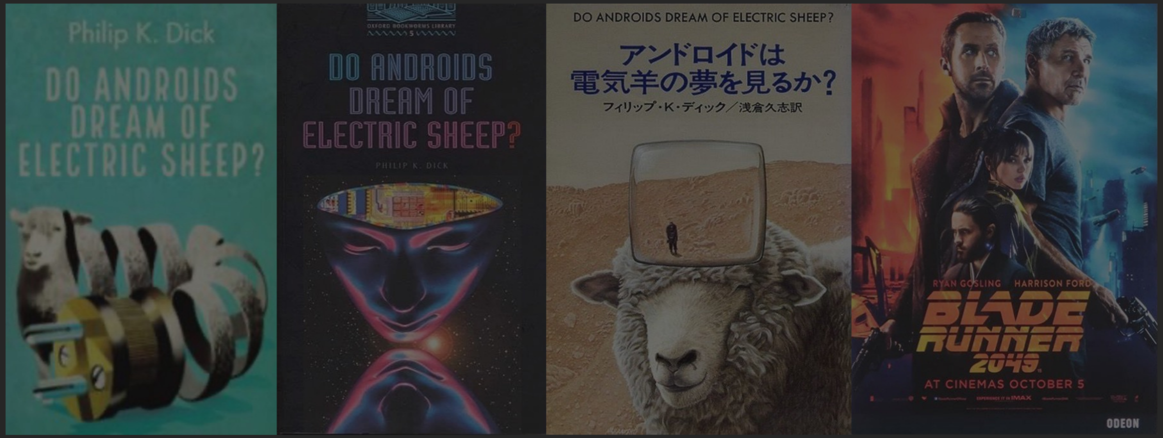
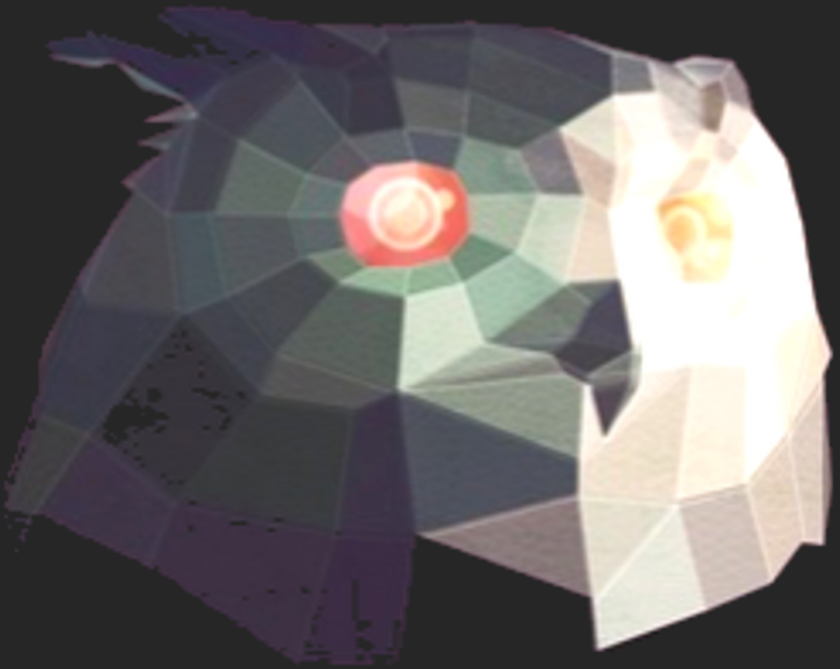
CYBER-UNIVERSES

DO ~~ANDROIDS~~ DREAM OF ELECTRIC ~~SHEEP~~? ALIENS

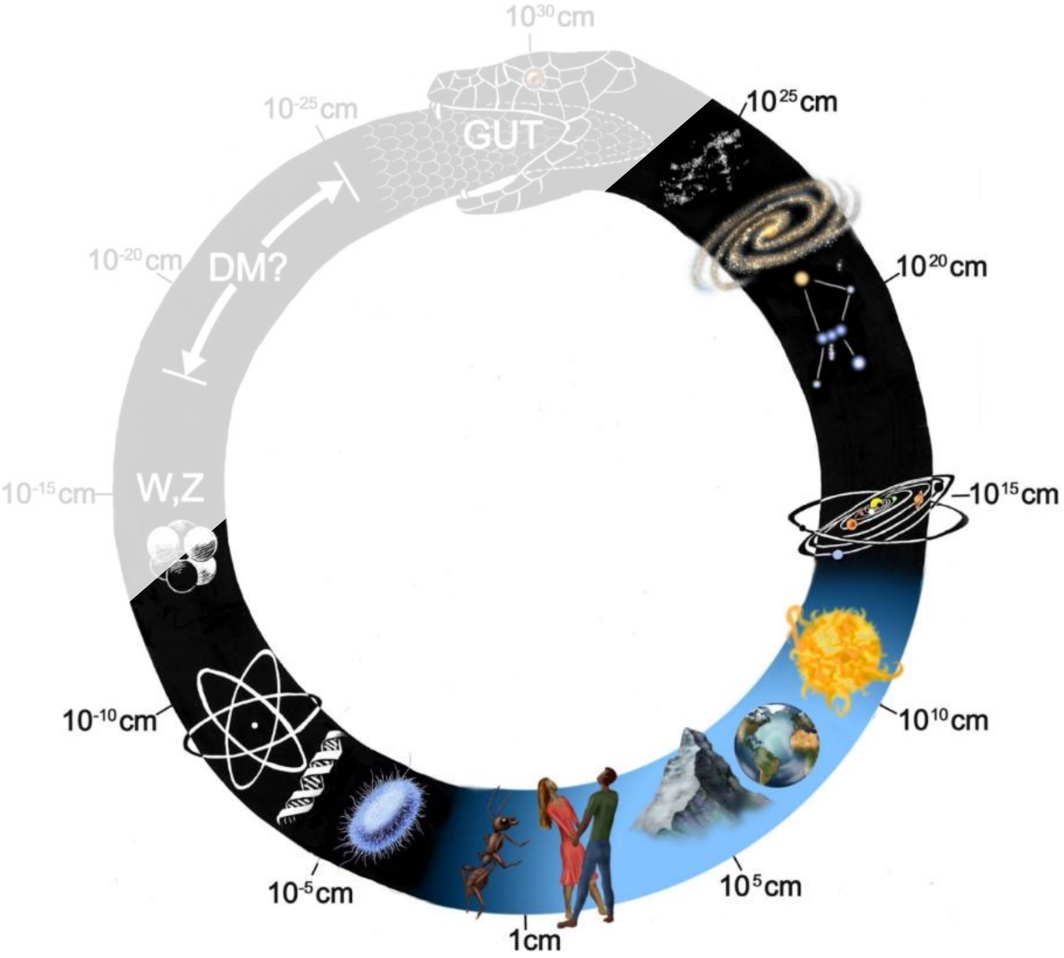




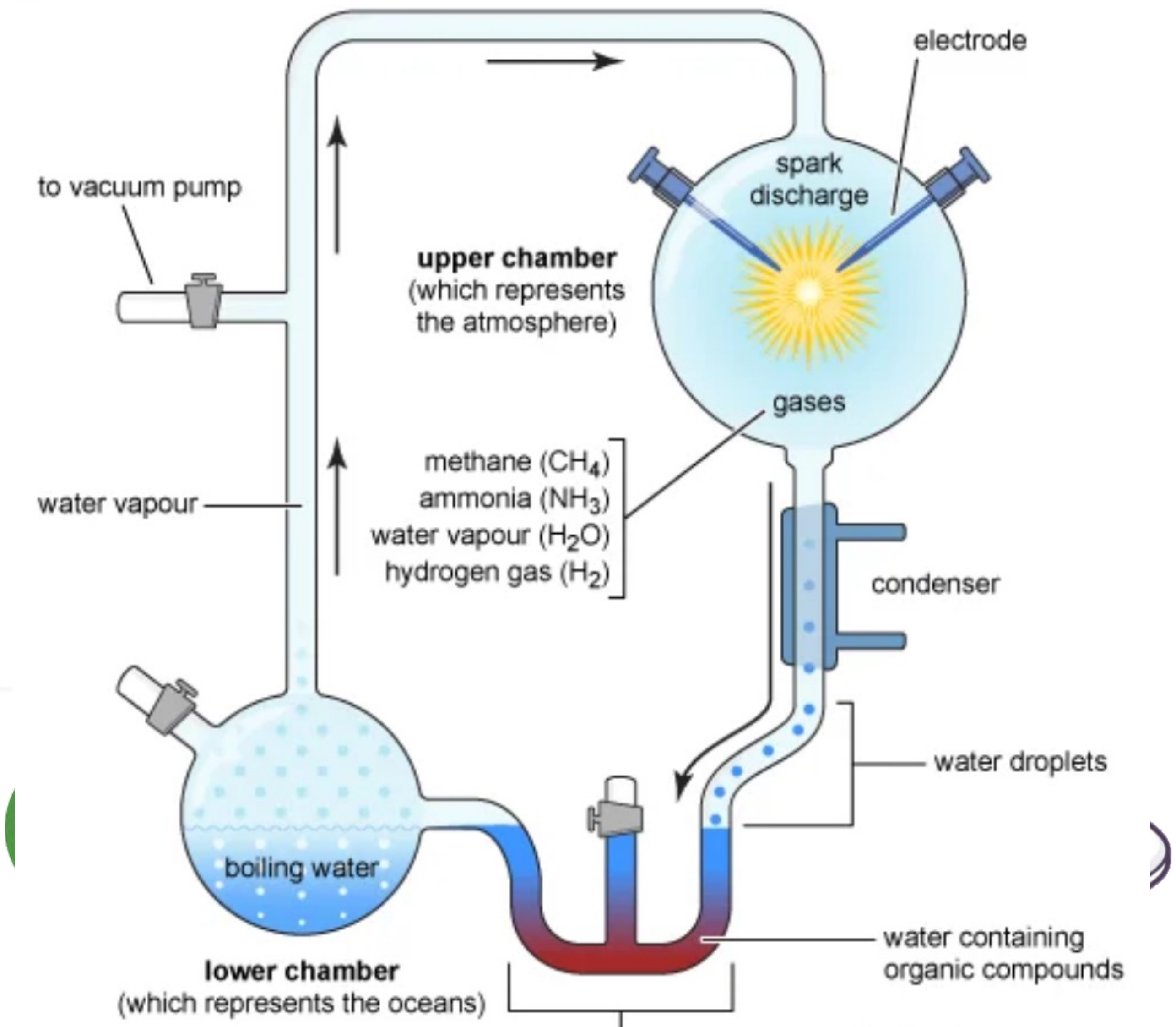
Wang 2025a, ApJS, 227, 63; arXiv:2501.02317
Wang 2025b, submitted to ApJS; arXiv:2504.04941
Zhang, Yi, Wang et al. 2025, ApJ, 990, 105; arXiv:2504.14180
Liu, Wang & Peng, 2025 ApJ in-press; arXiv:2505.10524
and many more...

Lile Wang （王力乐）
Kavli Institute for Astronomy and Astrophysics
Department of Astronomy, Peking University

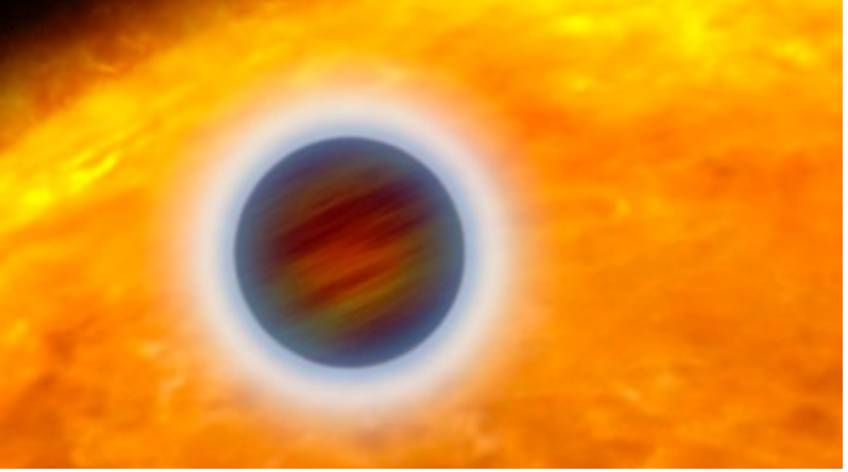
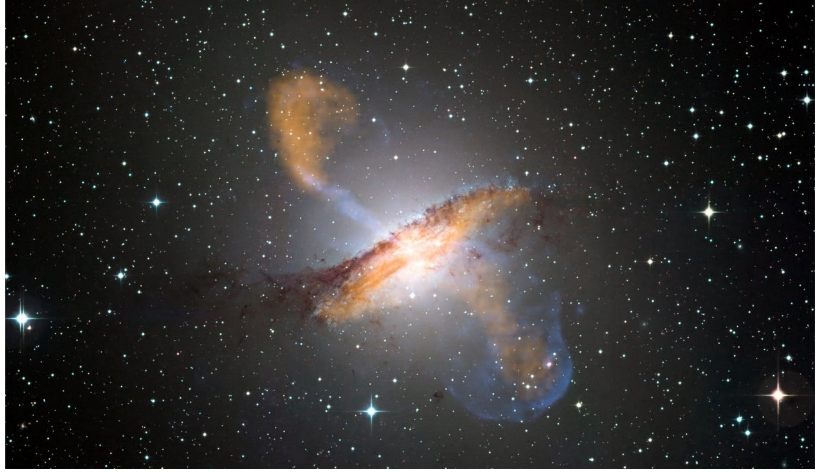
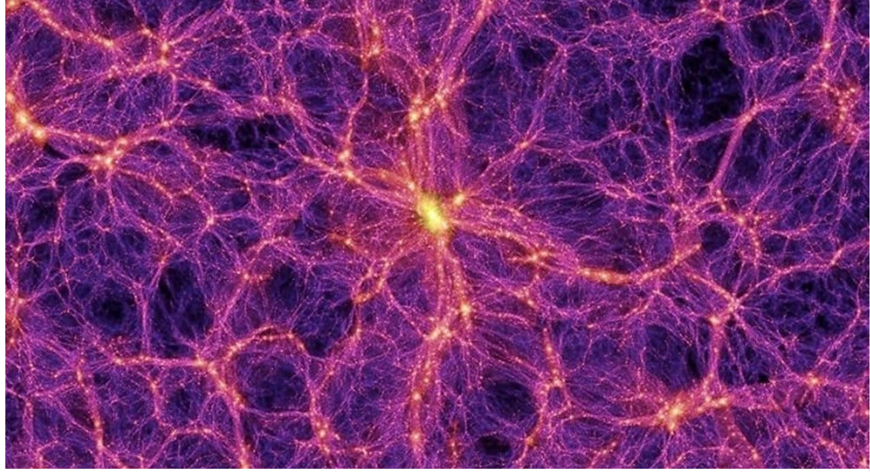
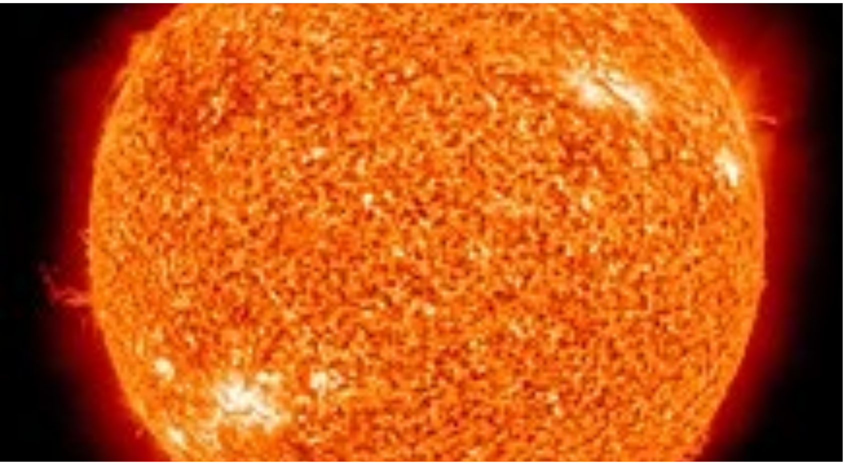
Largest Phenomena Determined by Fundamental Processes But How?



Miller-Urey experiment



© Encyclopædia Britannica, Inc.

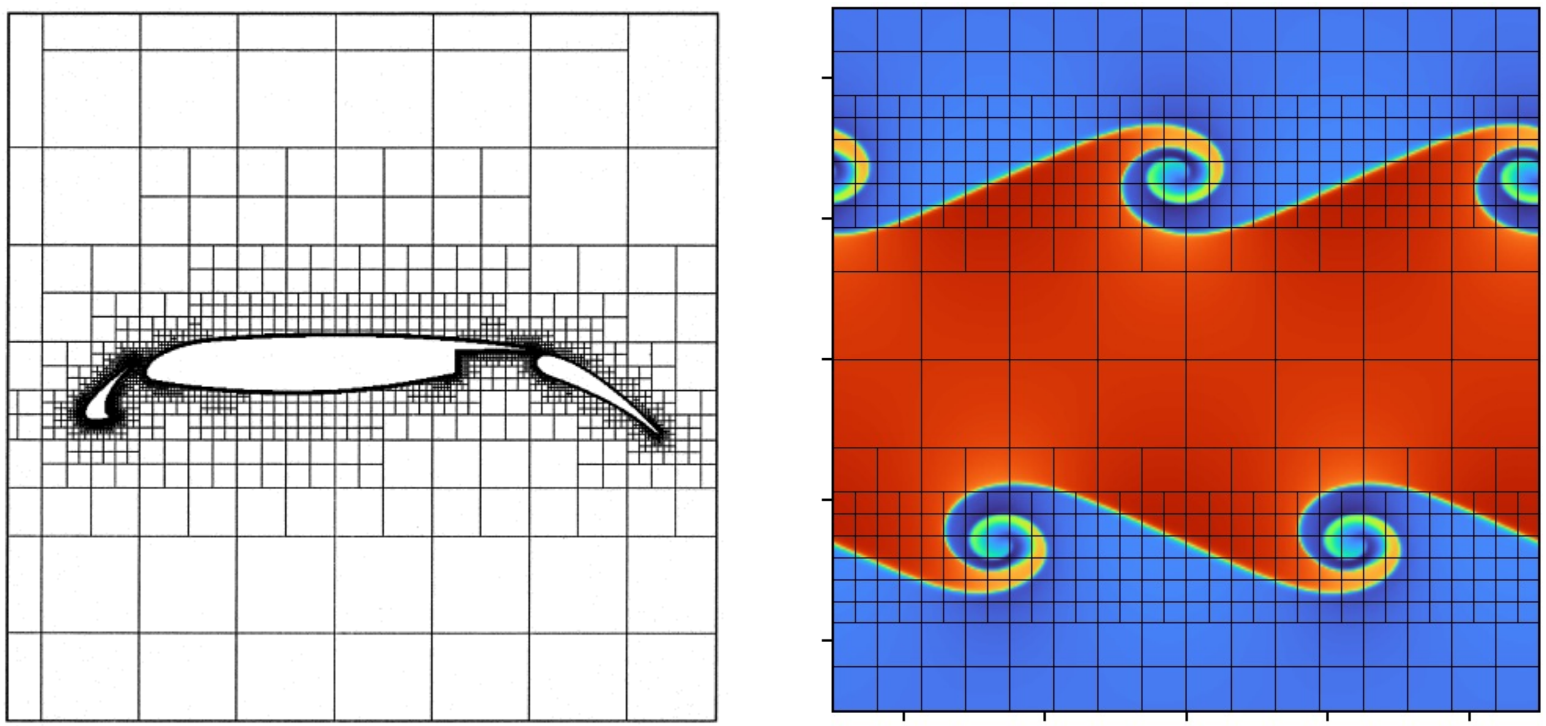






We Simulate the Universe, on All Scales

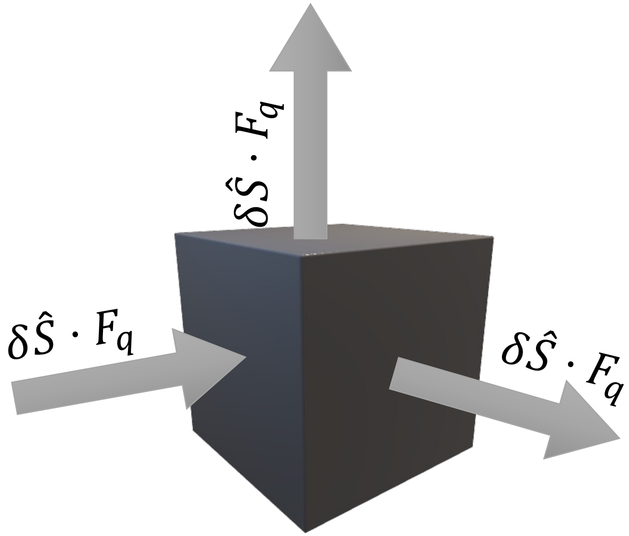
Because, Astronomically:

(1) We Can Manipuate Nothing

(2) Things Are Complicated

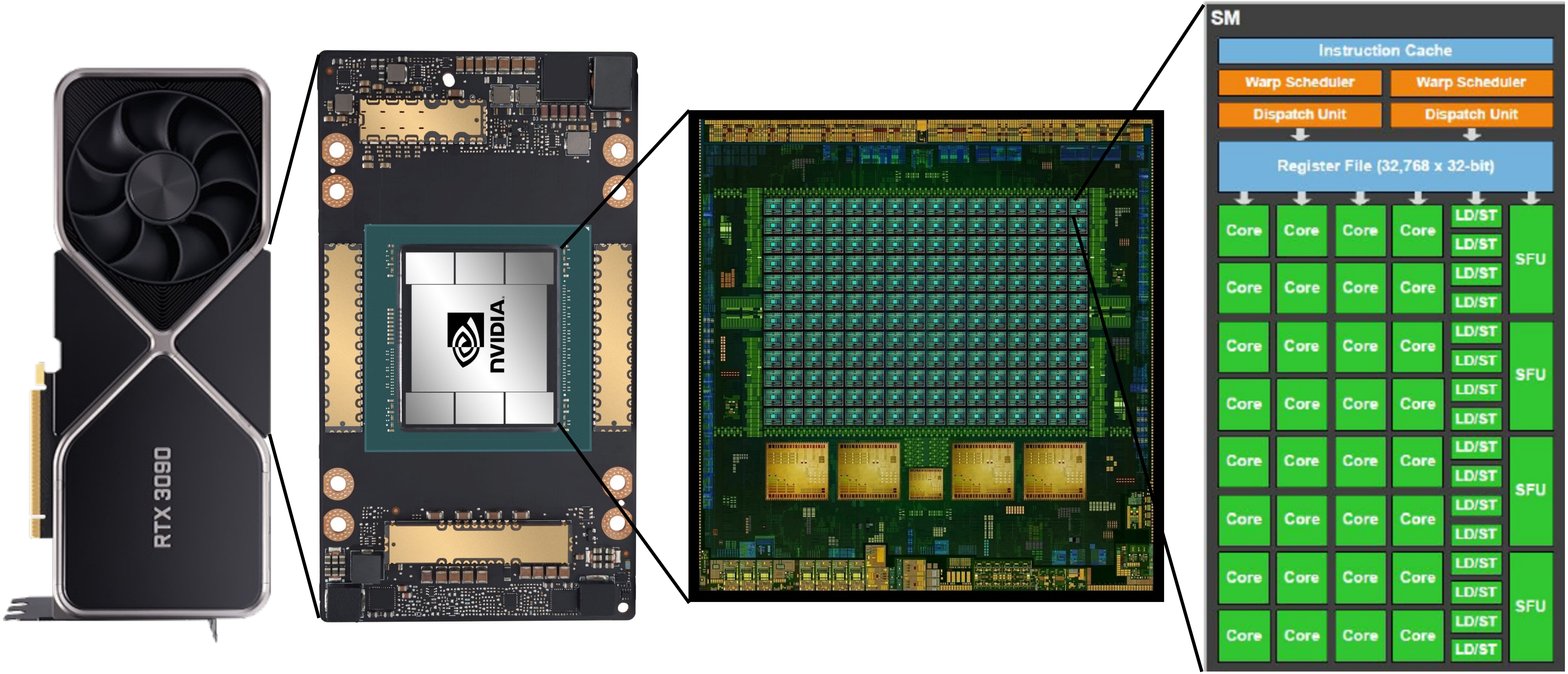


$$\Delta \int q \, \mathrm{d}V = \sum_{\text{surface}} \int \mathrm{d}t \int \mathrm{d}\hat{S} \cdot F_q$$



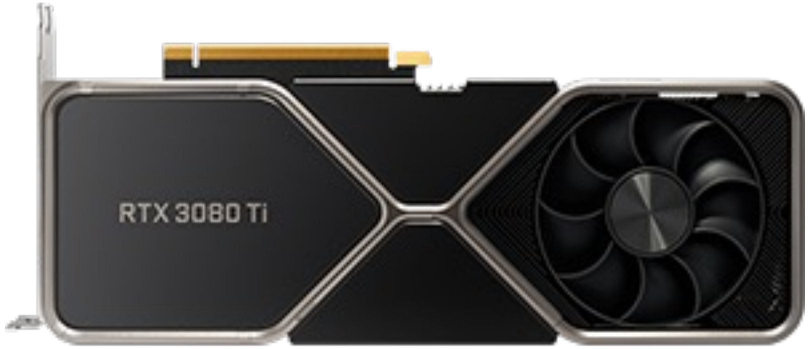
Simulations on Discretized Space…

Wang 2025a
ApJS, 227, 63



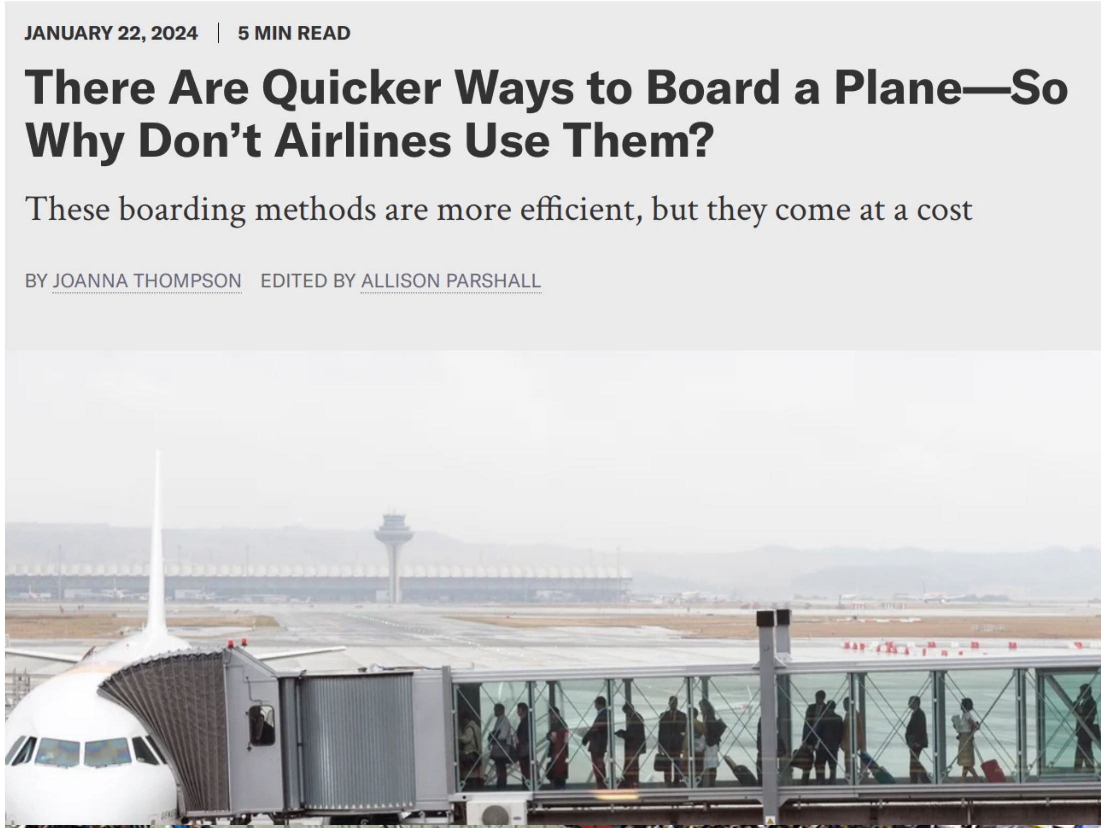
… and GPUs Are Very Suitable for Those

Wang 2025a
ApJS, 227, 63



~800 km/h
Best at transporting
100 people from PEK to CJU

~2000 km/h
Best at doing things that
need speed and
manuverbility



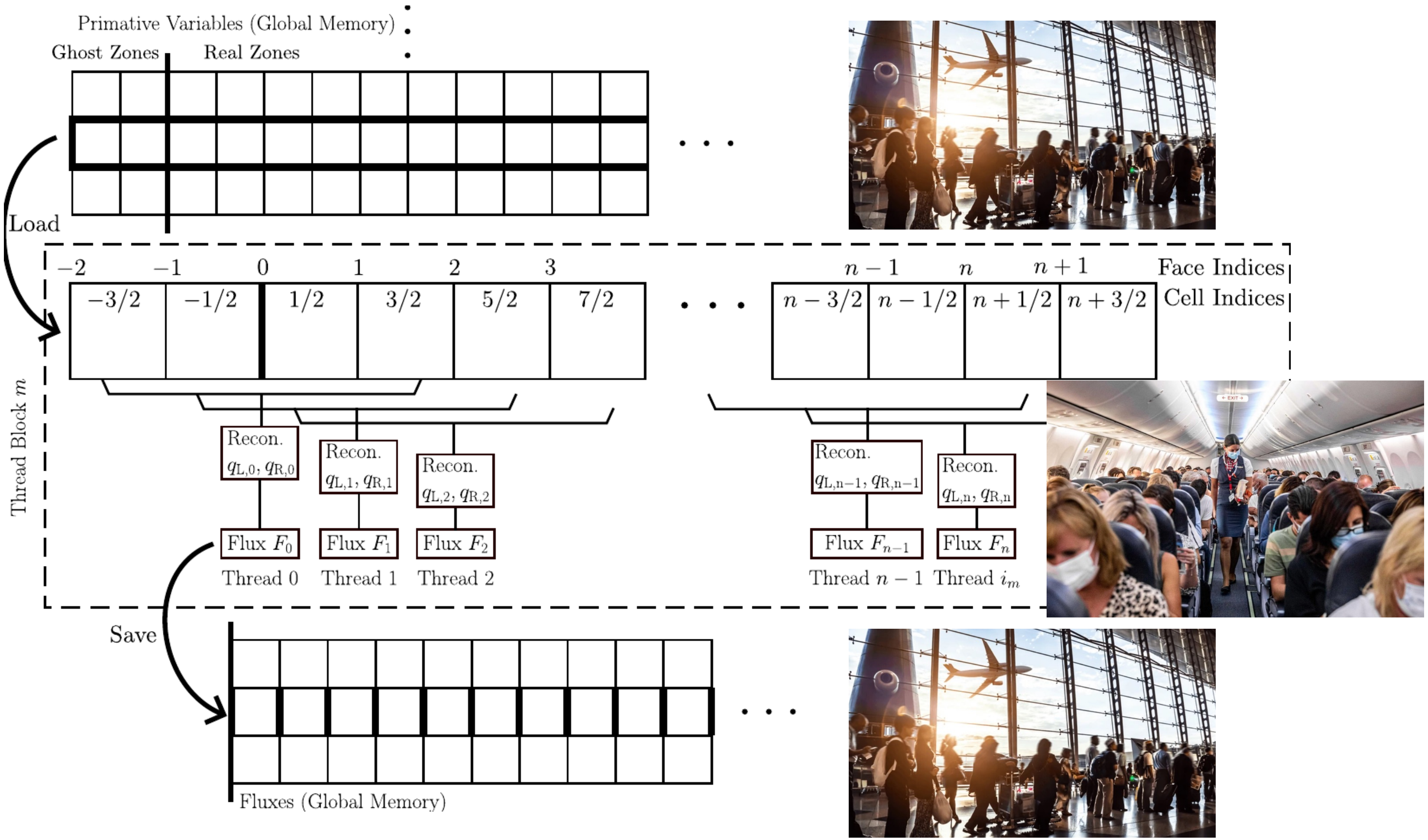
JANUARY 22, 2024 | 5 MIN READ

There Are Quicker Ways to Board a Plane—So Why Don't Airlines Use Them?

These boarding methods are more efficient, but they come at a cost

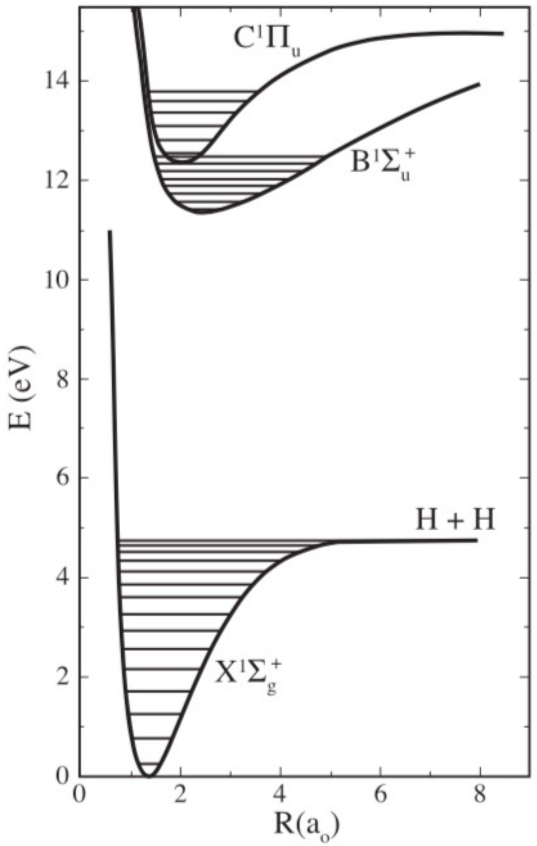
BY JOANNA THOMPSON EDITED BY ALLISON PARSHALL

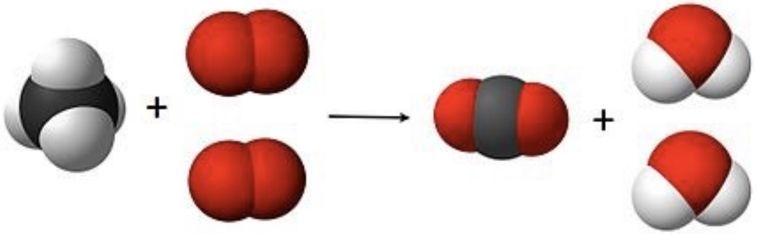
- One column read from GRAM (concourse) to L1 cache (seats on board)
- Reconstruction, Riemann solver, and probably flux integration, implemented on L1 Cache
- Write back to the GRAM only when necessary
- Do not get board and unboard frequently



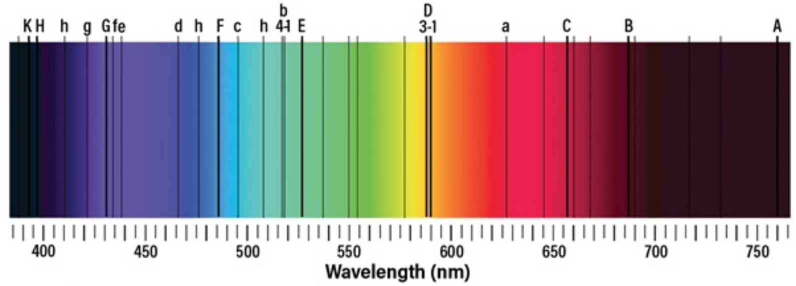
Optimized GRAM and Cache Access

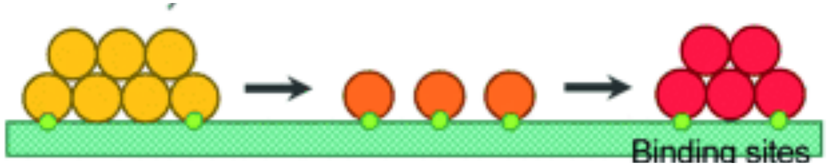
Wang 2025a
ApJS, 227, 63

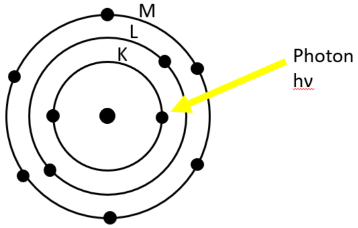


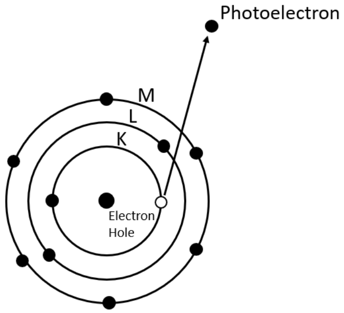


$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$









Chemistry (“Microphysics”) is Necessary

Why we need it —or, why not equilibrium?

Because sometimes we have

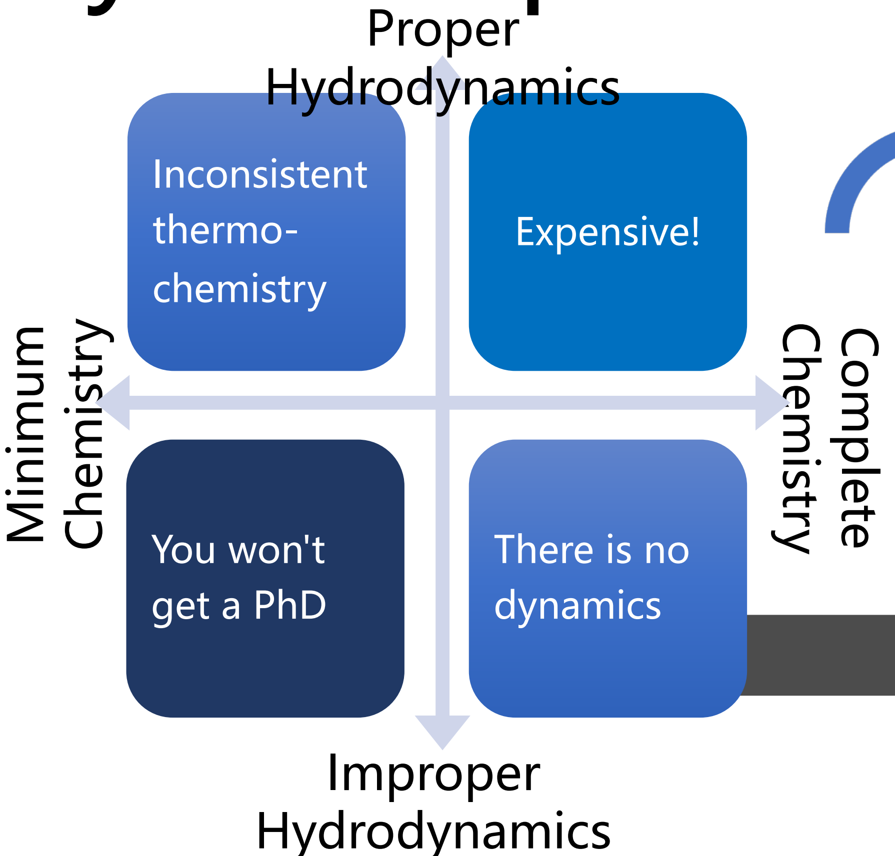
$$\tau_{\mathrm{dyn}} \lesssim \tau_{\mathrm{chem}}$$

Which occurs quite often

>30 Species >130 Reactions

Real-time Non-equilibrium

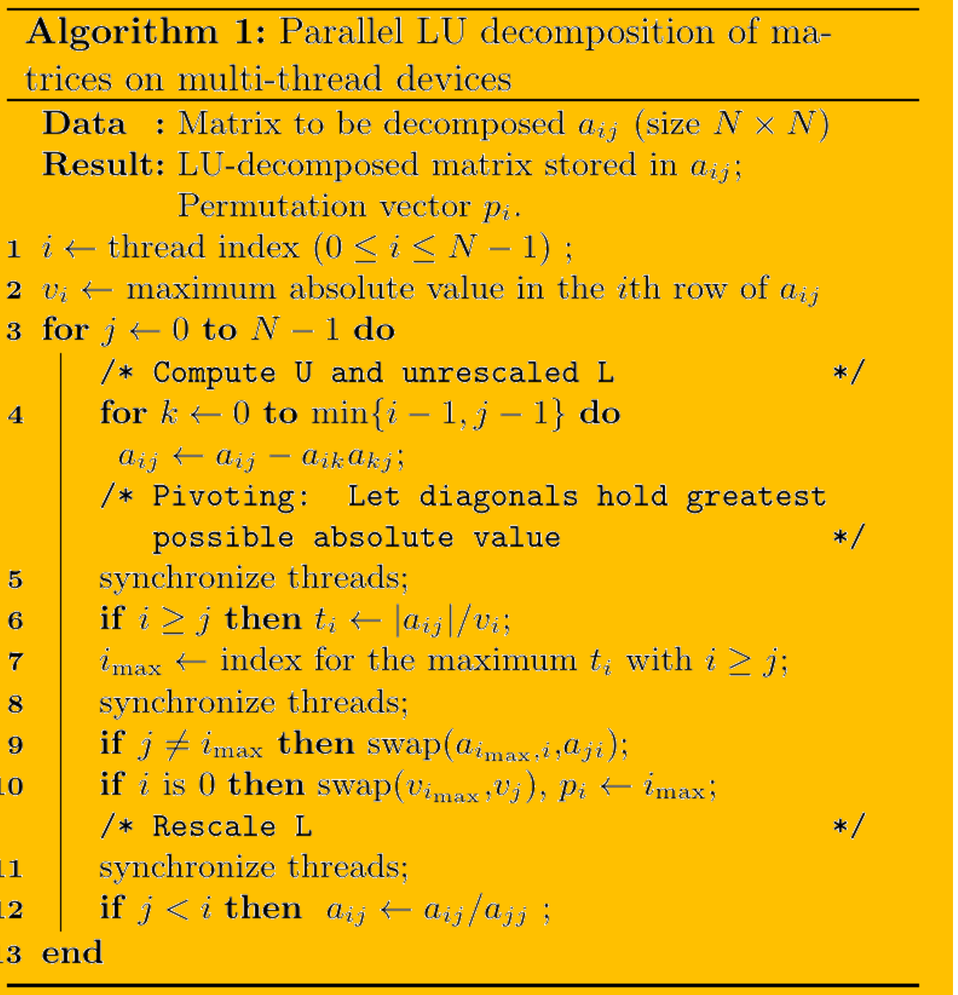
Cooling/Heating: Species by species, process by process



	Minimum Chemistry	Complete Chemistry
Proper Hydrodynamics	Inconsistent thermo-chemistry	Expensive!
Improper Hydrodynamics	You won't get a PhD	There is no dynamics

?

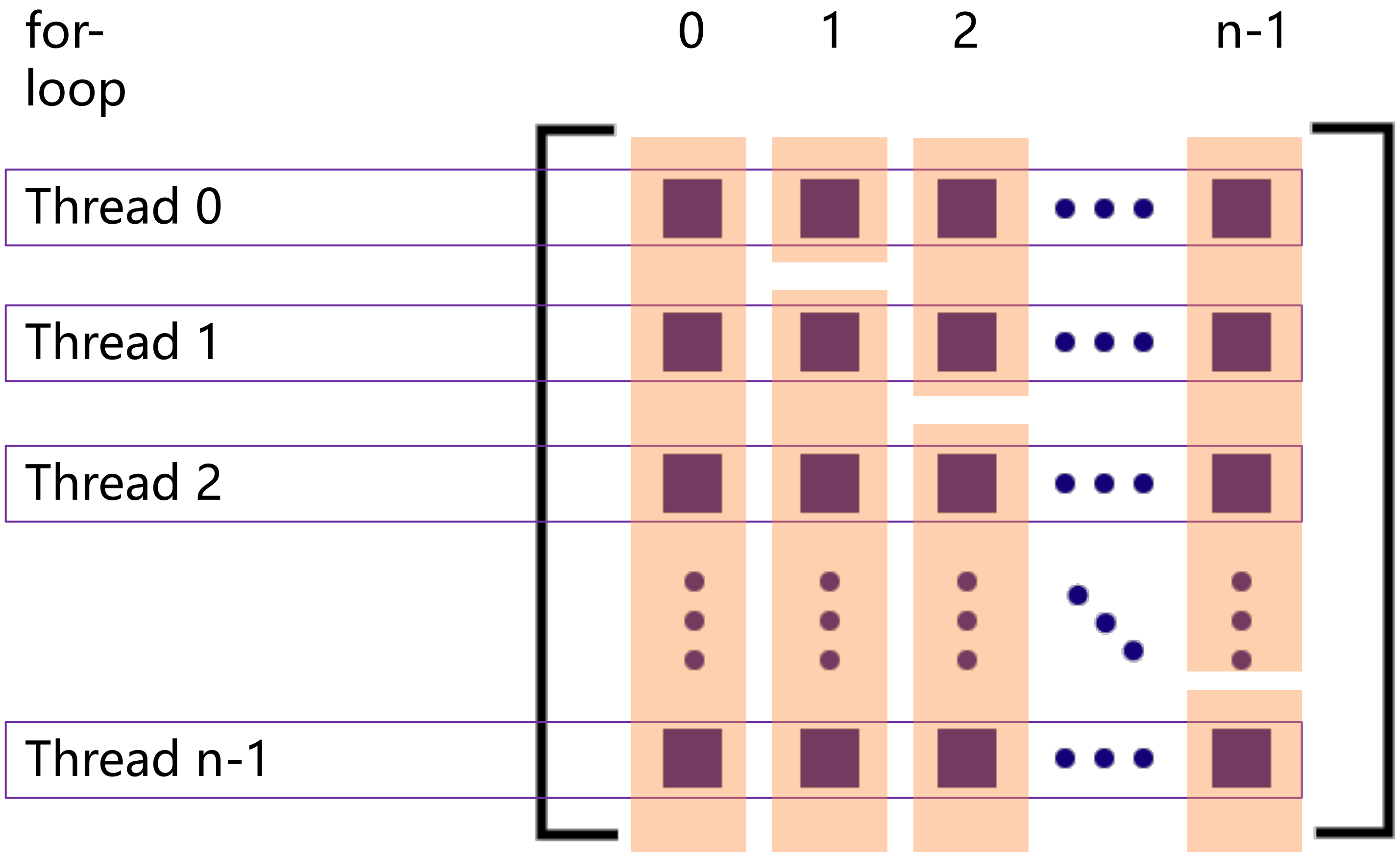
Concurrent LU Decomposition on L1



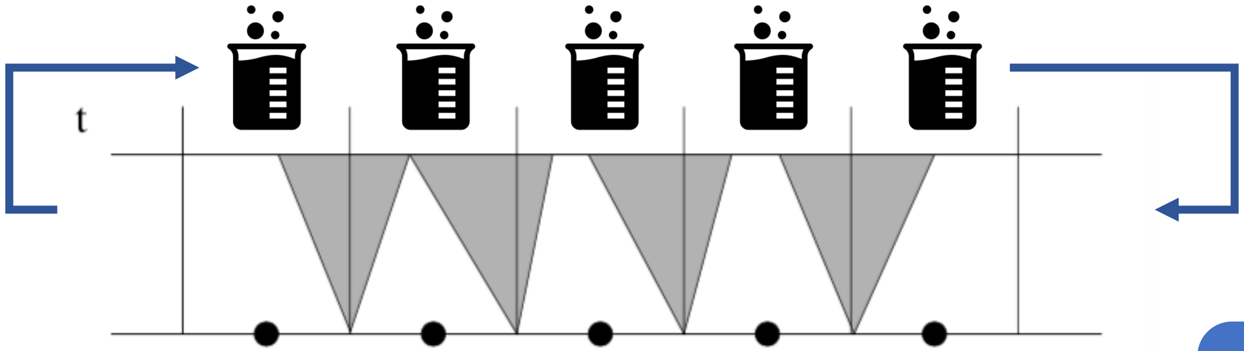
Algorithm 1: Parallel LU decomposition of matrices on multi-thread devices

```
Data   : Matrix to be decomposed $a_{ij}$ (size $N \times N$)
Result: LU-decomposed matrix stored in $a_{ij}$;
        Permutation vector $p_i$.
$i \leftarrow$ thread index $(0 \le i \le N-1)$ ;
$v_i \leftarrow$ maximum absolute value in the $i$th row of $a_{ij}$
for $j \leftarrow 0$ to $N-1$ do
    /* Compute U and unrescaled L                          */
    for $k \leftarrow 0$ to $\min\{i-1, j-1\}$ do
        $a_{ij} \leftarrow a_{ij} - a_{ik}a_{kj}$;
    /* Pivoting: Let diagonals hold greatest
       possible absolute value                             */
    synchronize threads;
    if $i \ge j$ then $t_i \leftarrow |a_{ij}|/v_i$;
    $i_{\max} \leftarrow$ index for the maximum $t_i$ with $i \ge j$;
    synchronize threads;
    if $j \ne i_{\max}$ then swap($a_{i_{\max},i}$,$a_{ji}$);
    if $i$ is 0 then swap($v_{i_{\max}}$,$v_j$), $p_i \leftarrow i_{\max}$;
    /* Rescale L                                           */
    synchronize threads;
    if $j < i$ then $a_{ij} \leftarrow a_{ij}/a_{jj}$ ;
end
```

$$y_i|_{x=x_1} \simeq y_i|_{x=x_0} + \Delta x \, (\delta_{ij} - J_{ij}|_{x_0}\Delta x)^{-1} \left[\frac{\mathrm{d}y_j}{\mathrm{d}x}\right]_{x=x_0}$$



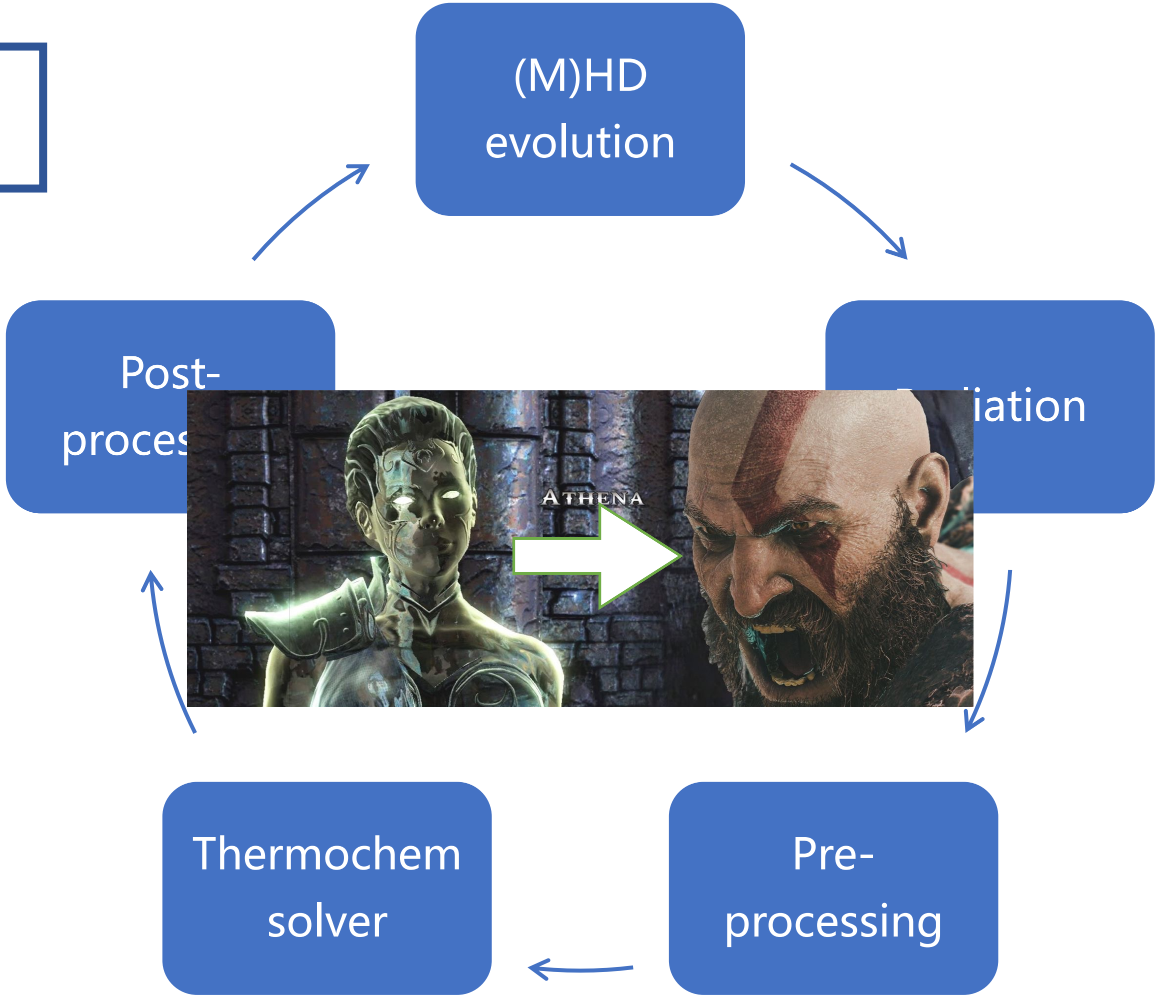
Wang 2025b
arXiv:2504.04941



Post-processing

Eliminate inconsistency before data rejoin (M)HD procedures

- Fix violations of conservations in elements and charge
- Detect non-converged chemistry, retry/reset
- Update energy density and chemical abundances
- Update non-ideal MHD diffusivities



(M)HD evolution

iation

Pre-processing

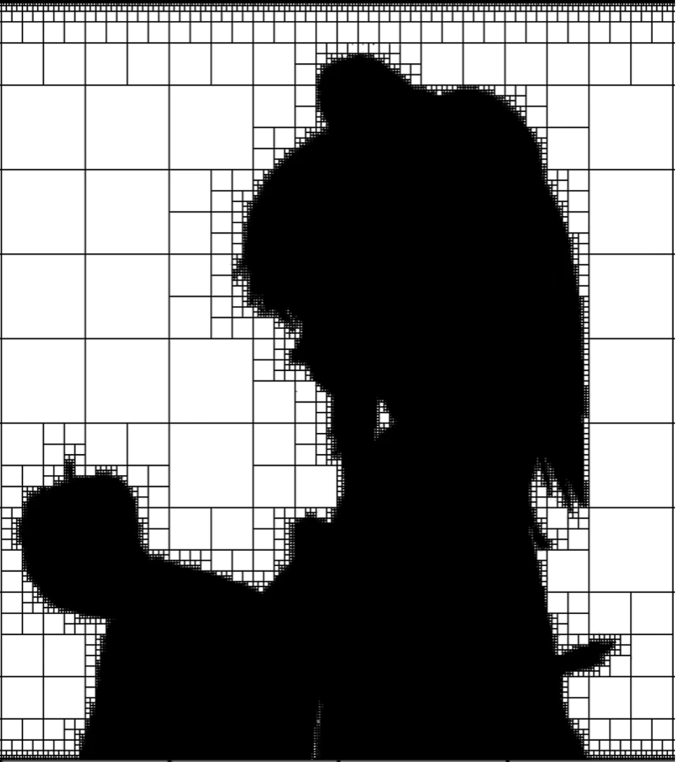
Thermochem solver

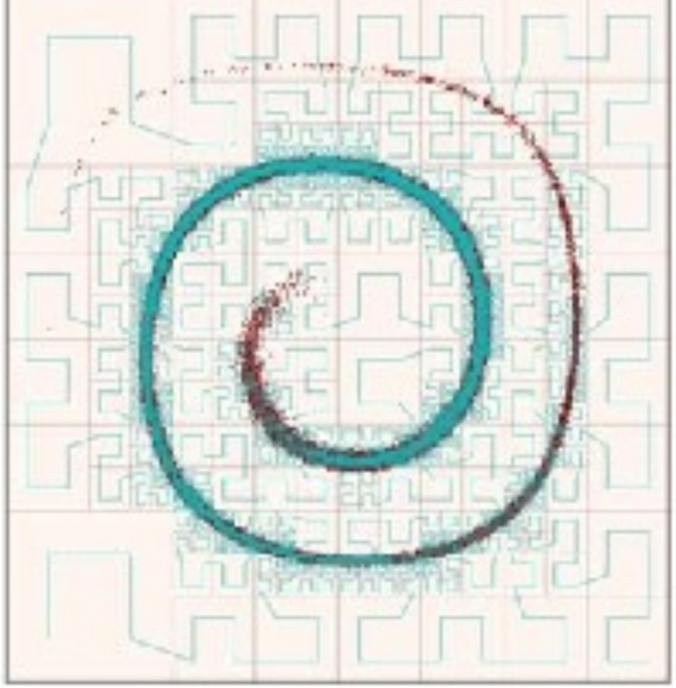
Post-

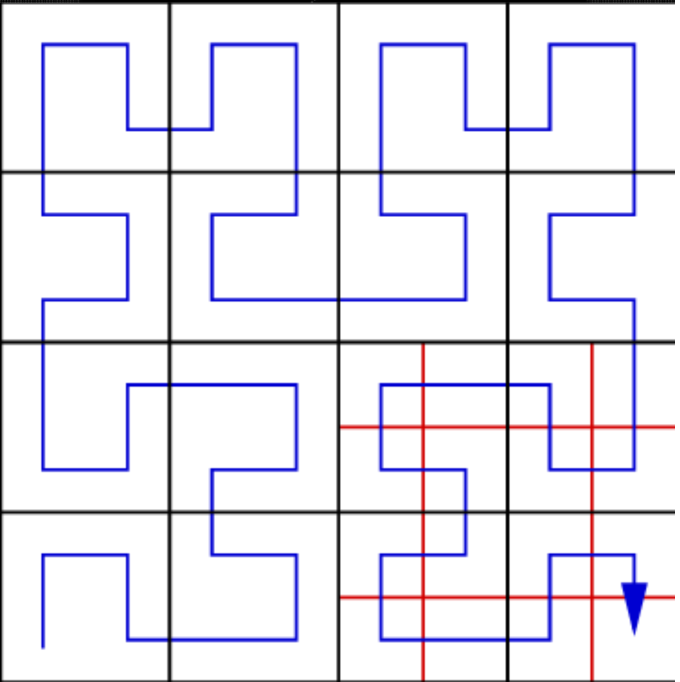
proces

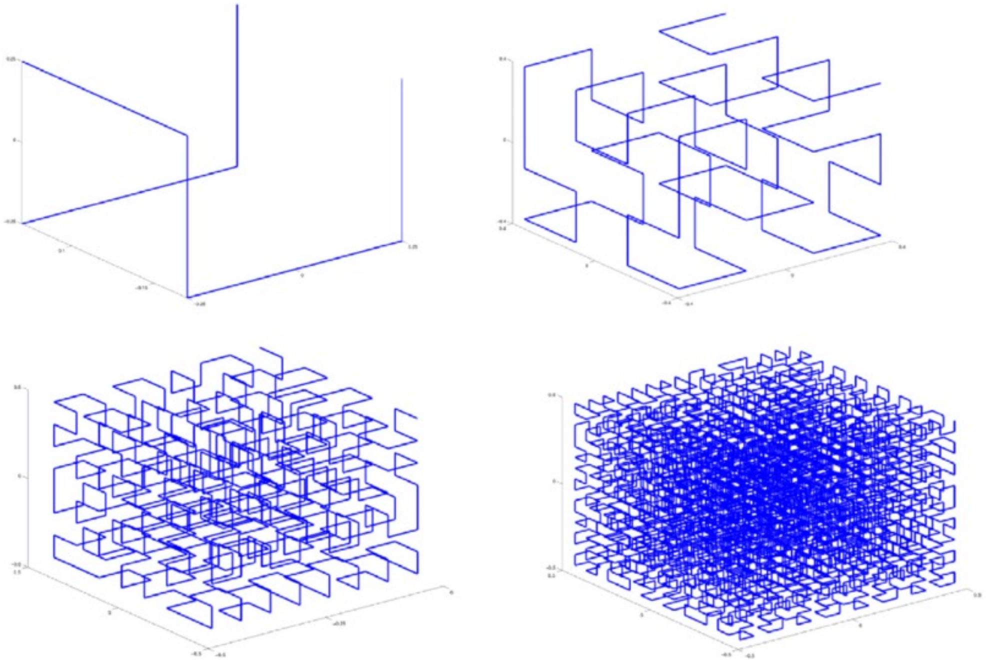
Realtime GPU Microphysics

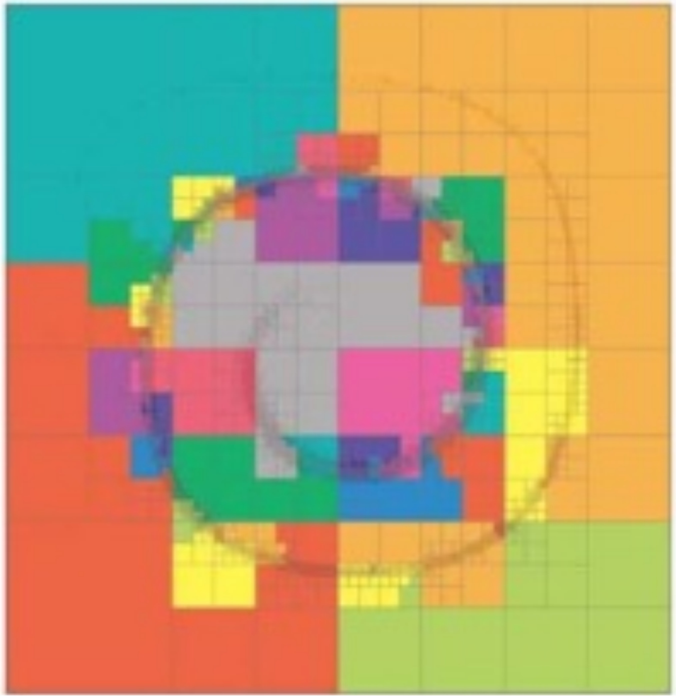
Wang 2025b
arXiv:2504.04941



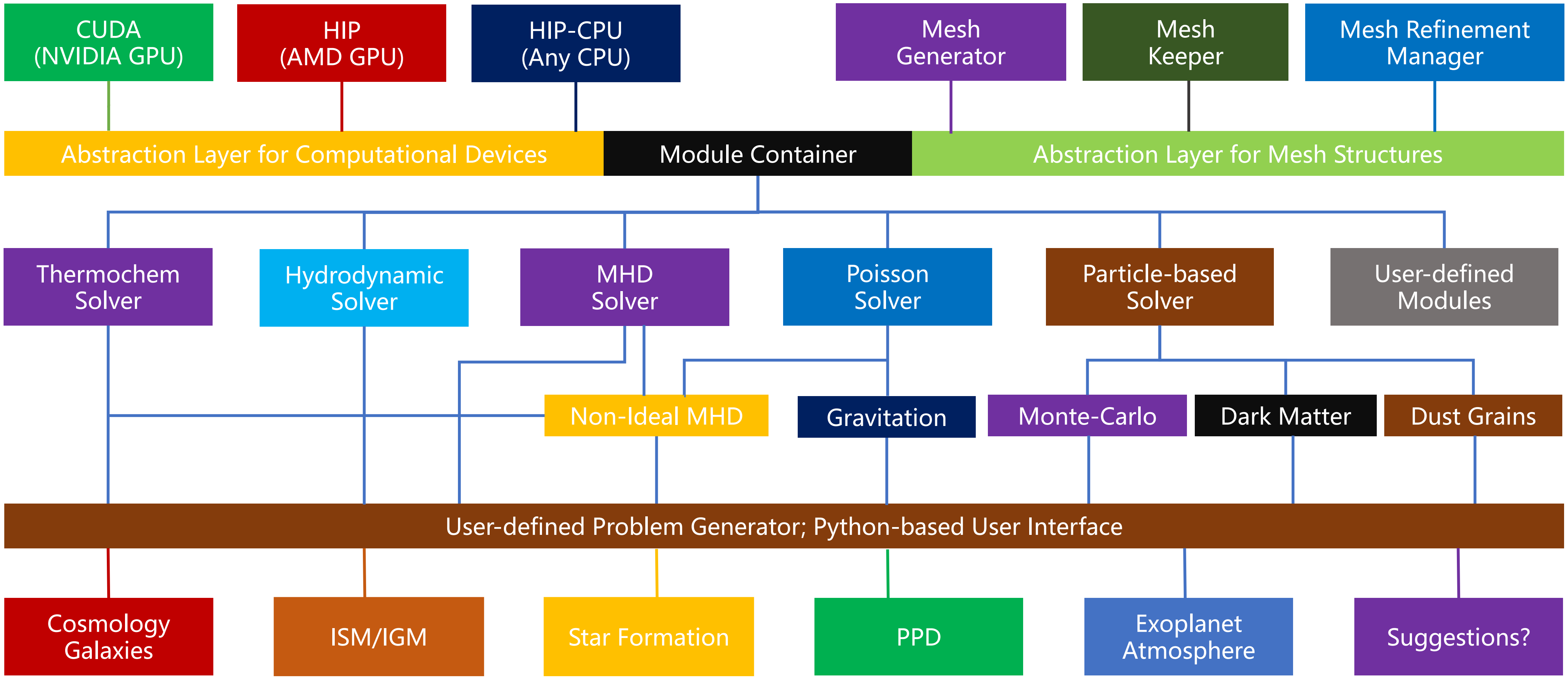








New Heterogeneous Code: Structures



CUDA (NVIDIA GPU)

HIP (AMD GPU)

HIP-CPU (Any CPU)

Mesh Generator

Mesh Keeper

Mesh Refinement Manager

Abstraction Layer for Computational Devices

Module Container

Abstraction Layer for Mesh Structures

Thermochem Solver

Hydrodynamic Solver

MHD Solver

Poisson Solver

Particle-based Solver

User-defined Modules

Non-Ideal MHD

Gravitation

Monte-Carlo

Dark Matter

Dust Grains

User-defined Problem Generator; Python-based User Interface

Cosmology Galaxies

ISM/IGM

Star Formation

PPD

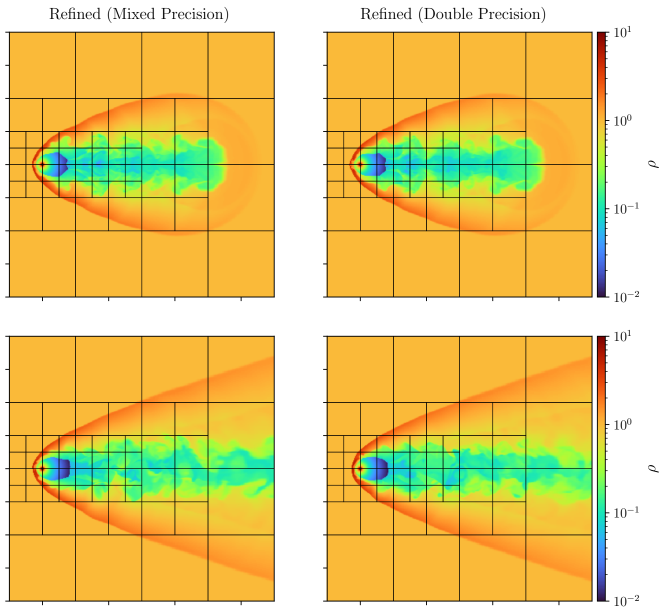
Exoplanet Atmosphere

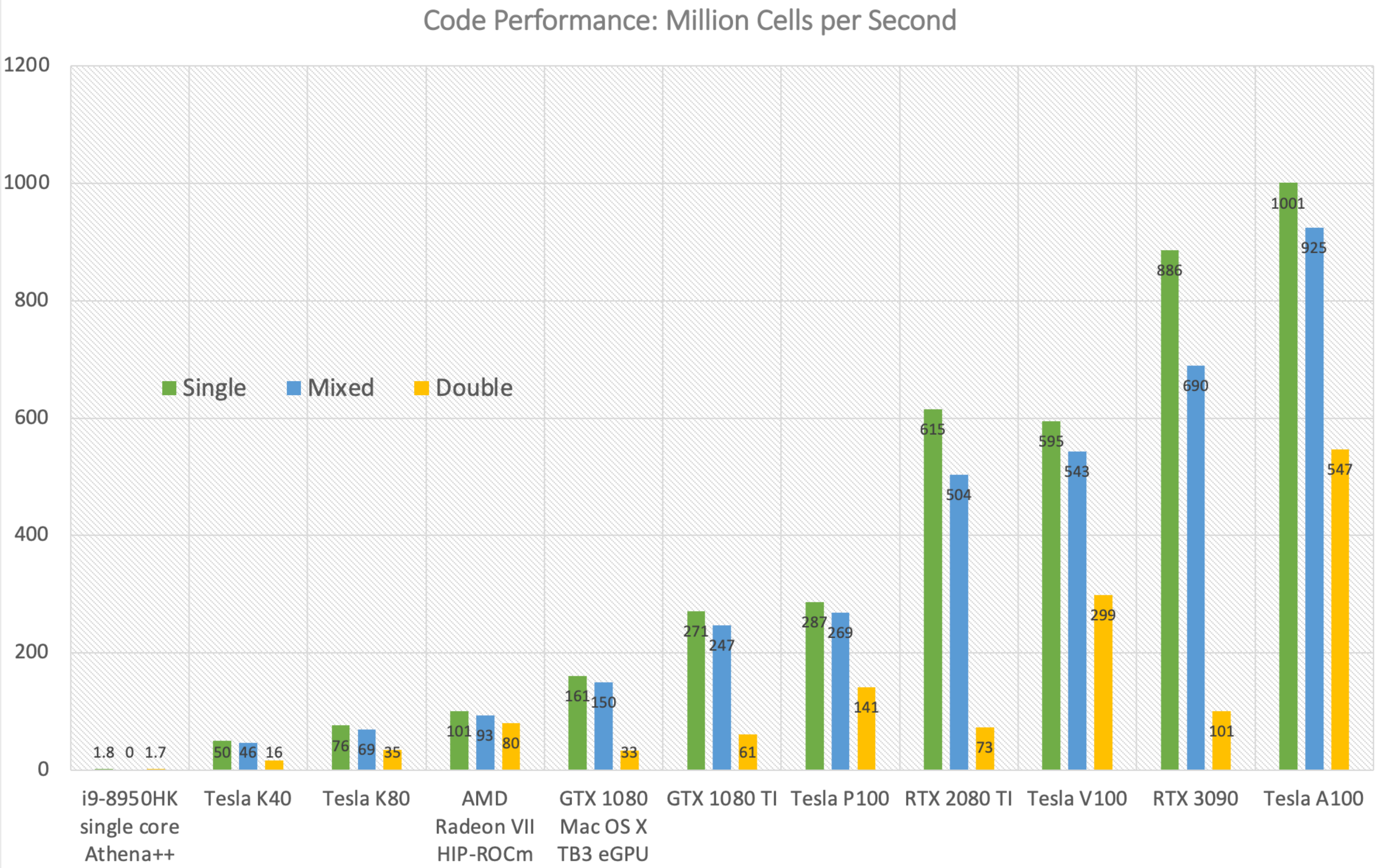
Suggestions?

Wang 2025a
ApJS, 227, 63

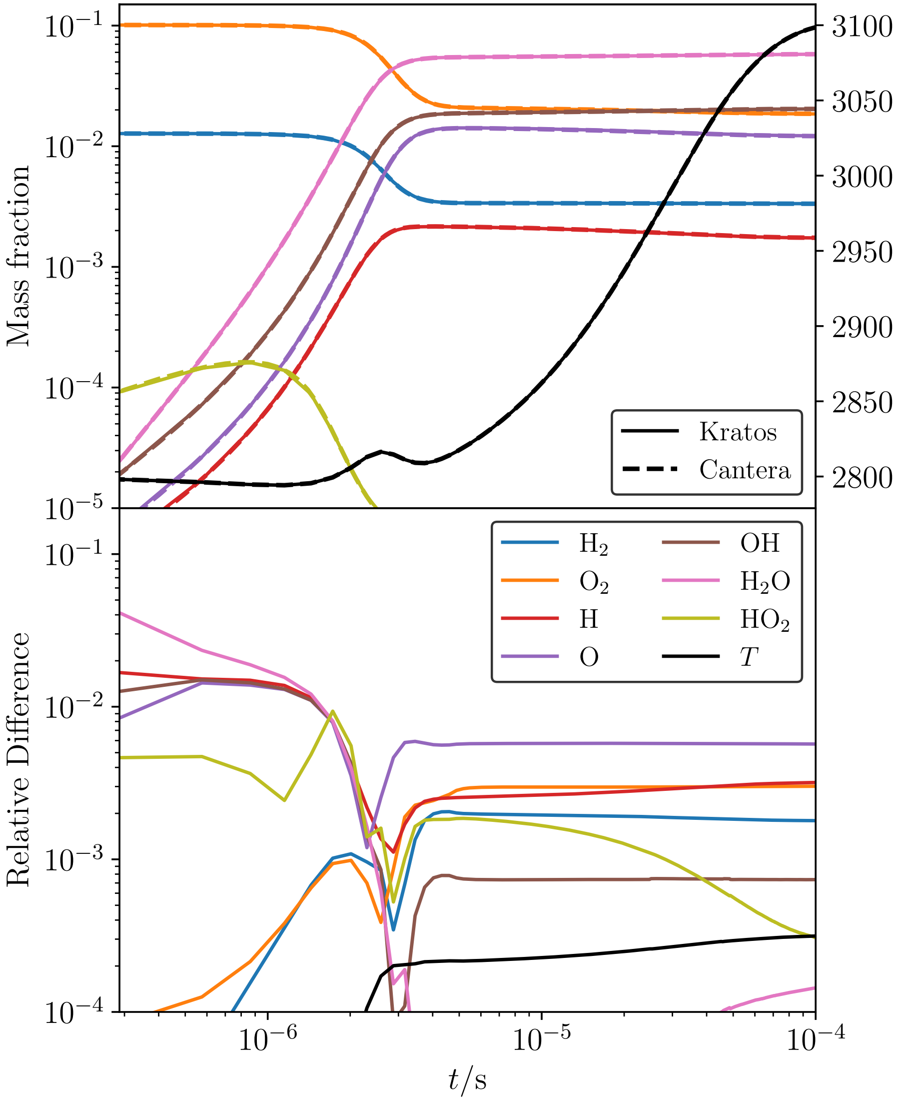
How Fast is Fast

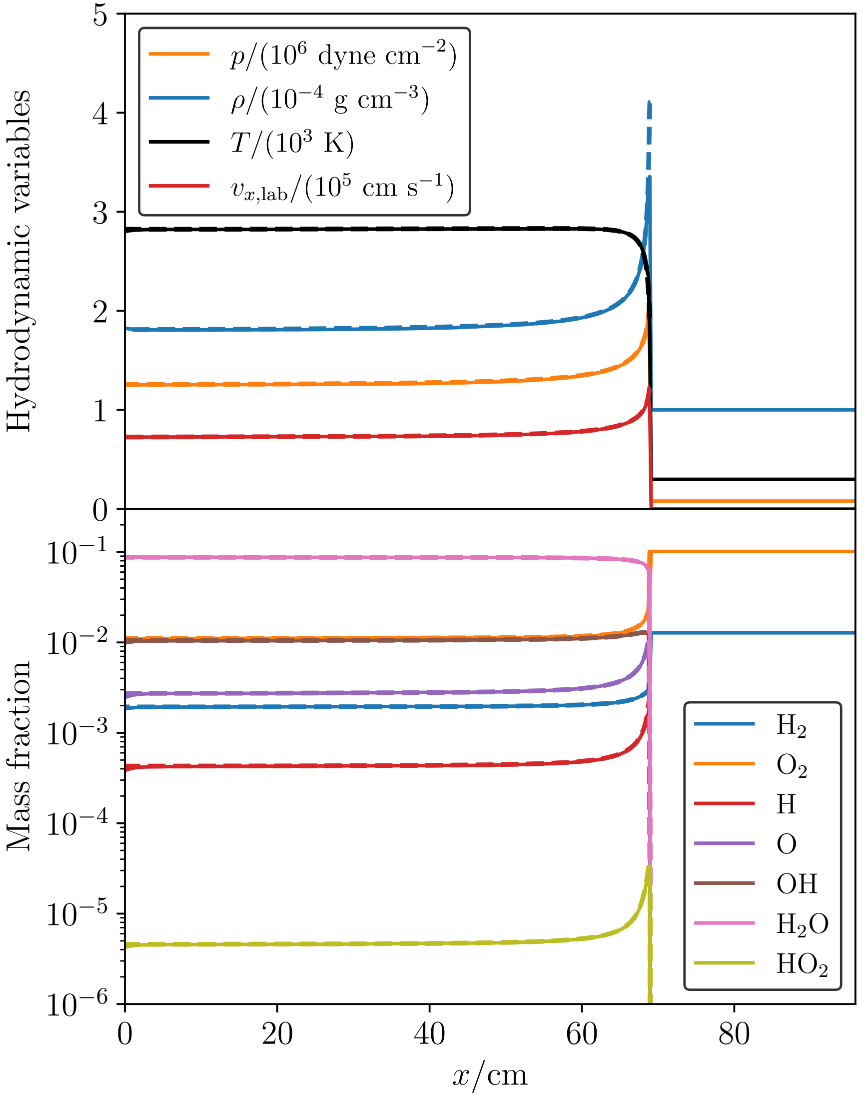
- Test case: Outflows and Bow Shocks
- Single-card: 10^9 cells/s on A100
- Mixed-precision: 10^9 cells/s on 4090
- Also quick on 7900XTX

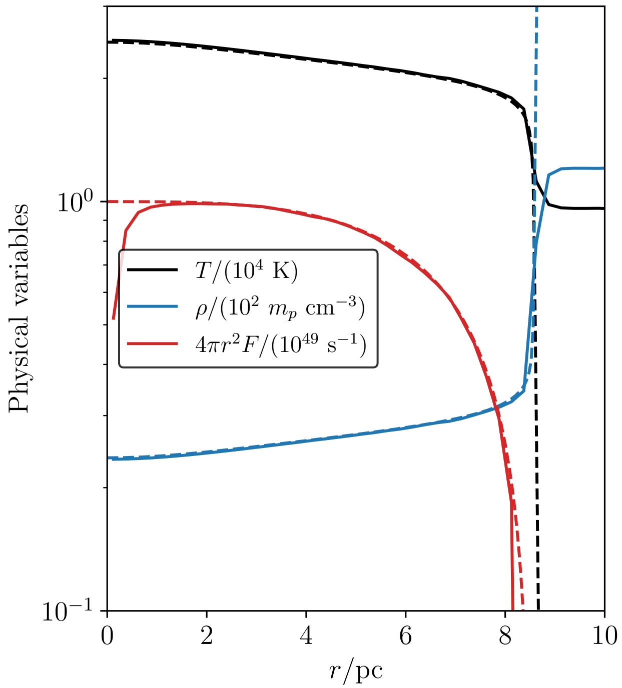


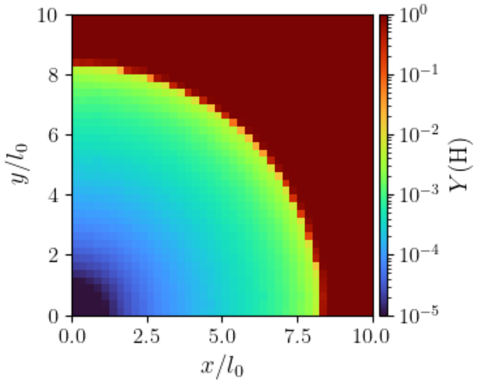


Wang 2025a
ApJS, 227, 63









(Semi-)Analytically Accurate

Wang 2025b
arXiv:2504.04941

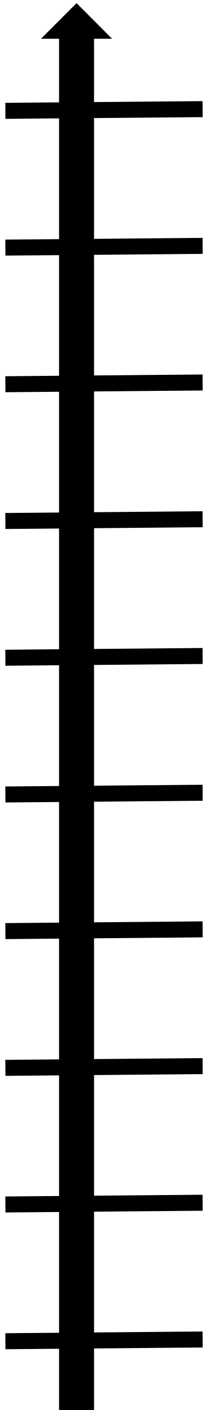
What can we do with Kratos?

There is a Chinese joke:

拿着一把锤子，看谁都是钉子

When your best tool is a hammer,

every job looks like a nail.



10^{26} cm IGM, Cosmology

10^{22} cm CGM, CMZ

10^{18} cm ISM, Mol. Clouds

10^{15} cm PPD Winds

10^{9} cm Planetary Atmospheres

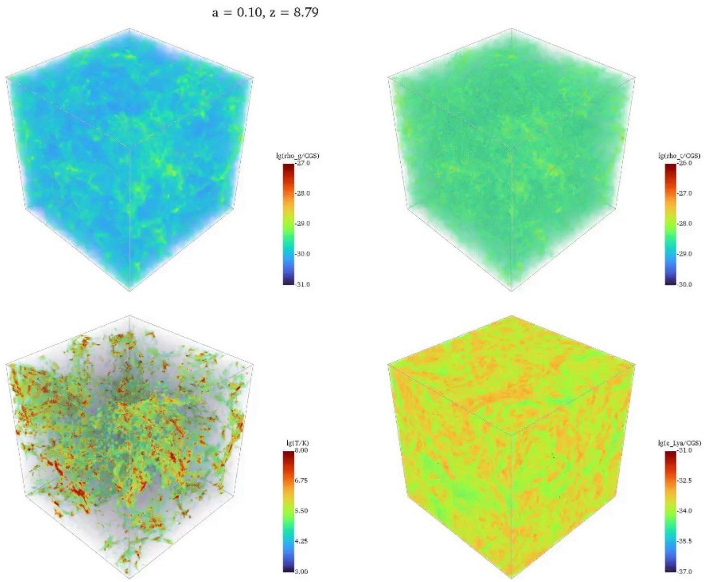
10^{1} cm Jet Engine

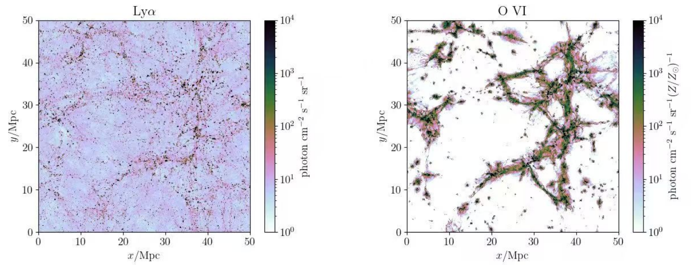
10^{0} cm Laser Plasmas

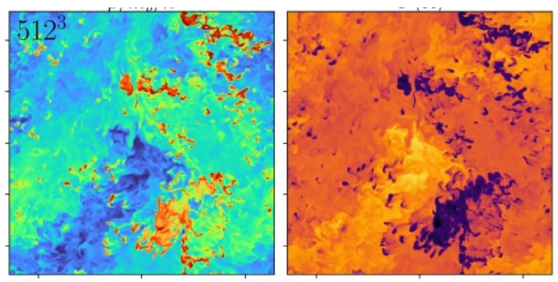
10^{-4} cm PPD Dust Opticals

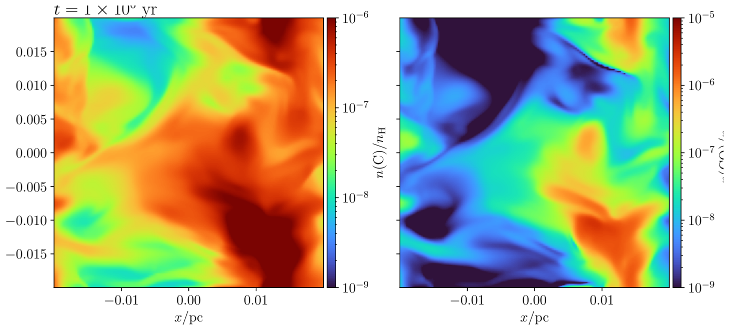
10^{-6} cm Li-ion Battery SEI

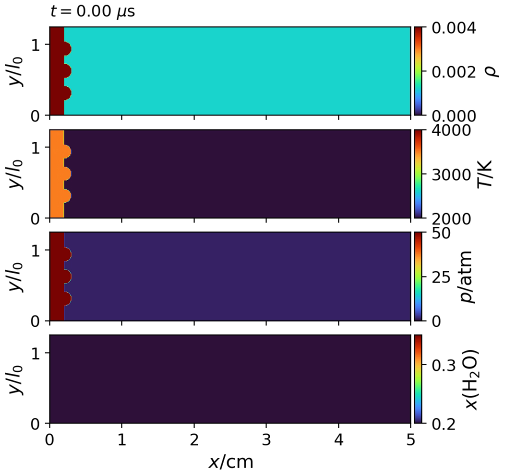
10^{-8} cm Multiphase Astrochem

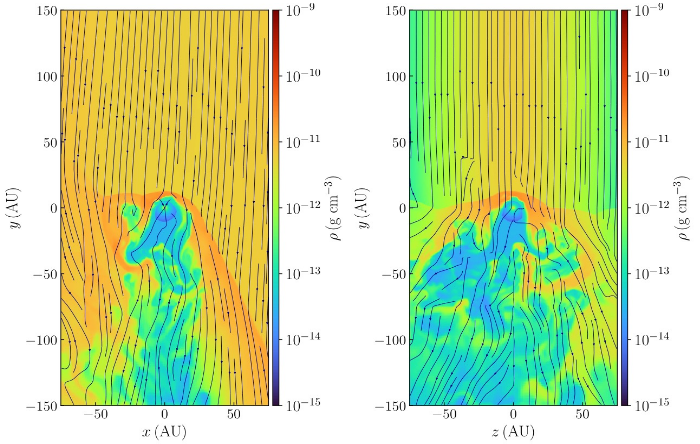


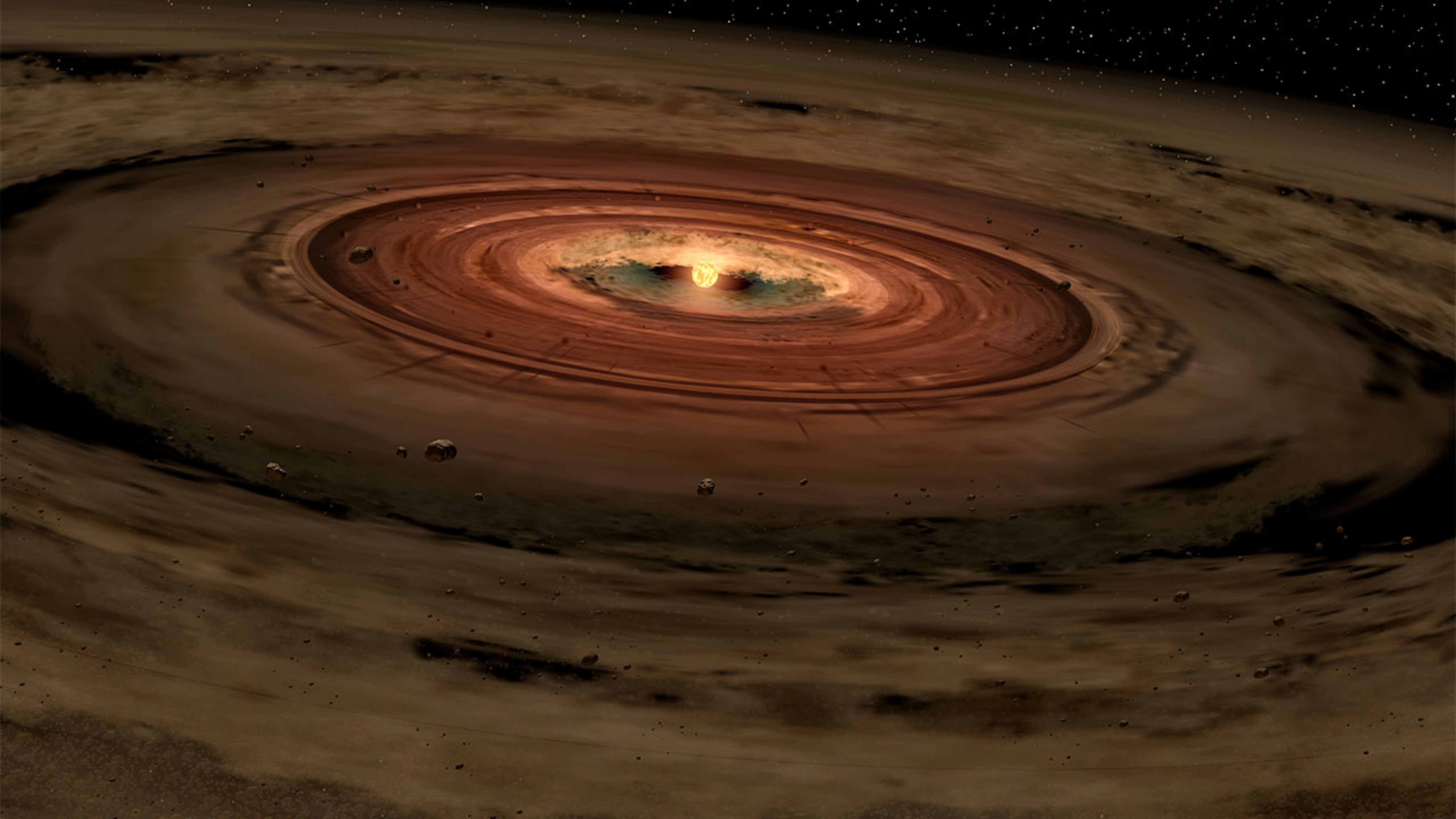


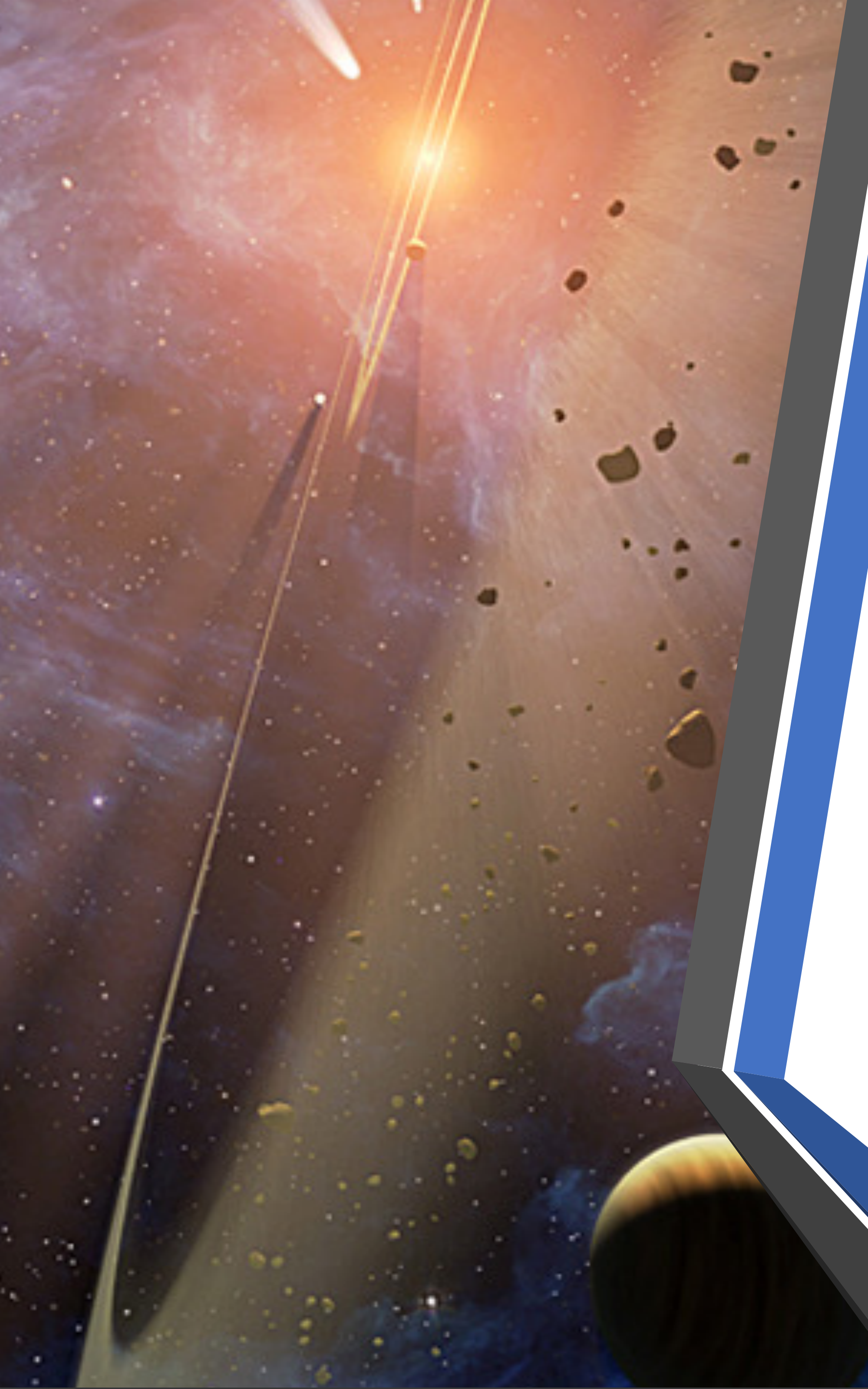






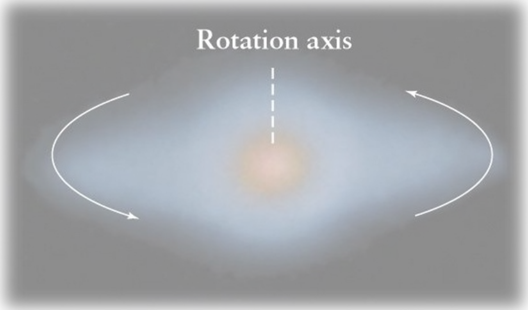






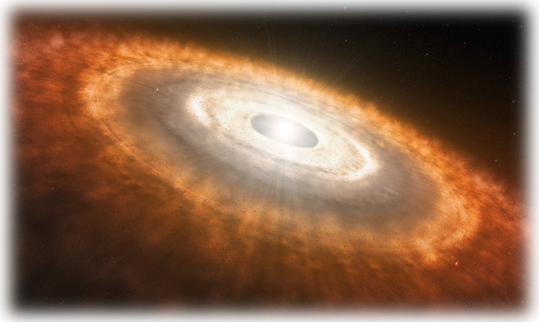
Class 0/1

~ 0.5 Myr (?)



Class 2

$\sim 10^{0-1}$ Myr



Class 3

“Transitio

~ 0.1 Myr (?)

Candidate: Photoevaporation

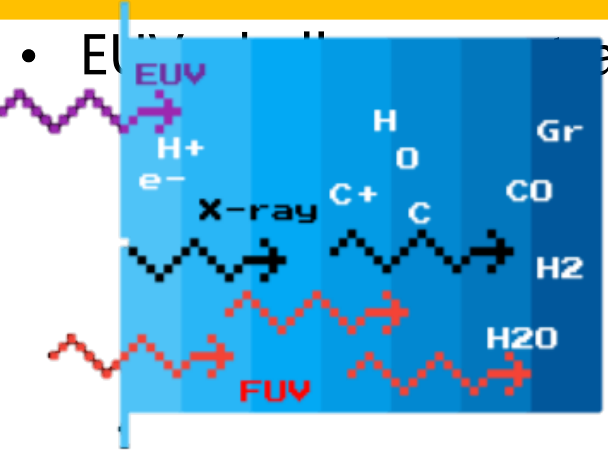
- Photoionization heating:

  $\Delta E = hv - I$

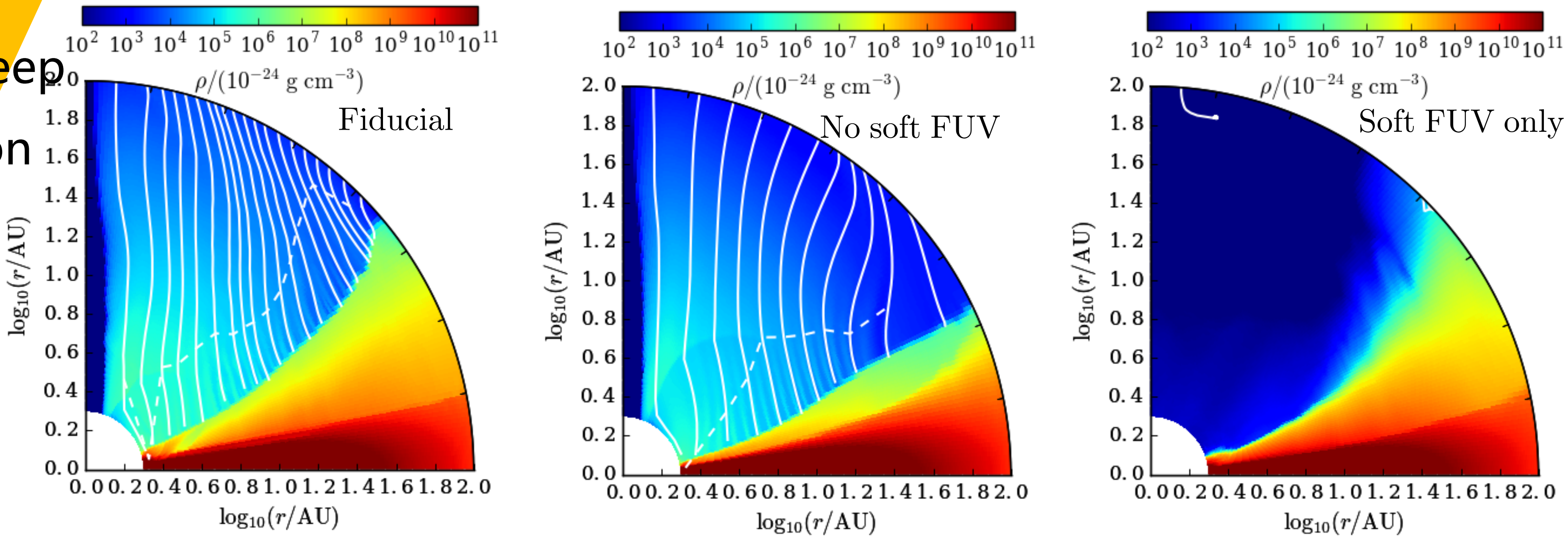
  (per reaction)
- Similar Heating Mechs:
  - Photodissociation
  - Photoelectric
- $\Delta E > |\varphi|$, Gas Likely Escapes
- Important Facts:
  - 1 proton @ 1 AU, $|\varphi| \sim 9.2\ \mathrm{eV}$
  - Energy thermalized quickly
  - NOT driving accretion...

Photoevaporation: Needs EUV!

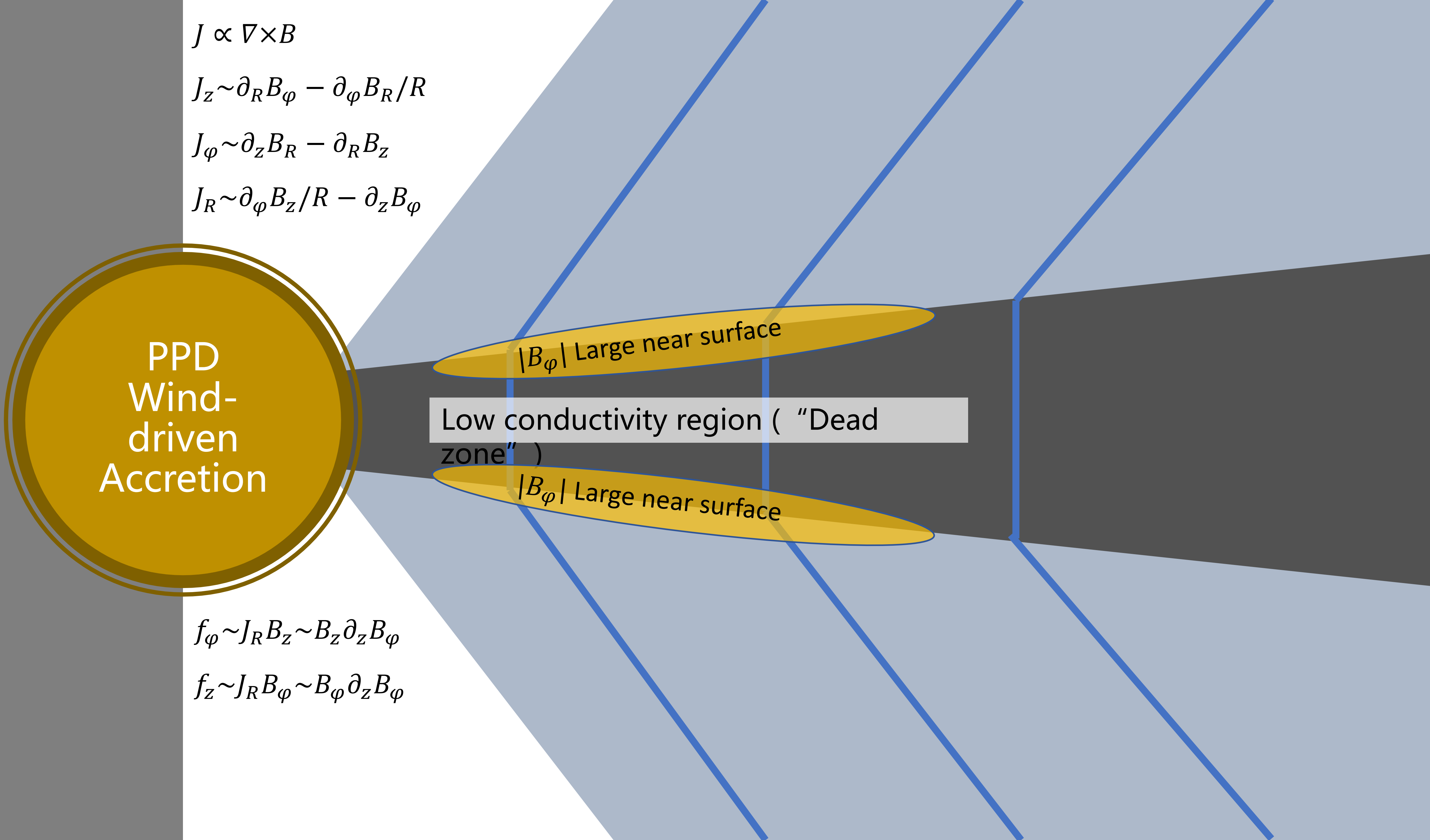
- $\sim 10^{-9}\, M_{\odot}/\mathrm{yr}$ mass loss
- Deep penetrators absorbed in places with too many coolants
- FUV and X-ray photons always penetrate too deep
- EU ation



$$\tau_{\mathrm{dyn}} \lesssim \tau_{\mathrm{chem}}$$



Wang & Goodman 2017
ApJ, 847, 11



$J \propto \nabla \times B$

$J_z \sim \partial_R B_\varphi - \partial_\varphi B_R / R$

$J_\varphi \sim \partial_z B_R - \partial_R B_z$

$J_R \sim \partial_\varphi B_z / R - \partial_z B_\varphi$

PPD
Wind-driven
Accretion

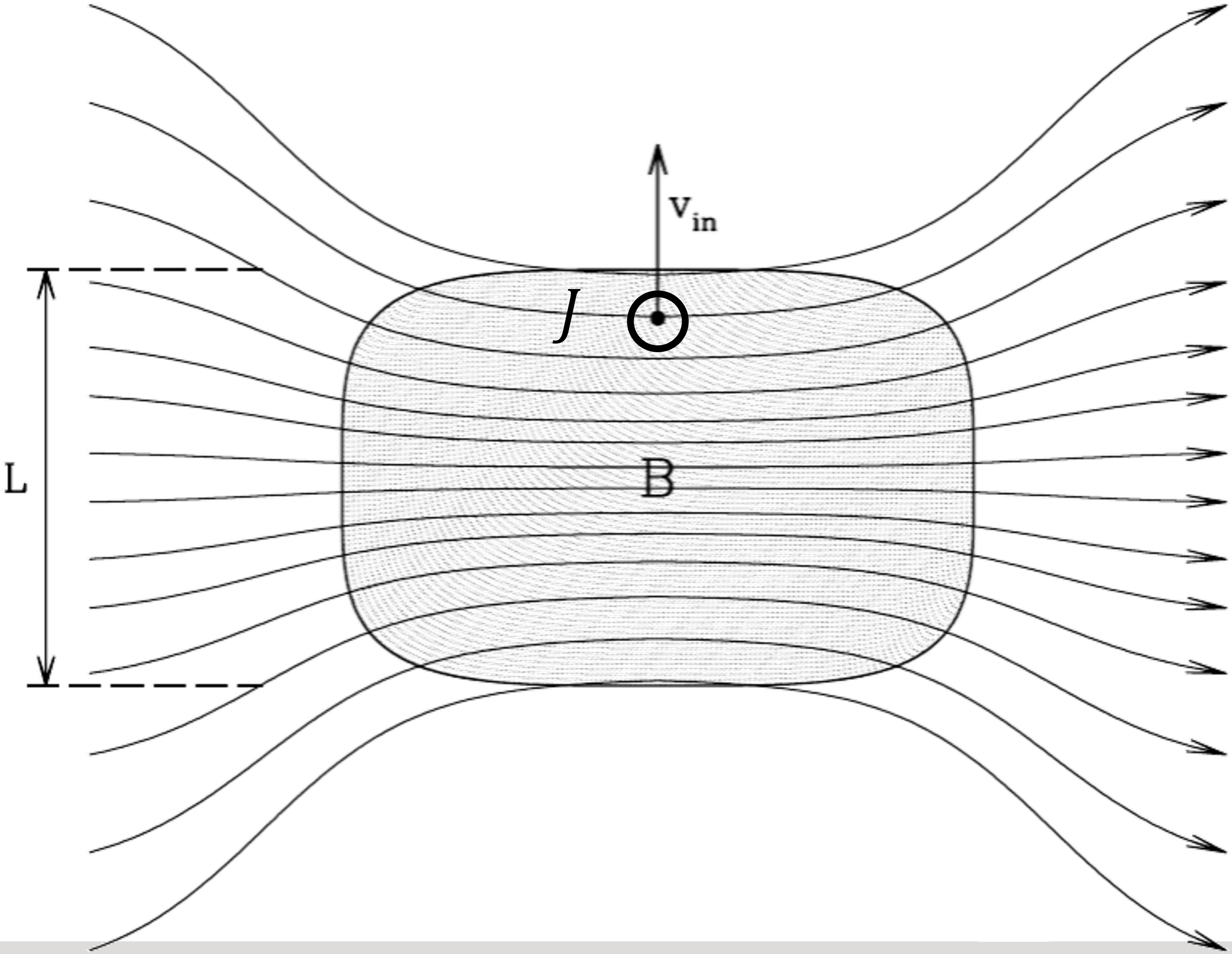
$|B_\varphi|$ Large near surface

Low conductivity region ("Dead zone")

$|B_\varphi|$ Large near surface

$f_\varphi \sim J_R B_z \sim B_z \partial_z B_\varphi$

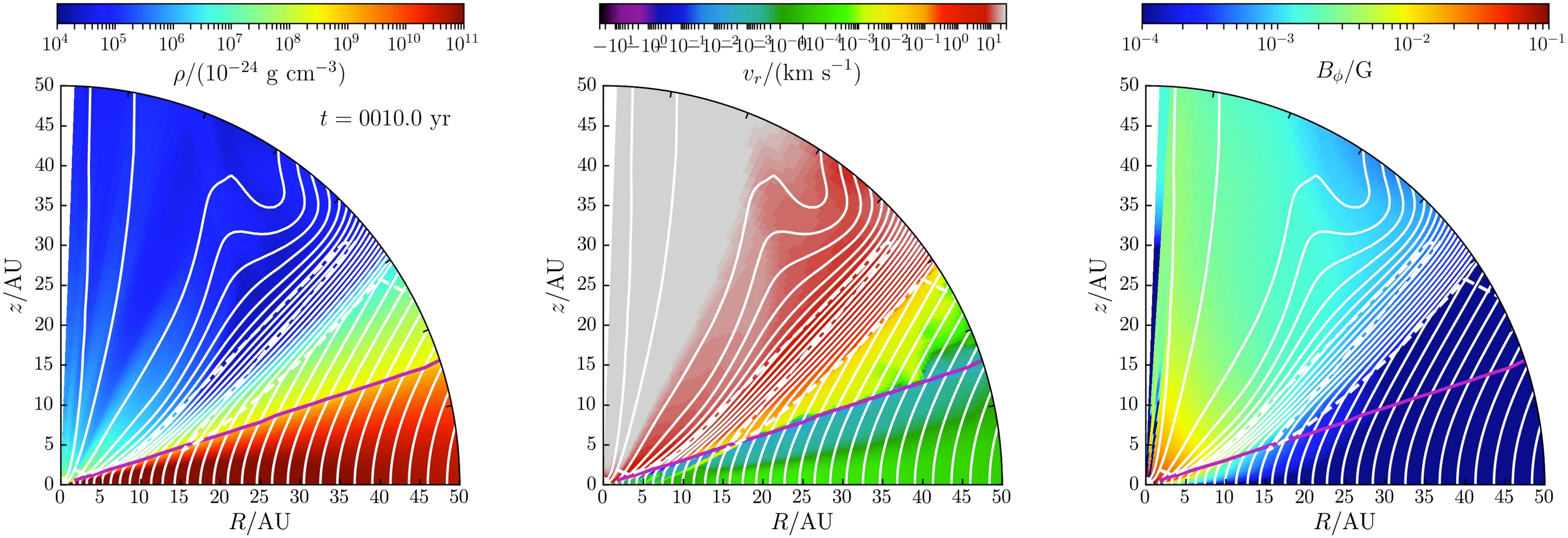
$f_z \sim J_R B_\varphi \sim B_\varphi \partial_z B_\varphi$



- Field lines want to stretch
- Ionized part does not want to move (due to pressure)
- Flux freezing: You two shall fight
- Neutral: No worries, I will help you coordinate
- **Low ionization eases the "formation of structures"**

Ambipolar Diffusion: An Easy Intro

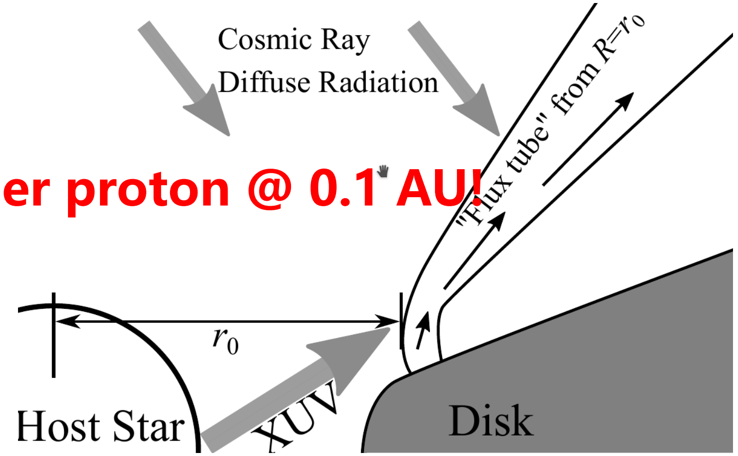
Draine (2011)



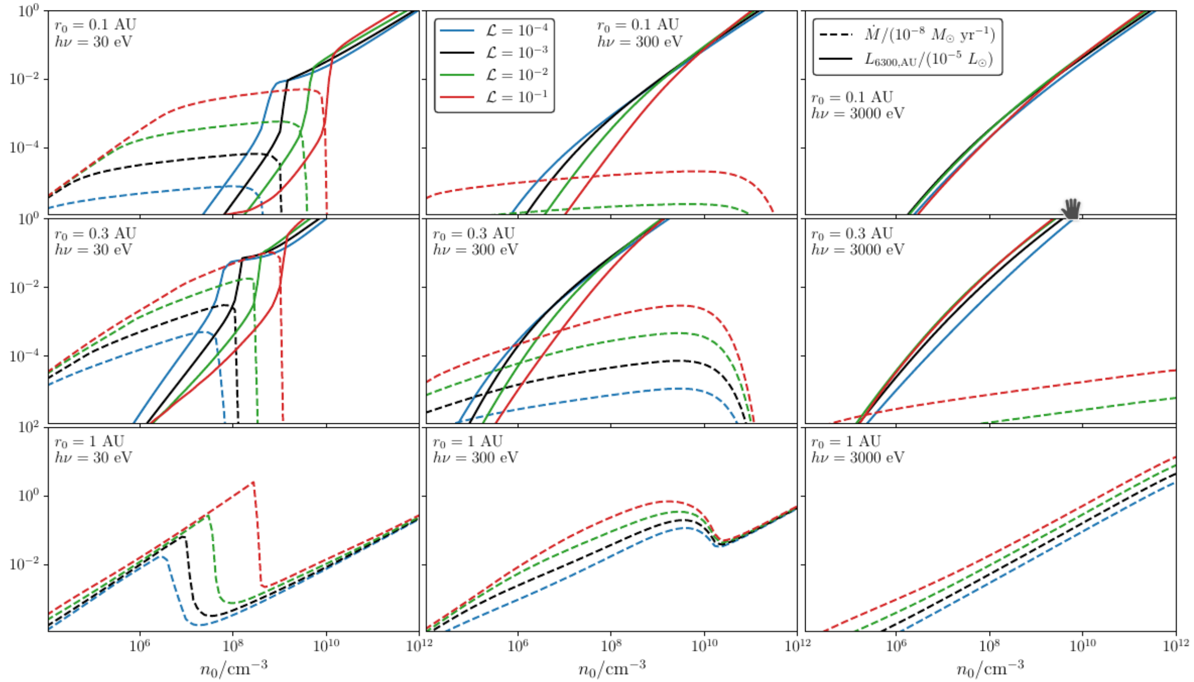
Wind-driven Accretion: Consistent Microphysics

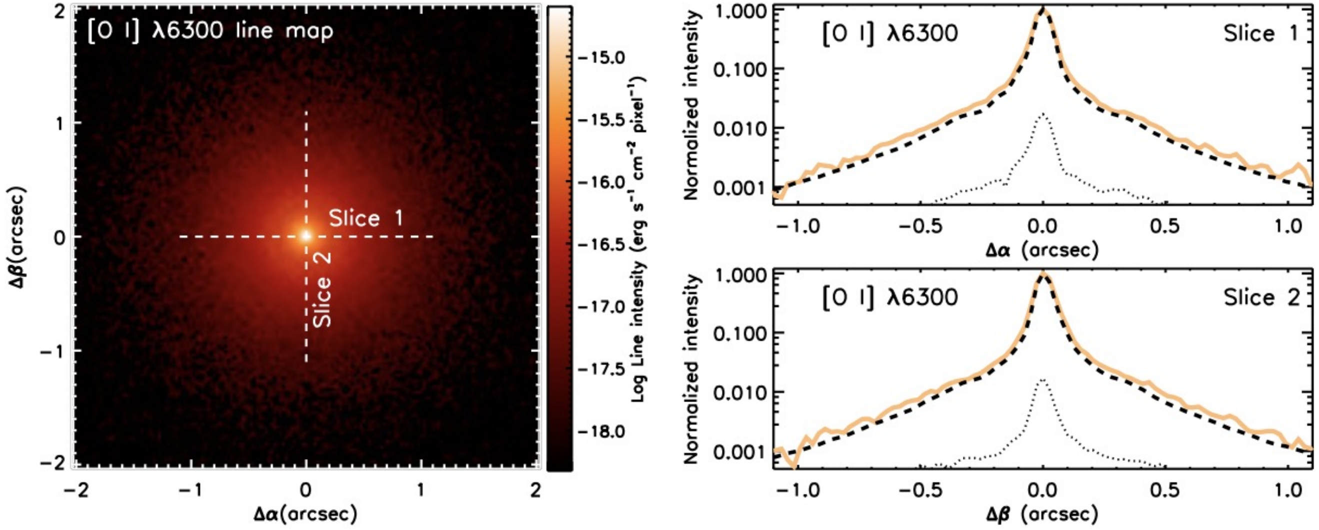
Wang, Bai & Goodman
2019 ApJ, 874, 90

Lin, Wang, Fang, Ahmad & Goodman (arXiv:2401.15419)

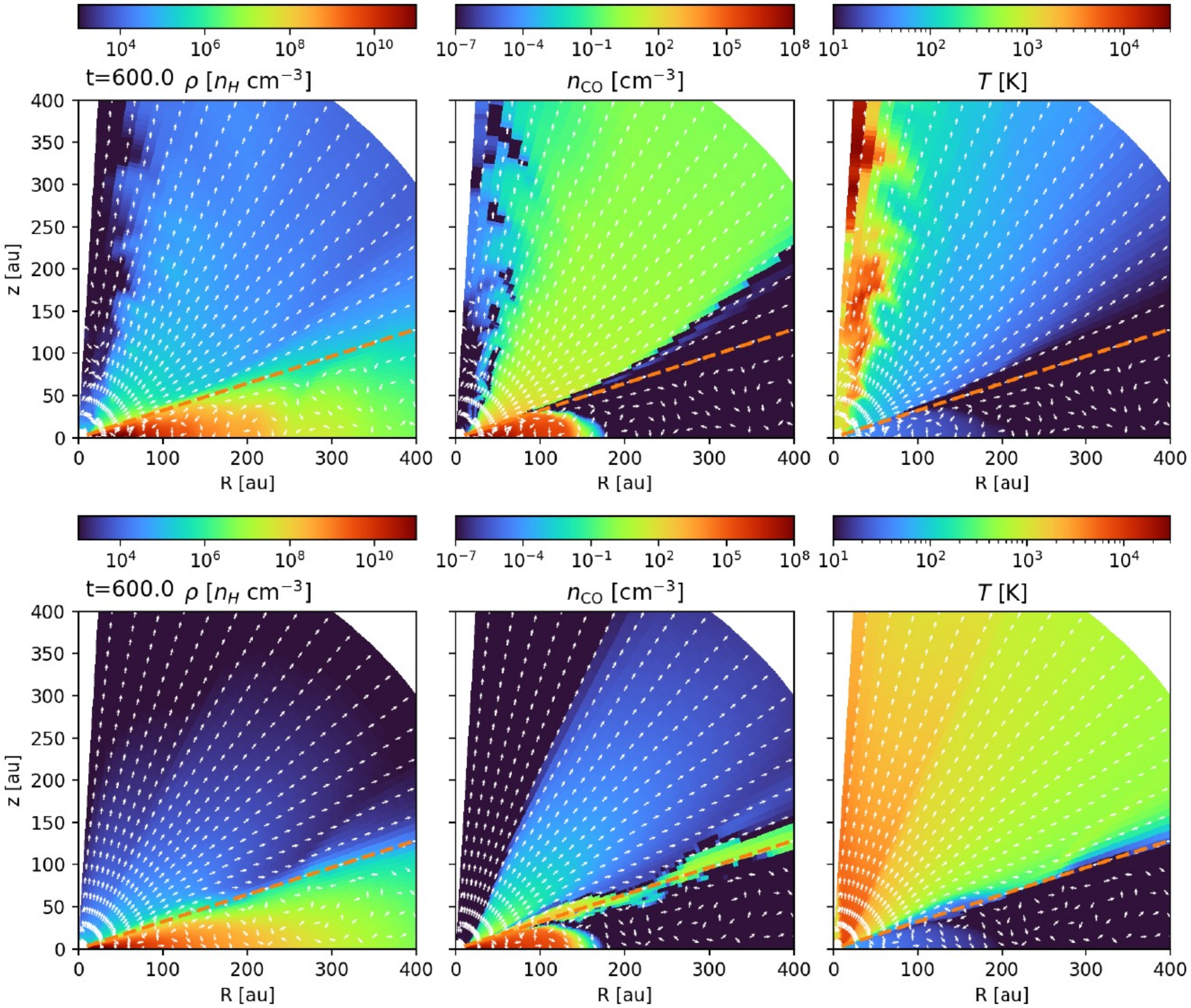


46 eV per proton @ 0.1 AU!





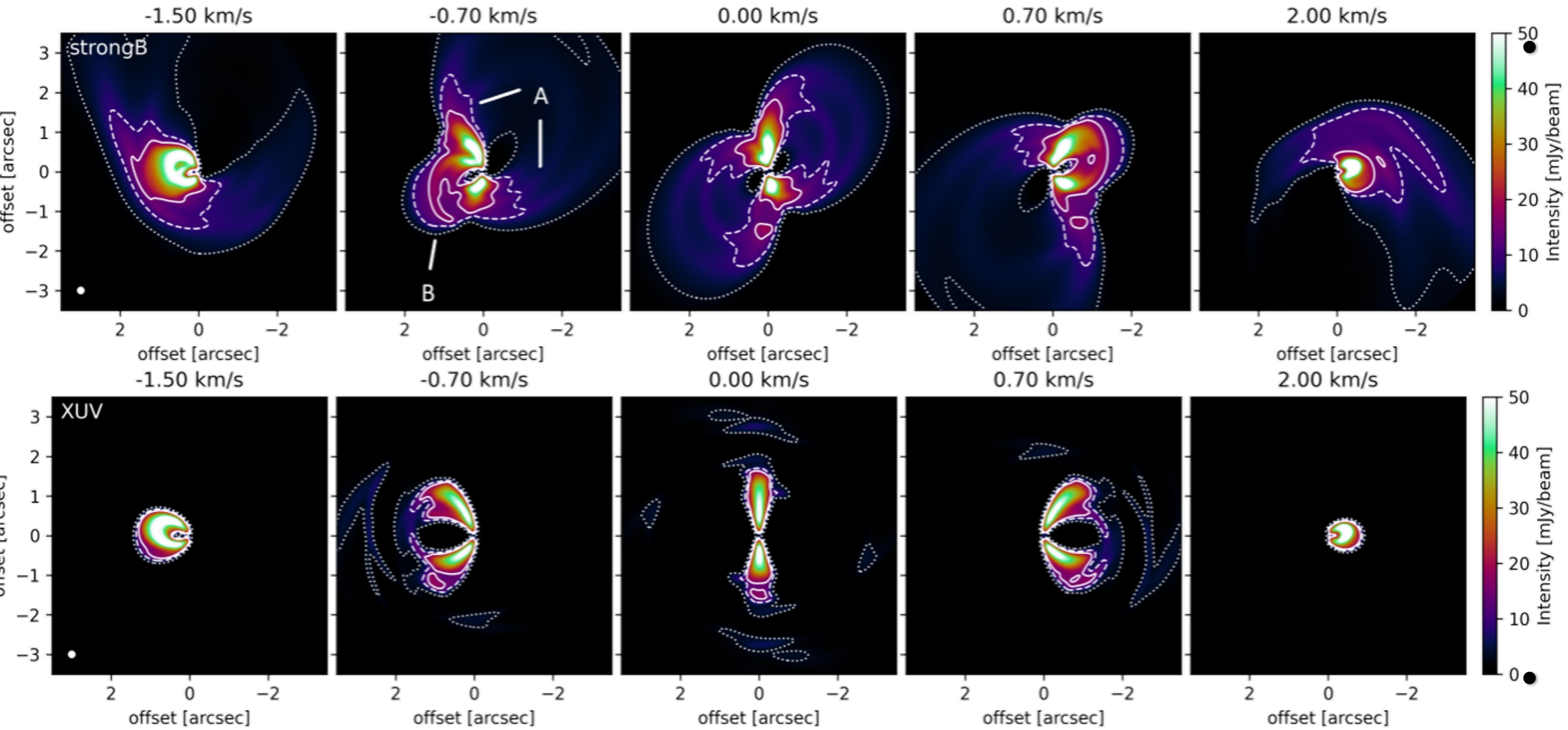
Fang, Wang, Herczeg et al., Nature Astronomy (2023 Aug Cover Paper)



- CO “Last Emission Surface”
  - MHD: Higher, broader, brighter, dual-components (CO survives due to shielding)
  - Photoevaporation: Lower, narrower, fainter (dissociated at evaporation)

What about Channel Maps of Molecules?

Hu, Zhu,
Bae & Wang,
2025 ApJ, 986, 161



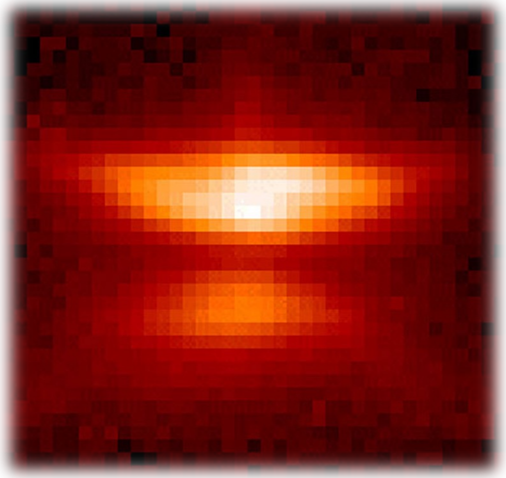
- CO “Last Emission Surface”
  - MHD: Higher, broader, brighter, dual-components
    (CO survives due to shielding)
  - Photoevaporation:
    Lower, narrower, fainter
    (dissociated at evaporation)
- Channel Maps:
  Possible to Tell the Difference!

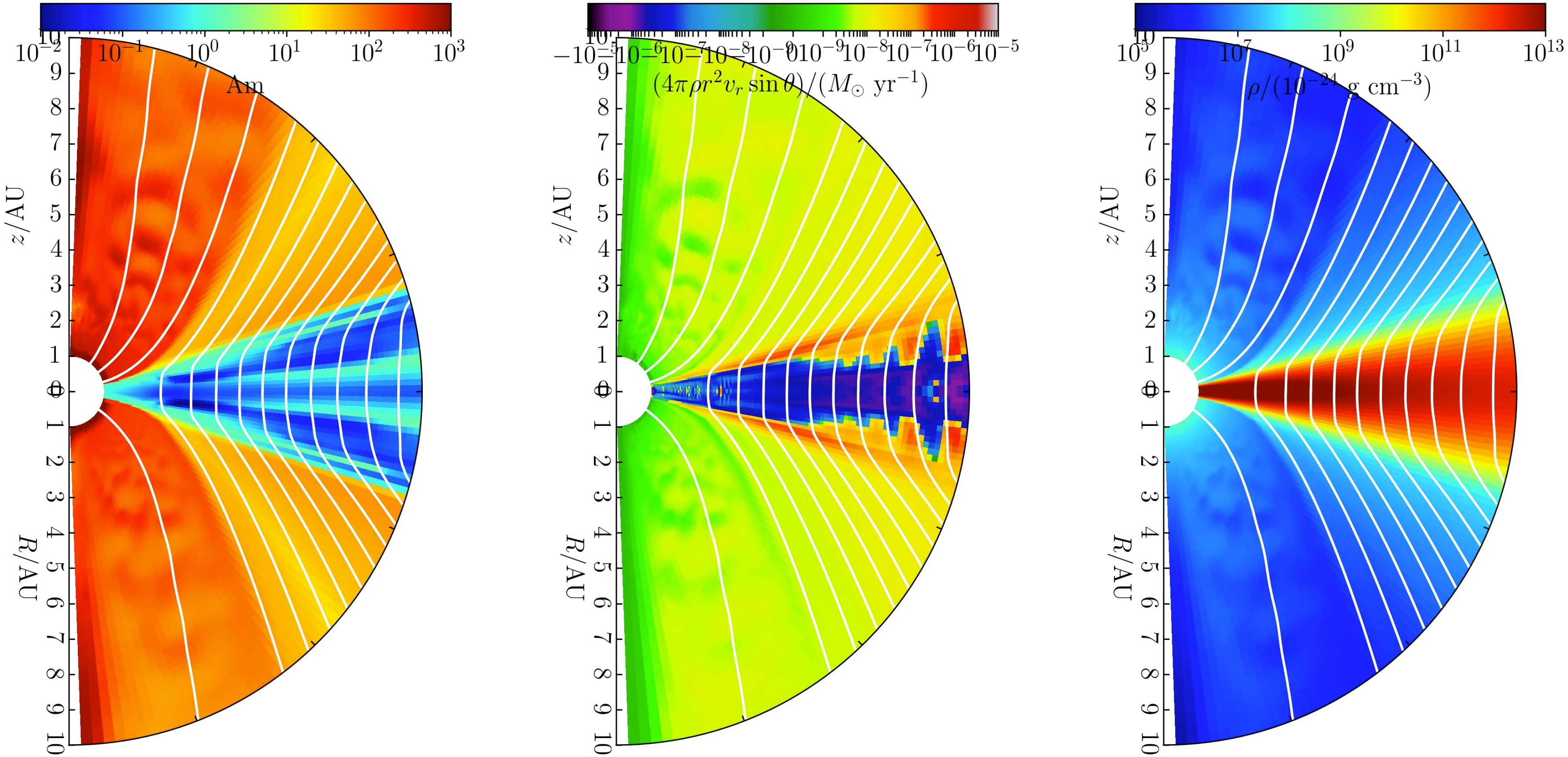
What about Channel Maps of Molecules?

Hu, Zhu,
Bae & Wang,
2025 ApJ, 986, 161

“Spontaneous symmetry breaking”

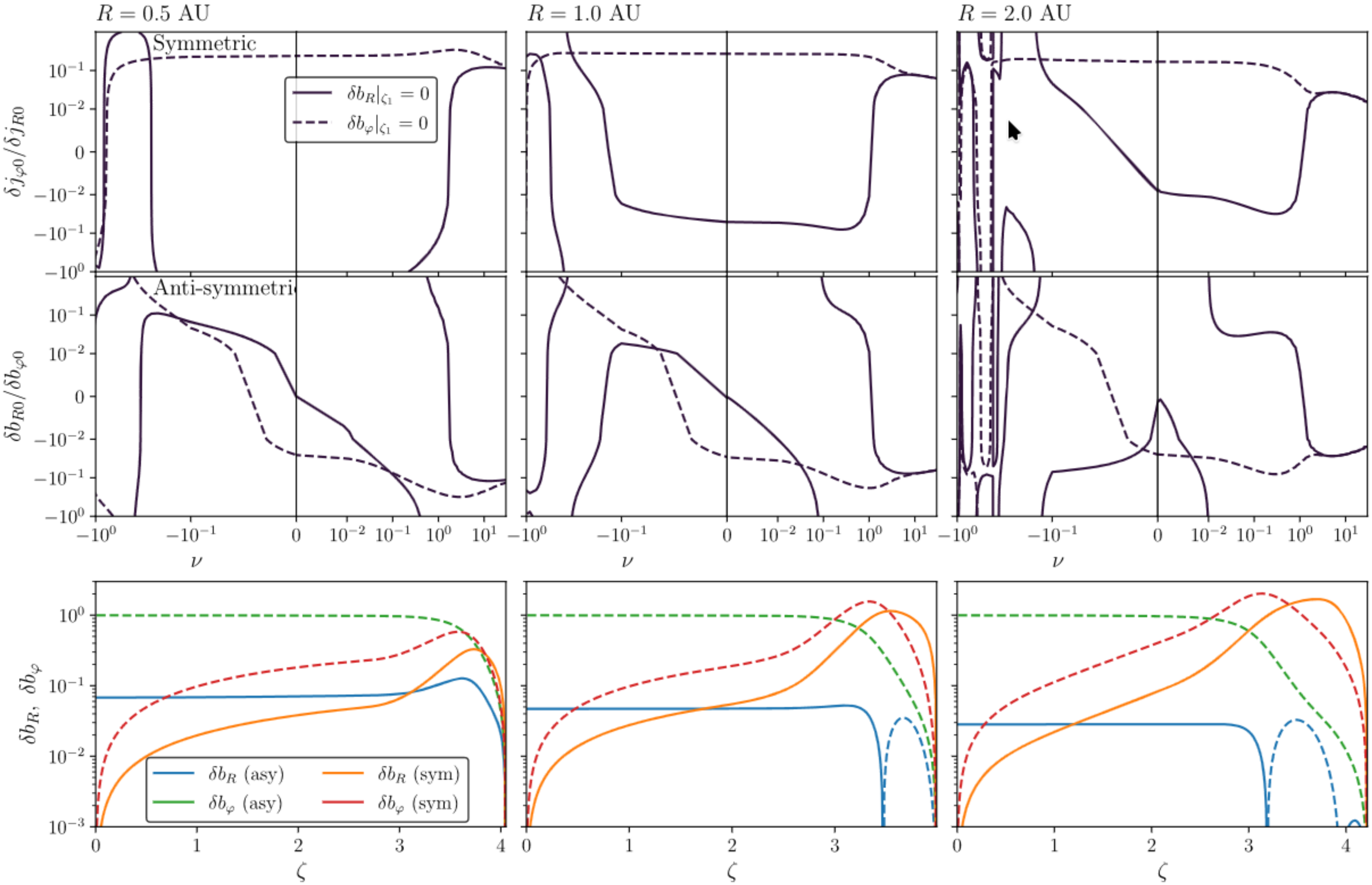
HH30



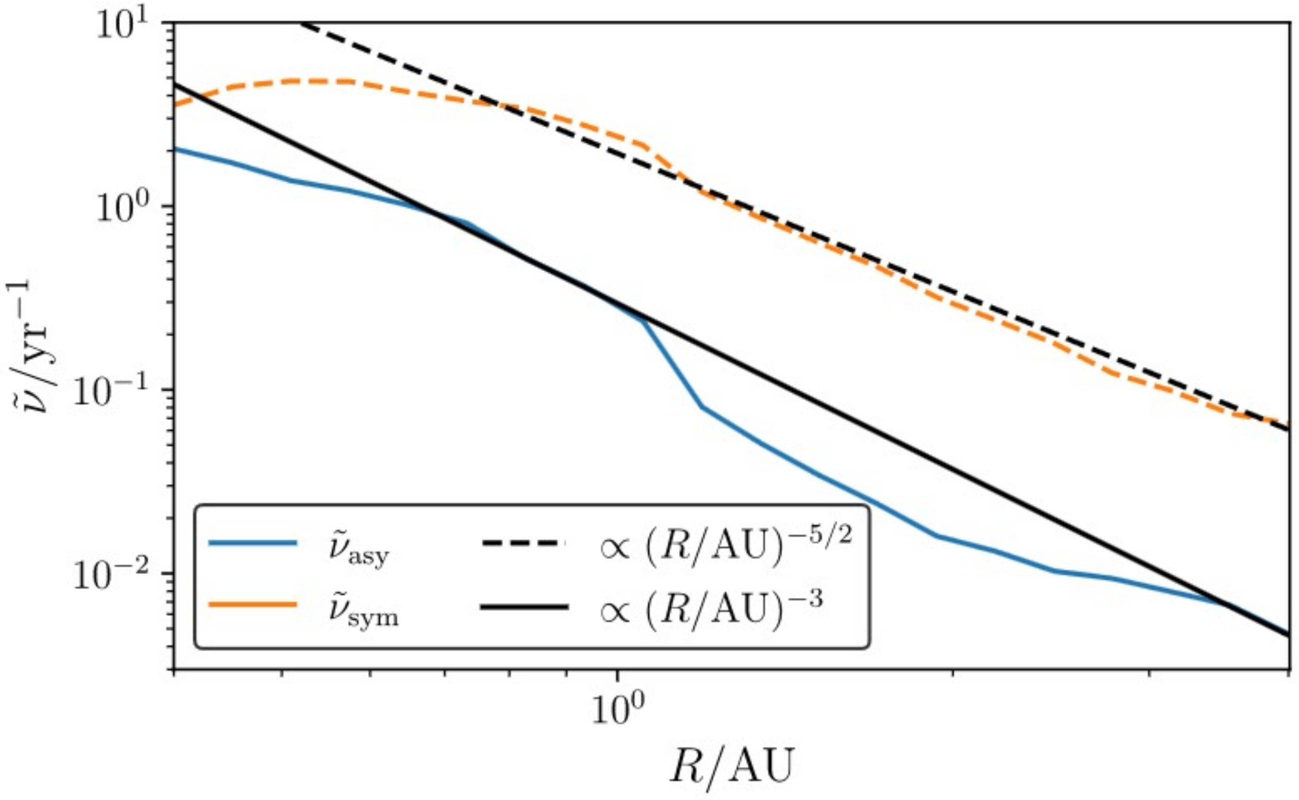


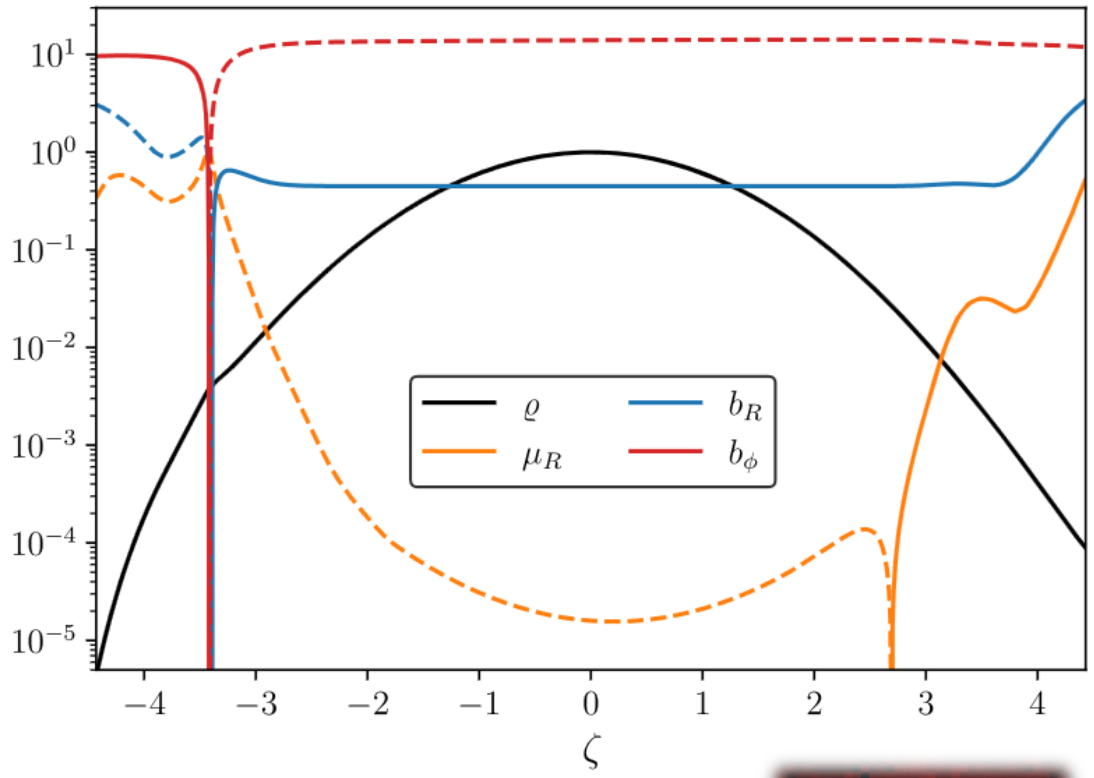
Disk Asymmetric Wind-driven Accretion

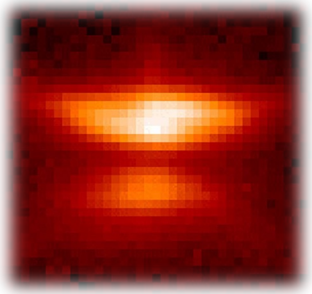
Wang et al., 2024 ApJ, 972, 142



Wang et al., 2024 ApJ, 972, 142





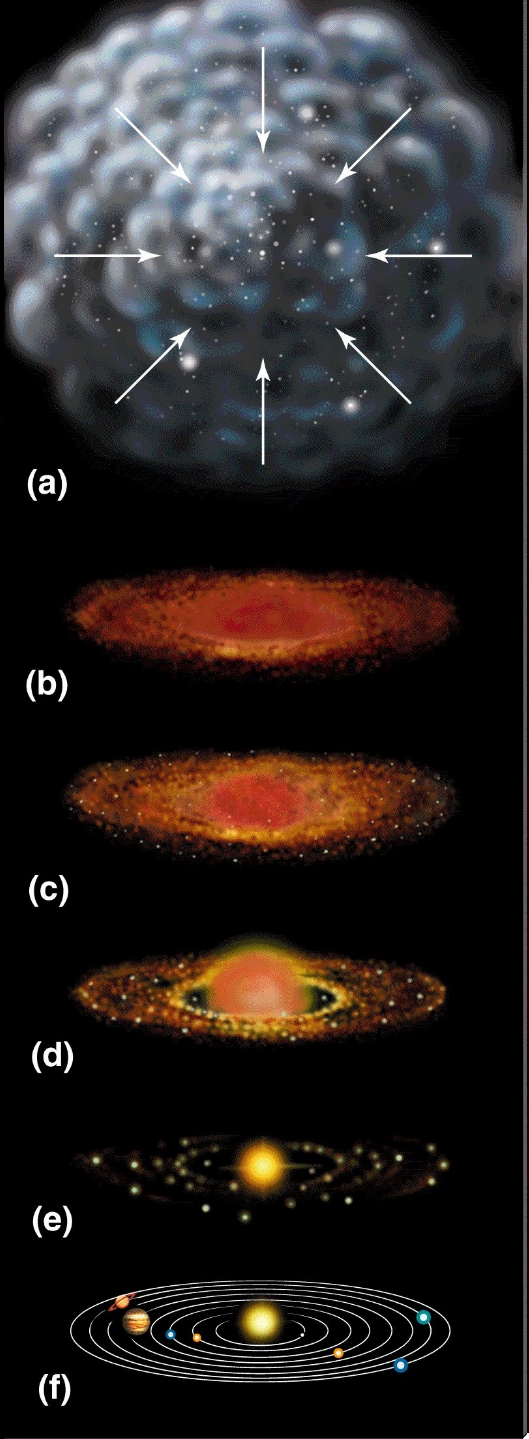


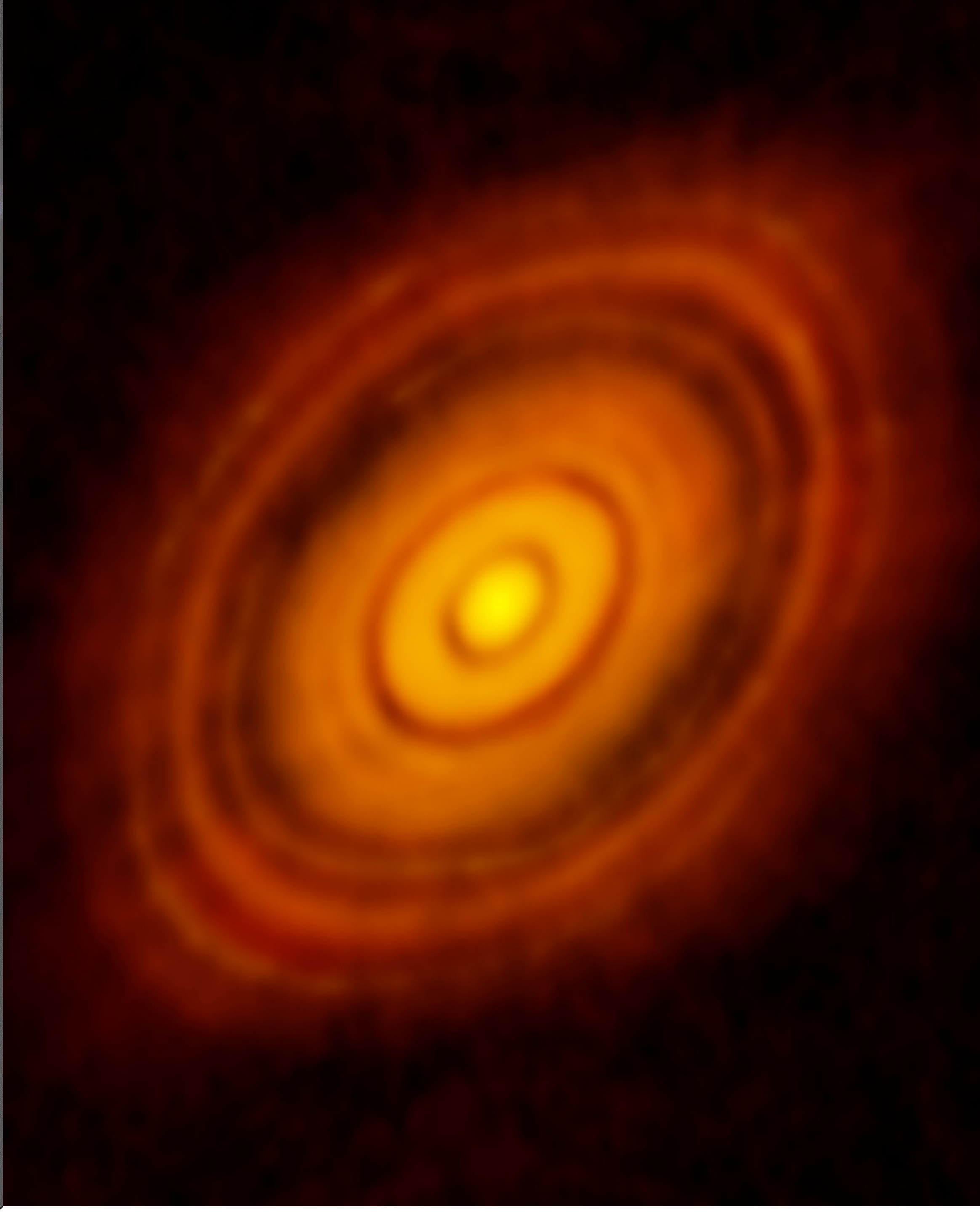
HH30

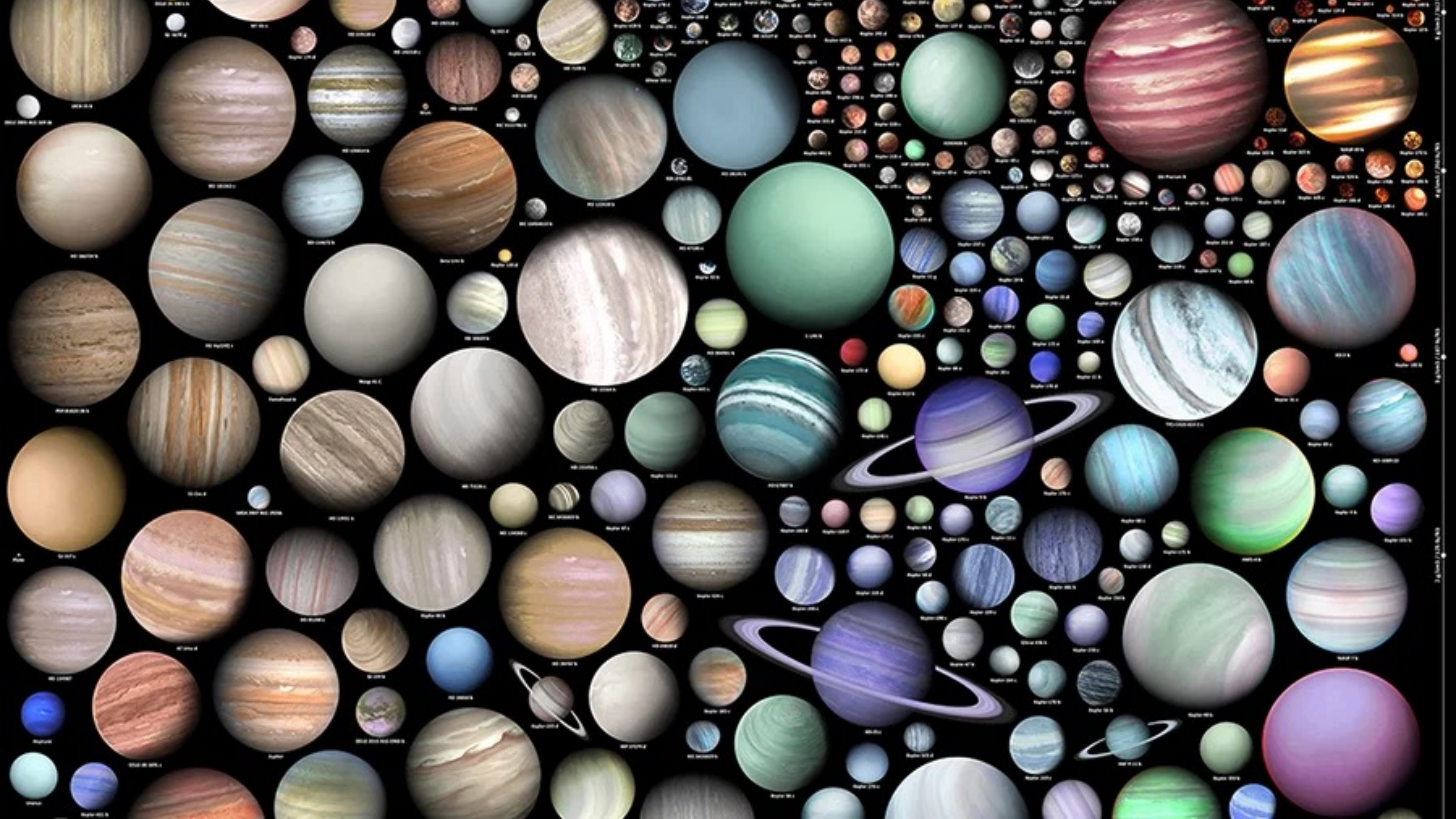
Disk Asymmetric Wind-driven Accretion

Wang et al.,
2024 ApJ, 972, 142

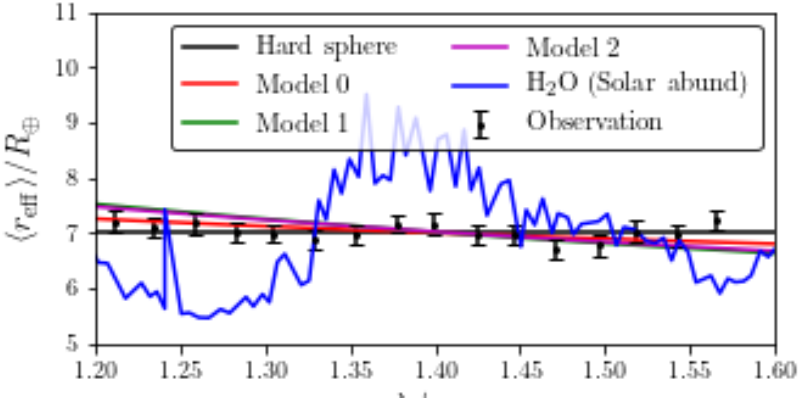

WE ARE
MADE OF
STAR
STUFF
-CARL SAGAN


(a)
(b)
(c)
(d)
(e)
(f)



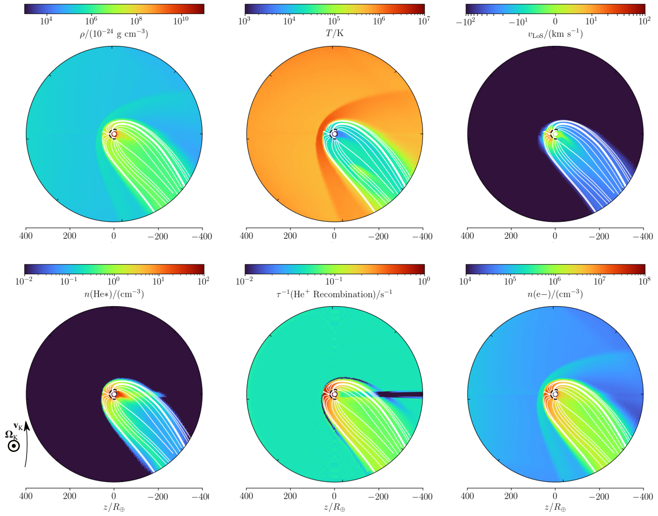


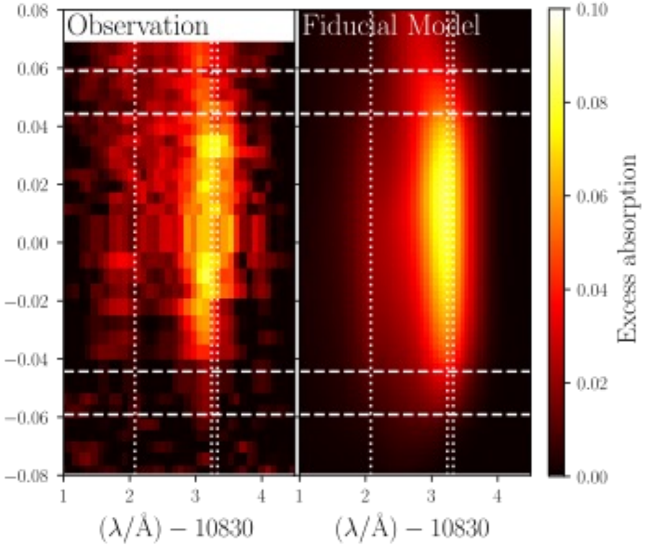
“Super-Puff”, Wang & Dai, ApJL (2019 March Cover Paper)

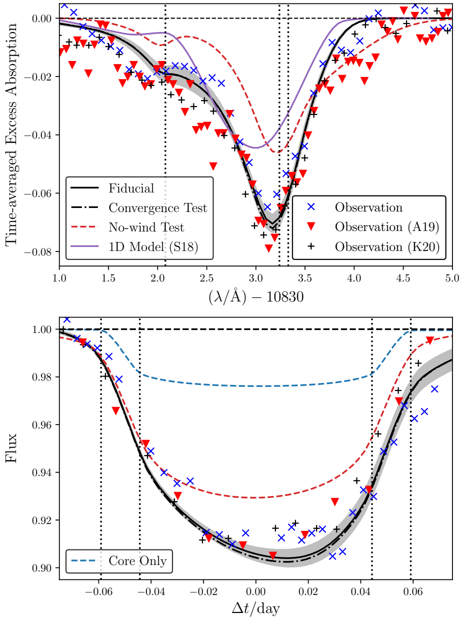


10^{15} cm PPD Winds

10^9 cm Planetary Atmospheres







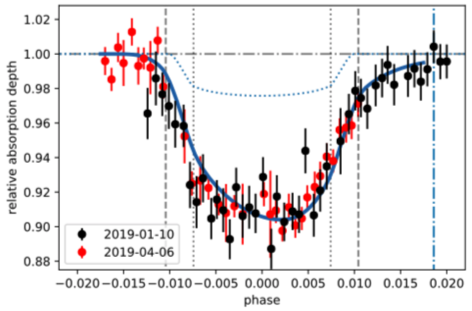
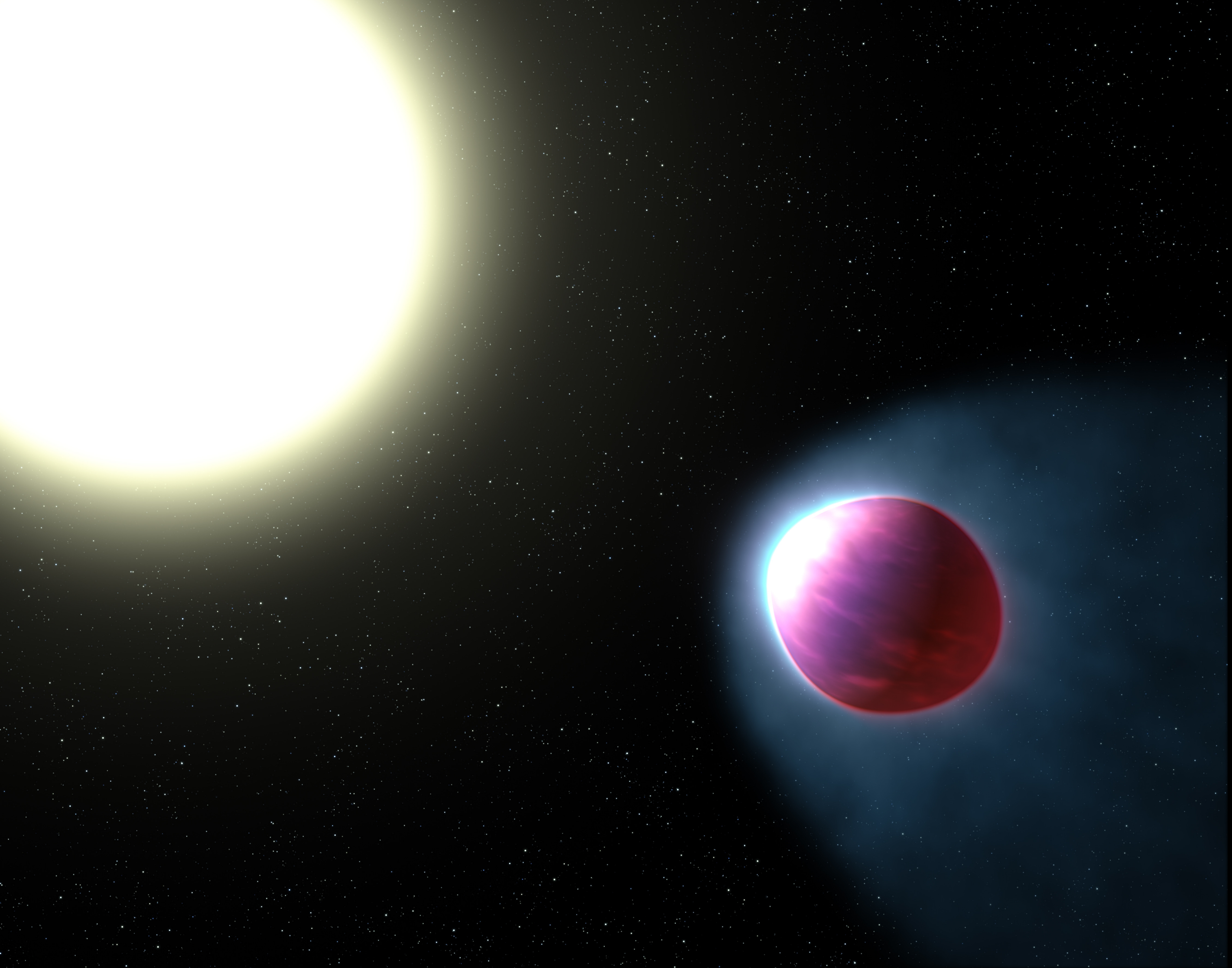


Figure 4. Top panel: Light curves showing excess helium absorption integrated over wavelengths between 1082.983 nm and 1083.058 nm. The gray(red) area shows phases used for the construction of the out-of-transit spectrum for the January(April) night. Bottom panel: same as top panel, but both light curves are added to the white-light curve from Spake et al. (2018) (dotted blue curve), and then normalized so that the transit depths match. Solid blue curve is the light curve based on the fiducial hydrodynamic simulation from Wang & Dai (2020). Dash-dotted vertical line indcates the end of the post-transit absorption.

Stellar-Winded Planet Evap for WASP-107b, Wang & Dai, ApJ (2021a,b)

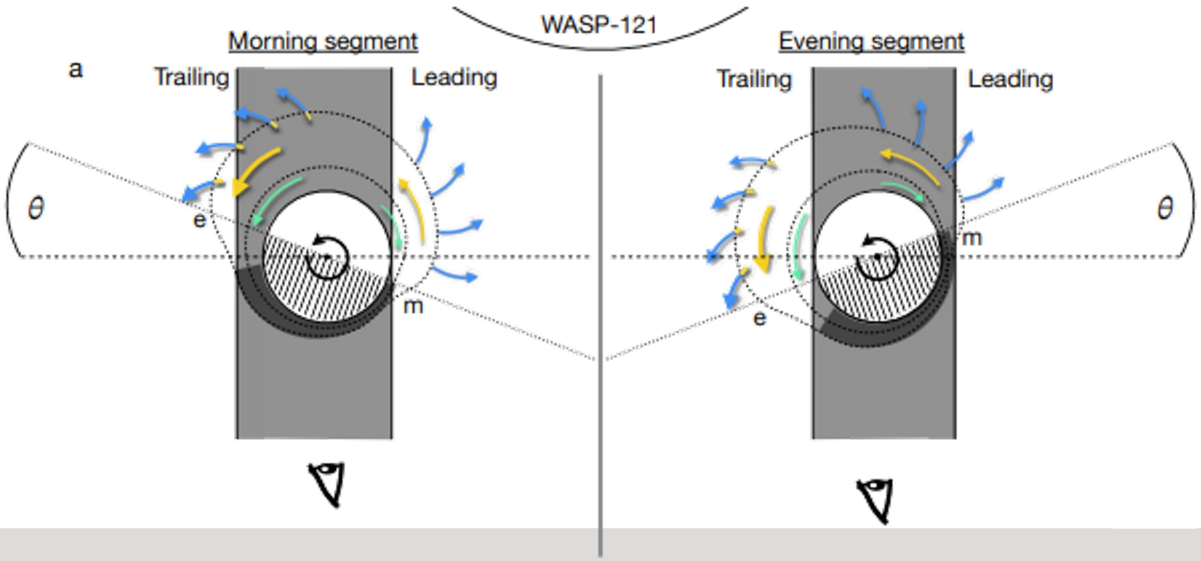


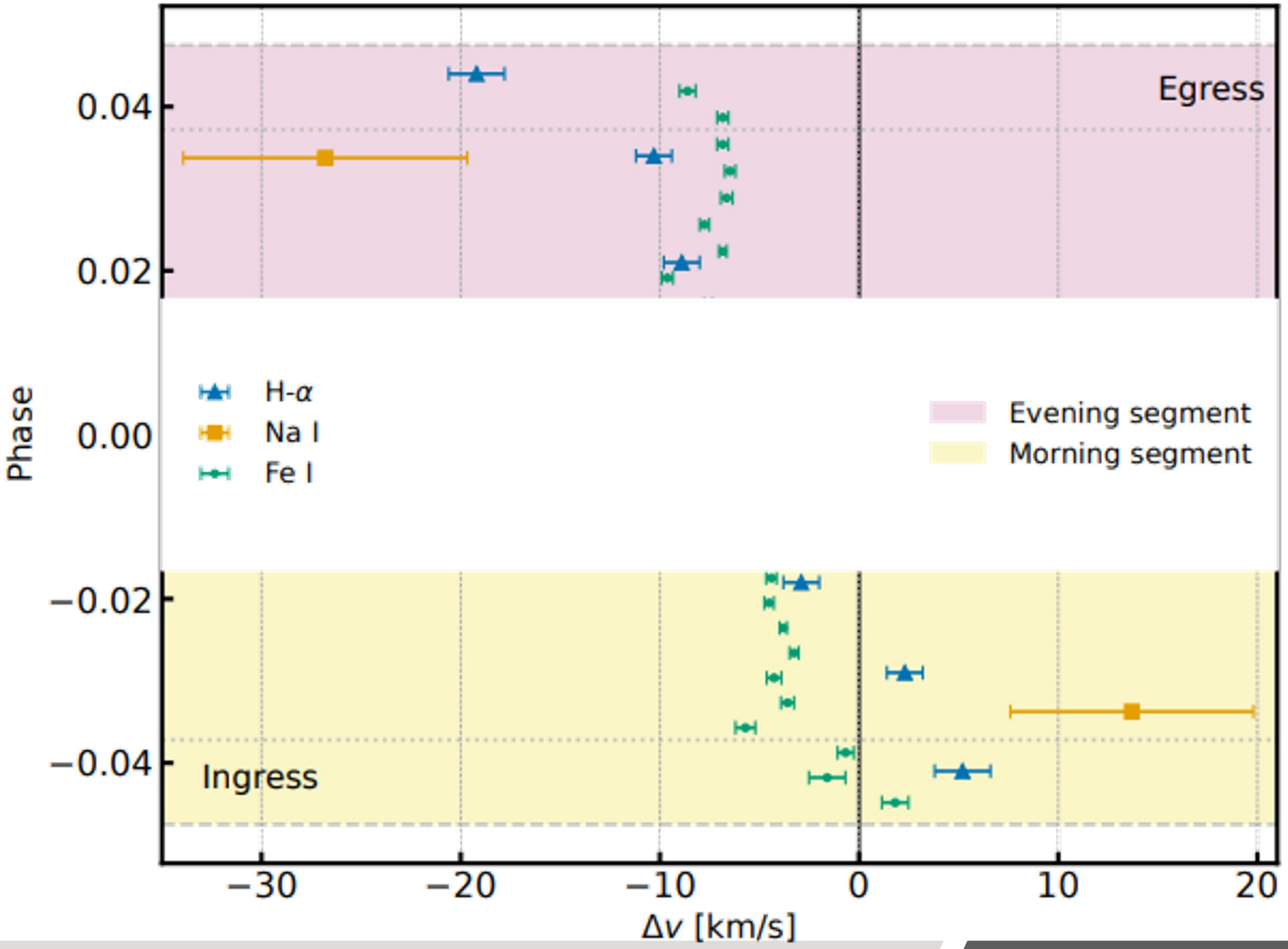
- Ultra-hot Jupiter:
  - Very close to star
  - $T_{\mathrm{eq}} > 2200\ \mathrm{K}$
  - Tidally locked
- Example: WASP-121b
  - $a = 0.026\ \mathrm{AU}$
  - $T_{\mathrm{eq}} = 2700\ \mathrm{K}$
  - $R = 1.753\ R_{\mathrm{J}}$
  - $M = 1.157\ M_{\mathrm{J}}$
  - Special note:

    $R_{\mathrm{Hill}} \approx 3\ R_{\mathrm{J}}$

Conventionally, GCM for ATM

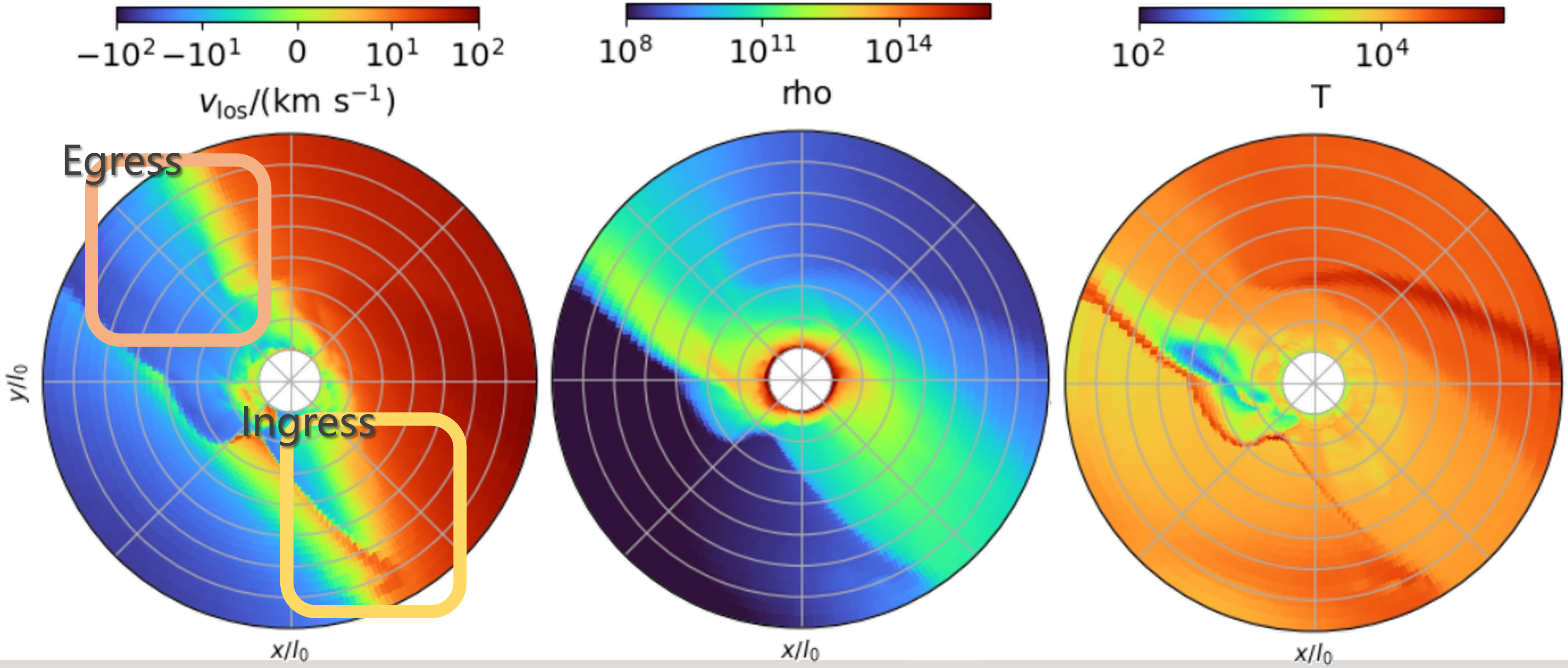
- GCM: General Circulation Model
- Well-developed,
  well-defined for planetary atmospheres
- Wait, for a tidally-locked ultra-hot...
- Day-night circulation beneath rotation?!

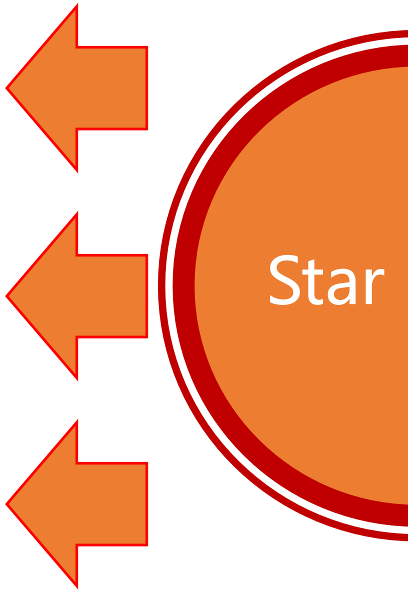




Seidel et al. (2025)
Nature 639, 902

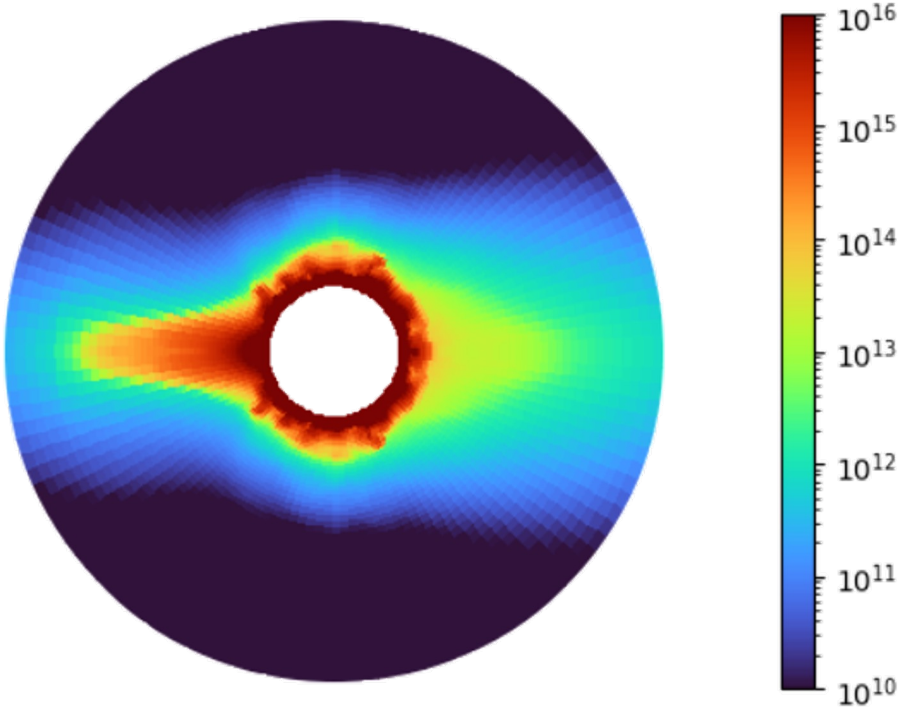
- Simulations with consistent thermochemistry conducted in 3D with **Kratos**
- 31 chemical species + internal energy + radiation (ray tracing, $7\ \mathrm{eV}$ to $3\ \mathrm{keV}$)
- Orbital motion and stellar gravity necessary (Covering $R < 160\ R_{\mathrm{earth}}$)

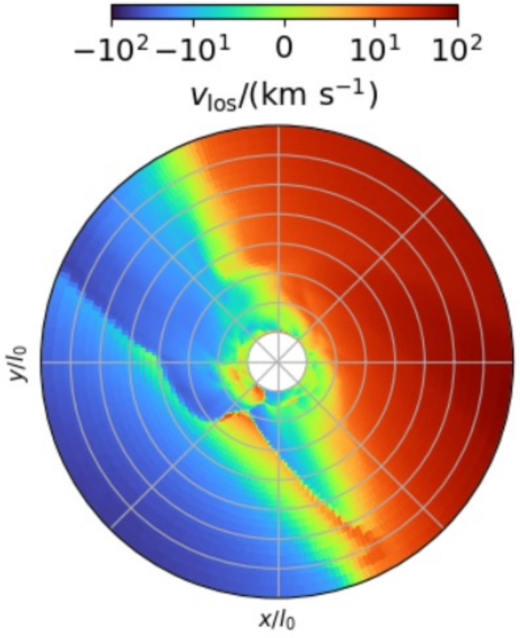


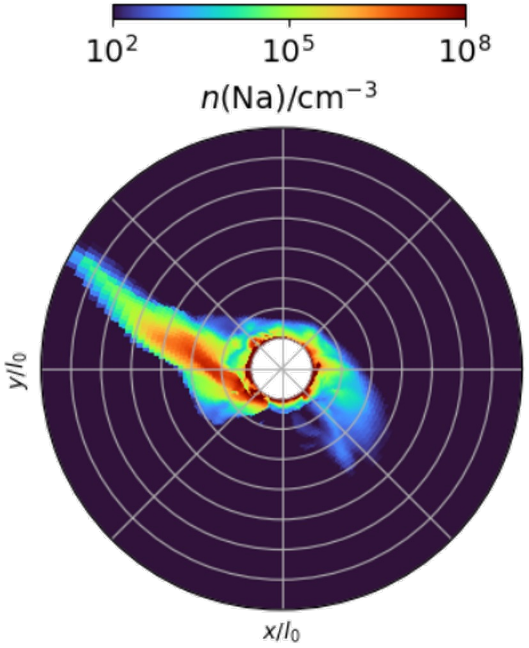


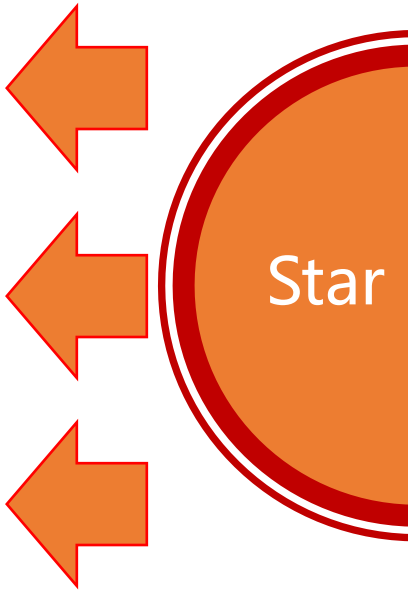
Consistent 3D Simulations Necessary…

- $I(\mathrm{Na}) = 5.14\ \mathrm{eV}$, but less susceptible to X-ray





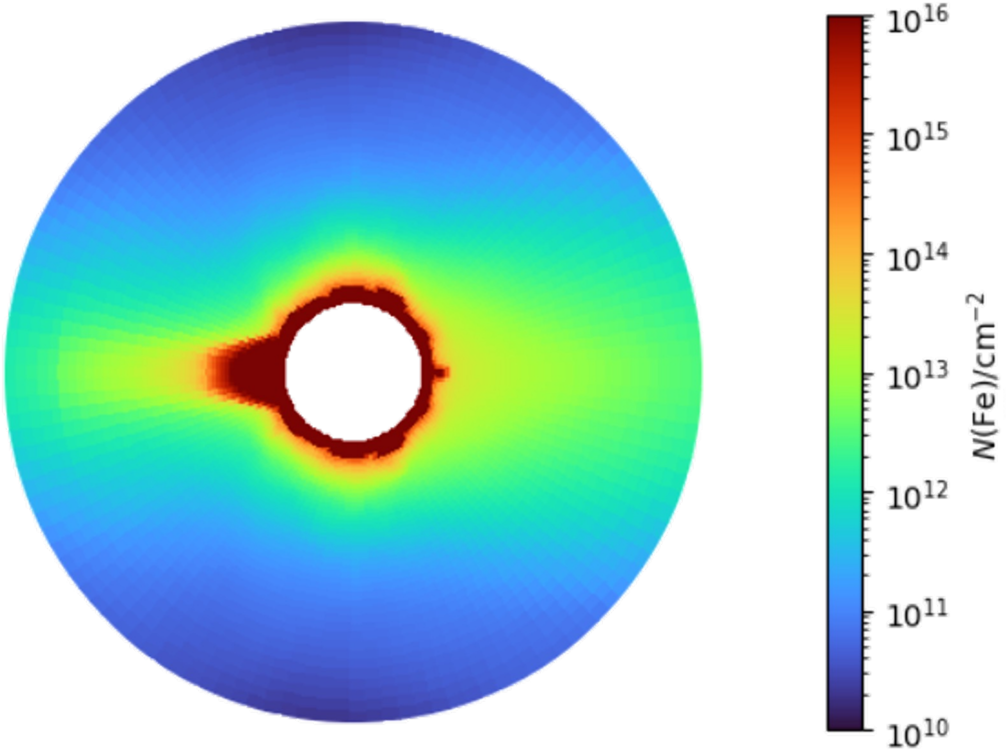


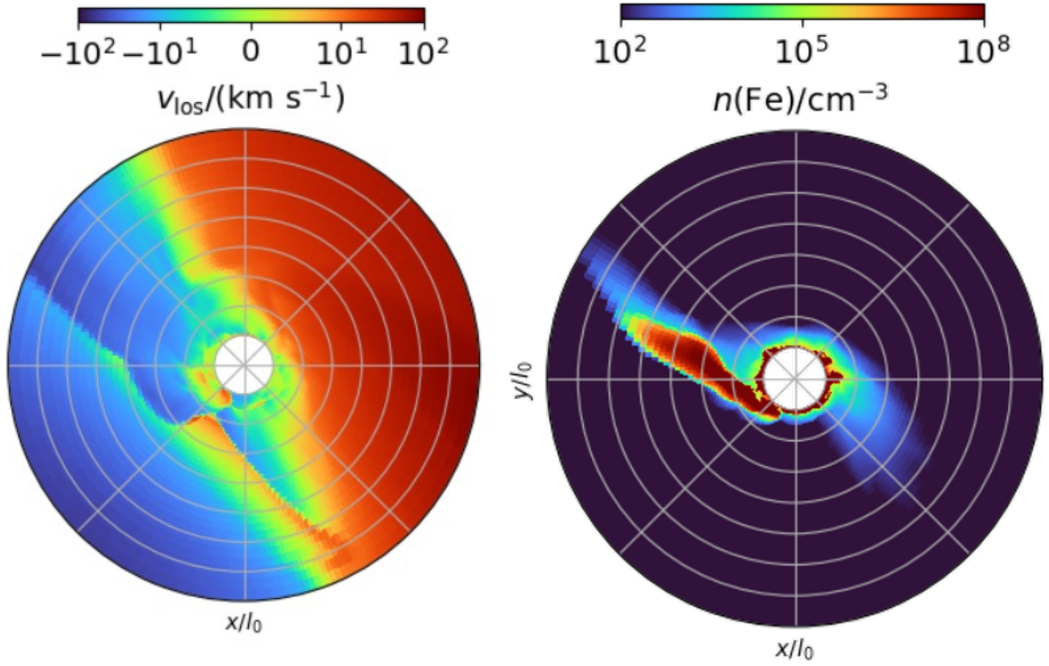


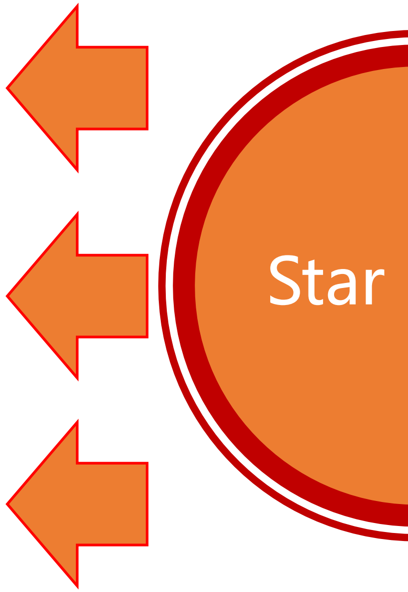
Spatial Distribution of Species: Na I

WORK IN PROGRESS

- $I(\mathrm{Fe}) = 7.90\ \mathrm{eV}$, but more susceptible to X-ray





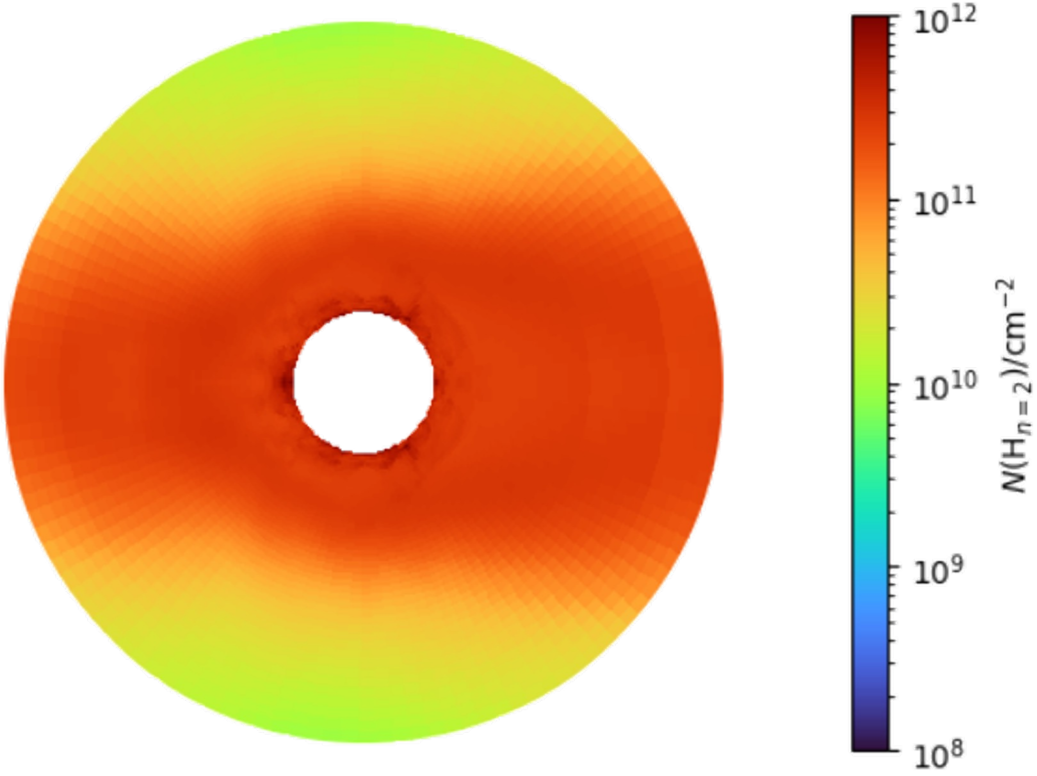


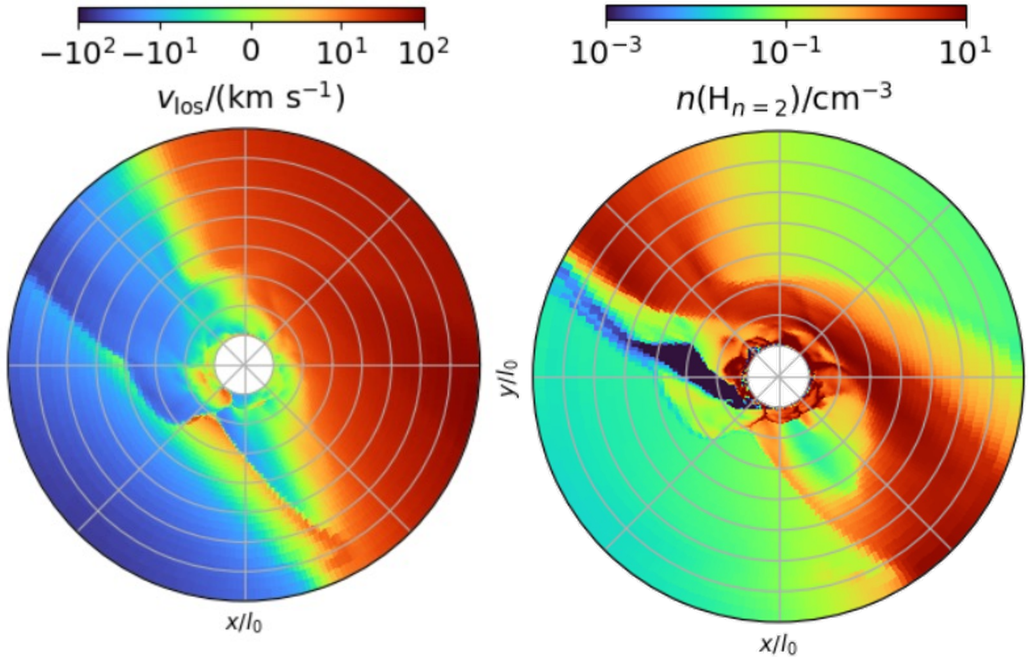
Spatial Distribution of Species: Fe I

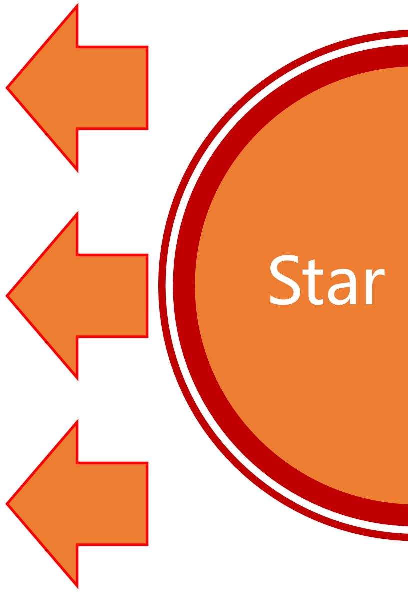
WORK IN PROGRESS

Spatial Distribution of Species: Hα

- $n(\mathrm{H}_{n=2})$ should be evaluated based on $n(\mathrm{H}^{+}), n(e^{-}), T$, and UV fluxes

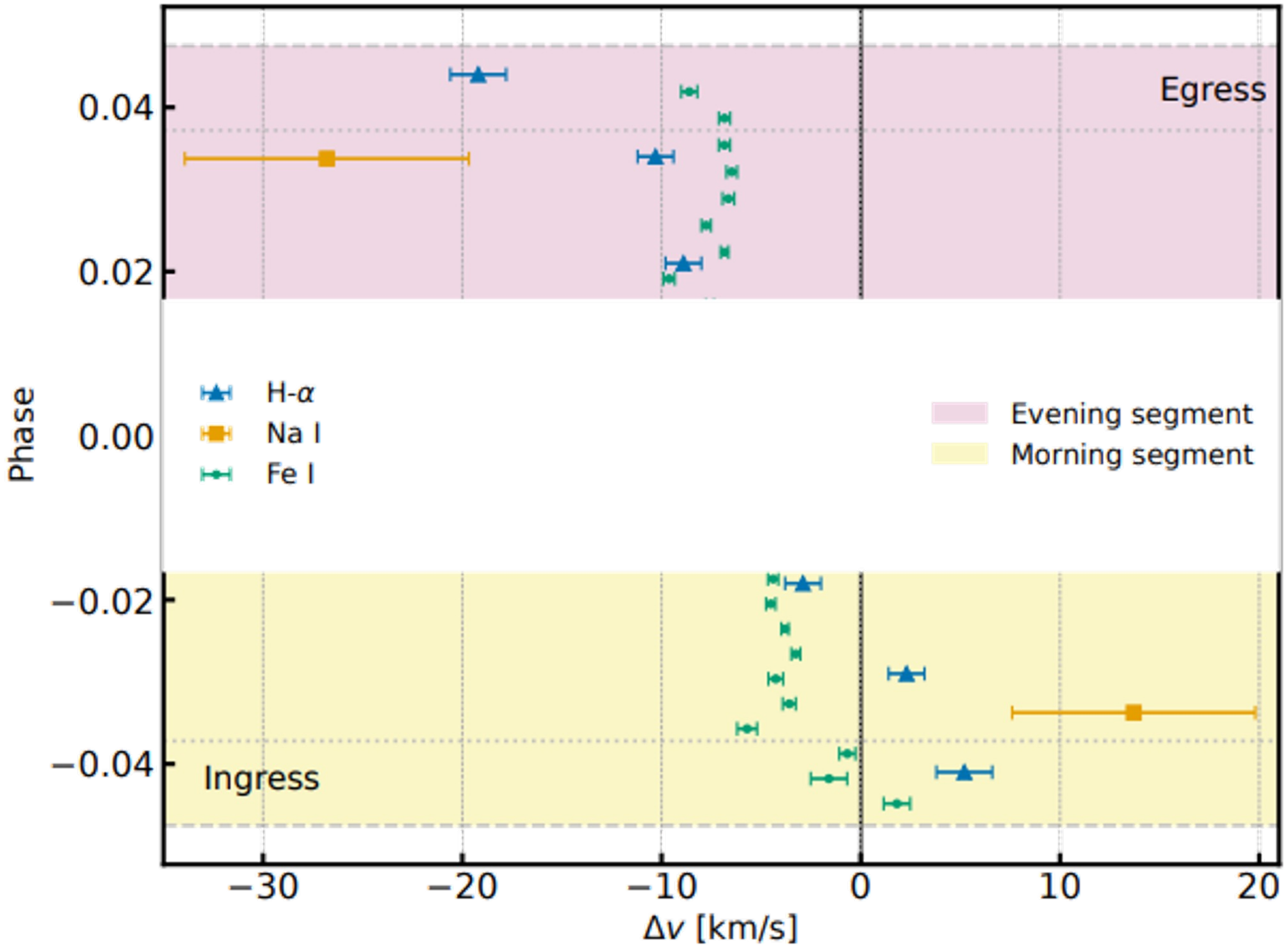


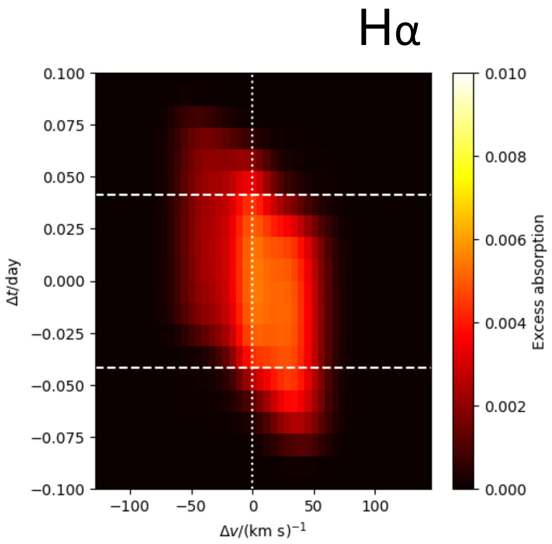


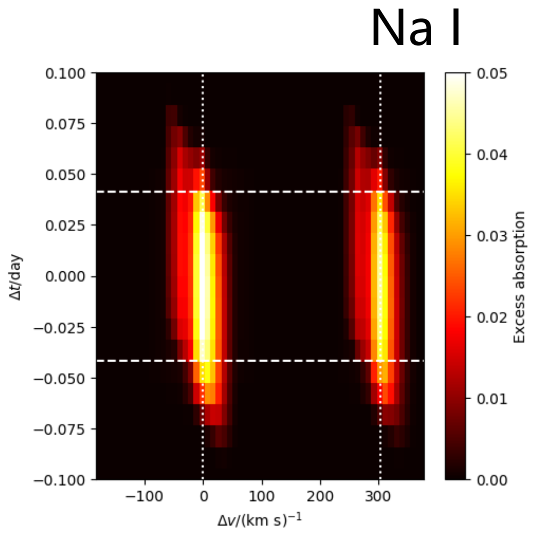


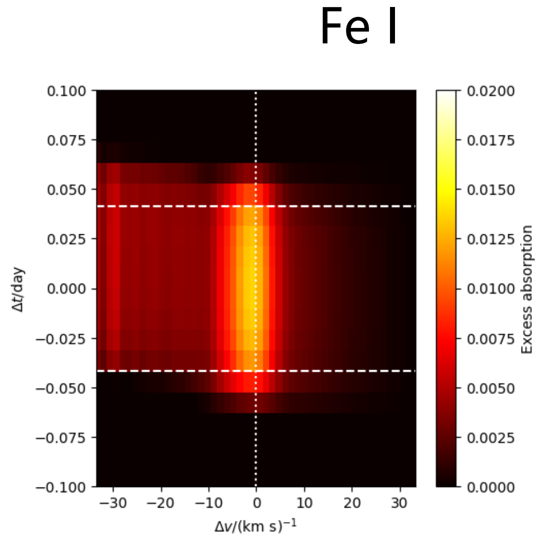
WORK
IN PROGRESS

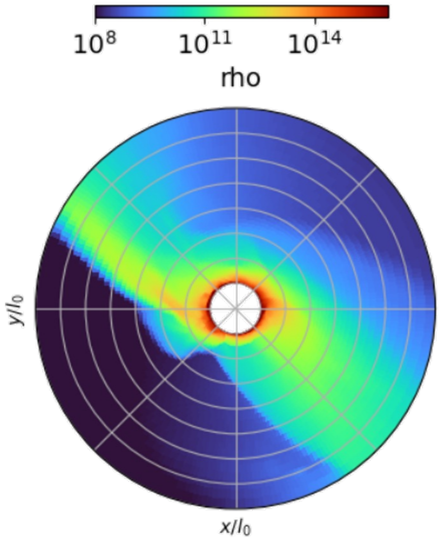
Synthetic Spectra for Better Comparisons







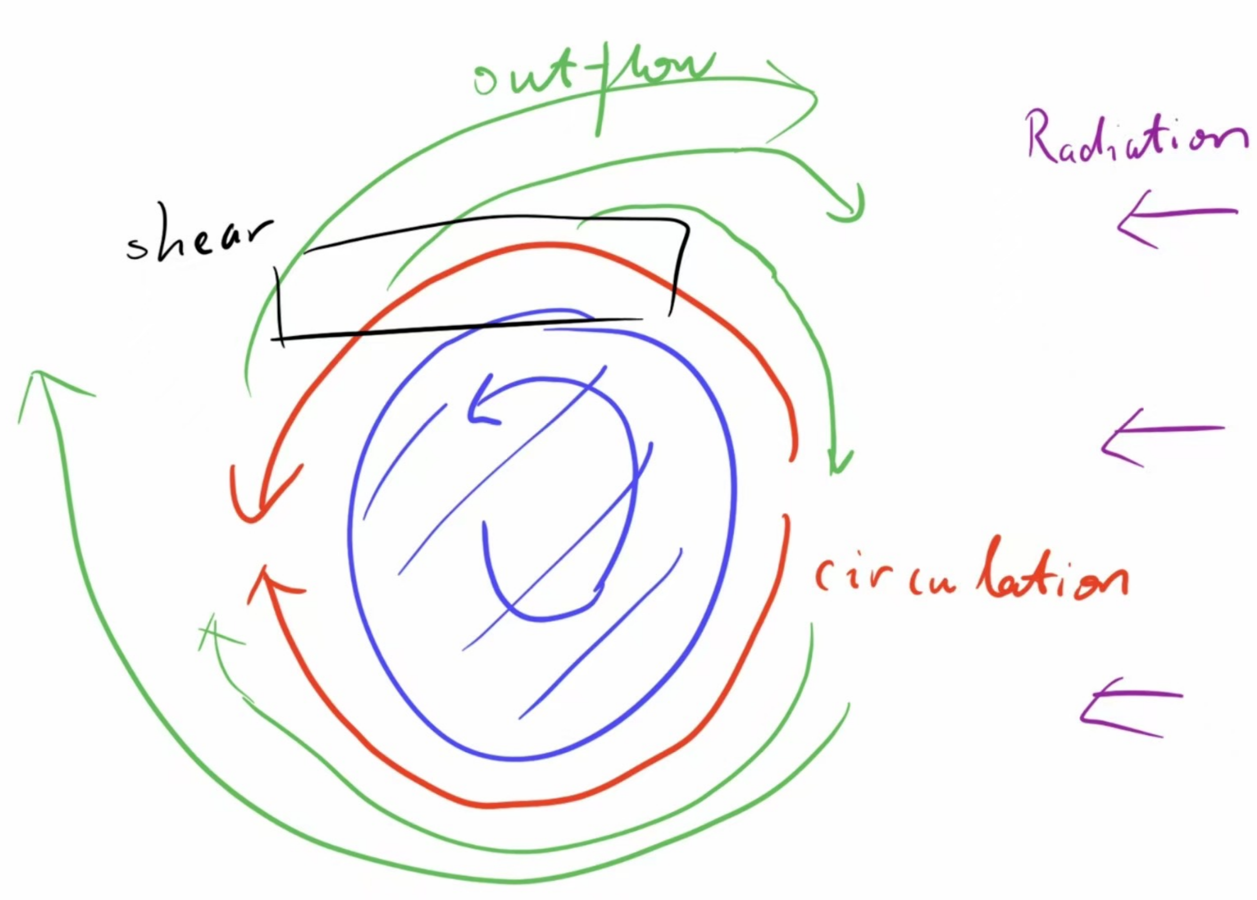


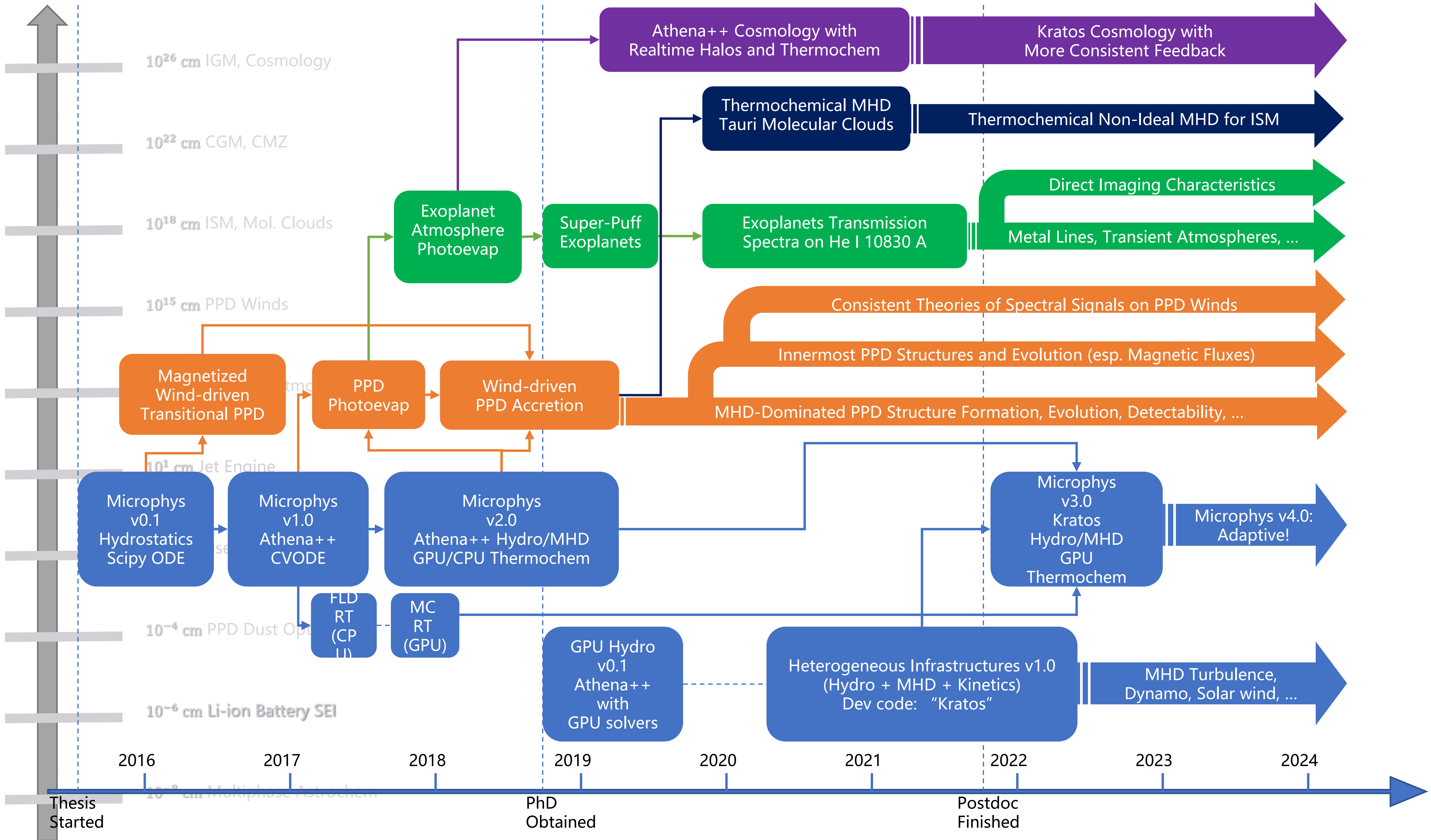


WORK
IN PROGRESS

Day-night Circulation and Kelvin-Helmhotz

- Sub-stellar point, irradiated:
  Heated, driving day-night circulations
- Sub-stellar point, not irradiated:
  Replenishing the mass source
- Outflows: shaped by Coriolis force
- 3 layers, 2 shears at $\sim 10^{0-1}\ \mathrm{km/s}$
- Variations at hours timescale:
  to be further verified by observations





10^{26} cm IGM, Cosmology

10^{22} cm CGM, CMZ

10^{18} cm ISM, Mol. Clouds

10^{15} cm PPD Winds

10^{1} cm Jet Engine

10^{-4} cm PPD Dust Op

10^{-6} cm Li-ion Battery SEI

10^{-8} cm Multiphase Astrochem

Athena++ Cosmology with Realtime Halos and Thermochem

Kratos Cosmology with More Consistent Feedback

Thermochemical MHD Tauri Molecular Clouds

Thermochemical Non-Ideal MHD for ISM

Exoplanet Atmosphere Photoevap

Super-Puff Exoplanets

Exoplanets Transmission Spectra on He I 10830 A

Direct Imaging Characteristics

Metal Lines, Transient Atmospheres, ...

Consistent Theories of Spectral Signals on PPD Winds

Innermost PPD Structures and Evolution (esp. Magnetic Fluxes)

Magnetized Wind-driven Transitional PPD

PPD Photoevap

Wind-driven PPD Accretion

MHD-Dominated PPD Structure Formation, Evolution, Detectability, ...

Microphys v0.1 Hydrostatics Scipy ODE

Microphys v1.0 Athena++ CVODE

Microphys v2.0 Athena++ Hydro/MHD GPU/CPU Thermochem

Microphys v3.0 Kratos Hydro/MHD GPU Thermochem

Microphys v4.0: Adaptive!

FLD RT (CPU)

MC RT (GPU)

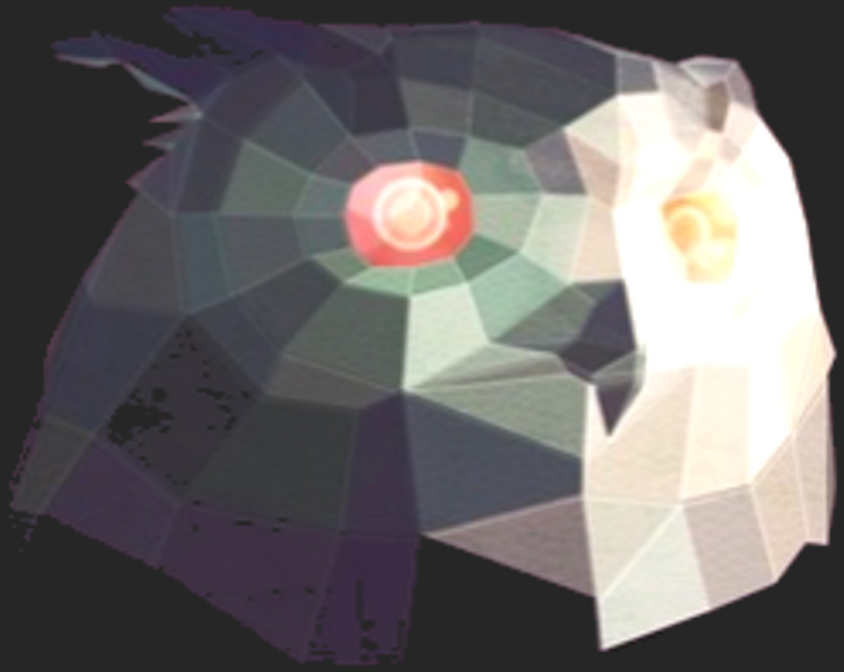
GPU Hydro v0.1 Athena++ with GPU solvers

Heterogeneous Infrastructures v1.0 (Hydro + MHD + Kinetics) Dev code: “Kratos”

MHD Turbulence, Dynamo, Solar wind, ...

CYBER-UNIVERSES

DO ~~ANDROIDS~~ DREAM OF
ELECTRIC ~~SHEEP~~?
ALIENS



- GPUs are extraordinarily suitable for simulations, especially multi-scale complex ones
- Kratos has special algorithms maximizing the efficiency on GPUs
- Protoplanetary disk dispersal deciphered with GPU-accelerated simulations:
  - MHD overwhelming;
  - Spontaneous breaking of reflection symmetry
- Exoplanetary atmospheres need 3D simulations to explain observed transmission spectra

Wang 2025a, ApJS, 227, 63; arXiv:2501.02317
Wang 2025b, submitted to ApJS; arXiv:2504.04941
Zhang, Yi, Wang et al. 2025, ApJ, 990, 105; arXiv:2504.14180
Liu, Wang & Peng, 2025 ApJ in-press; arXiv:2505.10524
and many more...