



清华大学天文系
Department of Astronomy, Tsinghua University

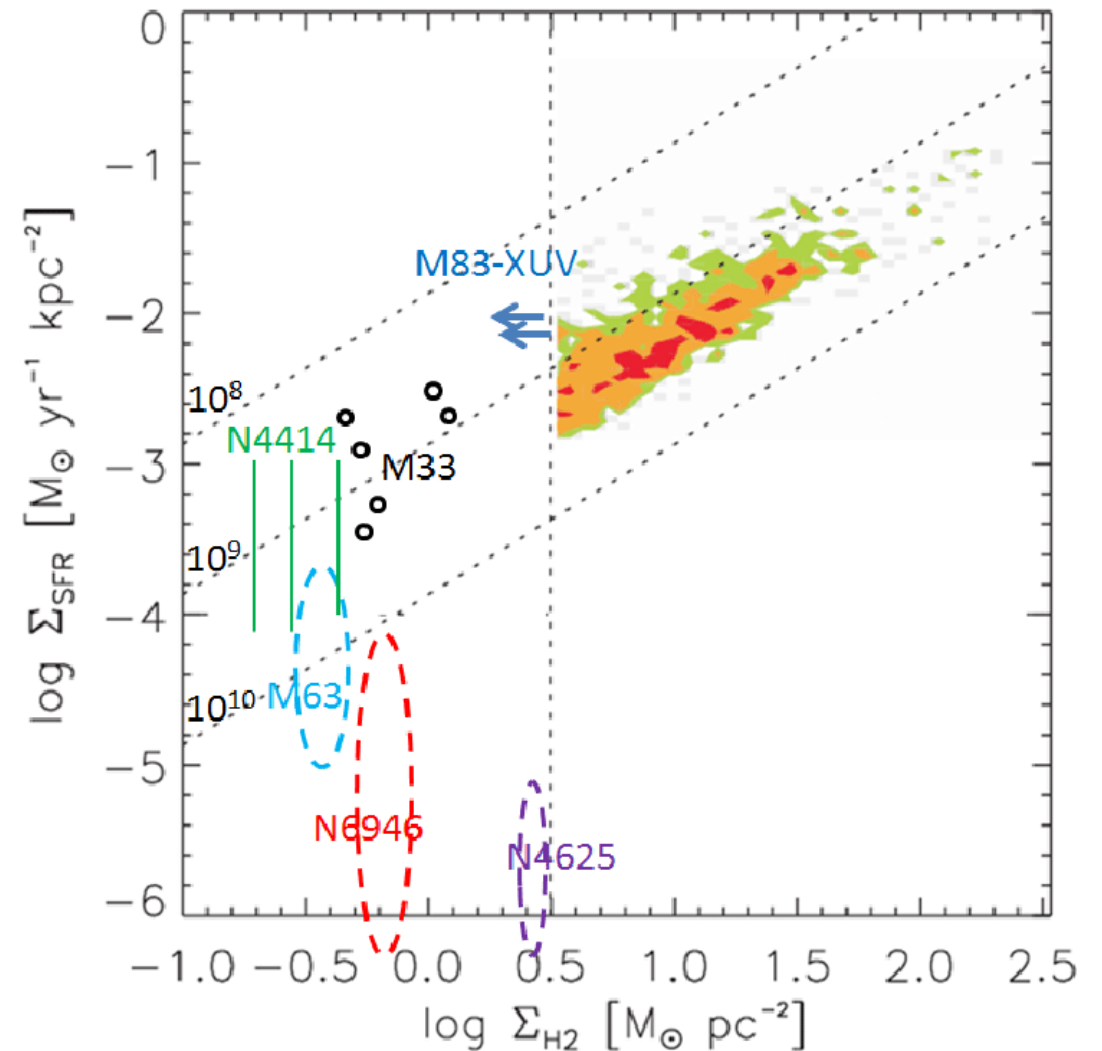
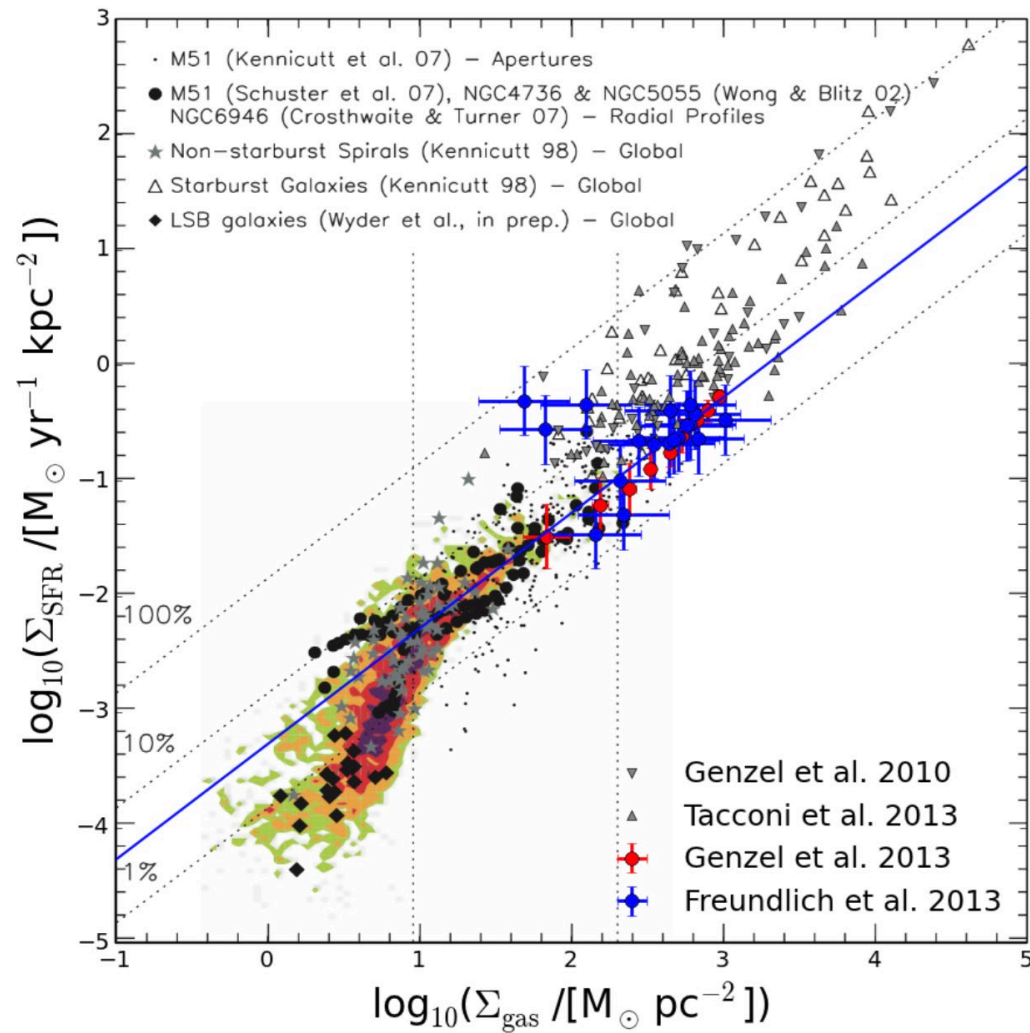
10. Star Formation

Instructor: Hui Li TA: Chengzhe Li

Department of Astronomy

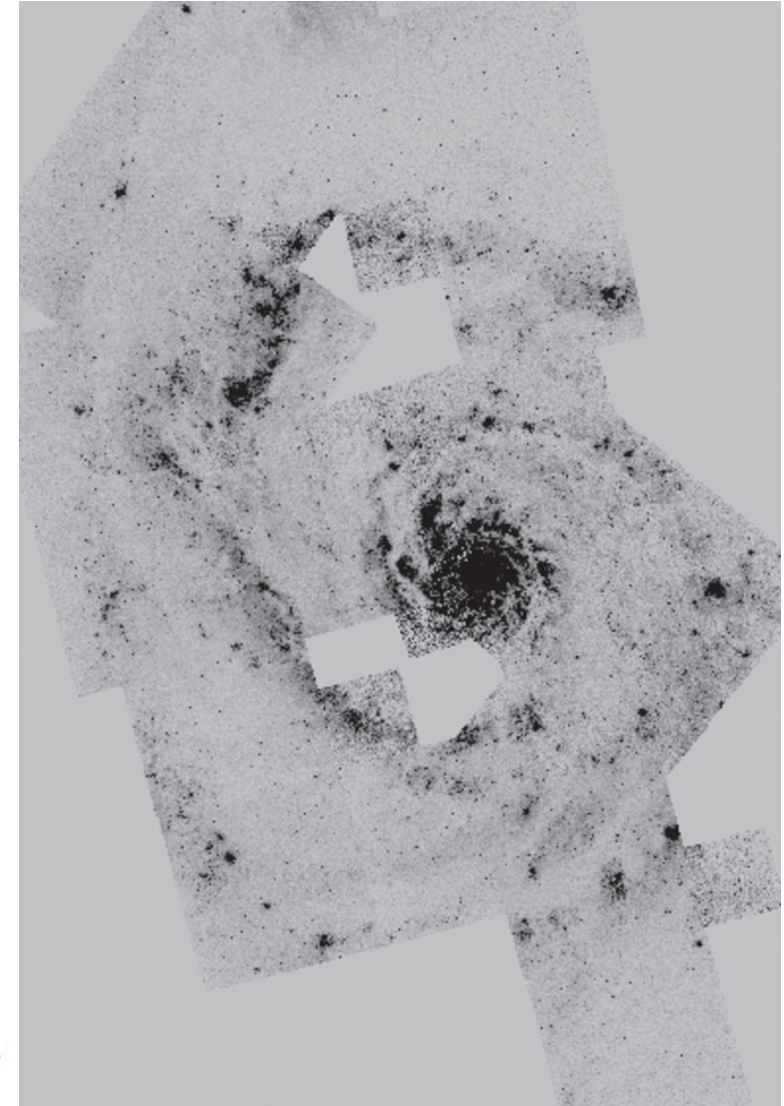
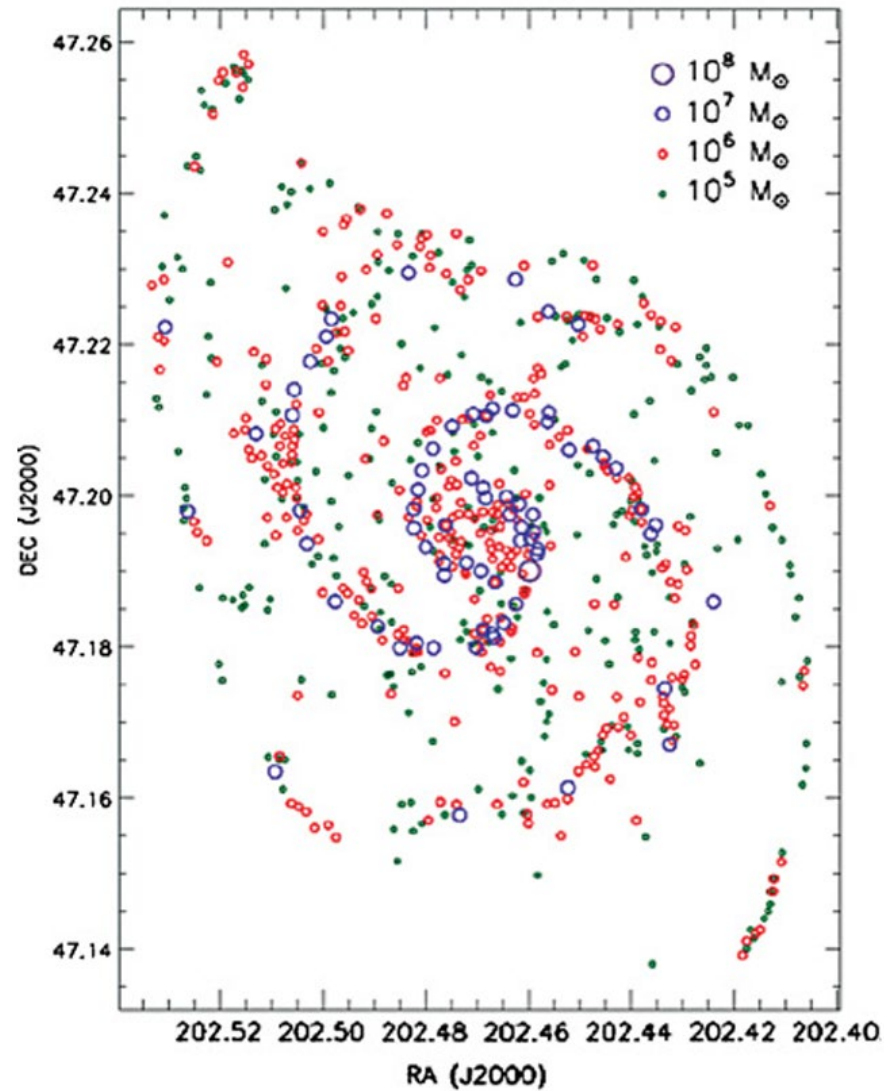
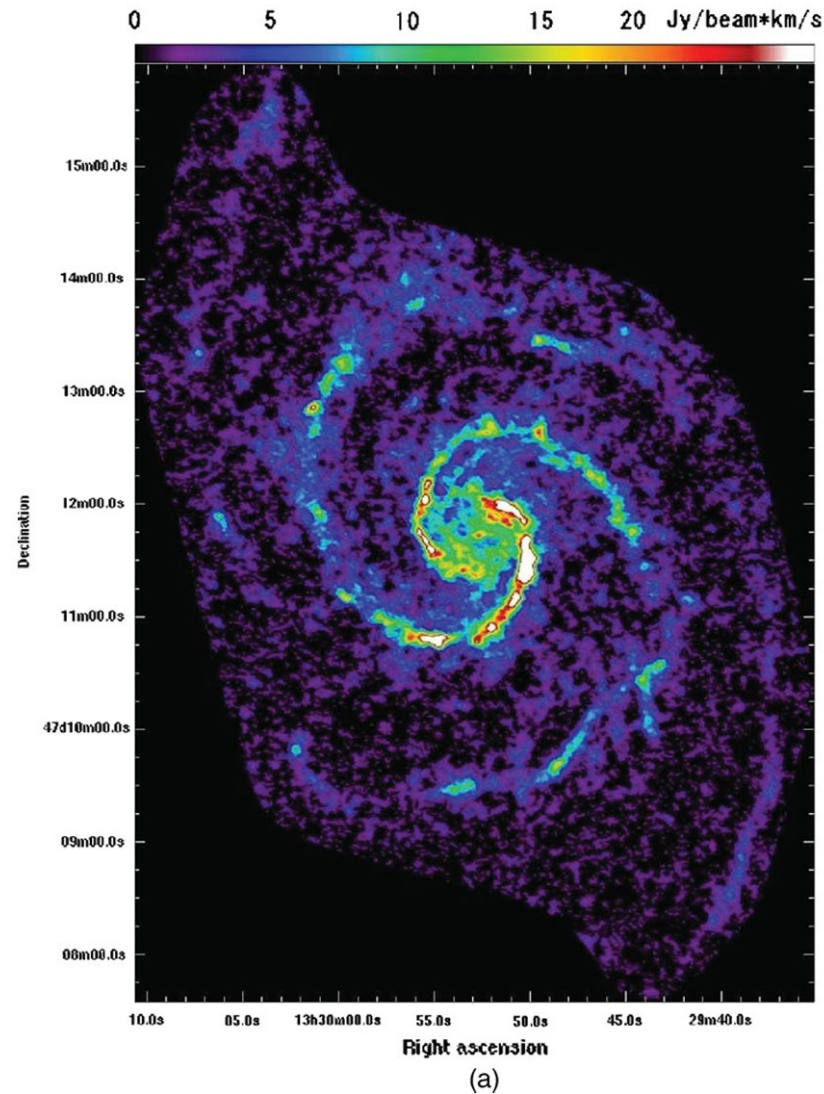
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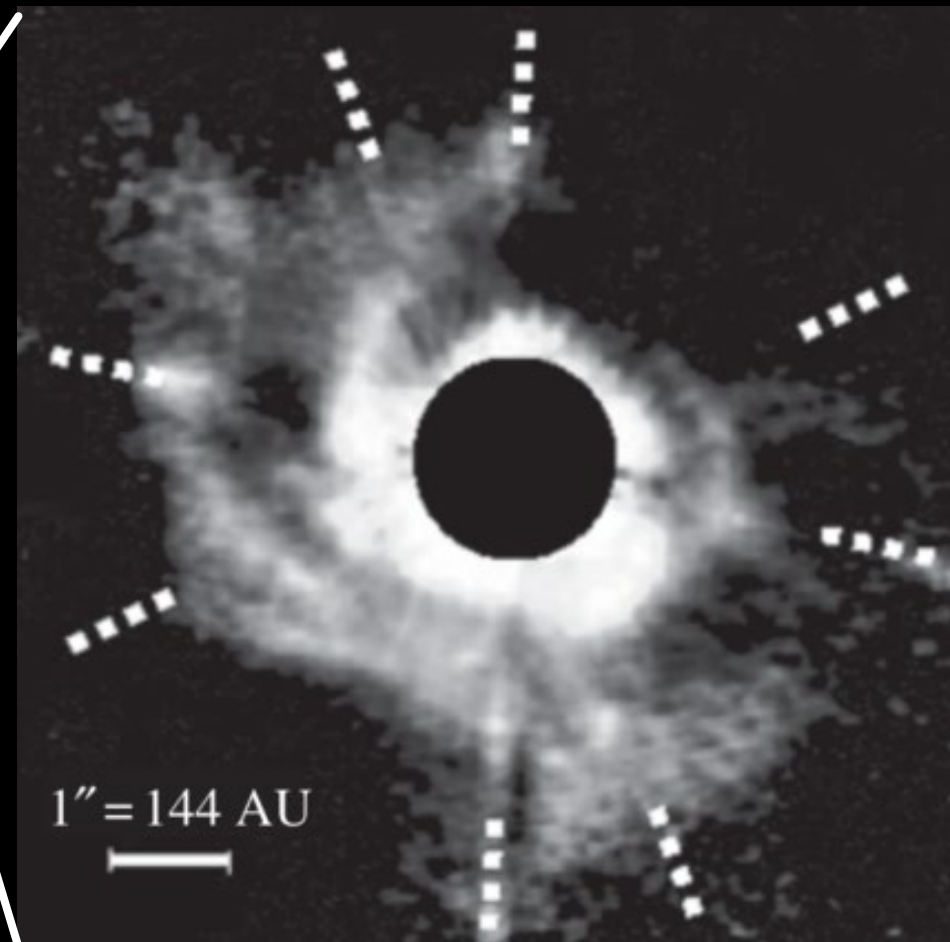
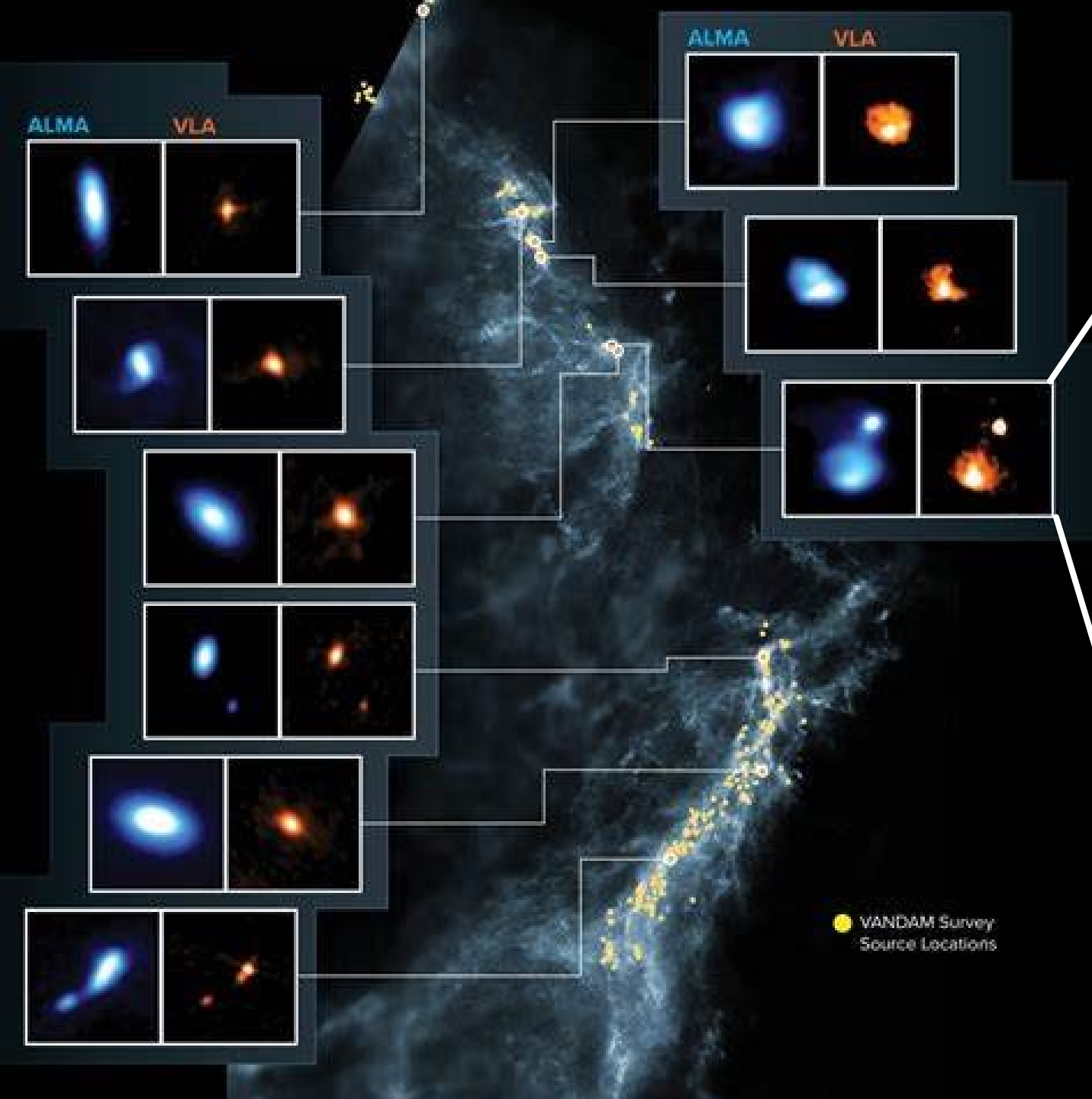
Kennicutt-Schmidt Relation





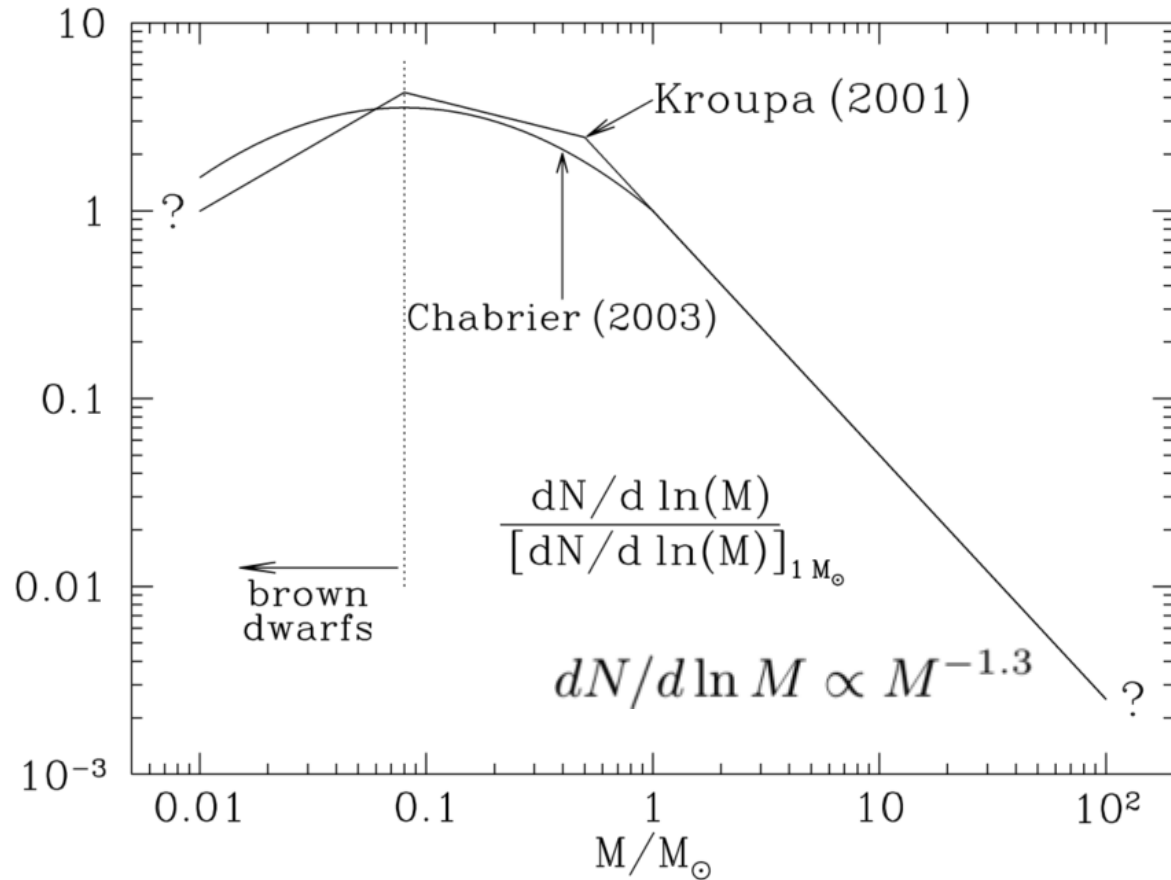
Spatially-resolved molecular gas distribution in M51





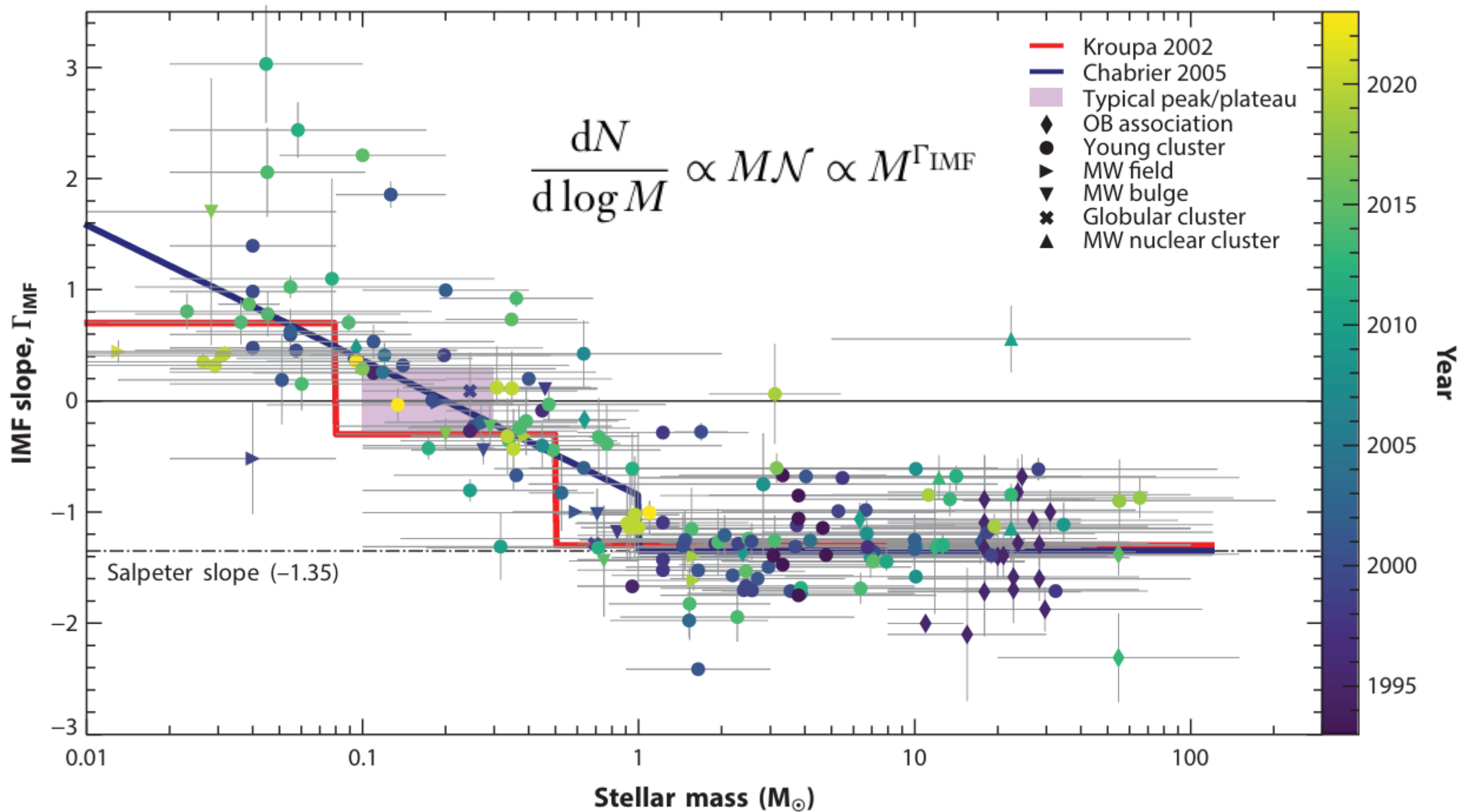
Adaptive optics coronagraphic image
of Herbig Ae star AB Aur with Subaru

Initial mass function: a unique laboratory to test theories



Mass range (M_{\odot})	mass/total mass	$\langle M \rangle / M_{\odot}$
0.01–0.08	0.0482	0.0379
0.08–1	0.3950	0.2830
1–8	0.3452	2.156
8–16	0.0749	10.96
16–100	0.1369	32.31
8–100	0.2118	19.14
0.01–100	1.0000	0.3521

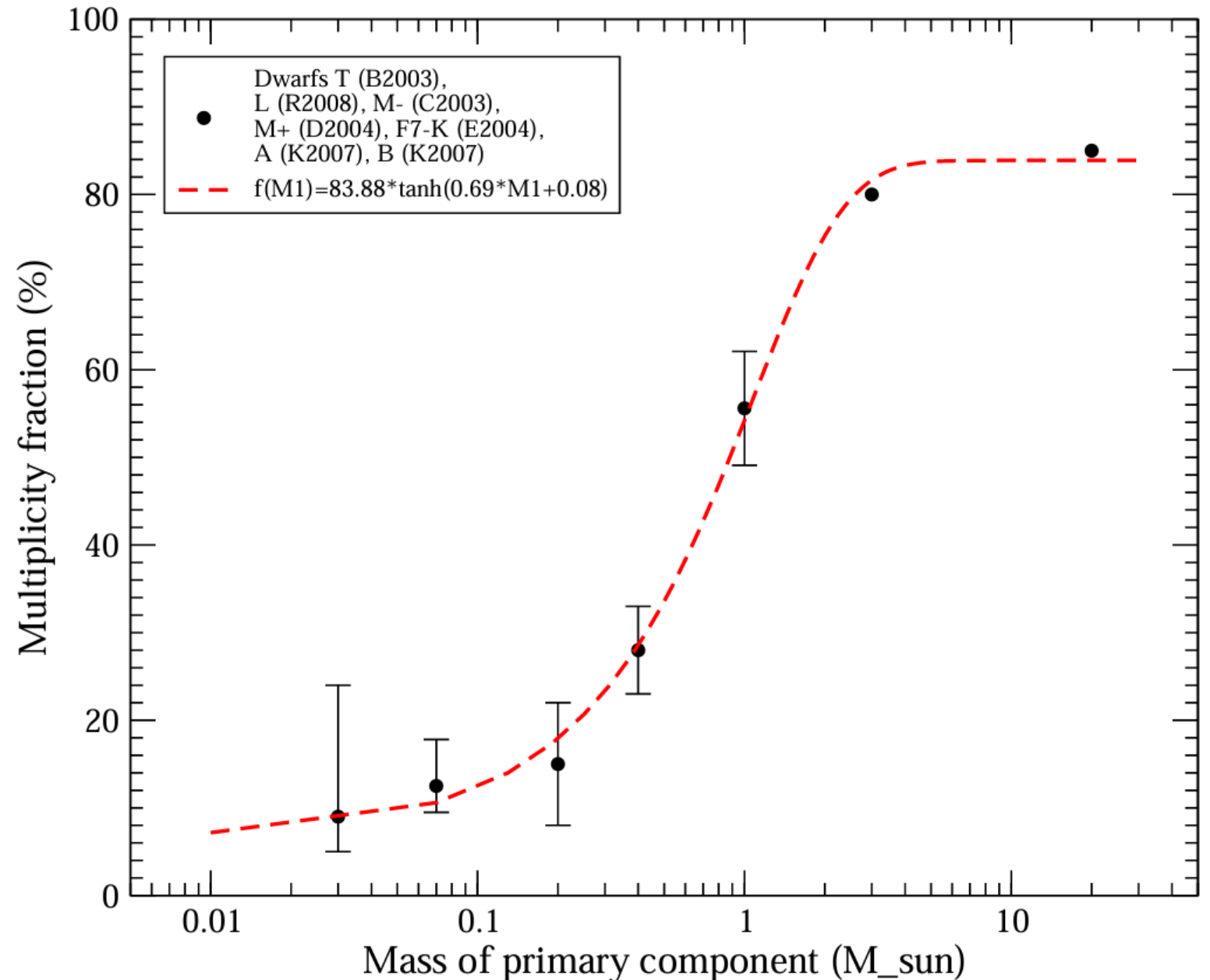
^a For lower and upper cutoffs of 0.01 and $100 M_{\odot}$.



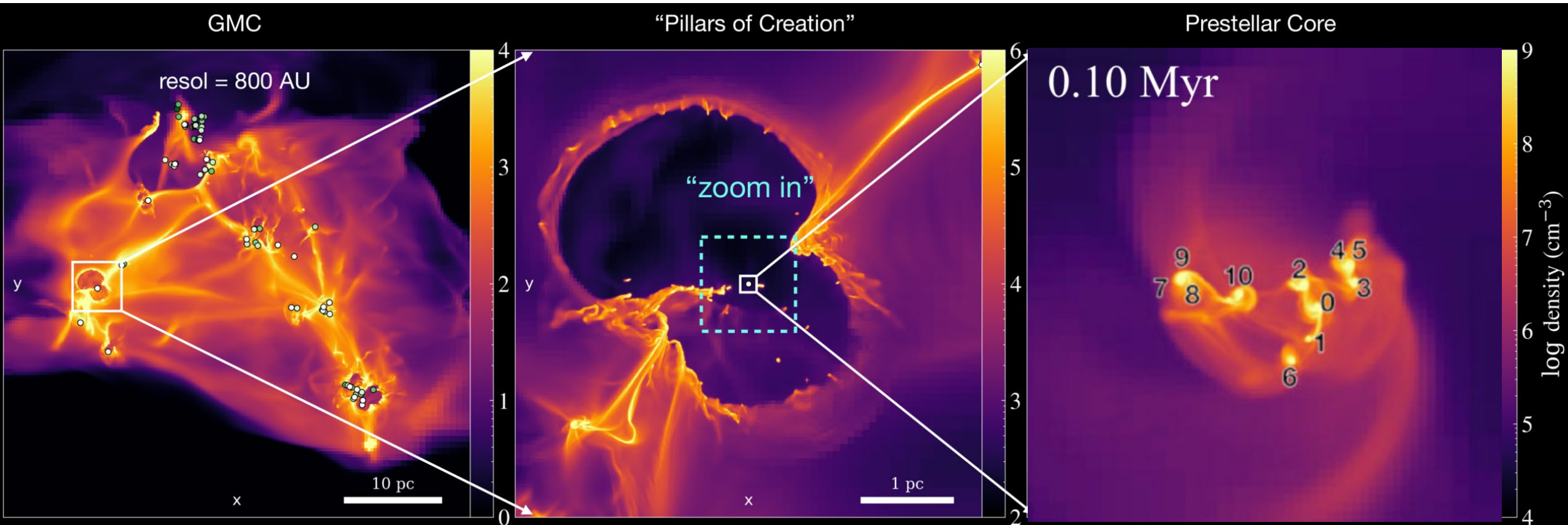
Binary fraction vs primary mass

Binaries!

- Binary (multiplicity) fraction is a strong function of the primary mass.
- Almost all massive stars are formed in multiple systems.
- Primordial vs. dynamical-captured binaries?

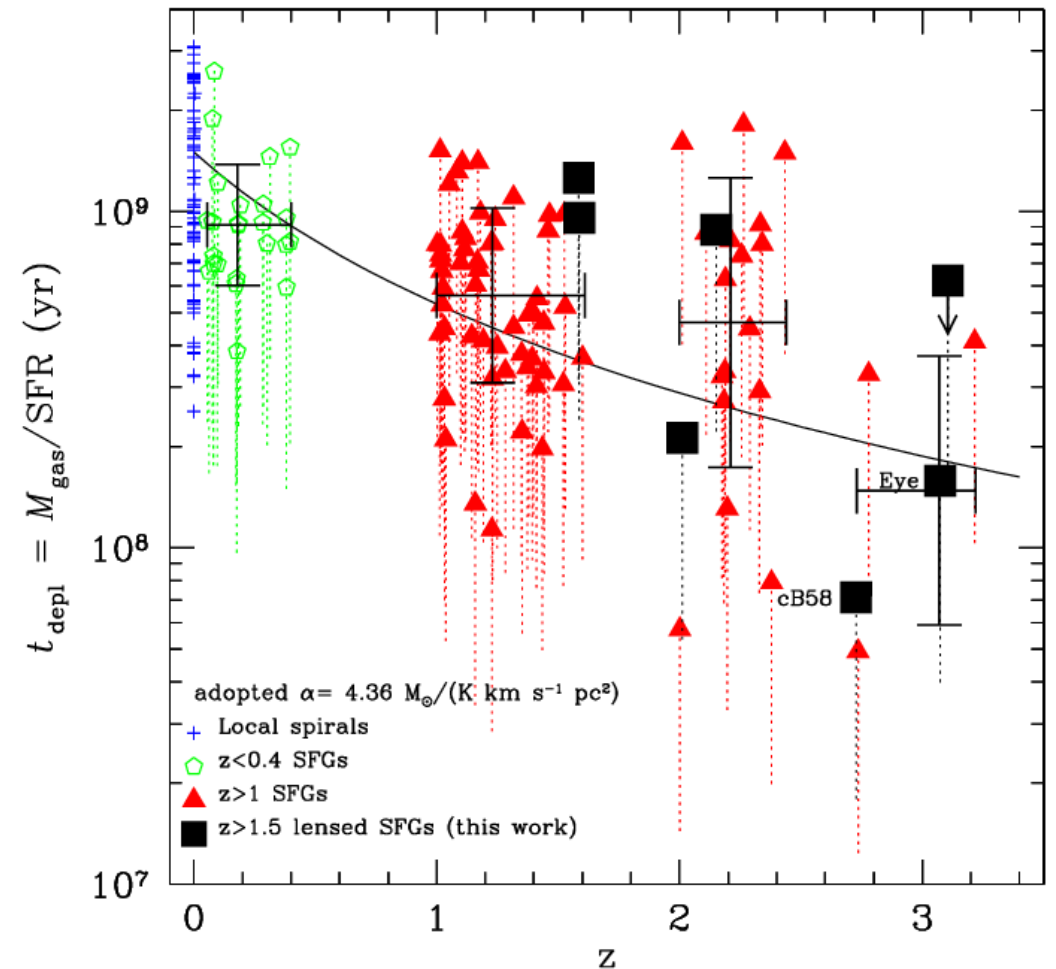


Understanding the whole sequence of star formation processes requires multi-scale, multi-physics numerical simulations



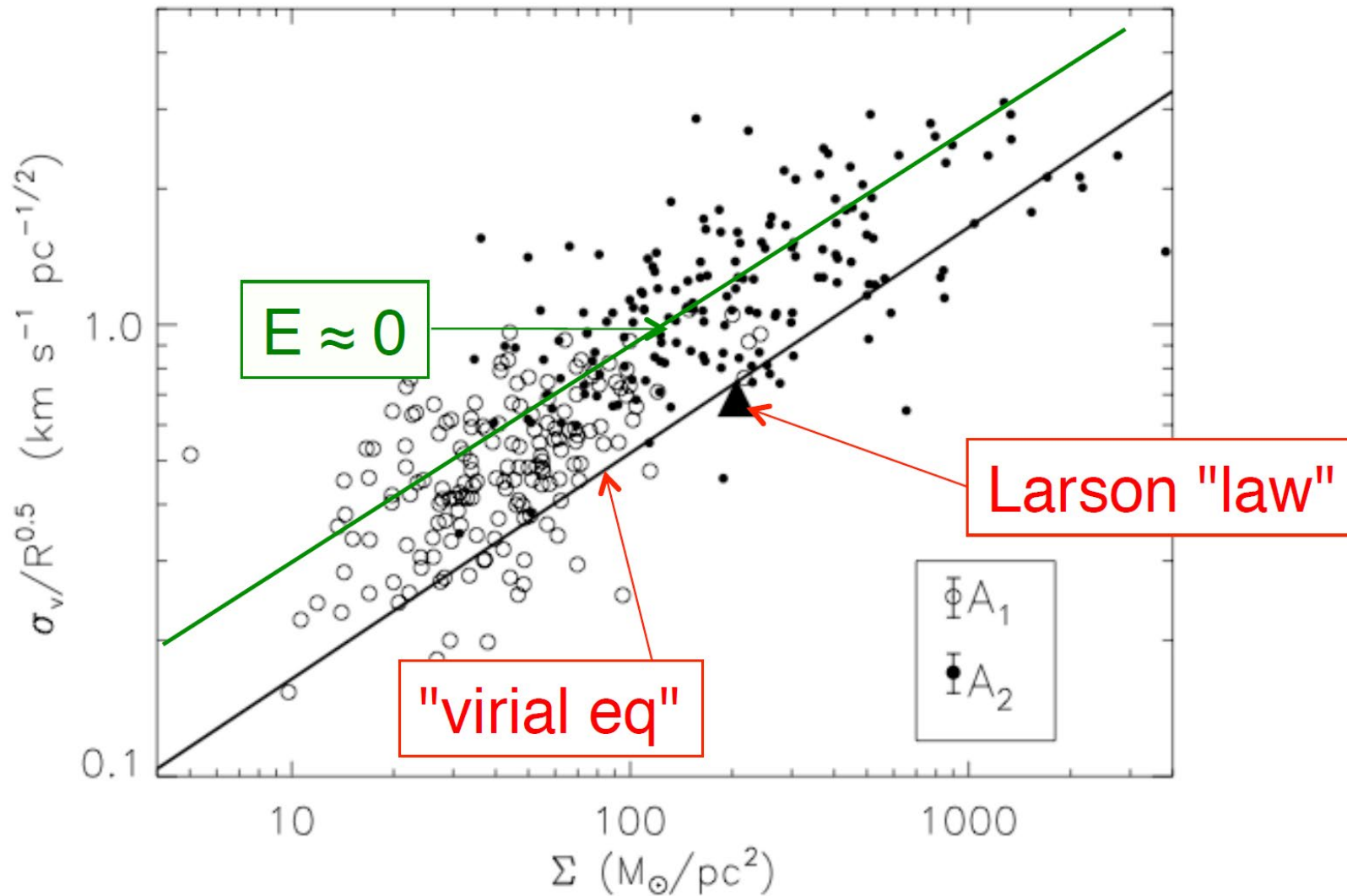
Comparing relevant timescales

- Gas depletion timescale $M_{\text{gas}}/\text{SFR}$ is around 5-10 Gyr. For example, MW has gas mass $\sim 10^{10} M_{\odot}$ and $\text{SFR} \sim 1-2 M_{\odot}/\text{yr}$.
- Dynamical time (i.e. orbital time) of star-forming galaxies is ~ 200 Myr. It takes 20-50 orbits to consume all gas.
- Turbulent ($\sigma \sim 10 \text{ km/s}$) crossing time for disk scale height (100-300 pc) is $\sim 10-30$ Myr.
- Free-fall time of dense molecular gas is ~ 10 Myr, much longer than the global crossing time or gas depletion timescale.
- Why is star formation so inefficient?

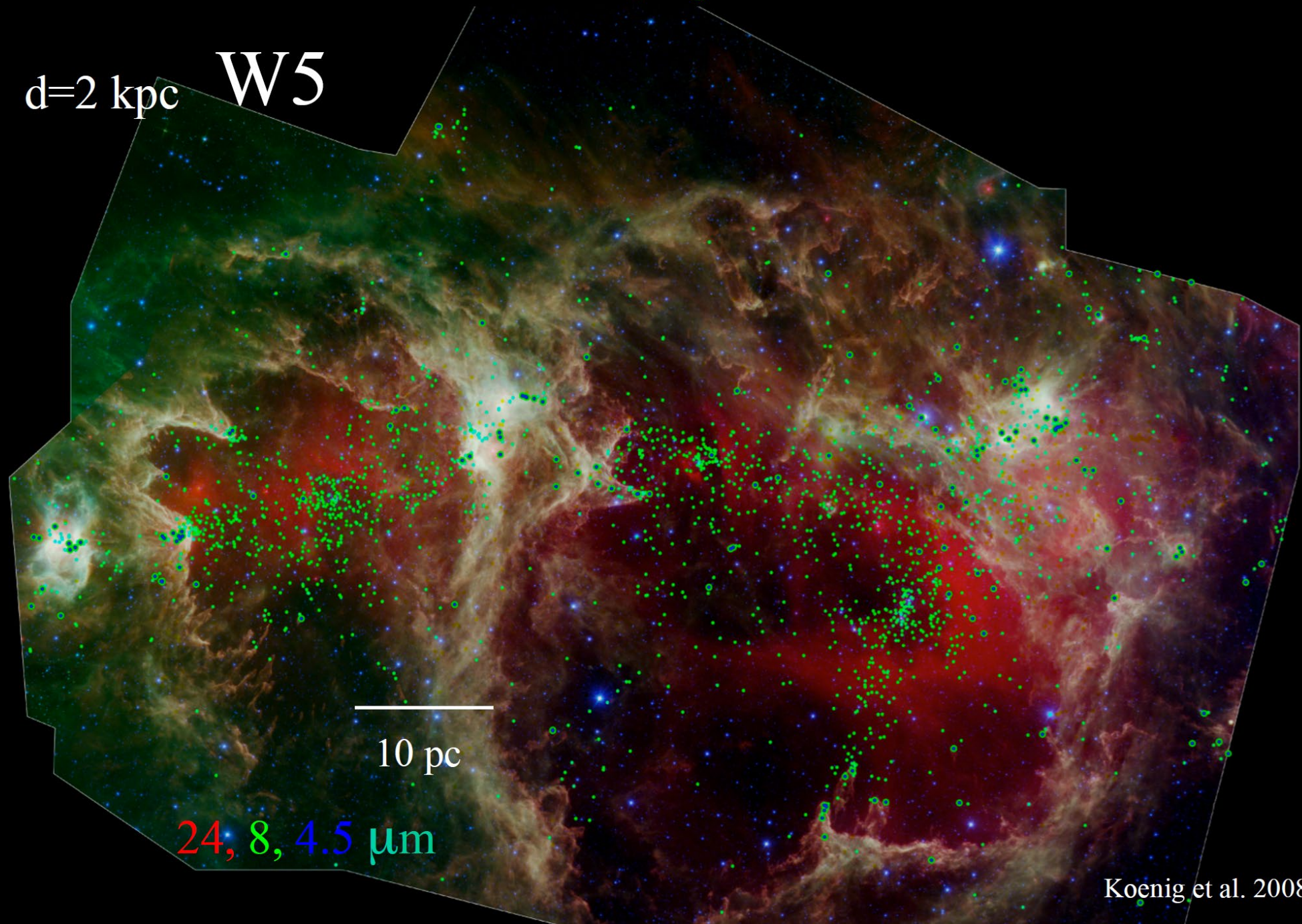


$$\sigma_v \approx (G \Sigma R)^{1/2} \approx (GM/R)^{1/2}$$

Larson's relation or Heyer's relation



Small Green Circles: IR-ex sources, Big Green/Blue Circles: Protostars



Koenig et al. 2008

Gravitational Instabilities: Jeans instability

- Jeans 1928 considered a perturbation of an initially uniform, stationary, non-rotating, unmagnetized gas.
- There exists a critical Jeans length, above which the region becomes unstable.

$$\lambda_J = \left(\frac{\pi c_s^2}{G \rho_0} \right)^{1/2}$$

- Correspondingly, there are Jeans mass and Jeans time.

$$\begin{aligned} M_J &\equiv \frac{4\pi}{3} \rho_0 \left(\frac{\lambda_J}{2} \right)^3 = \frac{1}{8} \left(\frac{\pi k T}{G \mu} \right)^{3/2} \frac{1}{\rho_0^{1/2}} \\ &= 0.32 M_\odot \left(\frac{T}{10 \text{ K}} \right)^{3/2} \left(\frac{m_H}{\mu} \right)^{3/2} \left(\frac{10^6 \text{ cm}^{-3}}{n_H} \right)^{1/2} \end{aligned}$$

- It is interesting to see that the Jeans mass for the typical density and temperature of dark clouds is similar to the typical mass of stars!

Free-fall timescale

- Defined as the time to collapse from a uniform density sphere to a point without pressure support.

$$\frac{d^2r}{dt^2} = -\frac{4\pi G r_0^3 \rho_0}{3r^2}$$

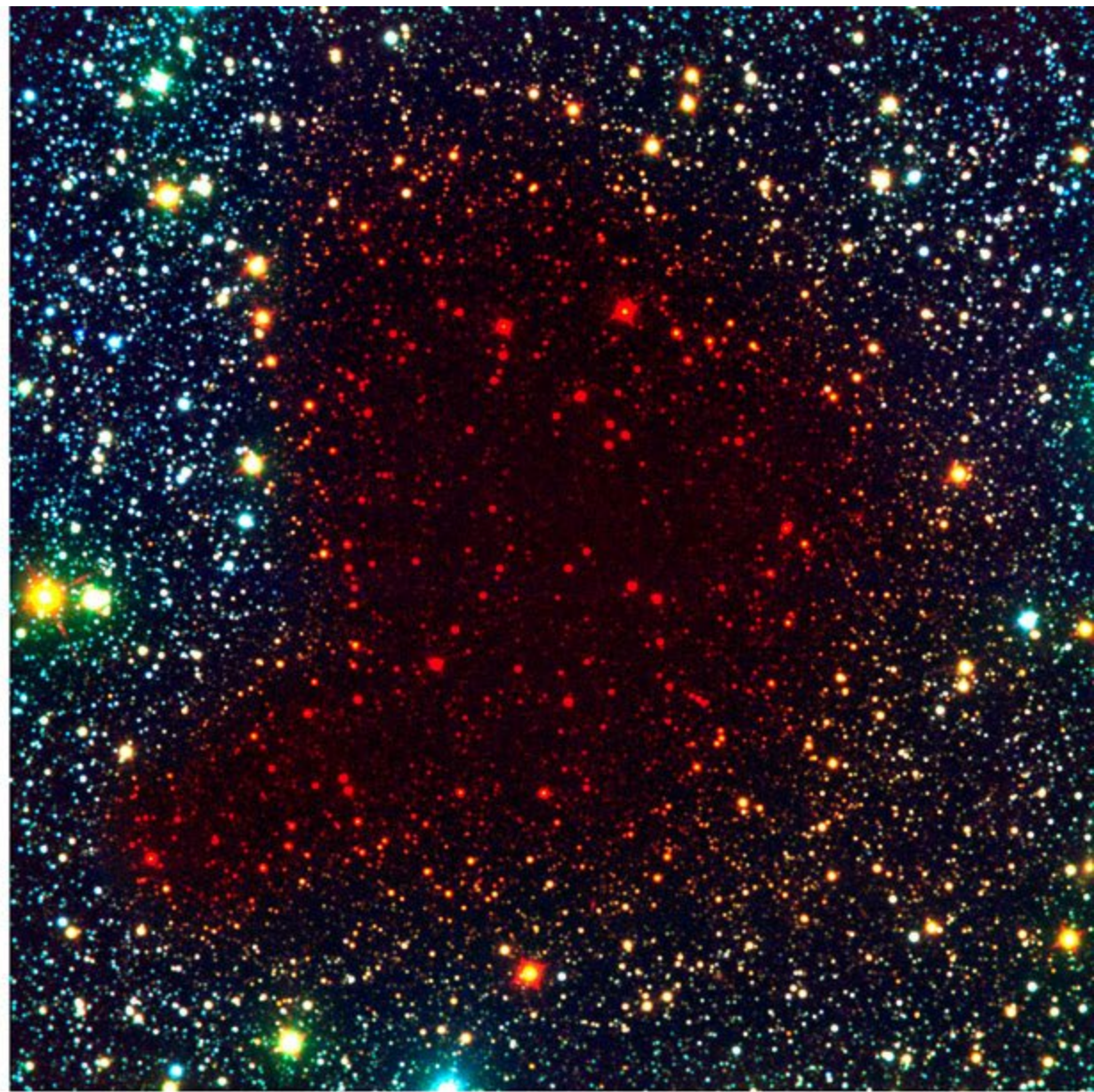
- By integrating the above equation from the starting radius r_0 to 0, we can obtain the total timescale (**homework**).

$$\tau_{\text{ff}} = \left(\frac{3\pi}{32G\rho_0} \right)^{1/2} = \frac{4.4 \times 10^4 \text{ yr}}{\sqrt{n_{\text{H}}/10^6 \text{ cm}^{-3}}}$$

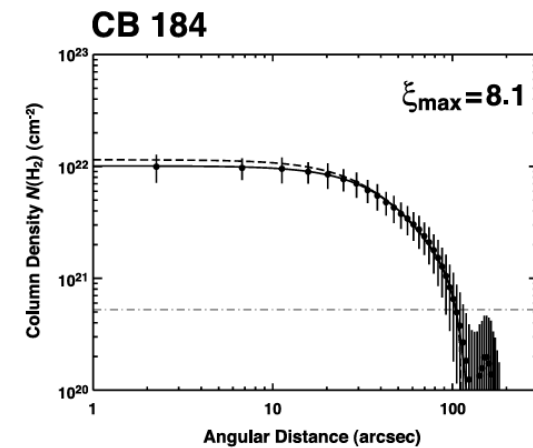
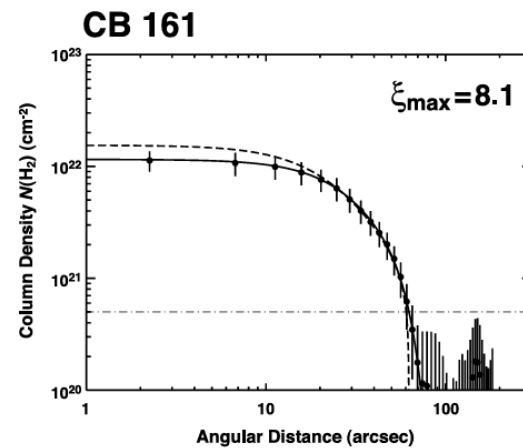
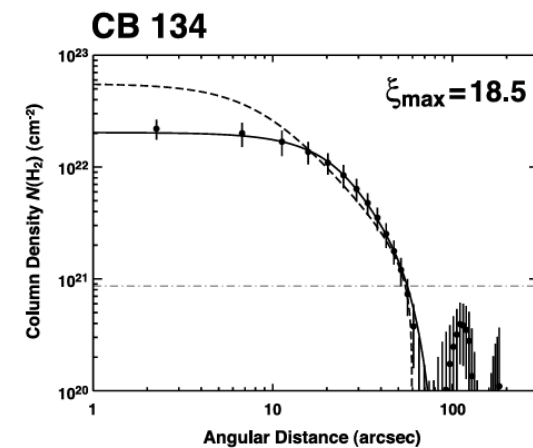
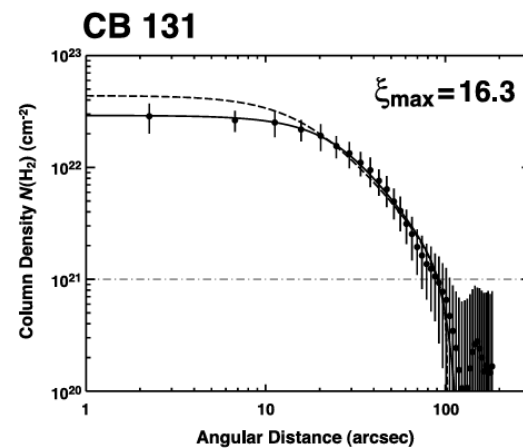
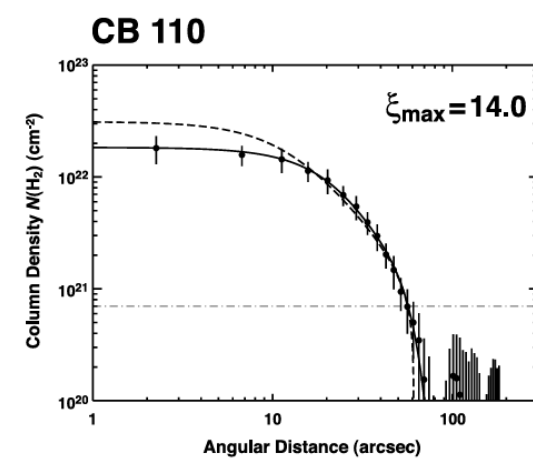
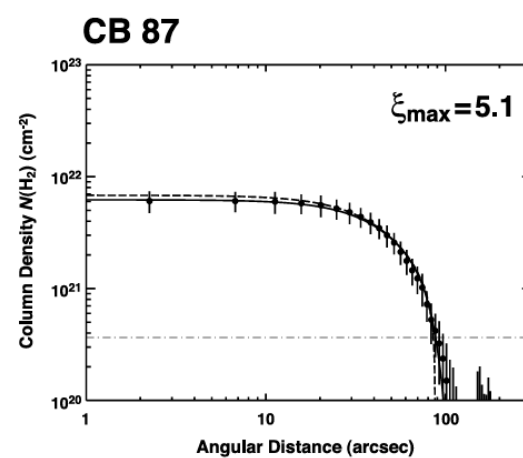
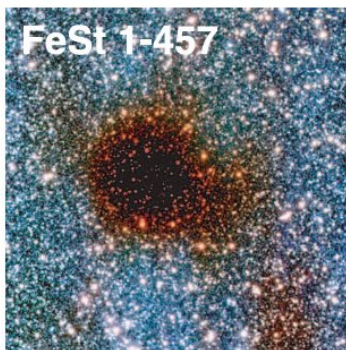
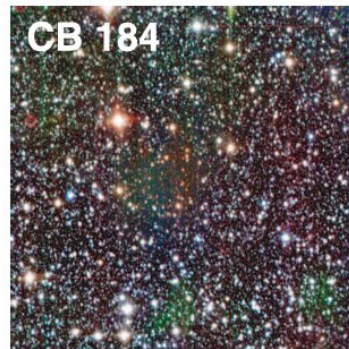
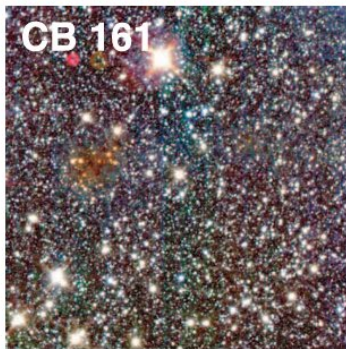
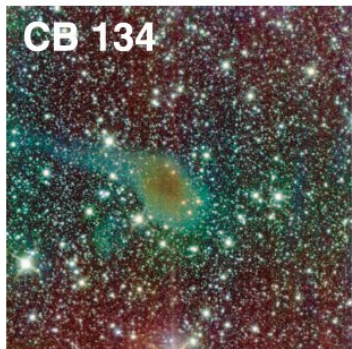
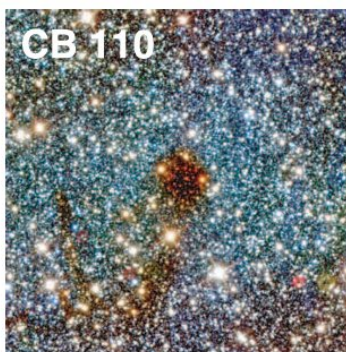
- The Jeans criterion can be interpreted as meaning that sound cannot traverse the region (and hence pressure cannot operate) in time to prevent the collapse.



B, V, I



B, I, K



More realistic cloud model: Bonnor-Ebert sphere

- The most important configuration for spherically-symmetric hydrostatic equilibrium.

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2}$$

- The equation can be simplified to the classical Lane-Emden equation:

$$\frac{1}{\xi^2} \frac{d}{d\xi} \xi^2 \frac{du}{d\xi} = e^{-u} \quad \ln(\rho/\rho_c) \equiv -u$$
$$\xi = r / (c_s^2 / 4\pi G \rho_c)^{1/2}$$

- The pressure-bounded isothermal Bonnor-Ebert mass for a given pressure P_0 is:

$$M_{\text{BE}}(p_0) = \frac{225}{32\sqrt{5\pi}} \frac{c_s^4}{(aG)^{3/2}} \frac{1}{\sqrt{p_0}}$$
$$= 0.26 \left(\frac{T}{10 \text{ K}} \right)^2 \left(\frac{10^6 \text{ cm}^{-3} \text{ K}}{p_0/k} \right)^{1/2} M_\odot$$

Can self-gravitation clumps/cores collapse?

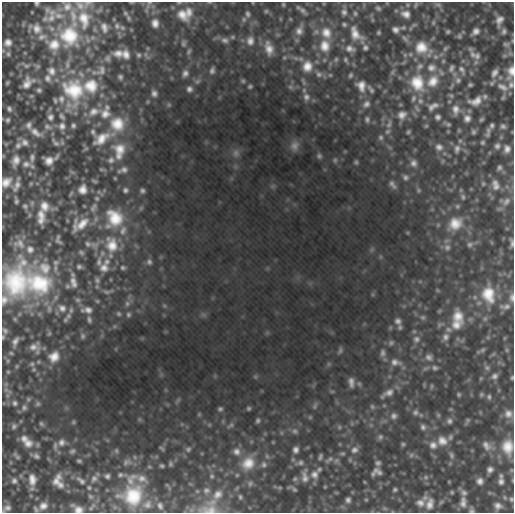
- Magnetic flux problem: magnetic field in the ISM often acts as though the field lines are “frozen” into the fluid. If flux-freezing continues to hold in a collapsing clump, flux will be conserved.

$$\frac{\Phi}{M} > \left(\frac{\Phi}{M} \right)_{\text{crit}} = 3\pi \sqrt{\frac{2aG}{5b}} = 1.54 \times 10^{-3} \sqrt{\frac{a}{b}} \text{ gauss cm}^2 \text{ g}^{-1}$$

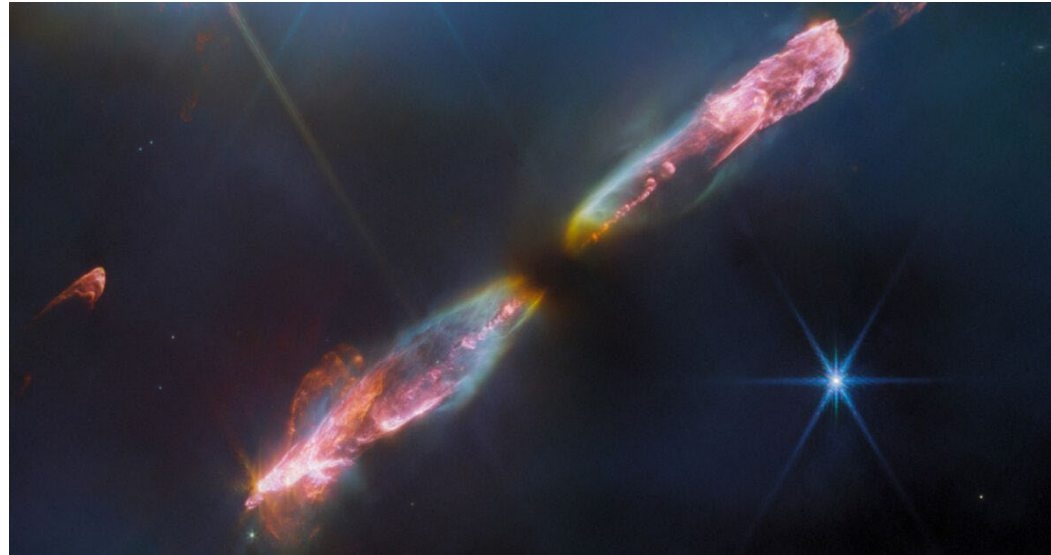
- Angular momentum problem: Clumps/cores always have some sort of angular momentum. Core collapse conserves angular momentum. From the simplest energy argument, when rotational energy exceeds gravitational energy, the core has to stop collapsing at a radius:

$$R_{\text{min}} \approx \frac{(J/M)^2}{GM} = 8 \times 10^{15} \left(\frac{J/M}{10^{21} \text{ cm}^2 \text{ s}^{-1}} \right)^2 \frac{M_{\odot}}{M} \text{ cm}$$

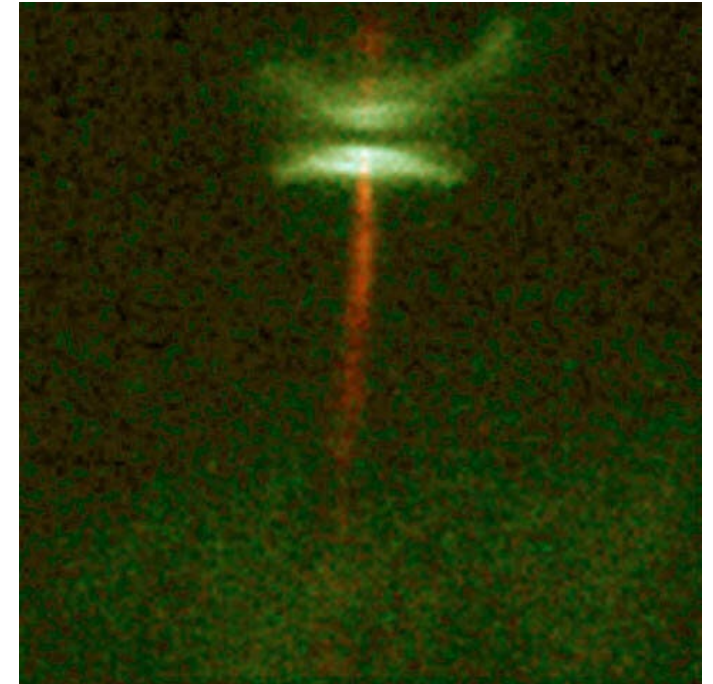
Evolution from cores to proto-stars



0.1 pc large core B68



HH 211 by JWST



HH 30 by HST

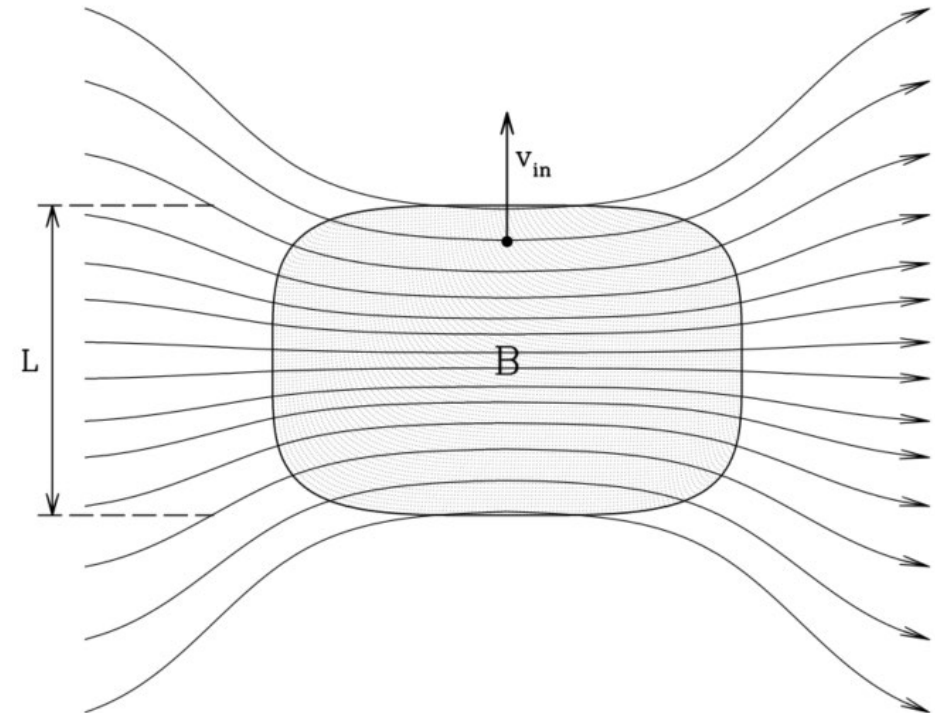
Magnetic flux problem: Ambipolar diffusion

- Typical T Tauri stars have surface magnetic fields strength 2 kG, corresponding to a flux-to-mass ratio $\sim 3 \times 10^{-8}$ gauss cm²/g. This is 6 orders of magnitude below the ratio for clumps and the critical threshold ratio!!!

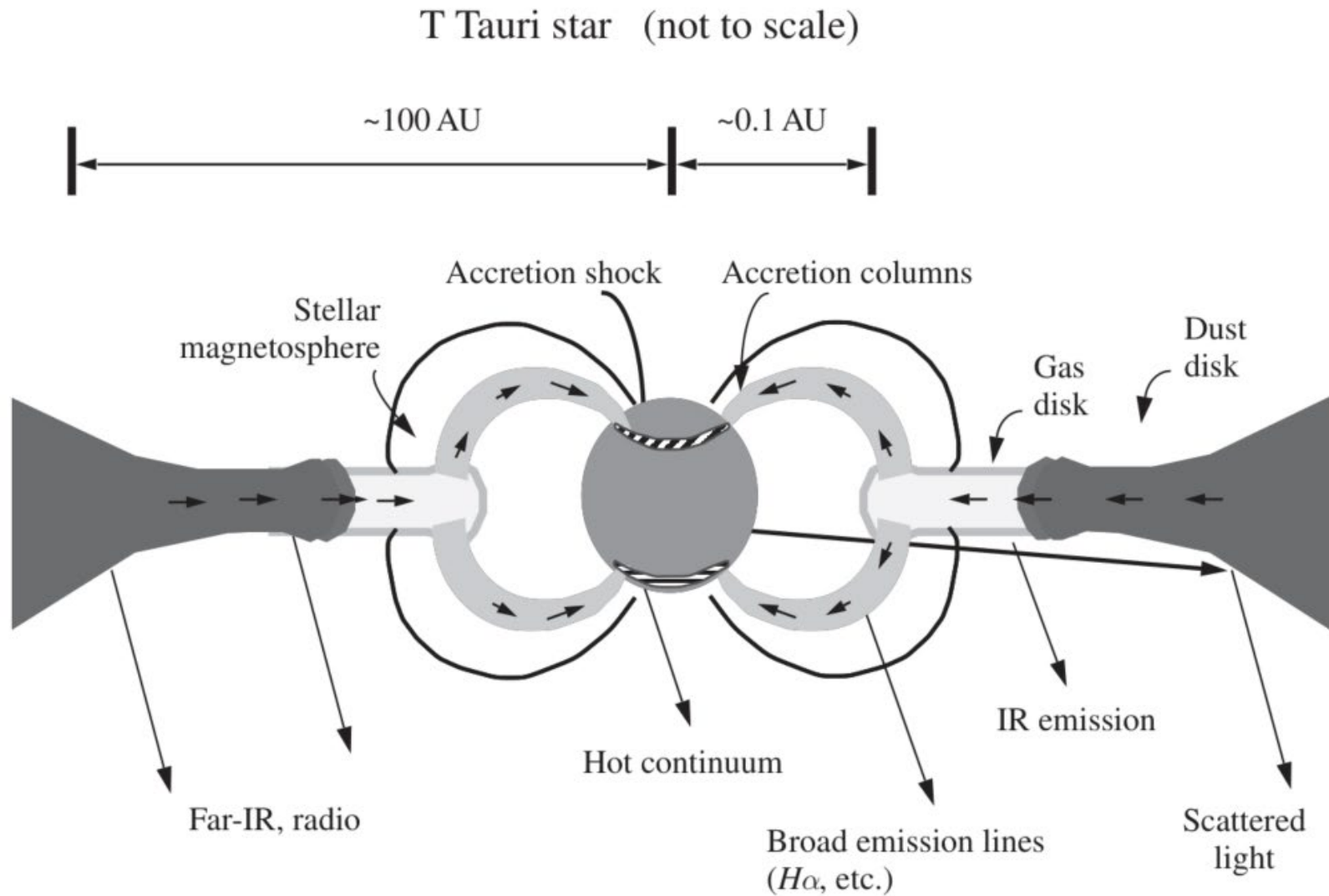
$$\frac{\Phi}{M} = 5.8 \times 10^{-3} n_4^{-0.02} \left(\frac{M}{M_\odot} \right)^{-1/3} \text{ gauss cm}^2 \text{ g}^{-1}$$

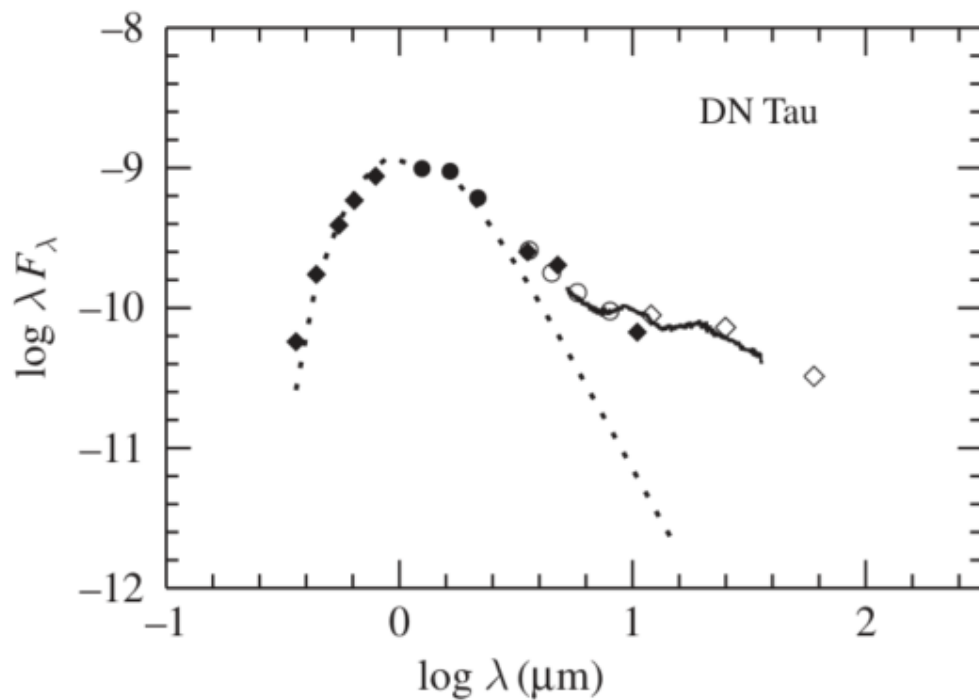
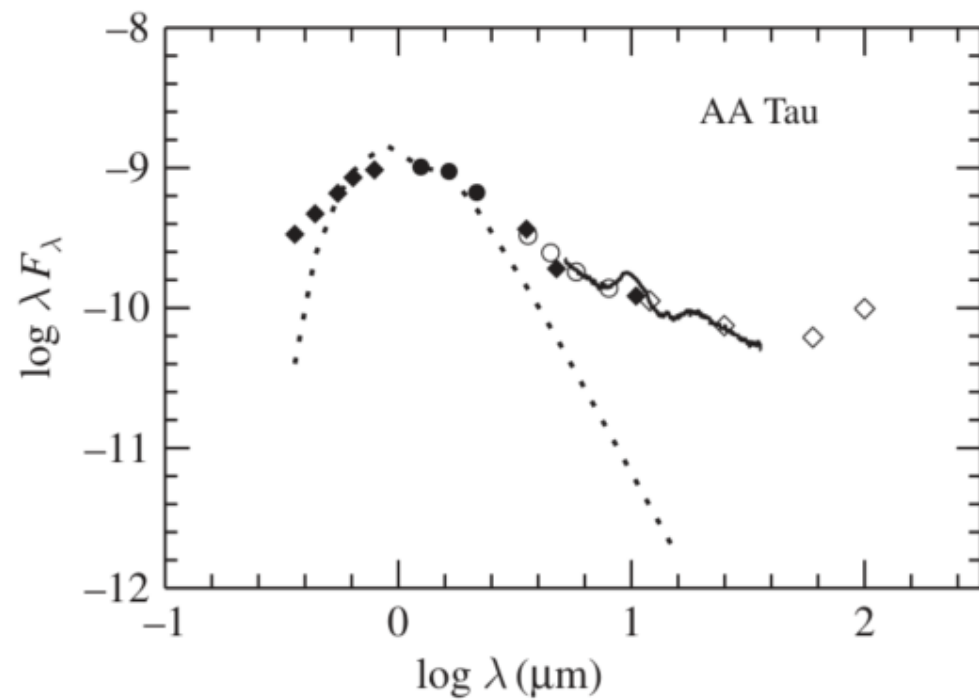
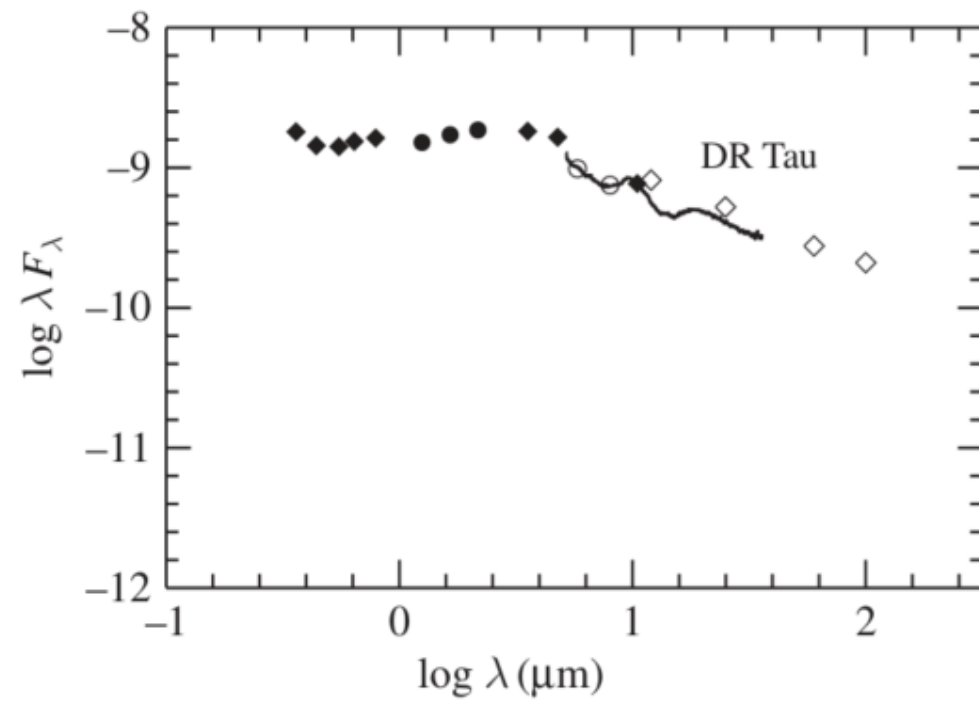
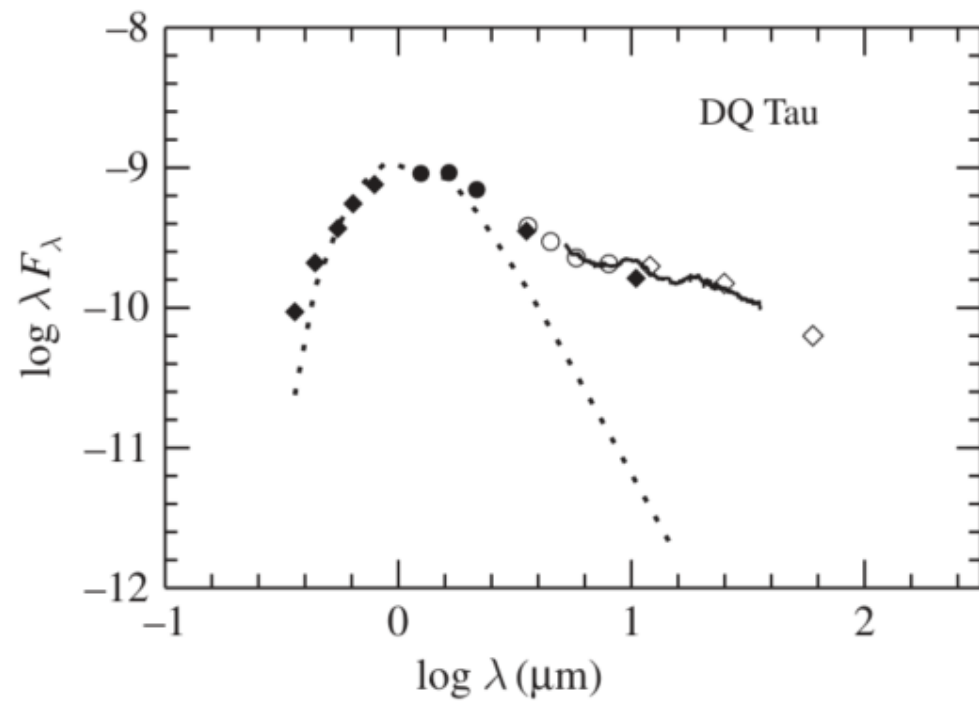
- Almost all magnetic flux that was initially present in the core escape before forming stars. How?
- Ambipolar diffusion may be important here.
- Magnetic fields only couple ionized plasma, not the neutral.
- Magnetic field lines slip out of the clumps with a rate that depends on the balance between the Lorentz force provided by the magnetic fields and ion-neutral collision.

$$\tau_{\text{slip}} = \frac{L/2}{|\mathbf{v}_i - \mathbf{v}_n|} = \frac{8\pi(L/2)^2}{B^2} n_i n_n \langle \sigma v \rangle \frac{m_i m_n}{(m_n + m_i)} \approx 7 \times 10^7 n_4^{-1.42} \text{ yr}$$



Angular momentum problem: accretion disk





Thermal structure of the accretion disks

- For a steady accretion flow, accreted material dissipates their potential energy locally to heat up the disk. The energy is then radiated away by the disk surface via blackbody radiation.

$$\frac{GM_* \dot{M}}{2R} \frac{\Delta R}{R} \sim 2 \times 2\pi R \Delta R \sigma T_d^4 \longrightarrow T_d \sim \left(\frac{GM_* \dot{M}}{8\pi \sigma R^3} \right)^{1/4}$$

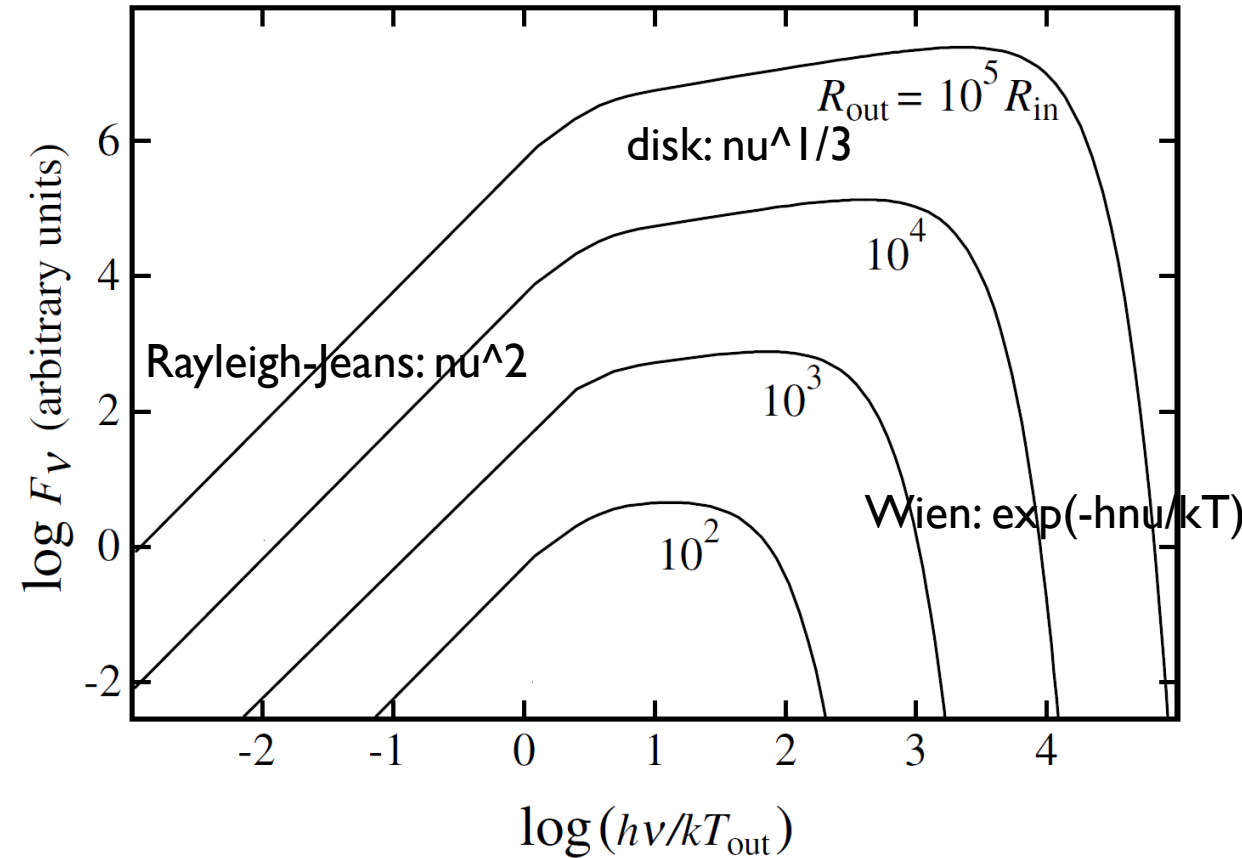
- While accretion disks around blackholes don't have central sources, accretion disks around proto-stars are shined by the radiation from the proto-stars powered by infalling material hitting the surface of the stars and the deuterium nuclear reaction.

$$\frac{L_*}{4\pi R^2} \langle \cos \gamma \rangle \sim \sigma T_d^4 \longrightarrow T_d \sim \left(\frac{L_* R_*}{4\pi \sigma R^3} \right)^{1/4}$$

Thermal emission from accretion disks

- The luminosity of the hot disk is the sum of blackbody radiation from different annular of disk with radius-dependent temperature!
- Remember, $T \sim R^{-3/4}$!

$$L_\nu = \int_{R_{\text{in}}}^{R_{\text{out}}} \pi B_\nu[T_d(R)] 2\pi R dR$$
$$= \frac{16\pi^2 h R_{\text{in}}^2}{3c^2} \left(\frac{kT_{\text{in}}}{h} \right)^{8/3} \nu^{1/3} \int_{x_{\text{in}}}^{x_{\text{out}}} \frac{x^{5/3} dx}{(e^x - 1)}$$



But how to get rid of angular momentum to accrete?

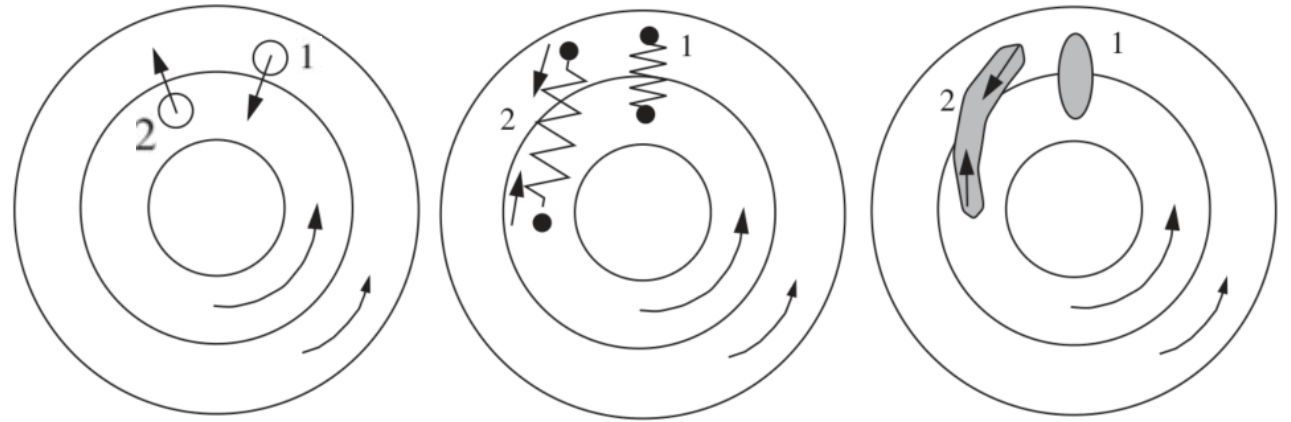
- Consider an idealized situation involving only two bodies (m_1 and m_2) orbiting around a central mass of M .
- The total energy and angular momentum:

$$E = -\frac{GM}{2} \left(\frac{m_1}{r_1} + \frac{m_2}{r_2} \right)$$

$$J = (GM)^{1/2} (m_1 r_1^{1/2} + m_2 r_2^{1/2})$$

- Perturb the system while conserving total angular momentum by nagging r_1 with Δr_1

$$m_1 r_1^{-1/2} \Delta r_1 = -m_2 r_2^{-1/2} \Delta r_2$$



$$\Delta E = -\frac{GMm_1 \Delta r_1}{2r_1^2} \left[\left(\frac{r_1}{r_2} \right)^{3/2} - 1 \right]$$

Feedback questionnaire

