Csillagkeletkezés

A csillagközi anyagtól a Naprendszerig

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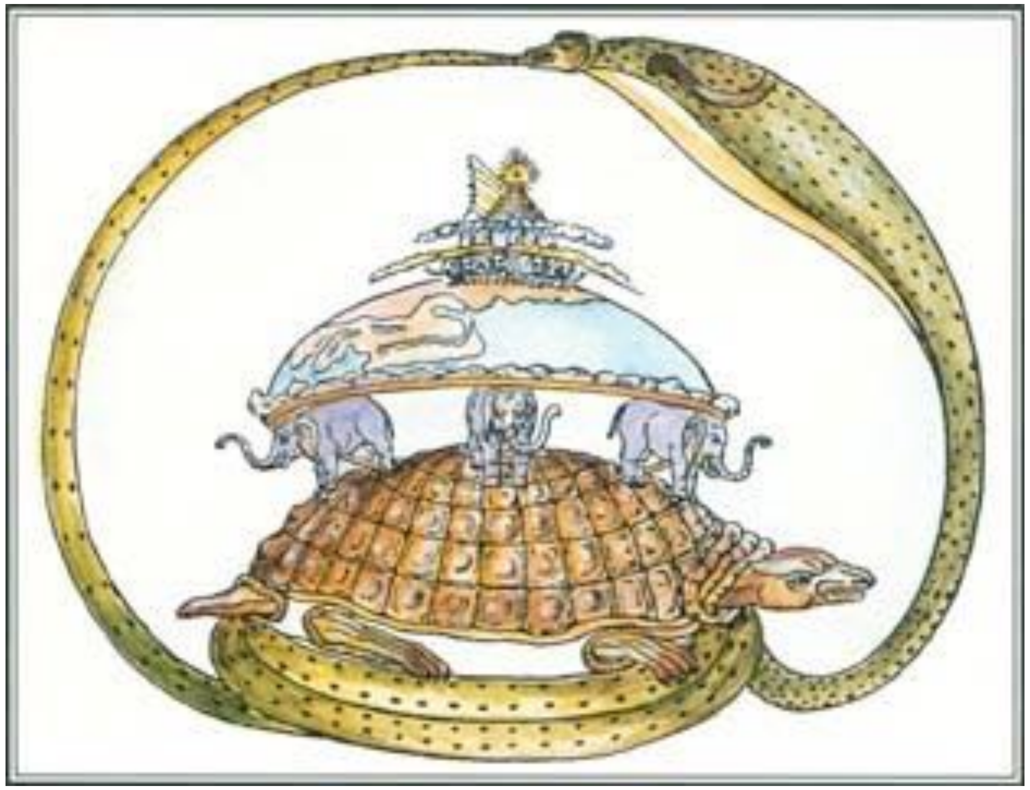
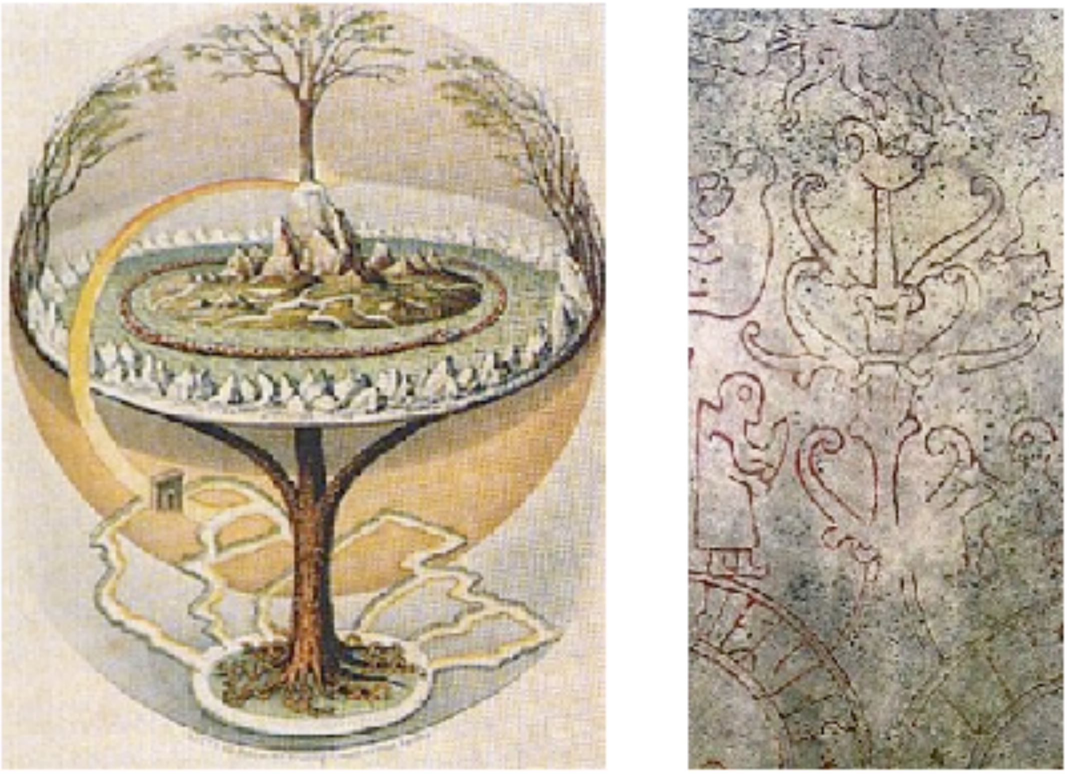
MTA Csillagászati és Földtudományi Kutatóközpont
Konkoly-Thege Miklós Csillagászati Intézet

2017 szeptember 20.

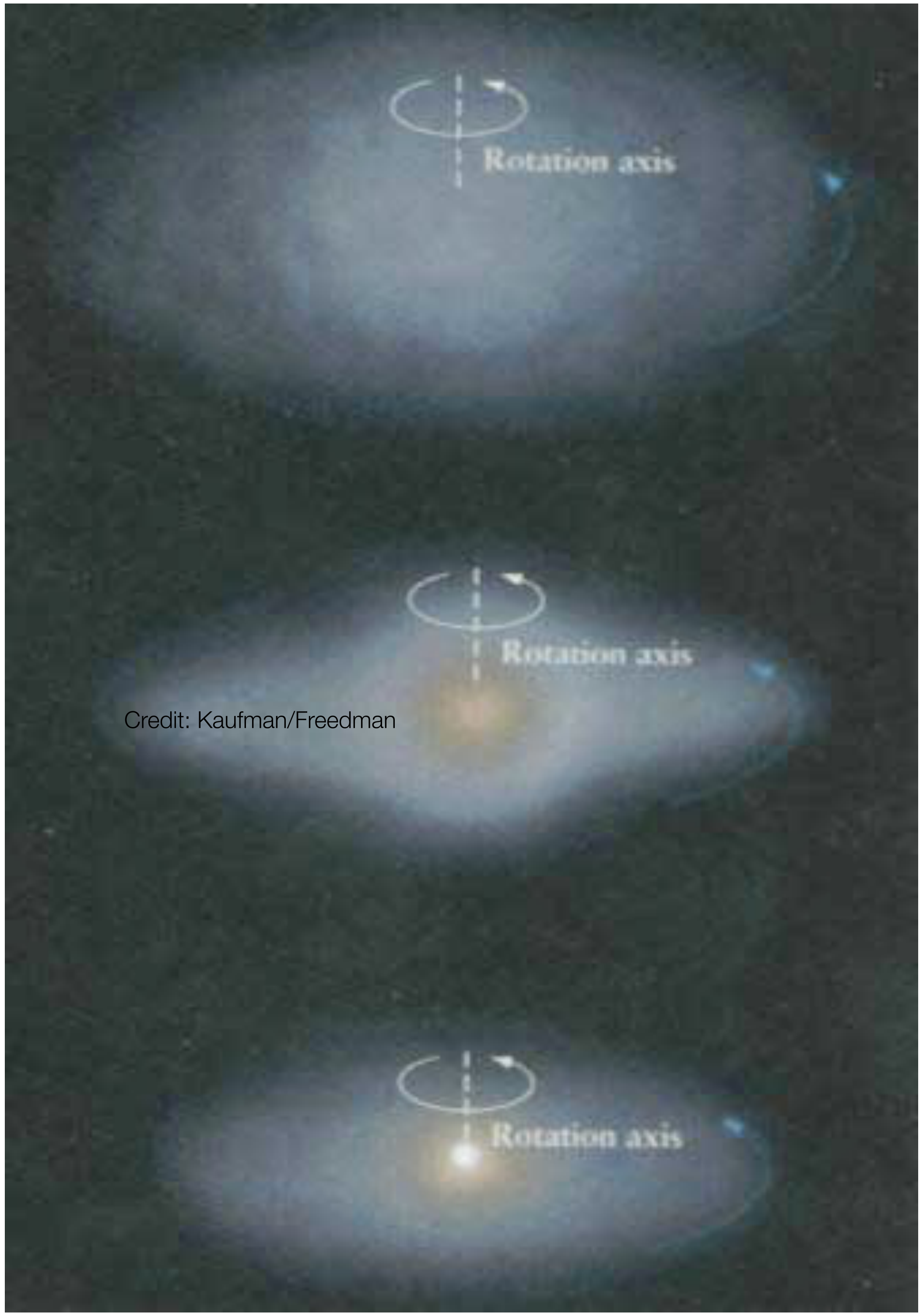
Minden civilizáció (egyik) alapkérdése…





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

Tudományos megközelítés: XVII-XVIII. sz.



Credit: Kaufman/Freedman

Az állatövi fény jelenségének helyes értelmezése (Cassini, 1683)

DÉCOUVERTE
DE LA LUMIERE
CELESTE
QUI PAROIST
DANS LE ZODIAQUE.
PAR MONSIEUR CASSINI
de l'Academie Royale des Sciences.

A PARIS,
DE L'IMPRIMERIE ROYALE,
Par SEBASTIEN MABRE-CRAMOISY, Imprimeur de Sa Majeſté
& Directeur de ſon Imprimerie Royale.

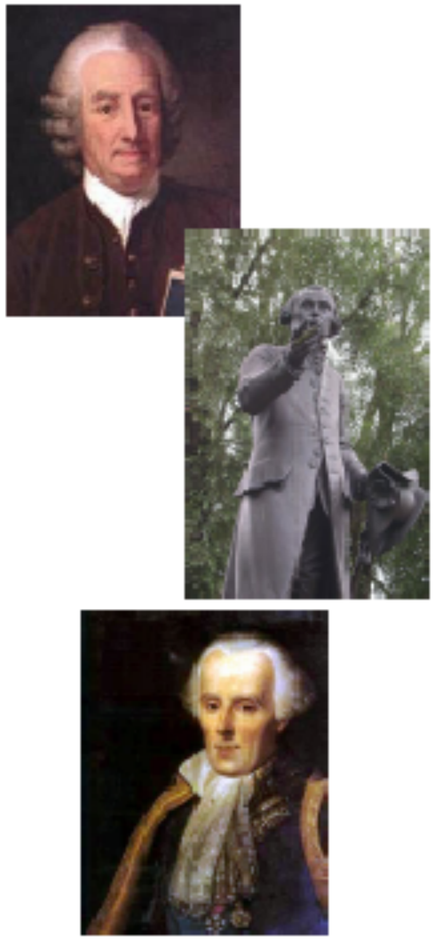
M. DC. LXXXV.

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

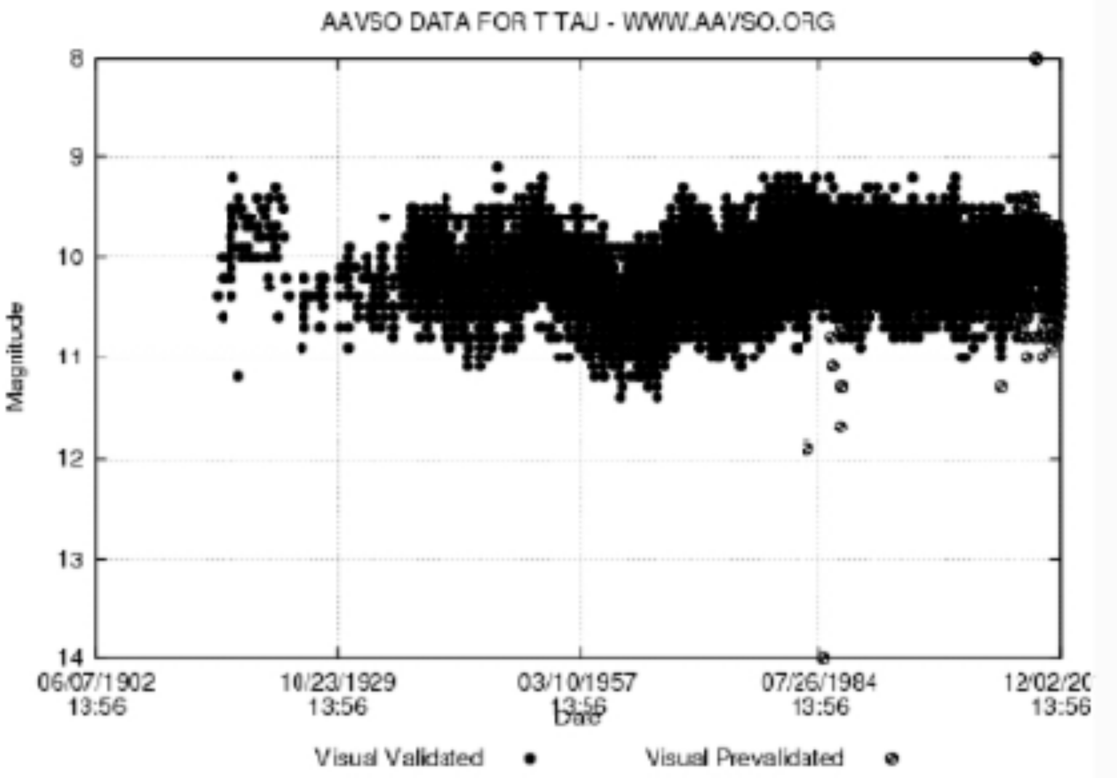
⇒ *First full explanation of the formation of the Sun & Planets*

The solution: ***Disc solves the angular momentum problem!***

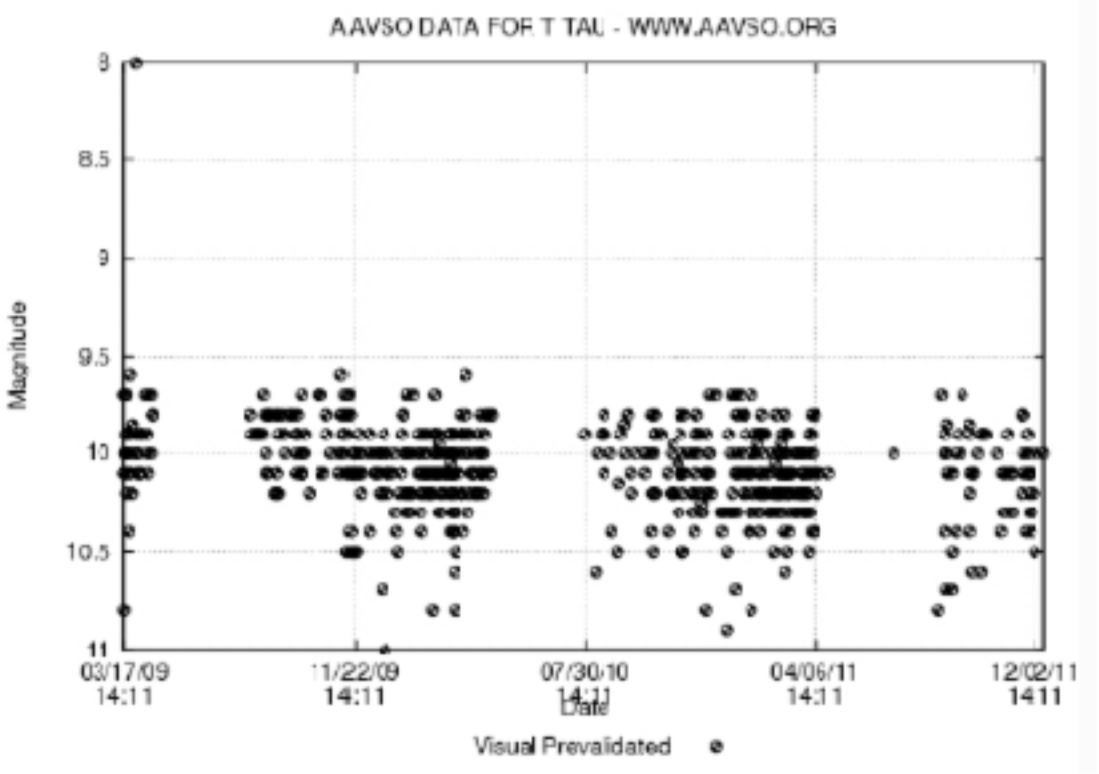
1974: ***Lynden-Bell & Pringle:*** Calculation of full disc model

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

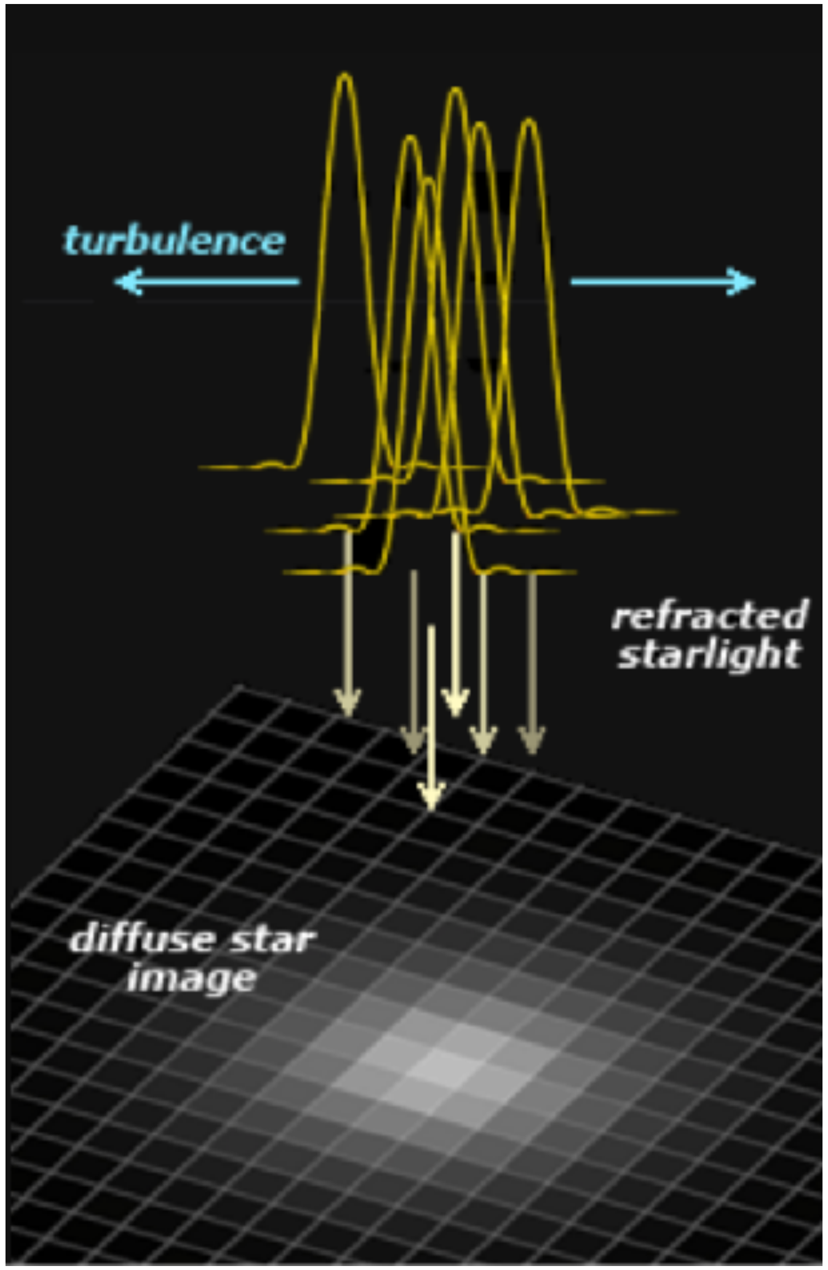
Közvetett bizonyítékok a csillagkörüli korongok létezésére: a perdület megmaradása, infravörös többletsugárzás, “fényelnyelés érv”, a Naprendszer szerkezete stb.

A “nebula” (csillagkörüli korong) megfigyelhetősége

- A hideg hidrogéngázt (H_2) nehéz megfigyelni
- A “nebula” a gáz mellett port (nehezebb elemeket) is tartalmaz:
  - porszemcséken szóródó fény
  - porszemcsék hősugárzása
- Szögmásodpercnél jobb térbeli felbontás (<seeing)
- Infravörös technológia
- Milliméteres molekulavonalak (CO)

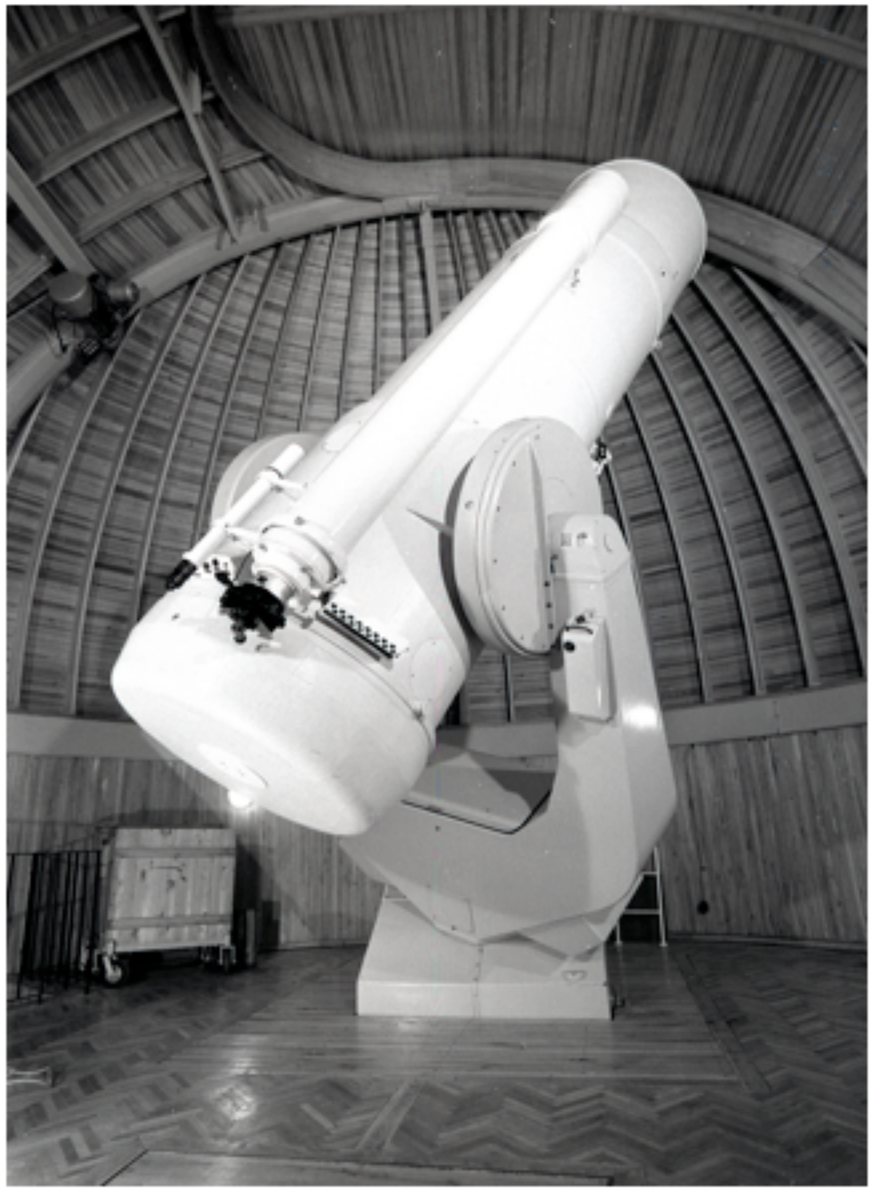
Taurus csillag-keletkezési terület (450 fényév)

1 CSE (Föld)	0.007”
5 CSE (Jupiter)	0.035”
50 CSE (Plutó)	0.35”
100 CSE (korong)	0.7”
1000 CSE	7”



Forrás: handprint.com

Egy kis történelem: hazai előzmények

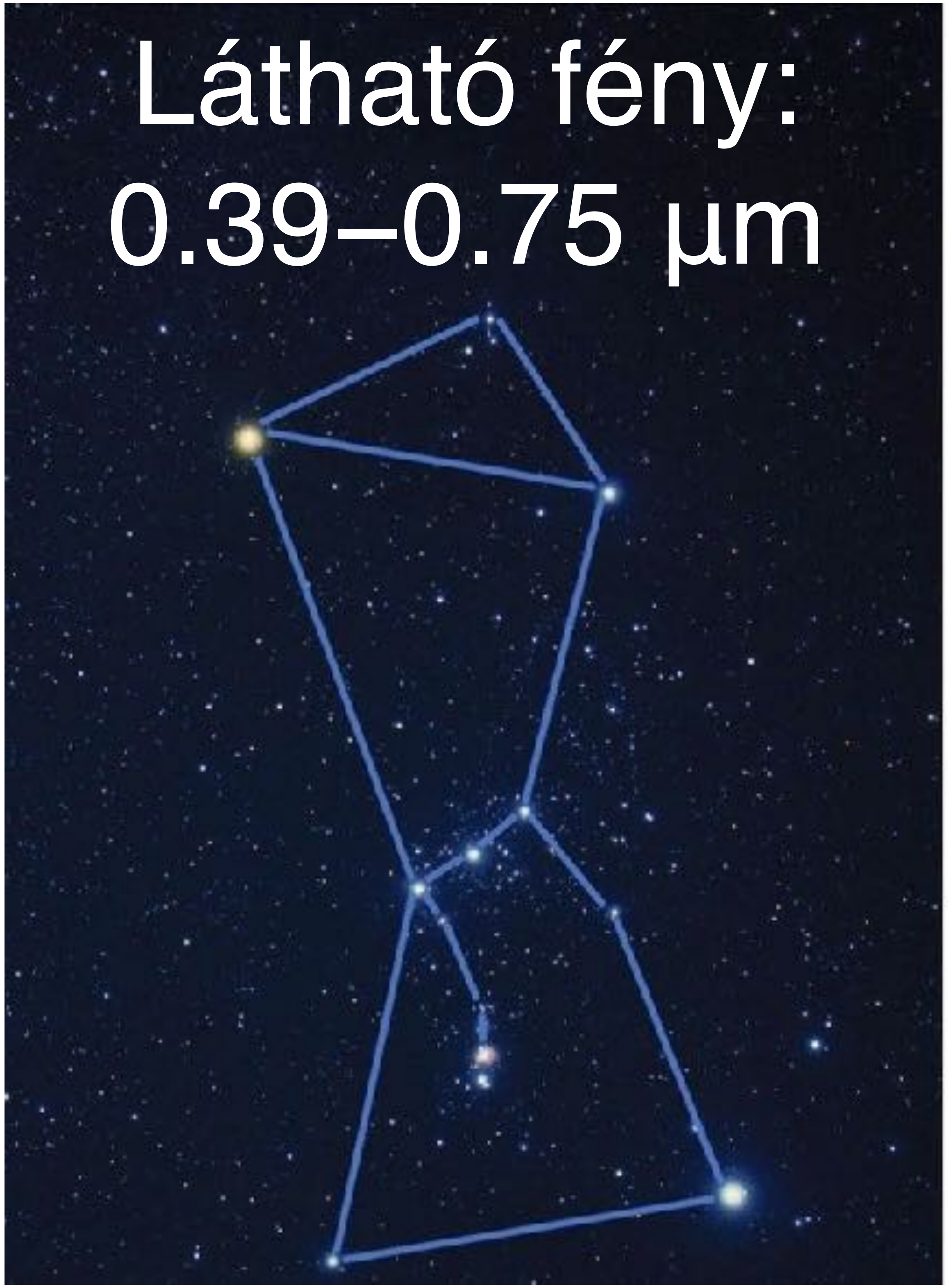


1962. Schmidt teleszkóp: üstökösök, fiatal csillagok, csillagközi por

Egy kis történelem...

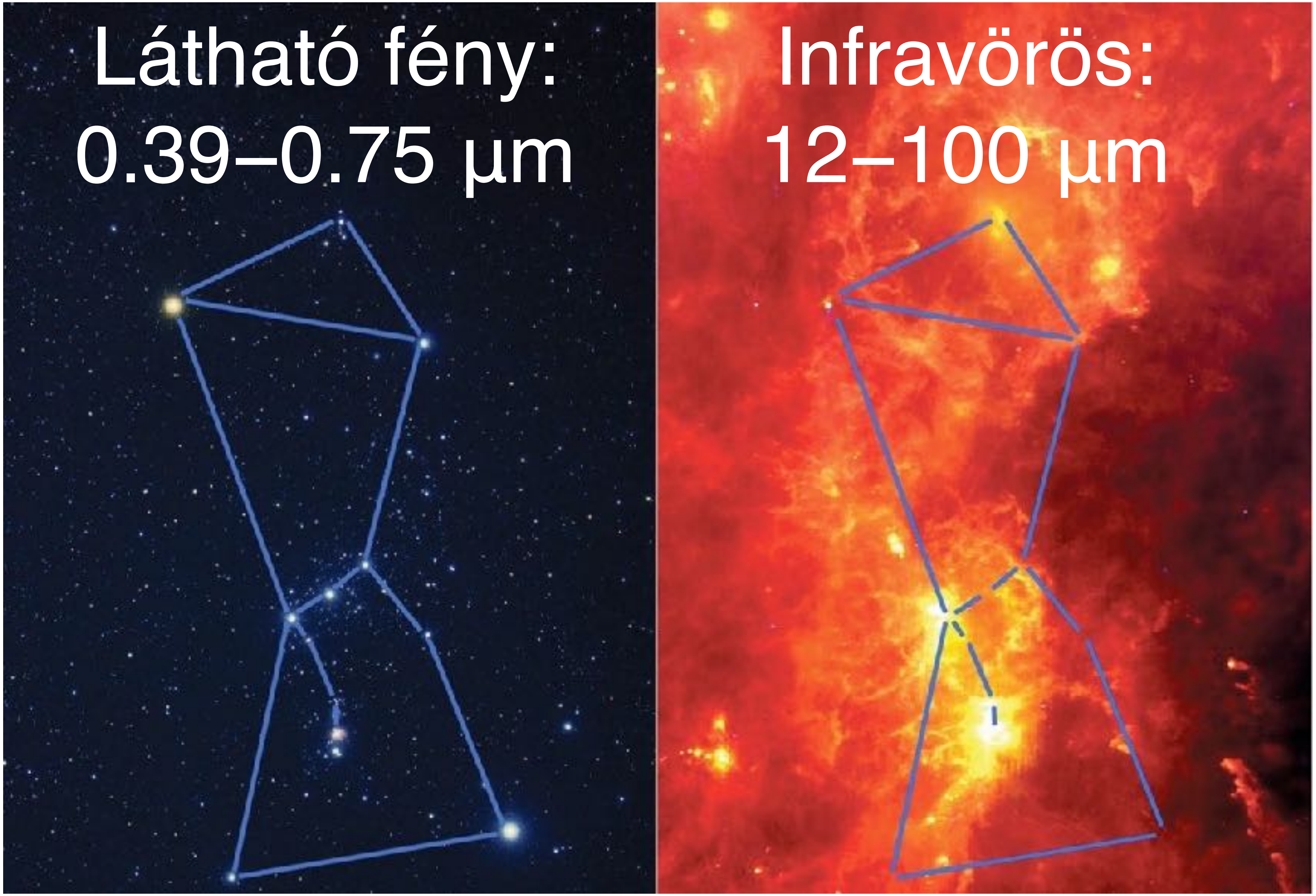
IRAS 1983

Az univerzum infravörösben



Látható fény:
0.39–0.75 µm

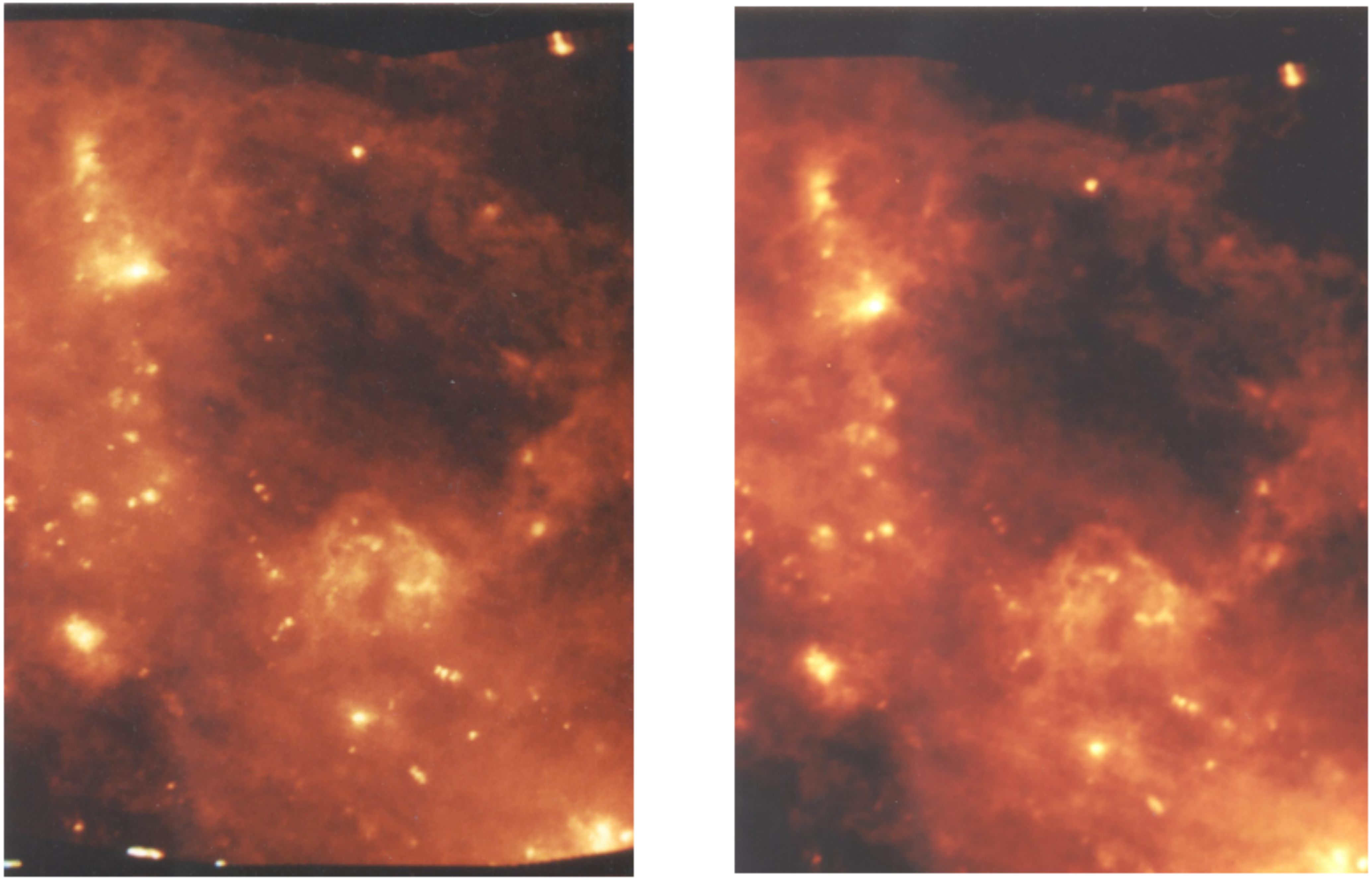
Az univerzum infravörösben



Látható fény:
0.39–0.75 μm

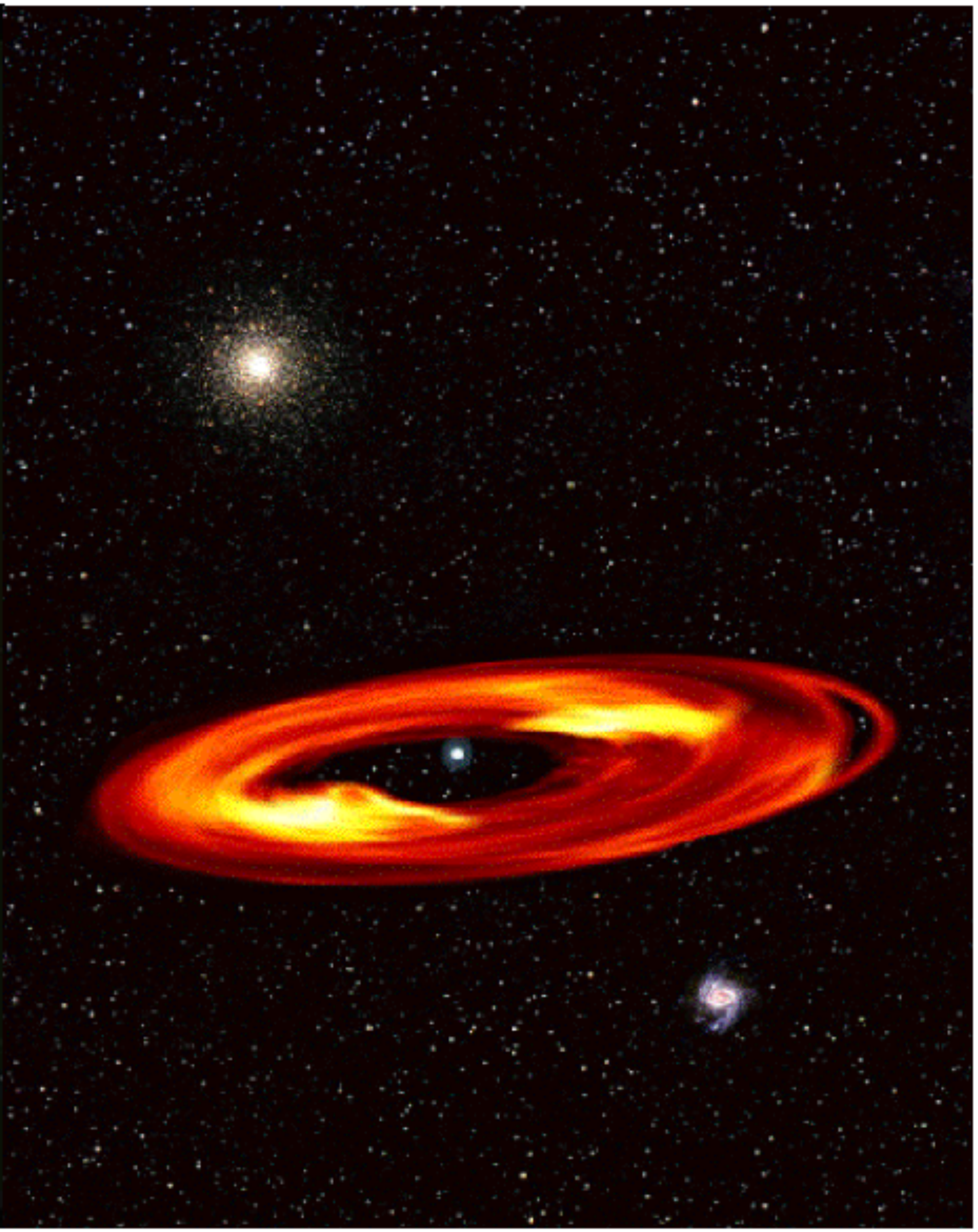
Infravörös:
12–100 μm

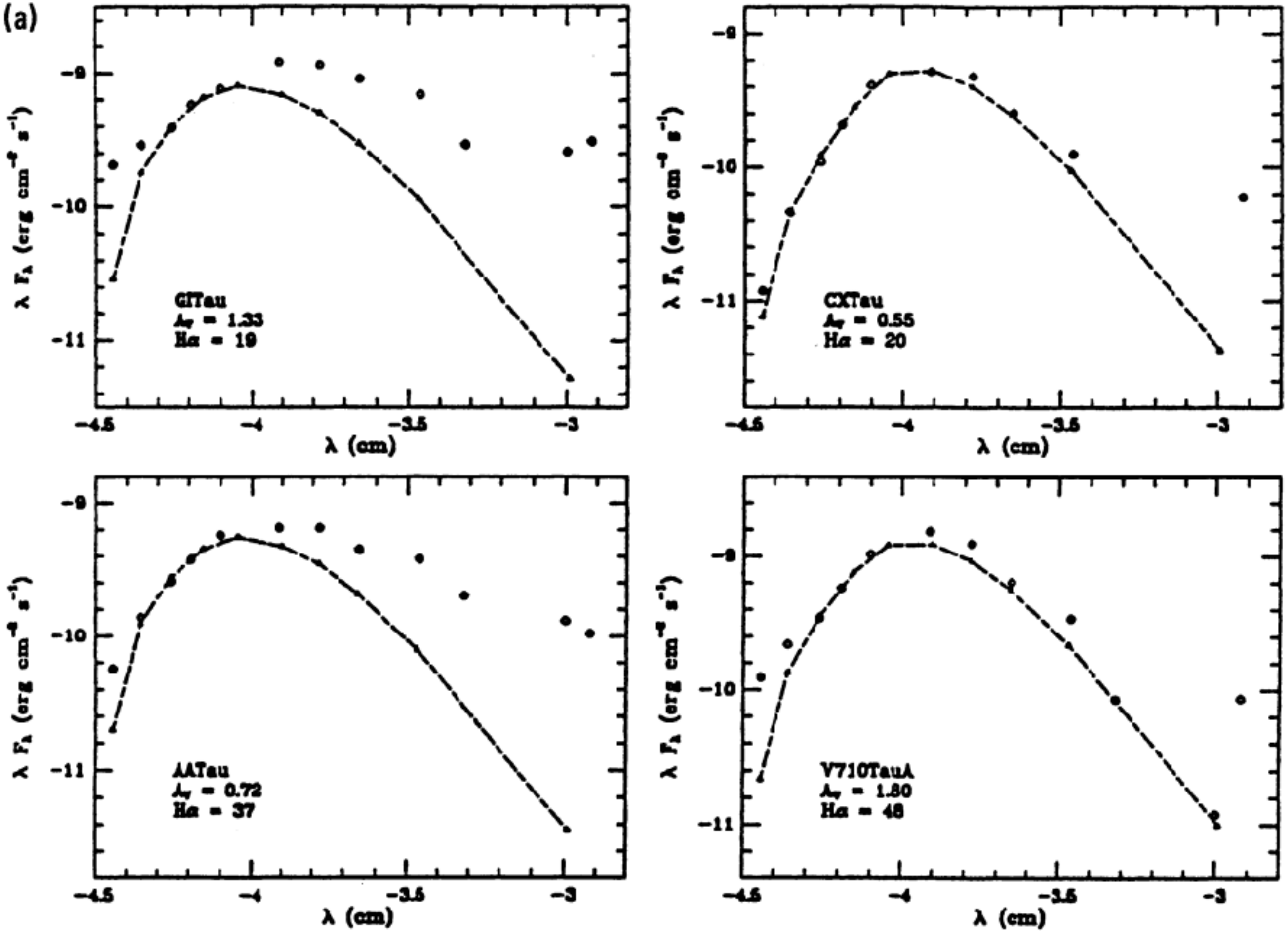
Cepheus Buborék



Kun, M., Balázs, L.G. & Tóth, I. 1987

Egy kis történelem...

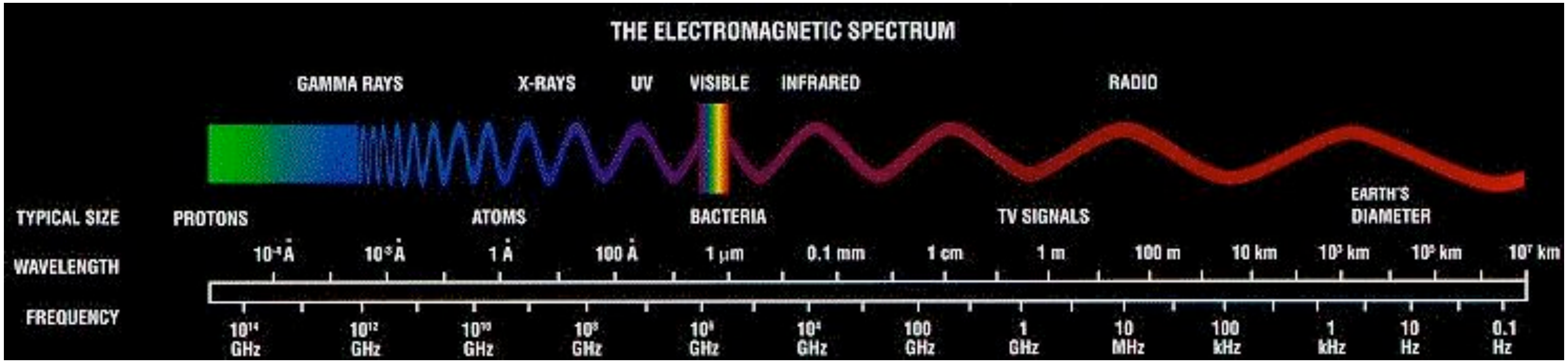


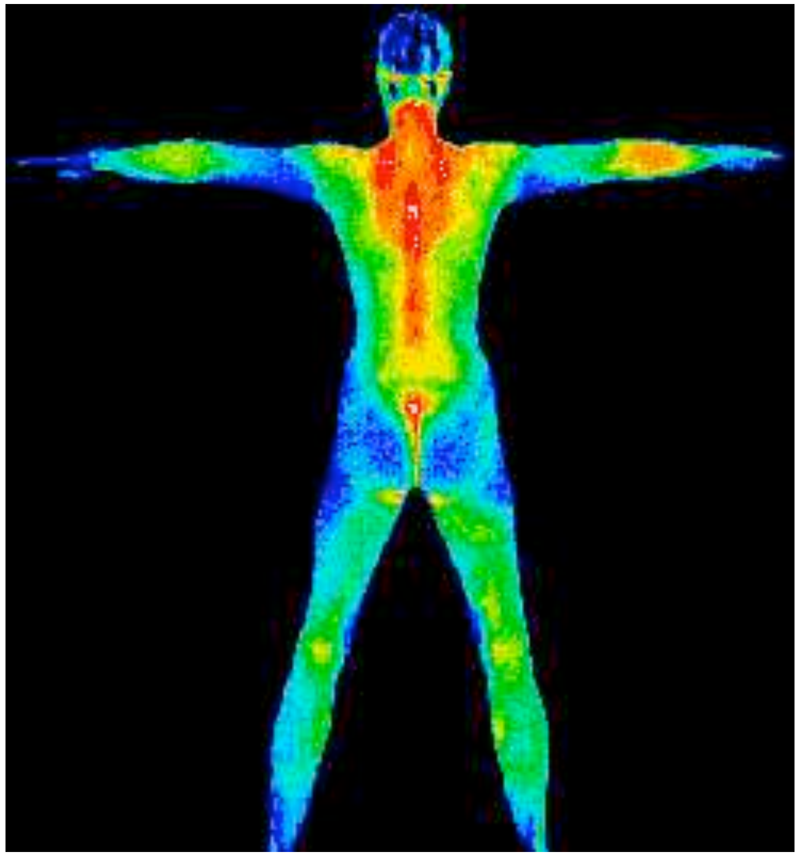


Strom et al. 1989

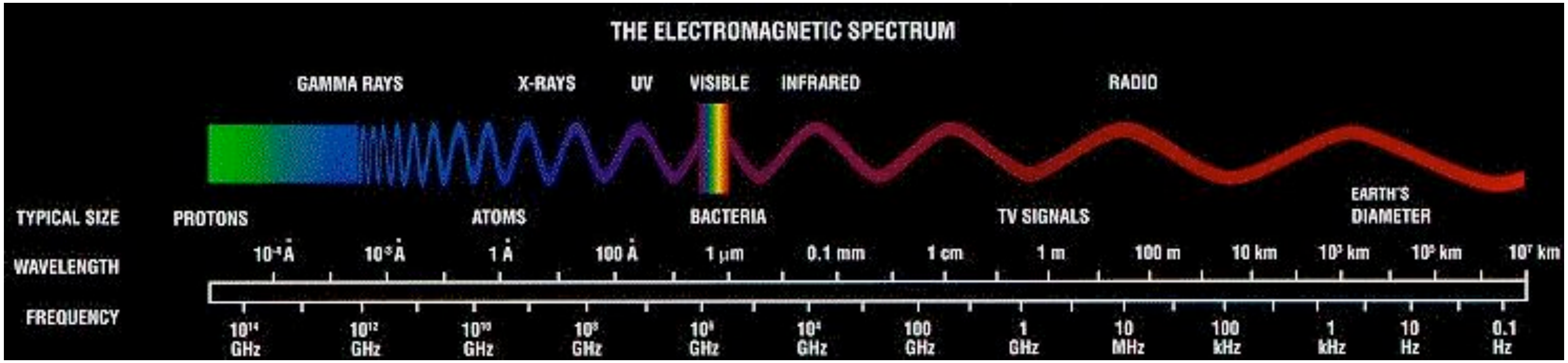
Sir William Herschel (1800)

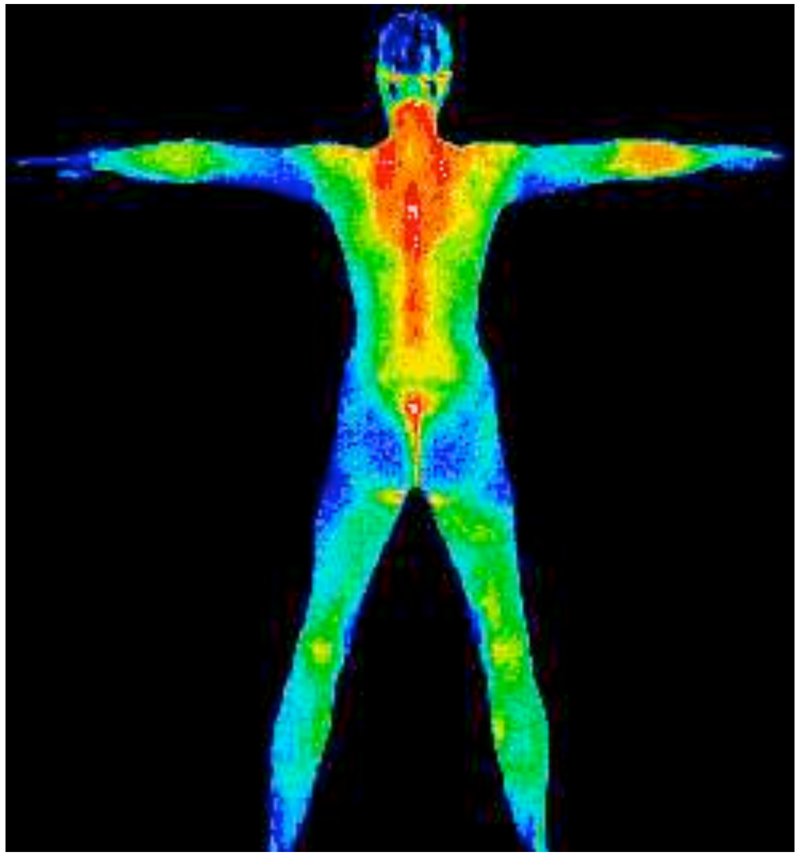
A világ infravörösben...

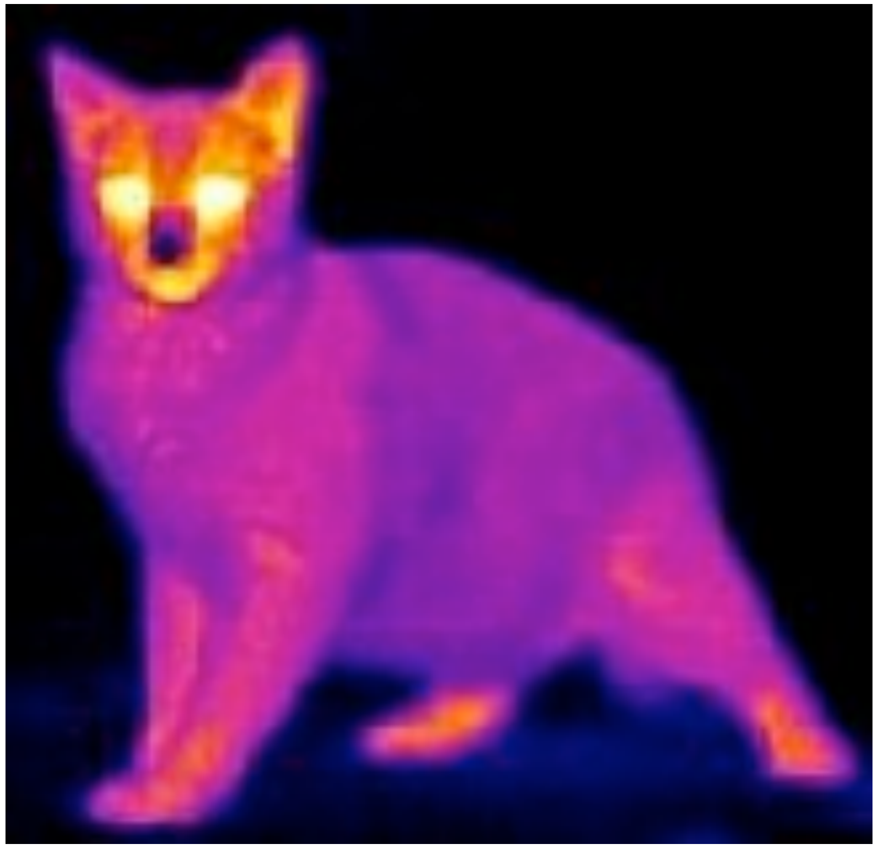




A világ infravörösben...







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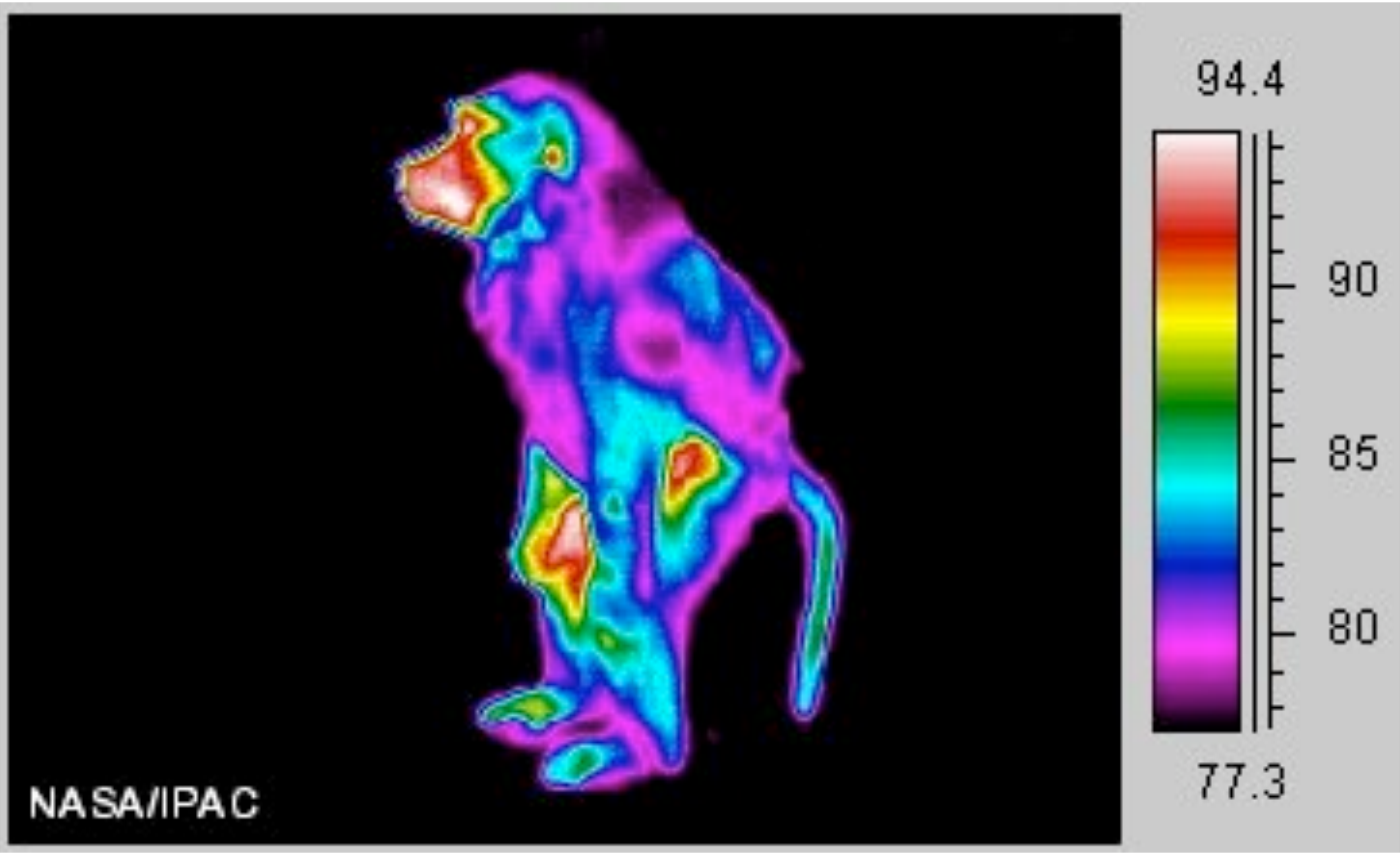
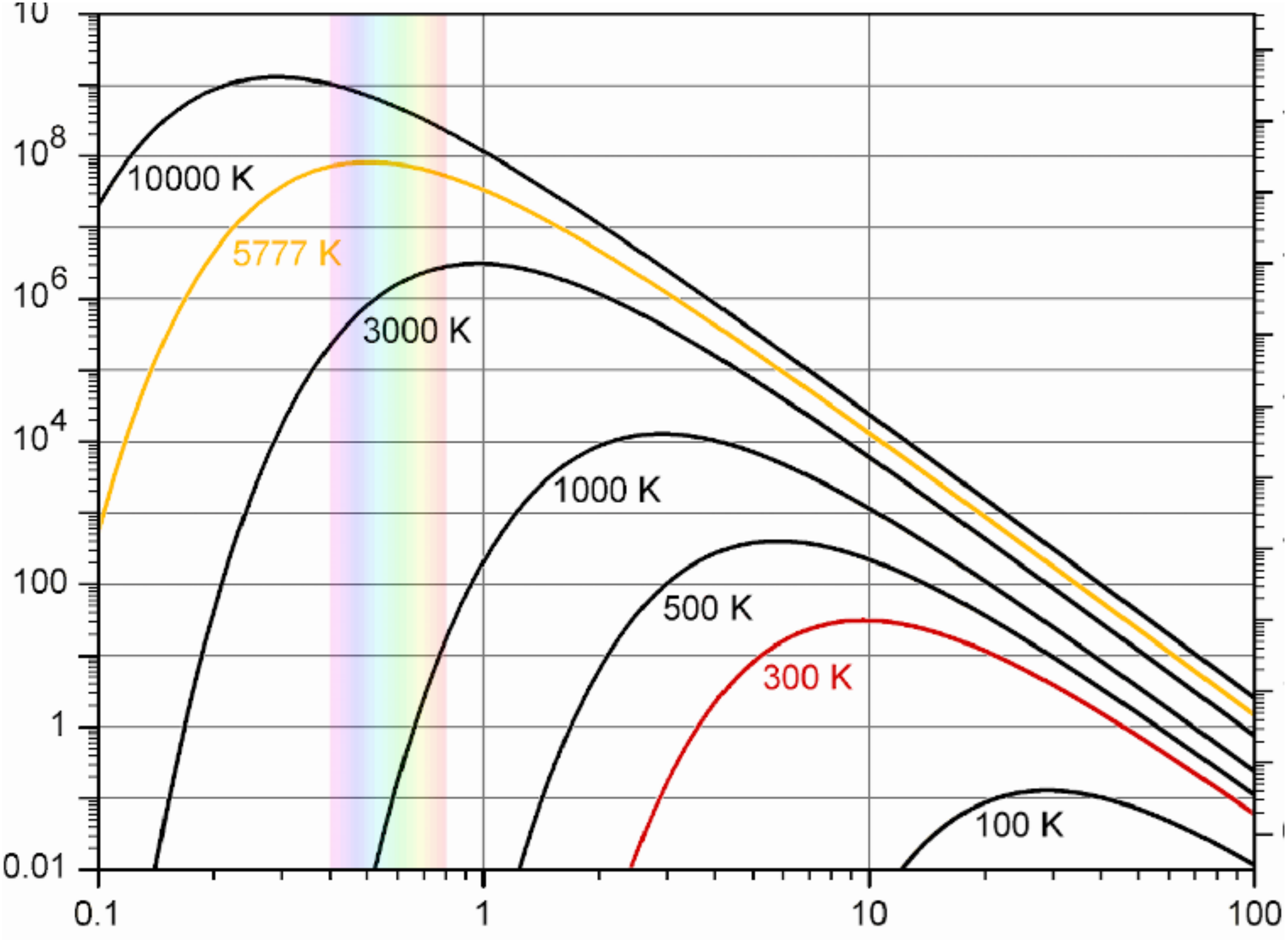


A világ infravörösben...

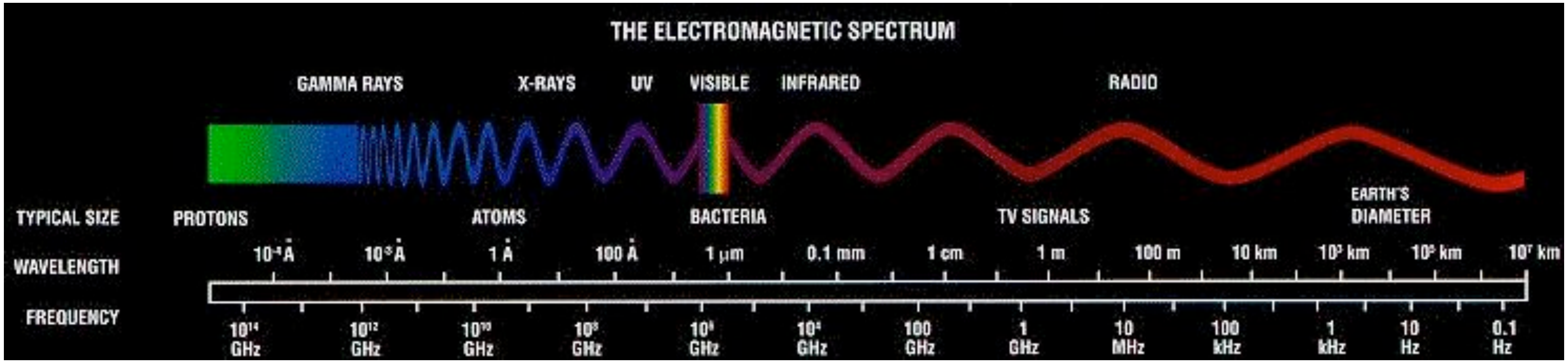
Hősugárzás - infravörös csillagászat

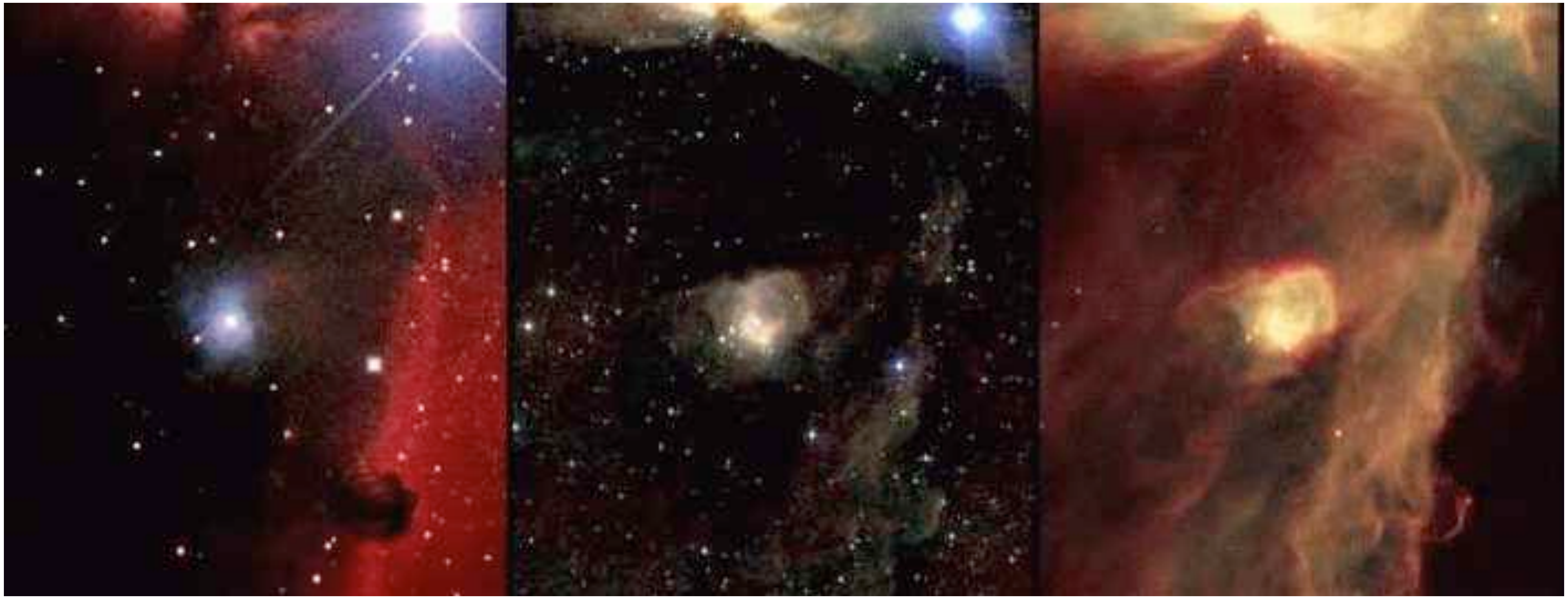


Hullámhossz (mikrométer)

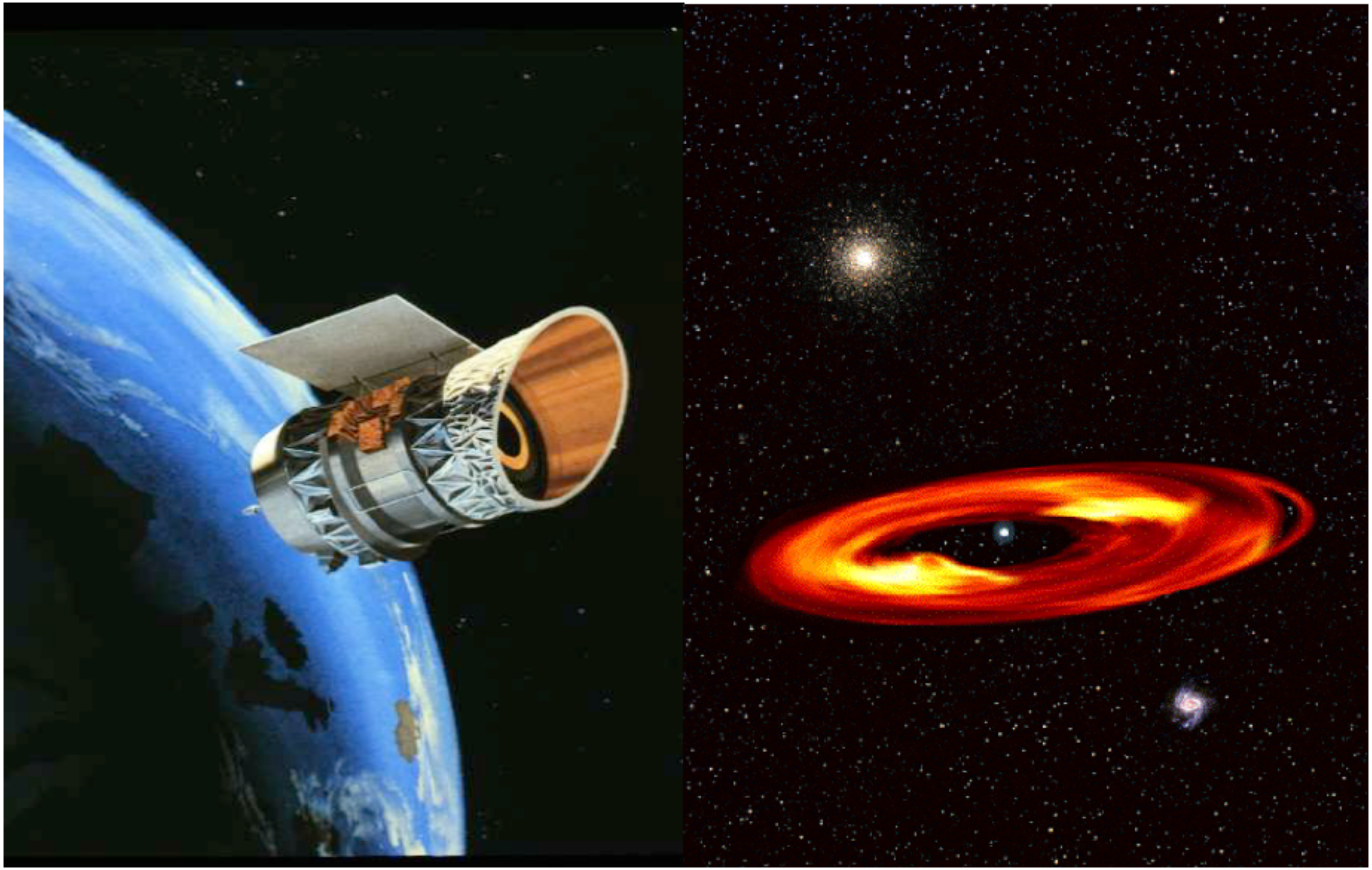
Forrás: Wikimedia Commons

A világ infravörösben...

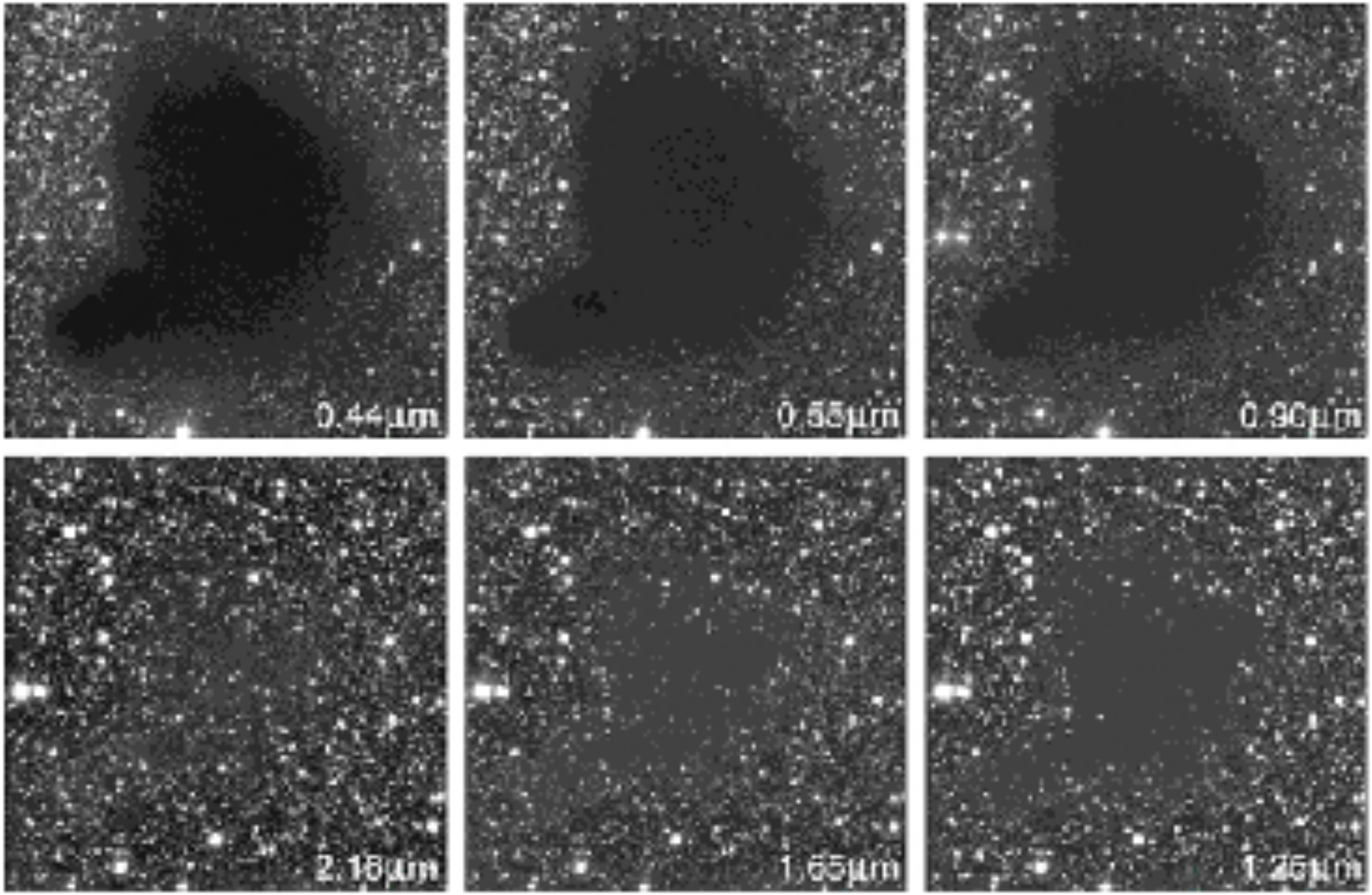


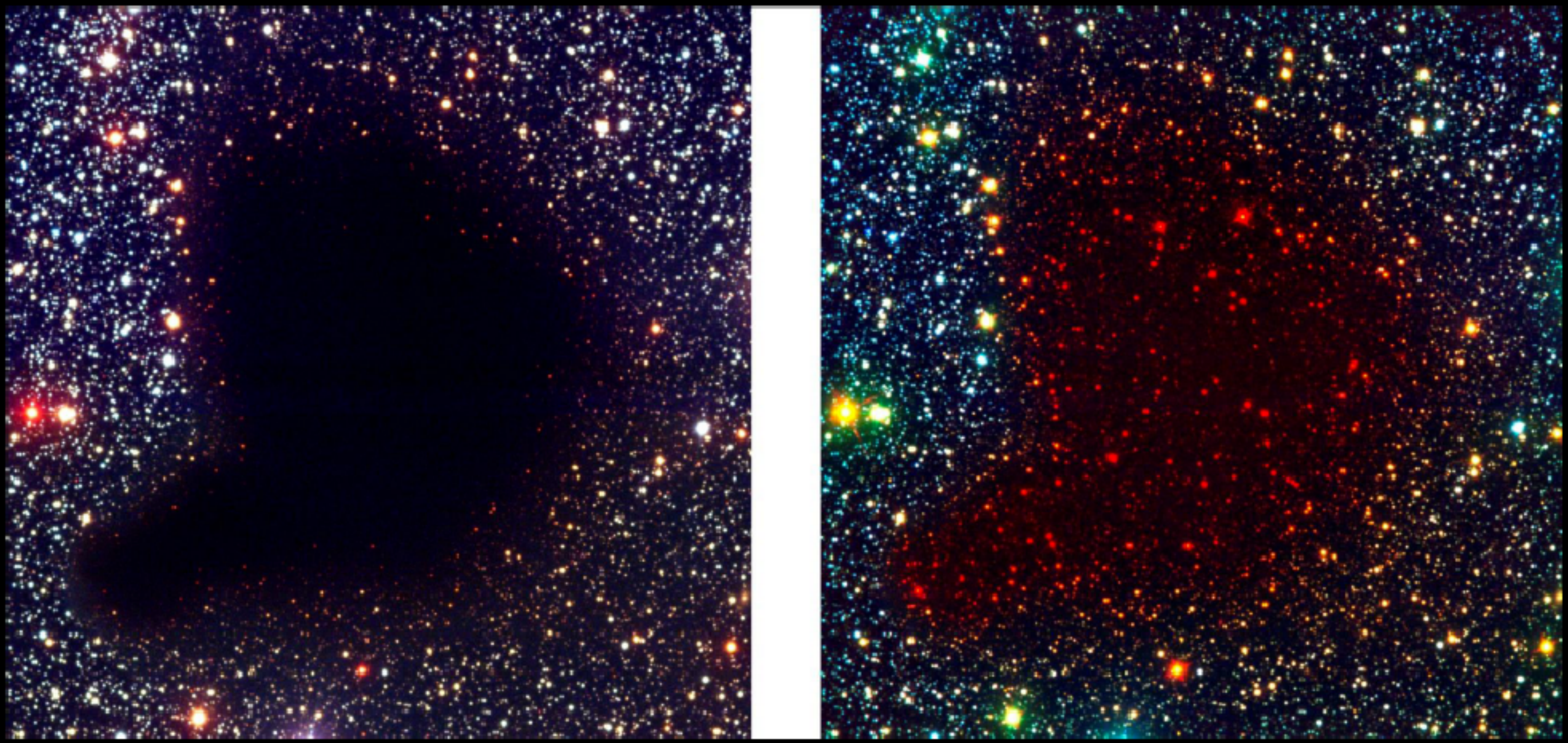


Egy kis történelem...



A Barnard 68 sötét globula





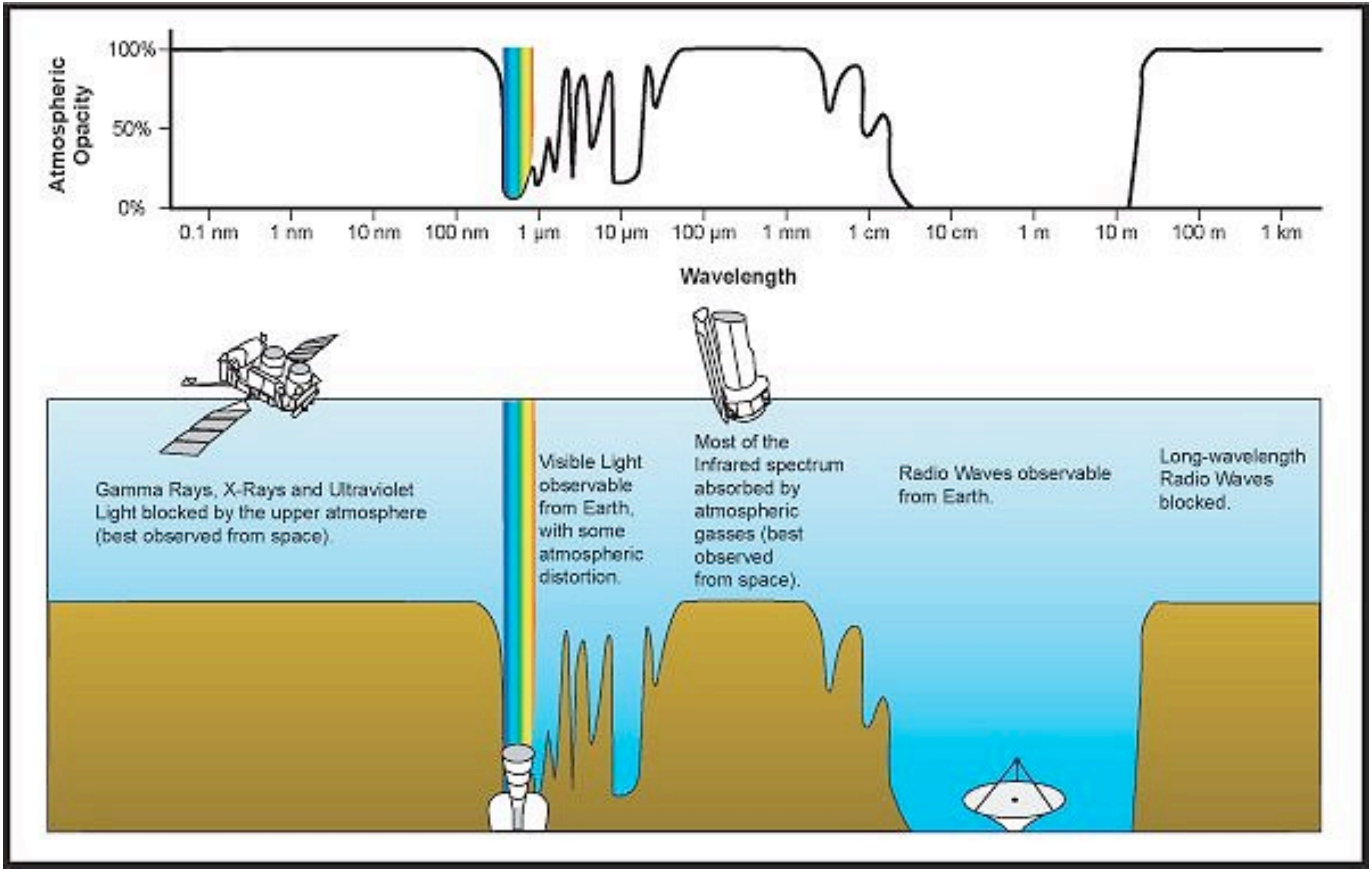
Optical

Infrared

Extinction map agrees with submm emission map

Alves et al. 2001

Légköri áteresztés



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

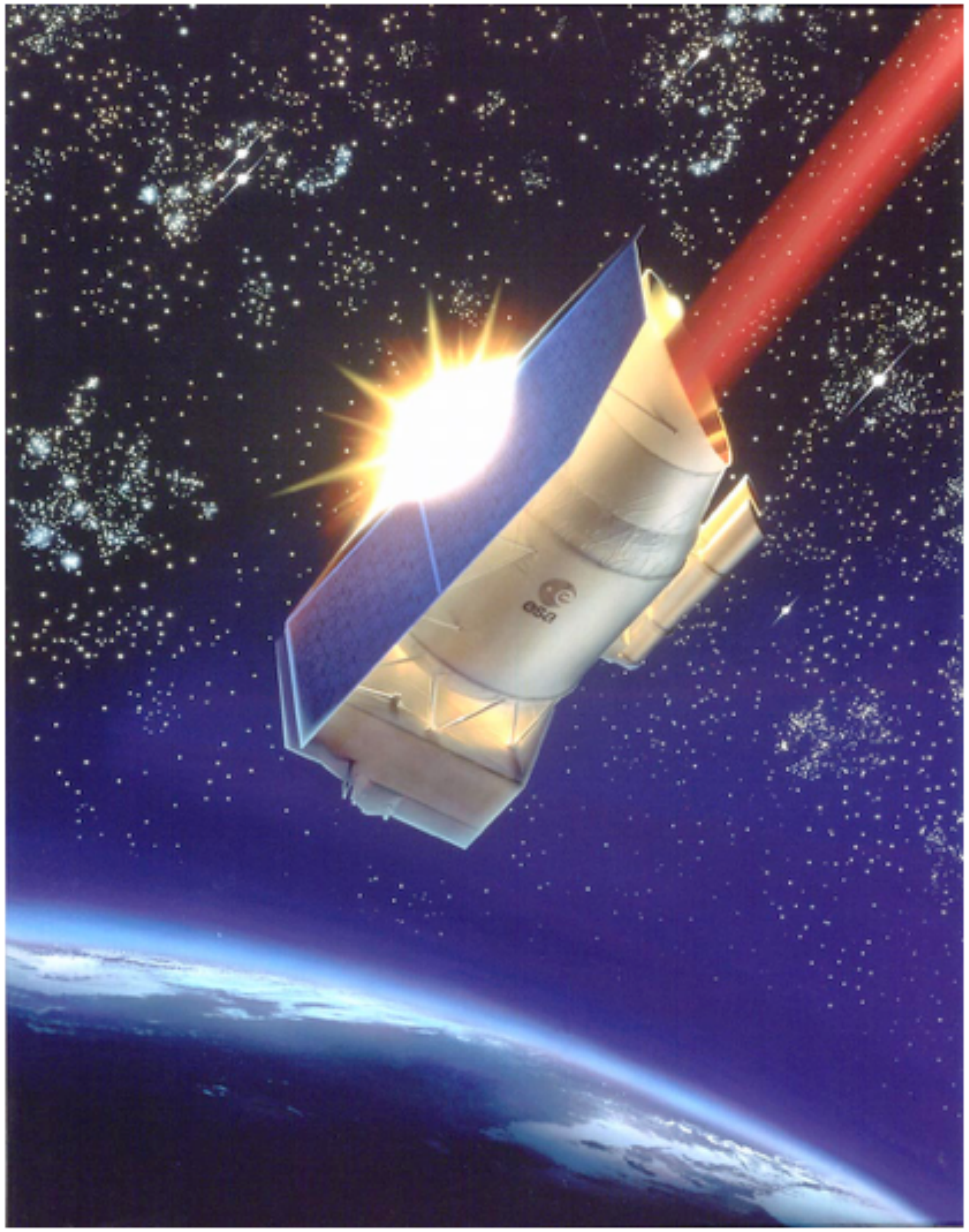
Long-wavelength Radio Waves blocked.

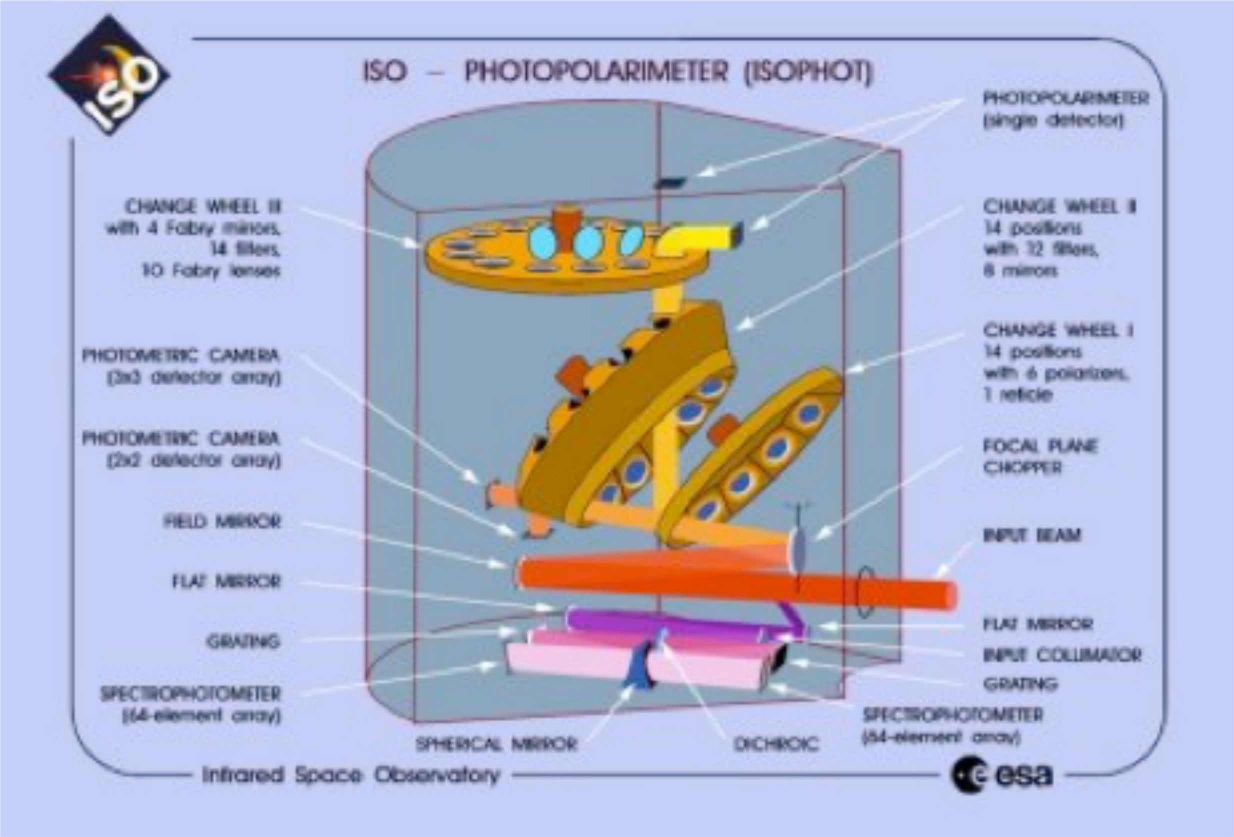
Az infravörös műszerek

Mauna Kea (4200 m)

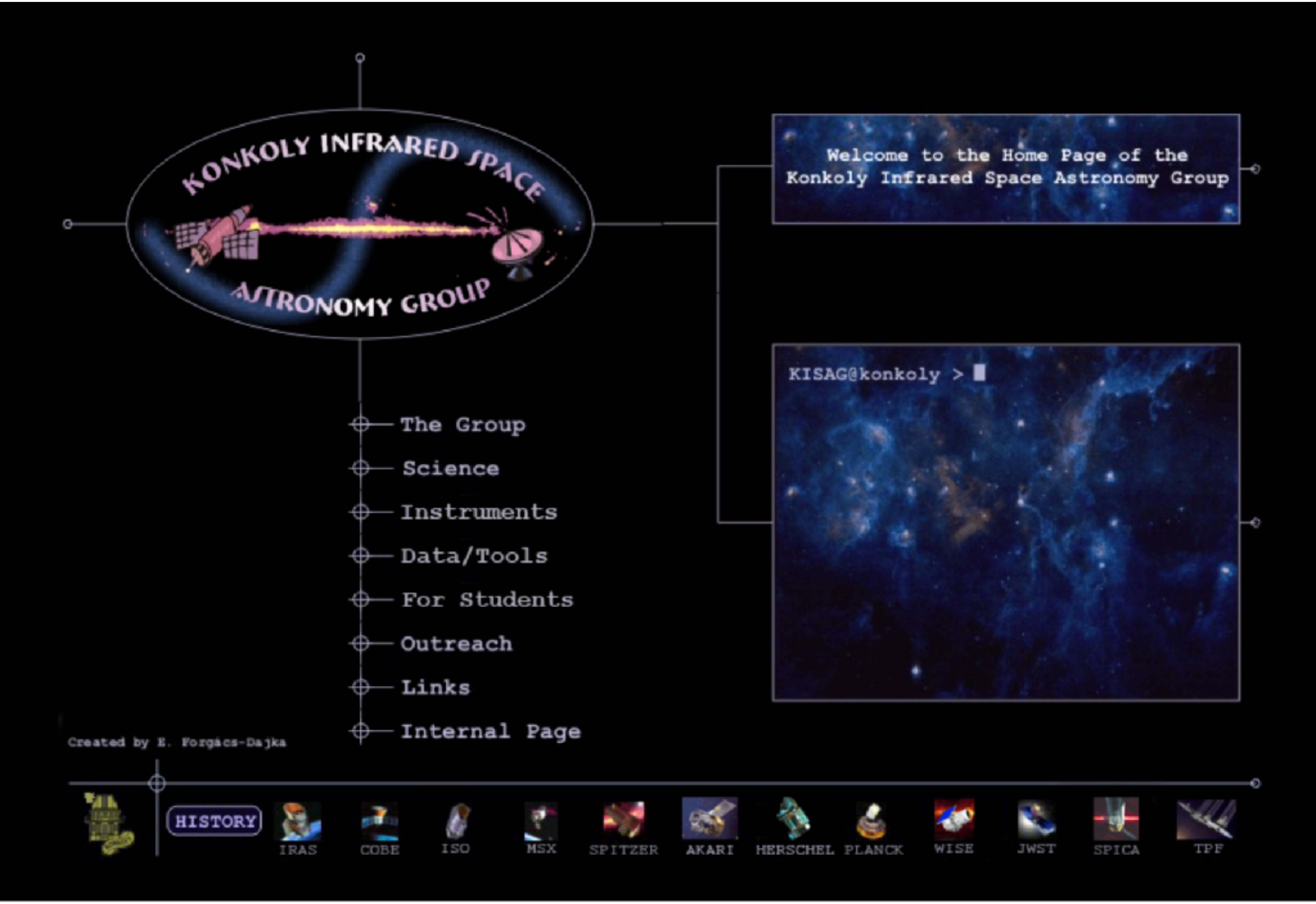
Infrared Space Observatory

Infrared Space Observatory





ISO/ISOPHOT
1995-98



Welcome to the Home Page of the Konkoly Infrared Space Astronomy Group

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KISAG@konkoly > █
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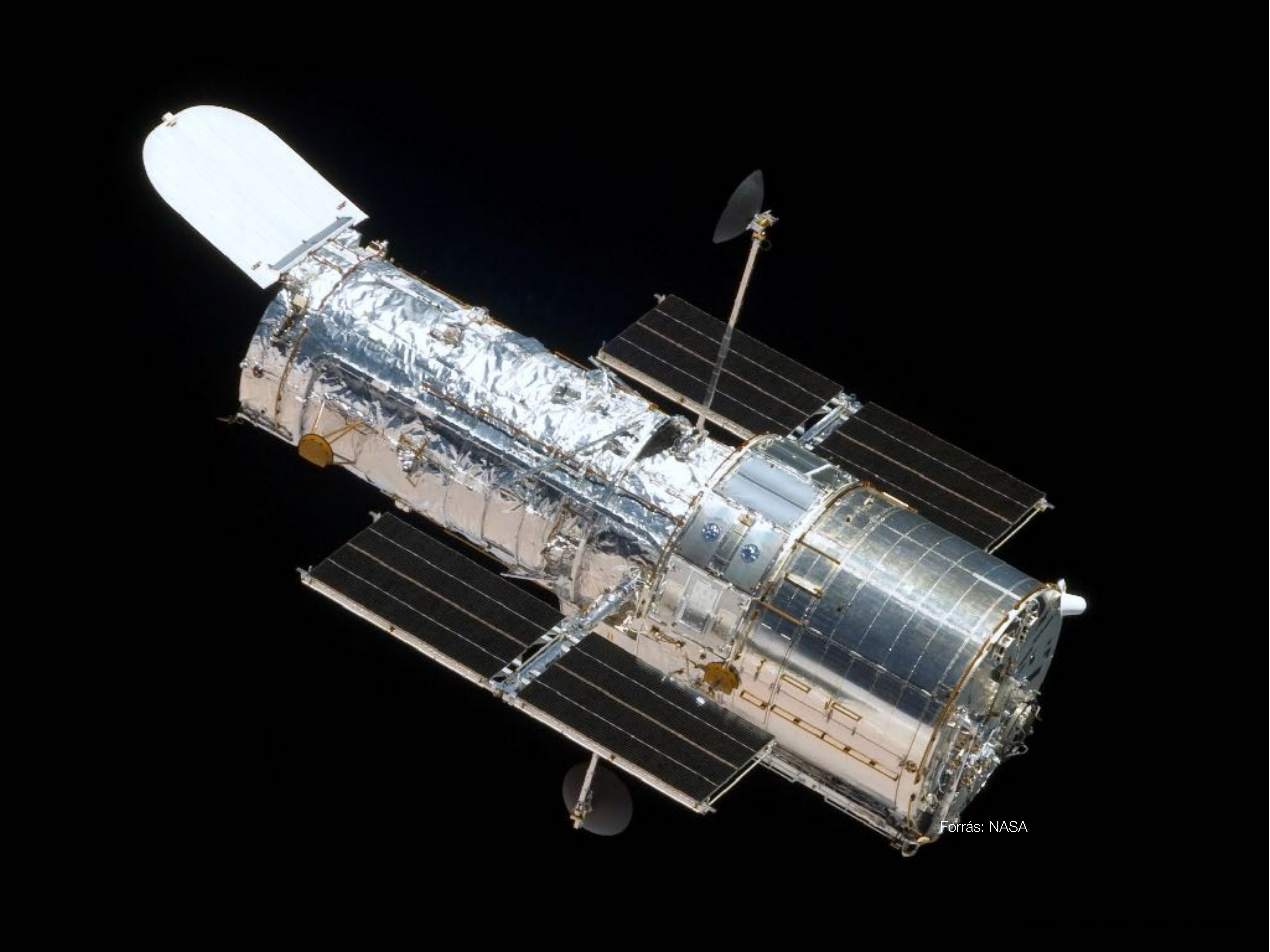
Created by E. Forgács-Dajka

VISITOR


HERSC

ALMA

Atacama Large Millimeter/submillimeter Array

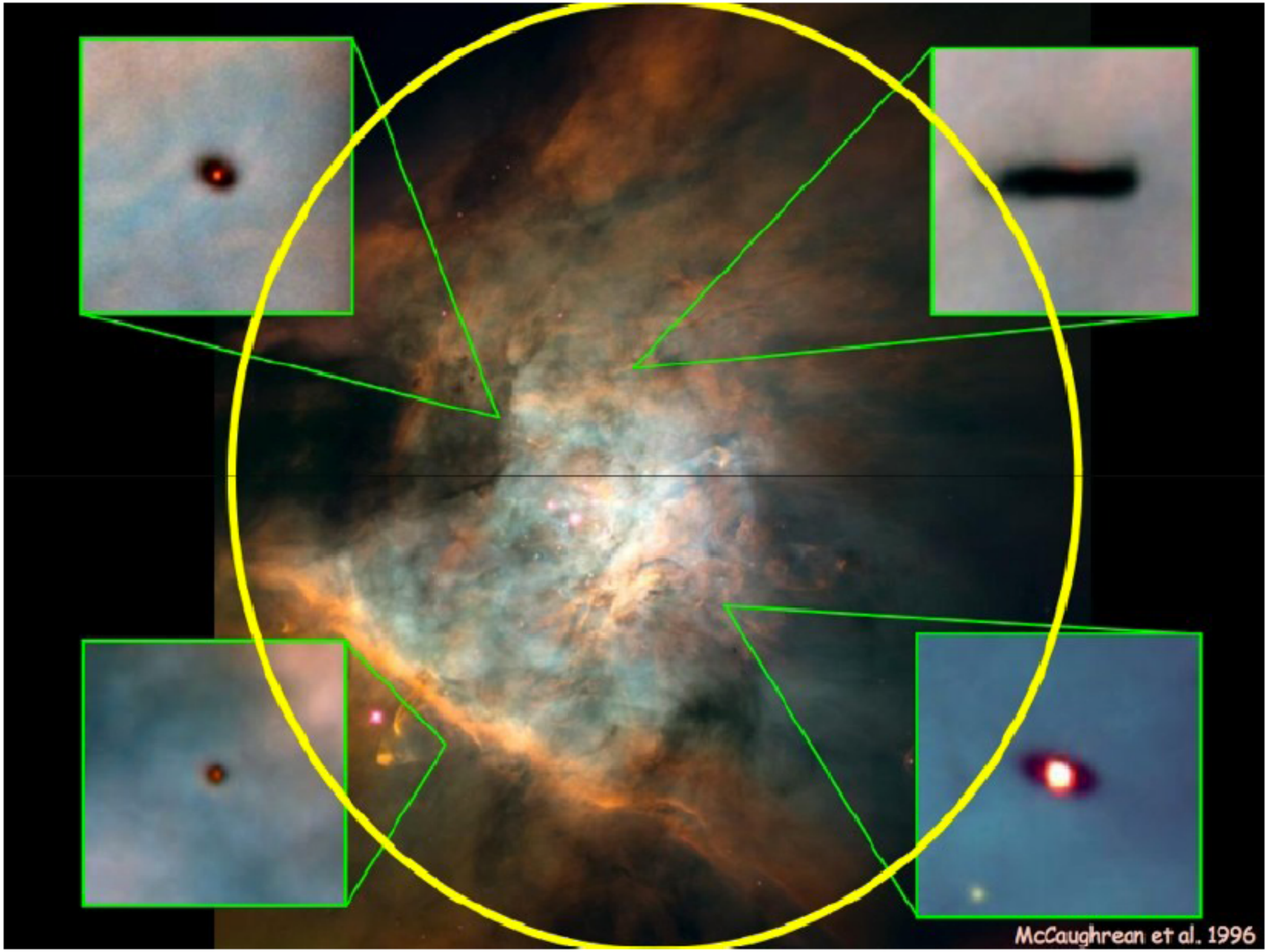


Forrás: NASA

Direct detection of young, circumstellar discs

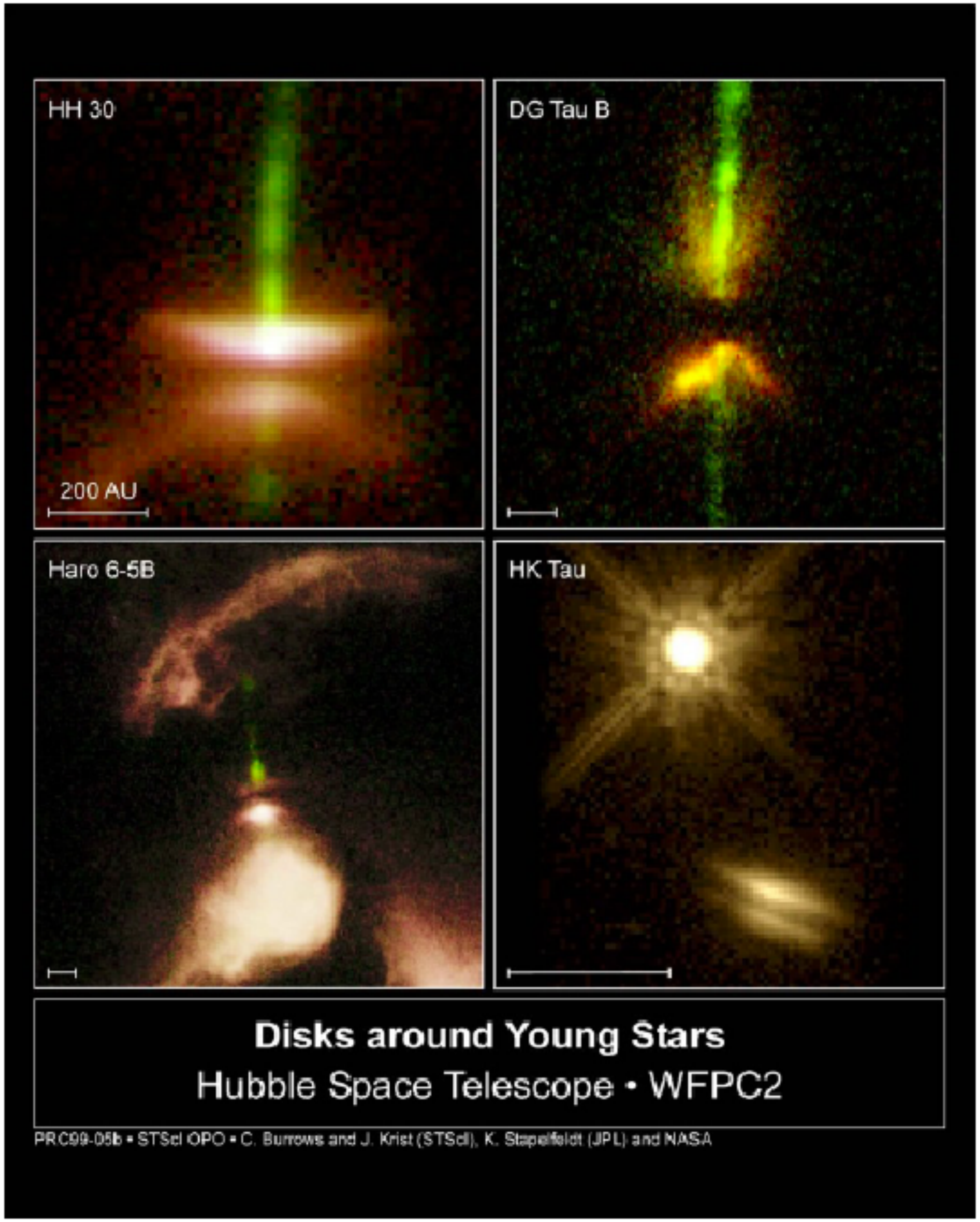
in shadowed light...

"silhouette discs"



slide courtesy Sebastian Wolf

Direct detection of young, circumstellar discs

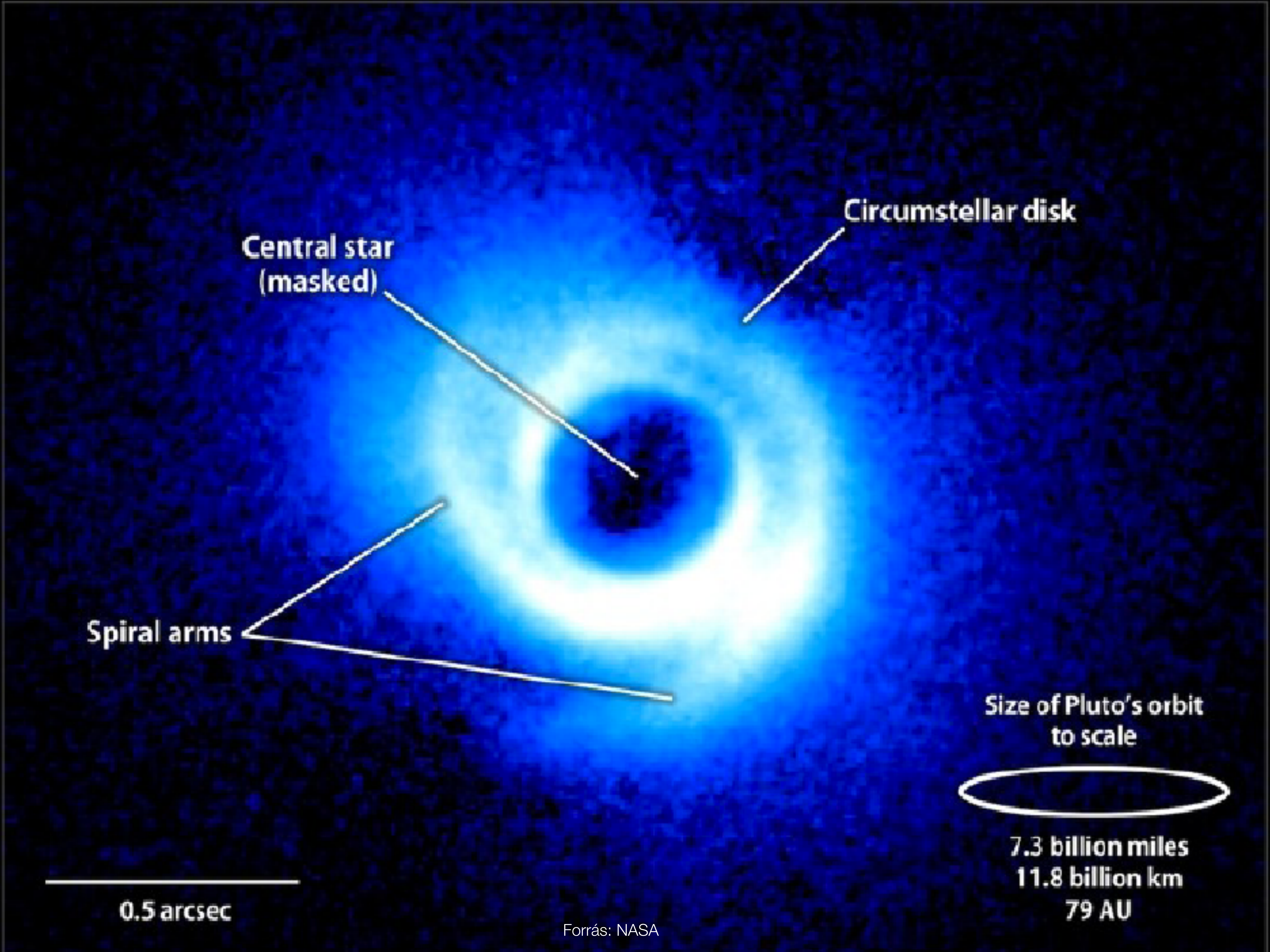


Disks around Young Stars

Hubble Space Telescope • WFPC2

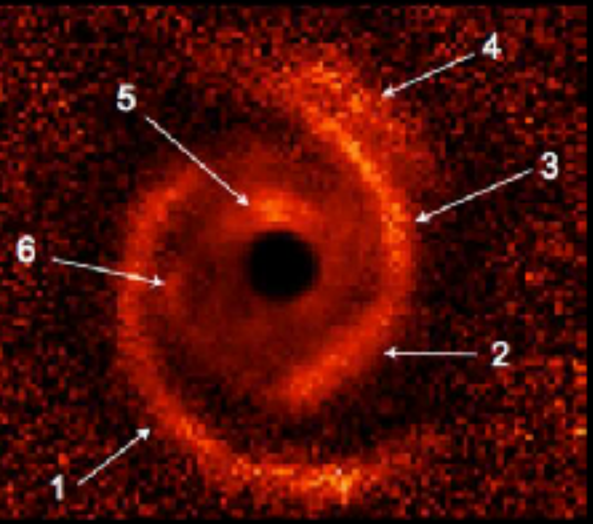
PRC99-05b • STScI OPO • C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Spiral features revealed in SAO 206462's dust disk



Forrás: NASA

Sphere disk image gallery

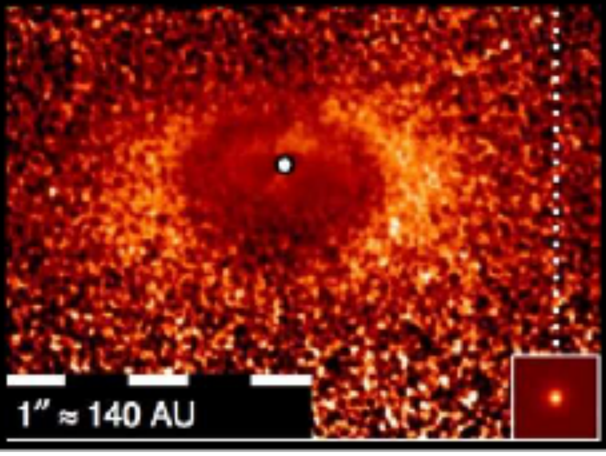


MWC 758

SVT

HD142527

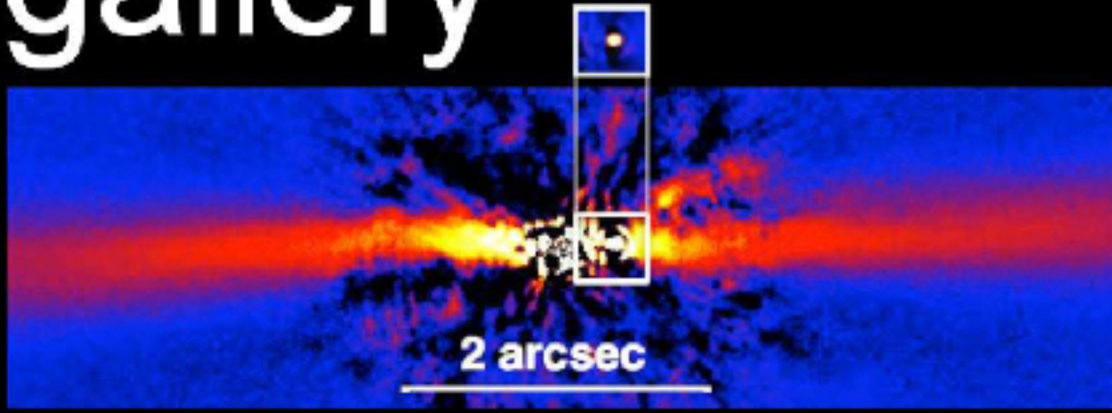
COMM/GTO



LkCa 15

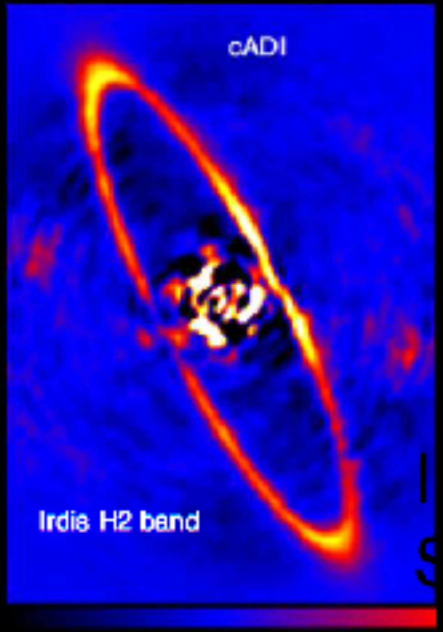
SVT

β Pic



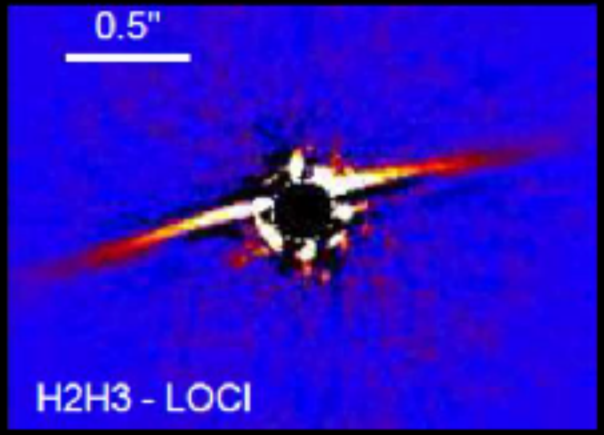
HR4796A

COMM



HD 106906

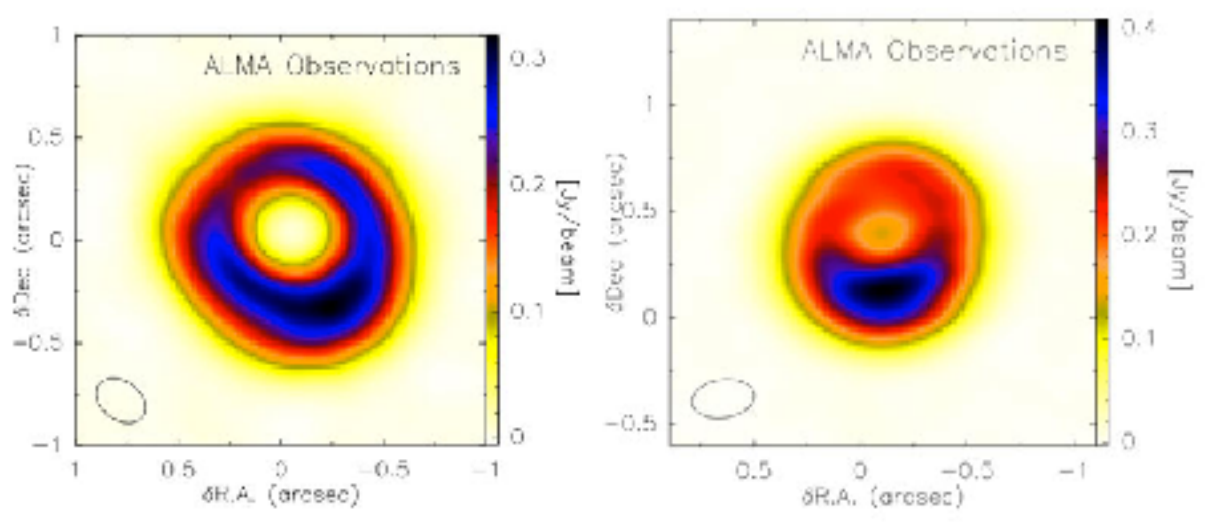
GTO

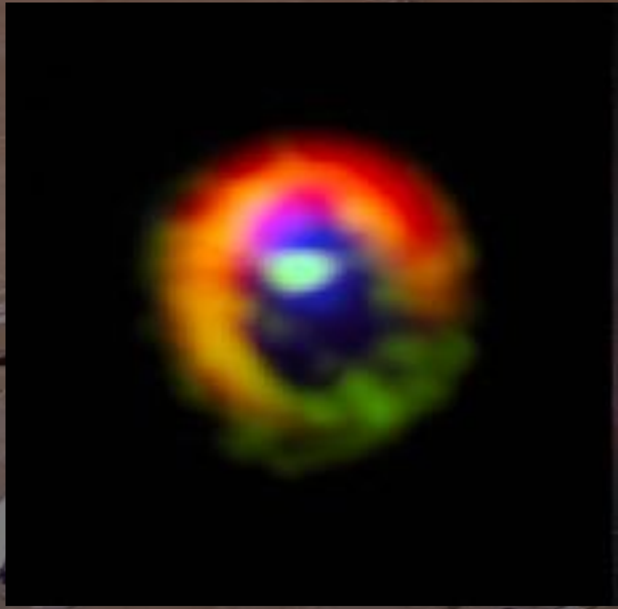


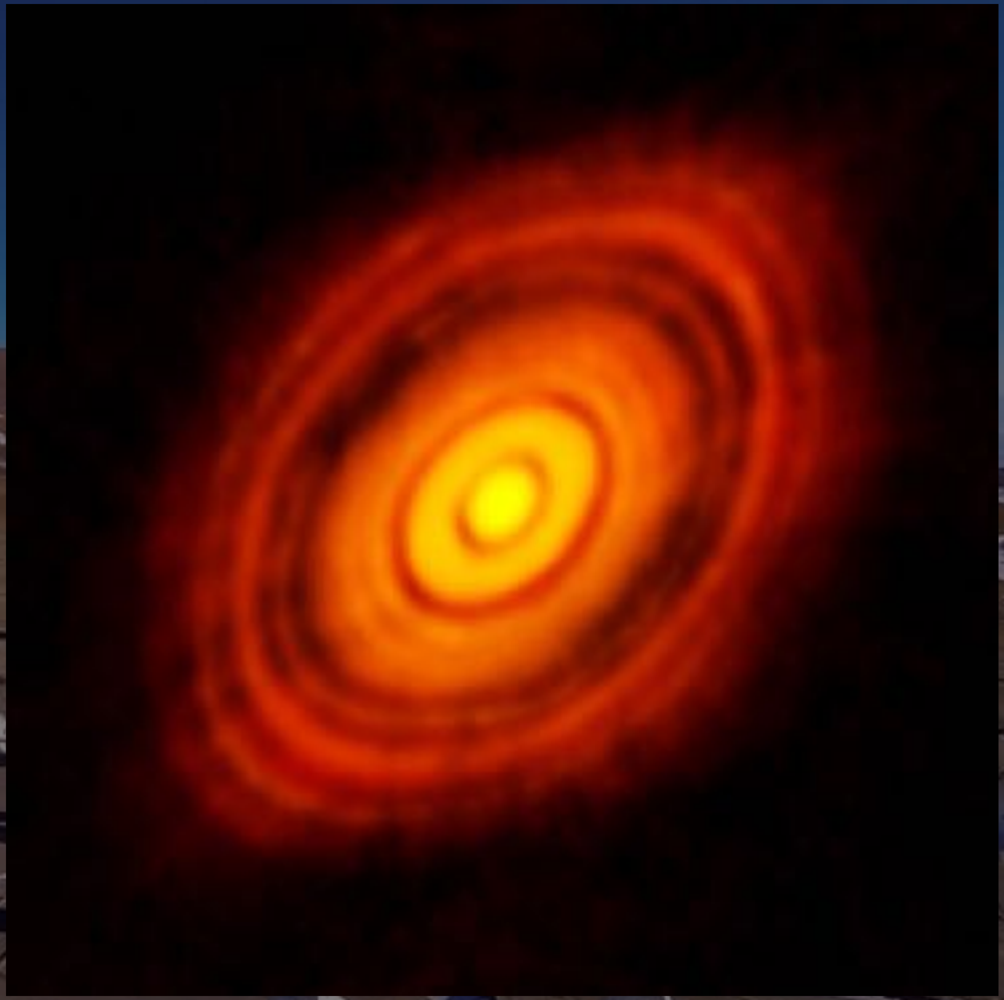
AU Mic

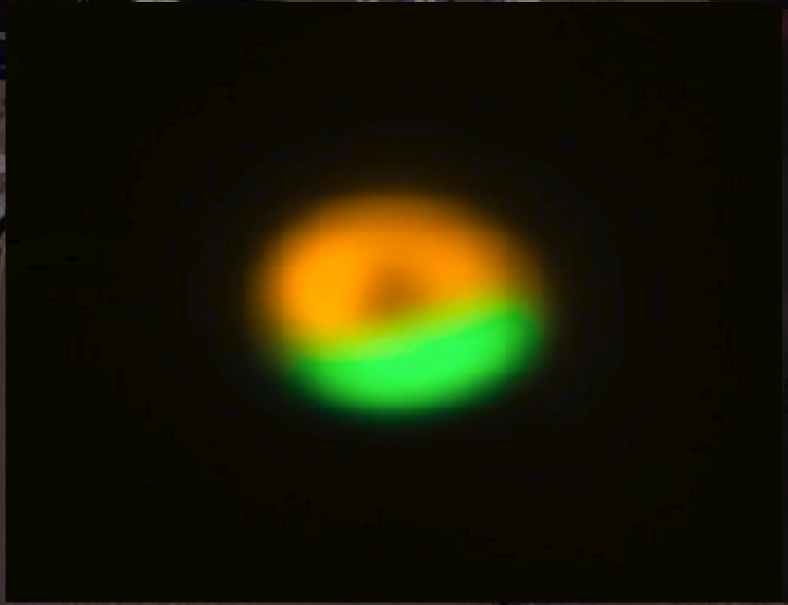
COMM/GTO

Korongok az ALMA-val



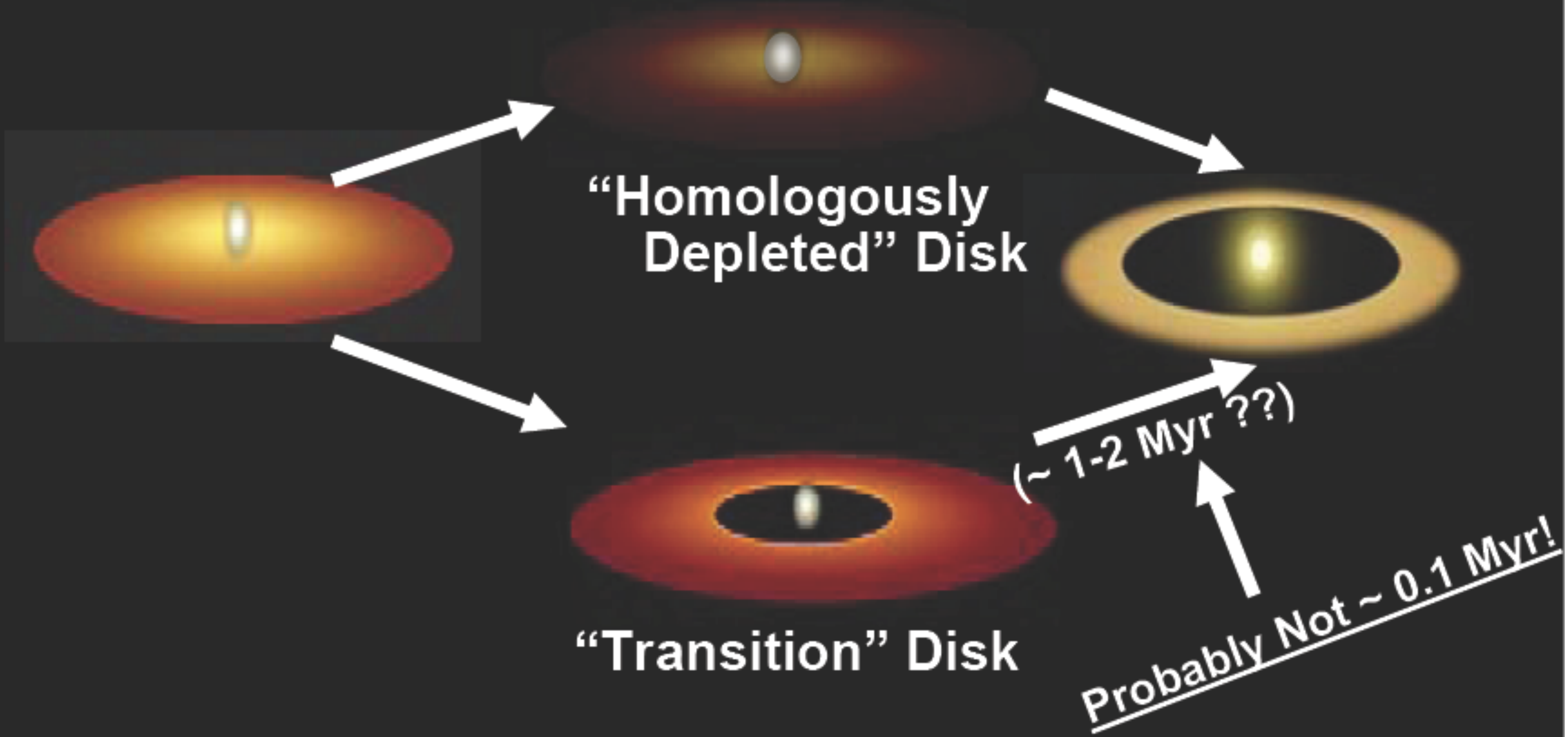






Circumstellar Disk Evolution

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



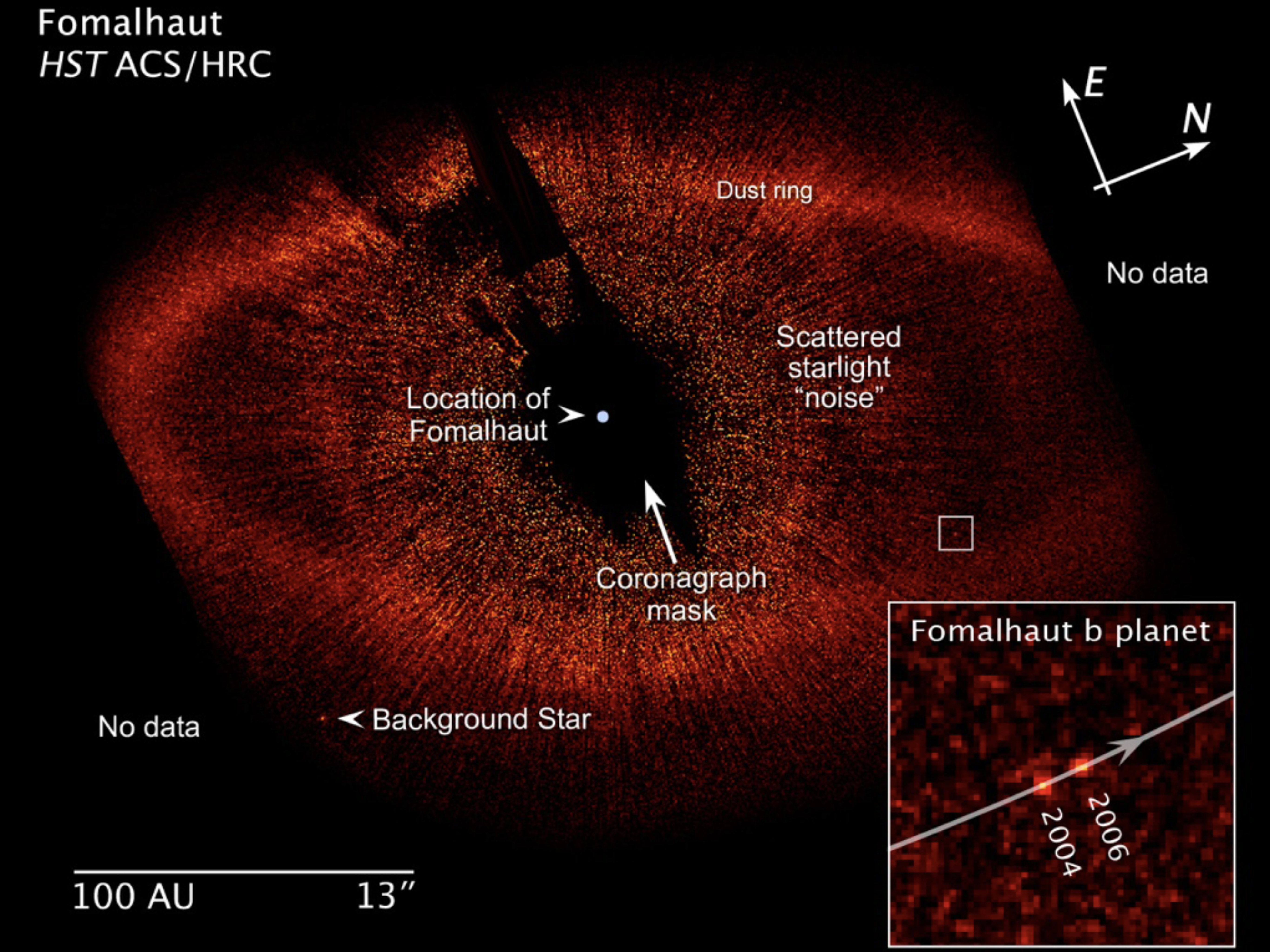
"Homologously Depleted" Disk

(~ 1-2 Myr ??)

"Transition" Disk

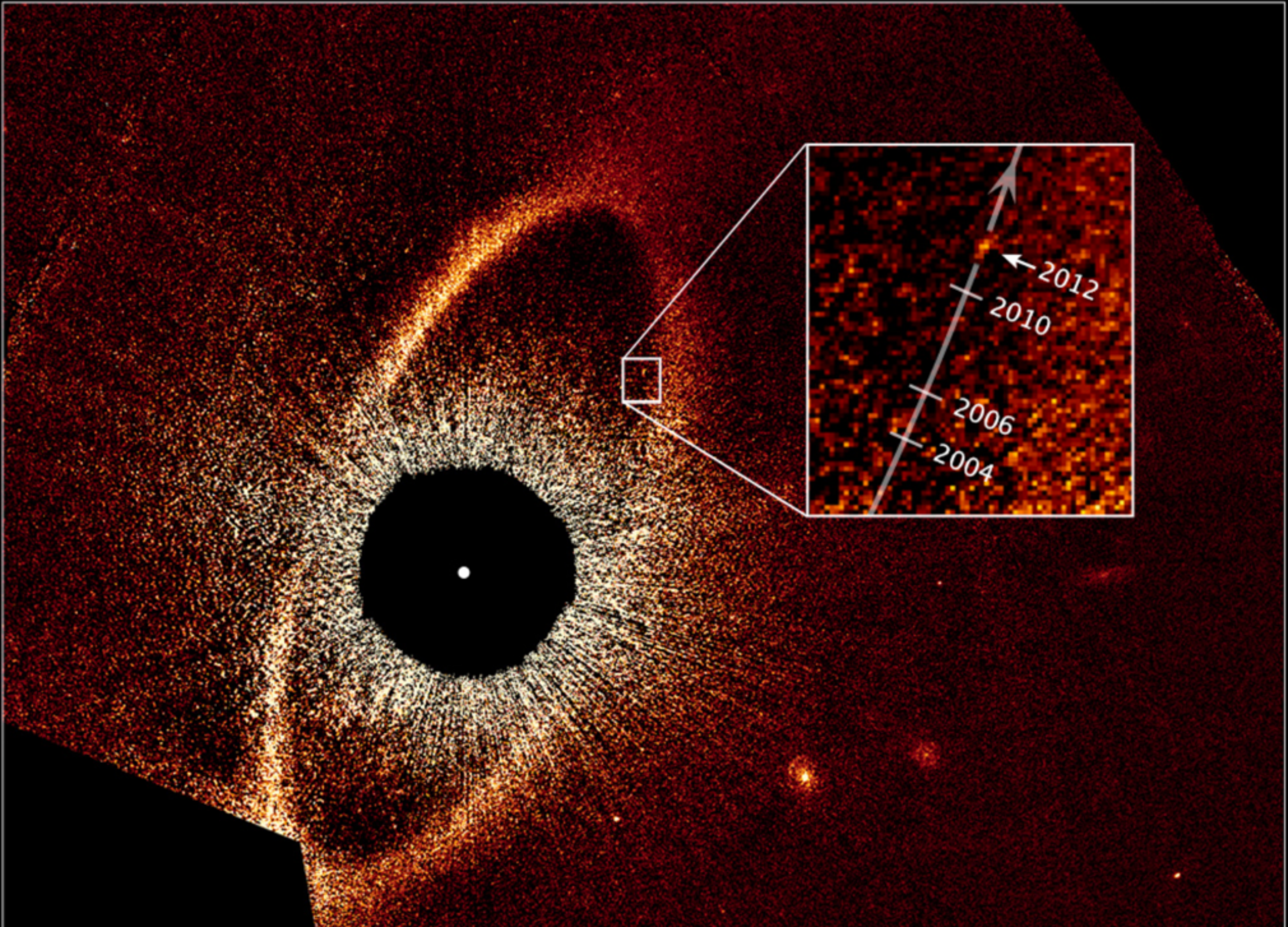
Probably Not ~ 0.1 Myr!

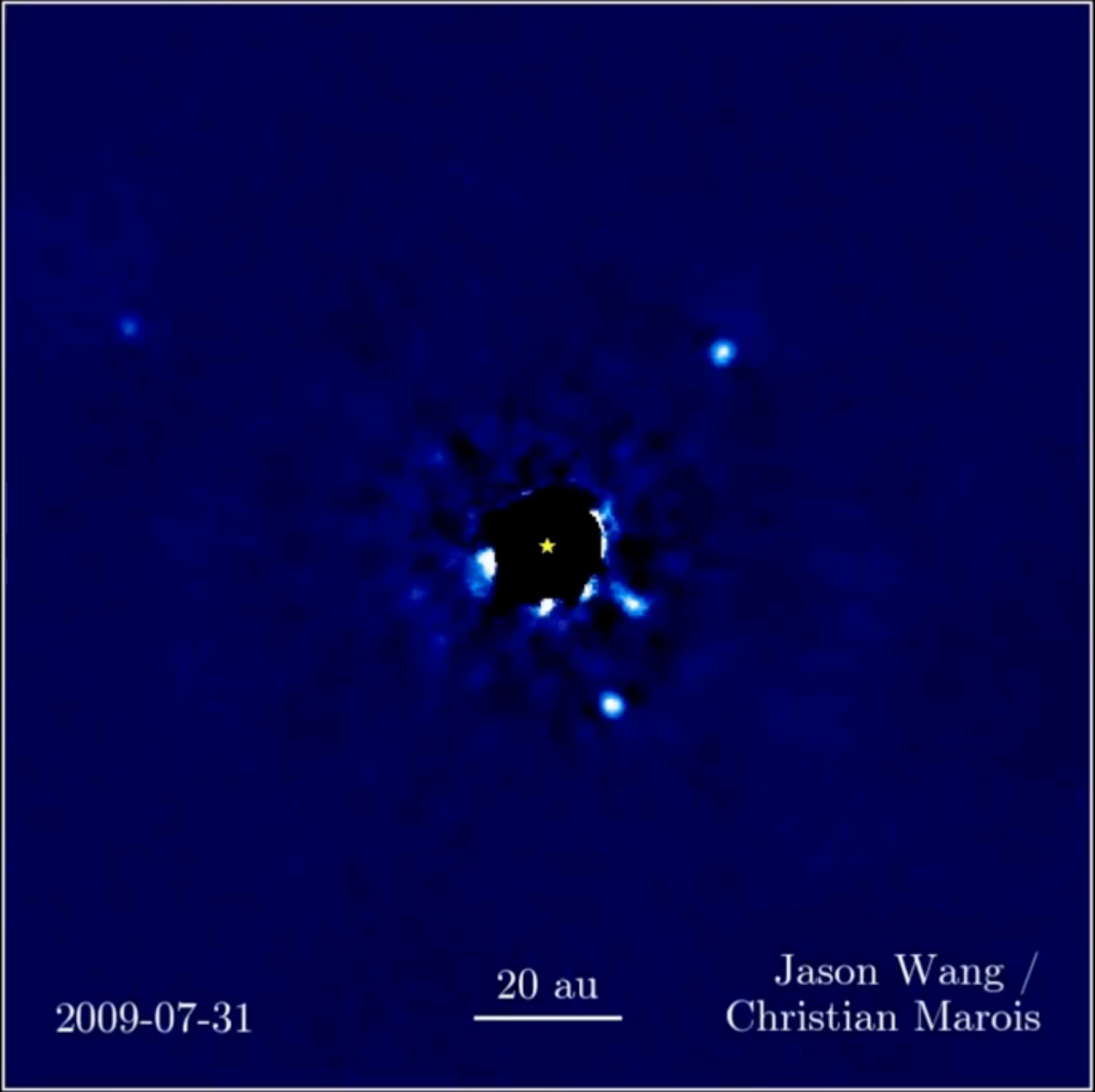
Currie & Lada et al. 2008, ApJ submitted


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"

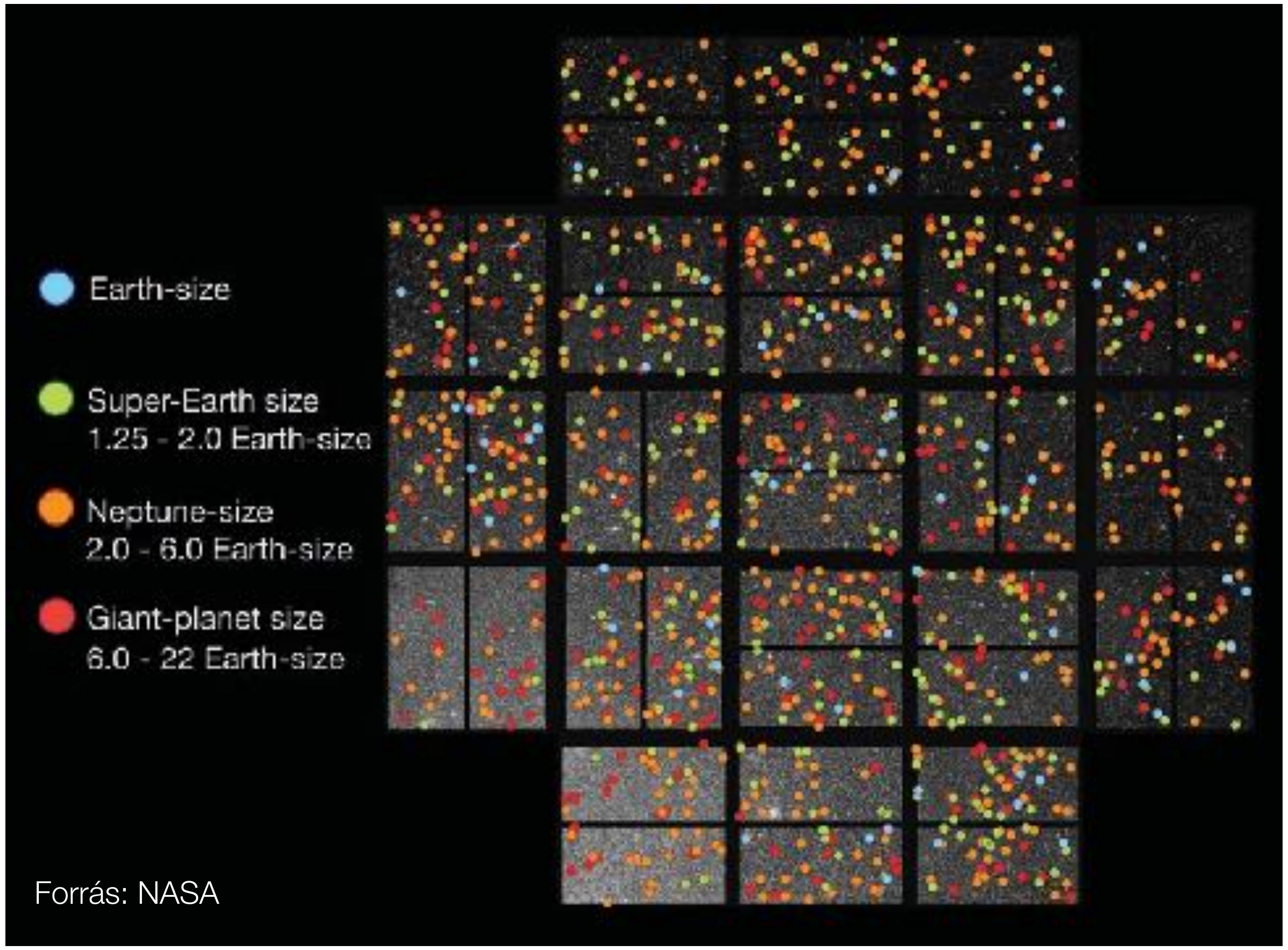
Fomalhaut System

Hubble Space Telescope • STIS

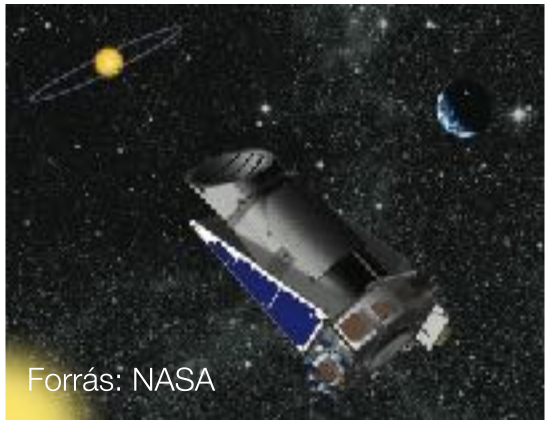



2009-07-31
20 au
Jason Wang /
Christian Marois

Az exobolygórendszerek számossága…



Forrás: NASA



Forrás: NASA

NASA Kepler űrtávcső
(0.0001% fényváltozás)

Összes exobolygó 3414

Tranzit mérésből: 2679

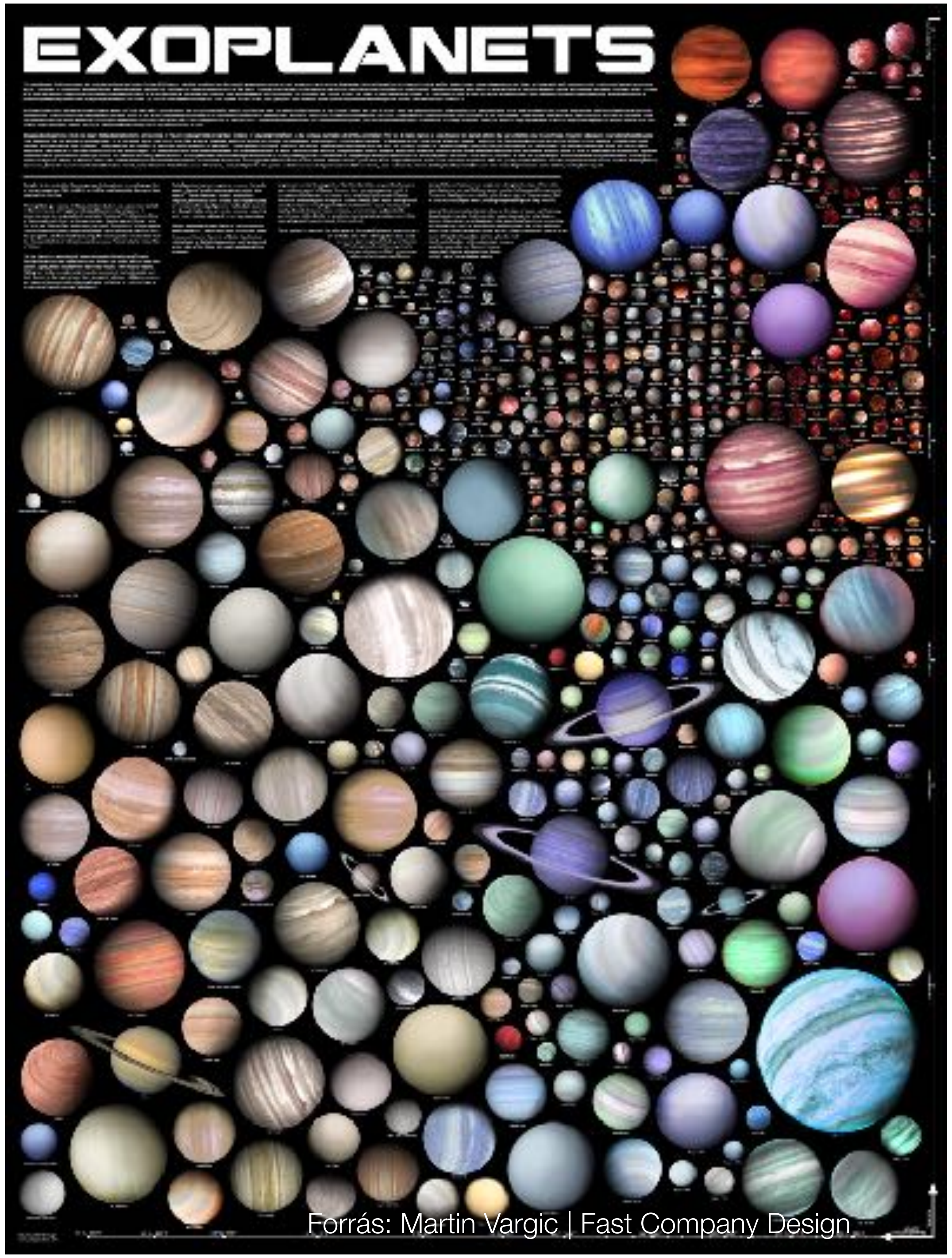
Látóirányú sebesség: 611

Közvetlen képalkotás: 44

Forrás: Wikipedia

HARPS spektrográf (Chile) - 30 cm/s

Az exobolygórendszerek változatossága…



Forrás: Martin Vargic | Fast Company Design

Napközeli “Forró Jupiterek/Neptunuszok”, Szuperföldek

Excentrikus pályák

Sűrűn telepakolt bolygórendszerek (Kepler-11 hat bolygóval)

Bolygók rezonáns pályákon (pl. Gliese 876e,b,d - 1:2:4)

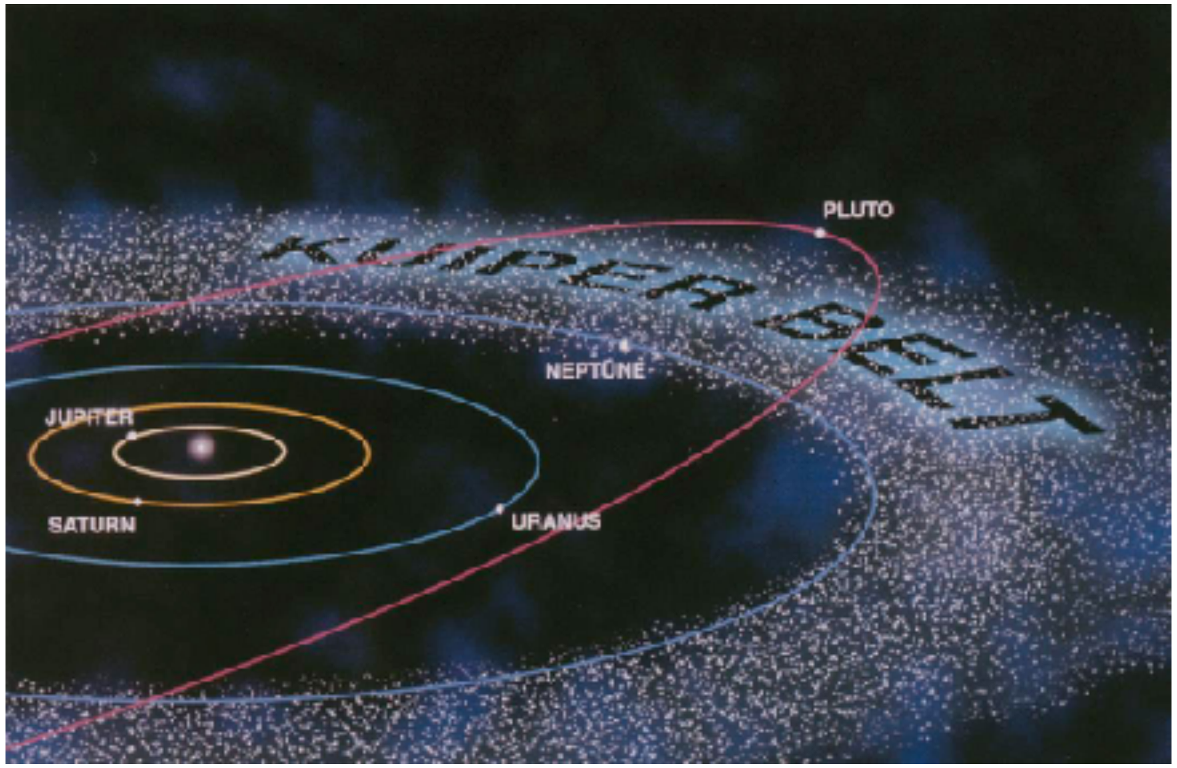
Bolygók nagy naptávolságra (HR8799)

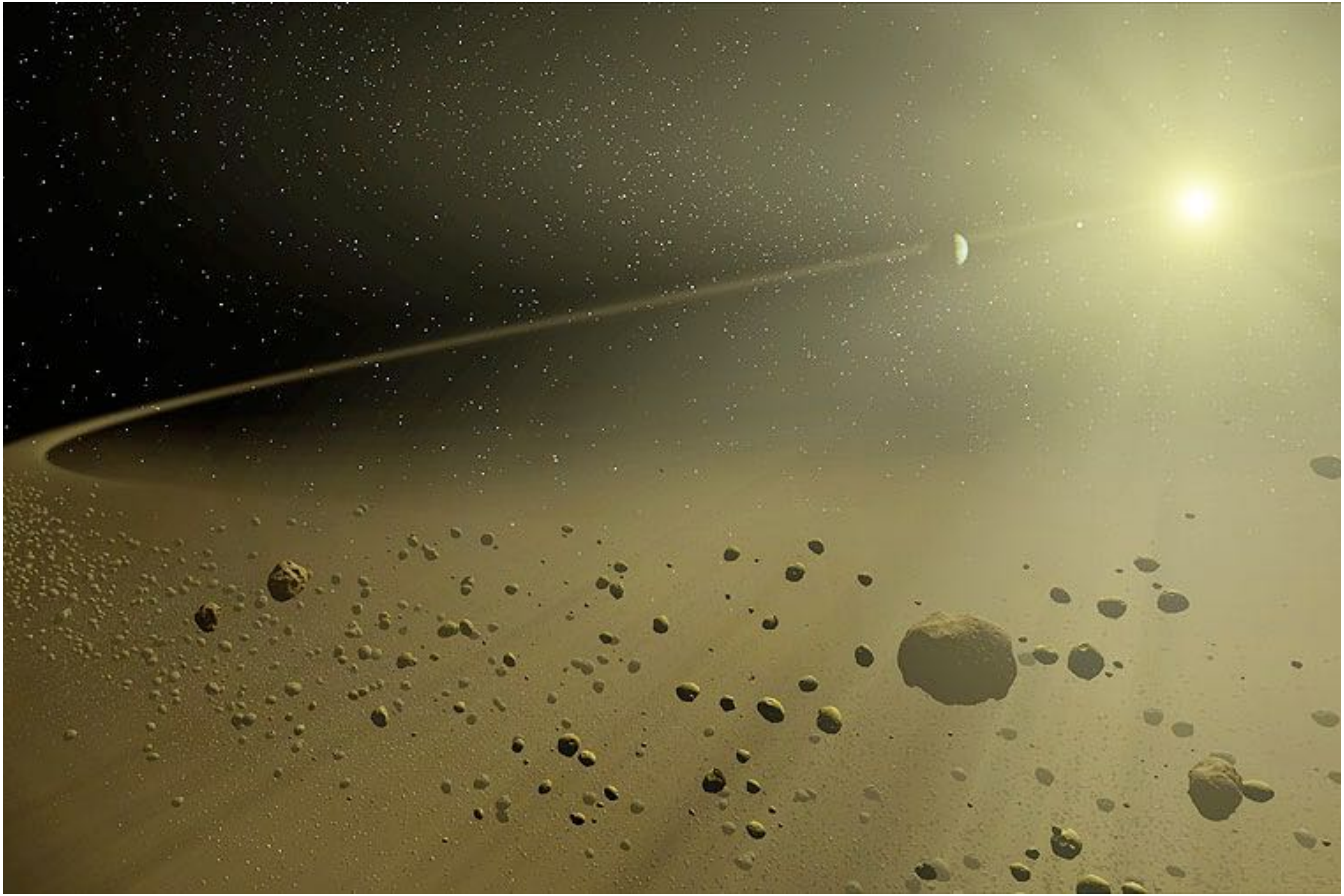
Szögben hajló vagy retrográd pályák

Bolygók többes rendszerekben (Kepler 16 b, Kepler-34 b, Kepler-35 b)

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





Együtt élünk a korongunkkal...

- A Föld napi kapcsolatban van a Nap törmelékkorongjával

- A Naprendszer ma megfigyelhető szerkezetének feltárása ÉS a más csillagok körüli korongok tanulmányozása együtt el fog vezetni a bolygókeletkezés megértéséhez

Miért olyan nehéz tudomány a csillag- és bolygókeletkezés?

“A csillagkeletkezés folyamata során a sűrűség 10^4 cm^{-3}-ről 10^{24} cm^{-3}-re változik, szerepet játszik benne a természetben megismert valamennyi erő, megfigyeléséhez használni kell a teljes spektrumot, és tanulmányoznunk kell a Naprendszerben fellelhető primitív anyagokhoz.” (Shu 1993)

Csillagközi felhőmag	**Fiatal csillag**
$n \sim 10^5$ cm^{-3}	$n \sim 10^{23}$ cm^{-3}
$T \sim 10-30$ K	$T \sim 10^6$ K
$R \sim 10^{17}$ cm	$R \sim 10^{11}$ cm
B~ 20-30 mikroGauss	B~ 1 kiloGauss
Szögsebesség ~ $3x10^{-14}$ rad s^{-1} (egy fordulat 7 millió év)	Szögsebesség ~ 10^{-5} rad s^{-1} (egy fordulat: 1 hét)

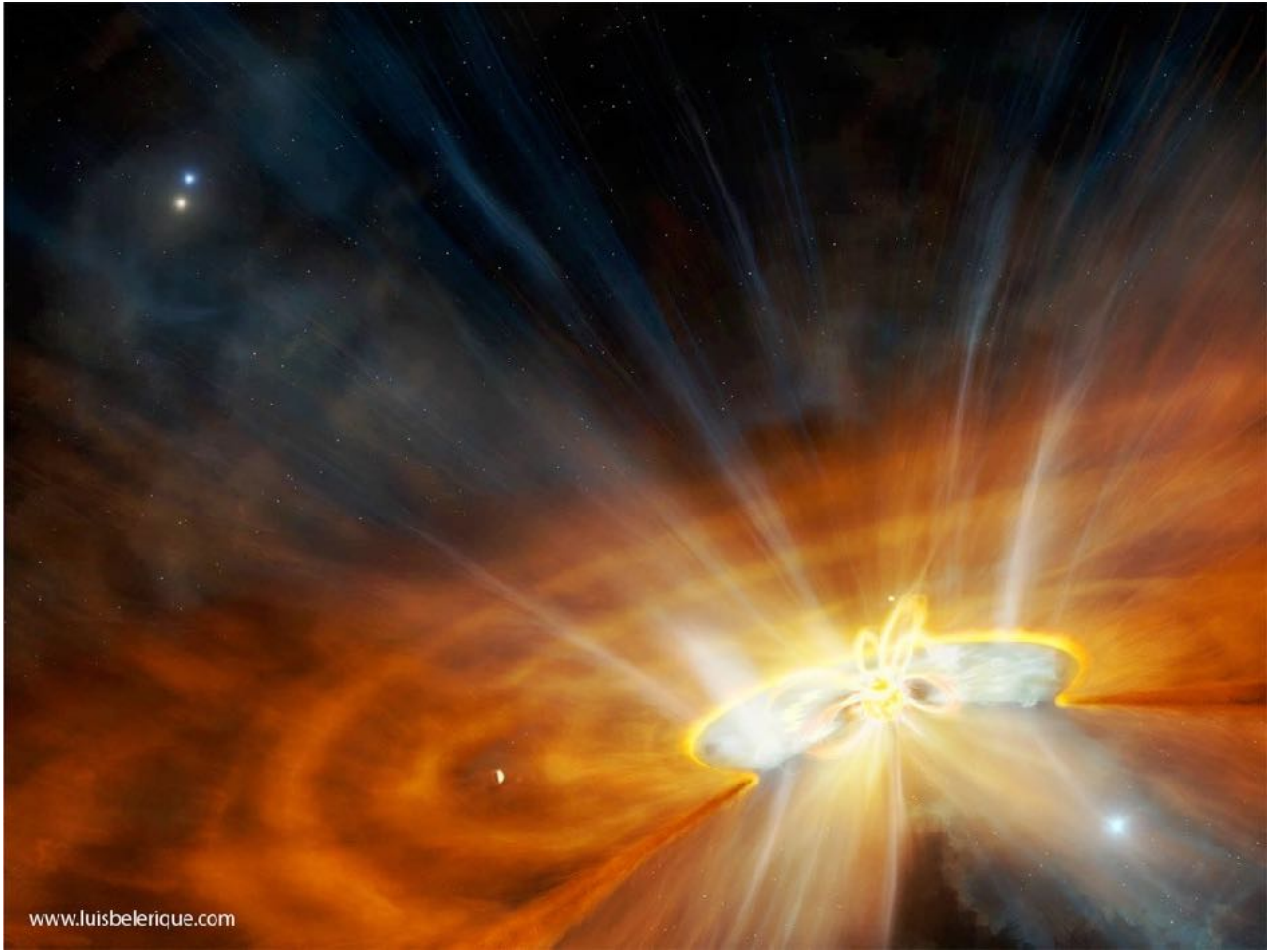
Már a csillagkörüli korongok is sokfélék (bolygókeletkezés kezdőfeltételei)

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


www.luisbelerique.com

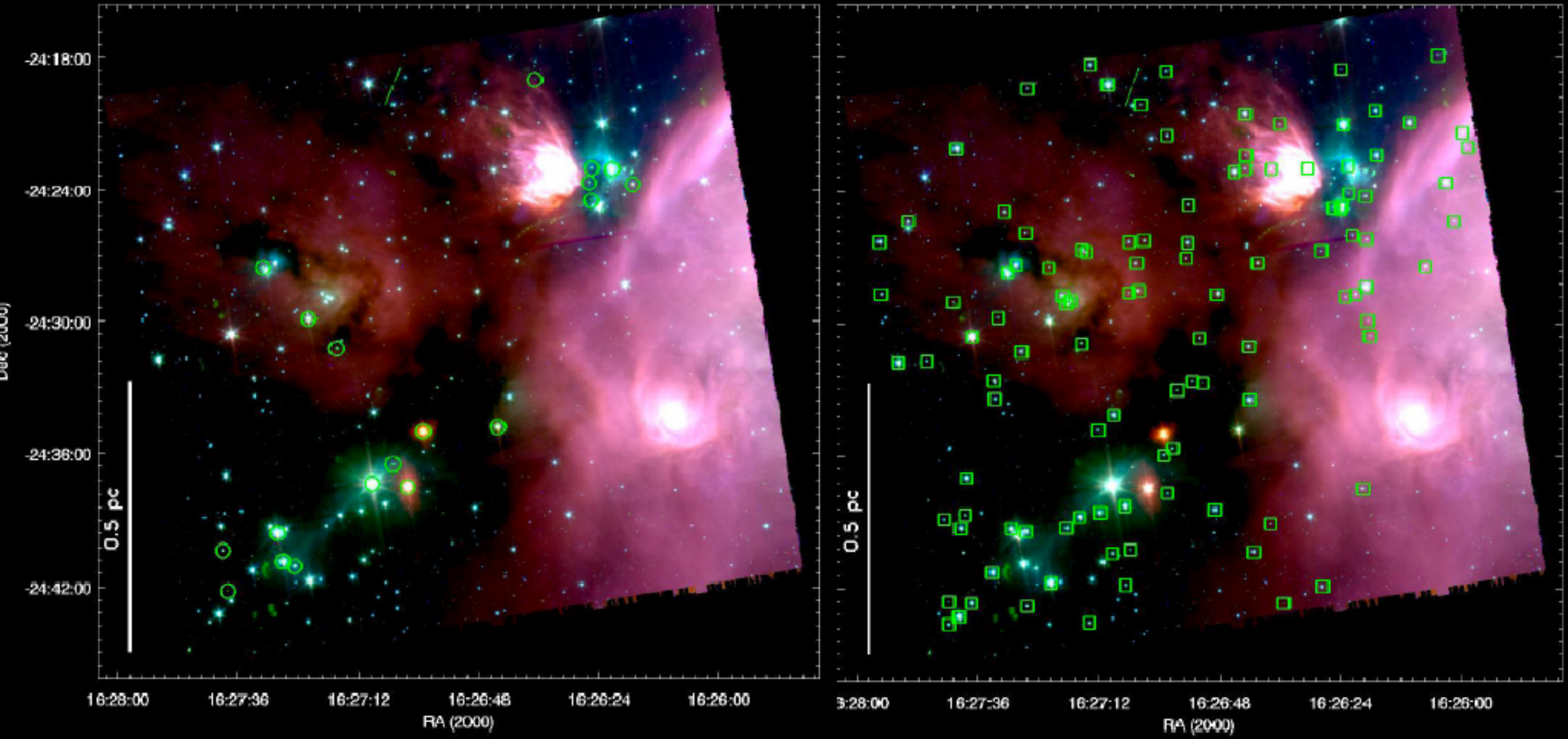
Észak-Amerika köd

NASA/JPL-Caltech www.spitzer.caltech.edu

Ophiuchus

NASA/JPL-Caltech www.spitzer.caltech.edu

Spatial distributions Oph



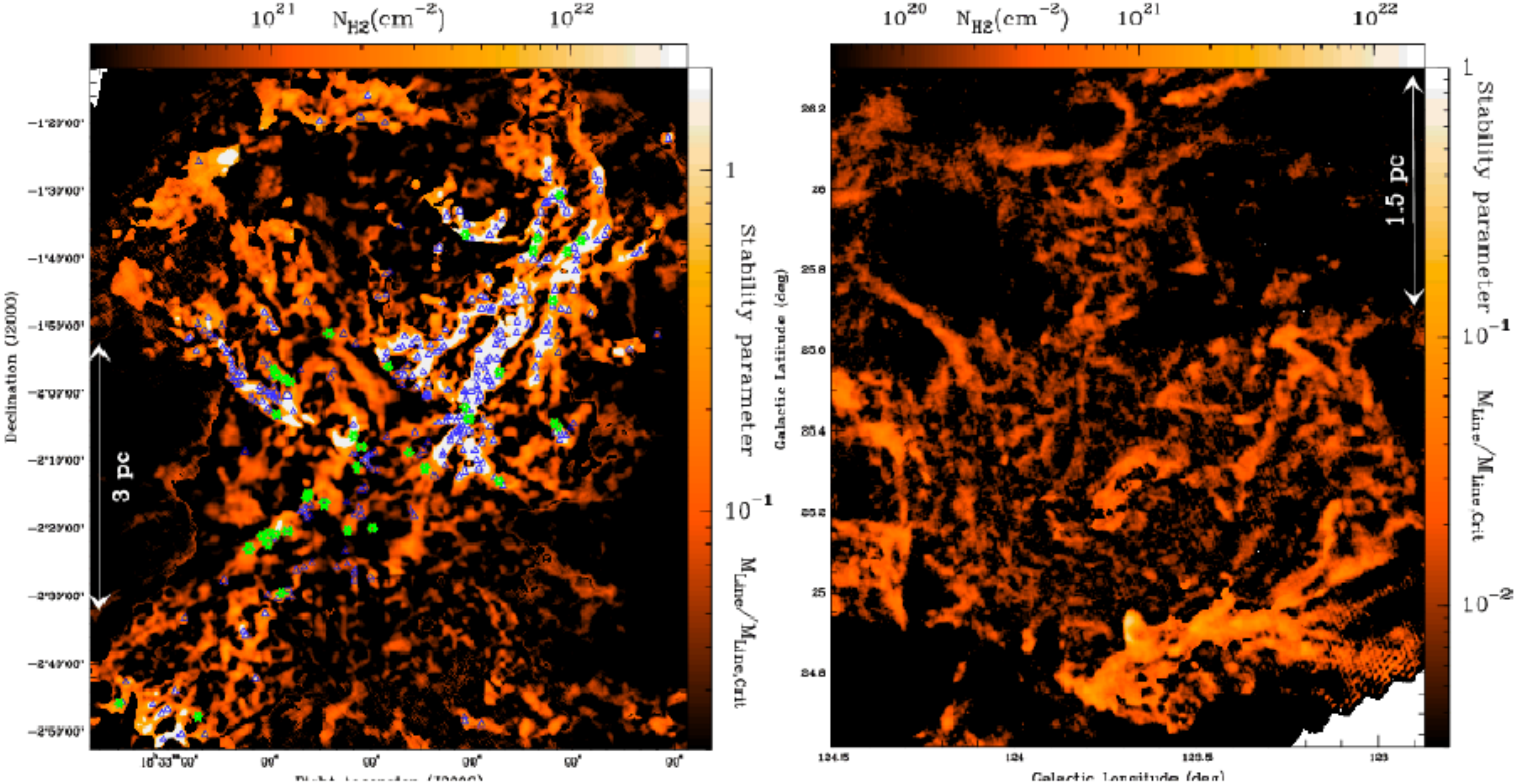
Class I=embedded

Class II=stars+disks

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

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 $t_{\mathrm{AD}} \sim 10\ t_{\mathrm{ff}}$

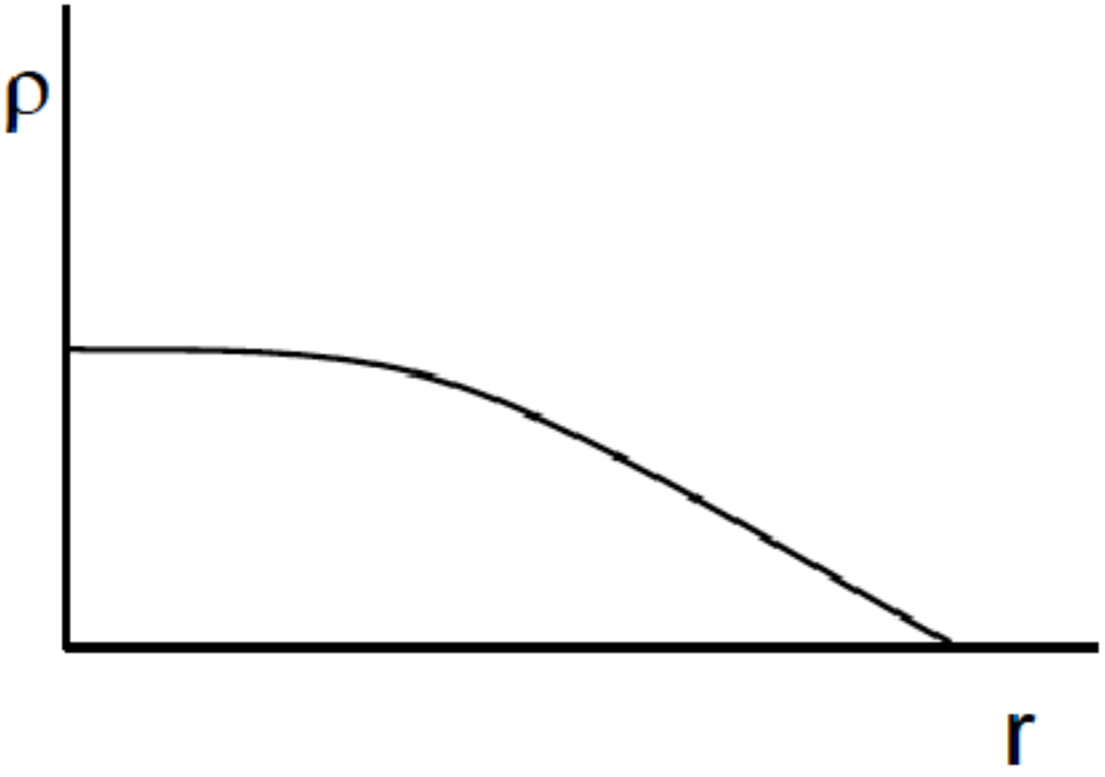
Shu et al. 1987
Mouschovias 1991

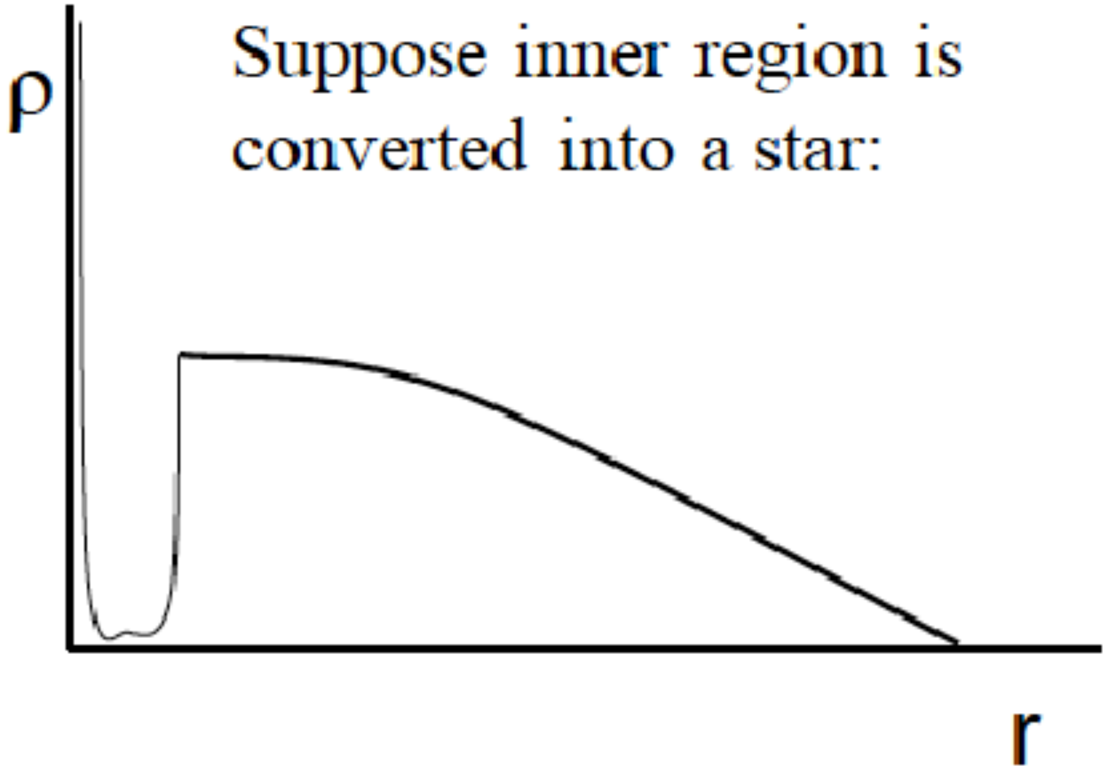
b. Fast gravo-turbulent fragmentation

- 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

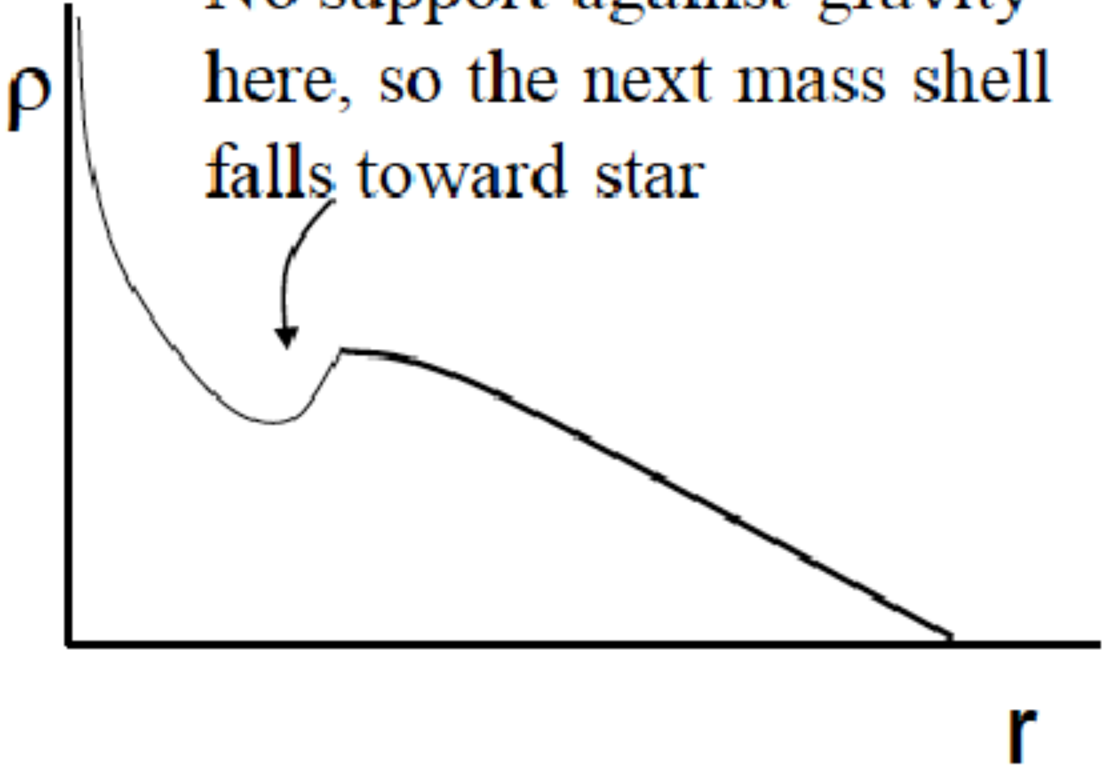
Ballesteros-Paredos et al. 2003
MacLow & Klessen 2004

Inside-out collapse of metastable sphere

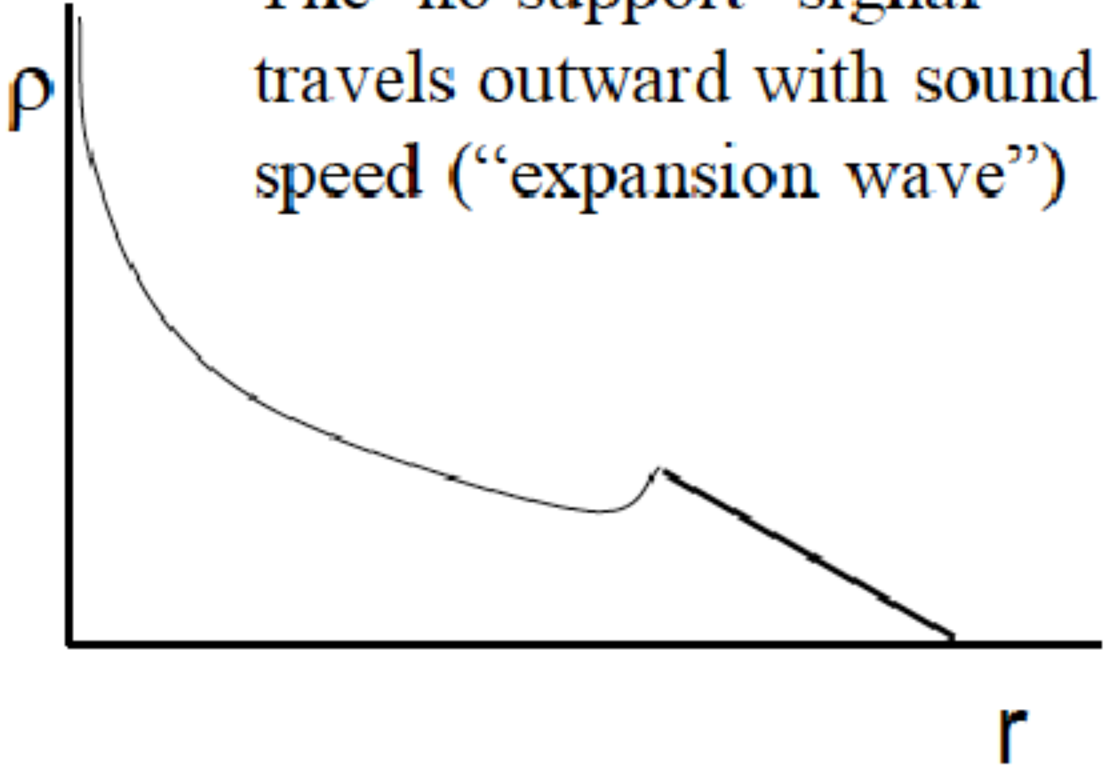




Suppose inner region is converted into a star:

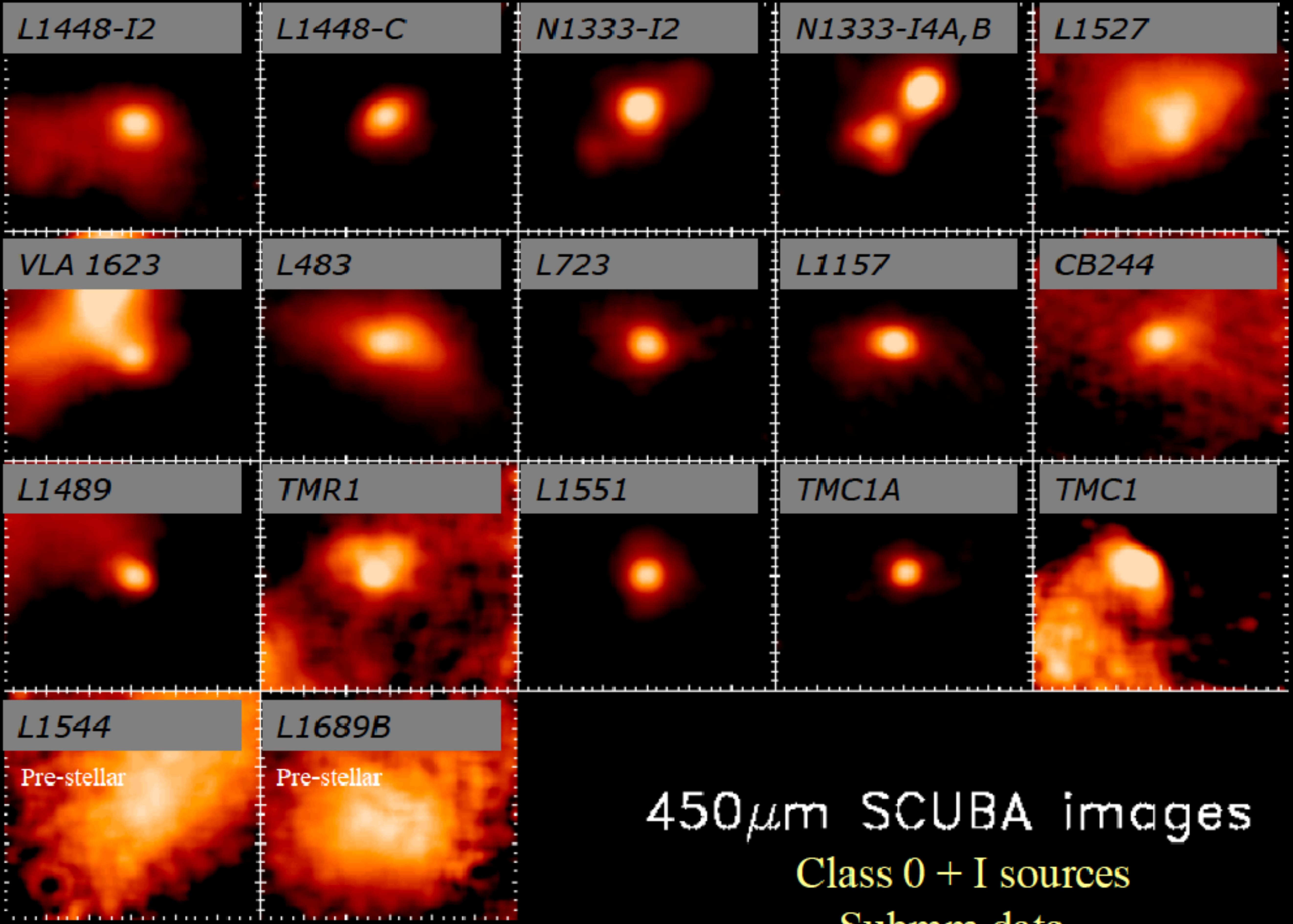


No support against gravity here, so the next mass shell falls toward star



The ‘no support’-signal travels outward with sound speed (“expansion wave”)

(warning: strongly exaggerated features)



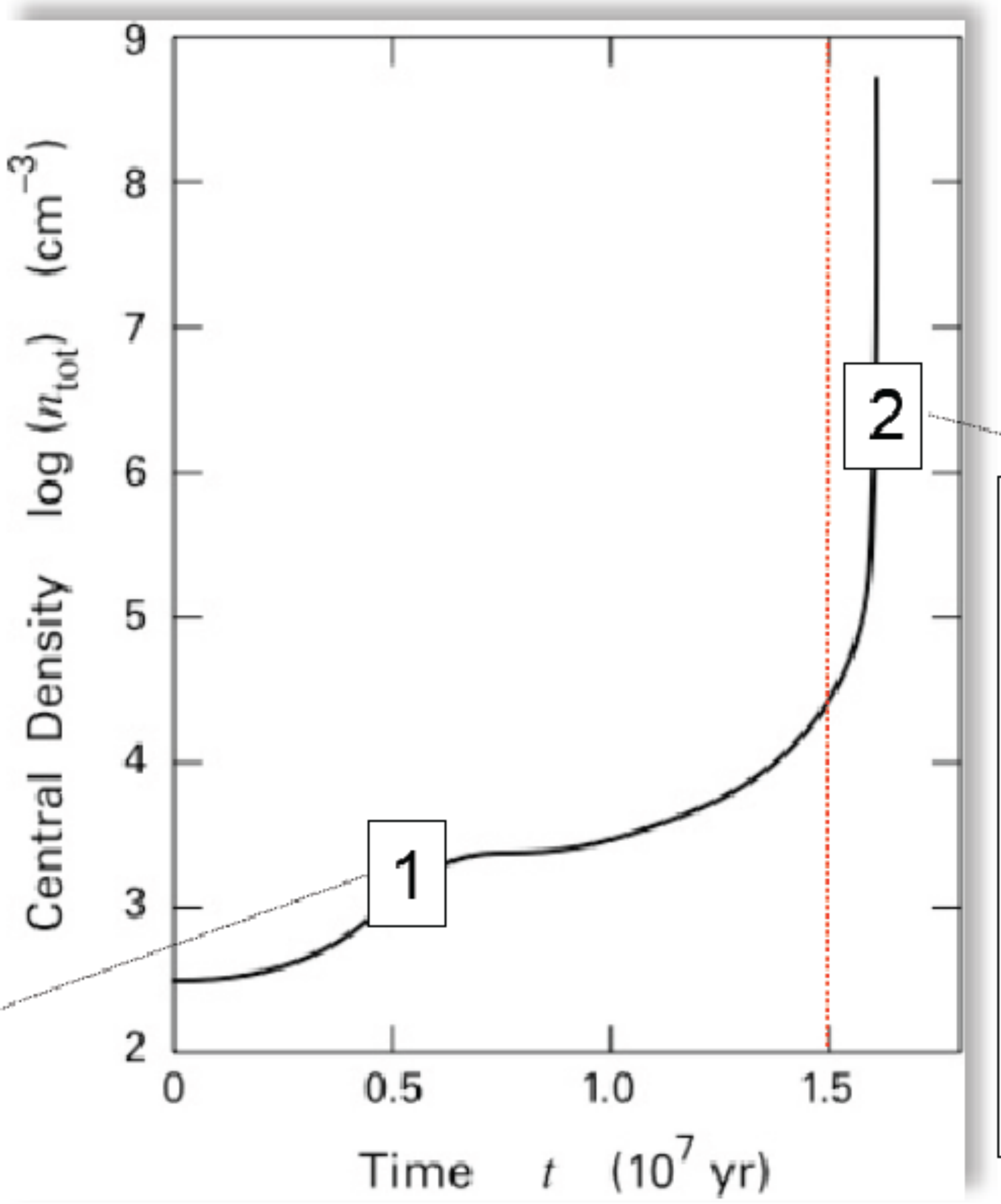
450μm SCUBA images

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.

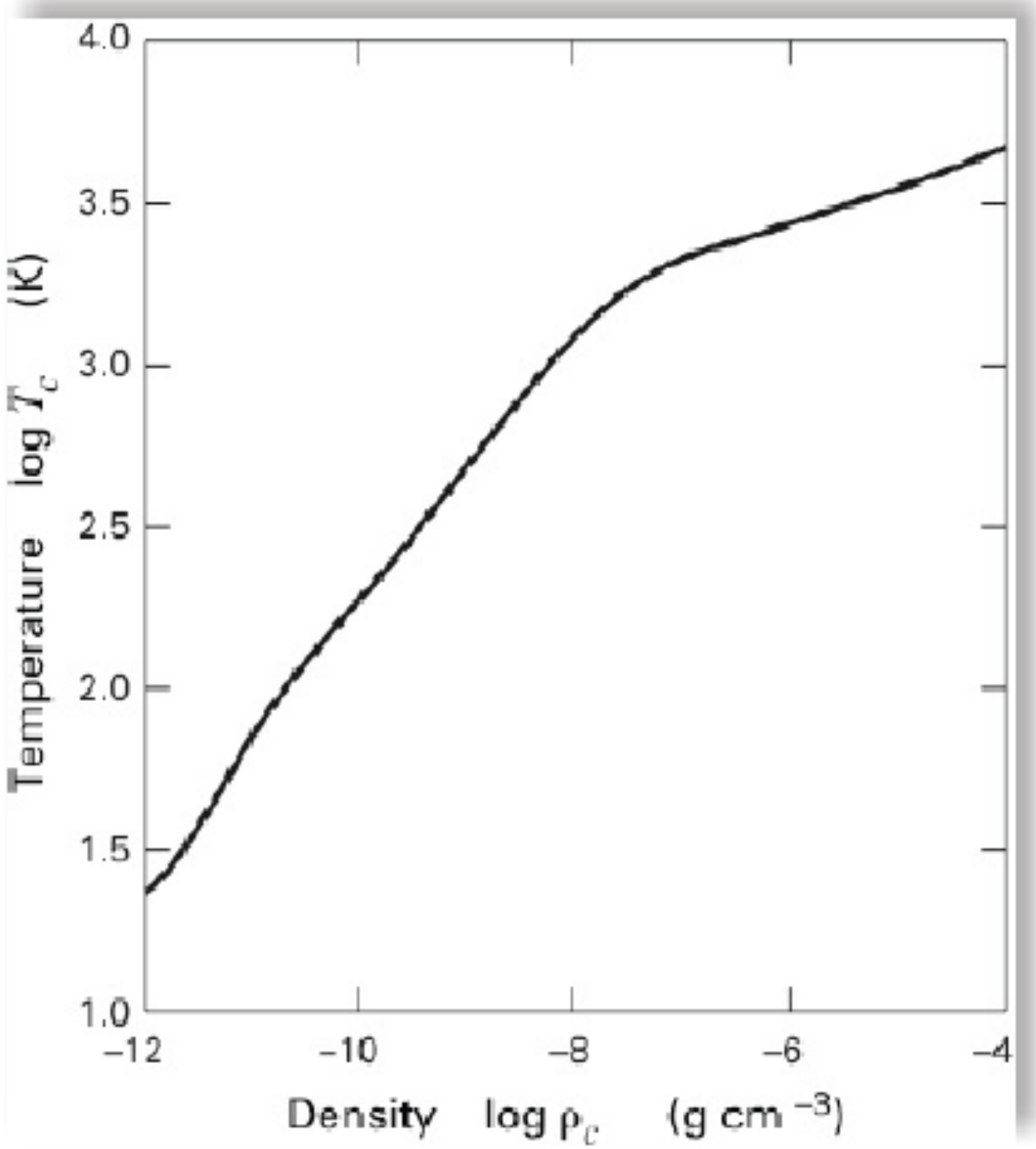
The structure that arises from the contraction is not yet a *protostar* but a temporary configuration known as the first core. To describe its growth and rapid demise, let's neglect (for now) the important element of rotation and magnetic support.

- 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.



$M \sim 5\text{x}10^{-2}\,M_\odot$, R ~ 5 AU

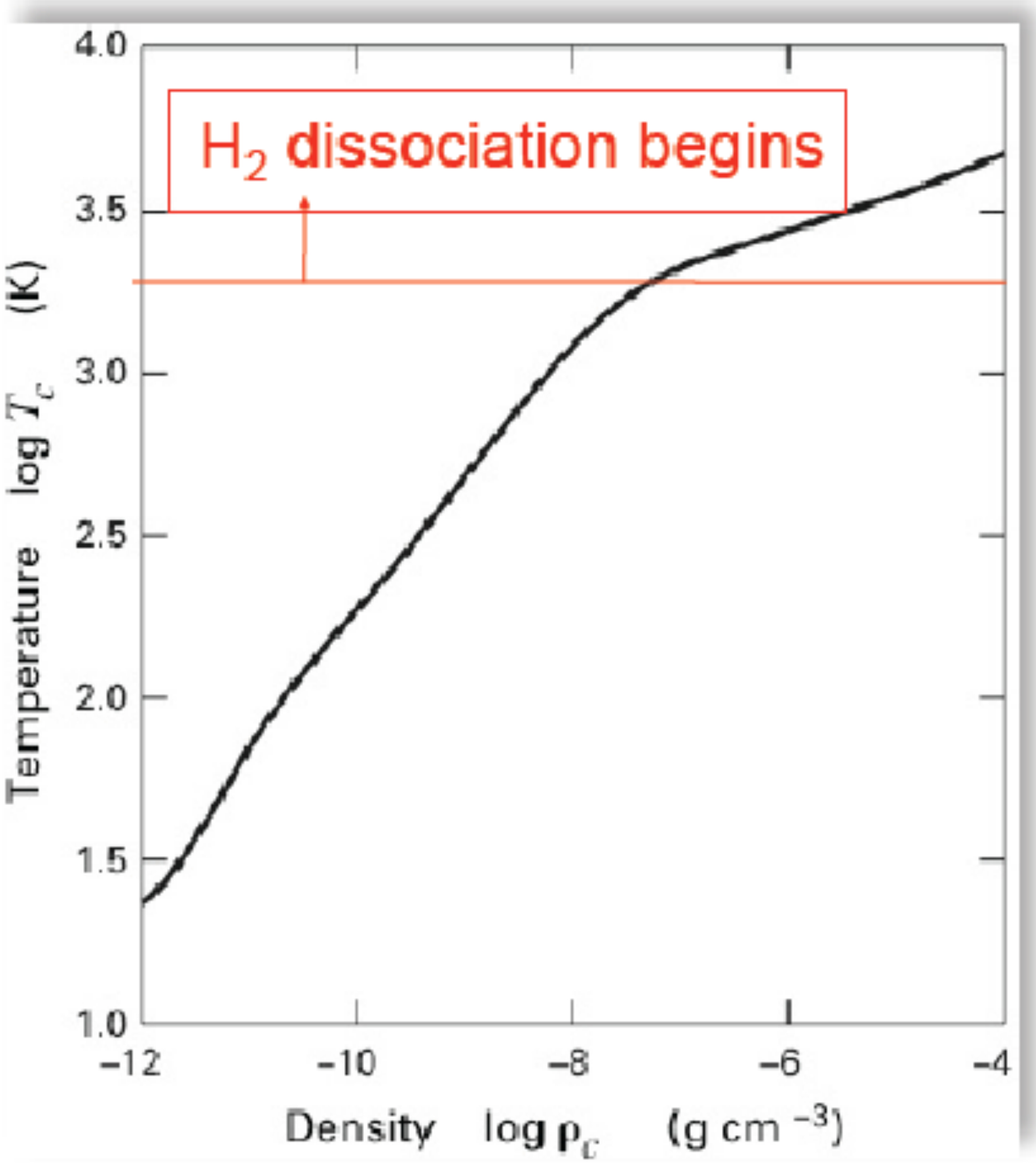
$\rightarrow \rho \sim 10^{-10}$ g cm^{-3}

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}.

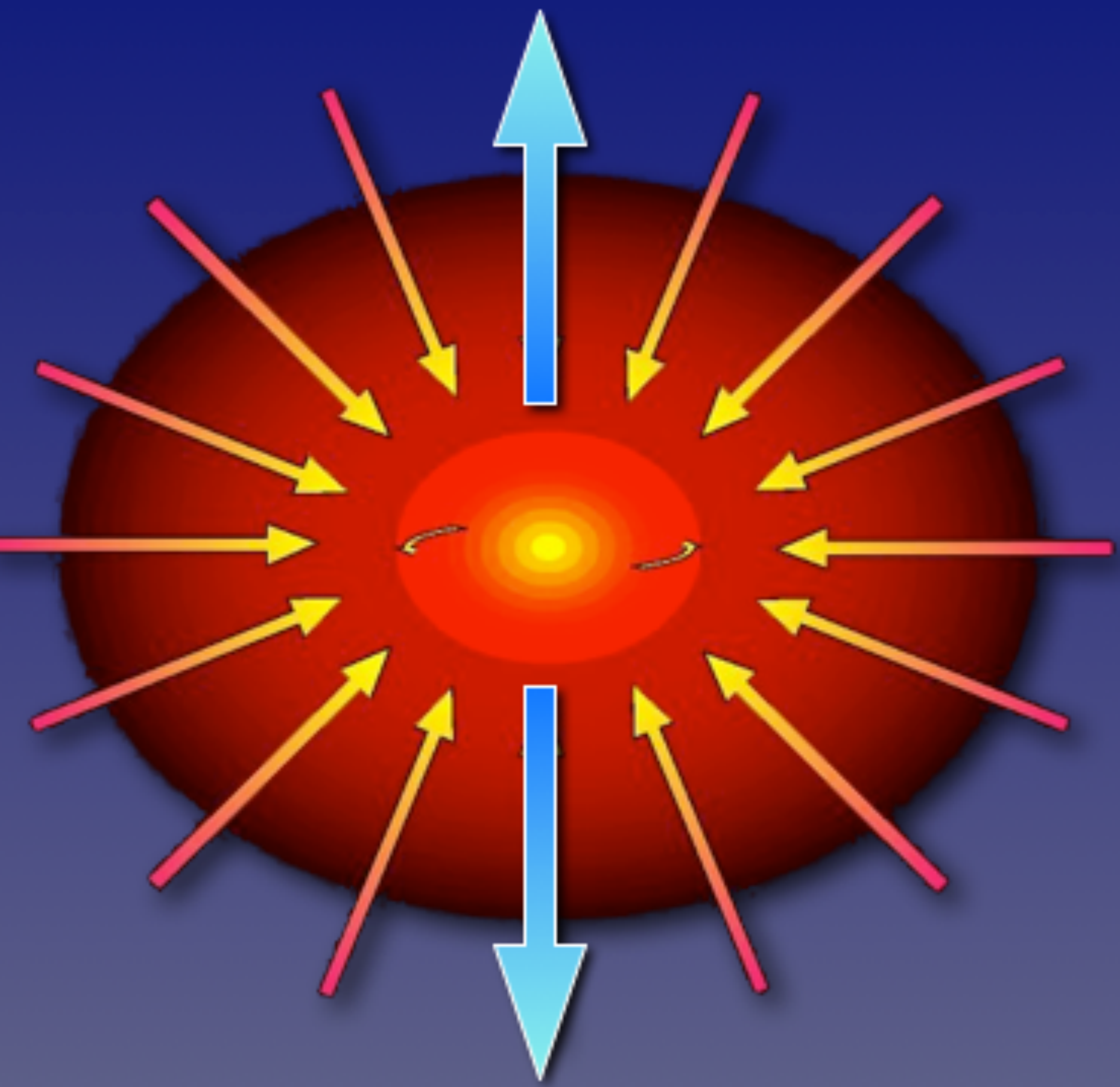
The gas approaching the protostellar surface now travels at free-fall velocities >> local sound speed. The steady rise in the protostellar mass gradually inflates this supersonic infall region and the cloud collapse proceeds inside-out ➔ main accretion phase.

Accretion Luminosity

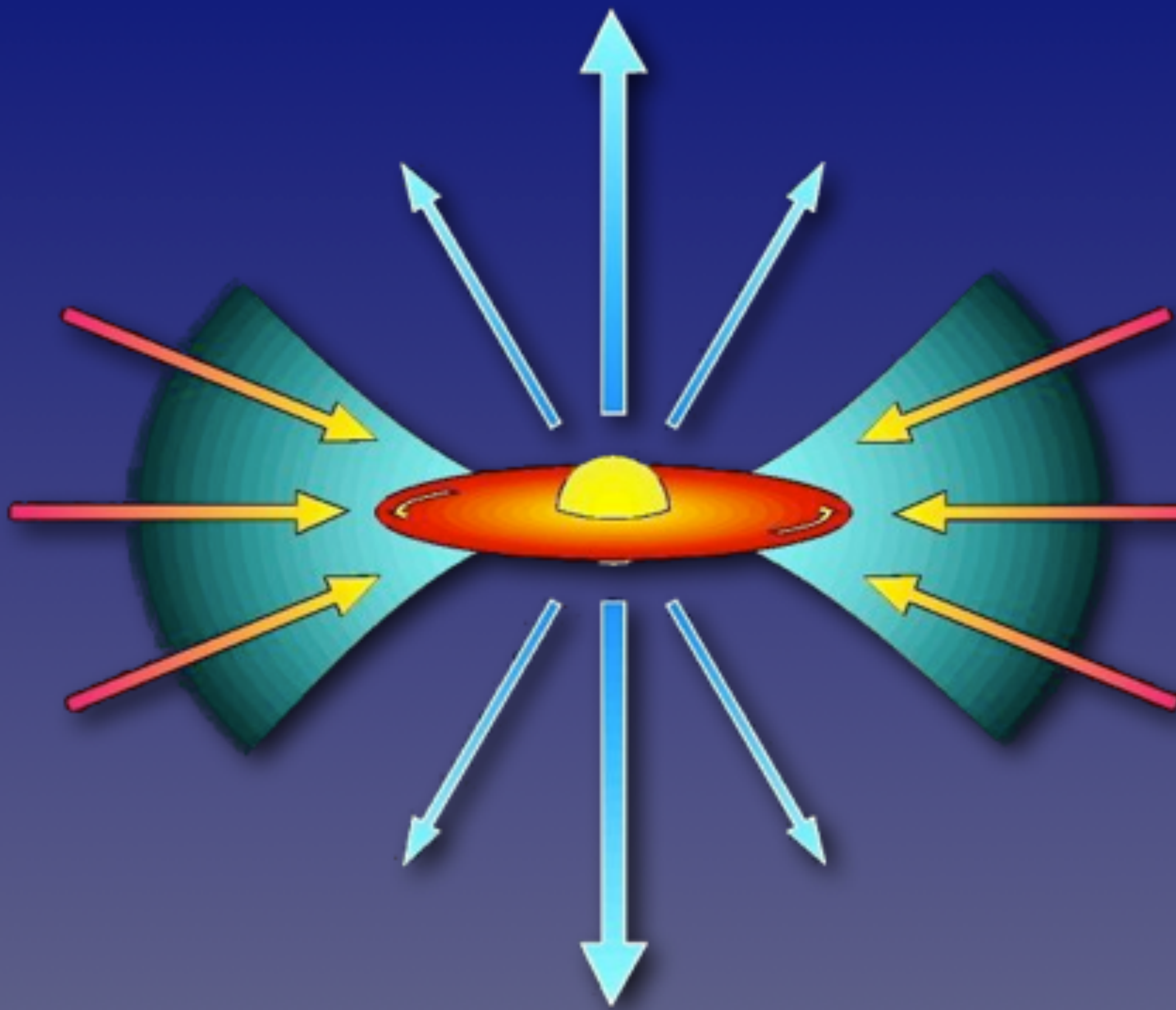
$$L_{acc} \equiv \frac{GM_*\dot{M}}{R_*} = 61\,L_{sun}\left(\frac{\dot{M}}{10^{-5}\,M_{sun}\ \mathrm{yr}^{-1}}\right)\left(\frac{M_*}{1M_{sun}}\right)\left(\frac{R_*}{5R_{sun}}\right)^{-1}$$

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

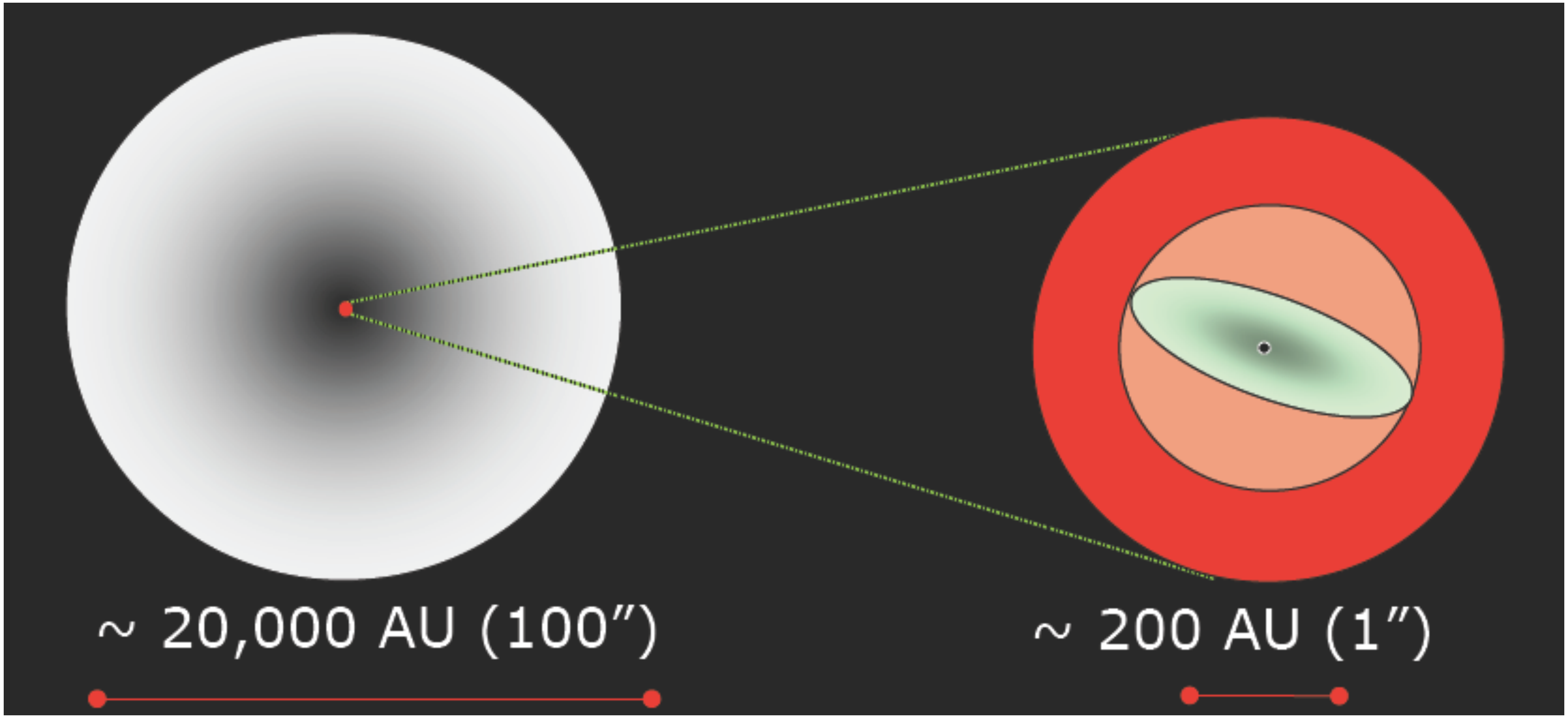
  0.5-1 < M(T Tauri) < 2-3 Msun

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

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

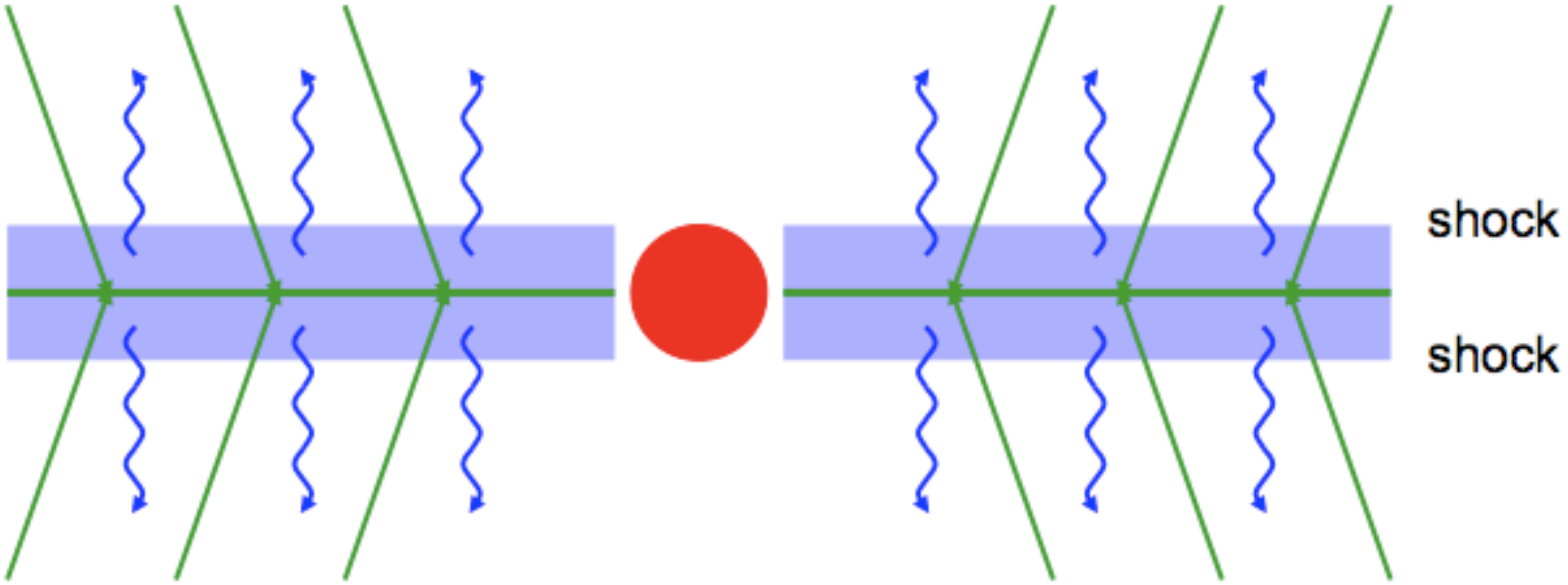
As in T Tau, HAeBe also show disc emission.

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

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

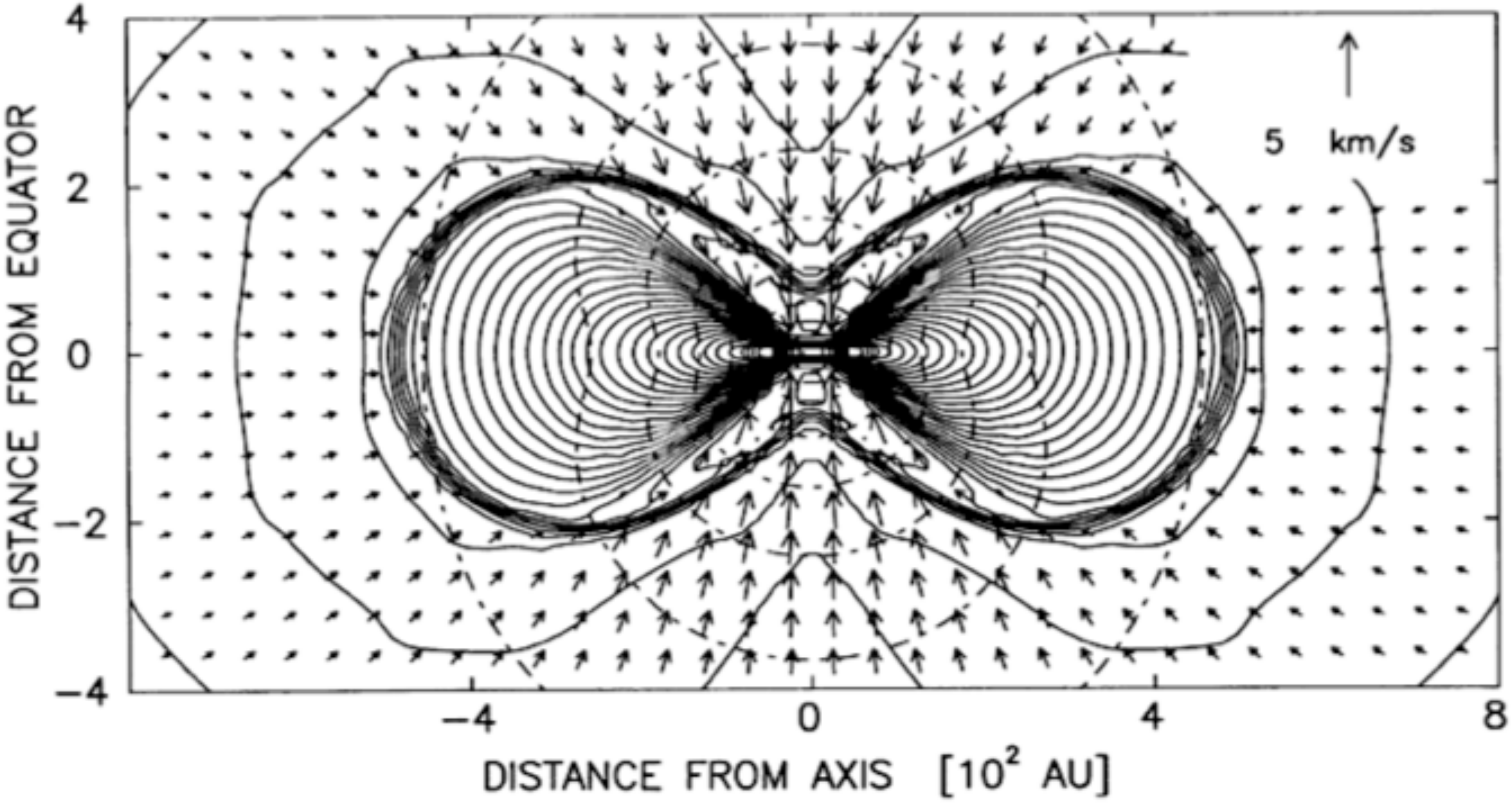
At 10 AU from $1M_\odot$ star:

$$T \approx 25000\,K$$

- 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:

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

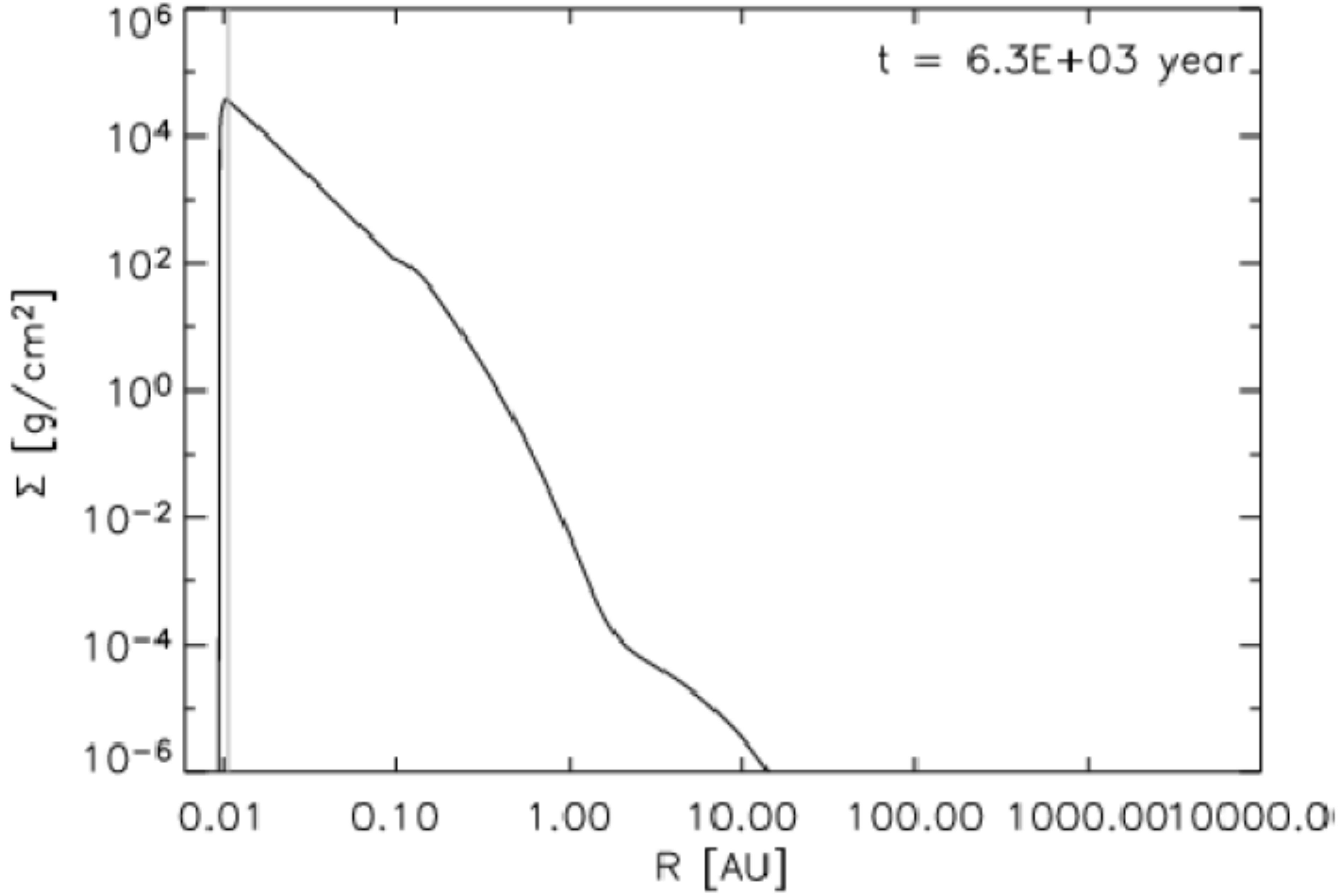
$$\Omega_K \equiv \sqrt{\frac{GM_*}{r^3}}$$

Kepler frequency

A perdületmegmaradás problémája

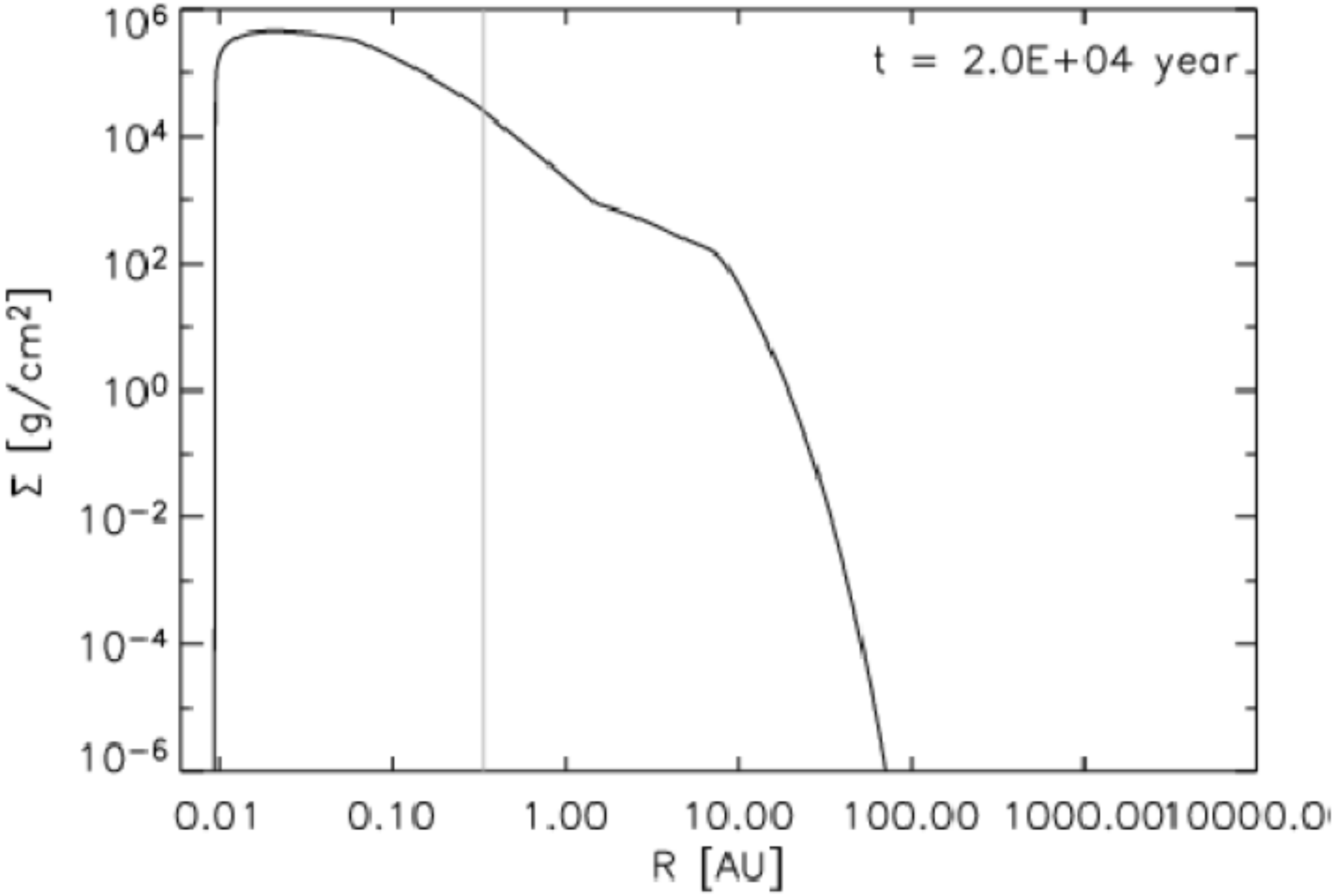
- Angular momentum of 1 $M_\odot$ in 10 AU disk:
  3×10^{53} cm²/s
- Angular momentum of 1 $M_\odot$ in 1 $R_\odot$ star:
  $<<6 \times 10^{51}$ cm²/s (=breakup-rotation-speed)
- Original angular momentum of disk = 50x higher than maximum allowed for a star
- Angular momentum is strictly conserved!
- 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

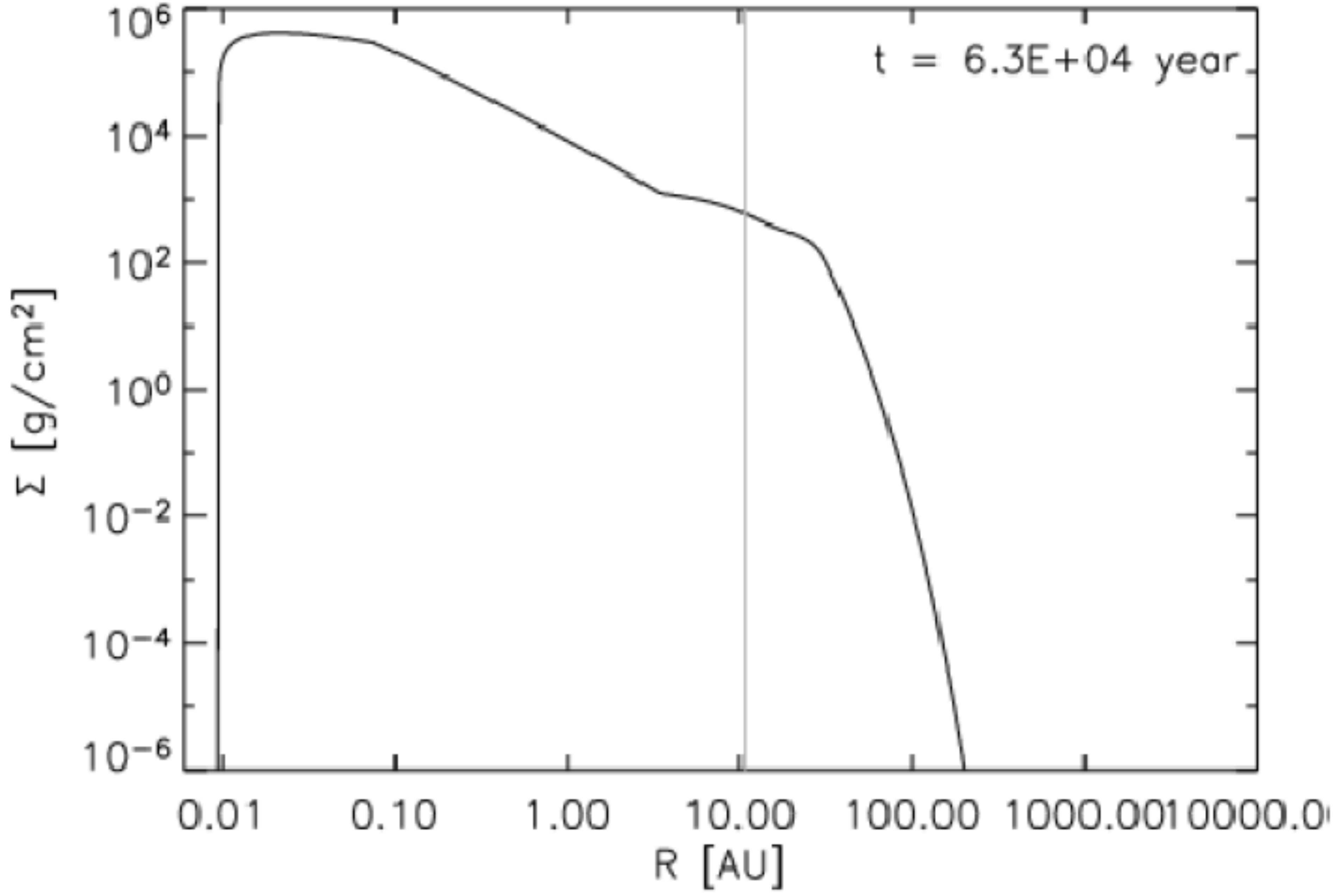


CD

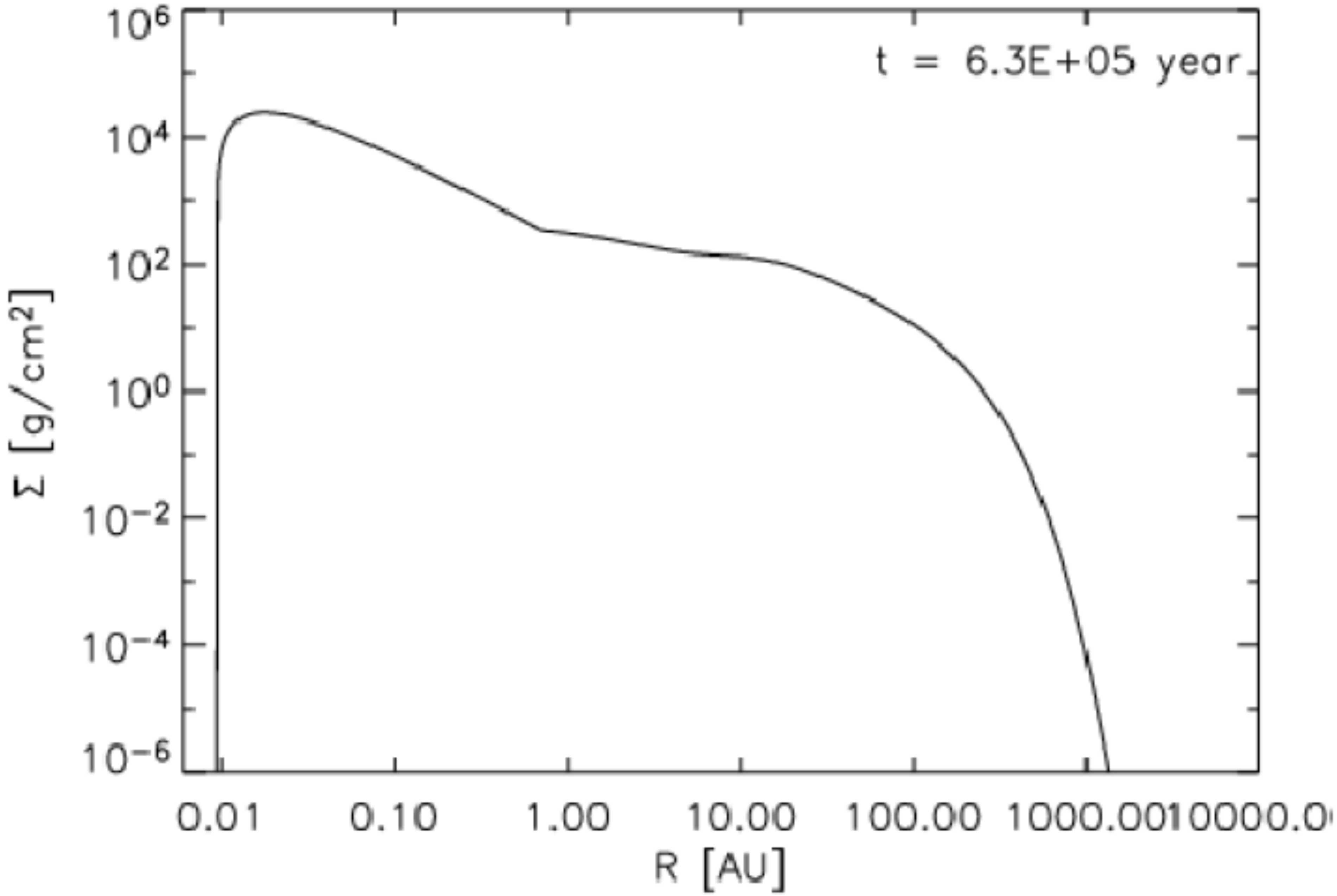
Formation & viscous spreading of disk



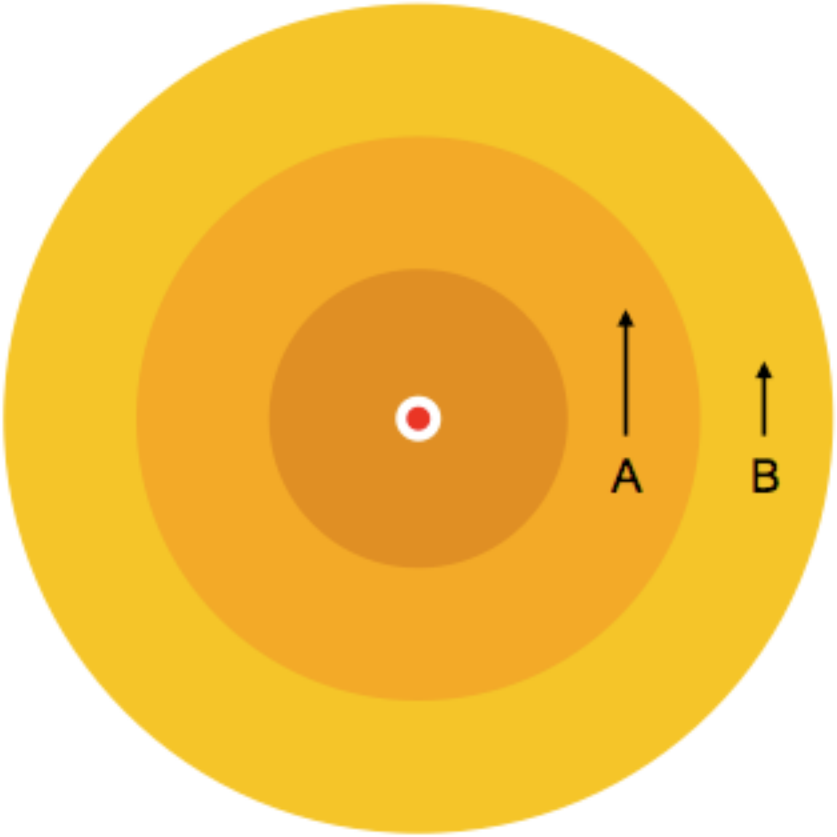
Formation & viscous spreading of disk



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:

$$l = rv_{\phi} = r^2\Omega_K = \sqrt{GM_* r}$$

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.)

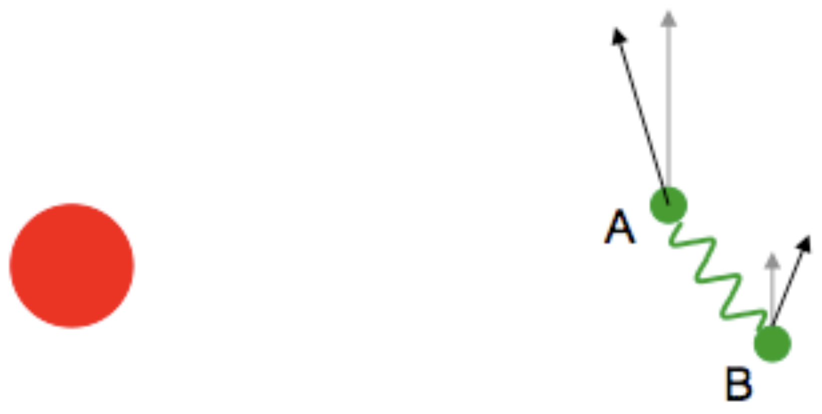
But most people believe that turbulence in disks can have only one origin: *Magneto-rotational instability (MRI)*

Magneto-rotational instability (MRI)

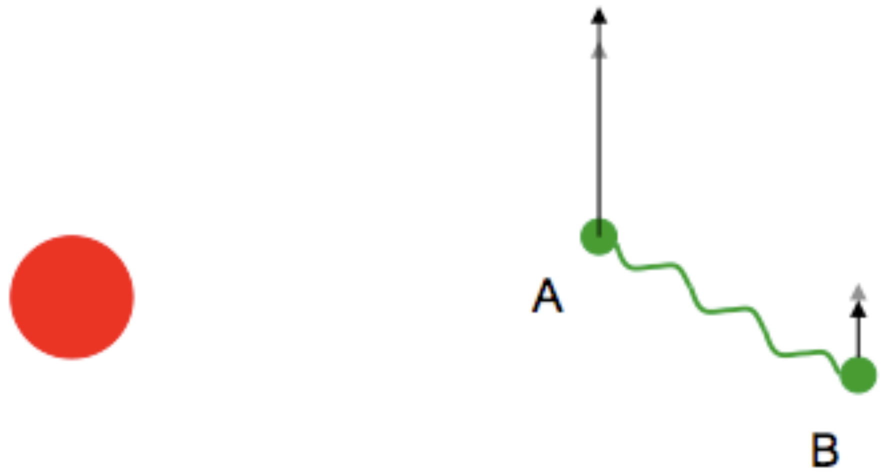
(Also often called Balbus-Hawley instability)

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!

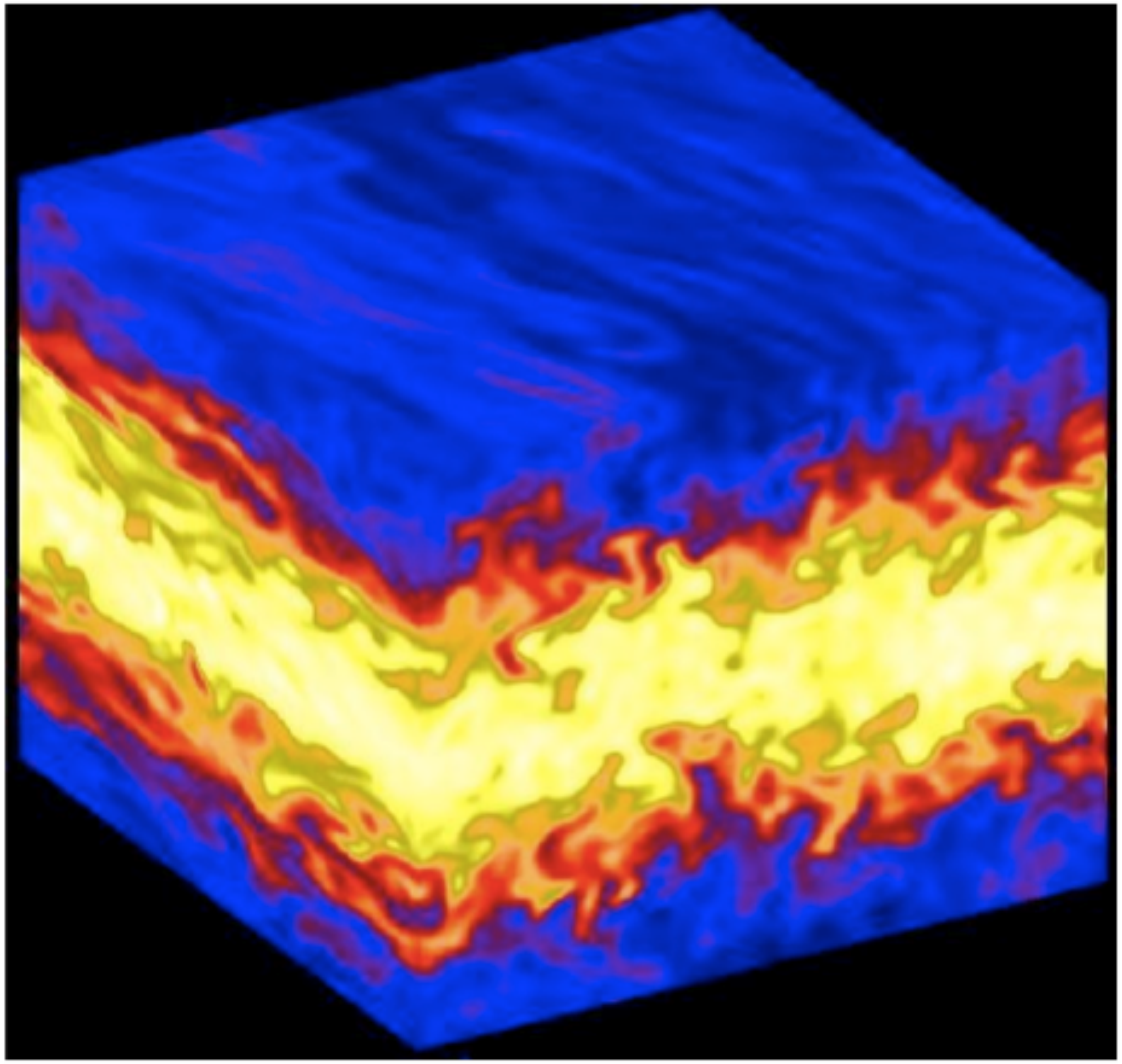


The lower orbit of A causes an increase in its velocity, while B decelerates. This enhances their velocity difference! This is positive feedback: an instability.



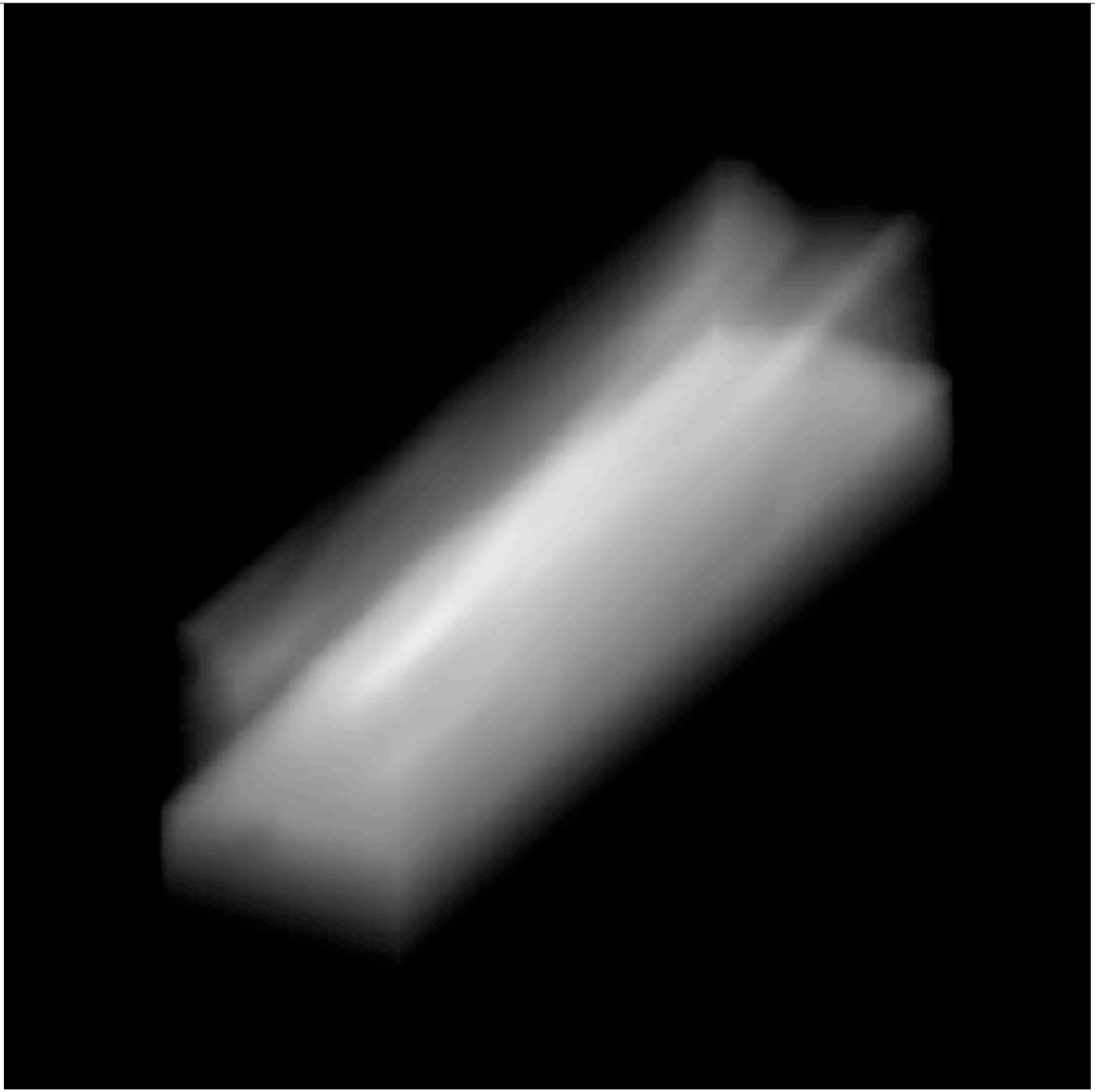
Causes turbulence in the disk

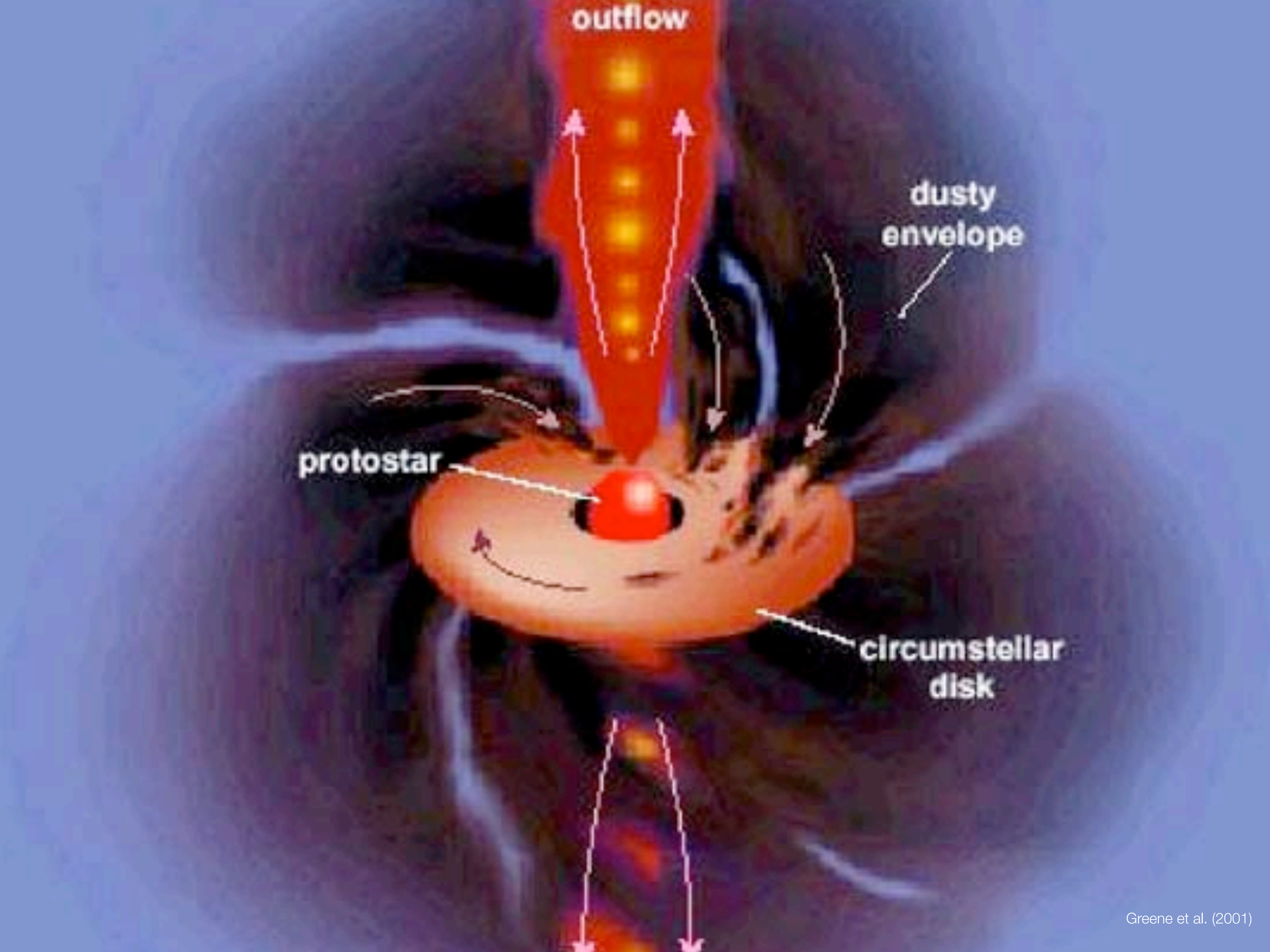
Magneto-rotational instability



Johansen & Klahr (2005); Brandenburg et al.

Magneto-rotational instability





Greene et al. (2001)