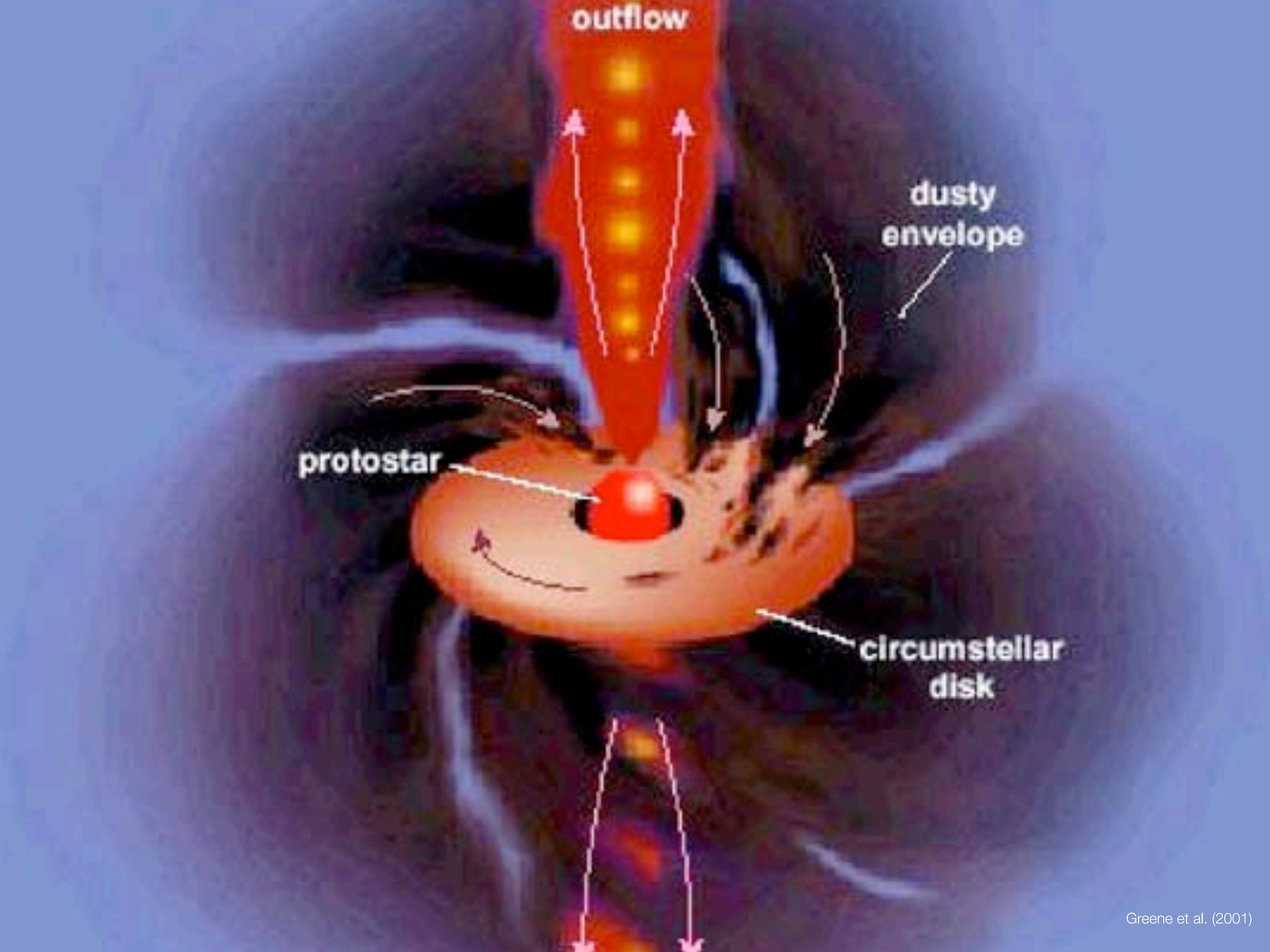
Magneto-rotational instability



Johansen & Klahr (2005); Brandenburg et al.

Magneto-rotational instability





Greene et al. (2001)