Class 3: Observing young stars

ASTR 4008 / 8008, Semester 2, 2020

Mark Krumholz

Outline

From small to large scales

- Individual young stars — stages and classes
- Resolved stellar systems: multiplicity, clustering, and the IMF
- Unresolved systems: star formation rates and indicators

Single star formation

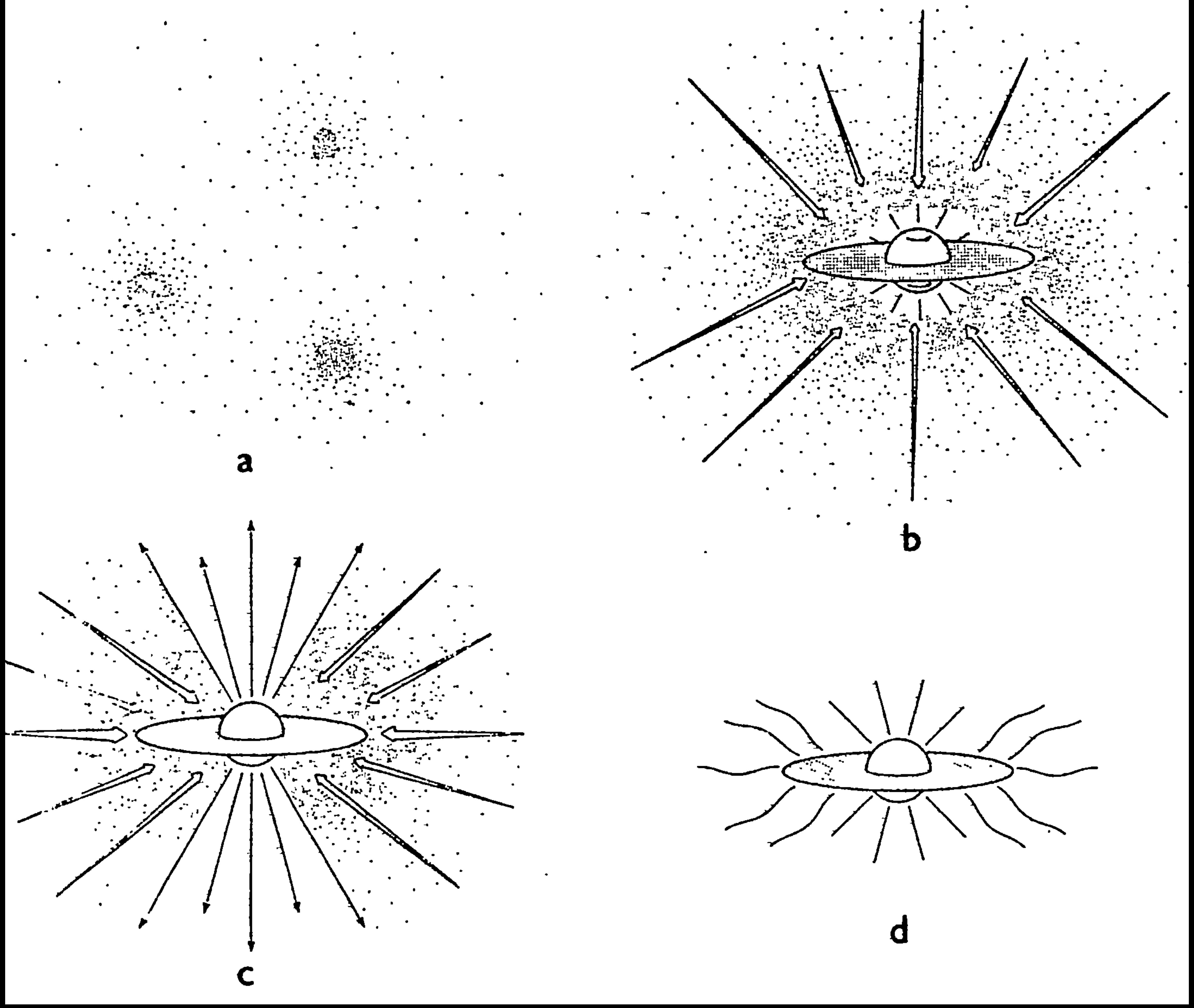
Rough overview of stages

A. No star formed yet, just a dense cloud of molecular gas (“core”)

B. Protostar exists and accretes, but dense dust hides star in the optical / IR — star not seen

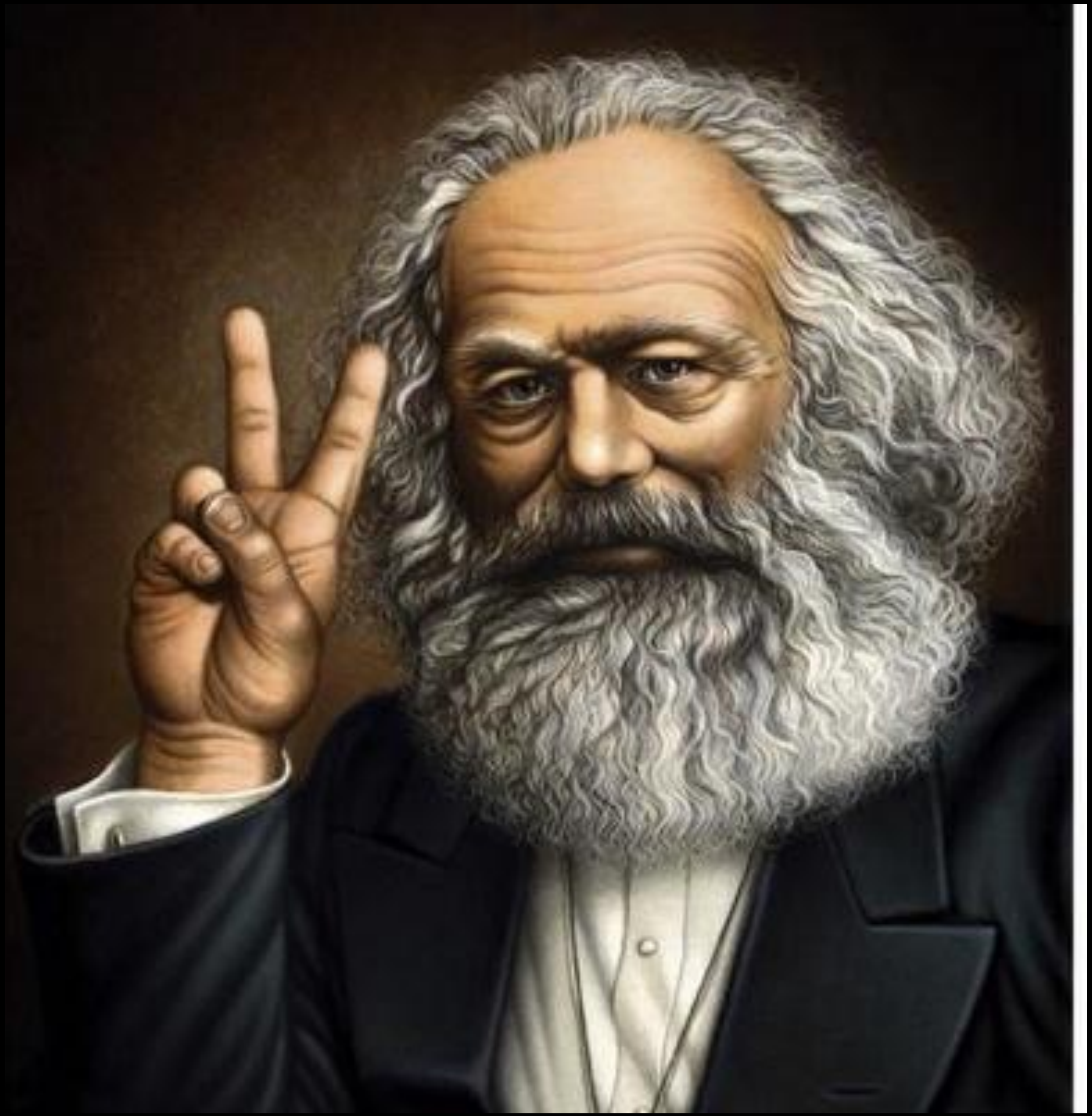
C. Enough dust cleared that stellar surface is revealed; star still has a visible disc

D. All circumstellar dust and most of disc gone, but star still young

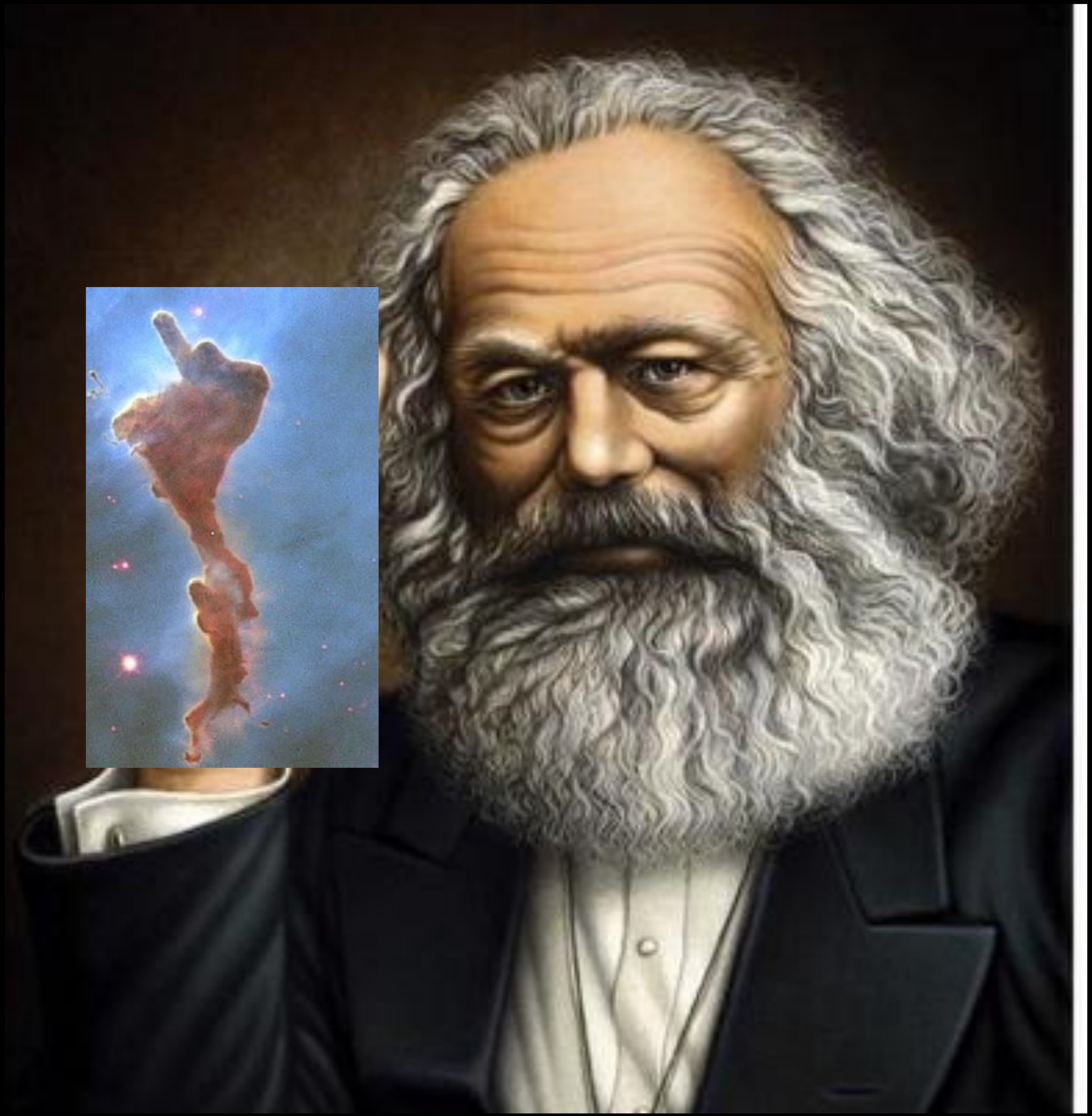


Shu, Adams, & Lizano 1987

The class system



The *protostellar* class system



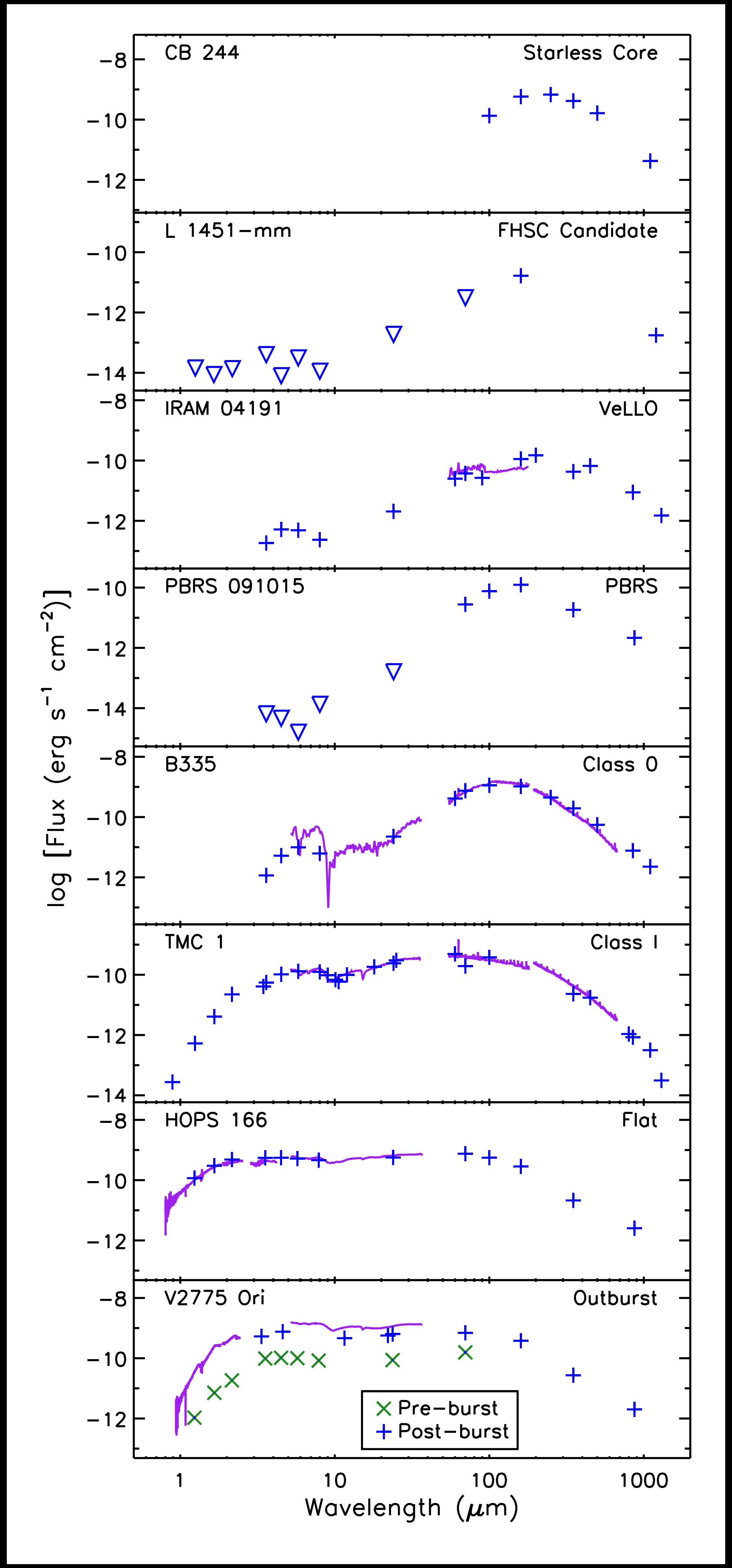
Basic considerations for observing protostars

Motivation for the system we use

- Molecular cloud of mass 10^5 $M_\odot$, size 20 pc corresponds to surface density ~0.05 g cm^{-2}
- Opacity to visible light ~10^3 cm^2 g^{-1}, so GMCs have τ_V ~ few; columns much higher toward denser regions
- Opacity less at longer wavelengths, $\tau \sim \lambda^{-2}$
- Dust at ~10 K emits at $\lambda \gtrsim 400$ μm; warm dust (T ~ 100 K) emits at $\lambda \sim 50$ μm
- This suggests that IR - visible SED is a good way of thinking about protostellar evolution

The SED class system

- Class 0: warm dust undetected or nearly so; energy output > 99% at λ > 350 μm
- Class I: warm dust detectable, but central star still blocked by dust; SED slope > 0 from 2 - 25 μm
- Class II: enough gas gone that star is visible directly, but circumstellar material still contributes IR; SED slope –1.6 to 0
- Class III: no or very weak IR from circumstellar material, but still pre-MS; SED slope < –1.6, expected for RJ tail



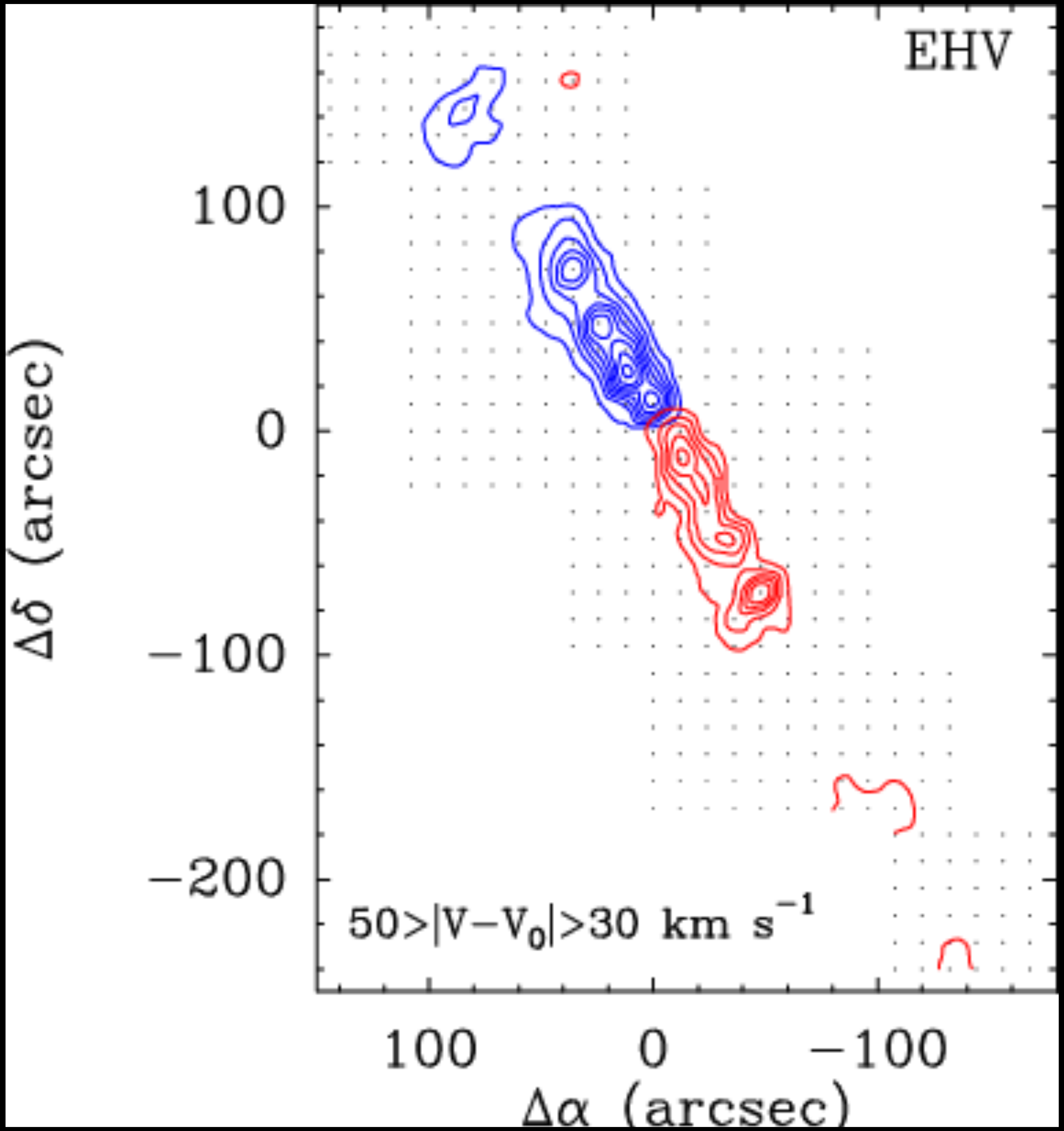
Dunham+ 2014

More on classes

Class 0

- Often no detectable IR emission — so how do we know there is a protostar there at all?

- Answer: other signs, including:
  - Presence of an outflow
  - Molecular evidence of high-speed shocks (e.g., SiO line emission)
  - Compact unresolved dust structure down to < 100 au scales



Tafalla+ 2004; red and blue show CO 2→1 emission moving at velocities of 30 - 50 km s^{-1}, much faster than normally seen in molecular clouds

More on classes

Class I - II

- Once detected in IR, classification from slope: $\alpha_{IR} \equiv \log[(\lambda F_\lambda)_{20\text{-}25\mu m} / (\lambda F_\lambda)_{2.2\mu m}]$
- Why these wavelengths? Because they are what the IRAS satellite from the 1980s used, and it was the first to observe large numbers of protostars!
- Class I: $\alpha_{IR} > 0$. Positive slope means more emission from longer wavelengths, so light we see is dominated by warm dust, not by the star
- Class II: $-1.6 < \alpha_{IR} < 0$. Negative slope means star is contributing a lot of light, but there is additional emission from dust in the IR as well; –1.6 is value expected for a bare stellar photosphere

More on classes

Class III

- Near-IR SED now looks like a bare star, but there are still signs of youth:
  - There may be additional far-IR emission ($> 100\ \mu$m), indicating cool dust far from the star
  - Stellar radius larger / effective temperature lower than expected for a main sequence star
  - Rapid rotation / high magnetic activity / high X-ray emission (all related)
  - Lines in optical spectrum indicative of accretion, e.g., Hα line seen in emission rather than absorption
  - Presence of Li in stellar atmosphere — this gets destroyed in $\lesssim 1\ M_\odot$ stars by ages of ~20-25 Myr

Brief note on nomenclature

- There is an almost entirely parallel naming system for young stars based on older, optical diagnostics, from the days before plentiful IR satellite data
- Most common: T Tauri stars, based on presence of certain optical lines. “Classical” T Tauri stars correspond roughly to class II objects, “weak line” T Tauri stars to class III. However, the mapping is not exact.
- Many other optical classifications exist. Some of the most common:
  - Herbig Ae/Be stars — these are basically like T Tauri stars, just more massive, so they have spectra like an A or B star
  - FU Ori stars — these are stars experiencing a burst of accretion; will return to these later in the course
  - Many more… optical astronomers love to name things and invent classifications…

Statistics of young stellar populations

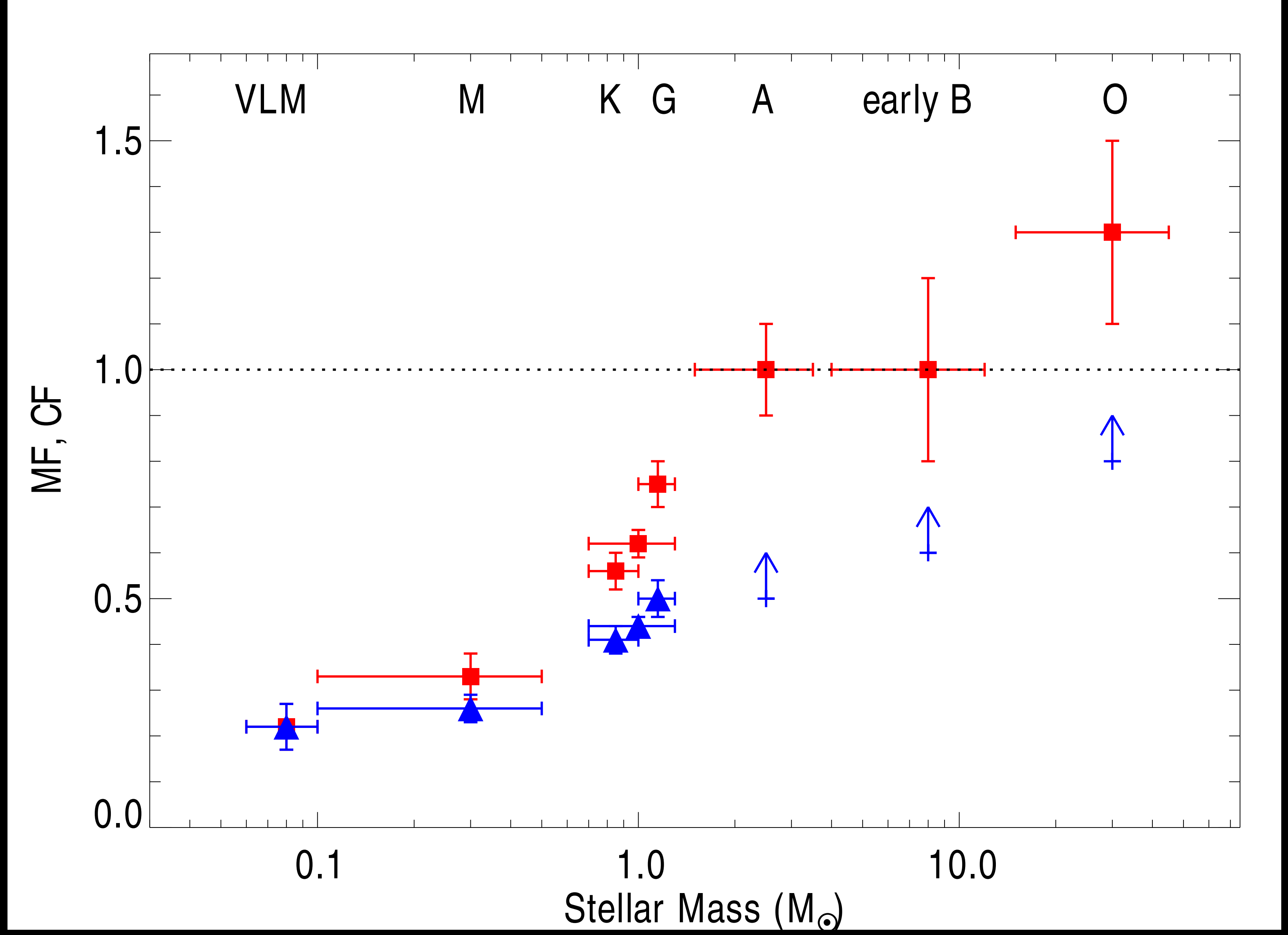
Resolved vs. unresolved

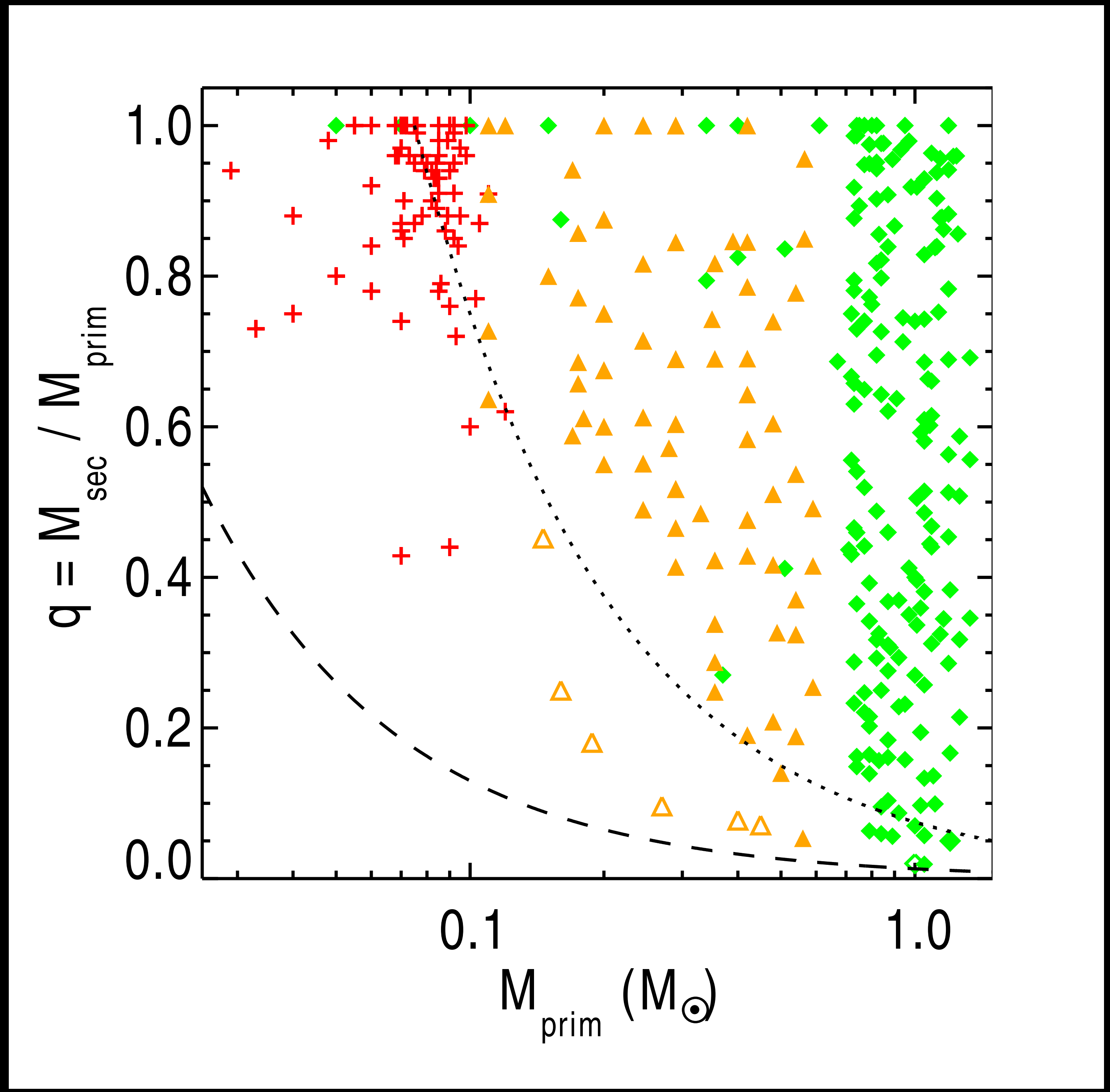
- An important distinction: a stellar population is *resolved* if we can see individual stars and measure their properties
- For more distant objects, the population is *unresolved*, meaning that we see only the collective light of the stars, but not individual stars
- Some statistics are more easily measured on one type of stellar population than on the other, and techniques tend to be different in the two cases
- Usually we go from resolved to unresolved at distances of ~5 Mpc, but this depends which which stars we want to resolve (down to ~0.08 $M_\odot$? to 1 $M_\odot$? only massive stars?), how crowded the region is, and what wavelength we're using to observe

Multiplicity properties

for resolved stars

- Many stars are members of multiple star systems (binaries, triples, quadruples, etc.)
- Multiplicity more common among more massive stars
- Can also examine many other statistics:
  - Mass ratio distribution
  - Period / semi-major axis distribution
  - Eccentricity distribution
  - Ratio of singles to binaries to triples to quadruples, etc.

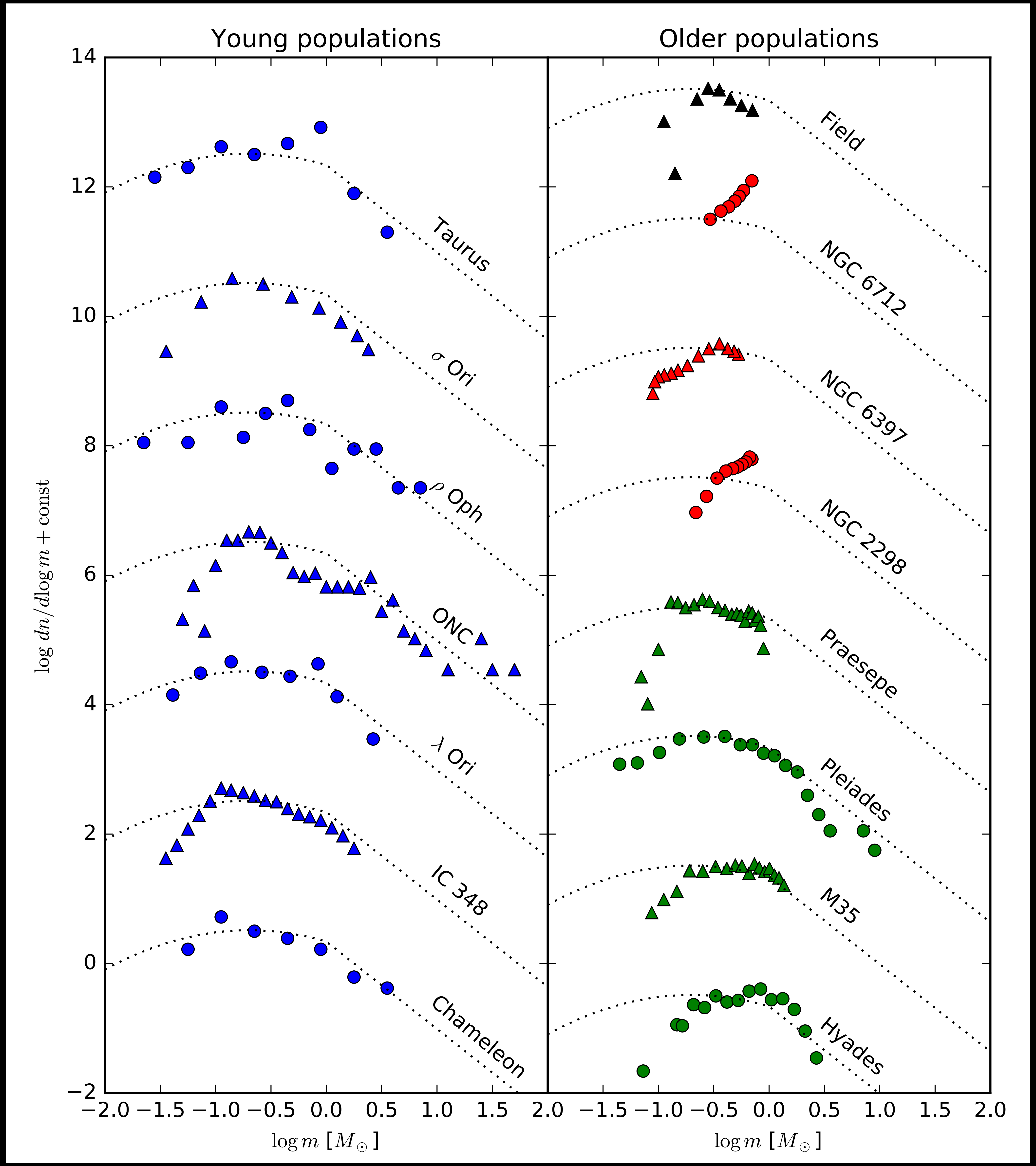




The IMF

Maybe the most important distribution astrophysics

- IMF = initial mass function: distribution of stellar masses at birth
- Can be measured in many ways — discussion deferred to later in class
- Important features: broad peak at ~few x 0.1 $M_\odot$, power law tail extending to high mass
- Surprisingly little variation; if not universal, then closer to it than one might expect



IMF parameterisations

Sorting out Salpeter, Kroupa, Chabrier, etc.

- Many published parameterisations of IMF. Two common ones (note $m \equiv M/\mathrm{M}_\odot$):

$$\frac{dn}{d\log m} \propto \begin{cases} \exp\left[-\frac{(\log m - \log m_0)^2}{2\times\sigma_{10}^2}\right], & m < 1 \\ \exp\left[-\frac{(-\log m_0)^2}{2\times\sigma_{10}^2}\right] m^{-1.35}, & m \geq 1 \end{cases} \quad \begin{aligned} m_0 &= 0.22 \\ \sigma_{10} &= 0.57 \end{aligned}$$

(Chabrier 2003, 2005)

$$\frac{dn}{d\log m} \propto \begin{cases} \left(\frac{m}{m_0}\right)^{-\alpha_0}, & m_0 < m < m_1 \\ \left(\frac{m_1}{m_0}\right)^{-\alpha_0}\left(\frac{m}{m_1}\right)^{-\alpha_1}, & m_1 < m < m_2 \\ \left[\prod_{i=1}^{n}\left(\frac{m_i}{m_{i-1}}\right)^{-\alpha_{i-1}}\right]\left(\frac{m}{m_n}\right)^{-\alpha_n}, & m_n < m < m_{n+1} \end{cases} \quad \begin{aligned} \alpha_0 &= -0.7\pm0.7, & m_0 &= 0.01 \\ \alpha_1 &= 0.3\pm0.5, & m_1 &= 0.08 \\ \alpha_2 &= 1.3\pm0.3, & m_2 &= 0.5 \\ \alpha_3 &= 1.3\pm0.7, & m_3 &= 1,\ m_4 \to \infty \end{aligned}$$

(Kroupa 2001, 2002)

- Older and extragalactic papers sometimes use Salpeter (1955): power powerlaw with slope –1.35 for all masses from 0.1 - 120 $\mathrm{M}_\odot$

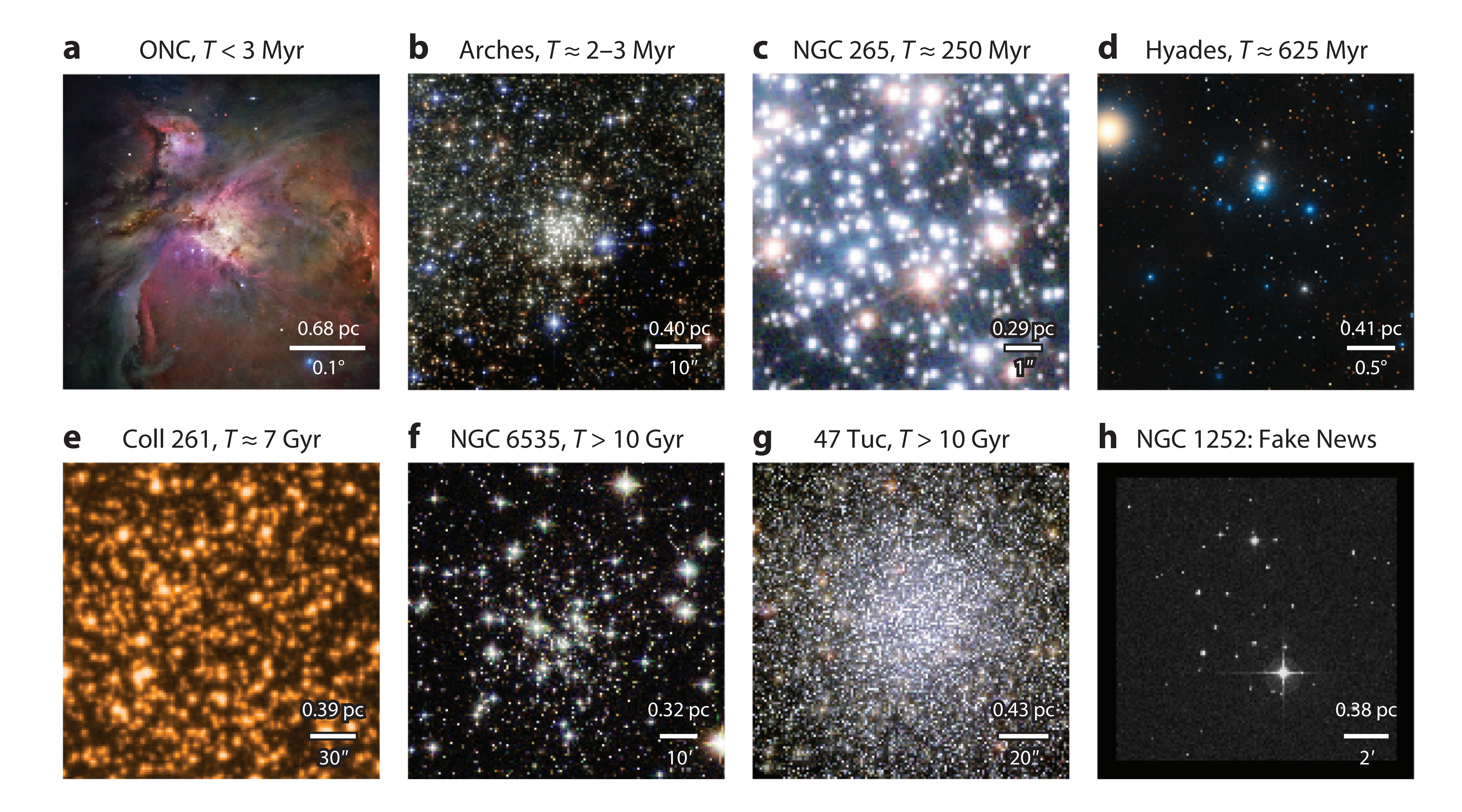
Exercise

Using one of the functional forms of the IMF, estimate:

- Mean mass of a star, assuming IMF goes from 0.01 - 120 $M_\odot$
- Number of supernovae per 100 $M_\odot$ of stars formed, assuming all stars with initial mass >8 $M_\odot$ end as SNe
- Fraction of all stellar mass in stars that go SN
- Fraction of stellar mass in brown dwarfs ($M < 0.08\ M_\odot$)
- Luminosity-weighted mean stellar mass, assuming (very crudely) that luminosity varies as $m^{3.5}$

Stellar clustering

- Stars form closer to one another than the mean distance between old stars
- Some fraction of these overdensities will go on to be bound star clusters, but vast majority dissolve over ~10 Myr
- Huge range of densities, masses, etc.; masses distributed as roughly $dN/dM \sim M^{-2}$



Unresolved populations

What we can and can't measure

- Measuring IMF for unresolved populations is possible but hard and uncertain — more on this later in the course
- Multiplicity nearly impossible to measure for unresolved populations
- Clustering measurable in semi-resolved cases, where one can resolve individual clusters but not individual stars — maximum distance ~100 Mpc, depending on limiting cluster mass one wants to measure
- Most common thing to measure: total star formation rate (SFR)
- For resolved populations, this is fairly easy: just count young stars! Unresolved populations are a bit trickier…

Theory of SFR measurement
Part I

- Consider a stellar population with a known, constant IMF dn/dm ($= 1/m \, dn / d \log m$)
- Mean mass $\langle m \rangle = \int m \, (dn/dm) \, dm = \int (dn / d \log m) \, dm$
- Let $L(m,t)$ be the luminosity (in some photometric band, line, etc.) of a star with initial mass m and age t
- Then the luminosity of a population of N stars, all of the same age t, is given by $L(t) = N \int L(m,t) \, (dn/dm) \, dm$. Since total mass is $\langle m \rangle N$, luminosity per unit mass is $(L/M)(t) = \langle m \rangle^{-1} \int L(m,t) \, (dn/dm) \, dm$.

Theory of SFR measurement

Part II

- In a region where stars have been forming at a constant rate *SFR* for time *T*, total luminosity is $L(T) = \int^T (L/M)(t)\, dt = (SFR / \langle m \rangle) \iint L(m,t)\, (dn/dm)\, dm\, dt$

- Swap order of integration, write $L(T) = (SFR / \langle m \rangle) \int \langle E \rangle_{m,T}\, (dn/dm)\, dm$, where $\langle E \rangle_{m,T} \equiv \int^T L(m,t)\, dt$ is the total energy radiated by a star of initial mass *m* by the time it reaches age *T* in whatever waveband / line *L* describes

- *T* usually unknown, but for some wavebands $\langle E \rangle_{m,T}$ is almost independent of *T* for large enough *T*. Example: ionising luminosity is negligibly small for all but very massive stars ($m \gtrsim 20\ M_\odot$), and for these stars ionising emission drops to ~0 as soon as star leaves main sequence, so $\langle E \rangle_{m,T} \sim$ constant for $T \gtrsim 5$ Myr

- In this case we can treat $\langle E \rangle_{m,T}$ as known, so $SFR = L \langle m \rangle / \int \langle E \rangle_{m,T}\, (dn/dm)\, dm$

SFR measurement

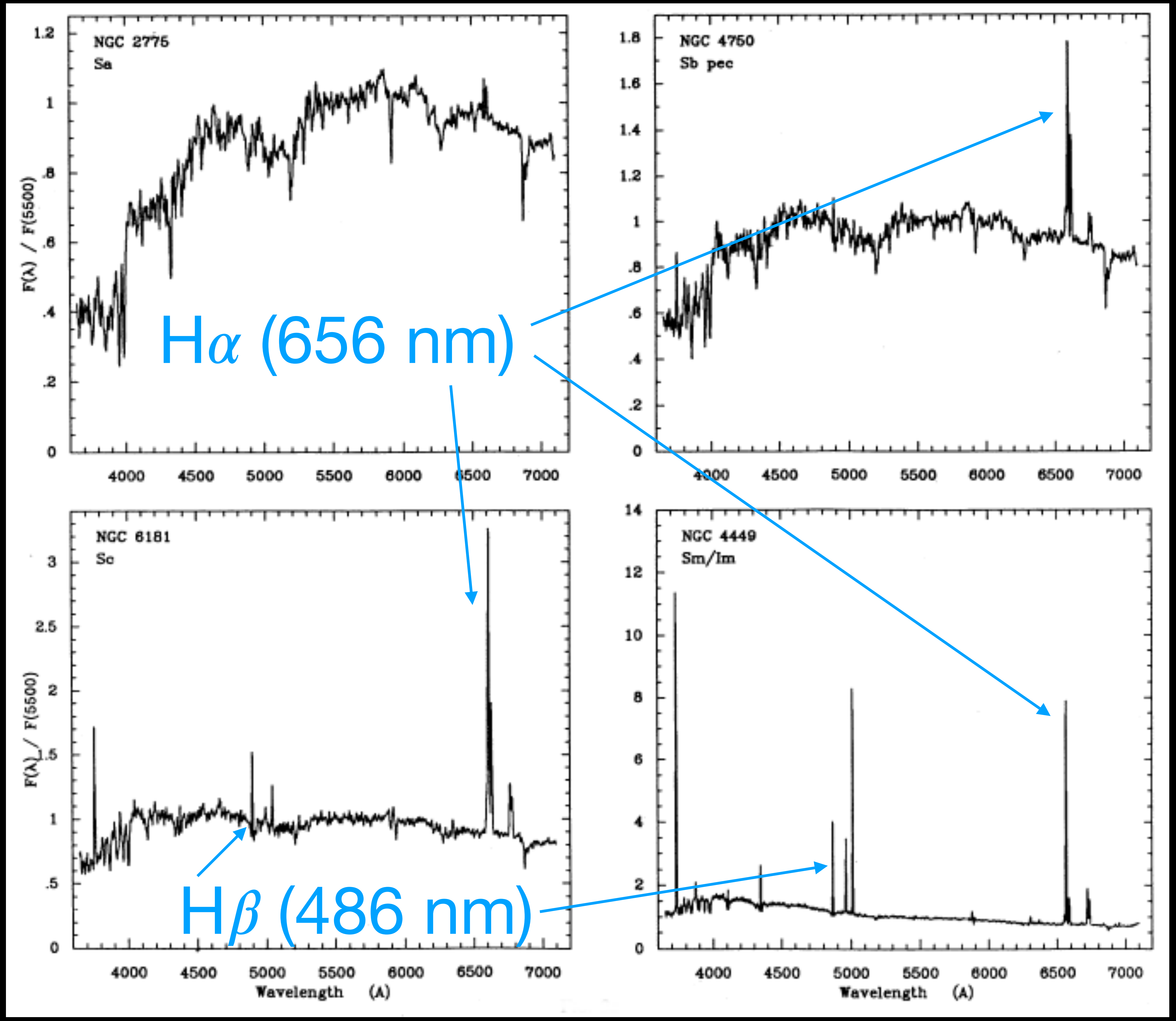
Caveats and warnings

- Method requires knowledge of both IMF ($\langle m \rangle$, dn/dm) and stellar evolution ($\langle E \rangle_{m,T}$); measurement only as good as this knowledge
- Requires roughly constant SFR over time T probed by choice of waveband — may or may not be reasonable depending on region being examined and value of T
- Assumes stellar population is large enough that we can approximate luminosity as coming from a stellar population that samples all ages and masses — may not be a good assumption in small / low-SFR regions
- Plenty of examples in published literature of forgetting these warnings!

Recombination lines

SFR tracers I

- Ionising photons work well due to short lifetime, but can't see directly: host galaxy and MW opaque
- However, can see lines produced when ionised gas recombines, and use these to work out ionising photon injection rate
- Examples: Hα, Hβ (optical), Paα, Paβ (IR), H66α (radio)
- Biggest caveat: dust extinction



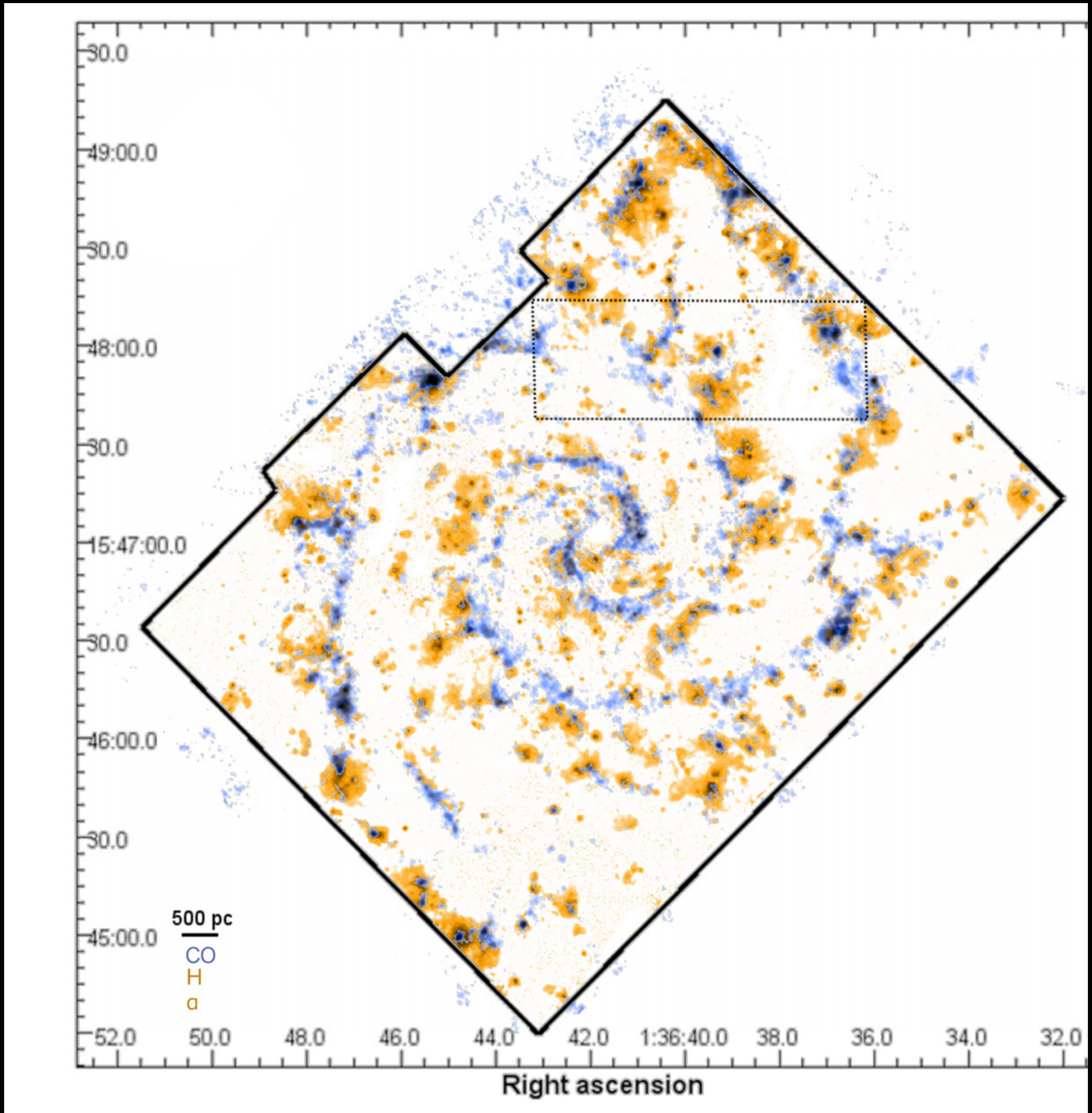
Kennicutt 1992

Example galaxy: NGC 628

Orange = Hα

Blue = CO 2→1

Kreckel+ 2019



Radio free-free

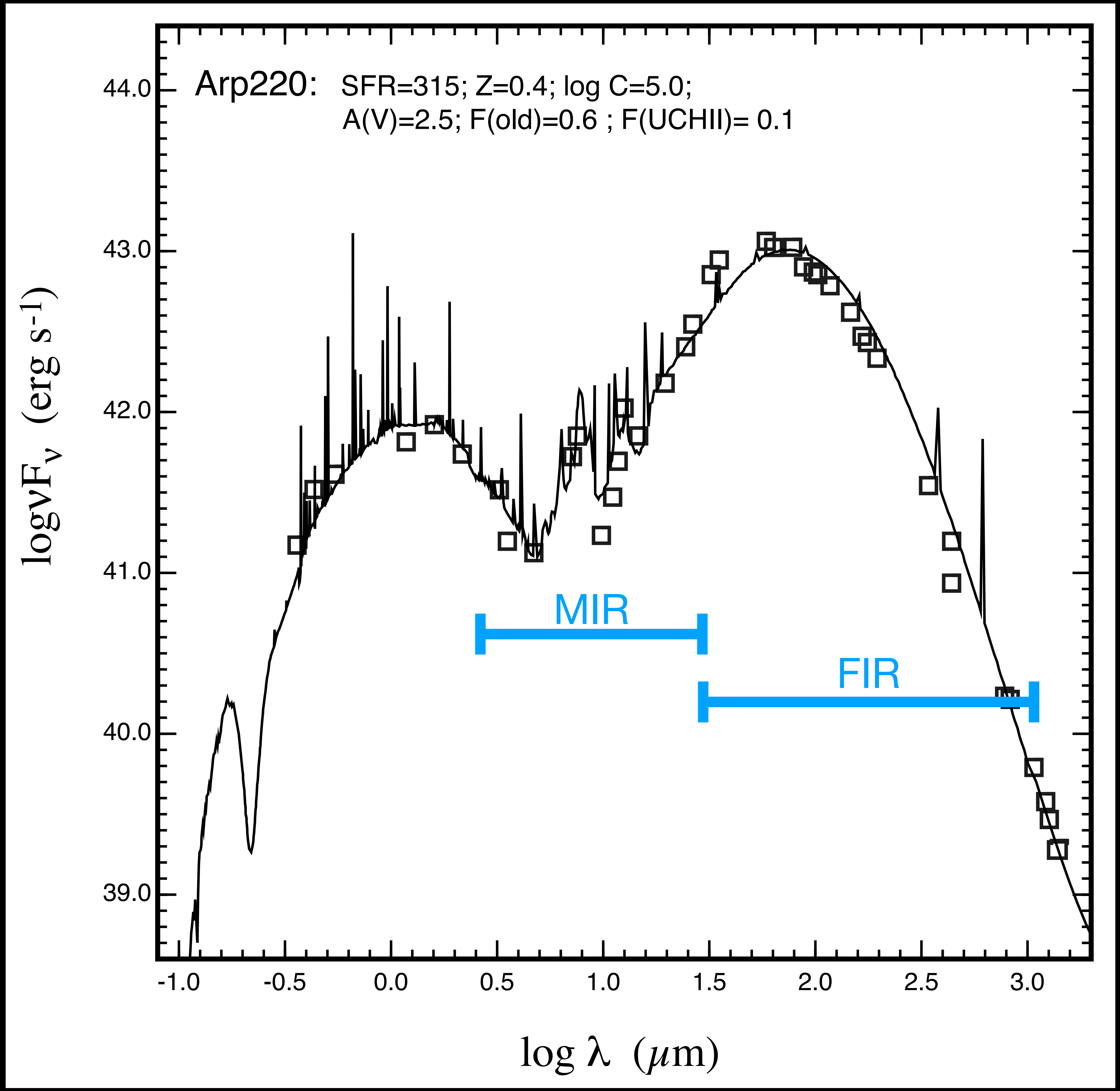
SFR tracers II

- Same regions that produce recombination lines also produce free-free emission (also called bremmstrahlung); can convert observed luminosity to ionising photon injection rate as for recombination
- Big plus: free-free is in radio, so dust opacity is negligible — preferred tool for highly-obscured regions like toward Galactic centre
- Big minuses:
  - Not a line, so can be confused with other continuum-producing processes at similar wavelengths (most often, synchrotron emission)
  - Much fainter than recombination lines, so very hard to detect outside MW

IR continuum

SFR tracers III

- In very dusty regions / galaxies, almost all starlight is absorbed by dust and re-emitted in IR, so IR luminosity ≈ total luminosity
- For actively star-forming galaxies, total luminosity dominated by massive stars, reaches saturation at ~10 Myr → good SFR indicator
- Caveat: dust heating by old stars and AGN

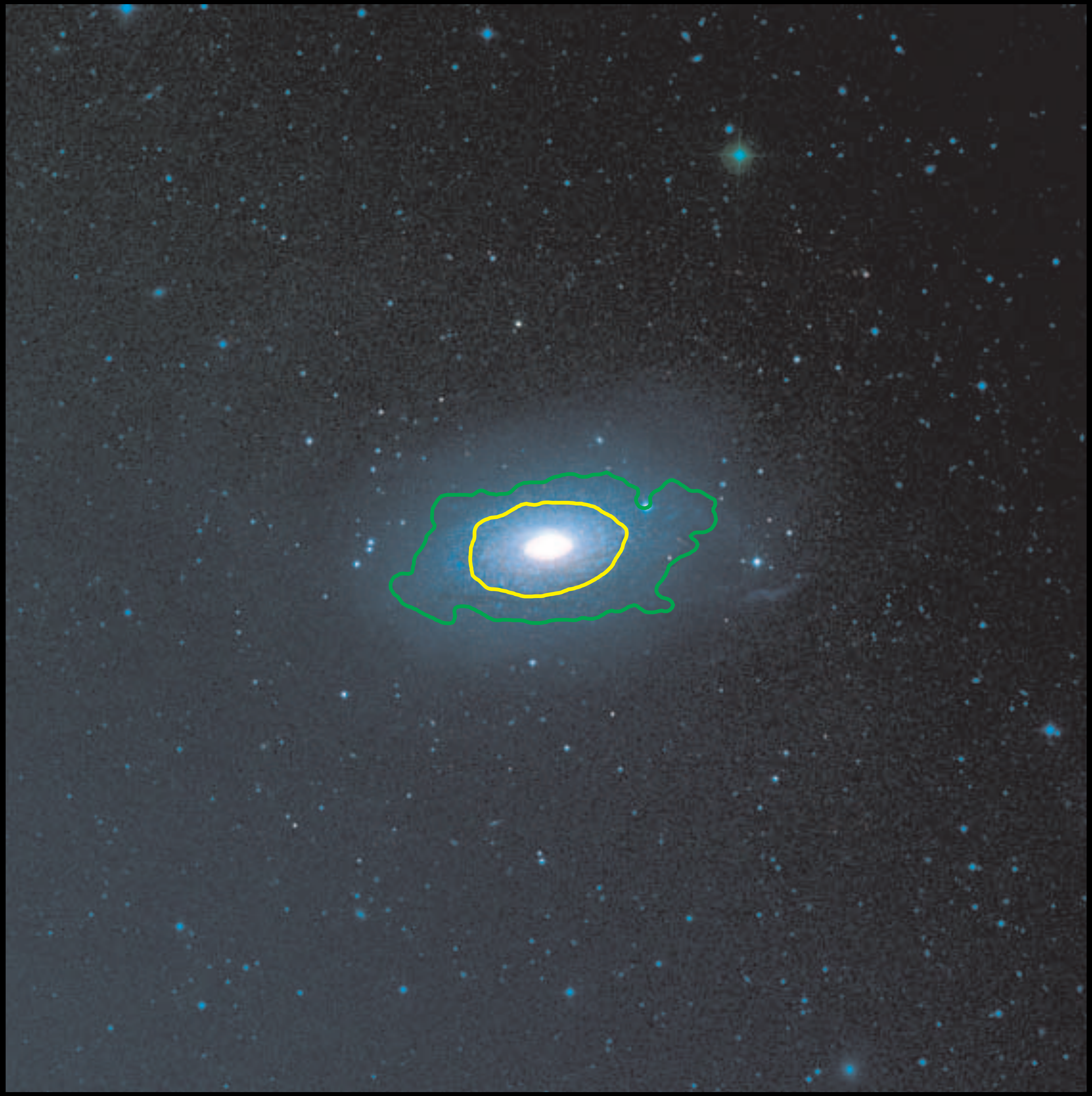


Arp 220 observed SED (boxes) plus model fit (line); Groves+ 2008

FUV continuum

SFR tracers IV

- O and B stars produce significant FUV (~130 - 170 nm)
- Saturates at ~30 - 50 Myr, so can be used as SFR indicator on those timescales
- Good: more sensitive to low levels of SF than Hα or similar; near-zero background
- Bad: space-only, very vulnerable to dust extinction



NGC 5055 in FUV; Thiker+ 2007

Combined estimators

SFR tracers V

- Most reliable estimators use multiple bands, usually one to capture dust-obscured star formation and one to capture unobscured
- Common examples: Hα (ground) + 24 μm (Spitzer), FUV (GALEX) + 24 μm (Spitzer), Hα (ground) + 160 μm + 250 μm (Herschel), etc.
- Important note: combined estimators essentially all require some form of space-based data — no real way to get dust-reprocessed IR contribution from the ground