The journey of carbon from the ISM to Planets and Disks

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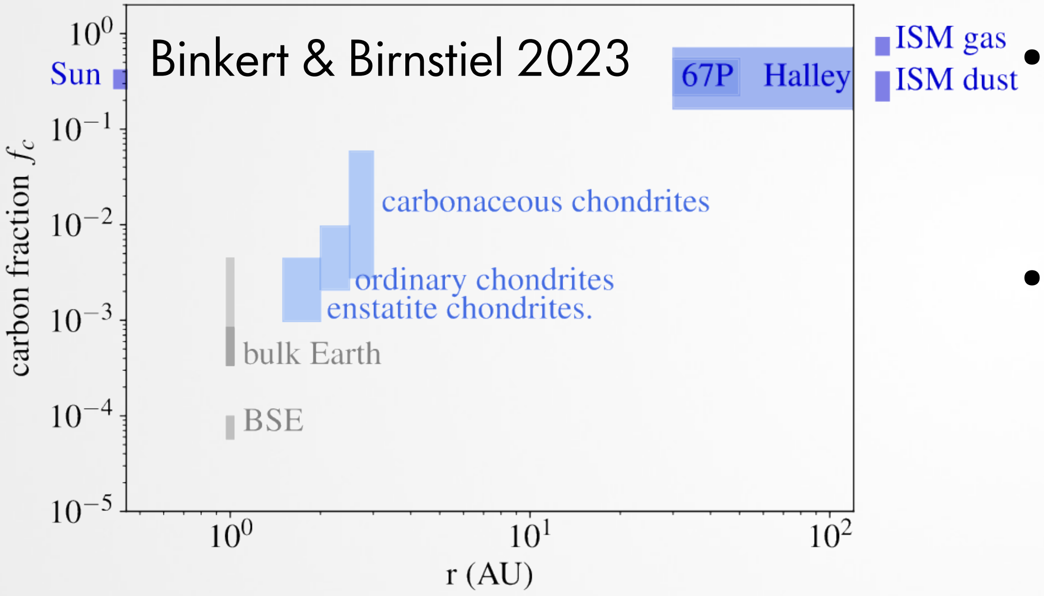
Perspectives of Planet and Star Formation
MPIA, Heidelberg

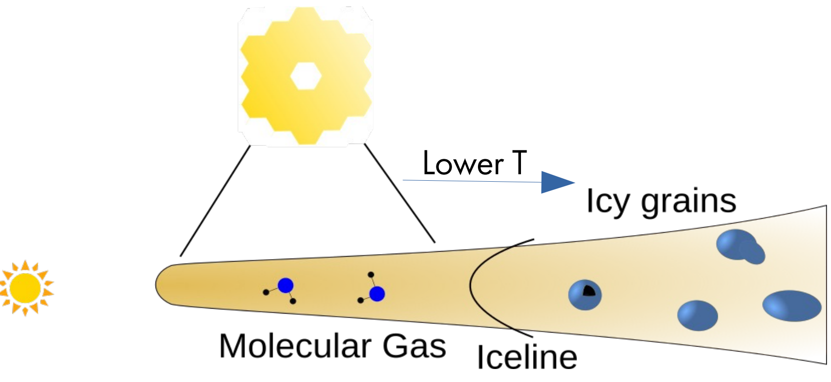
Context

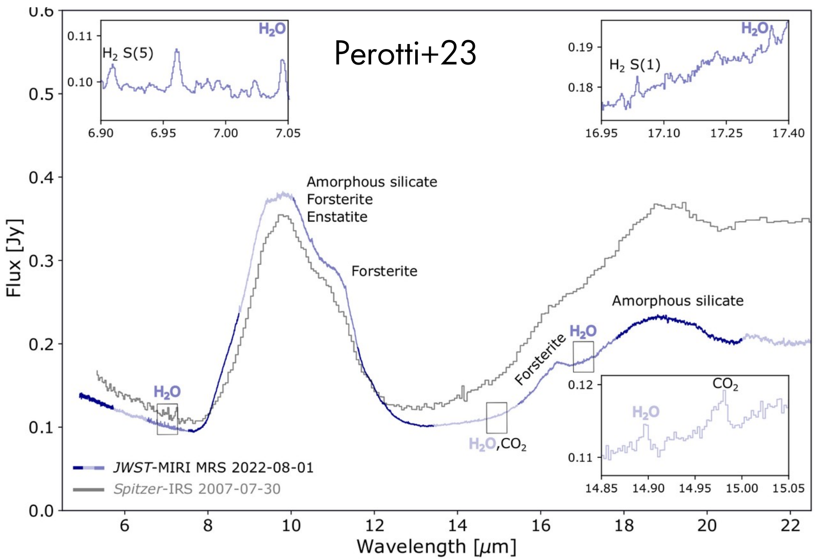


- Inner Solar System is depleted in C
- Bulk Earth heavily depleted
  - could however harbor some C in metallic core (Allegre+2001, Li+2021)
- Depletion by a factor 100 in disk solids necessary
  - Differentiated planetesimals might lose C (Hirschmann+2021)

Context

- Compositions are probed by disk infrared spectroscopy w/ JWST
  - emission of warm (300-1000 K) gas





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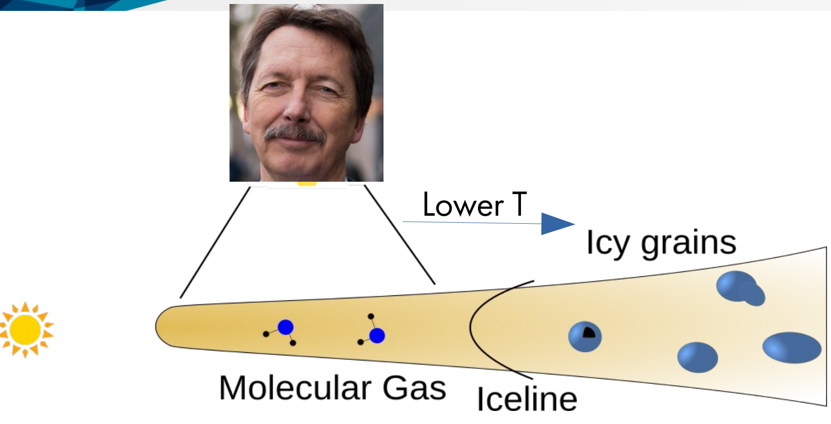

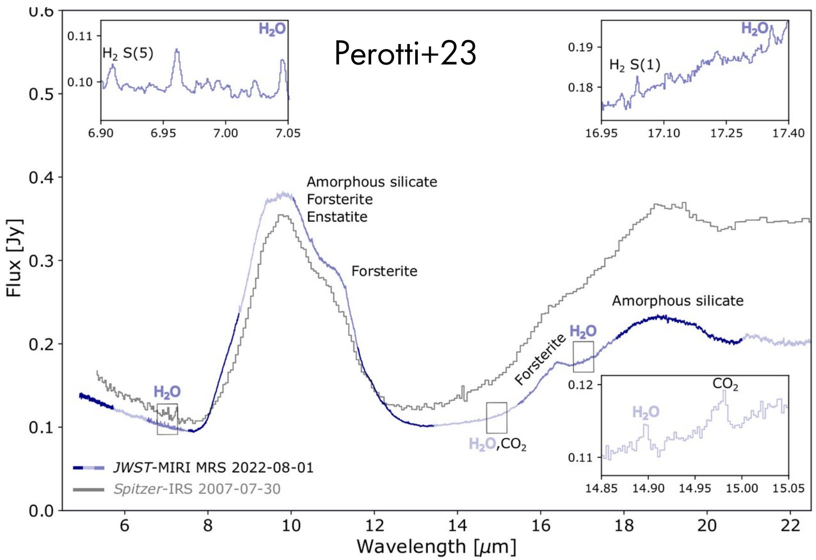

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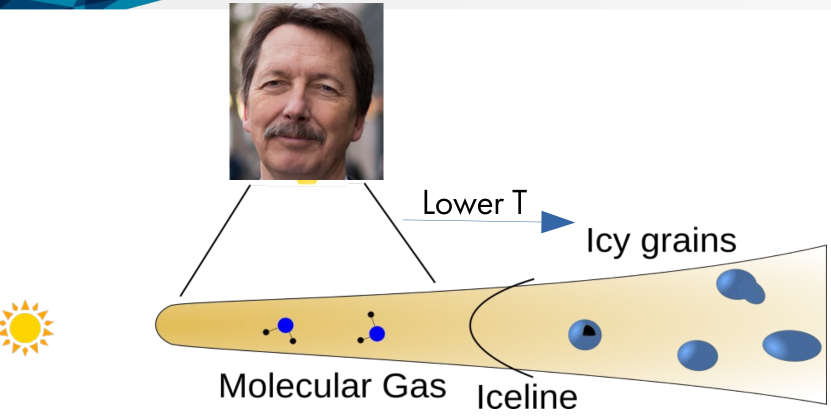
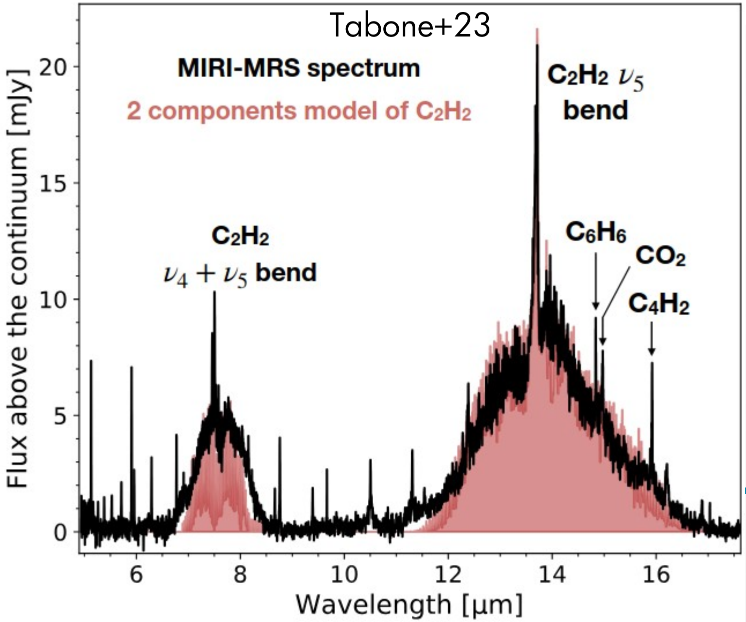


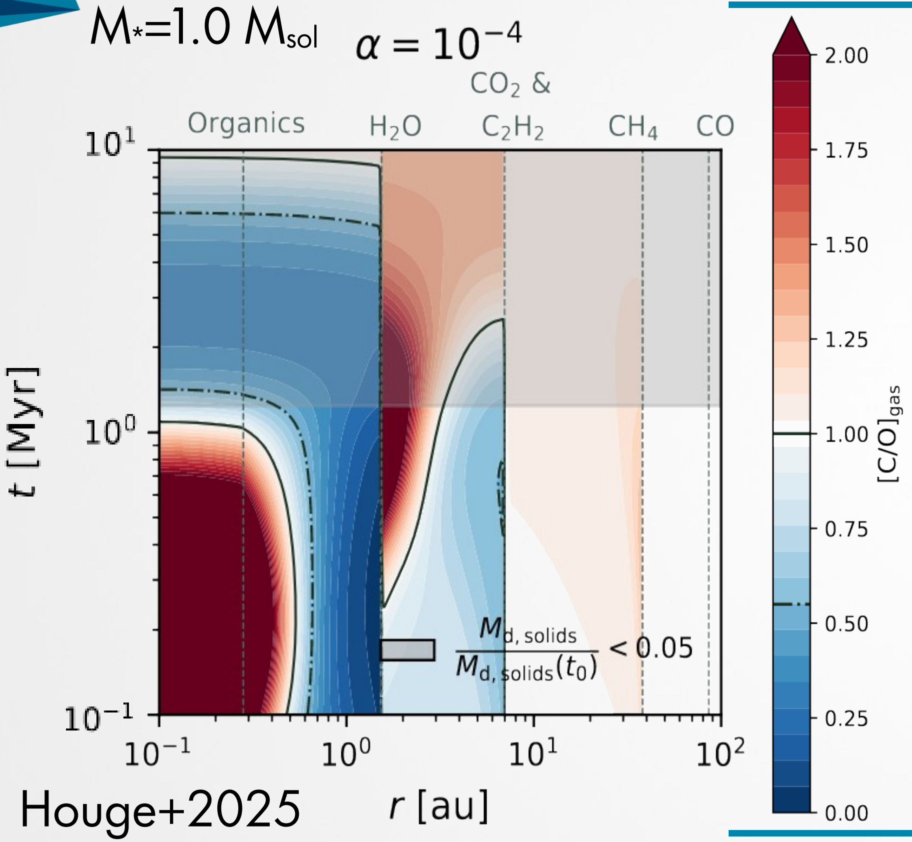


- Some disks are rich in hydrocarbons (Tabone+ 2023, Kanwar+ 2024, Arabhavi+ 2024, Colmenares+ 2024, Volz+ 2026)
- C/O >1 impossible w/ H_2O, CO, CO_2
- Carbon-rich disks around M dwarfs? (Tabone+2023, Arabhavi+2024)
  - But also around low-accreting (Colmenares+2024) & transitional Solar-mass stars (Volz+2026)

Context

- C-enrichment mechanism or O-depletion? (Mah+2023, Arabhavi+2024)
- 40-60% of ISM C in refractory form (e.g. Henning&Salama 1998)
  - Natural candidate for C enrichment

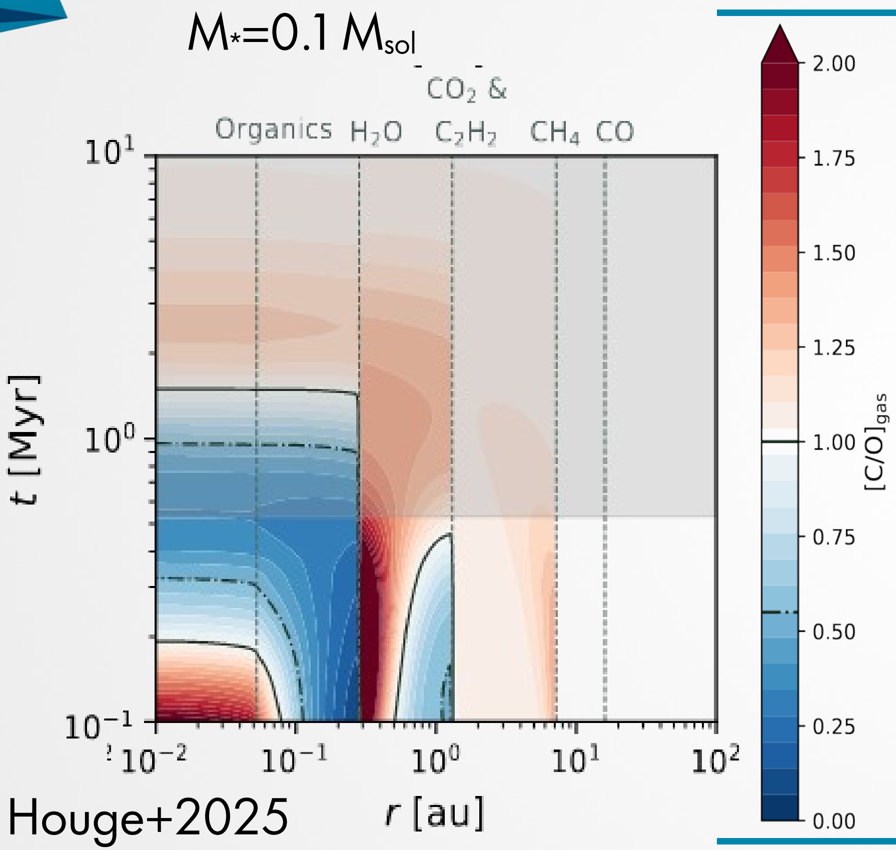
Context



Houge+2025

- Houge+2025: Irreversible sublimation of refractory organic material can enhance C
  - Due to recondensation further out, more persistent in gas phase than H_2O

Context

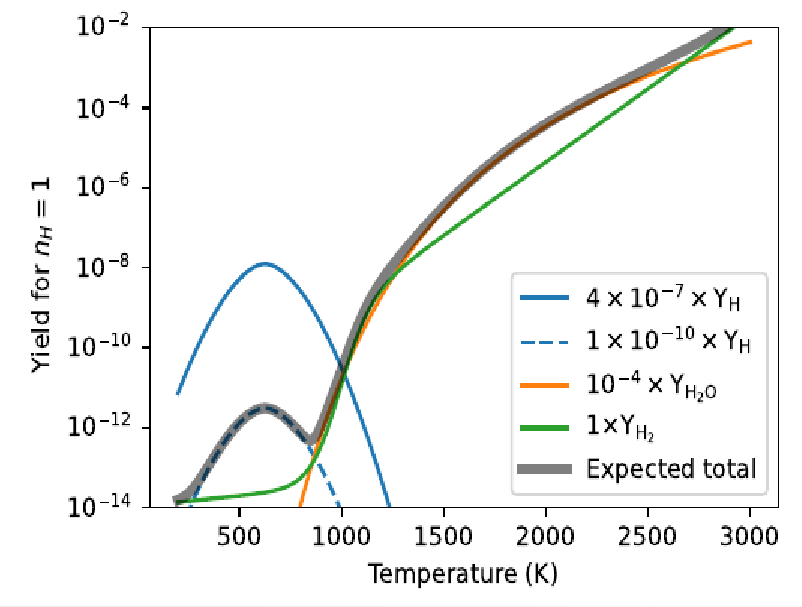


- Houge+2025: Irreversible sublimation of refractory organic material can enhance C
  - Due to recondensation further out, more persistent in gas phase than H_2O
  - High C late phase better reproduced for low stellar masses

Context

- Soot line at ~350K might be optimistic
  - Thermal destruction at ~300-500K of relatively volatile kerogen-like material possible
  - But residue can remain (Nakano+2003, Sephton+2004)
  - Interstellar refractory carbon is likely to include significant fraction of more refractory phases (Pendleton+1999,2025, Schnaiter+1999)

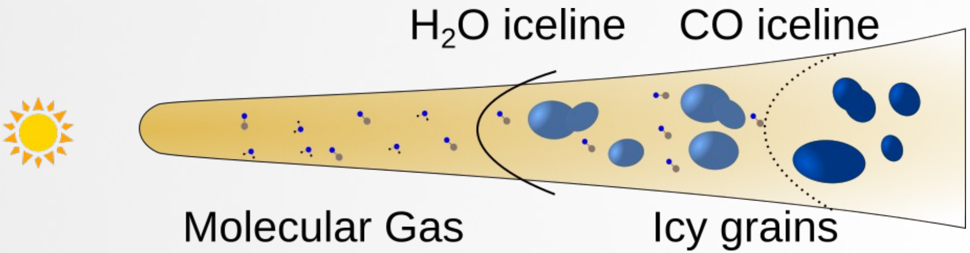
Chemisputtering Reactions



$C(s)+H_2O(g) \rightarrow CO+H_2$
$C(s)+H_2(g) \rightarrow C_2H_2$

- Chemisputtering of amorphous carbon with H_2O and H_2 (Lenzuni+95)
- Difference to 'soot' model: composition
  - Amorphous, pure carbon (T_{subli}>1000K) instead of organic compounds (kerogen, T_{subli}~400K)

Composition Tracking



- Trace evolution of gas and solid species

Composition Tracking

$$\frac{d\Sigma_{\mathrm{g},X}}{dt} + \underbrace{\frac{1}{r}\frac{d}{dr}\left(r\Sigma_{\mathrm{g},X}v_{\mathrm{g}}\right)}_{\text{Advection with overall gas}}$$

$$- \underbrace{\frac{1}{r}\frac{d}{dr}\left(rD_X\Sigma_{\mathrm{g}}\frac{d}{dr}\left(\frac{\Sigma_{\mathrm{g},X}}{\Sigma_{\mathrm{g}}}\right)\right)}_{\text{Diffusion due to concentration gradient}} = \underbrace{L}_{\text{sinks \& sources}}$$

$$\frac{d\Sigma_{\mathrm{d},X}}{dt} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\Sigma_{\mathrm{d},X}\bar{u}\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{\mathrm{d}}\Sigma_{\mathrm{g}}\frac{\partial}{\partial r}\left(\frac{\Sigma_{\mathrm{d},X}}{\Sigma_{\mathrm{g}}}\right)\right) = L\,,$$

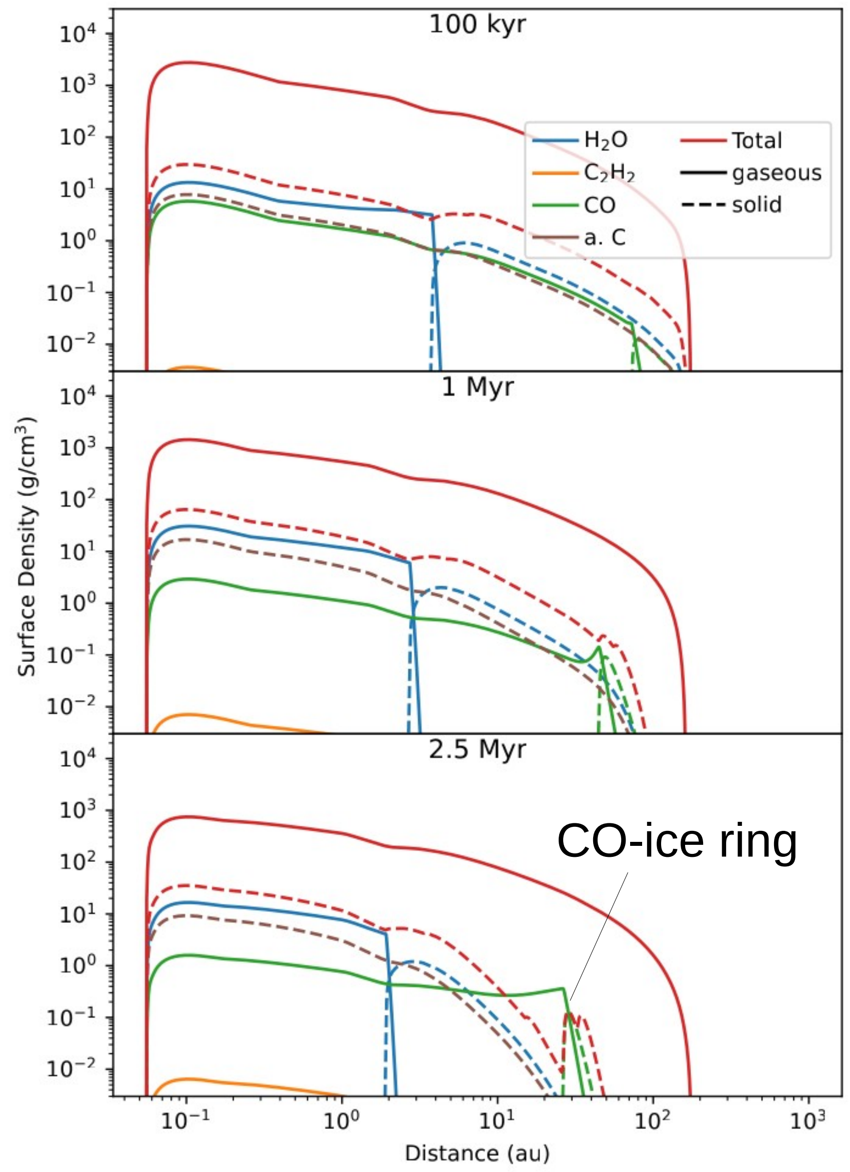
- Trace evolution of gas and solid species
- Tracers are advected and diffused with the gas with flux limiter
  - D_X, D_d set to viscosity, i.e. Sc=1
- Evap&Cond relaxation scheme toward equilibrium
  - Maximum rate of 0.05 x Omega

Model

Parameter	Symbol	Value (variation)
Stellar Mass	$M_\star$	$1\,M_\odot$
Disk Mass	M_{disk}	$0.1\,M_\odot$
Gas Surf. dens. (5.2 au)	Σ_0	$391.6\,g\,cm^{-2}$
Disk Viscosity	α	1×10^{-3} $(1\times10^{-4})^{(a)}$
Gas slope	β_g	0.9
Inner edge	r_{in}	0.055 au
Exponential cut-off	r_{out}	62.59 au
X-ray luminosity	L_X	3.802×10^{29} erg/s
Ext. UV field	$\mathcal{F}_{FUV}$	$10.9\,G_0$
Ini. dust to gas ratio	δ_{dg}	$0.0158^{(b)}$
Frag. velocity	v_{frag}	$2\ (10)\ m/s^{(c)}$
Dust grain density	ρ_s	$1.675\,g/cm^3$
Dust monomer size	a_{min}	1×10^{-5} cm
Infall simulation variations		
Initial Disk Mass	M_{disk}	$0.01\,M_\odot$
Gas Surf. dens. (5.2 au)	Σ_0	$39.16\,g\,cm^{-2}$
Initial Infall Rate	$\dot{M}_0$	9×10^{-7} (5×10^{-6}) $M_\odot/yr$
Infall Timescale	τ_{inf}	1×10^5 (1×10^6) $yr^{(e)}$
Late M dwarf simulation variations		
Stellar Mass	$M_\star$	$0.1\,M_\odot$
Disk Mass	M_{disk}	$0.01\,M_\odot$
Gas Surf. dens. (5.2 au)	Σ_0	$130\,g\,cm^{-2}$
X-ray luminosity	L_X	3.802×10^{28} erg/s
Ext. UV field	$\mathcal{F}_{FUV}$	$1.09\,G_0$
Exponential cut-off	r_{out}	19.79 au
Initial Infall Rate	$\dot{M}_0$	$0\ (9\times10^{-8}\,M_\odot/yr)^{(f)}$

Notes and References.
[a] Values in brackets are used in separate variational runs, here: low-viscosity case
[b] Magg et al. (2022)
[c] bracket: Fast drift variation
[d] bracket: Large Infall variation
[e] bracket: Extended Infall variation
[f] bracket: M dwarf simulation with infall, in addition uses a lower initial disk mass.

- Include amorphous carbon (50% of C)
  - Solar metallicity and elemental abundances
- Model general set-up
  - Bern/Heidelberg framework
    (No planetesimals or planets)
  - Viscous disk evolution (incl. Viscous heating)
  - Two-pop solid drift (Birnstiel+2012)
  - Modern photoevaporation prescriptions with entrainment (Haworth+2018, Picogna/Ercolano 2021, Burn+2022)



No chemisputtering

- Disk cools, icelines move, solid evolution somewhat faster than gas
- Amorphous carbon remains in inner disk

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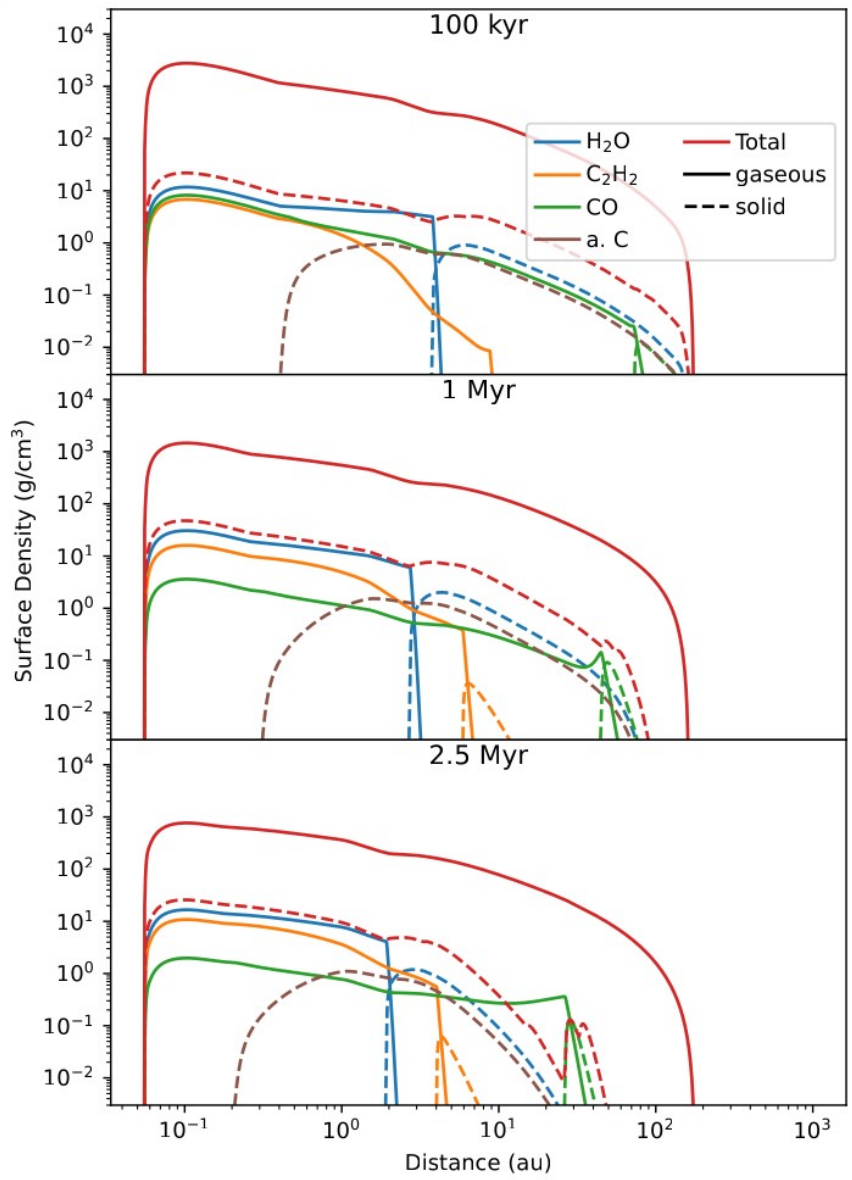
  / implies high bulk C□O for all rocky planets within water iceline



Chemisputtering Results

- Reaction of ref. C to C_2H_2
  - CO production only relevant in early stage
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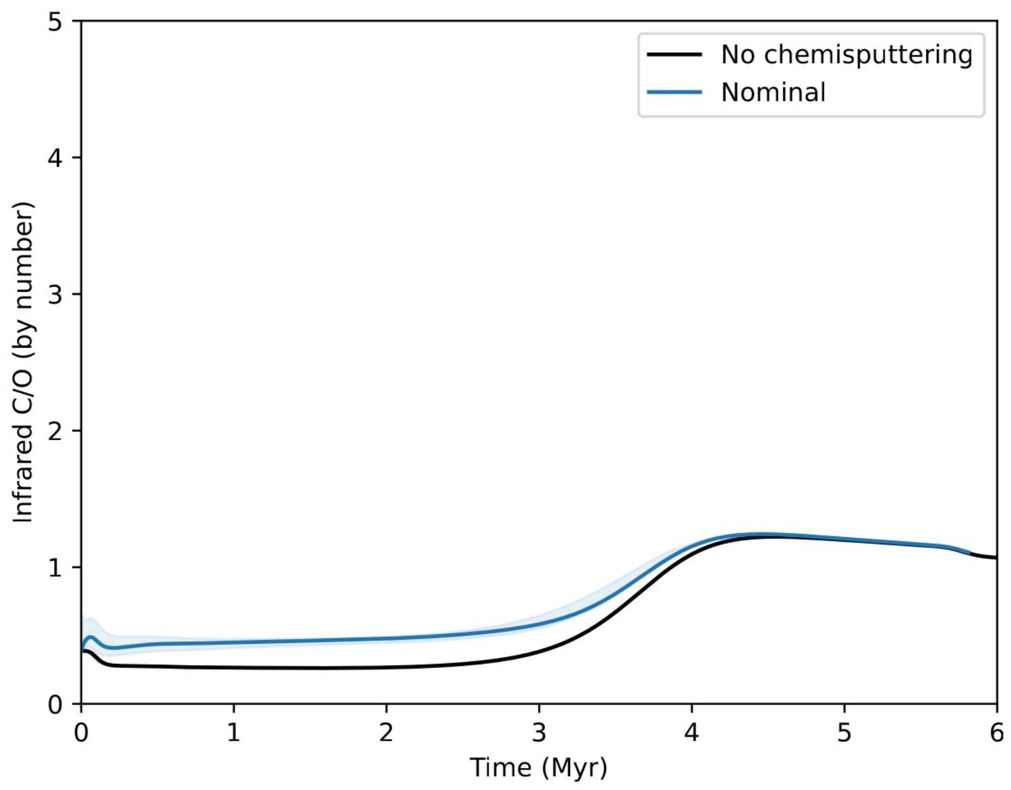

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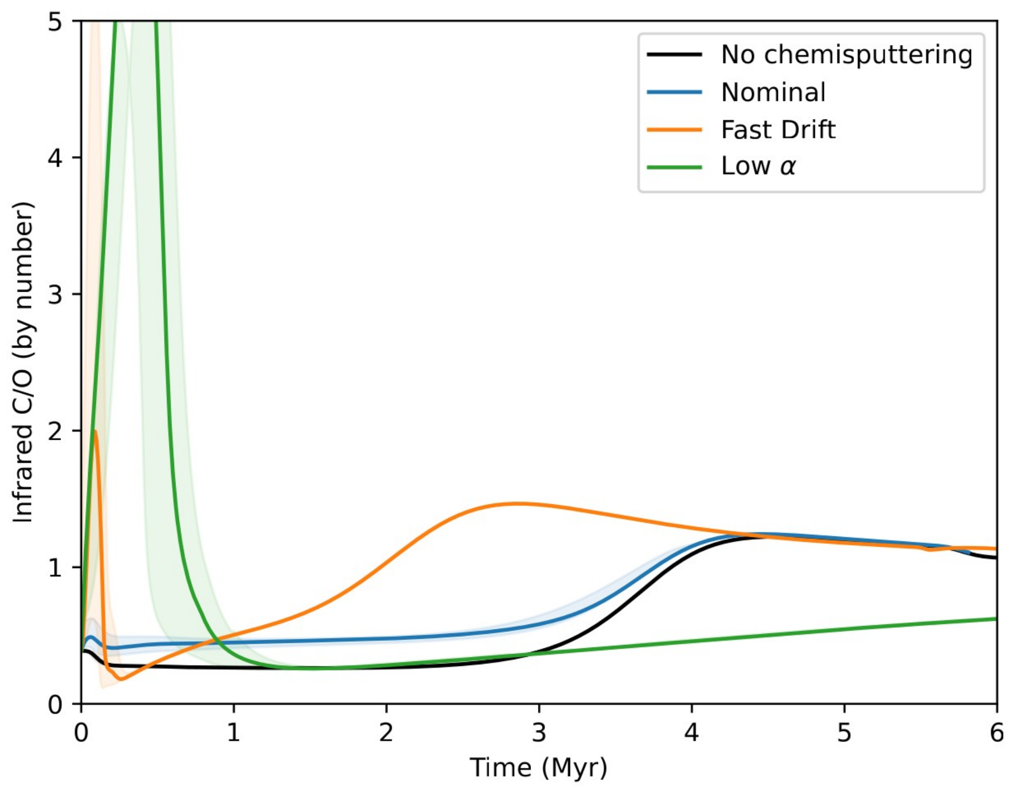

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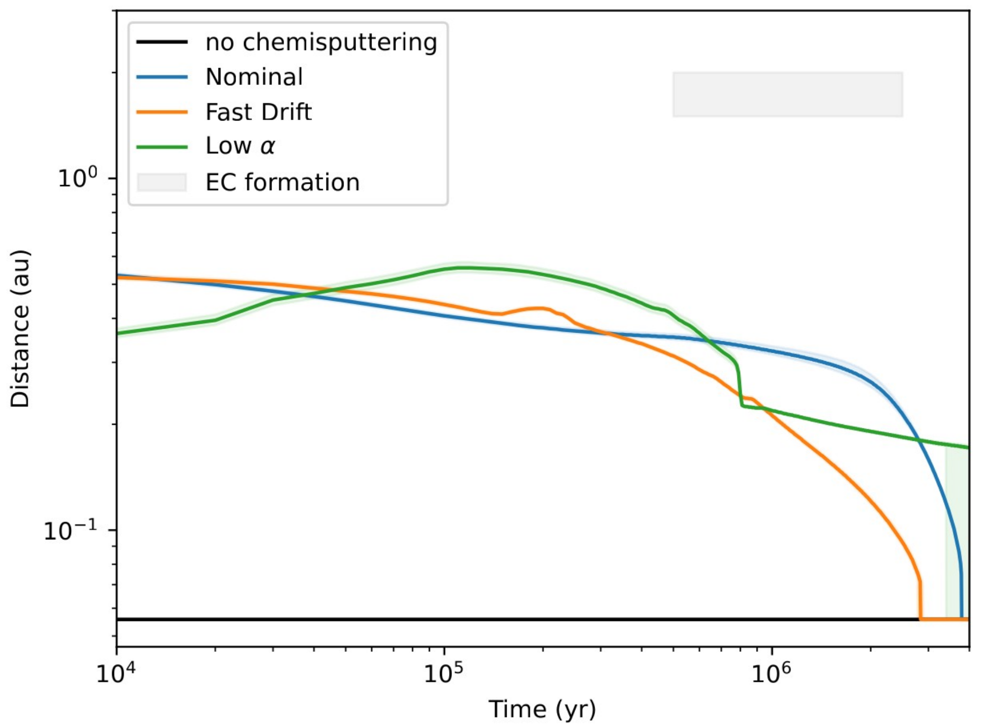
Chemisputtering Results

Depletion location of carbon fraction corresponding to Enstatite Chondrites



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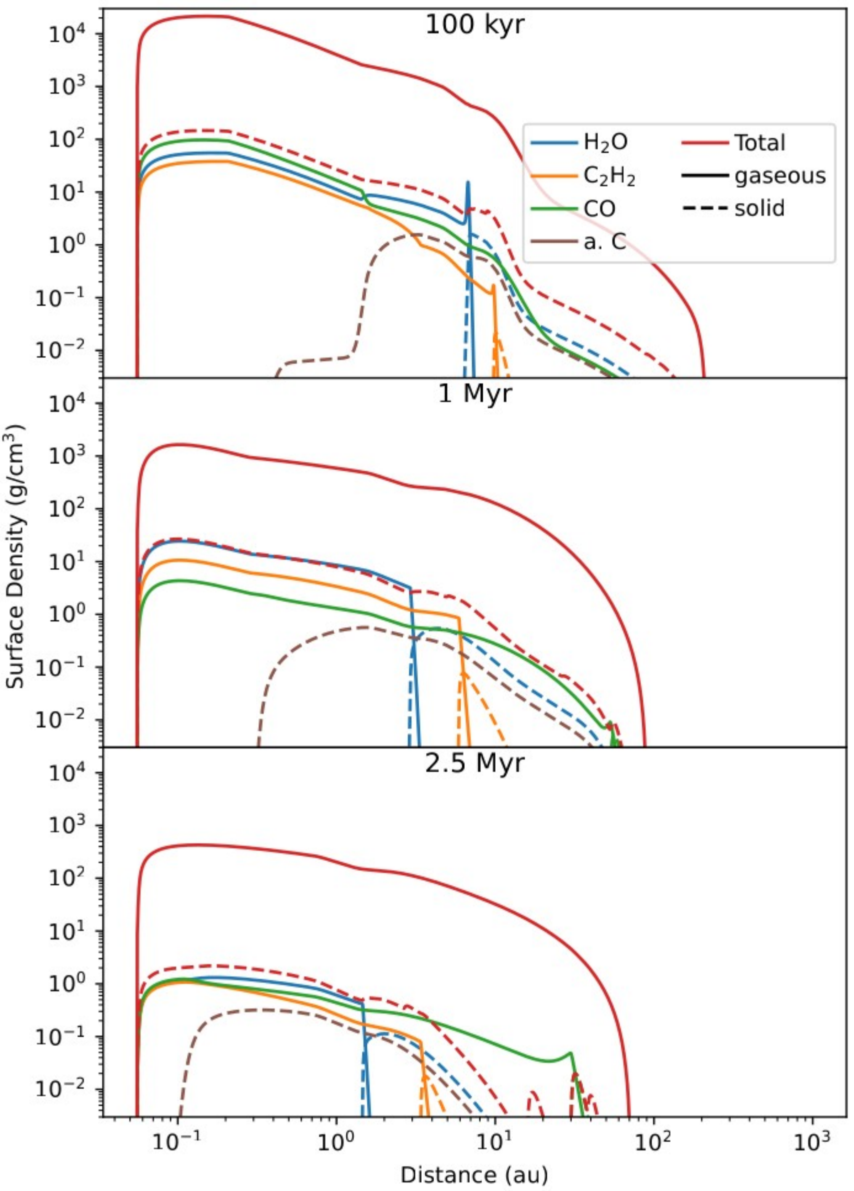
- C_2H_2 diffuses outward, condenses outside H_2O line
- Higher C/O in warm (300-1000K) early disk
  - similar late CO-dominated phase
- More pronounced with faster drift
- No enstatite-like carbon depletion

Start Early!

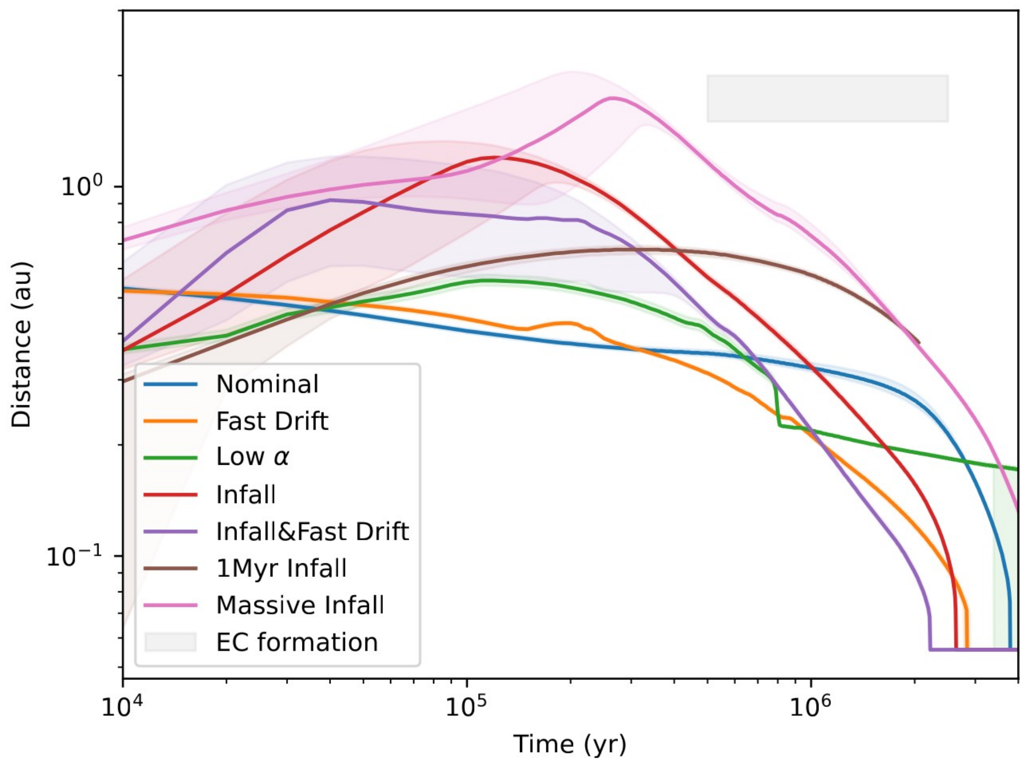
- Reactions are T dependent
- Need warmer disk for low-C solids at ~1 au
- Infall prescription
  - Exponential decay of infall with time (τ=100kyr) (Morbidelli+22)
  - Centrifugal radius of 3.5 au instead of 0.35 au
  - Total infall mass equal to total disk mass in nominal case (0.1 Msol)



Infall

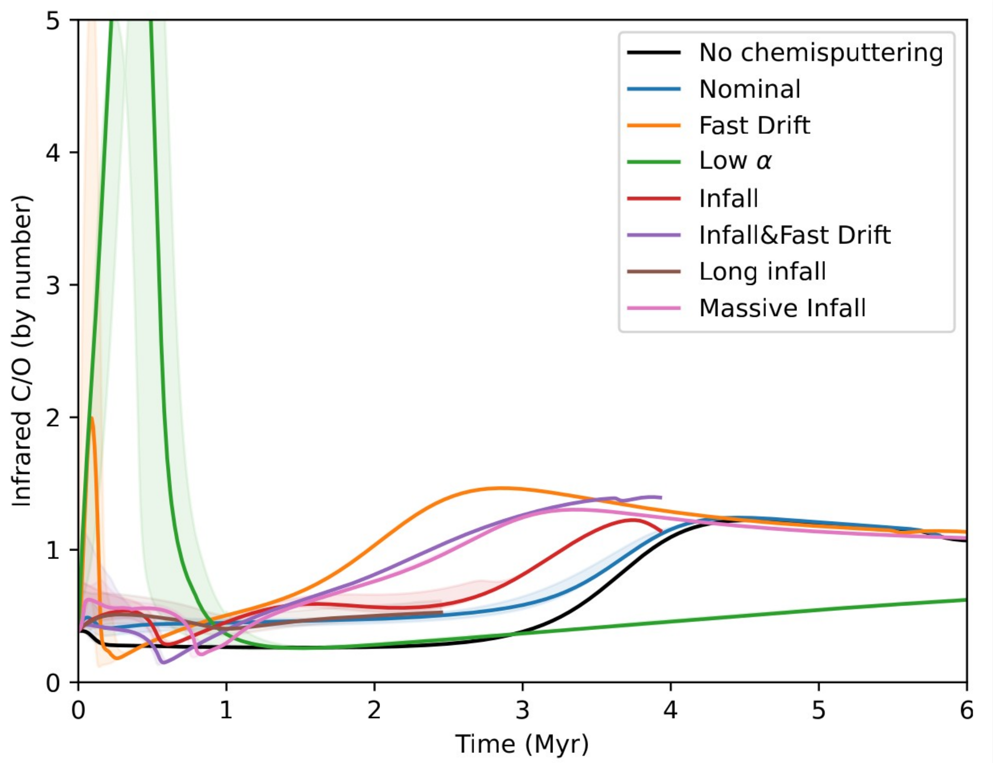
- During short infall phase
  - Removal of refractory C from 1 au solids
- Later, qualitatively similar evolution to no infall
  - Delayed, slightly more massive disk

Infall



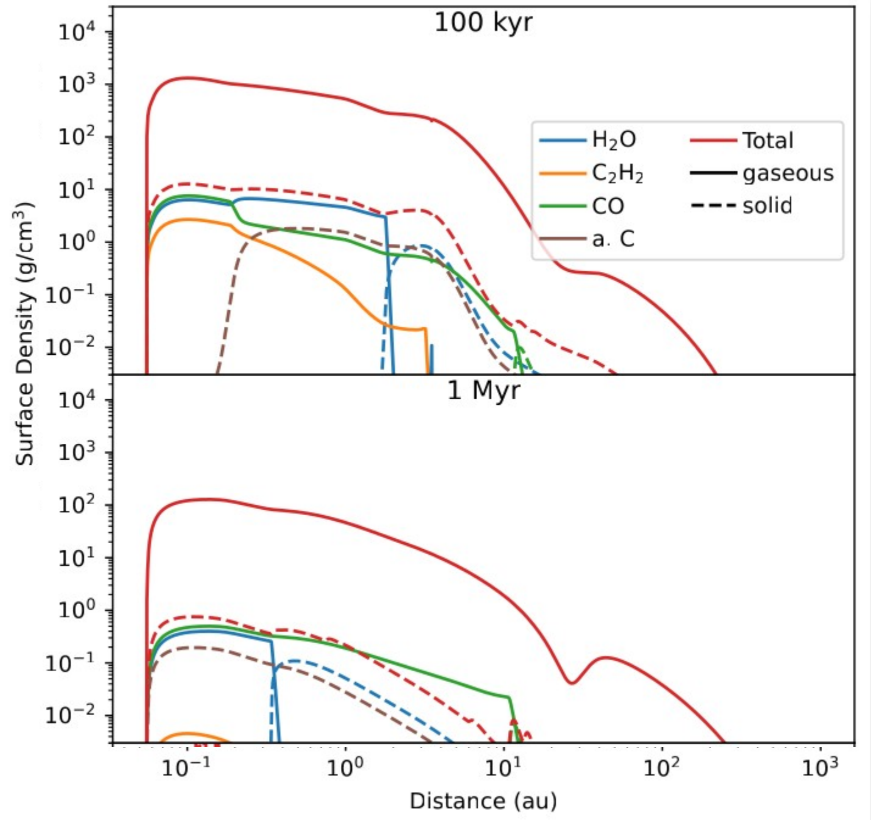
- Carbon depletion up to 1.5 au for massive infall (5×10^{-6} Msol/yr)

Infall



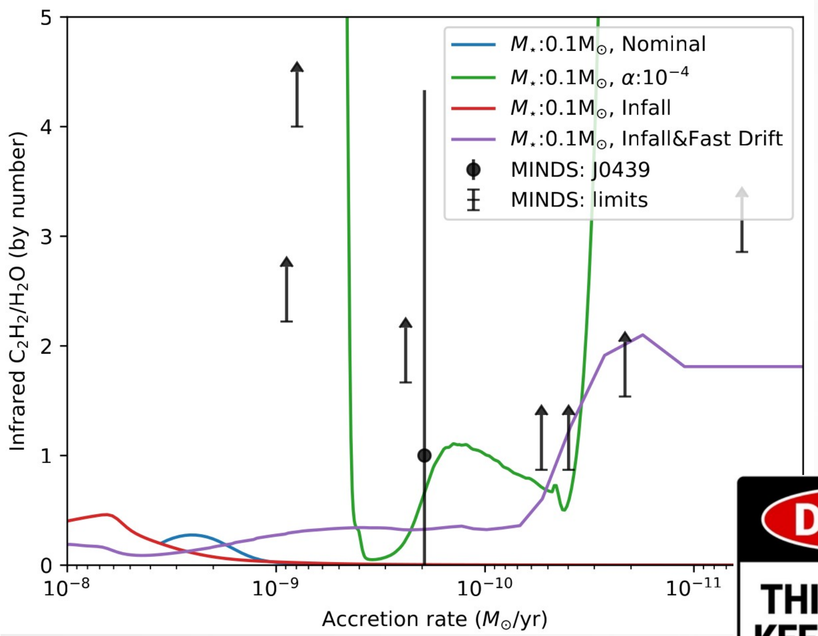
- Carbon depletion up to 1.5 au for massive infall ($5x10^{-6}$ Msol/yr)
- High late-stage C/O for Infall&Fast drift

Low stellar mass



- Release of carbon more restricted to innermost regions
  - Quick replenishment of outer, cold composition

Low stellar mass



- Release of carbon more restricted to innermost regions
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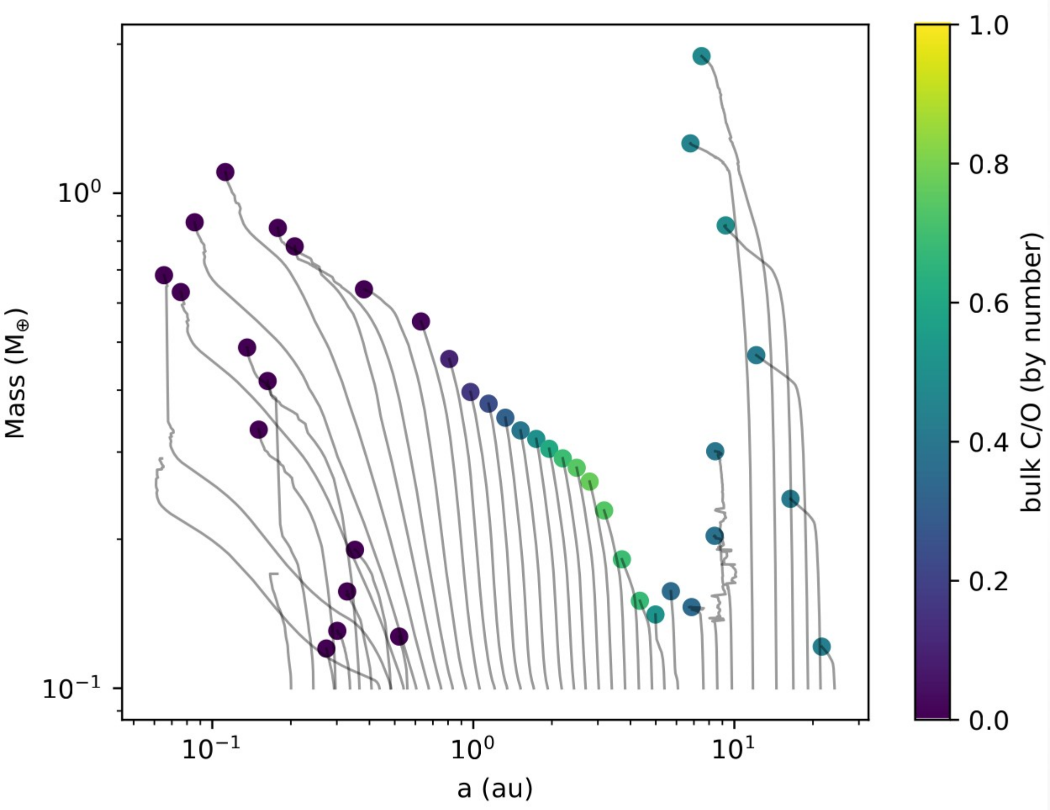
- Nevertheless, high late C_2H_2 vs H_2O can be reproduced in fast drifting scenarios
  - But not high C/O due to presence of CO

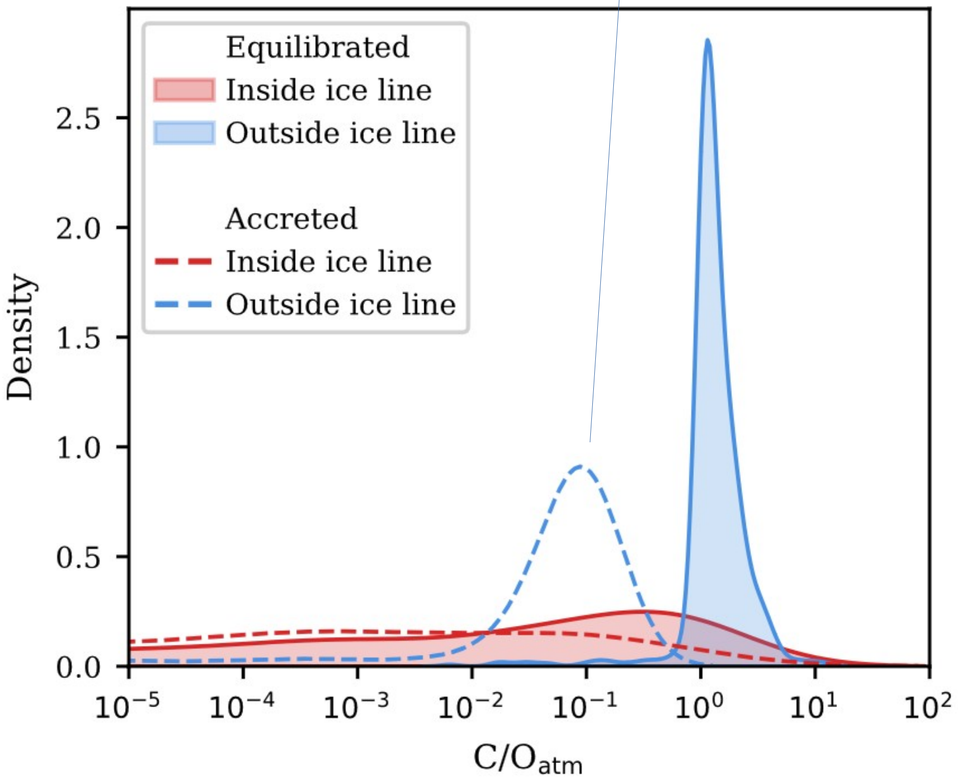
To Planets and Beyond



- Full simulations from dust to planets
  - Hybrid pebble&planetesimal acc.
- Potential to form bulk C/O~0.75 planets exterior to Earth-like low C/O~10^{-5}

Werlen+2026
Reset initial abundances,
plot includes volatiles only

To Planets and Beyond



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- Potential to form bulk C/O~0.75 planets exterior to Earth-like low C/O~10^{-5}
- Coupled Interior-Atmosphere chemistry then sets observable abundances (Werlen+2025,2026,Dorn+in prep.)

Conclusions

- Amorphous carbon challenging to remove from solids
  - High disk temperatures needed
  - Infall scenario promising to match Ordinary & Enstatite Chondrite → additional depletion of differentiated planetesimals
- High C/O gas from early-produced hydrocarbons
  - requires hot early stage & fast drift
  - Never much larger than 1 in late state
  - C_2H_2/H_2O more easily enhanced due to lack of H_2O
- carbon-rich planets might exist?