Star Formation

Hsi-Wei Yen (ASIAA)

Image credit: NASA, ESA, CSA, STScI


100 billion stars in our galaxy
Image credit: ESO/S. Brunier

Wide ranges of stellar properties

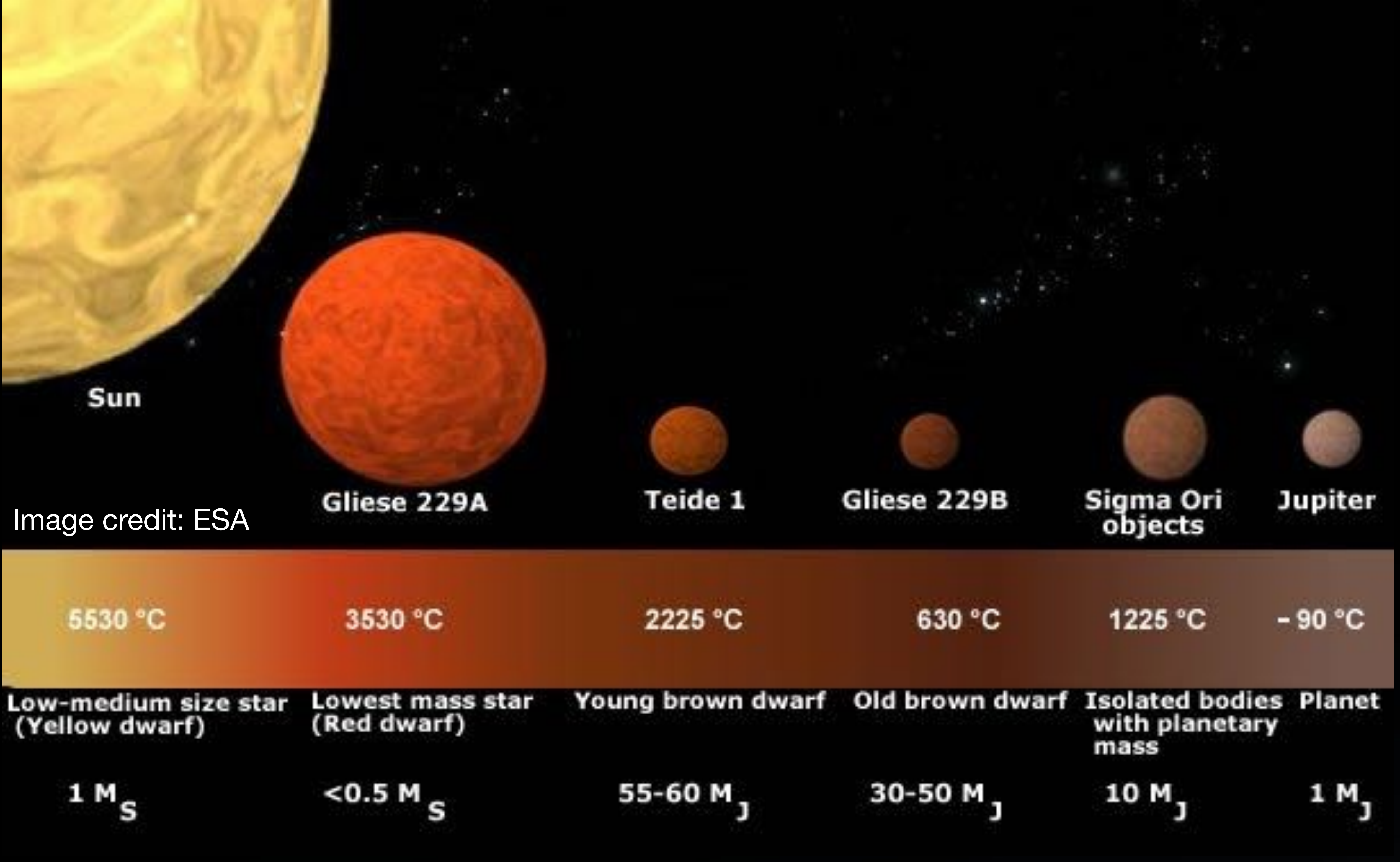


Image credit: ESA

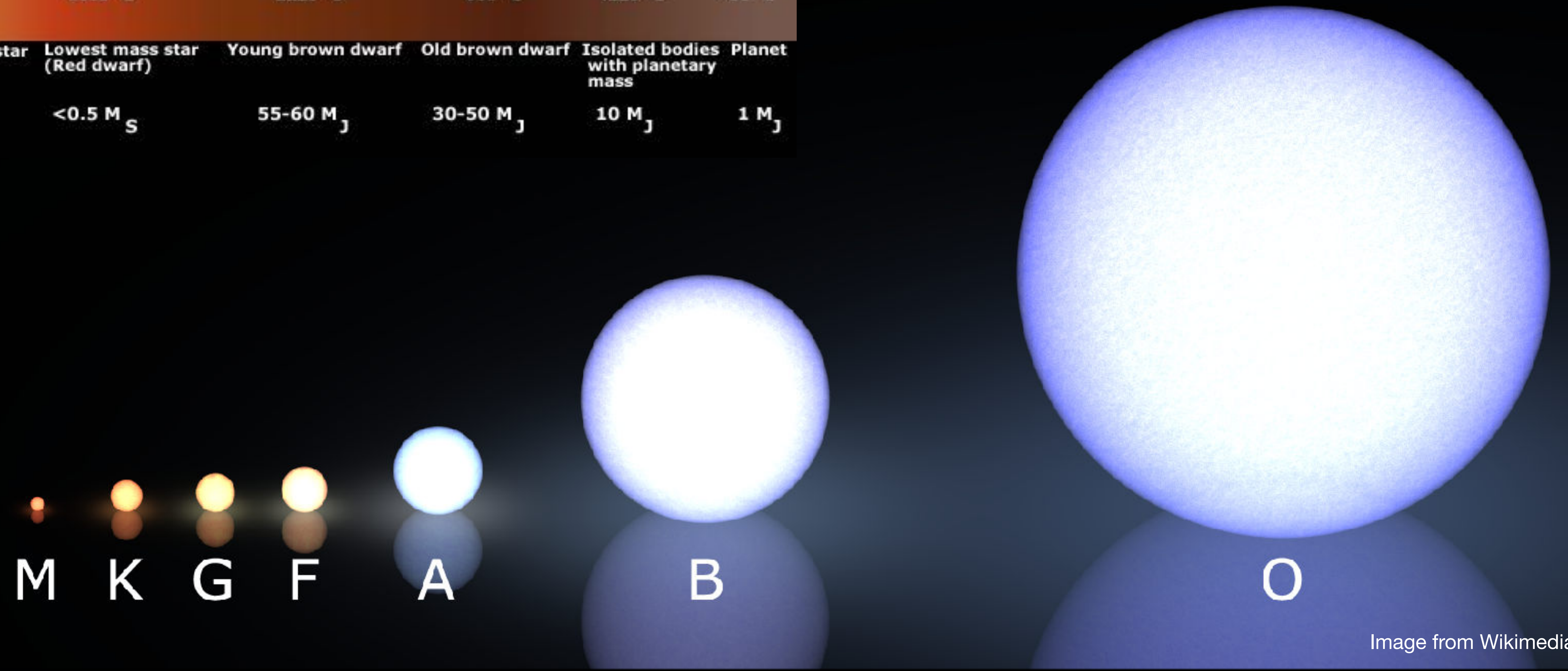


Image from Wikimedia Commons (LucasVB.)

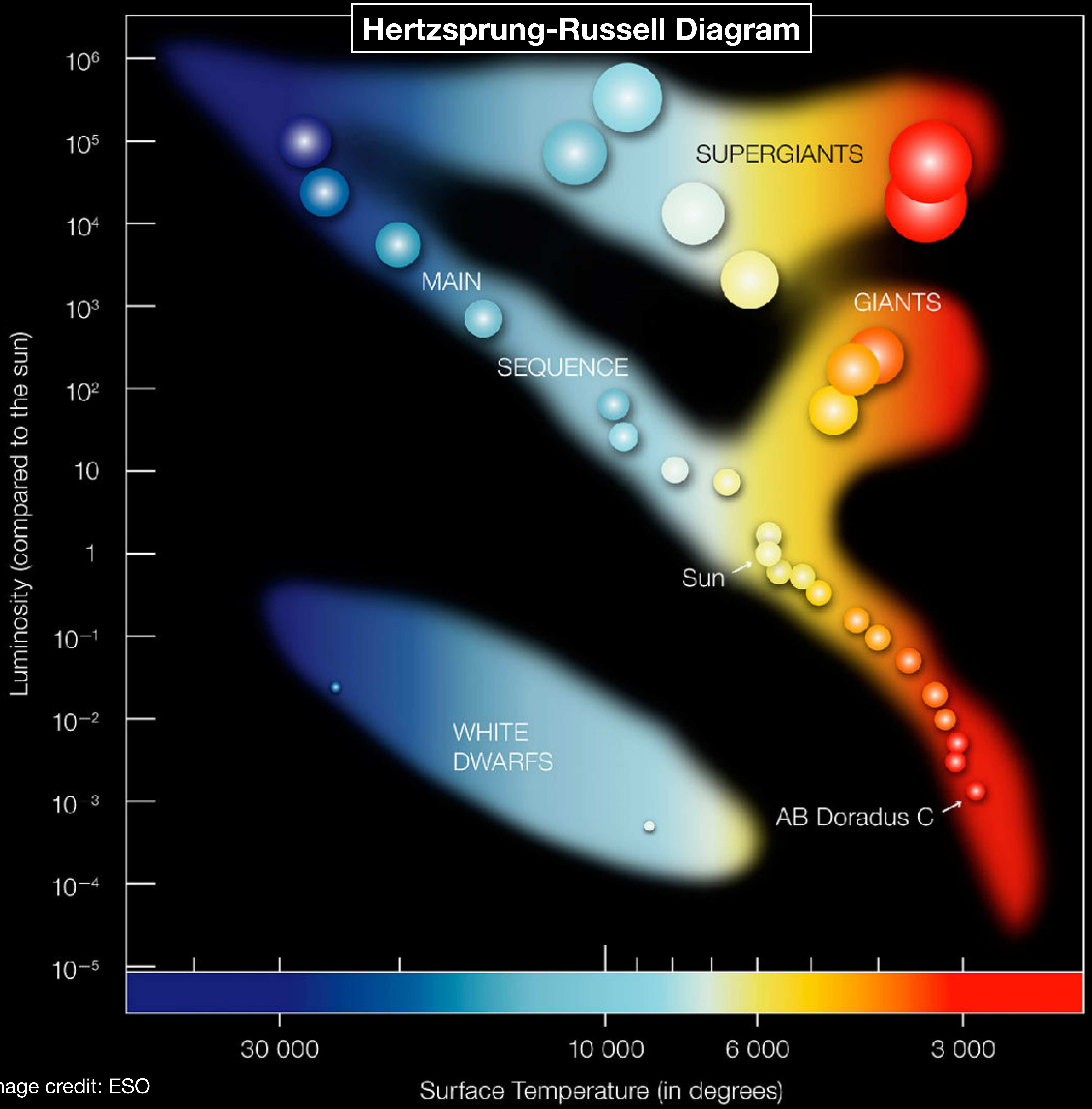


Image credit: ESO

The key parameter is mass

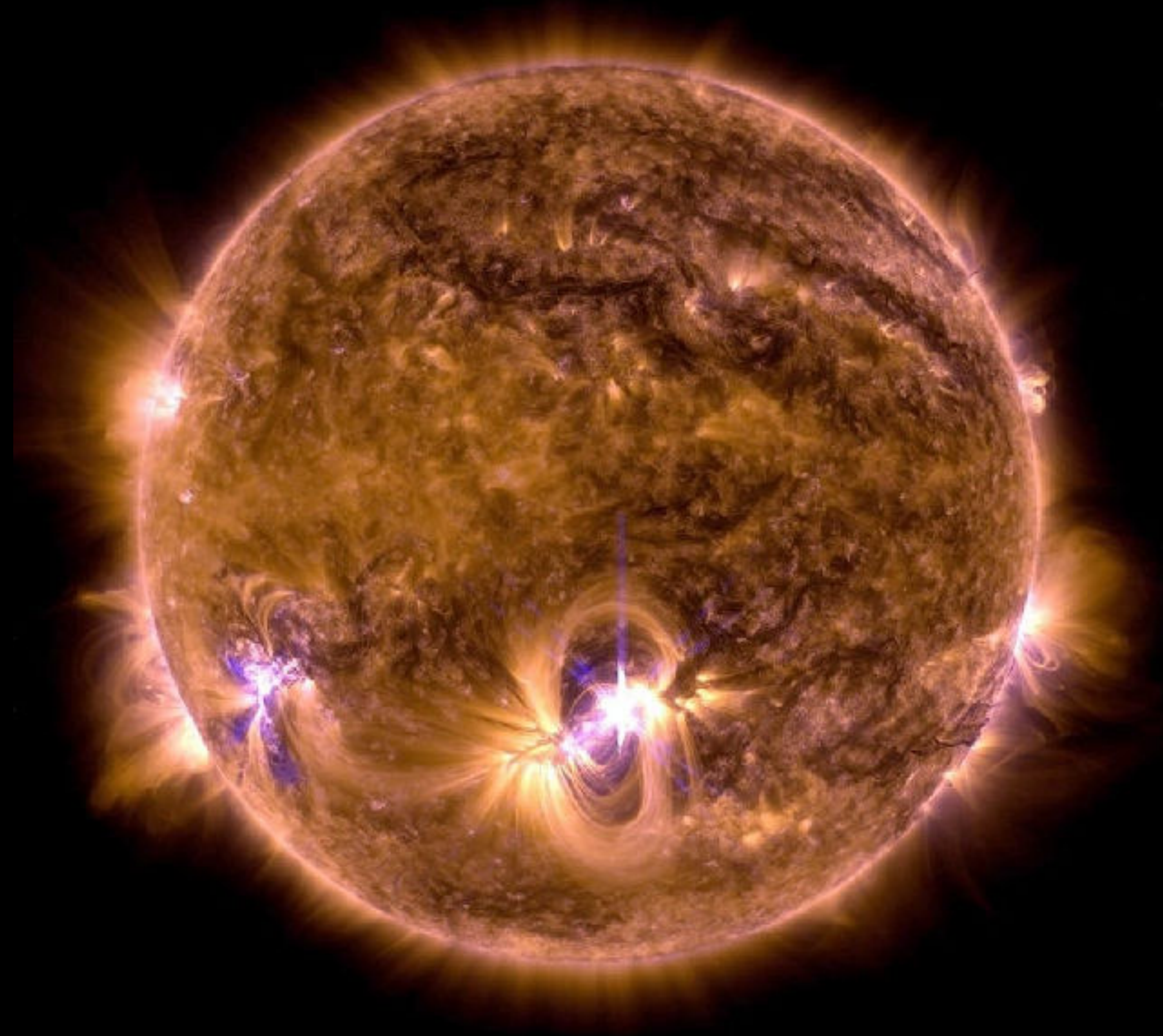


Image credit: NASA/SDO

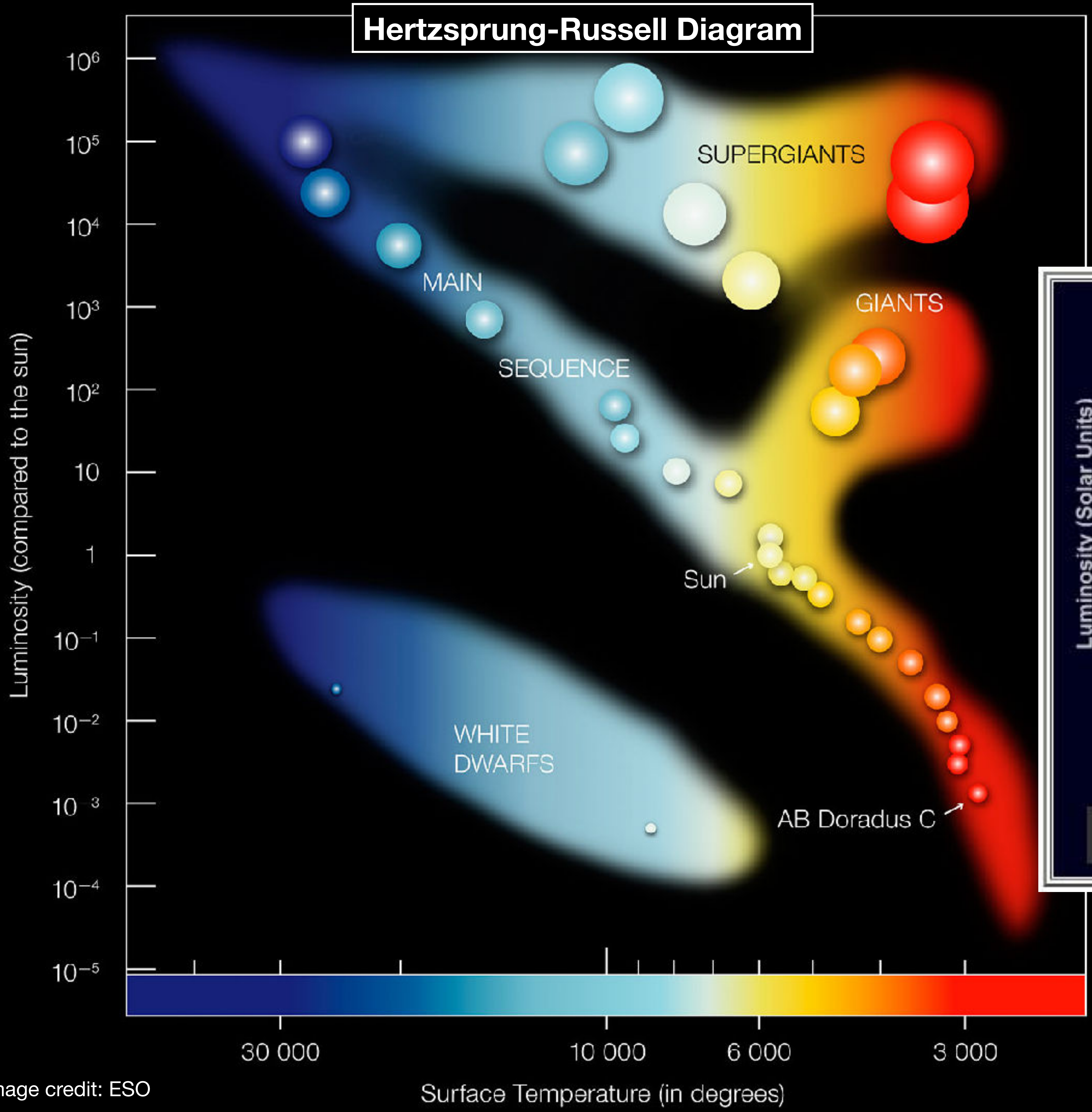


Image credit: ESO

Evolutionary tracks

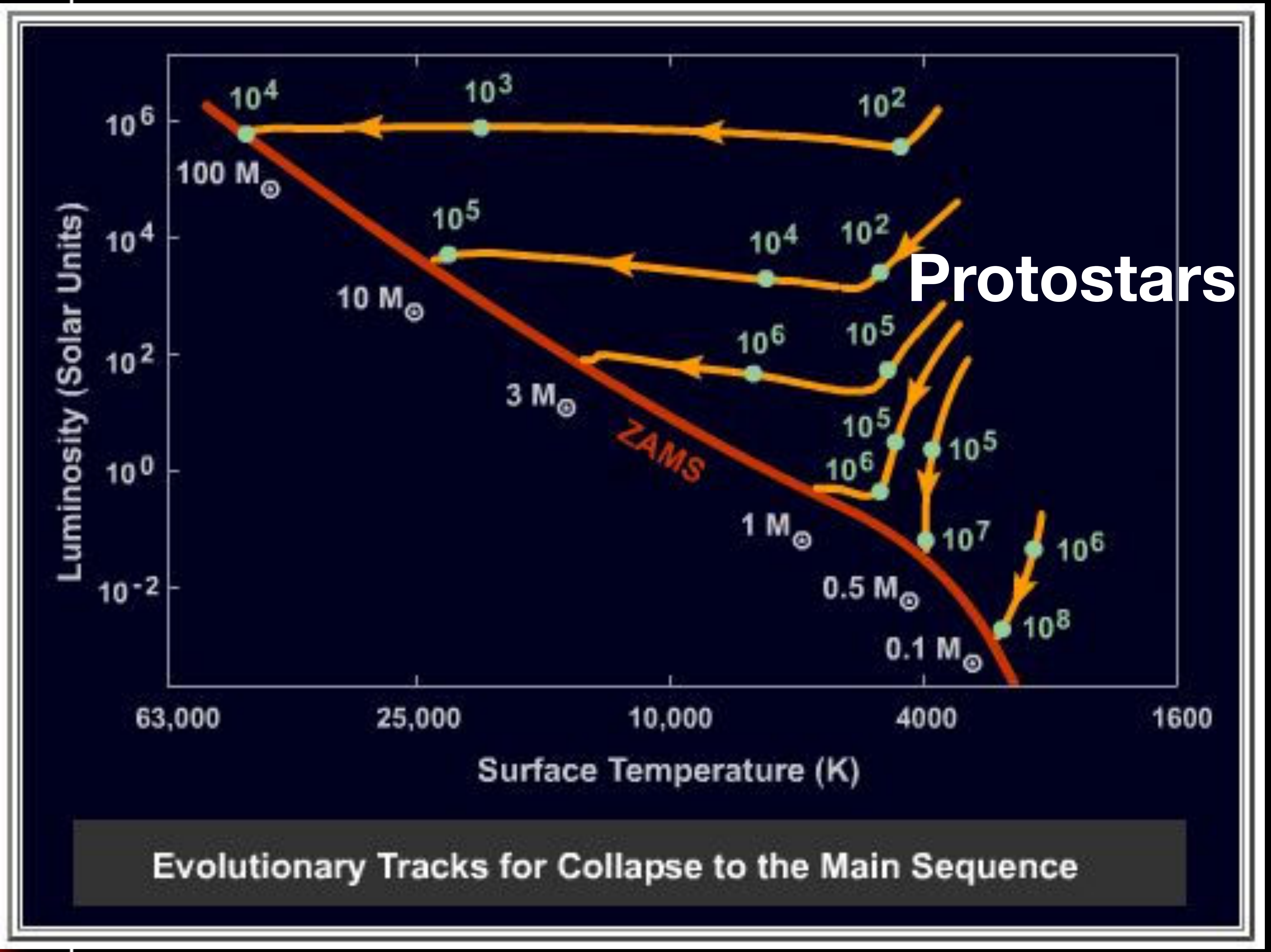


Image credit: CfA

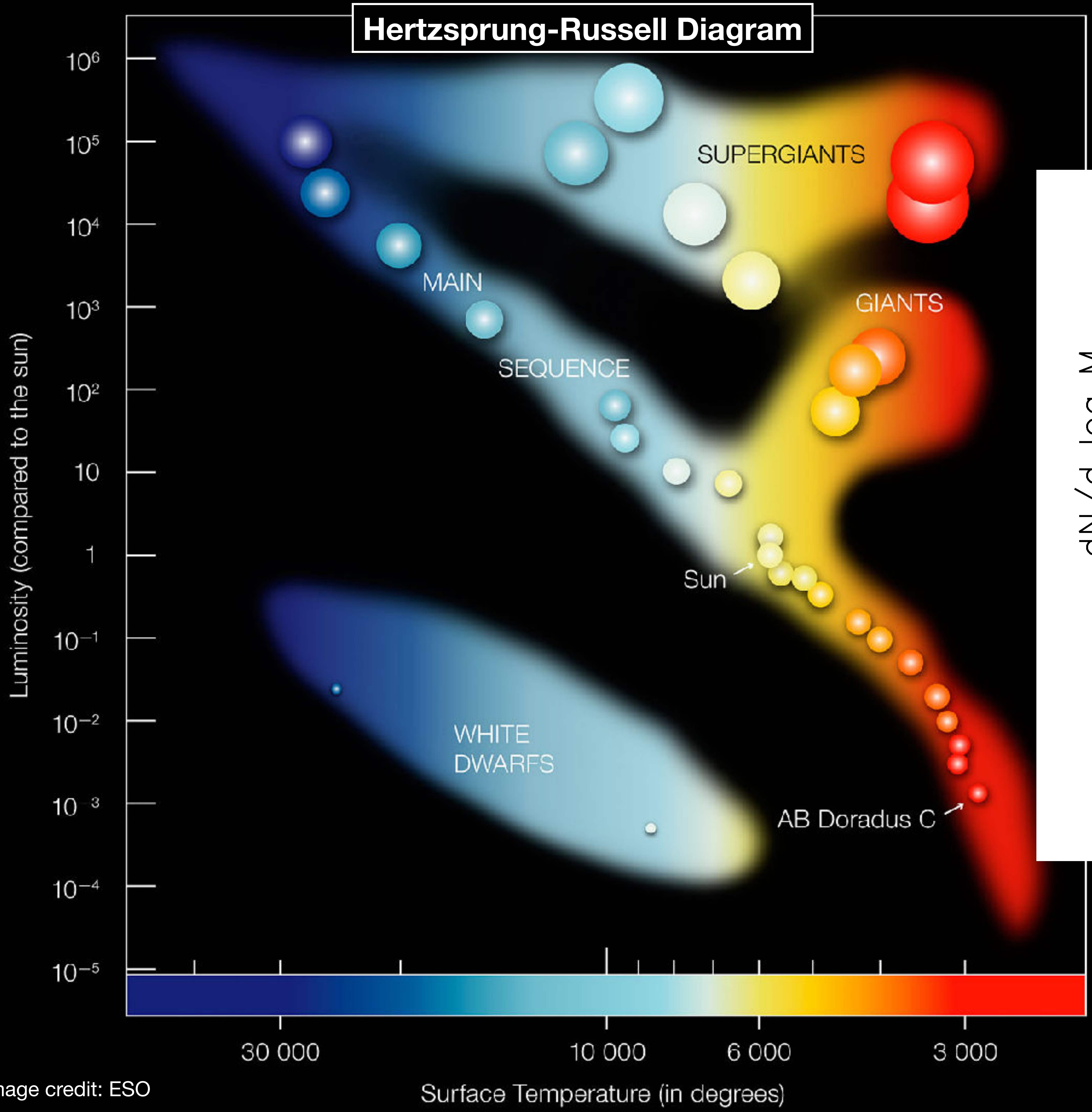
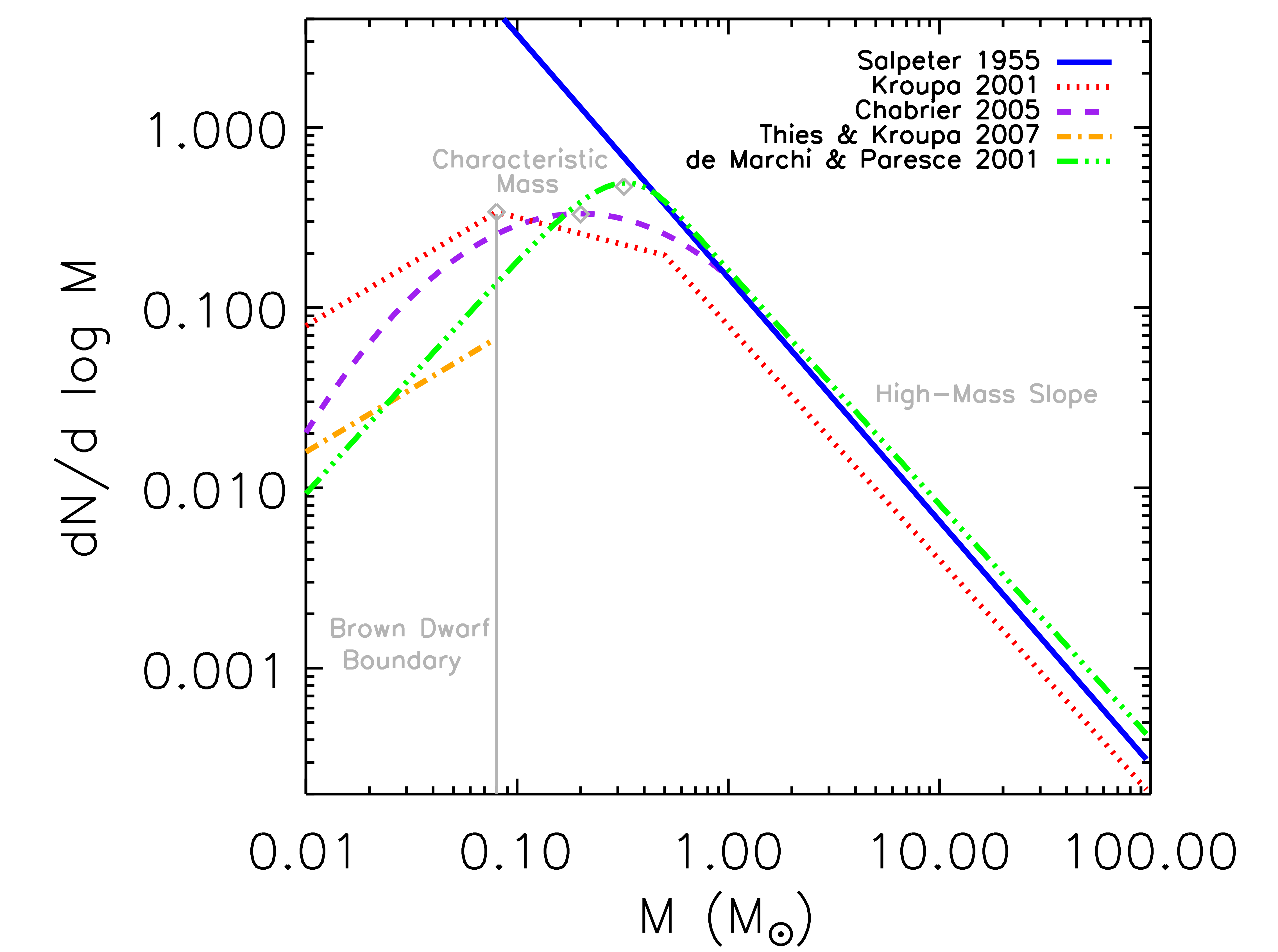


Image credit: ESO

Initial Mass Function (IMF)



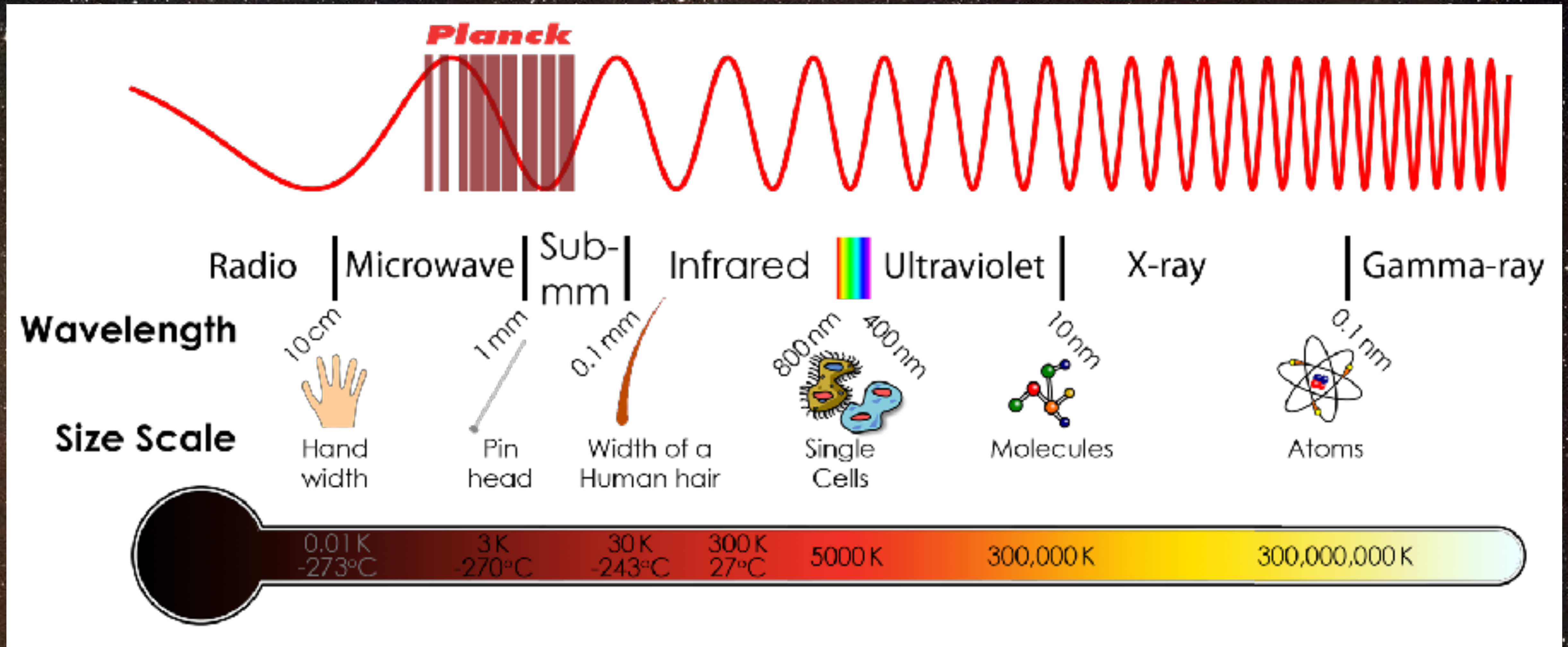
Offner et al. 2013

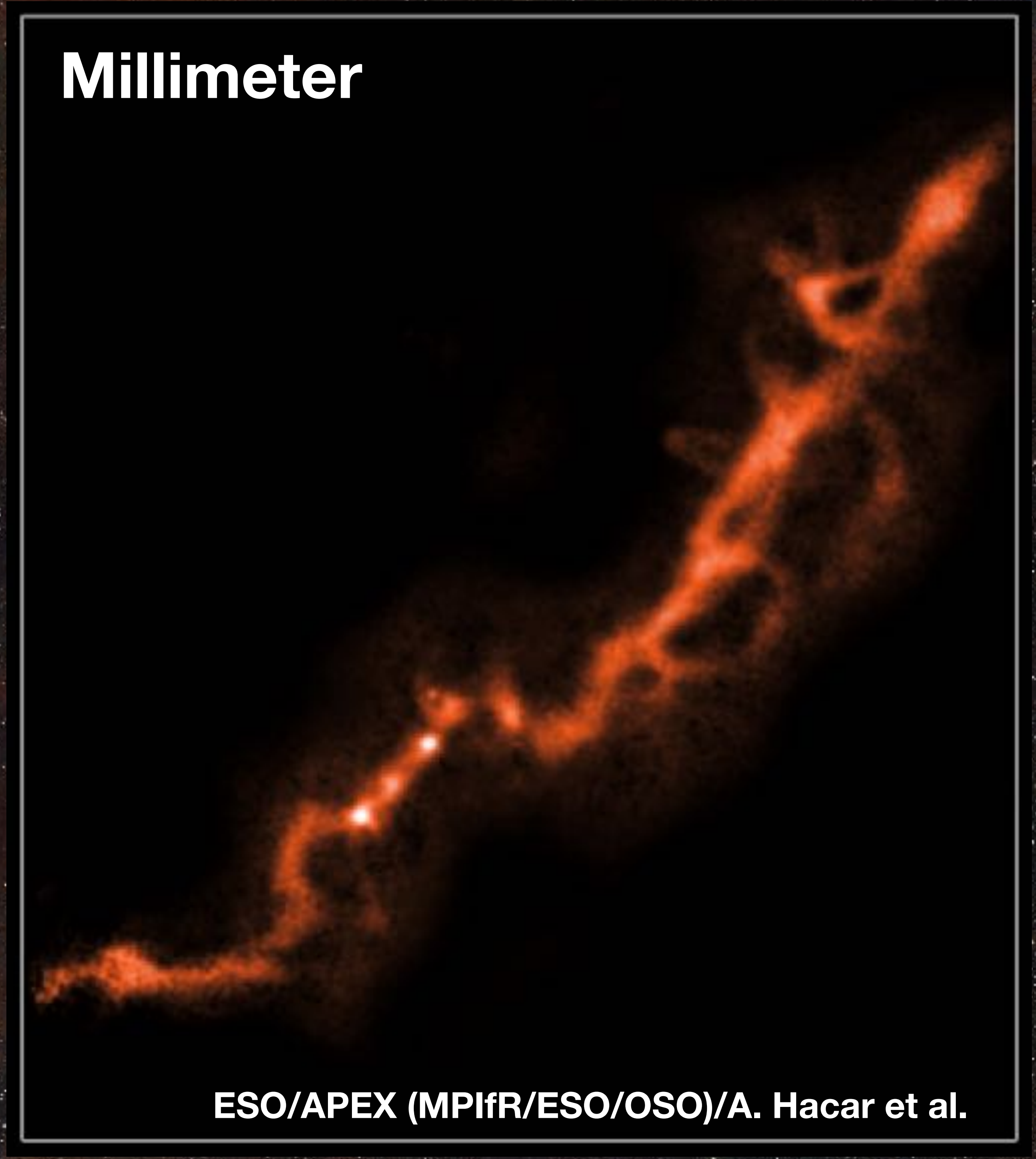
Galaxies are full of structures in gas and dust

Image credit: NASA, ESA, CSA, STScI,
J. Lee (STScI), T. Williams (Oxford), PHANGS Team, E. Wheatley (STScI)

Origins of stars and planets — Molecular clouds

Image credit: Digitized Sky Survey 2/D.D. Martin



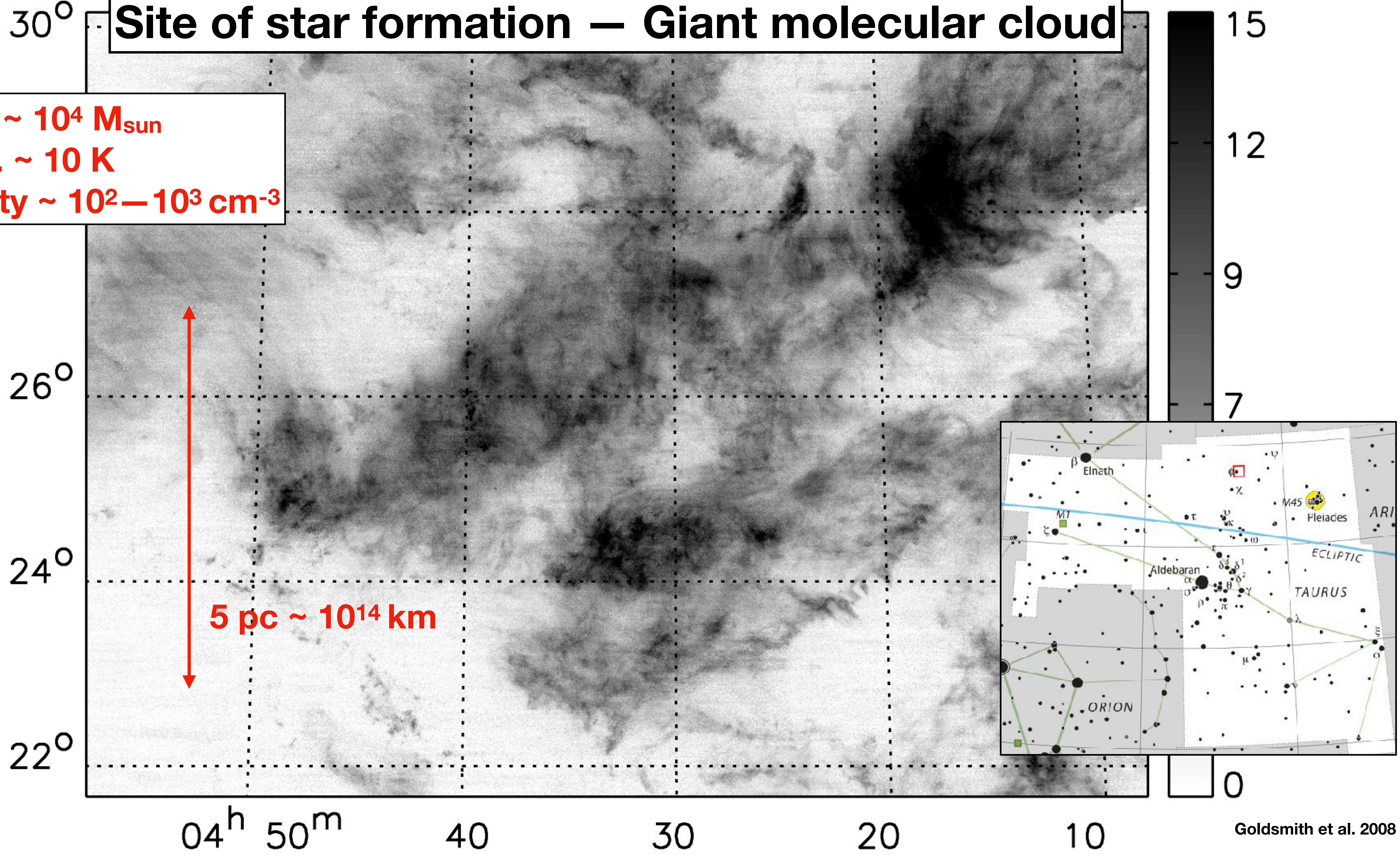


Radio image - Dust thermal emission

Image credit: Digitized Sky Survey 2/D.D. Martin

Site of star formation — Giant molecular cloud

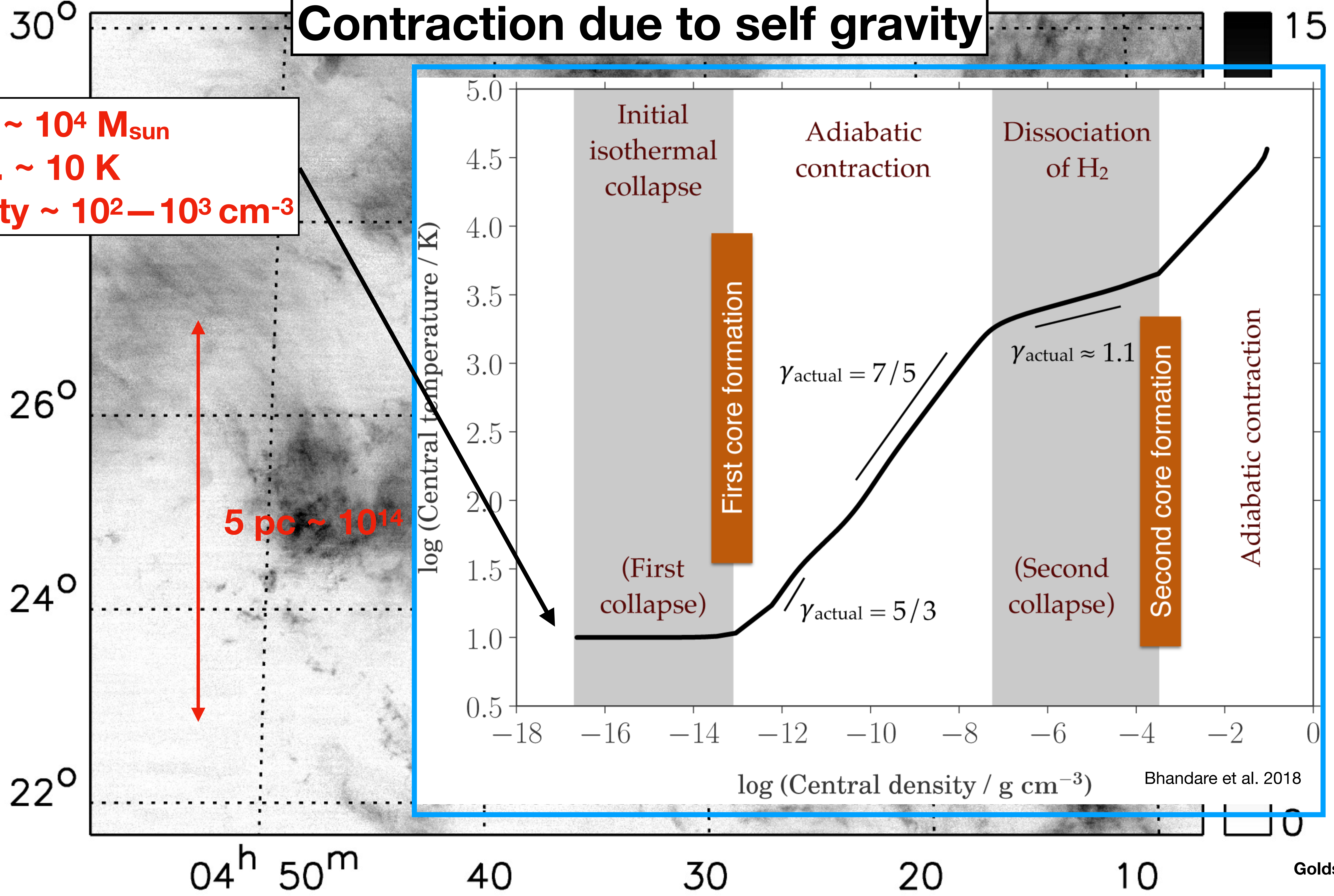
Mass ~ 10^4 M_{sun}
Temp. ~ 10 K
Density ~ $10^2 — 10^3$ cm^{-3}



Goldsmith et al. 2008

Contraction due to self gravity

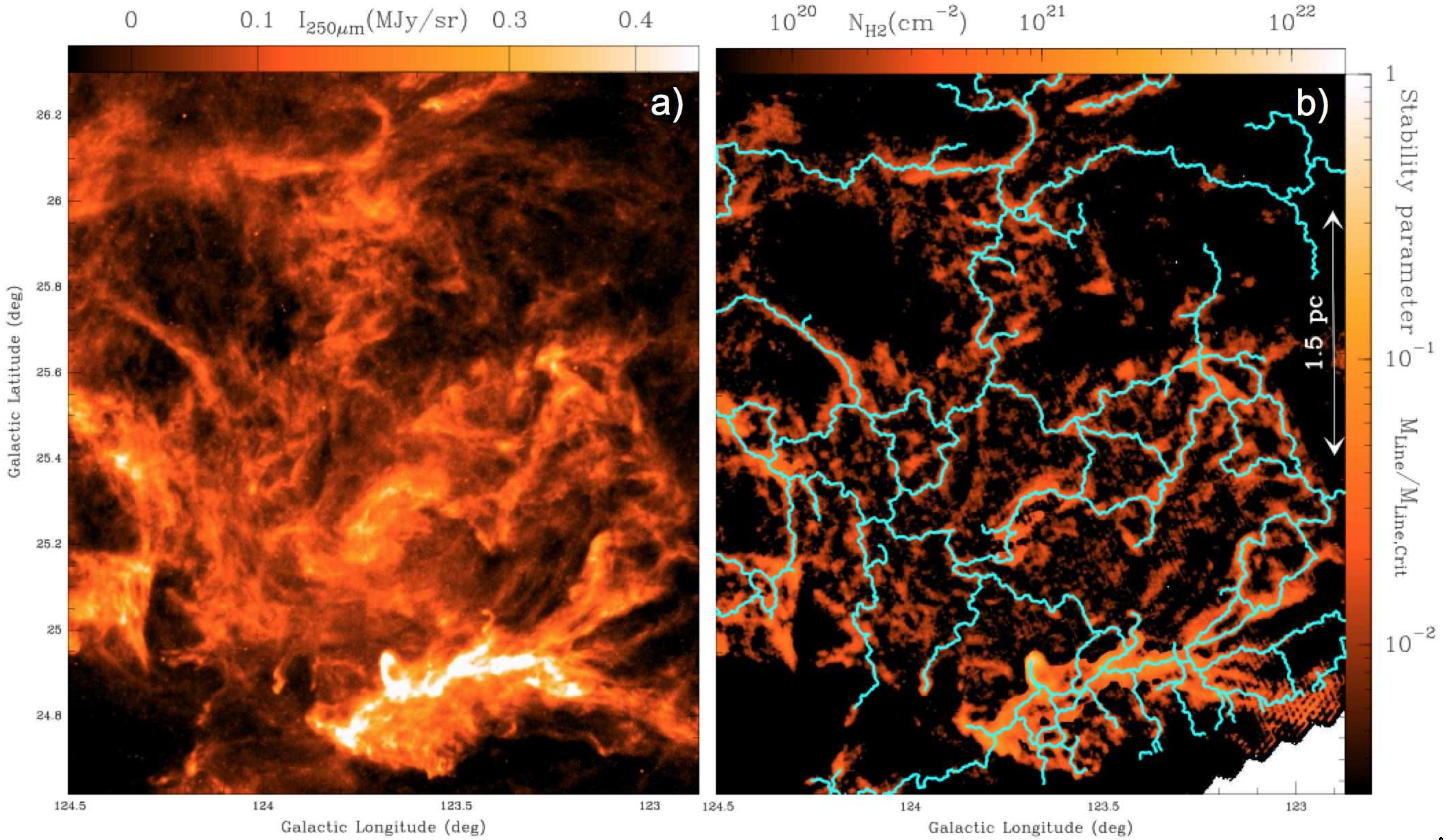
Mass ~ 10^4 M_{sun}
Temp. ~ 10 K
Density ~ 10^2—10^3 cm^{-3}



Goldsmith et al. 2008

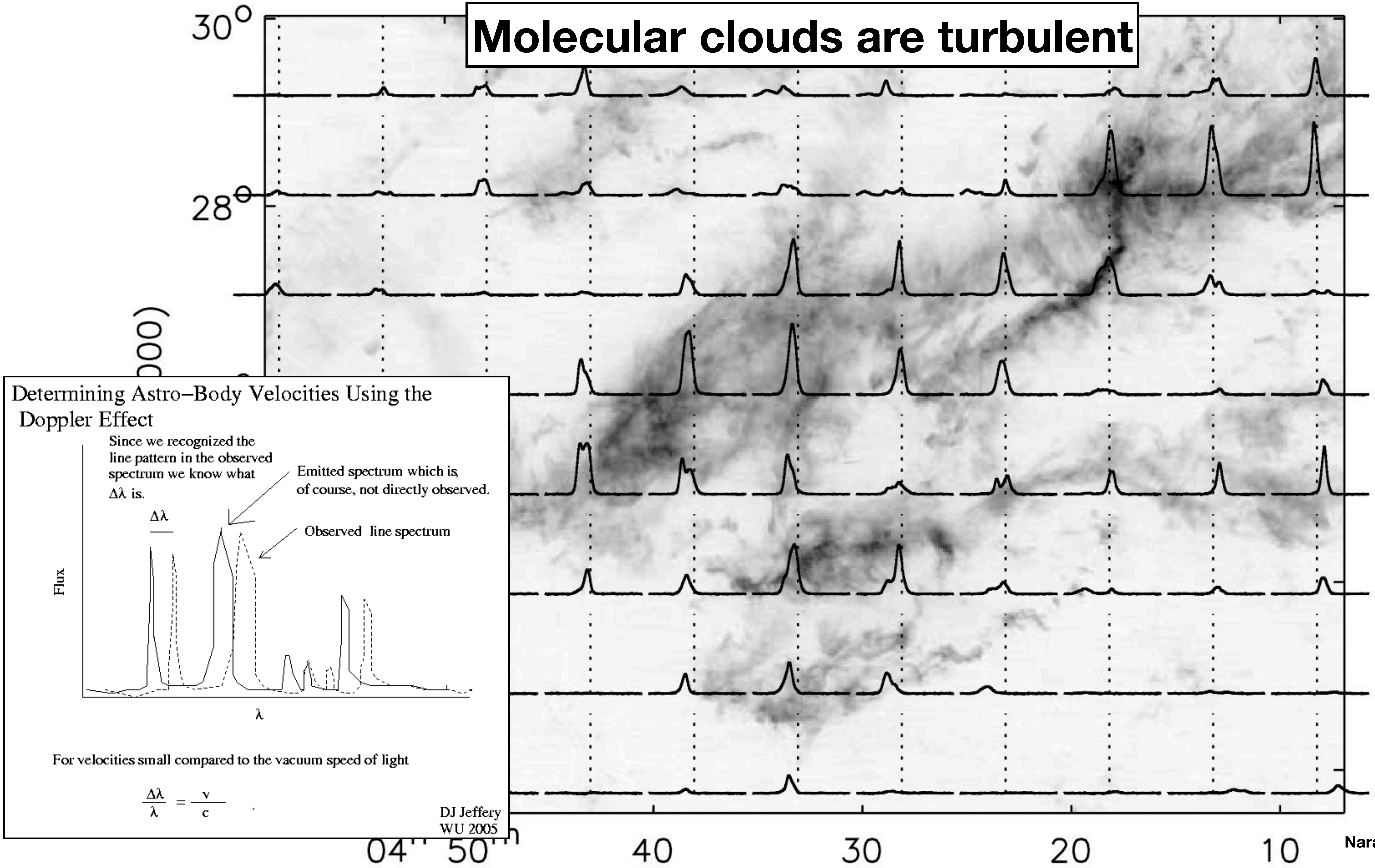
Molecular clouds are filamentary

Molecular clouds are filamentary



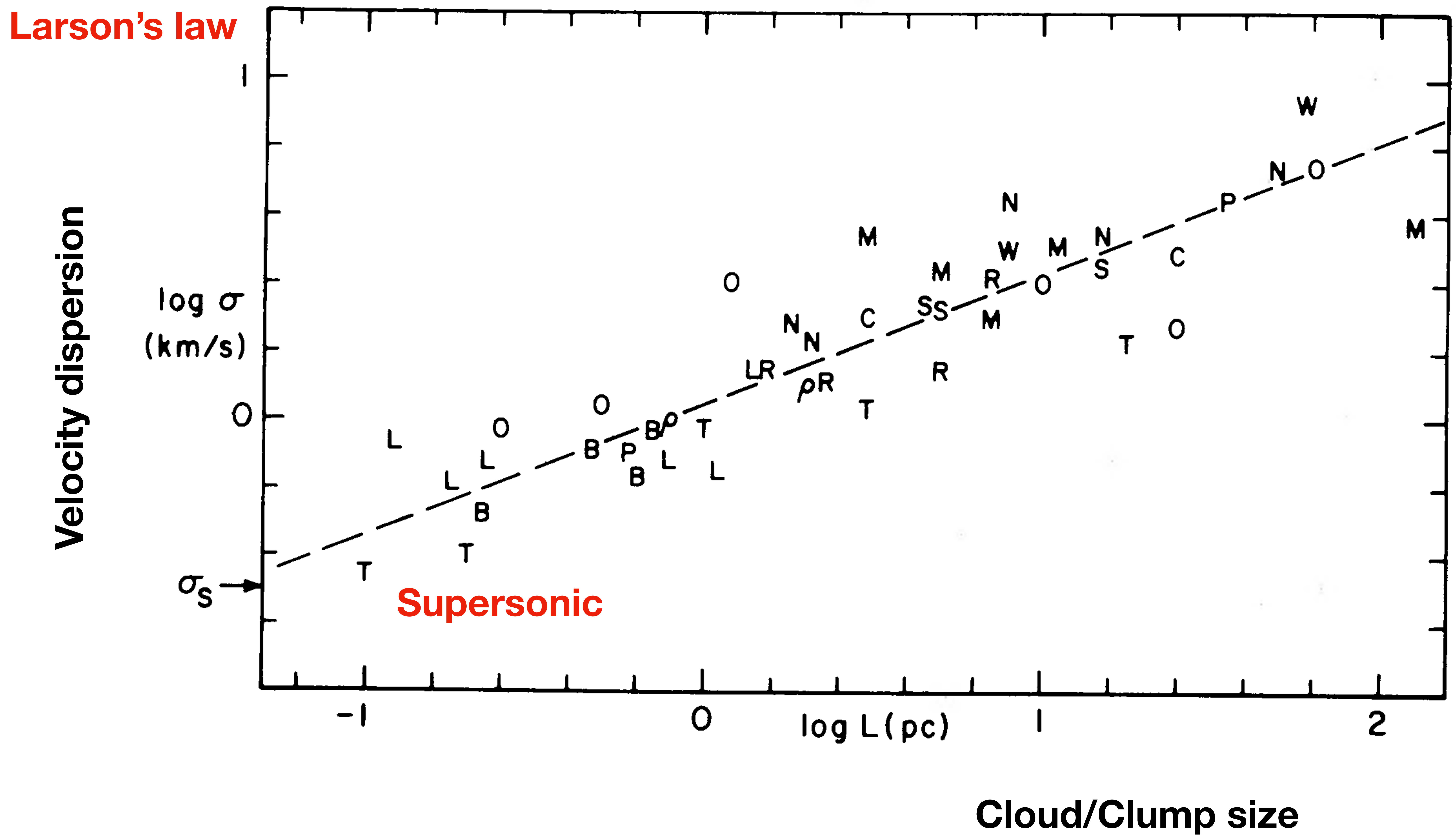
Andre et al. 2014

Molecular clouds are turbulent



Narayanan et al. 2005

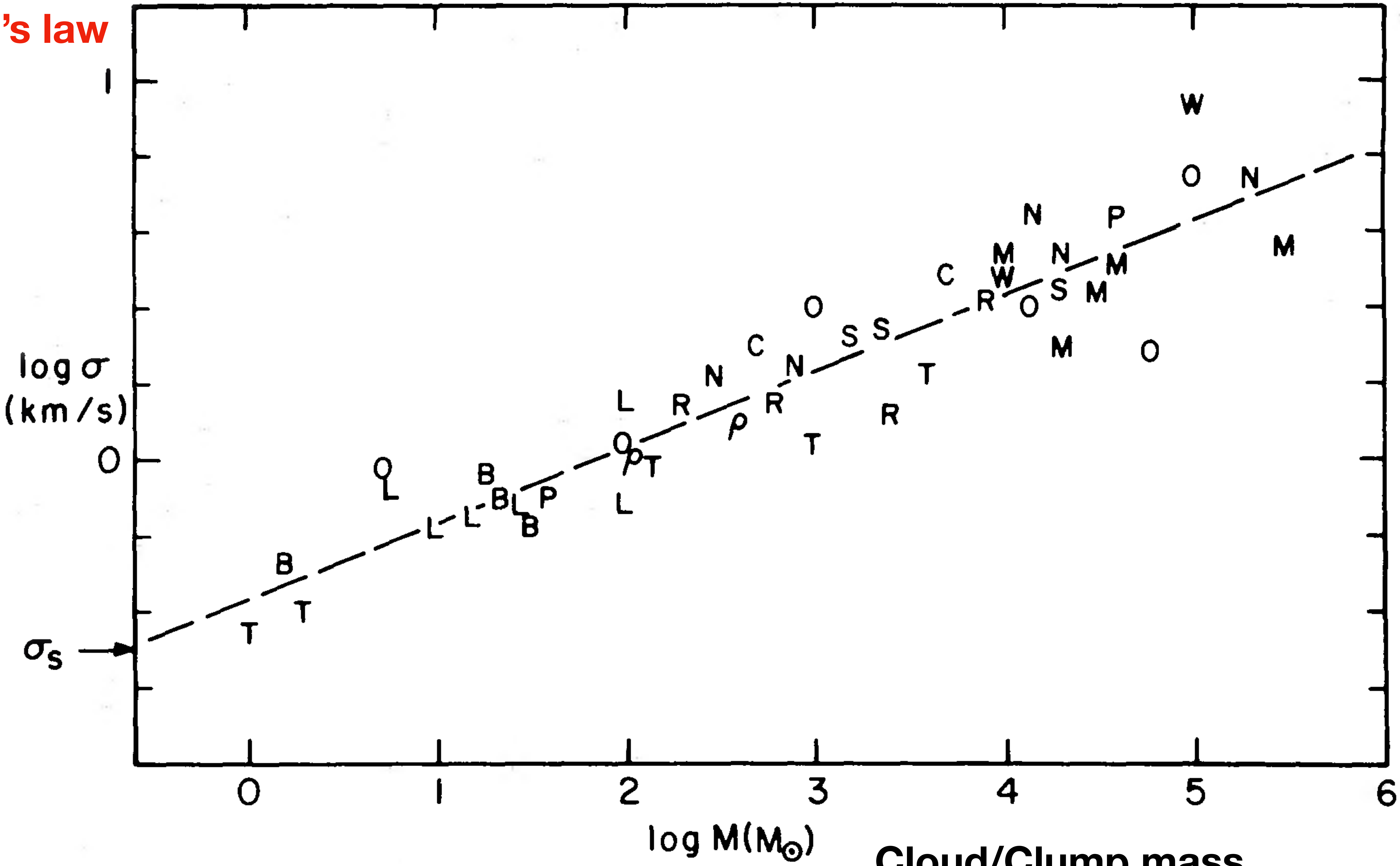
Molecular clouds are turbulent



Larson 1981

Molecular clouds are turbulent

Larson's law



Velocity dispersion

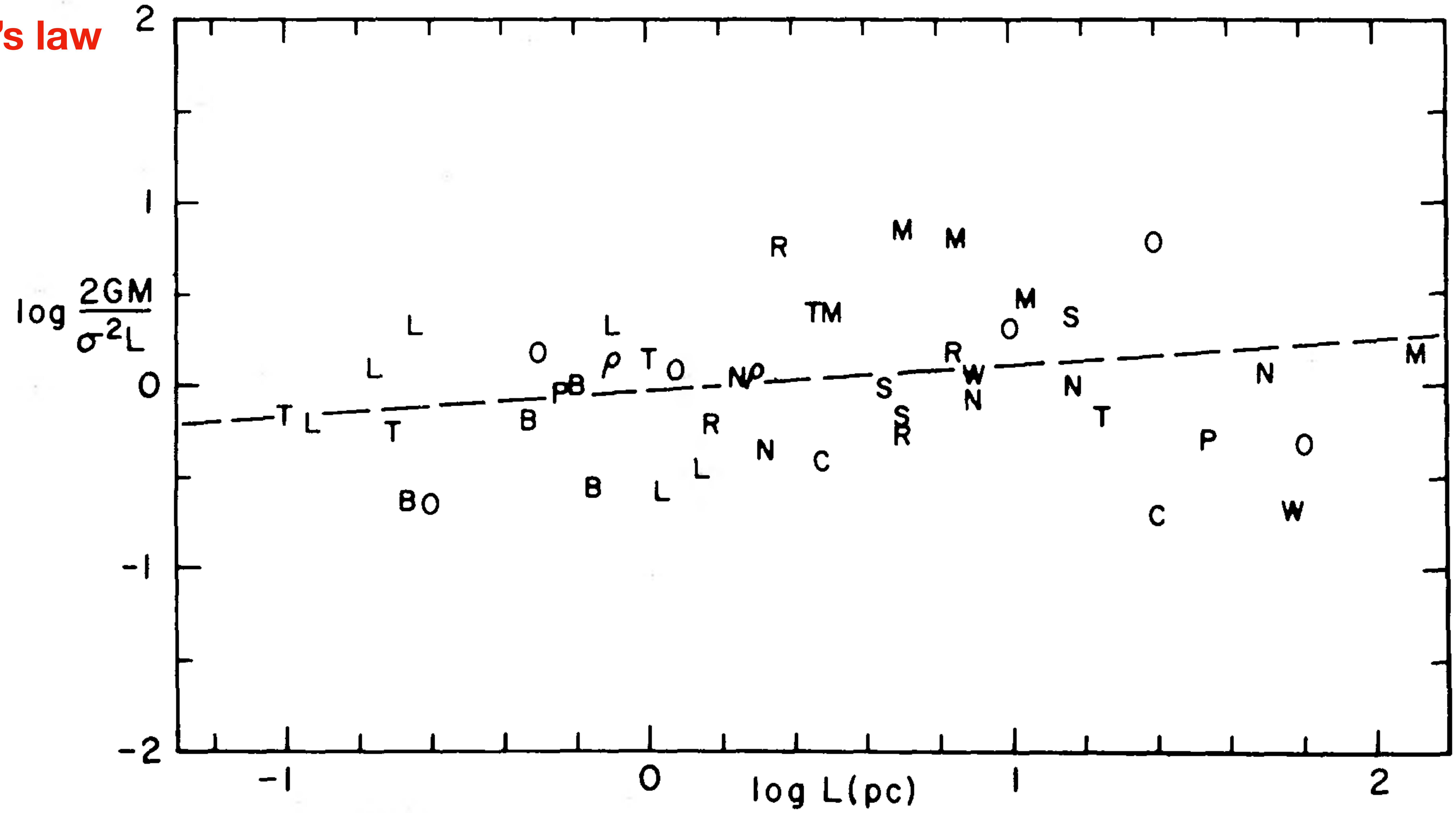
Cloud/Clump mass

Larson 1981

Turbulence can provide support against gravity

Larson's law

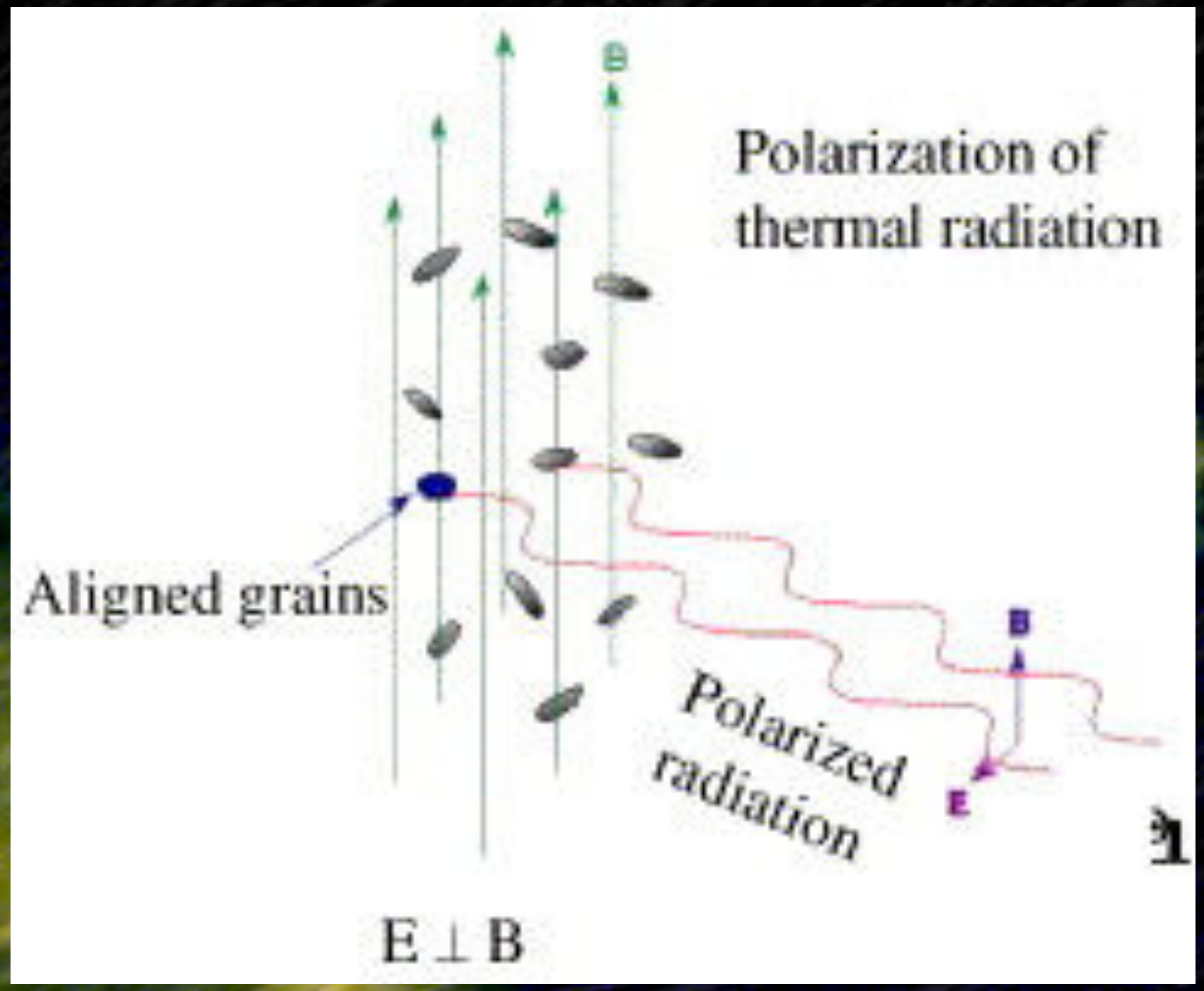
Gravitational / Turbulent energy



Cloud/Clump size

Larson 1981

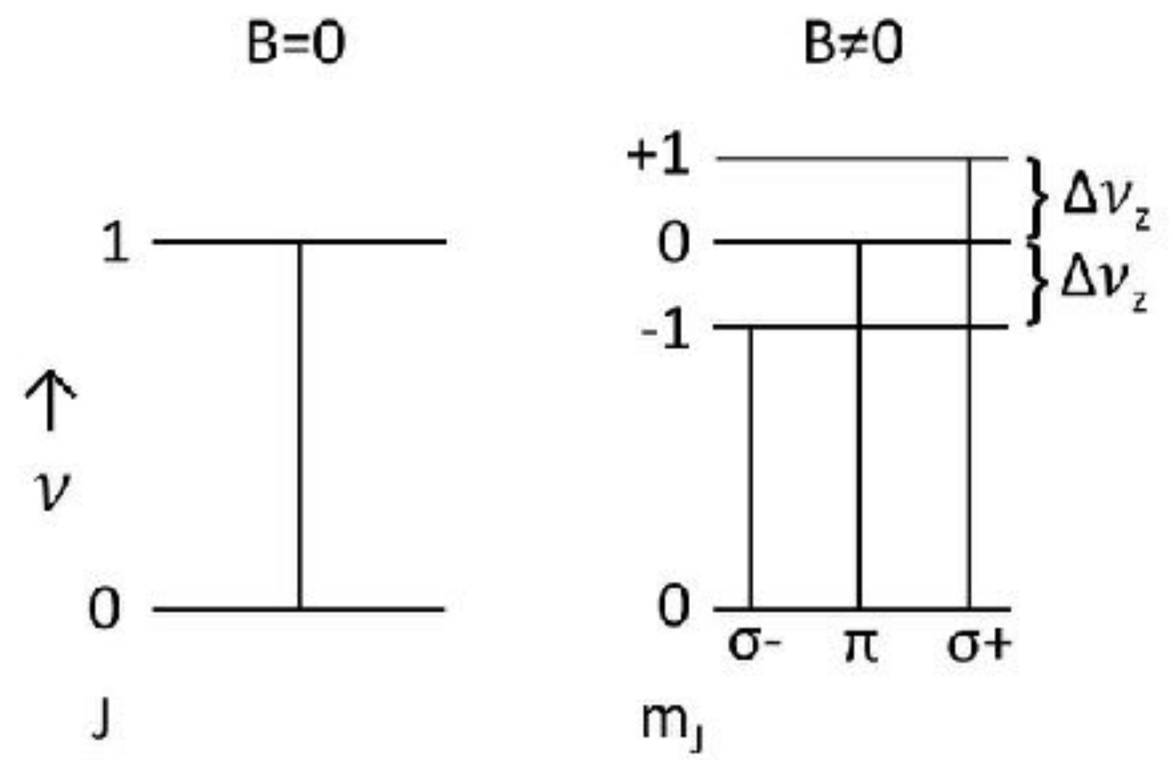
Molecular clouds are Magnetized

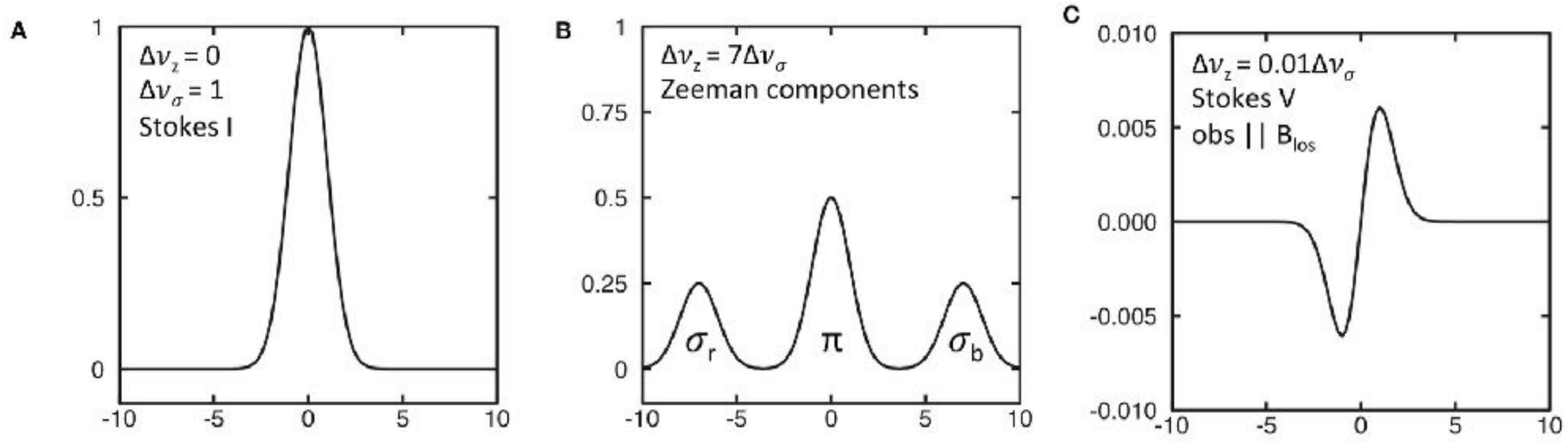


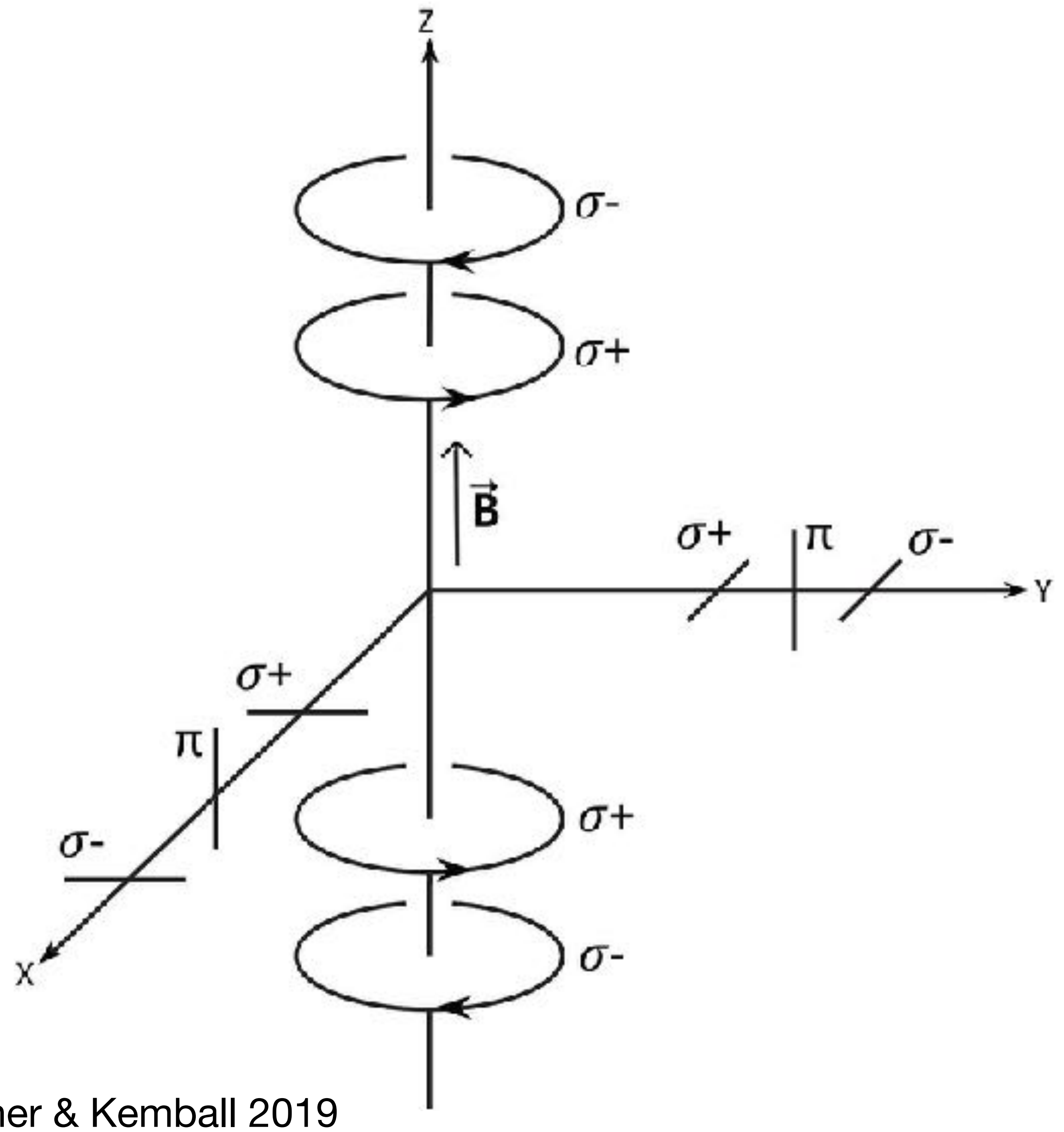
Far-infrared image & Dust polarization

Image credit:
ESA/Herschel/Planck; J. D. Soler, MPIA

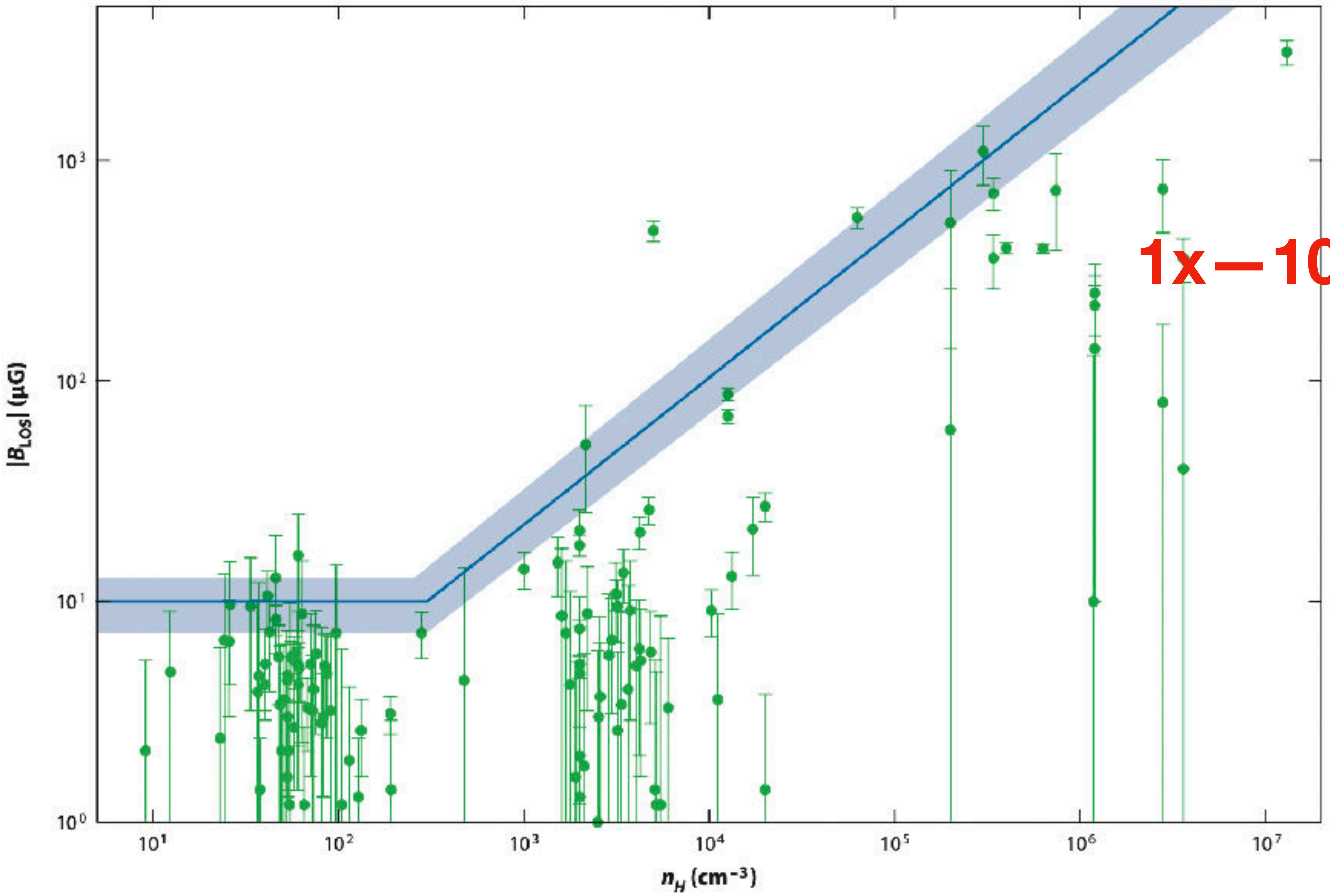
Molecular clouds are Magnetized: Zeeman effect







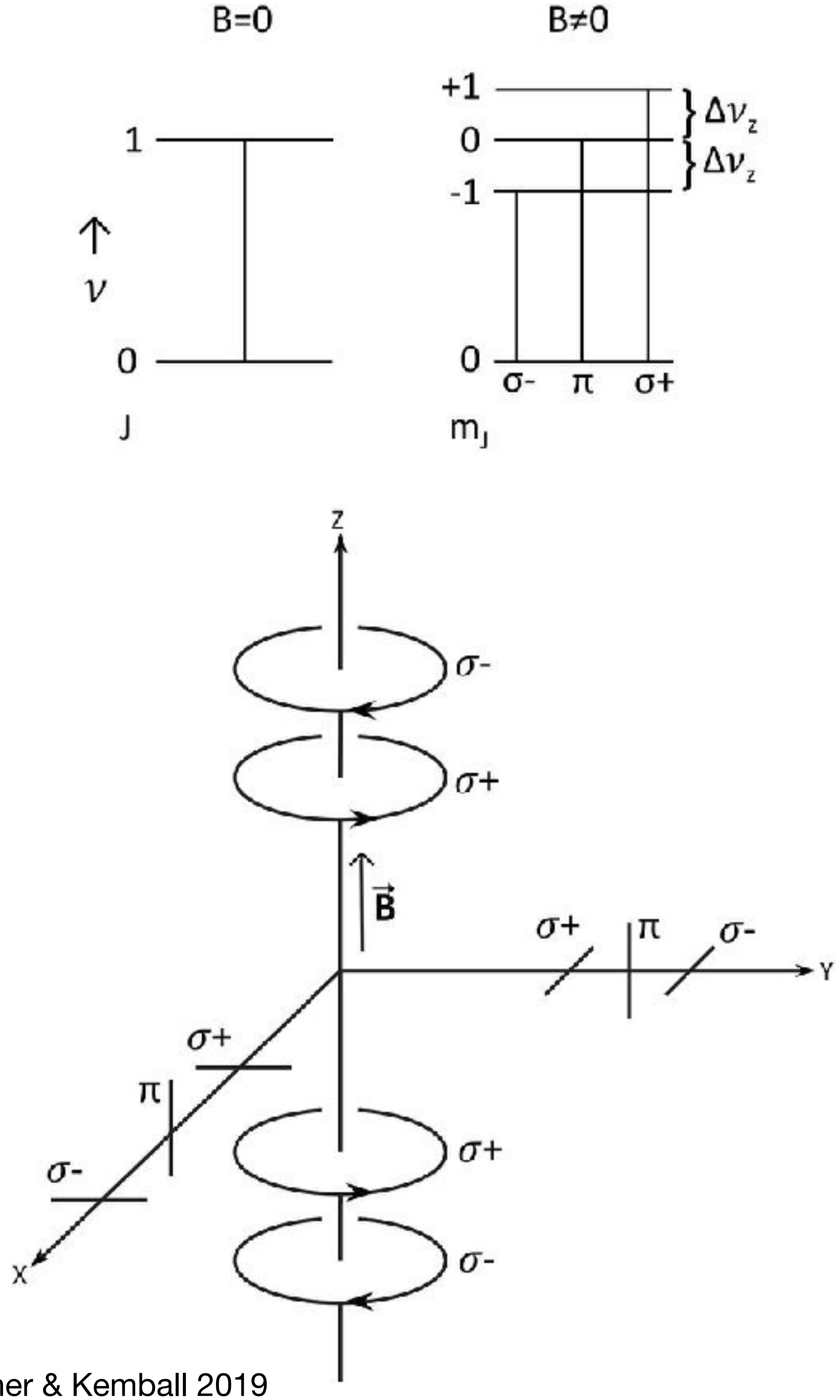
Crutcher & Kemball 2019



1x—10x uG

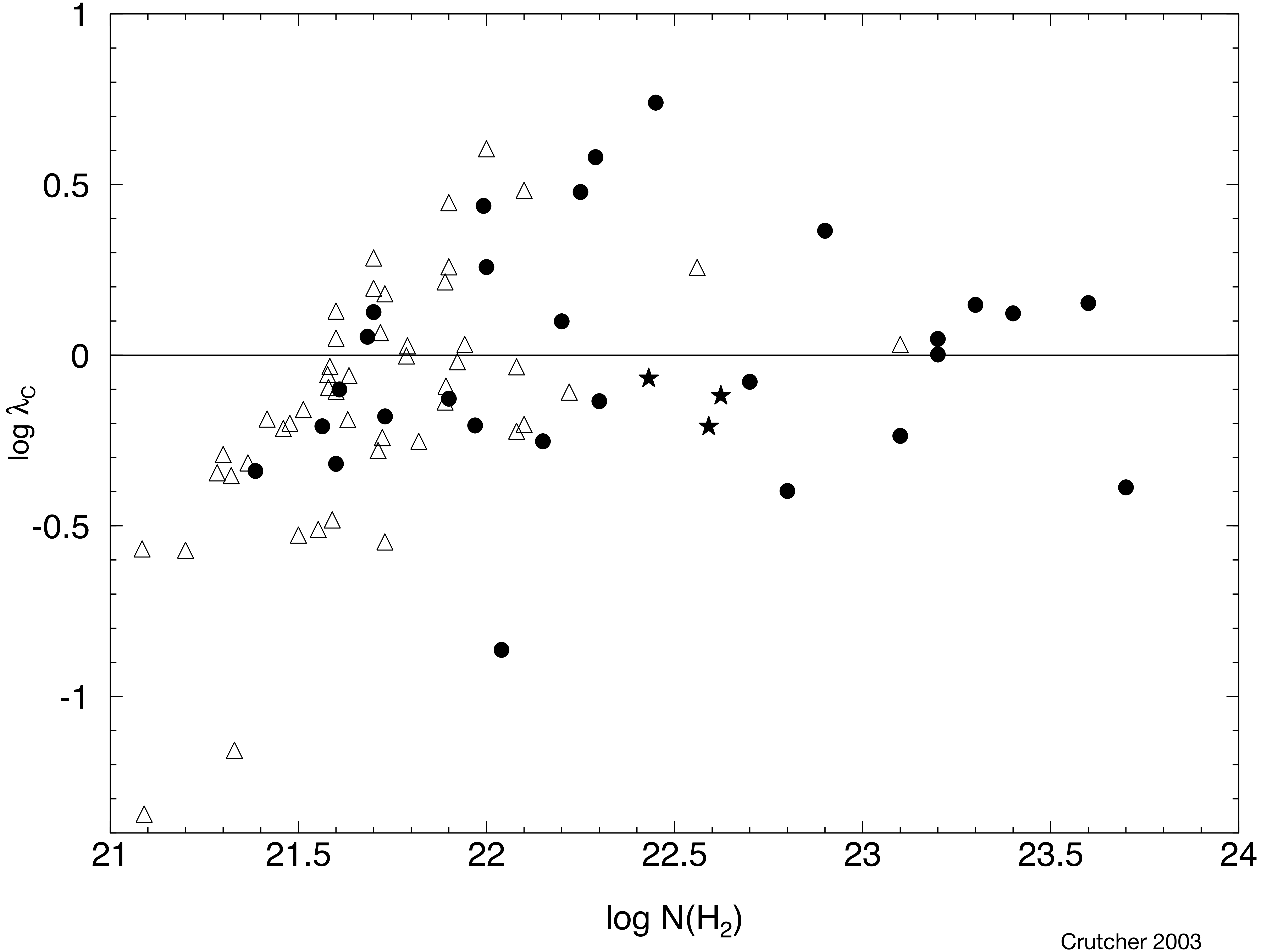
Crutcher 2012

Magnetic fields can provide support against gravity



Crutcher & Kemball 2019

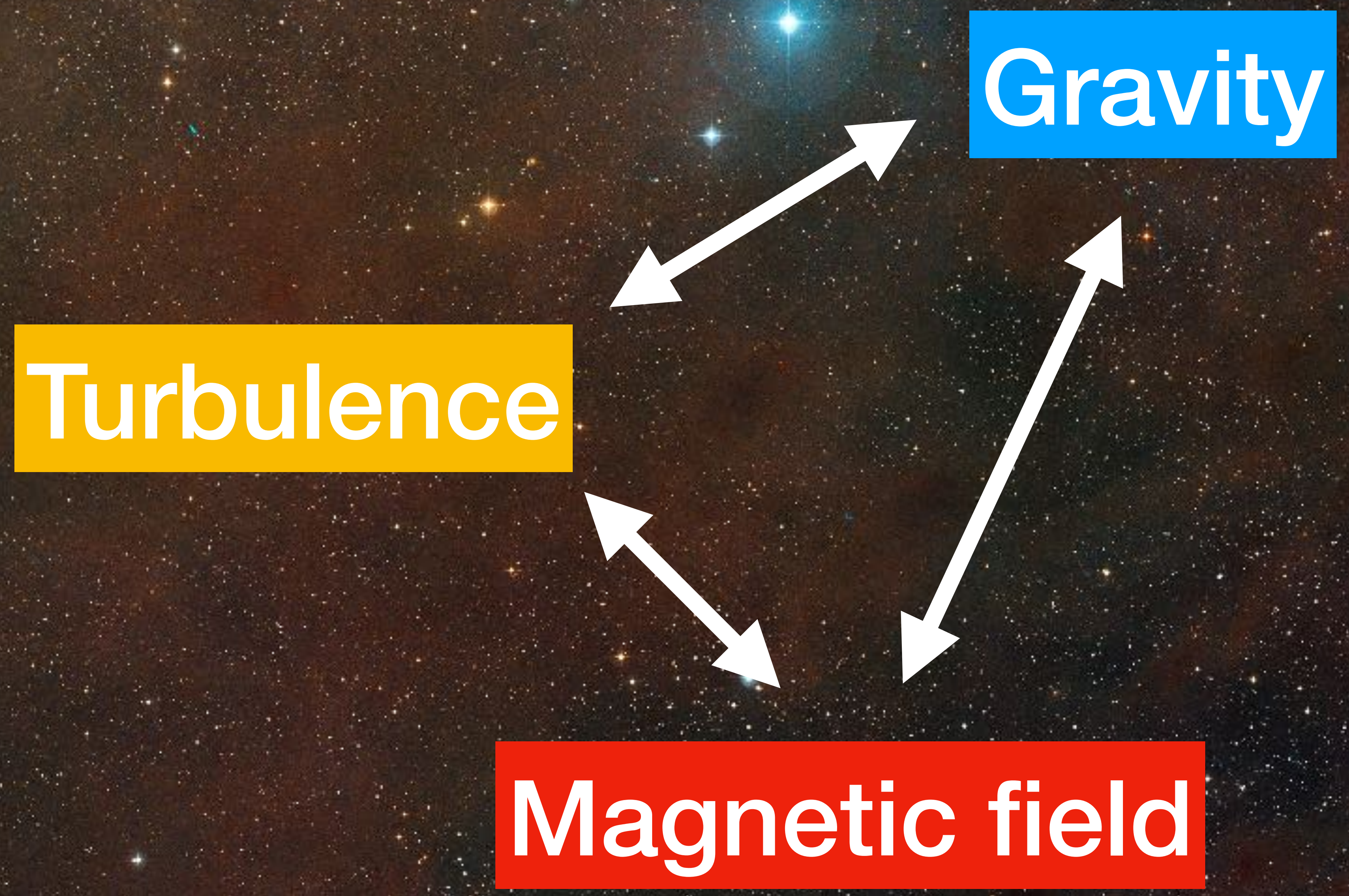
Gravitational / Magnetic energy



Crutcher 2003


Star formation process
Gravity
Turbulence
Magnetic field
Millimeter
ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al.
Optical image
Image credit: Digitized Sky Survey 2/D.D. Martin

Jeans Fragmentation



- The gravitational potential of a spherical cloud of uniform density and mass M_c and radius r_c is

$$U \sim -\frac{3}{5}\frac{GM_c^2}{r_c} \quad , \tag{1}$$

and this must exceed twice the virial kinetic temperature $K = 3NkT/2$ to seed collapse. Here $N = M_c/\mu m_H$. Hence $2K < |U|$ and the criterion is

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5}\frac{GM_c^2}{r_c} \quad . \tag{2}$$

If we set $r_c = (3M_c/4\pi\rho_c)^{1/3}$, then we arrive at the **Jeans criterion**

$$M_c > M_{\rm J} = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_c}\right)^{1/2} \tag{3}$$

where $M_{\rm J}$ is called the **Jeans mass**, or equivalently

$$r_c > R_{\rm J} = \left(\frac{15kT}{4\pi G\mu m_H\rho_c}\right)^{1/2} \tag{4}$$

where $R_{\rm J}$ is called the Jeans length.

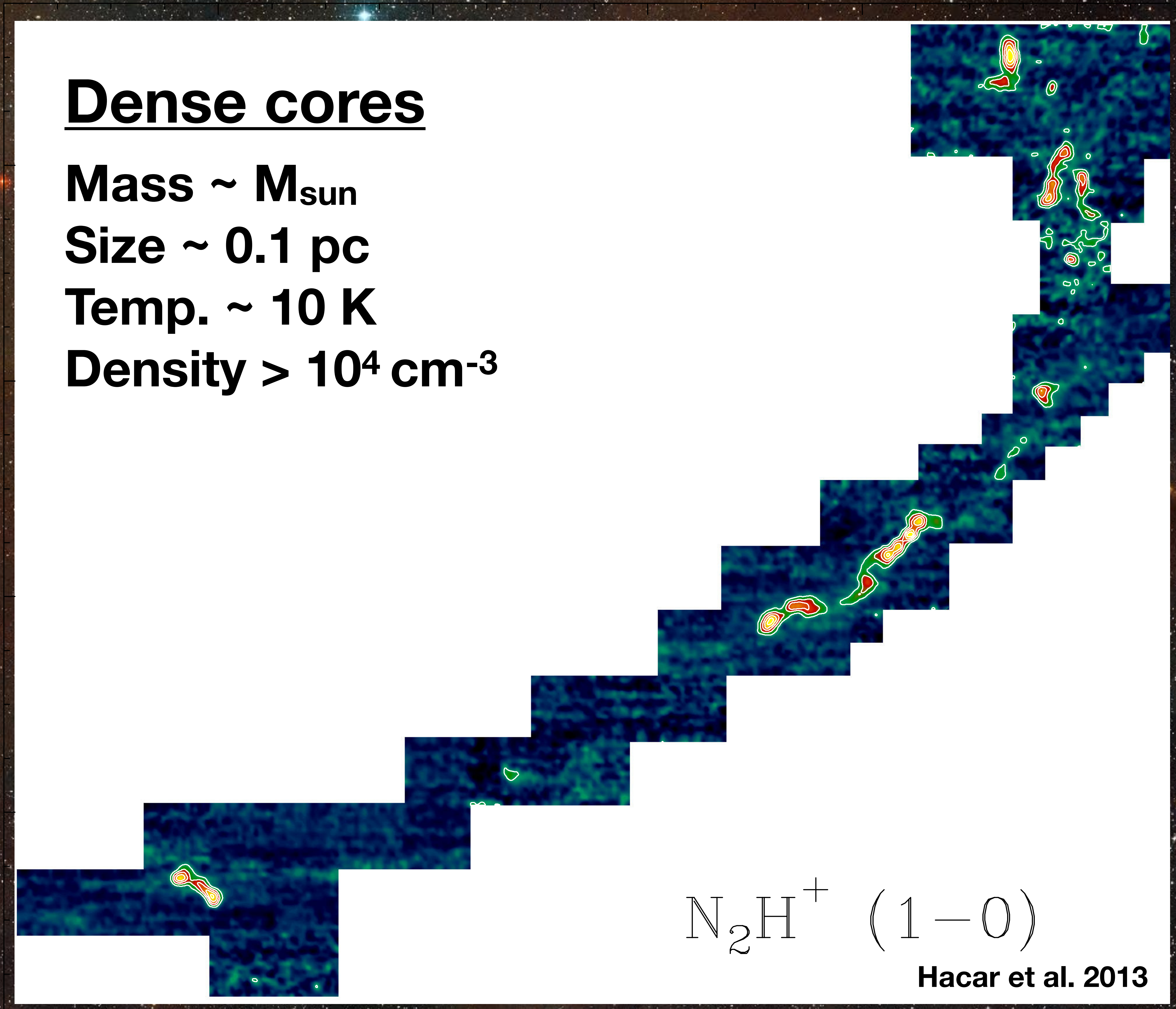
Lecture note from Rice U.

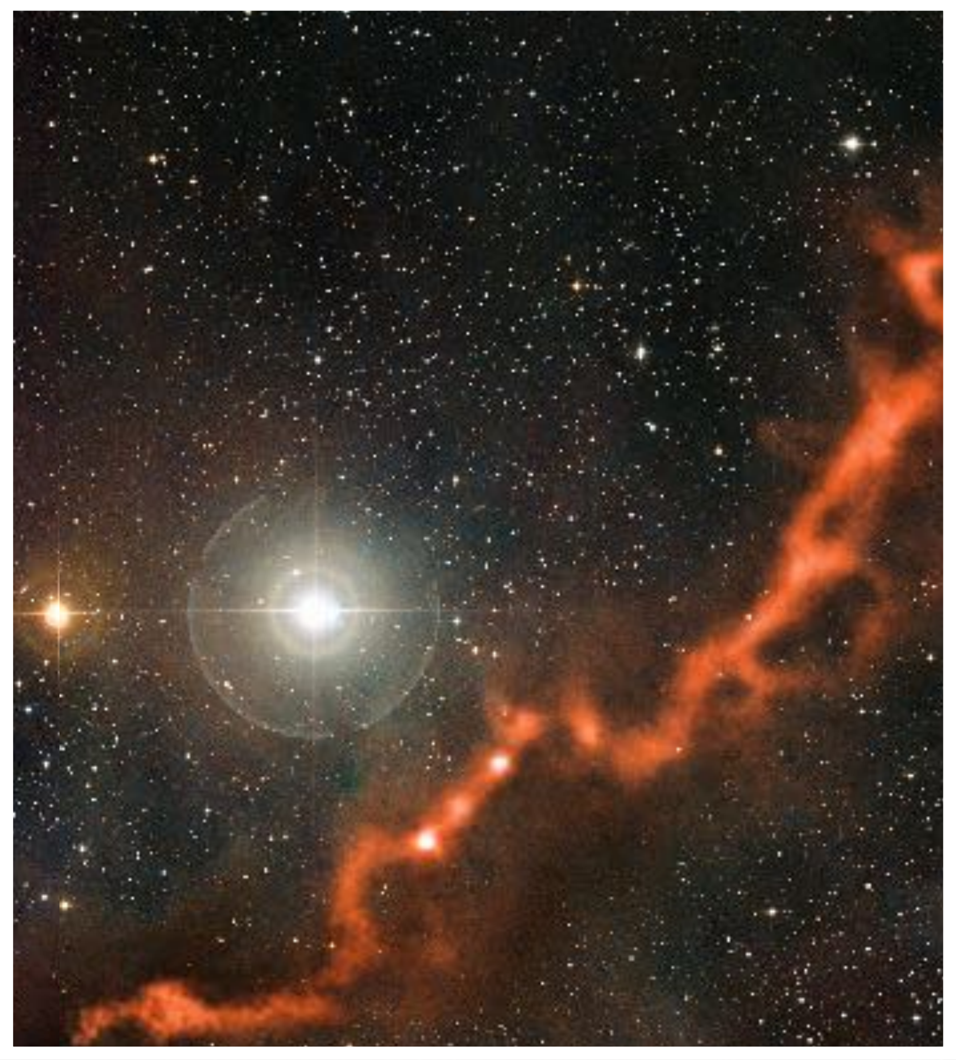
Optical image

Image credit: Digitized Sky Survey 2/D.D. Martin

Dense cores

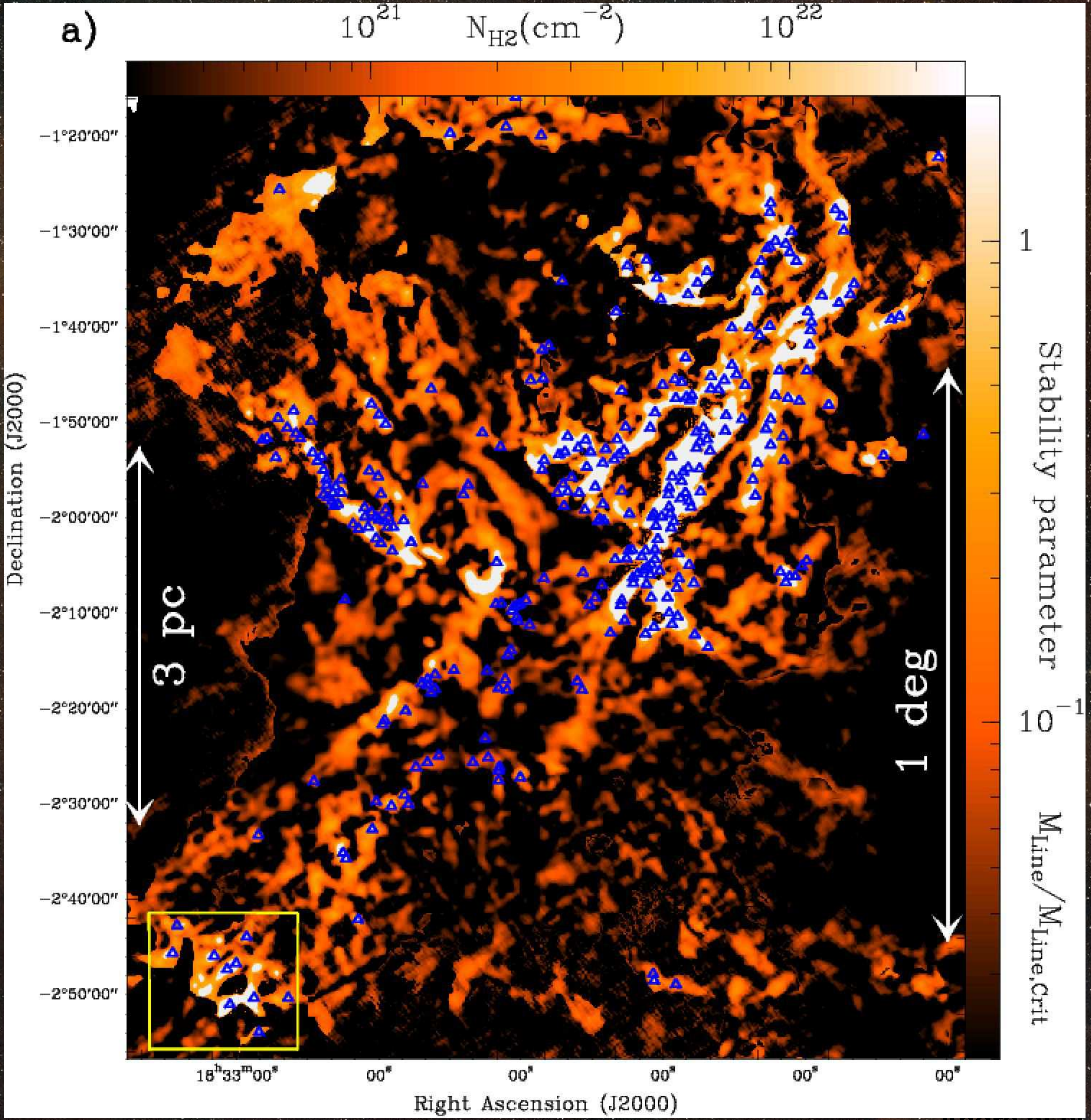
Mass ~ M_{sun}
Size ~ 0.1 pc
Temp. ~ 10 K
Density > 10^4 cm^{-3}





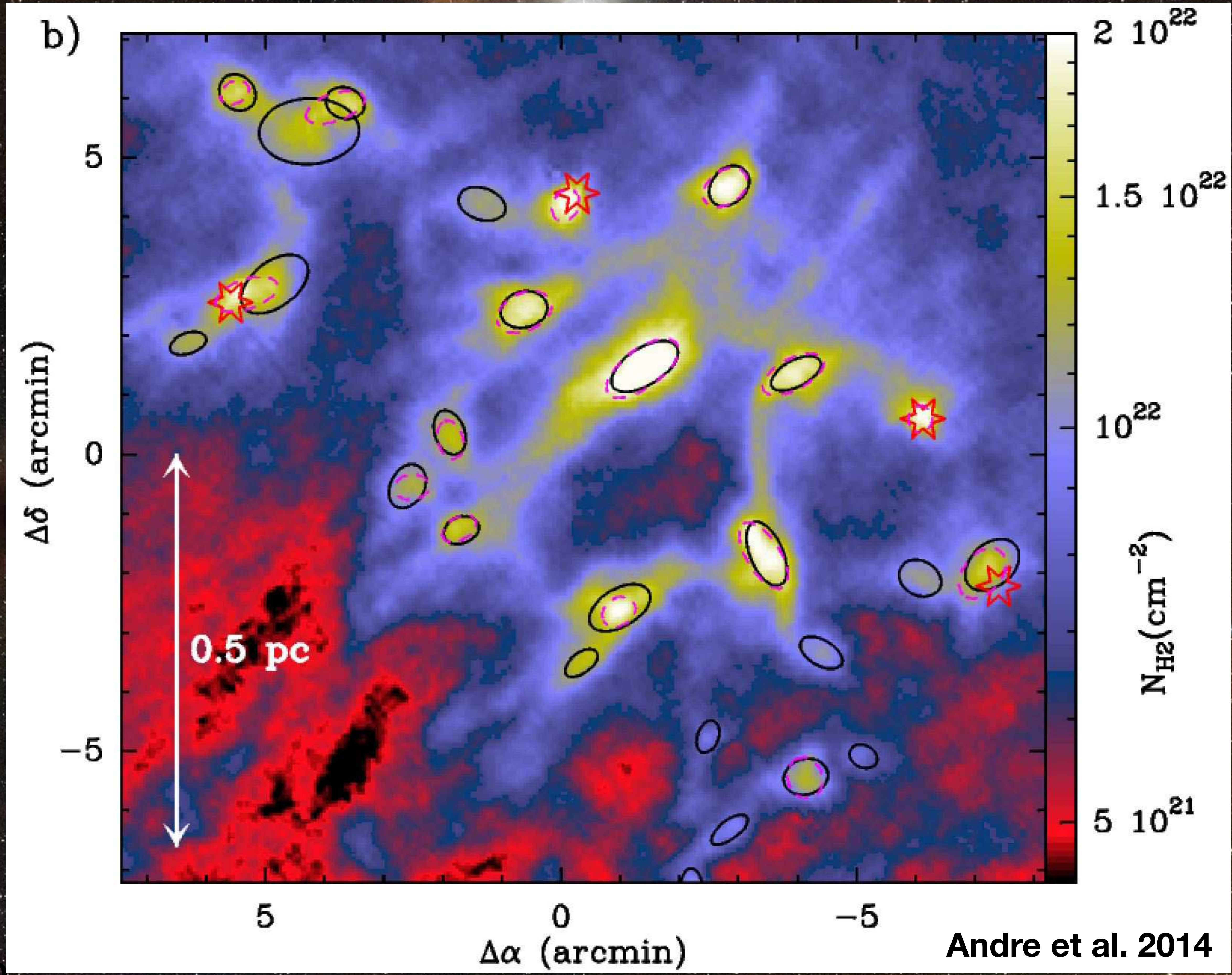
Radio image - Molecular-line emission

Image credit: Digitized Sky Survey 2/D.D. Martin
ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al.



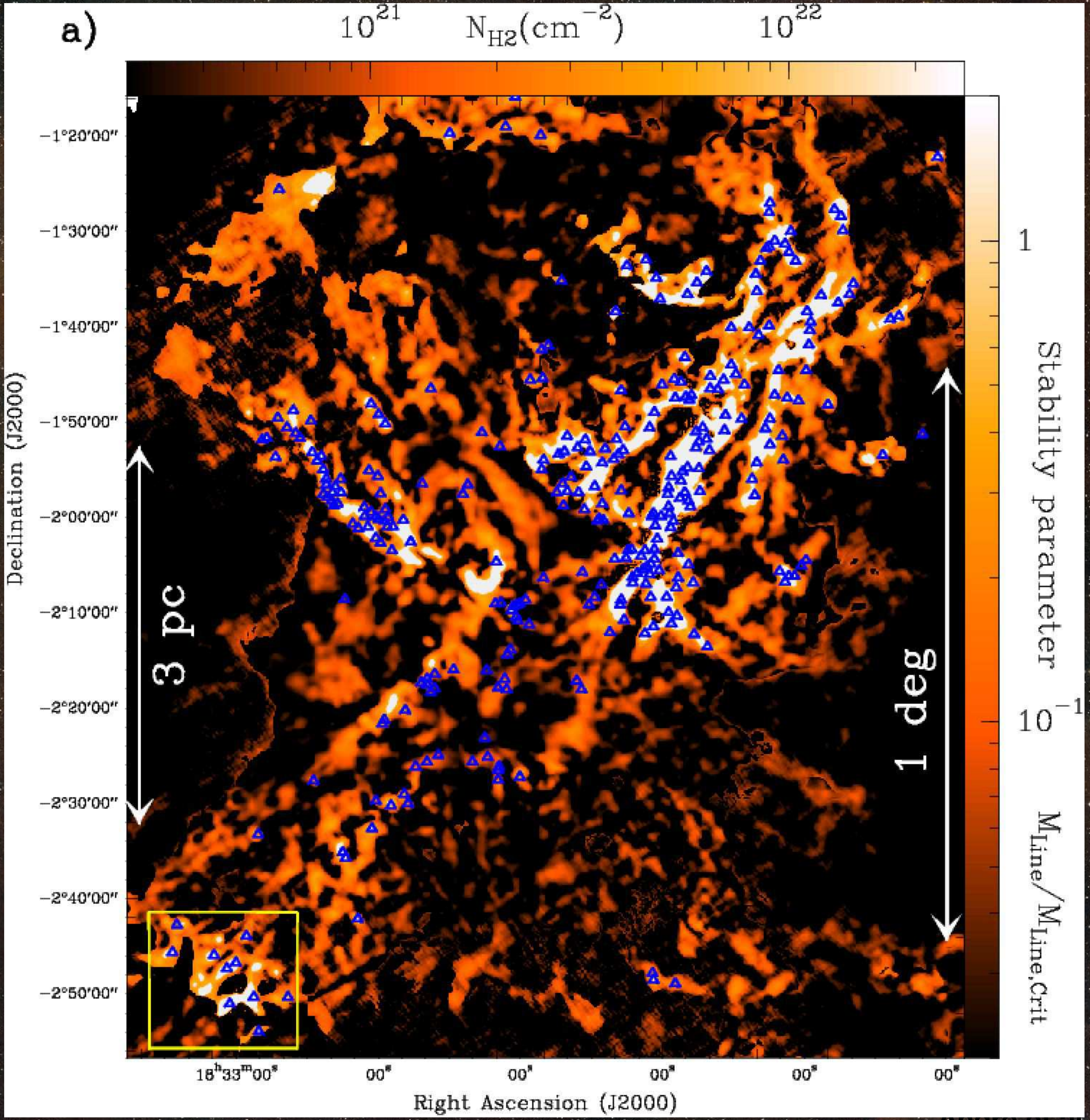
Andre et al. 2010

Core Mass Function (CMF)

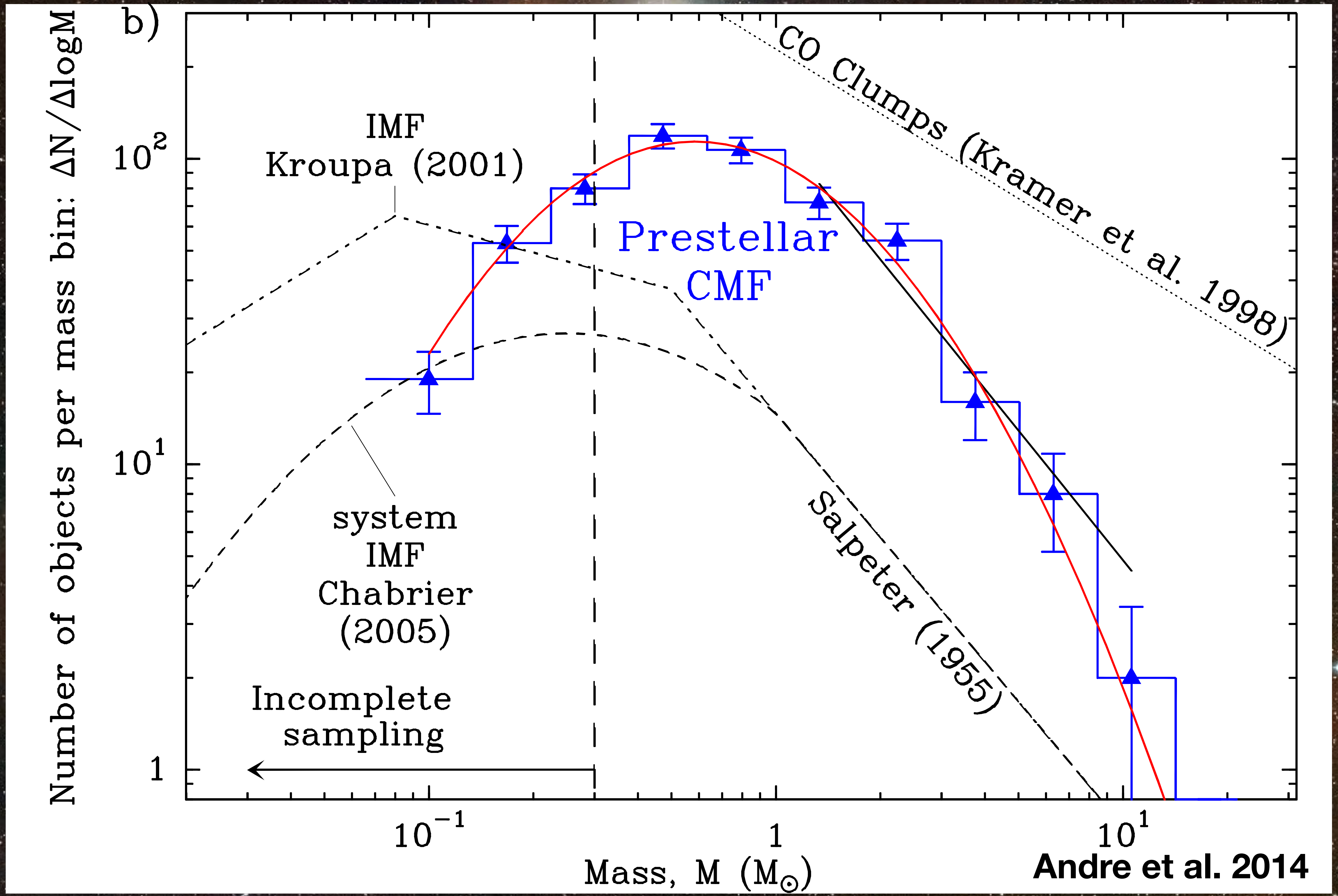


Andre et al. 2014

Core Mass Function (CMF)



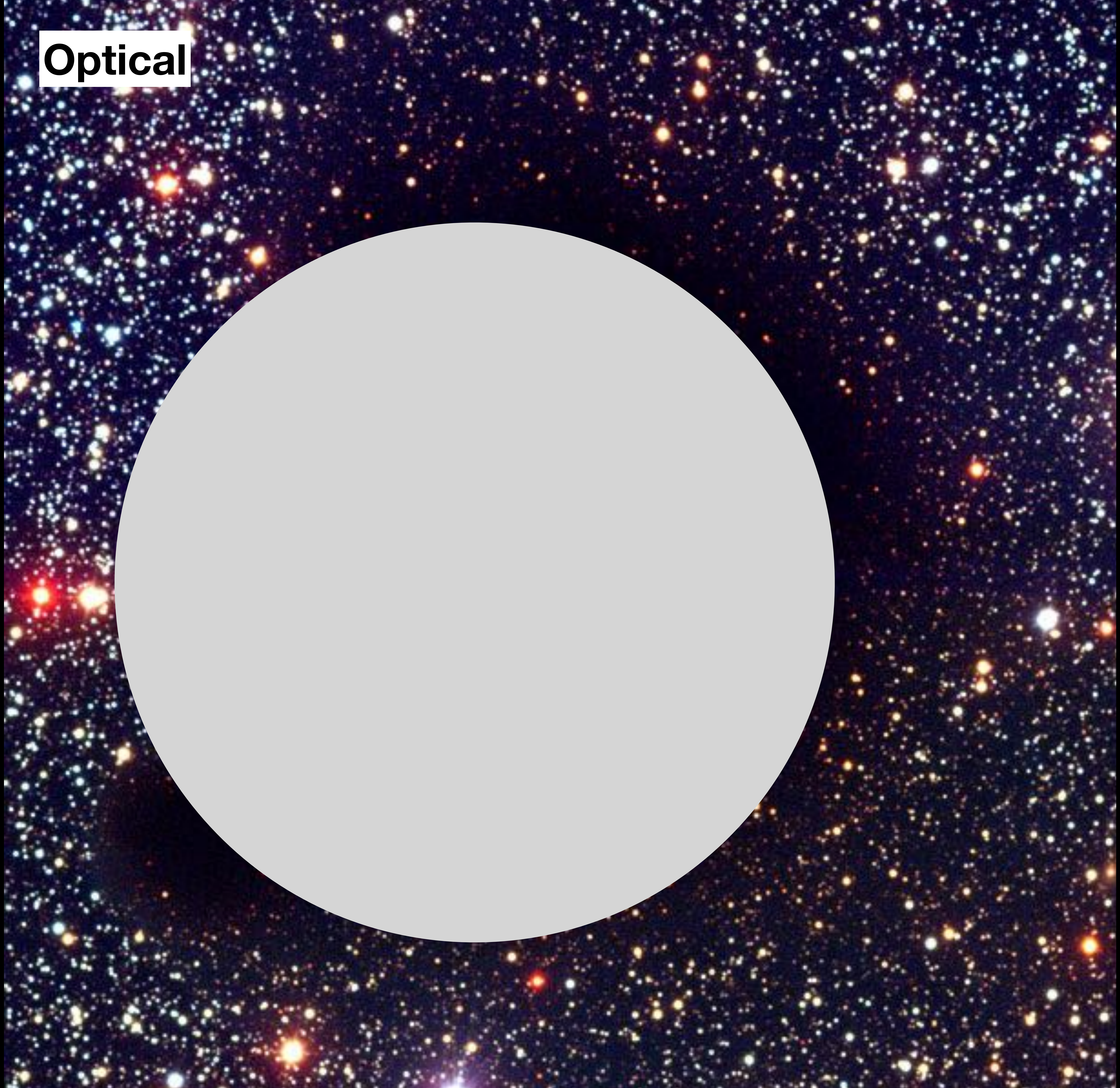
Andre et al. 2010



Andre et al. 2014

Gravitational bound dense cores

Image credit: ESO

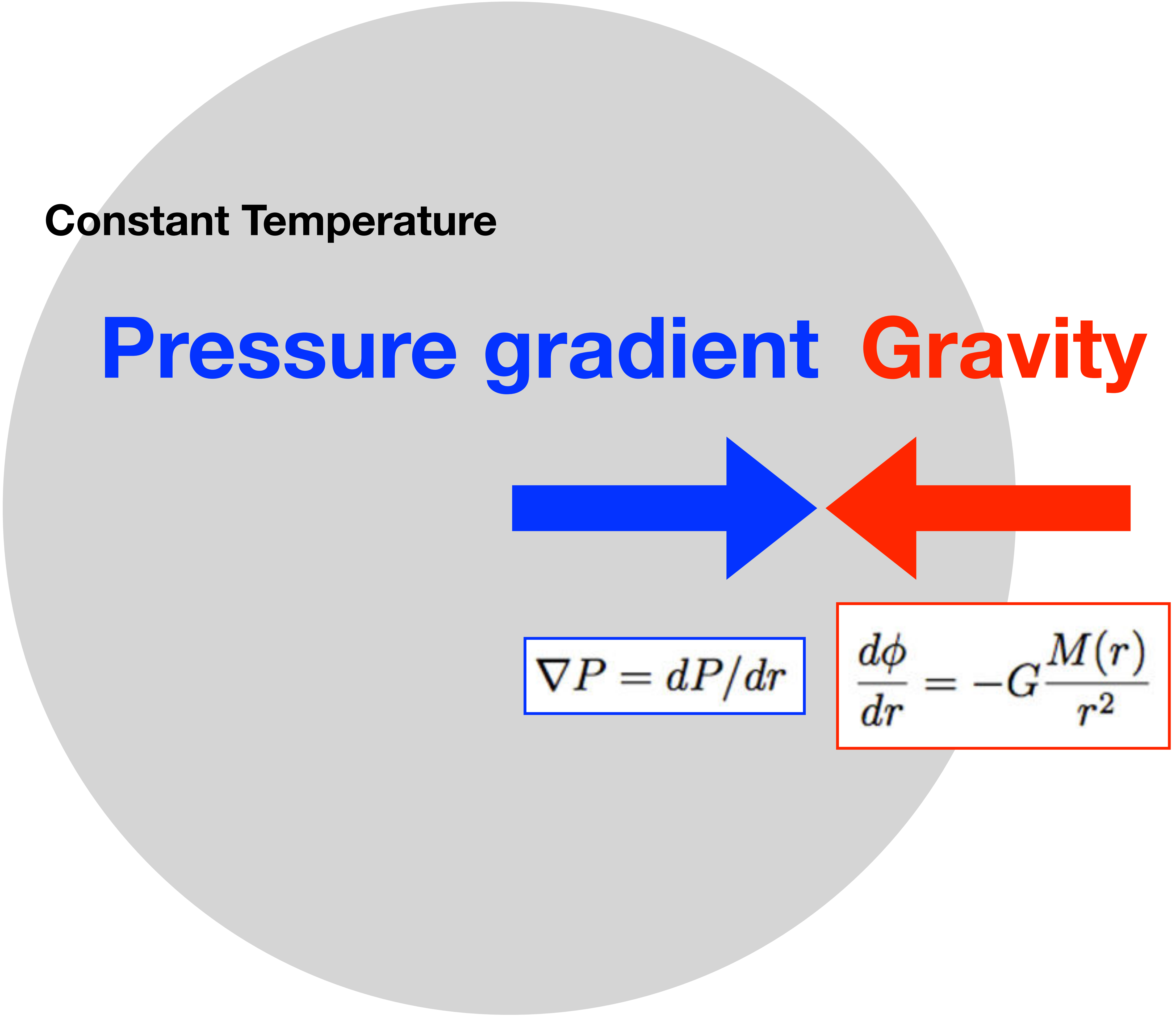


Gravitational bound dense cores

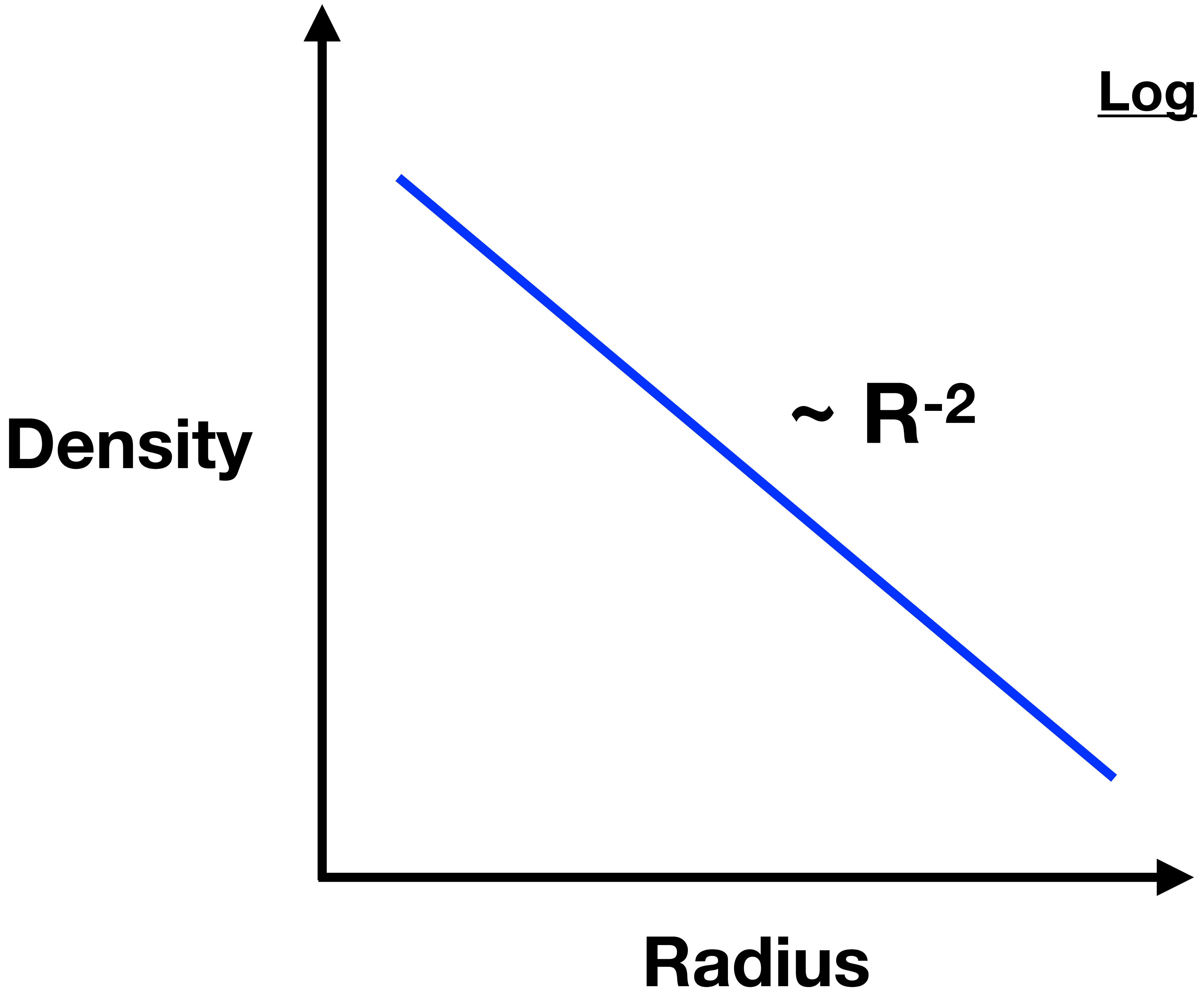
Image credit: ESO

Gravitational bound stable dense core

$$\frac{1}{\rho(r)}\frac{dP(r)}{dr} = -\frac{d\phi}{dr}$$

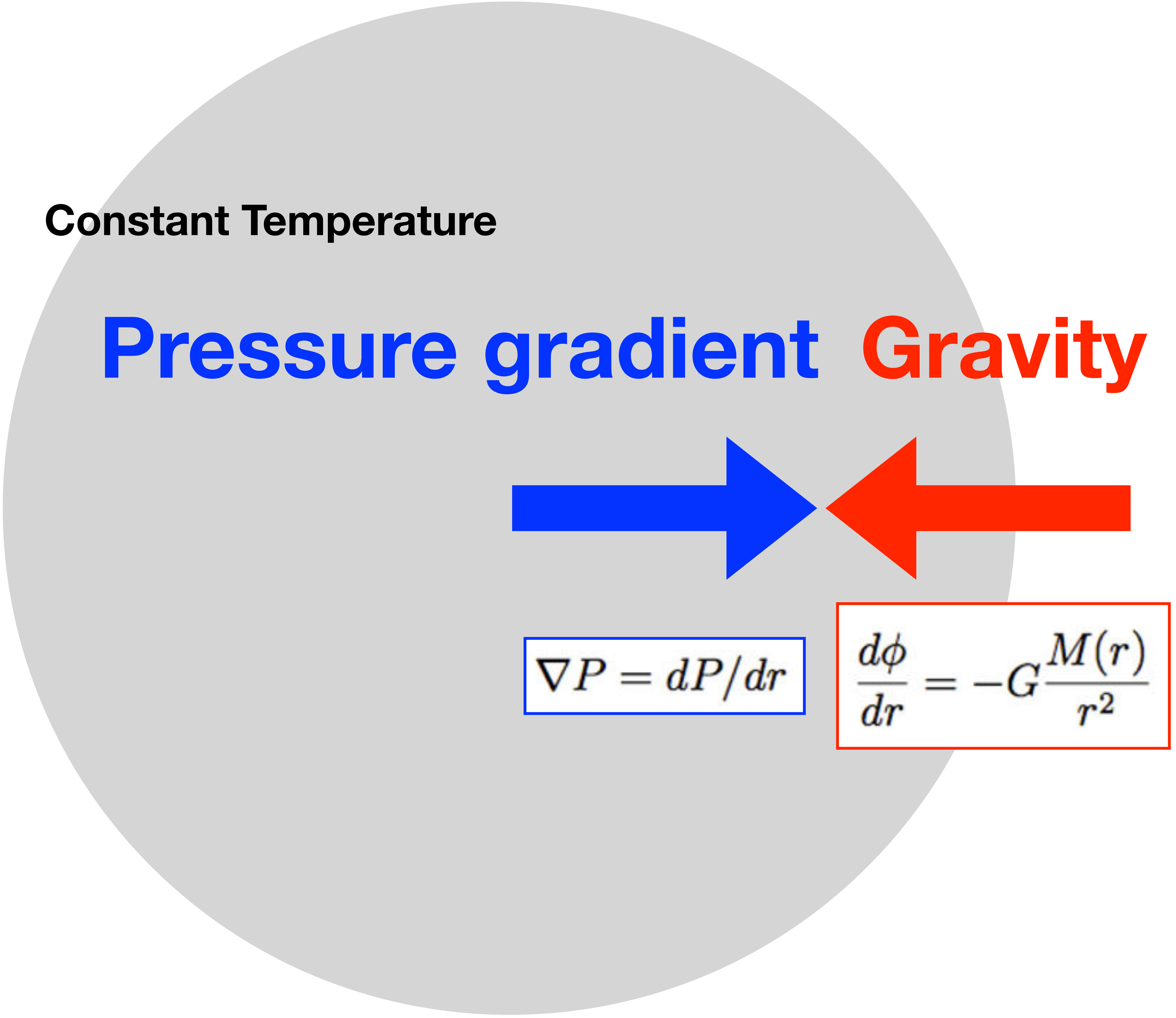


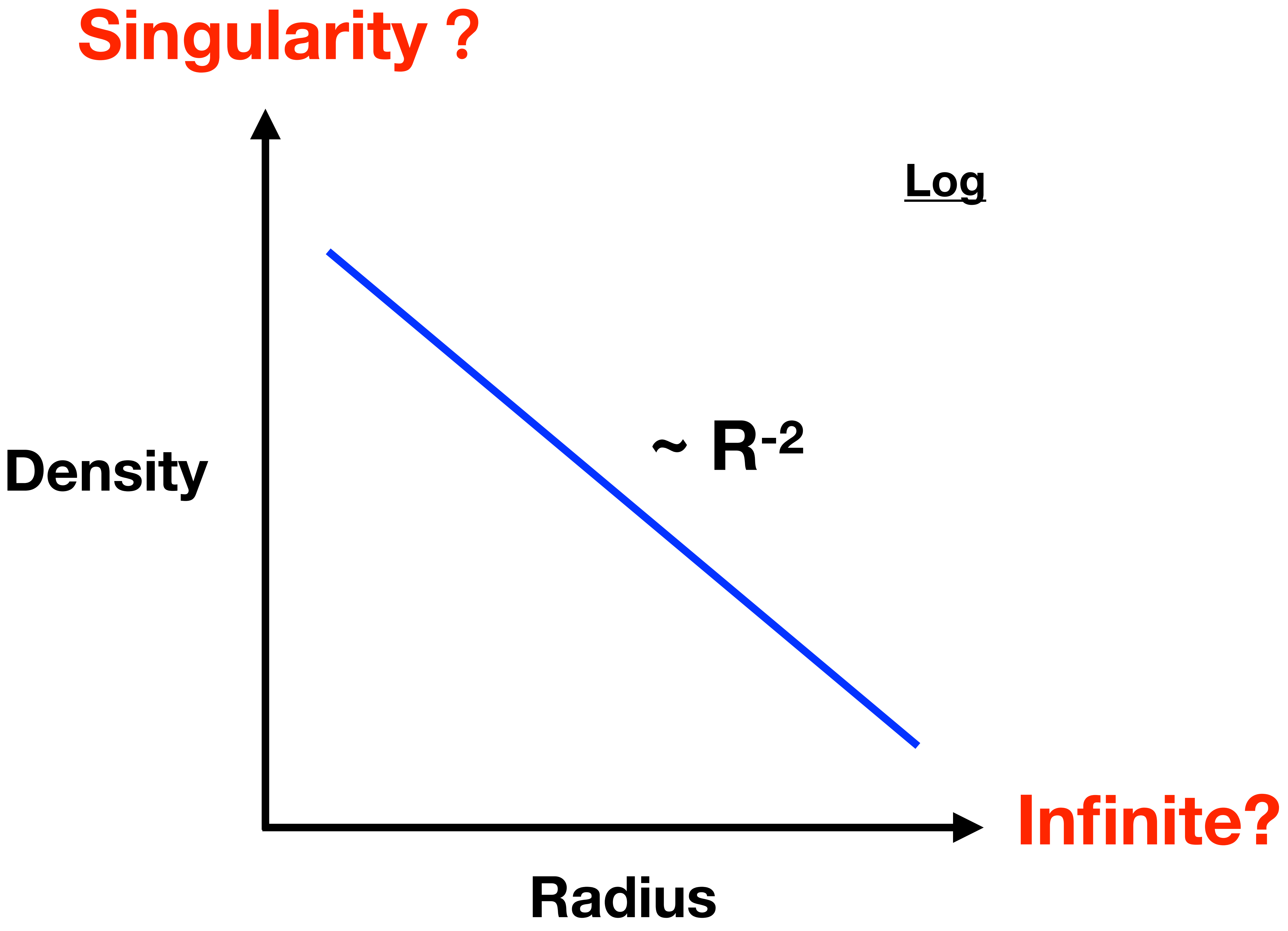
Singular Isothermal Sphere



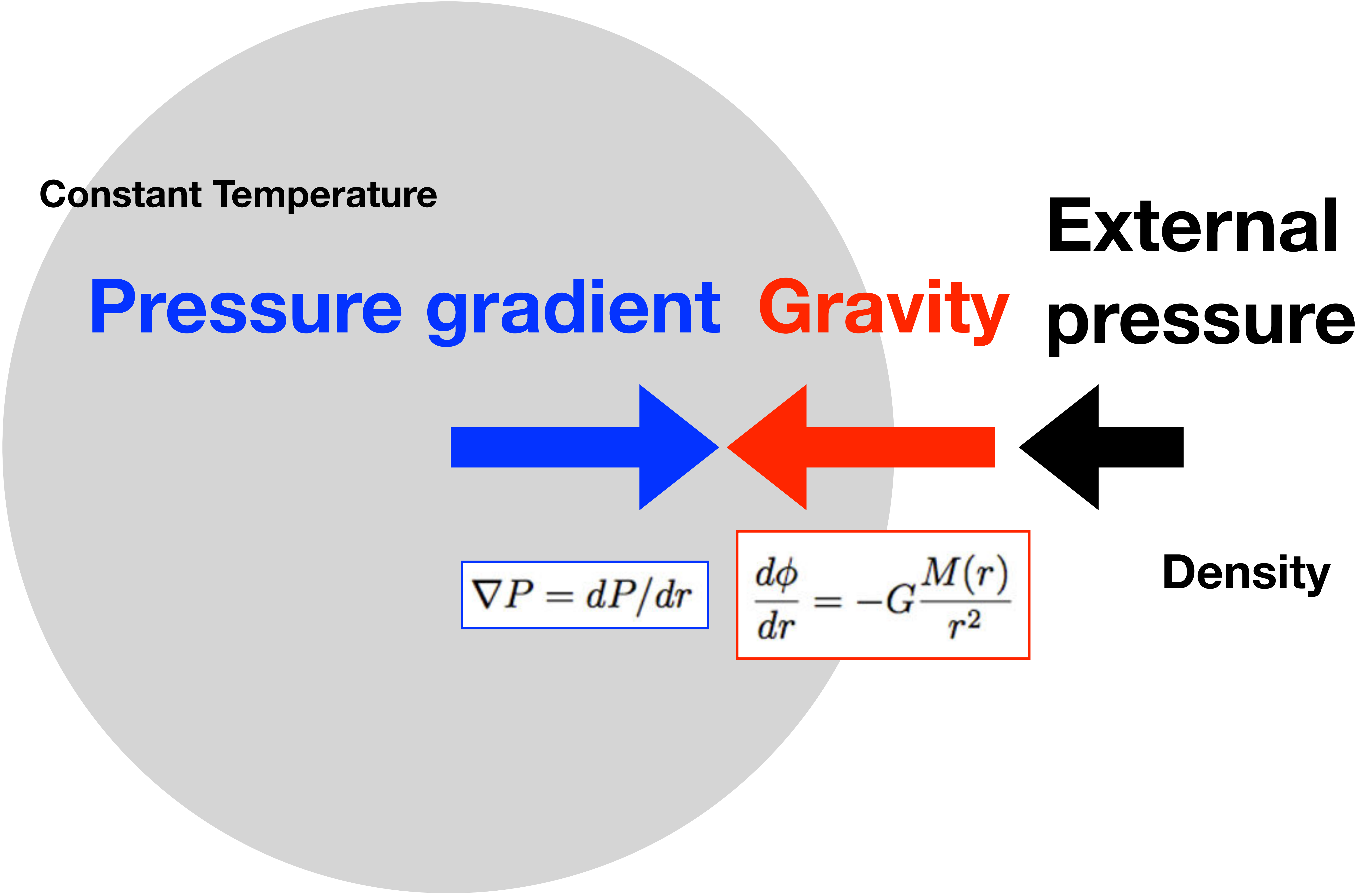
Gravitational bound stable dense core

$$\frac{1}{\rho(r)}\frac{dP(r)}{dr} = -\frac{d\phi}{dr}$$





Gravitational bound stable dense core

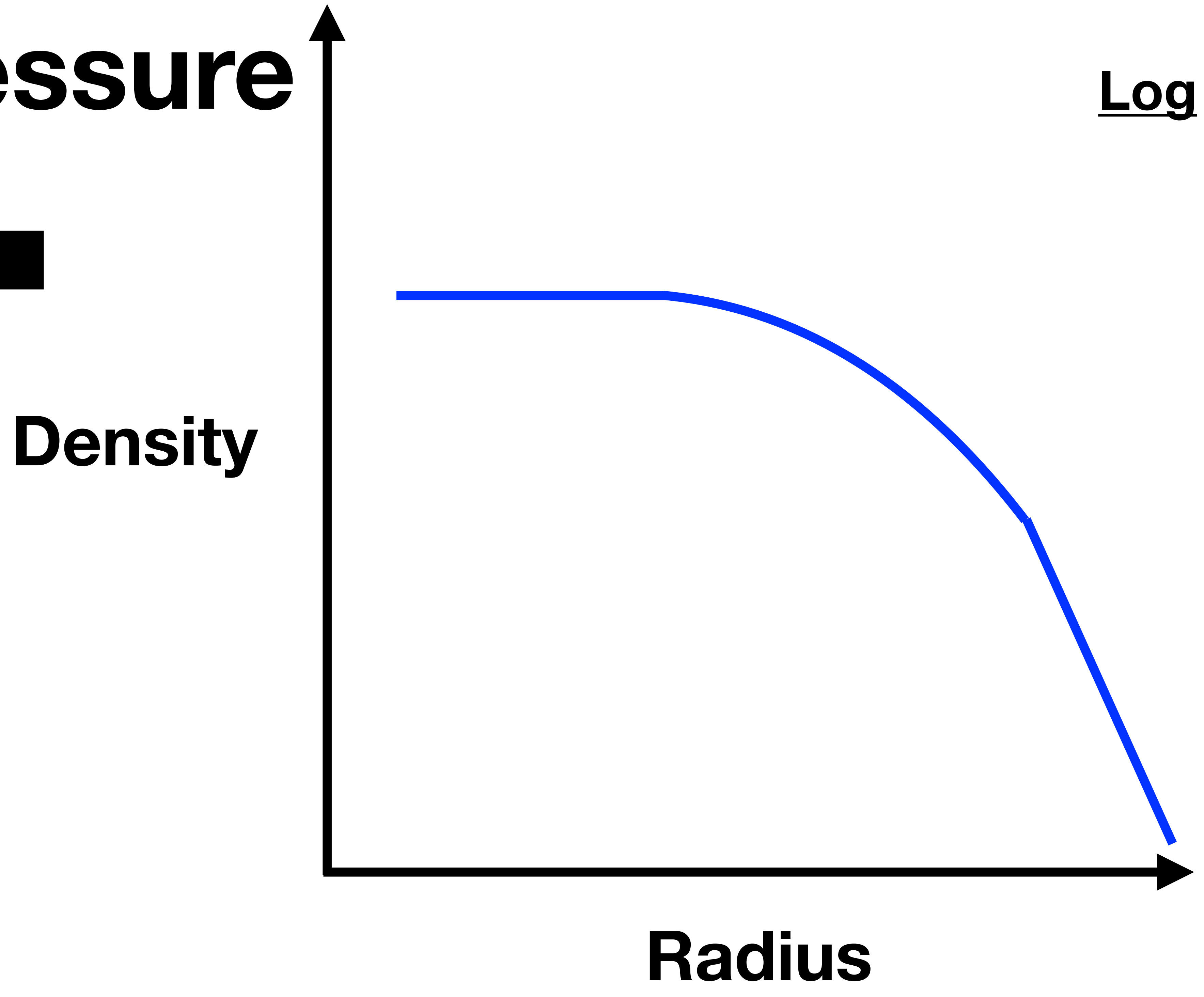


$$\nabla P = dP/dr$$

$$\frac{d\phi}{dr} = -G\frac{M(r)}{r^2}$$

Bonnor-Ebert Sphere

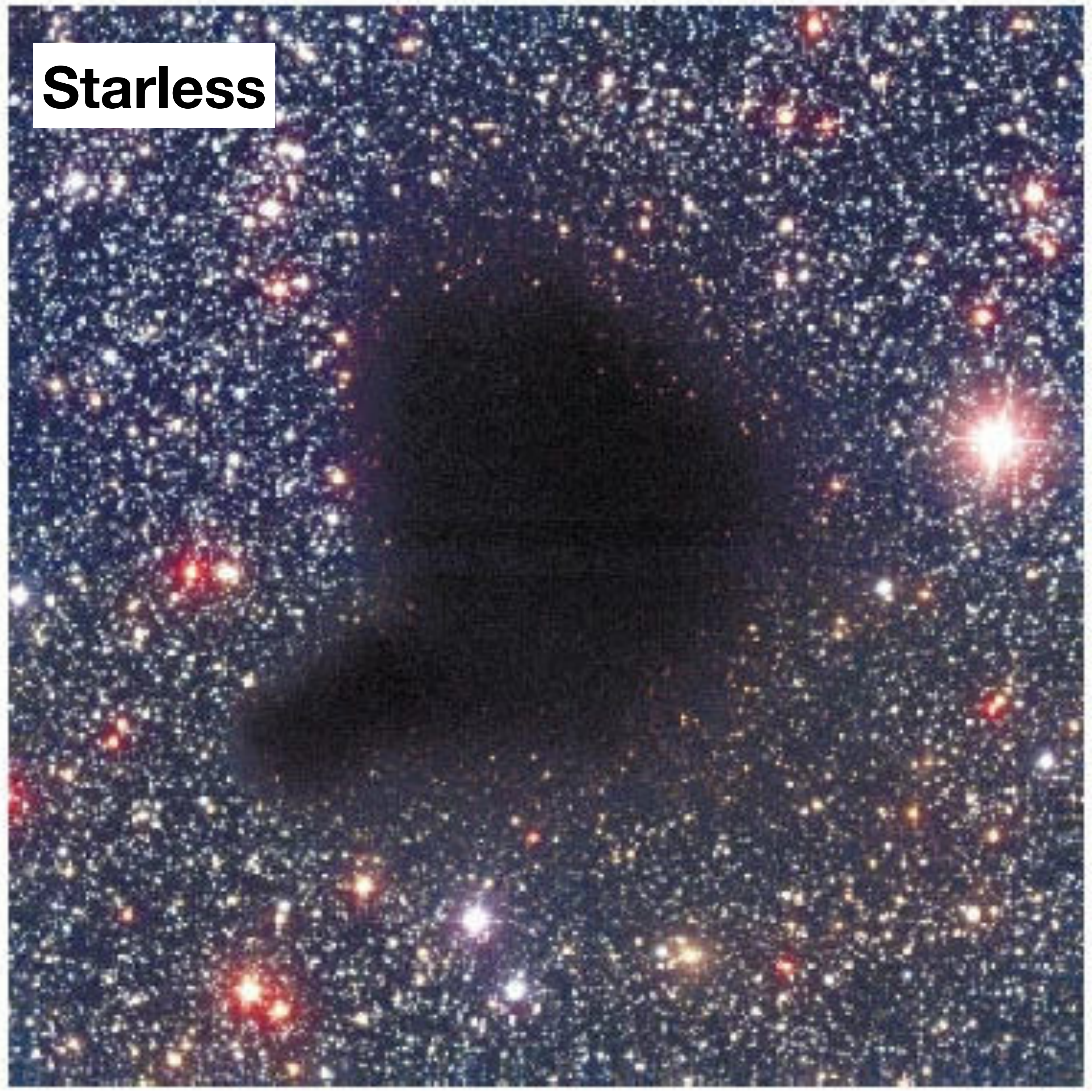
(Bonnor 1956; Ebert 1955)



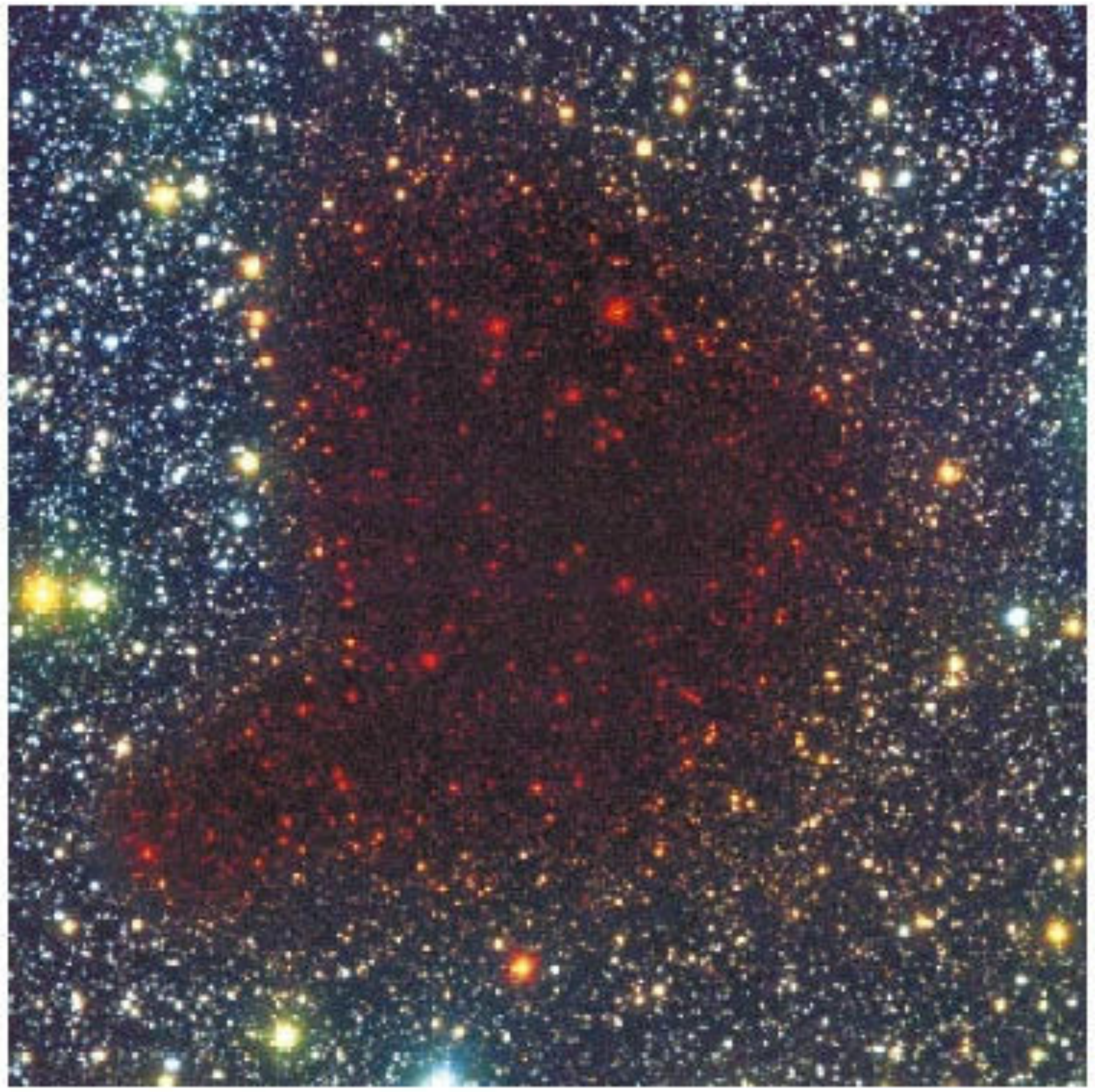
Gravitational bound stable dense core

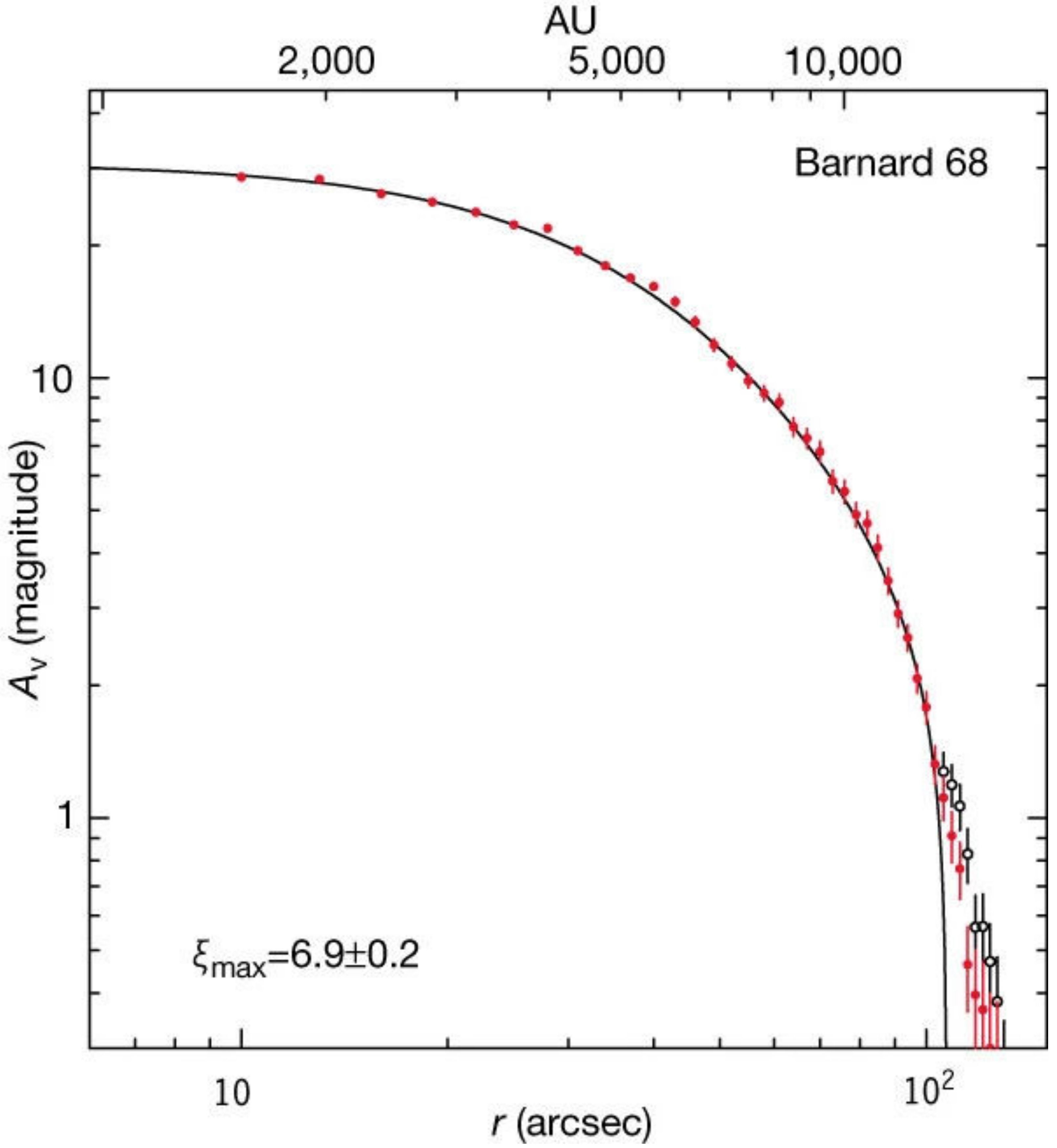
Bonnor-Ebert Sphere!!

Optical



Infrared

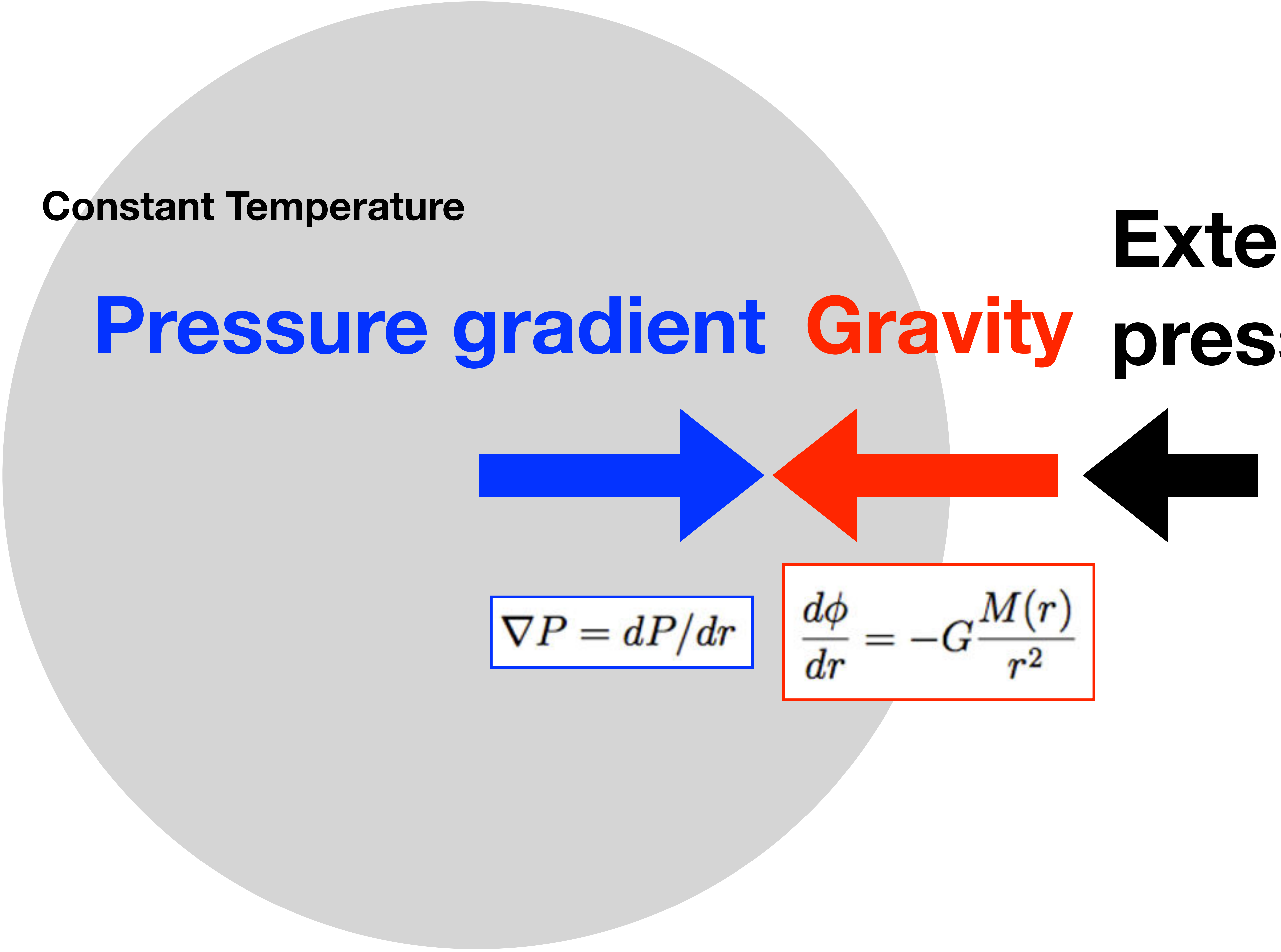




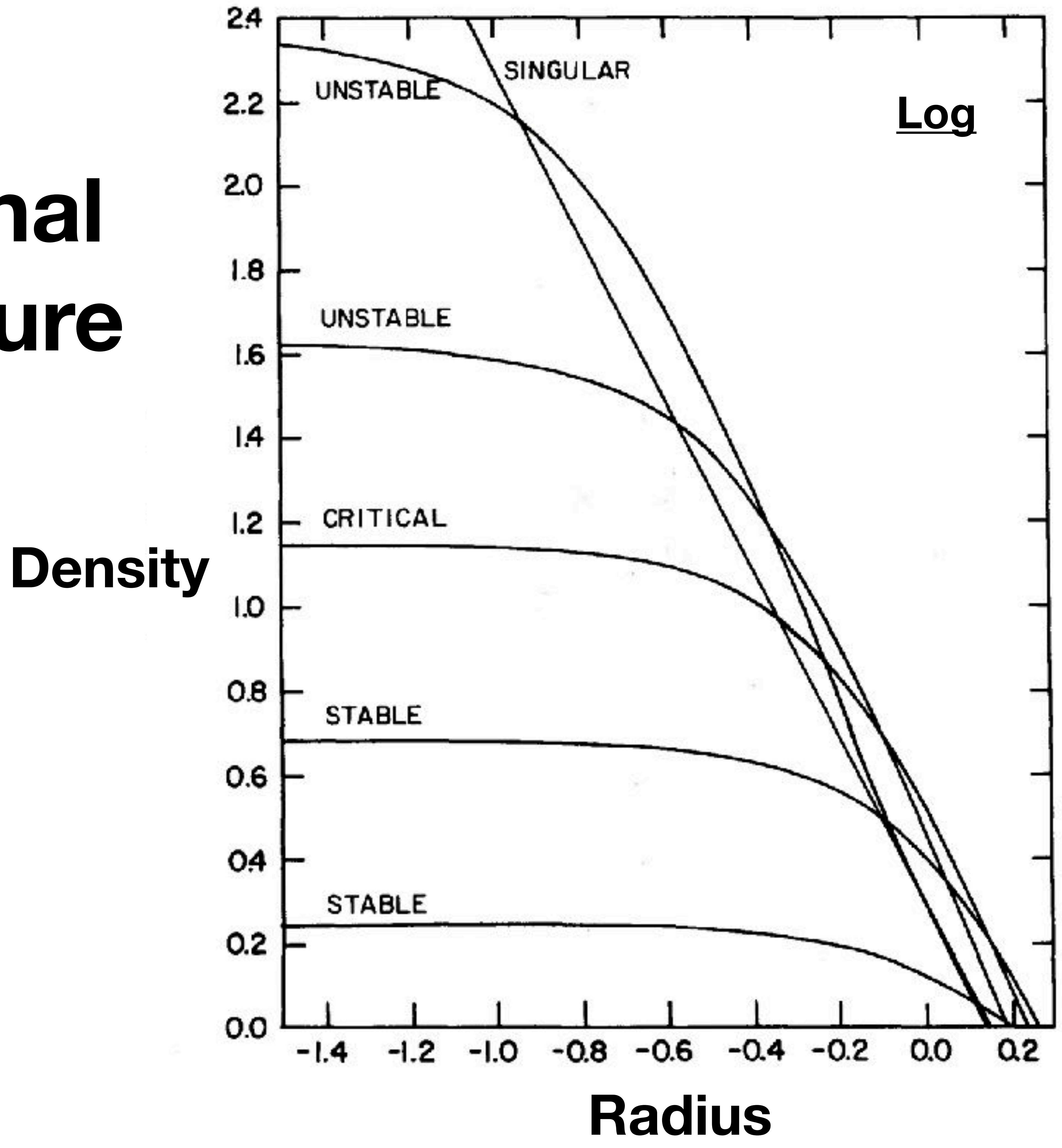
Extinction => Density

Alves et al. (2001)

Gravitational bound stable dense core

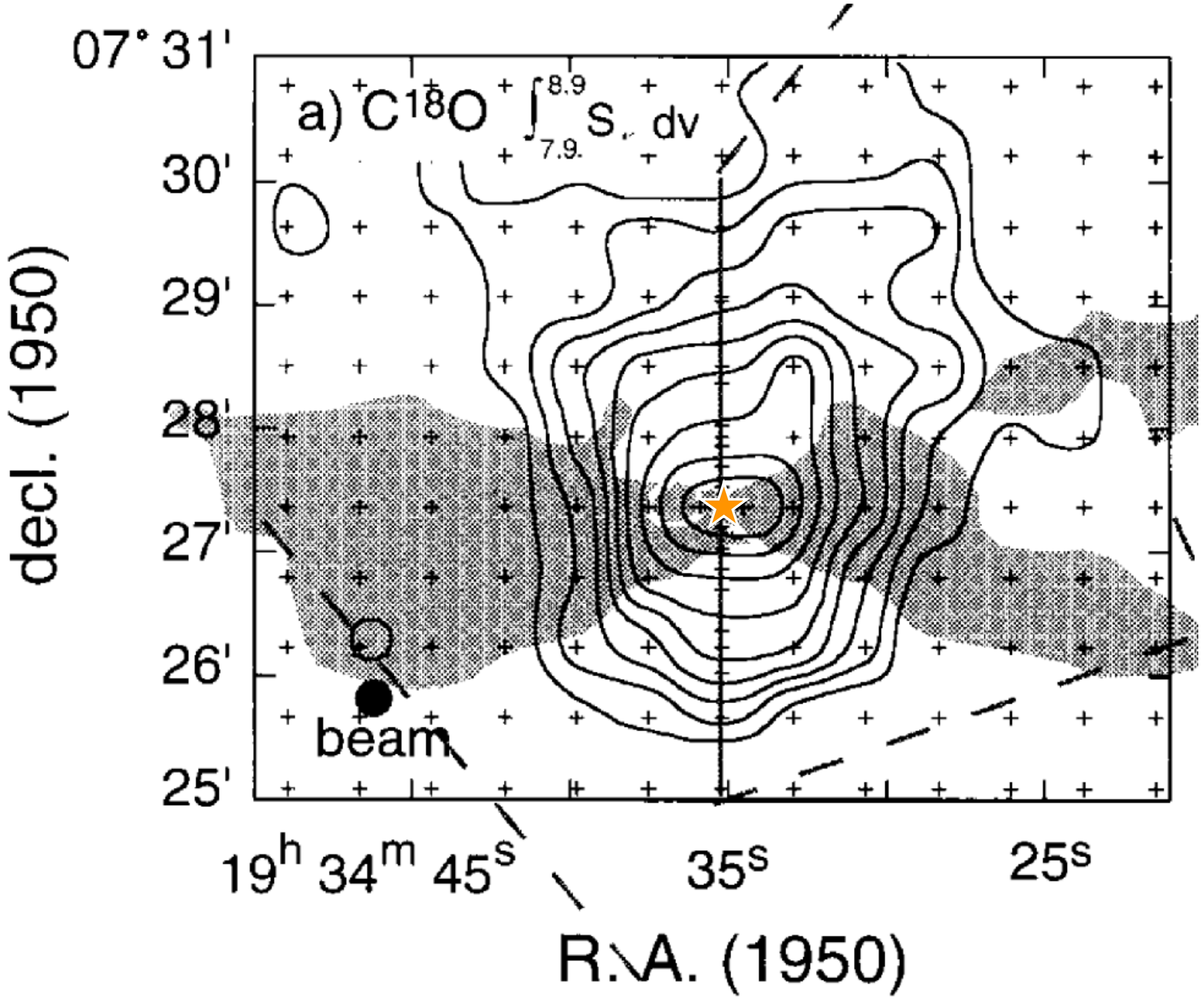


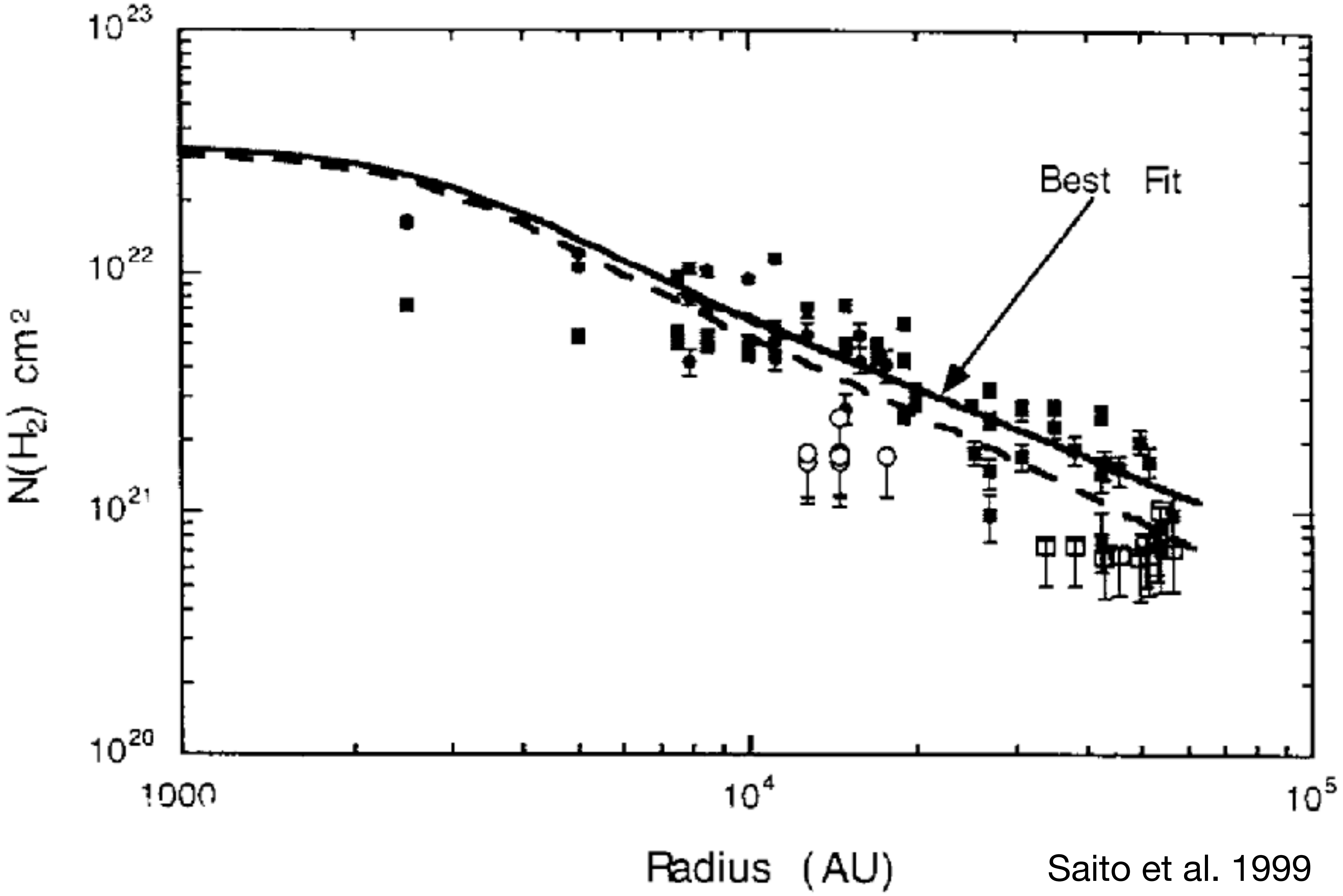
Shu 1977



Gravitational bound stable dense core

$$\frac{1}{\rho(r)}\frac{dP(r)}{dr} = -\frac{d\phi}{dr}$$





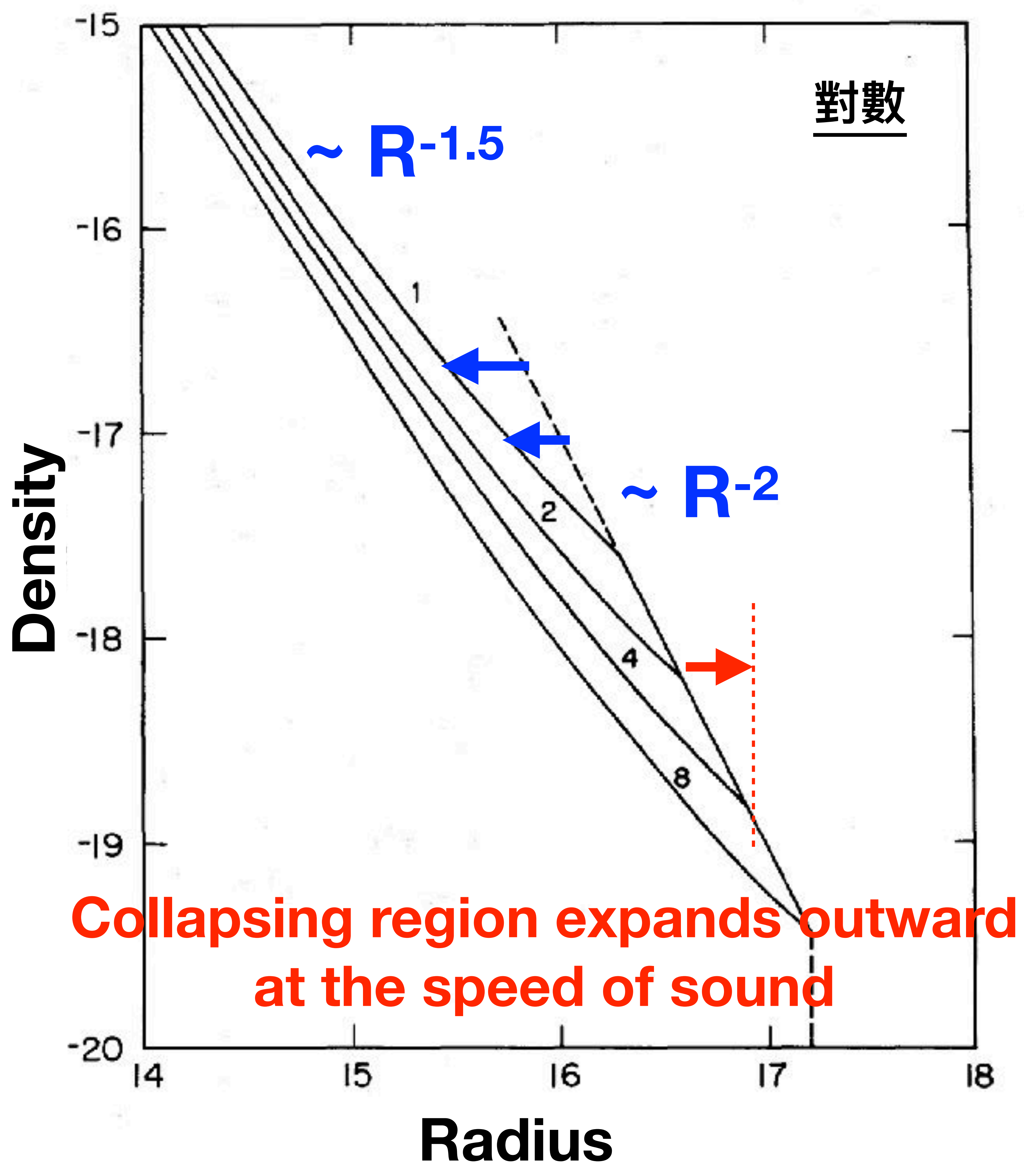
Saito et al. 1999

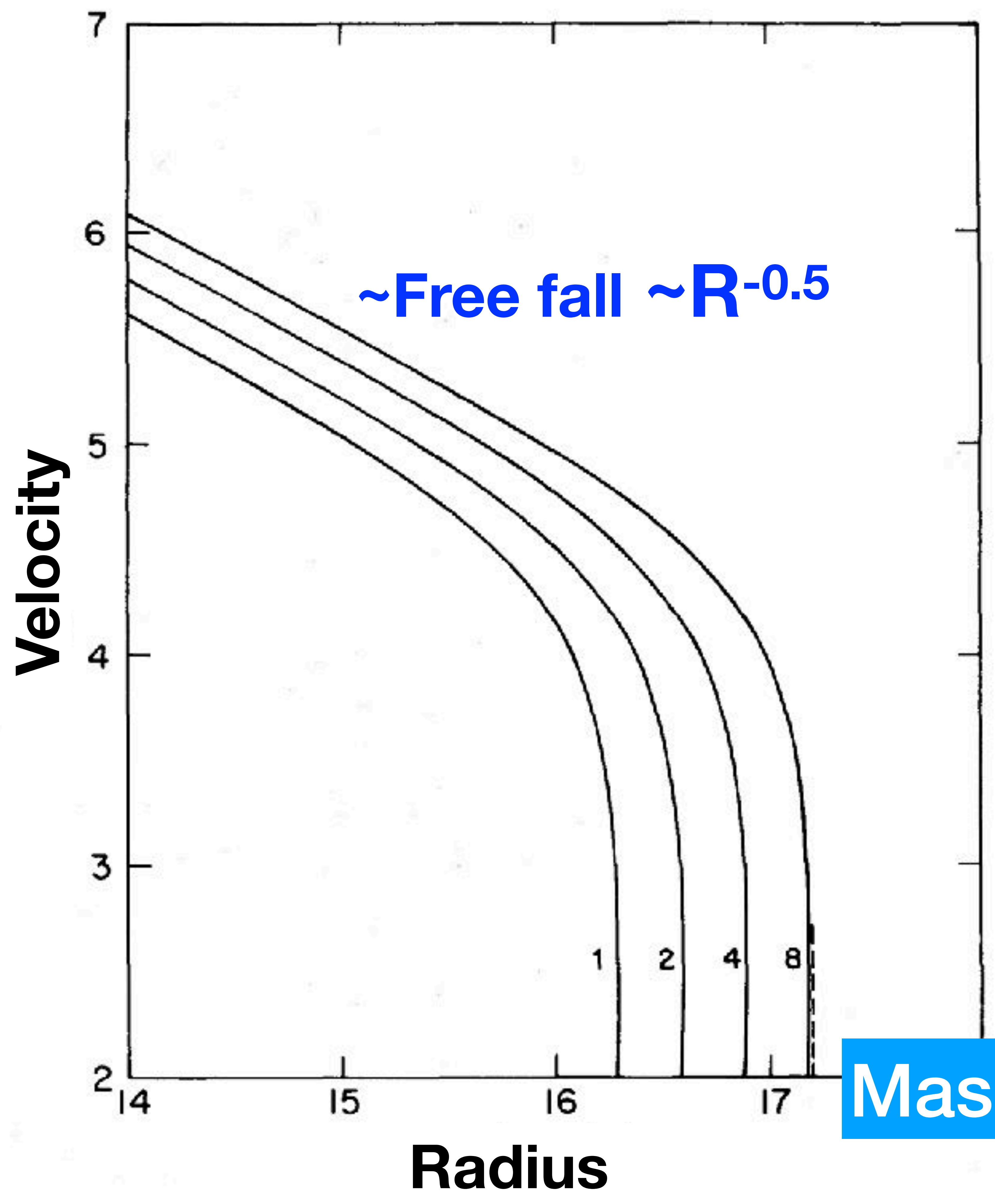
Intensity => Column density

Column density *(N)* ~ *R*$^{-0.95}$ *cm*$^{-2}$

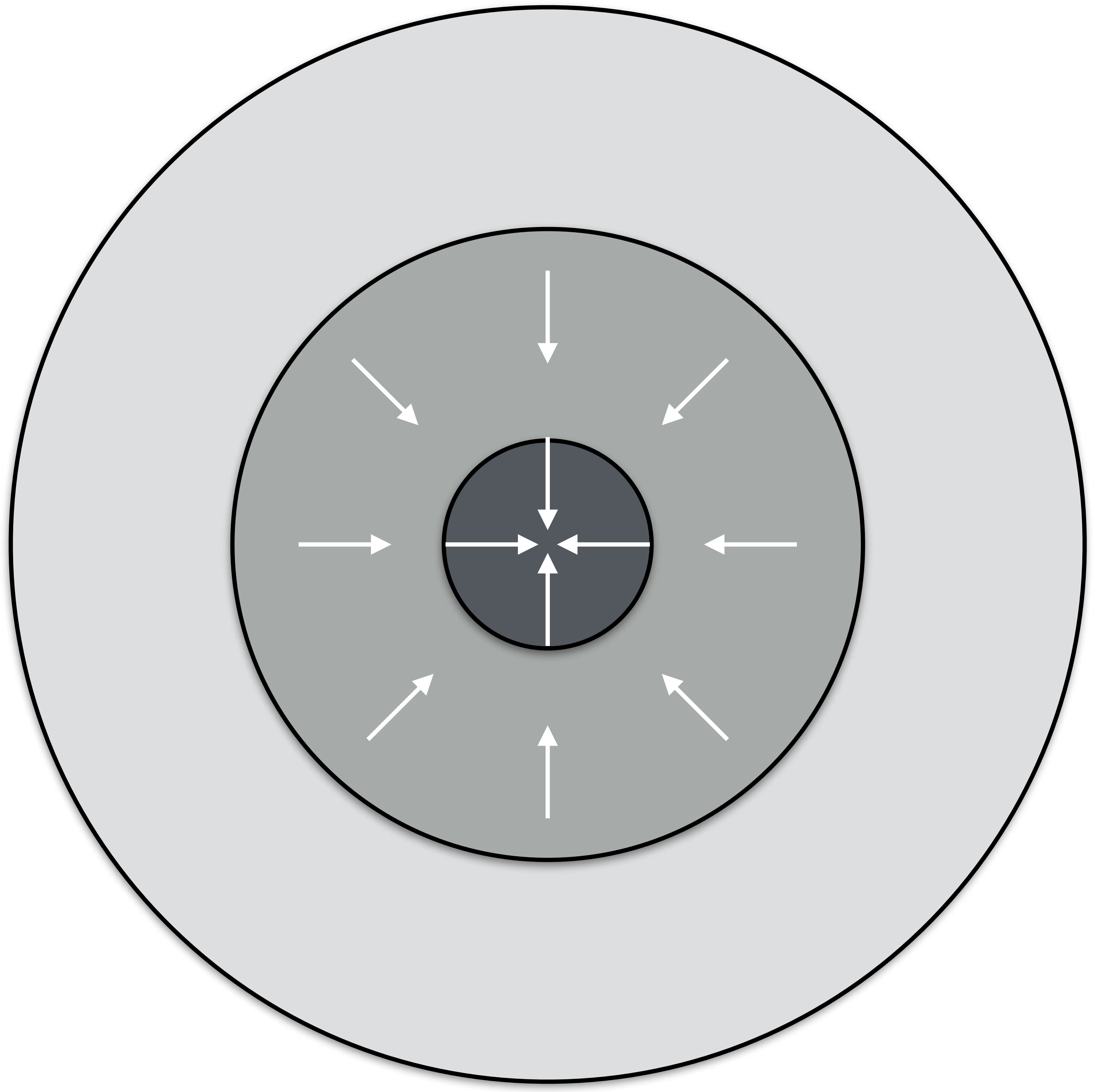
Volume density *(n)* ~ *R*$^{-1.95}$ *cm*$^{-3}$

Gravitational collapse





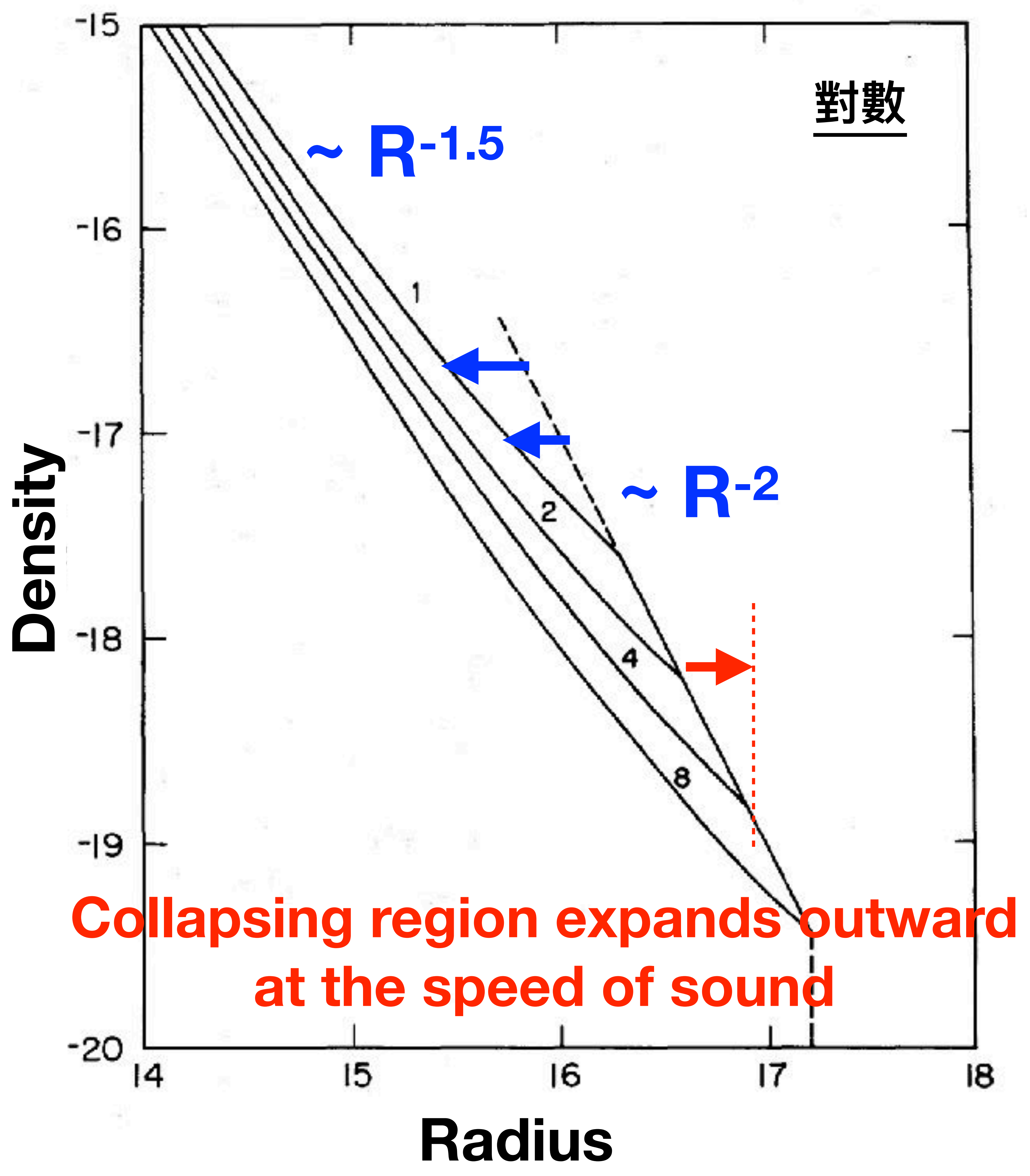
Inside-out collapse

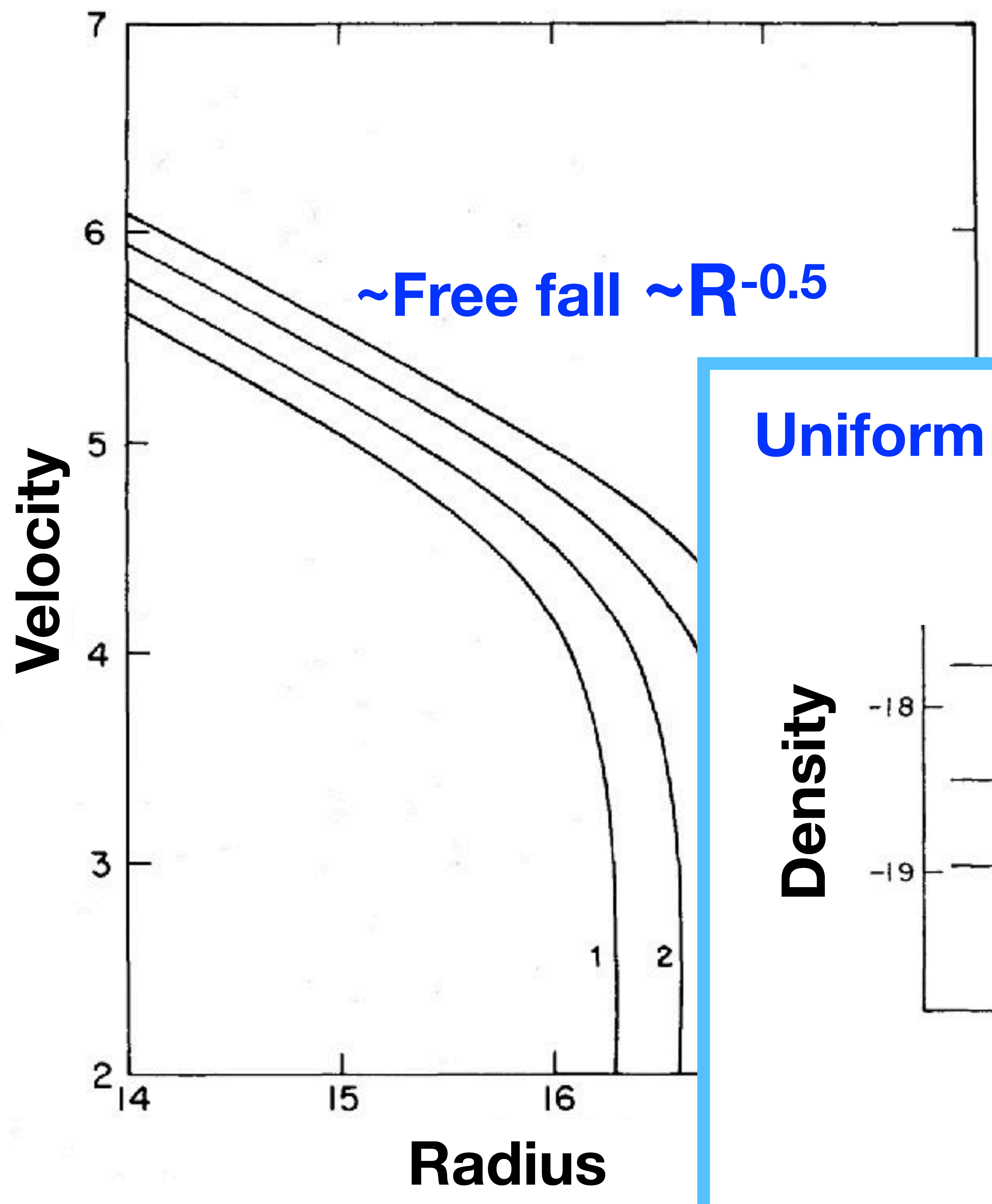


Mass infall rate ~ x10^{-6} Msun/yr

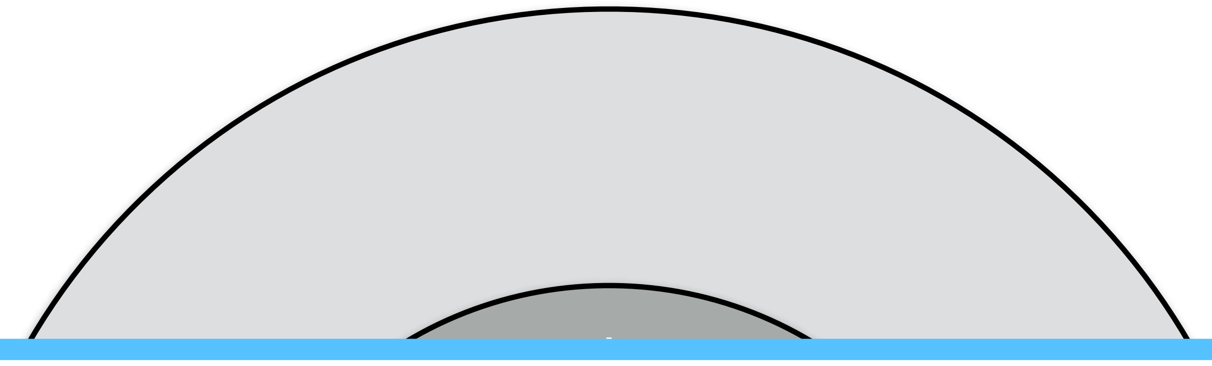
Shu 1977

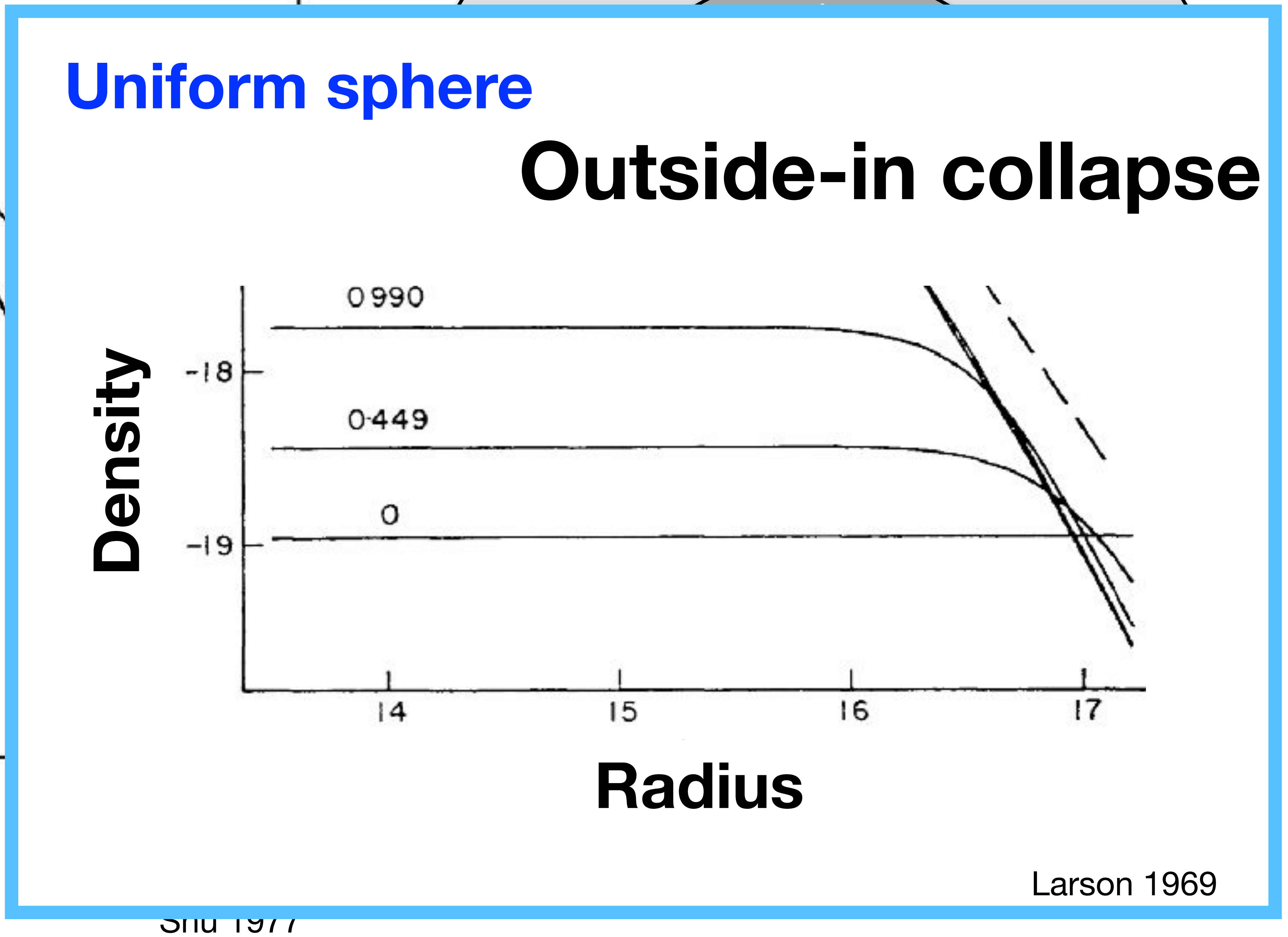
Gravitational collapse





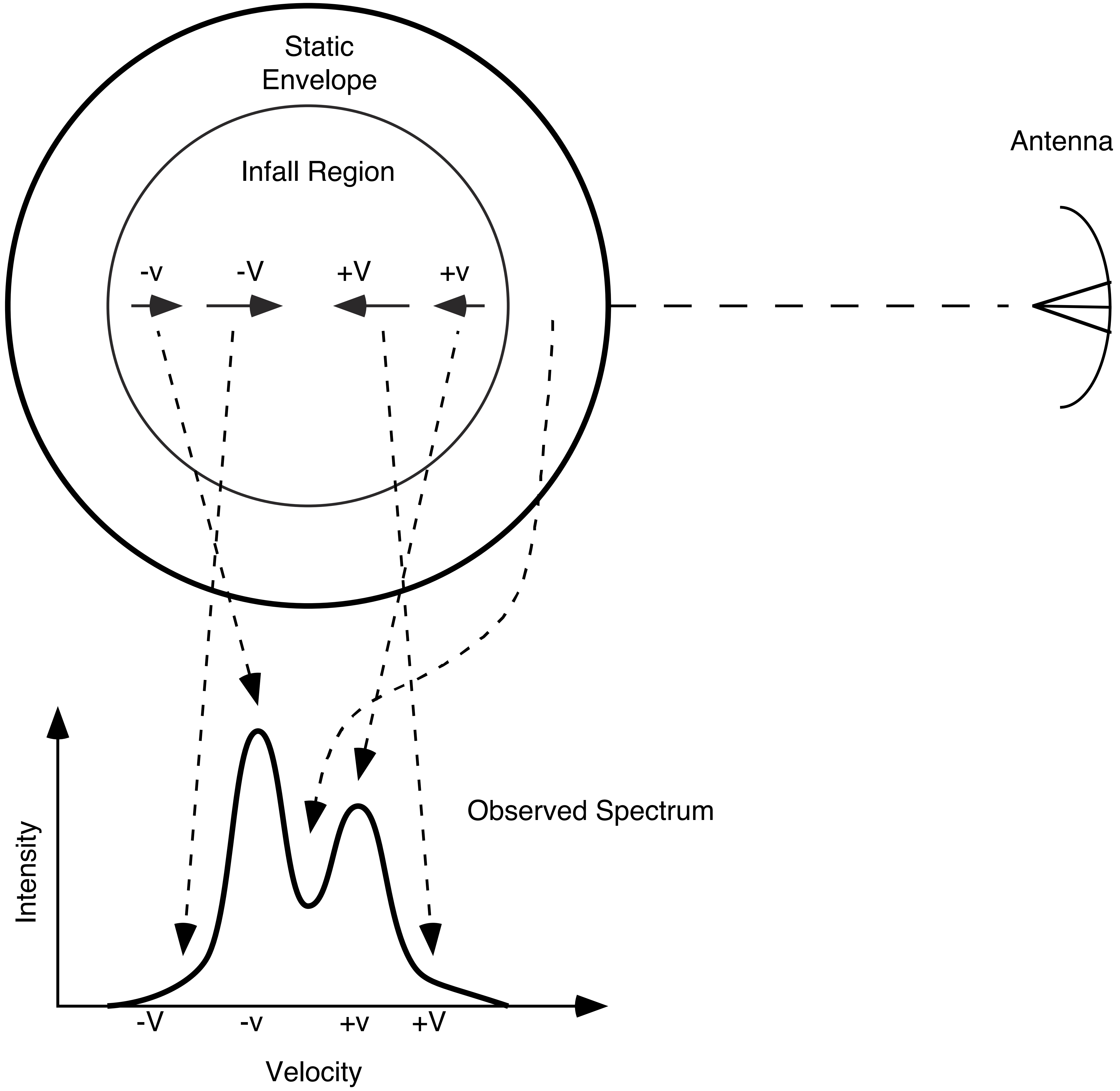
Inside-out collapse

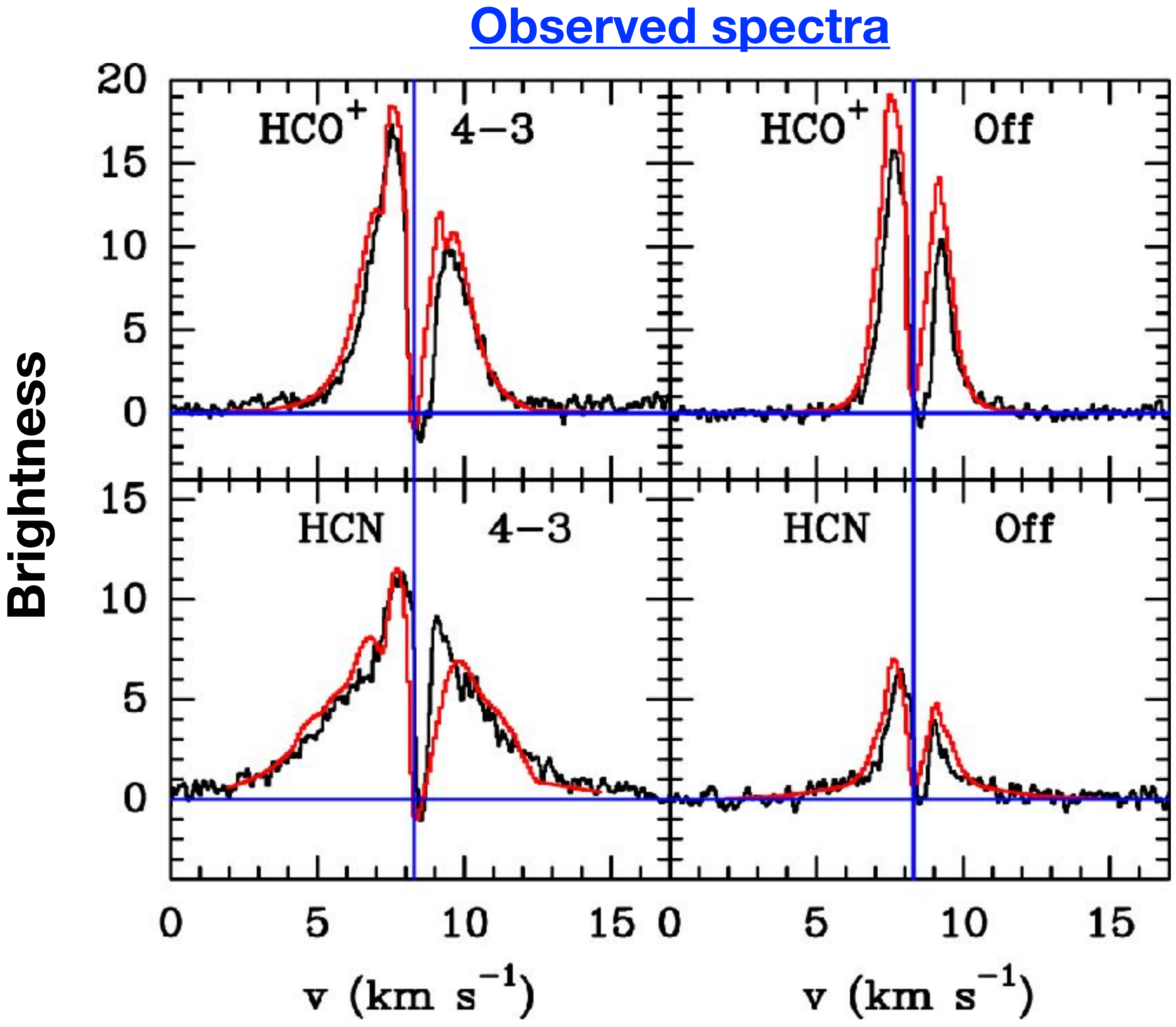




Shu 1977

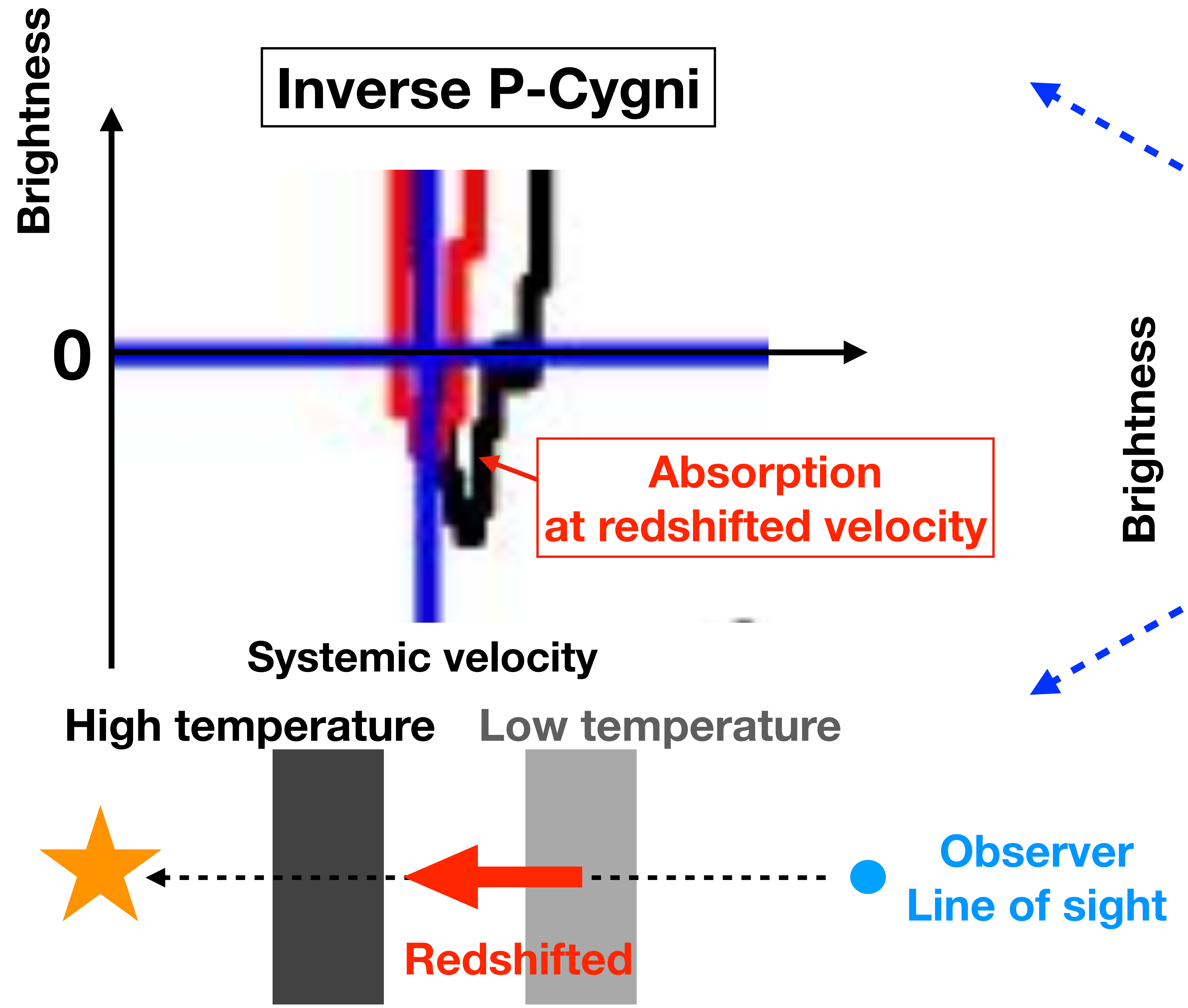
Gravitational collapse

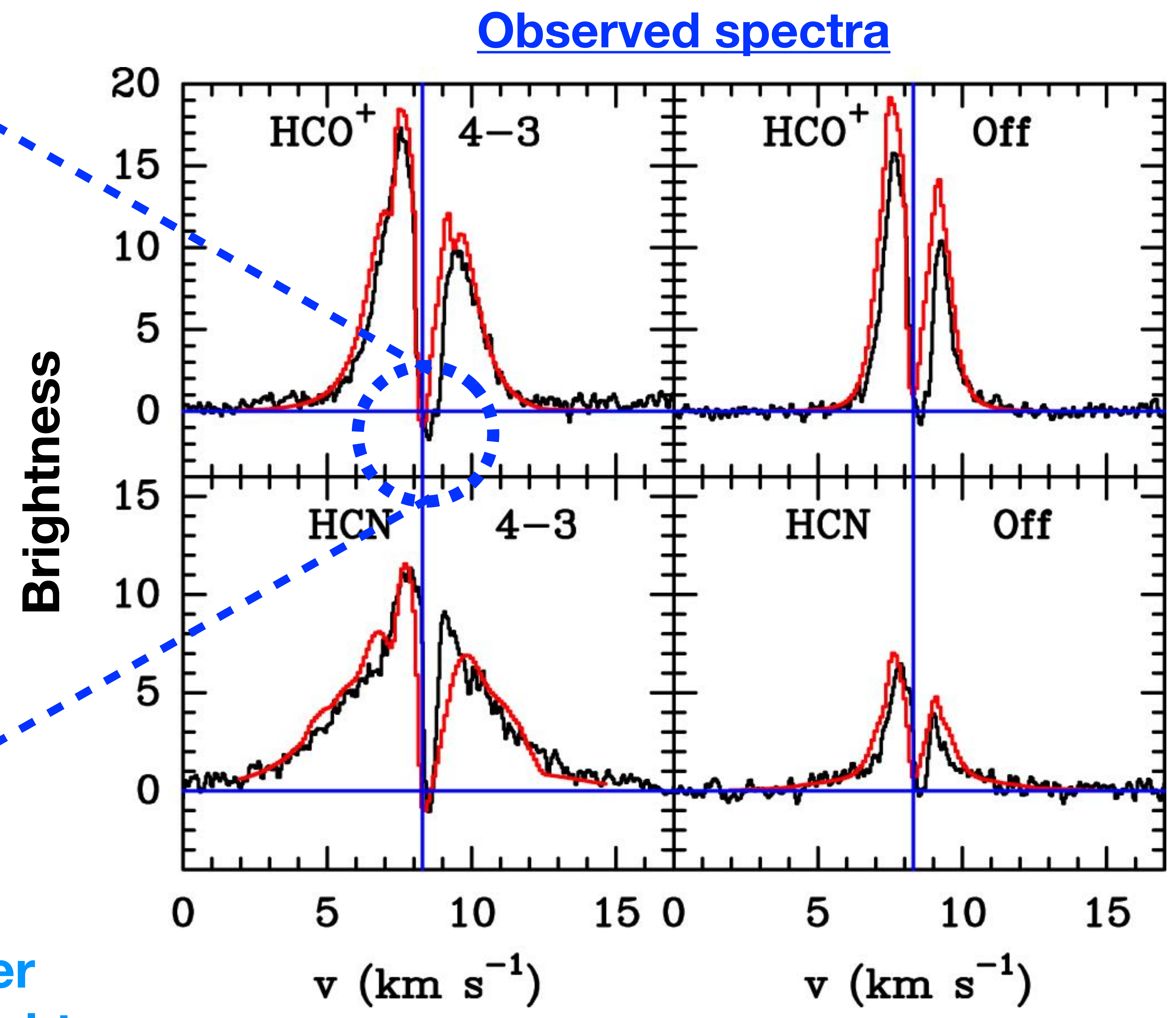




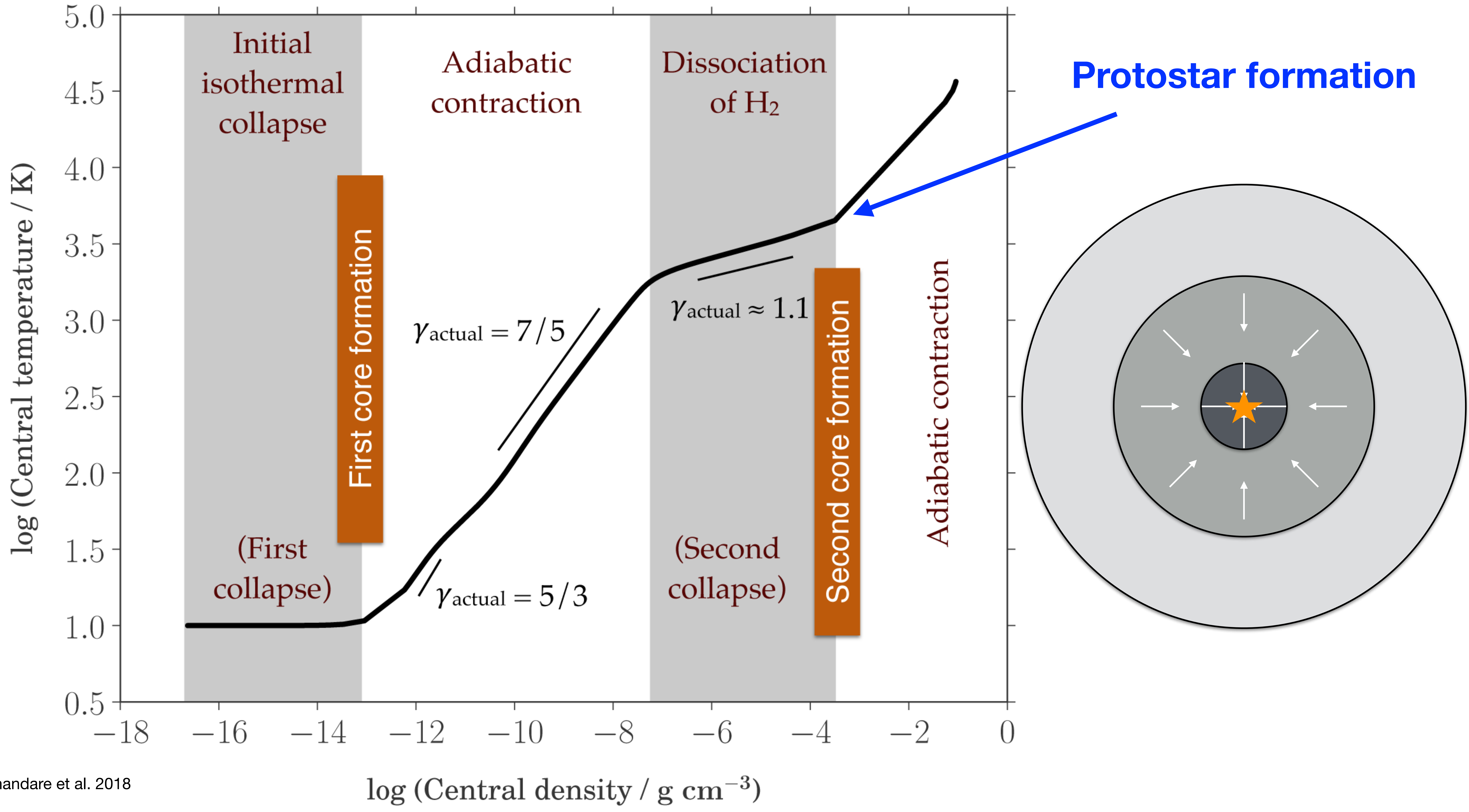
Evans et al. 1999, 2015

Gravitational collapse





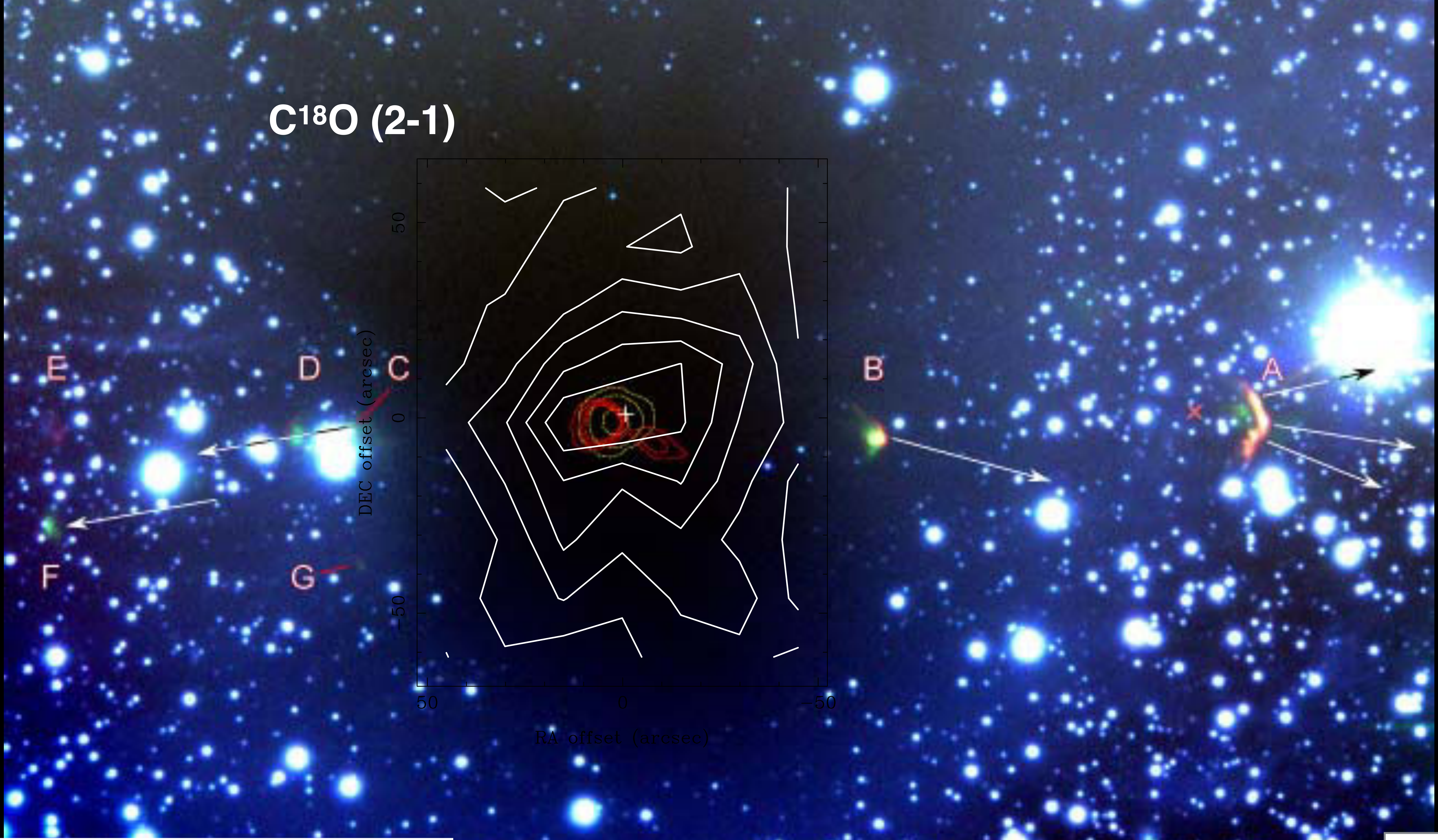
Evans et al. 1999, 2015



Bhandare et al. 2018

Dense cores

C^{18}O (2-1)



Contours: Molecular-line emission

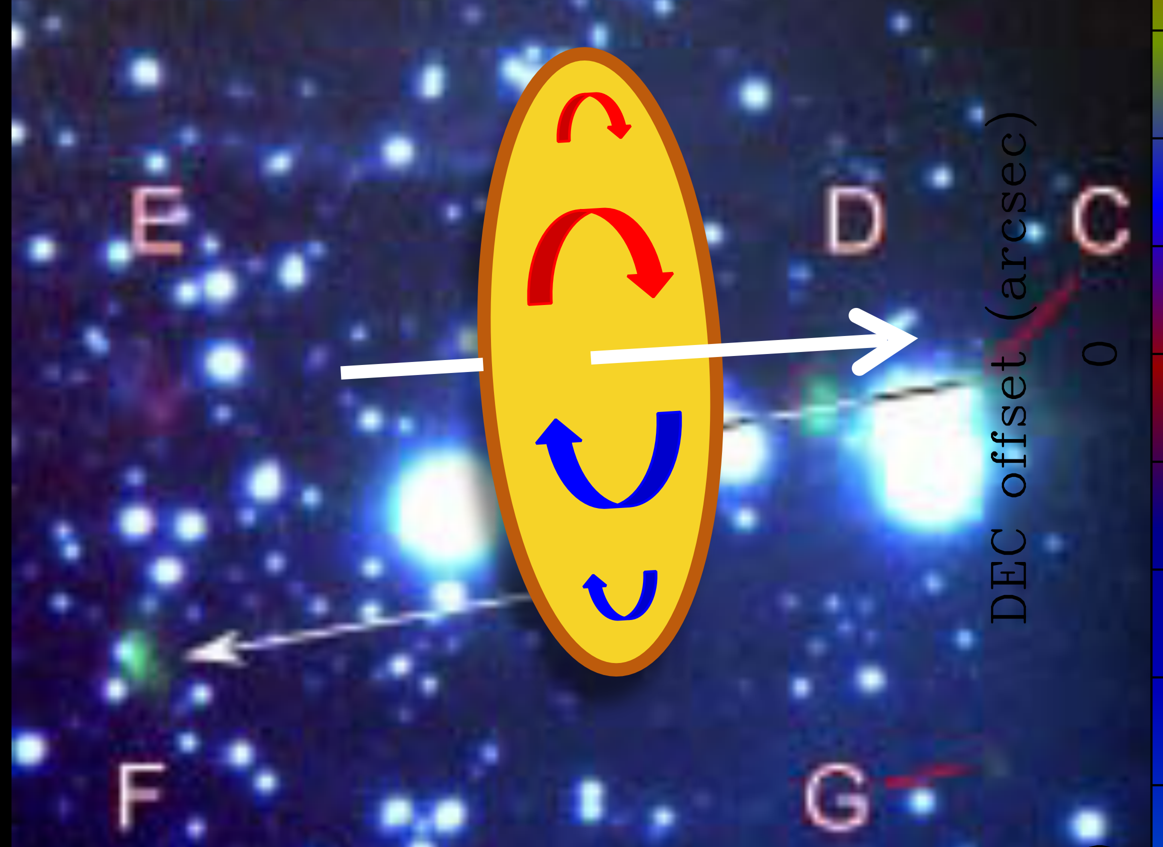
Gâlfalk & Olofsson 2007
Yen et al. 2011

Dense cores are rotating

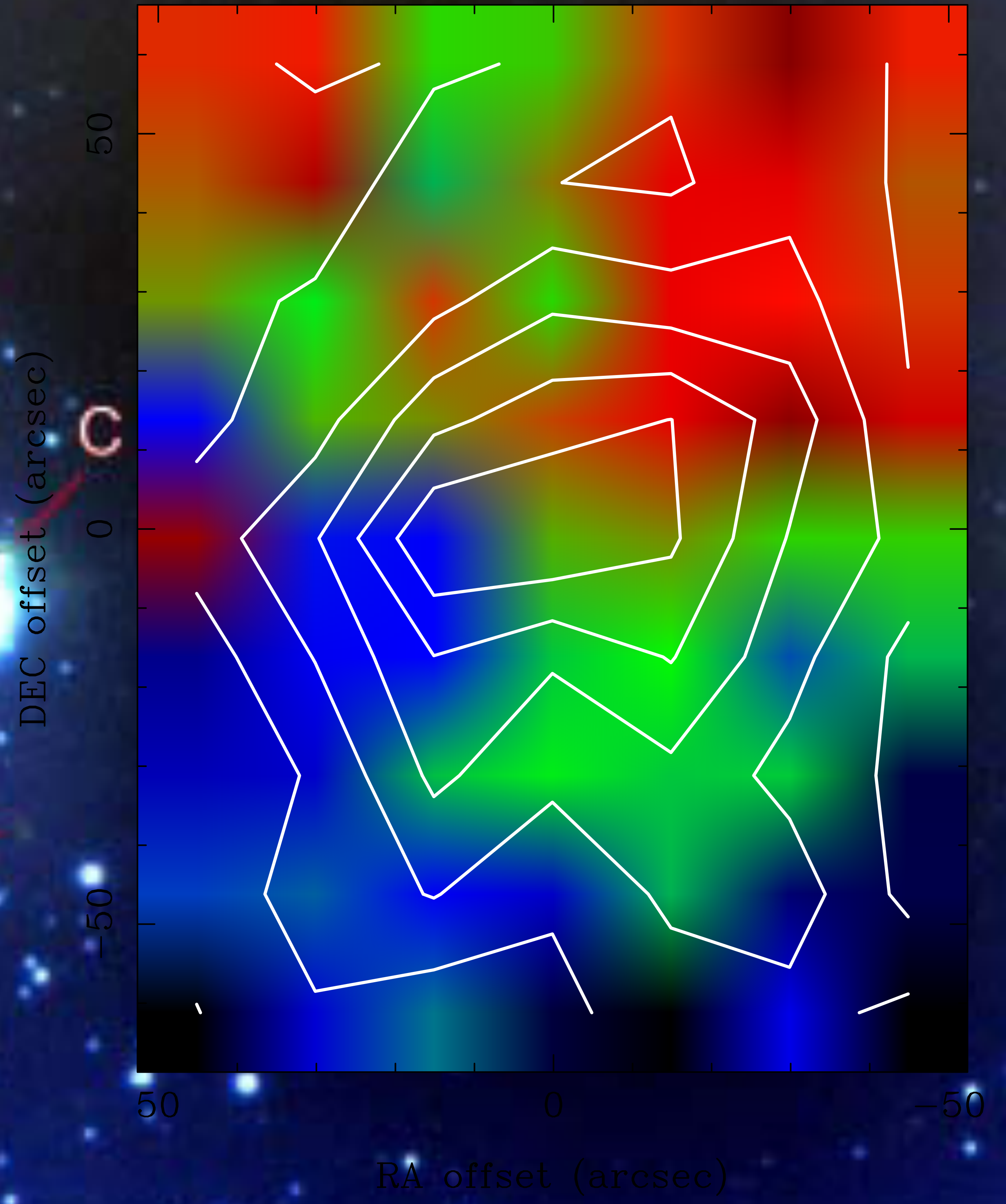
Doppler effect

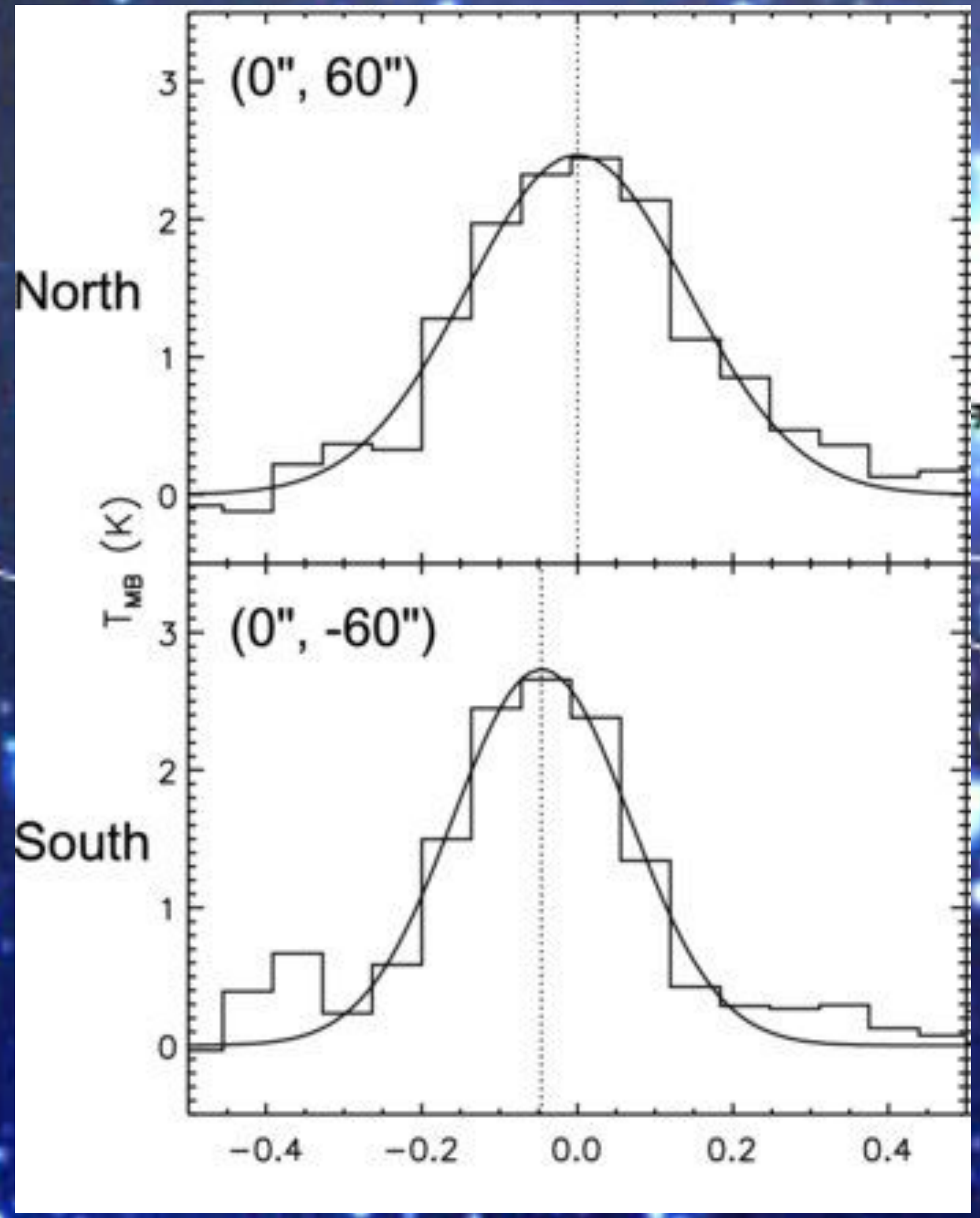
red: redshifted

blue: blueshifted



C^{18}O (2-1)

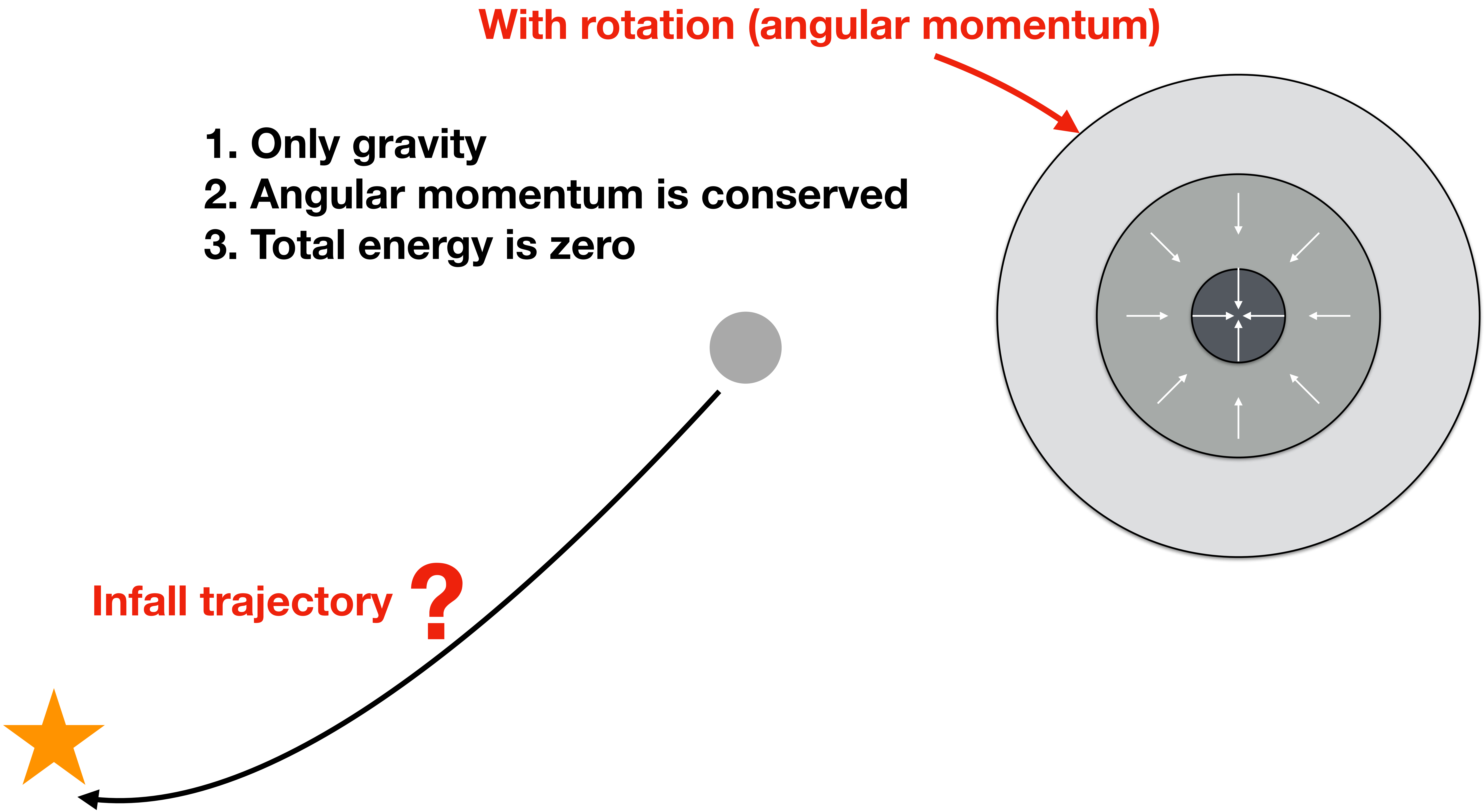




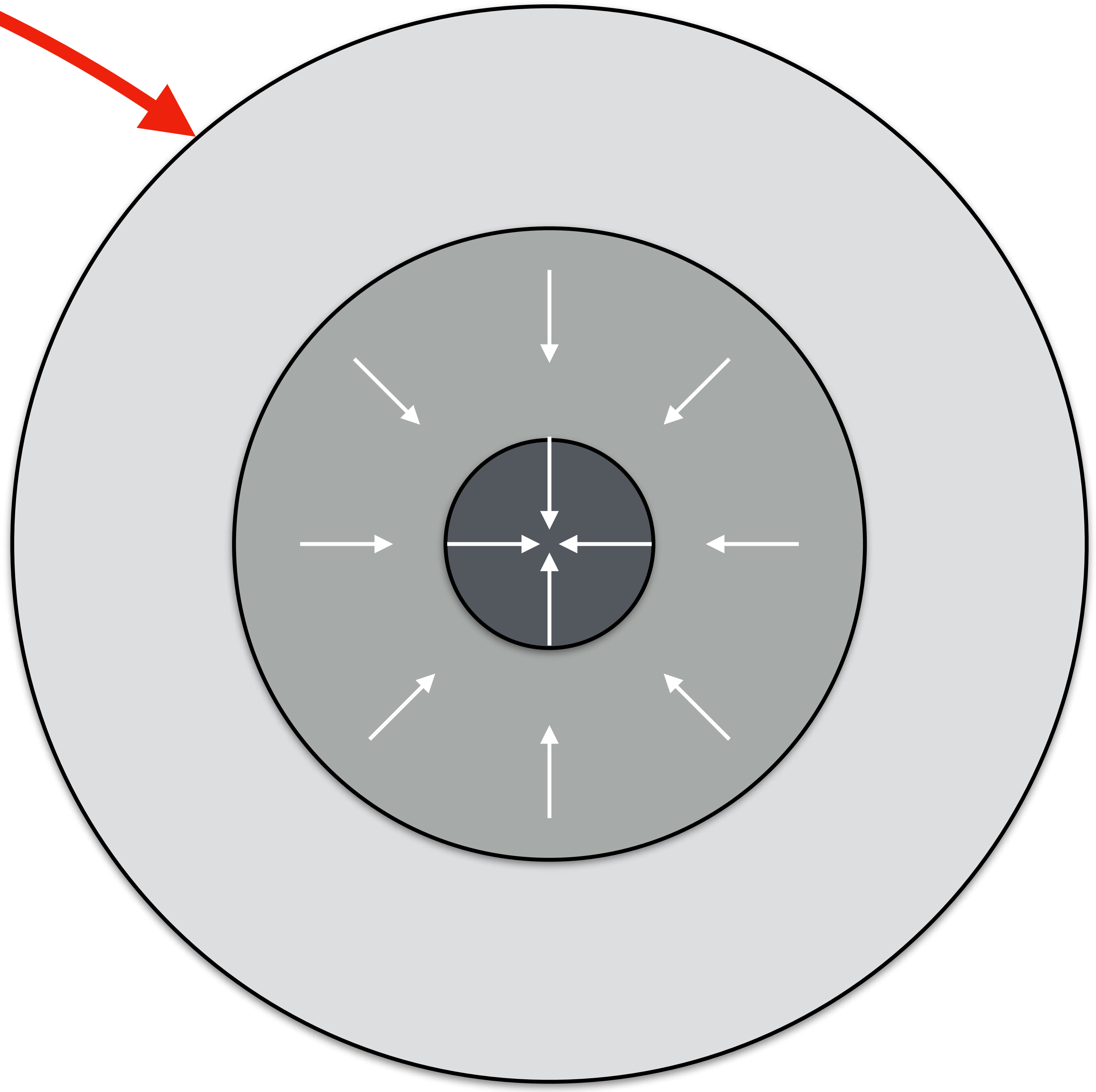
Contours: Molecular-line emission
Color: Velocity

Gâlfalk & Olofsson 2007
Yen et al. 2011

1. Only gravity
2. Angular momentum is conserved
3. Total energy is zero



With rotation (angular momentum)

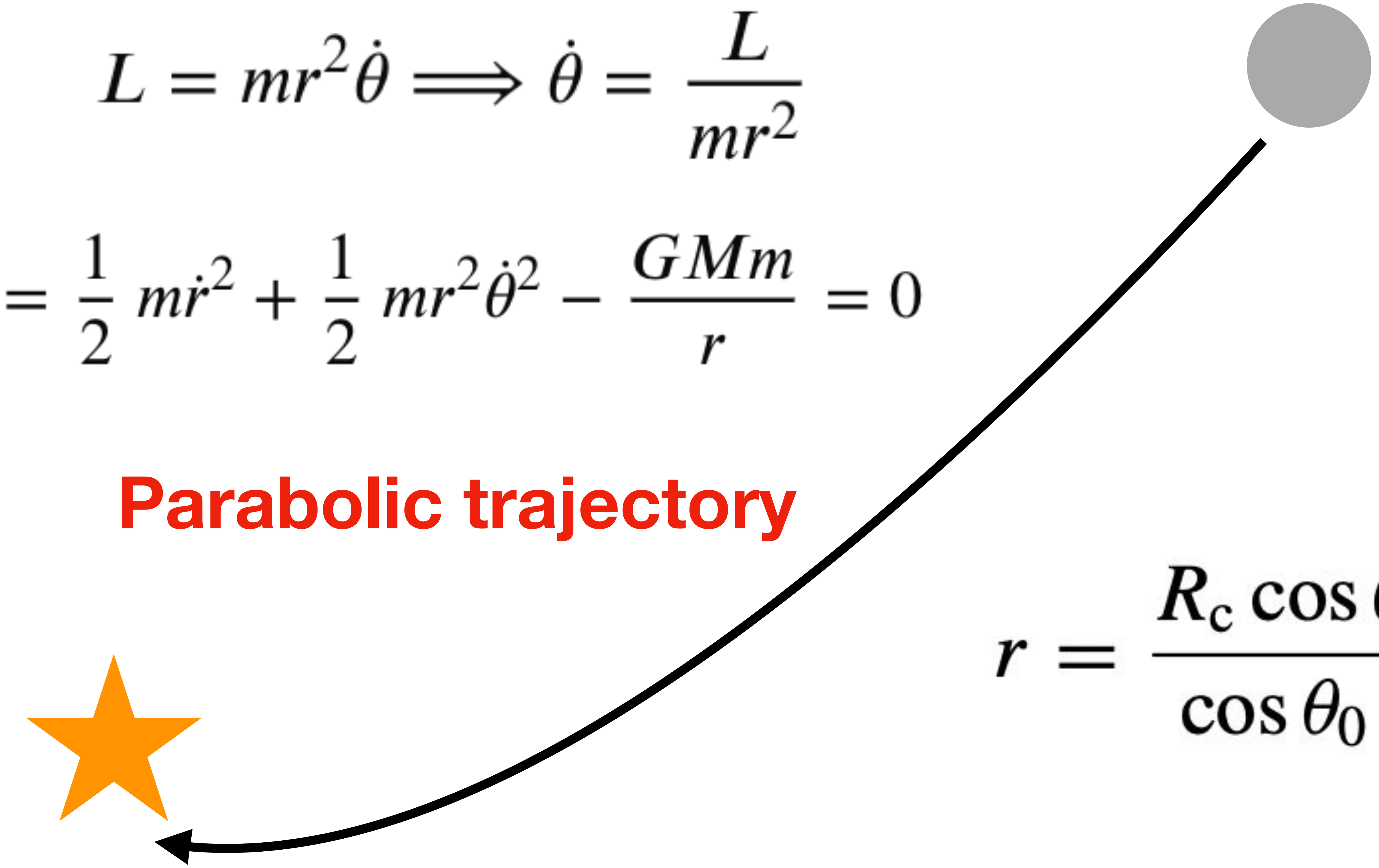


1. Only gravity
2. Angular momentum is conserved
3. Total energy is zero

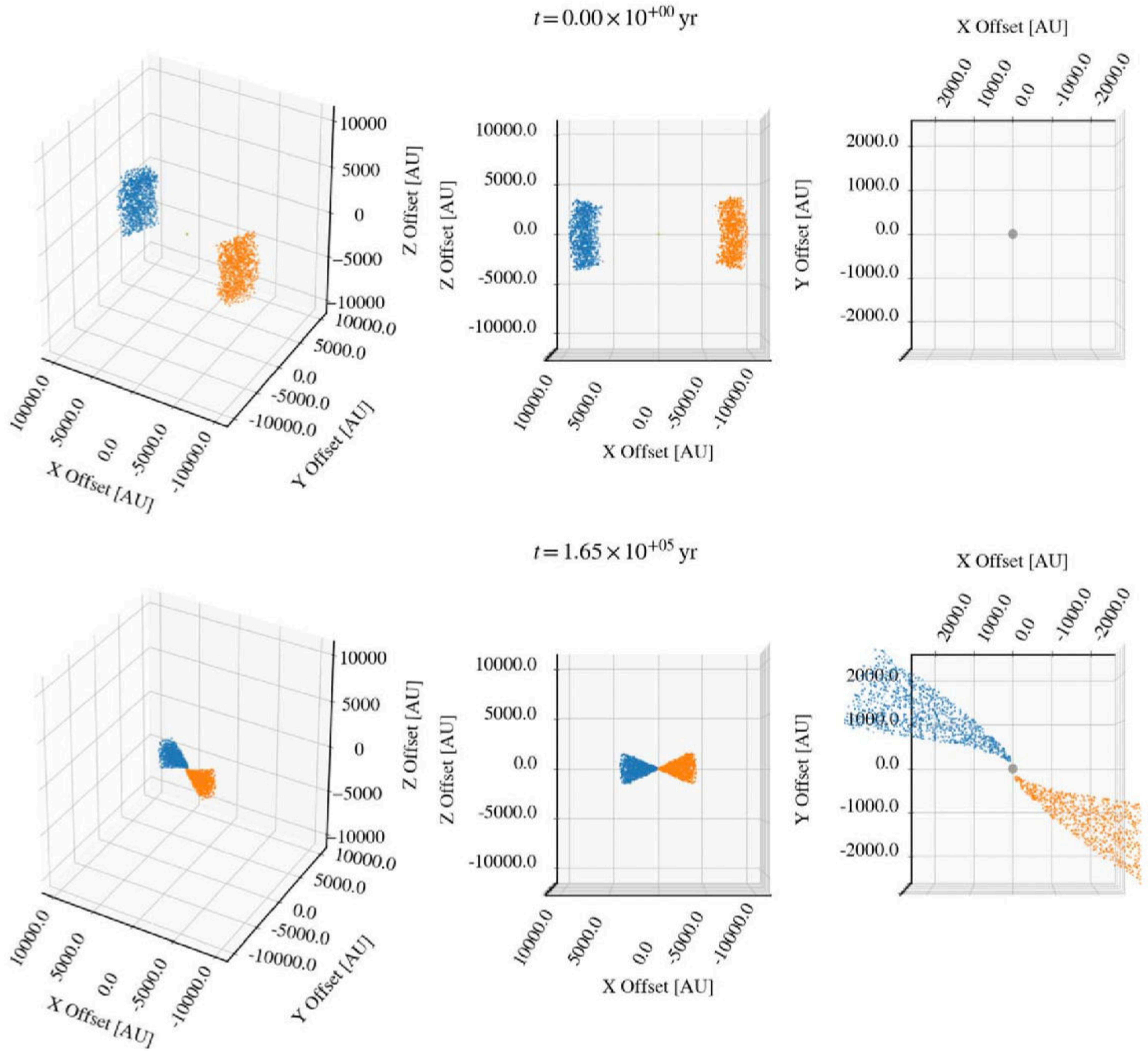
$$L = mr^2\dot{\theta} \Longrightarrow \dot{\theta} = \frac{L}{mr^2}$$

$$E = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\theta}^2 - \frac{GMm}{r} = 0$$

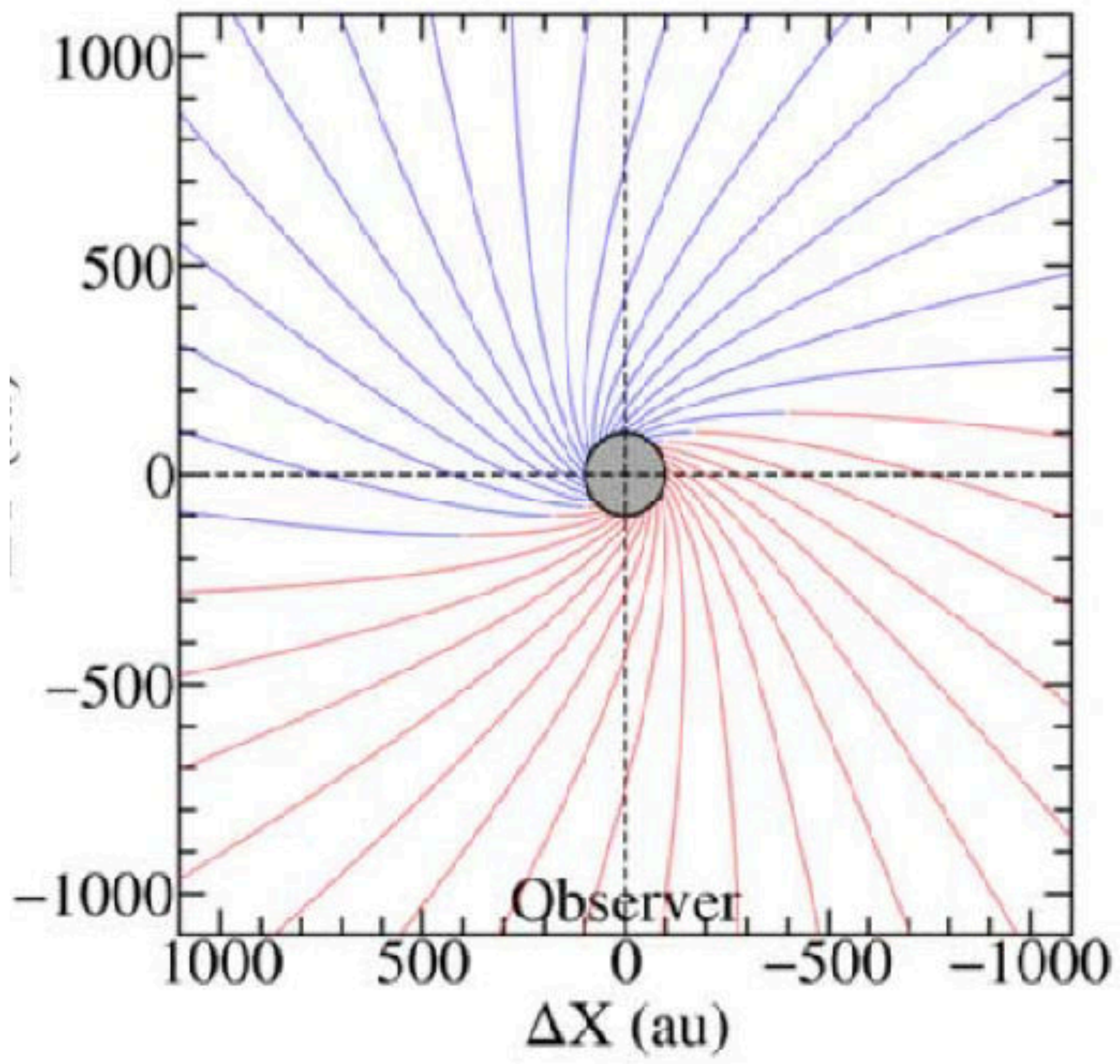
Parabolic trajectory



$$r = \frac{R_c \cos\theta_0 \sin^2\theta_0}{\cos\theta_0 - \cos\theta}$$

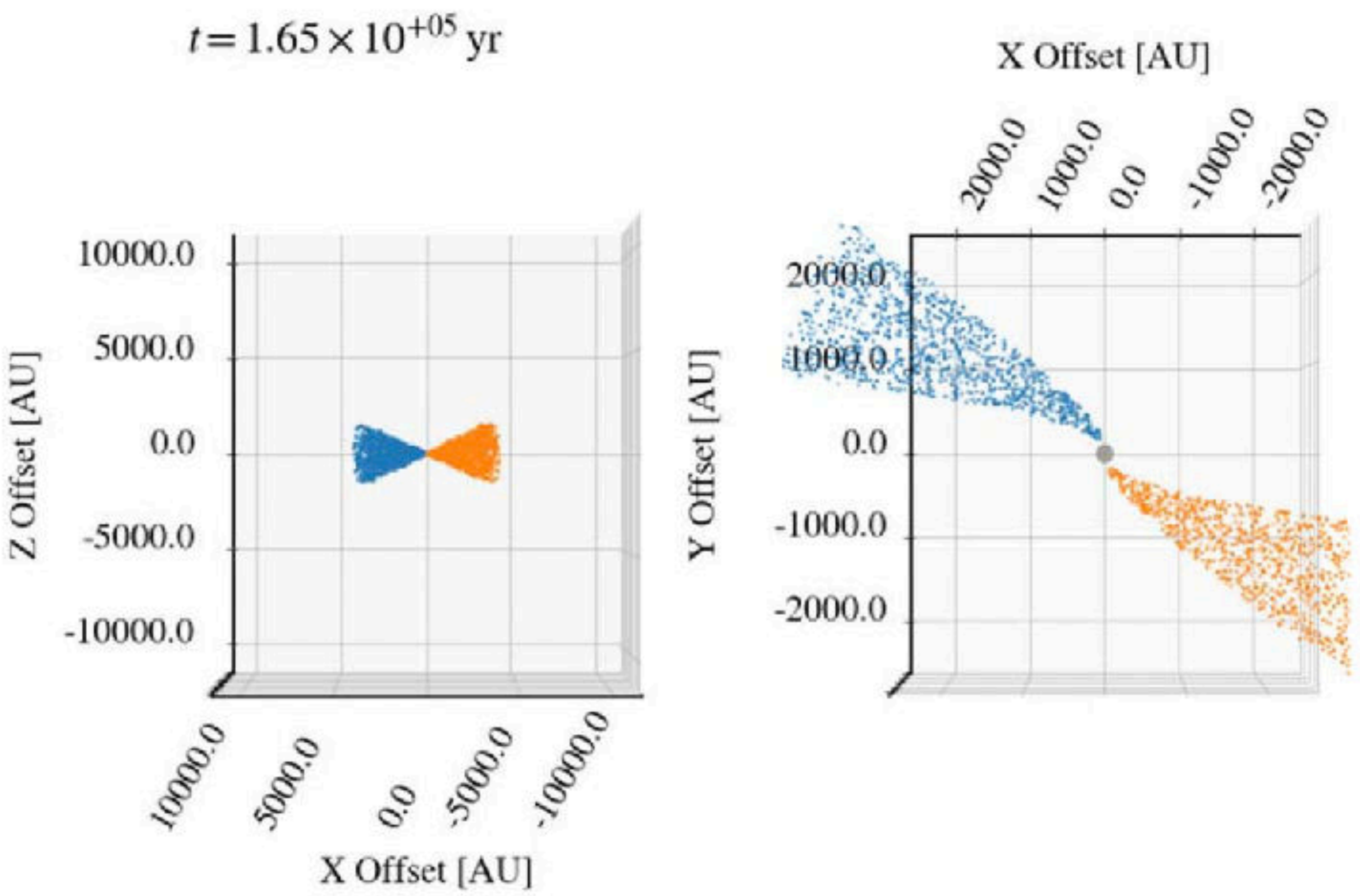


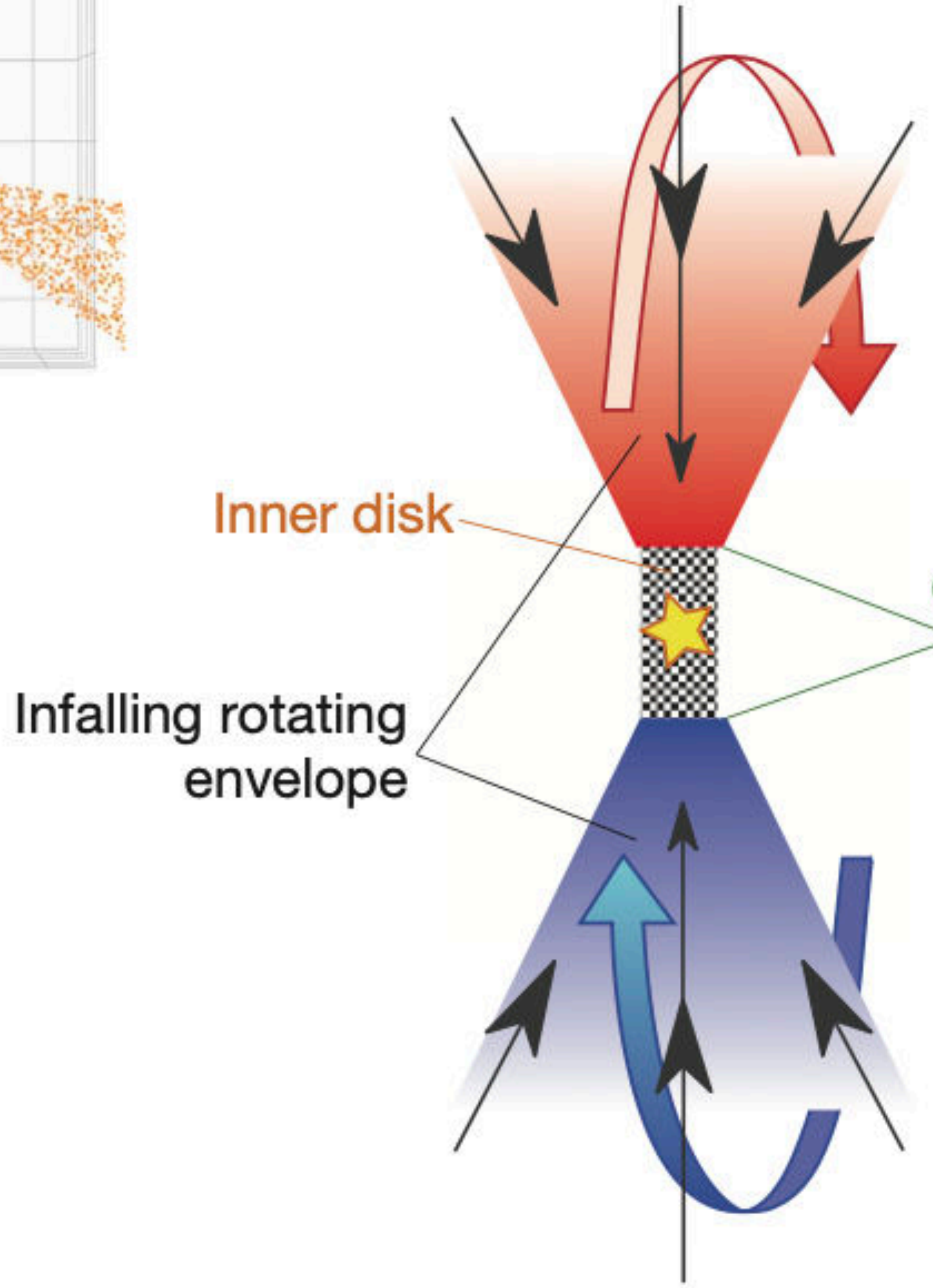
Axisymmetric infall and rotation



Thieme et al. 2022

Rotating and collapsing dense core





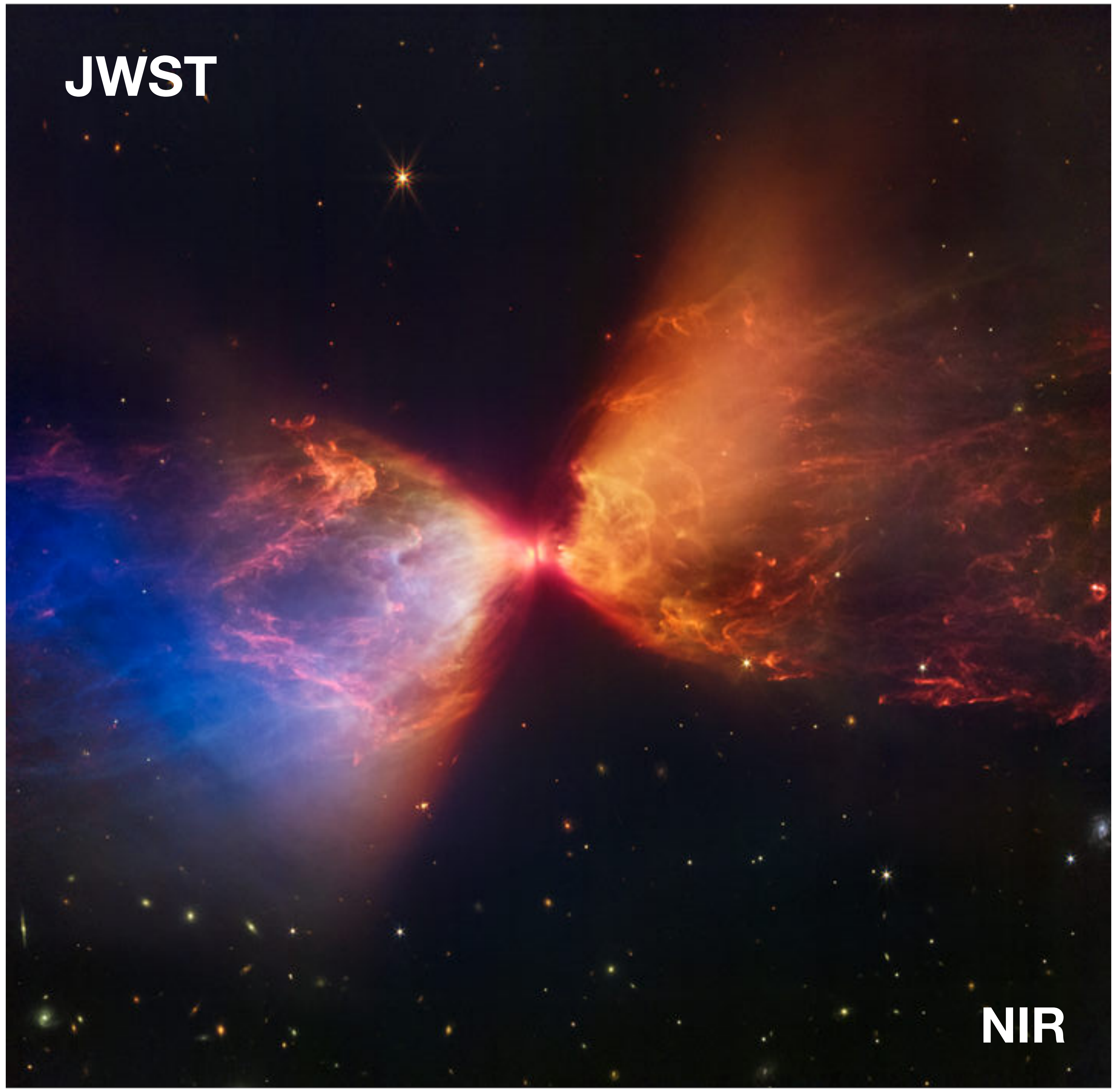
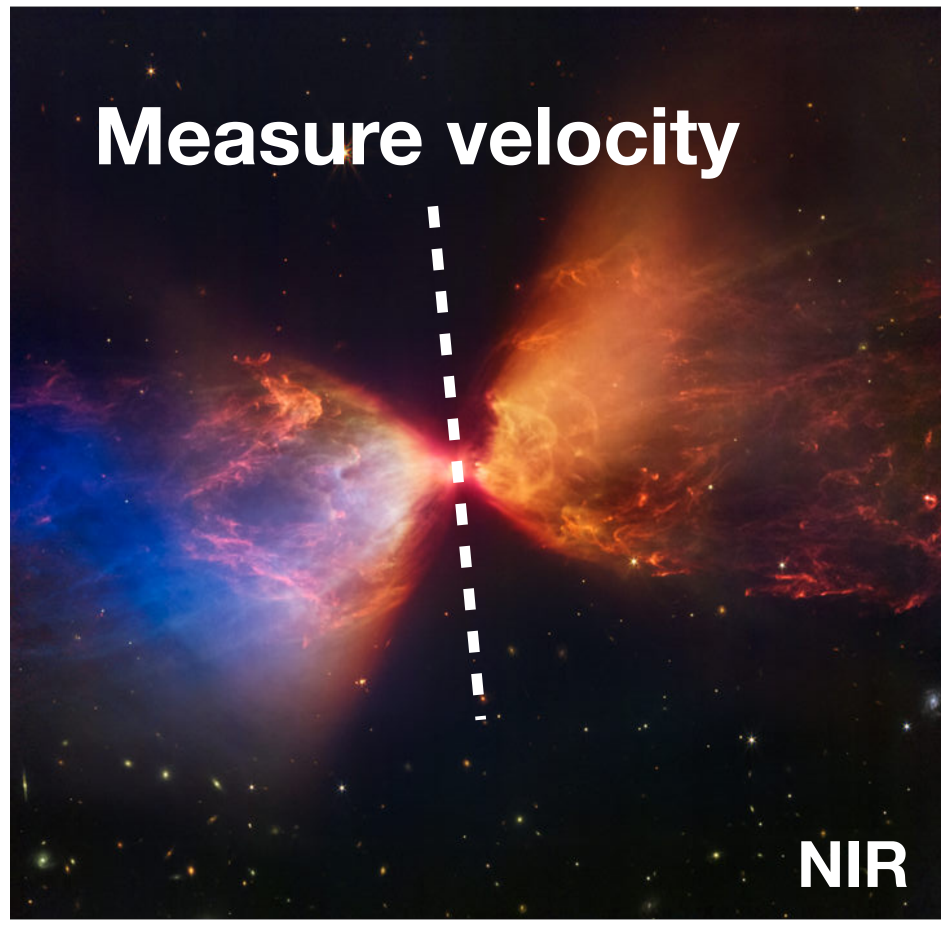
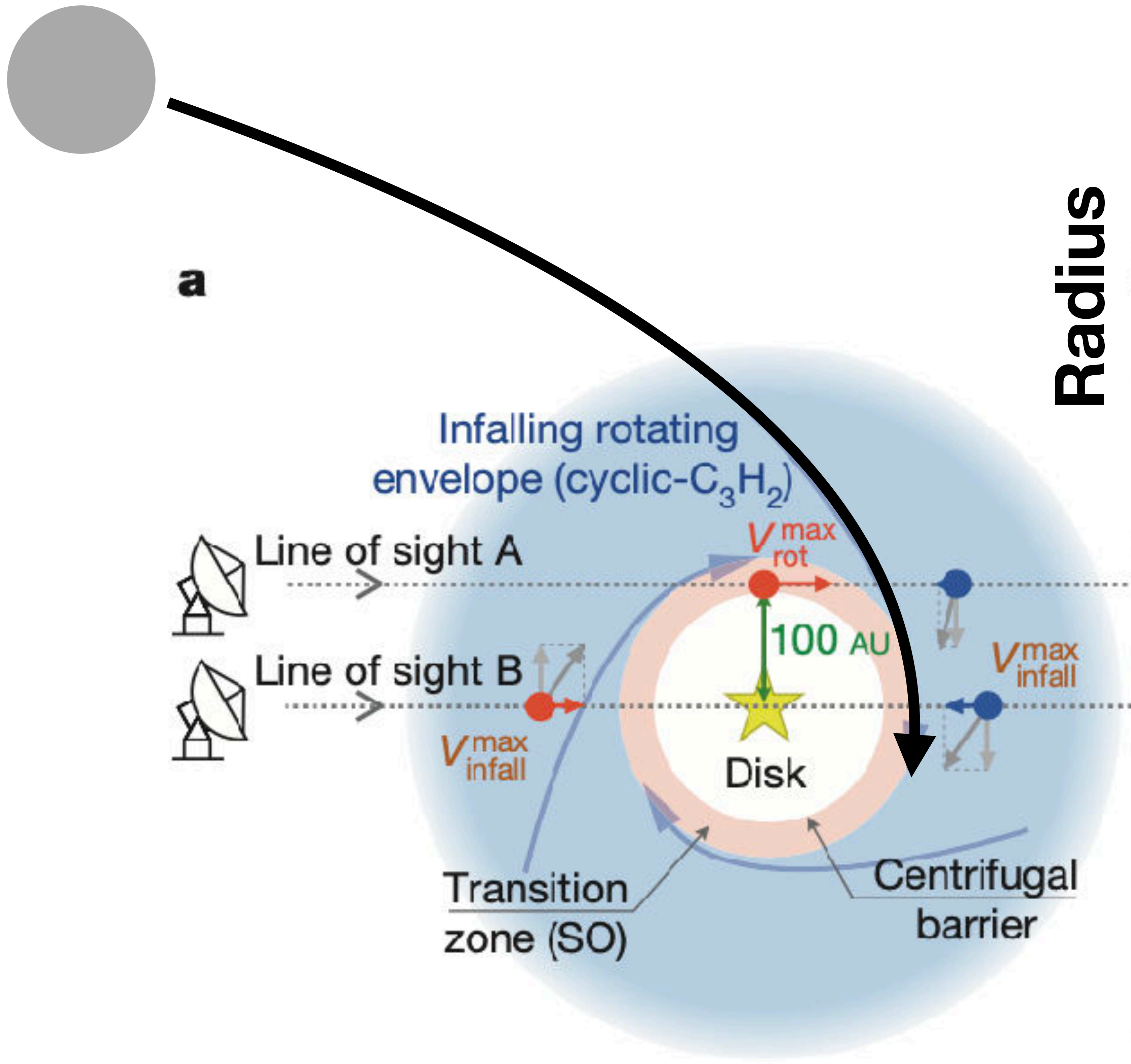


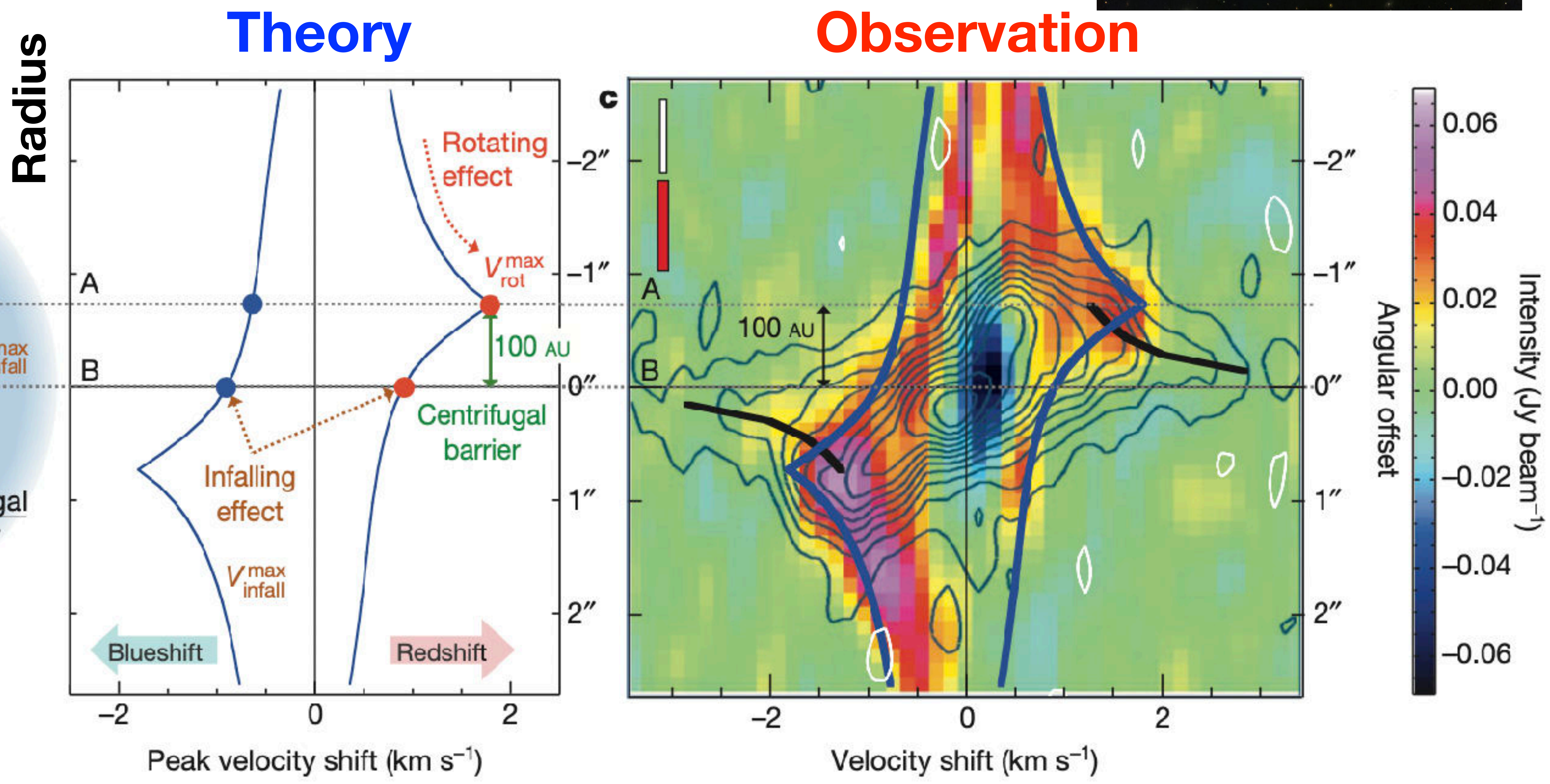
Image credit: NASA, ESA, CSA, STScI

Rotating and collapsing dense core



Gravity and Angular momentum conservation



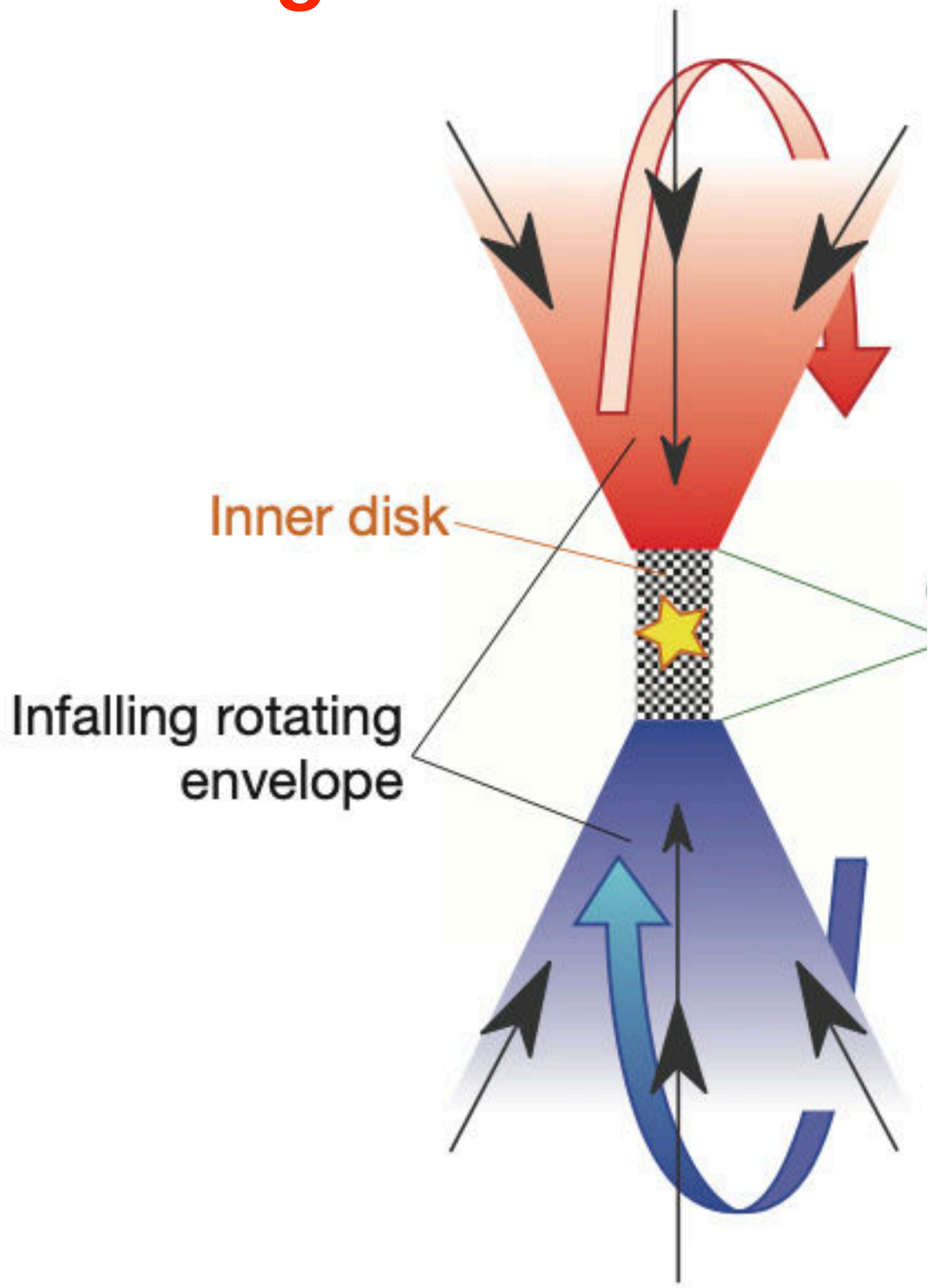


Sakai et al. 2014

Formation of protostellar disks -> Protoplanetary disk (rotationally supported)

Infalling and rotating material

Angular momentum



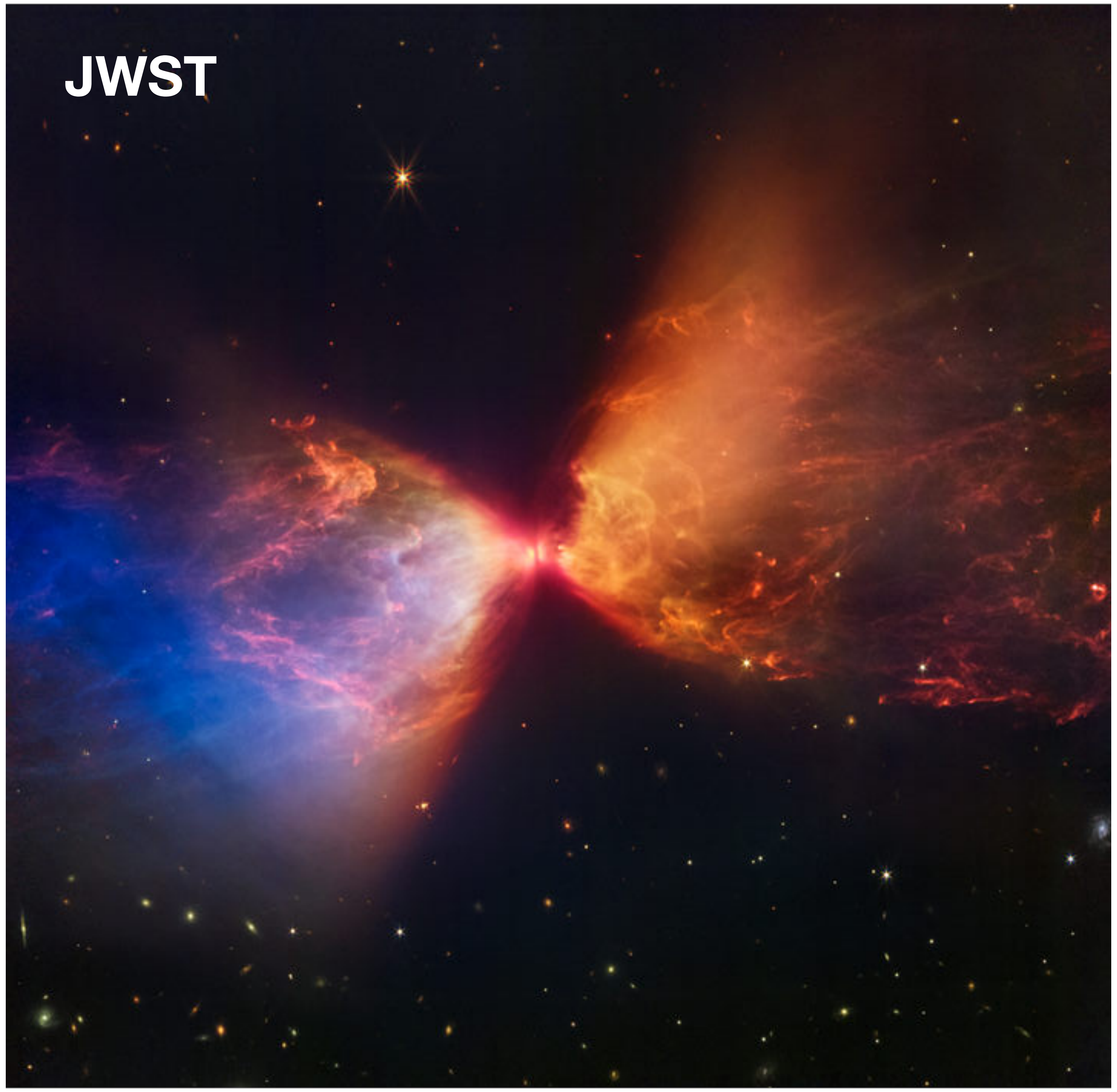


Image credit: NASA, ESA, CSA, STScI

Formation of protostellar disks -> Protoplanetary disk (rotationally supported)

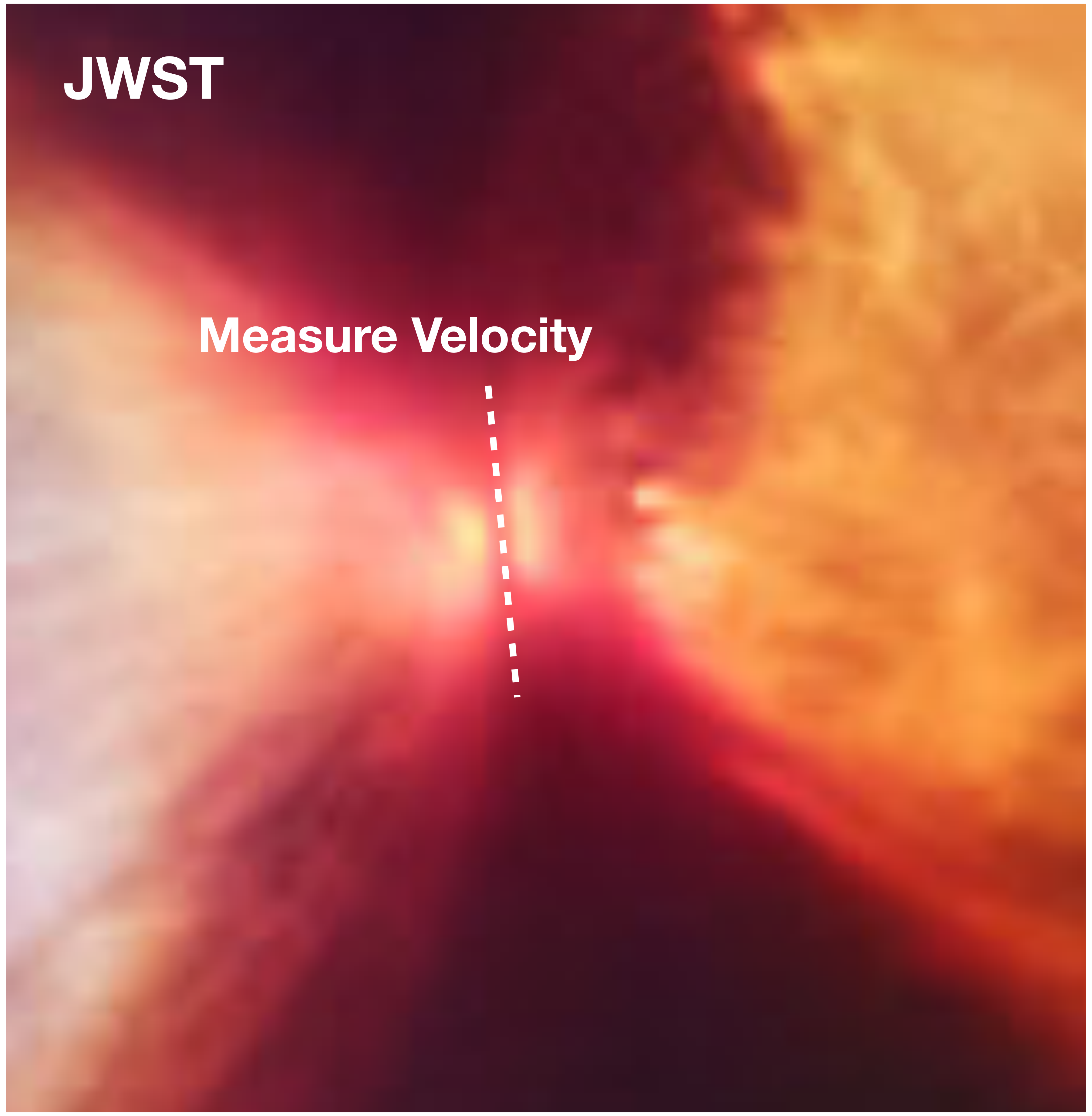
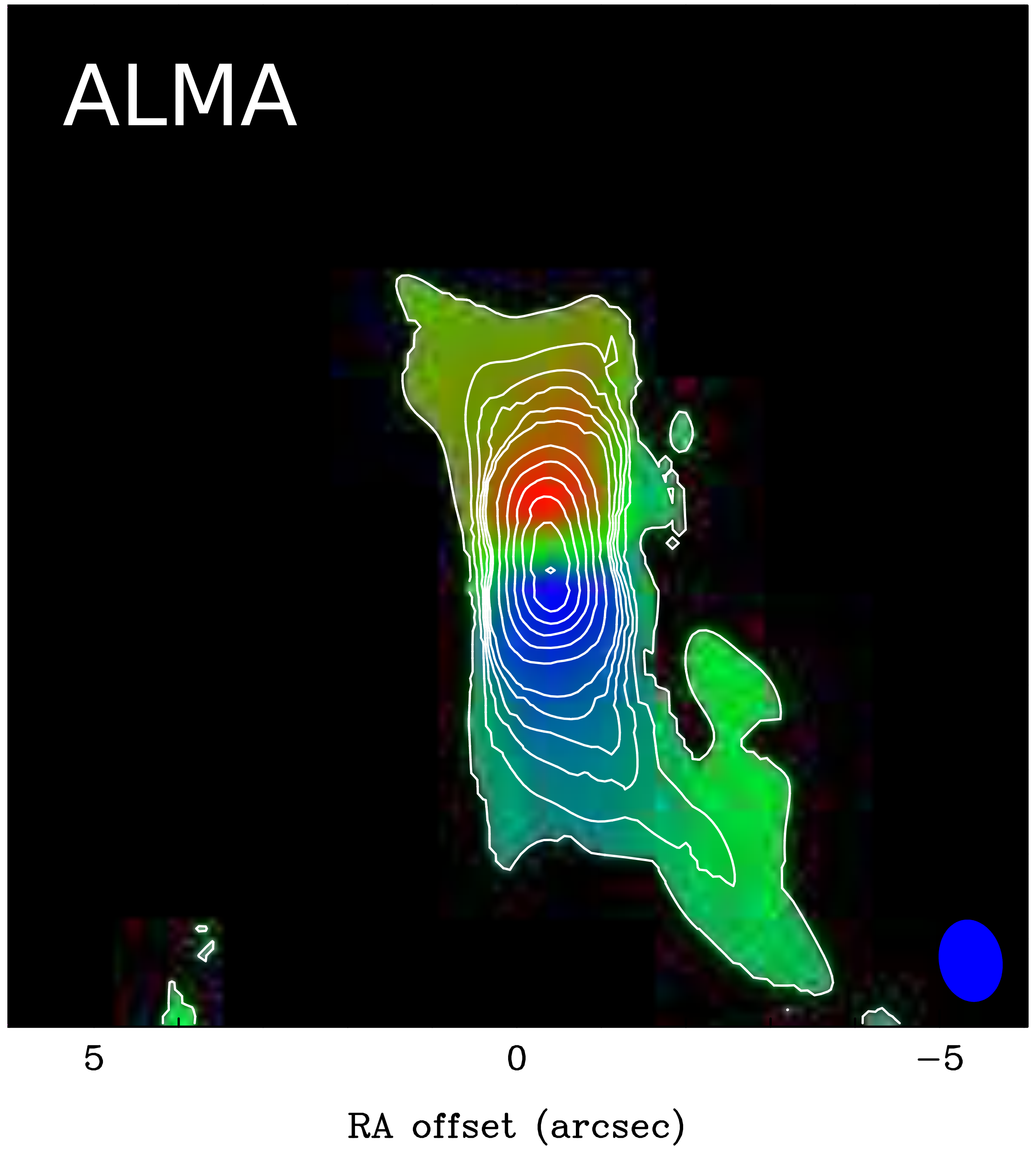
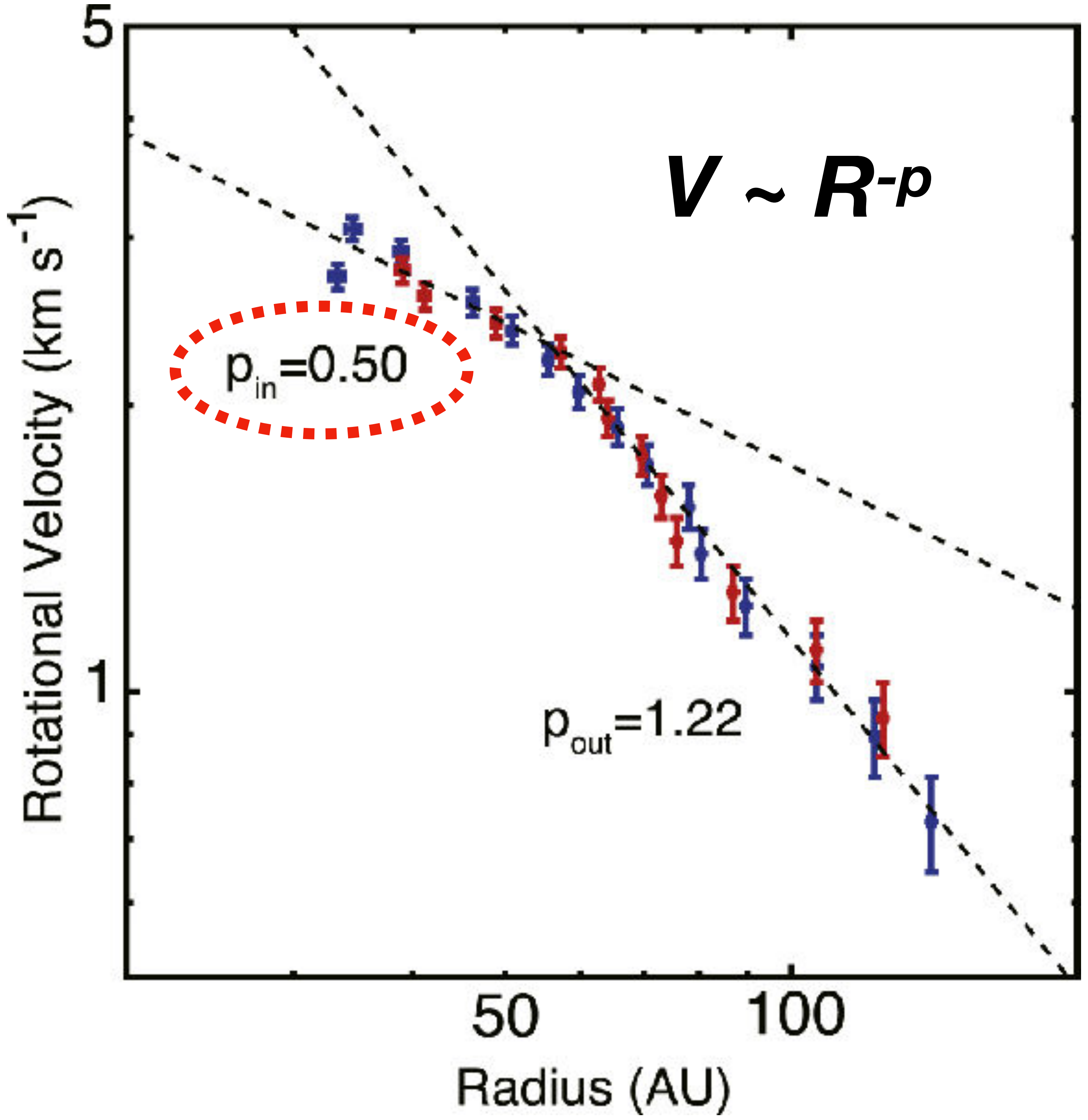


Image credit: NASA, ESA, CSA, STScI

Observed gas distribution and velocity





Formation of protostellar disks -> Protoplanetary disk (rotationally supported)

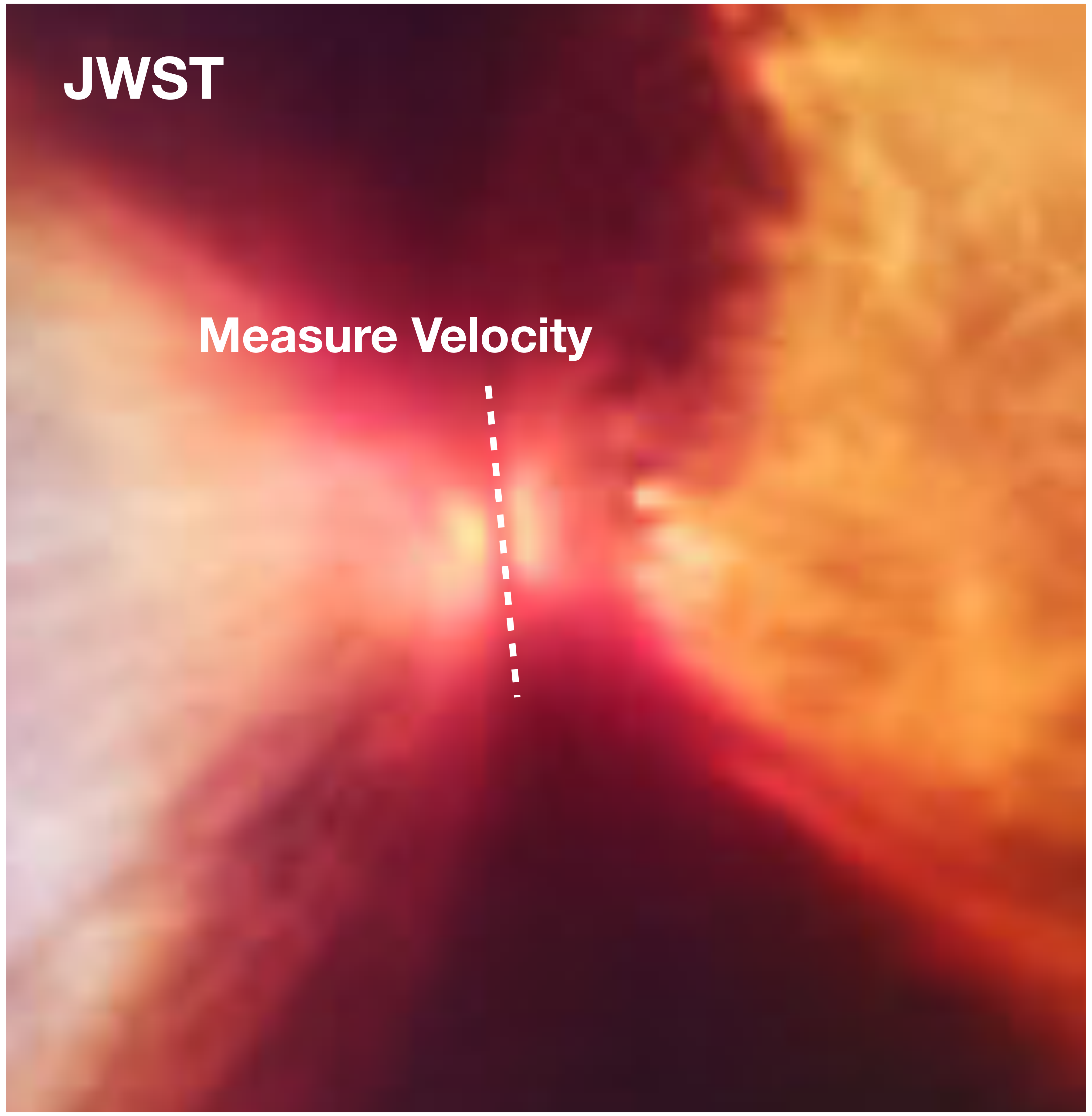
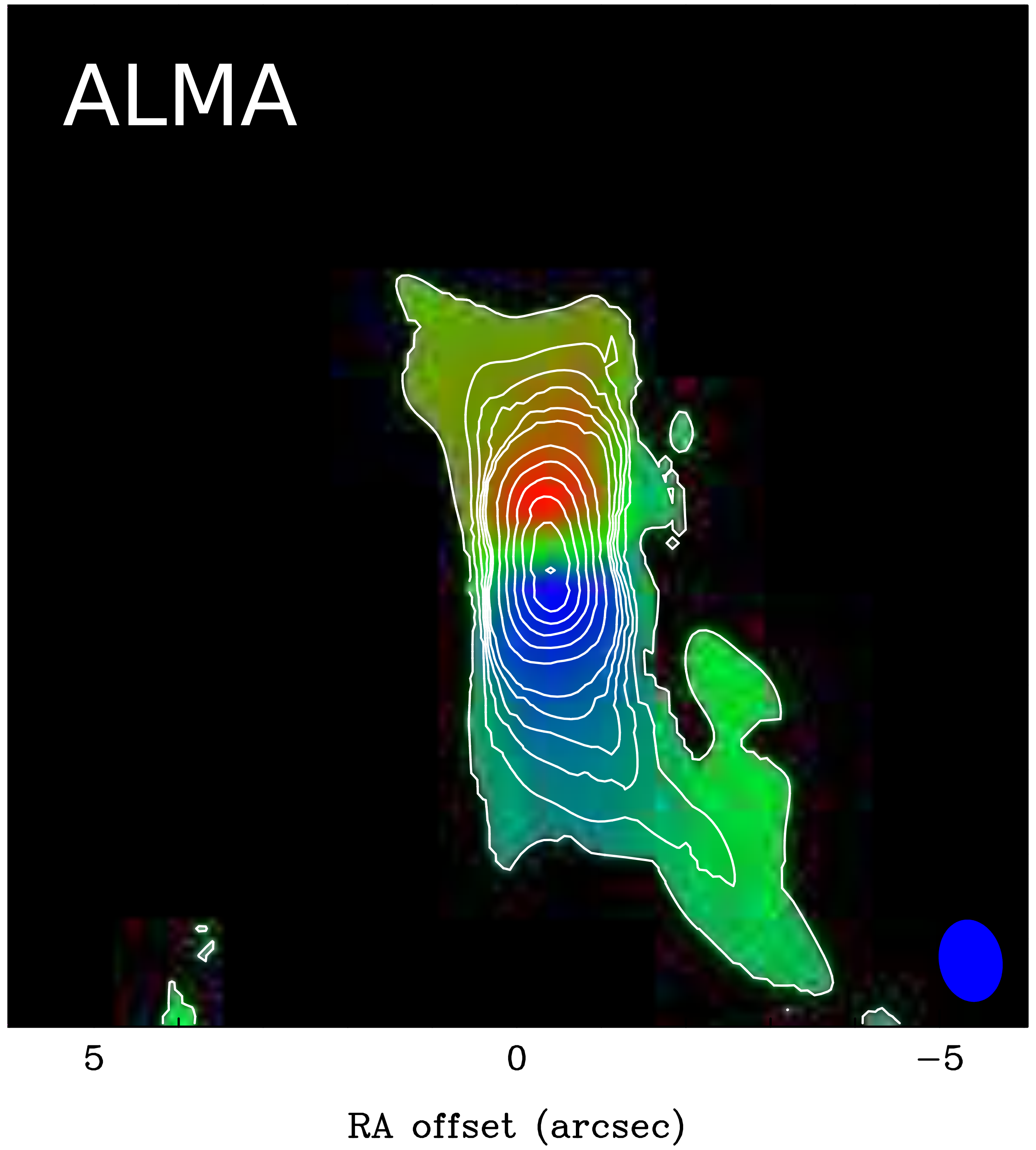
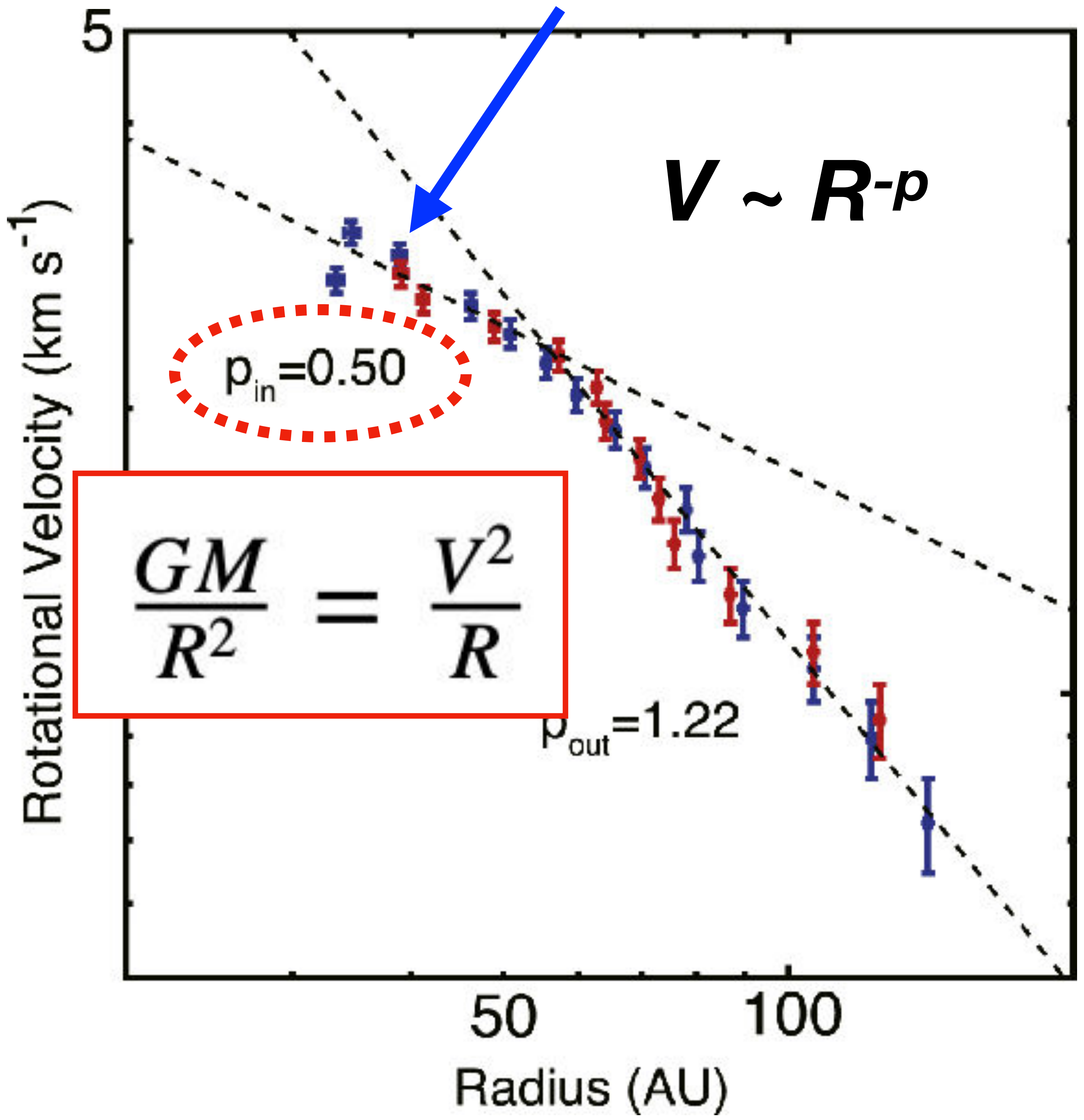


Image credit: NASA, ESA, CSA, STScI

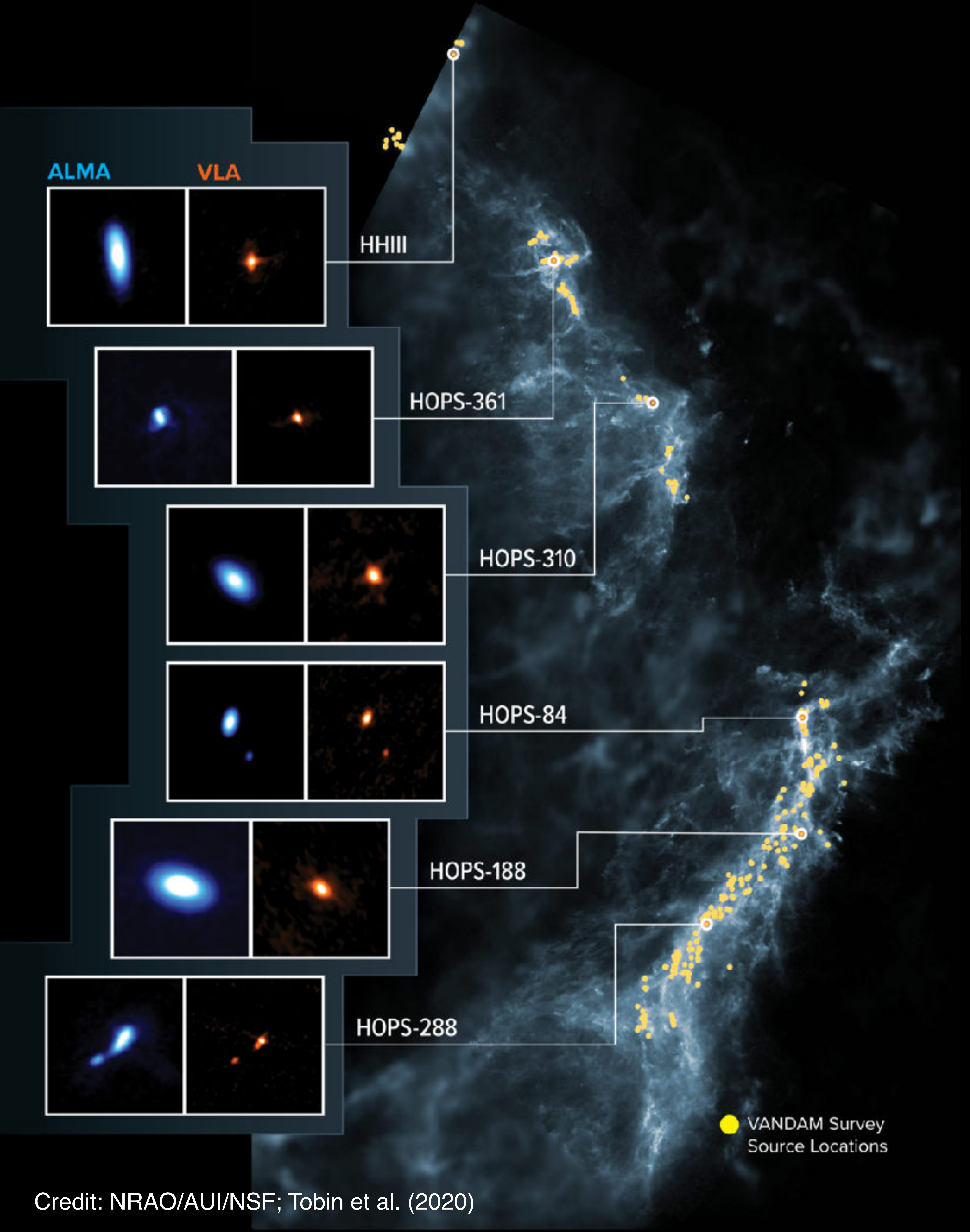
Observed gas distribution and velocity



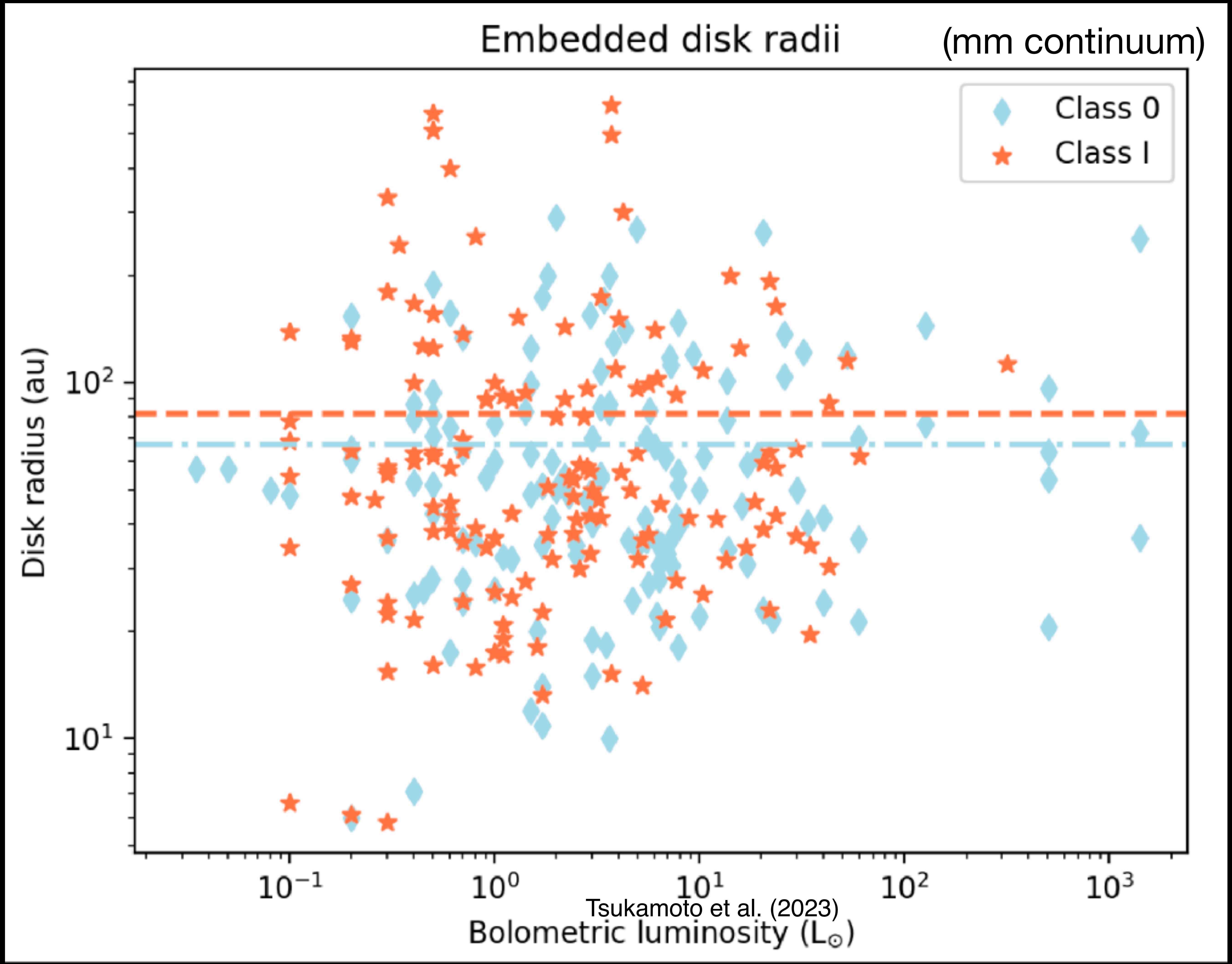
Keplerian motion



Almost all protostars have disks



Credit: NRAO/AUI/NSF; Tobin et al. (2020)



Tsukamoto et al. (2023)

Image credit: NASA, ESA, CSA, STScI

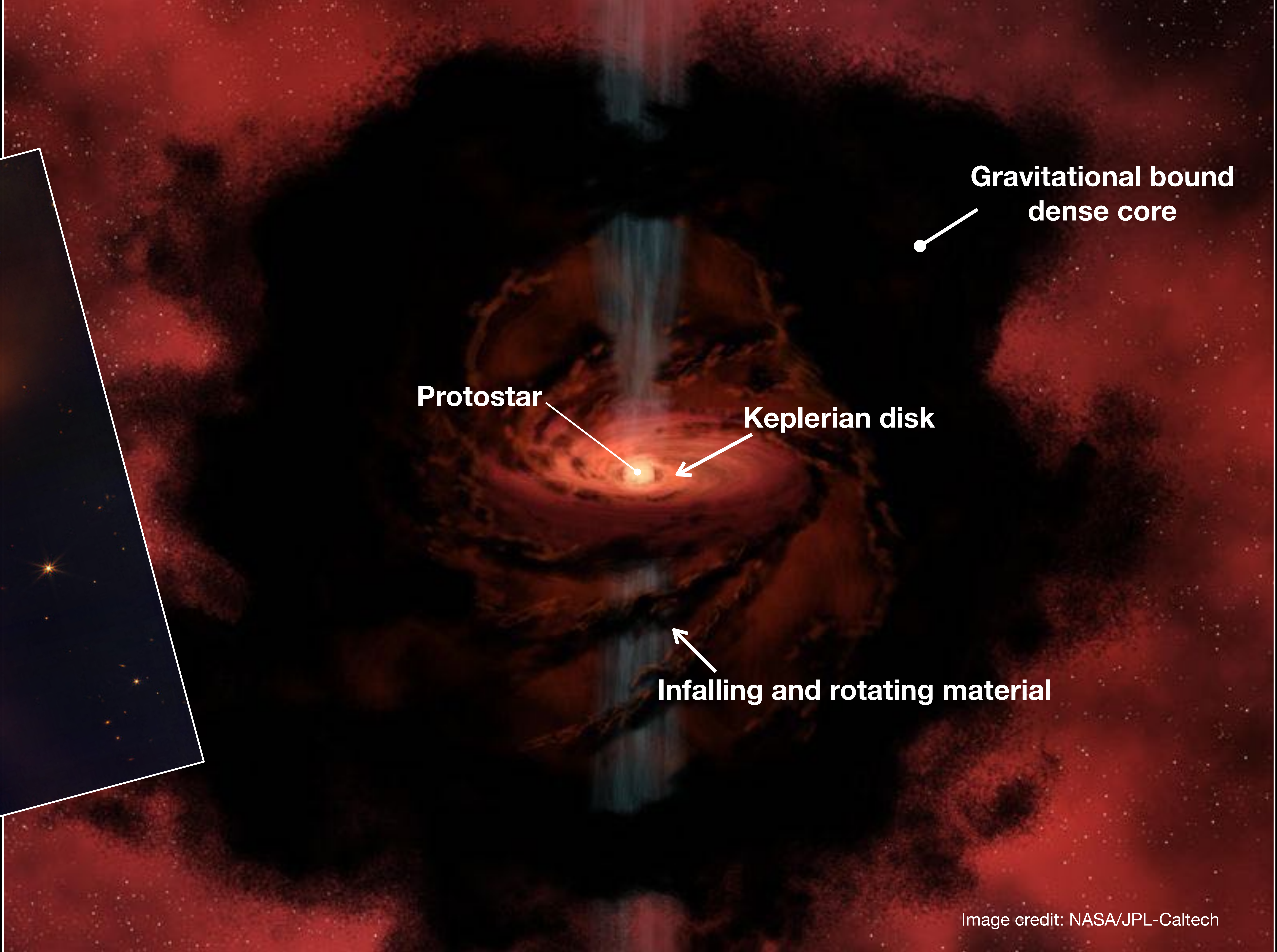


Image credit: NASA/JPL-Caltech

Outflows can remove angular momentum from the disk

Image credit: NASA, ESA, CSA, STScI

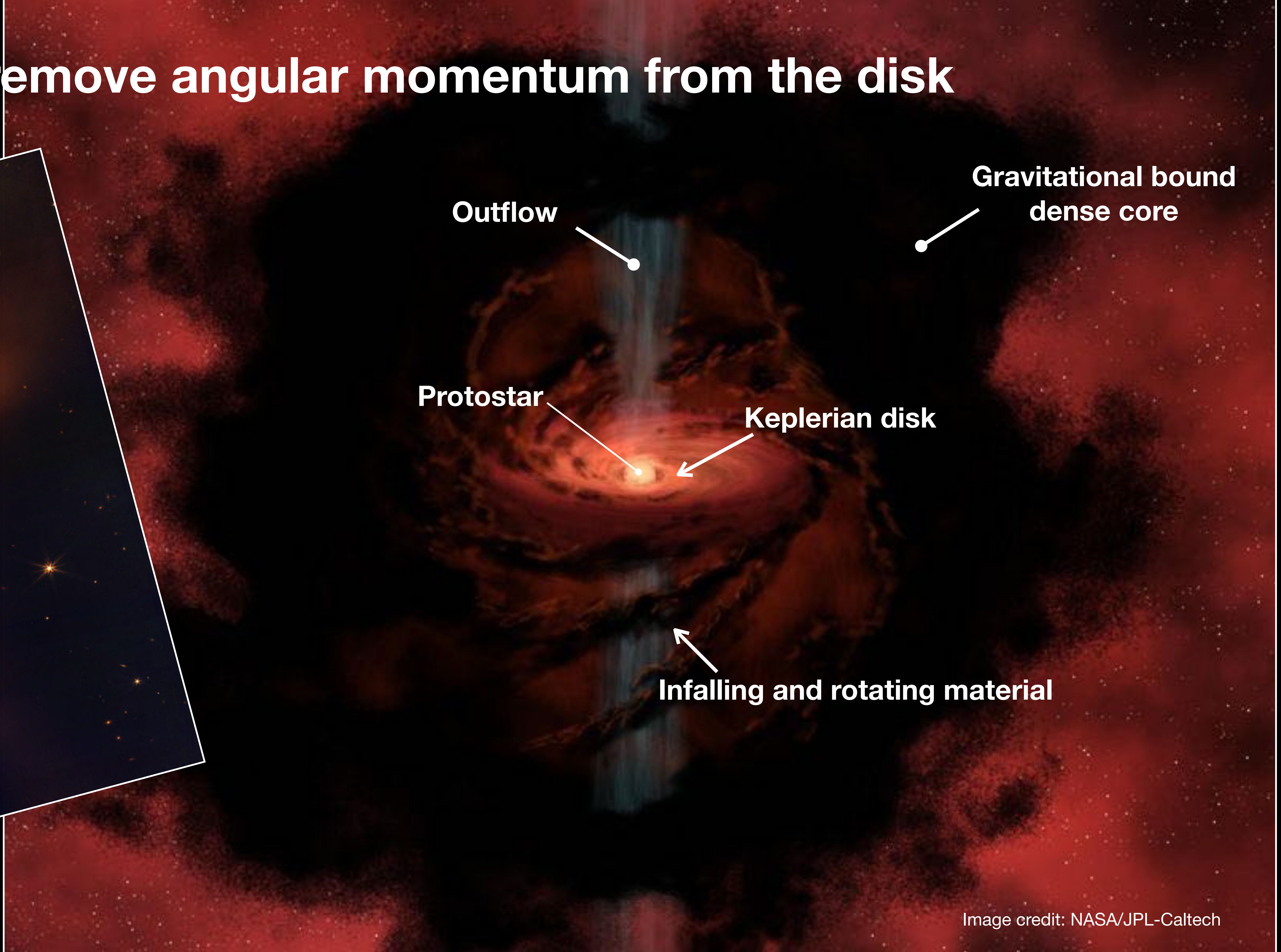
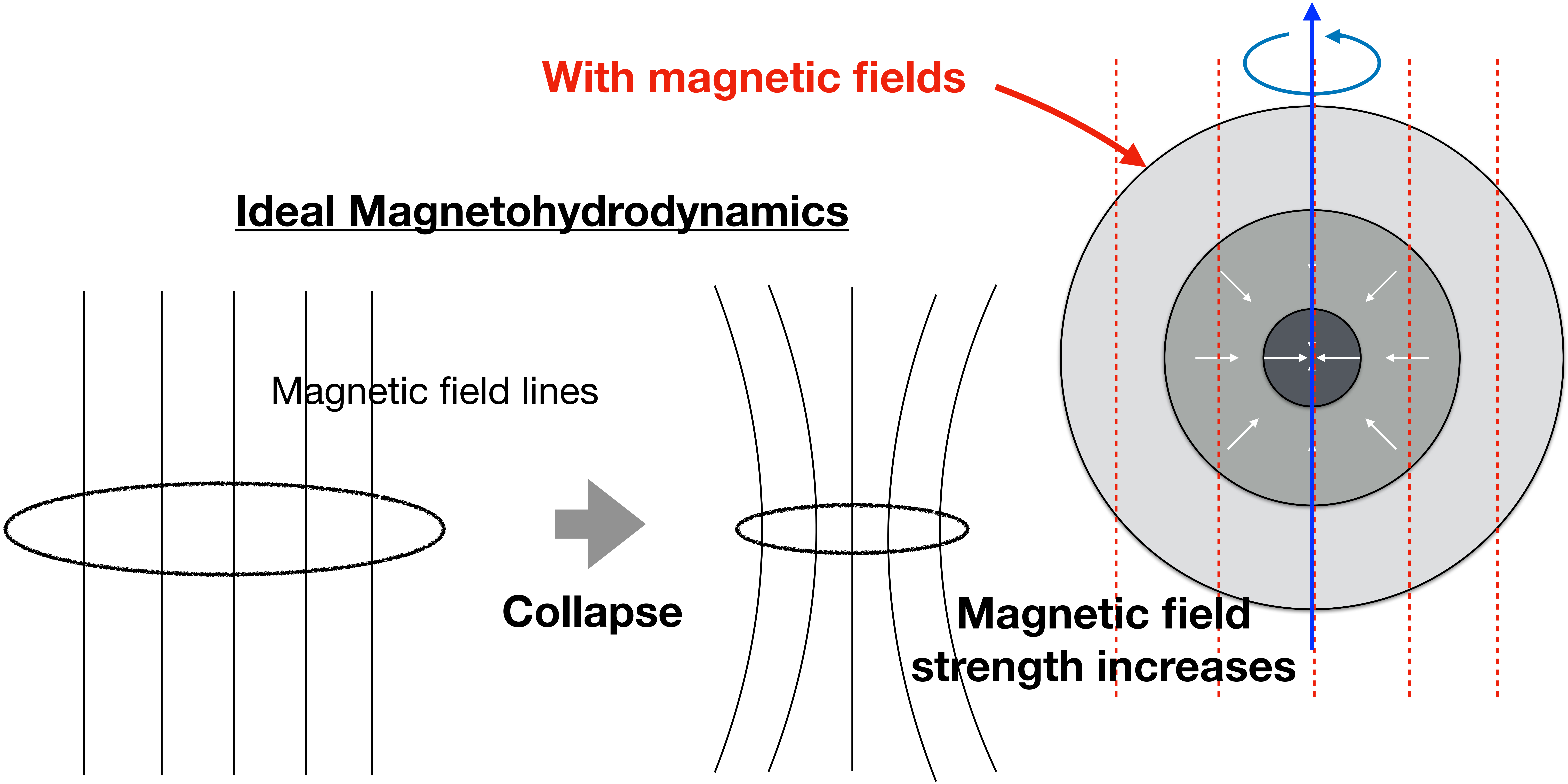


Image credit: NASA/JPL-Caltech

Molecular clouds are Magnetized

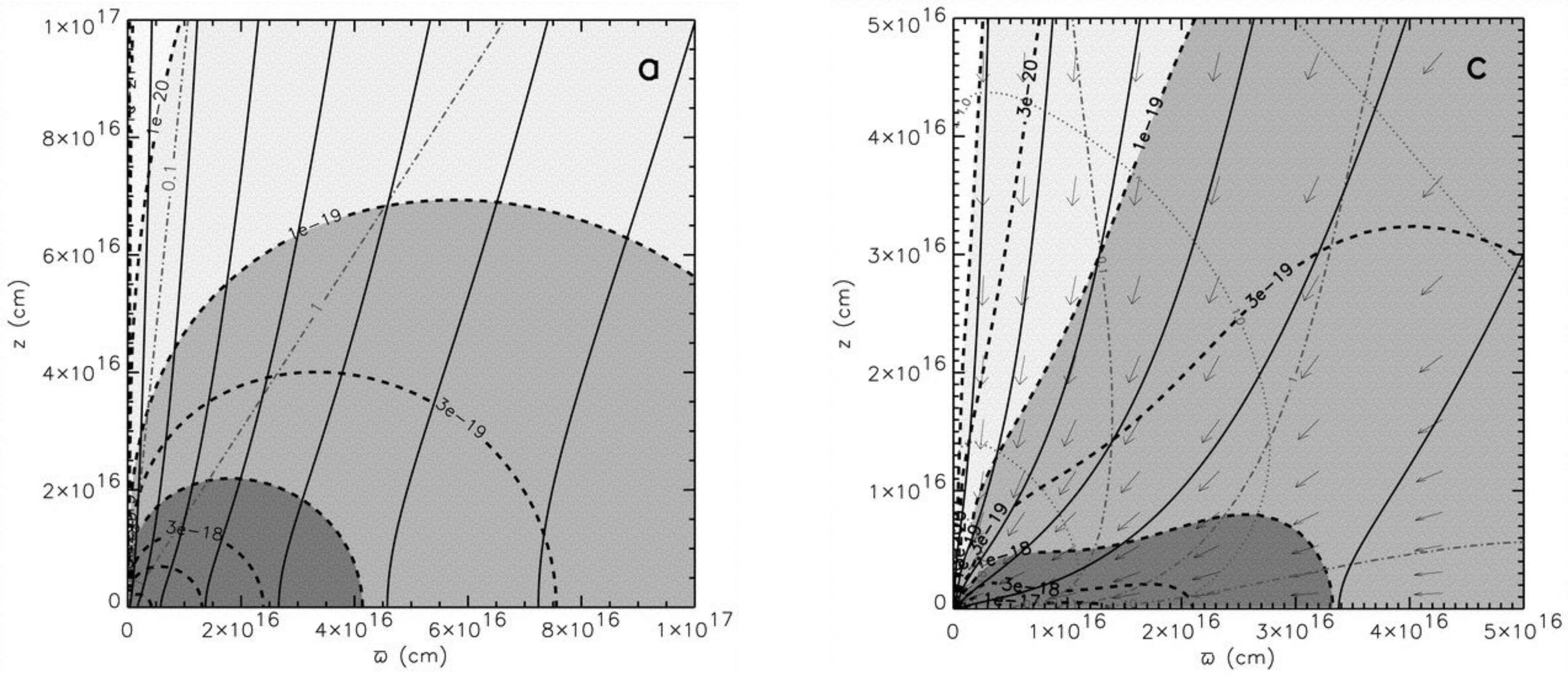
Far-infrared image & Dust polarization

Image credit:
ESA/Herschel/Planck; J. D. Soler, MPIA


With magnetic fields
Ideal Magnetohydrodynamics
Magnetic field lines
Collapse
Magnetic field
strength increases

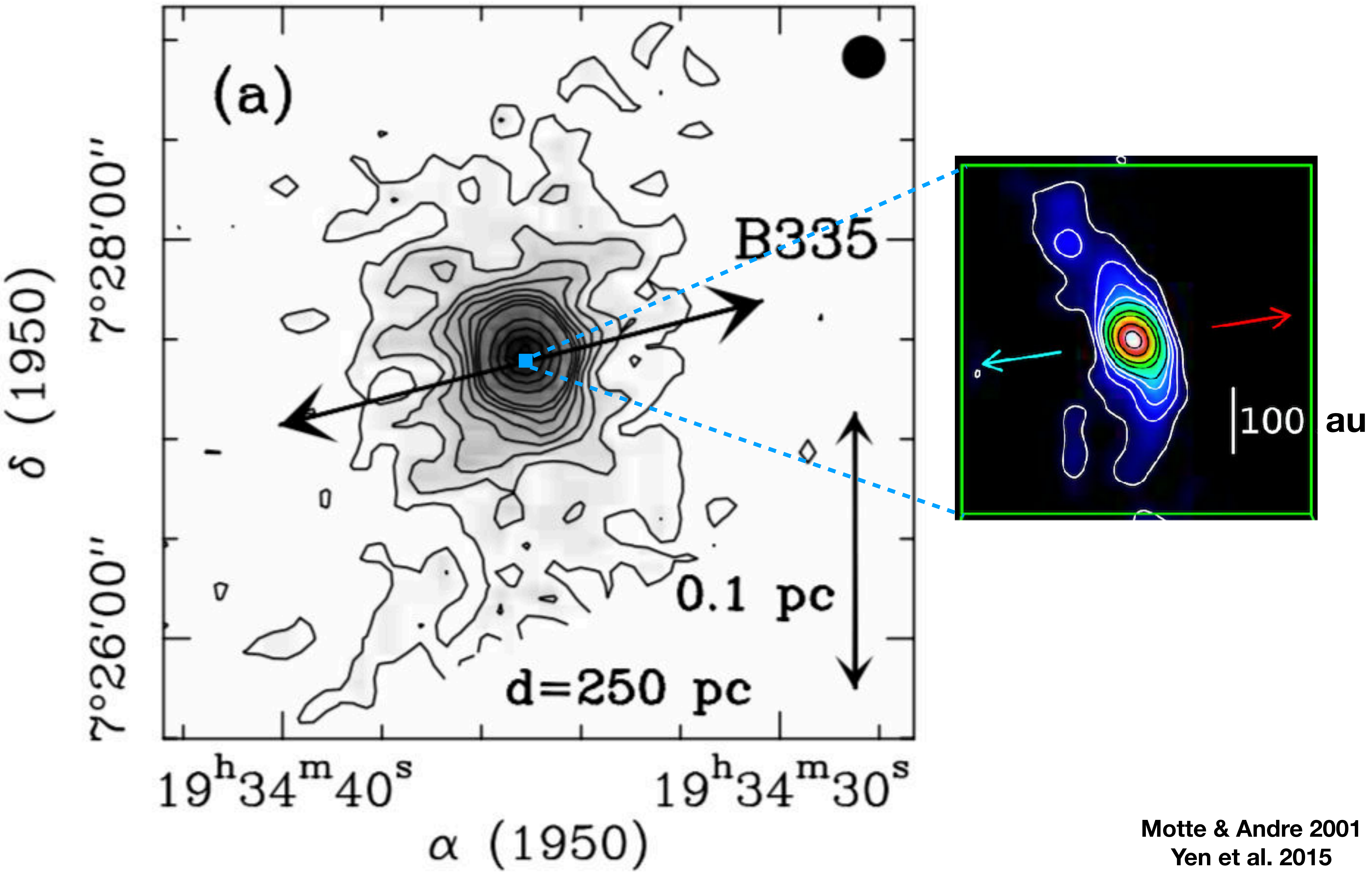
Flattened envelope or pseudo disk

With magnetic field,



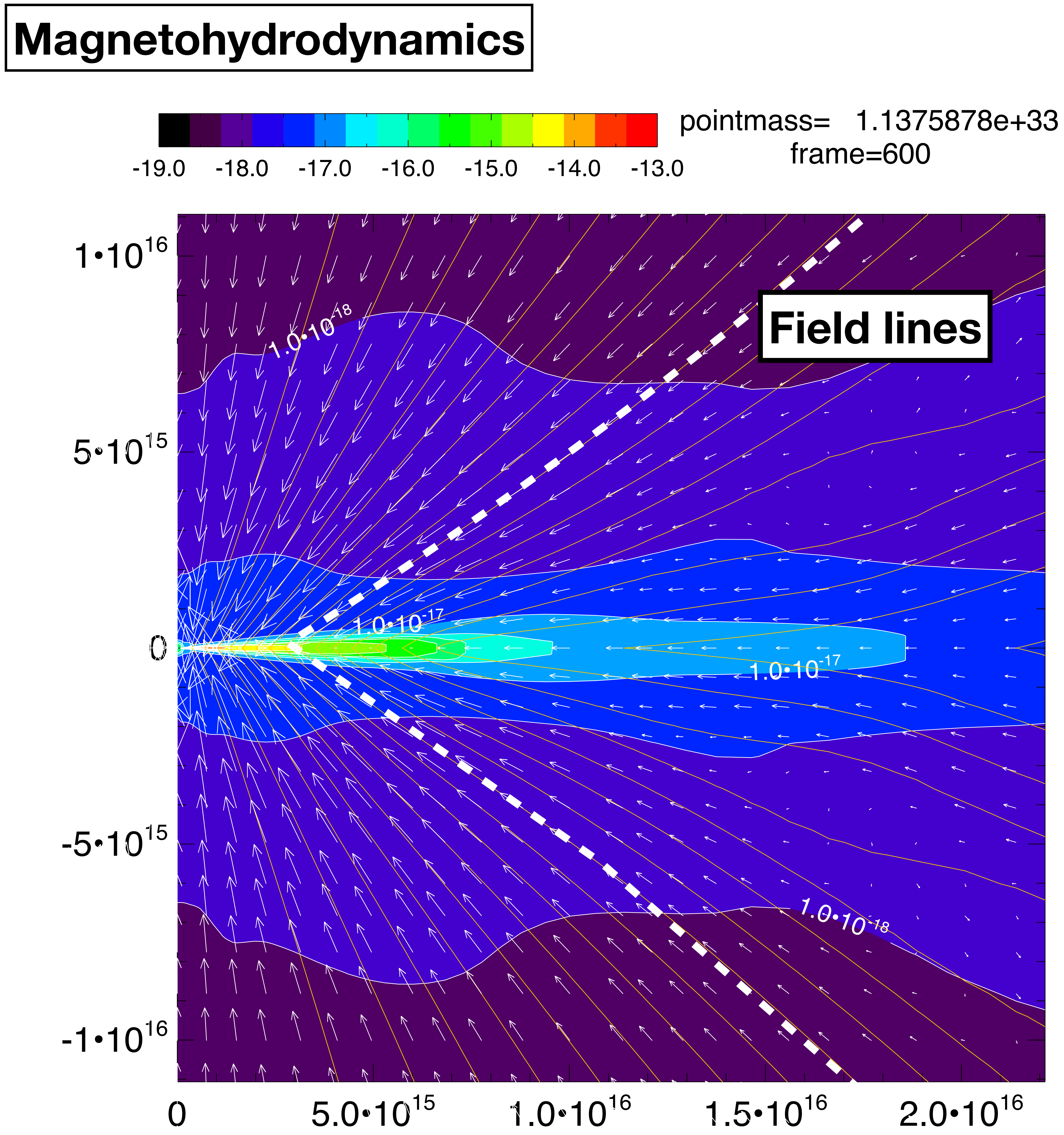
Allen et al. 2003

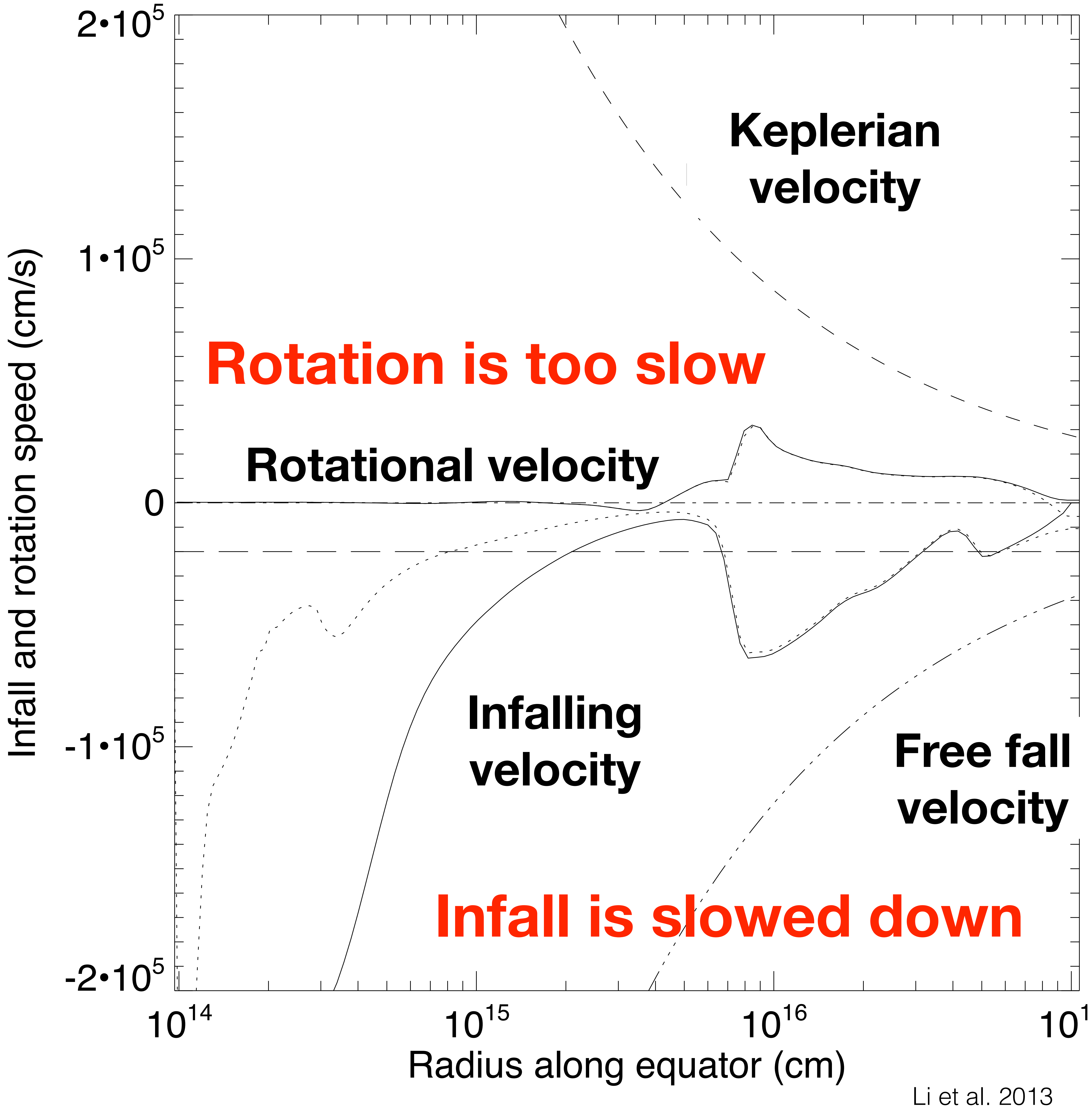
Observations of flattened envelope or pseudo disk



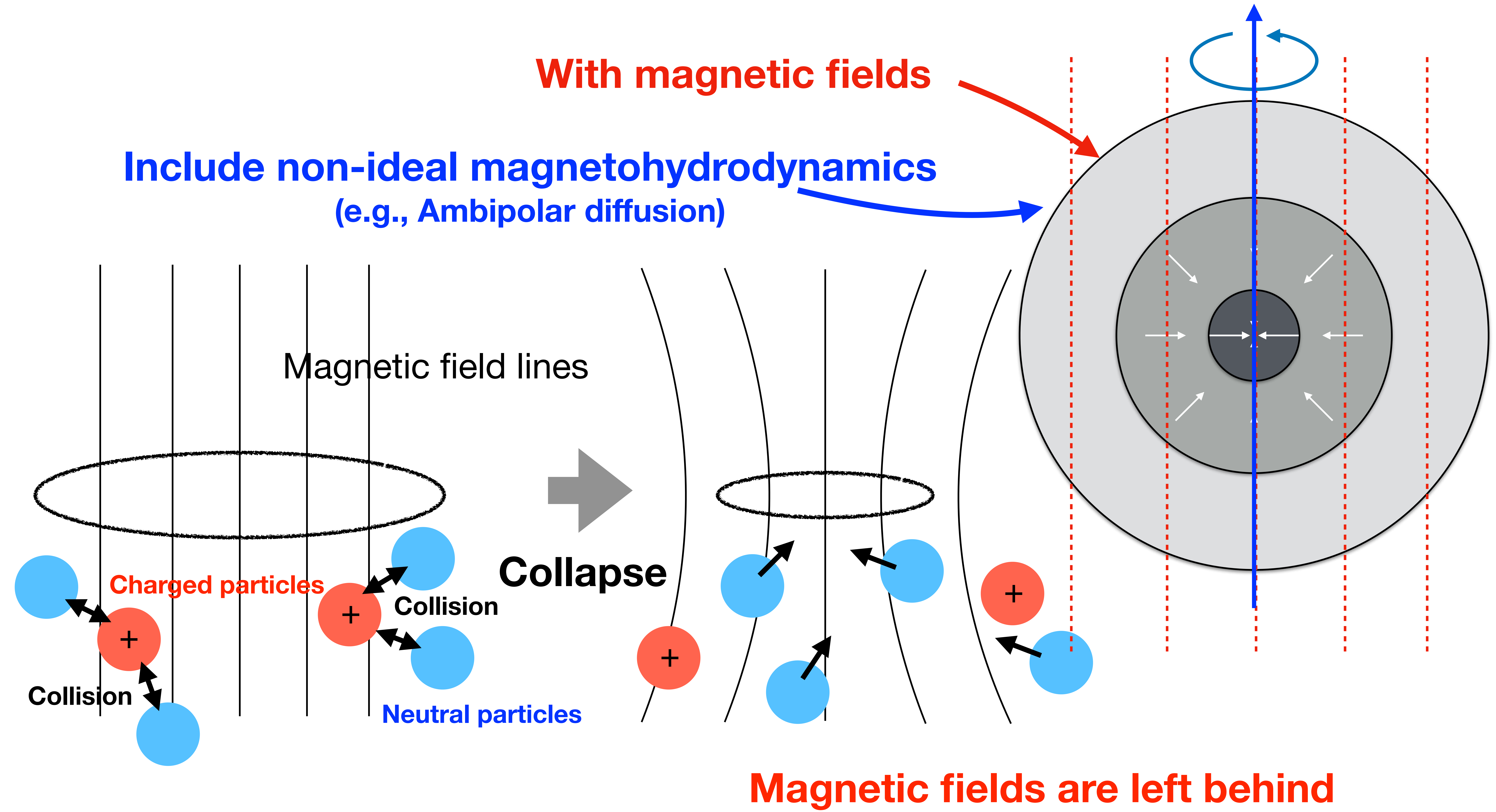
Motte & Andre 2001
Yen et al. 2015

Infalling and rotating magnetized dense core

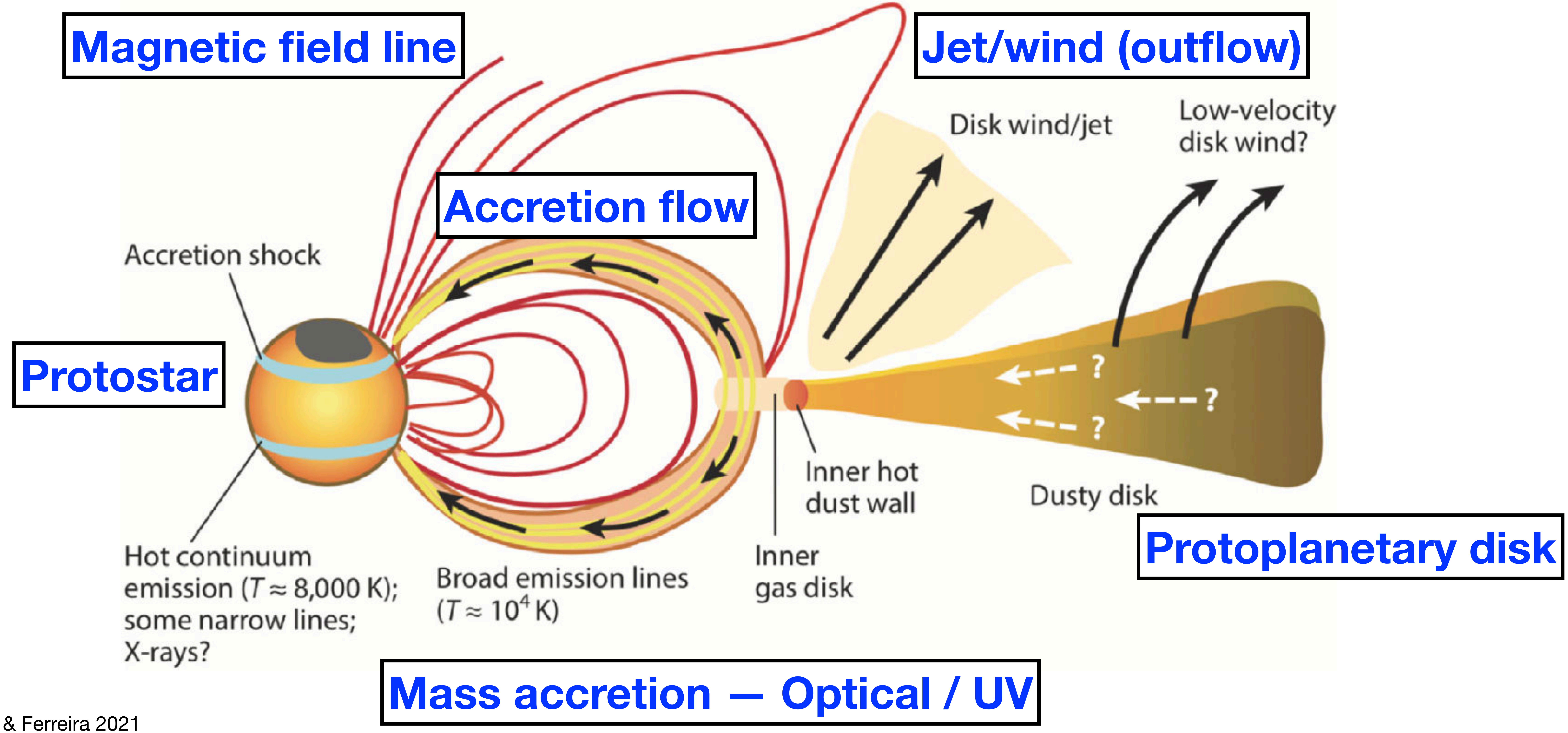




Li et al. 2013


With magnetic fields
Include non-ideal magnetohydrodynamics
(e.g., Ambipolar diffusion)
Magnetic field lines
Charged particles
Collision
Collision
Neutral particles
Collapse
Magnetic fields are left behind

Gravity (collapse), Angular momentum (disk), Magnetic field (outflow)



Ray & Ferreira 2021

High-velocity jets（10x — >100 km/s）

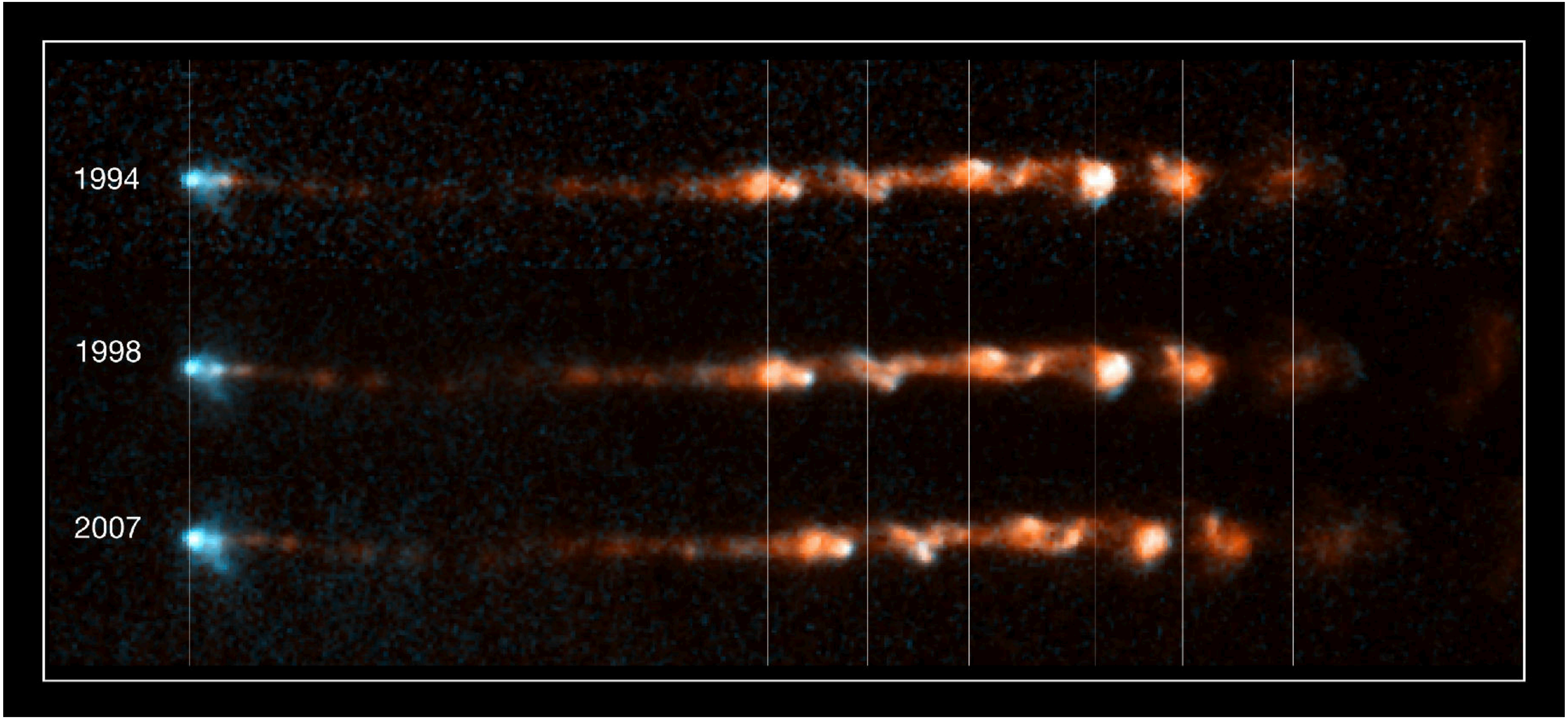
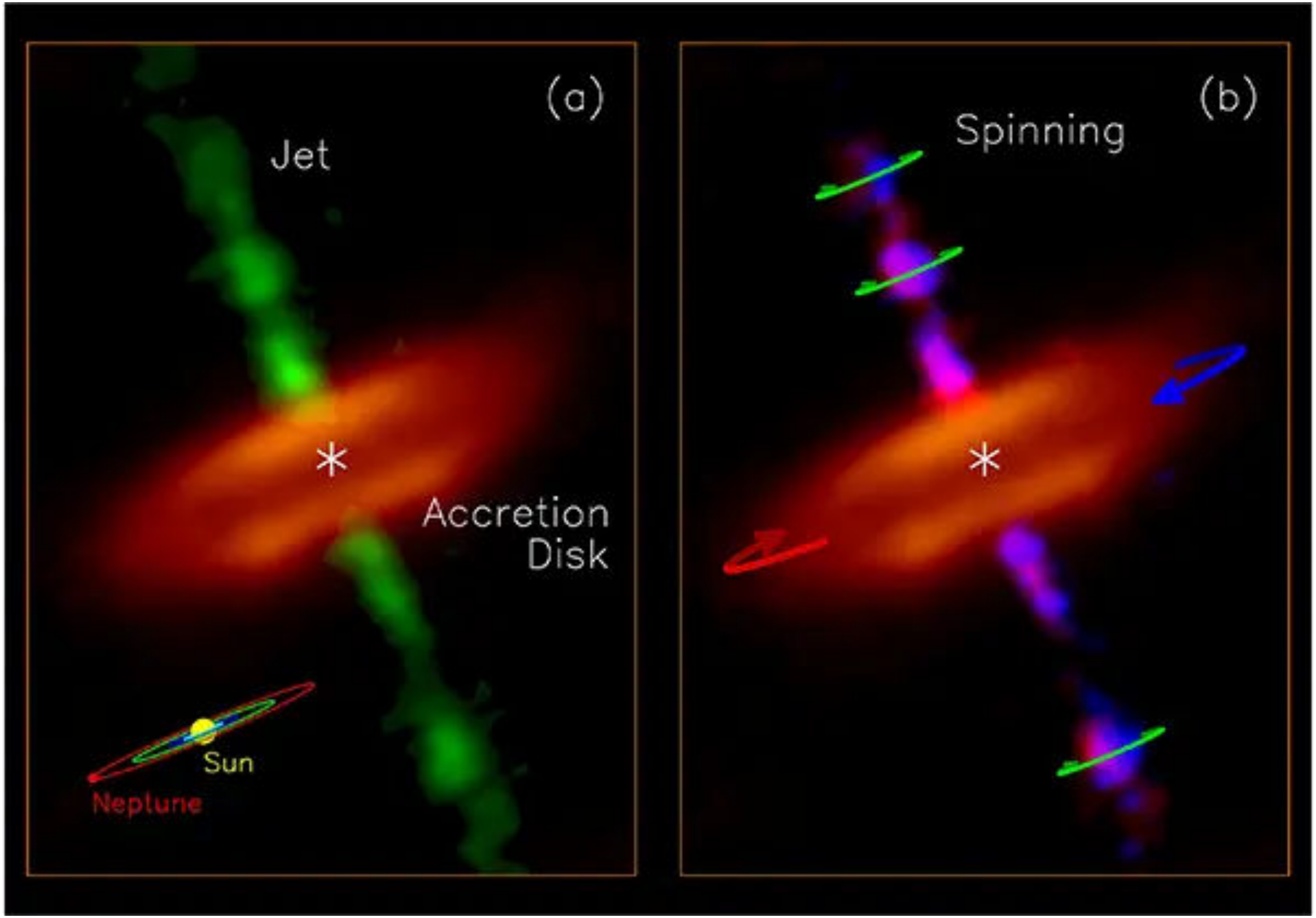
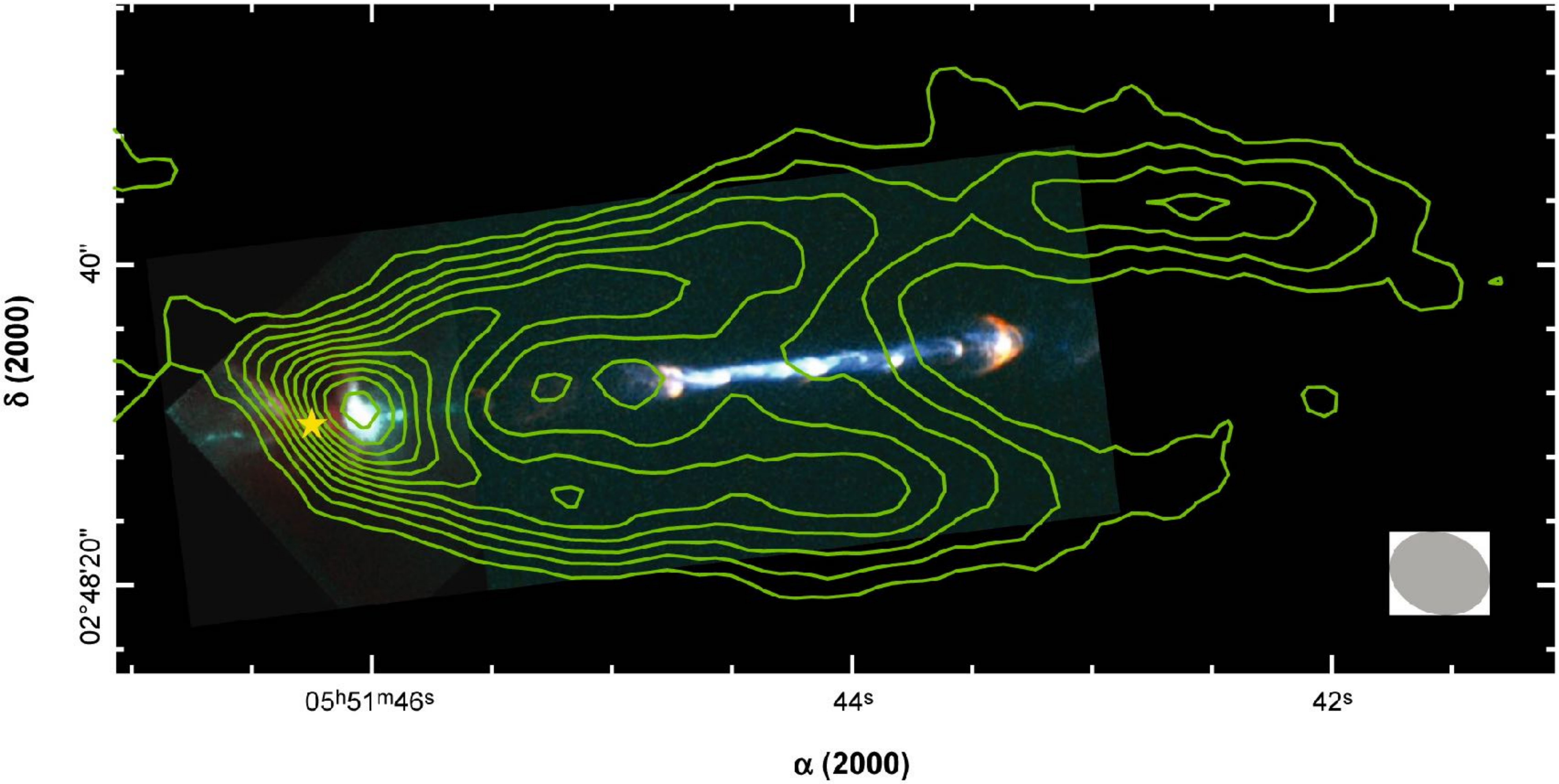


Image credit: NASA, ESA, and P. Hartigan (Rice University)

Jets are rotating



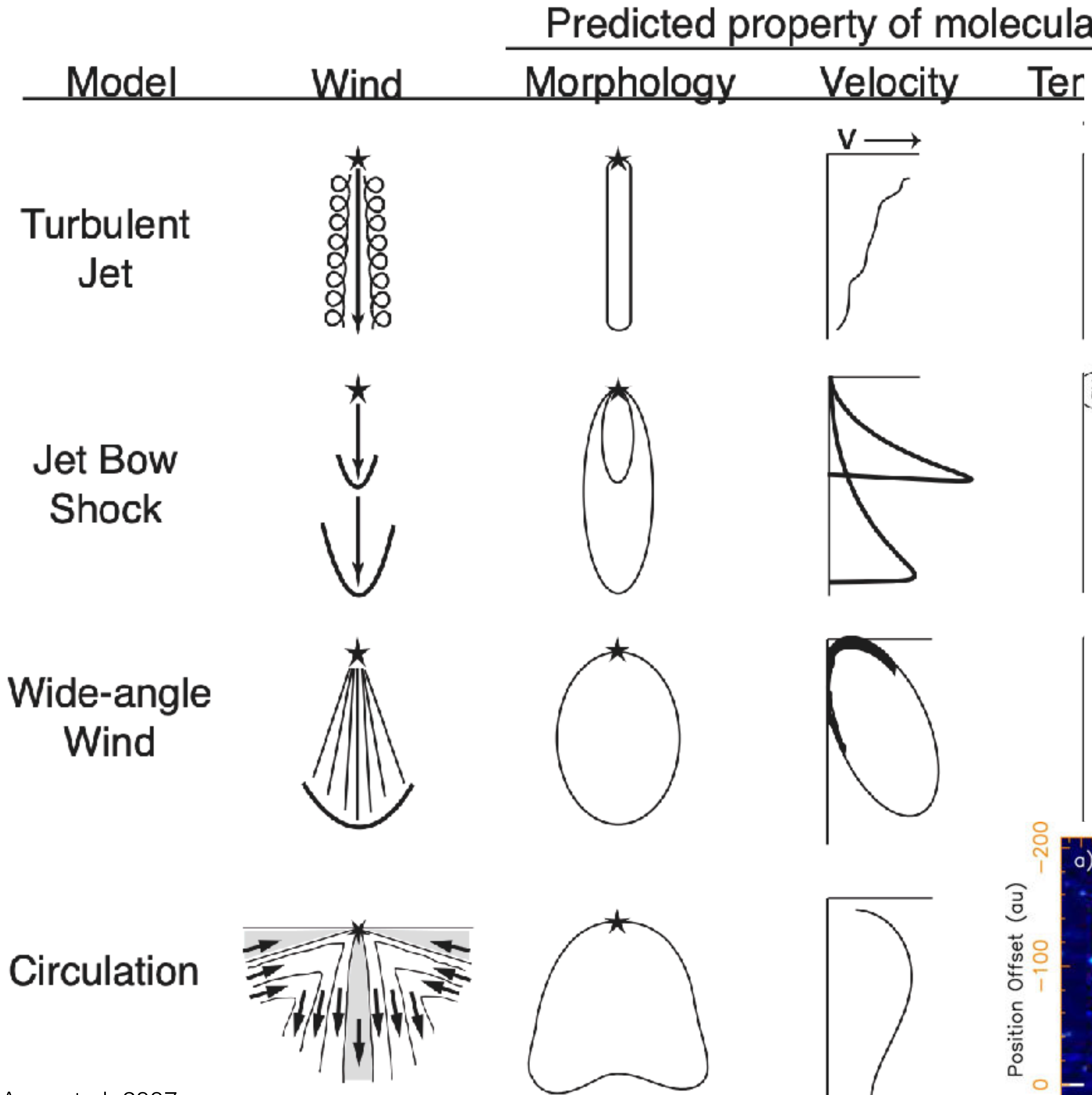
Lee et al. 2017



Mckee CF, Ostriker EC. 2007.
Annu. Rev. Astron. Astrophys. 45:565–687

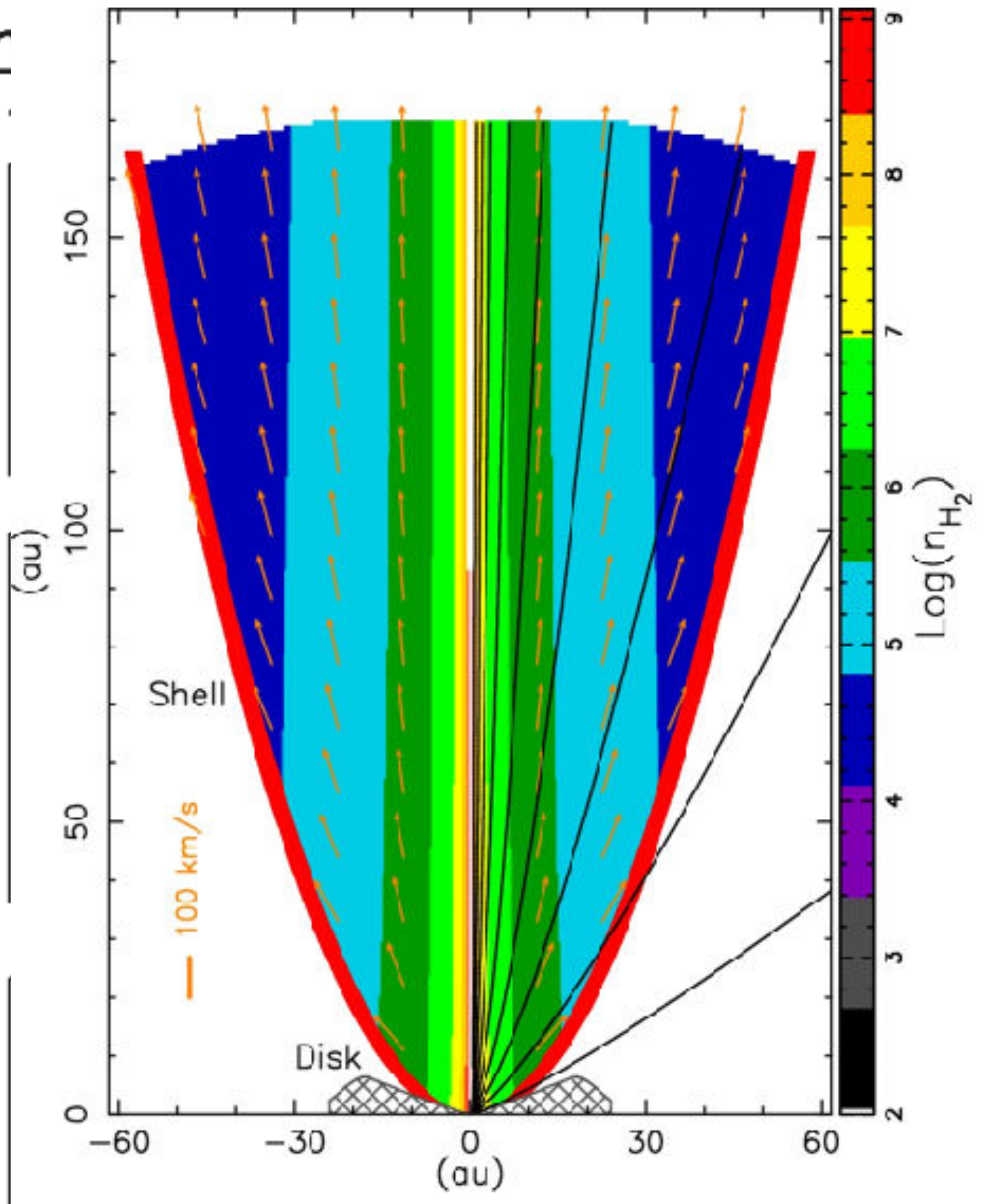
jets and swept-up material (low-velocity outflow)
-> gravitational unbound

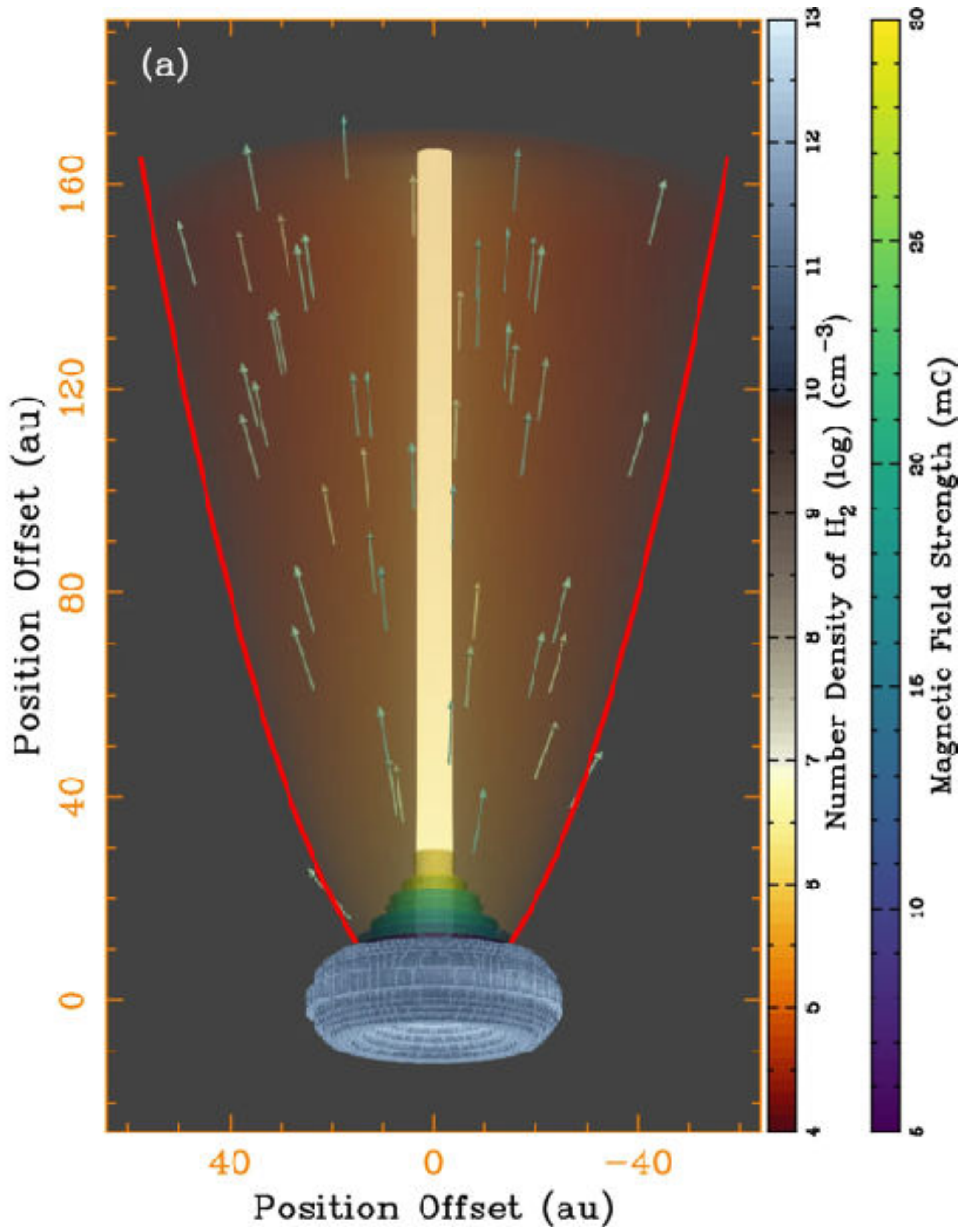
Molecular outflow properties predicted by different models

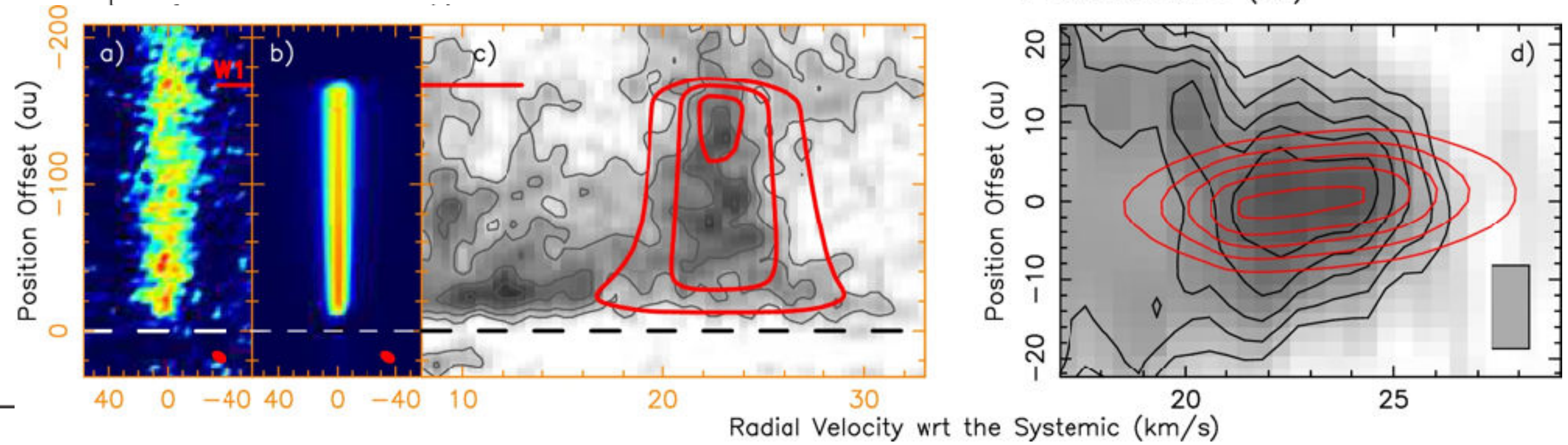


Arce et al. 2007

a Assuming an underlying density distribution of r^{-1} to r^{-2}.

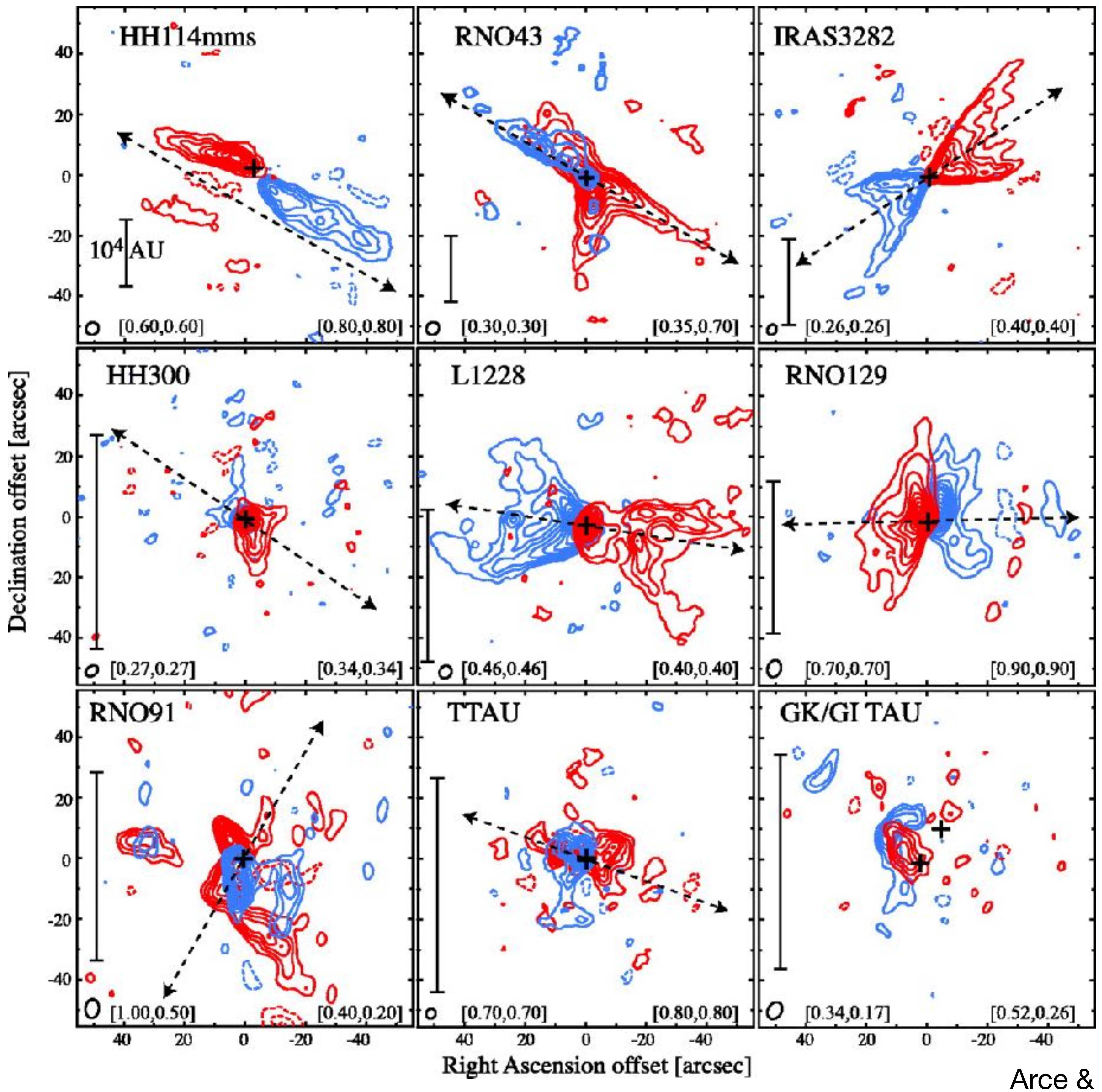






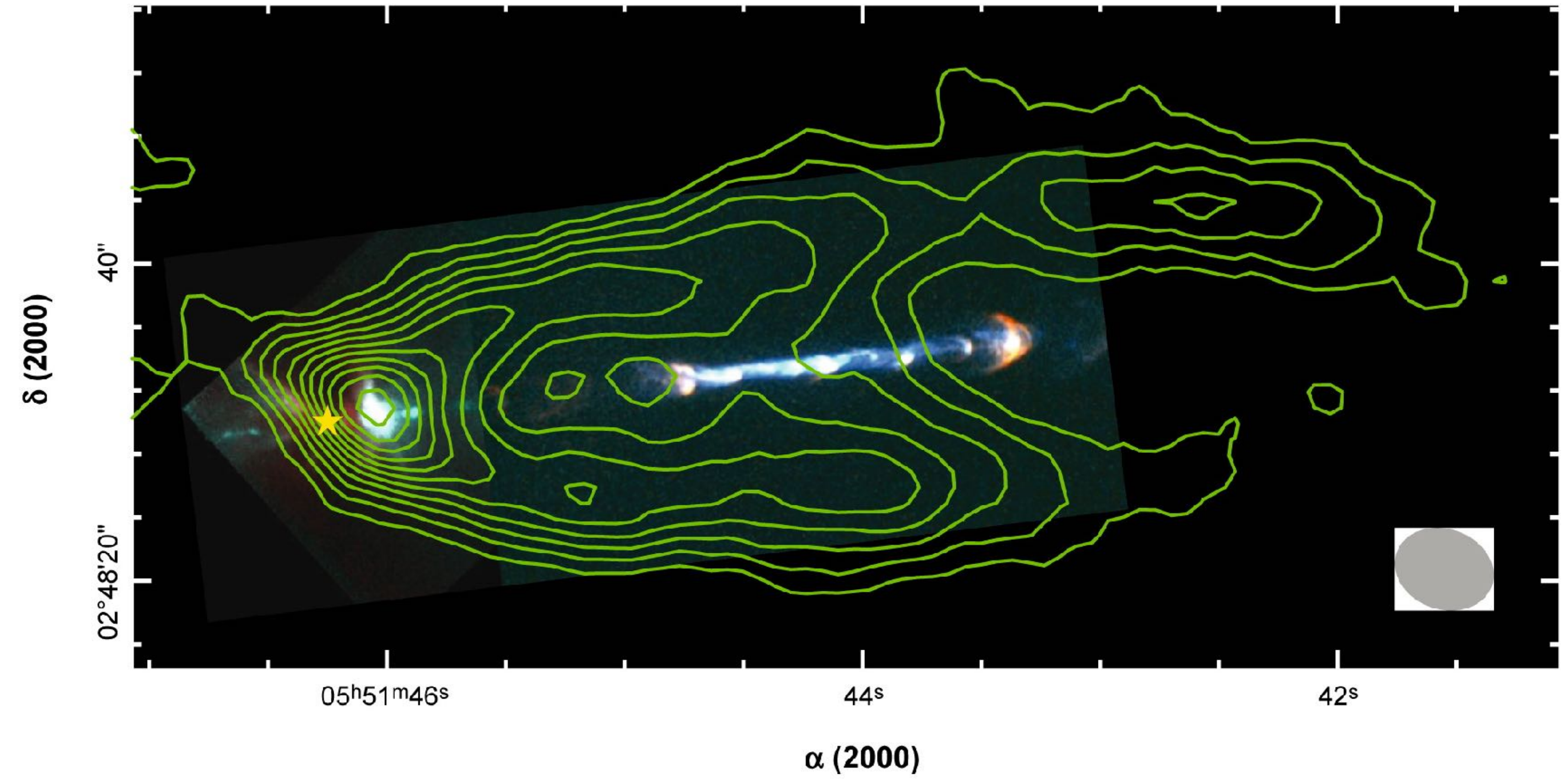
Lee et al. 2025

Evolution of outflow morphology

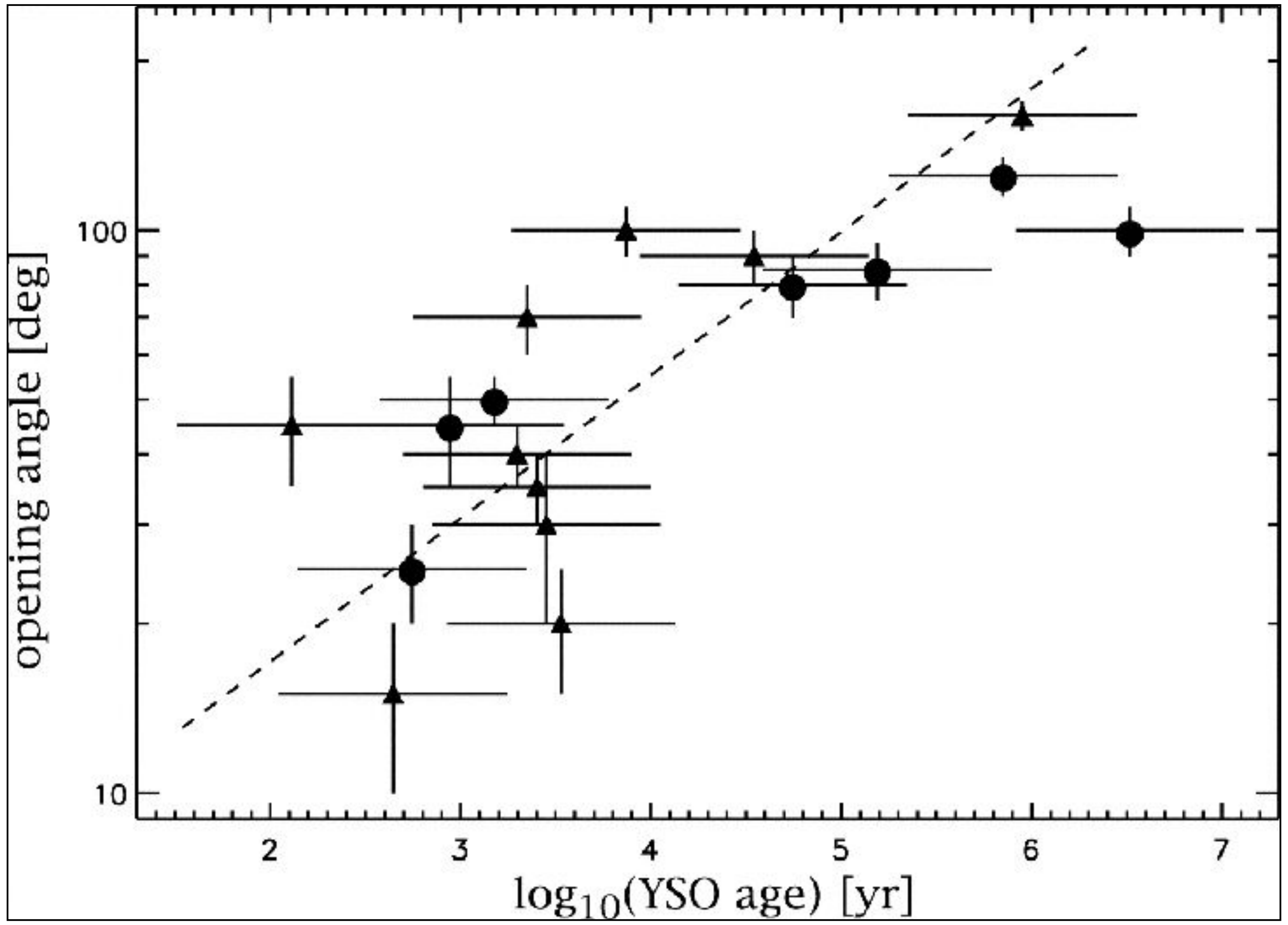


Age

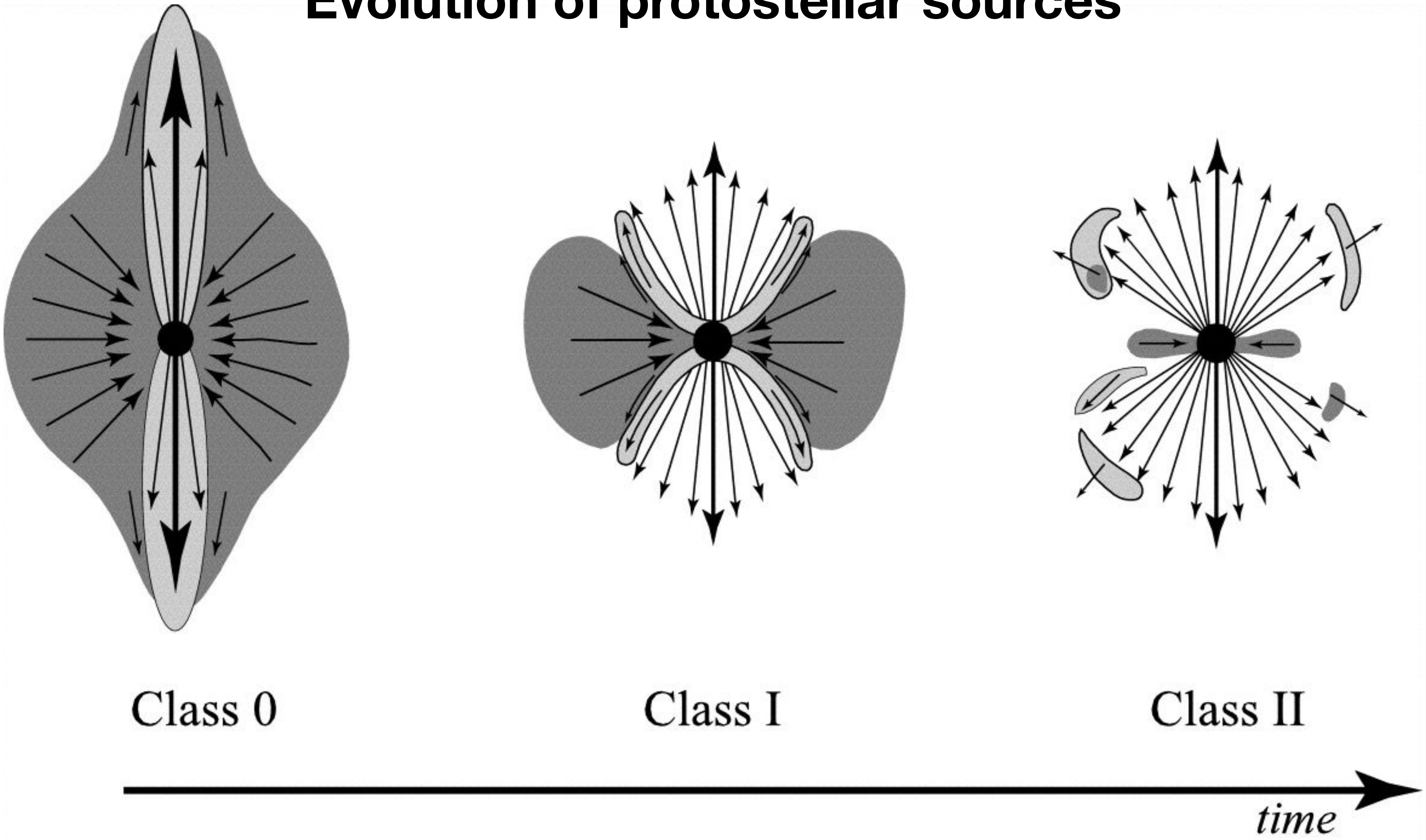
Arce & Sargent 2006



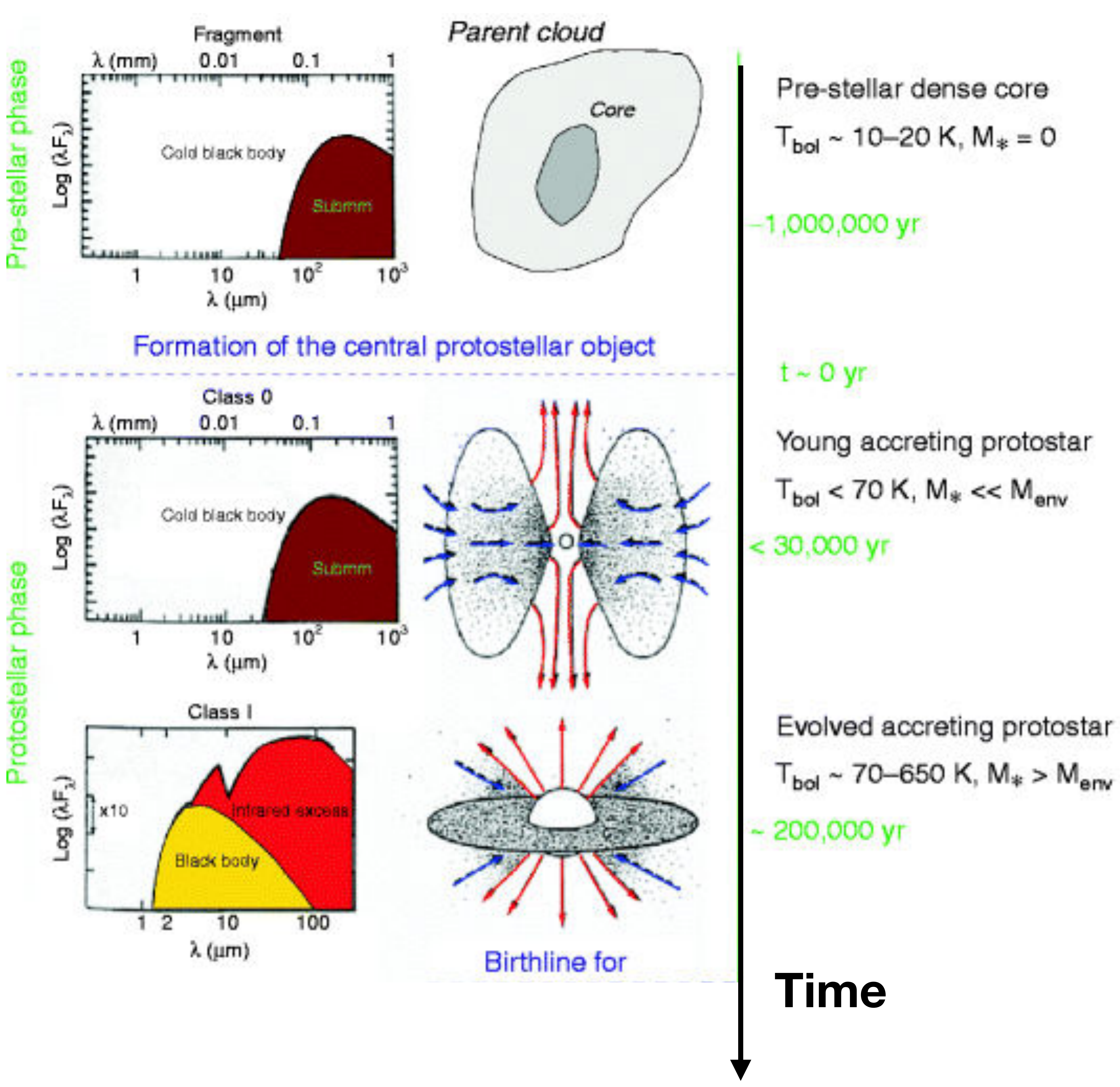
Mckee CF, Ostriker EC. 2007.
Annu. Rev. Astron. Astrophys. 45:565–687



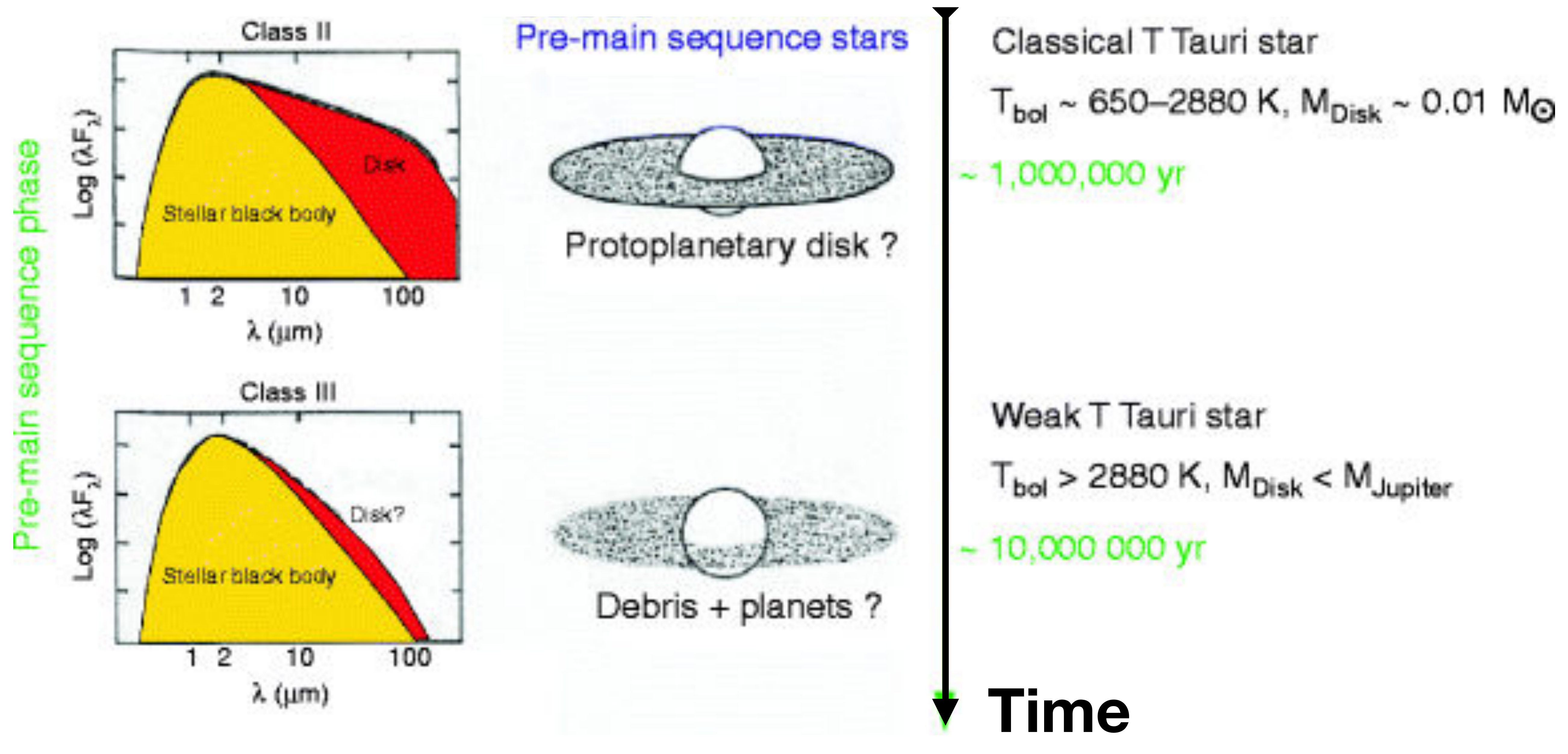
Evolution of protostellar sources

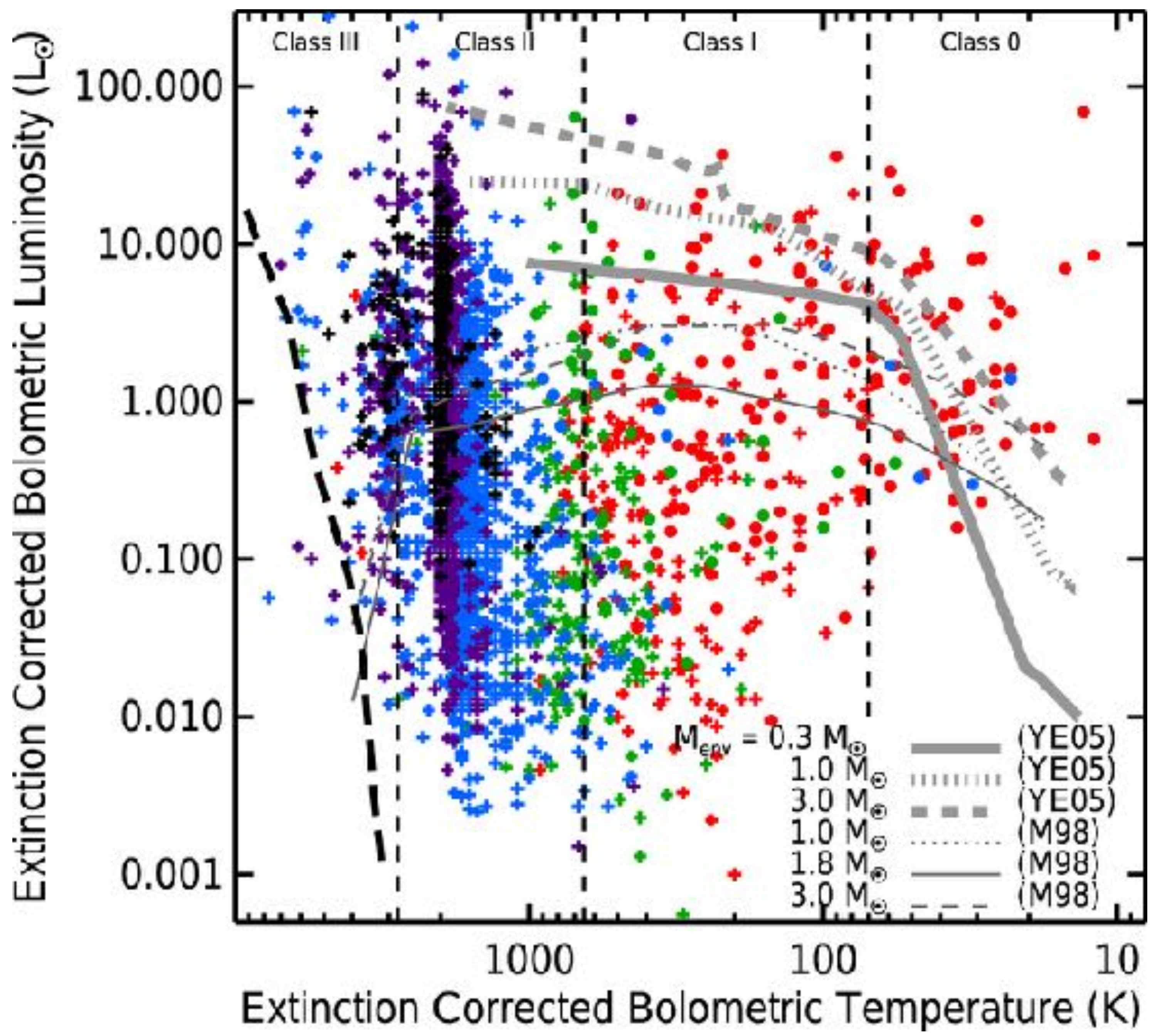


Arce & Sargent 2006



Andre 2011

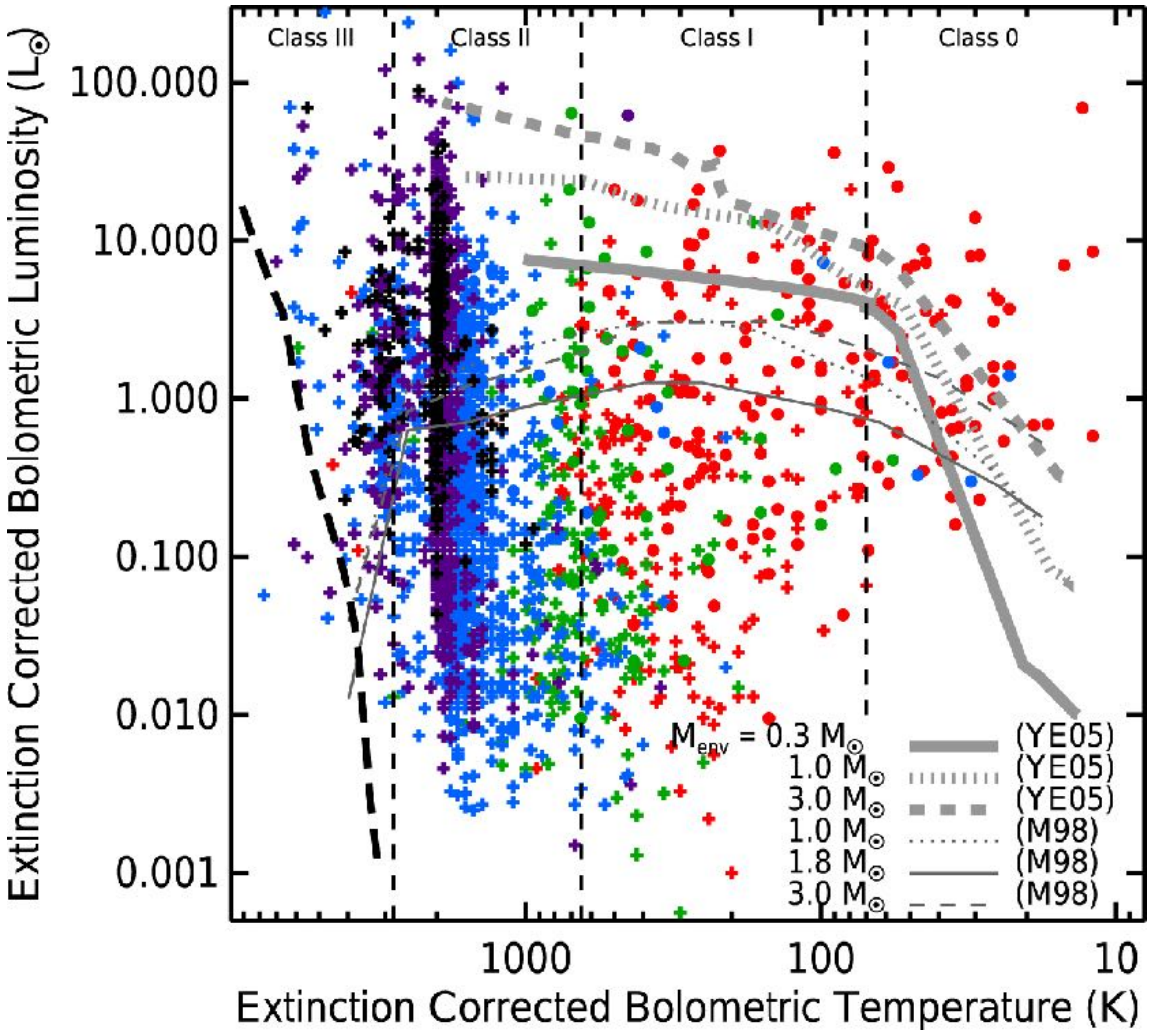




$$L_{acc} = \frac{G M_\star \dot{M}}{R_\star}$$

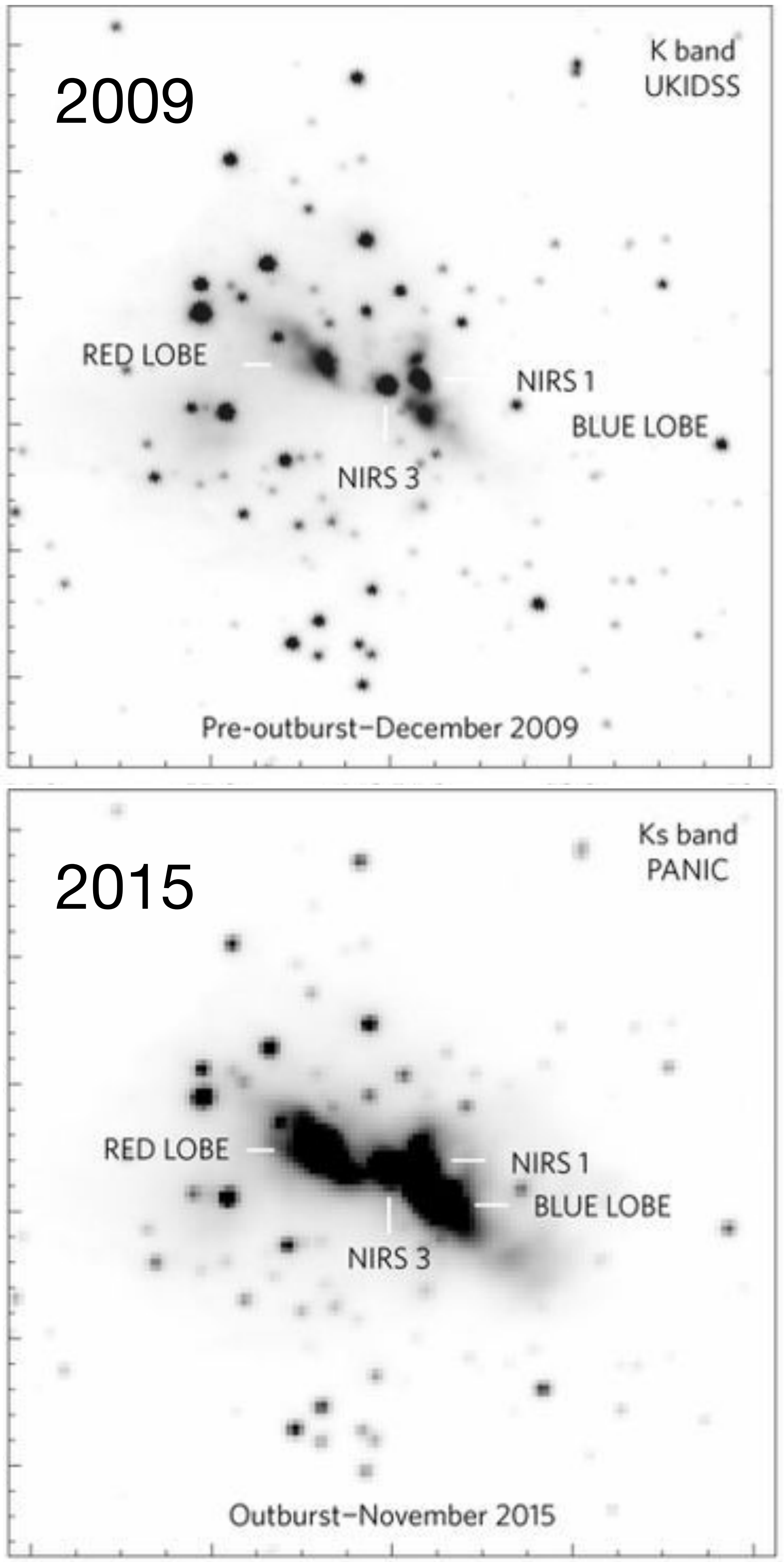
Dunham et al. 2015

Episodic mass accretion

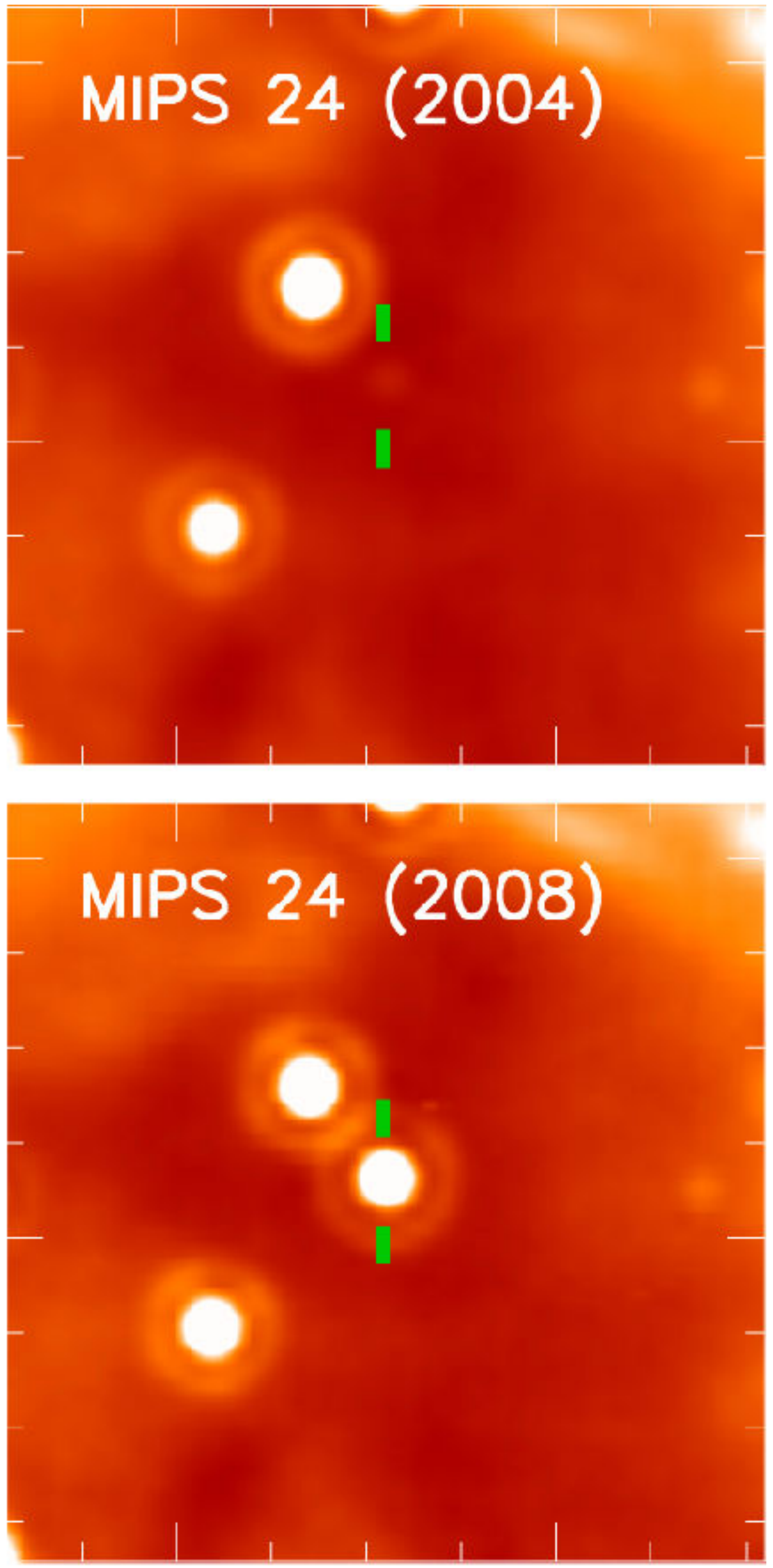


Dunham et al. 2015

low luminosity sources — quiescent phase?

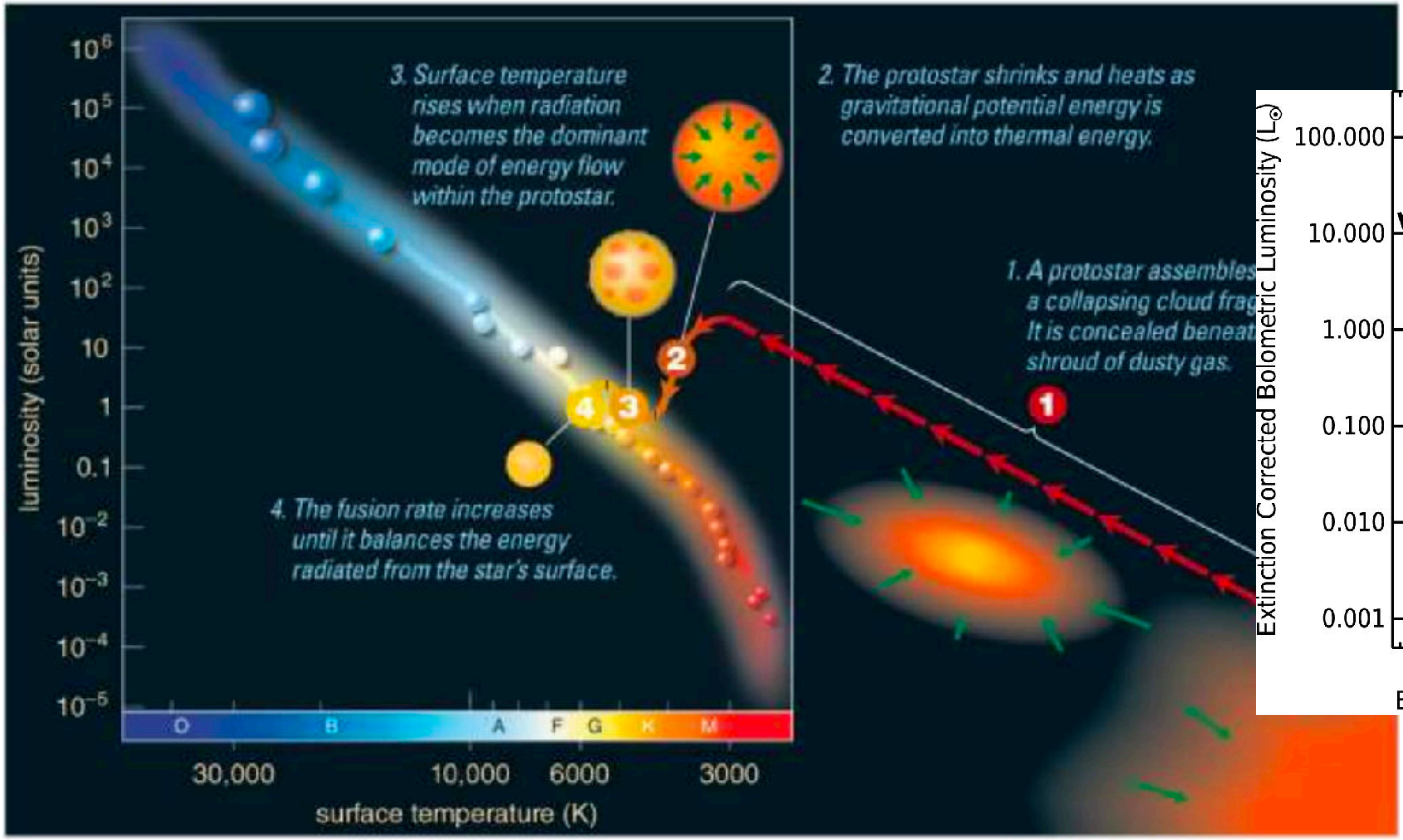


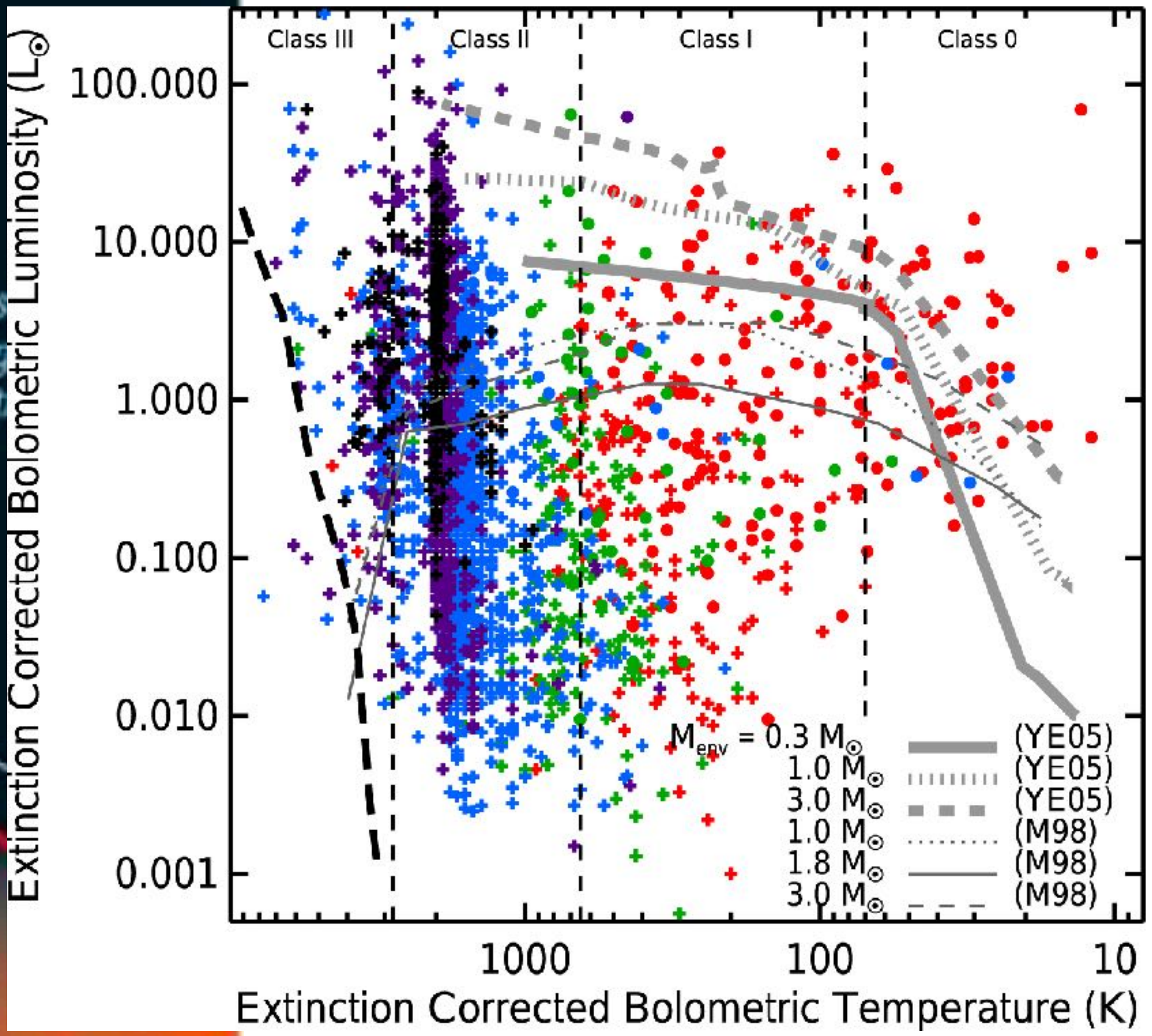
Garatti et al. 2017



Safron et al. 2015

恒星形成

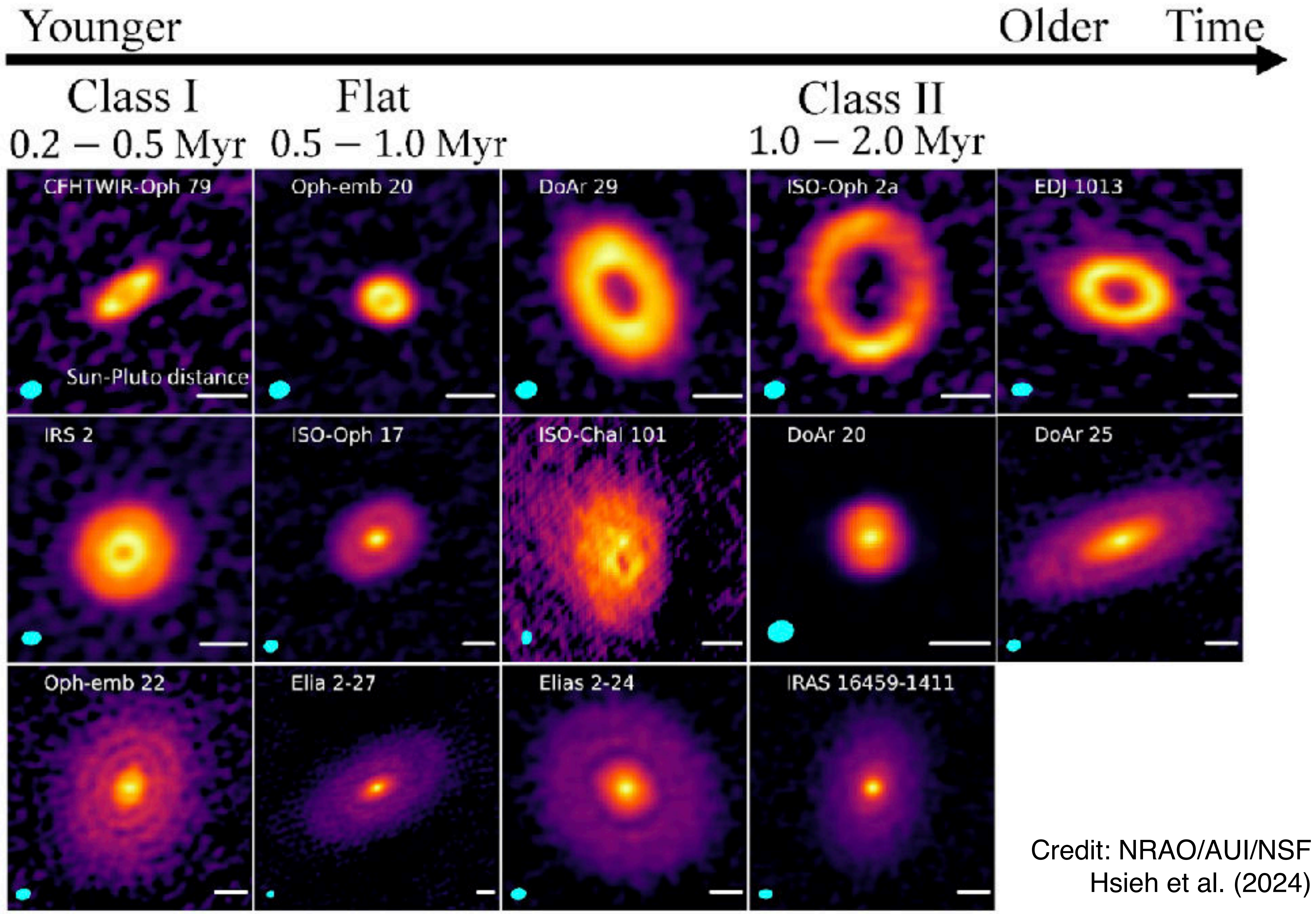




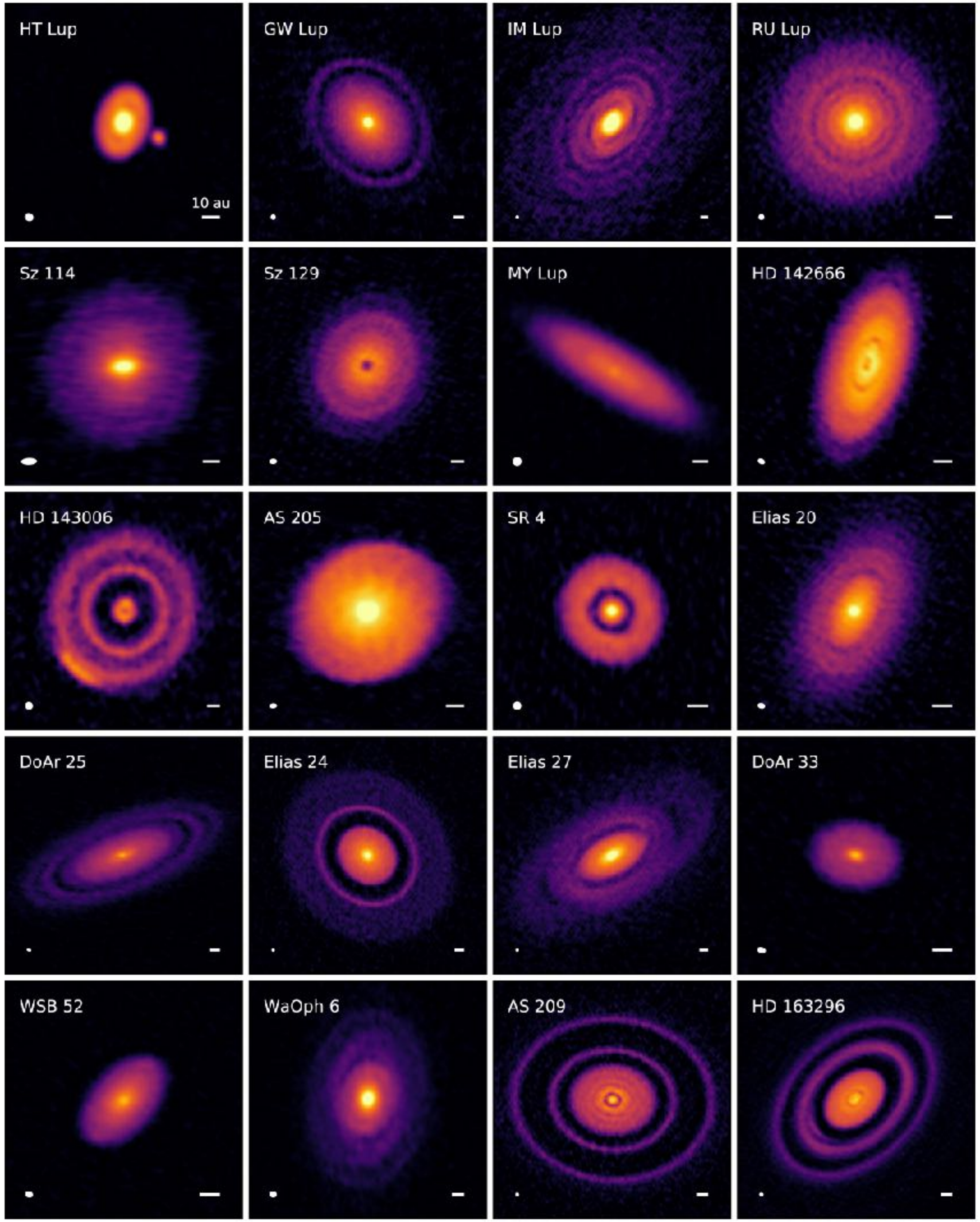
Dunham et al. 2015

Bennett, Donahue, Schneider, Voit

Disks evolve

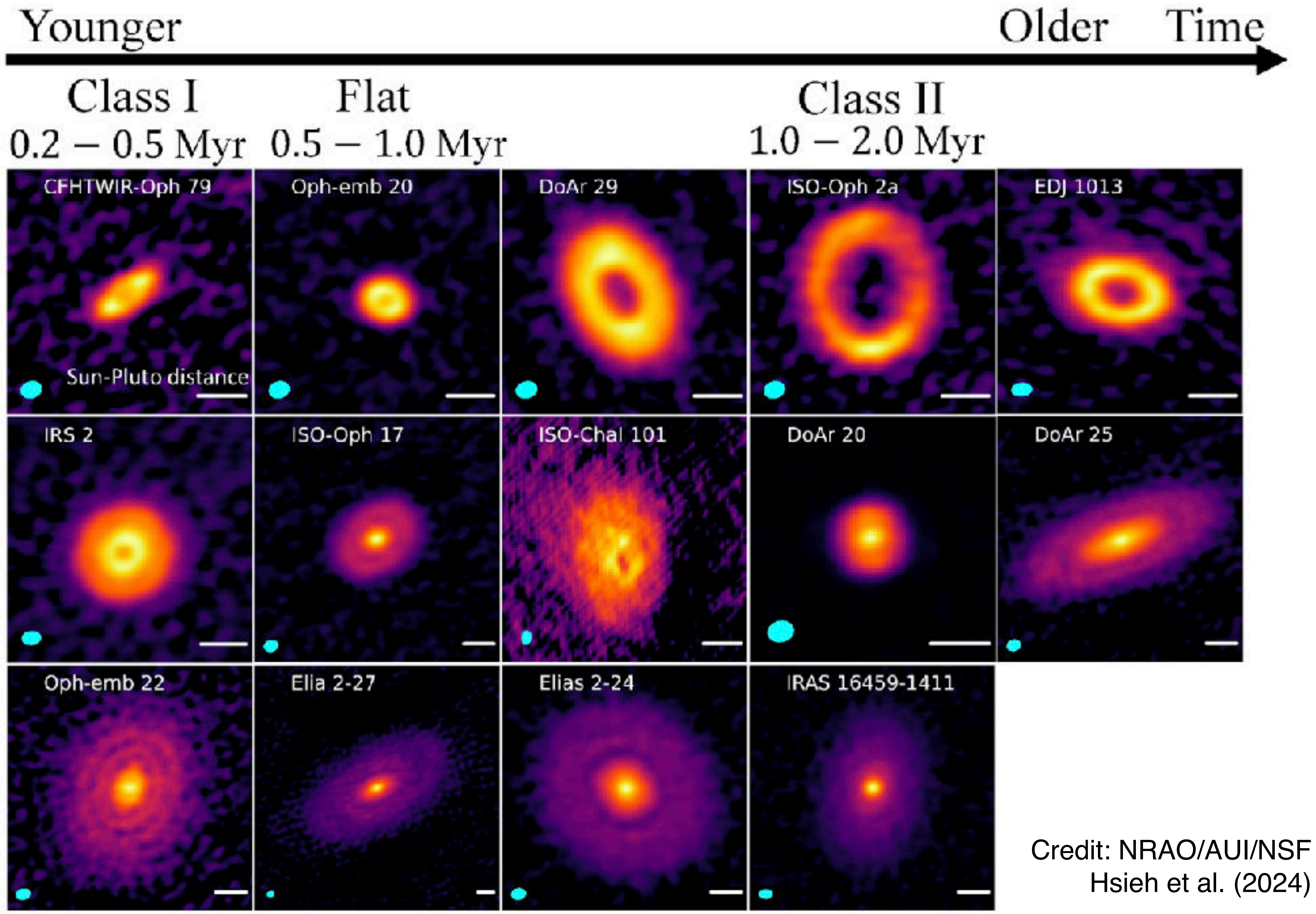


Credit: NRAO/AUI/NSF
Hsieh et al. (2024)

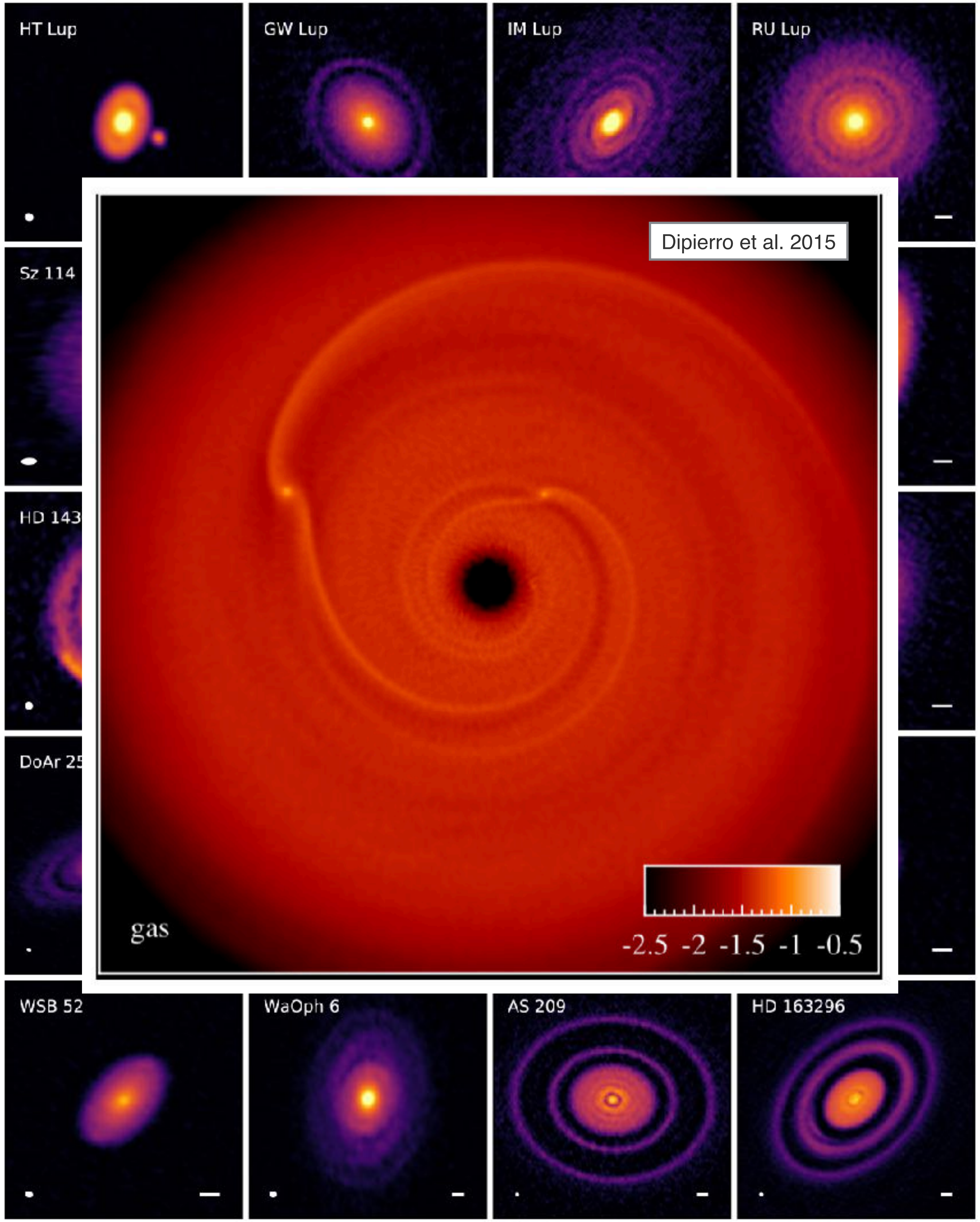


Andrews et al. 2018

Disks evolve

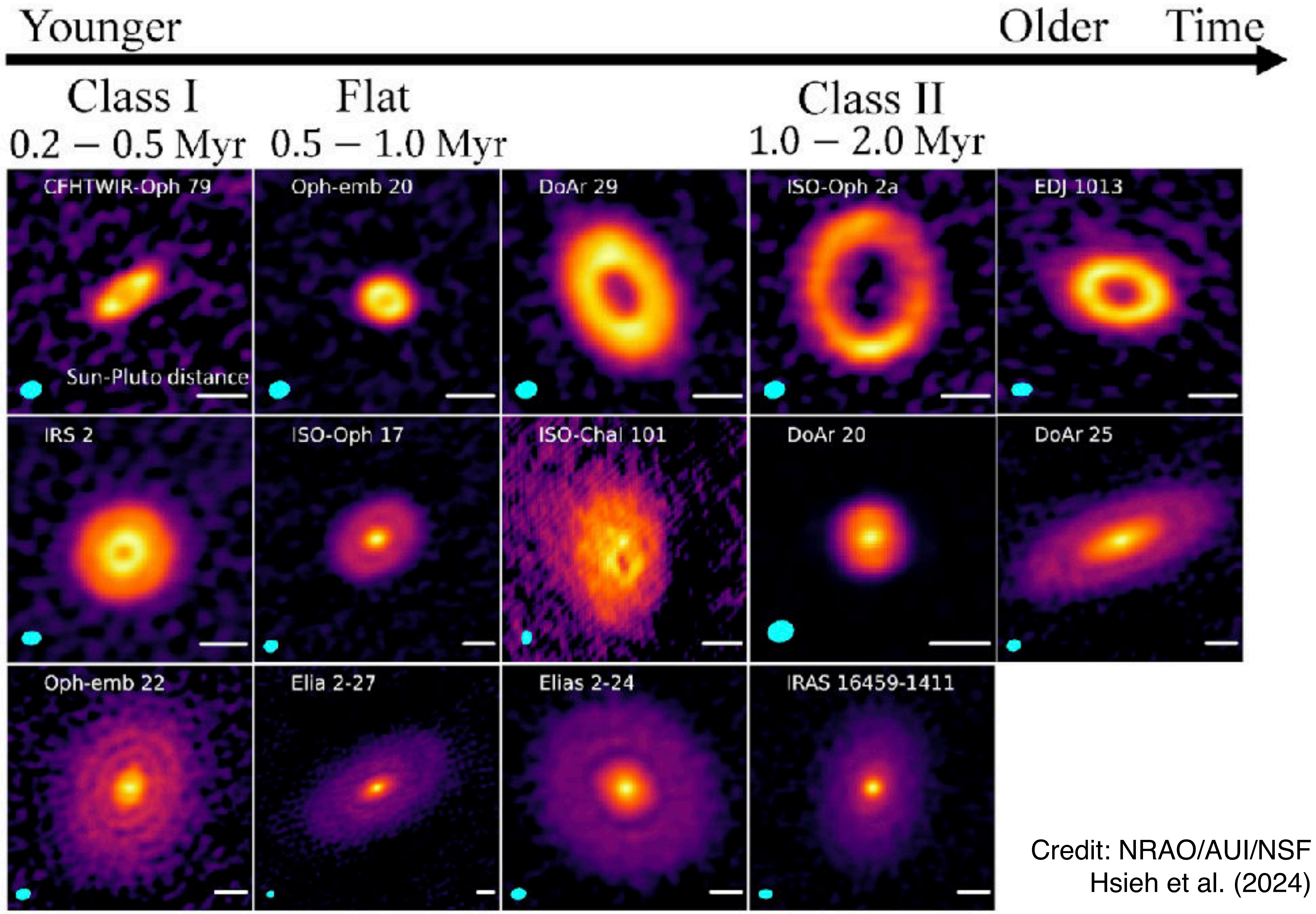


Credit: NRAO/AUI/NSF
Hsieh et al. (2024)

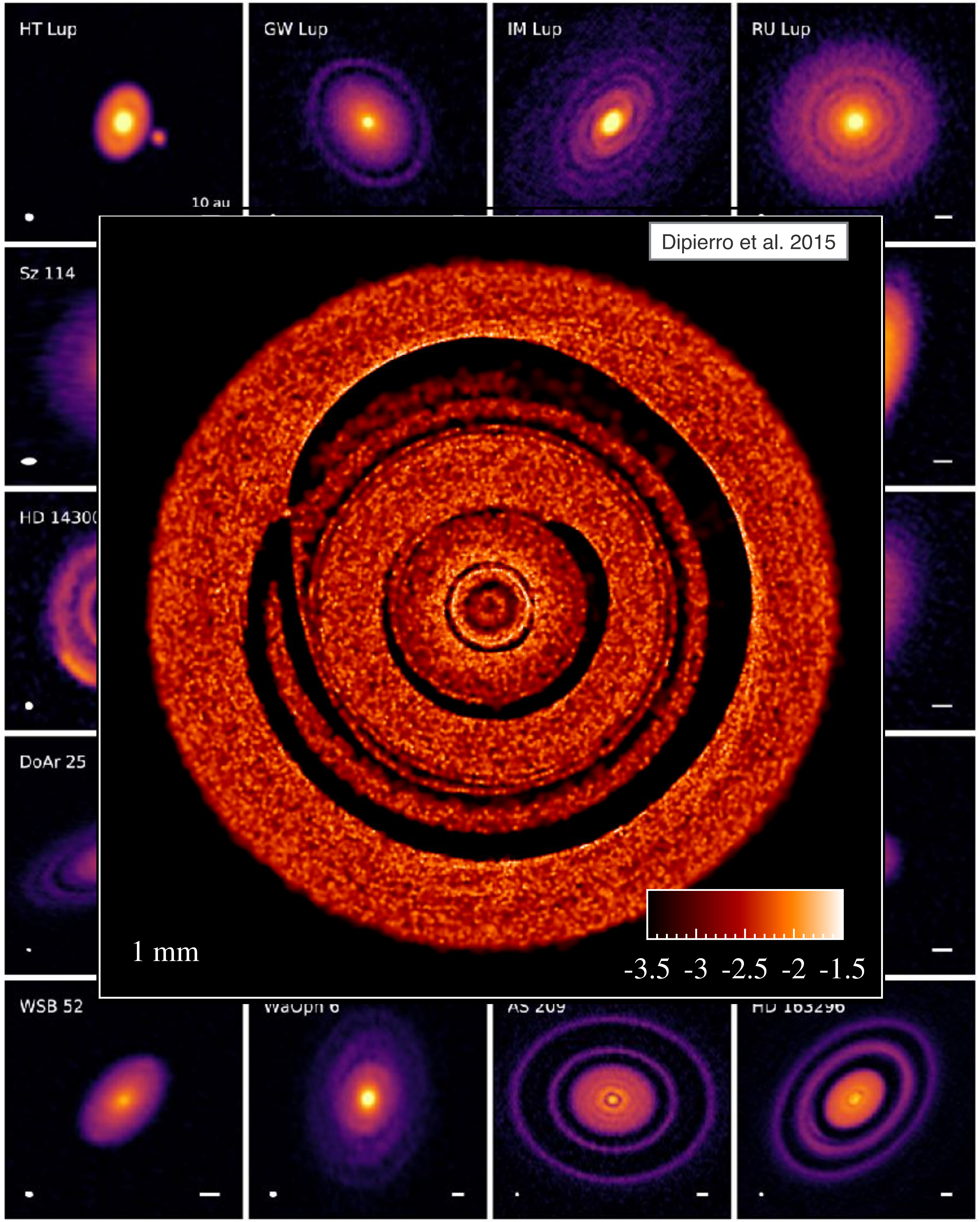


Andrews et al. 2018

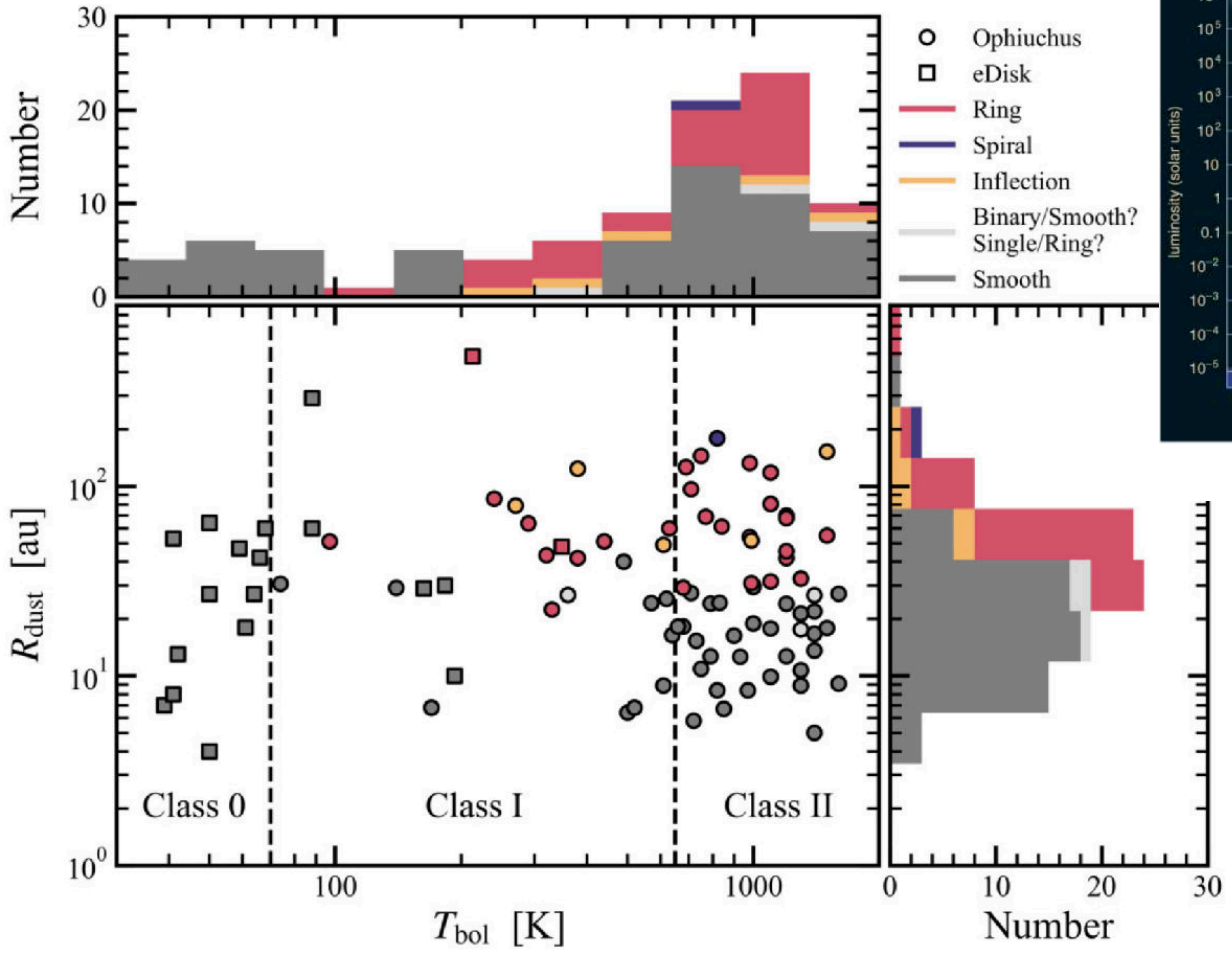
Disks evolve



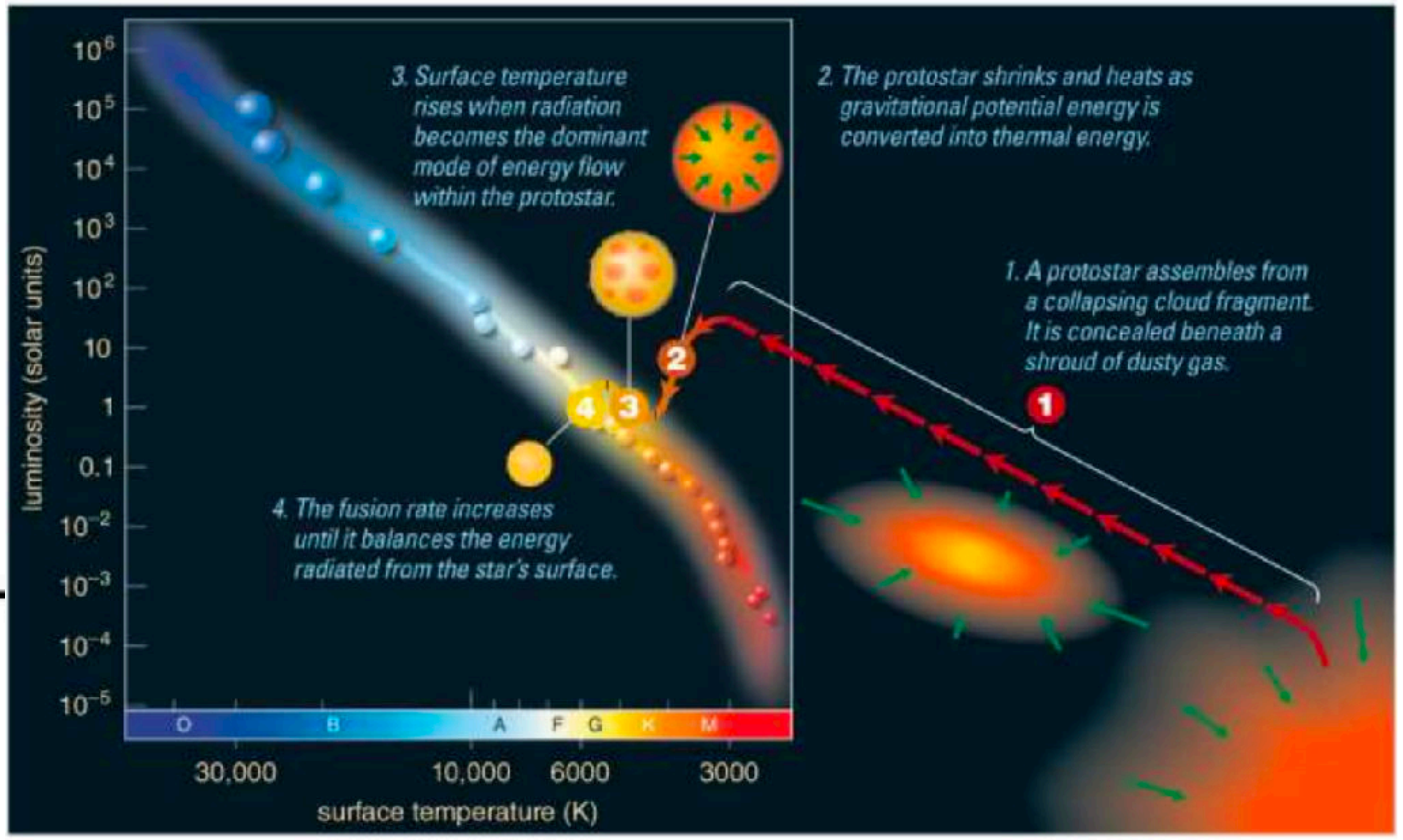
Credit: NRAO/AUI/NSF
Hsieh et al. (2024)



Andrews et al. 2018



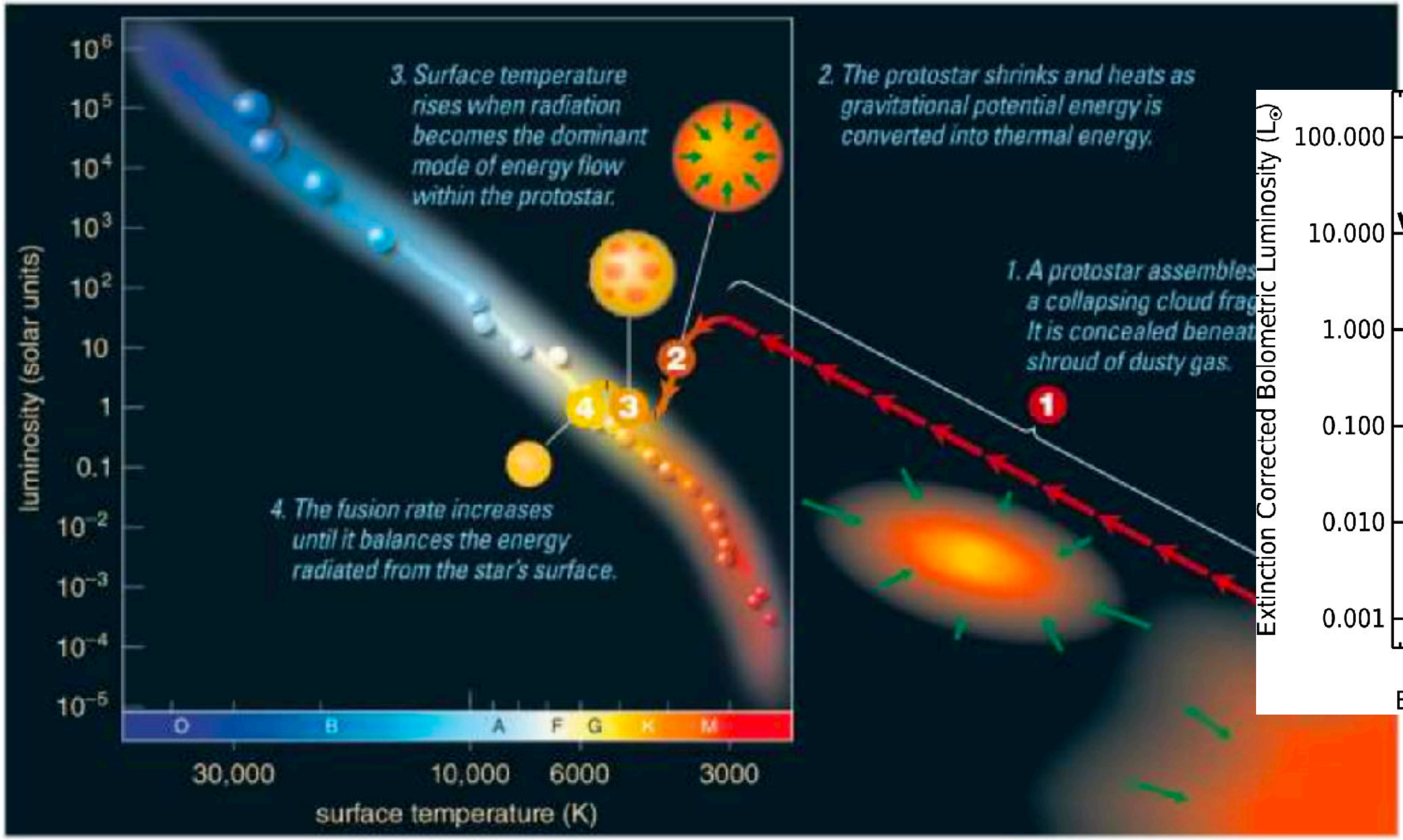
Shoshi et al. 2025

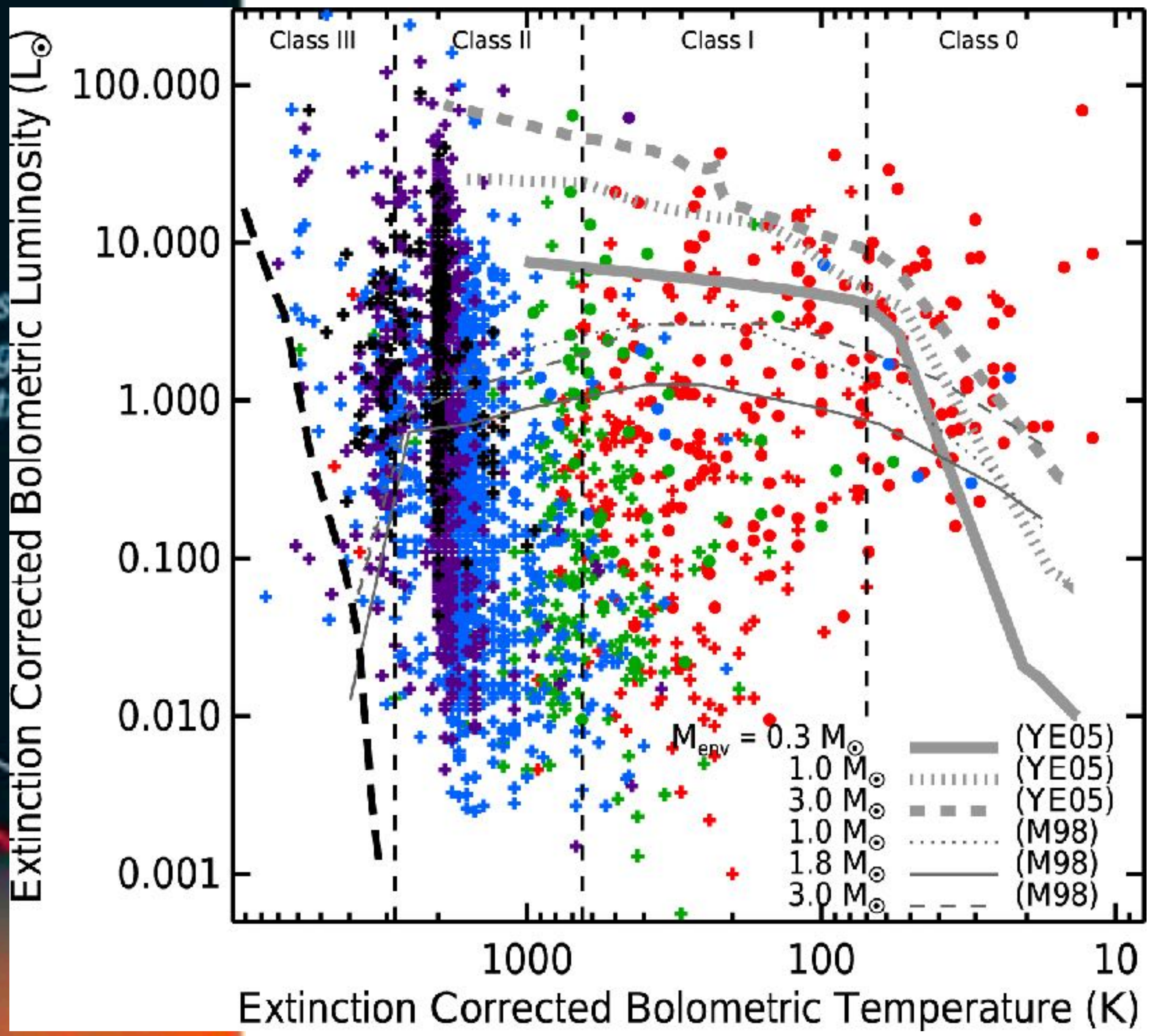


Bennett, Donahue, Schneider, Voit

Tentative sign of planet formation
< 0.5 Myr

恒星形成



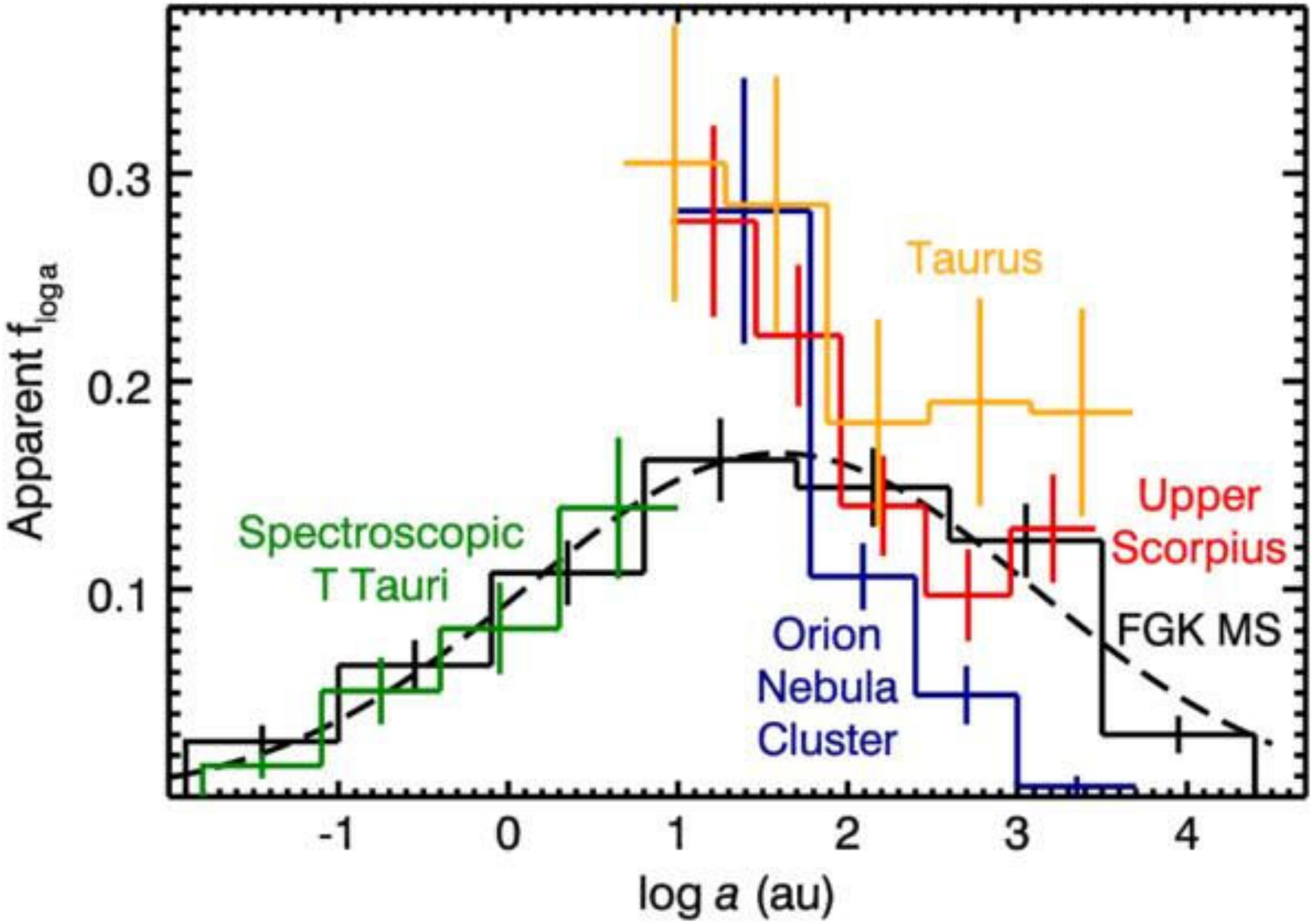


Dunham et al. 2015

Bennett, Donahue, Schneider, Voit

Image credit: NASA, ESA, G. Duchene (Universite de Grenoble I)

About half of stars are in multiple system



Eastlund et al. 2025

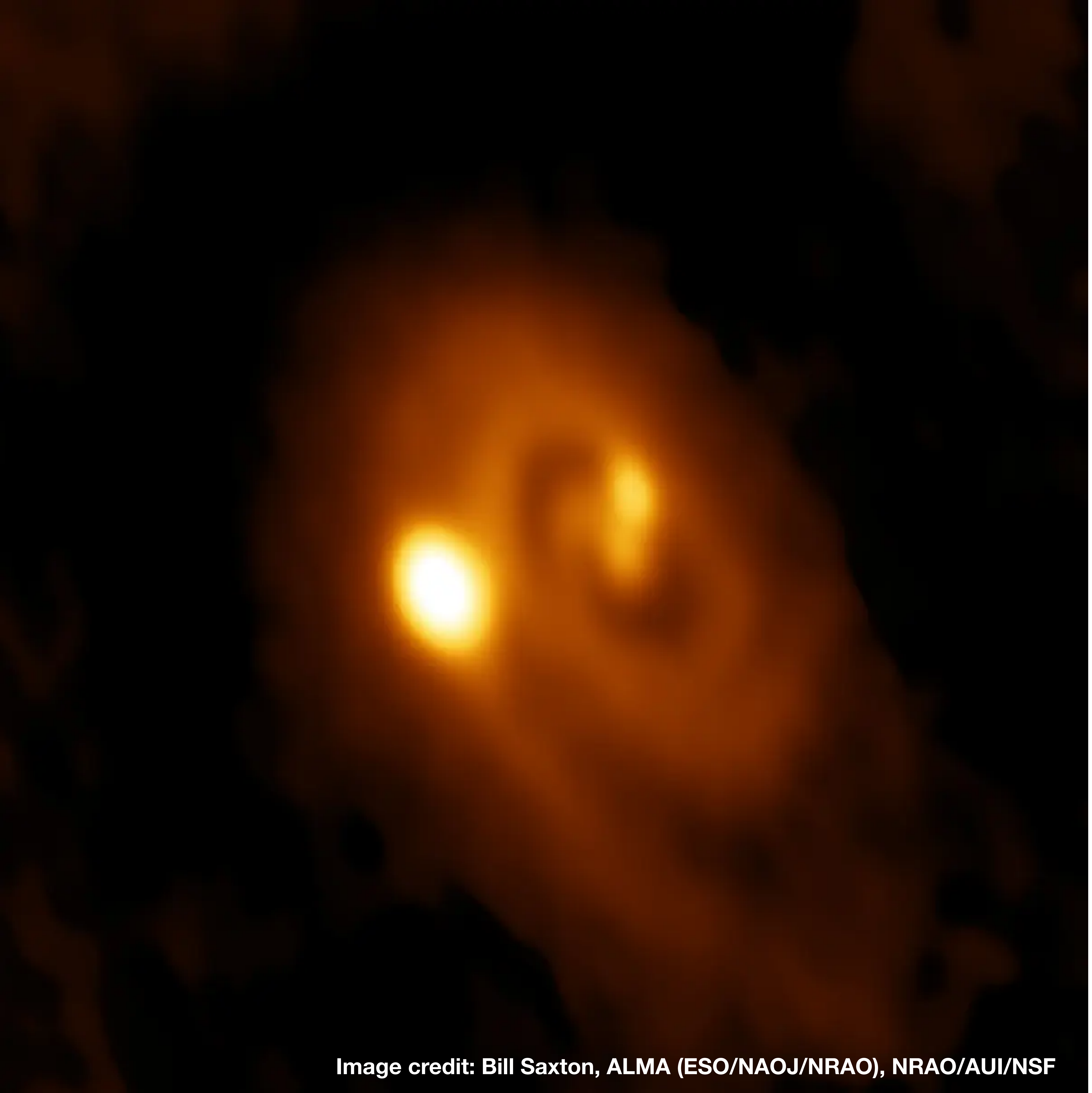
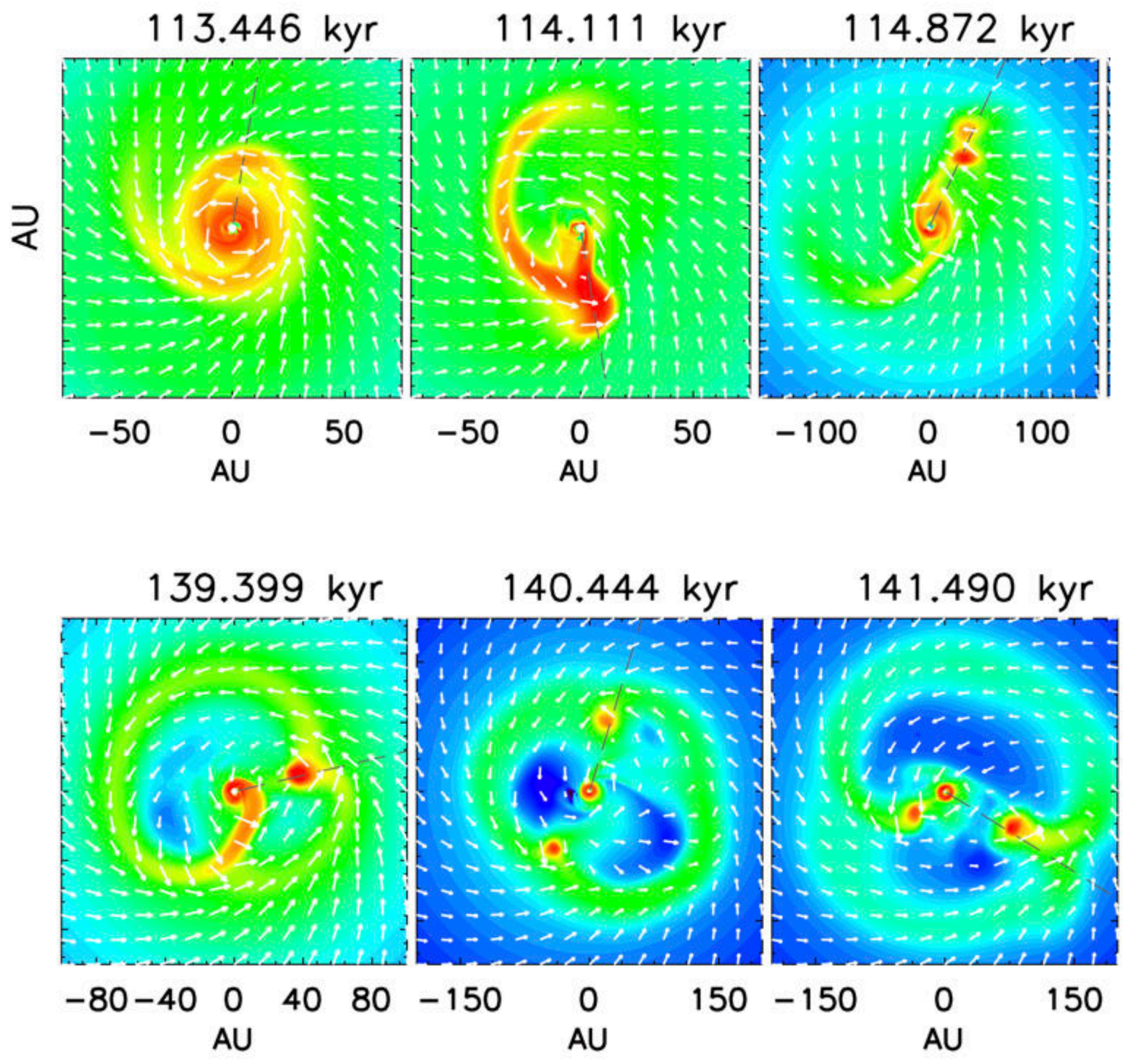
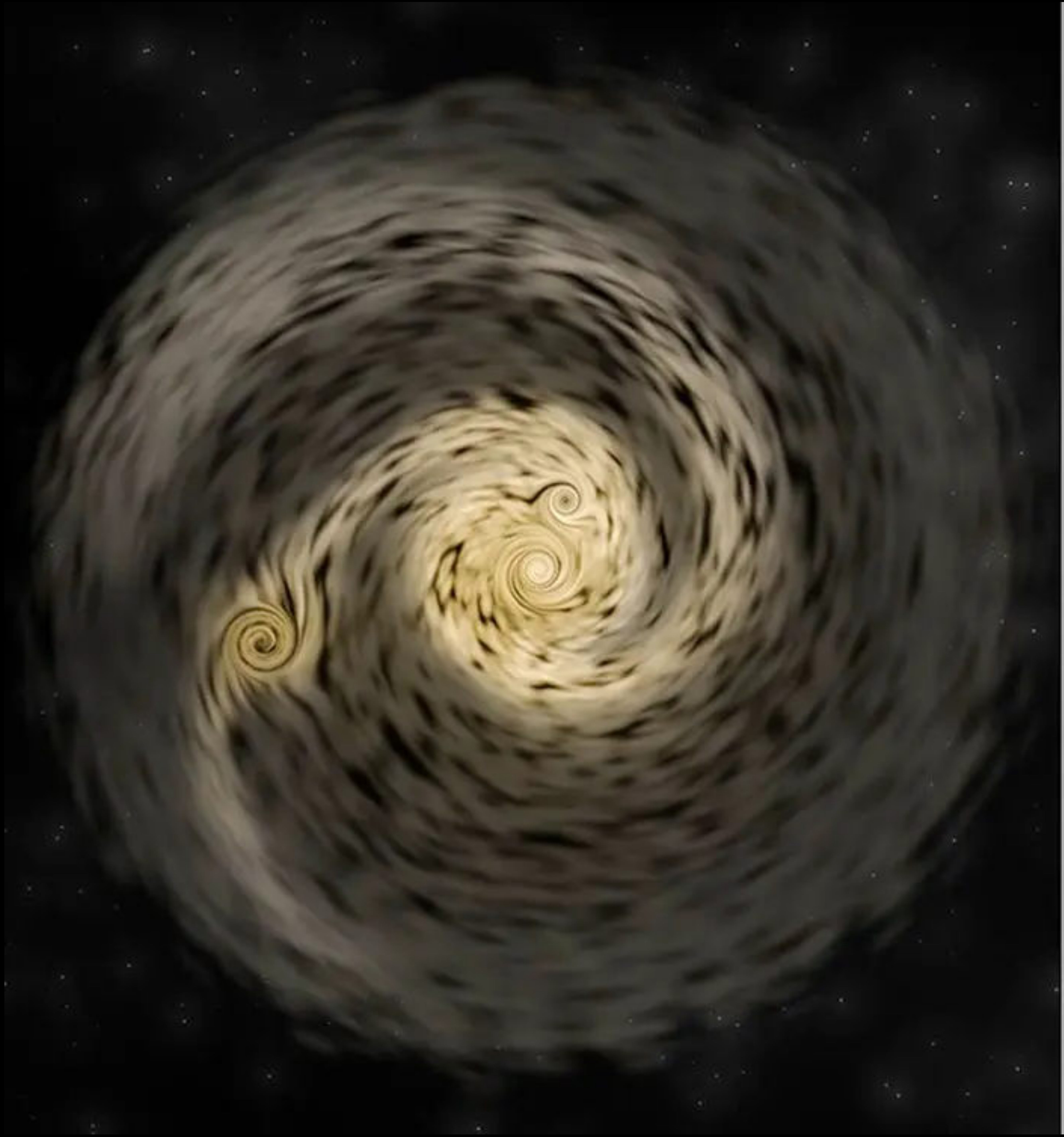


Image credit: Bill Saxton, ALMA (ESO/NAOJ/NRAO), NRAO/AUI/NSF

Disk fragmentation



Zhao et al. 2018



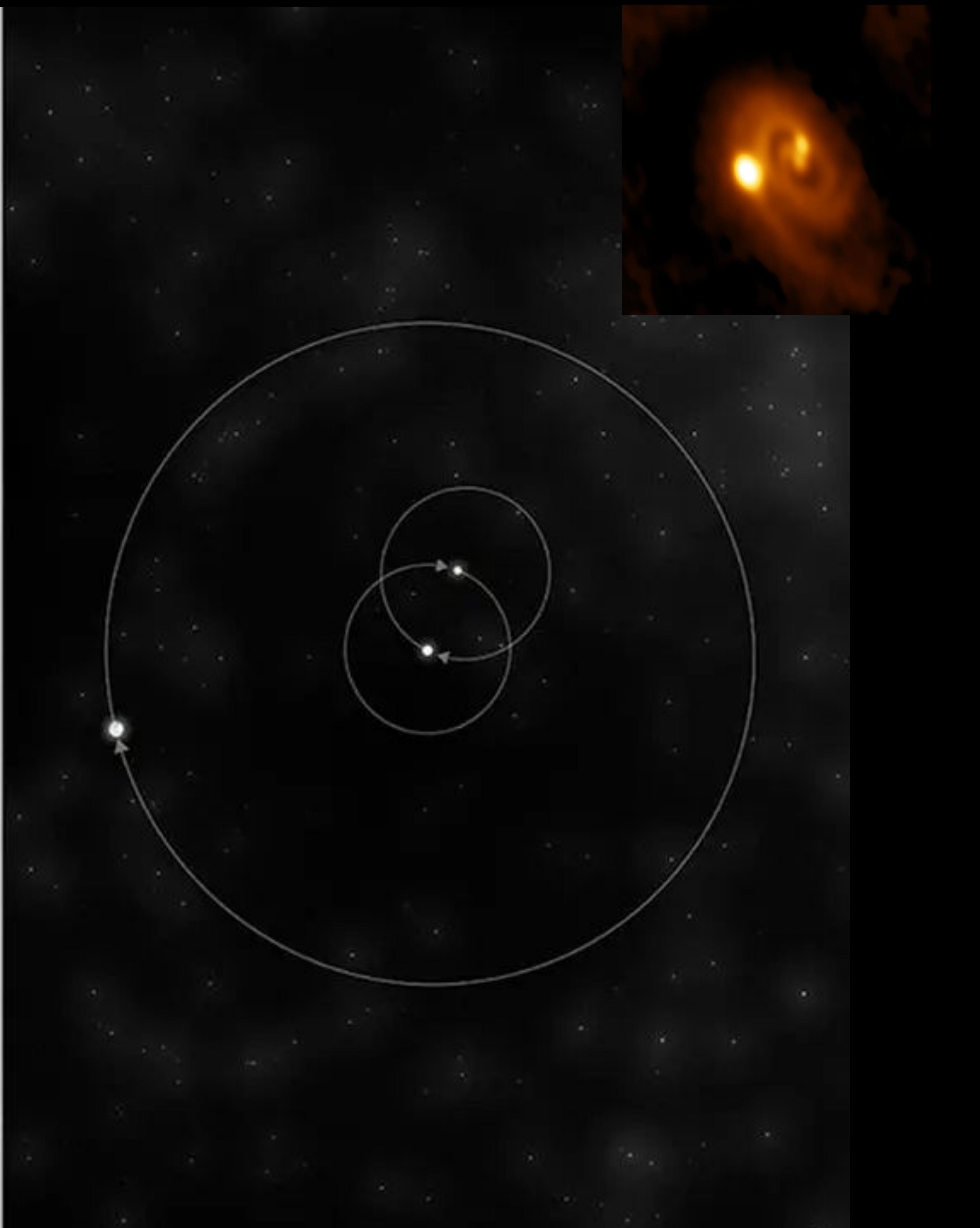
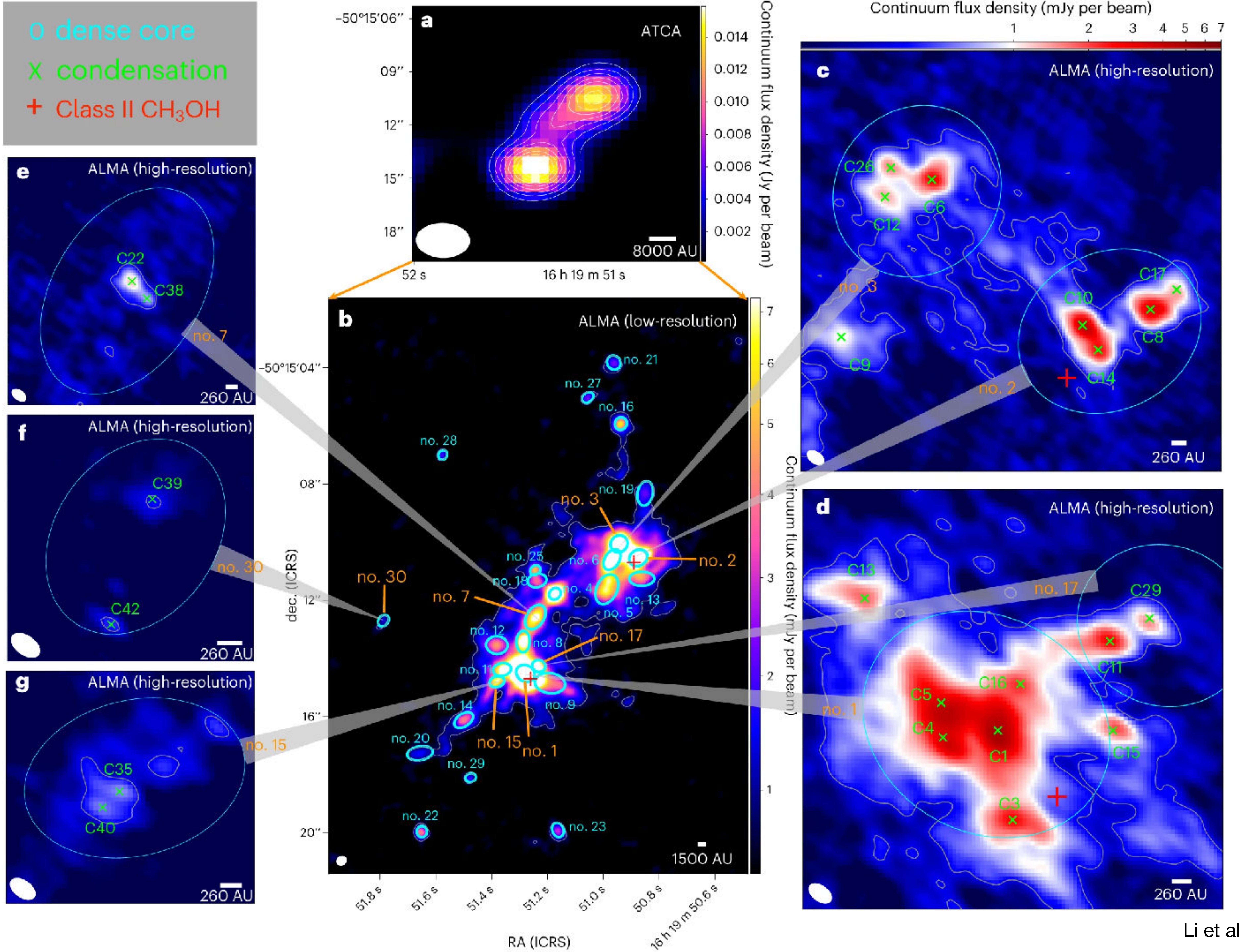
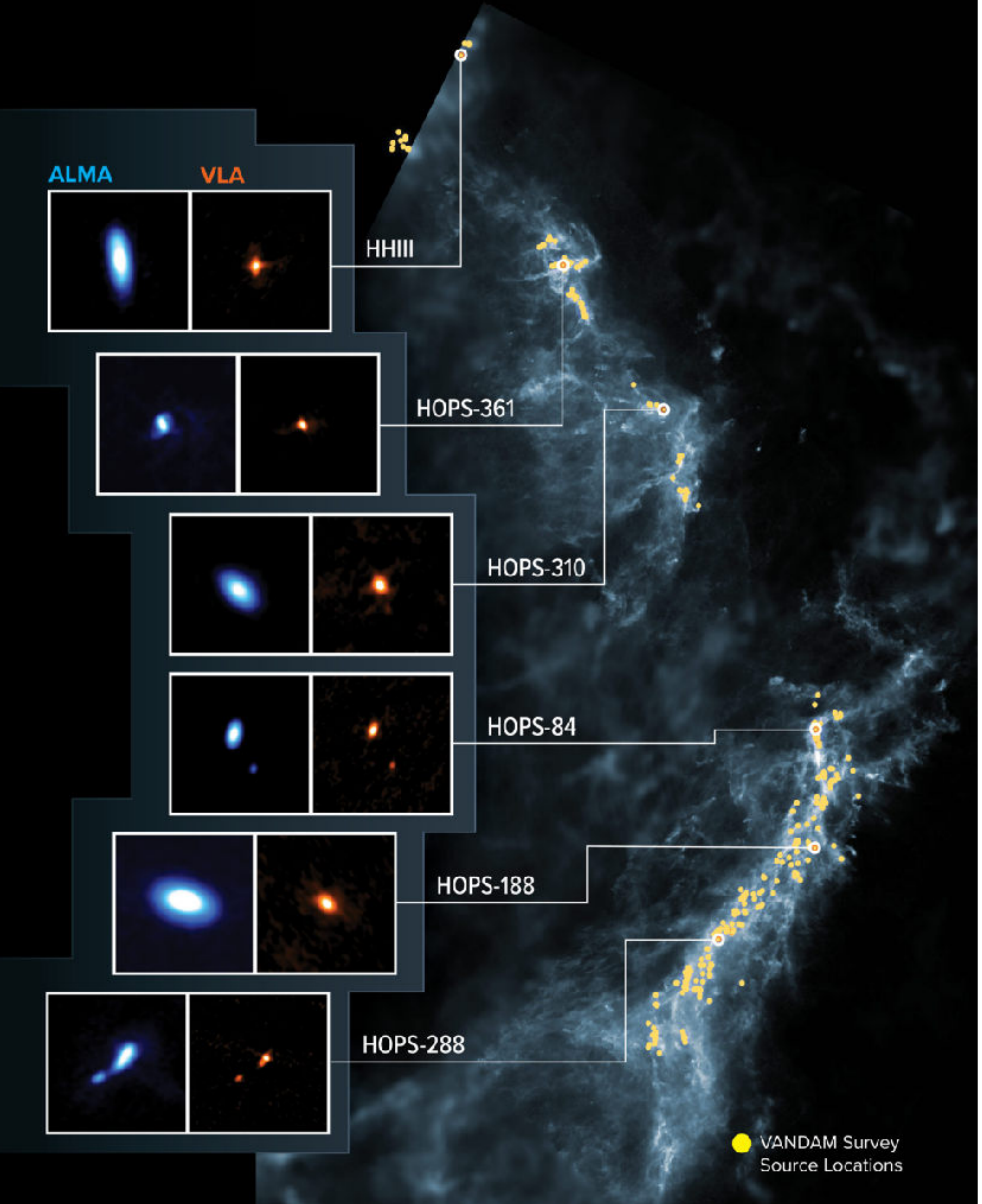


Image credit: Bill Saxton, NRAO/AUI/NSF

Core/Clump fragmentation

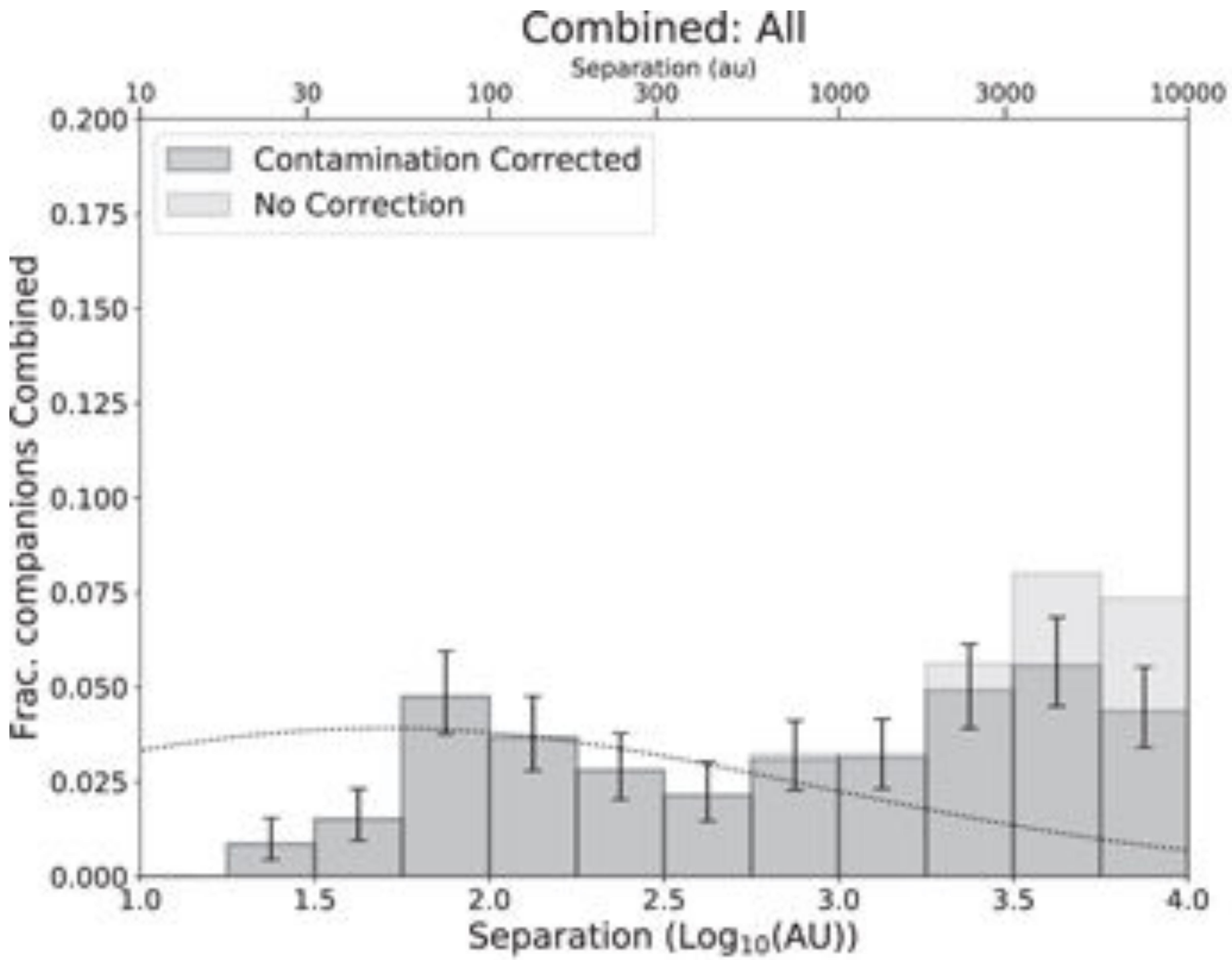


Li et al. 2024



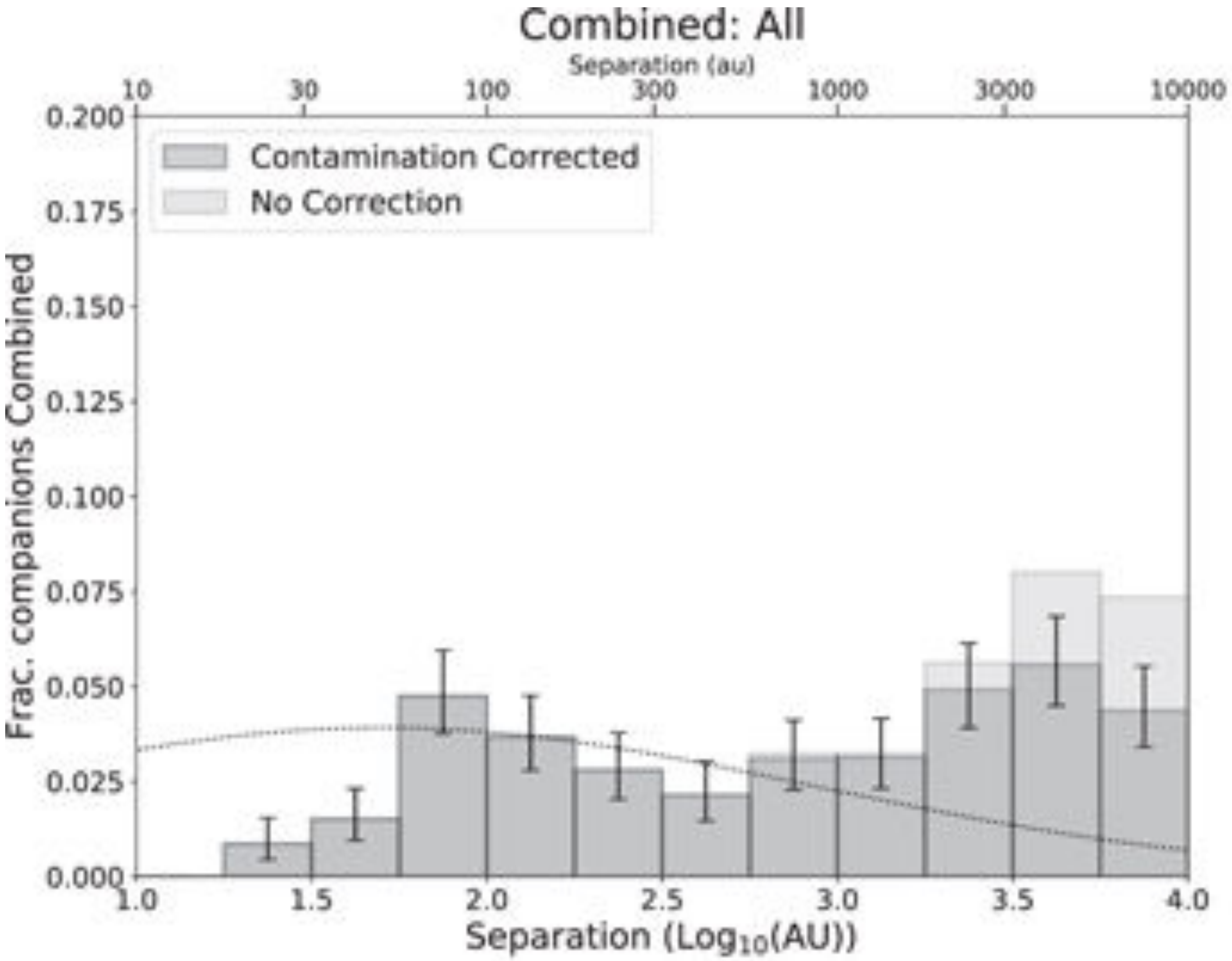
Credit: NRAO/AUI/NSF; Tobin et al. (2020)

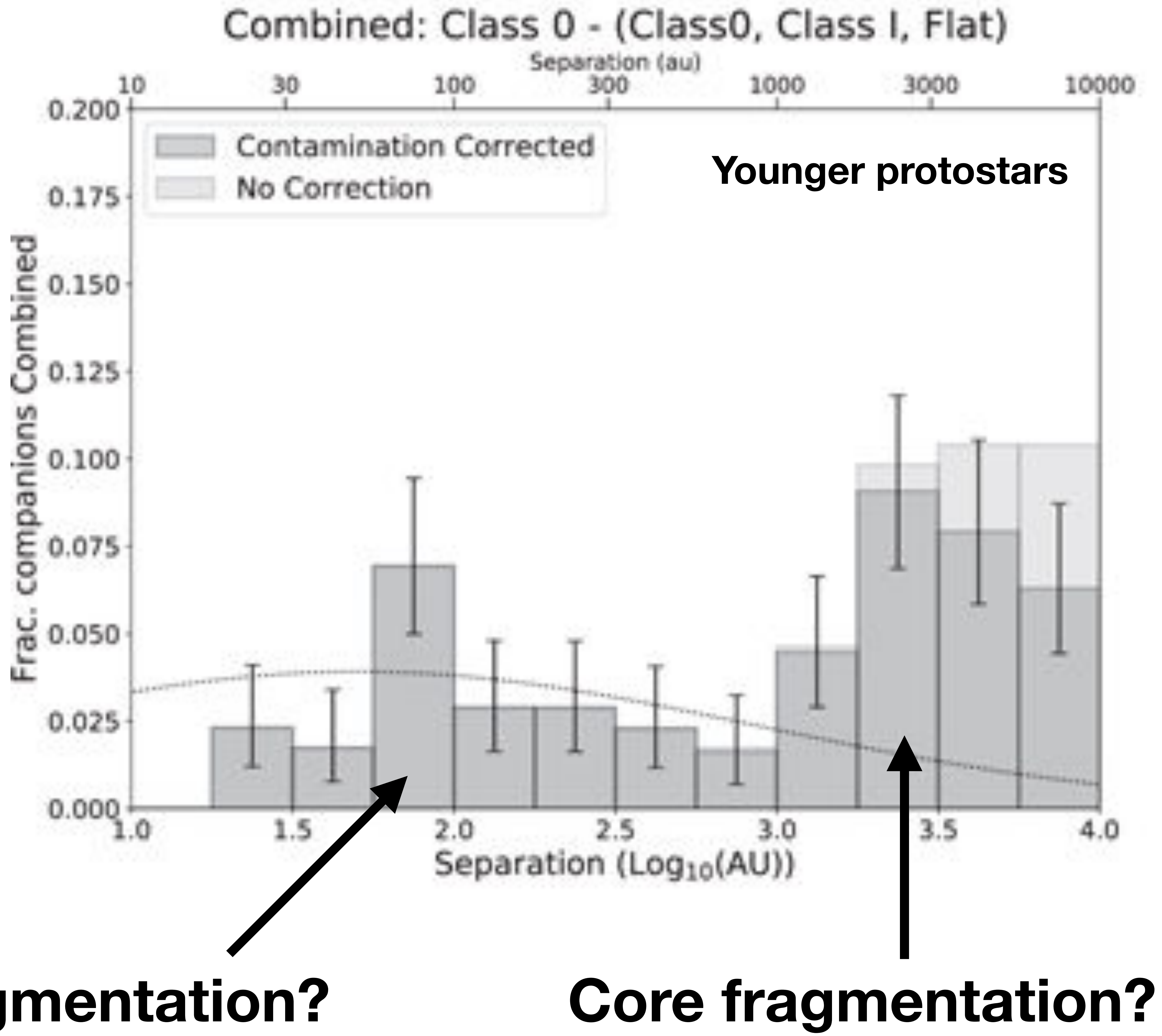
About half of protostars are in multiple system



Tobin et al. 2022

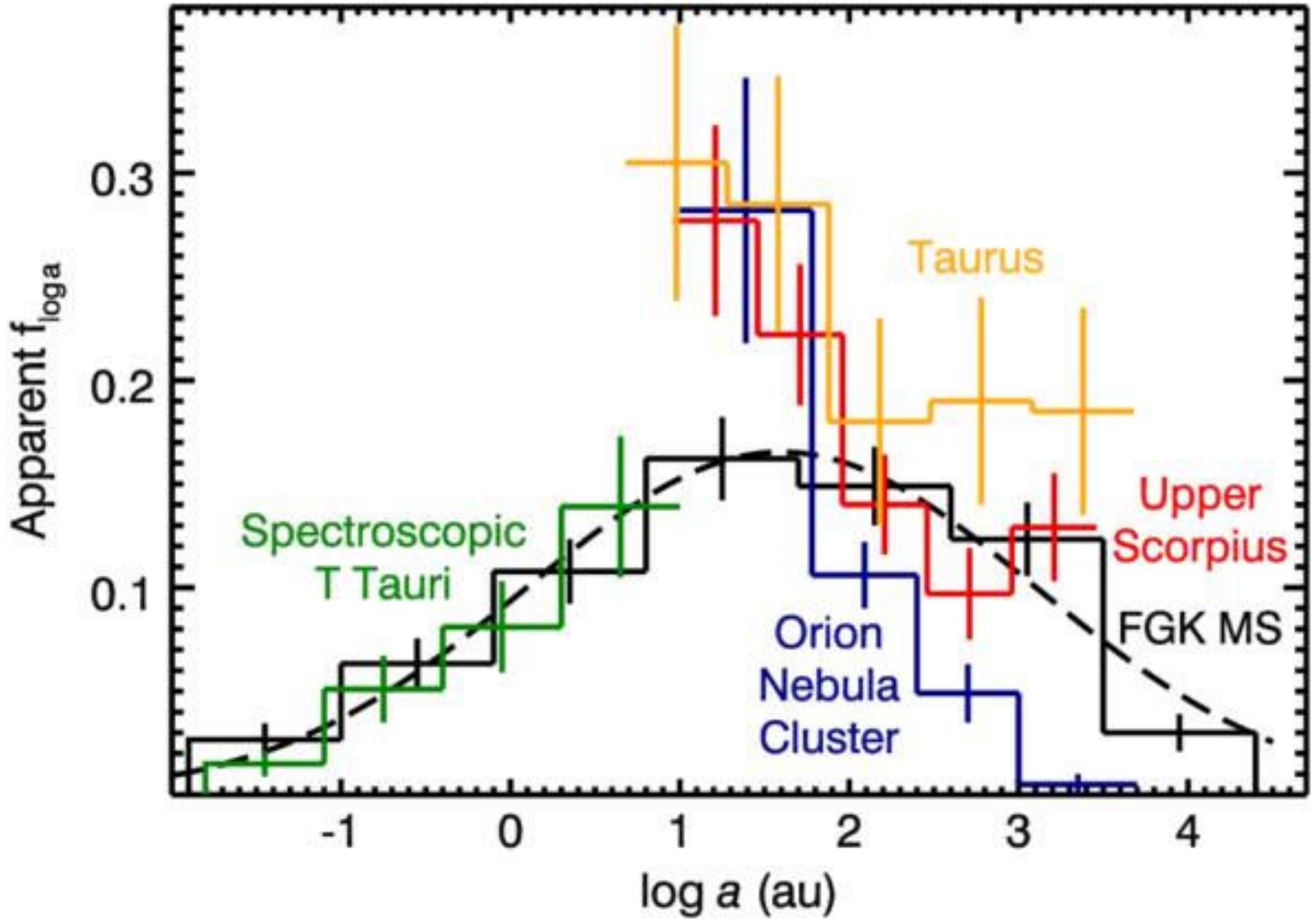
Bimodal Distribution => Two fragmentation mechanisms?



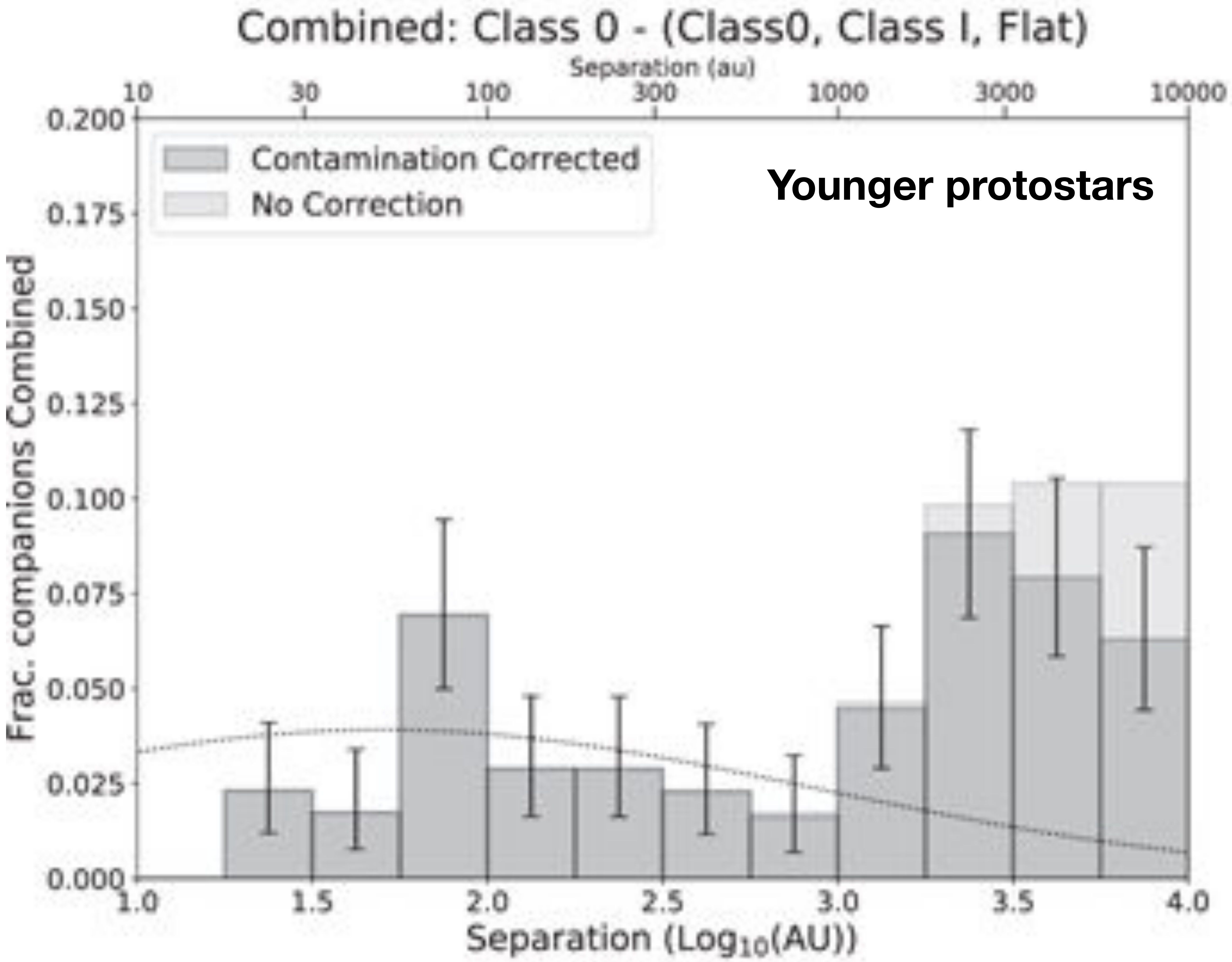


Tobin et al. 2022

Configuration of multiple systems evolves

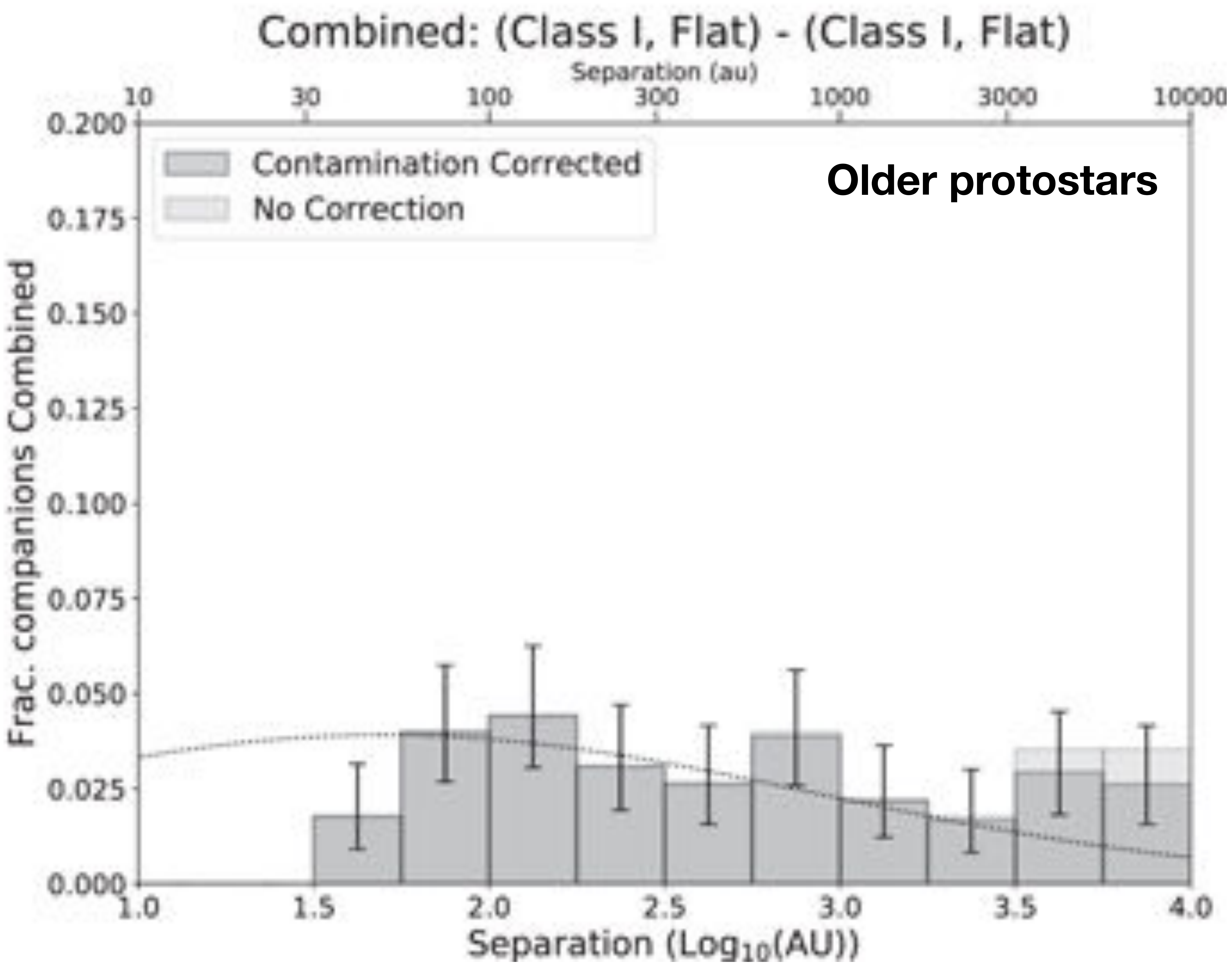


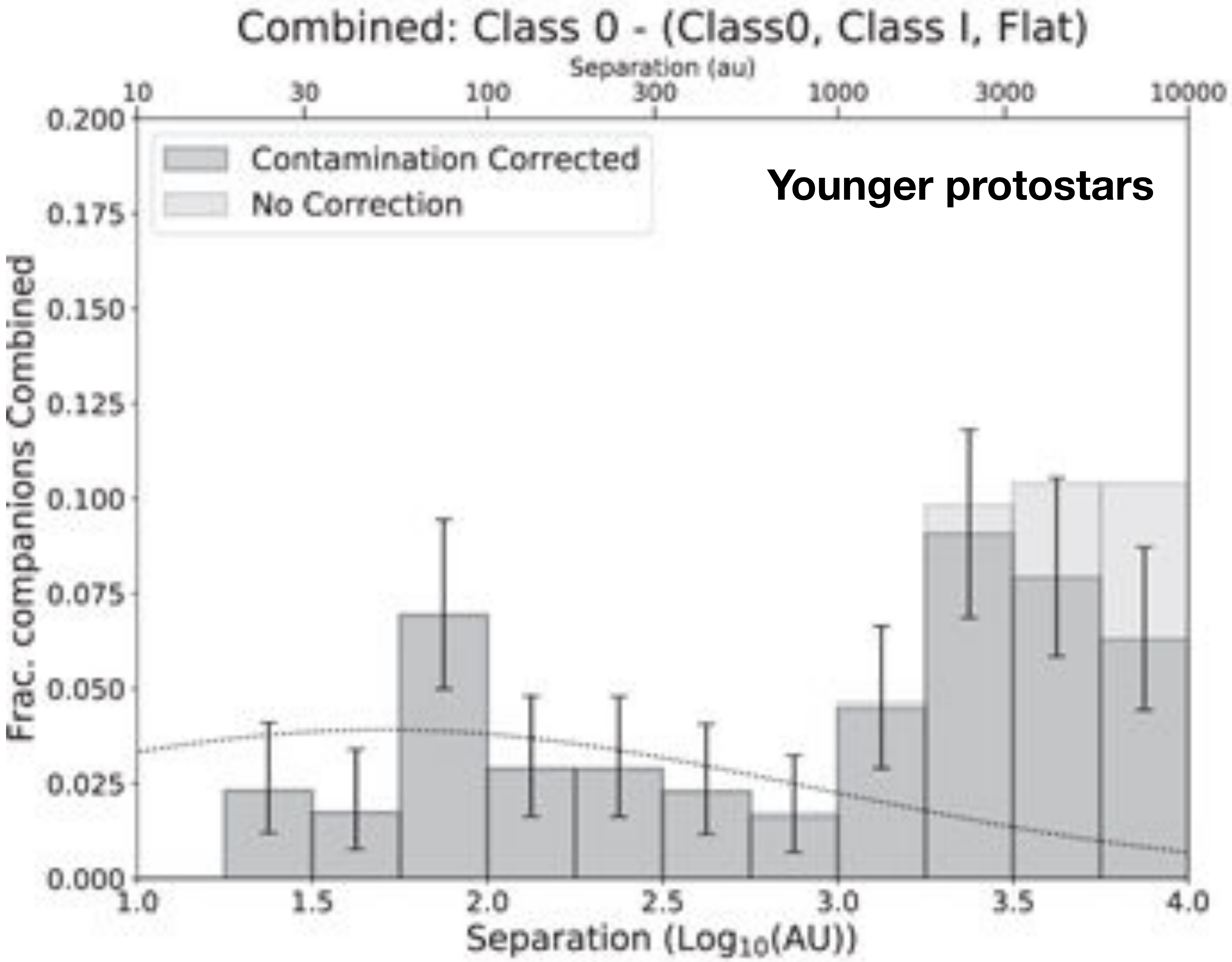
Eastlund et al. 2025



Tobin et al. 2022

Configuration of multiple systems evolves

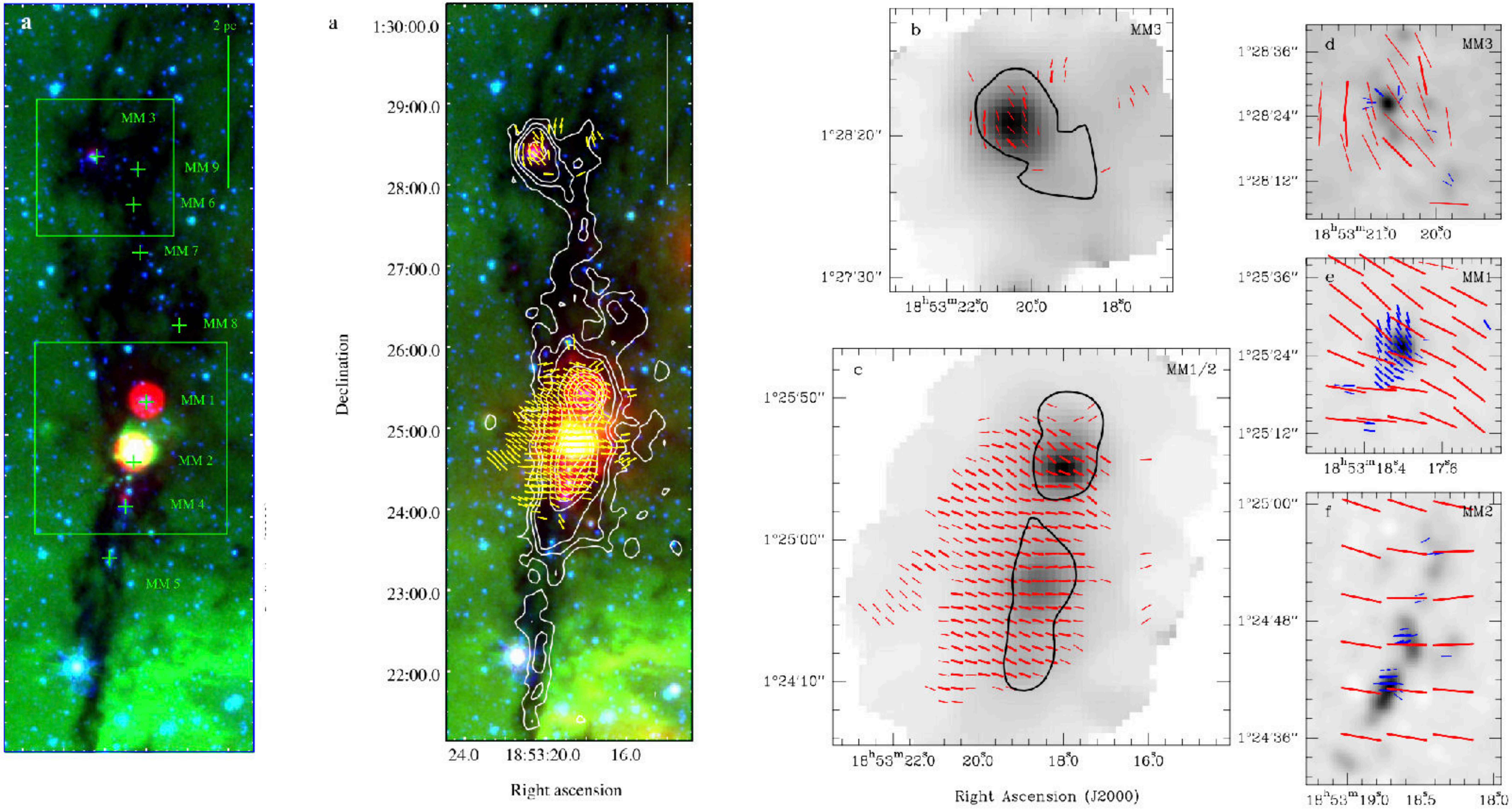




Migration? Ejection?

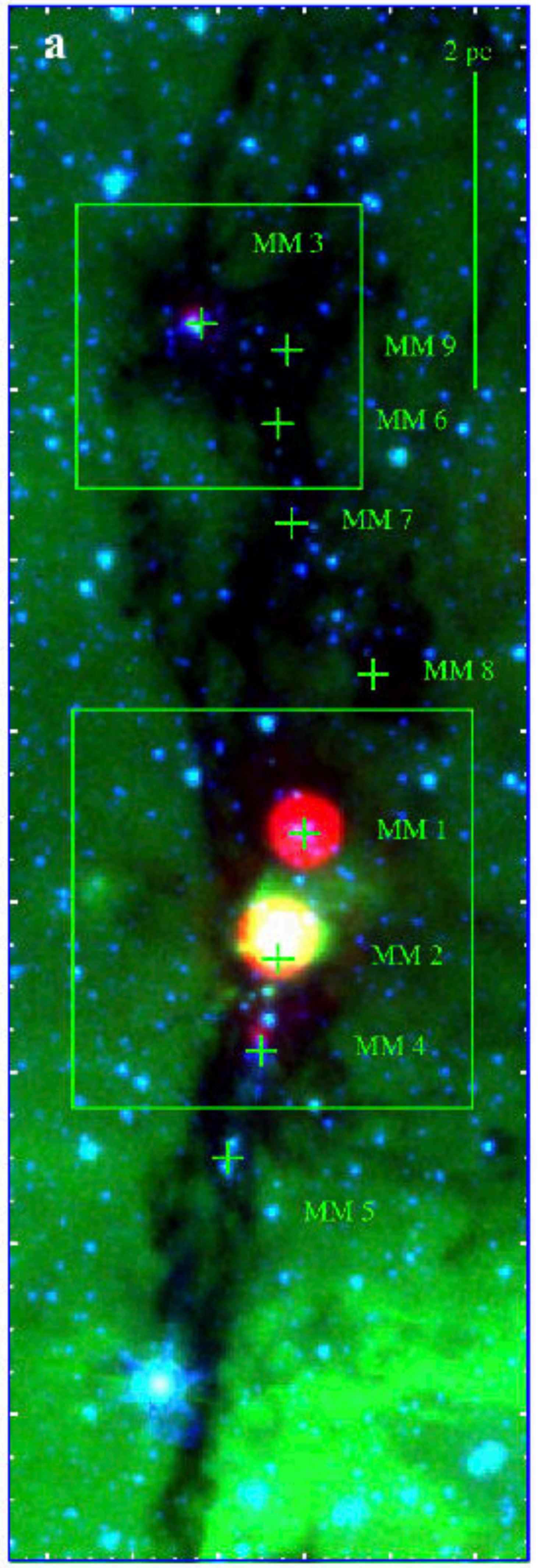
Tobin et al. 2022

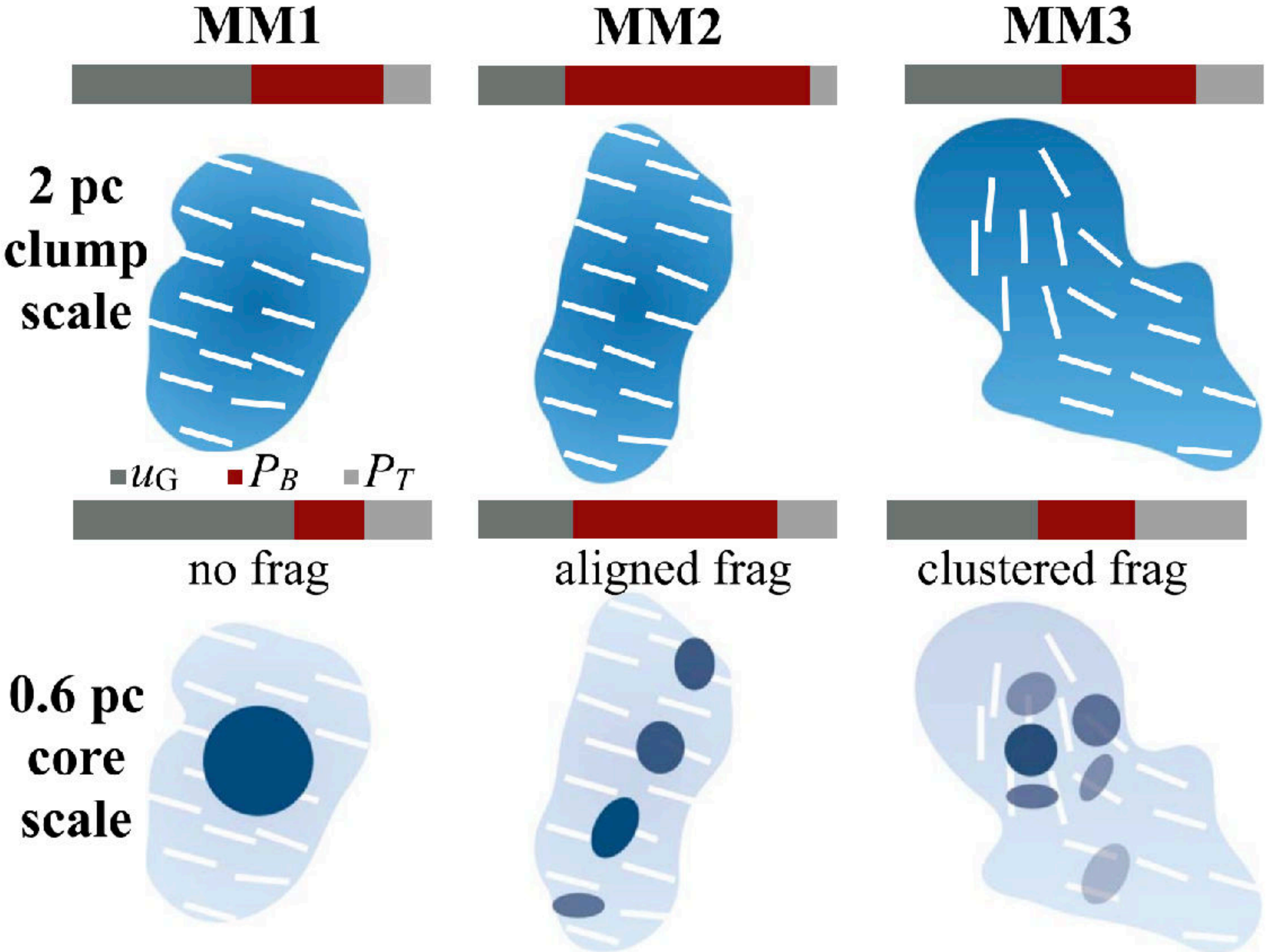
Physical parameters determining fragmentation?



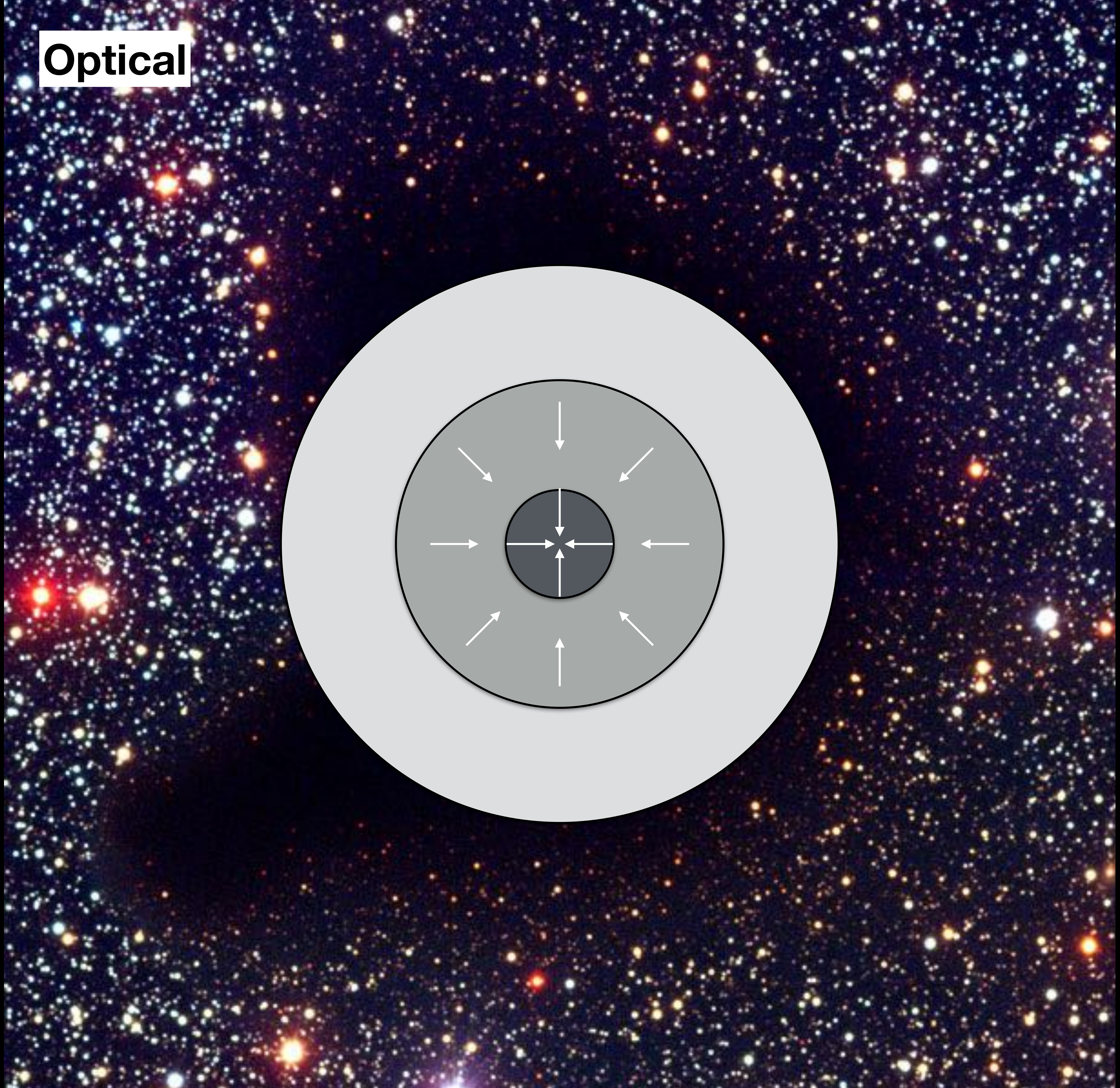
Tang et al. 2019

Physical parameters determining fragmentation?





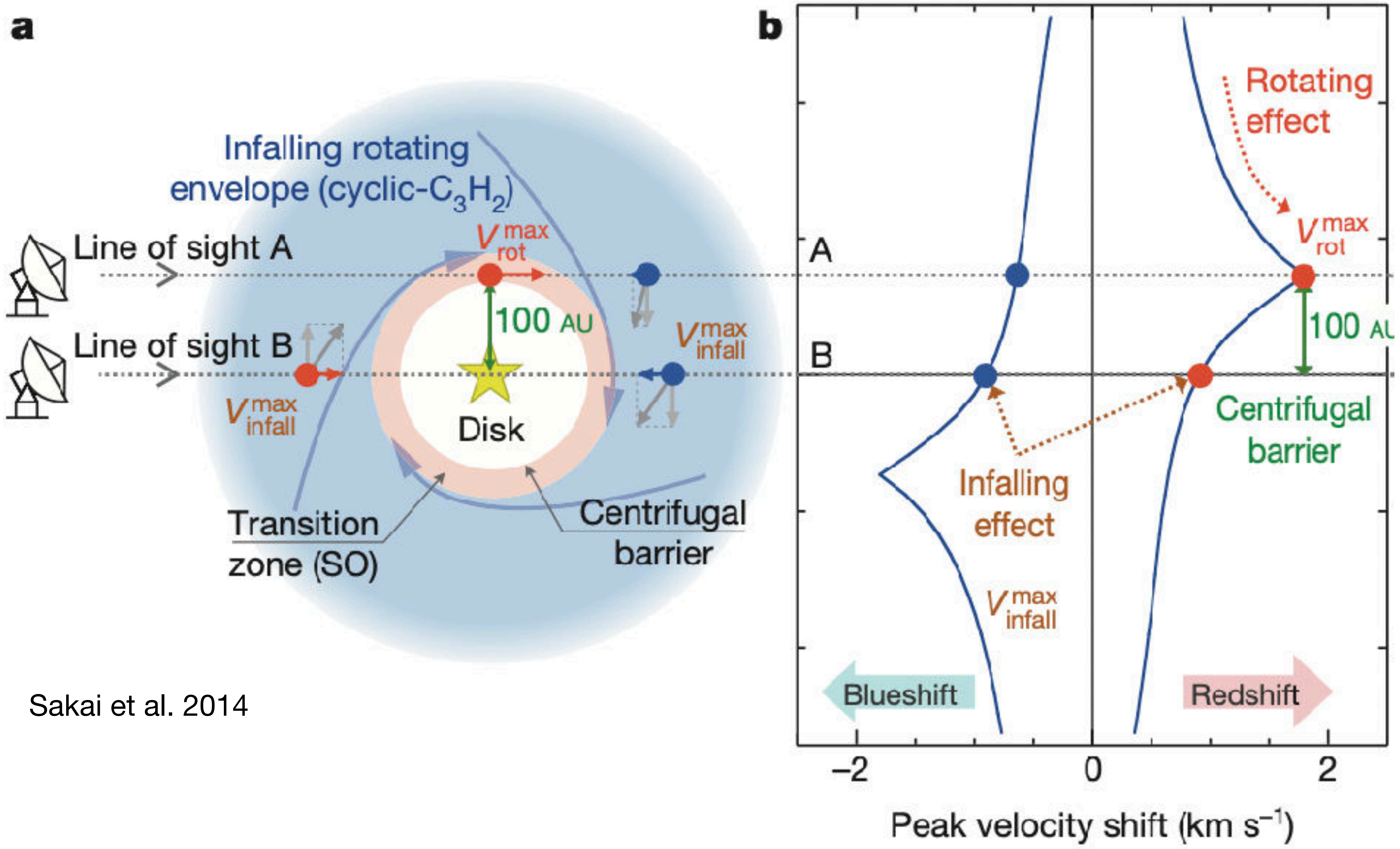
Tang et al. 2019



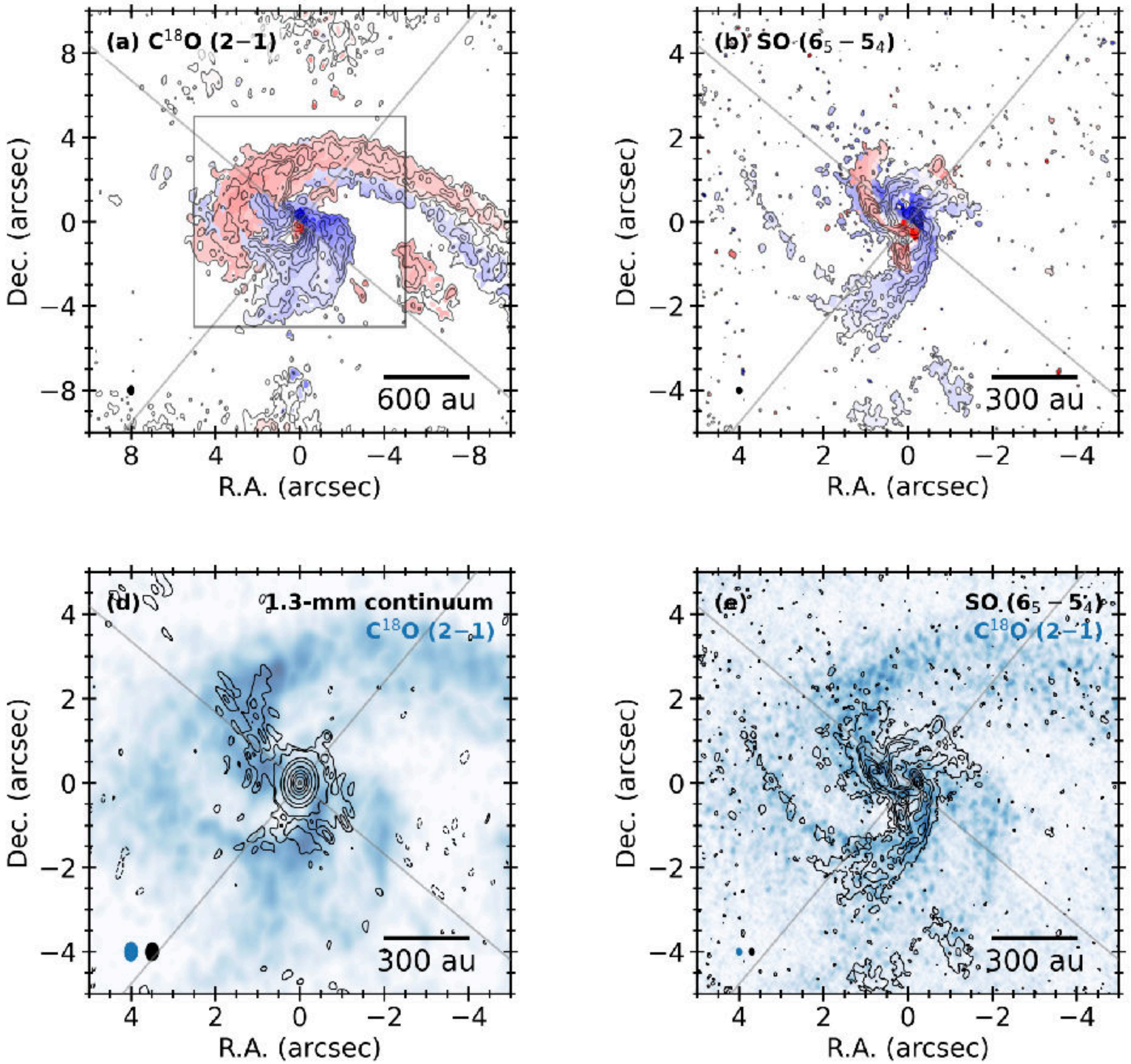
Gravitational bound dense cores

Image credit: ESO

Distribution of infalling material is not symmetric

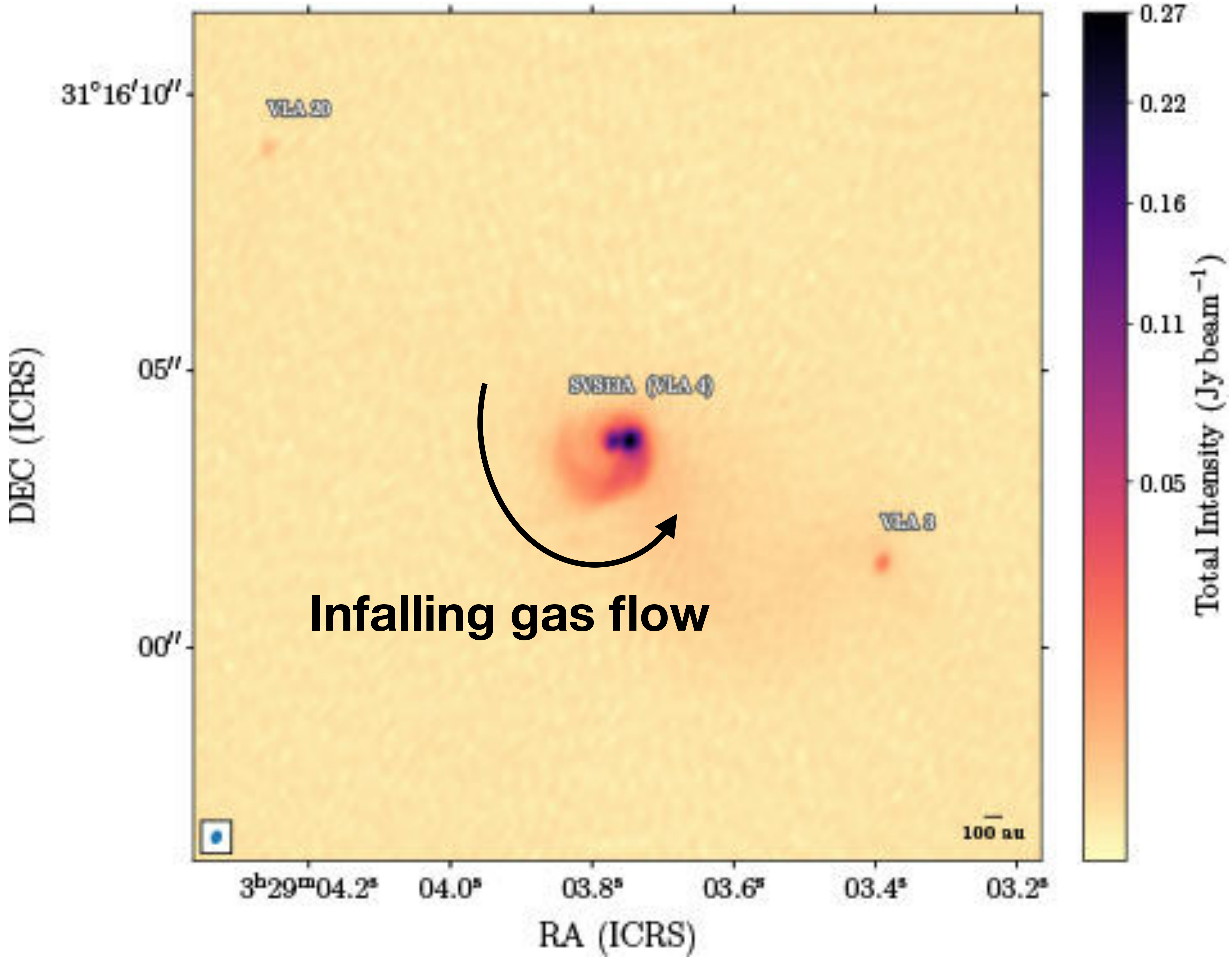


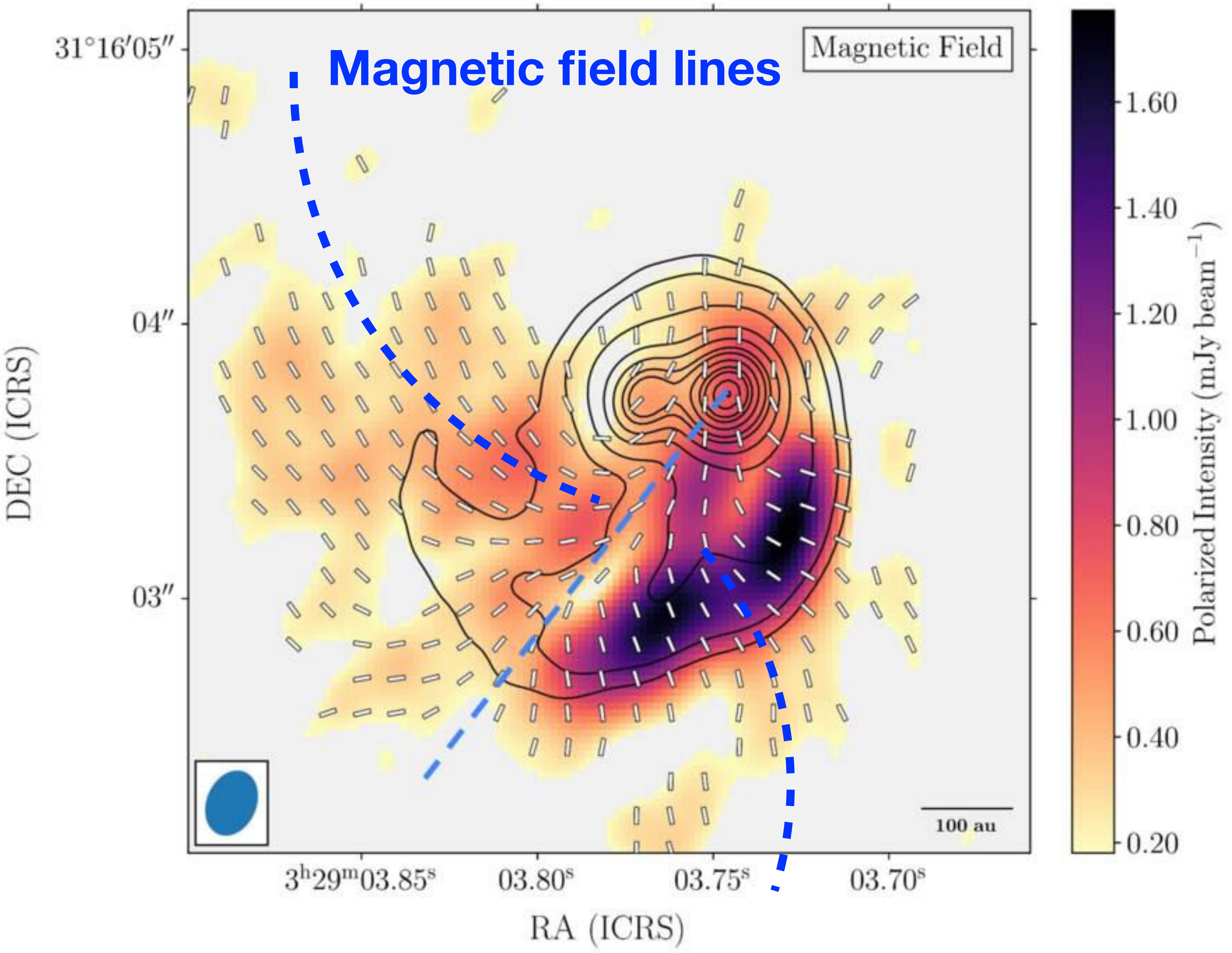
Sakai et al. 2014



Han et al. 2025

Interplay between infalling material and magnetic fields

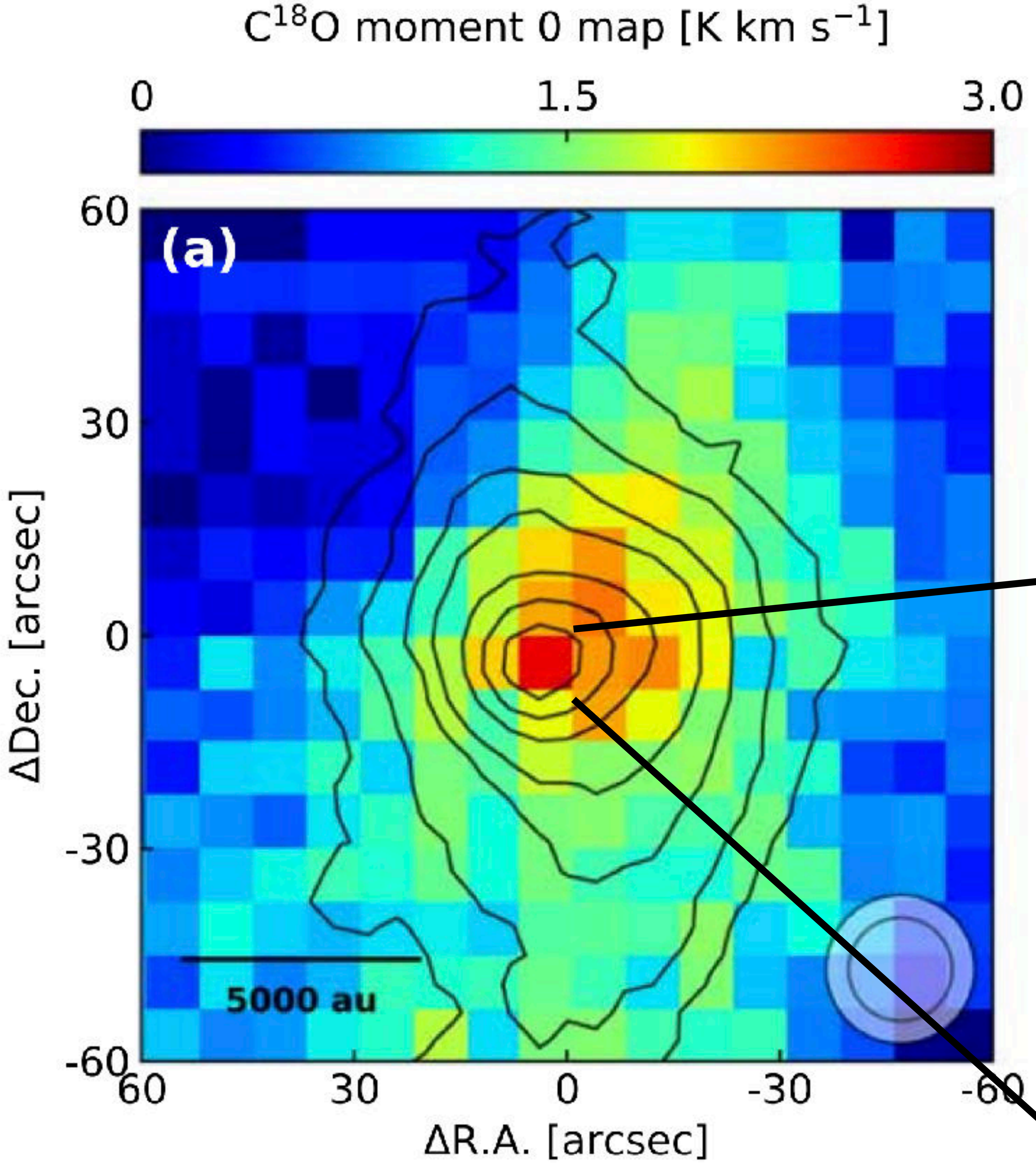


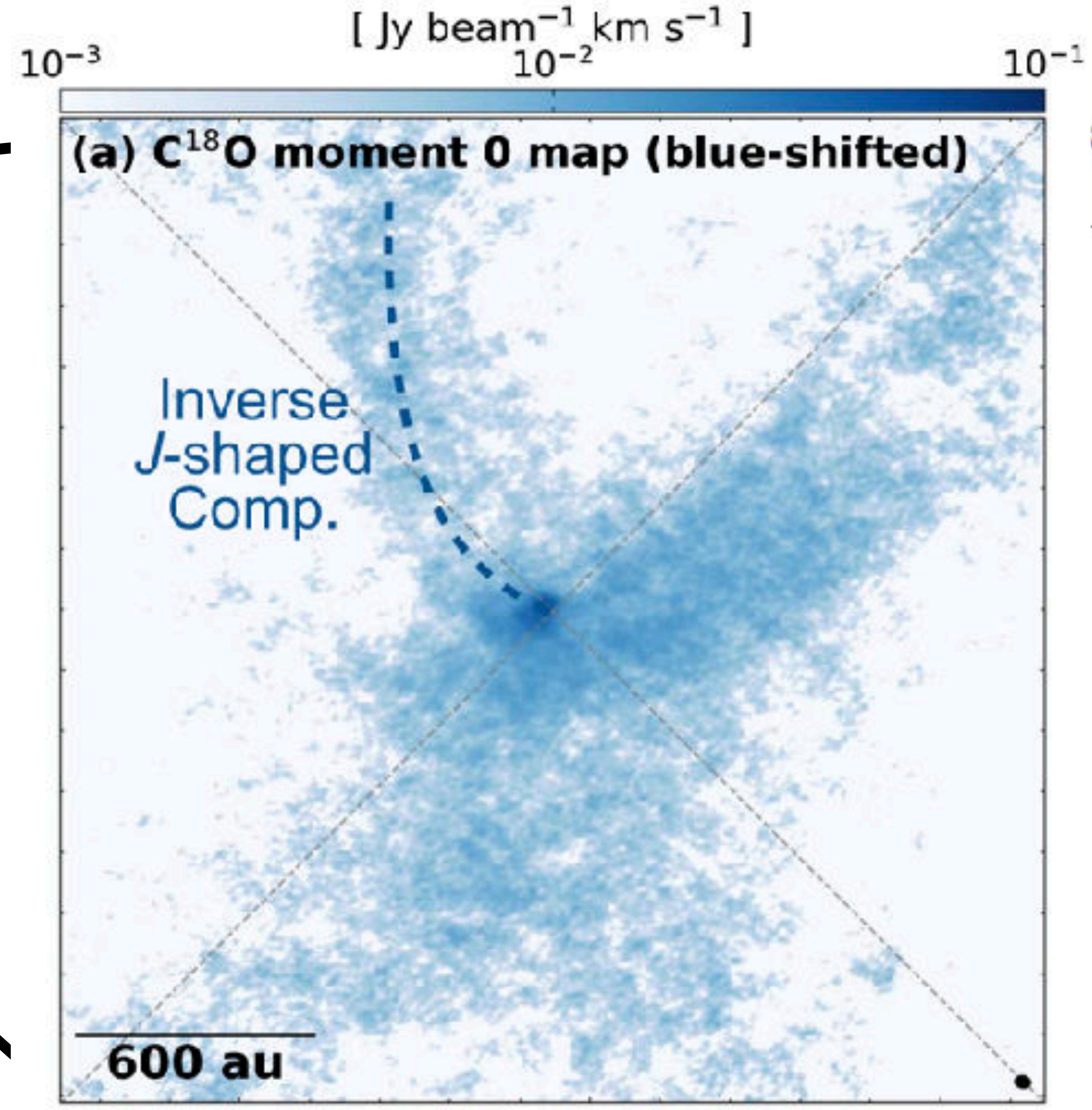


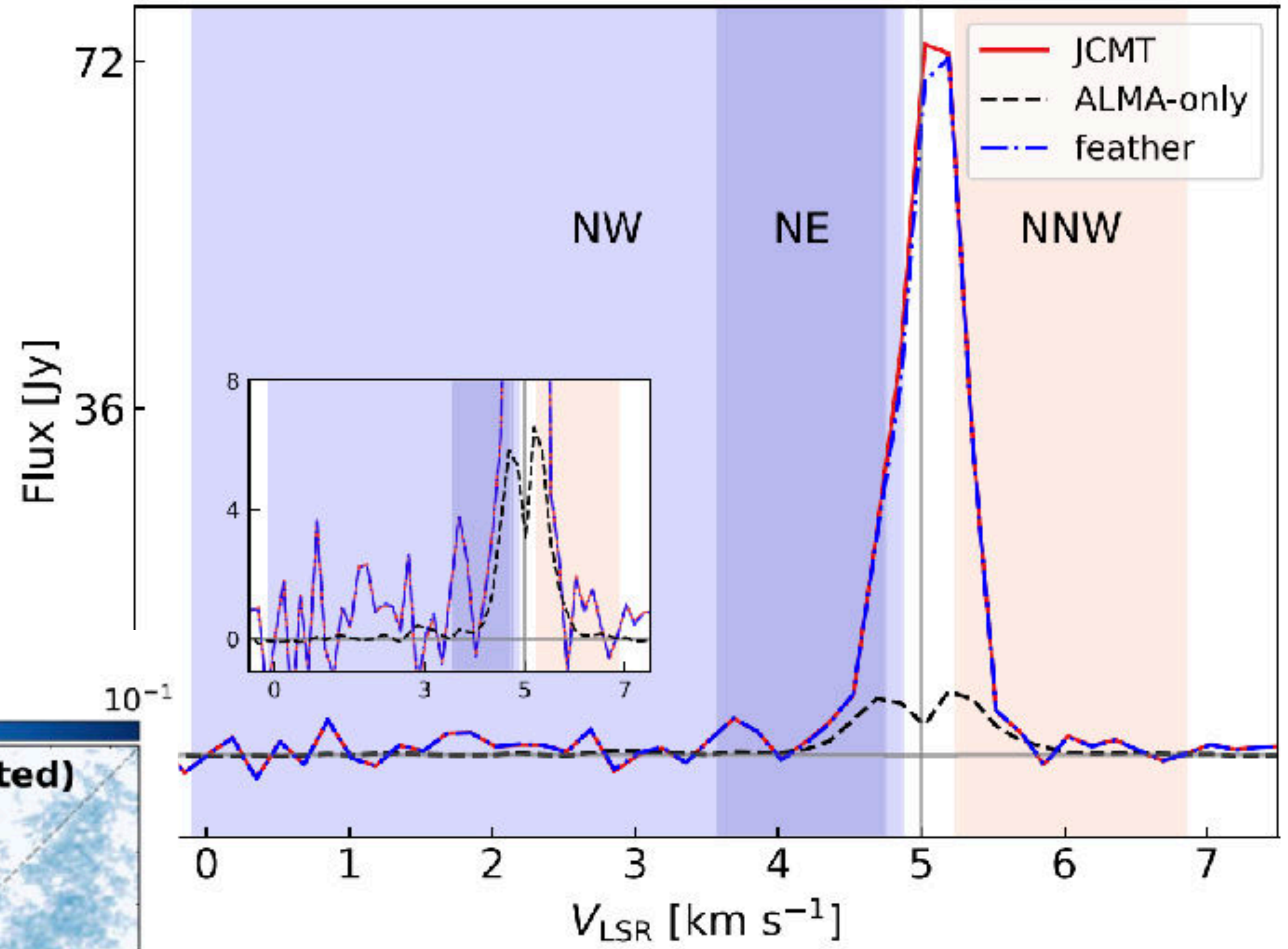
Hsieh et al. 2023; Cortés et al. 2025

Mass infall rate ~ x10^{-6} Msun/yr

Actual mass contribution by asymmetric infalling structures?



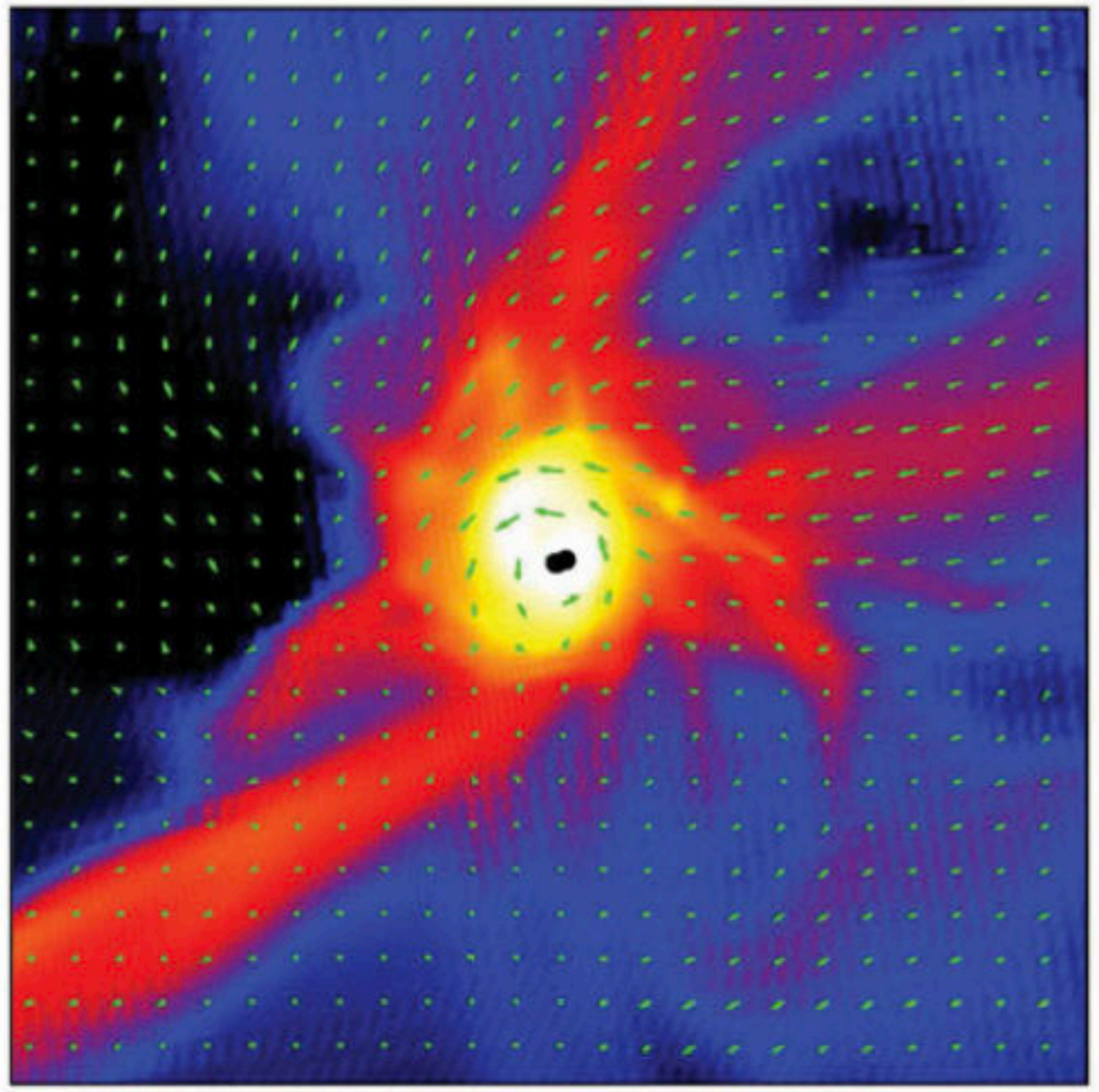




Kido et al. 2023, 2025

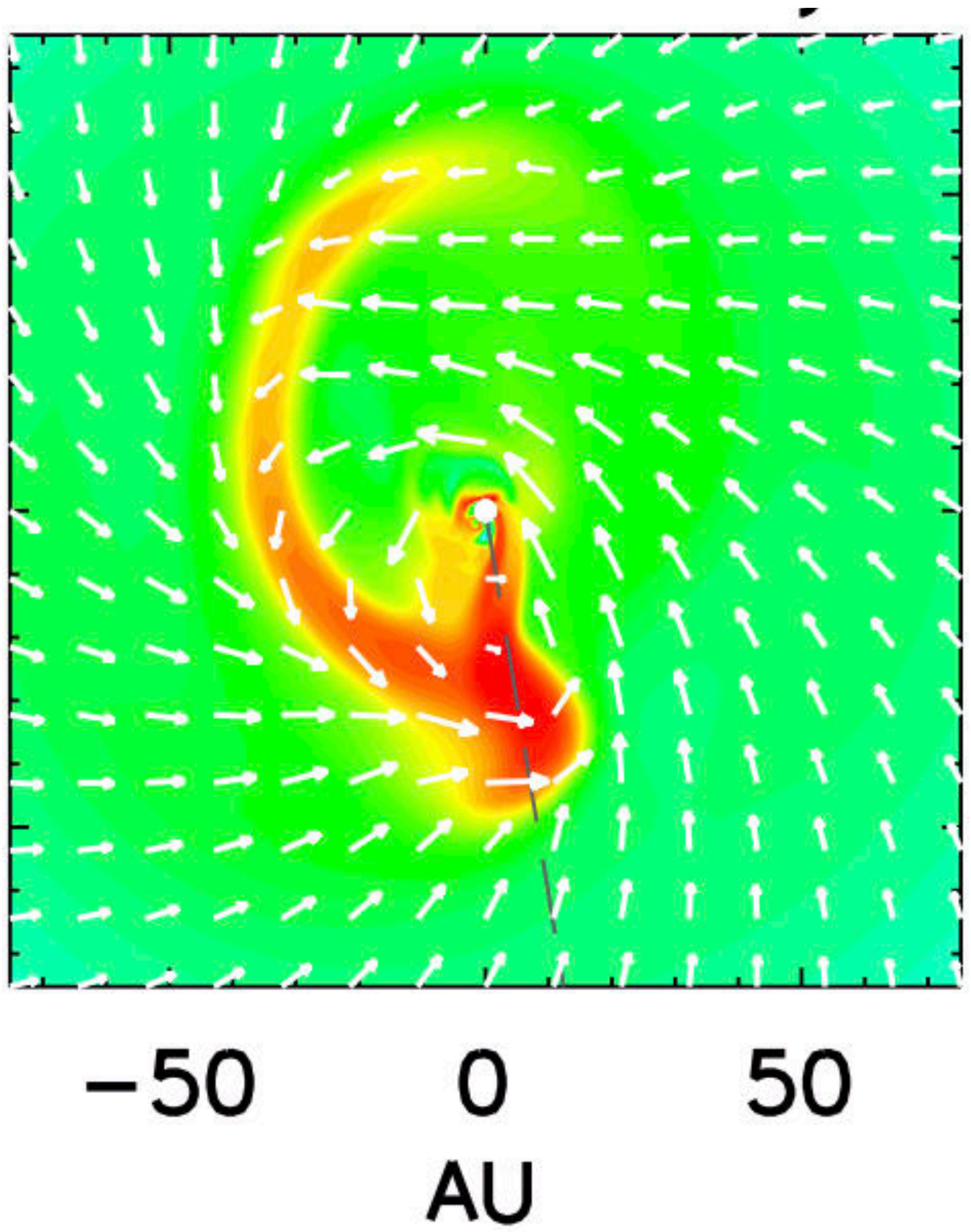
Formation of asymmetric infalling structures?

Turbulence

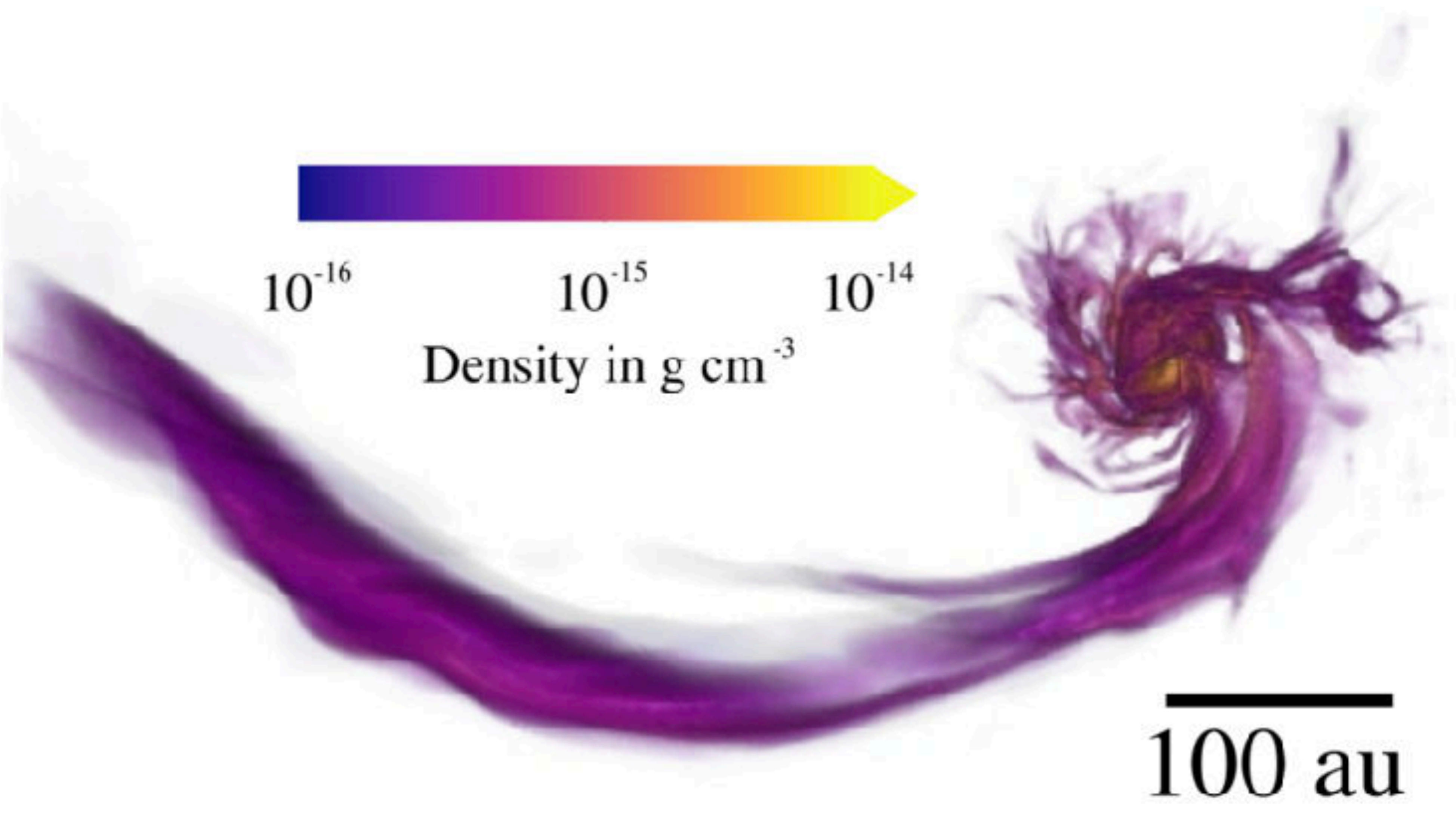


200 au

Instability

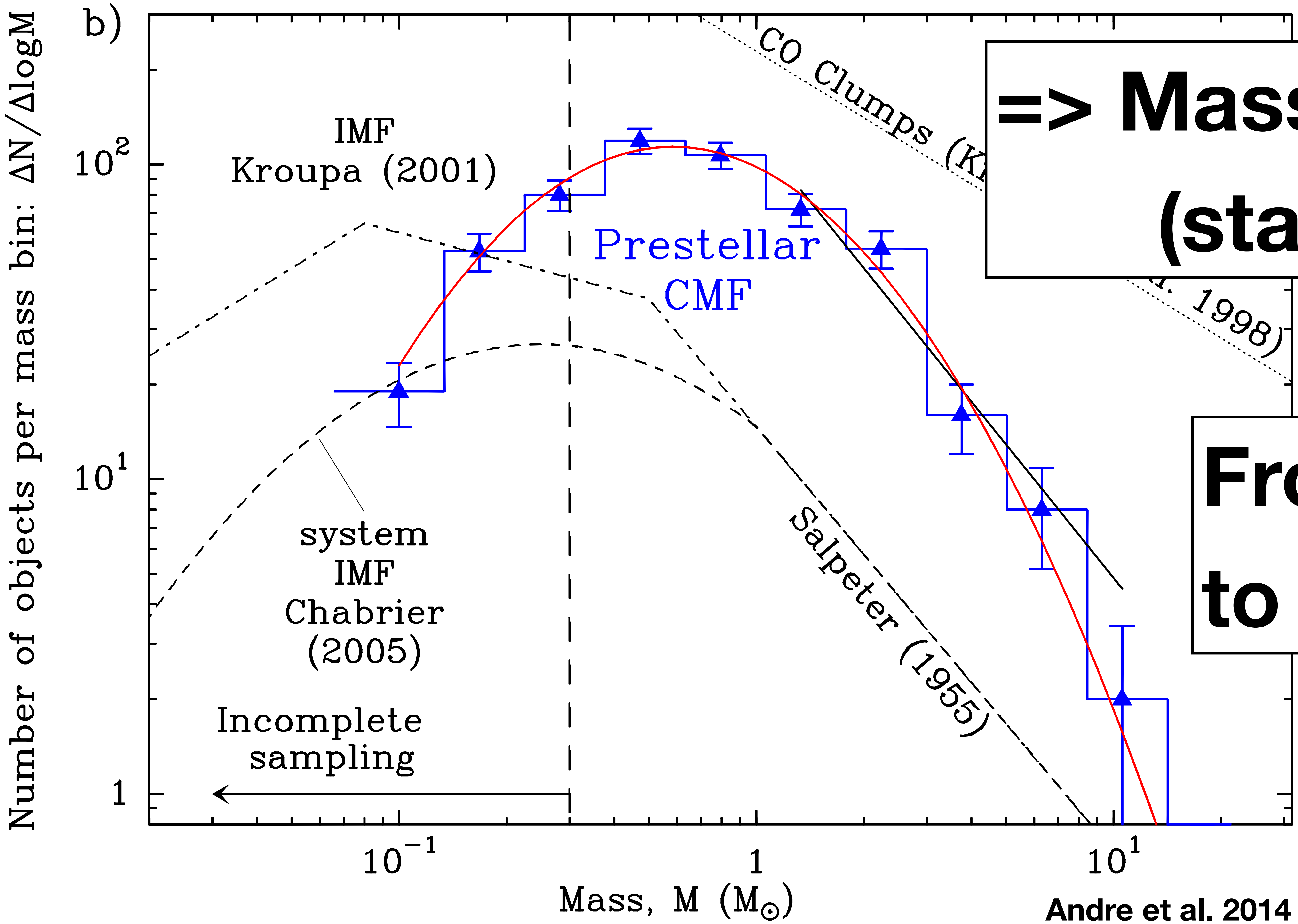


Feeding from large-scale environments



Seifried et al. 2013; Zhao et al. 2018; Kuffmeier et al. 2019; Pineda et al. 2023

Why do we care about
Infall / Outflow / Multiplicity / Fragmentation?



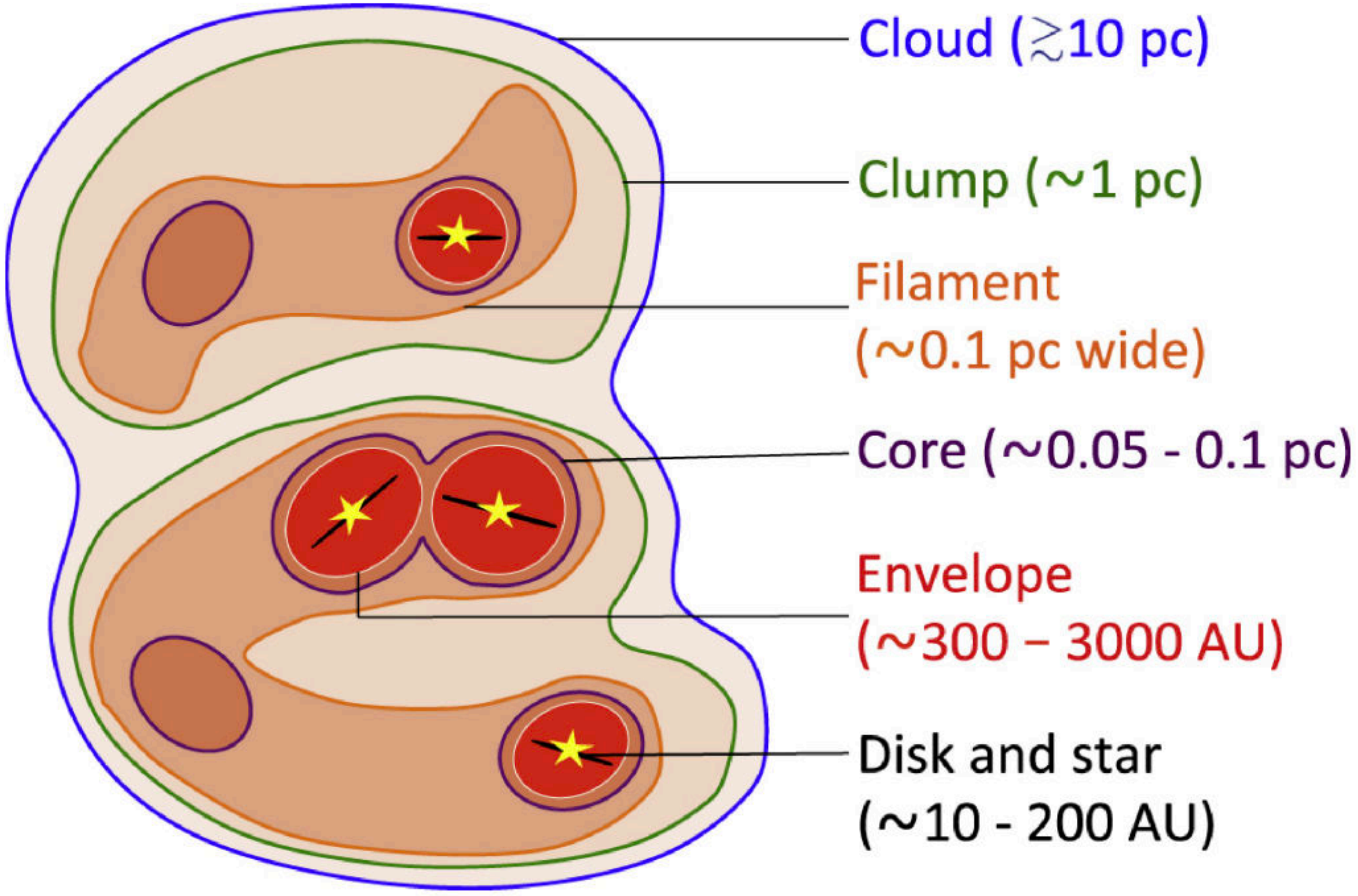
Andre et al. 2014

=> Mass assemble and distribution (star formation efficiency?)

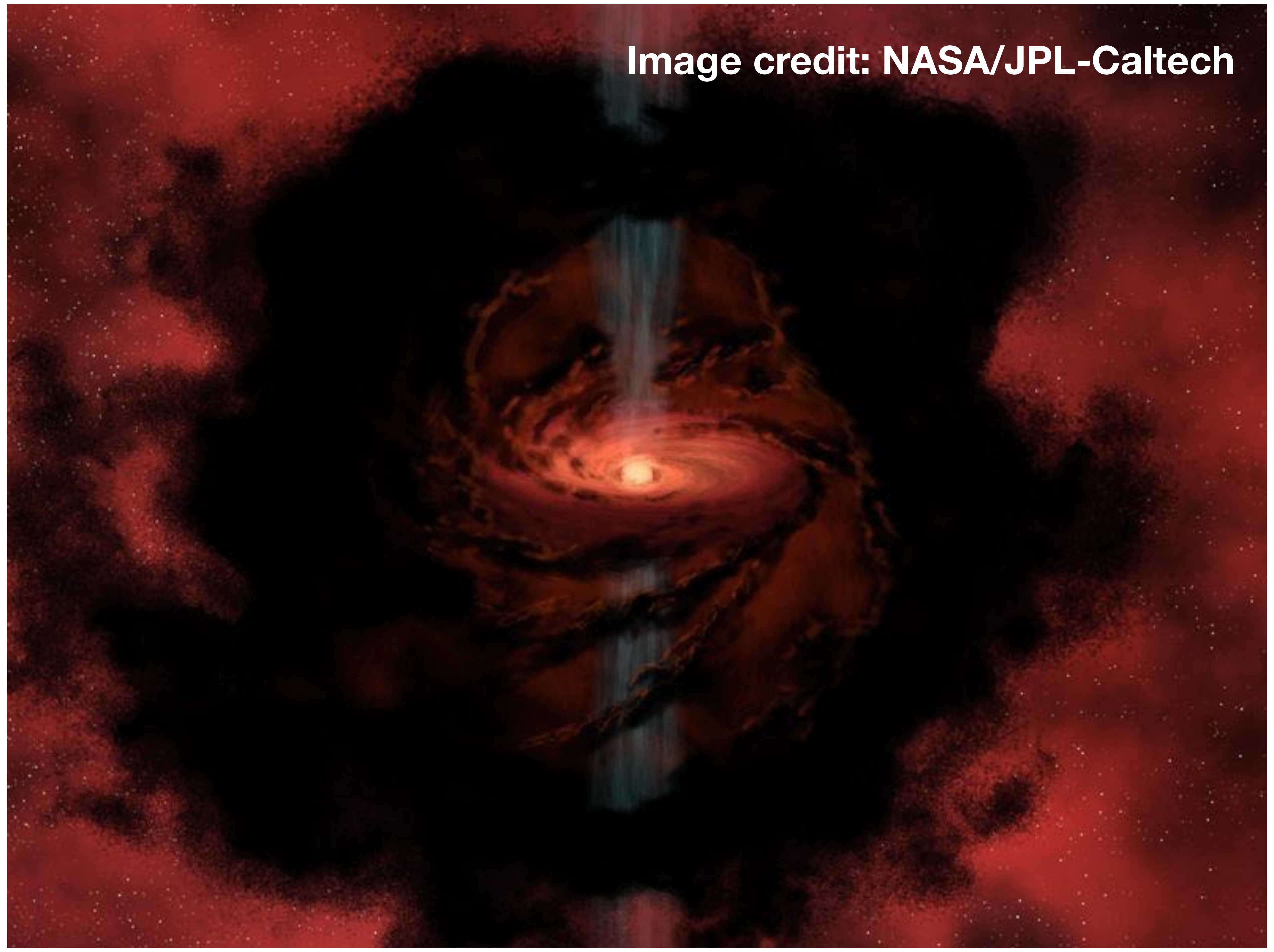
From initial condition (CMF) to end products (IMF)

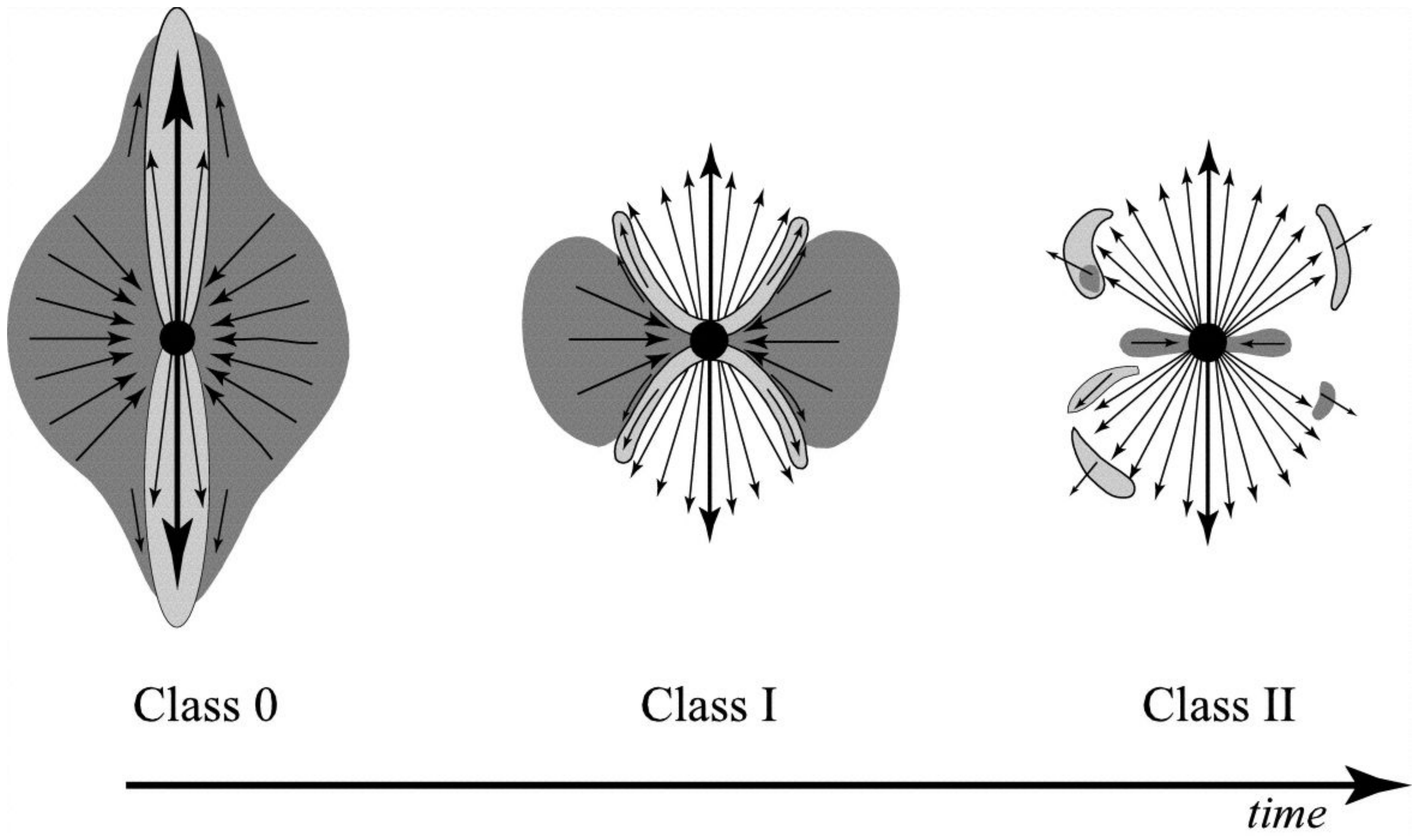

Image credit: NASA, ESA, CSA, STScI,
J. Lee (STScI), T. Williams (Oxford), PHANGS Team, E. Wheatley (STScI)
NGC 3351
NGC 0628
IC 5332
NGC 4321
NGC 4254
M
K
G
F
A
B
O
Image from Wikimedia Commons (LucasVB.)

Summary



Rosen et al. 2020





Arce & Sargent 2006

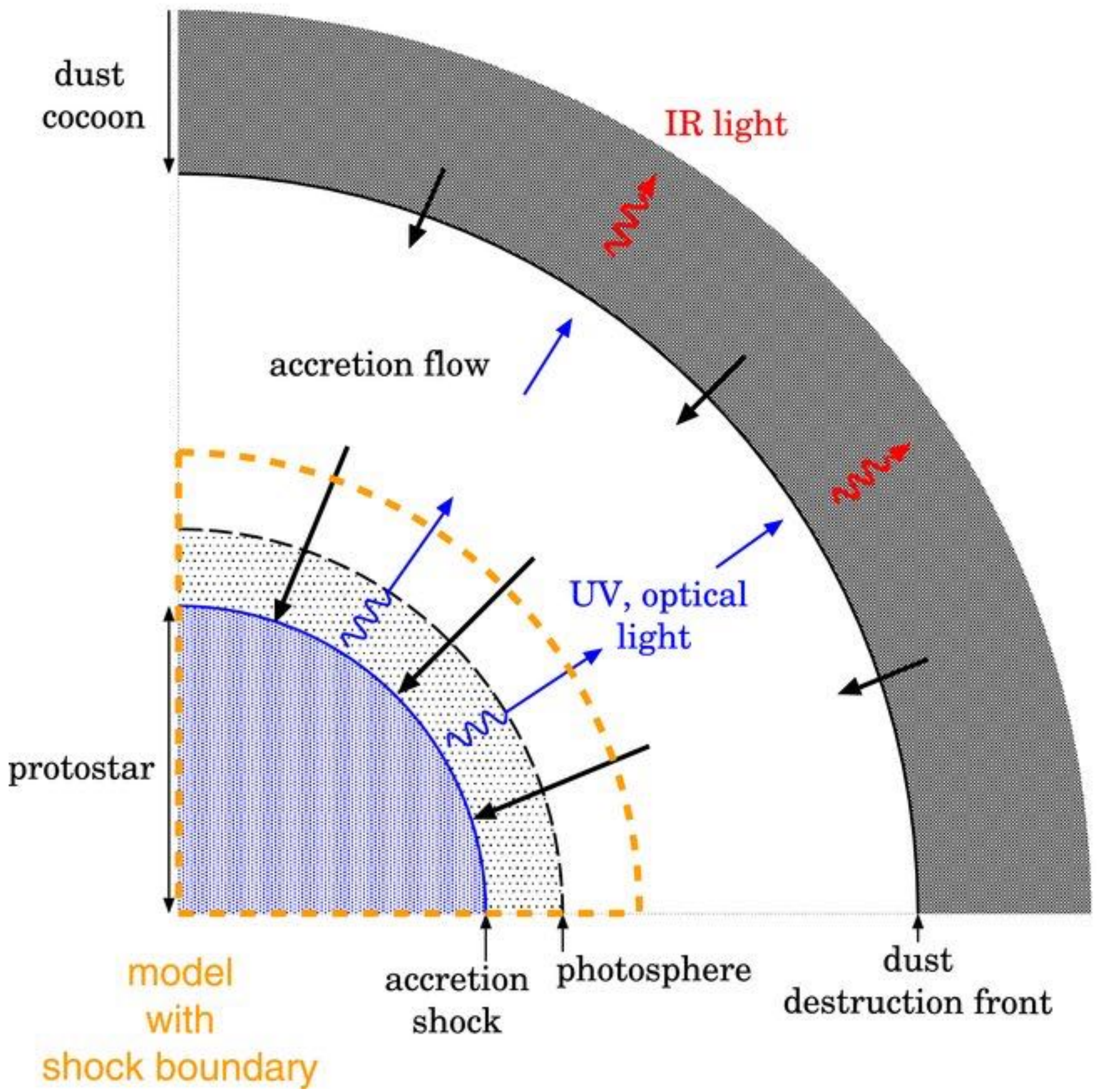
Massive stars form in clusters

- Need more material
- Shorter time scales
- Higher mass accretion rate
- Strong radiation & HII regions

Image credit: NASA, ESA and the Hubble Heritage Team (STScI / AURA)

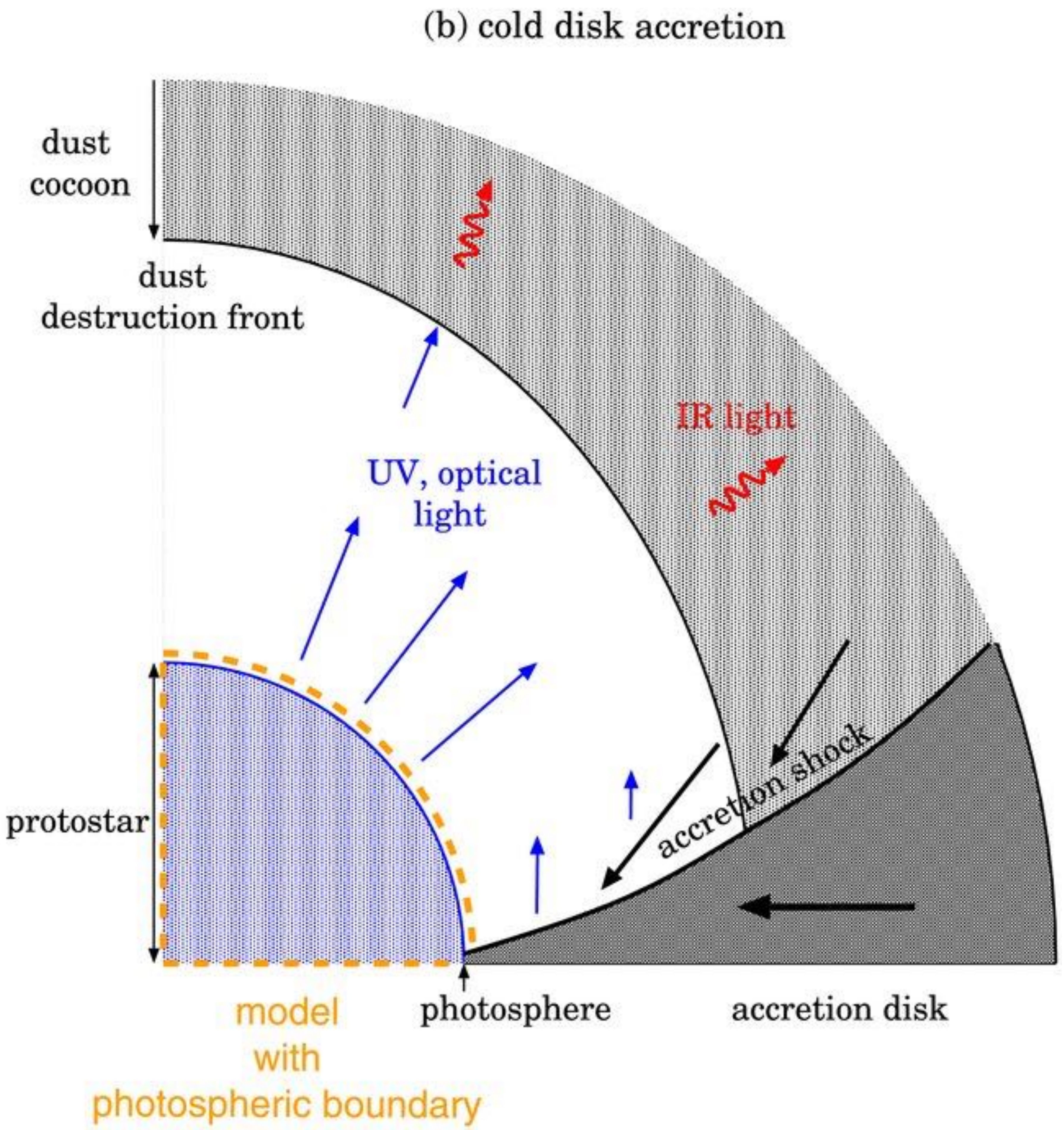
Strong radiation can halt infalling gas

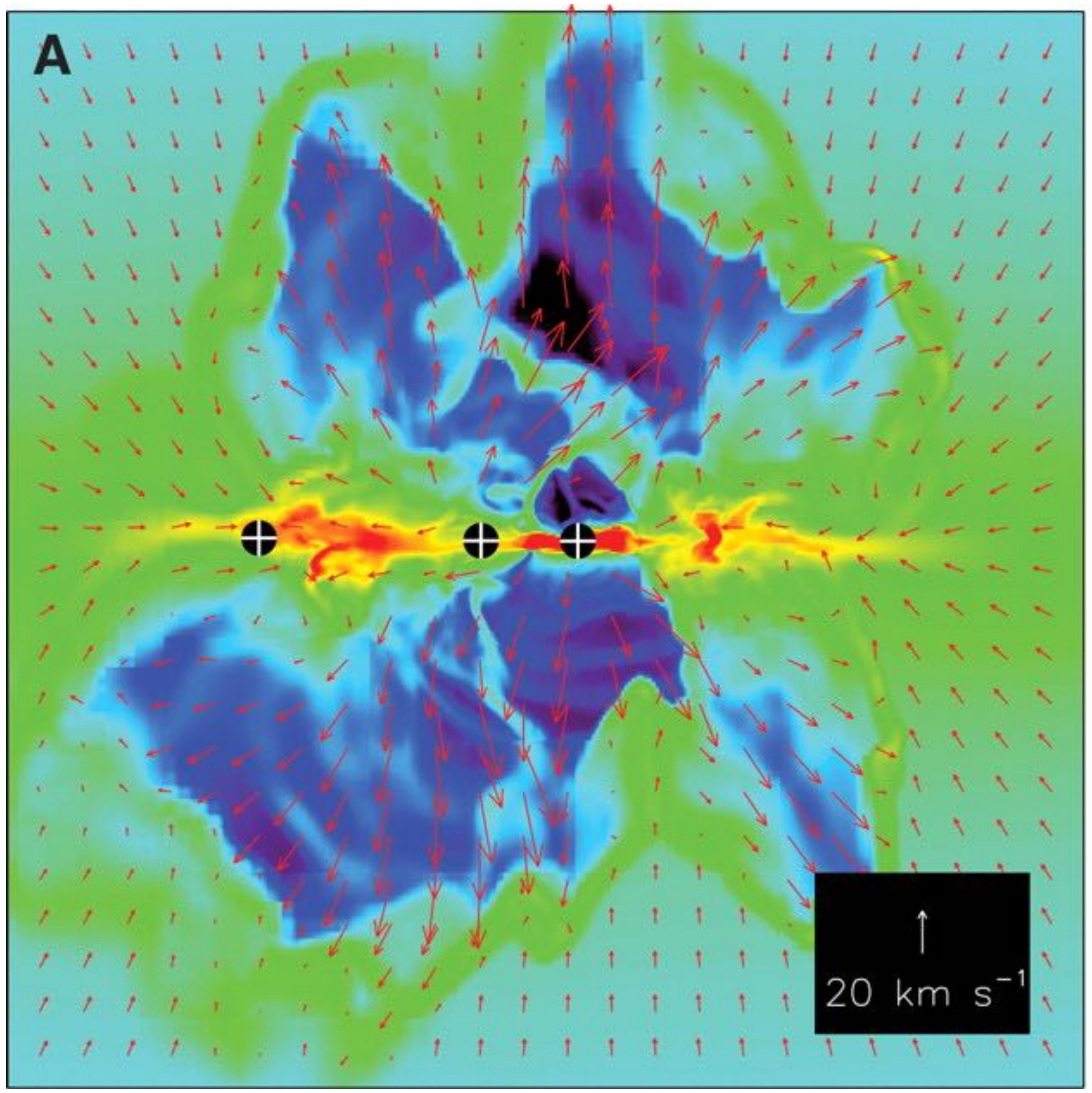
(a) spherical accretion



Hosokawa et al. 2010

Accretion along disks or filamentary structures

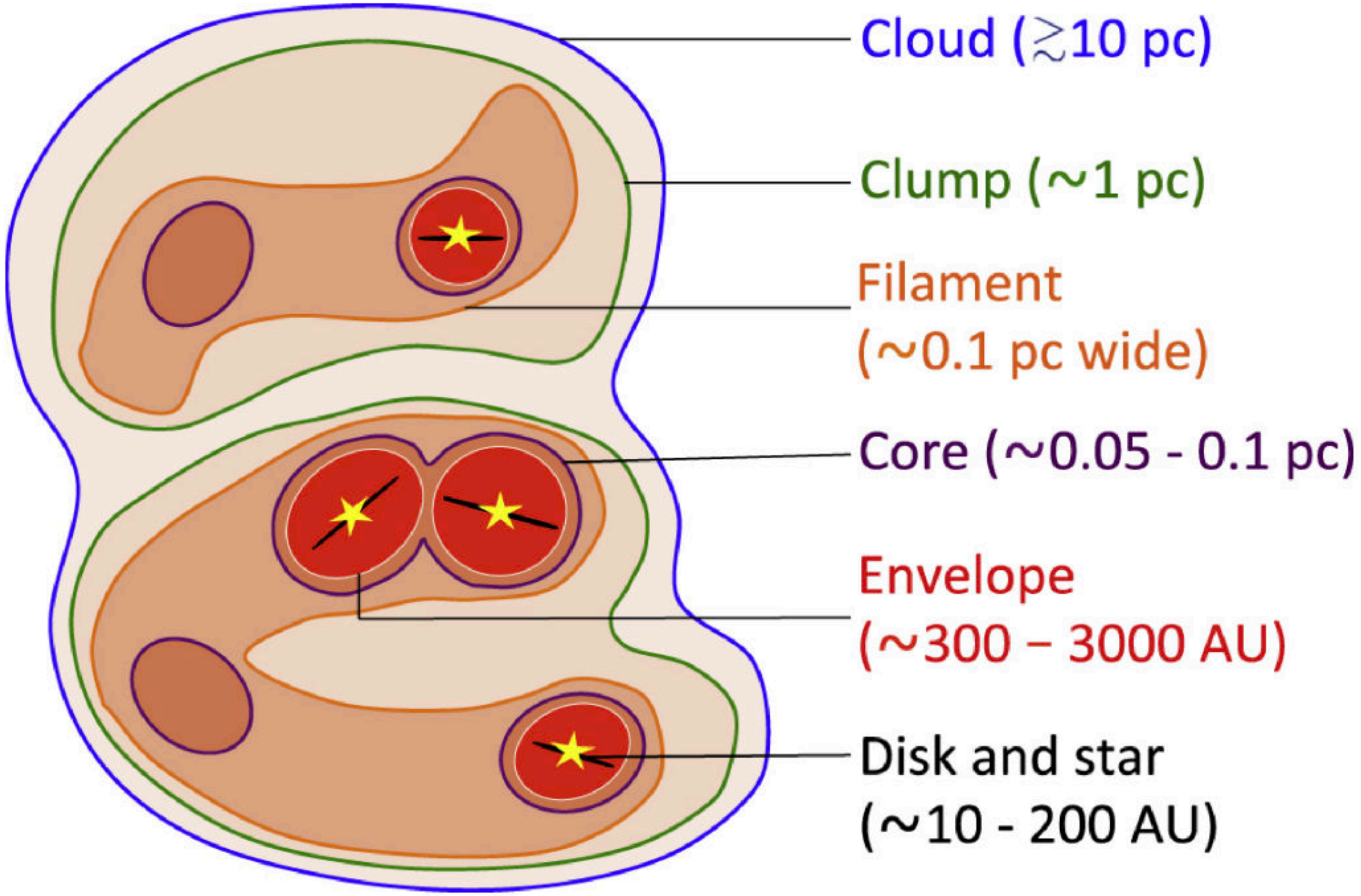




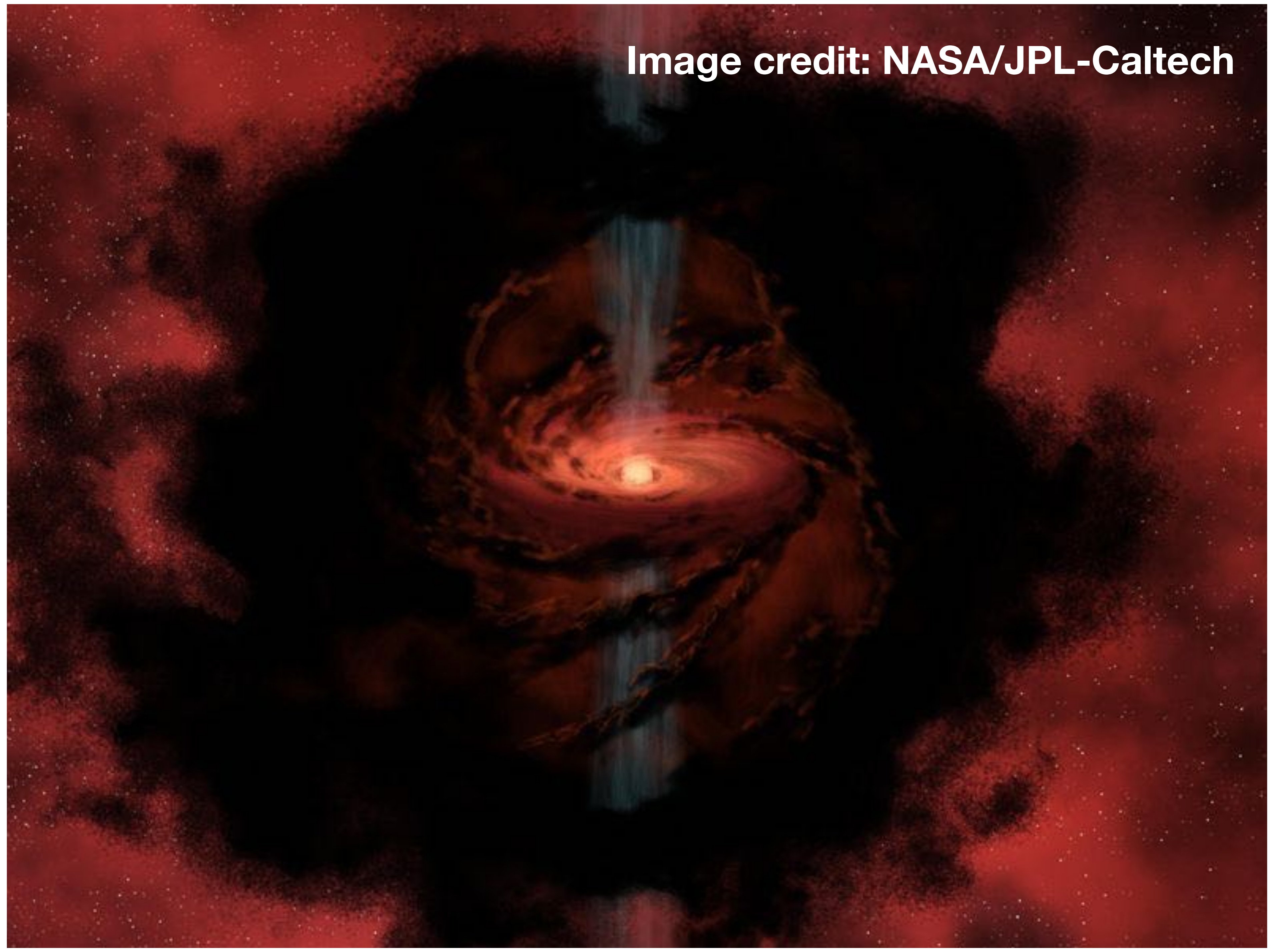
Hosokawa et al. 2010

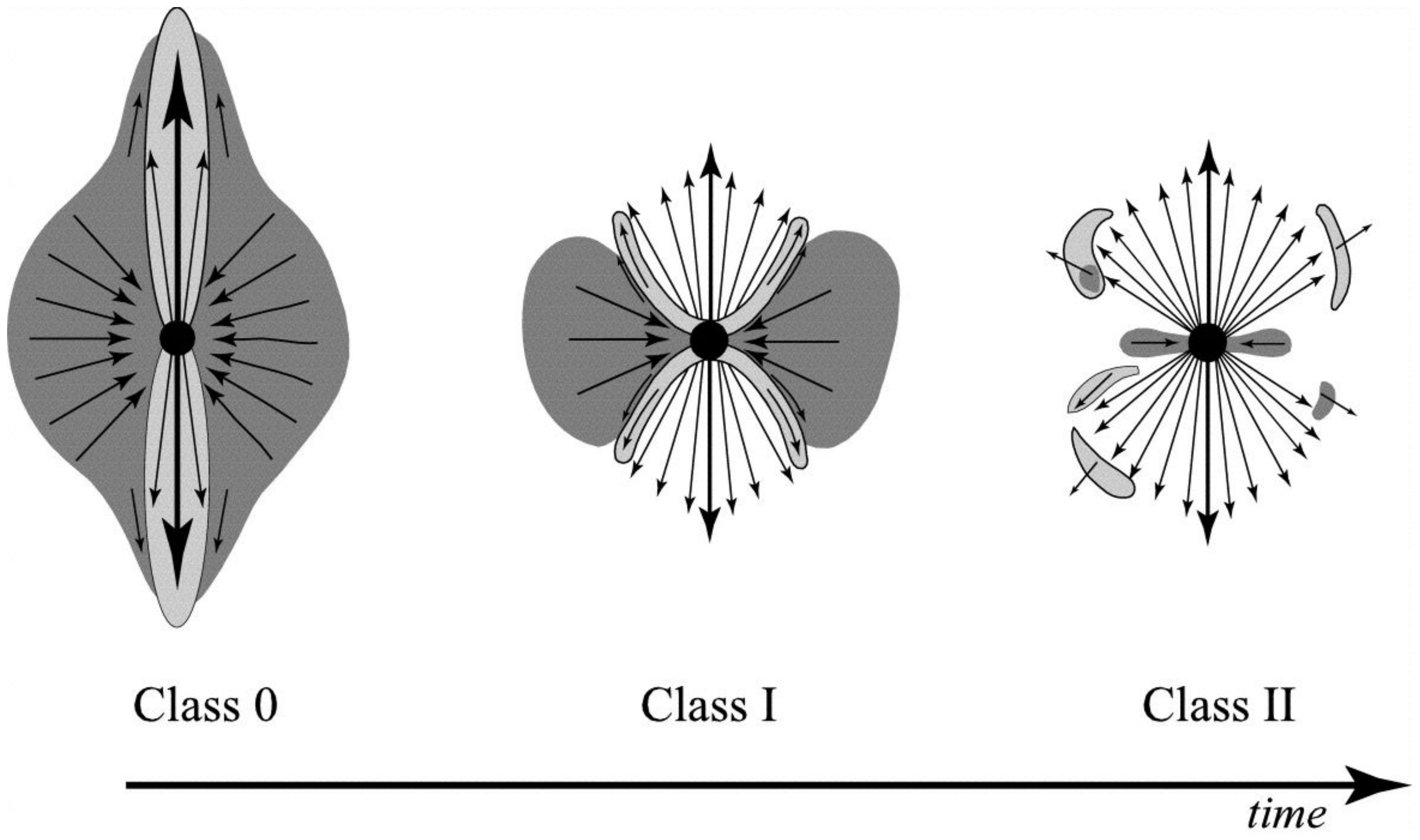
Krumholz et al. 2009

Summary



Rosen et al. 2020





Arce & Sargent 2006