PHANTOM

WELCOME, WHAT'S NEW & ROADMAP

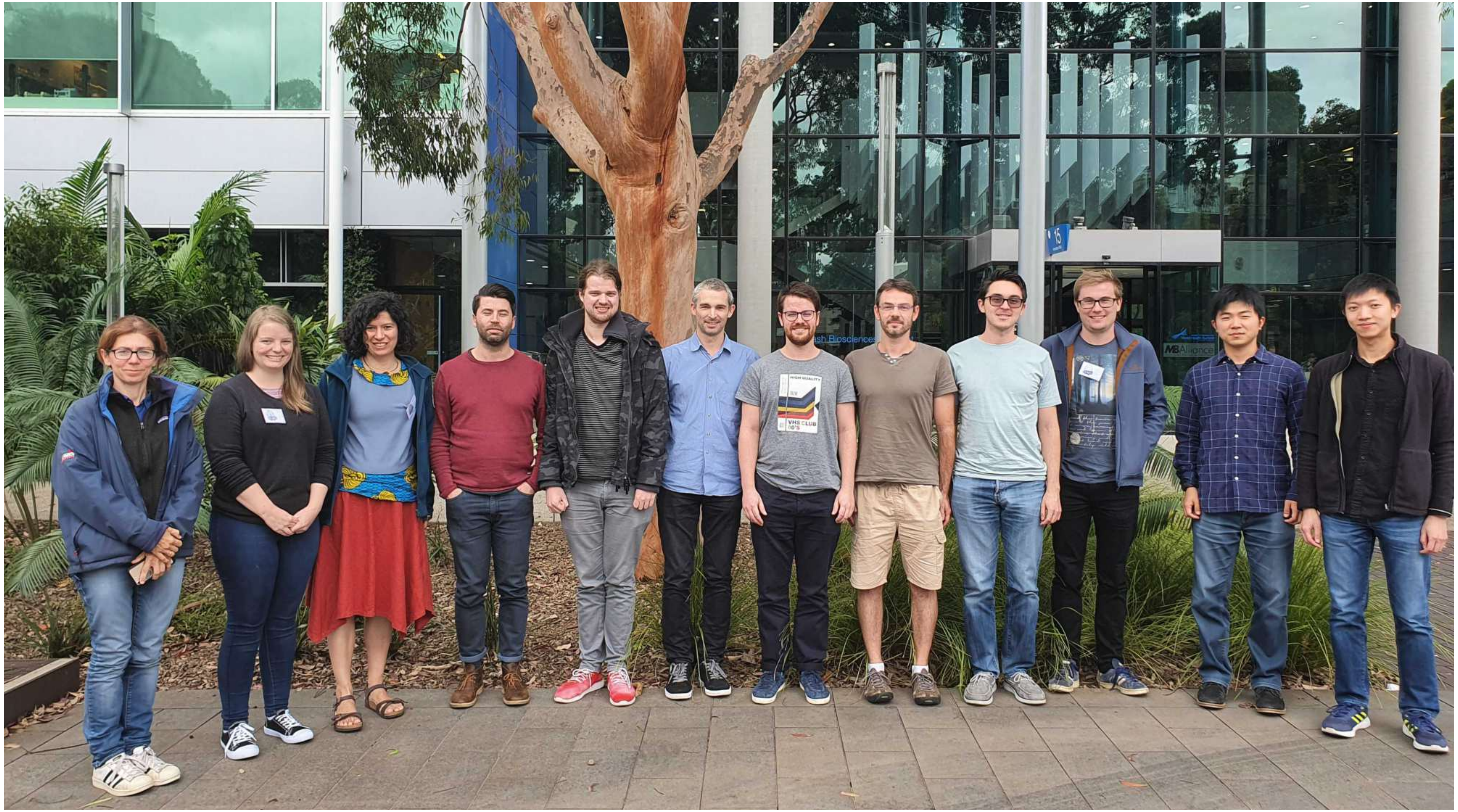
DANIEL PRICE @ 7TH PHANTOMFEST, GRENOBLE, FRANCE, JUNE 2025

WELCOME

1ST PHANTOM USERS WORKSHOP (2018)

1ST EUROPEAN PHANTOM USERS WORKSHOP (2018)

3RD PHANTOM USERS WORKSHOP (2020)

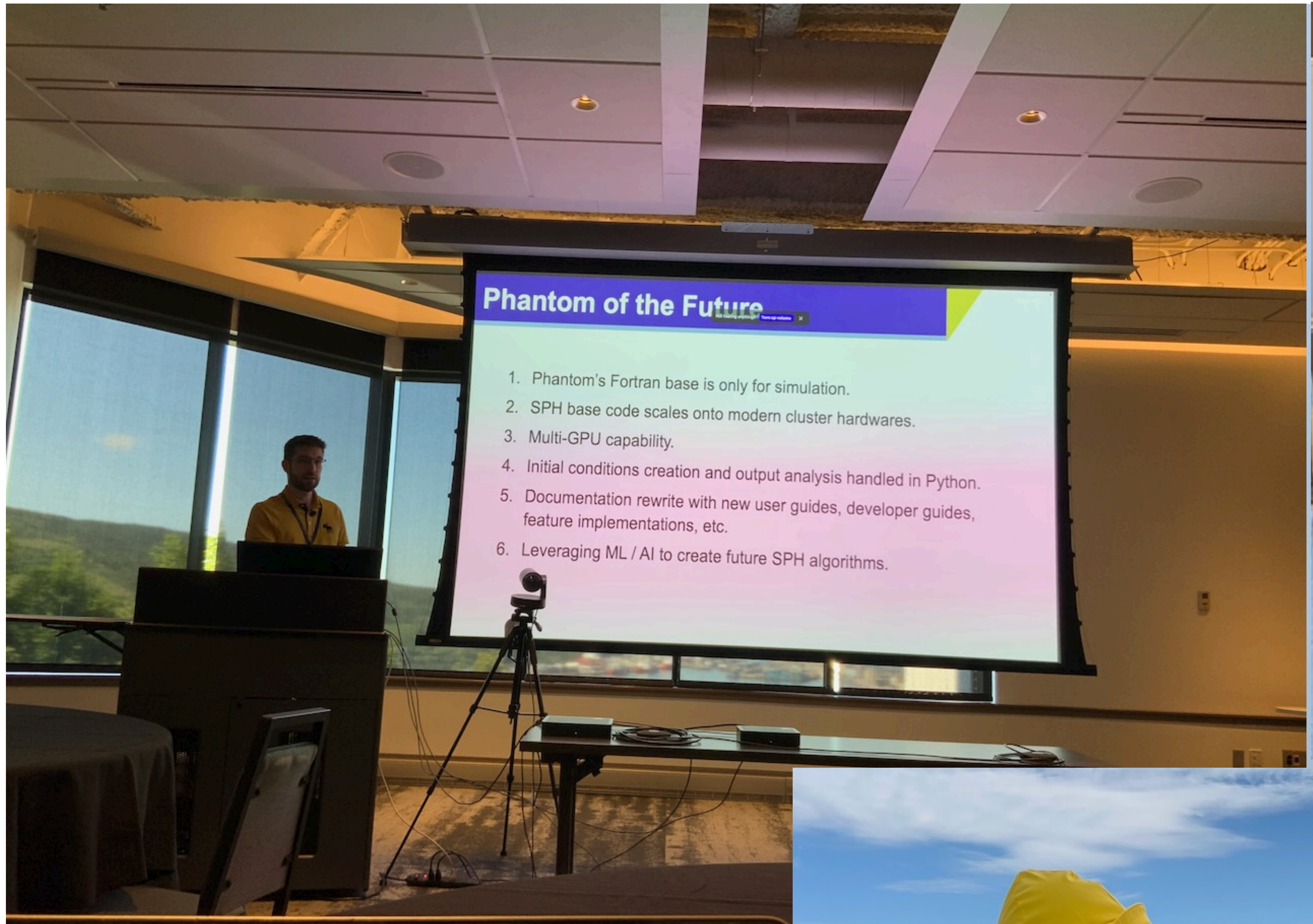


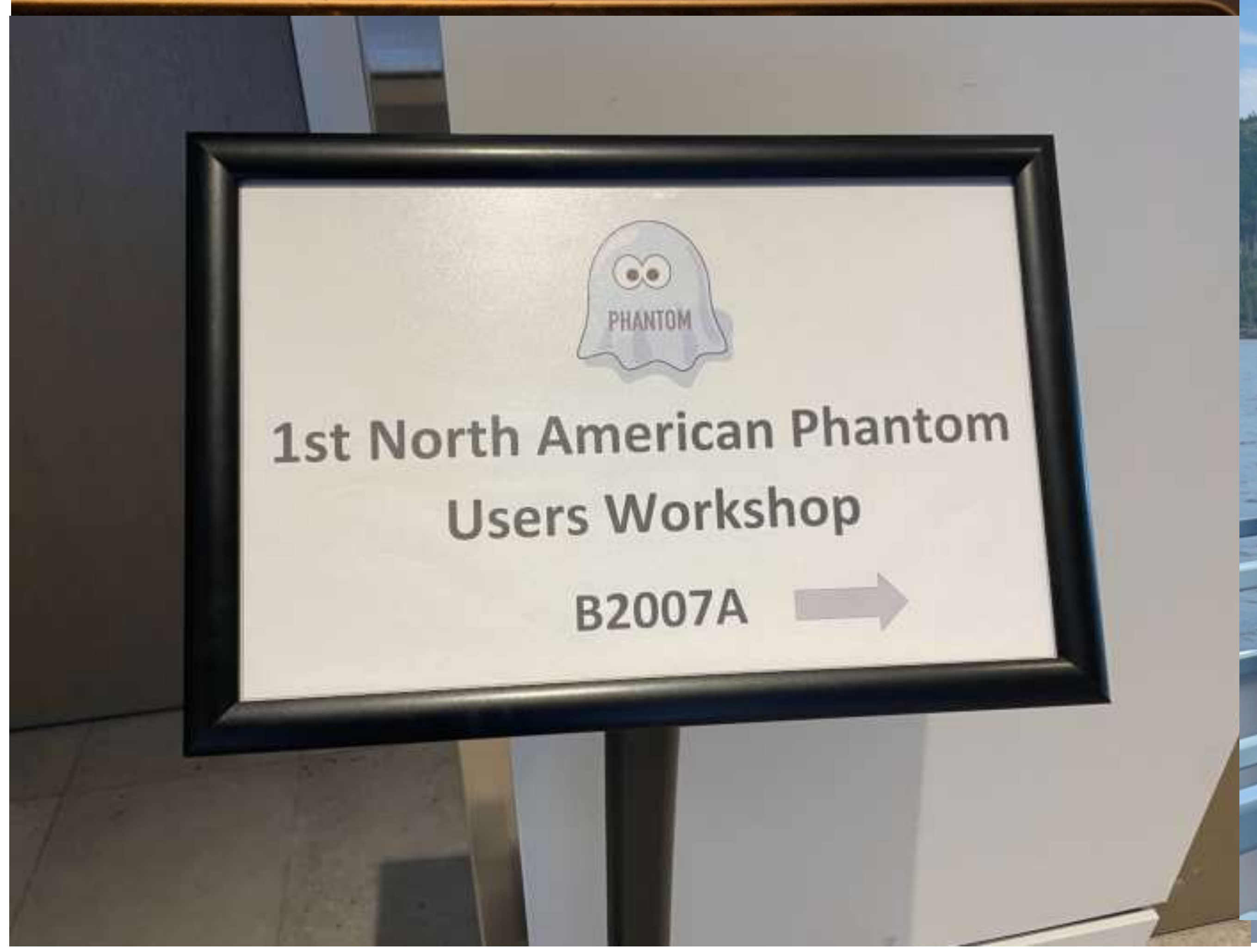
4TH PHANTOM USERS WORKSHOP (2023)

5TH PHANTOM USERS WORKSHOP (FEB 2024)

With thanks to the Australian-French Association for Research and Innovation

1ST NORTH AMERICAN PHANTOM USERS WORKSHOP (2024)





Goals of the workshop

1. Hear about what others are working on
2. Get help: make the code(s) work for your problem!
3. Learn how to contribute to the codebase
4. Build community and enjoy getting to know each other
5. Share and discover best-practice software development
6. Improve the physics, documentation and usability of the entire code family (phantom, mcfost, sarracen, shamrock, splash)
7. Play with fun visualisations
8. Develop translational skills for industry (see Thursday session)
9. ~~Mutate the phantom logo~~

EVOLUTION OF THE PHANTOM LOGO (2017-2025)

D. Price (2017)

D. Price (2018)

A. Vericel (2018)

L. Siess (2023)

A. Vericel (2018)

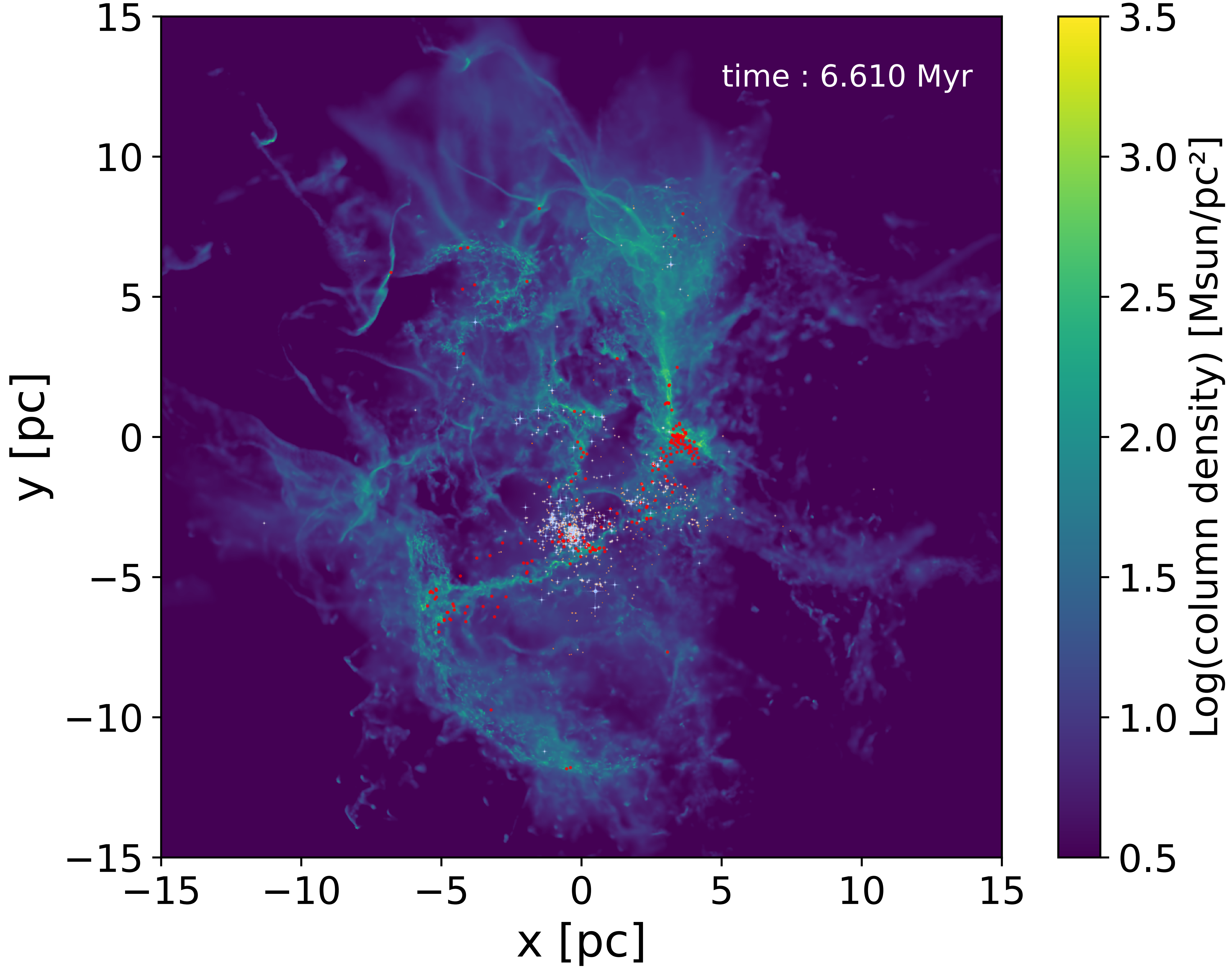
S. Rowther (2024)

C. Longarini (2025)

WHAT'S AFTER HAPPENING NOW?

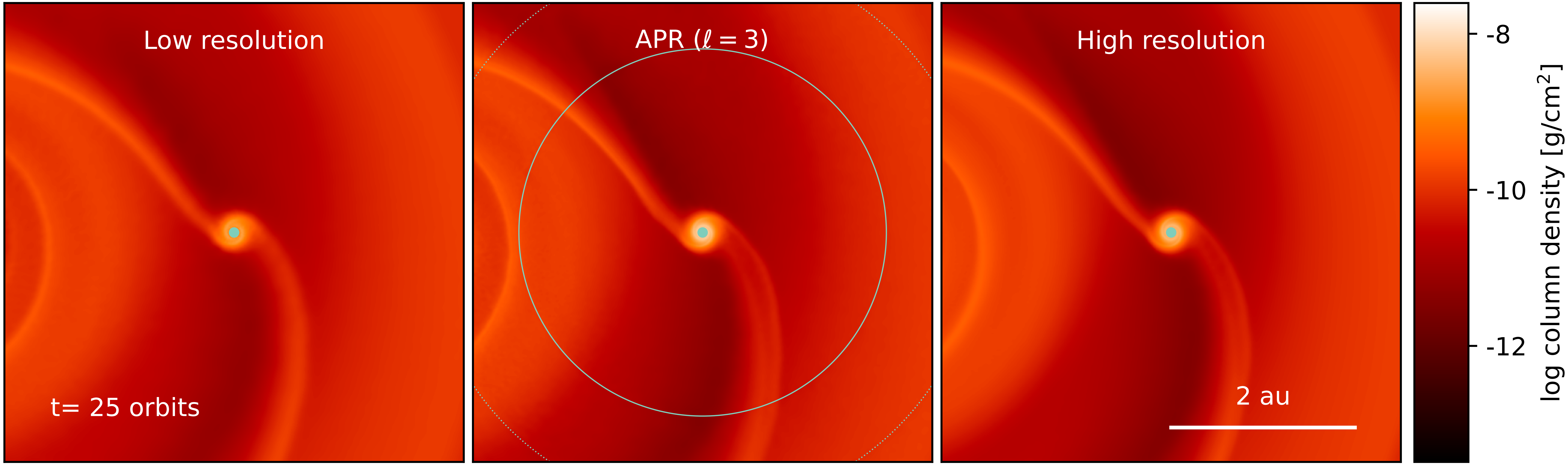
FAST N-BODY ALGORITHMS FOR STAR CLUSTER FORMATION & EVOLUTION

Bernard+2025



ADAPTIVE PARTICLE REFINEMENT

Nealon & Price (2024)



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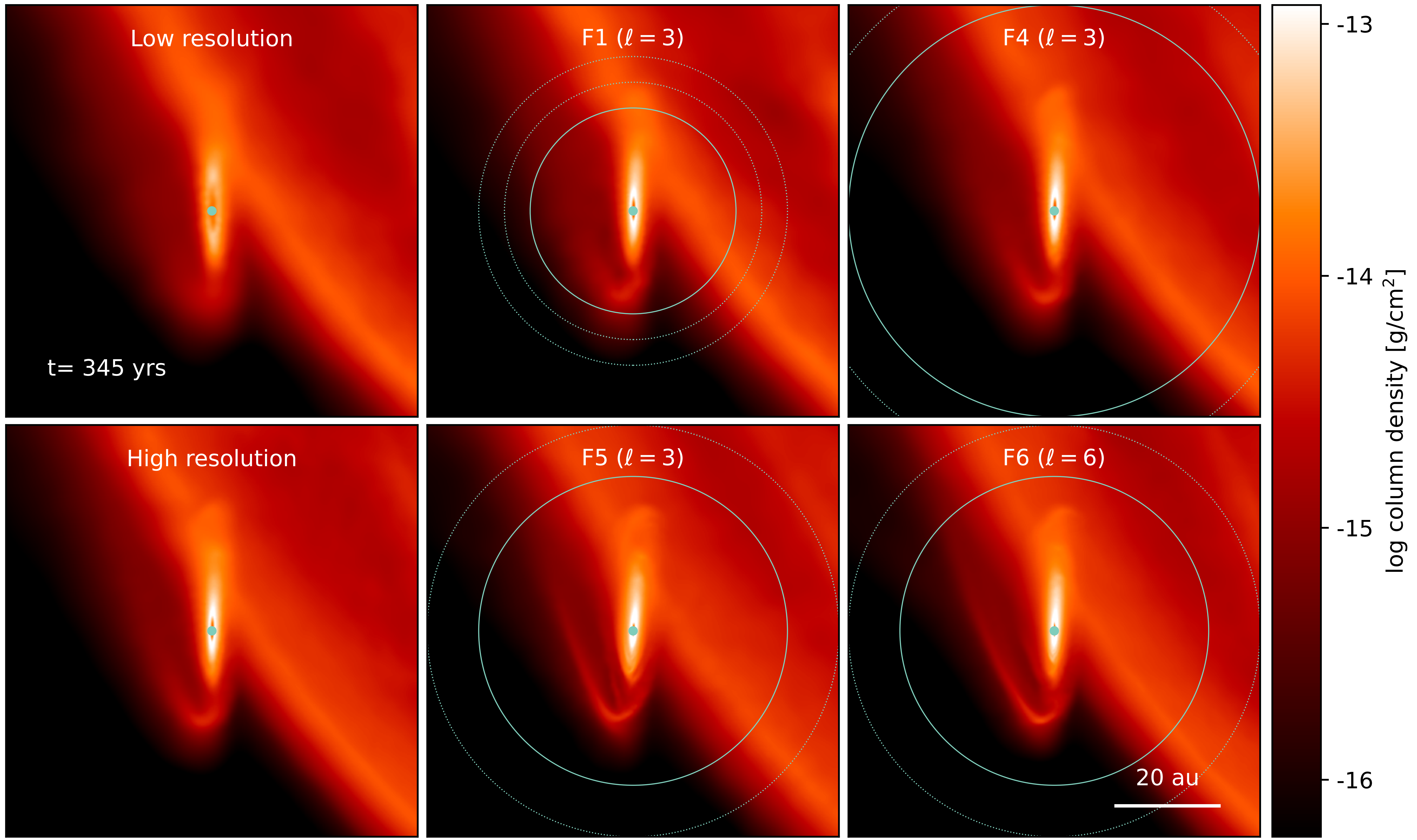
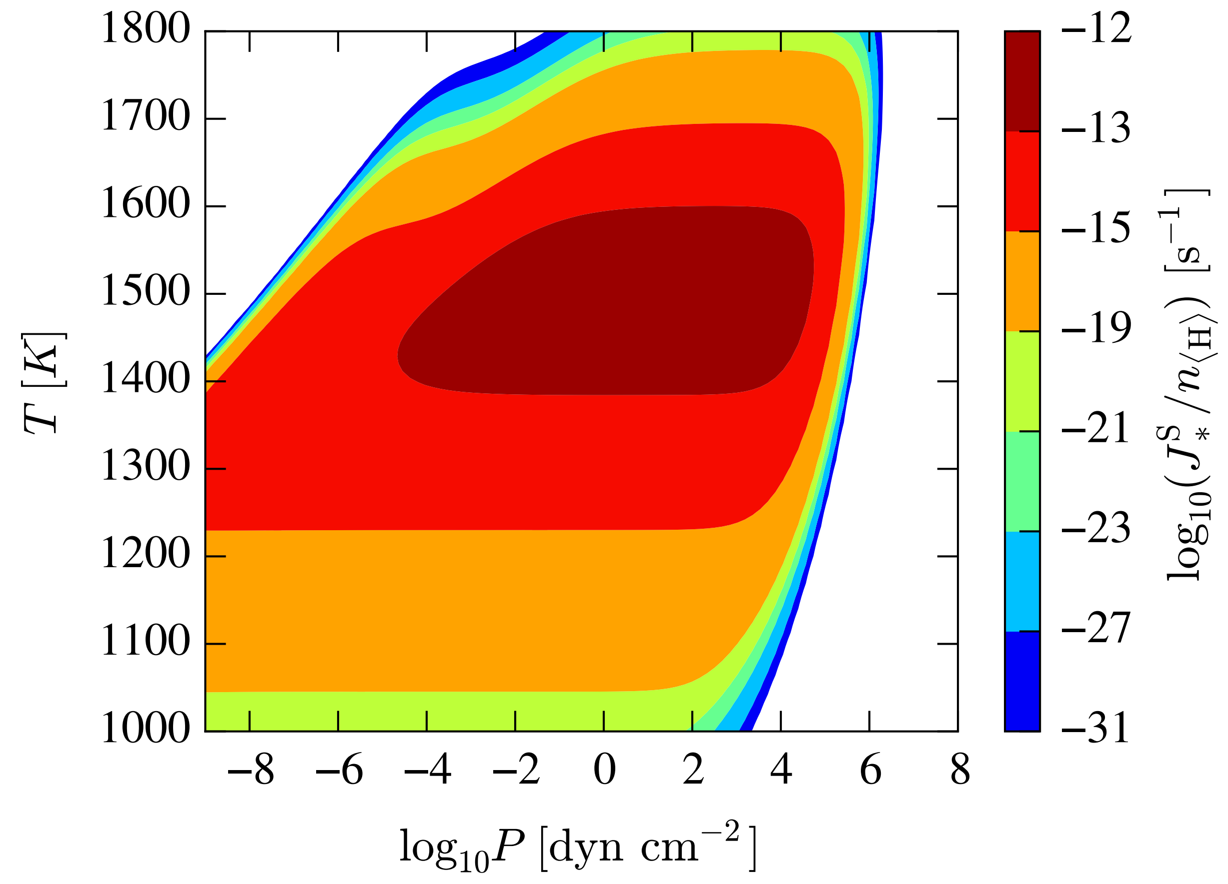


DUST FORMATION

Gail & Sedlmyer (1988);
Siess et al. (2022)



- Carbon dust only!
- Compute nucleation rate as a function of density, temperature and available Carbon from equilibrium chemical network
- Evolve moments of the grain size distribution
- Use this to obtain dust opacity: use this to accelerate wind

$$J_*^{\mathrm{S}} = \beta \mathcal{A}_{N_*} Z \mathring{n}_{\mathrm{d}}(N_*).$$

$$\mathring{n}_{\mathrm{d}}(N) = n_{\mathrm{C}} \exp\left\{-\frac{\Delta F}{kT_{\mathrm{g}}}\right\} = n_{\mathrm{C}} \exp\left\{(N-1)\ln \tilde{S} - \frac{\theta_N (N-1)^{2/3}}{T_{\mathrm{g}}}\right\},$$

$$\mathcal{K}_i = \sum_{N=N_l}^{\infty} N^{i/3} f(N,t), \qquad \widehat{\mathcal{K}_i} = \frac{\mathcal{K}_i}{n_{\langle \mathrm{H} \rangle}} = \frac{\mathcal{K}_i \, \bar{m}_{\mathrm{H}}}{\rho},$$

$$\kappa_{\mathrm{d}} = \frac{\pi}{\rho} Q'_{\mathrm{ext}}(\lambda) \int_0^{\infty} a^3 n(a)\, \mathrm{d}a = \frac{\pi a_0^3}{\rho} Q'_{\mathrm{ext}}(\lambda)\, \mathcal{K}_3,$$

$$\frac{\mathrm{d}\widehat{J_*}}{\mathrm{d}t} = \frac{\widehat{J_*^S} - \widehat{J_*}}{\tau_*},$$

$$\frac{\mathrm{d}\widehat{\mathcal{K}_0}}{\mathrm{d}t} = \widehat{J_*},$$

$$\frac{\mathrm{d}\widehat{\mathcal{K}_i}}{\mathrm{d}t} = \frac{i\,\widehat{\mathcal{K}_{i-1}}}{3\tau} + N_l^{i/3}\widehat{J_*},$$

WIND-COMPANION INTERACTION + DUST FORMATION

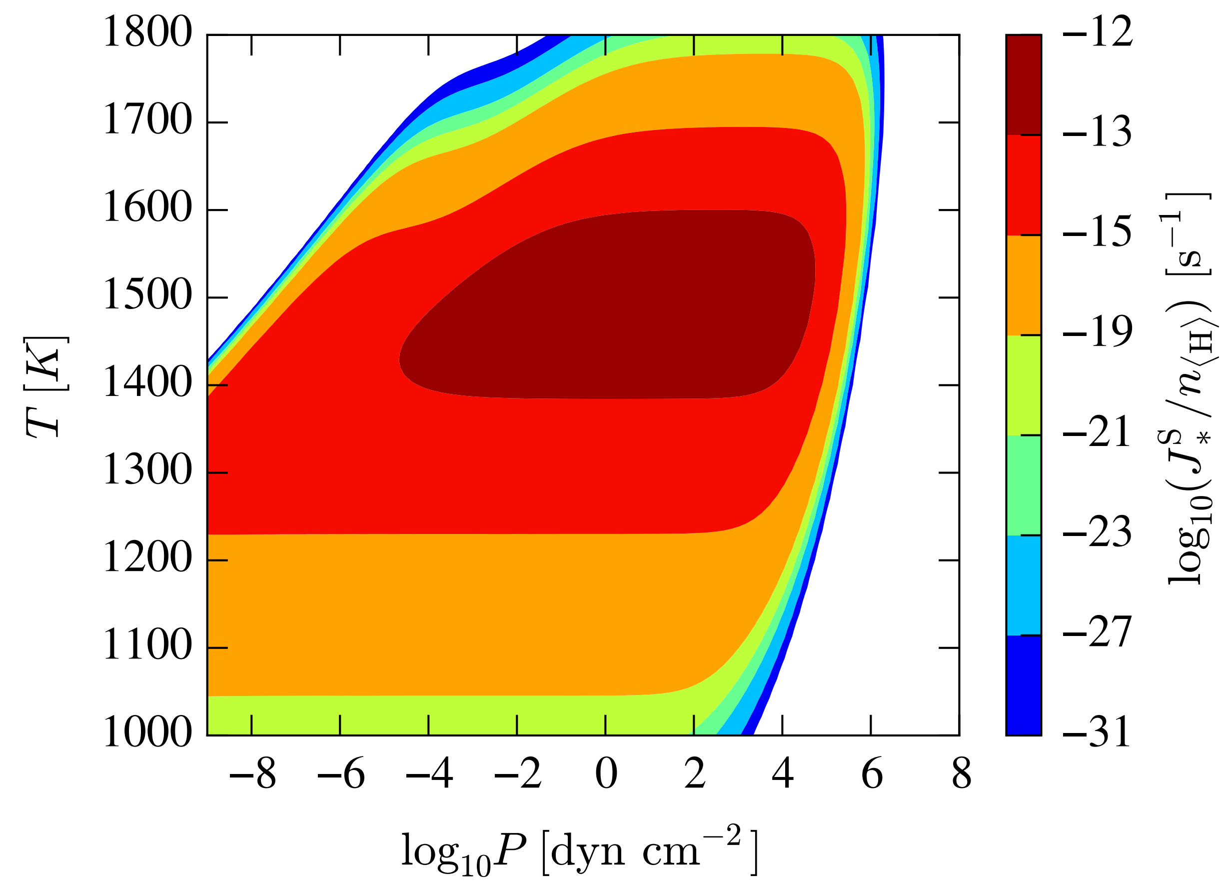
A&A 667, A75 (2022)
https://doi.org/10.1051/0004-6361/202243540

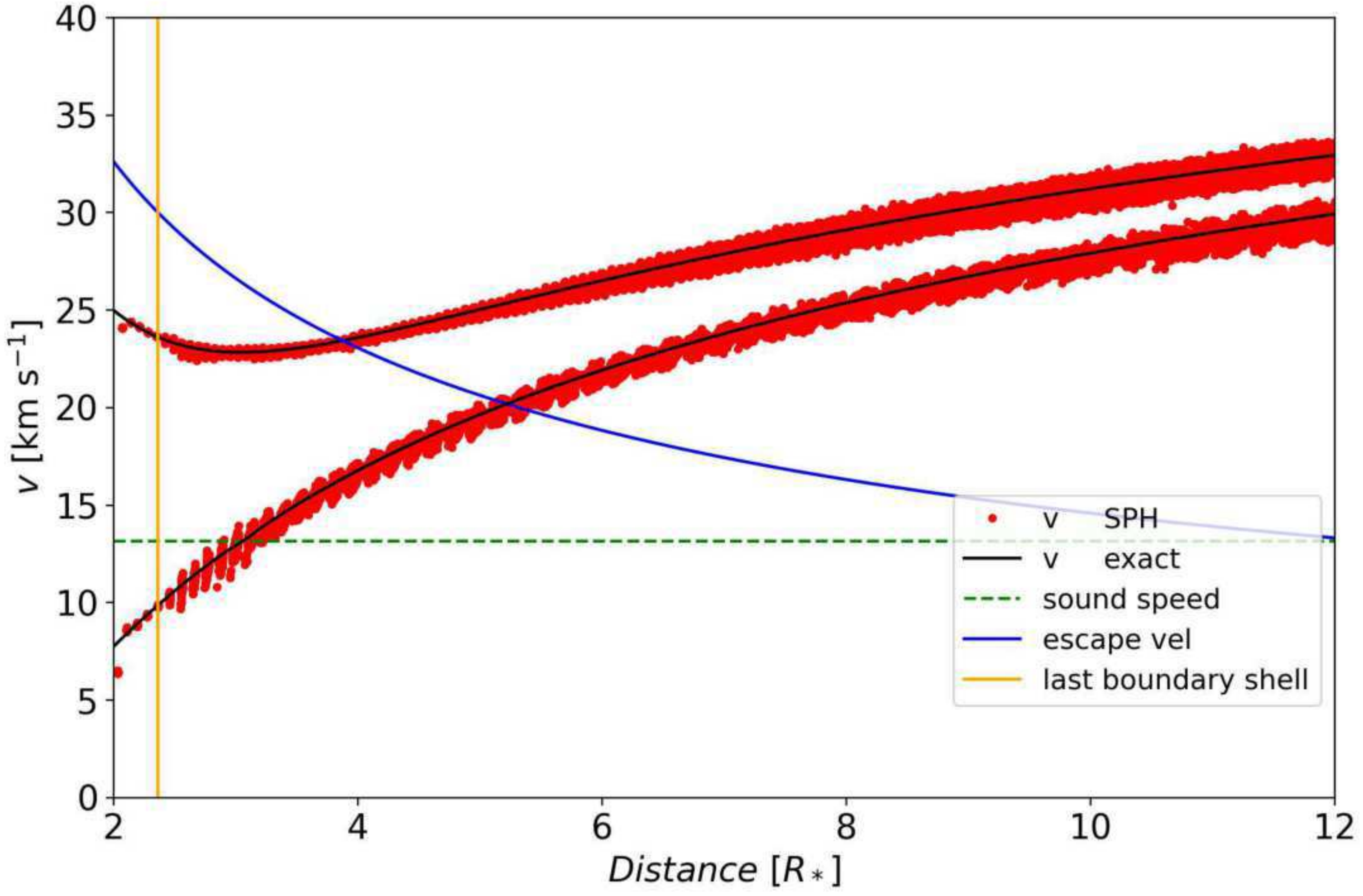
Astronomy & Astrophysics

3D simulations of AGB stellar winds

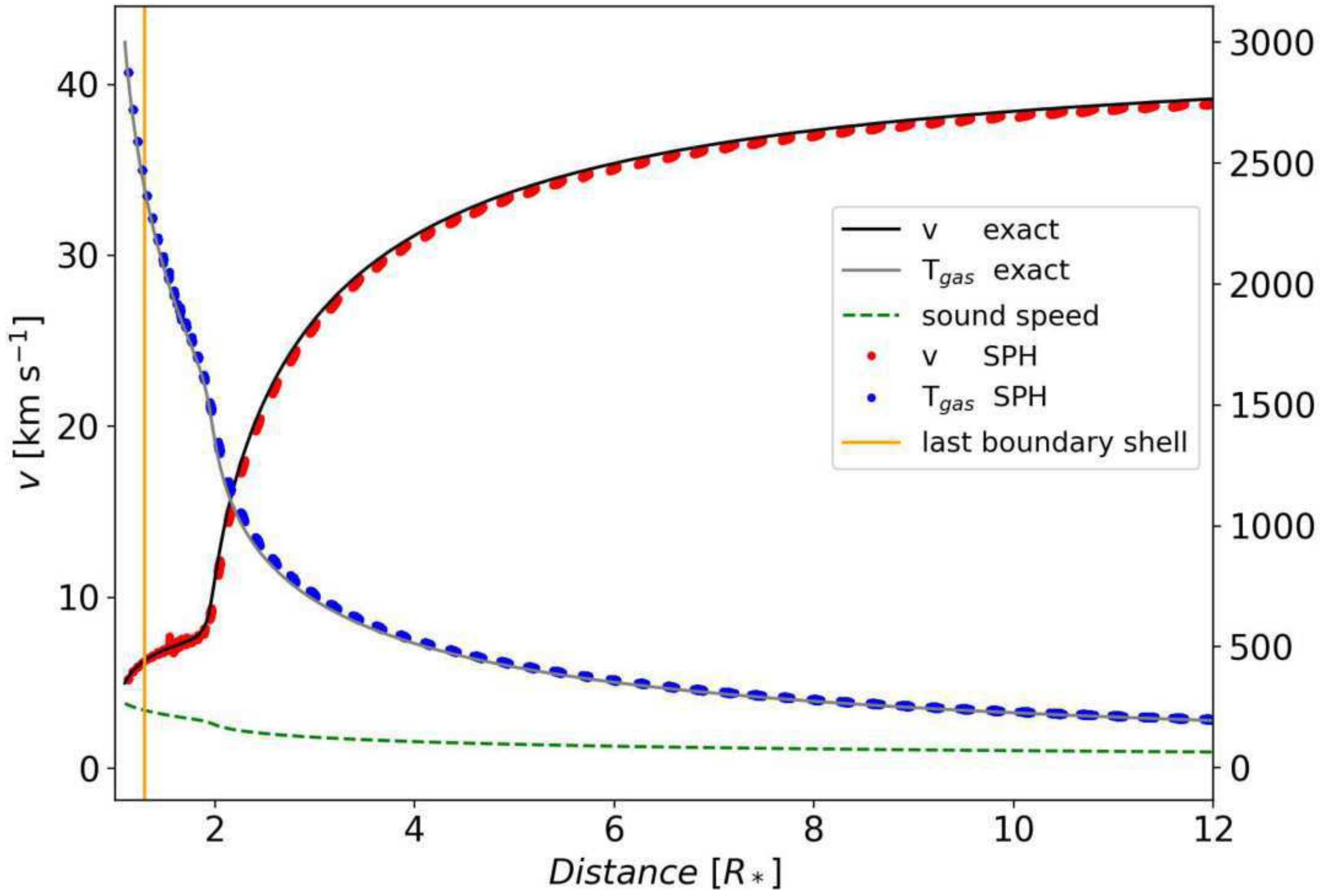
I. Steady winds and dust formation

L. Siess[1], W. Homan[1], S. Toupin[1], and D. J. Price[2]





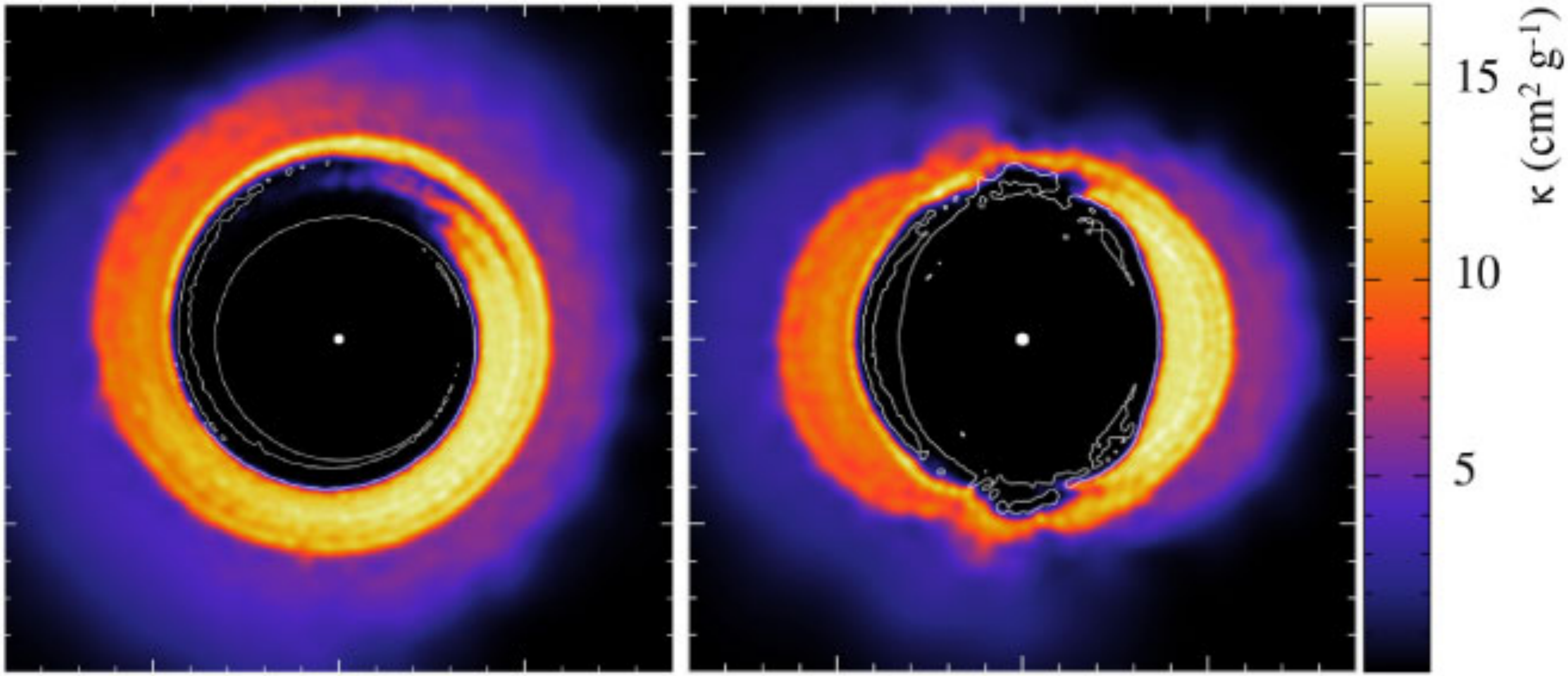
No dust nucleation



With dust nucleation

DUST FORMATION IN COMMON ENVELOPE EVOLUTION

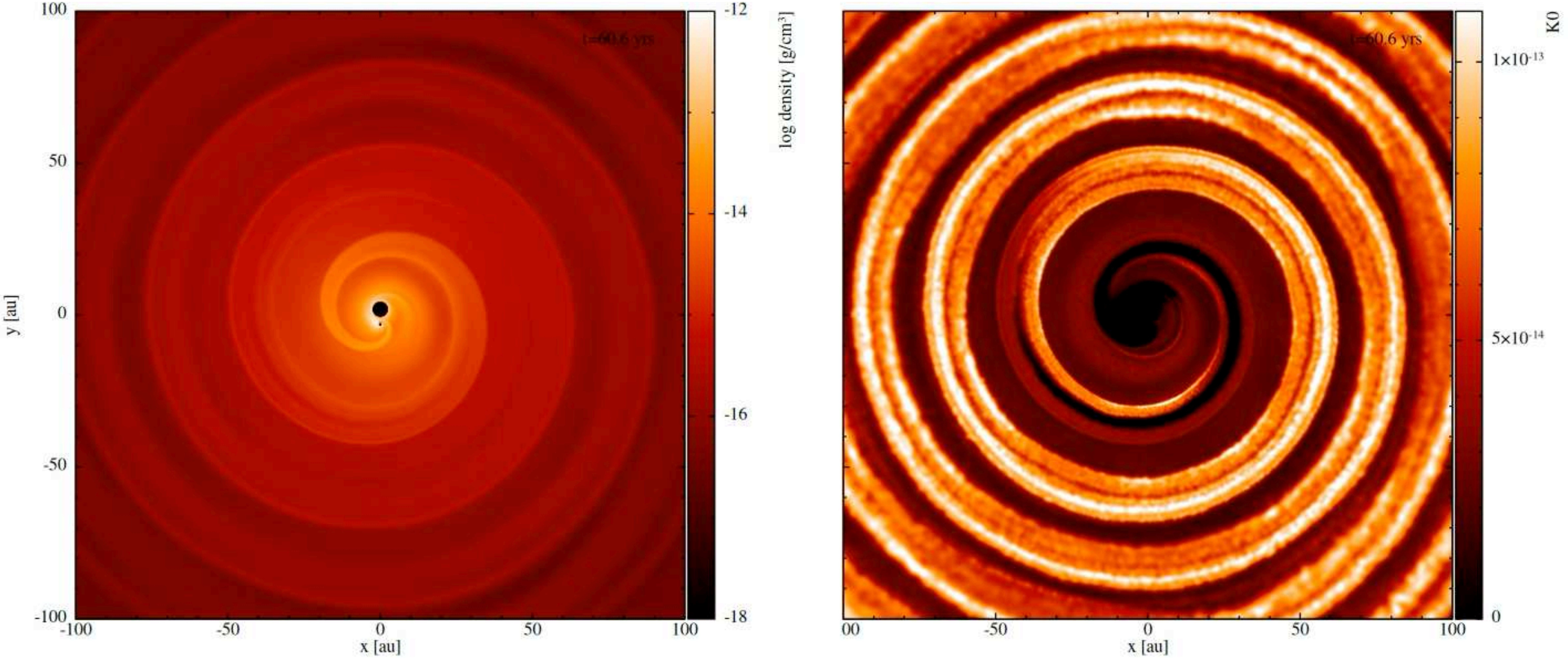
Gonzalez-Bolivar+2024; Bermudez-Bustamante+2024



Does not significantly change the outcome as dust formation/wind acceleration mostly occurs in material that is already unbound

DUST FORMATION IN WAKE OF COMPANIONS?

Samaratunge, Danilovich, Price+ (in prep)



Could this imply that orbiting companions set the mass loss rate of AGB stars?
(e.g. Danilovich+2025 ATOMIUM continuum paper)

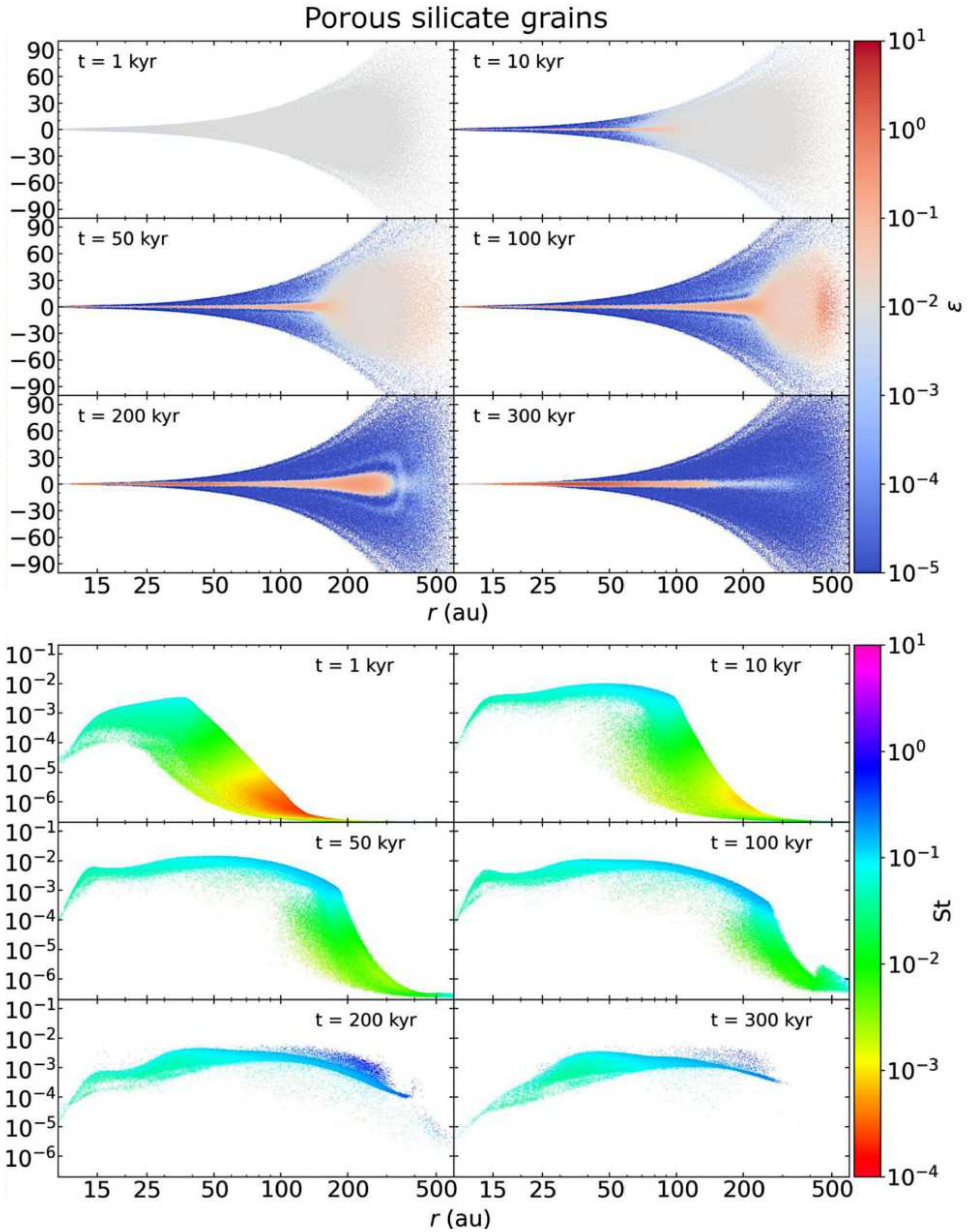
DUST GROWTH WITH POROSITY

Vericel+(2021); Michoulier, Gonzalez & Price (2024)

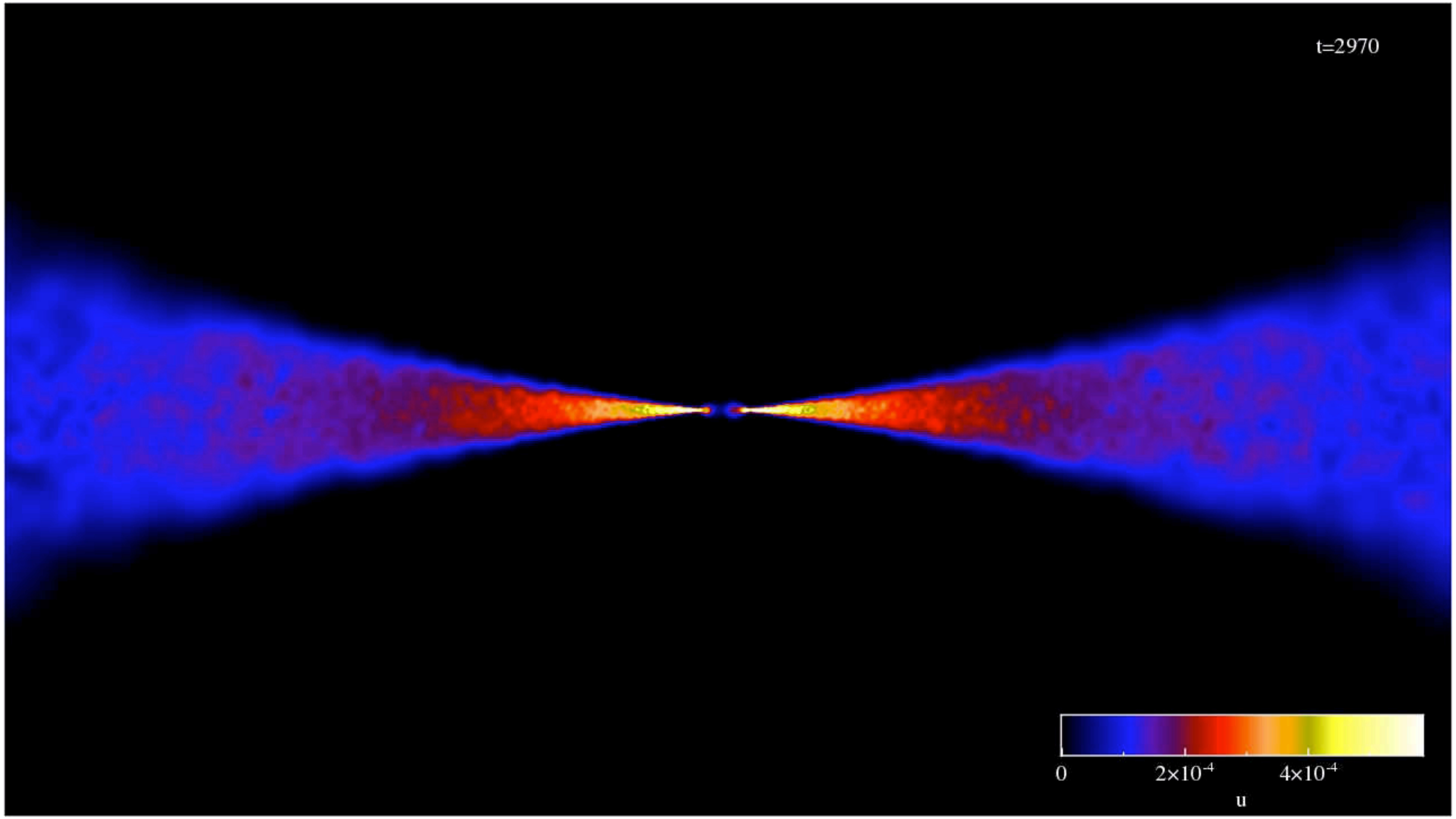
$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{grow}} \approx \frac{m}{\tau_{\mathrm{coll}}}.$$

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{frag}} = -4\pi \frac{v_{\mathrm{rel}}^3}{v_{\mathrm{rel}}^2 + v_{\mathrm{frag}}^2} \rho_{\mathrm{d}} s^2.$$

```
Compute φ_coll, φ_gas, φ_grav
Compute φ_min = max(φ_coll, φ_gas, φ_grav)
if v_rel < v_frag then
    Compute φ_grow
    if (Grains can bounce) then
        Compute φ_coll & bounce
        Compute φ_f = max(φ_coll & bounce, φ_min)
    else
        Compute φ_f = max(φ_grow, φ_min)
    end if
else
    if (Fragmentation with compaction) then
        Compute φ_frag−comp
        Compute φ_f = max(φ_frag−comp, φ_min)
    else
        Compute φ_f = max(φ_i, φ_min)
    end if
end if
φ_final = min(φ_f, 0.74)
```



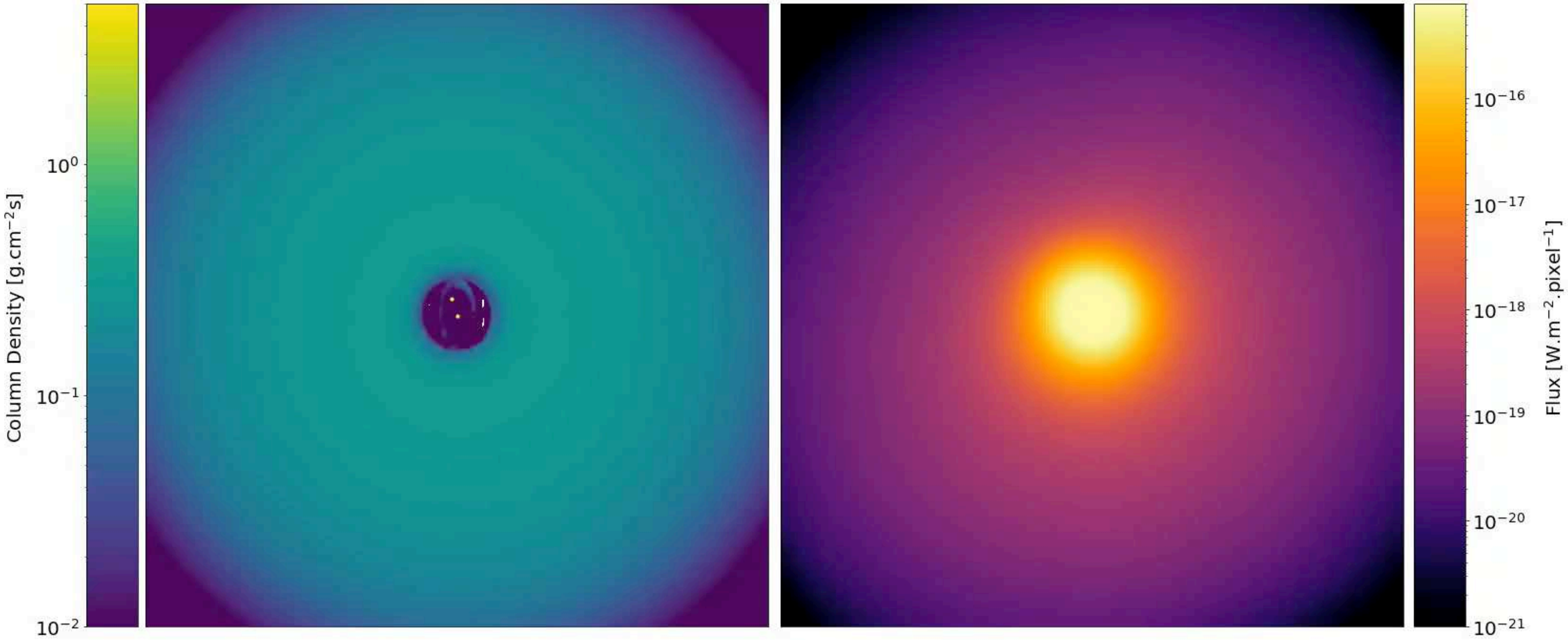
PHANTOM+MCFOST



Pinte, Price, Mentiplay, Biriukov, Borchert+ (methods paper not yet published)

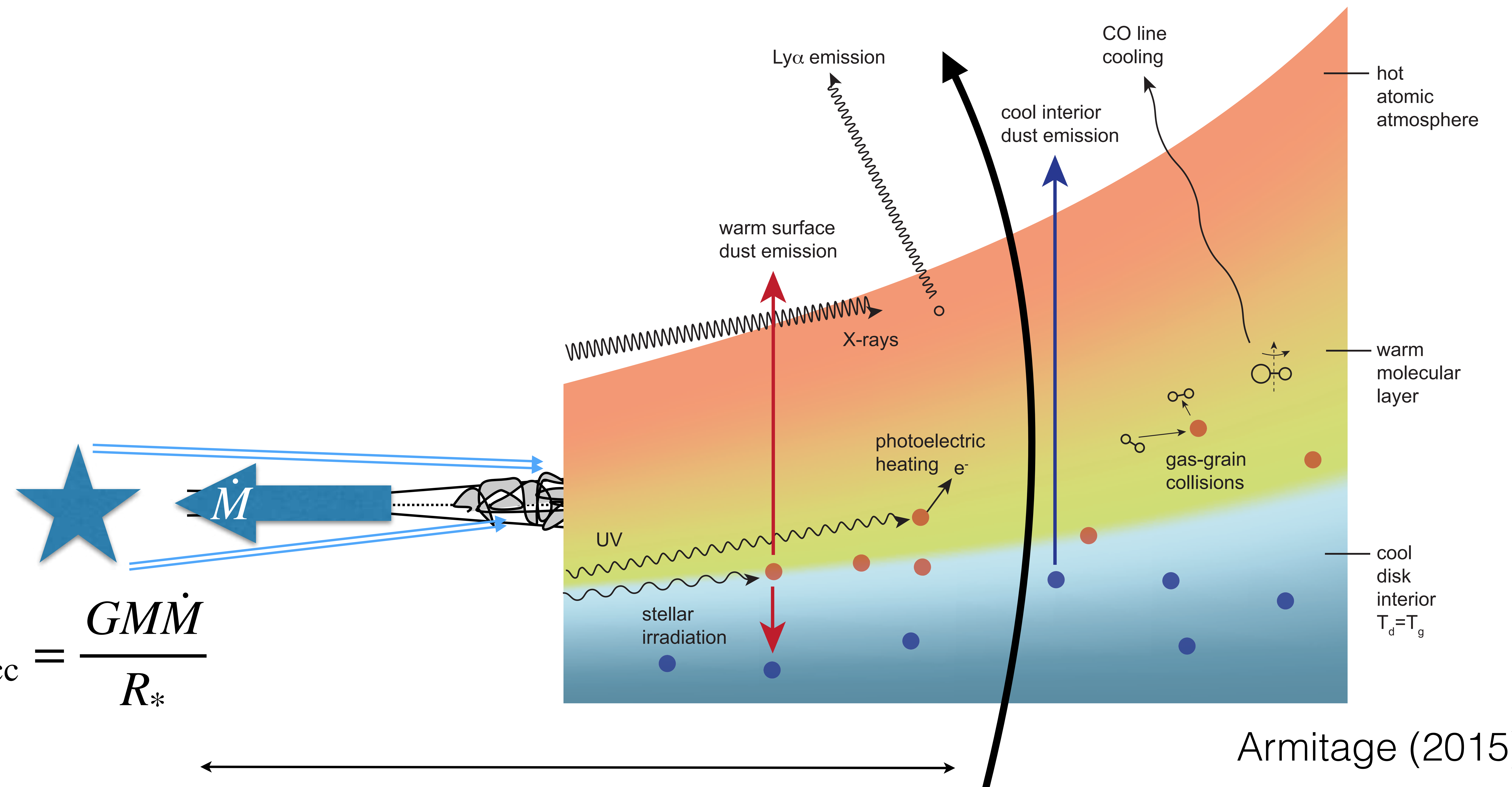
PHANTOM+MCFOST

Nealon et al. (2020)



First publication using live coupling between PHANTOM and MCFOST

MODELLING DISC OUTBURSTS WITH
3D HYDRO + ON-THE-FLY MONTE CARLO RADIATIVE TRANSFER



$$L_{\rm acc} = \frac{GM\dot{M}}{R_*}$$

Armitage (2015)

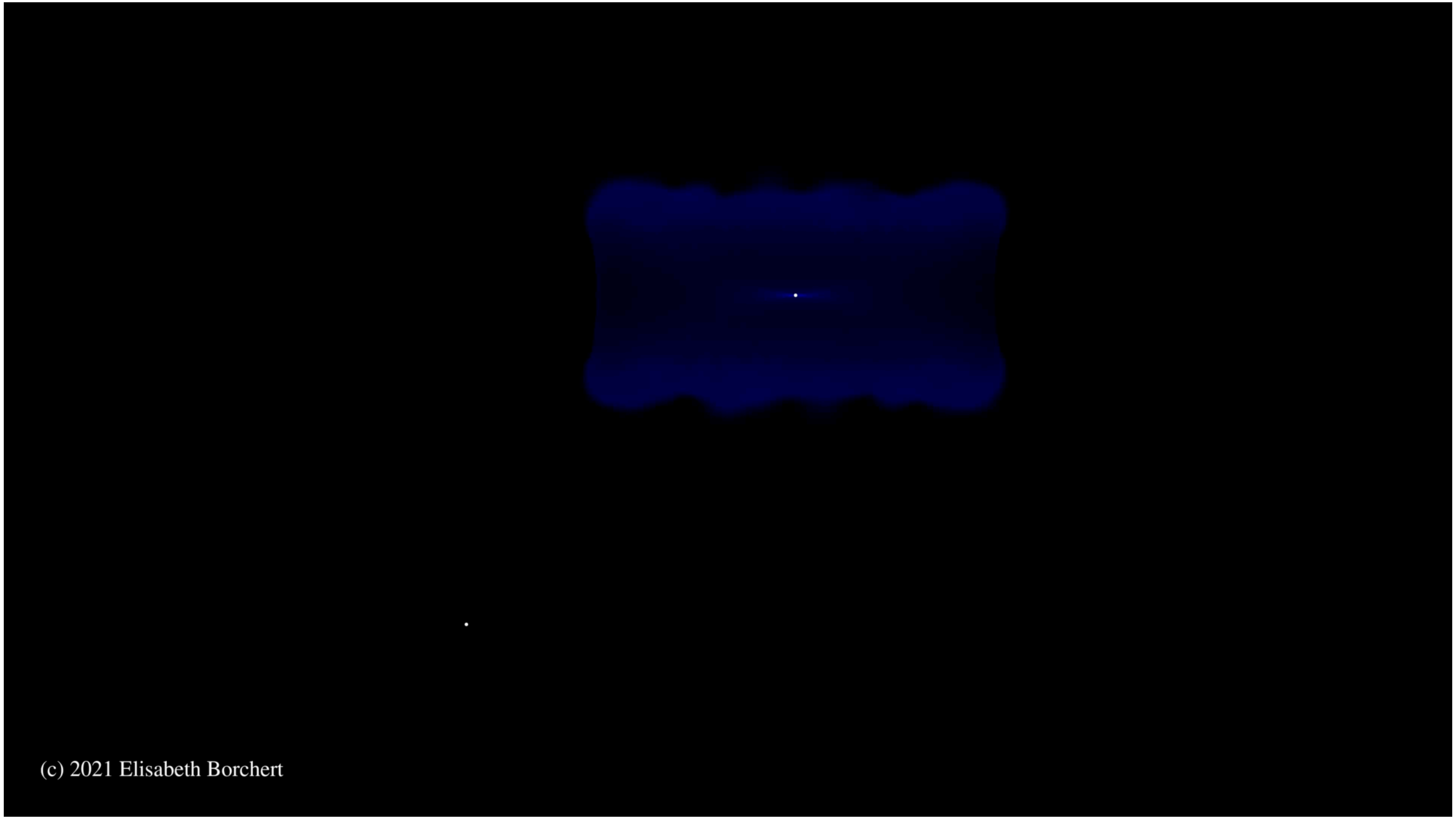
$$\frac{\mathbf{I}_\lambda(\mathbf{r},\mathbf{n})}{ds} = -\left(\kappa_\lambda^{\rm abs}(\mathbf{r}) + \kappa_\lambda^{\rm sca}(\mathbf{r})\right)\mathbf{I}_\lambda(\mathbf{r},\mathbf{n}) + \kappa_\lambda^{\rm abs}(\mathbf{r})B_\lambda(T(\mathbf{r}))\,\mathbf{I}_0 + \kappa_\lambda^{\rm sca}(\mathbf{r})\frac{1}{4\pi}\iint_\Omega \mathbf{S}_\lambda(\mathbf{r},\mathbf{n}',\mathbf{n})\mathbf{I}_\lambda(\mathbf{r},\mathbf{n}')d\Omega',$$

PHANTOM + MCFOST

github.com/danieljprice/phantom
github.com/cpinte/mcfost

Phantom: Price+ 2018
MCFOST: Pinte+ 2006, 2009
Phantom+MCFOST: Pinte+2019; Nealon, Price & Pinte 2020; Borchert+2022a,b; Rowther+2024

PHANTOM+MCFOST WITH ACCRETION FEEDBACK



Borchert et al. (2022a,b)

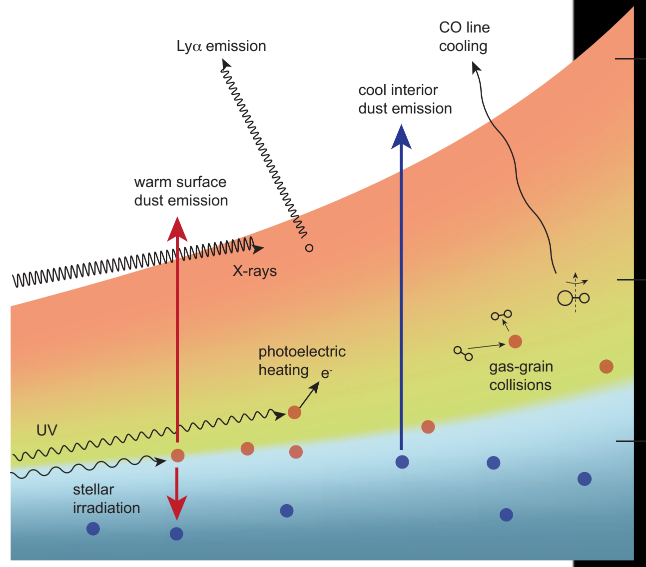
GRAVITATIONAL INSTABILITY IN IRRADIATED DISCS

Rowther, DP+2024

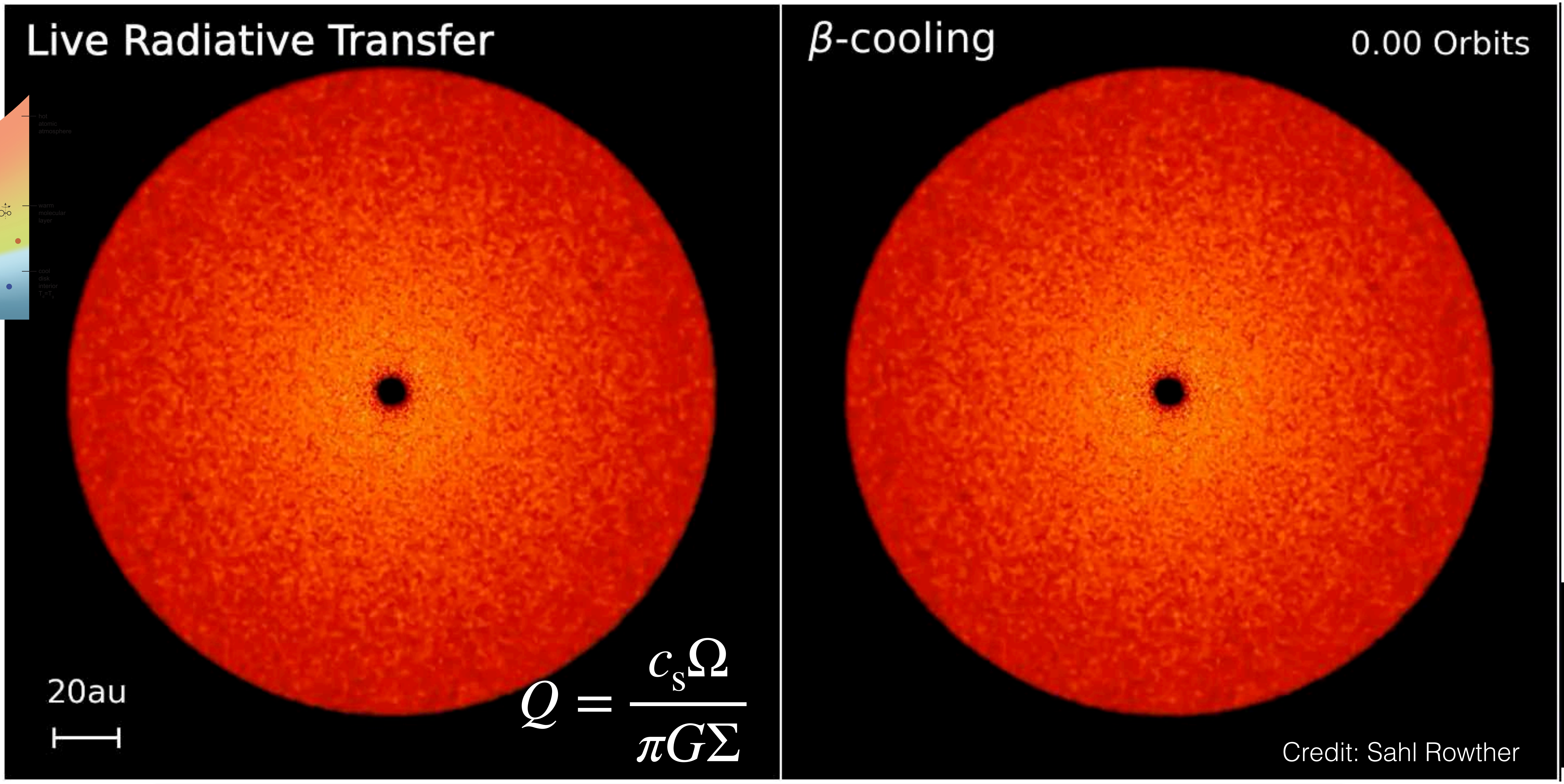
Heating and cooling (including shock heating) treated self-consistently with Phantom+MCFOST

Assume radiative equilibrium at each step

$$t_{\rm rad} = 1.1\,{\rm days} \left(\frac{\kappa}{5\,{\rm cm^2/g}}\right)\left(\frac{\rho}{2\times 10^{-13}{\rm g/cm^3}}\right)\left(\frac{H}{3.0\,{\rm au}}\right)^2$$



Phantom calls MCFOST every ~7 years, less than fastest orbital period at 4 au



Irradiation dominates the thermal energy budget: surface density drops with time due to angular momentum transport, which quenches the instability

Also found by Matzner & Levin 2005; Cai+2008, Meru & Bate 2010, Kratter & Murray-Clay 2011, Forgan & Rice 2013, Cadman+2020

RADIATIVE TRANSFER IN THE FLUX LIMITED DIFFUSION APPROXIMATION

Whitehouse & Bate 2004; Whitehouse+ 2005

$$\frac{D\boldsymbol{v}}{Dt} = -\frac{\nabla p}{\rho} + \frac{\chi}{c}\boldsymbol{F},$$

$$\frac{D\xi}{Dt} = -\frac{\nabla\cdot\boldsymbol{F}}{\rho} - \frac{\nabla\boldsymbol{v}\boldsymbol{:}\boldsymbol{P}}{\rho} - ac\kappa\left[\frac{\rho\xi}{a} - \left(\frac{u}{c_{\rm v}}\right)^4\right],$$

$$\xi = E/\rho$$

$$\frac{Du}{Dt} = -\frac{p\nabla\cdot\boldsymbol{v}}{\rho} + ac\kappa\left[\frac{\rho\xi}{a} - \left(\frac{u}{c_{\rm v}}\right)^4\right],$$

$$R = |\nabla E|/(\chi\rho E)$$

$$-\frac{\nabla\cdot\boldsymbol{F}}{\rho} = \frac{1}{\rho}\nabla\cdot\left(\frac{c\lambda}{\kappa\rho}\nabla E\right)$$

$$\lambda(R) = \frac{2+R}{6+3R+R^2}.$$

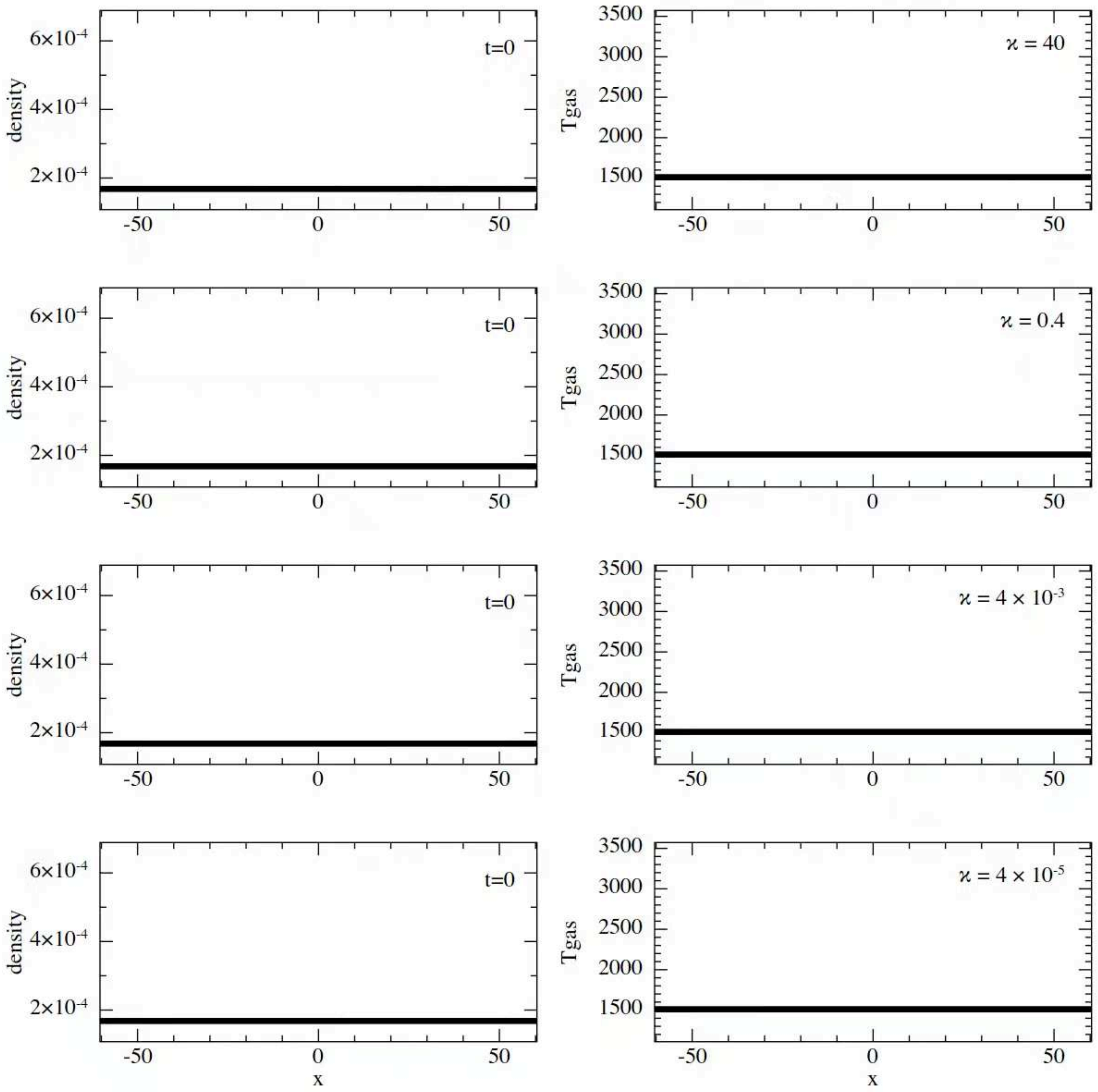
method rather than iterating over the exchange of energy between pairs of particles. The new algorithm is typically many thousands of times faster than the old one, which will enable more

Levermore & Pomraning (1981)

RADIATION WITH FLUX LIMITED DIFFUSION

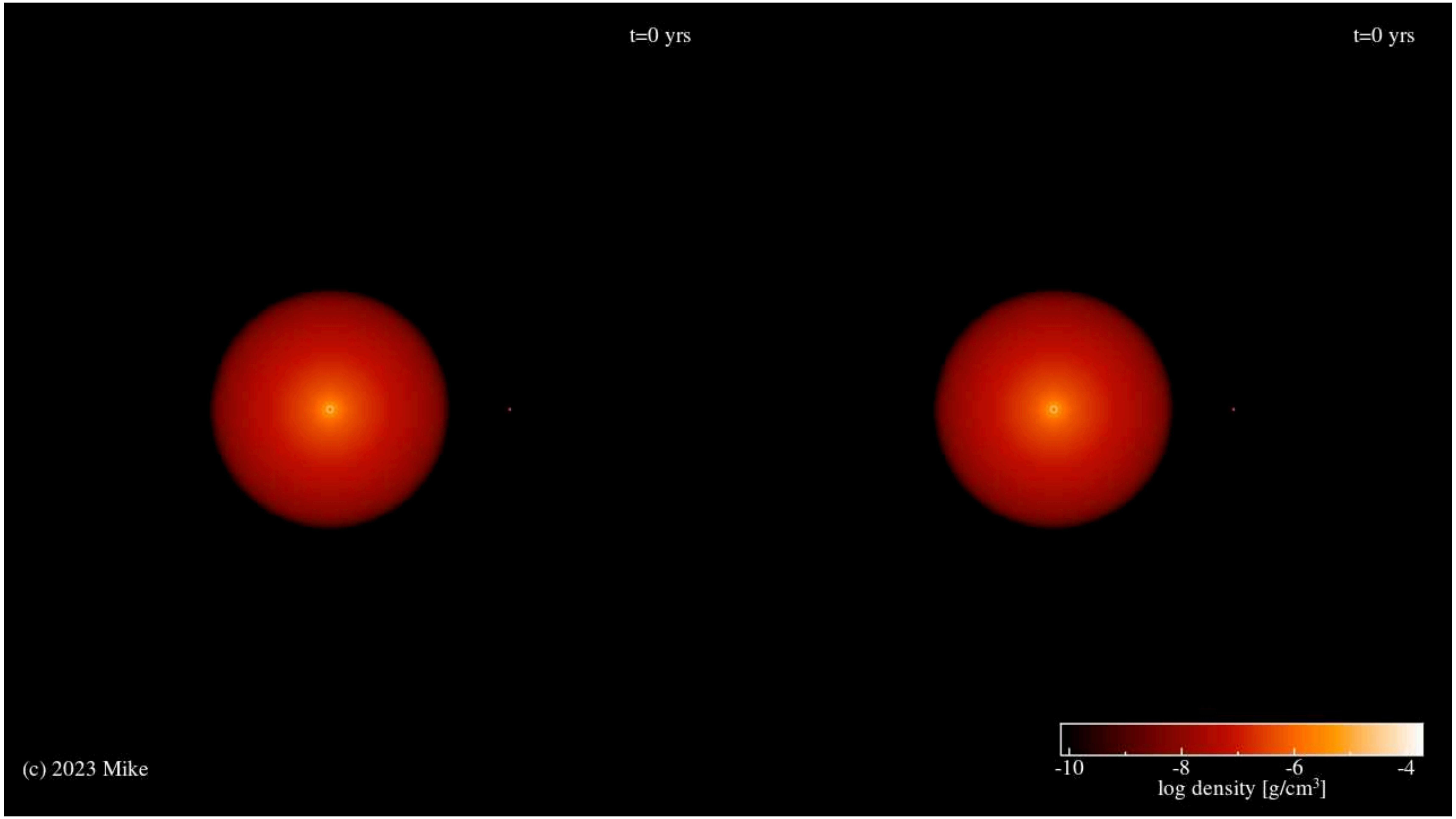
- Direct port of sphNG algorithm (Whitehouse & Bate 2004)
- Fast (Whitehouse, Bate & Monaghan 2005)
- Available in code with RADIATION=yes!

Radiation shock tube test, showing heat “leaking” through the shock front as opacity is lowered



COMMON ENVELOPES WITH RADIATIVE TRANSFER IN THE FLUX LIMITED DIFFUSION APPROXIMATION

Lau+2025, arXiv:2503.20506



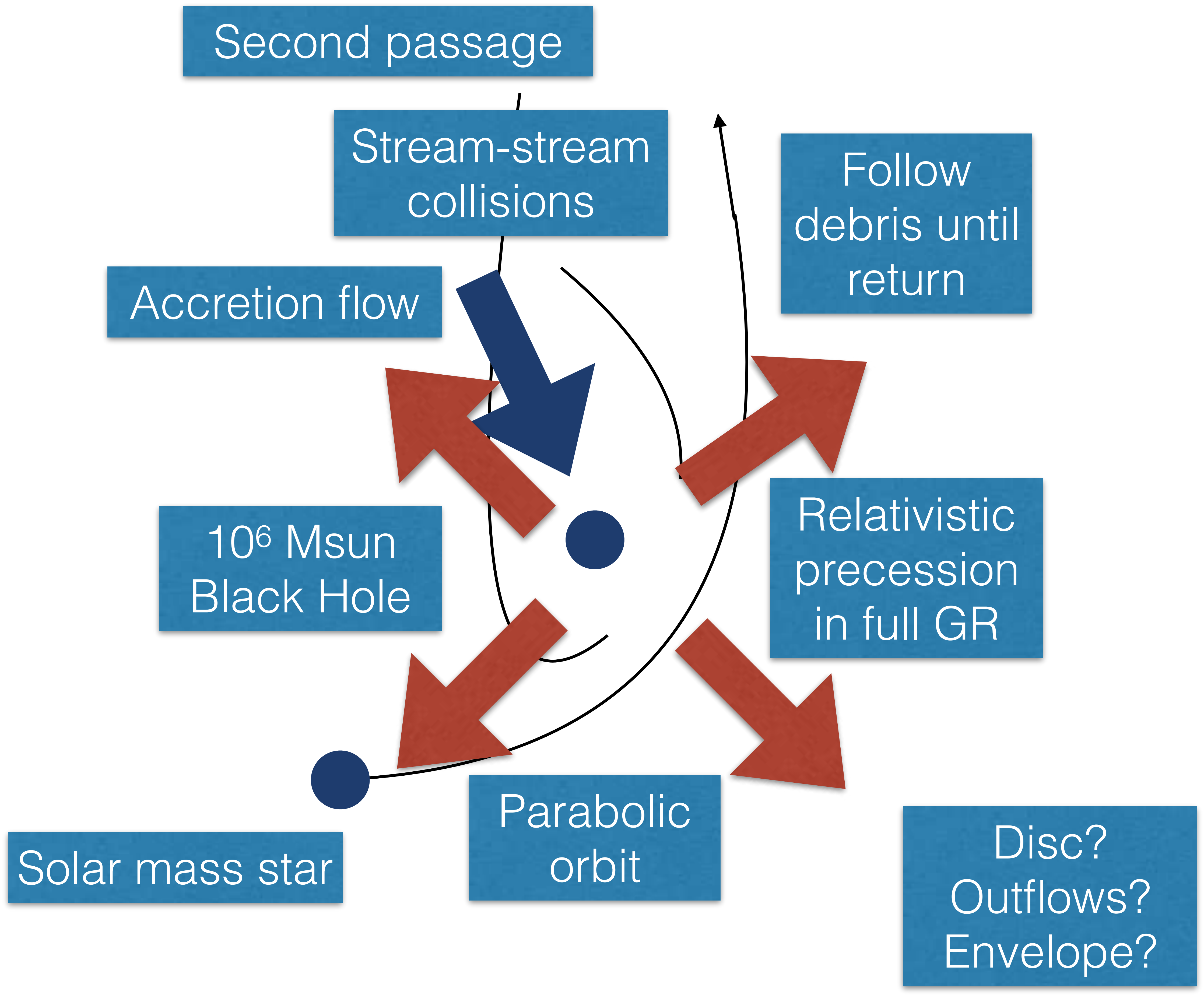
With core luminosity + radiation diffusion

Adiabatic EOS

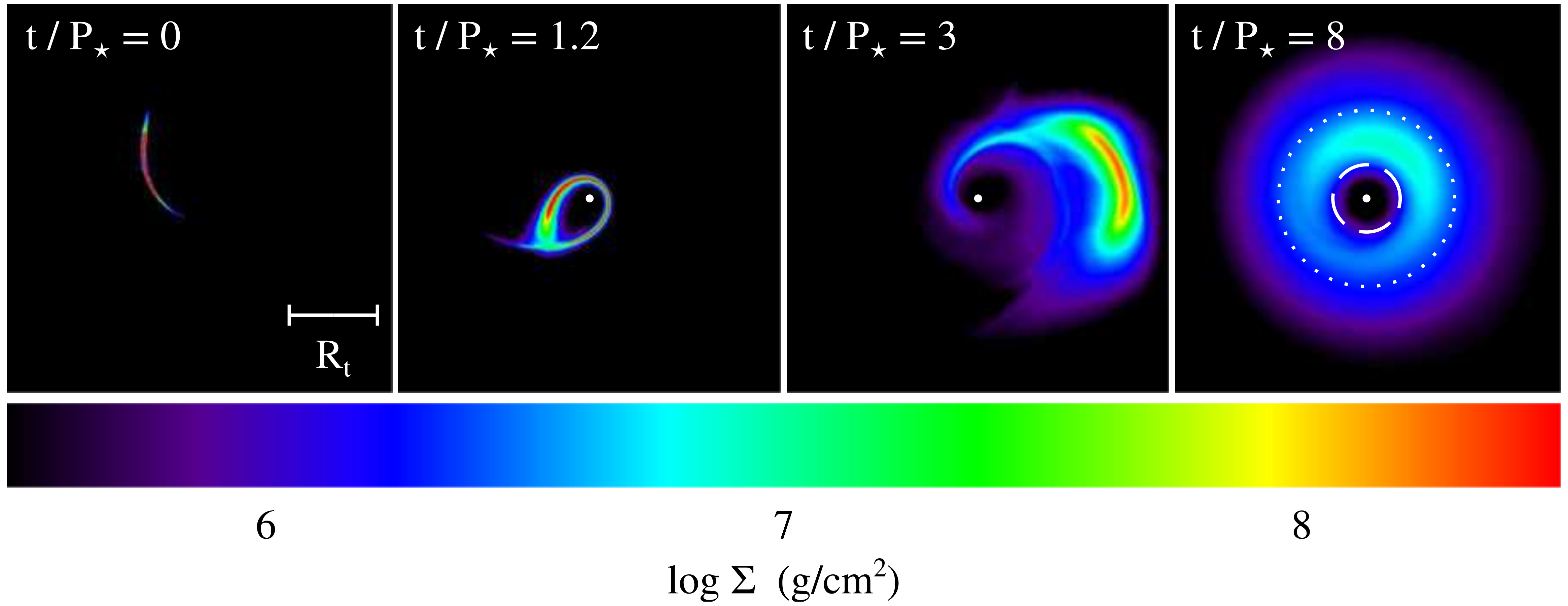
Also allows for steady simulations of the convective envelope incl. pulsations!

Need to couple this scheme to the dust formation

THE GRAND CHALLENGE OF TIDAL DISRUPTION EVENTS



DISC FORMATION IN TIDAL DISRUPTION EVENTS 101



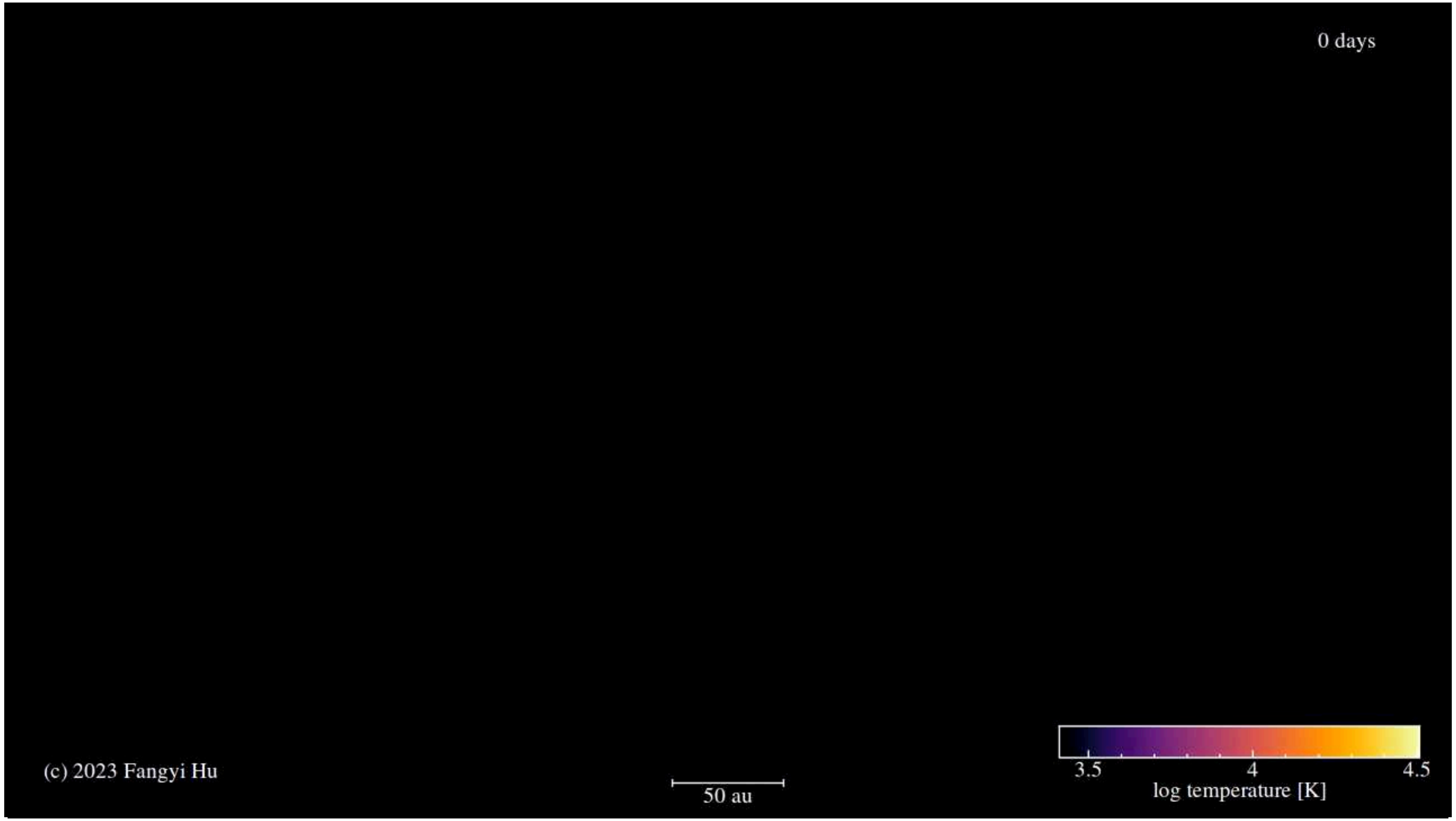
Bonnerot et al. (2016):
post-Newtonian gravity,
polytropic stars

Stream self-intersection due to GR precession leads to rapid disc formation and accretion

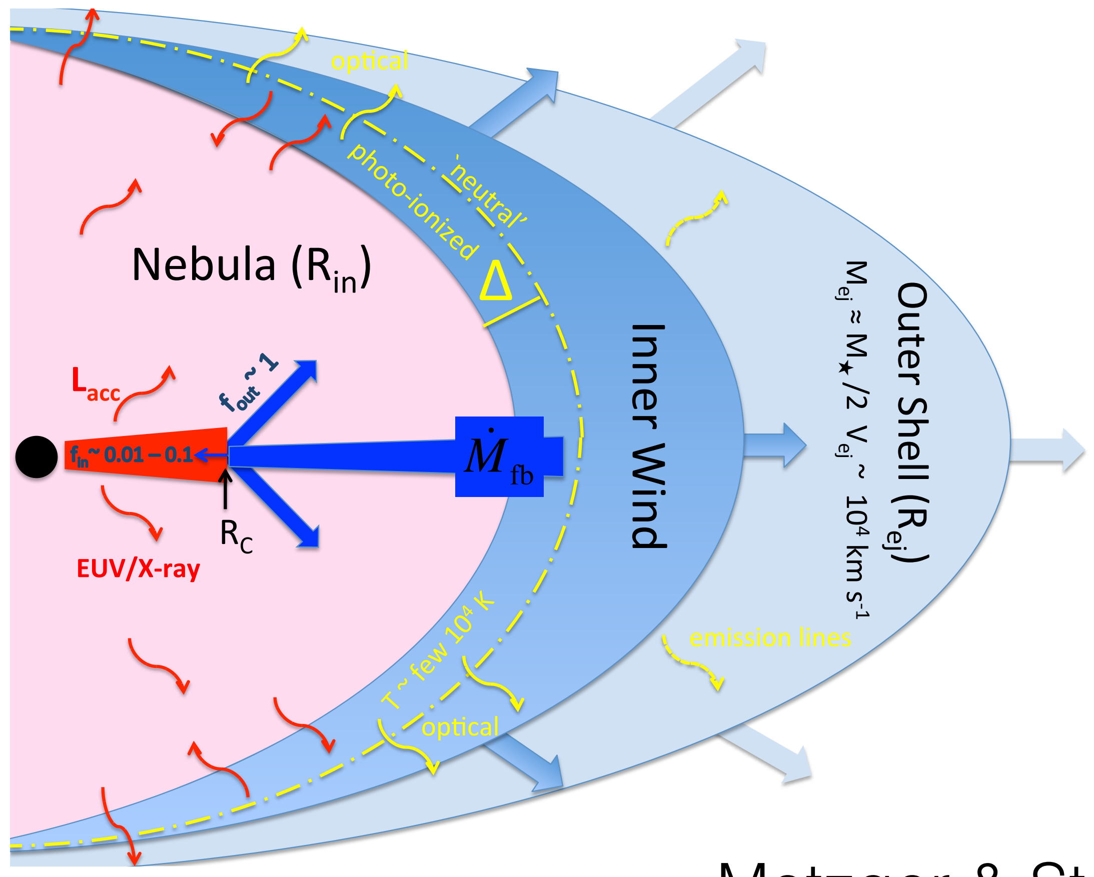
Hu et al. (2024):
GR-Phantom in Schwarzschild metric (Liptai & Price 2019), real stars imported from MESA (with phantom's relax-o-matic™ star setup)

Stream self-intersection due to GR precession leads to rapid disc formation and accretion

DISC FORMATION IN TIDAL DISRUPTION EVENTS 102



- Super-Eddington outflows smother the black hole!
- Material is optically thick
- Natural explanation for the "reprocessing layer" or "Eddington envelope" hypothesised to explain why TDEs mostly emit in optical rather than X-rays



Metzger & Stone (2016)

Post-processed using "splash calc lightcurve" which assumes blackbody emission from each particle with T=Tgas

c.f. Loeb & Ulmer (1997), Menou & Quataert (2001), Strubbe & Quataert (2009), Coughlin & Begelman (2014), Jiang et al. (2016), Metzger & Stone (2016), Mockler et al. (2019), Metzger (2022), Price et al. (2024)

OTHER RECENT DEVELOPMENTS MERGED TO MASTER

- HII region feedback (Bernard+2025)
- 4th order integration scheme for gravitational forces + regularisation of tight binaries (Bernard+2025)
- Implicit dust scheme from Loren-Aguilar & Bate (Michoulier 2023; global timestepping only)
- Eccentric disc setup (Ragusa+)
- Tillotson equation of state for asteroids / solids (Price, Tilly+ in prep.)
- Easy setup of solar system objects ("add_body", like in REBOUND)
- General set_stars module to set up arbitrary number of any kind of star in any kind of configuration, also can enter properties in arbitrary units
- New set_orbit module to accept all kinds of ways to set up orbits, in arbitrary units
- Live coupling of GR code with numerical relativity (Magnall+2023)
- Sink particles now working in GR code
- Development work in progress on GRMHD code
- Support for ifx compiler, flang support in progress
- Downloaded data files now hosted on Zenodo, not DP's web page. You can even add your own!

WHAT’S NEXT?

Mission statement:

Develop phantom into a world-leading code for computational astrophysics that "just works", with a toolkit that makes comparing simulations with observations easy

Credit: wikipedia/Piotr Małecki

MAJOR DEVELOPMENT AREAS / WISH LIST

- Improved parallel scaling, especially in MPI code
- Radiation hydrodynamics
- Dust formation
- Dust evolution
- On-the-fly chemistry
- GRMHD
- <your ideas here>

EXAMPLE DISCUSSION (FROM 1ST PHANTOM WORKSHOP)

- Annual meeting? (YES)
- Anyone want to host one? (Chris: Eclipse in Chile in July 2019? Also possibility for small workshop in Milan during DP visit in June/July 2018)
- How to best support user base? - use of mailing list, slack channel. Can we create some kind of stack-overflow type user forum?
- Host Monthly dev telecons. First Tuesday of the month, maybe linked to the release schedule? Minutes should be taken
- Resourcing of code dev tools (e.g. pipeline minutes)? Merchandise! t-shirts, mugs, hats, beach towels (don't panic + phantom), laser-cubes, keep calm and use phantom, keep cups, drink bottles
- Code releases: First ok of the month should become a release…
- Create a simulation datastore similar to the PASA datastore? Could link existing datastore from wiki page (.setup, .in, output files)
- Should create phantom data tables repository in bitbucket, so data files do not live on DP personal website