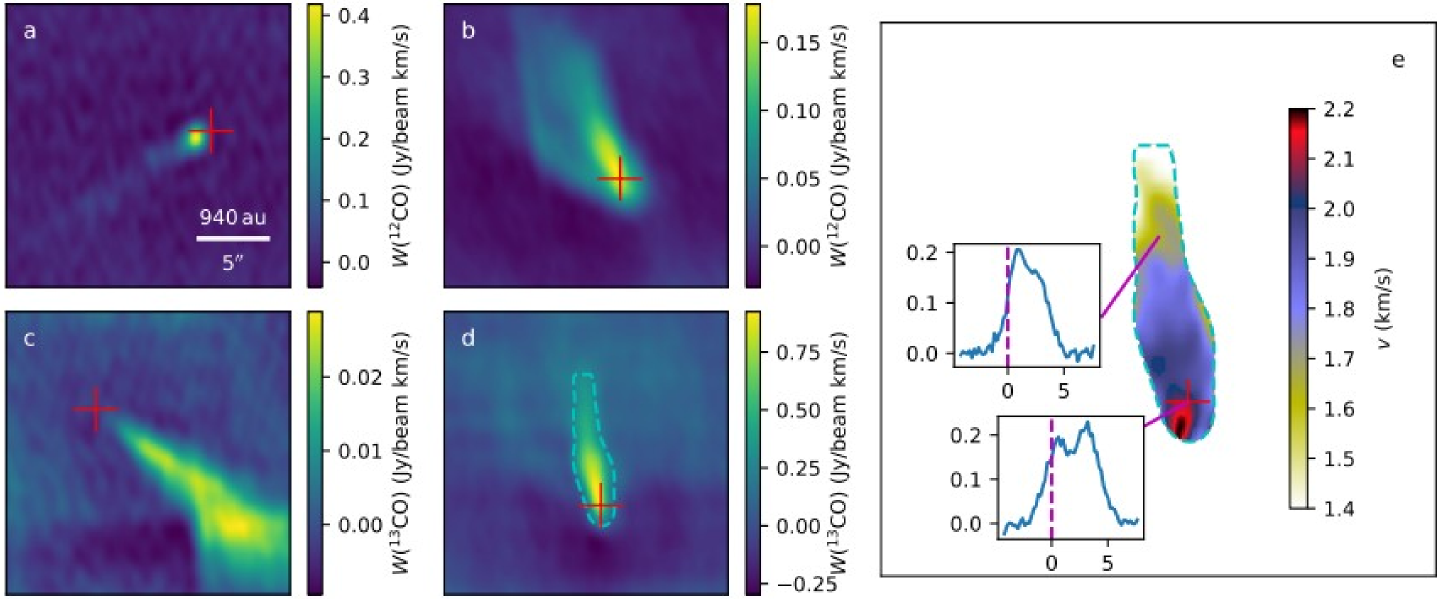


# Large-scale accretion in Class II YSOs

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# Problems with disk mass depletion
**(in traditional core-collapse view with one isolated core)**

### When do the planets form?

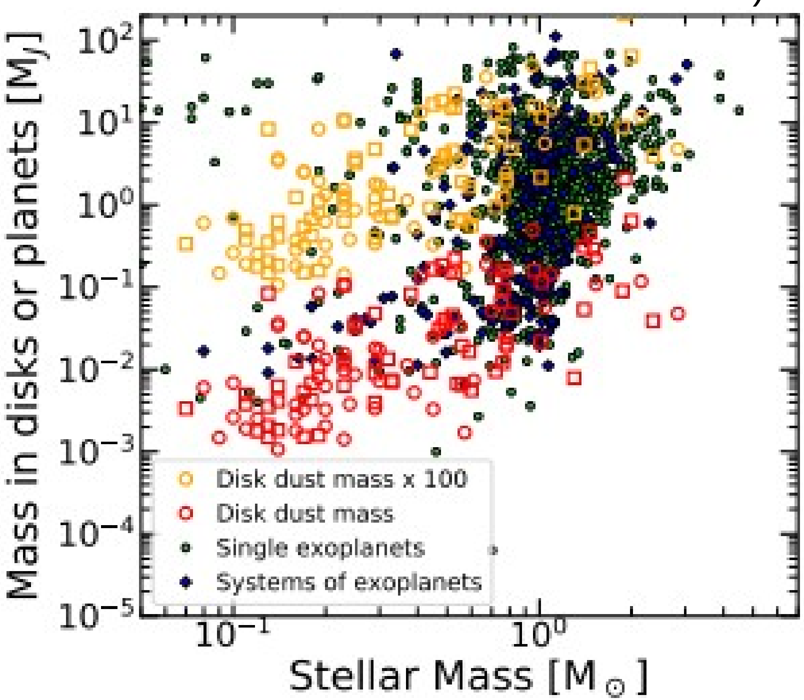
- Growing evidence that planet formation is a rapid process happening in the first few Myr of a star's life (e.g., Sheehan & Eisner 2017; Segura-Cox et al. 2020).
- Half-life of the disks ~2-3 Myr (Richert et al. 2018) supports a rapid planet formation.

→ the planet formation epoch ~ Class II protostars

### Mass budget problems

- Class II disks might not be massive enough to form the observed population of exoplanets (e.g., Manara et al. 2018).
- The observed mass accretion rates (Manara et al. 2020) would deplete the disks too quickly.

Credit: Manara et al. 2018)

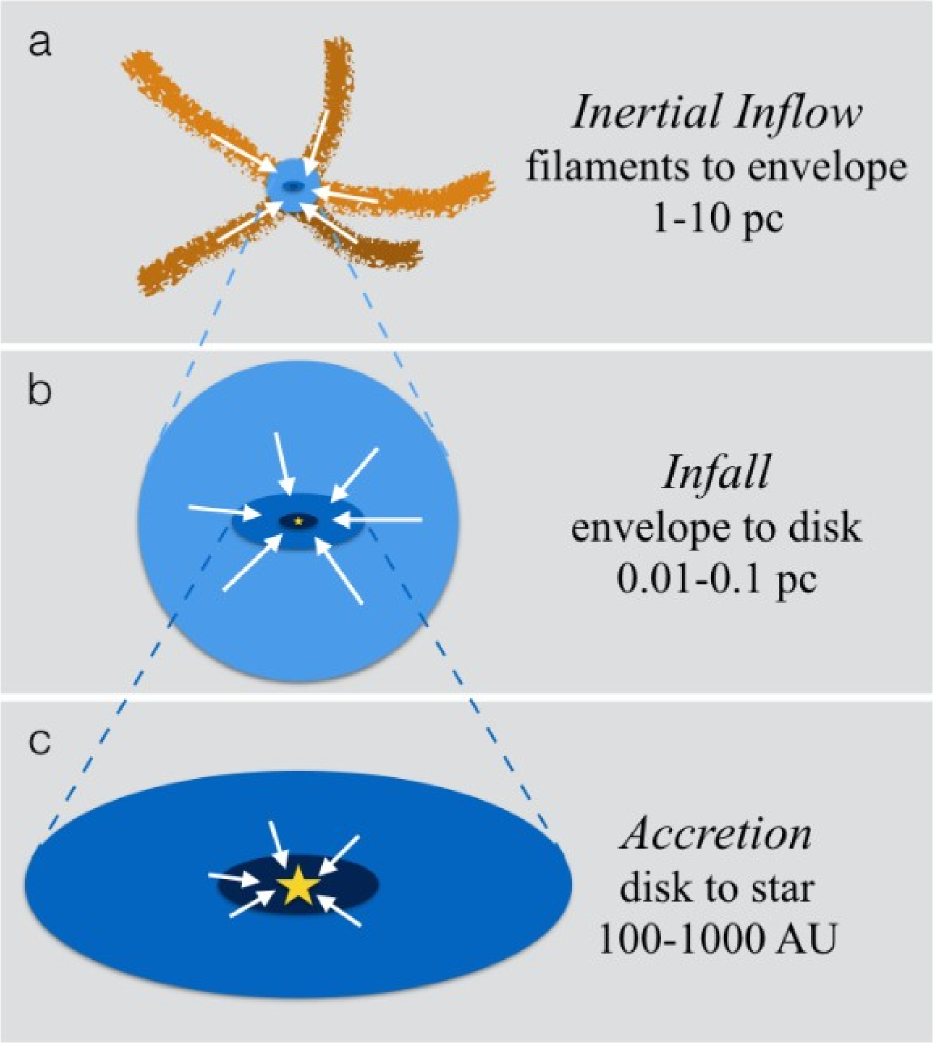


# New star formation scenario

**Inertial-Inflow (Padoan et al. 2017, 2020)**

- Rather than gravity working alone, turbulence plays a key role. Converging flows build up nodes which may collapse. Prestellar cores do not suddenly stop accreting, and turbulence can feed more mass into the forming star even after the collapse has started

  → wide range of final masses regardless of the initial core mass (also Pelkonen et al. 2021)





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# Accretion in Class II YSOs

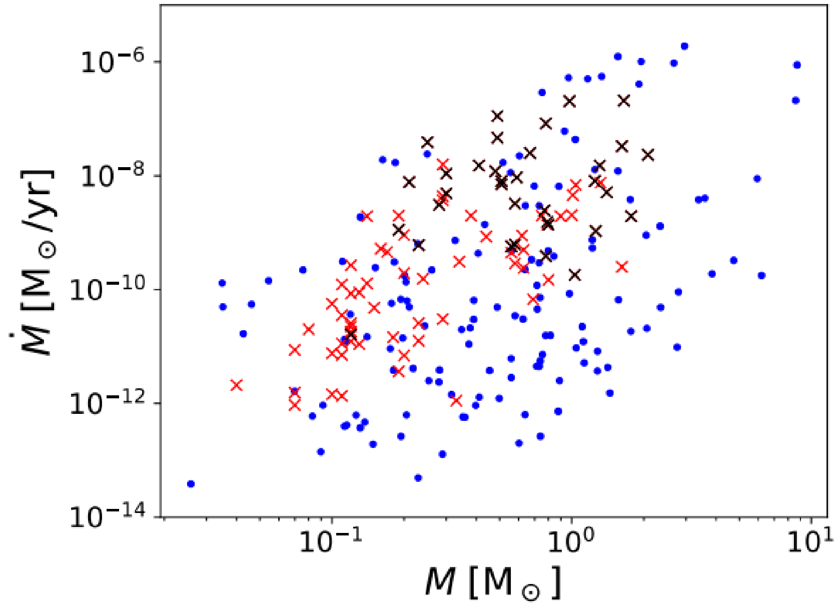
**Is it a Class II YSO if it is still being fed by the converging flows?**

- Probably not; Küffmeyer et al. (2023) showed that the protostars can become ‘rejuvenated’, becoming embedded again and looking more like Class I.

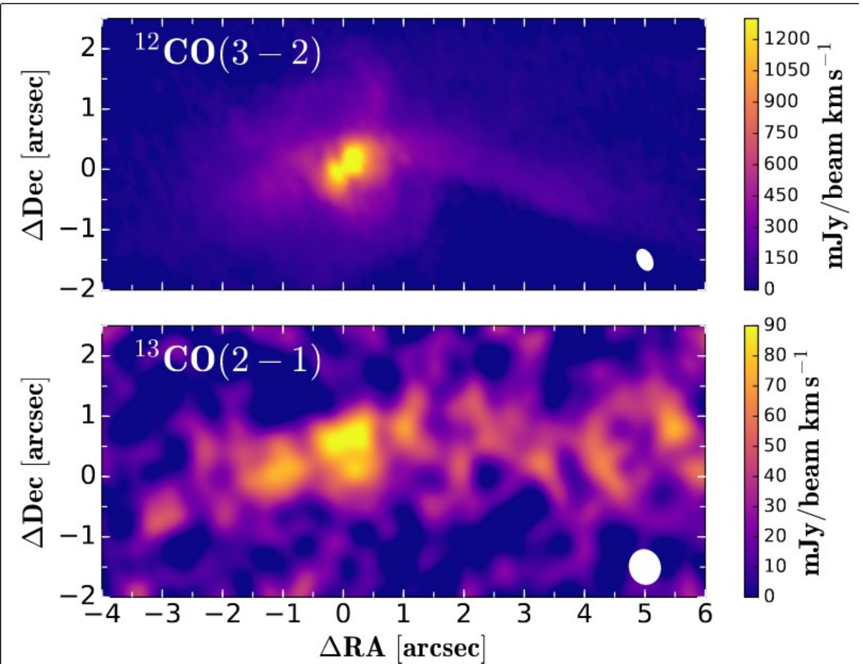
**What happens after the protostar becomes Class II YSO, having accreted most of its mass?**

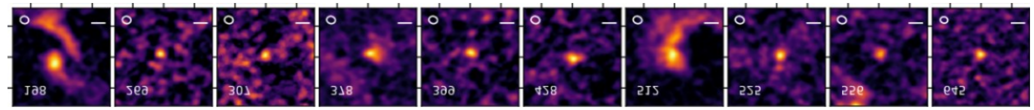
- It can still accrete at lower rate from the surrounding gas (Bondi-Hoyle accretion, e.g. Padoan et al. 2005, 2014), and this may be a significant contributor to the disk mass reservoir: disk ~1% star
- The infall rates in simulations match the observed disk-to-star accretion rates (Manara et al. 2020).
- Disks act like conveyor belts?

Blue points = infall in a 4pc simulation (512 rootgrid → 25 au resolution)
Red and black crosses = Cha I Class II YSO accretion (Manara et al. 2020)



# Streamers: serendipitous discoveries of accretion in Class II YSOs

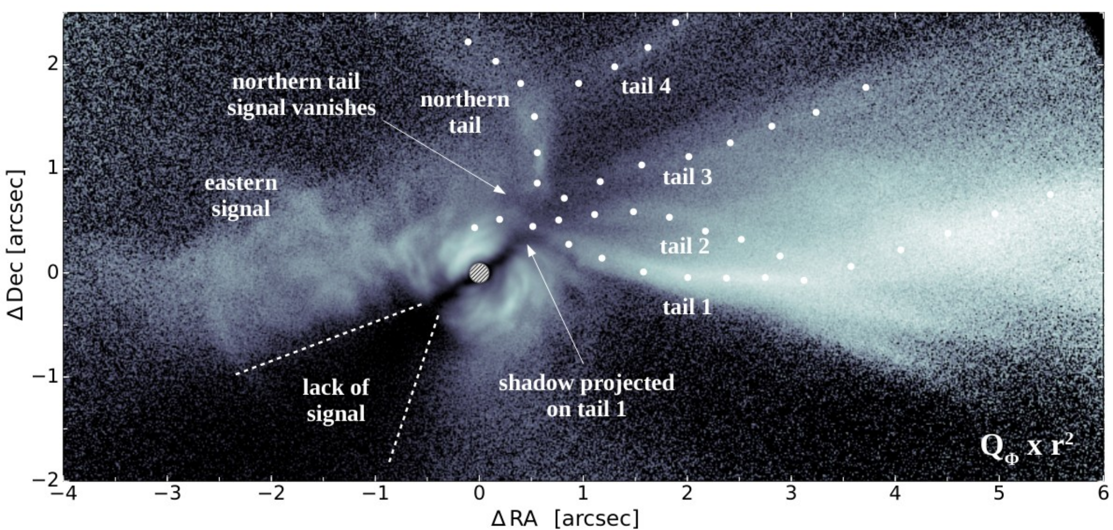


Top: ALMA 13CO data (Grant et al. 2021). Short exposure time ~ 2min, but still two targets that seem to have streamers.

Left: ALMA data (Akiyama et al. 2019) showing the late infall onto the disk of SU Aur. et al. (2019)

And of course the streamers in Alvaro's talk, too!




Ginski et al. 2021 estimated that the mass of the SU Aur tail is higher than that of the disk and the cause for misalignment of the disks.

Left: VLT/SPHERE, scattered light in H-band with radial Stokes parameter $Q_\varphi$, showing the extended dust structures at 7 au resolution (t_exp ~1h) (Ginski et al. 2021).

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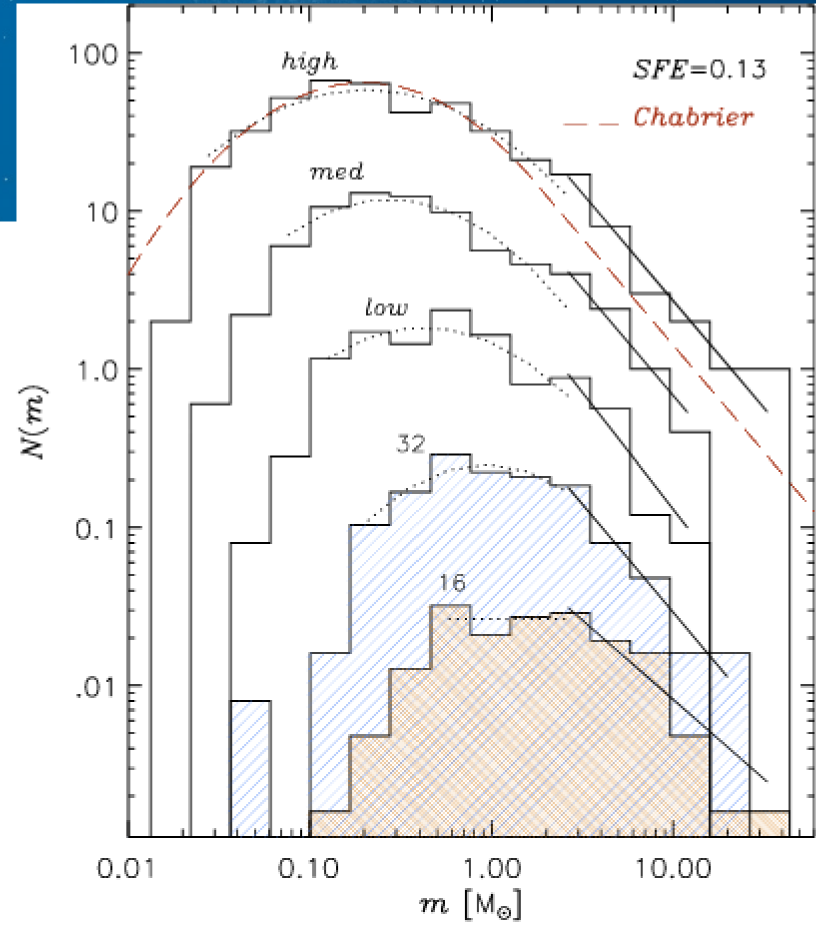
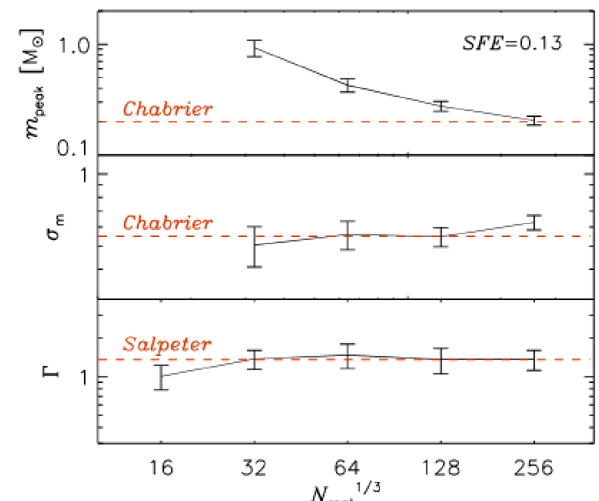
# MHD model of a star-forming cloud

- Detailed in Haugbølle et al. 2018
- 4pc periodic box, mass 3000 Msol
- RAMSES AMR MHD code, 256 root-grid, AMR 6 levels → 50 AU
- Randomly driven supersonic turbulence
- Run ~2.5 Myr with self-gravity, resulting in 413 sink particles with a realistic IMF
- Simulation does not include disks, and feedback is modelled by an accretion efficiency of 50% → matches the results of protostellar jets of Federrath et al. 2014

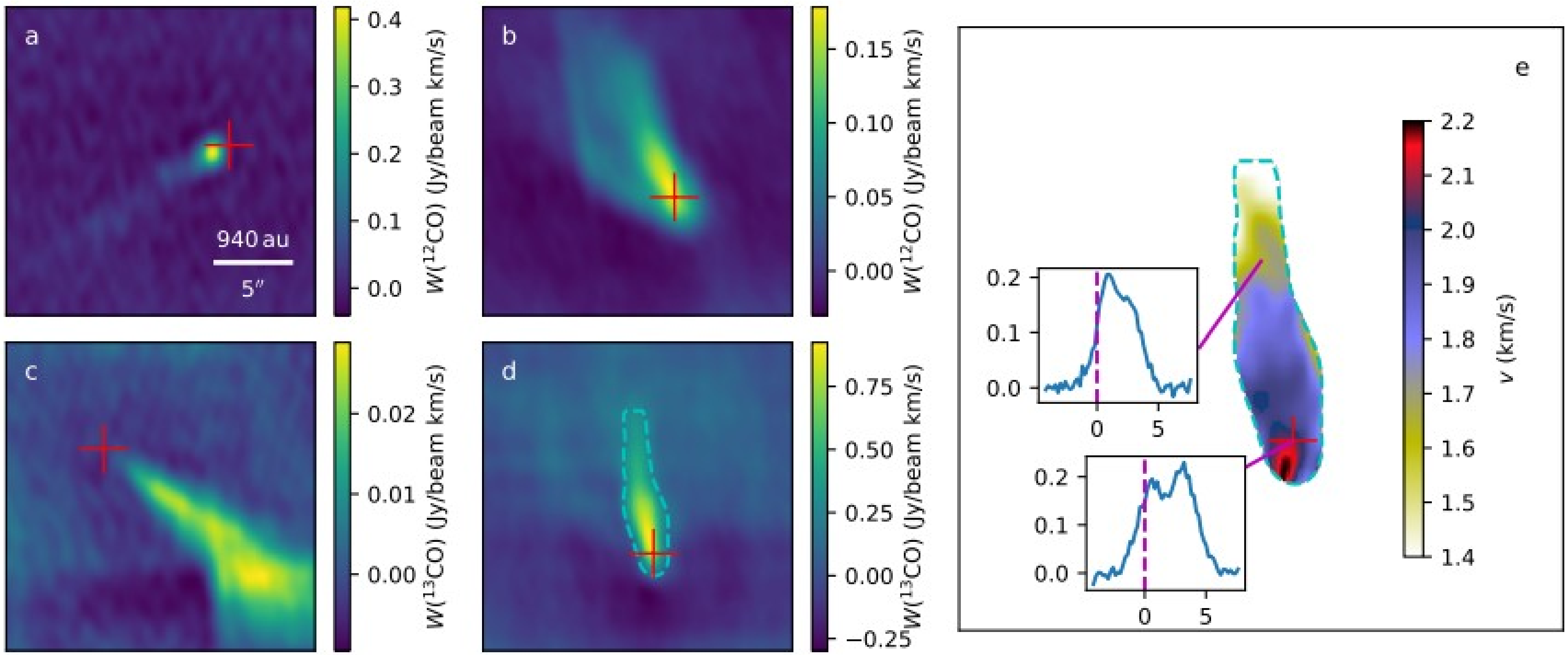


# Late accretion (Class II YSOs)

- Of the ~300 sink particles that are older than 0.5 Myr, ~200 are still accreting > 1e-12 Msol/yr.
- A majority shows signs of continuing significant accretion that is clearly visible in the local column density maps.
  - ~50 are still actively accreting from converging flows, with pseudodisks (order of 1000 AU radius) forming around them, and accretion rates typically 1e-7 to 1e-5 Msol/yr.
  - ~15 have strong Bondi-Hoyle accretion wakes with accretion rates from 1e-10 to 1e-8 Msol/yr.
    - Bondi-Hoyle accretion wakes have usually small apparent opening angles (< 30$^{\circ}$), and reach several thousands of au from the star particle.

# Detectability with ALMA




*a-d:* Simulated ALMA 12CO 2-1 (a,b) and 13CO 2-1 (c,d) observations, 30 min exposure time. (Using Mika Juvela’s LOC code & CASA.)
e*:* Velocity gradient in the dash-marked region in panel d.

→ ALMA is able to detect the stronger (> 1e-10 Msol/yr) Bondi-Hoyle accretion wakes, but it can take a lot of telescope time.

# Synthetic Scattered NIR Light ~ NIRCam/JWST

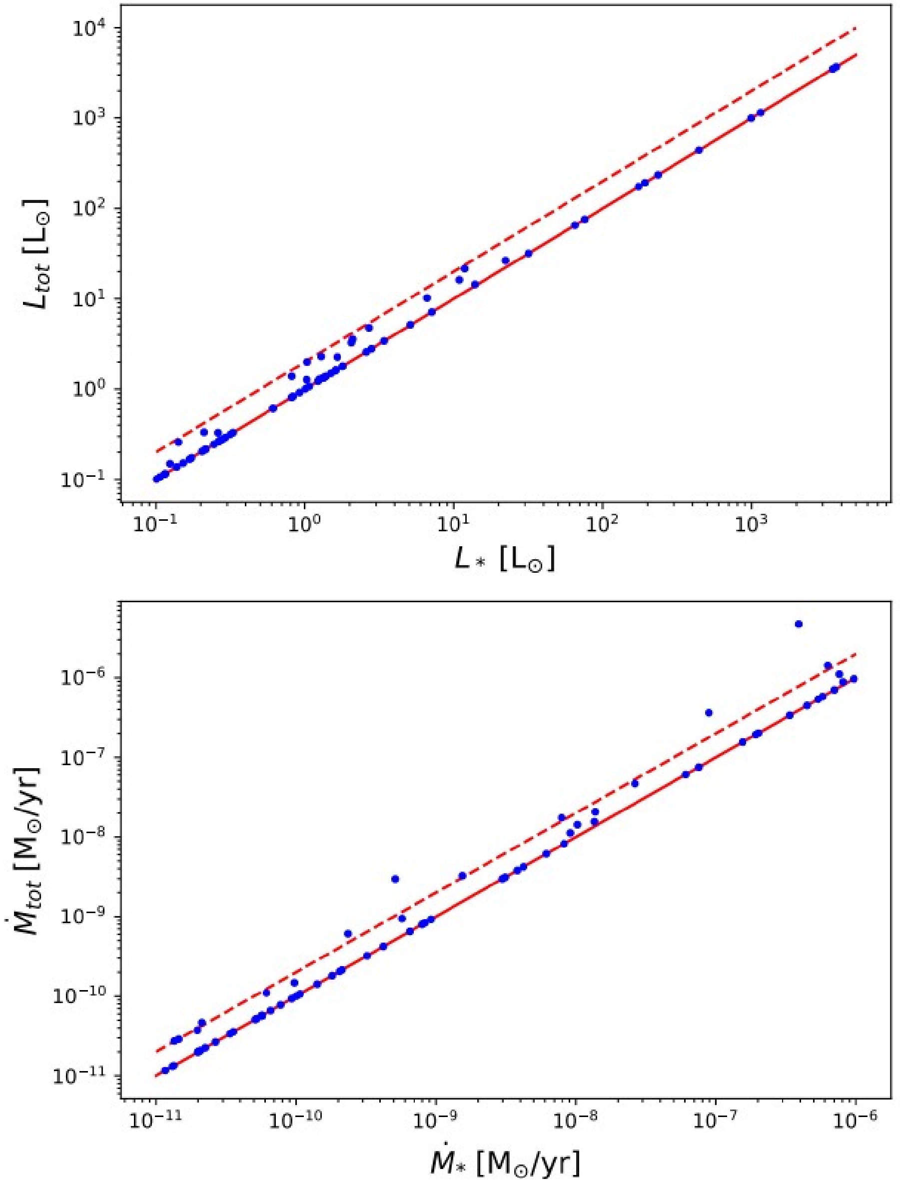
- 512 root-grid 4pc cloud simulation: ~ 2.0 Myr, 317 sink particles
- SOC code (Juvela 2019) was used to calculate the scattered NIR light
  - assuming a solar-neighborhood ISRF illuminating the cloud from the outside, and adding all sink particles with the luminosity higher than 0.5 Lsol as point sources within the cloud.
  - luminosity is estimated from MESA tracks and include Lacc
  - Due to computational issues, the scattered light maps were calculated at 50 AU resolution.
  - Artefacts in the final maps due to the AMR grid → new calculations in 12800 AU unigrid for subcubes for sinks with L > 0.1 Lsol and accretion rates $10^{-11}$ Msol/yr < Macc < $10^{-6}$ Msol/yr. All the sources within these subcubes were included as point sources.
    - 110 sinks fulfilled these criteria → 3 directions and 2 wavelengths →660 maps to be analyzed

# Alas, stars love company!

Out of the 110 stars, only 48 were the only star in their subcube.

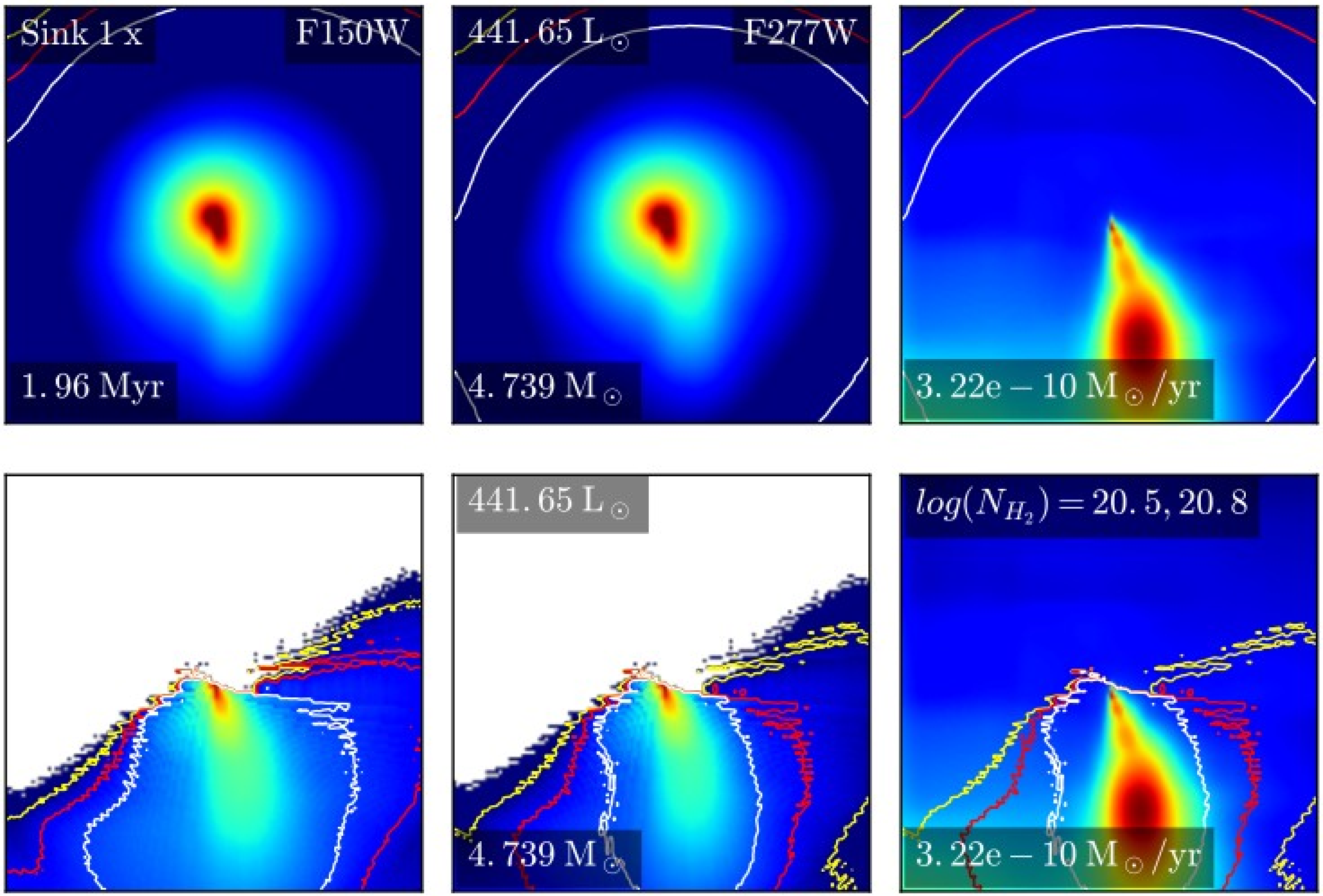
Additional 21 stars were the ‘dominant star’ in their subcube, by luminosity. In the following, they are included, but use the summed up luminosity, mass and infall rate of all the stars in the subcube.

The companion stars could not be included, since generally the dominant star dominates in luminosity and hence in scattered light surface brightness. However, they may accrete at a comparable or even higher rate.



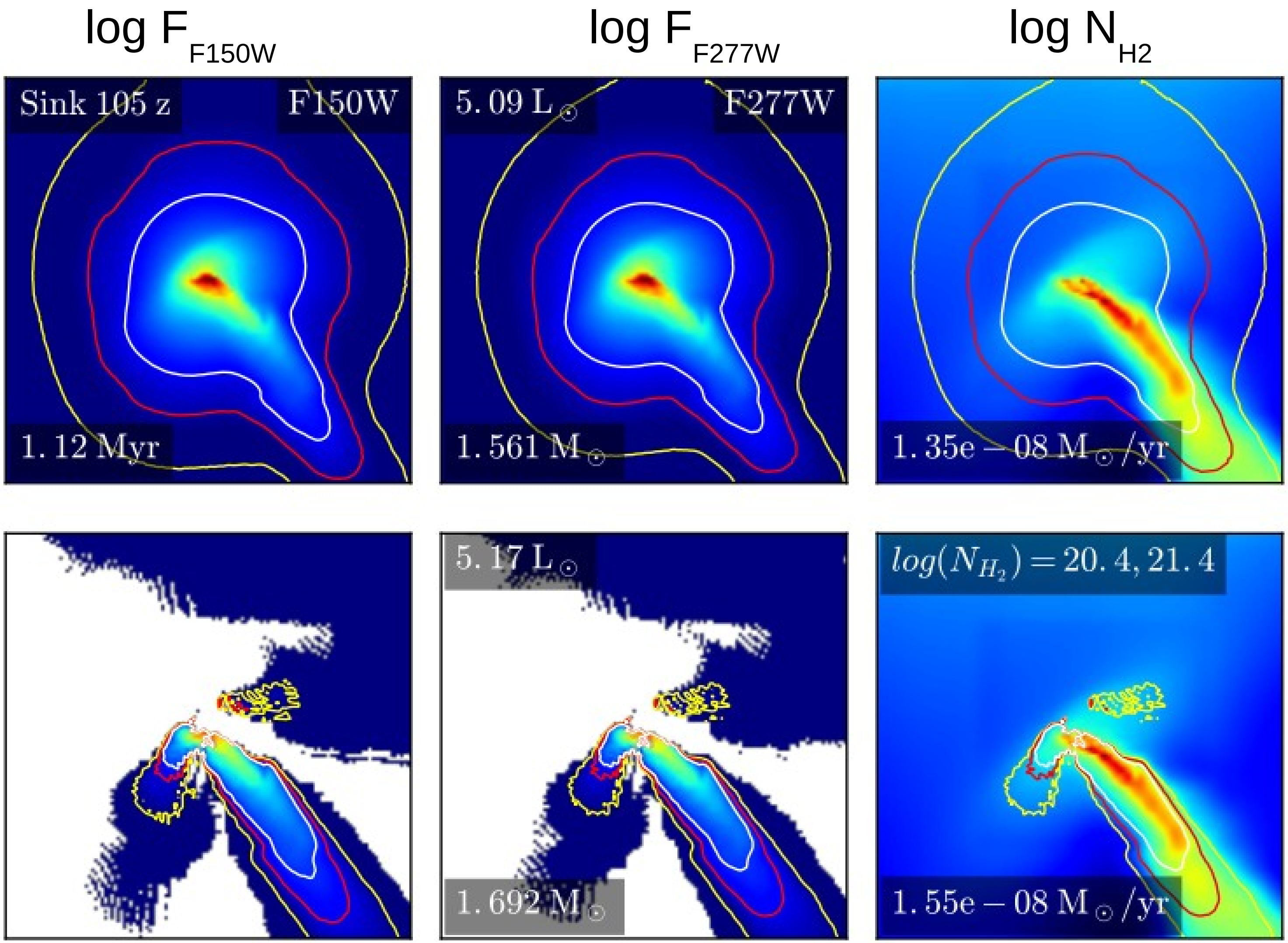
# NIR Scattering with JWST

log $F_{F150W}$ | log $F_{F277W}$ | log $N_{H2}$




- White, red and yellow contours are 5-sigma detections, with 2, 8, and 50 min of NIRCam.
- Bottom row: subtracting the median in each distance ring.

# NIR Scattering with JWST

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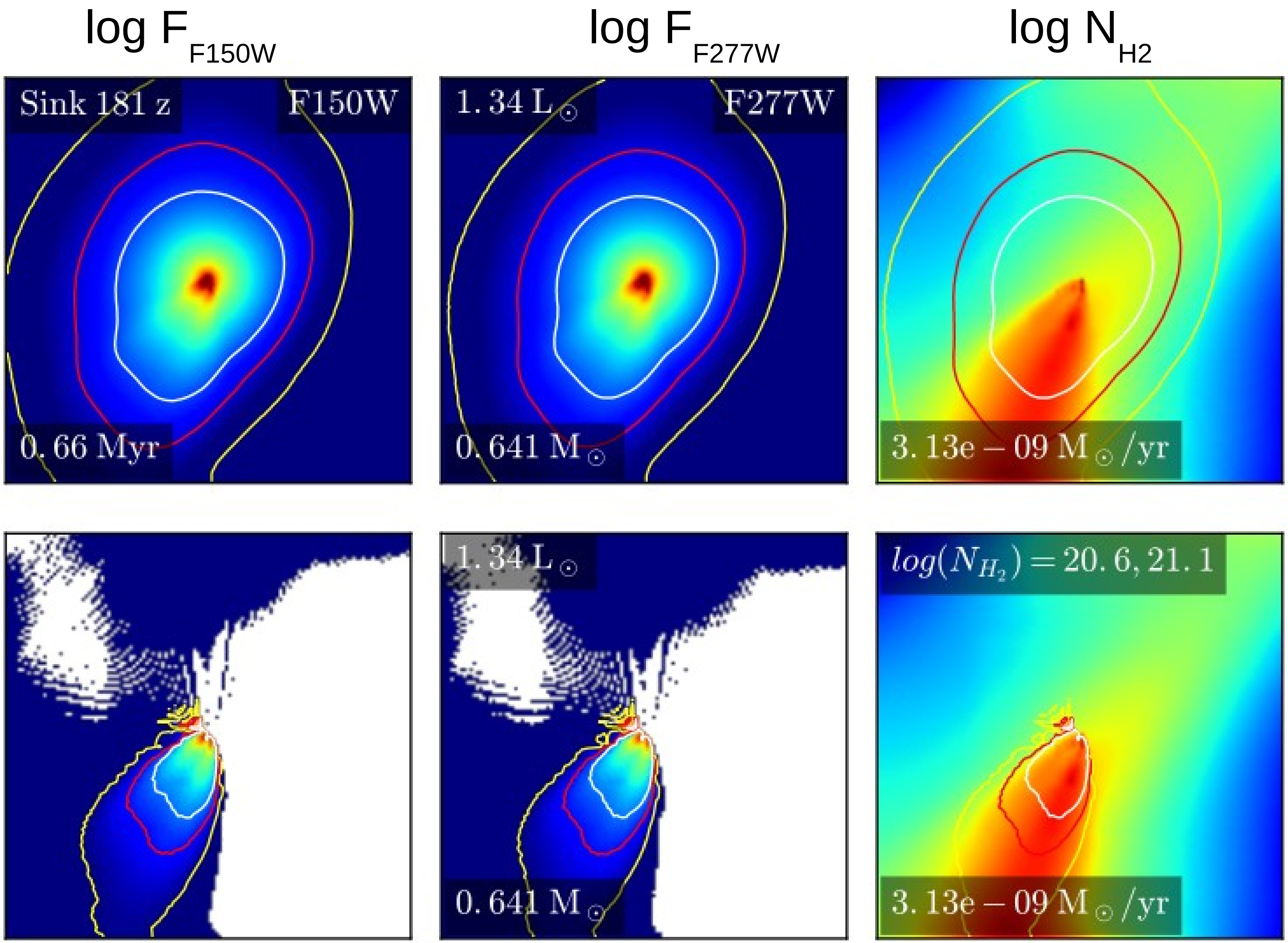
# NIR Scattering with JWST




- White, red and yellow contours are 5-sigma detections, with 2, 8, and 50 min of NIRCam.
- Bottom row: subtracting the median in each distance ring.

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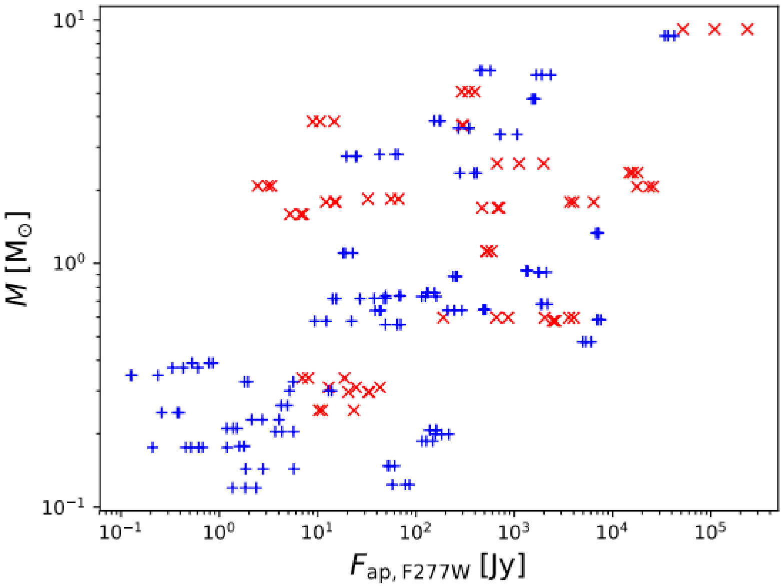
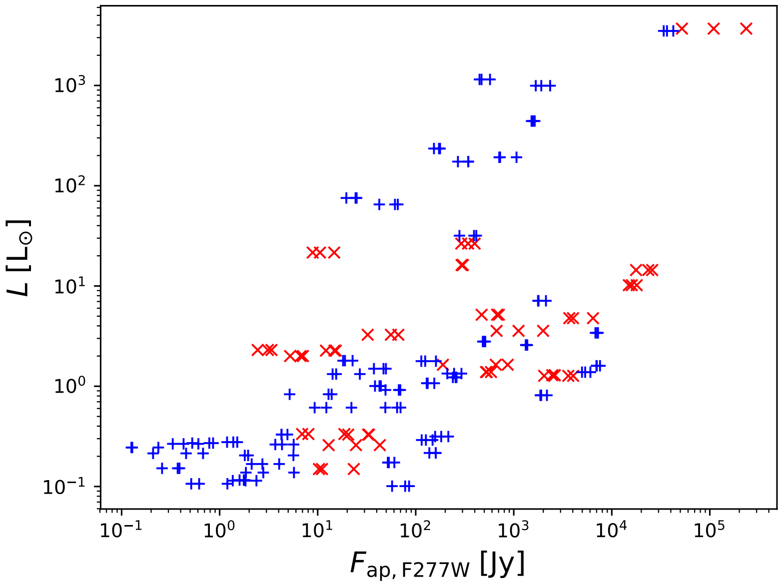
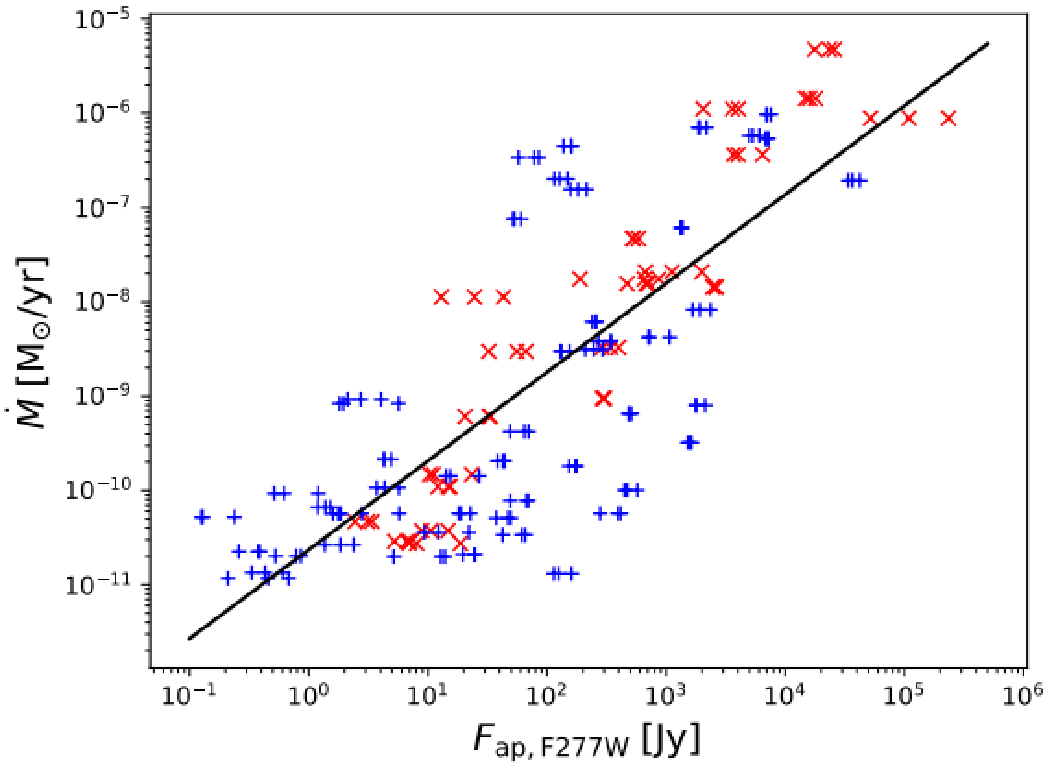
# NIR scattering vs. Mass, L, Accretion



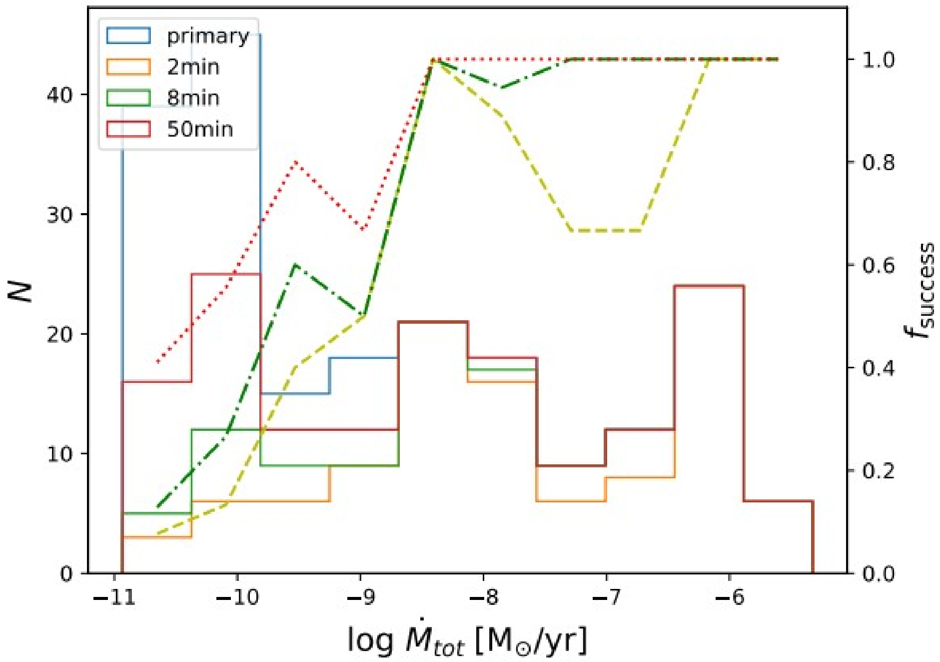

- Flux in aperture 250 – 1000 au
- NIR surface brightness is a predictor for the accretion (infall) rate, but with lots of scatter.

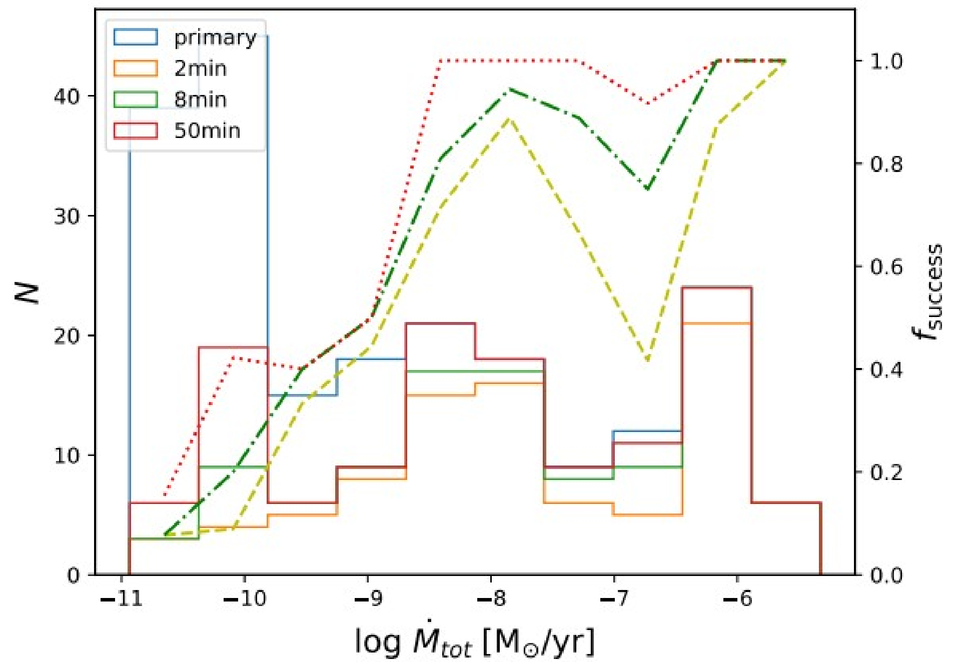
log (Macc) = 0.94 * log (F) – 10.6

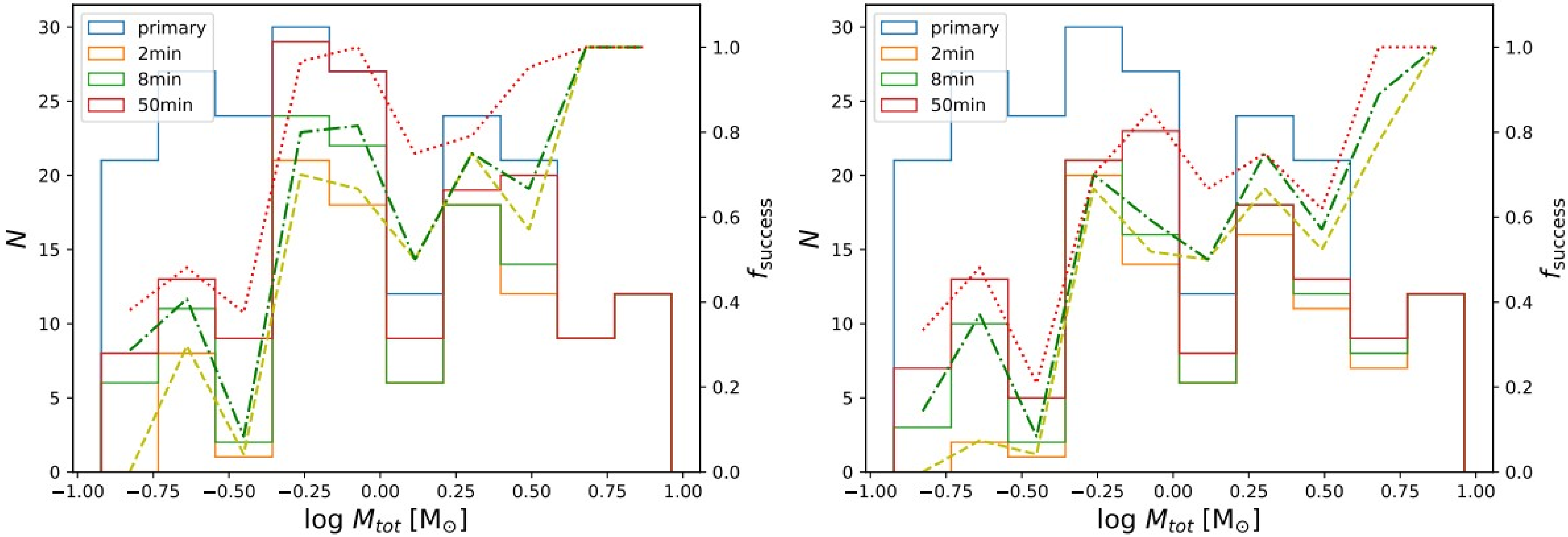


# Measure of success: extent of structures

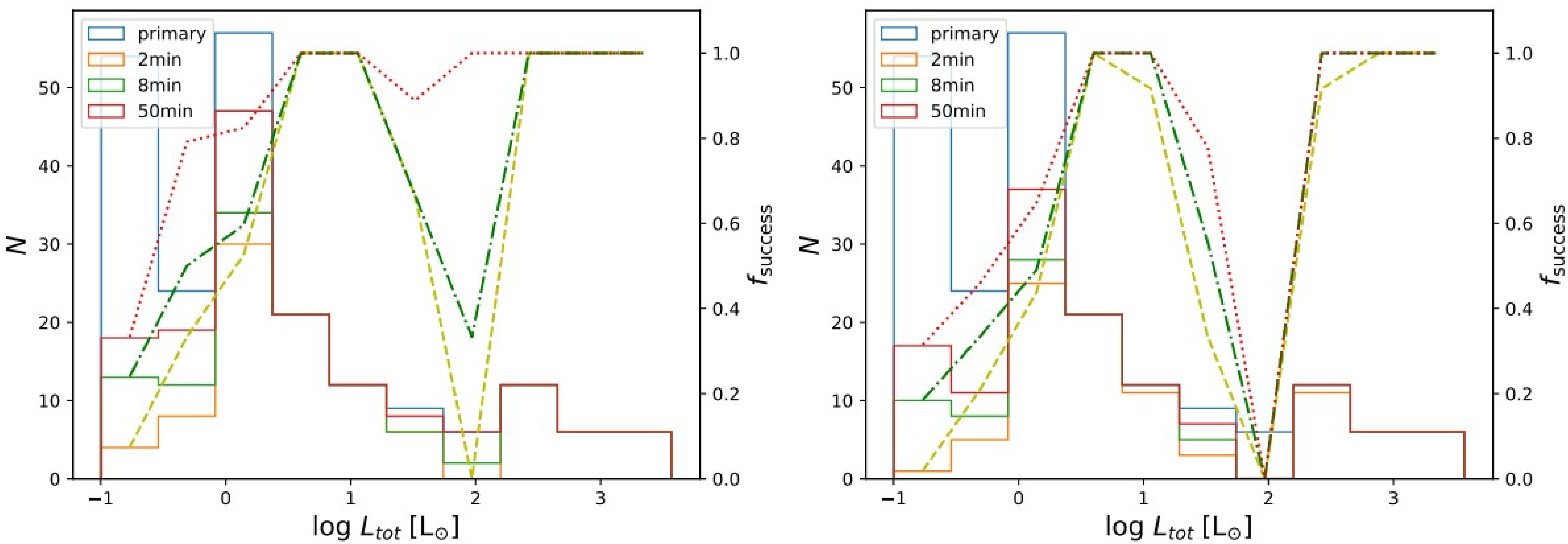
- 3 different exposure times: 2 min, 8 min and 50 min
- Do we have detections (SN > 5) over 1000 AU from the star?
- Obviously, we can only compare to the stars that are single (or at least dominant) in their subcube.
- Even with the 2 min exposure and ring-subtracted maps (right), we get ~50% success rate for infall rate ~1e-9 Msol/yr.



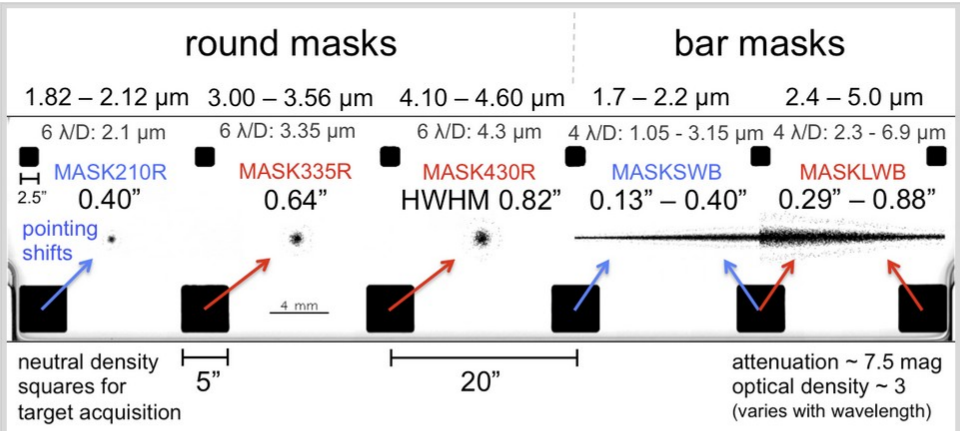


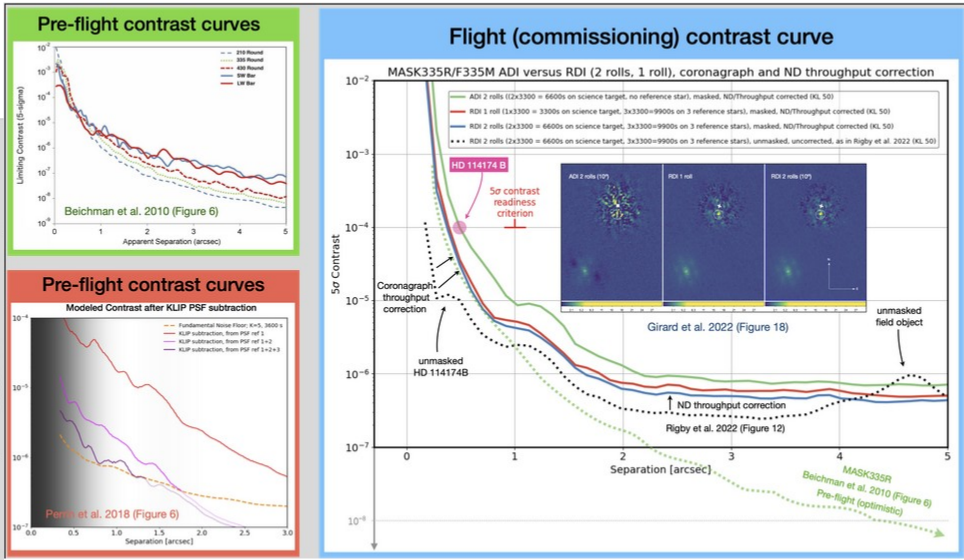

~50% success rate with ~0.5 Msol and ~1 Lsol



# Next…

- Take the stars for which we get a good detection of a streamer, and then do synthetic ALMA observations to get the kinematics like the observers would, and that allows us to calibrate/test these methods of measuring the infall from the observations.
- Also, take a look at the ones where we failed to understand why.
- Something I didn't dwell on… we will need to use coronagraphy to block out the light from the Class II YSO itself, since the contrast is too high otherwise. This imposes some limits on the filters we can use, on the shorter wavelength side.



# Summary

- We find large-scale accretion into Class II protostars in the simulations. As this is of the same order as the observed disk-to-star accretion, protoplanetary disks may act more like conveyor belts, transfering mass from large-scale flows to the central star.
  - One caveat: Since the simulation does not have real disks, we have to have large-scale accretion if there is mass accretion. It would be possible for a real Class II YSO to feed from its disk.
- We have done synthetic observations and conclude that these kinds of accretion flows (>1e-10 Msol/yr) can be detected by ALMA in CO molecular lines and JWST in NIR scattered light.
- Late infall will have an impact on the planet formation: providing more material for the planets (e.g., Manara et al. 2018), possibly triggering planet formation via gravitational instabilities (Ginski et al. 2021), and being the source for the spin-orbit misalignment (Thies et al. 2013).

# Observation proposals for streamers

- We managed to get an SMA proposal through! 27 hours to observe three sources (including SU Aur) in Taurus-Aurigae, ~ 500 au resolution, [12CO, 13CO, C18O] J=2-1 transitions. Alas, Taurus is currently too close to the Sun, but maybe in late summer?
- We applied again to ALMA (34 sources in Cha I), and let's see how that goes. (And yes, I  got my 10 proposal review assignment from ALMA, too...)
- We could try making a proposal for JWST in the next call. Obviously having this kind of modelling paper out by then would be a very good idea.