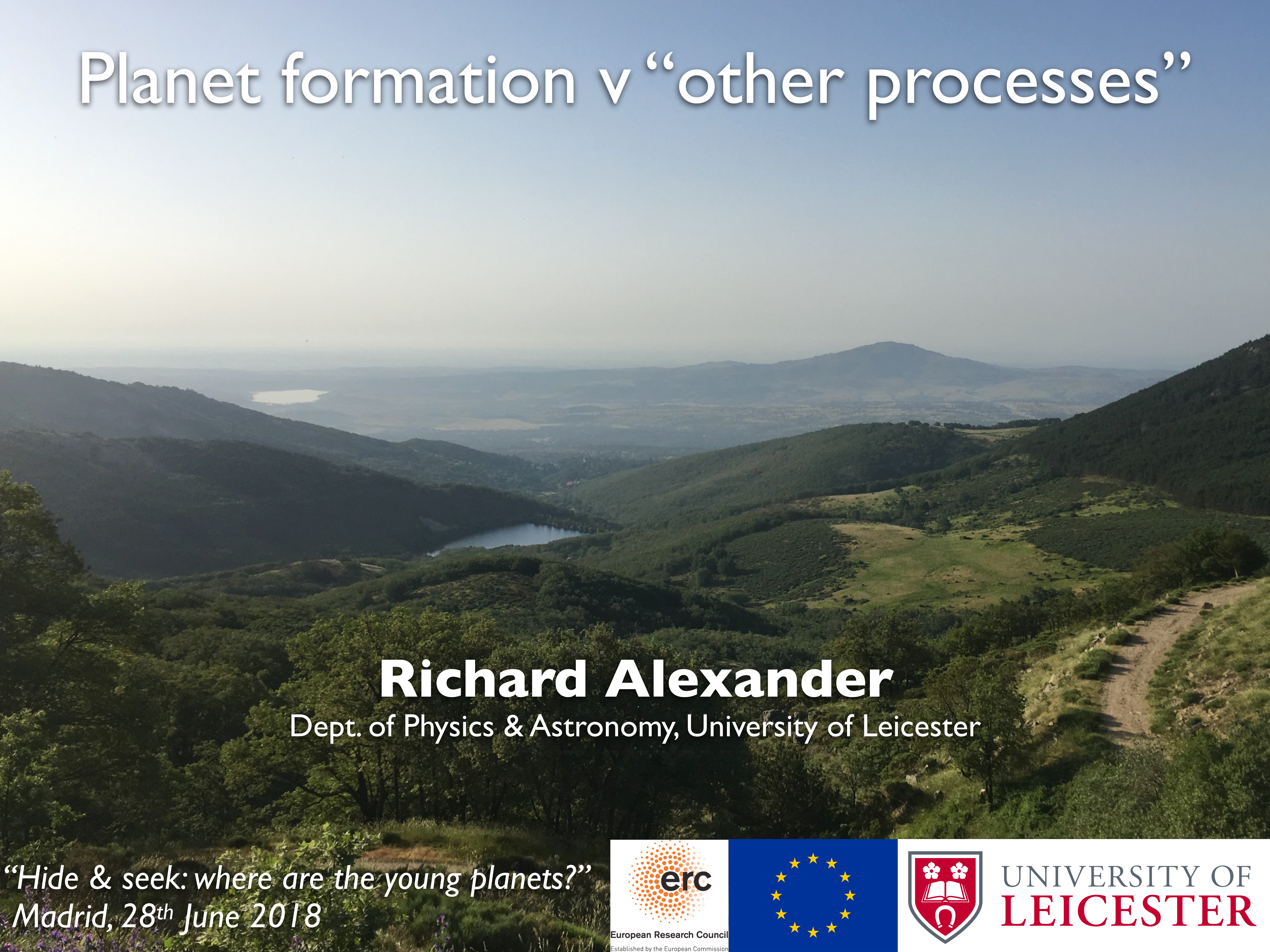

Planet formation v "other processes"

Richard Alexander

Dept. of Physics & Astronomy, University of Leicester

"Hide & seek: where are the young planets?"
Madrid, 28th June 2018

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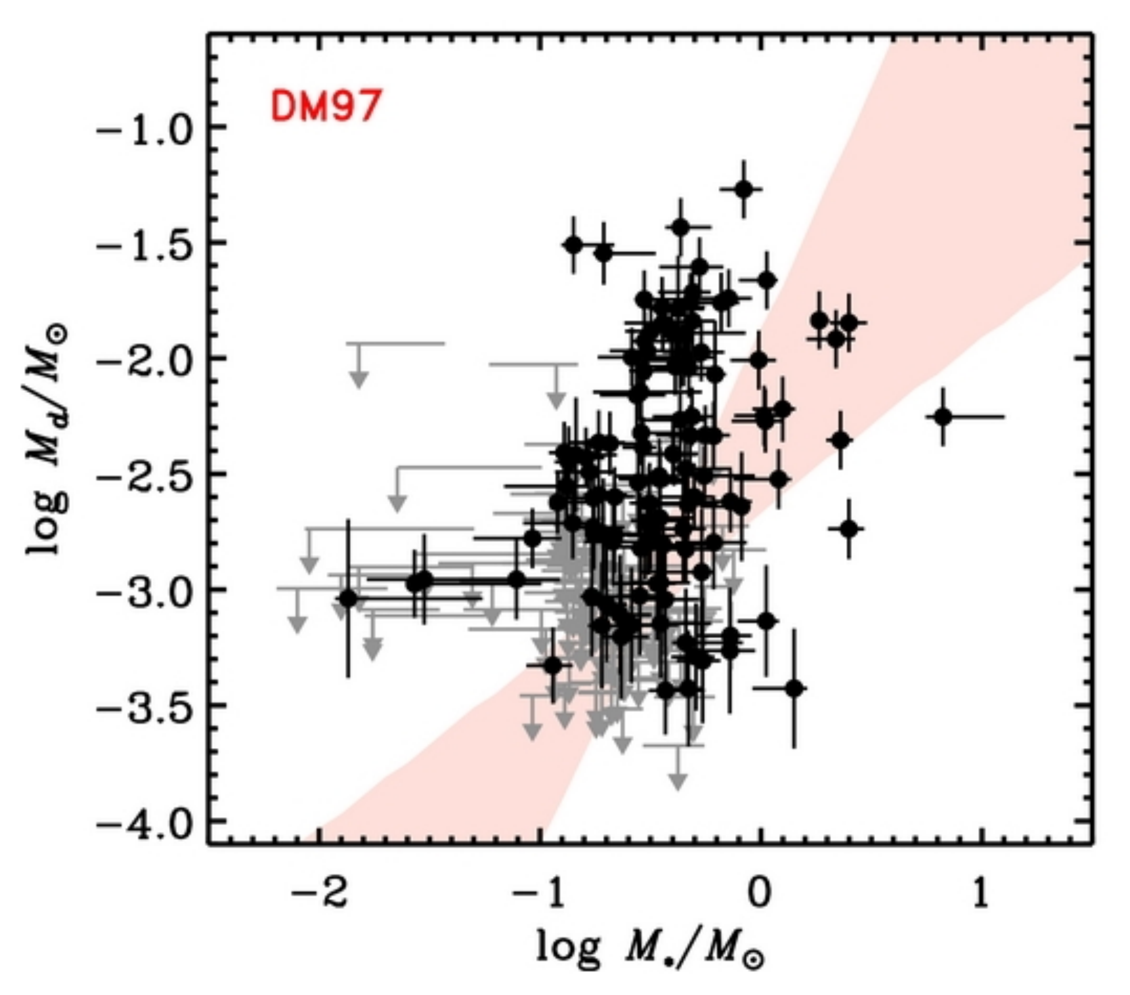
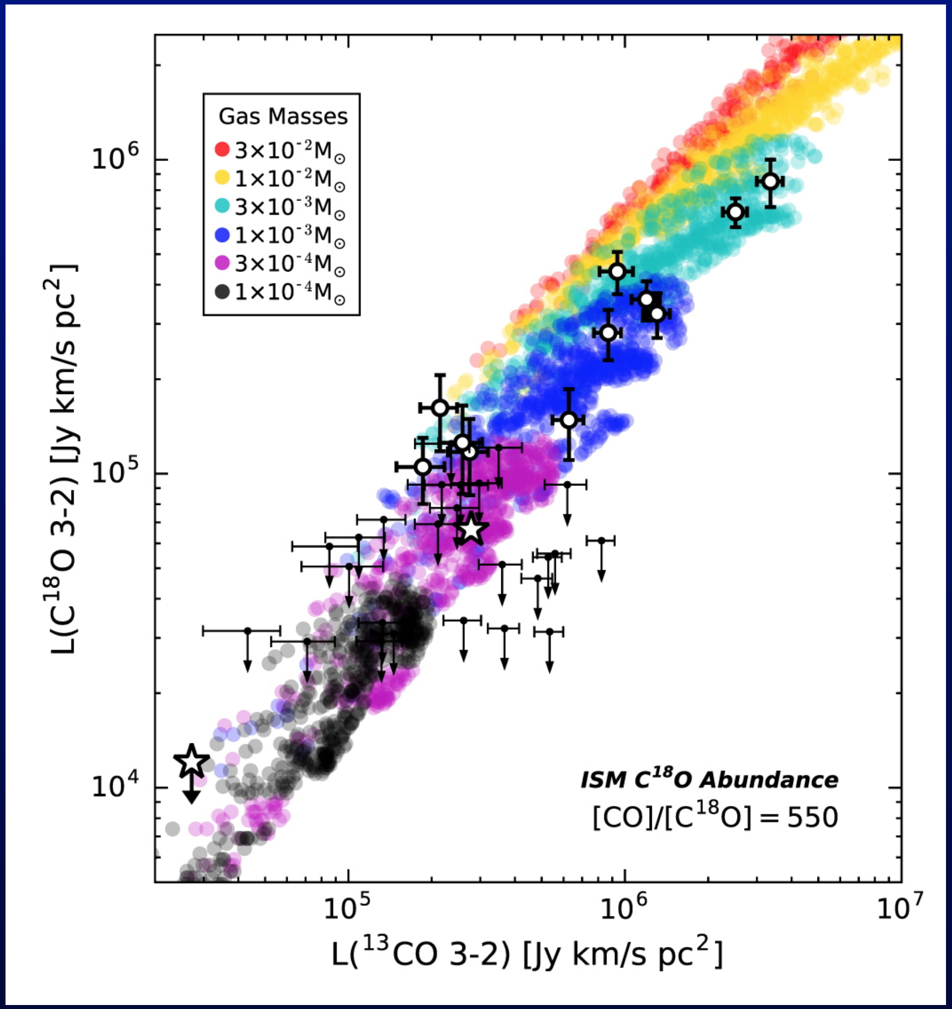
It’s not only about planets…



Andrews+ (2013)



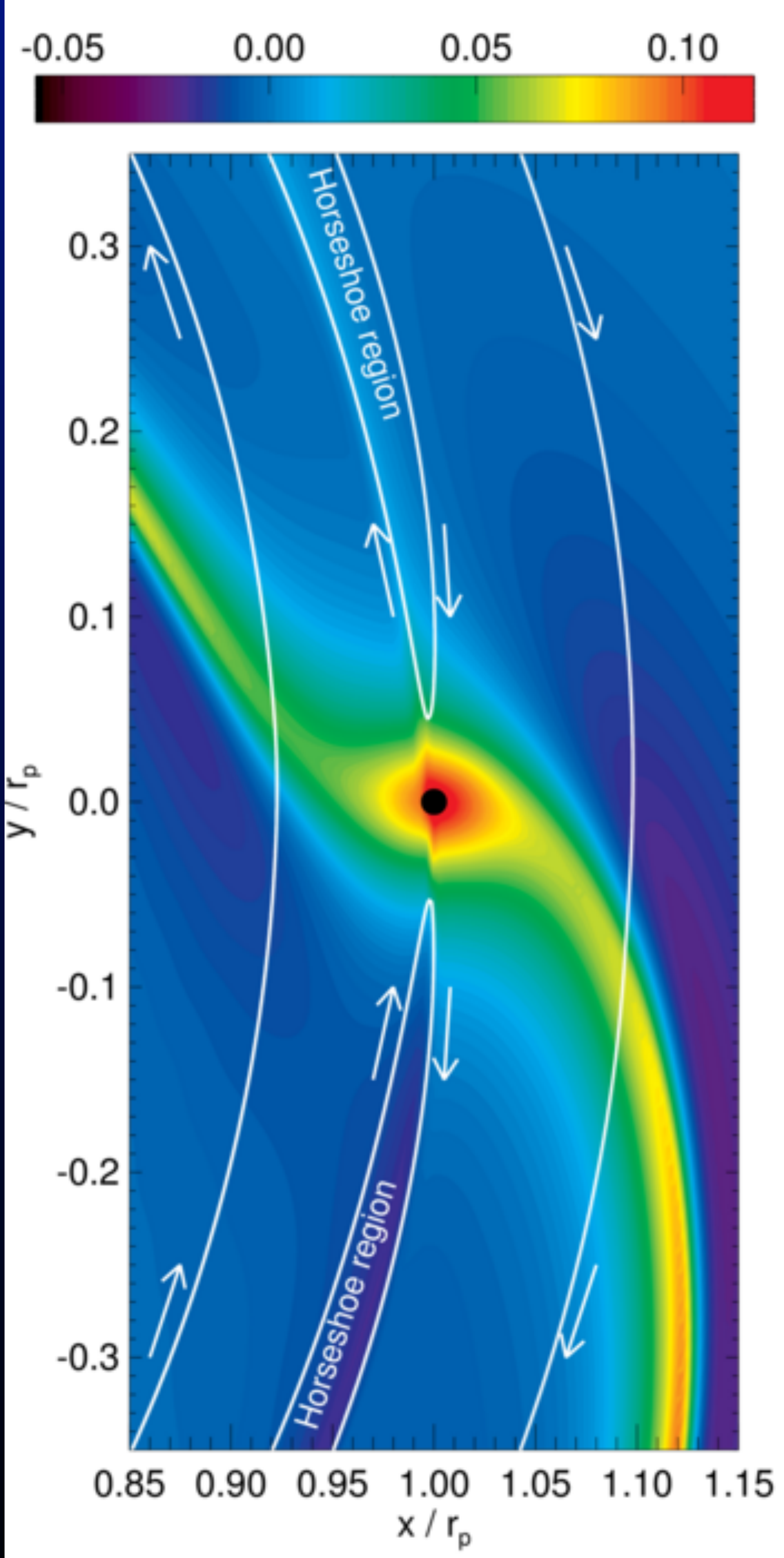
Andsell+ (2016)

- Median Class II disc mass ~5M_{Jup}.
  Class 0/I disc masses up to ~100M_{Jup}.
  Total mass accreted through disc ~1000M_{Jup}.
- Total mass in planets usually <1M_{Jup}.
- Planet formation is inefficient: >90% of disc (gas) mass does not end up in planets.

It's not even about planet formation…

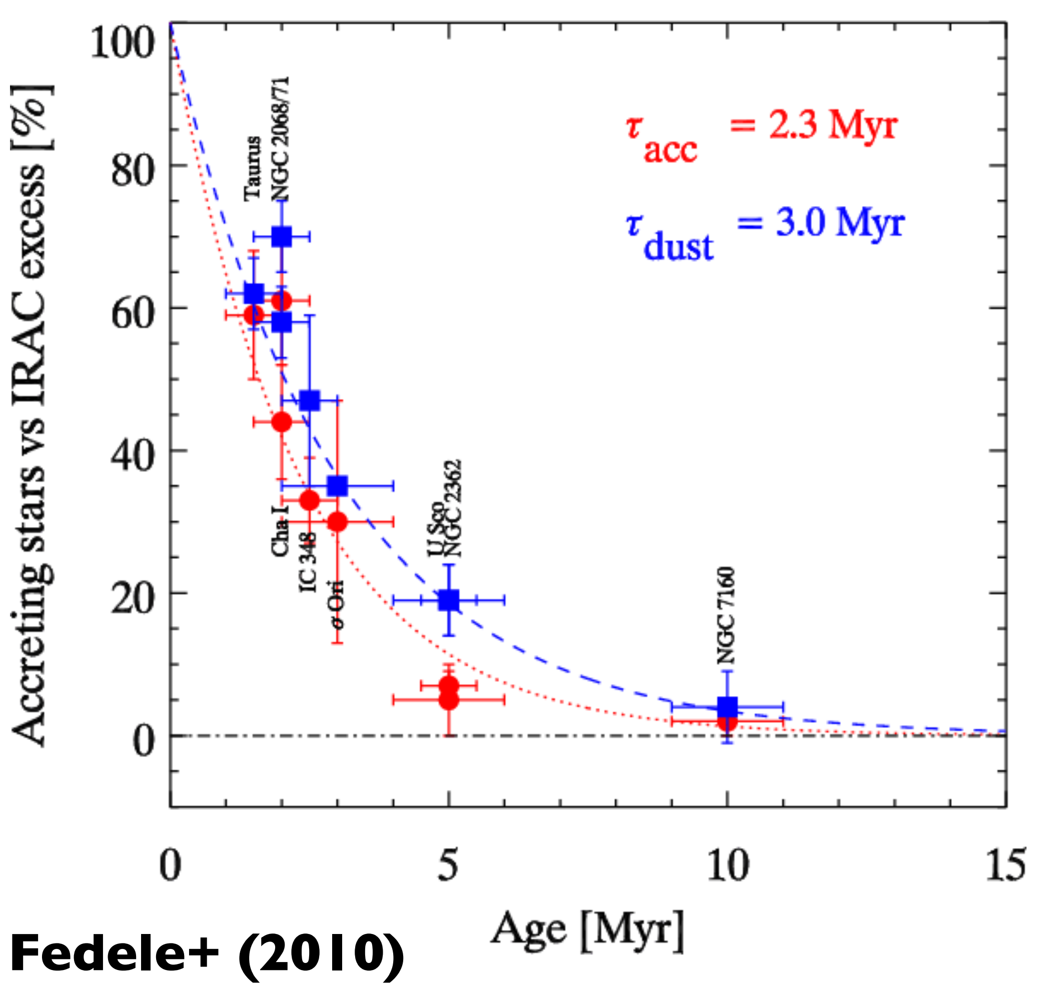
- Angular momentum is invariably dominated by the disc.
- Planet-disc interactions can drive rapid, large-scale migration. Expect ~100% changes in semi-major axis.
- Observed exoplanet orbits probably tell us more about migration than they do about formation.

$$\tau_{\rm mig} \sim 10^5 {\rm yr} \left(\frac{M_p}{10\,M_\oplus}\right)^{-1} \times \left(\frac{\Sigma}{100\,{\rm g\,cm^{-2}}}\right)^{-1}$$

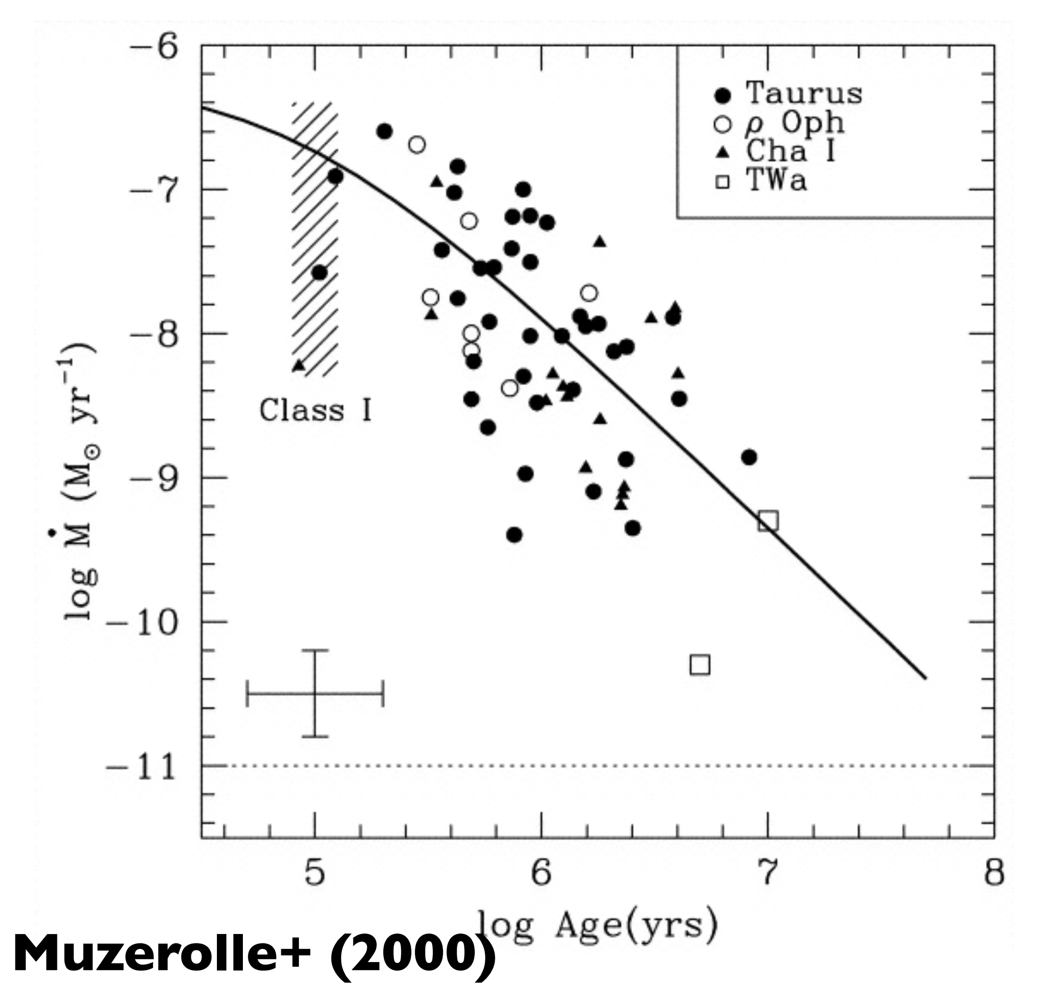


Baruteau+ (2014, PP6)

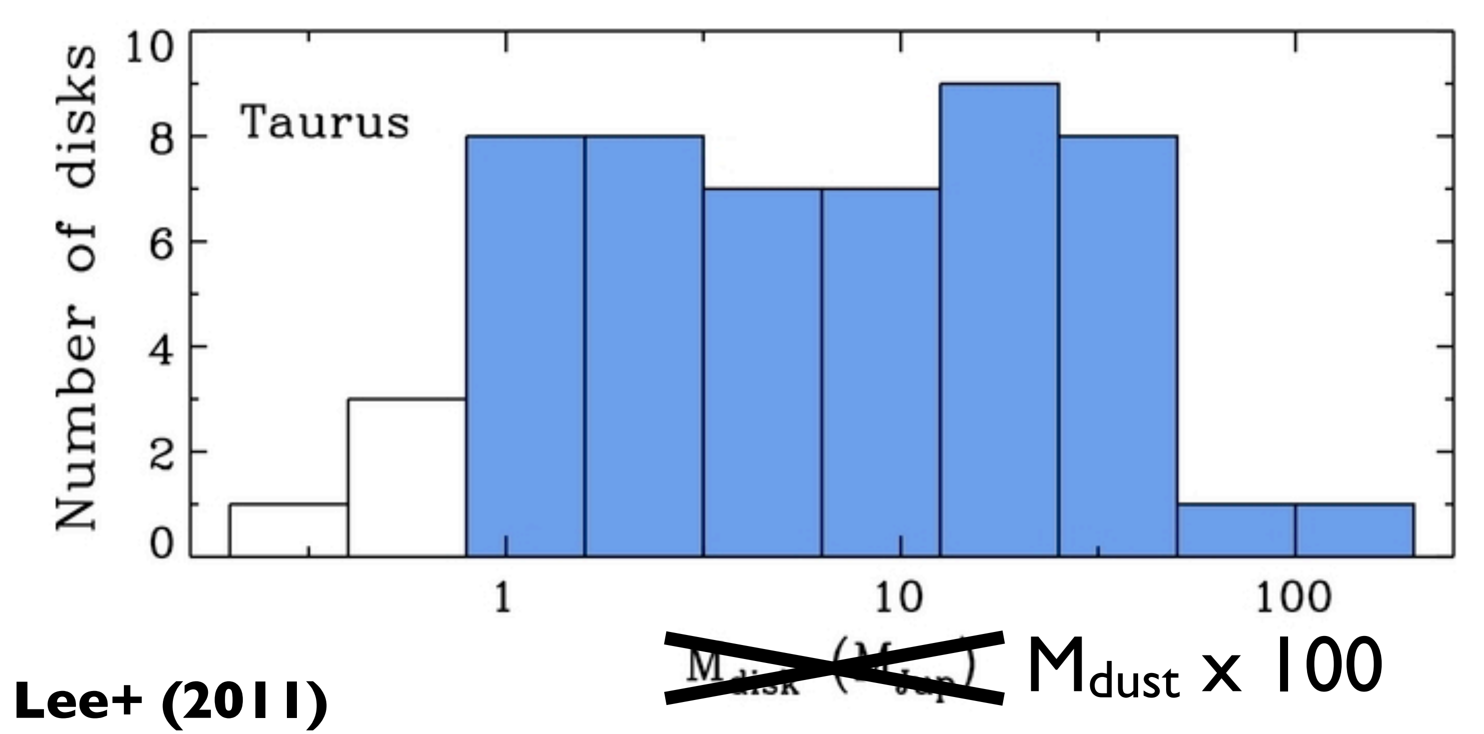
Gas accretes, so discs evolve



Fedele+ (2010)



Muzerolle+ (2000)



Lee+ (2011)

$$t_{\rm acc} = \frac{M_{\rm d}}{\dot{M}_{\rm acc}} \sim 10^{5-6}{\rm yr}$$

Understanding disc evolution is critical

- Disc evolution determines conditions for planet formation.
- Most disc material (gas) does not end up in planets.
- Disc lifetime (~Myr) is a strict upper limit on the formation time-scale for (giant) planets.
- Discs dominate the dynamics/evolution of young planetary systems (e.g., migration, gas accretion).

Impossible **to build predictive models of planet formation without first understanding disc dynamics & evolution.**

Why do discs evolve?

Angular momentum transport

Mass gain

Angular momentum loss

Mass loss

Gravitational perturbations

Disc evolution processes

Transport
“turbulence”, GI,
dust-gas drag

Mass gain
infall

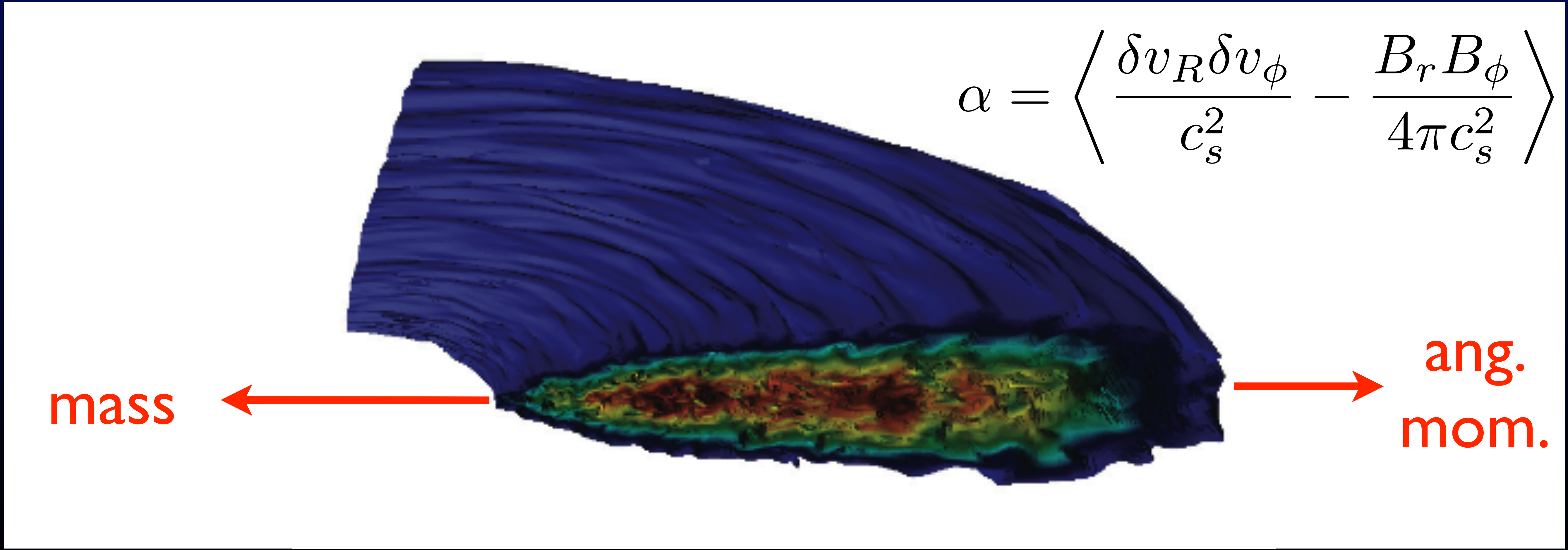
Ang mom loss
MHD winds/jets

Mass loss
evaporation

Perturbations
planets, binaries,
encounters

Angular momentum transport

- In ideal MHD, magnetorotational instability (MRI; Balbus & Hawley 1991) drives turbulence and ang. mom. transport.
- "Viscous" disc models a crude approximation (at best), but OK-ish(?) on long (>>dynamical) time-scales.
- Accretion can't be the only process: $t_\nu(100\mathrm{AU}) \gtrsim 1\mathrm{Myr}$.



$$\alpha = \left\langle \frac{\delta v_R \delta v_\phi}{c_s^2} - \frac{B_r B_\phi}{4\pi c_s^2} \right\rangle$$

Armitage (2011)

Angular momentum transport

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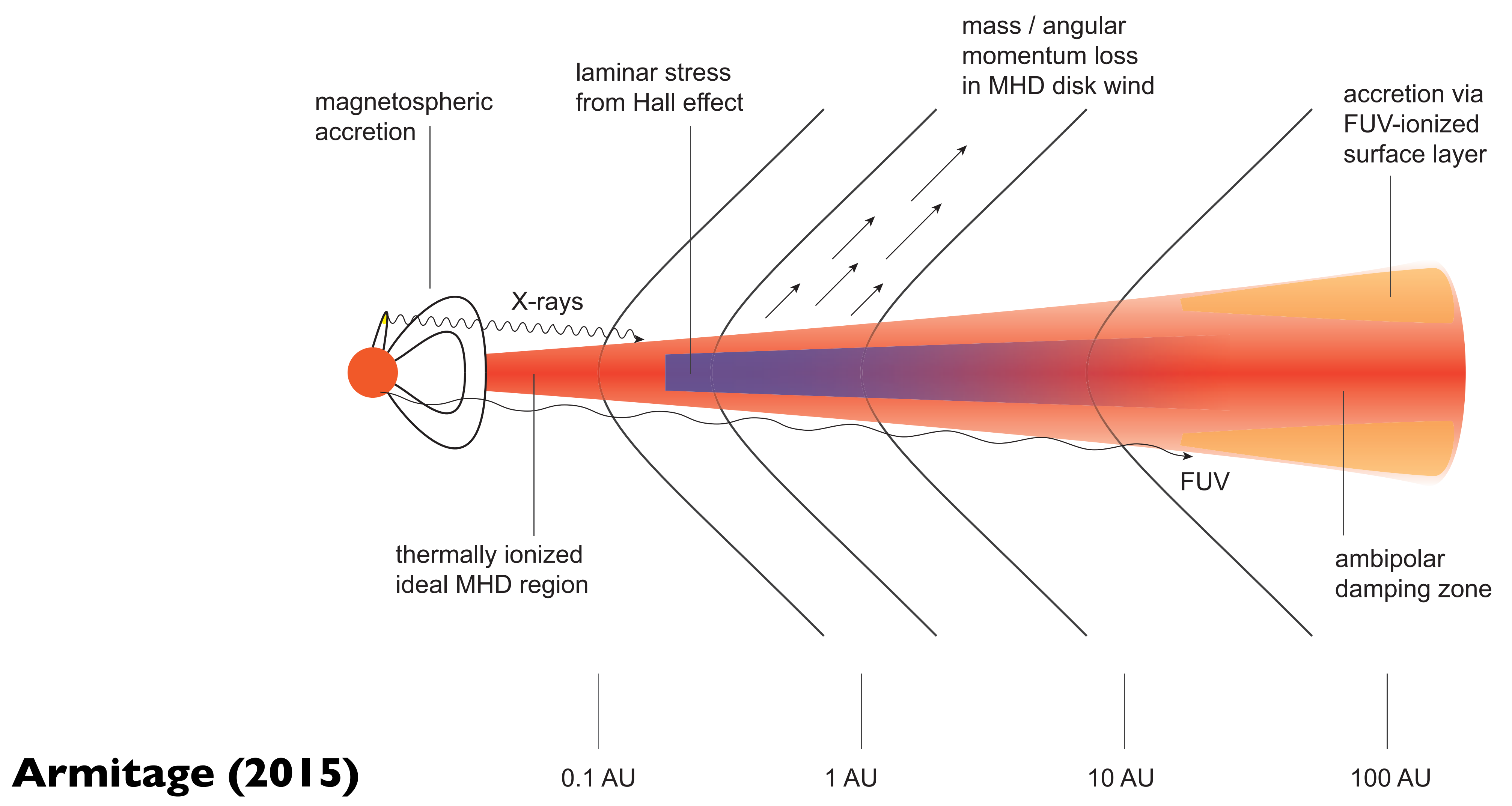
- Accretion can't be the only process: $t_\nu(100\mathrm{AU}) \gtrsim 1\mathrm{Myr}$.

- ***BUT...***
  - non-ideal effects (ambipolar diffusion & Ohmic dissipation) suppress the MRI in real discs (e.g., Turner et al., PPVI).
  - currently not at all clear that MHD turbulence is efficient enough to account for observed disc accretion rates.

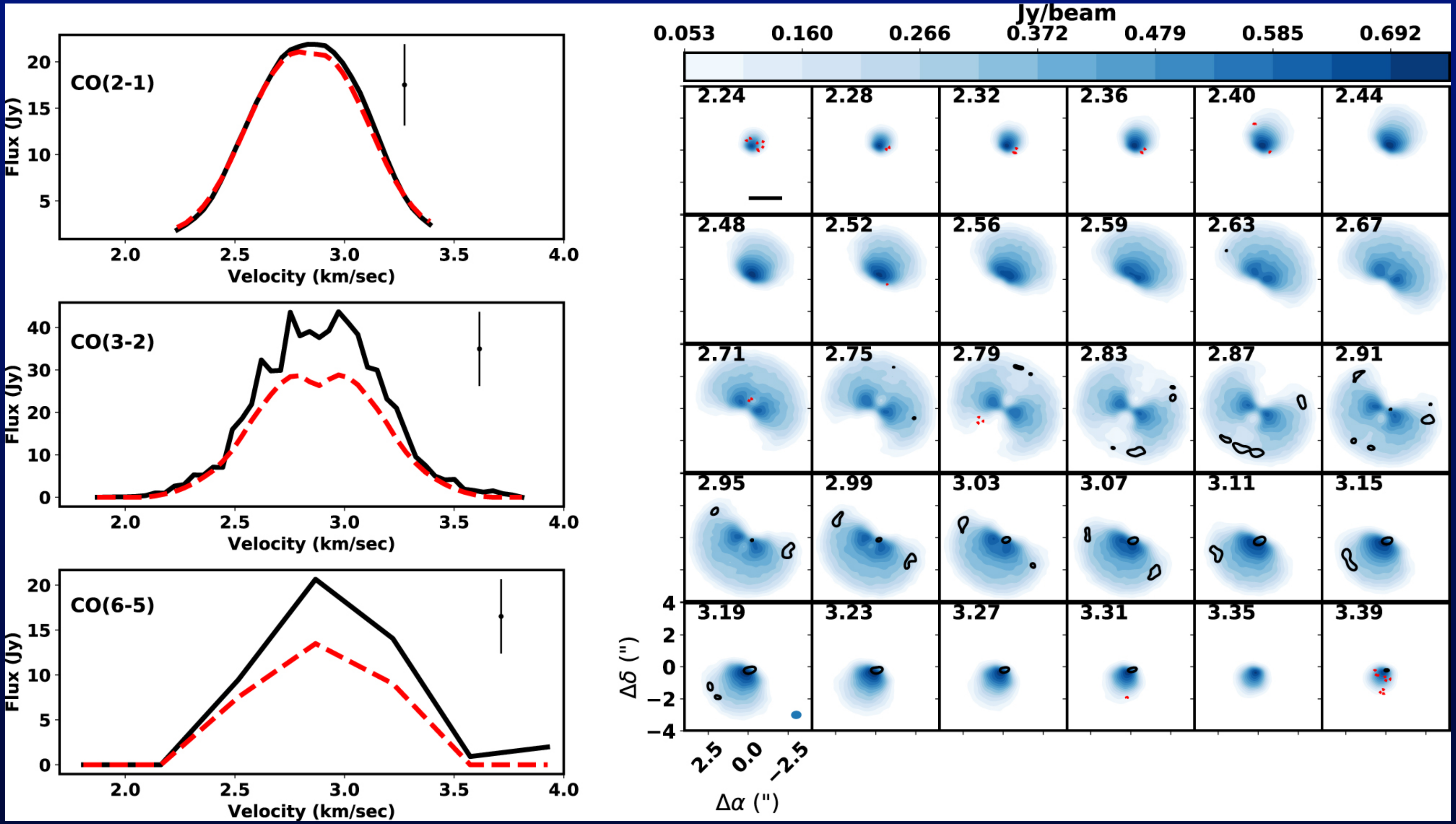
Angular momentum transport



Armitage (2015)

- non-ideal effects (ambipolar diffusion & Ohmic dissipation) <u>suppress the MRI</u> in real discs (e.g., Turner et al., PPVI).
- currently not at all clear that MHD turbulence is efficient enough to account for observed disc accretion rates.

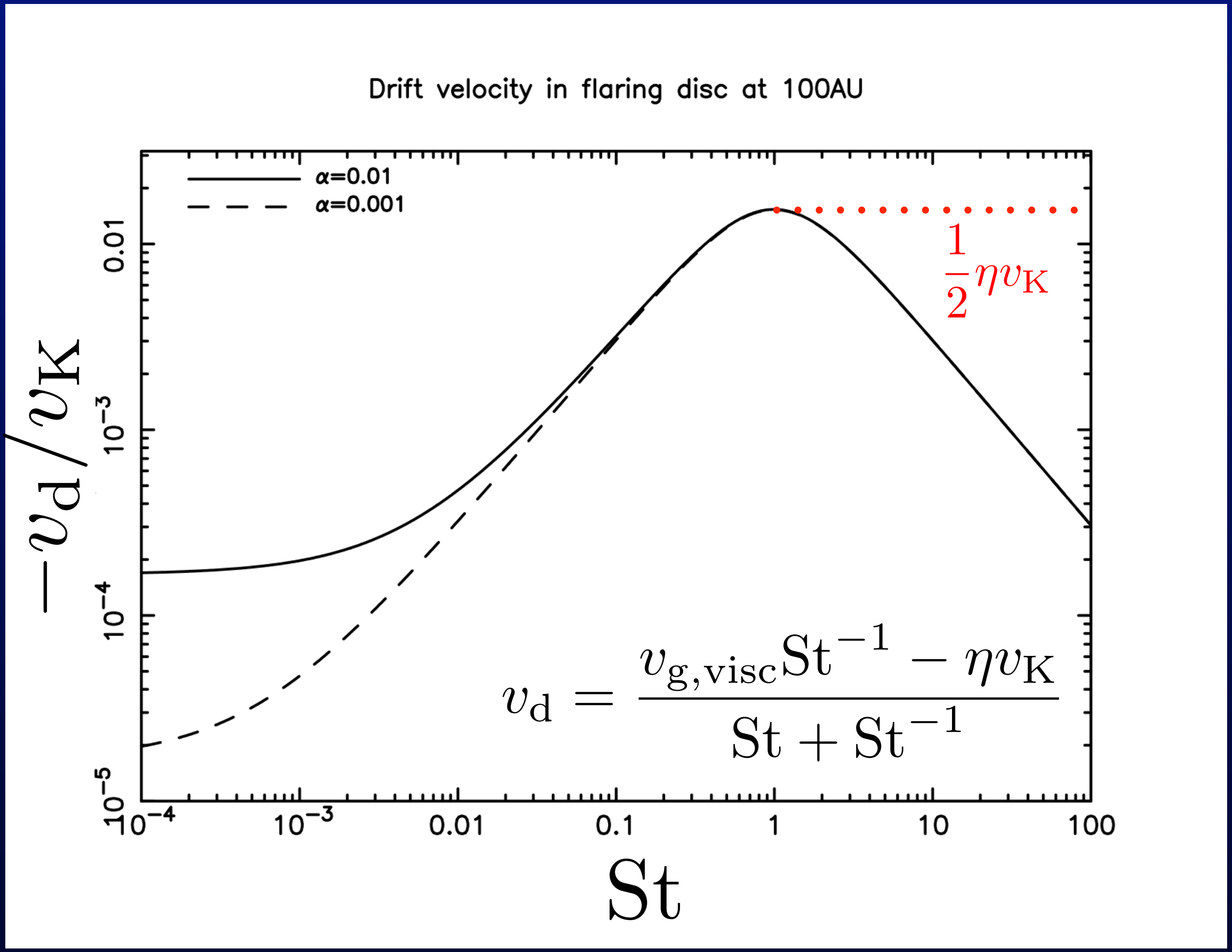
Are discs actually turbulent?



Flaherty+ (2018); see also Simon+ (2018)

- ALMA CO observations set very low upper limits on turbulent velocity dispersion in outer disc: $v_{\rm turb} \lesssim 0.05 c_{\rm s}$.
- Implies turbulence is inefficient ($\alpha \lesssim 10^{-3}$) beyond ~30AU.
- If there are no turbulent stresses, ***why do discs accrete?***

Does the dust move the gas?



$$v_{\rm d,max} \simeq (H/R)^2 v_{\rm K}$$

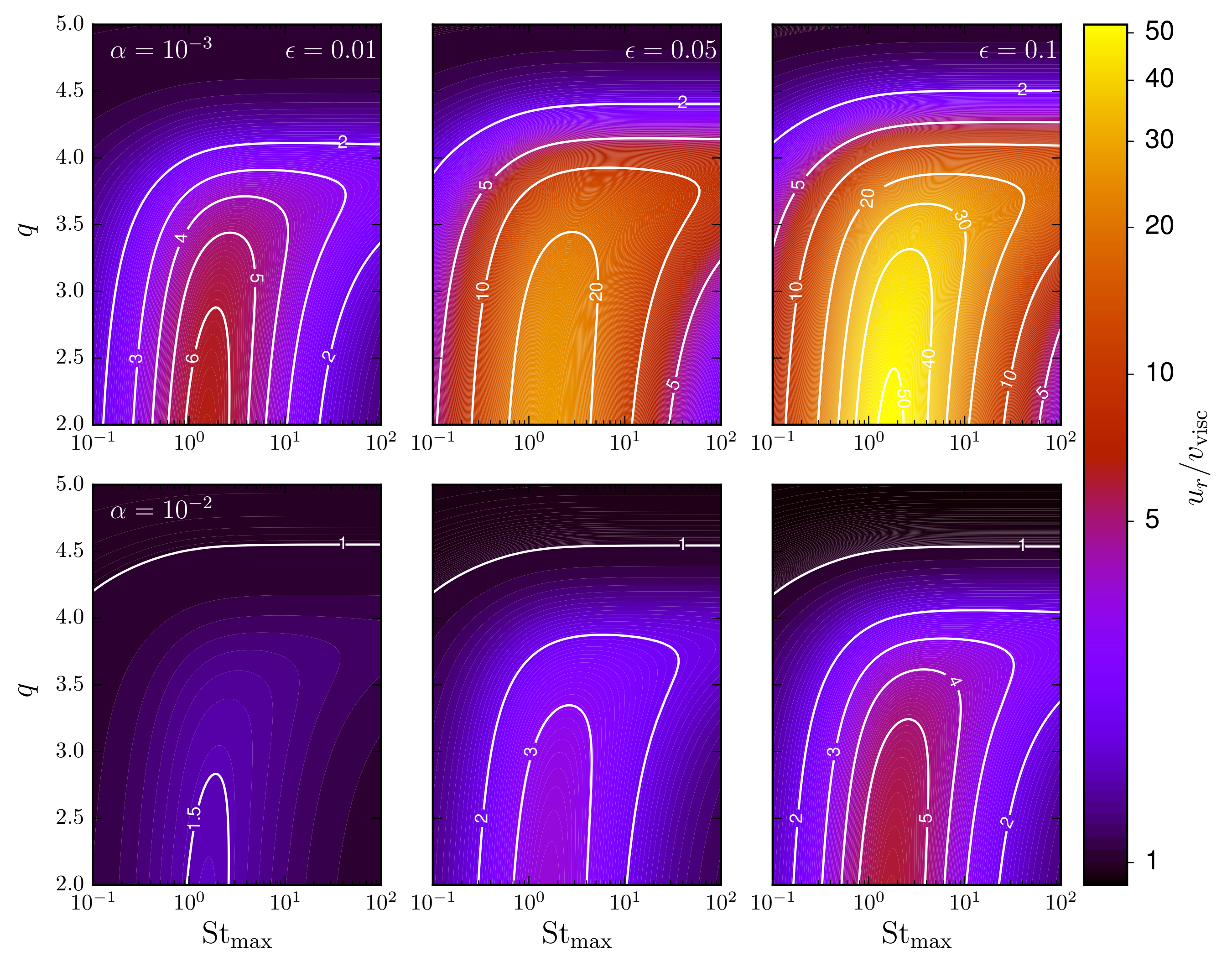
$$v_{\rm g,visc} \simeq \alpha(H/R)^2 v_{\rm K}$$

$$v_{\rm g,dust} \simeq \epsilon(H/R)^2 v_{\rm K}$$

$$\frac{v_{\rm g,dust}}{v_{\rm g,visc}} \simeq \frac{\epsilon}{\alpha}$$

- Gas-drag causes rapid inward drift of dust. Traditional analysis neglects “back-reaction” on the gas (e.g., Weidenschilling 1977).
- If dust-to-gas ratio (in St~1 particles) $\epsilon \gtrsim \alpha$, then “reflex” gas motion due to the dust back-reaction can dominate over viscous accretion (e.g., Bai & Stone 2010; Kanagawa+ 2017).

Does the dust move the gas?



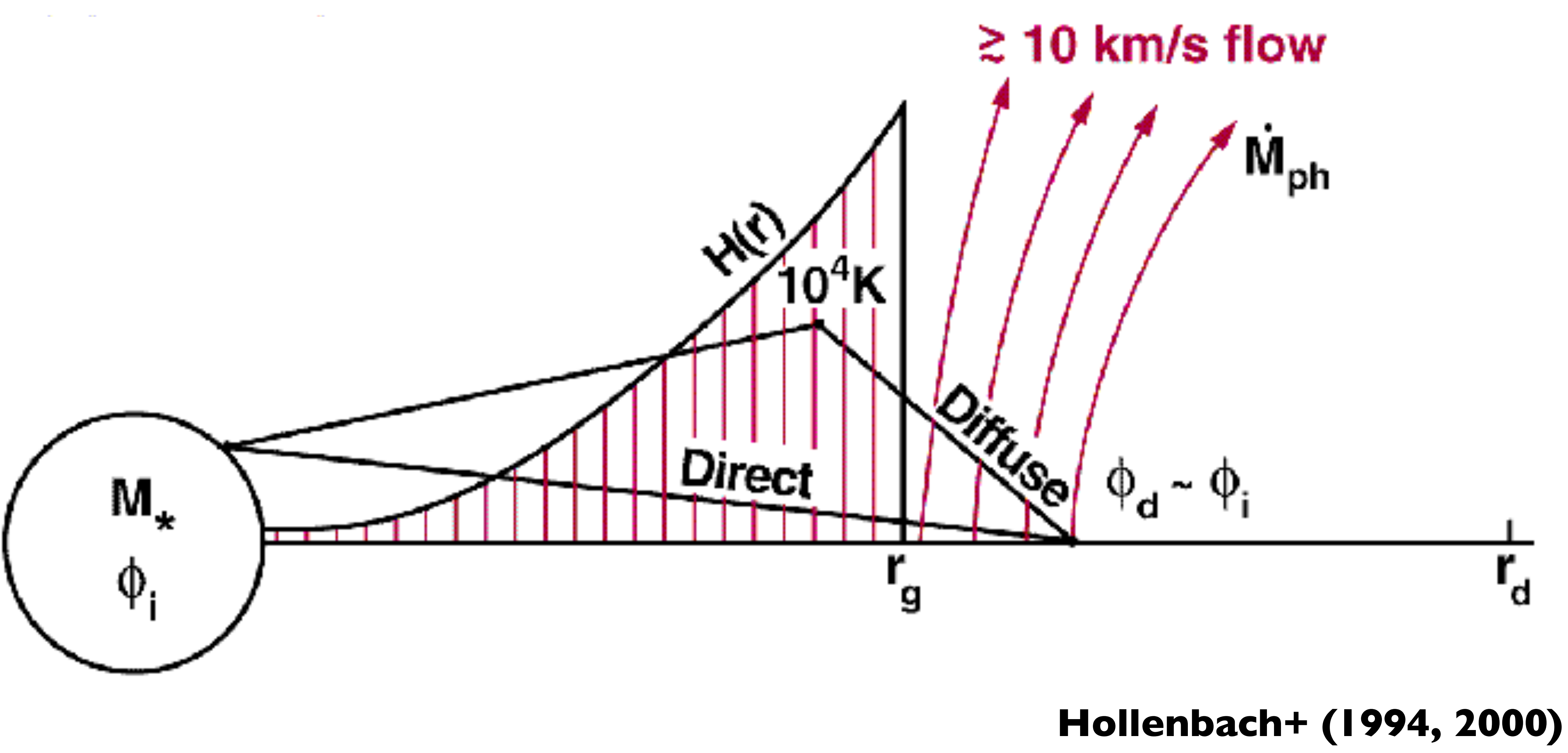
Dipierro+ (arXiv:1806.10148)

- Depends on grain sizes: need significant mass in large (St>0.1) particles for dust drag to dominate (e.g., Kanagawa+ 2017).
- Differential gas/dust motion can give rise to structures: rings, gaps, cavities. At large radii (~100AU) the dust-gas interaction can dominate the gas accretion flow (Dipierro+ 2018).

Mass-loss: disc photoevaporation

Hollenbach+ (1994); Font+ (2004); Gorti+ (2008,2009); Owen+ (2010,2012)

- High-energy irradiation creates a hot layer on disc surface.
- Outside some critical radius, hot gas is unbound and flows as a wind (Hollenbach+ 1994, 2000).



Hollenbach+ (1994, 2000)

Mass-loss: disc photoevaporation

Hollenbach+ (1994); Font+ (2004); Gorti+ (2008,2009); Owen+ (2010,2012)

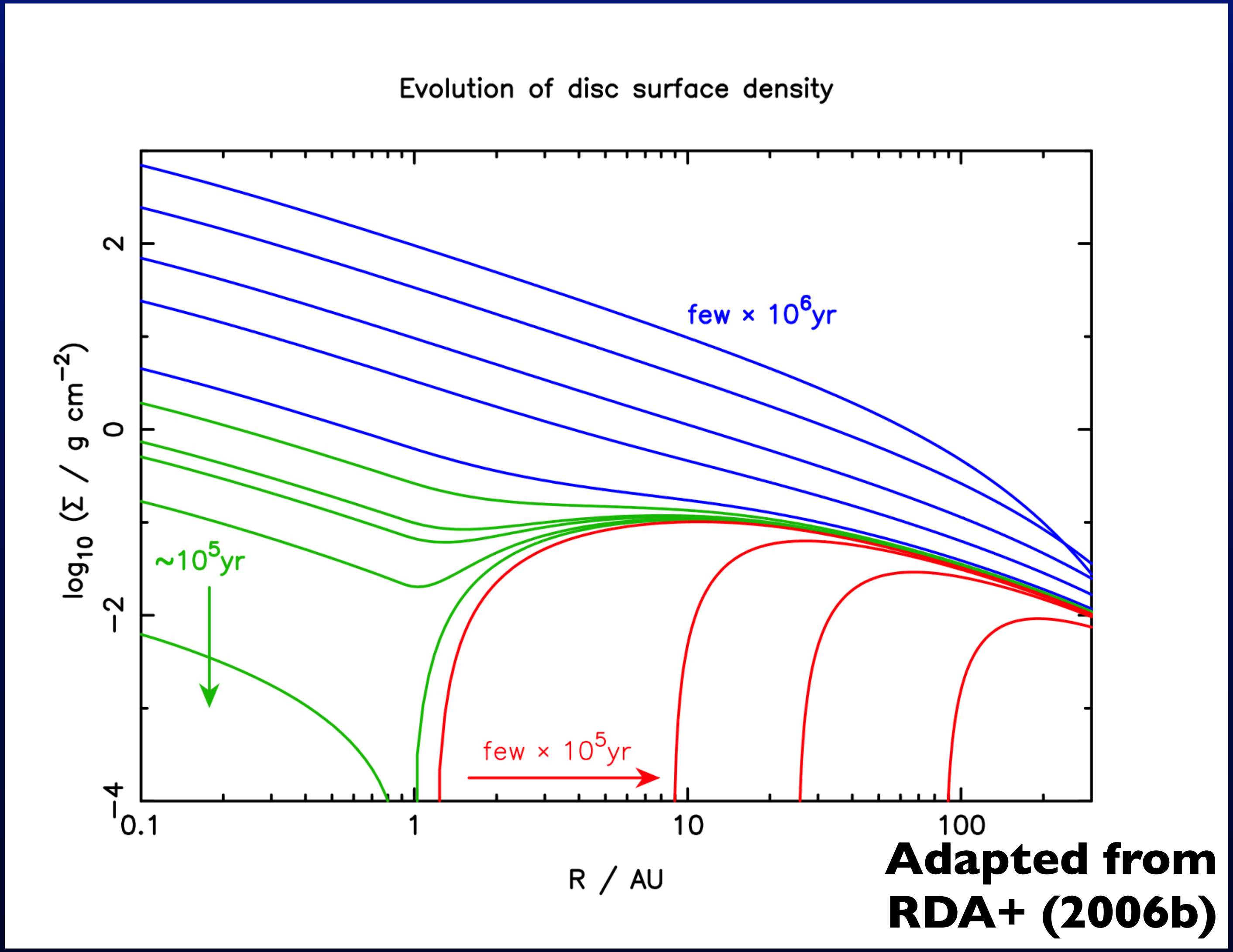
- Photoevaporation can be driven by FUV (6–13.6eV), EUV (13.6–100eV) or X-ray (>0.1keV) irradiation.
- External irradiation dominates in some cases (e.g., ONC proplyds), but most discs also undergo “internal” mass-loss.
- Critical radius varies with heating mechanism, but mass-loss per unit area typically peaks at ~1–10AU:

$$R_{\rm c} = \frac{0.2GM_*}{c_{\rm s}^2} \simeq 1.8{\rm AU}\left(\frac{M_*}{1{\rm M}_\odot}\right)\left(\frac{T}{10^4{\rm K}}\right)^{-1}$$

- Predicted mass-loss rates range from ~10^{-10}M$_\odot$yr^{-1} (EUV) to ~10^{-8}M$_\odot$yr^{-1} (X-rays, FUV).

Accretion + photoevaporation

Clarke+ (2001); RDA+ (2006a,b); Gorti+ (2009); Owen+ (2010)



Adapted from RDA+ (2006b)

- “Three-stage” model for gas disc evolution:
  - $\dot{M}_{\rm wind} \ll \dot{M}_{\rm acc}$, wind negligible, viscous evolution (few Myr).
  - $\dot{M}_{\rm wind} \sim \dot{M}_{\rm acc}$, gap opens, inner disc accretes (~10^5yr).
  - Inner hole, wind clears outer disc (few 10^5yr).

Qualitative behaviour is generic to this class of models: rapid inside-out dispersal after a long disc lifetime.
Inner clearing depends critically on viscosity (Morishima 2012).

Observing photoevaporation

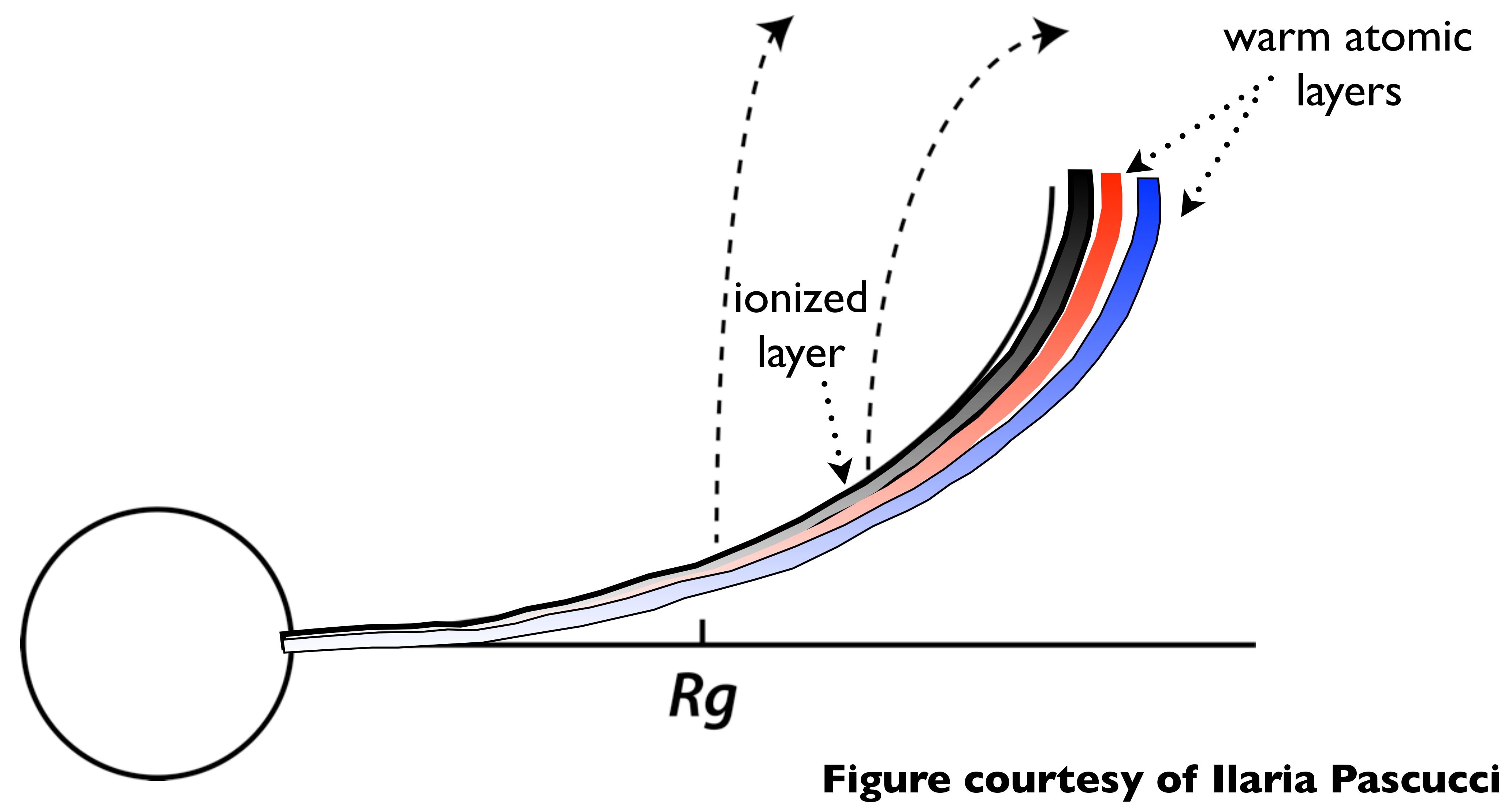
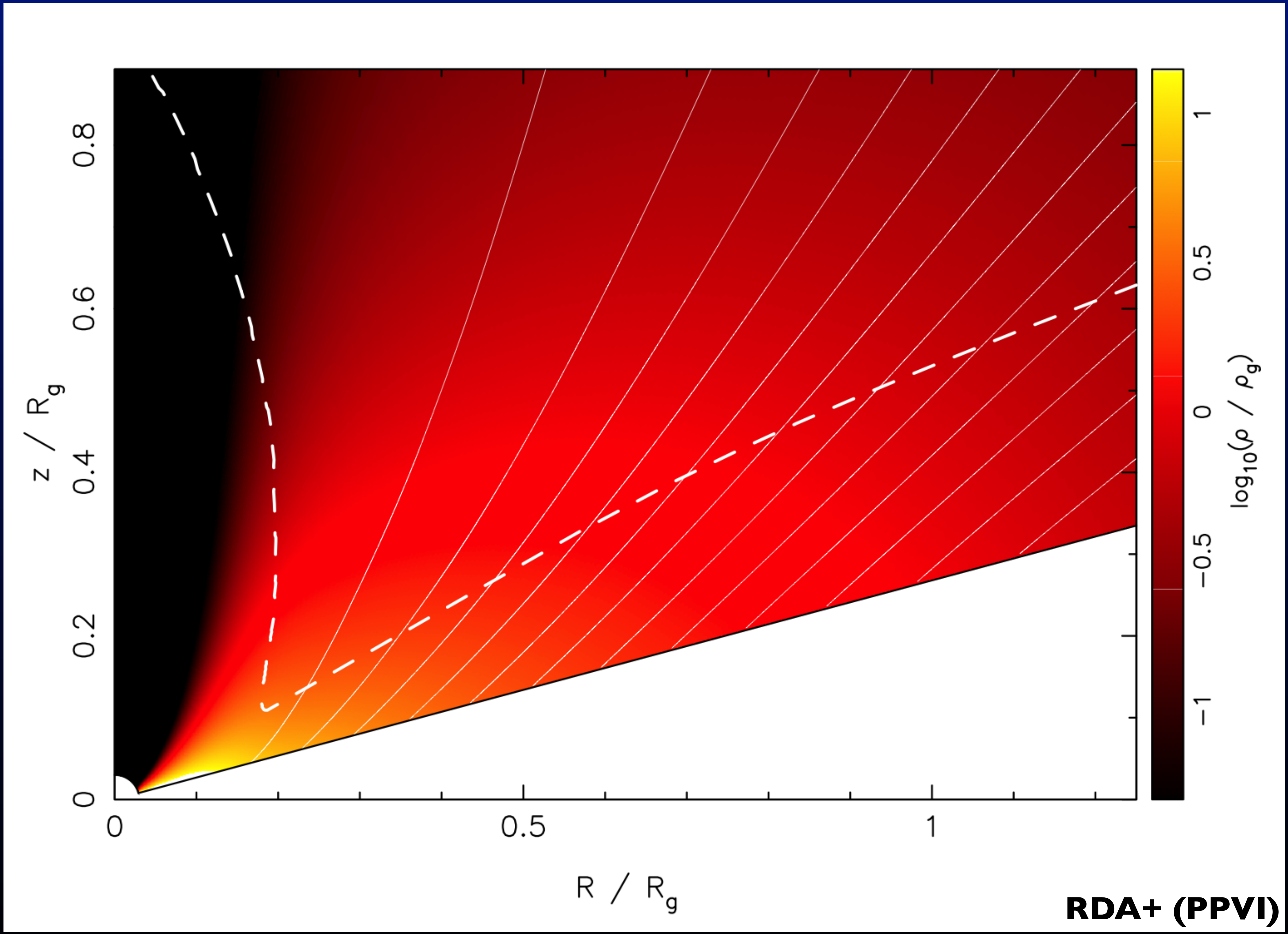


Figure courtesy of Ilaria Pascucci

- Emission lines from hot/ionized layers are a direct probe of the wind structure. Lines should be blue-shifted in face-on discs.
- Ionized gas can also be detected in free-free (radio) emission.

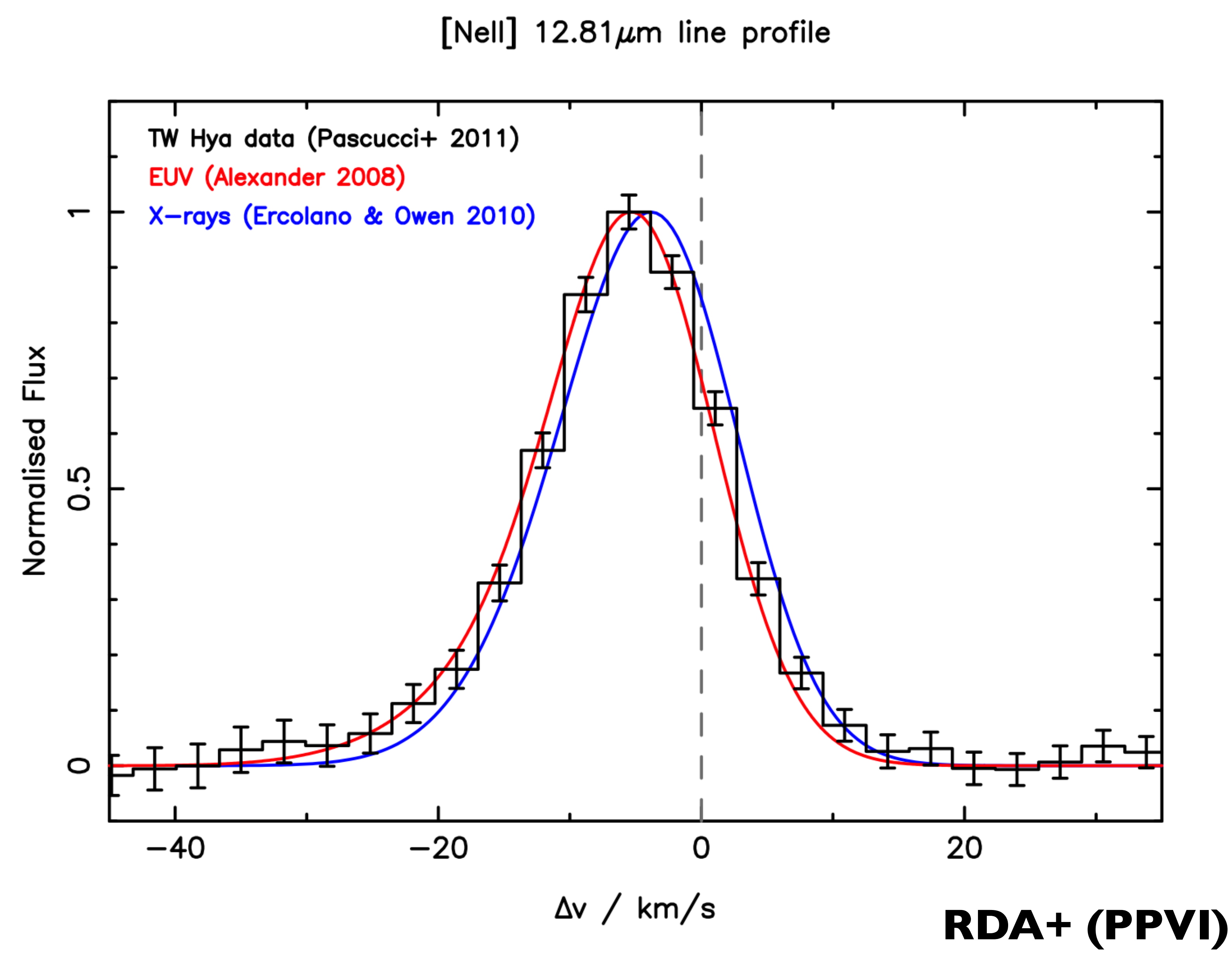
Disc photoevaporation

Hollenbach+ (1994); Font+ (2004); Gorti+ (2008,2009); Owen+ (2010,2012)



RDA+ (PPVI)

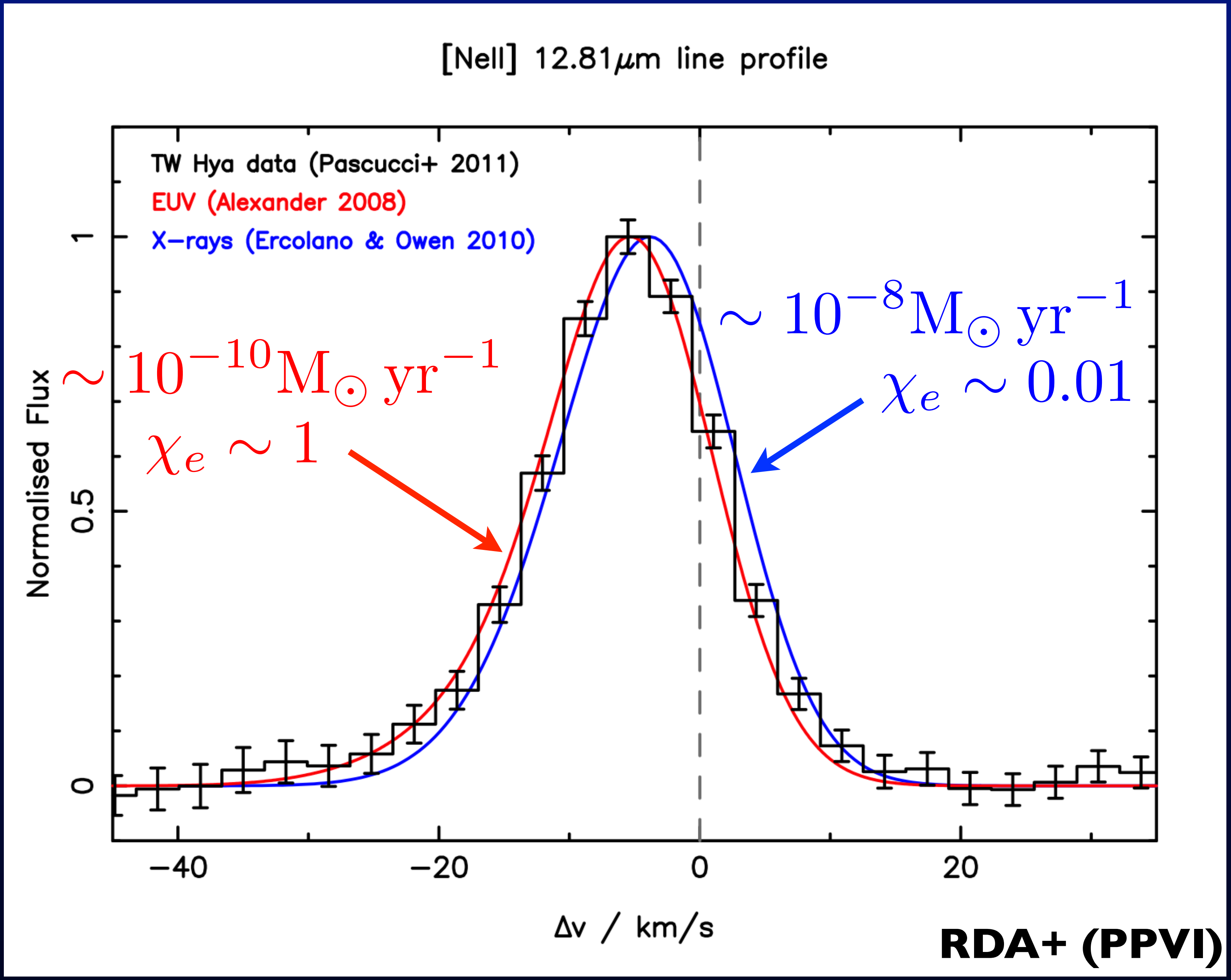
Observing photoevaporation: lines



RDA+ (PPVI)

- Blue-shifted [NeII] emission ($\Delta v \sim 10 \mathrm{km\,s}^{-1}$) now observed in tens of discs (e.g., Pascucci+ 2009; Sacco+ 2012).
- **Unambiguous detection of a slow, ionized wind.**

Observing photoevaporation: lines



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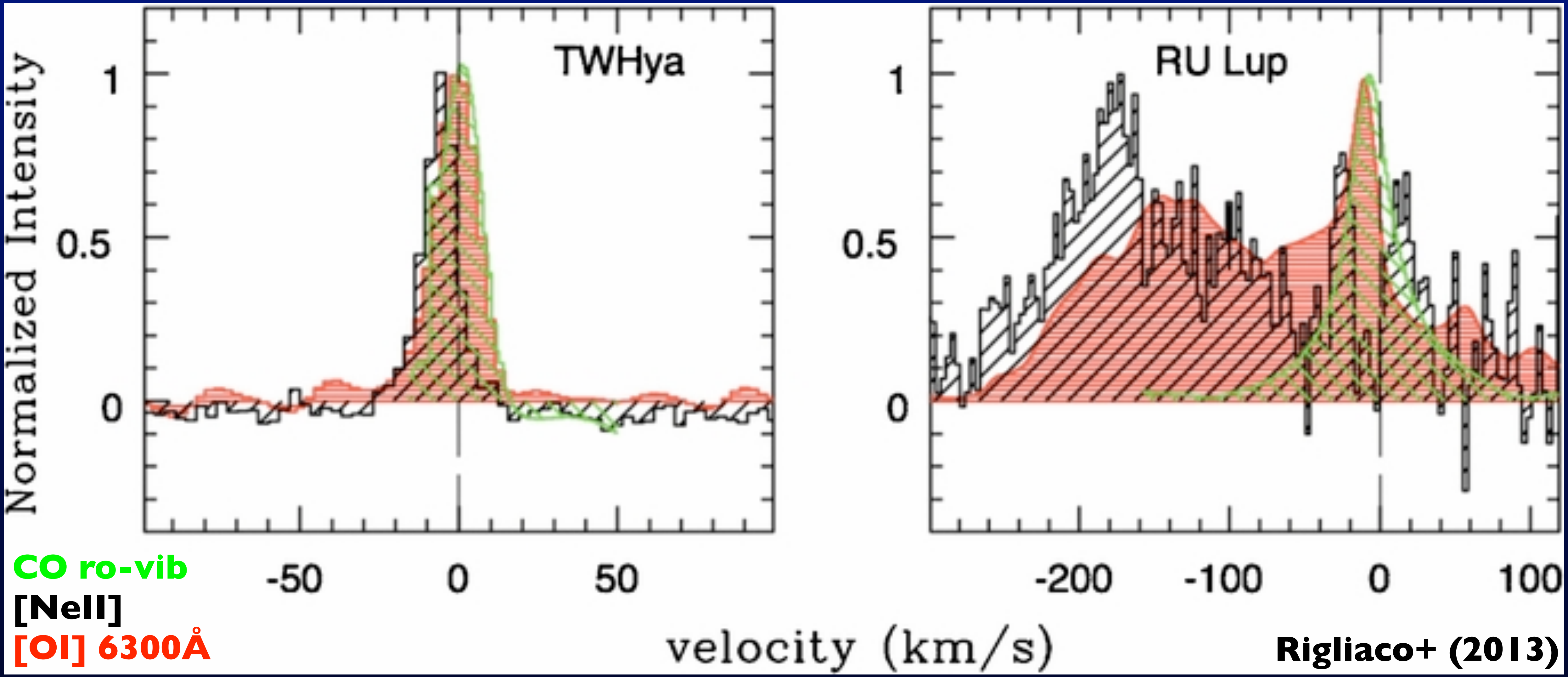
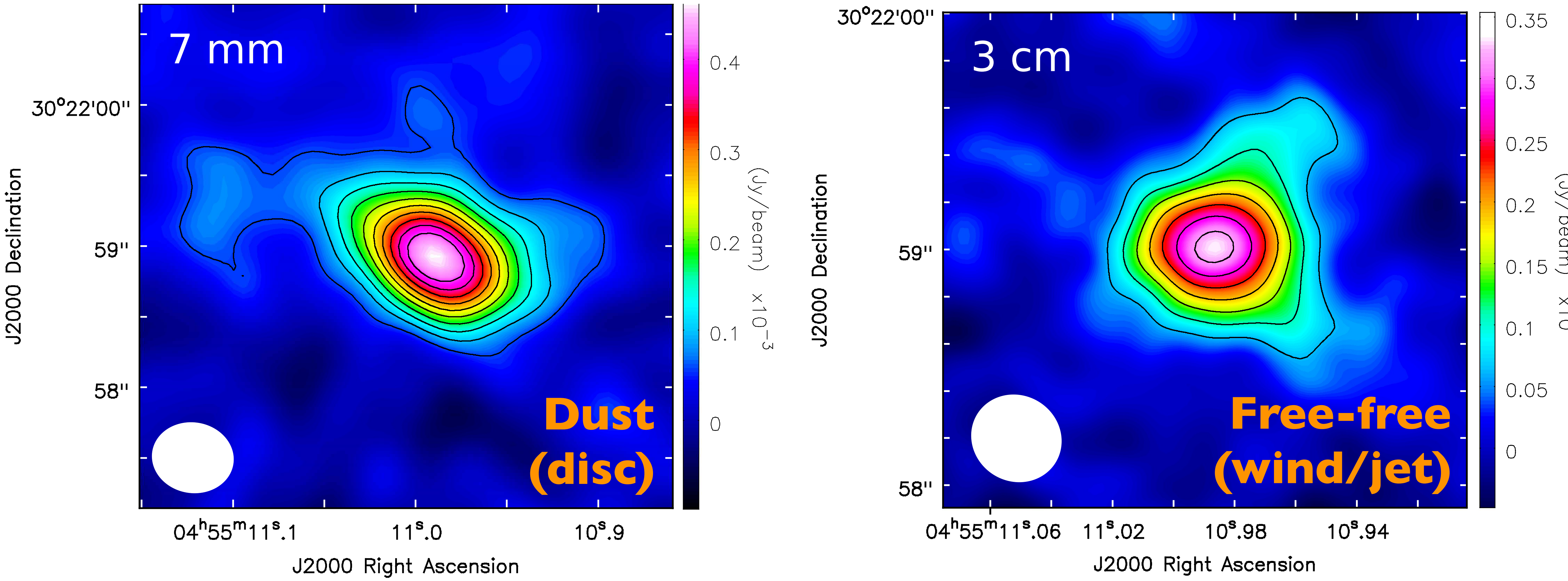
Observing photoevaporation: lines



Rigliaco+ (2013)

- Low-velocity component of [OI] 6300Å line often blue-shifted.
- Seems to trace FUV dissociation of OH (e.g., Simon+ 2016).
- Unbound component implies $\dot{M} \gtrsim 10^{-10} \mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ in *neutral* gas flow. Same flow as [NeII], or different?

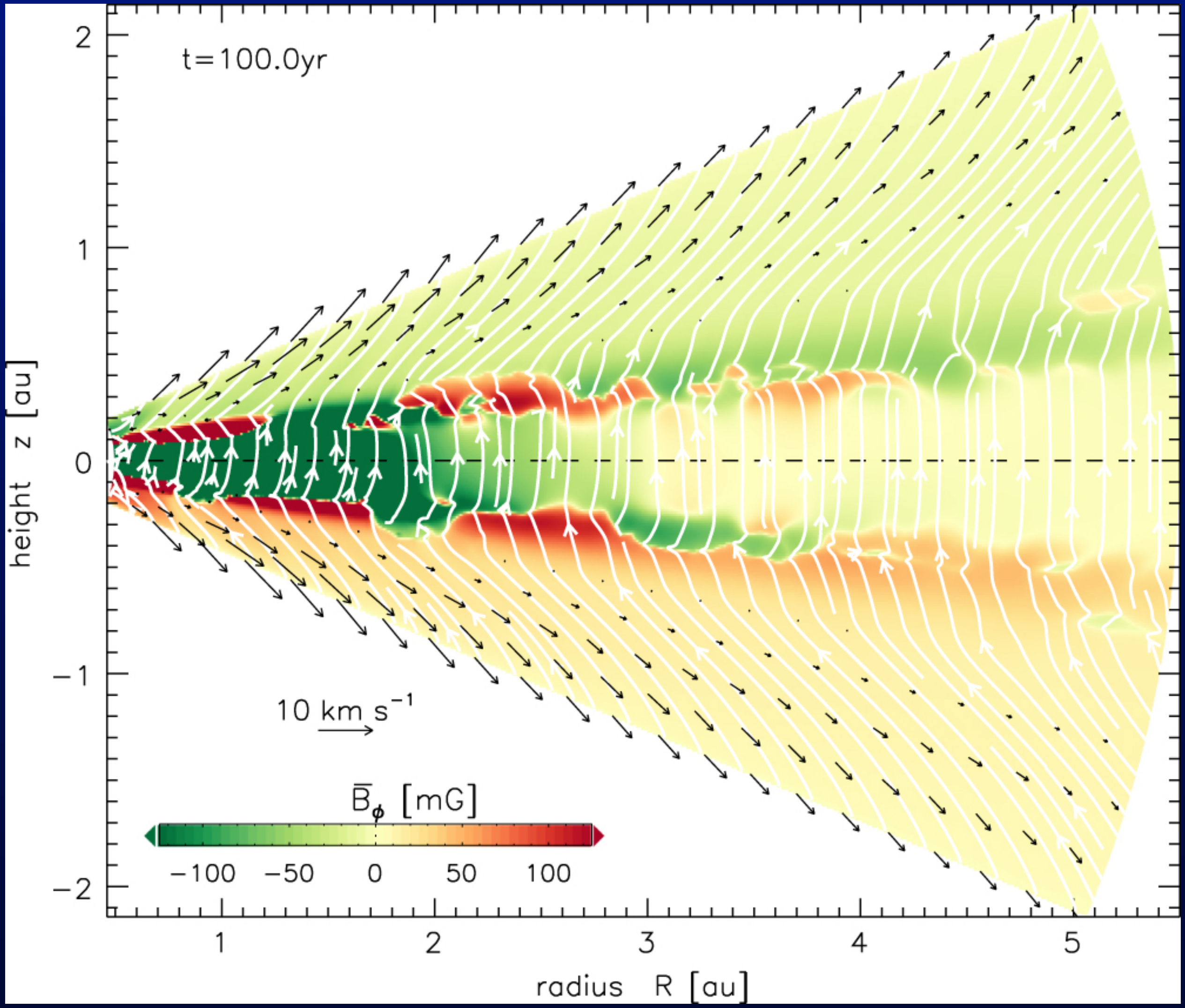
Observing photoevaporation: free-free



Macías+ (2016)

- Free-free emission in GM Aur inconsistent with X-ray ionization, suggests photoevaporation is EUV driven.
- Implies highly ionized wind, with relatively low mass-loss rate.

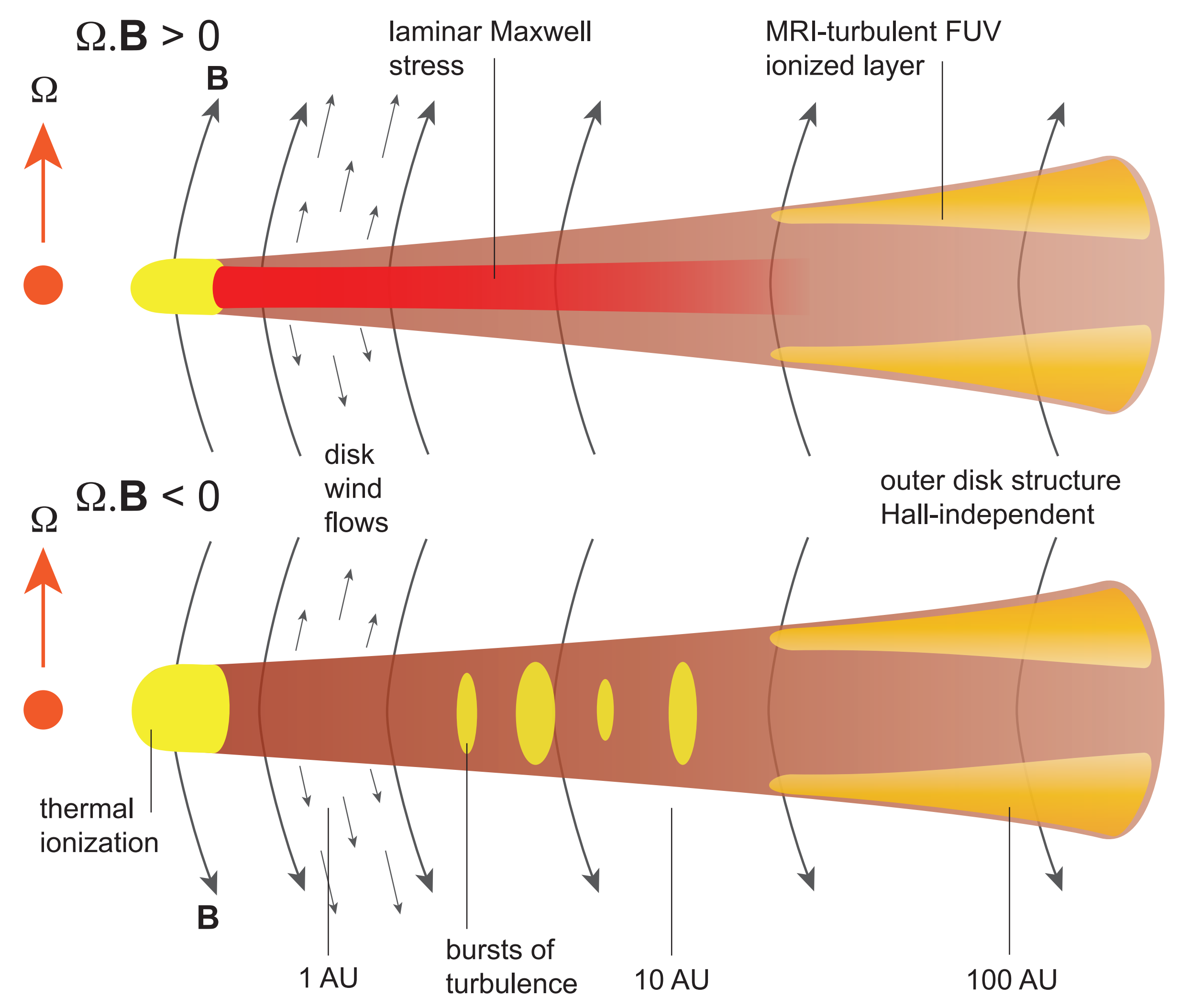
Angular momentum (& mass) loss



Gressel+ (2015)

- In non-ideal MHD simulations, ambipolar diffusion + vertical (poloidal) field results in a magnetised disc wind.
- Local simulations by several groups robustly show both suppression of the MRI and wind launching (e.g., Bai & Stone 2013a,b; Lesur+ 2014; Simon+ 2015; Gressel+ 2015).

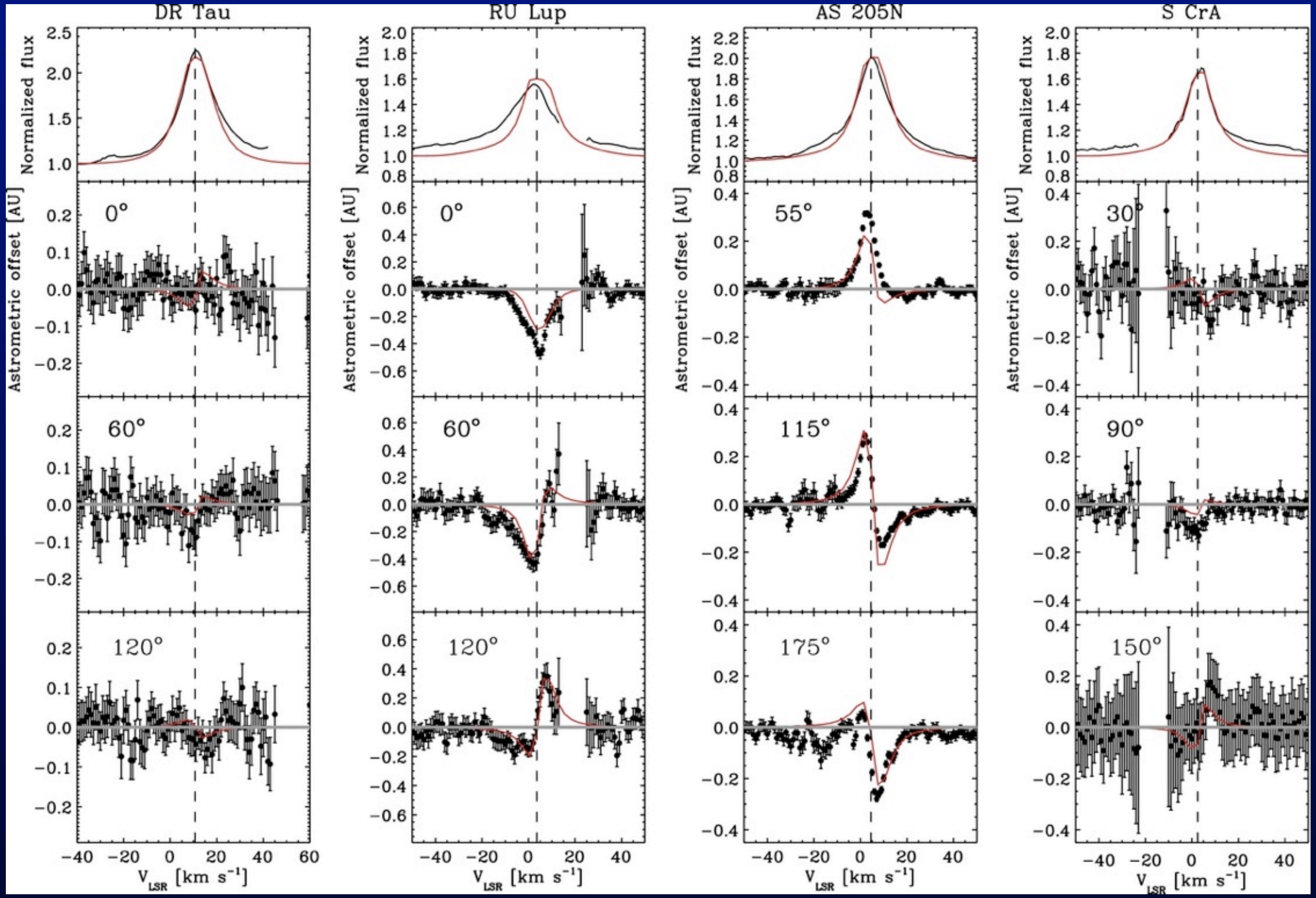
Angular momentum (& mass) loss



Simon+ (2015)

- Many uncertainties, most notably that mot simulations to date use local geometries (mostly shearing box). Robust mass & ang. mom. loss rates require global calculations.
- Likely that mass-loss is a combination of this process + photoevaporation: "magneto-thermal wind" (Bai+ 2016).

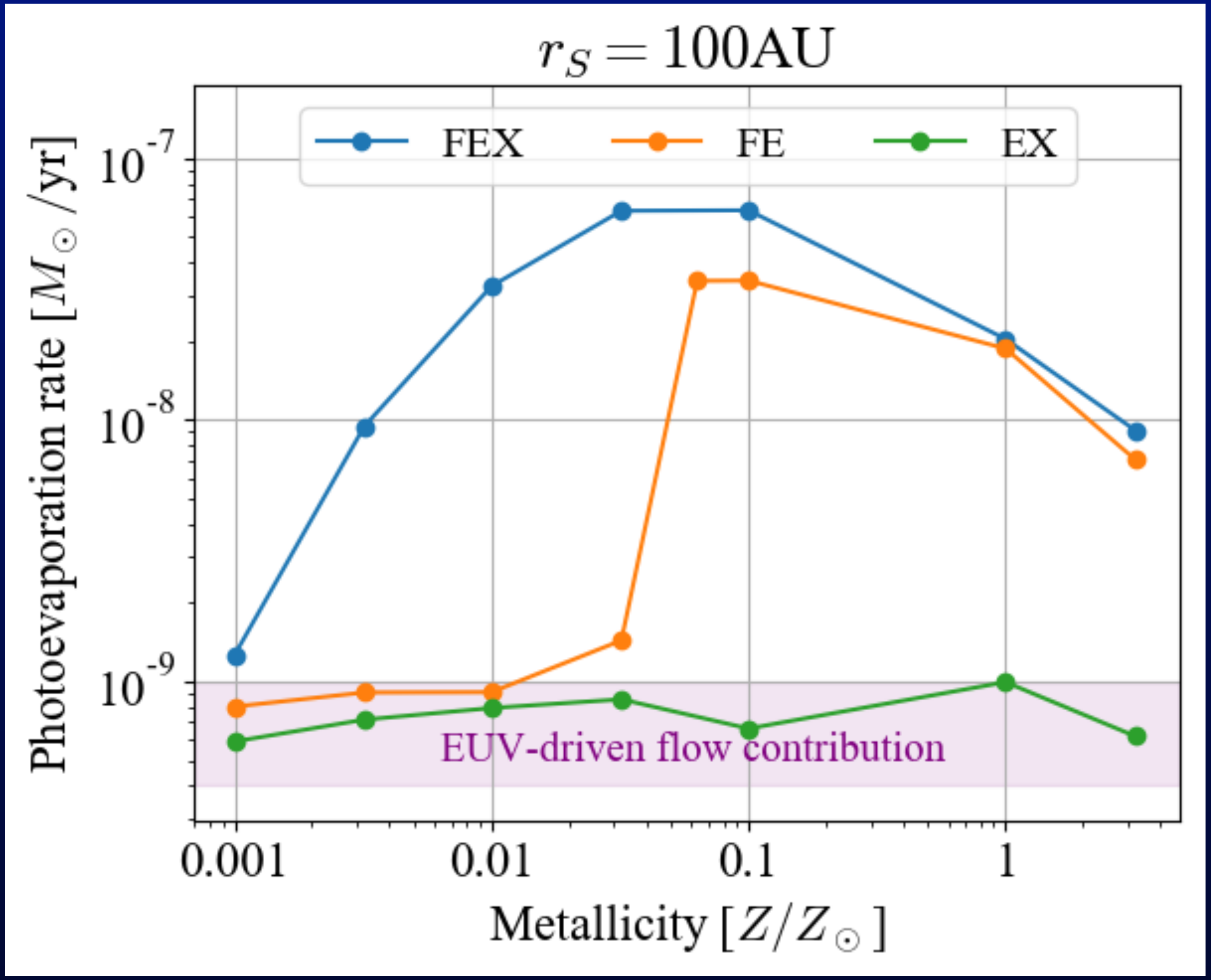
Angular momentum (& mass) loss



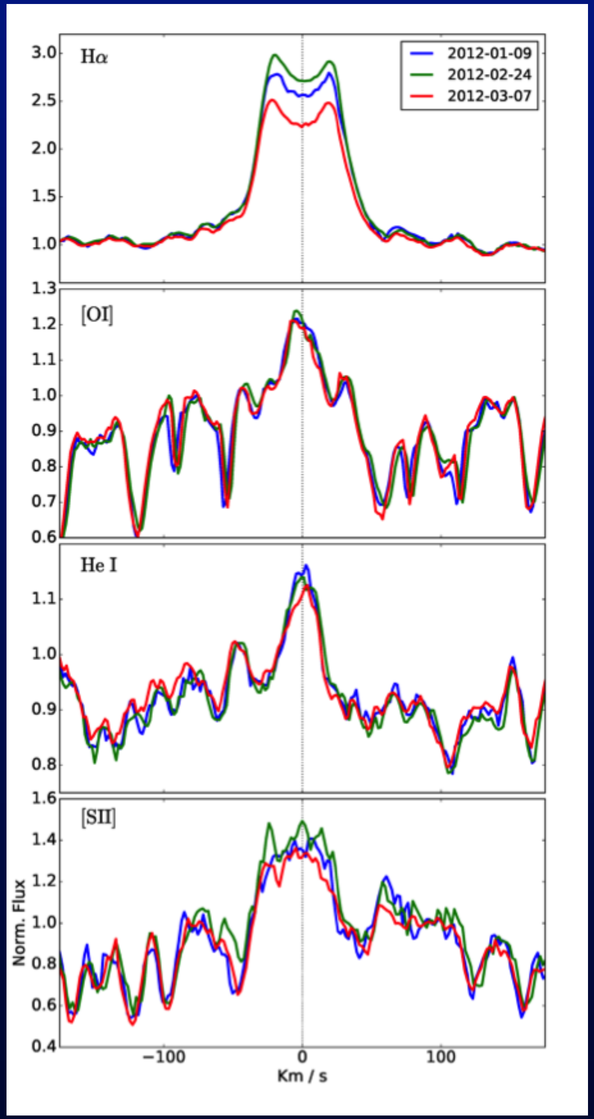
Pontoppidan+ (2011)

- Low-velocity (~km/s) ***molecular*** winds from ~AU radii may be common (e.g., Pontoppidan+ 2011; Bast+ 2011).
- Flows cannot be thermally-driven. Could these observations have detected MHD-driven mass-loss?

What are the wind mass-loss rates?



Nakatani+ (2018); see also Wang & Goodman (2017)



DZ Cha: Canovas+ (2018)

- Are winds primarily magnetic, thermal, or “magneto-thermal”?
- What are mass-loss and angular momentum-loss rates?
- How can we measure them?

Bai et al. (2016):

"…it appears unavoidable that in the inner regions of protoplanetary discs, accretion is largely wind-driven."

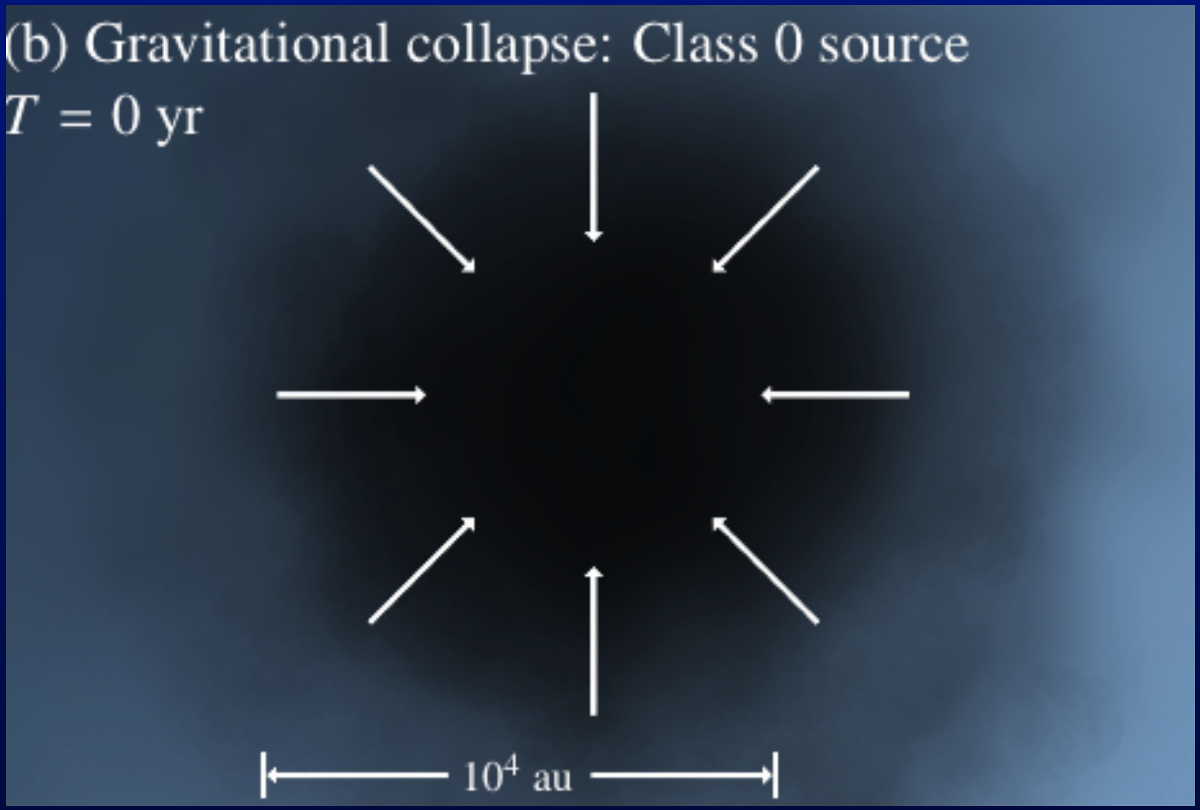
Dipierro et al. (2018):

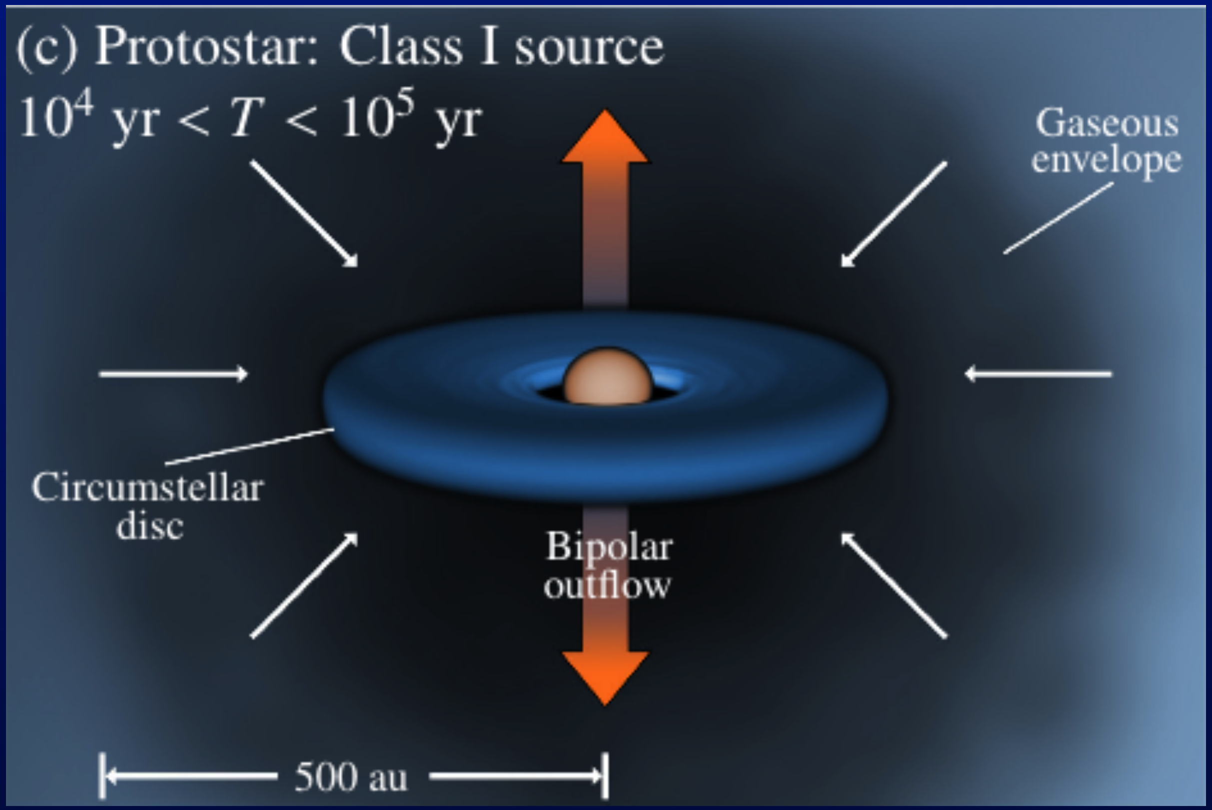
"In typical protoplanetary discs dust feedback strongly affects the gas dynamics, even for small dust/gas ratios…"

Either/both of these would represent a ***MAJOR*** shift in our picture of protoplanetary disc evolution.

Infall: (how much) does it matter?

(Schematic figures courtesy of Alex Dunhill; PhD thesis, 2013)





In Class 0/I phases, two different "modes" of accretion:

i) envelope → disc (quasi-spherical)

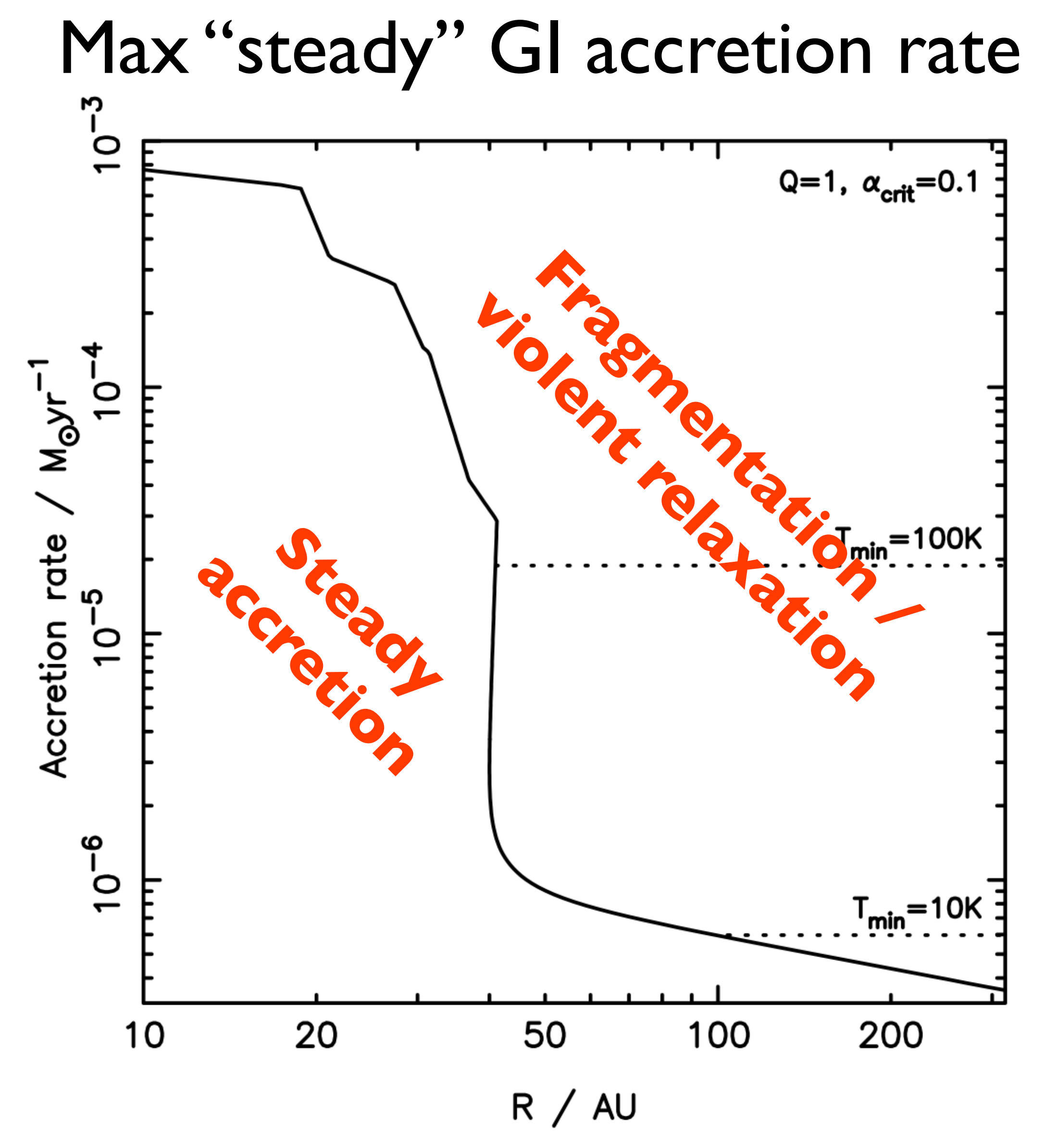
ii) disc → star (~Keplerian rotation)

$$\dot{M}_{\rm infall} \sim \frac{c_s^3}{G}$$

$$\dot{M}_{\rm disc} \sim \alpha \frac{c_s^3}{G}$$

Infall: the protostellar accretion problem

[Theorist's version of the luminosity problem; e.g., Kenyon & Hartmann 1995]



Harsono+ (2010), adapted from Levin (2003, 2007)

- To form a star, we must accrete at ~$10^{-5} M_\odot yr^{-1}$ for ~0.1Myr.
- This is ~ infall rate from envelope, but >> maximum "steady" disc accretion rate.
- Required accretion rate cannot be sustained at all radii in the disc (unless discs are v.compact).
- Early stellar accretion is probably not steady; most mass is accreted through outbursts.

Discs with high infall rates are *not* stable

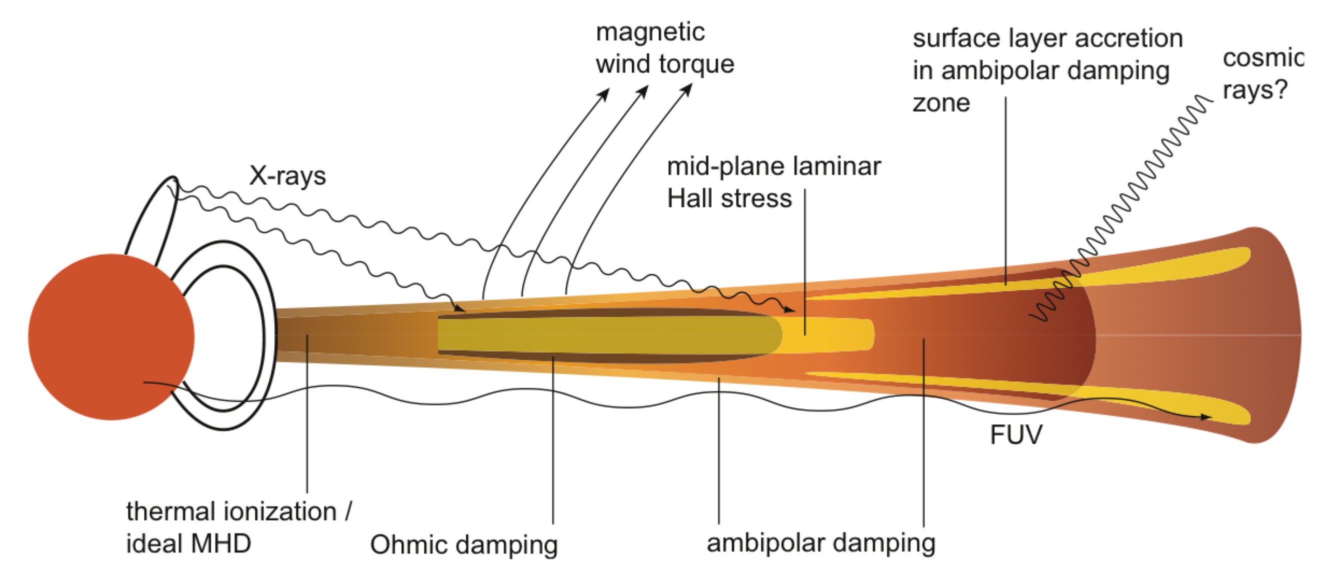
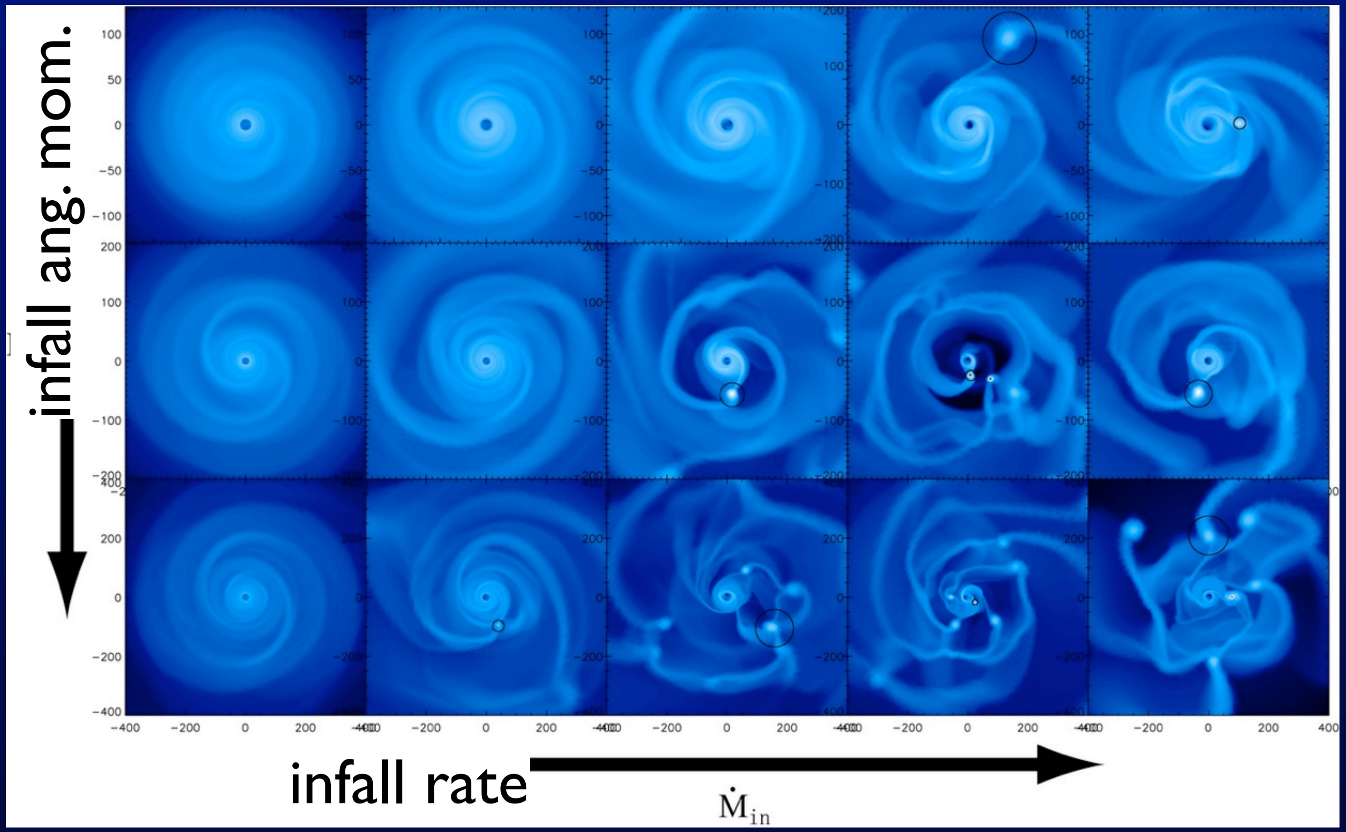


Figure from Phil Armitage, after Gammie (1996)

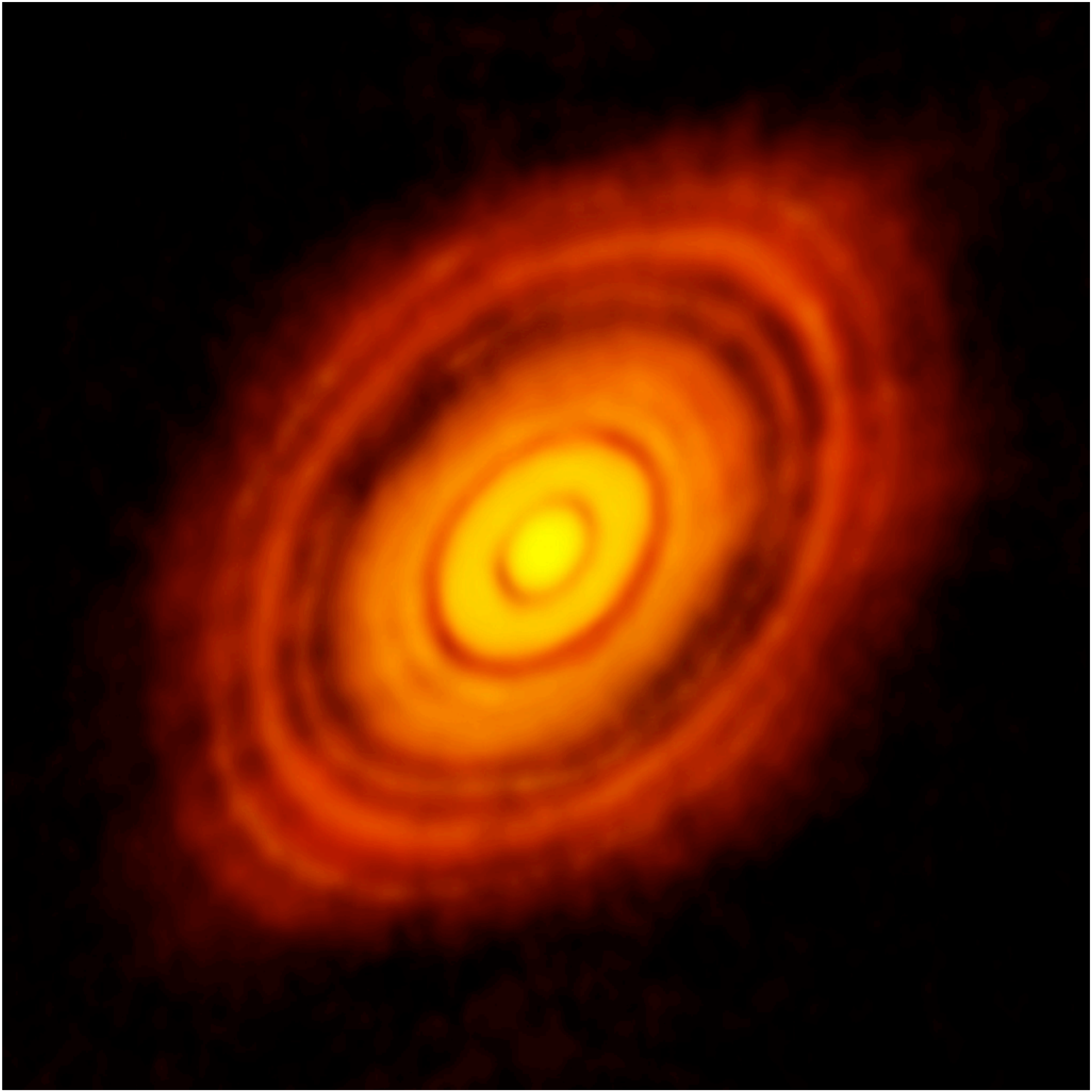


Zhu+ (2012)

- Outbursts probably triggered by some combination of GI (outer disc), dead zone, and/or thermal-viscous instability (inner disc).
- Role of infall and importance of fragmentation remain unclear.
- Disc properties at <1Myr are highly dependent on infall physics.

Do planets form during the infall phase?

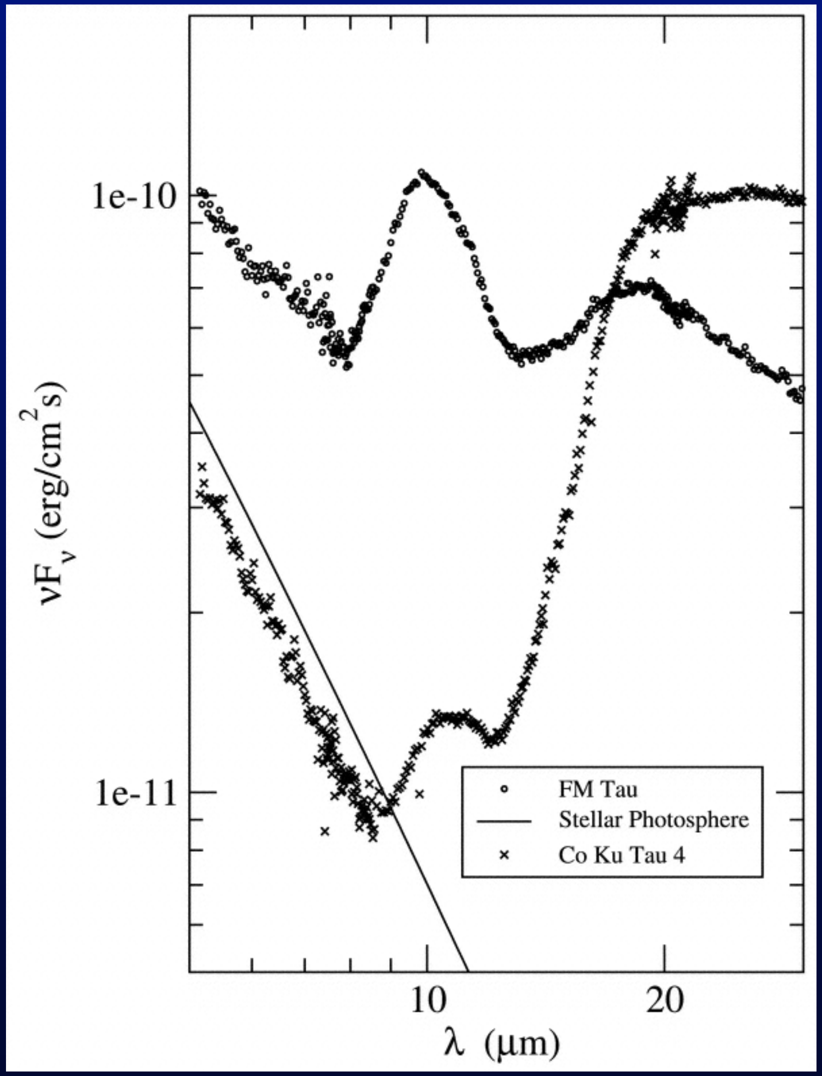
- HL Tau is Class I, massive, but shows no sign of non-axisymmetric structures.
- No GI at ~10^5yr suggests that "non-steady" disc accretion is a *very* short-lived evolutionary stage.
- Have planets already formed at ~10^5yr? If they have, understanding infall dynamics is critical.
- But $t_{orb} > 10^3$yr in outer disc…



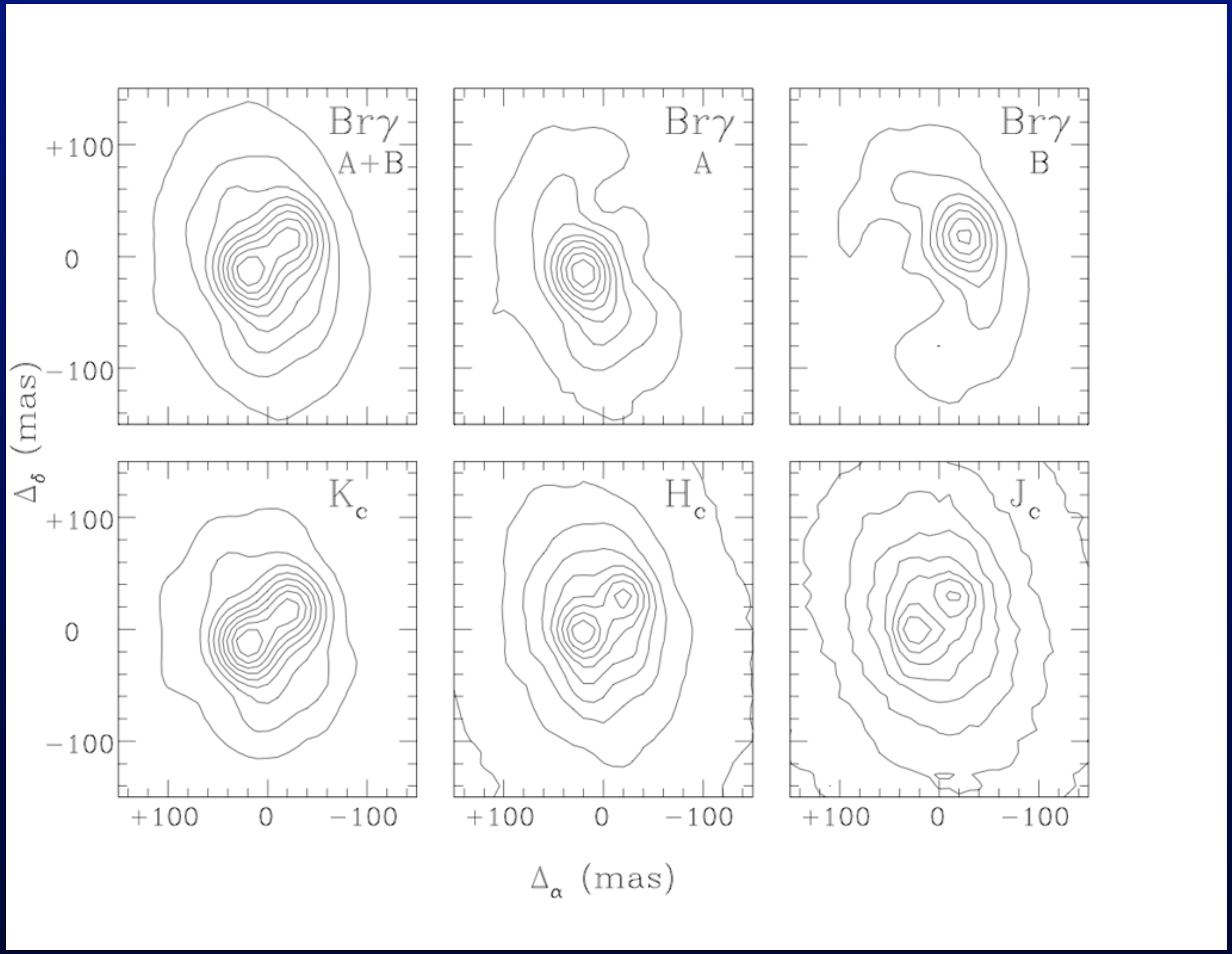
HL Tau: ALMA partnership (2015)

Modelling infall is…complicated

Binaries…



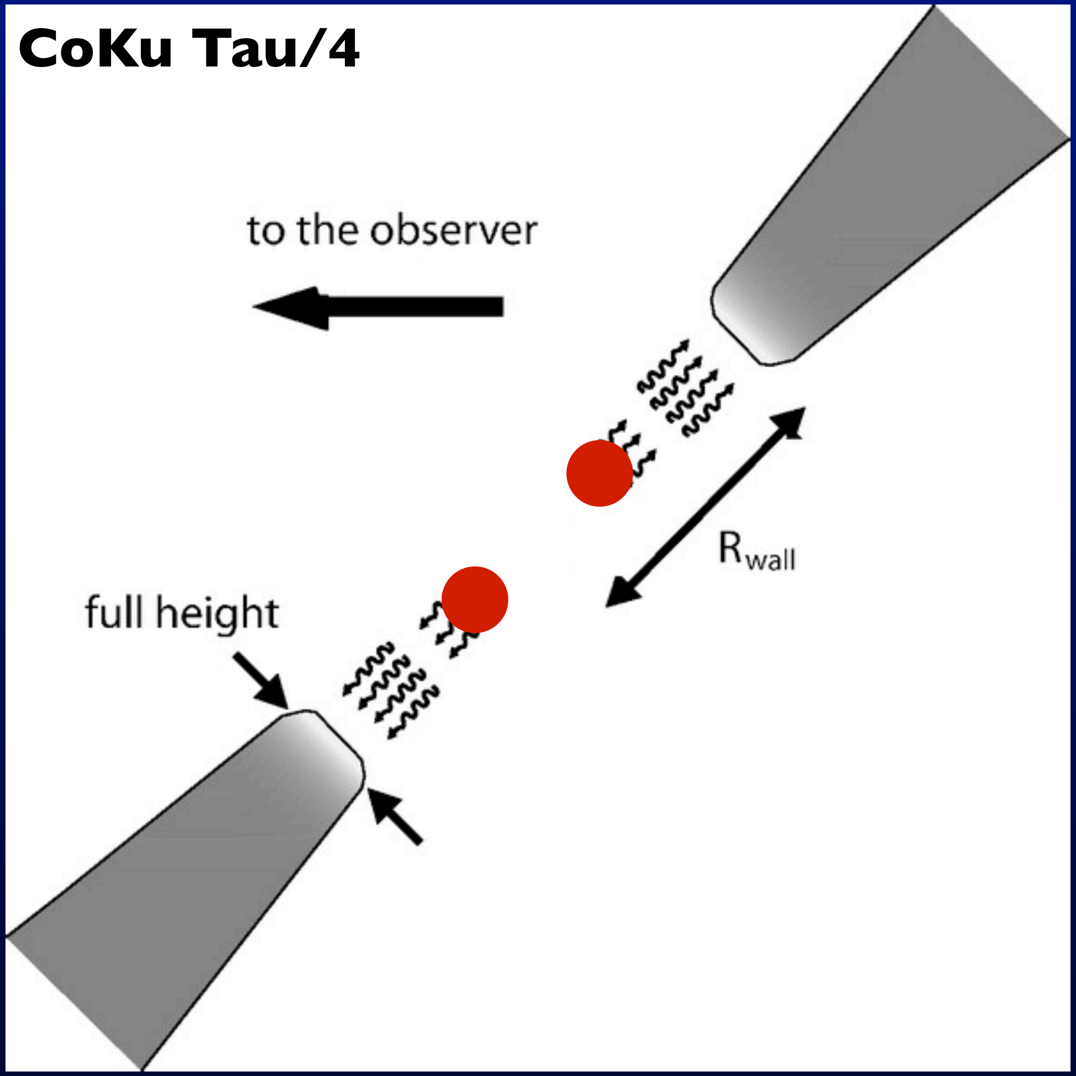
Forrest et al. (2004)



Ireland & Kraus (2008)

- Our field has a long and not very distinguished history of mis-interpreting binaries (often as “transitional” discs).
- We should expect *lots* of binaries: 10-15% of G- to K-type MS stars are binaries with 1-10AU separations.

Binaries…



Original figure from d'Alessio+ (2005)

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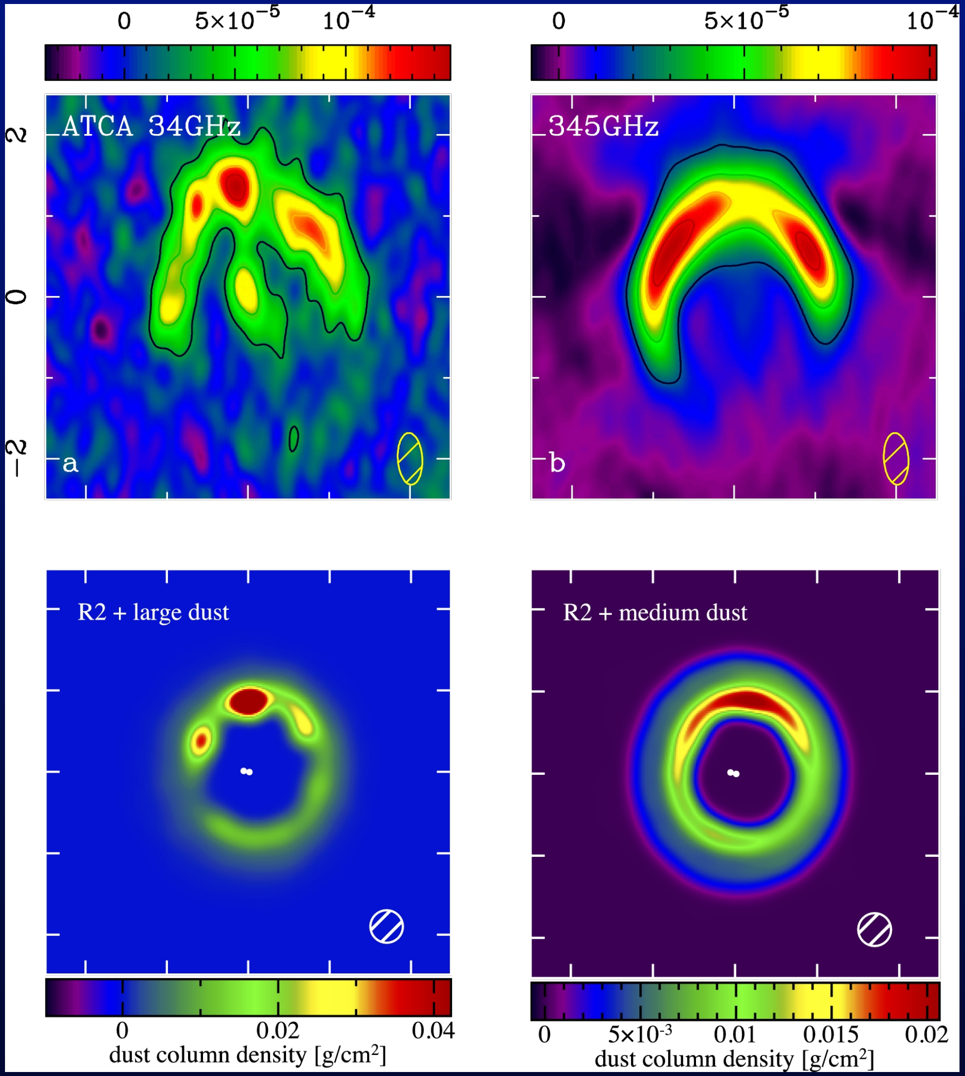
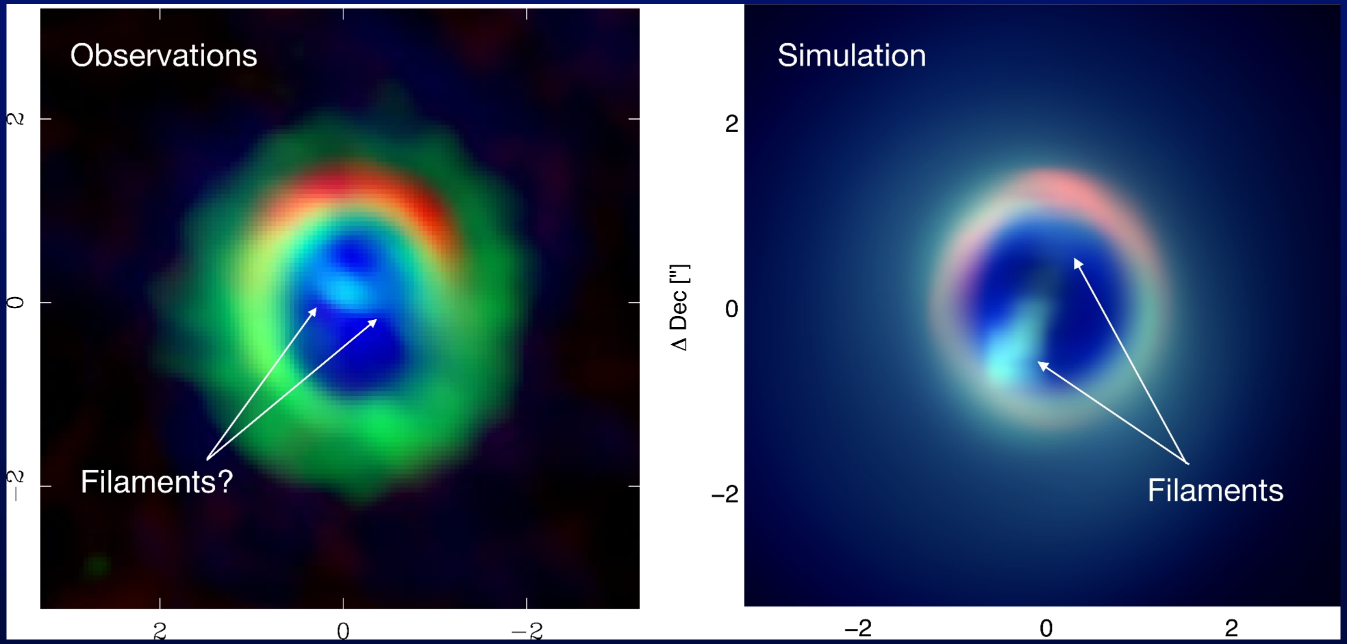
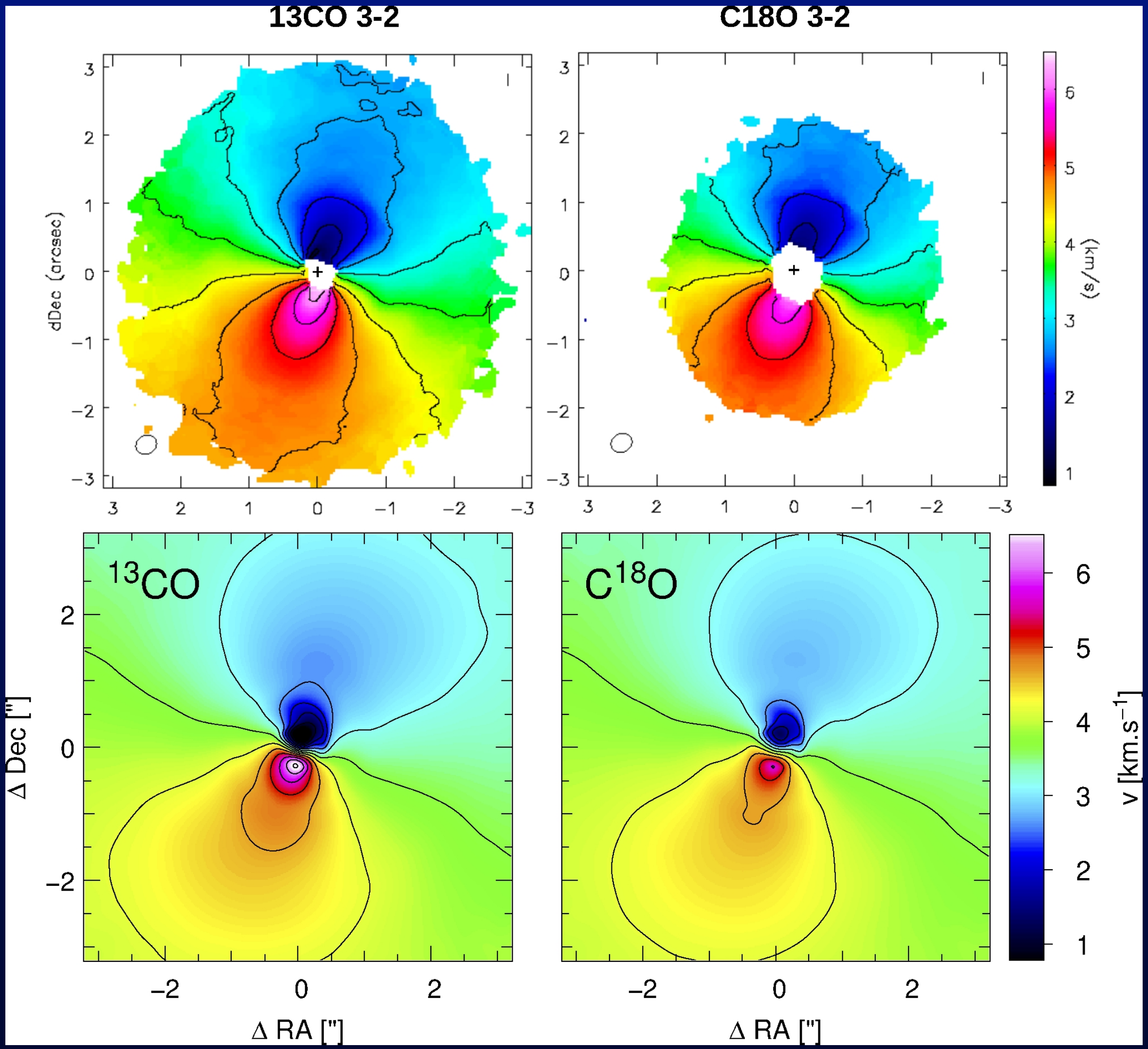




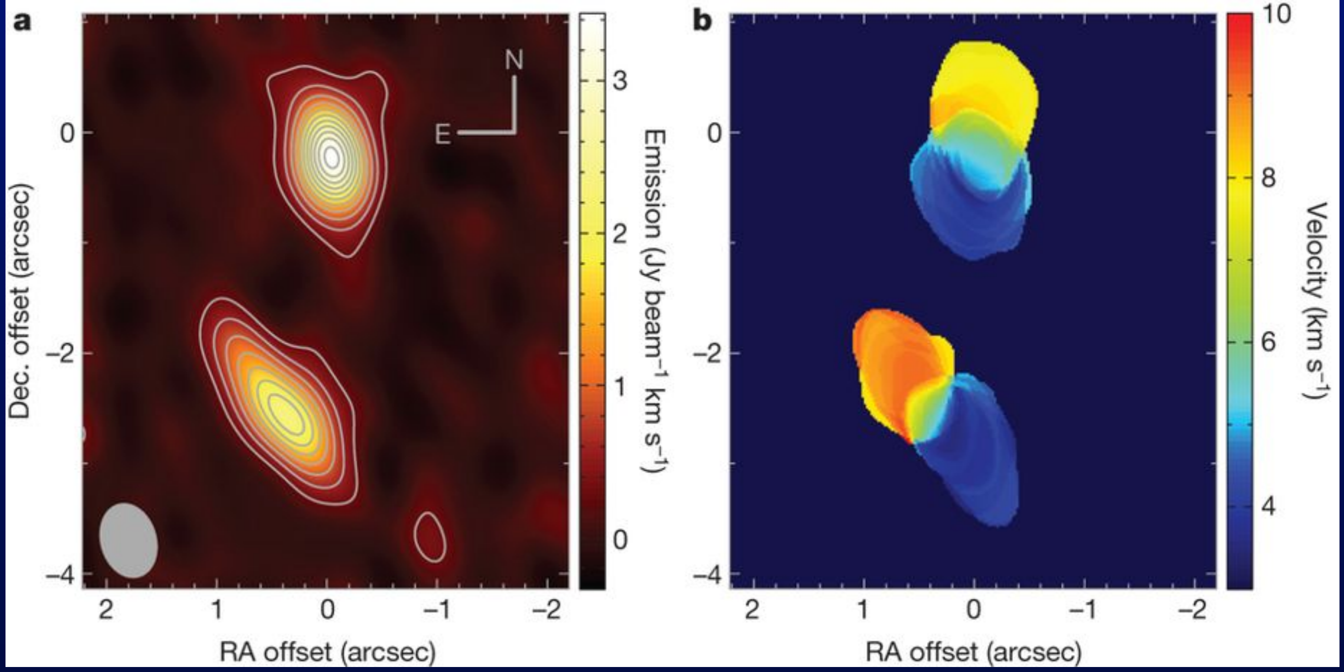
HD142527: Price+ (2018)

- Lots of observed disc structures are probably “just” binaries.
- But many are not: >50% of “transition” discs do not have stellar-mass companions (Ruíz-Rodríguez+ 2016).
- Not just “contaminants”; we can learn a lot from binaries.

Are discs warped?



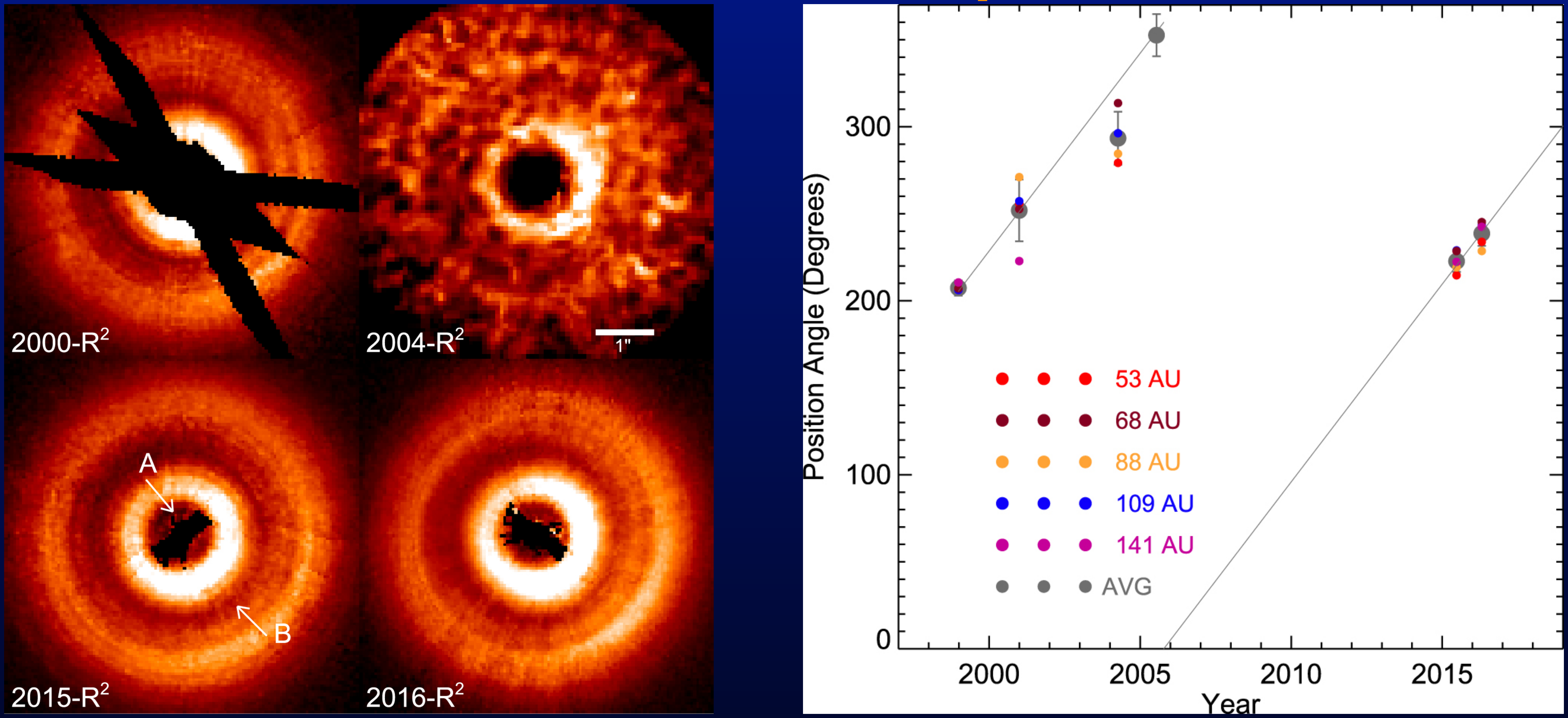
HD142157: Price+ (2018)



HK Tau: Jensen & Akeson (2014)

- Many discs in binary systems are ***not*** aligned with binary orbit.
- Also evidence of warped discs in several single-star systems.
- How common are these? And how often are we misinterpreting warps/tilts as gaps, spirals, etc?

Are discs warped?



TW Hya: Debes+ (2017); Poteet+ (2018)

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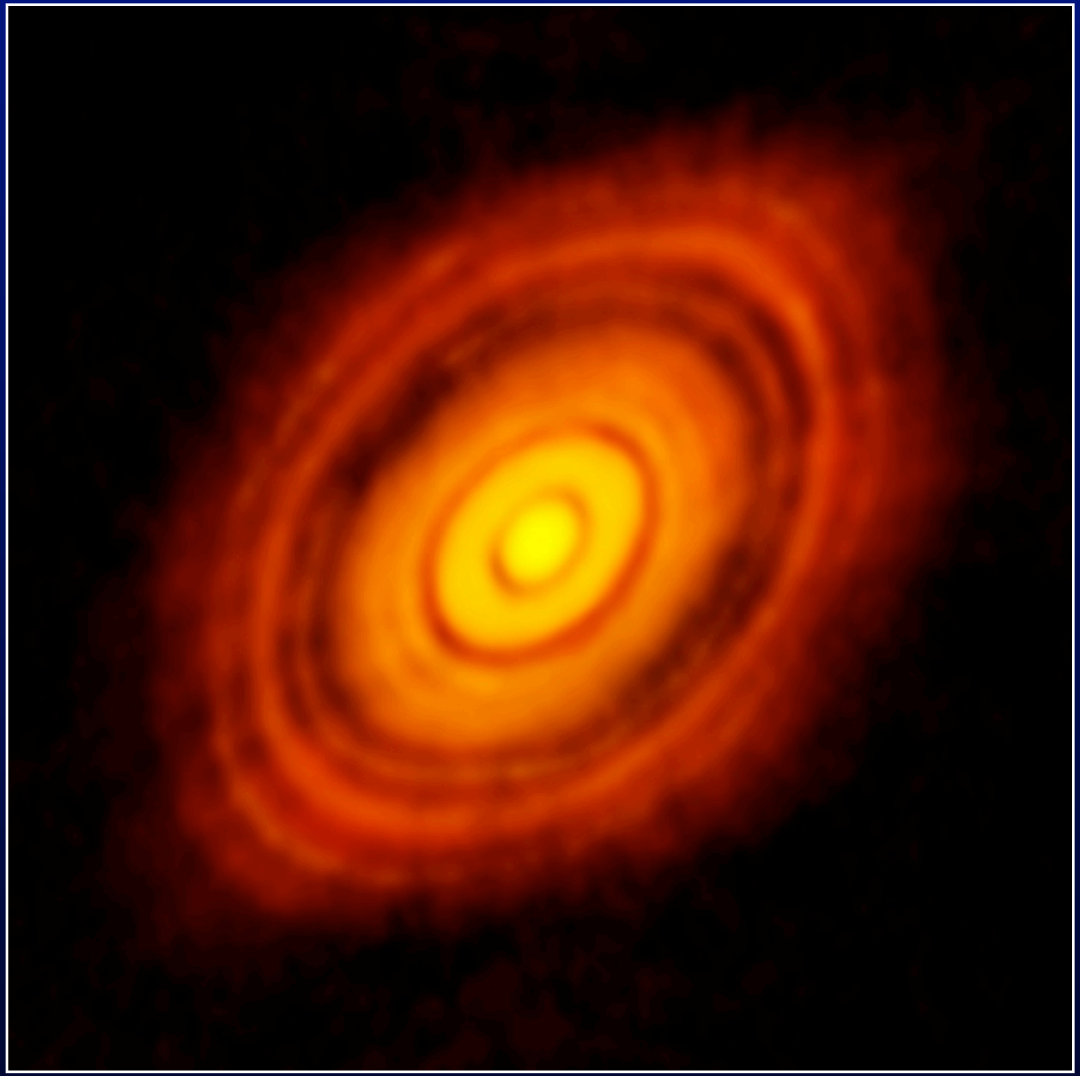
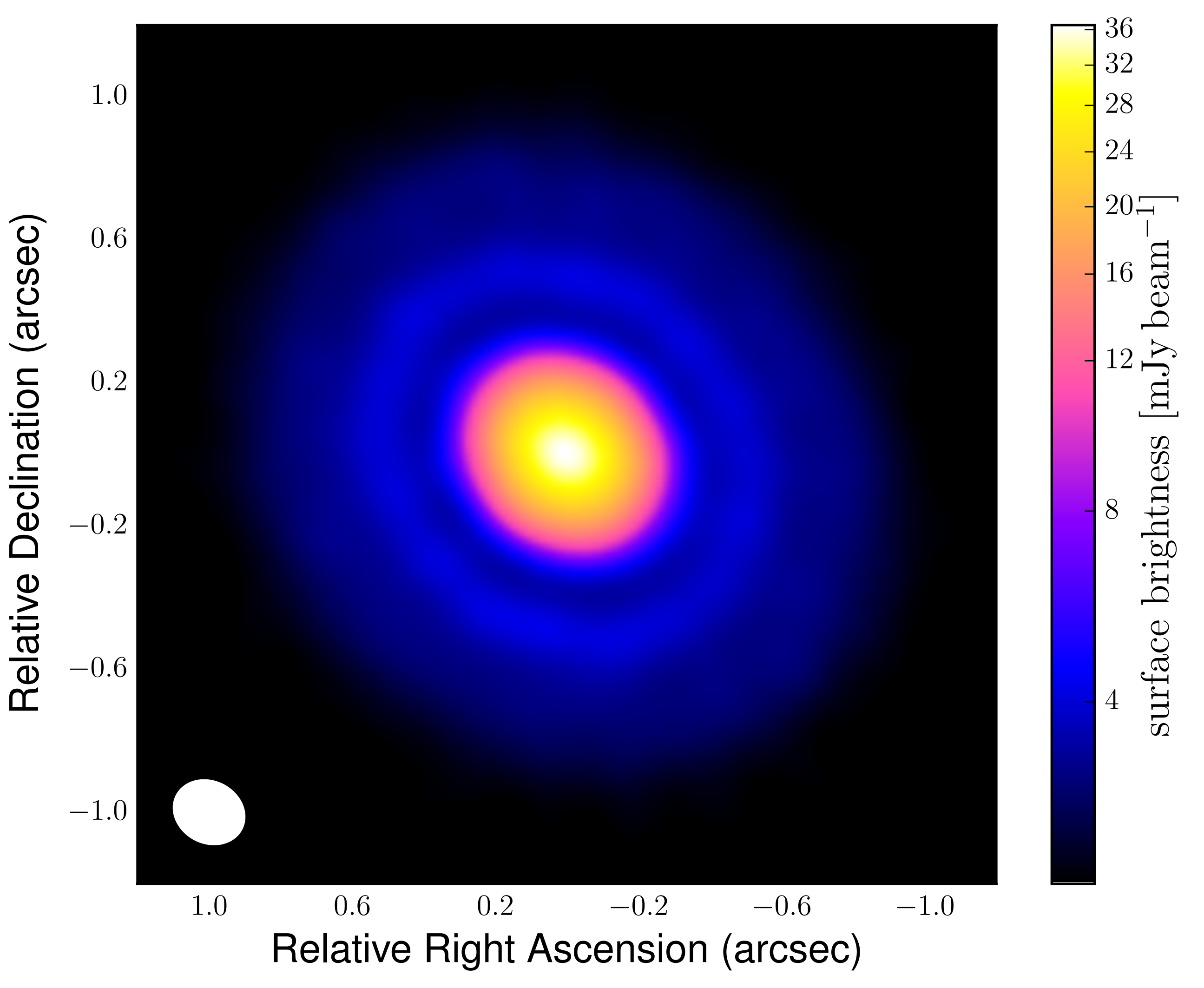
Is it actually all about planets?



HL Tau: ALMA partnership (2015)

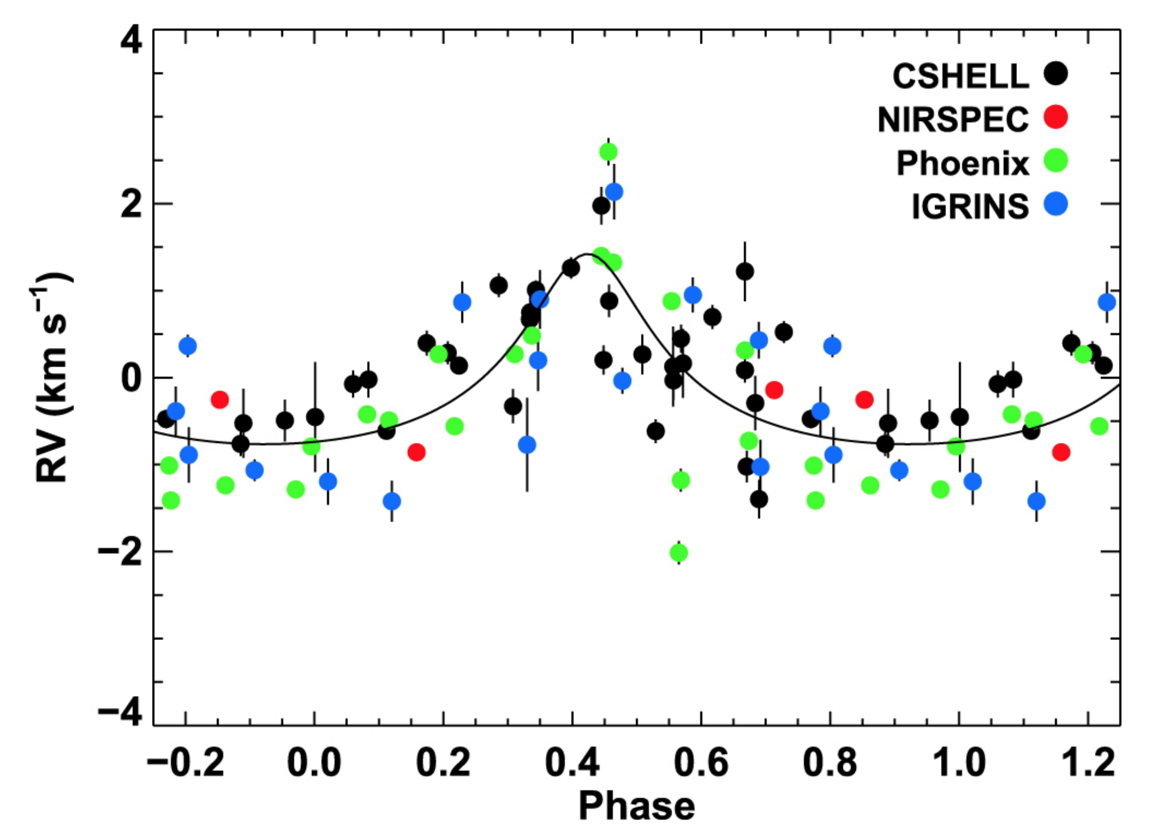


Elias 24: Dipierro+ (2018)

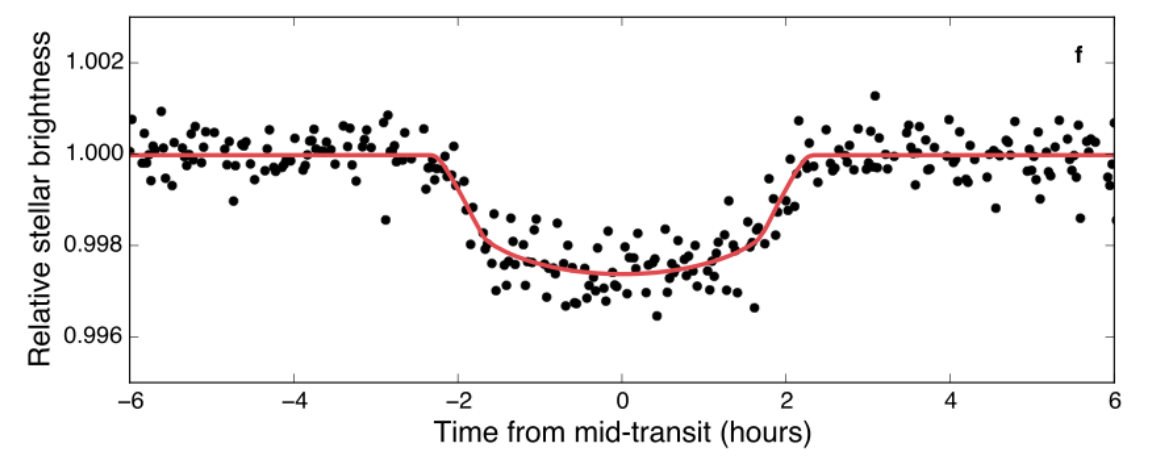
- Many discs now observed to have gaps/rings at >50AU.
- Individual objects all seem consistent with giant planets in discs.
- Possible tension with incidence of planets: gaps/rings seem common, but (hot) giant planets at >20AU are rare (<5%).

Where are the ***old*** planets?

- Several robust detections of hot/warm giant planets at ~Myr ages:
  - CI Tau (Crockett+ 2012).
  - V830 Tau (Donati+ 2016,17).
  - TAP-26b (Yu+ 2017).
  - K2-33b (David+ 2016).
- All gas giants with P ~ days, some are in accreting gas discs.
- Several detections in relatively small samples (~tens).
- Tension? Incidence of ~Gyr-age "hot Jupiters" is only 1%…

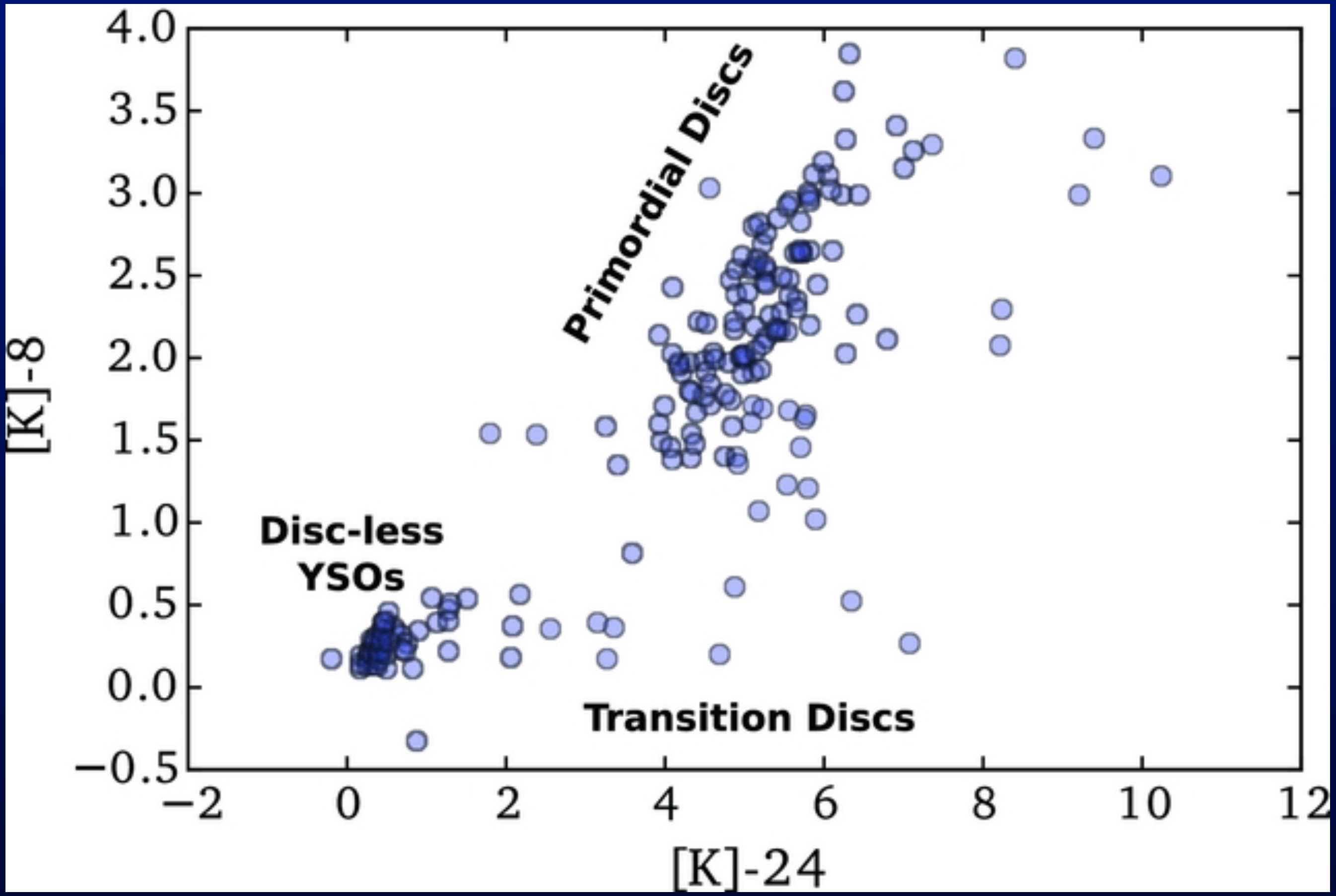


CI Tau: Johns-Krull+ (2016)

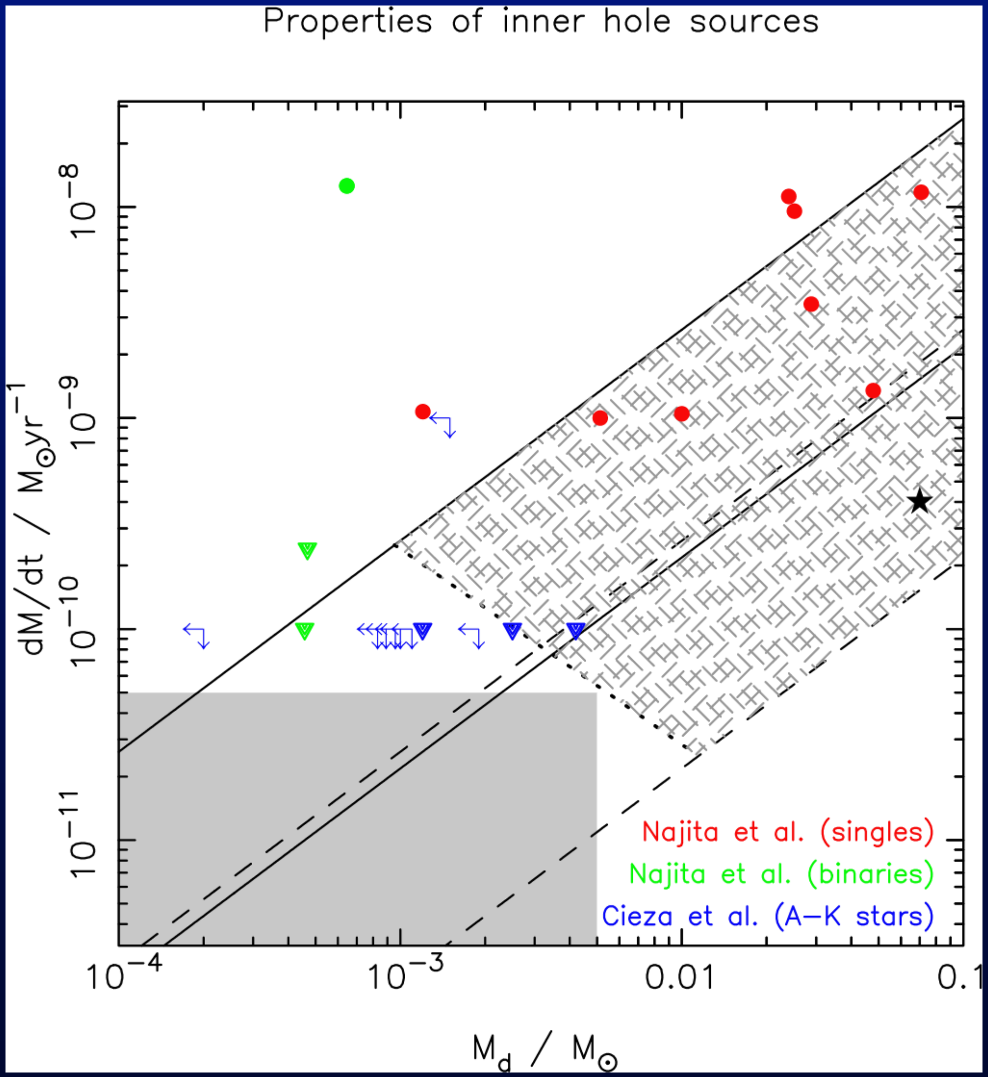


K2-33b: David+ (2016)

How can we tell these processes apart?



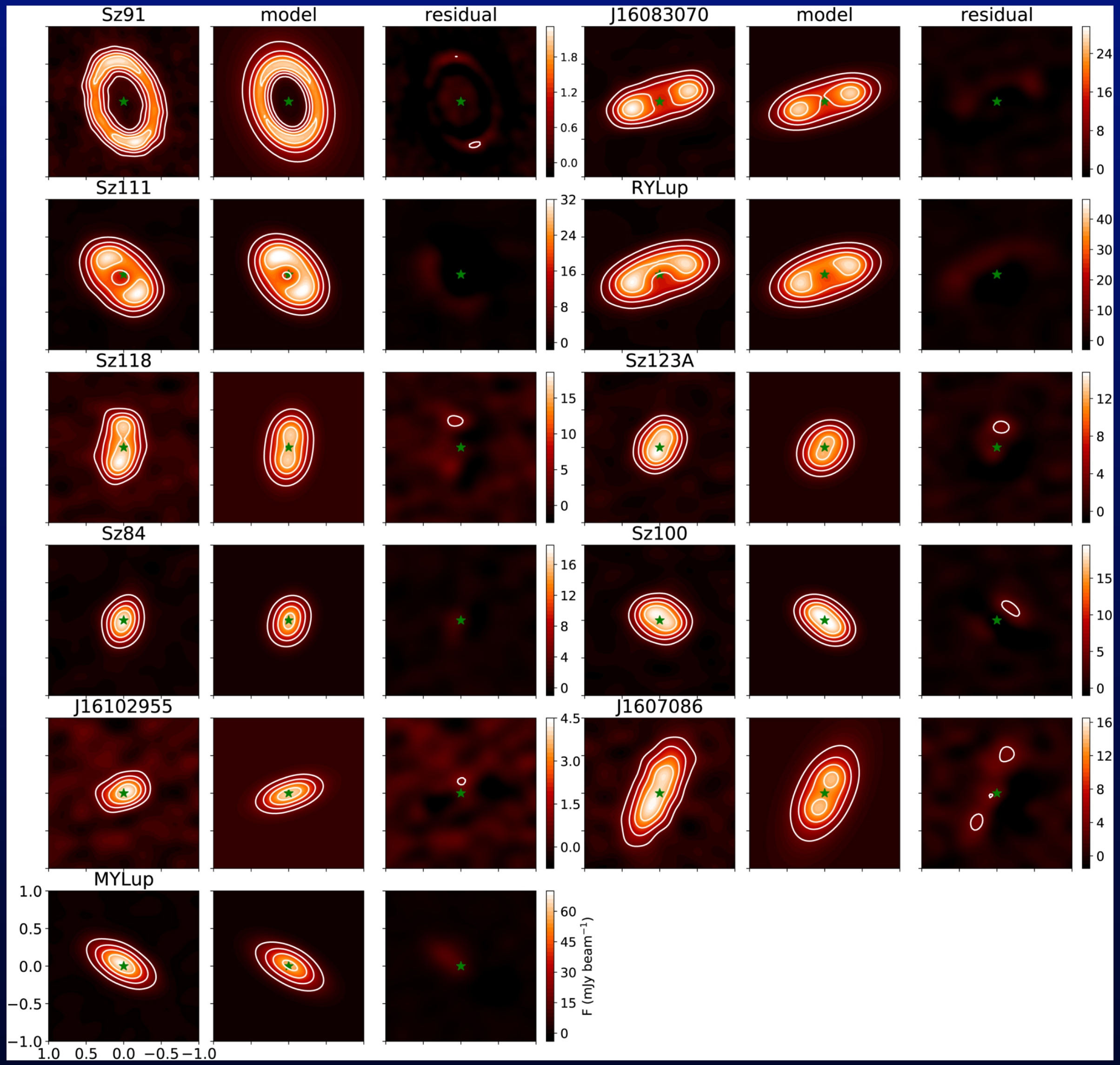
Owen (2016), after Strom+ (1989); Kenyon & Hartmann (1995); Hartmann (2005); many others

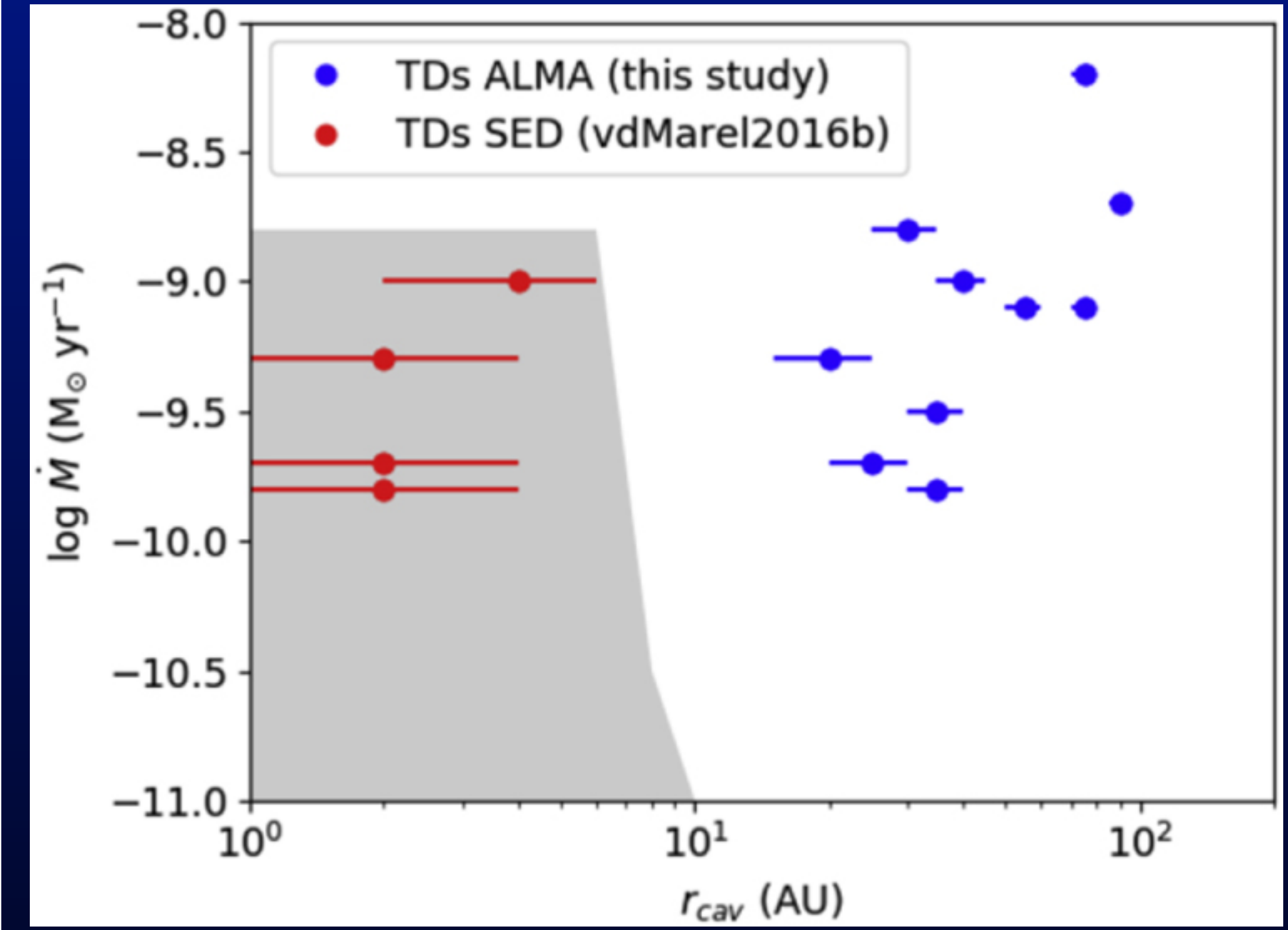


RDA & Armitage (2007); RDA (2008)

- Are "global" diagnostics relevant in the ALMA/SPHERE era? (e.g., Kamp+ 2017)
- What are "transitional" discs? Does the term still have meaning?
- What are the observations that can break the degeneracies?

How can we tell these processes apart?





van der Marel+ (2018)

- Are "global" diagnostics relevant in the ALMA/SPHERE era? (e.g., Kamp+ 2017)
- What are "transitional" discs? Does the term still have meaning?
- What are the observations that can break the degeneracies?

Open questions

- Do planets form early or late? Hard to form them late (low disc masses), hard to survive if they form early (rapid migration).
- Do planets (or cores) form as early as Class 0/I phases? If so, we need to think about infall / disc formation in much more detail.
- How do discs accrete?
- What drives disc mass-loss? UV, X-rays, or B-fields?
- If all these complex disc structures aren’t planets, what are they?
- Are you sure “interesting new object X” isn’t a binary?
- How common / important are misaligned / non-flat discs?
- What are we missing?