Class 15: Discs and outflows: observations

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Outline

- Order of magnitude estimates of disc properties, and their implications for observations
- Observations of discs
  - Spectral energy distributions
  - Optical / IR imaging
  - Millimetre continuum imaging
  - Molecular lines
- Observations of outflows
  - Optical
  - Radio

Disc properties

Physical considerations

- Before thinking about how to observe discs, it is helpful to have a general idea of characteristic sizes and masses
- Discs form due to conservation of angular momentum
- Consider a protostellar core of mass *M*, radius *R*, rotating at angular velocity Ω; define ratio of rotational to gravitational energy: $\beta = \frac{(1/2)I\Omega^2}{aGM^2/R}$
- For a uniform sphere with density ρ, $\beta = \frac{\Omega^2}{4\pi G\rho}$
- Observations and turbulence simulations both find that $\beta \sim 0.02$ is typical

Circularisation radius

Characteristic size of a disc

- Fluid starting at cylindrical radius ϖ_0 has specific angular momentum $j = \varpi_0^2\Omega$
- As it falls toward star of mass m, once it reaches radius $\varpi \ll \varpi_0$, conservation of energy implies total velocity is $v = (2Gm / \varpi)^{1/2}$
- Radial forces don't change j, so $j = v_\varphi\varpi = \varpi_0^2\Omega$; minimum radius to which material can fall at constant j is when $v_\varphi = v \rightarrow \varpi = \varpi_0^4\Omega^2 / Gm = 4\pi\rho\beta\varpi_0^4 / m$
- If star just consists of material that started interior to ϖ_0, $m \approx (4/3)\pi\rho\varpi_0^3$, so $\varpi \sim \beta\varpi_0 \rightarrow$ disc size is $\sim\beta R \sim 100$ AU for typical $R \sim$ few x 0.01 pc

Disc masses and surface densities

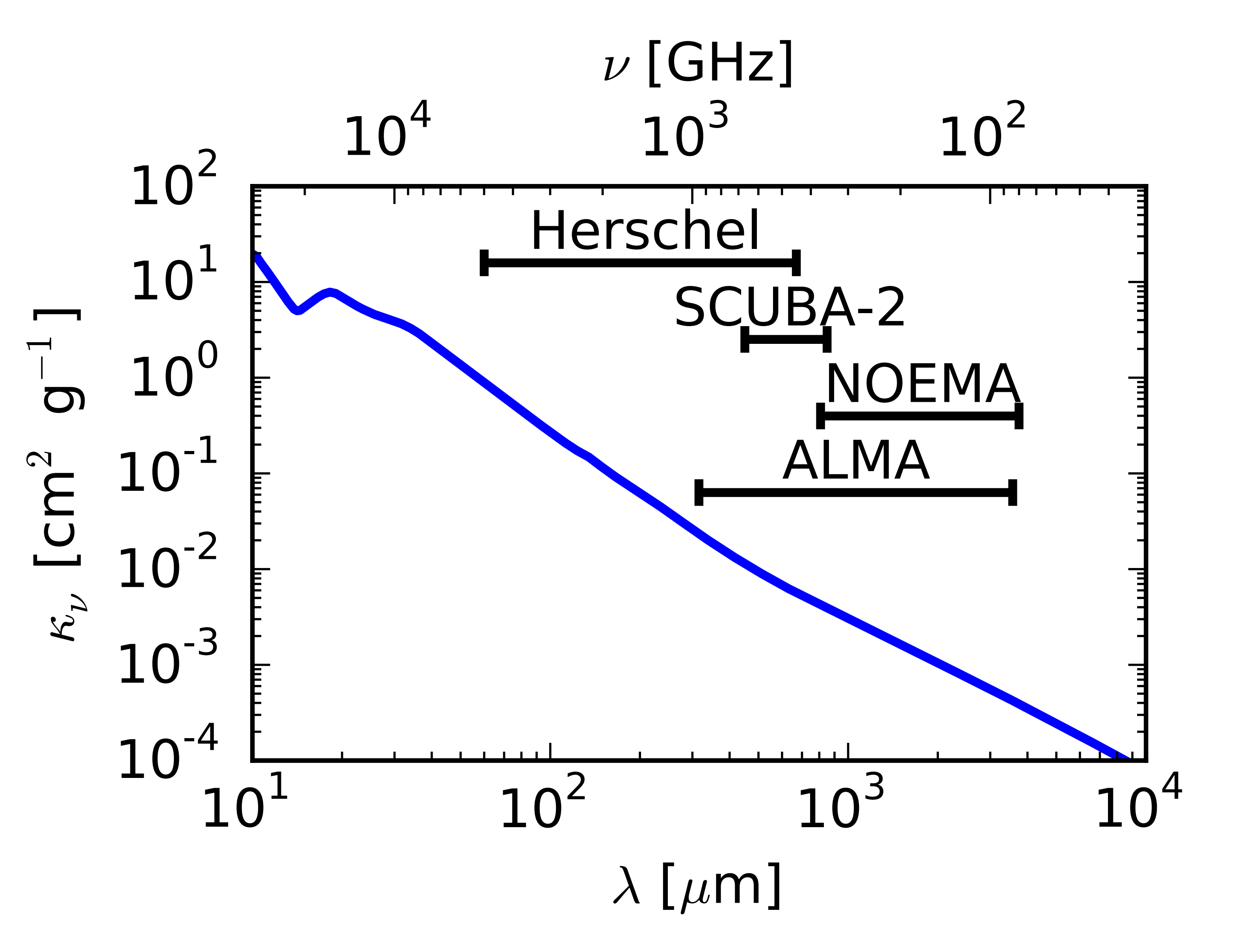
Expectations

- During main accretion onto star, disc mass can be tens of percent of star mass — any more and disc tends to fragment
- Thus for 1 $M_\odot$ star, expect ~0.1 $M_\odot$ disc, 100 AU in size → surface density $\Sigma \sim 10^3$ g cm^{-2}
- Surface densities will be larger at smaller radii, smaller at later stages of evolution when disc is less massive compared to central star

Observational implications

Of disc sizes and surface densities

- At a typical protostar distance ~150 - 400 pc, 100 AU = 0.25 - 0.7 arcsec; telescopes for comparison:
  - Herschel (FIR) → > 10 arcsec
  - Spitzer (MIR) → > 2 arcsec
  - HST / JWST / ground-based AO (NIR - NUV) → 0.05 - 0.2 arcsec
  - VLA / ALMA interferometry → ~0.01 arcsec
- Optically thick if $\kappa \gtrsim 10^{-3}$ cm^2 g^{-1} → opaque at wavelengths $\lesssim$ 1 mm (except for very late stage, low surface density discs), transparent at $\gtrsim$ 1 mm



What do the preceding statements imply about strategies for observing discs? What can and can't we measure in different wavebands (e.g. optical vs. IR vs. mm)? What kinds of measurements (imaging vs. photometry) work best where?

Observing strategies

Based on expectations

- Discs marginally resolvable in space-based optical and ground-based NIR AO, well-resolved by ground-based radio interferometers
- Observations at all wavelengths shorter than ~1 mm will only see the disc surface even if they resolve it → can’t measure masses
- Thus in most circumstances, imaging is best done by radio interferometers
- However, high-resolution radio interferometry is expensive — biggest samples are few hundred sources; by contrast, broadband photometry available for thousands of sources

Disc spectral energy distributions

What we can extract from broadband photometry

- To learn what we can extract from photometry, consider an idealised cylindrically-symmetric thin disc, characterised by surface density $\Sigma(\varpi)$, temperature $T(\varpi)$, going from ϖ_0 to ϖ_1
- Disc is inclined to line of sight by angle θ; $\theta = 0$ is face-on, $\theta = 90°$ is edge-on
- In broadband observations dust is only significant emitter / absorber; dust opacity per unit mass κ_λ at wavelength λ
- Cannot just assume ISM dust — grains tend to grow in discs; instead assume a generic power law $\kappa_\lambda = \kappa_0 (\lambda / \lambda_0)^{-\beta}$

Physics question: suppose grains grow in discs. How would you expect this to affect the opacity? Should it go up or down? At what wavelengths?

Calculation of observed flux

From an inclined disc

- Flux related to emergent intensity I_λ by $F_\lambda = \int I_\lambda \, d\Omega$
- Solid angle subtended by material from ϖ to $\varpi + d\varpi$ at distance D is $d\Omega = (2\pi\varpi/D^2) \cos\theta \, d\varpi$, so $F_\lambda = \frac{2\pi\cos\theta}{D^2}\int_{\varpi_0}^{\varpi_1} I_\lambda(\varpi)\varpi \, d\varpi$
- Assuming material in disc is in thermodynamic equilibrium (good assumption because density is high), $I_\lambda = B_\lambda(T)\left(1 - e^{-\tau_\lambda}\right)$
- Optical depth is $\tau_\lambda = \kappa_\lambda \Sigma / \cos\theta$
- Thus if we know $T(\varpi)$, $\Sigma(\varpi)$, and κ_λ, can evaluate integral and compute flux

Disc spectral energy distributions

Limiting cases

- We generally cannot find a unique solution for $T(\varpi)$, $\Sigma(\varpi)$ given the observed SED alone — too many degeneracies
- Can constrain approximate properties, however, by comparing to models
- We can also draw conclusions by considering limiting cases:
  - For IR observations, disc is almost certainly optically thick, so can assume $\tau_\lambda \gg 1$ and evaluate integral by setting $\exp(-\tau_\lambda) \approx 0$
  - For mm and longer wavelength observations, disc is transparent so can assume $\tau_\lambda \ll 1$ and $1 - \exp(-\tau_\lambda) \approx \tau_\lambda$

Disc SEDs

The optically thick limit

- In the optically thick limit, we have $F_\lambda = \frac{4\pi \cos\theta}{D^2} \frac{hc^2}{\lambda^5} \int_{\varpi_0}^{\varpi_1} \frac{\varpi}{\exp\left(hc/\lambda k_B T\right) - 1} d\varpi$
- Suppose that temperature falls as power law in radius, $T(\varpi) = T_0(\varpi/\varpi_0)^{-q}$
- Simplify via the substitution $x = \left(\frac{hc}{\lambda k_B T_0}\right)^{1/q} \frac{\varpi}{\varpi_0}$
- This gives $F_\lambda = \frac{4\pi \cos\theta}{D^2} \frac{hc^2}{\lambda^5} \left(\frac{hc}{\lambda k_B \varpi_0^q T_0}\right)^{-2/q} \int_{x_0}^{x_1} \frac{x}{\exp\left(x^q\right) - 1} dx$
- In general for an IR observation, we expect $x_0 \ll 1$ and $x_1 \gg 1$, so final integral is just a pure number that depends on q; no dependence on λ
- Implication: $\lambda F_\lambda \propto \lambda^{-4+2/q}$ → IR SED slope determines how T falls with radius

Disc SEDs

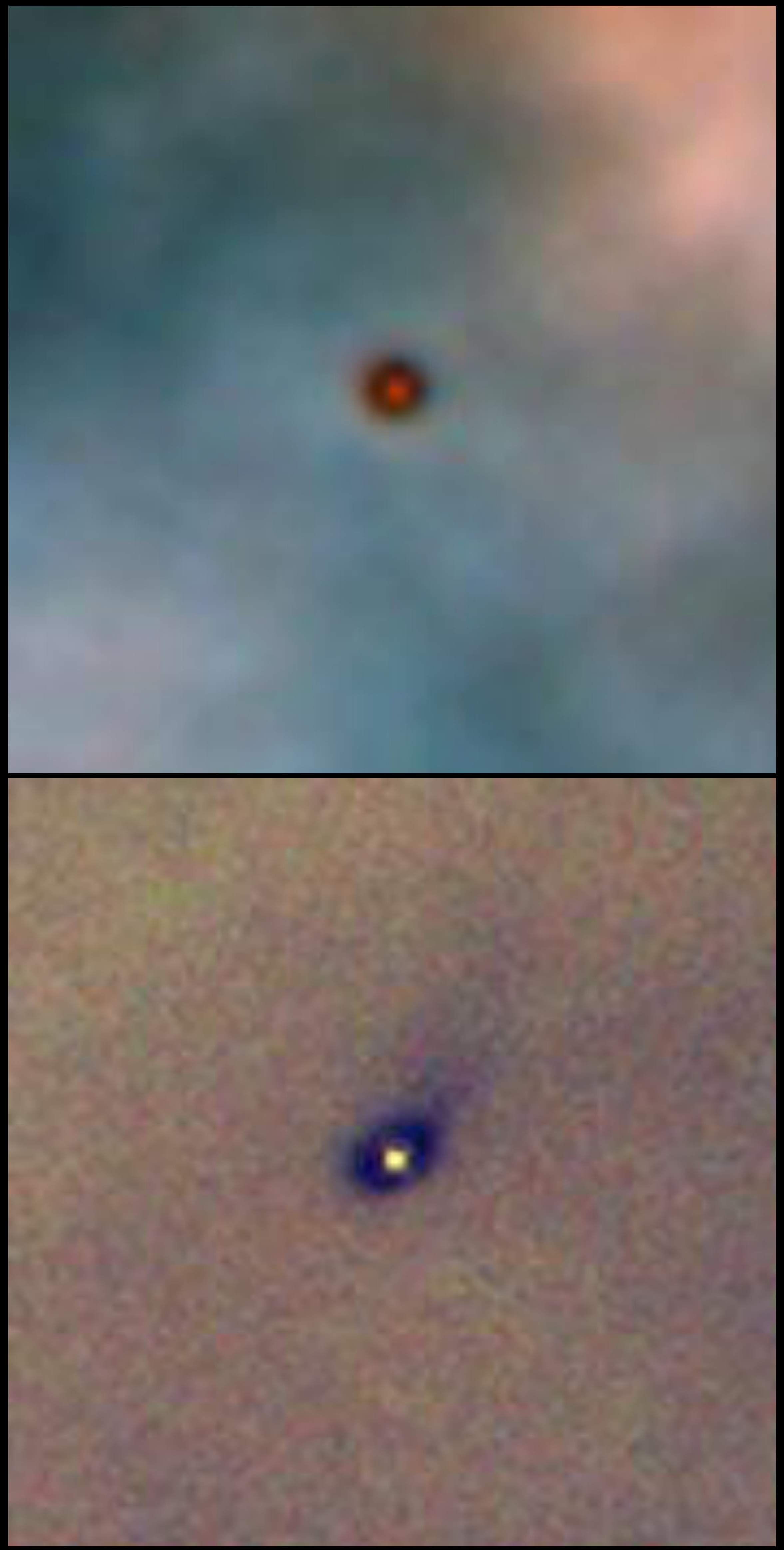
The optically thin limit

- In optically thin limit $1 - \exp(-\tau_\lambda) \approx \tau_\lambda = \kappa_\lambda \Sigma / \cos\theta$
- In mm (where optically thin limit applies), $hc/\lambda k_B T \ll 1$, so use long-wavelength limit of Planck function: $B_\lambda(T) \approx 2ck_B T/\lambda^4$
- Substitute into integral: $F_\lambda = \frac{4\pi c k_B \kappa_\lambda}{D^2 \lambda^4} \int_{\varpi_0}^{\varpi_1} \Sigma T \varpi \, d\varpi = \frac{4\pi c k_B \kappa_0}{D^2 \lambda^4} \left(\frac{\lambda}{\lambda_0}\right)^{-\beta} \int_{\varpi_0}^{\varpi_1} \Sigma T \varpi \, d\varpi$
- Therefore SED $\lambda F_\lambda \propto \lambda^{-3-\beta}$: SED shape constrains dust opacity index
- Moreover, if opacity constant κ_0 known at $T \approx$ constant (roughly true in outer disc where most mm emission arises), can estimate disc mass

Imaging discs

The O/IR regime

- Discs resolvable with HST or ground-based AO
- Only disc surface can be seen, and only in class II or later systems where envelope has been cleared
- Two regimes of interest:
    - Absorption against background nebulosity — probes outer disc
    - Scattered starlight coming off disc surface — mostly probes inner disc; interpretation complex due to dependence on grain optical properties

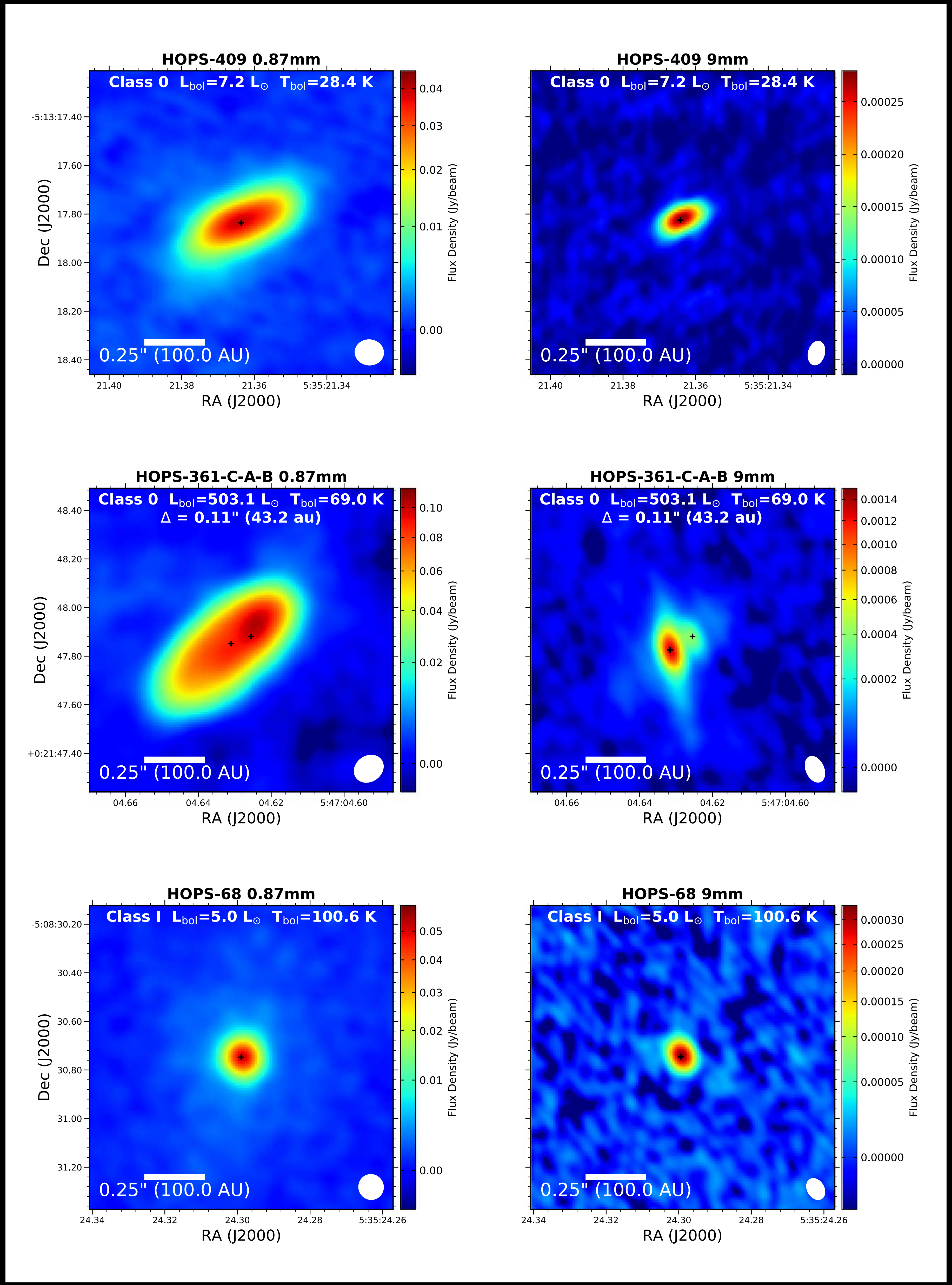


Discs on Orion imaged by HST, seen in absorption against the Orion nebula

Imaging discs

The mm regime

- Appearance depends on stage:
  - Class 0/I discs generally smooth
  - Class II discs have lots of structure (more on this later in course)
- Typical size ~50 AU at class 0/I, falling to ~25 AU at class II
- Can only measure dust mass, not gas mass, because dust opacity per unit gas mass not known in discs due to grain growth (more later in course)

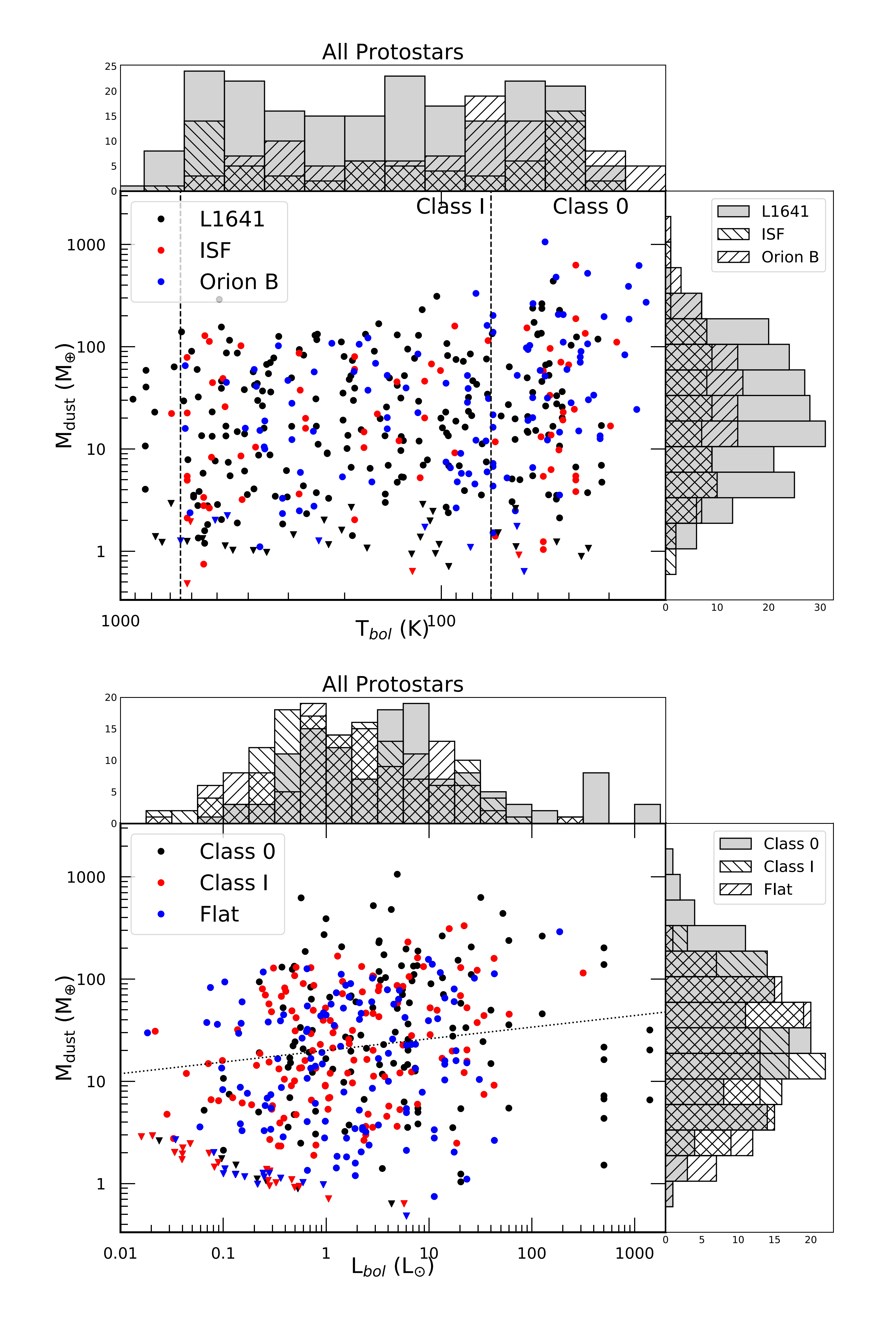


Three sample resolved discs from the VANDAM survey (Tobin+ 2020)

Disc statistics

Based on mm dust observations

- Huge range of dust masses, ~1 - 1000 $M_\oplus$
  - For a “normal” dust to gas ratio, this would imply gas mass ~3×10^{-4} - 0.3 $M_\odot$
  - Likely an underestimate, since grain growth typically lowers opacity / unit gas mass
- Only weak correlation with protostar stage or luminosity during class 0/I phase
- Stronger dependence at later ages: class II discs less massive than class 0 or class I

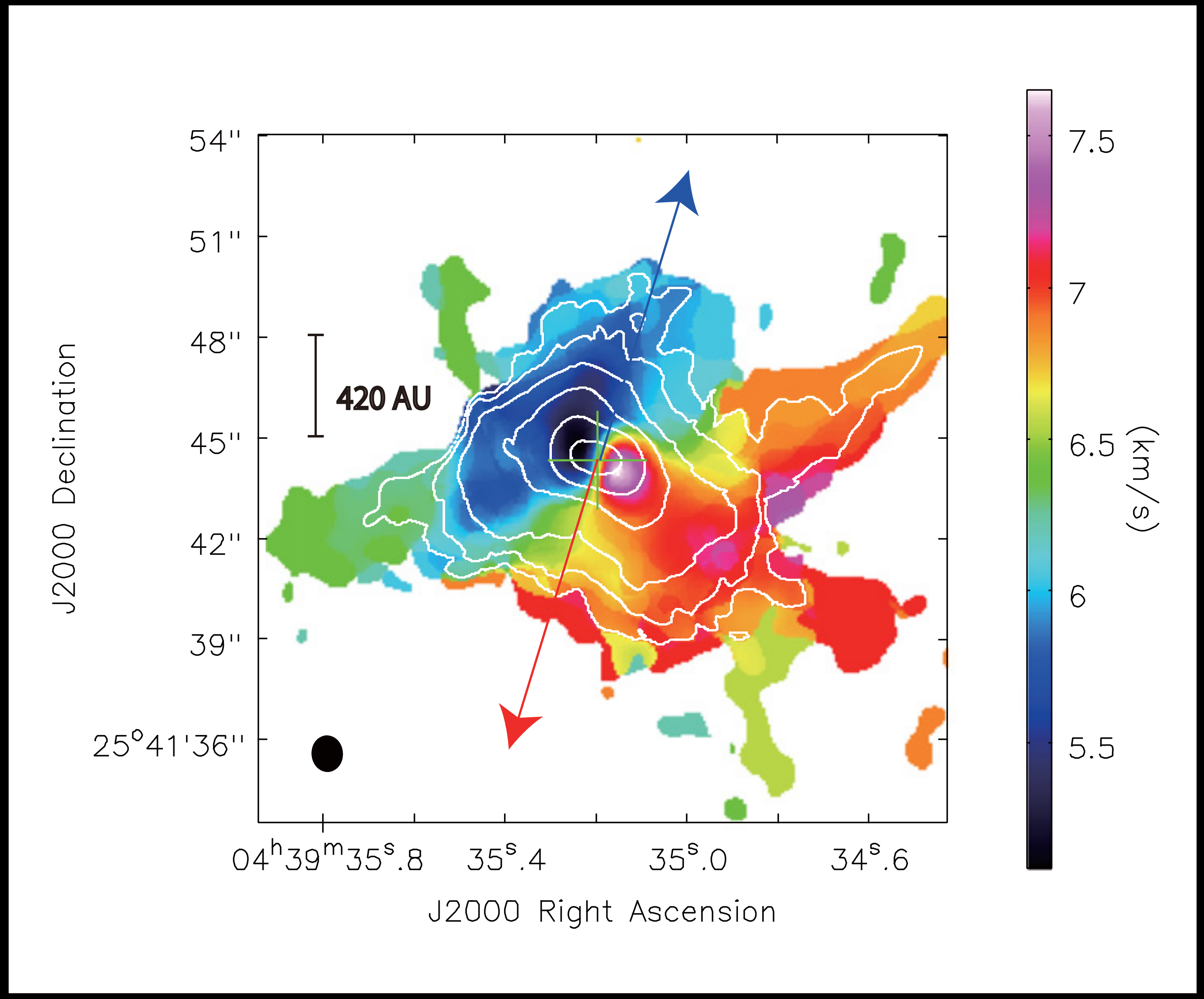


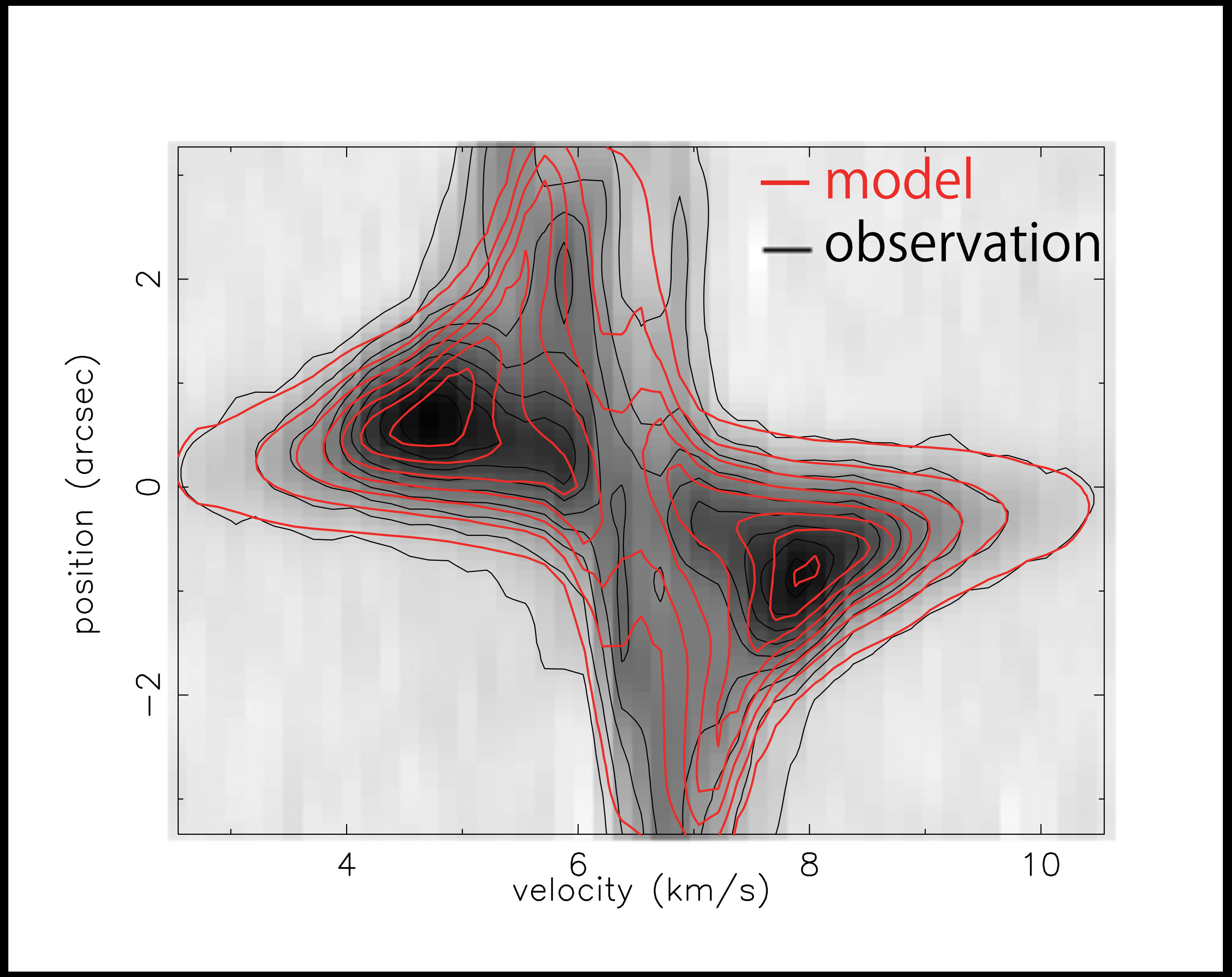
Tobin+ 2020

Imaging in molecules

Disc kinematics

- Molecules vs. dust tradeoff:
  - Dust is simple to interpret, brighter
  - Molecules provide information on temperature, chemistry, kinematics, etc.
- Need to use low-abundance molecules to avoid optical depth problems
- Observations show Keplerian rotation common around protostars from class 0 phase on; inner disc often joined to an outer inflow that is rotating at sub-Keplerian speeds





Kinematics of disc around TMC-1A in $C^{18}O$, Aso+ 2015

Outflows

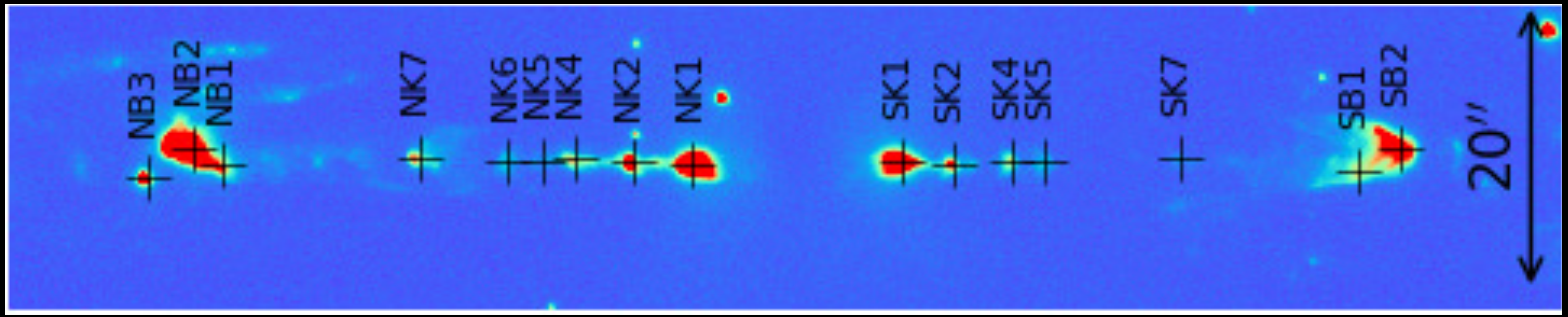
The inevitable accompaniment to discs

- Almost everywhere there are discs, they appear to be accompanied by bipolar outflows — discs around protostars are no exception
- Outflows observed to be perpendicular to planes of discs
- Two basic wavelength regimes for observing outflows:
  - O/IR — traces fastest-moving material, and locations where this fast material runs into the surrounding ISM
  - Molecular lines — traces bulk of material in outflow, moving at slower speeds, but can be difficult to trace over long distances due to mixing with ambient molecular gas

Outflows in O/IR

Commonly called jets or HH objects

- Material ejected at speeds ≳ 100 km s^{-1} shocks when it strikes dense ISM
- Shock-heated material emits optical (Hα, OI, NII, …) and IR (rotationally-excited H_2) lines
- Visible as a linear series of “knots”, often mirror-symmetric about star, sometimes with a bow shock



Top: HH jets seen with HST
Bottom: knots in H_2 rotational emission at 2.1 μm, imaged with Spitzer/IRAC (Noriega-Crespo+ 2020)

Properties of O/IR outflows

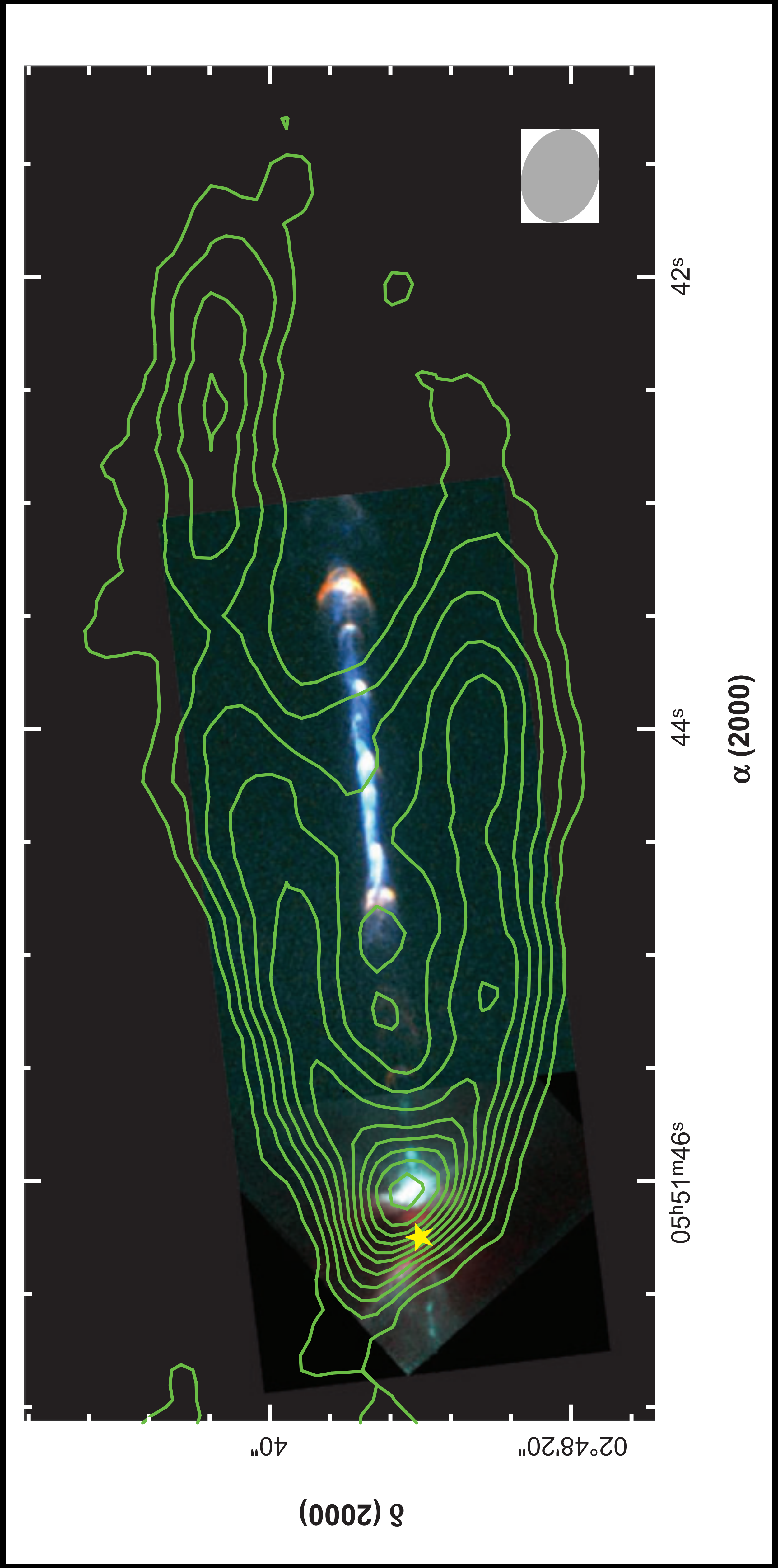
A quick summary

- HH knots move at speeds of hundreds of km s^{-1} — big enough to see proper motion over ~10 year baseline
- Material between knots visible at low surface brightness; can also be seen in radio free-free emission
- Mass outflow rate hard to estimate, but low — $\lesssim 10^{-7}\ M_\odot\ yr^{-1}$; estimated by modelling density of material in jet required to reproduce observed line emission spectra
- Extremely narrow — opening angle $\lesssim 1°$

Outflows in molecular lines

The bulk tracer

- Outflows also seen in high-velocity molecular lines, ~10 - 100 km s^{-1}
- Molecular material much wider angle, forms conical sheath around inner outflow seen in O/IR
- Molecular material also much denser — even accounting for lower speed, dominates total mass and momentum flux
- Interpretation: material launched at wide range of velocities, fastest close to axis, slower at larger angles



McKee & Ostriker (2007)