Star-by-star Evolution in RAMSES-RTZ

Radiative Feedback and Chemical Enrichment on the Individual-star Level

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Introduction

Star particles in simulations – Star “Clusters”, not stars

NASA, ESA, CSA, and STScI, A. Pagan (STScI) (https://esawebb.org/images/weic2518a/)

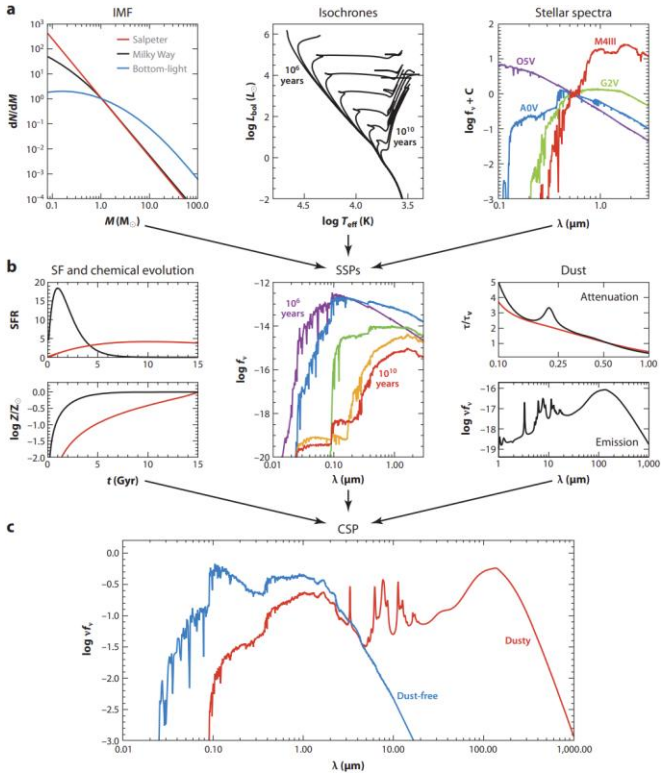


Figure 1 from Conroy 13 (Conroy C., 2013, ARA&A, 51, 393)

$m_\star = 10^7\ M_\odot$

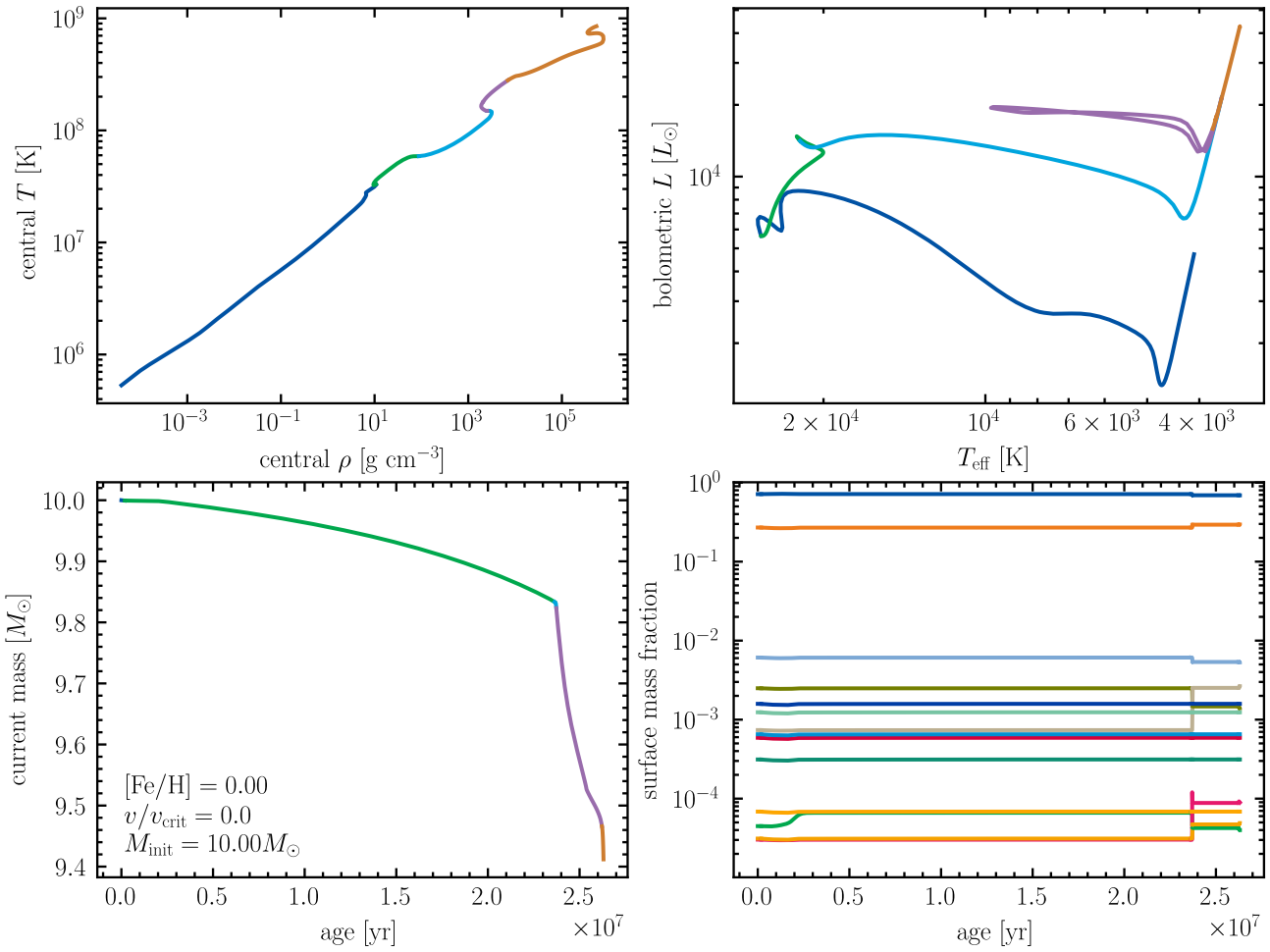
● $m_\star = 10^4\ M_\odot$

$m_\star = 10\ M_\odot$??

Star “cluster” particle becomes oversimplifications when $m_\star < 500 - 10^3\ M_\odot$ (Revaz+16, Smith 21)

RAMSES + MIST + POLLUX

What is MIST?



MESA Isochrones & Stellar Tracks

Papers:
Dotter A., 2016, ApJS, 222, 8
Choi J. et al., 2016, ApJ, 823, 102

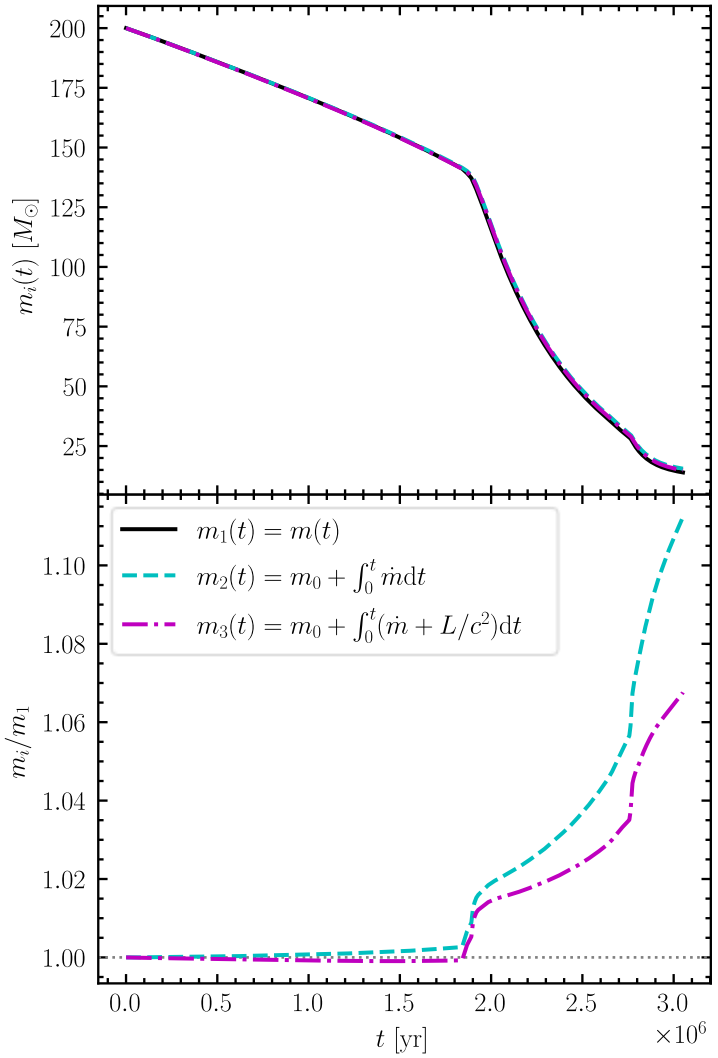
Stellar evolutionary models computed with the MESA code (Paxton+11) and isochrones extracted from them

Parameters:

- Metallicity $[\mathrm{Fe/H}]$: -4.0 - $+0.5$
- Rotation speed $v/v_{\rm crit}$: 0.0 and 0.4
- Initial mass $M_{\rm init}$: 0.1 $M_\odot$ - 300 $M_\odot$

RAMSES + MIST + POLLUX

To be cautious on MIST – 1. Mass loss rate



From one stellar evolutionary track file
(one combination of $[\mathrm{Fe/H}]$, v/v_{crit}, and m_0)

- $m(t)$: given current mass
- $\dot{m}(t)$: given mass-loss rate (with negative sign)

By the mass conservation,

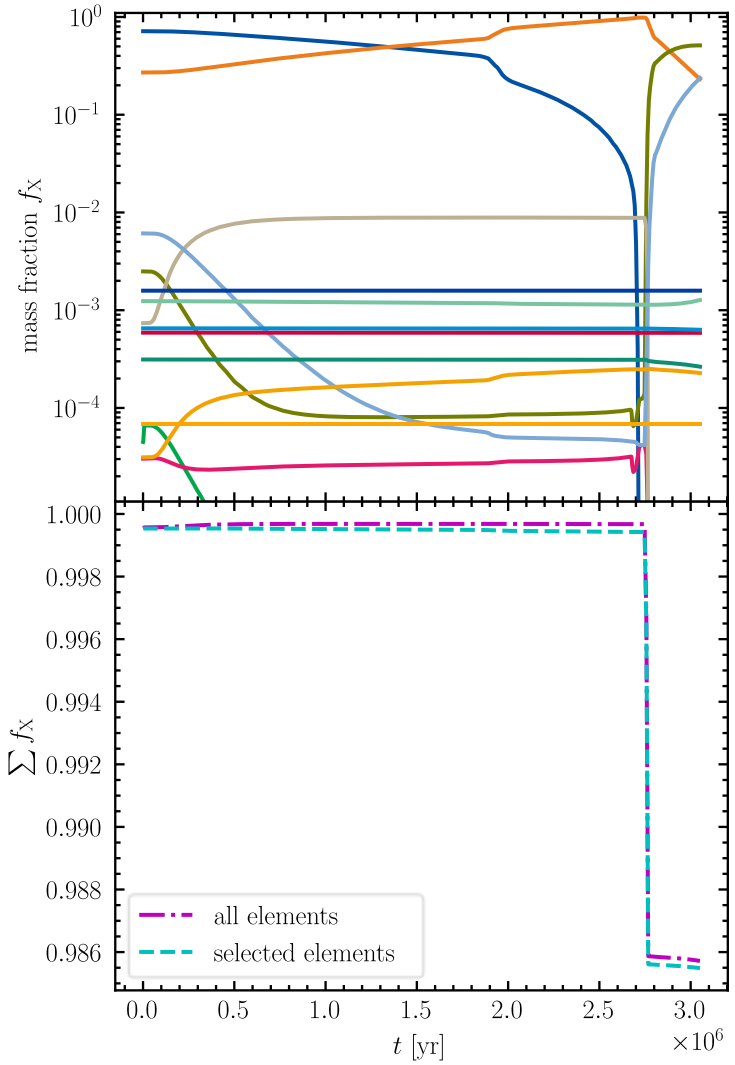
$$m(t) = m_0 + \int_0^t \dot{m}(t')\mathrm{d}t'$$

Being resampled from raw MESA runs, however, MIST does not guarantee a strict mass conservation in between current mass and ejected mass.

⇒ Based on the current mass, recalculate the ejected mass

RAMSES + MIST + POLLUX

To be cautious on MIST – 2. Mass fractions



MIST provides surface mass fractions of 19 chemical elements. Mass fractions should add up to a unity:

$$\sum_{\mathrm{X}} f_{\mathrm{X}} = 1$$

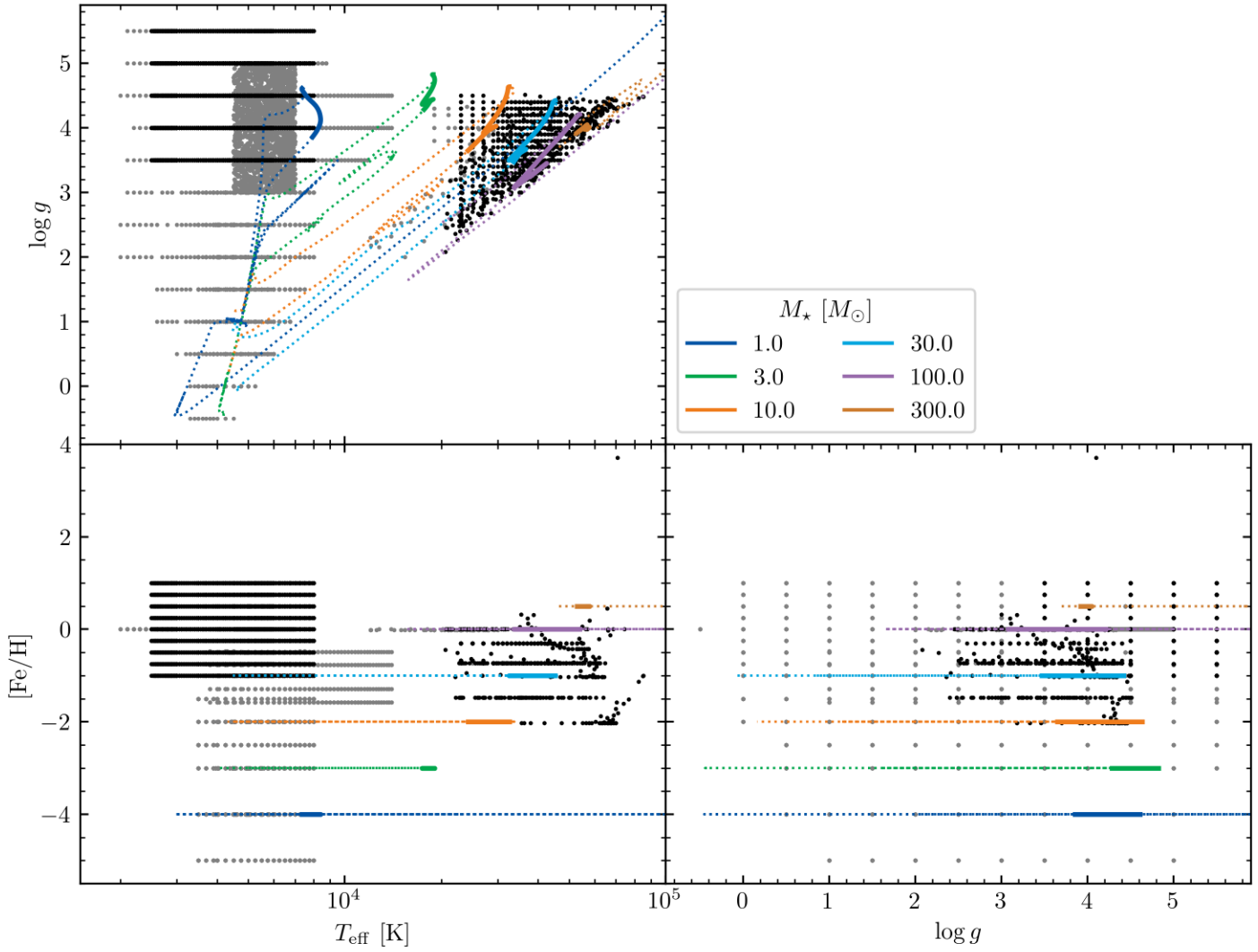
However, some elements were omitted in the MIST, so the summation of the mass fractions deviates from the unity. Plus, for the comparability with the RAMSES-RTZ code, 6 more elements were dropped.

⇒ H and He are “boosted” to ensure the mass conservation

$$m_{\mathrm{ej}}(t;\mathrm{X}) = \int_0^t \dot{m}(t') f_{\mathrm{X}}(t') \mathcal{B}(t') \mathrm{d}t'$$

RAMSES + MIST + POLLUX

What is POLLUX?



Public database of stellar synthetic spectra from multiple theoretical models

Paper:
Palacios A. et al., 2010, A&A, 516, A13

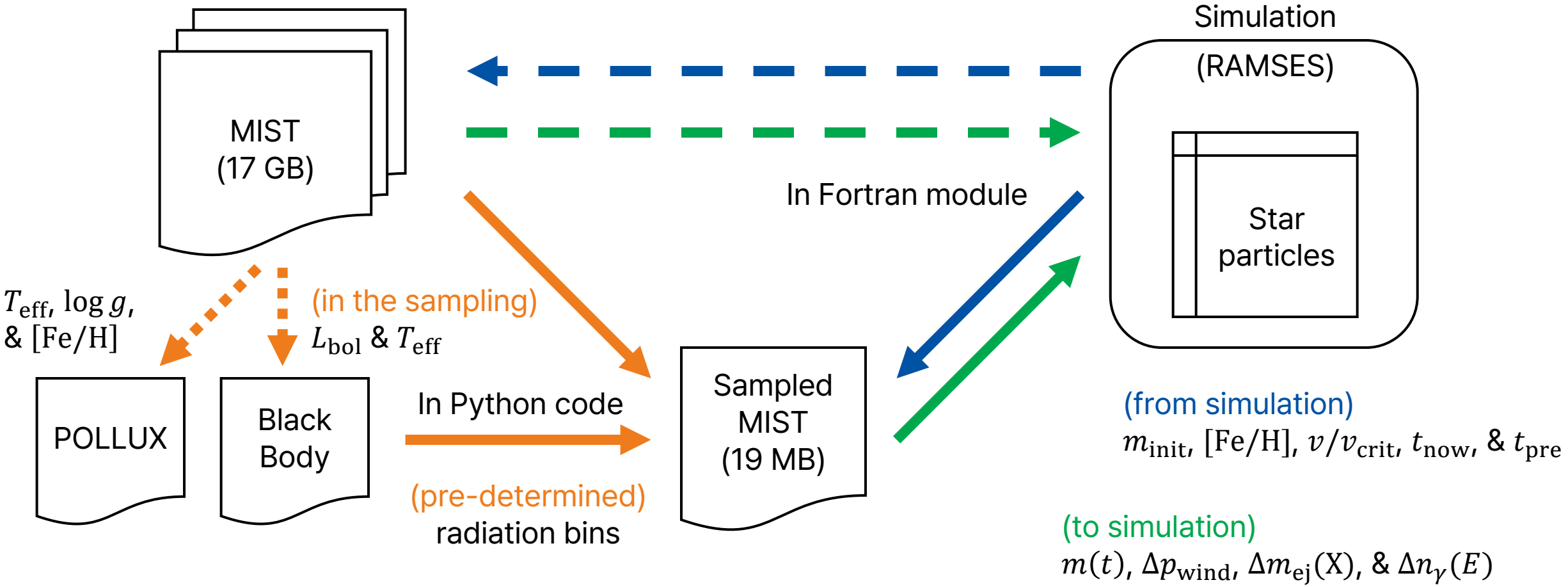
Webpage: https://pollux.oreme.org/

Stellar atmosphere models:

- ATLAS
- CMFGEN
- MARCS
- PHOENIX
- STAGGER

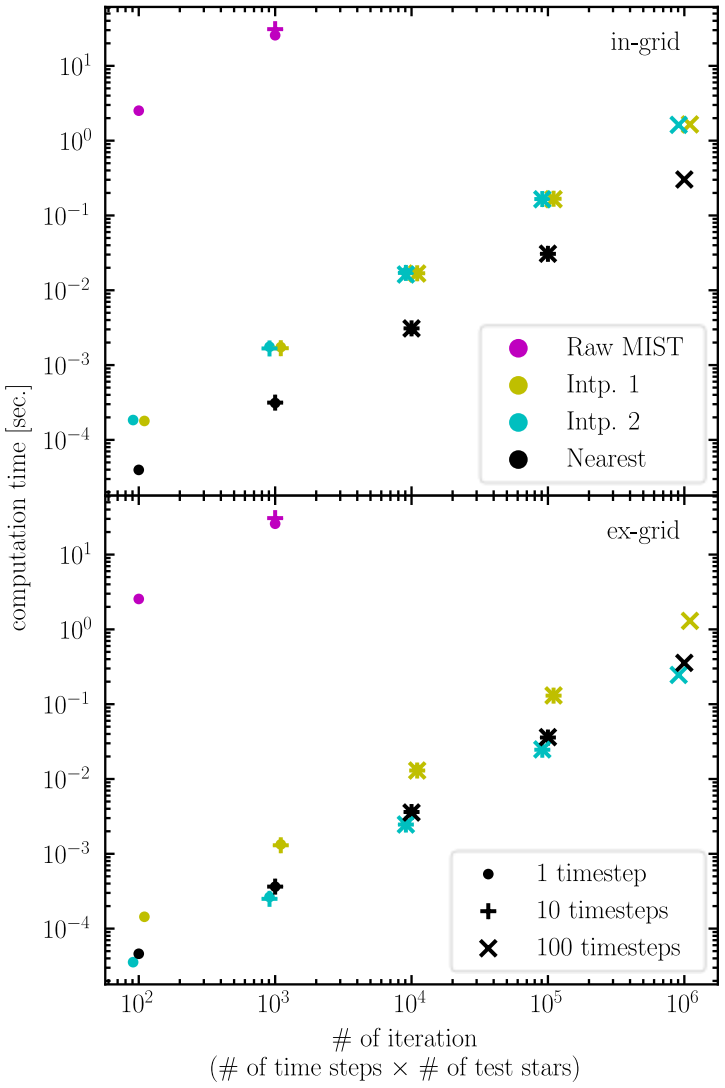
RAMSES + MIST + POLLUX

Data flow



Benchmarks on my module

Computation time



Before the module being implemented, several tests and comparisons are conducted.

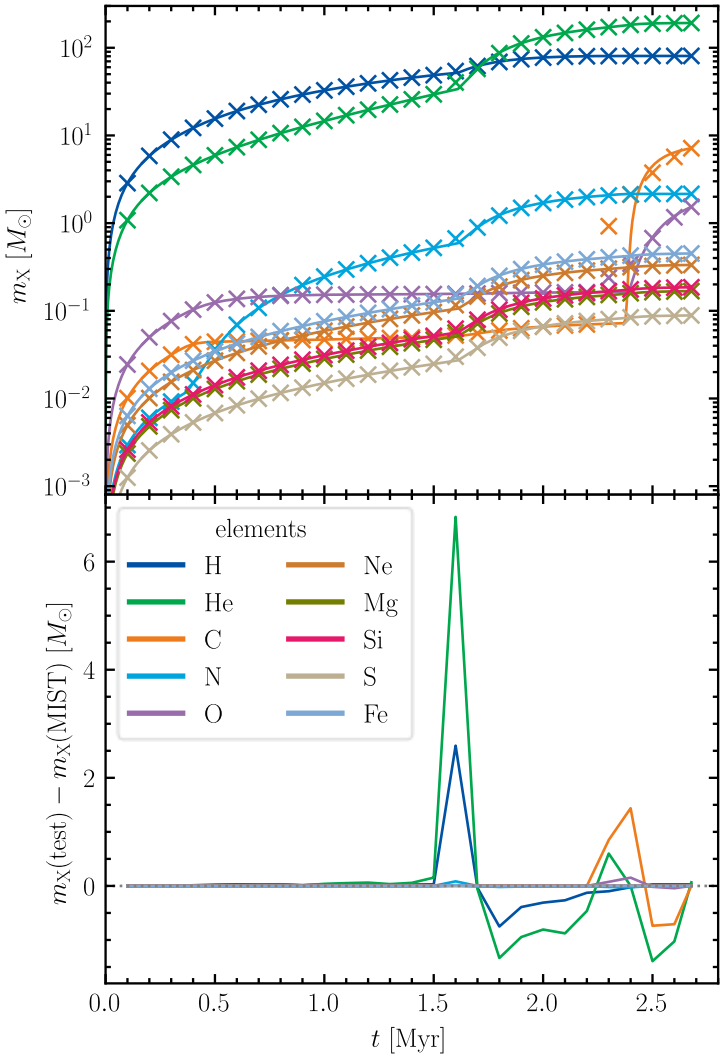
For each test particle, different methods do:

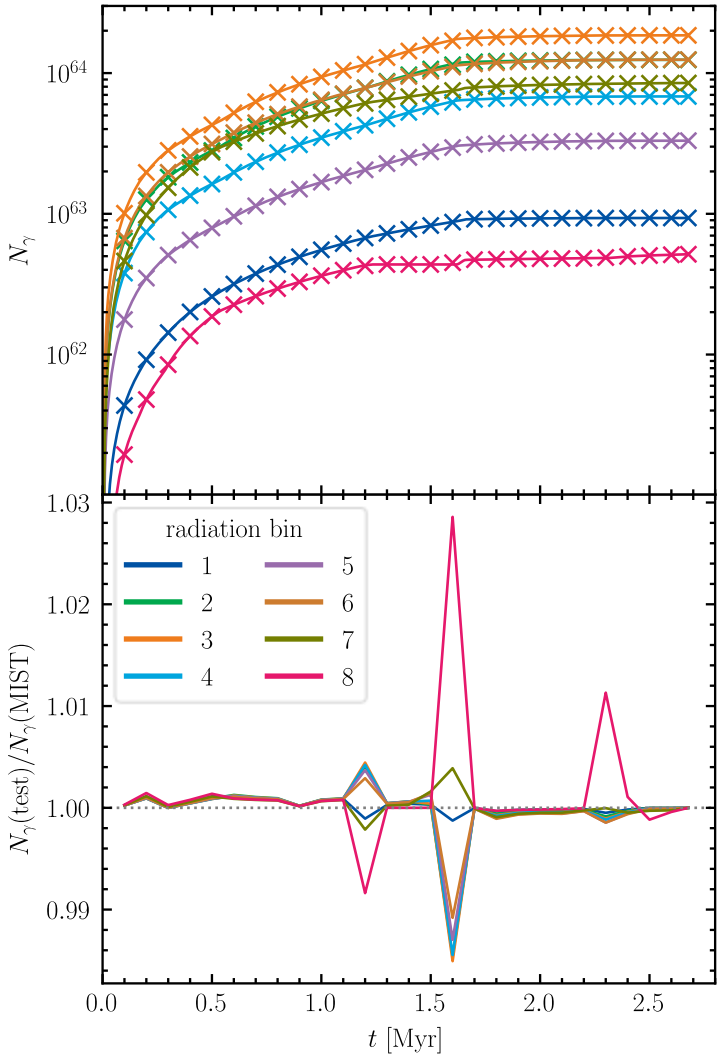
- Raw MIST: read raw MIST files in the Fortran module directly
- Intp. 1: do interpolations always
- Intp. 2: skip interpolations if it is outside of the parameter grid
- Nearest: take a grid point nearest to it

Except the extreme case, where test particles are all outside of the parameter grids, taking a nearest sample point is faster than interpolation methods by a factor of 5.

Benchmarks on my module

Conservations of mass ejecta and photons





After implementing my module in RAMSES, end-to-end tests are done to check the conservation of mass ejecta and photon numbers.

← Test result:

- $M_\star = 300\ M_\odot$
- $[\mathrm{Fe/H}] = 0.0$
- $v/v_{\mathrm{crit}} = 0.0$

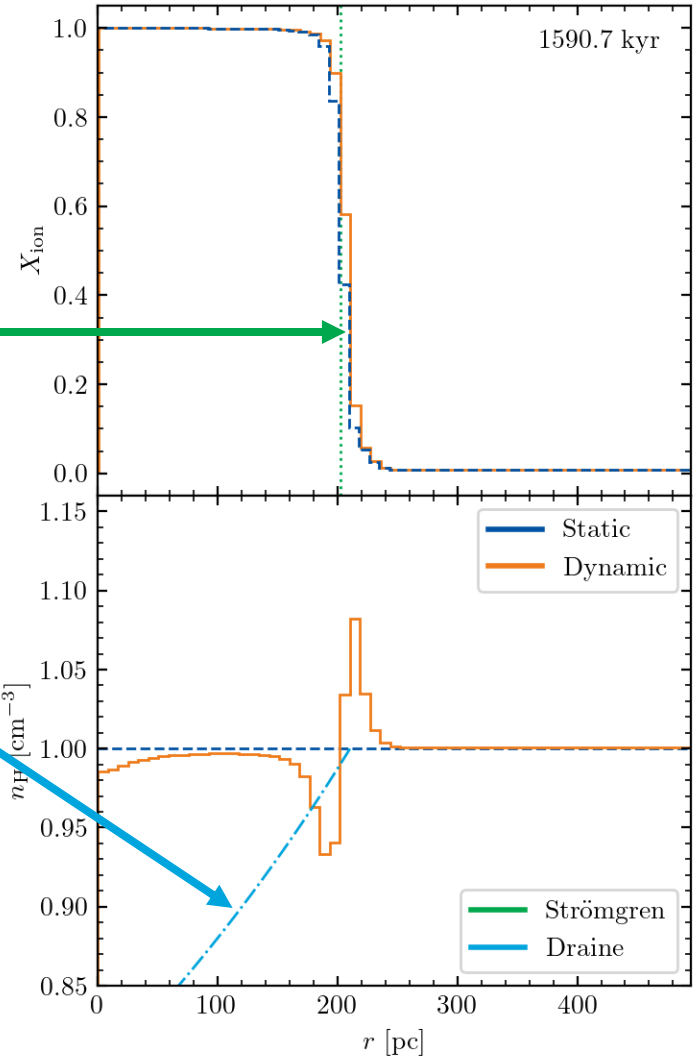
Because of the logarithmic bins along the time axis, there are some deviations.

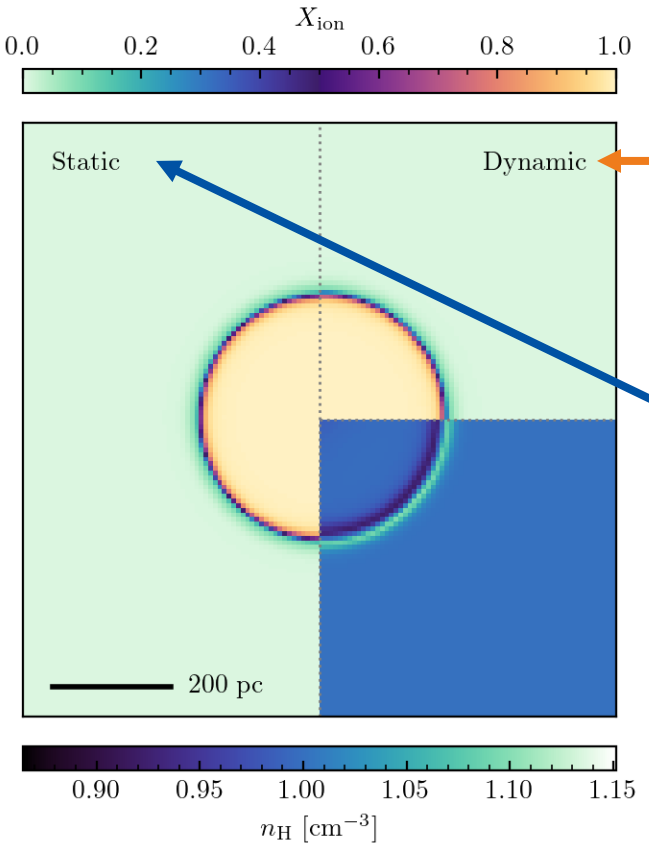
Benchmarks on my module

Strömgren sphere test

Expected Strömgren Sphere radius

Expected number density profile (Draine 11)





Gas motion
+
Ionizations

No gas motion;
Only ionizations

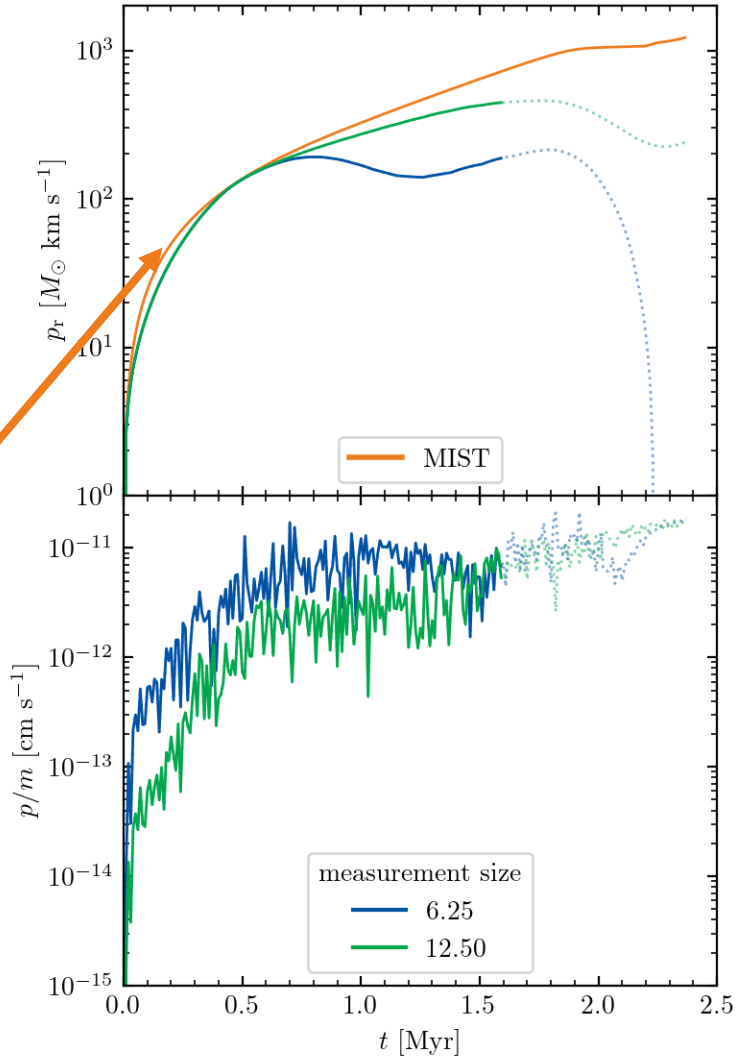
Benchmarks on my module

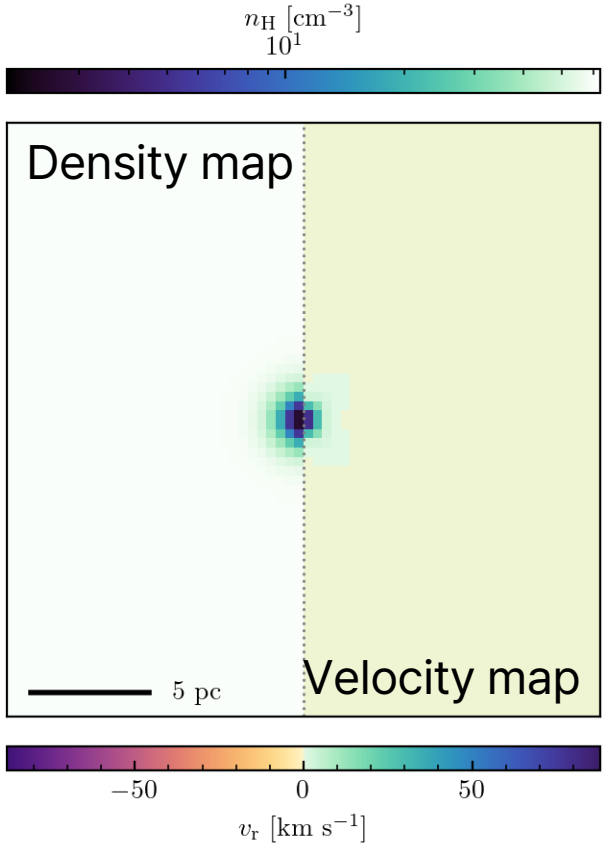
Conservations of momenta

Magnitude of radial momentum

Expected from MIST

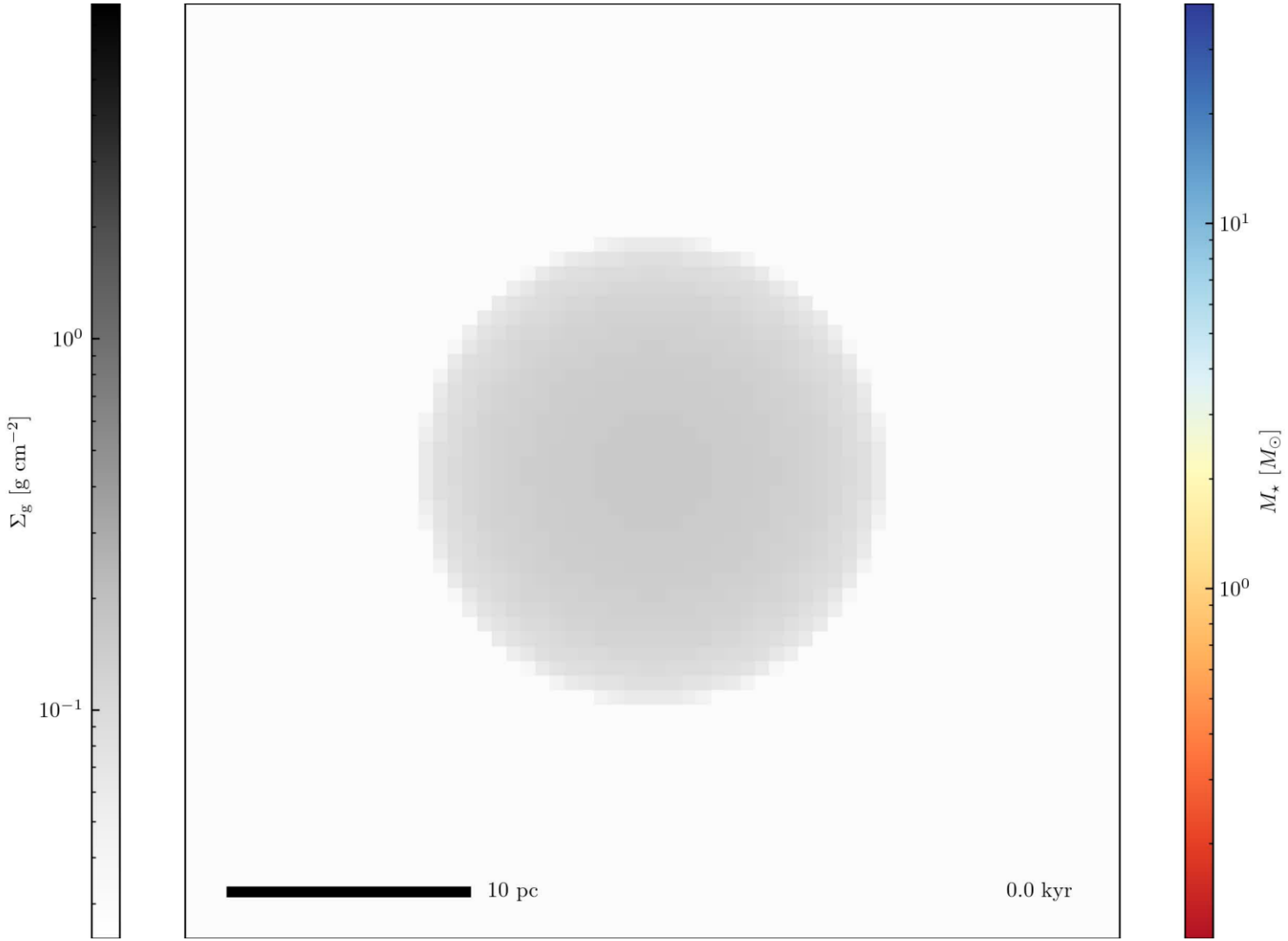
Magnitude of translational momentum divided by mass





On-going projects

Individual star formation in a giant molecular cloud



Summary

- Simulation on a level of individual star-forming cloud, with mass resolution approaching the mass of massive stars, needs **individual tracking** of the stellar evolution.

- **Combining MIST and POLLUX databases**, star-by-star chemistry and radiation evolution are enabled in the RAMSES-RTZ code.

- Mass ejecta, photon counts, and translational momenta are **strictly conserved** as expected.

- Individual stellar evolution module can help answer multiple questions:
  1. What determines the **star formation efficiency** of a cloud?
  2. How **observables** of a star-forming region can be affected by **different media properties**?
  3. … What will my verse be?

References

<Main slides>

Choi J., Dotter A., Conroy C. et al., 2016, ApJ, 823, 102

Conroy C., 2013, ARA&A, 51, 393

Dotter A., 2016, ApJS, 222, 8

Draine B. T., 2011, ApJ, 732, 100

Palacios A., Gebran M., Josselin E. et al., 2010, A&A, 516, A13

Paxton B., Bildsten L., Dotter A. et al., 2011, ApJS, 192, 3

Revaz Y., Arnaudon A., Nichols M. et al., 2016, A&A, 588, A21

Smith M. C., 2021, MNRAS, 502, 5417

<Images in main slides>

Slide 2: NASA, ESA, CSA, and STScI, A. Pagan (STScI), "Pismis 24"

<Appendices>

Eldridge J. J., Stanway E. R., Xiao L. et al., 2017, PASA, 34, 58

Ferland G. J., Chatzikos M., Guzmán F. et al., 2017, RMxAA, 53, 385

Gunawardhana M. L. P., Hopkins A. M., Bland-Hawthorn J. et al., 2013, MNRAS, 433, 2764

Katz H., Rosdahl J., Kimm T. et al., 2023, OJAp, 6, 44

Kennicutt R. C., Evans N. J., 2012, ARA&A, 50, 531

Kramarenko I. G., Rosdahl J., Blaizot J. et al., 2025, arXiv e-print:2509.05403

Medling A., Cortese L., Croom S. M. et al., 2018, MNRAS, 475, 5194

Michel-Dansac, L., Blaizot J., Garel T. et al., 2020, A&A, 635, A154

Stanway E. R., Eldridge J. J., 2018, MNRAS, 479, 75

<Images in appendices>

Slide 29: ESA/Hubble & NASA, J. Lee and the PHANGS-HST Team, "Eye in the Sky"