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Evidence of Enhanced Ionization in Protostellar Envelopes

Kamber Schwarz

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European Research Council
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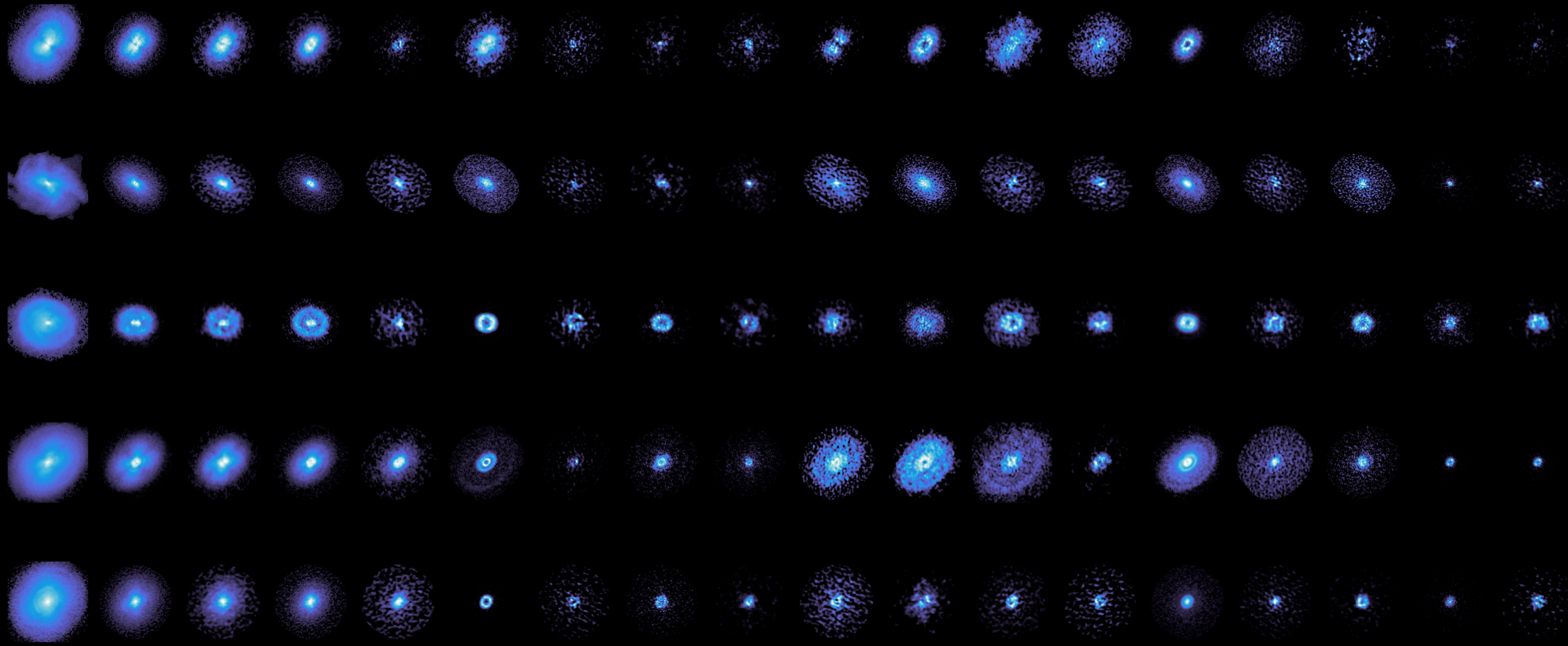
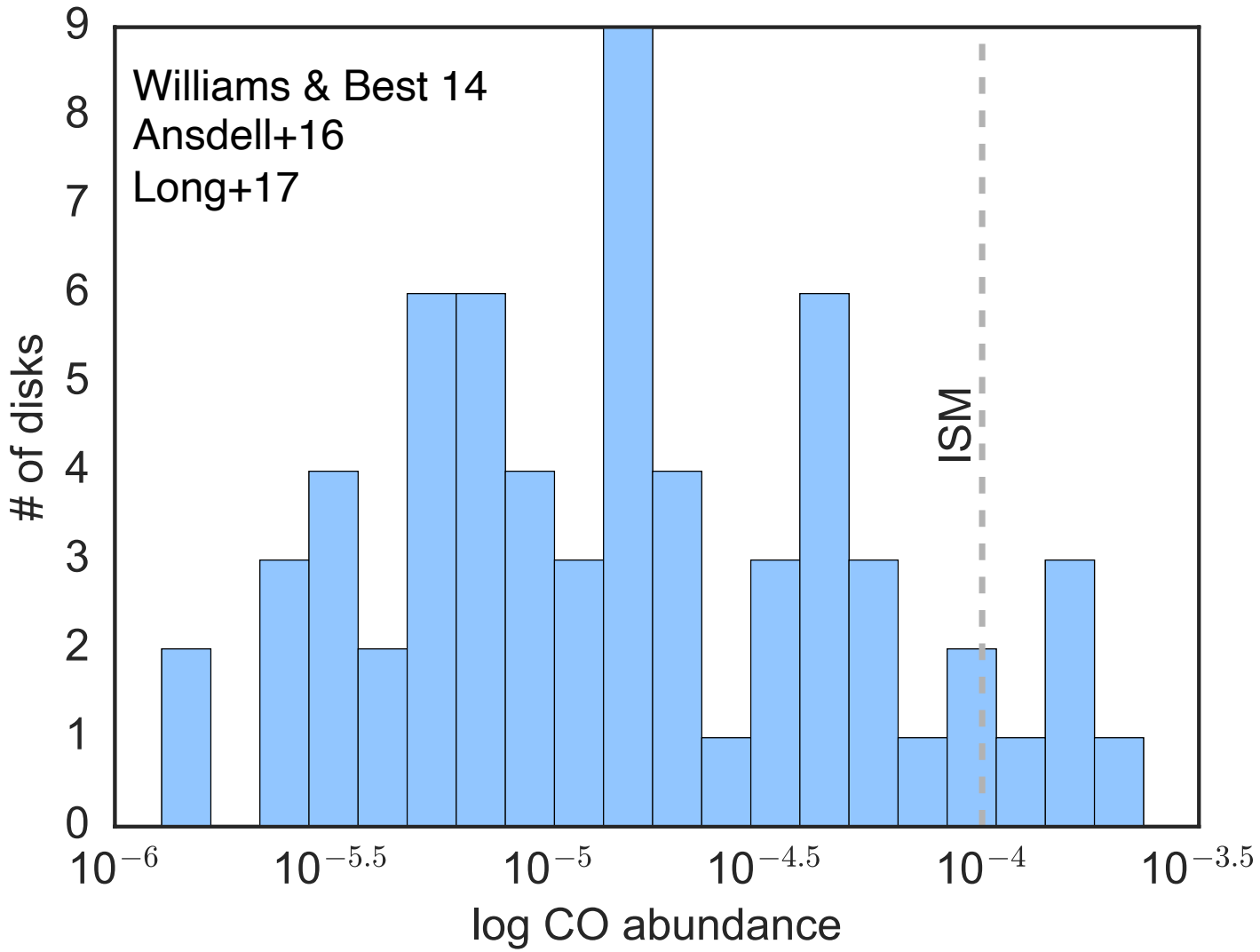


Credit: Charles Law, MAPS Large Program

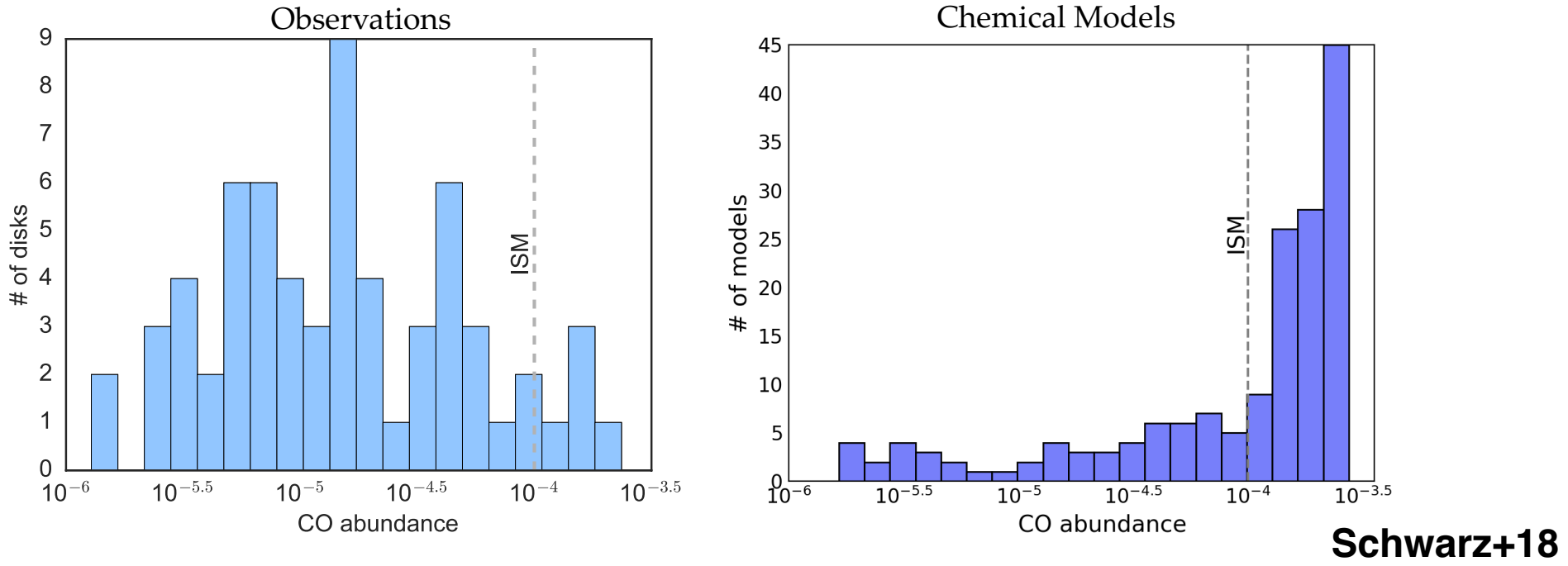
CO is under-abundant in disks

Depletion:

- Varies from source to source
- Varies with radius in a single source



Carbon Chemistry Needs Ionization

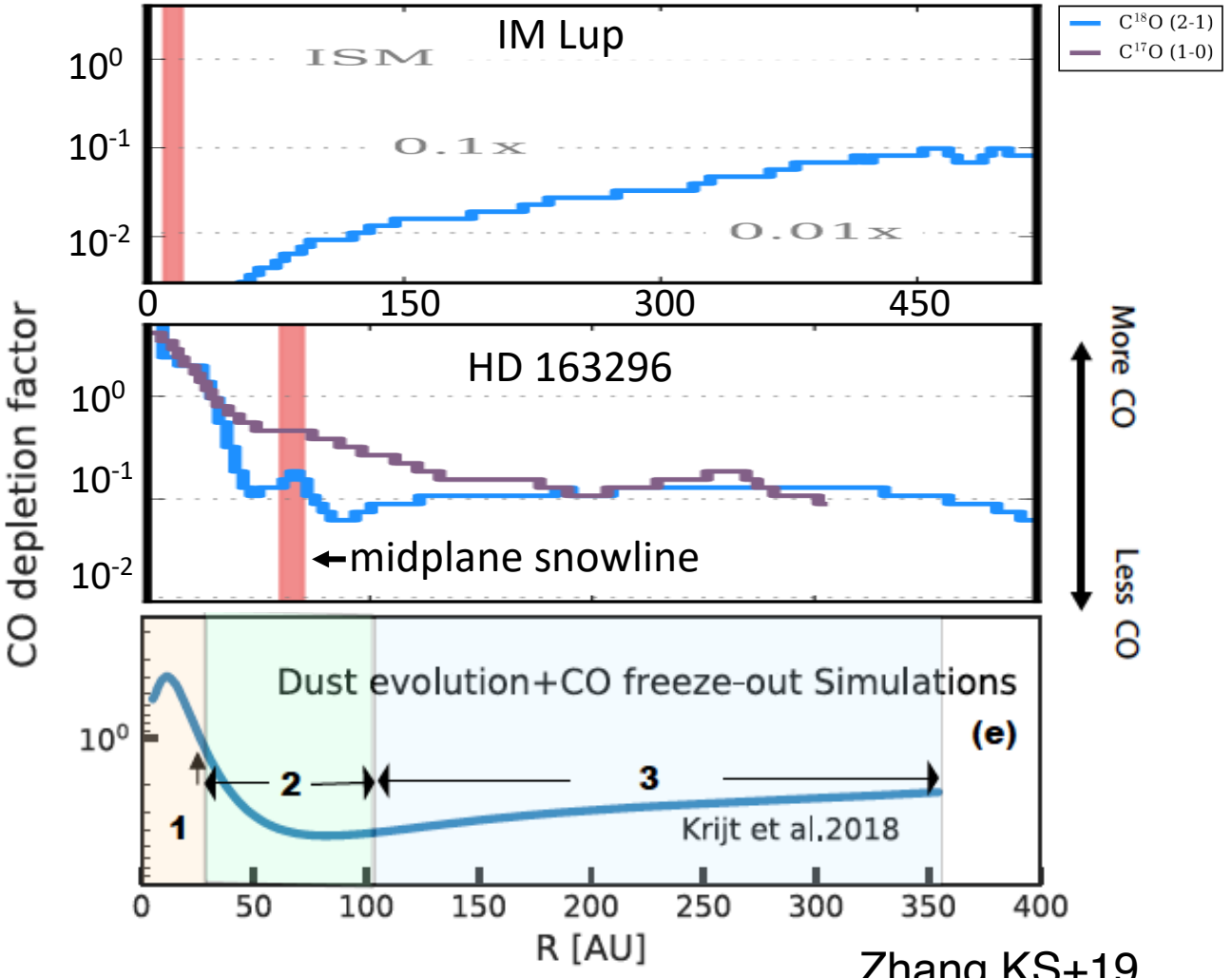


Schwarz+18

- Chemical C processing requires ISM level ionization $\zeta = 10^{-17}$ s^{-1} (Schwarz+18,19b)
  - Stellar winds modulate cosmic rays (talks by Donna, Deryl, Valentin)
  - Measured ionization is disks $\lesssim 10^{-18}$ s^{-1} (Cleeves+15,Seifert+21,Aikawa+21,Long+24)
- Depletion timescales longer than disk lifetime (3 Myr)

Inner Disk Enrichment from Dynamics

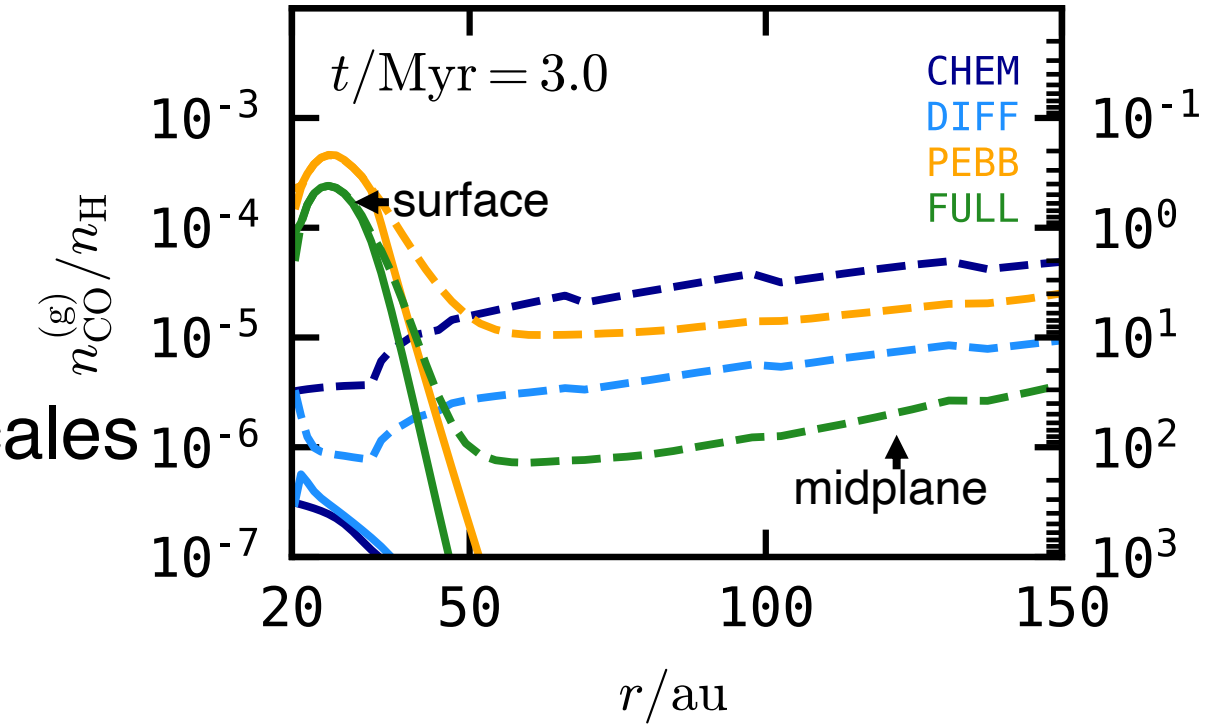
- Model dust evolution + CO freezeout (Krijt,KS+18)
- Match CO profile for high mass star
- Ice chemistry needed for low mass stars
  - Relevant for TESS sample



Zhang,KS+19
Zhang,KS+21

Chemistry + Dynamics

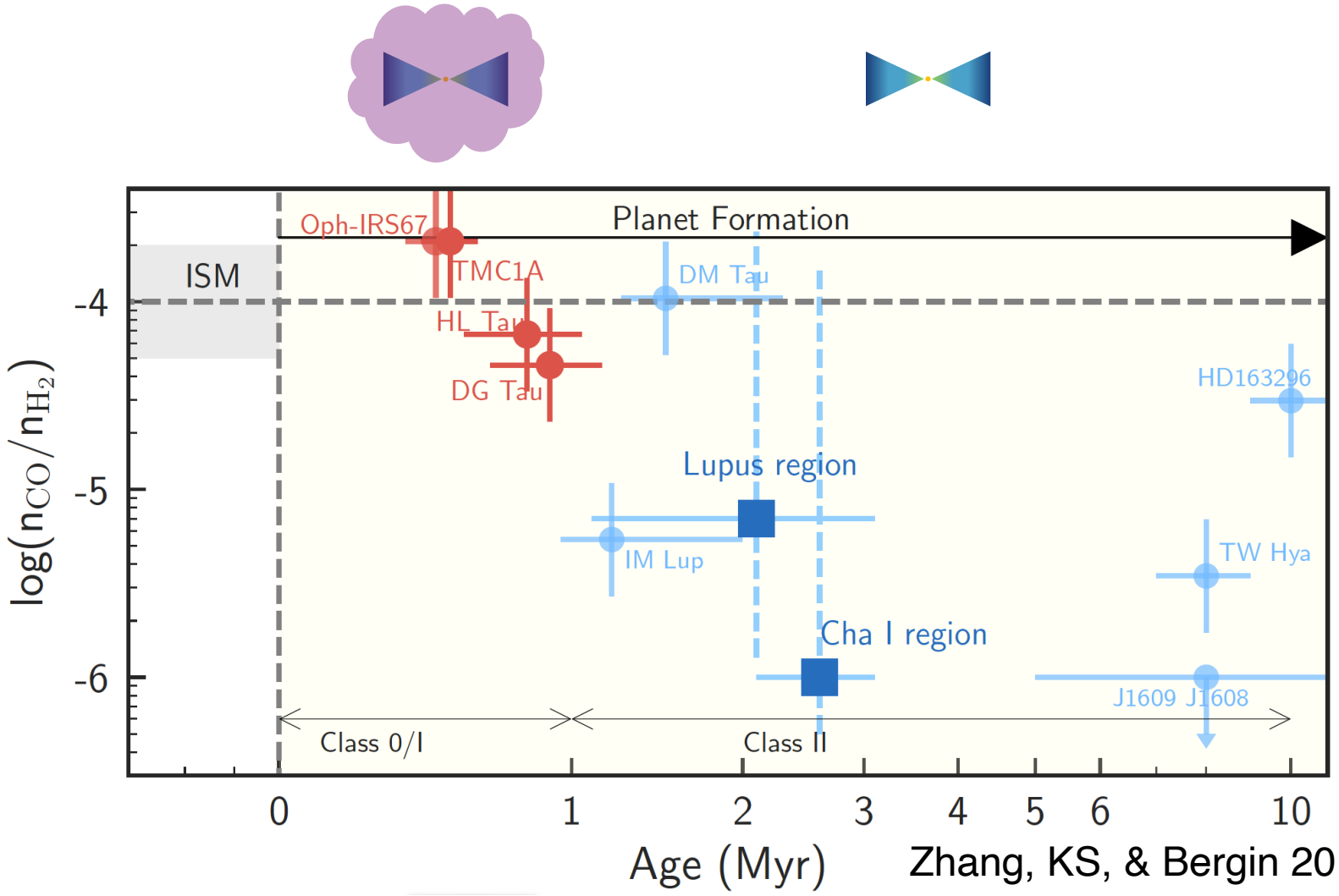
- Reproduce 100× depletion after 3 Myr combining:
  - Chemistry
  - Vertical diffusion
  - Dust growth
  - Pebble drift
- Observations require shorter timescales



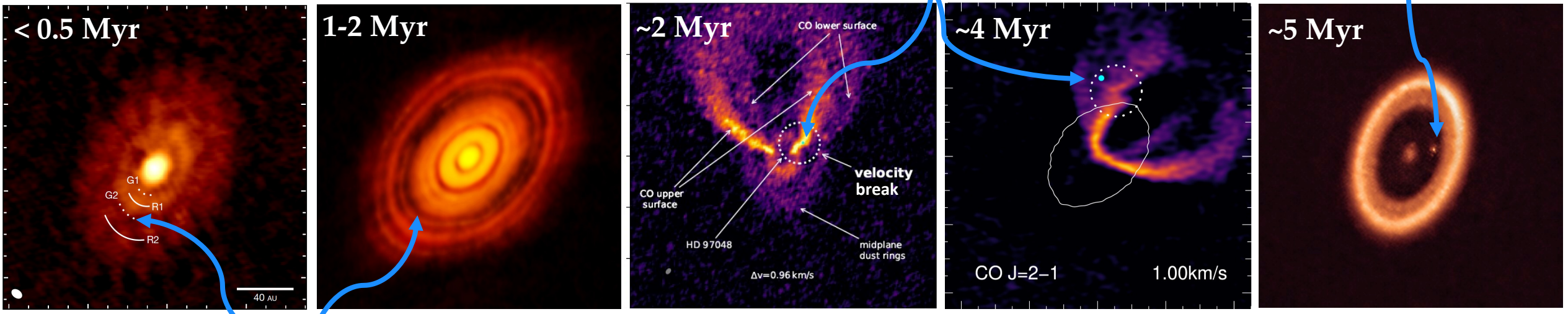
Krijt,KS+20

Carbon Depletion Timescales

- Factor 10-100 depletion by 2 Myr
- No depletion in embedded phase
- Gas phase C depletion occurs early



Planet Formation Starts Early



Probably planets

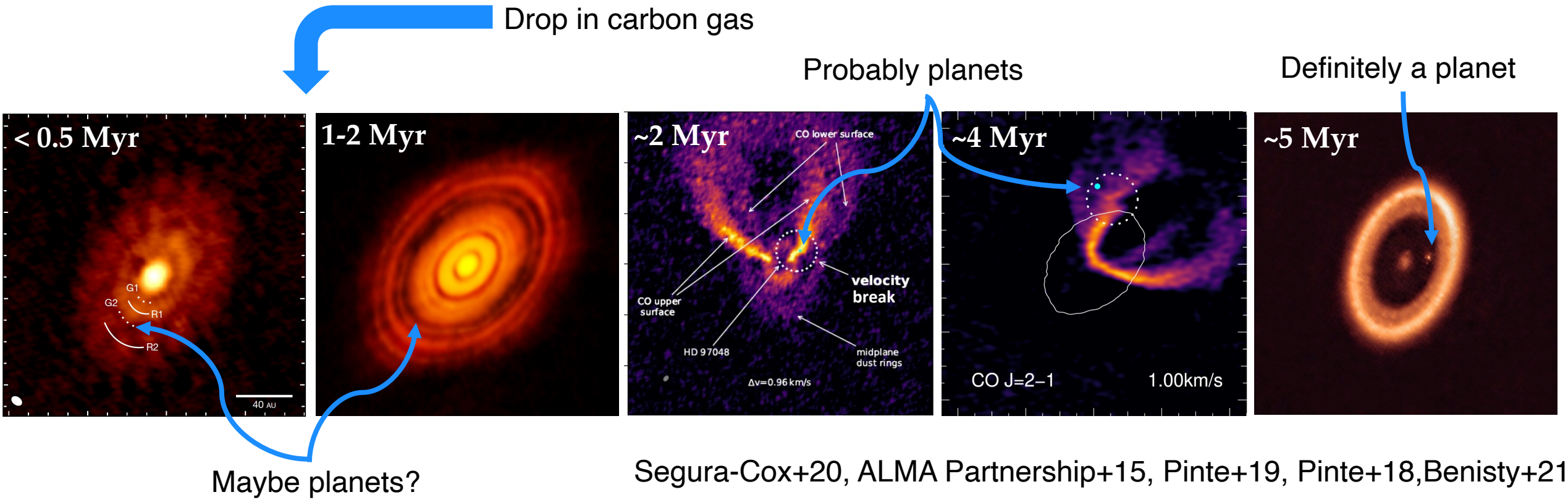
Definitely a planet

Maybe planets?

Segura-Cox+20, ALMA Partnership+15, Pinte+19, Pinte+18,Benisty+21

Carbon depletion & giant planet formation occur simultaneously

Planet Formation Starts Early



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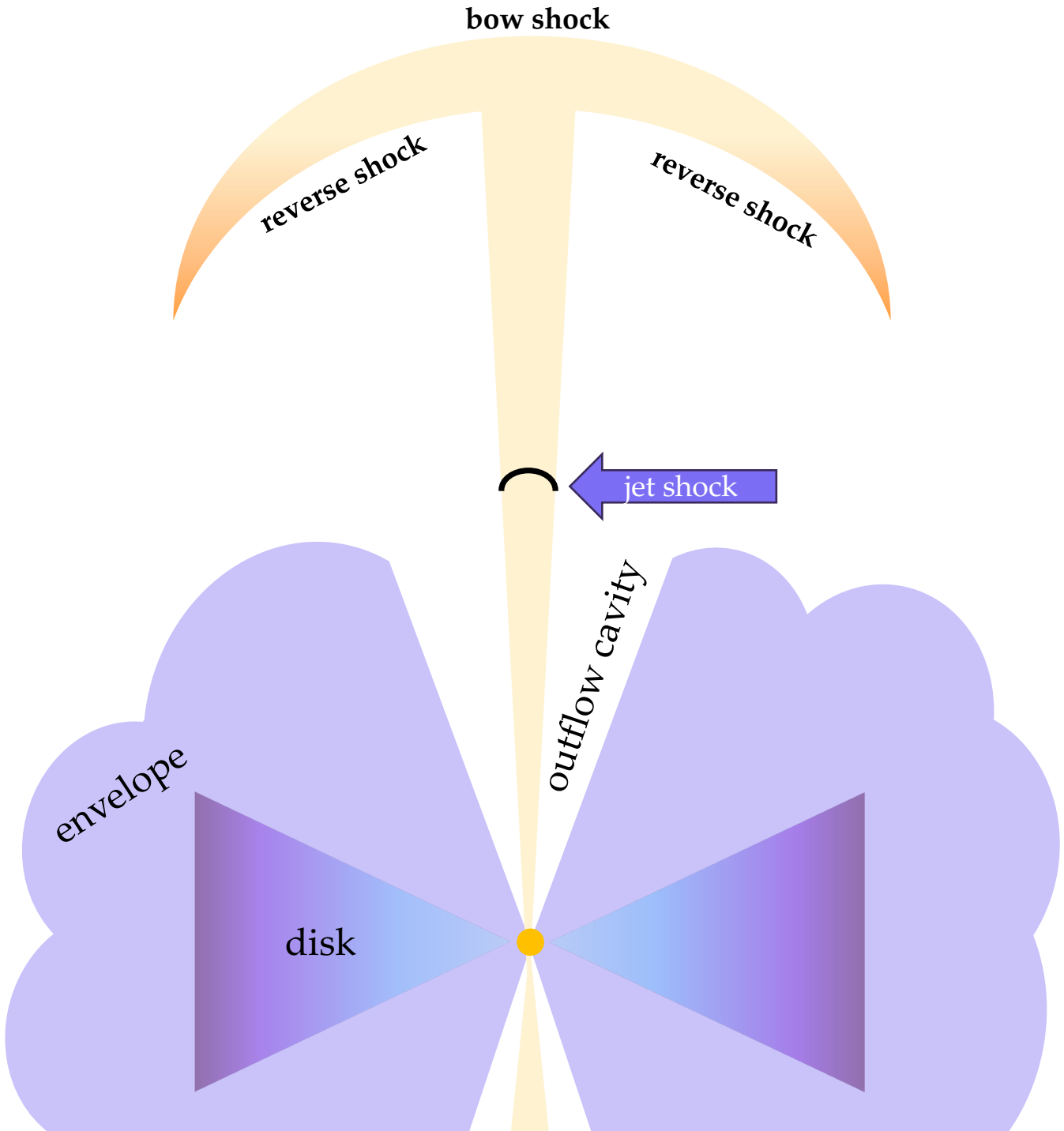
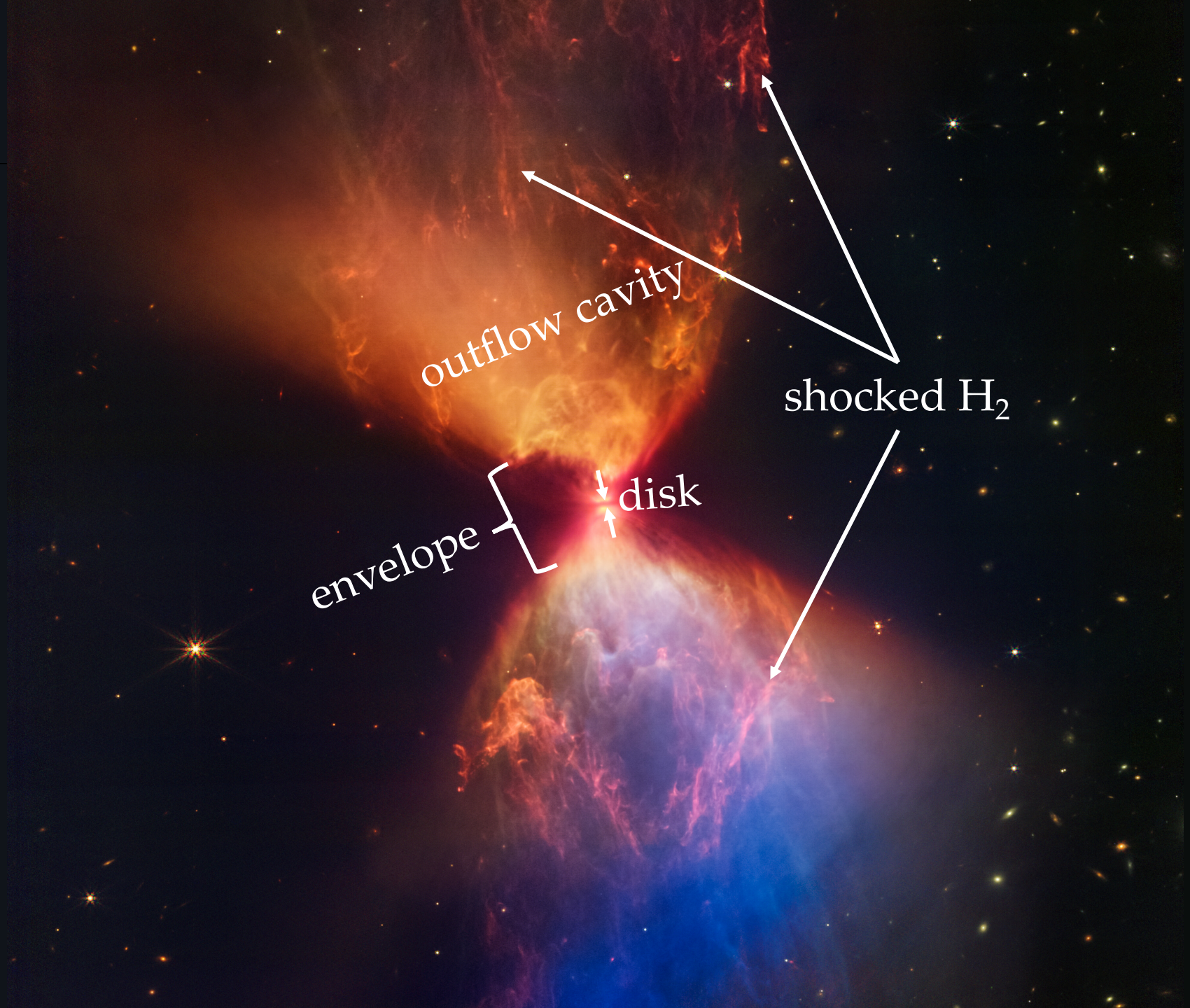
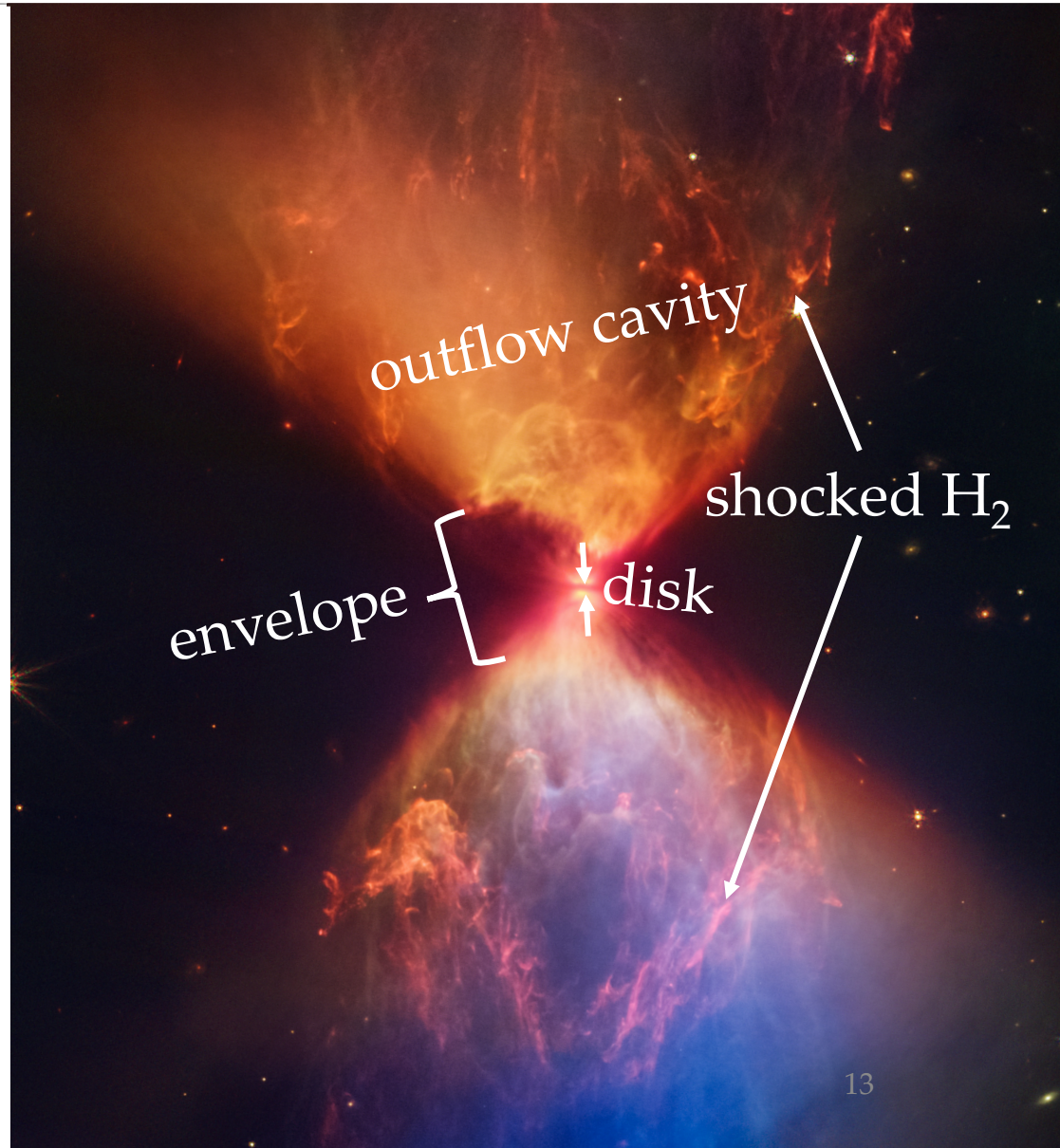

bow shock
reverse shock
reverse shock
jet shock
outflow cavity
envelope
disk


outflow cavity
envelope
disk


outflow cavity
shocked H_2
envelope
disk

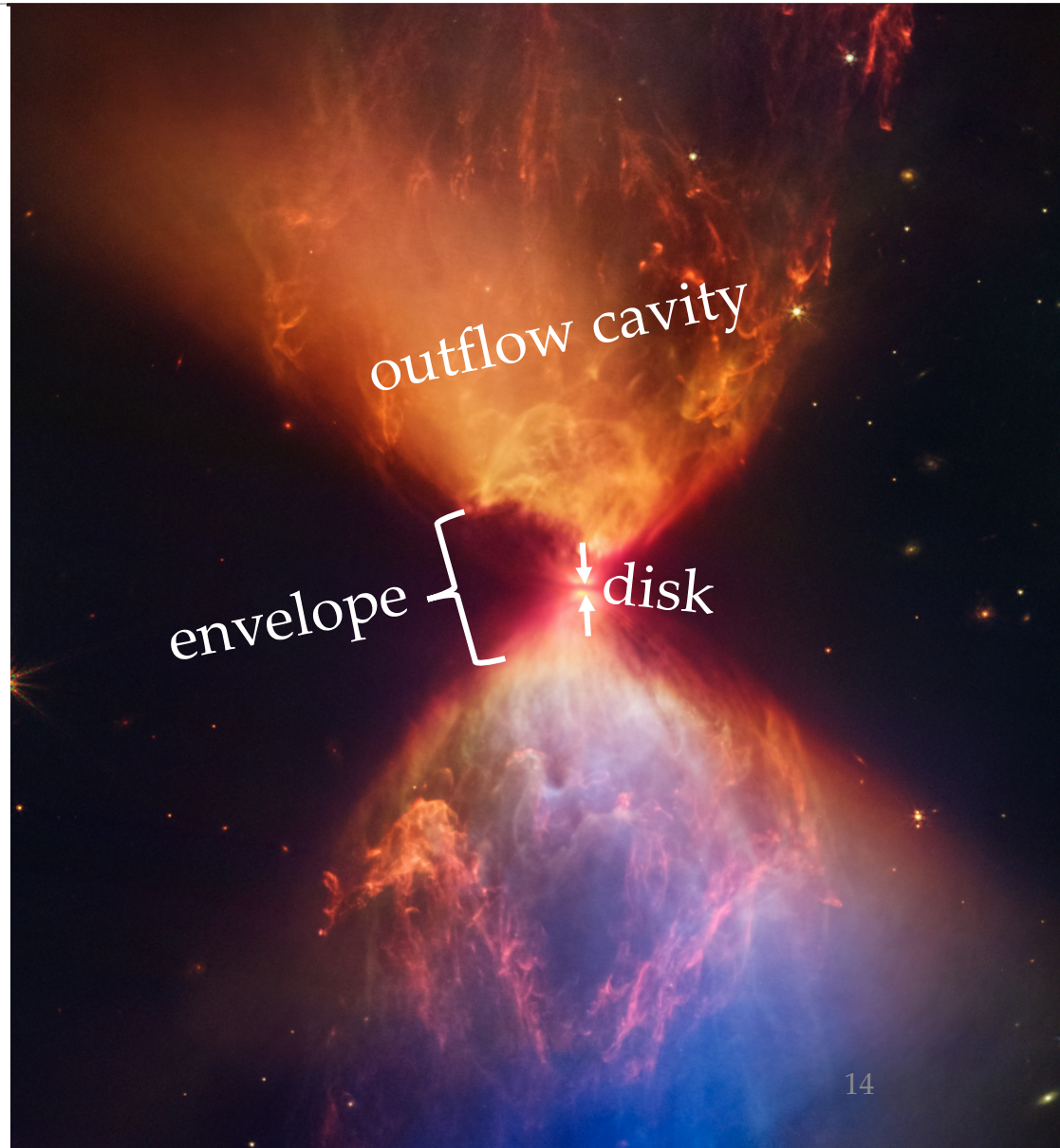
Protostellar Ionization+Chem

- Fast chemistry needs ionization
- Shocks etc. accelerate CRs (Alexandre's talk)
- Shocks at jet & protostellar surface can result in $\zeta_{CR} = 10^{-10}$-10^{-9} s^{-1} (Padovani+16)
  - ISM $\zeta_{CR} = 10^{-17}$ s^{-1}
  - Diffusion lowers rate



Enhanced Ionization?

- ζ_{CR}~10^{-16} s^{-1} in SFR (Pineda+24)
- Free-free emission along outflow/jet (Tychoniec+18)
- ζ_{CR}~10^{-16} s^{-1} in bow shock of L1157 (Podio+14)
- ζ_{CR}~10^{-14} s^{-1} in 2 envelopes (Ceccarelli+14, Cabedo+23)



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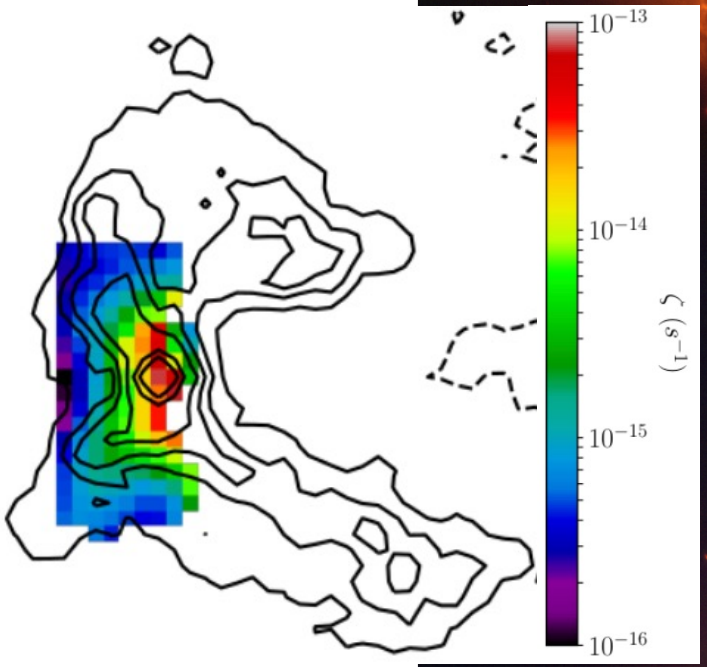
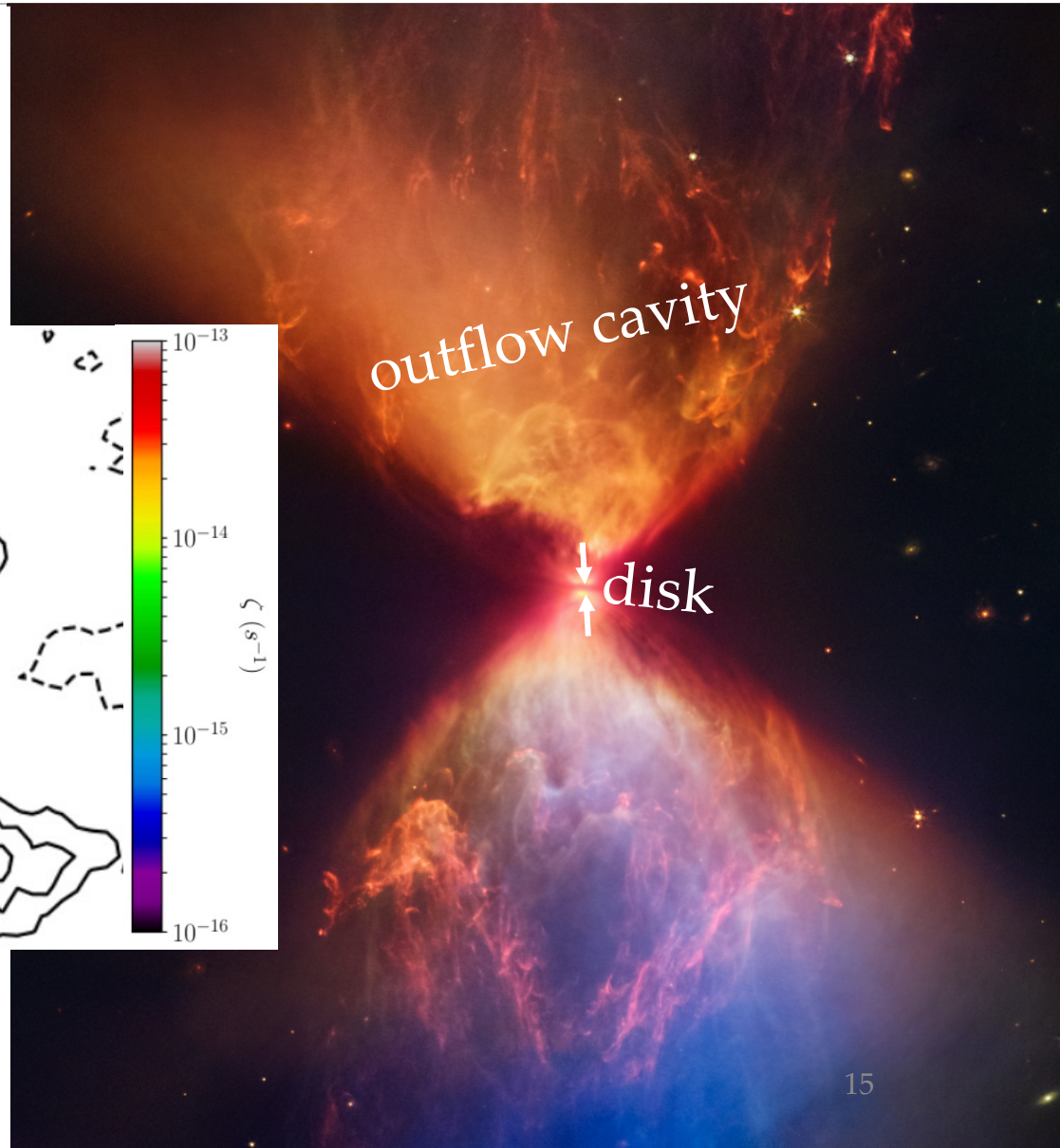
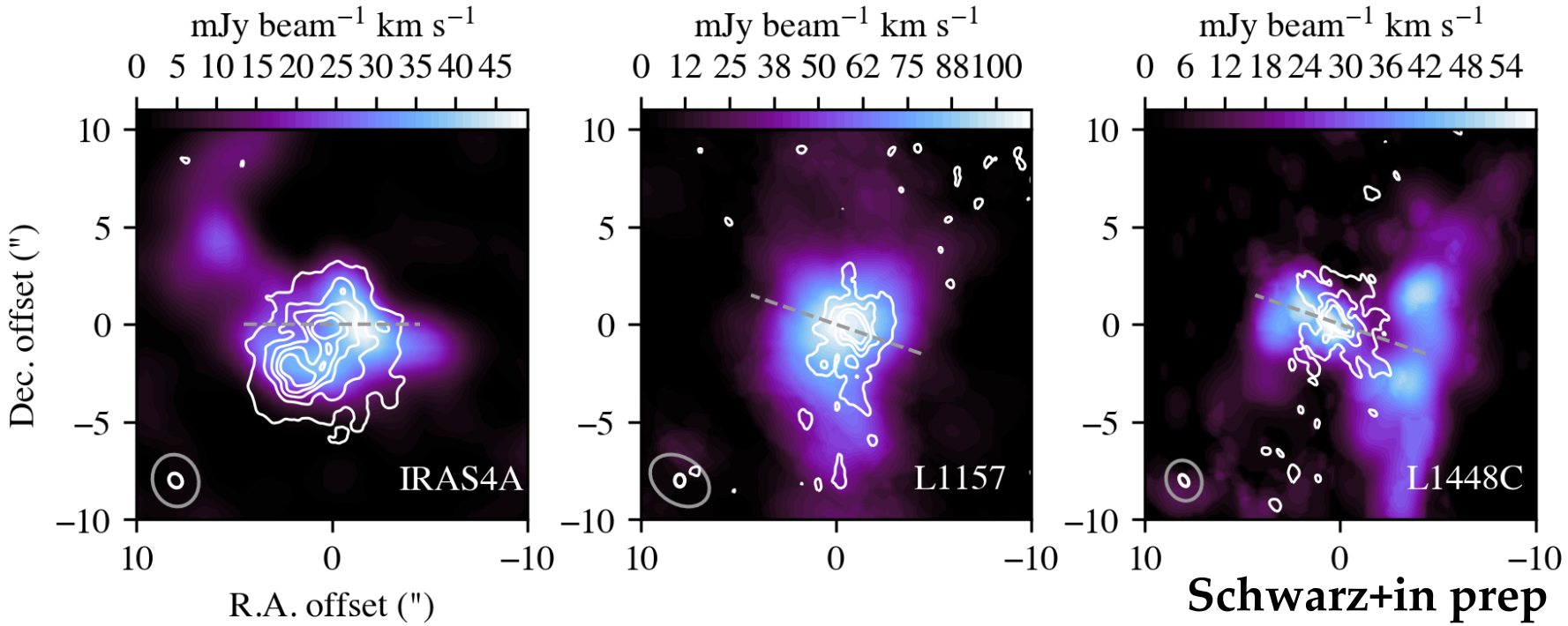


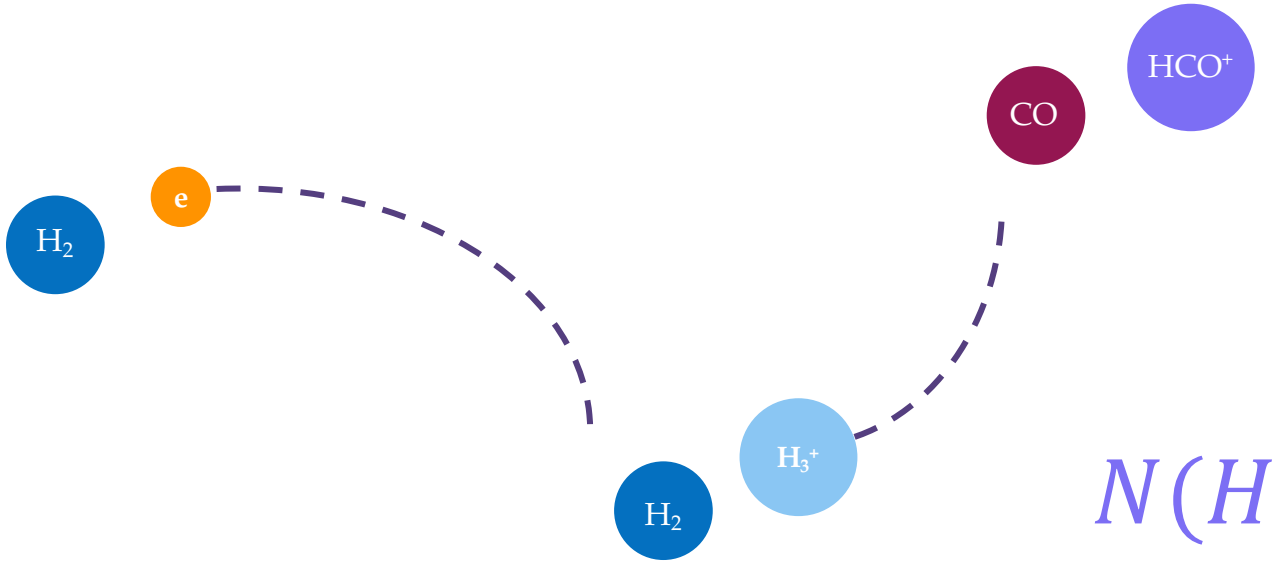


Measuring Envelope Ionization



- New NOEMA $H^{13}CO^+$ 1-0 observations (background)
- $C^{18}O$ from Maret+20 (contours)
  - Convolved with $H^{13}CO^+$ beam

Relating HCO^+ & Ionization

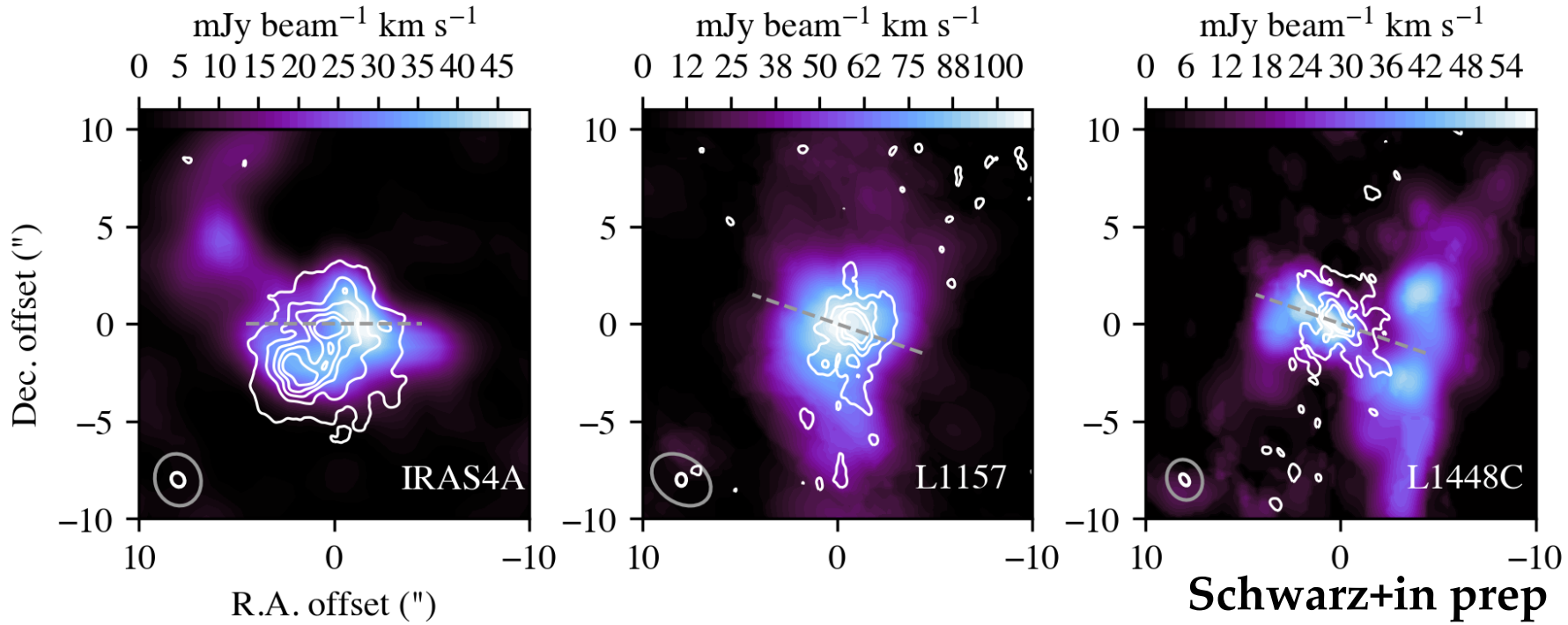


$$\frac{N(HCO^+)}{N(CO)} = \frac{[\zeta/n(H_2)]k_{H_3^+}}{[\beta\, x(e) + \delta]\beta' x(e)}$$

Ionization rate

Electron abundance

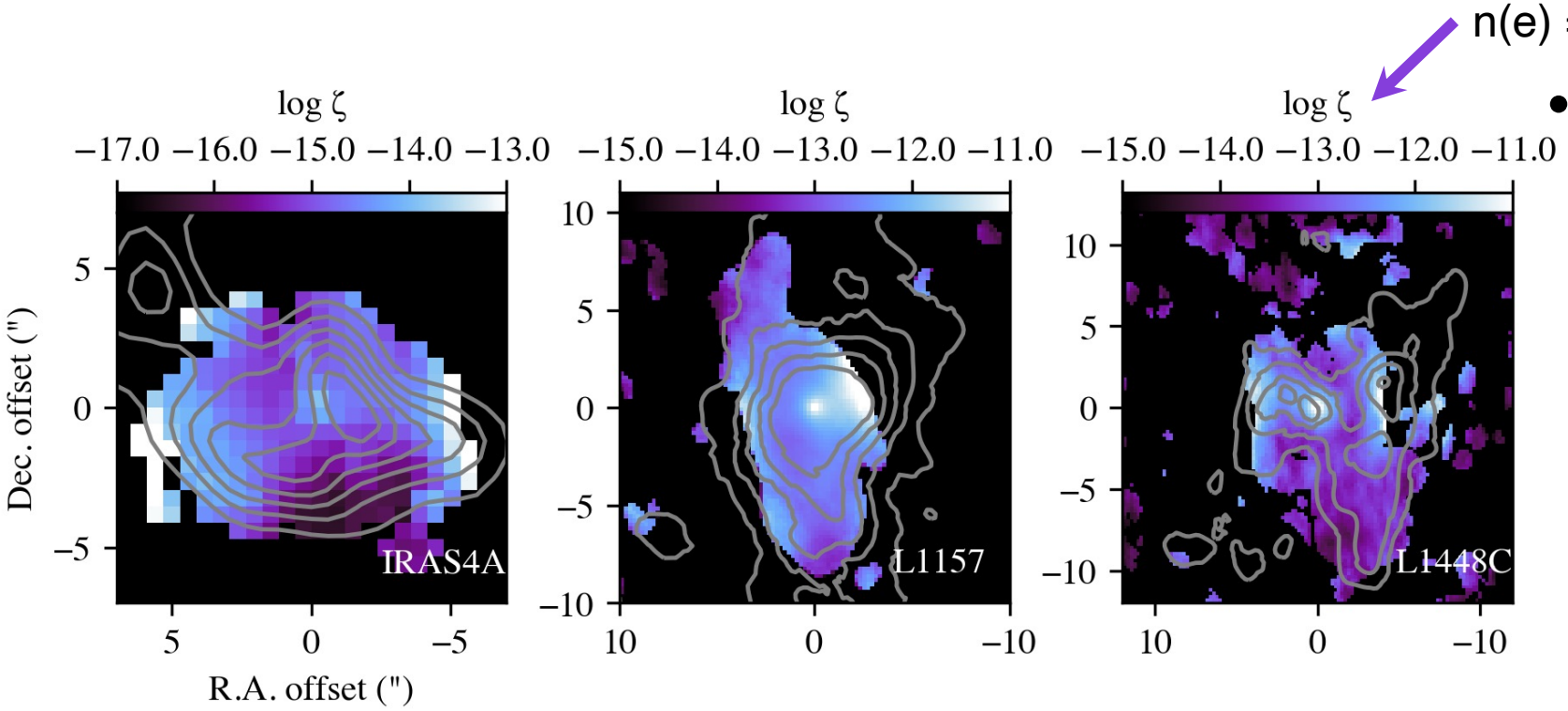
Measuring Envelope Ionization



$$\frac{N(HCO^+)}{N(CO)} = \frac{[\zeta/n(H_2)]k_{H_3^+}}{[\beta\, x(e) + \delta]\beta' x(e)}$$

- *n(H$_2$)* from Anderl+16 models
- *n(e)* = 1-3 *n(HCO$^+$)*

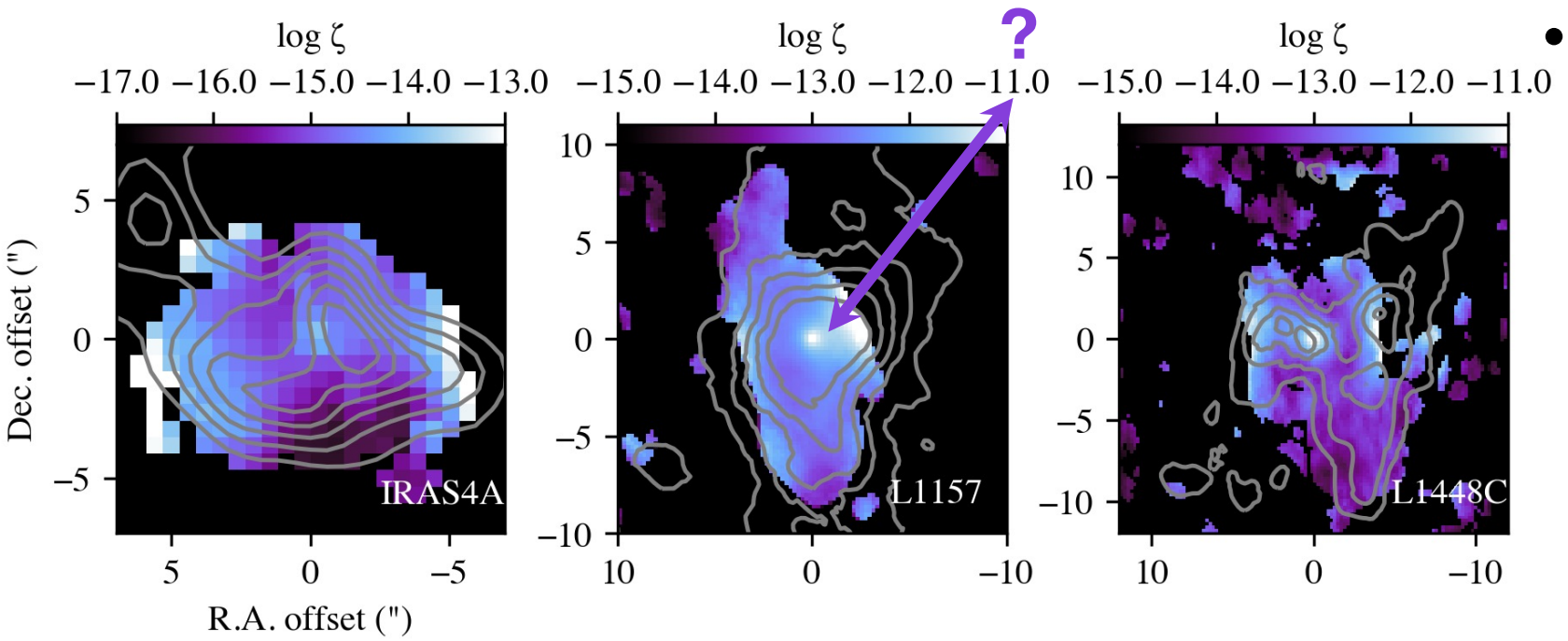
Measuring Enhanced Ionization



- ζ peaks above ISM value in all sources
  - Consistent w/ OMC-2 FIR 4
  - Highest ζ likely due to high line τ

Schwarz+in prep

Measuring Enhanced Ionization



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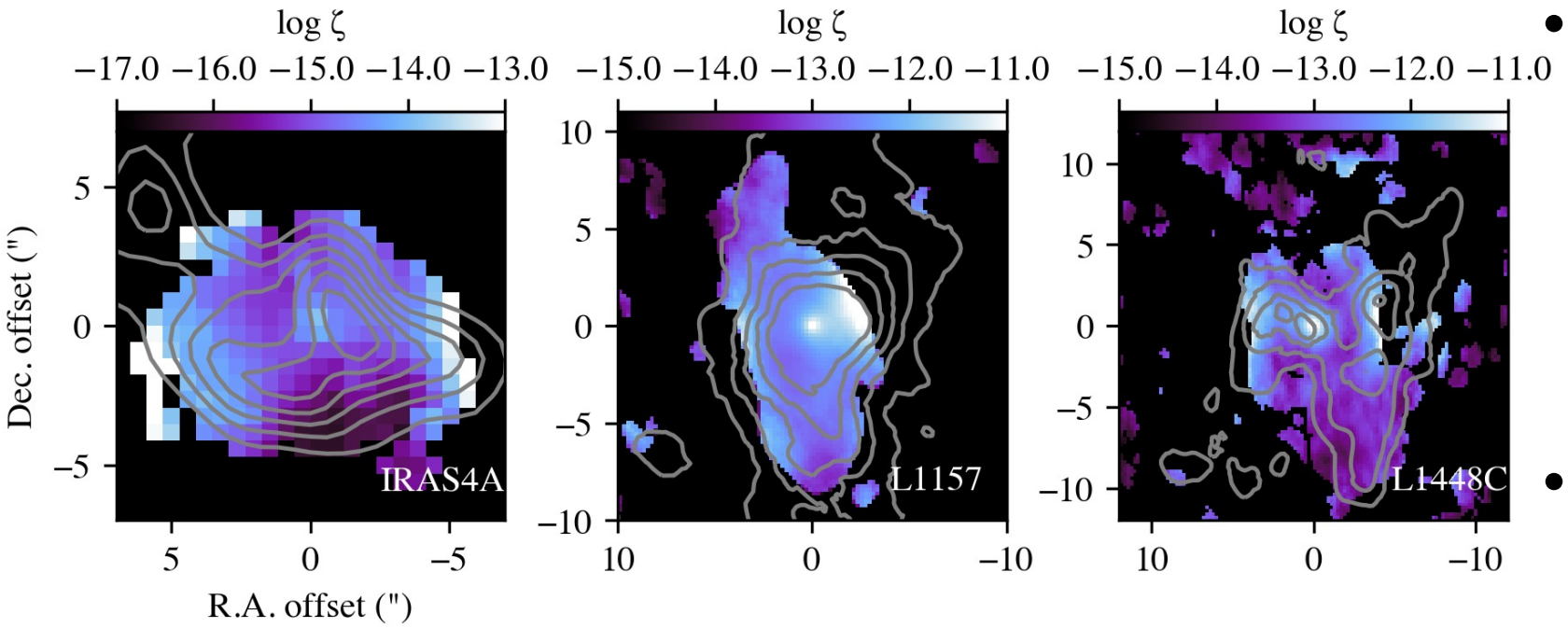
Measuring Enhanced Ionization

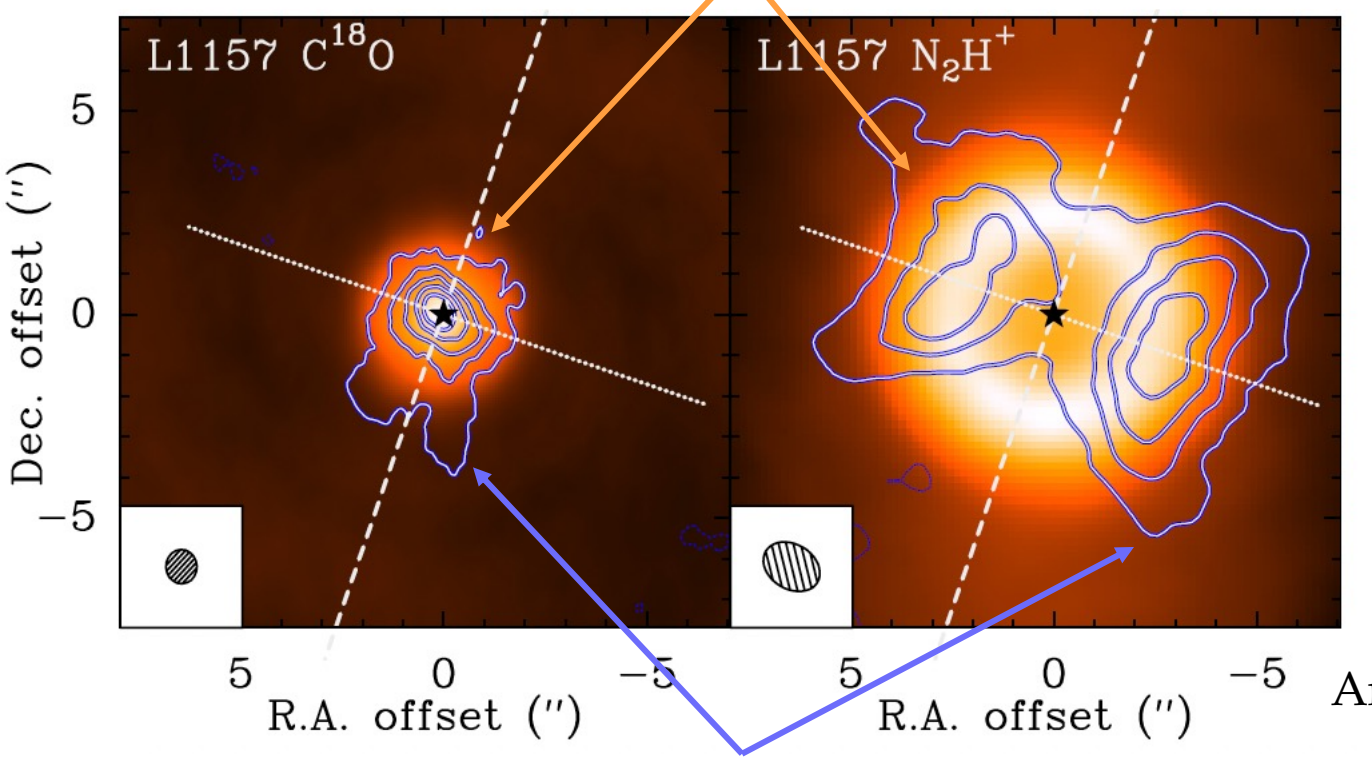


- ζ peaks above ISM value in all sources
  - Consistent w/ OMC-2 FIR 4
  - Highest ζ likely due to high line τ
- Large scale emission resolved out
  - Adding 30m obs.
- Models needed to better constrain H_2 & e^-

Schwarz+in prep

Protostellar envelopes often modeled as spheres

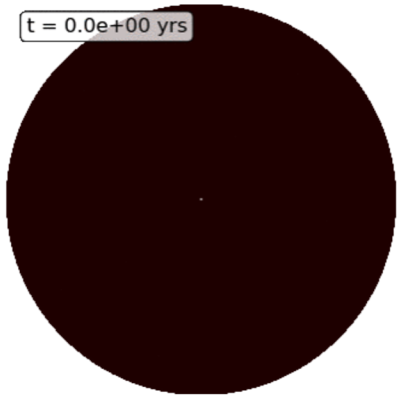
Spherical models



Anderl+16

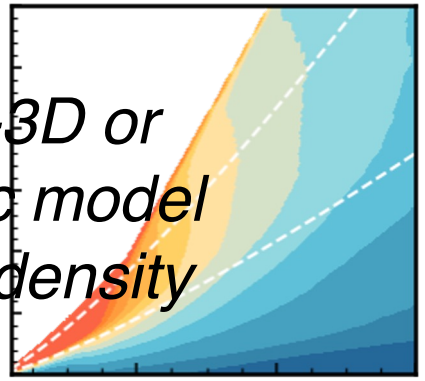
Not so spherical observations

New Chemo-Dynamic Models



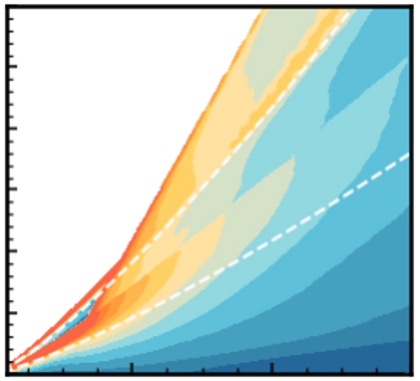
dynamical model

FARGO-3D or parametric model sets disk density

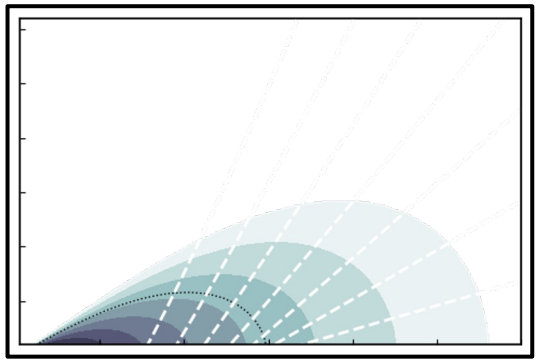


dust temperature

optional shock heating & viscous heating



gas temperature

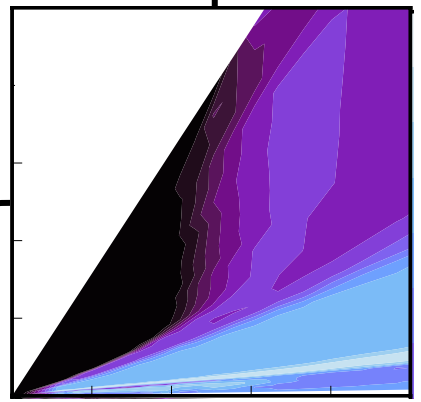


envelope solution

post-processed radiative transfer

Ulrich 1976 infall streams

radiation field



chemistry

fully self-consistent model

observables!

Kutnetsova & Schwarz in prep

Summary

- CO gas depletion in disks occurs early
  - Carbon chemistry jumpstarted by ionization
  - Proposed CR enhancement in protostellar environments
- Measured ionization rate in 3 envelopes using $H^{13}CO^+$ & $C^{18}O$
- Find enhanced ionization in all 3
  - Depends on H_2 & e^- abundance
  - Possible UV contribution
- Need measurements for additional sources