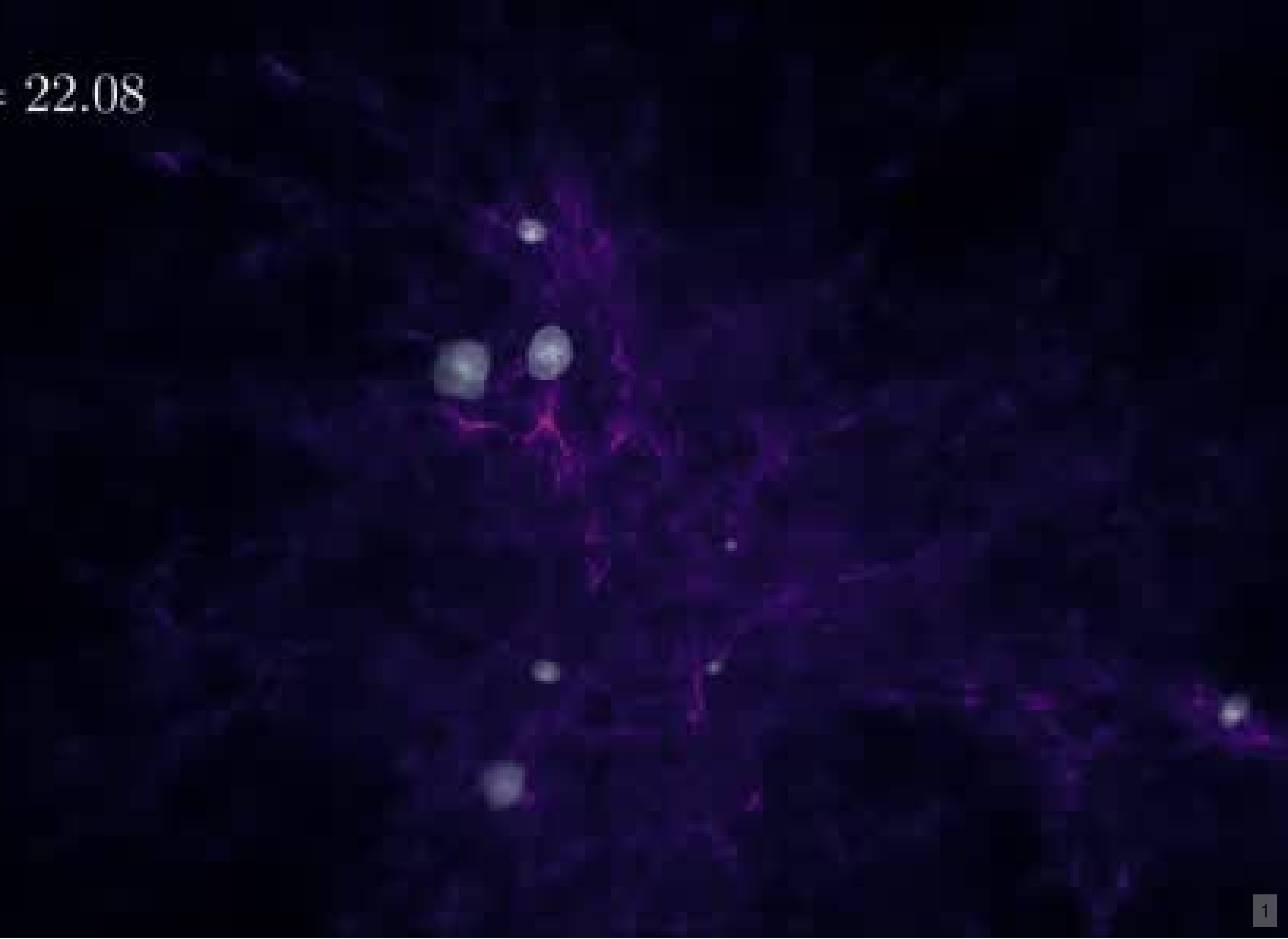

22.08

State of the Circum Galactic Medium in the Megatron simulations

Co-Is: Harley Katz, Martin Rey

Collaborators: Oscar Agertz, Jeremy Blaizot, Alex J. Cameron, Nicholas Choustikov, Julien Devriendt, Uliana Hauk, Gareth Jones, Taysun Kimm, Isaac Laseter, Aayush Saxena, Sergio Martin-Alvarez, Kosei Matsumoto, Camilla T. Nyhagen, Autumn Pearce, Francisco Rodriguez-Montero, Victor Rufo-Pastor, Joki Rosdahl, Adrianne Slyz, Richard Stiskalek, Anatole Storck, Wonjae Yee

First results in:

Rey+2025 — Katz+2025 — Cadiou+2025

&

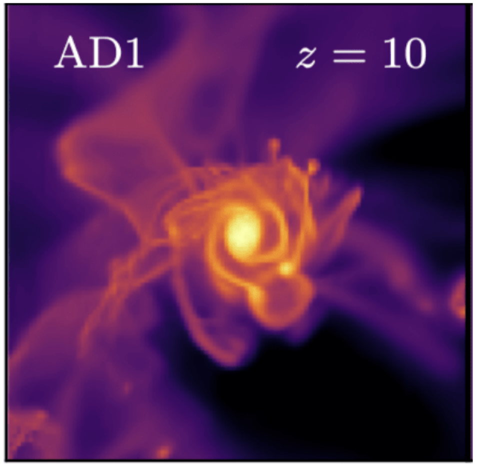
Choustikov+2025, Storck+2025

Corentin Cadiou

CNRS @ IAP, Paris

Typical path from sims to observations

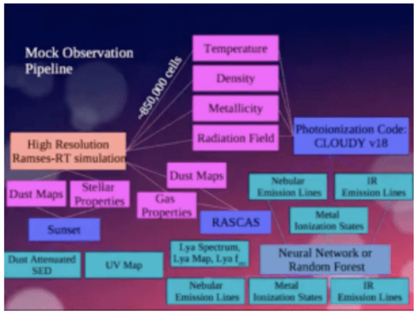
Physical space



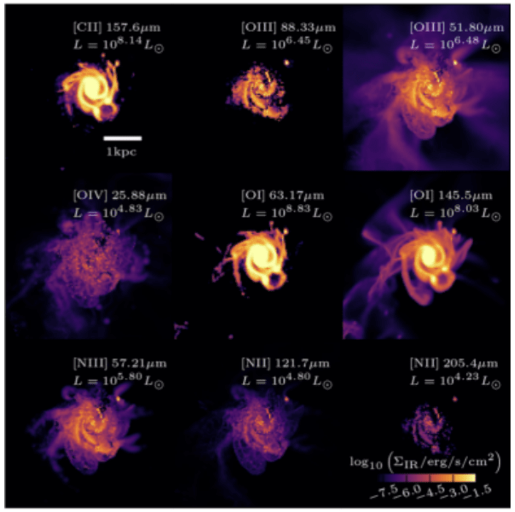
ρ, T, Z, v

sometimes

$n_{\mathrm{H}}, n_{\mathrm{H}^+}, n_{\mathrm{He}}, n_{\mathrm{He}^+}, n_{\mathrm{He}^{2+}}, n_{\mathrm{e}^-}$



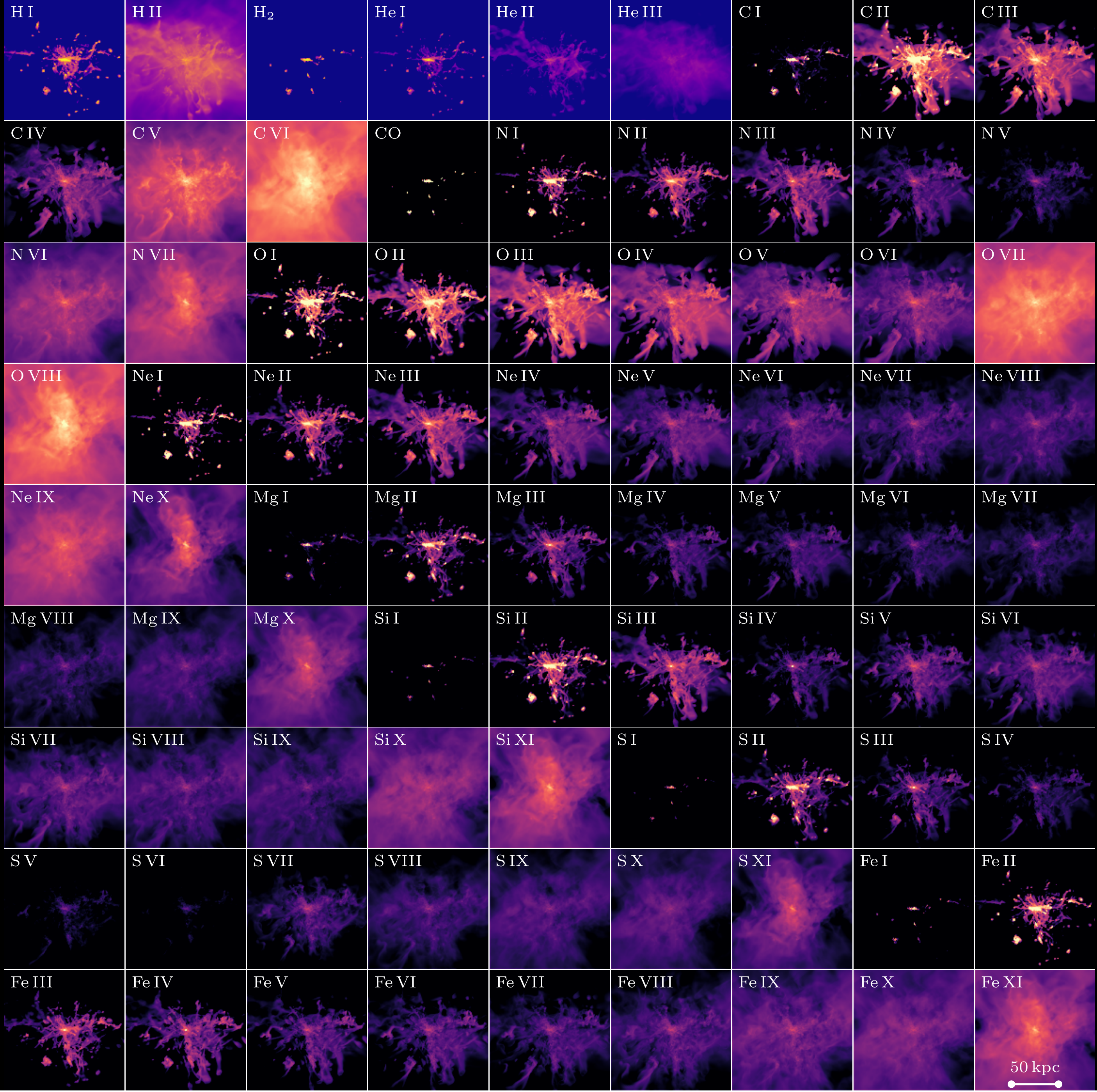
Observable

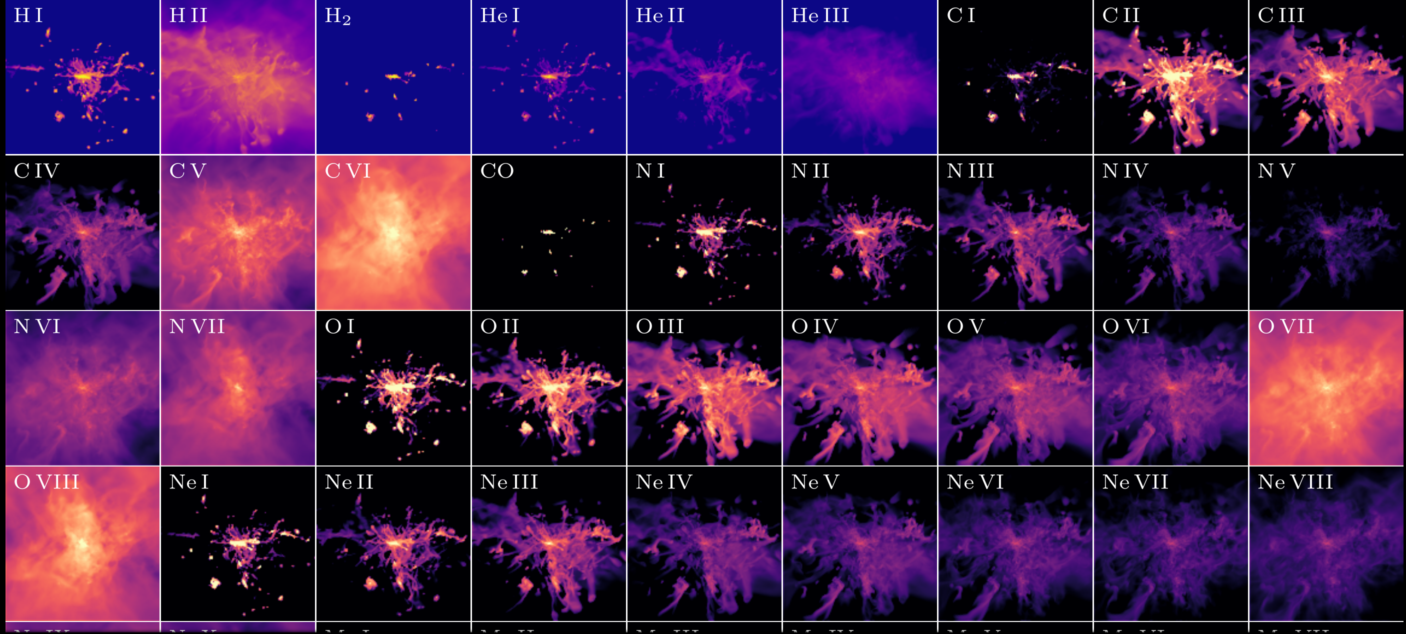


Katz+ 2019a

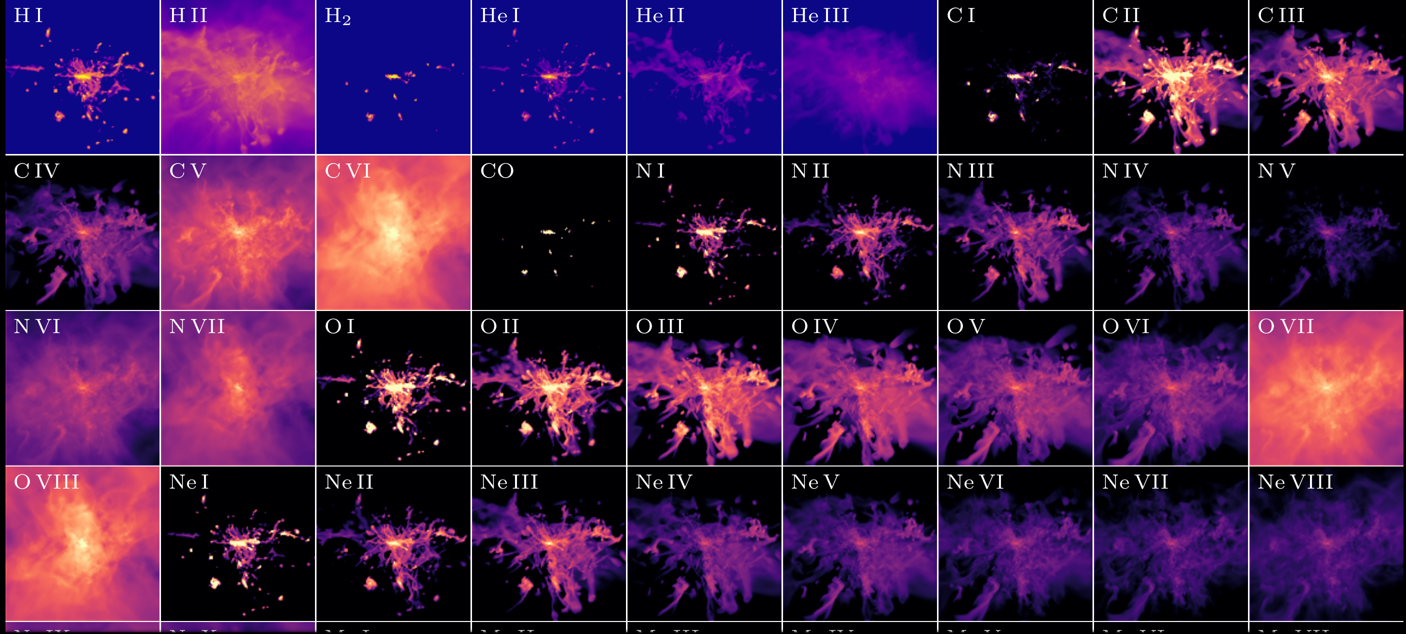
Lots of assumptions

(equilibrium, geometry, element abundances, ...)


H I
H II
$\mathrm{H_2}$
He I
He II
He III
C I
C II
C III
C IV
C V
C VI
CO
N I
N II
N III
N IV
N V
N VI
N VII
O I
O II
O III
O IV
O V
O VI
O VII
O VIII
Ne I
Ne II
Ne III
Ne IV
Ne V
Ne VI
Ne VII
Ne VIII
Ne IX
Ne X
Mg I
Mg II
Mg III
Mg IV
Mg V
Mg VI
Mg VII
Mg VIII
Mg IX
Mg X
Si I
Si II
Si III
Si IV
Si V
Si VI
Si VII
Si VIII
Si IX
Si X
Si XI
S I
S II
S III
S IV
S V
S VI
S VII
S VIII
S IX
S X
S XI
Fe I
Fe II
Fe III
Fe IV
Fe V
Fe VI
Fe VII
Fe VIII
Fe IX
Fe X
Fe XI
50 kpc

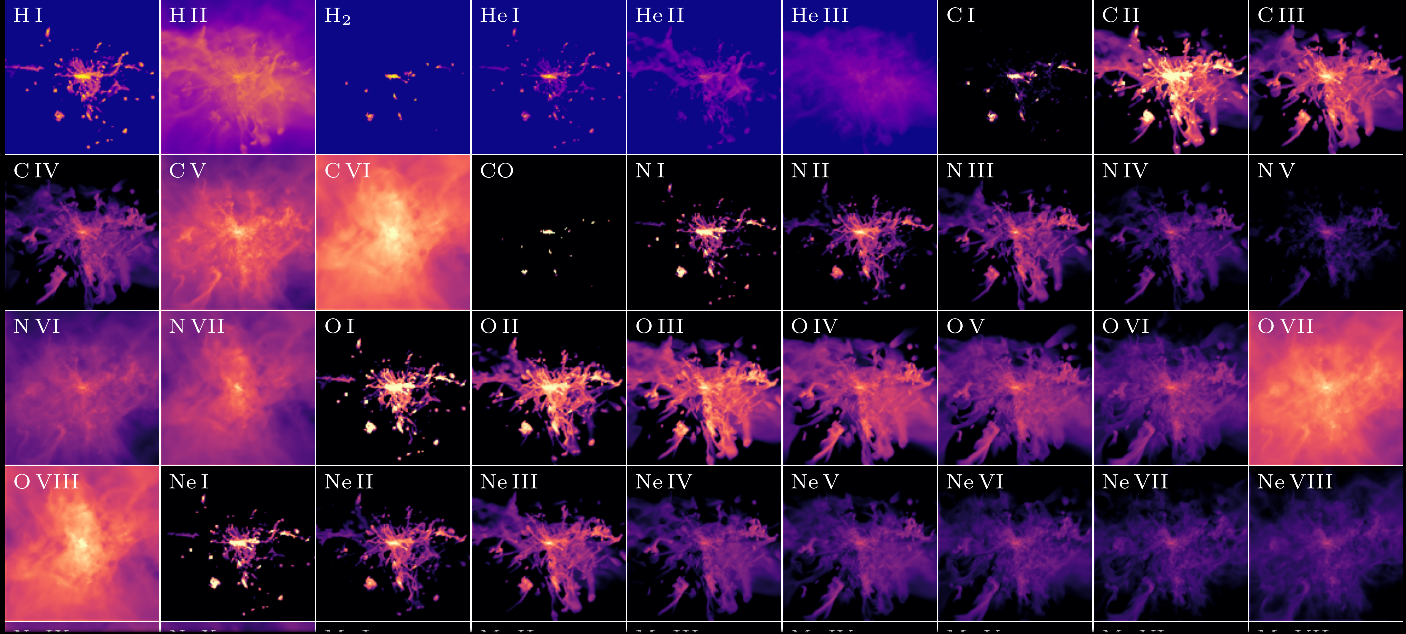


Megatron suite of simulations



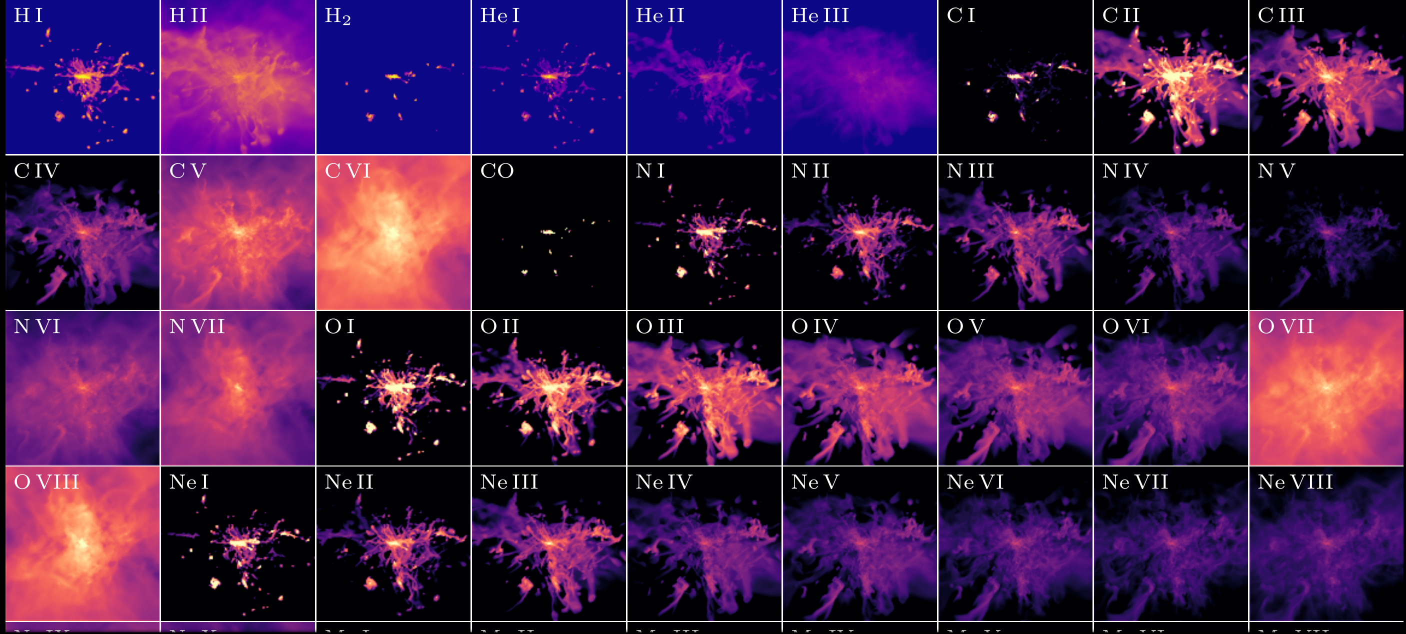
Megatron suite of simulations

1. On-the fly radiative transfer,



Megatron suite of simulations

1. On-the fly radiative transfer,
2. 81-ions non-equilibrium thermochemistry,



Megatron suite of simulations

1. On-the fly radiative transfer,
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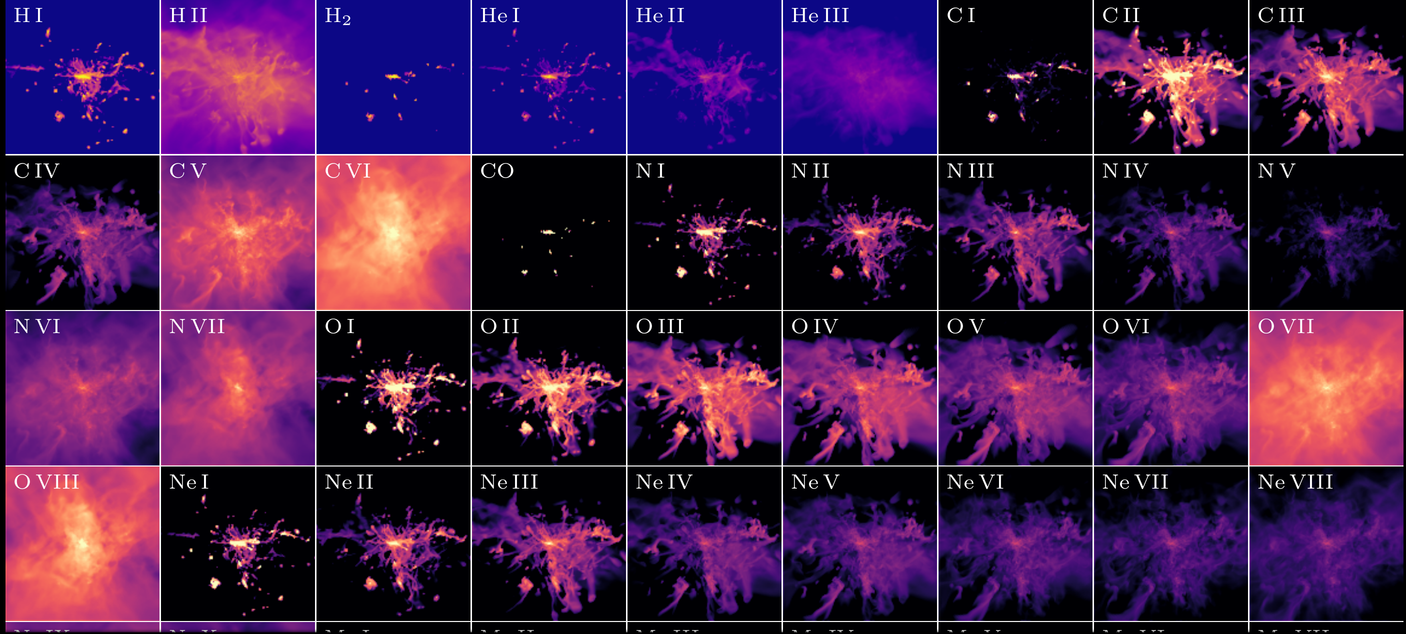
3. Chemical enrichment from SN and stellar winds,



Megatron suite of simulations

1. On-the fly radiative transfer,
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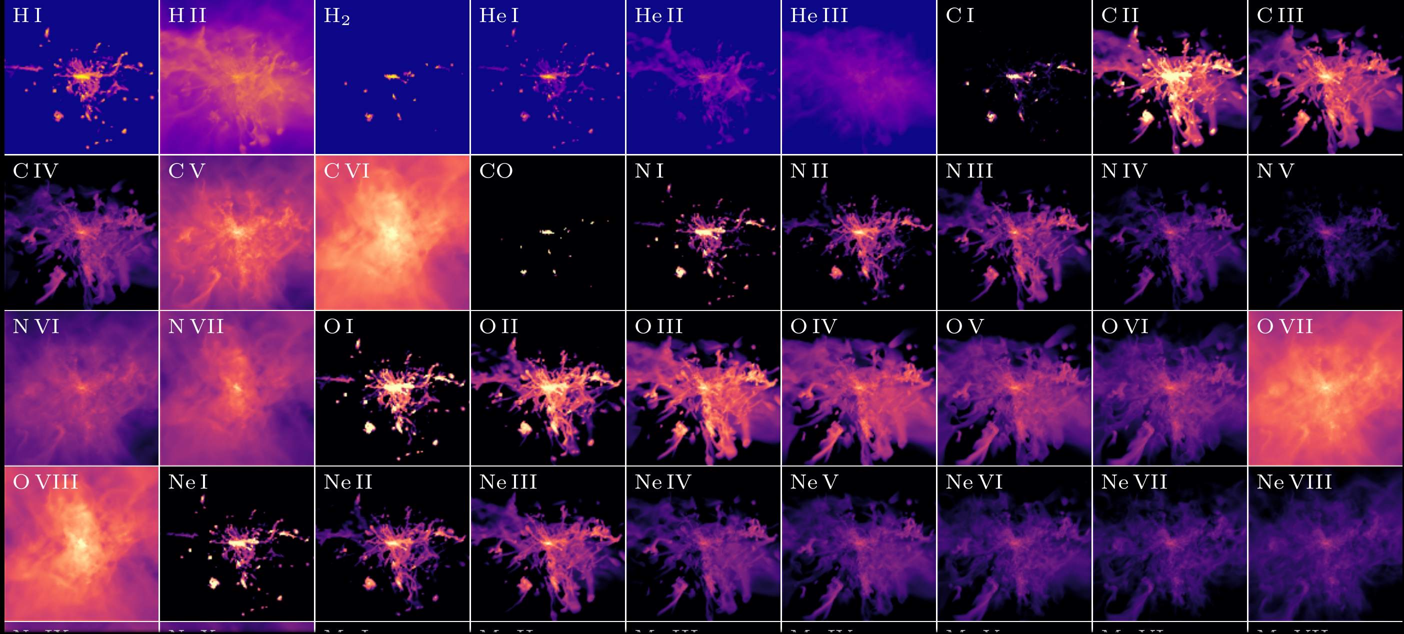
3. Chemical enrichment from SN and stellar winds,
4. Milky-Way progenitor,



Megatron suite of simulations

1. On-the fly radiative transfer,
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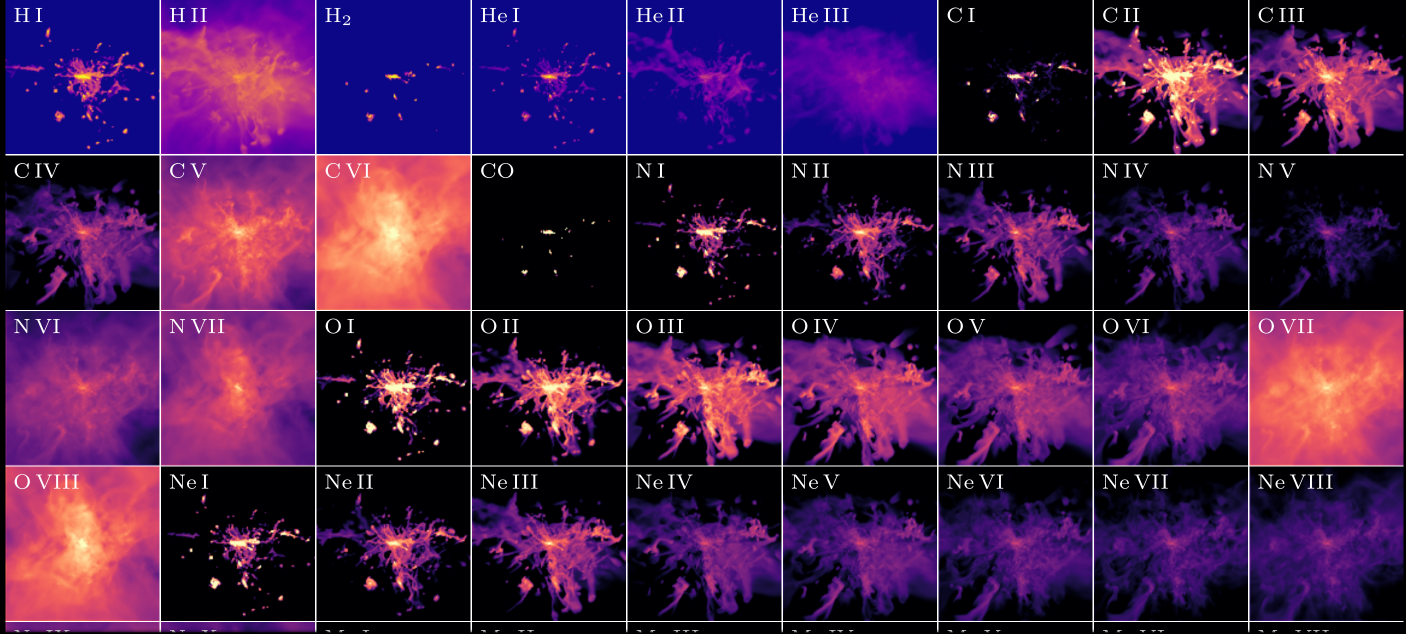
5. 4 “high-resolution” sims at $10\,\mathrm{pc}$ comoving,



Megatron suite of simulations

1. On-the fly radiative transfer,
2. 81-ions non-equilibrium thermochemistry,
3. Chemical enrichment from SN and stellar winds,
4. Milky-Way progenitor,
5. 4 “high-resolution” sims at $10\,\mathrm{pc}$ comoving,
6. 3+2 “low-z” sims at $23\,\mathrm{pc}$ proper.

ΣH I

ΣMg II

ΣH II

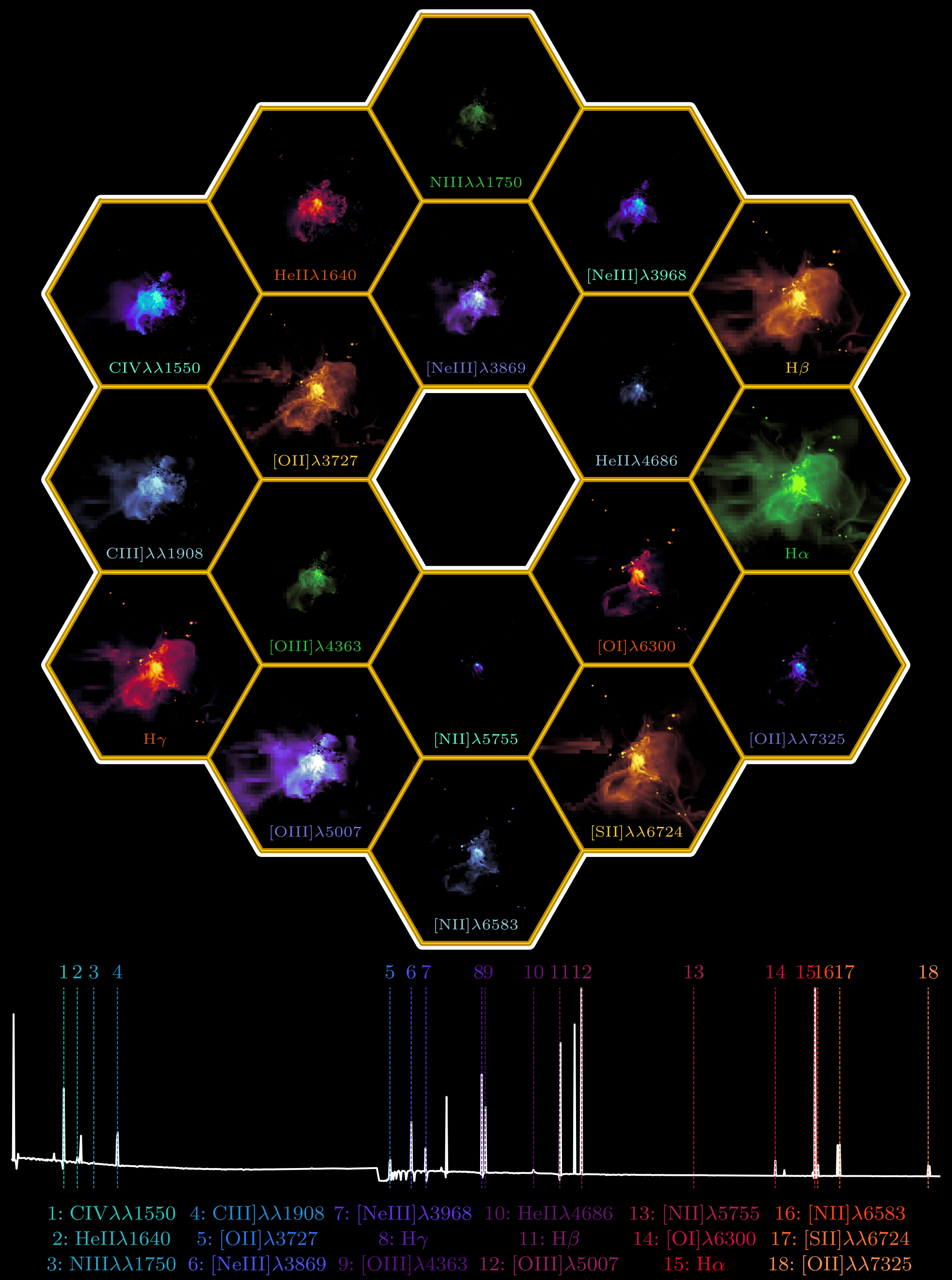
ΣO II

Mocks in absorption:

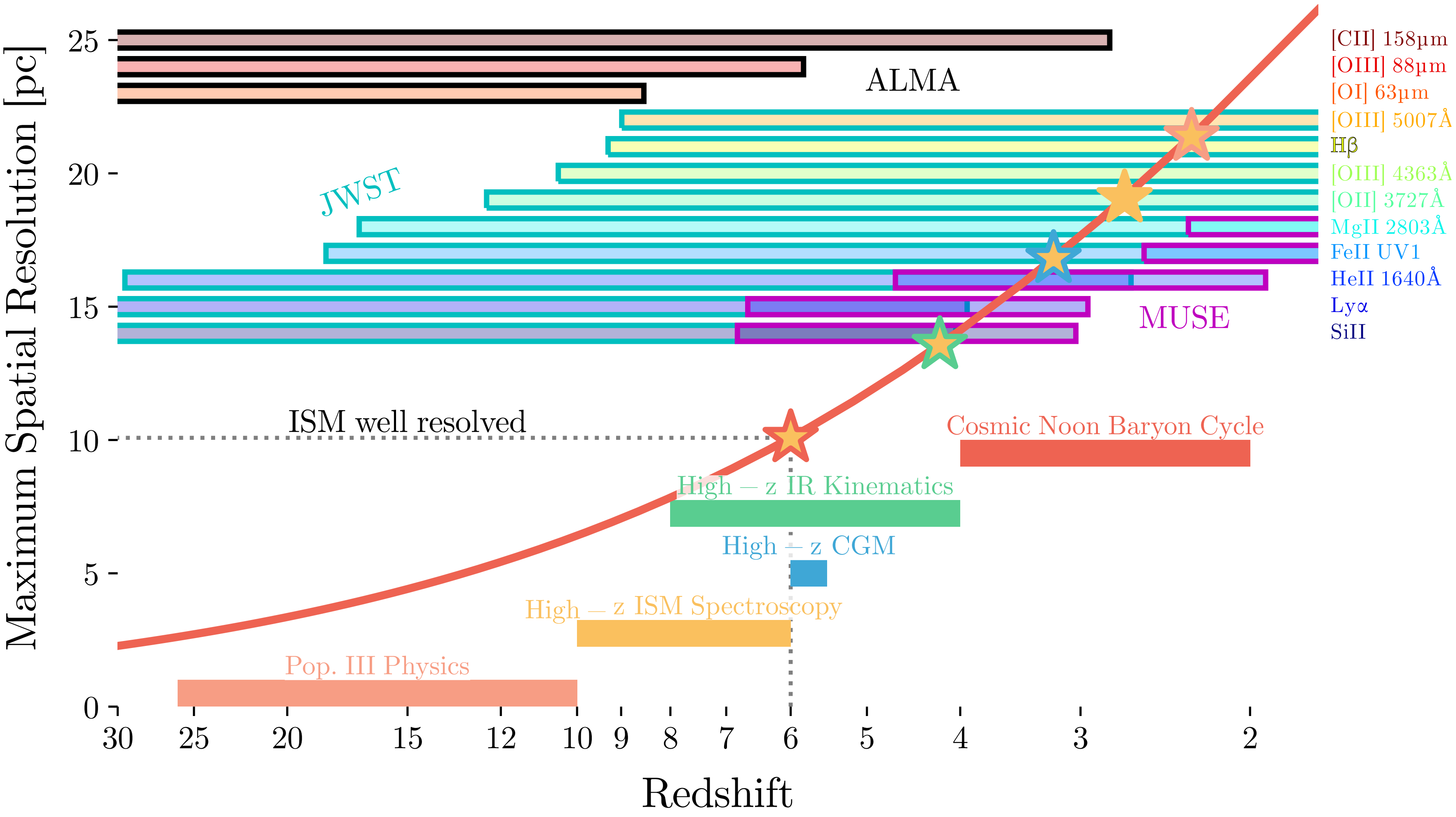
Main object, $z = 4$, raw file outputs, no postprocessing

Mocks in emission:

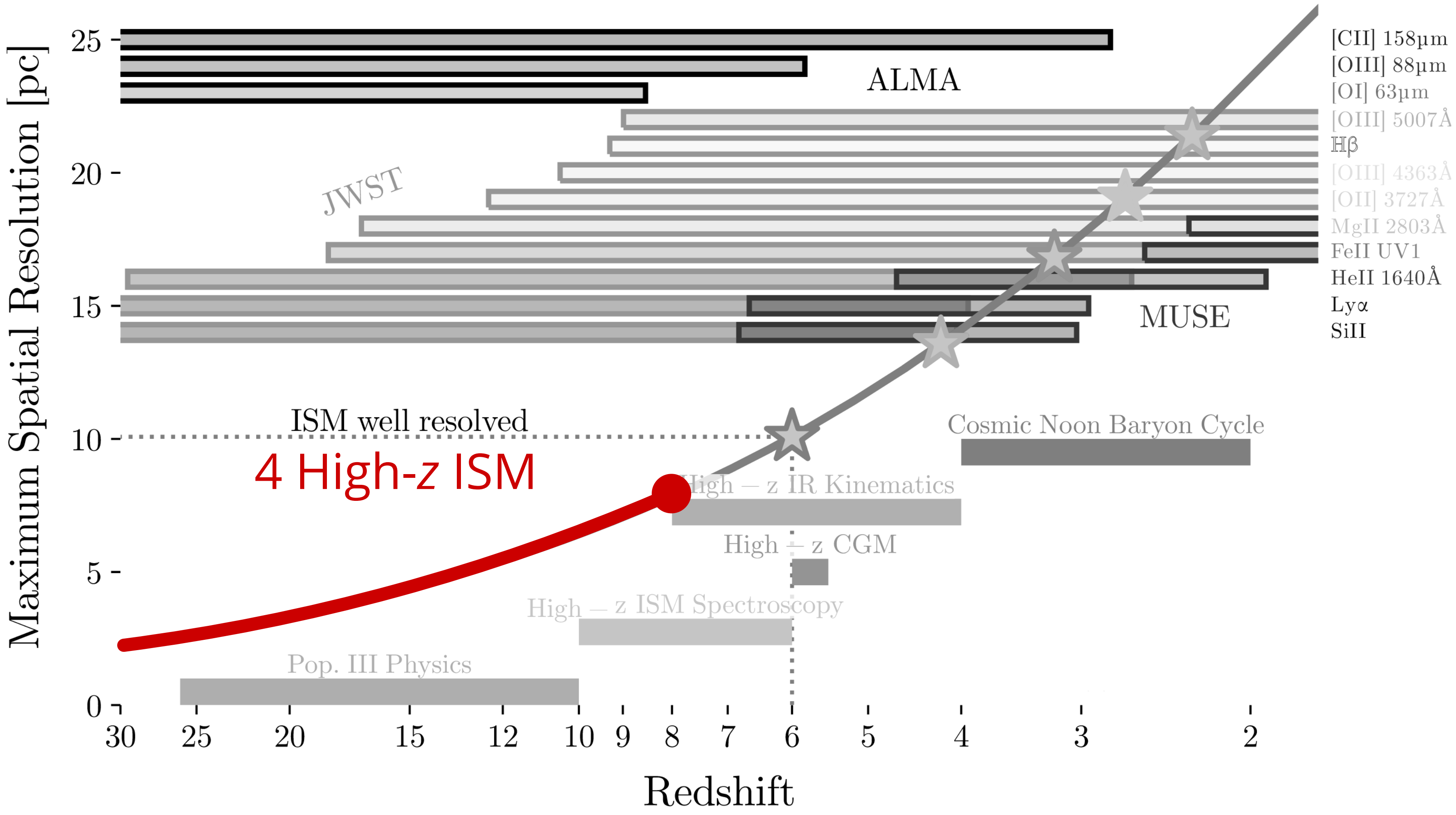
Main object, $z = 9$, w/ nebular cont. Pyneb (Luridiana+15) & coll. Chianti (Del Zanna+21)



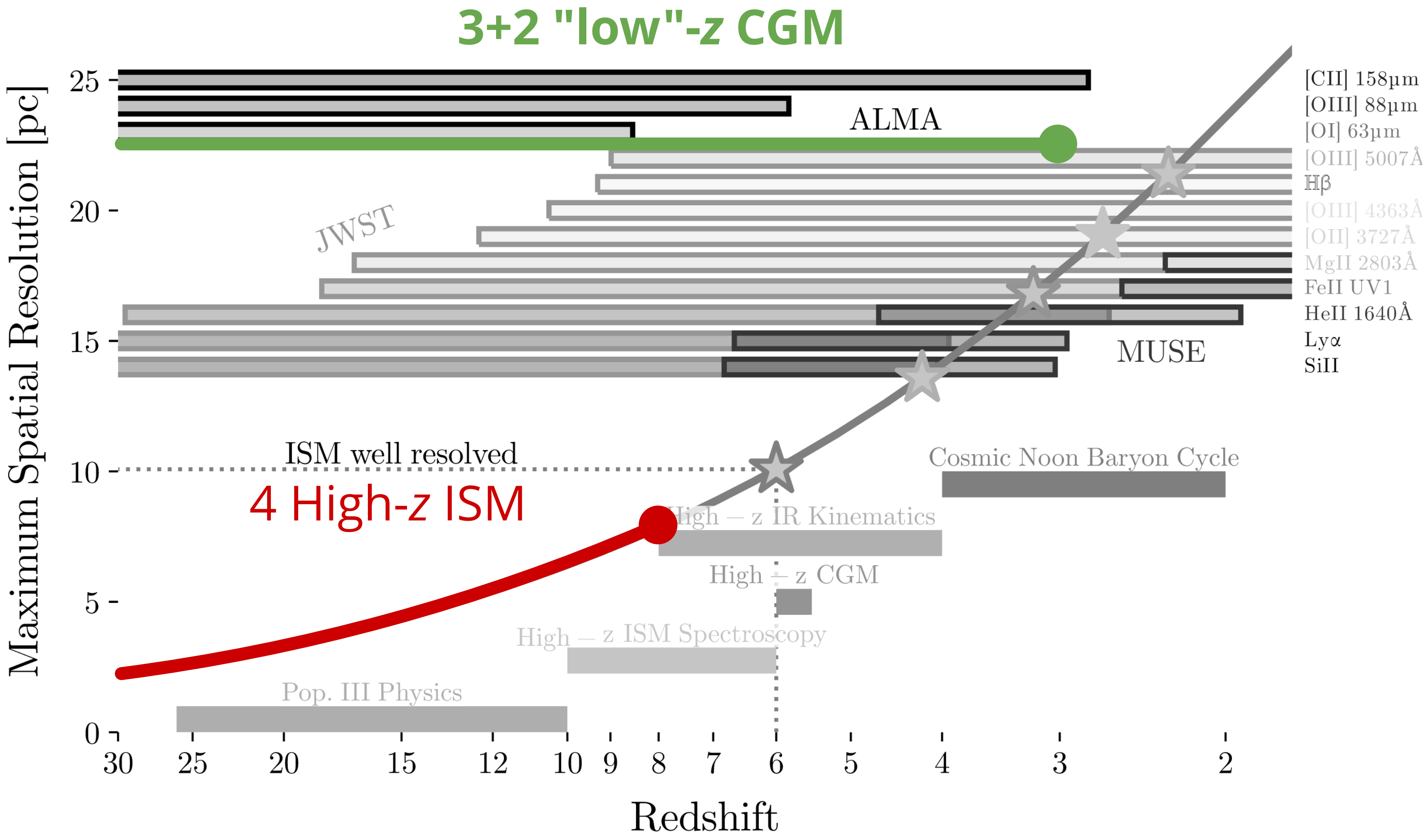
The Megatron suite of simulations



The Megatron suite of simulations



The Megatron suite of simulations



RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
$$- n_i\alpha_i n_\mathrm{e} - \left(\sum_k [n_i\xi_i + n_i\chi_i]n_k\right) - n_i(\beta_i n_\mathrm{e} + \Gamma_i)$$

$X^+ + e^- \to X$ (recombination)

$X^+ + Y \to X + Y^+$ (charge exchange recombination)

$X^- + Y \to X + Y^-$ (charge exchange ionization)

$X + e^{-*} \to X^+ + 2e^-$ (collisional excitation)

$X + h\nu \to X^+ + e^-$ (photoionization)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \sum_k^{\text{processes}} \sum_i^{\text{species}} n_i\Gamma_k - \sum_k^{\text{processes}} \sum_i^{\text{species}} \sum_j^{\text{species}} n_i n_j \Lambda_k$$

Katz 22, Katz+22, Katz+**CC**+24

RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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$$\frac{\mathrm{d}E}{\mathrm{d}t} = \boxed{\sum_k^{\text{processes}} \sum_i^{\text{species}} n_i\Gamma_k} - \boxed{\sum_k^{\text{processes}} \sum_i^{\text{species}} \sum_j^{\text{species}} n_i n_j \Lambda_k}$$

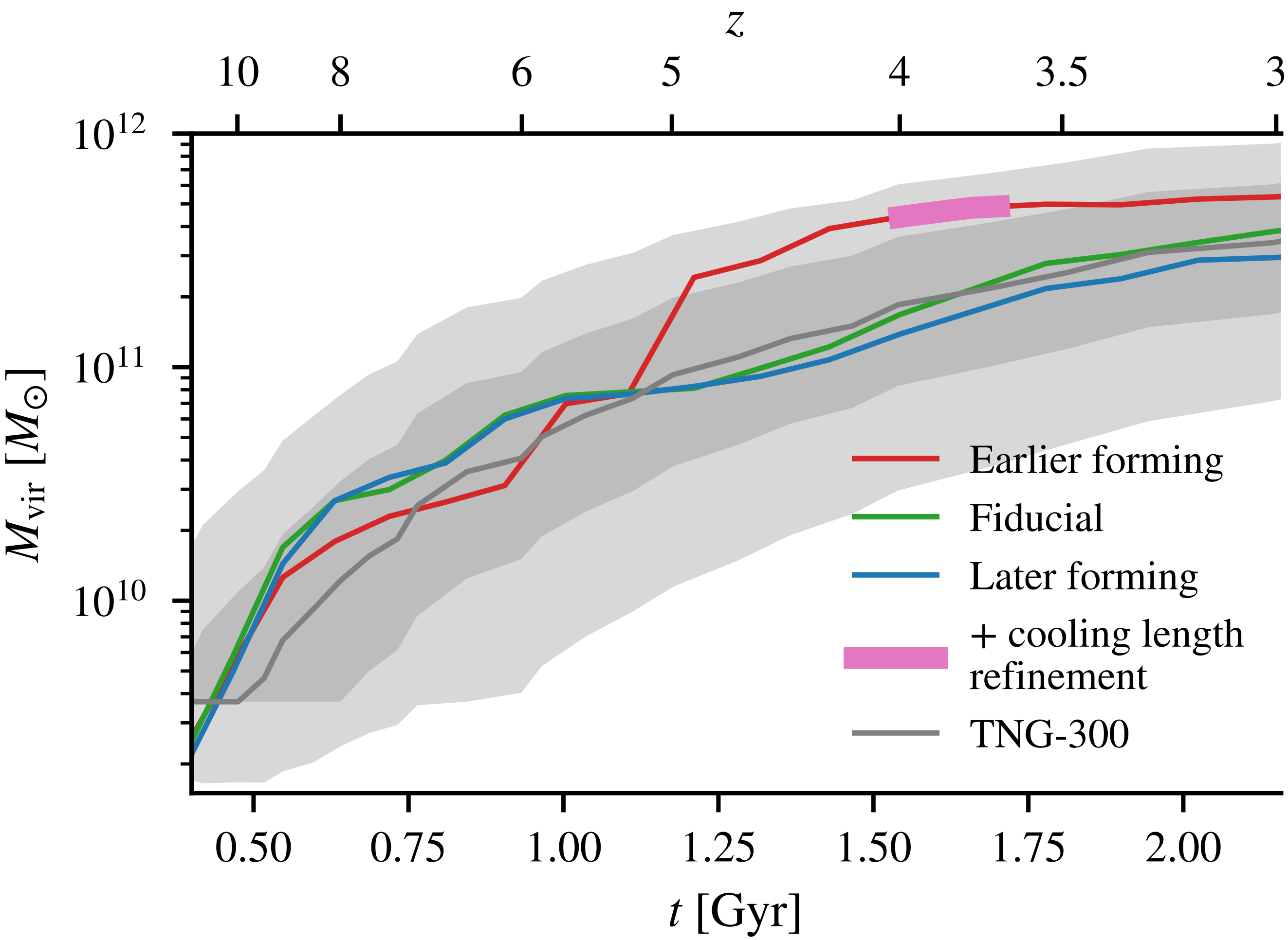
- CR heating
- photoheating
- H_2 heating (formation, dissoc., pumping)

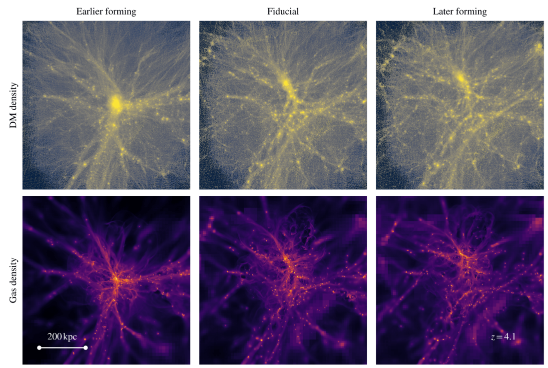
- H+He cooling ($T > 8000\,\mathrm{K}$)
- H_2 cooling (esp. $Z < 10^{-5}$)
- metal-line cooling
  fine-structure O I, O III, C I, C II, N II, Fe I, Fe II, Si I, Si II, S I, Ne II @ $T < 10^4\,\mathrm{K}$
  otherwise cloudy table
- CO cooling + dust recombination + grain-gas collisional cooling

Katz 22, Katz+22, Katz+**CC**+24

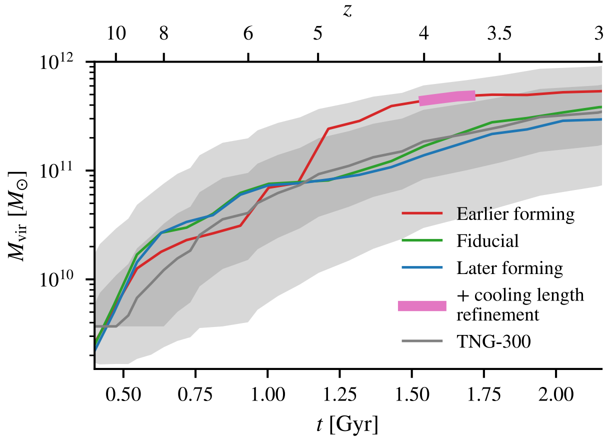
State of the CGM of a MW progenitor at $z \approx 3 - 4$

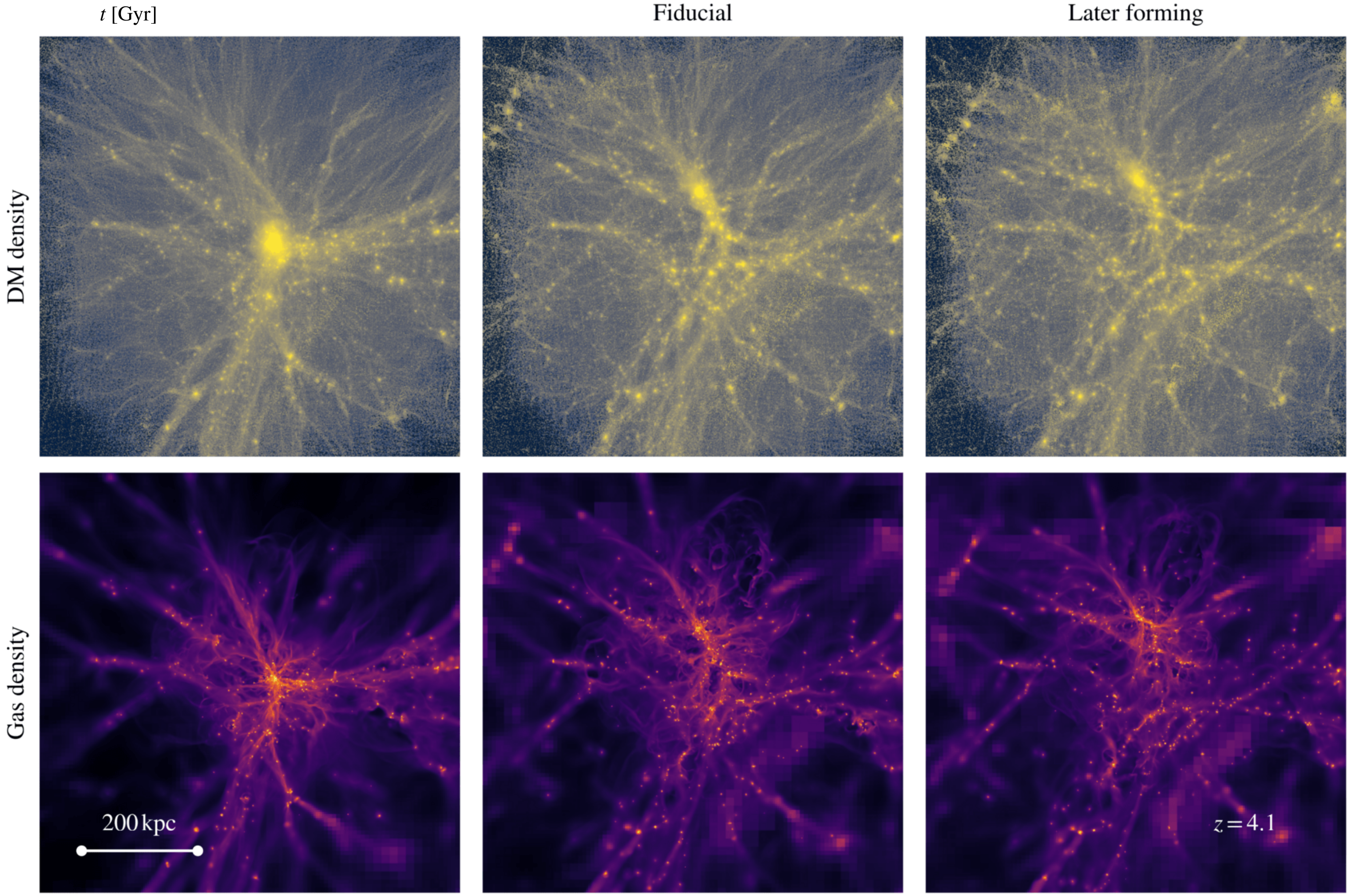
CGM at $z \approx 3 - 4$





CGM at $z \approx 3 - 4$





RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
$$- n_i\alpha_i n_\mathrm{e} - \left(\sum_k [n_i\xi_i + n_i\chi_i]n_k\right) - n_i(\beta_i n_\mathrm{e} + \Gamma_i)$$

- Out of equilibrium
- Depends on past thermochemical state
- Depends on local radiation field through Γ
- Ion-ion dependencies

RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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Photoionization equilibrium

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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Photoionization equilibrium

$$0 = n_{i+1}\alpha_{i+1}n_\mathrm{e} + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1}) - n_i\alpha_i n_\mathrm{e} - n_i(\beta_i n_\mathrm{e} + \Gamma_i)$$

- In equilibrium

RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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- In equilibrium
- Suppose $n_\mathrm{e} = n_{\mathrm{H\,II}} + n_{\mathrm{He\,II}} + 2n_{\mathrm{He\,III}}$

RTZ model

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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Photoionization equilibrium

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- In equilibrium
- Suppose $n_\mathrm{e} = n_{\mathrm{H\,II}} + n_{\mathrm{He\,II}} + 2n_{\mathrm{He\,III}}$
- Suppose Γ is UV background only

CGM at $z \approx 3-4$

Is the CGM in equilibrium?

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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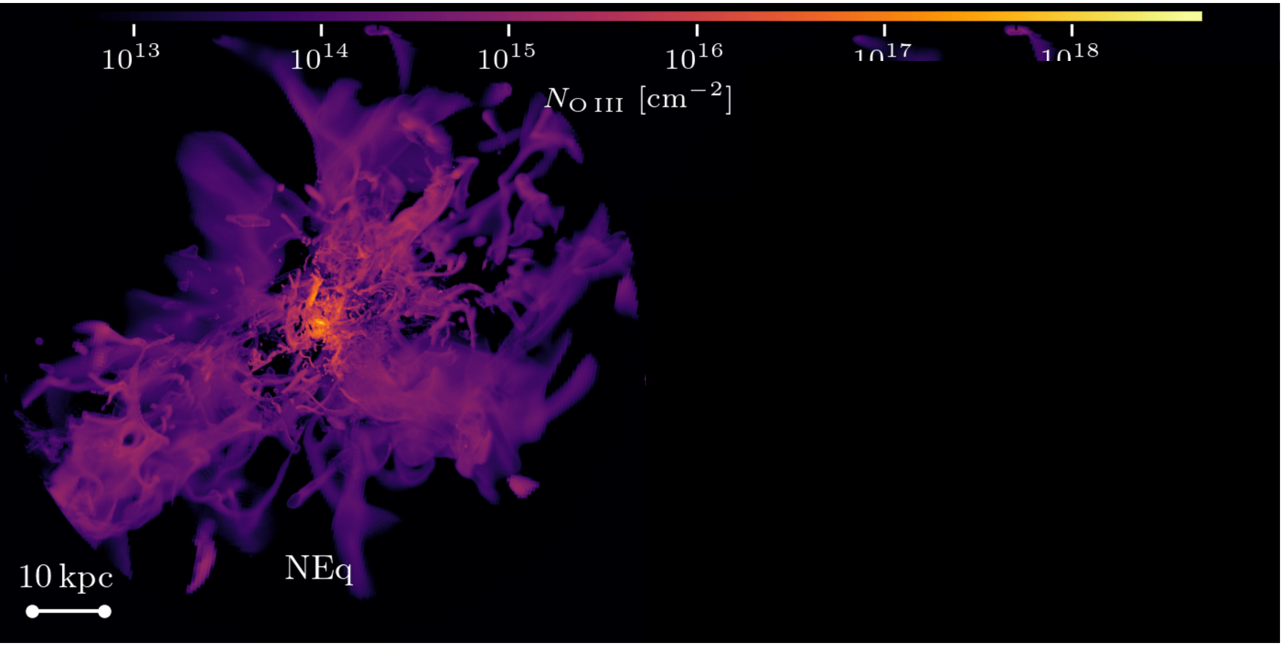

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Is the CGM in equilibrium?

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_\mathrm{e} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1})$$
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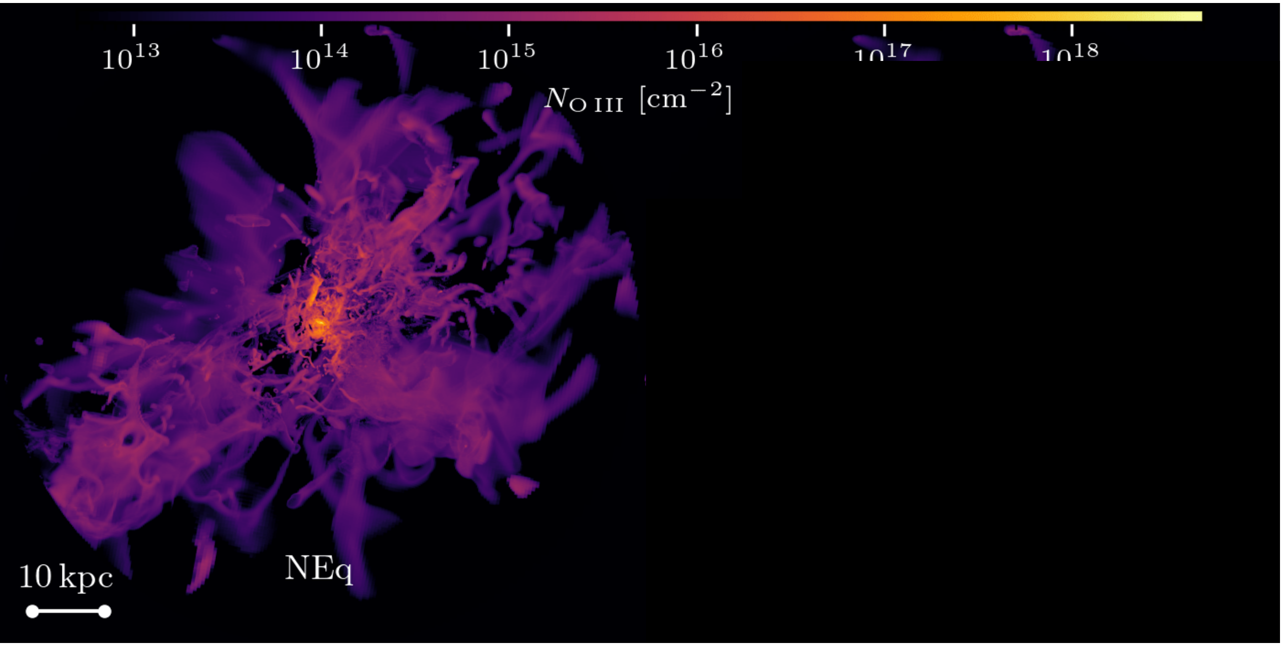

$$0 = n_{i+1}\alpha_{i+1}n_\mathrm{e} + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1}) - n_i\alpha_i n_\mathrm{e} - n_i(\beta_i n_\mathrm{e} + \Gamma_i)$$

Relax to photo-ionisation equilibrium (PIE)

No local radiation field, no time-dependence, assume n_e dominated by primordial species, self-shielding

CGM at $z \approx 3-4$

Is the CGM in equilibrium?

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i+1}\alpha_{i+1}n_{\mathrm{e}} + \left(\sum_k [n_{i+1}\xi_{i+1} + n_{i-1}\chi_{i-1}]n_k\right) + n_{i-1}(\beta_{i-1}n_{\mathrm{e}} + \Gamma_{i-1})$$
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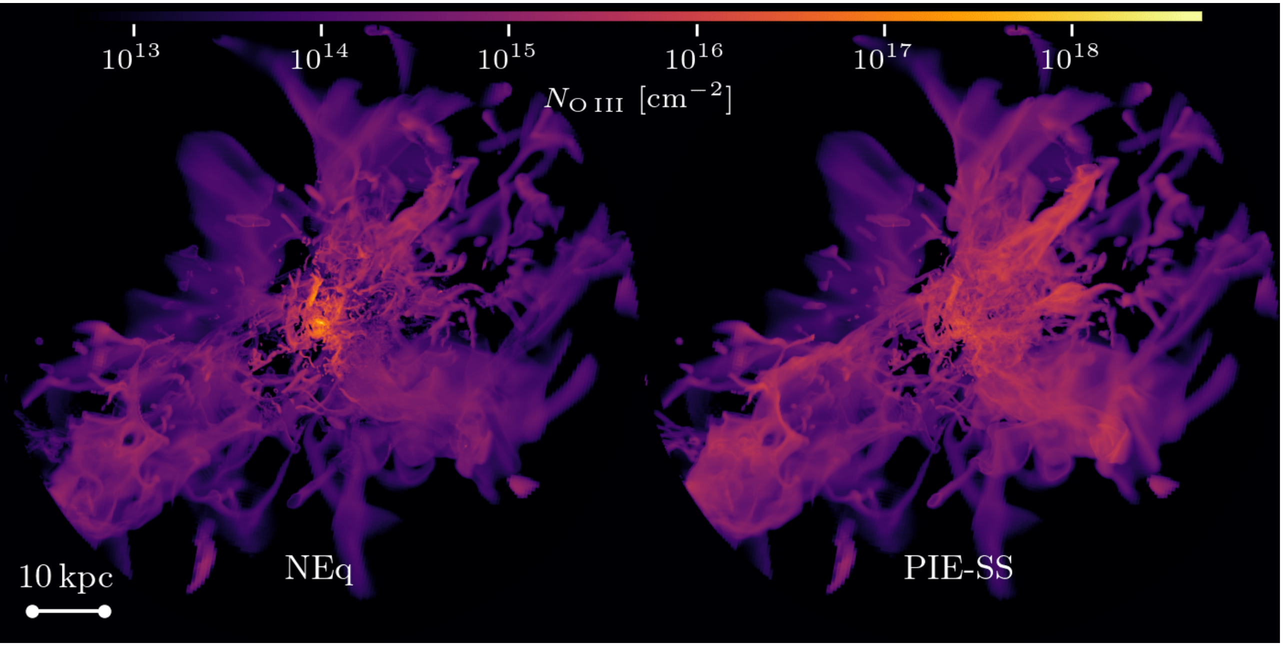

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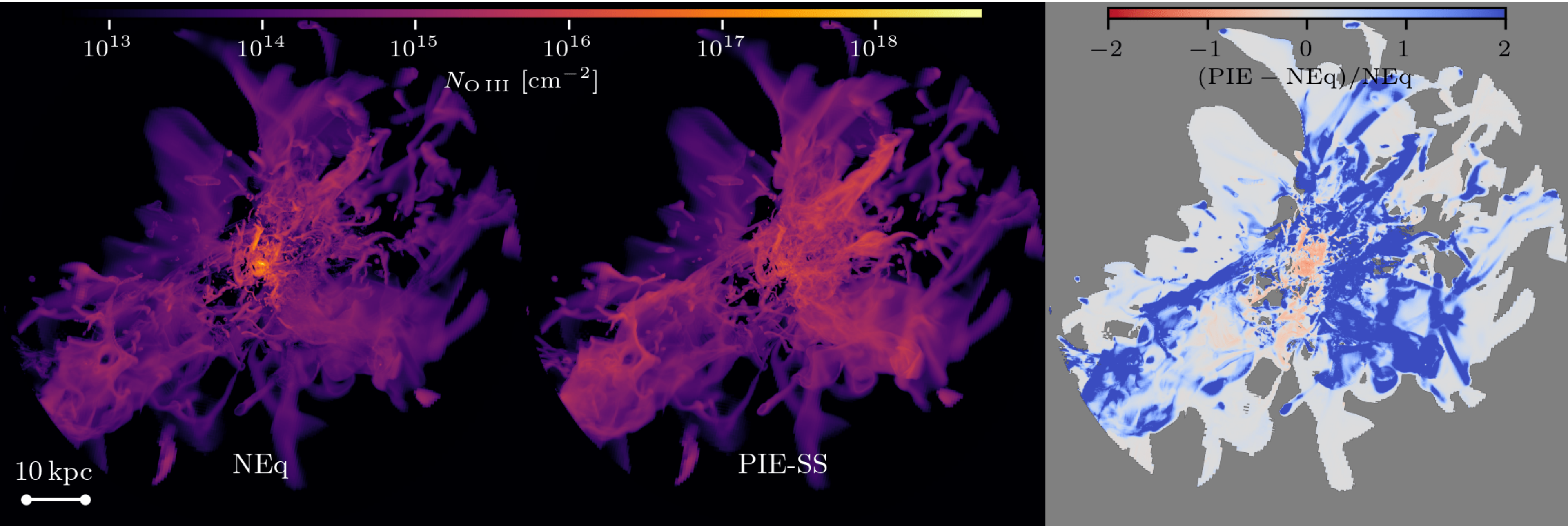


$$0 = n_{i+1}\alpha_{i+1}n_\mathrm{e} + n_{i-1}(\beta_{i-1}n_\mathrm{e} + \Gamma_{i-1}) - n_i\alpha_i n_\mathrm{e} - n_i(\beta_i n_\mathrm{e} + \Gamma_i)$$

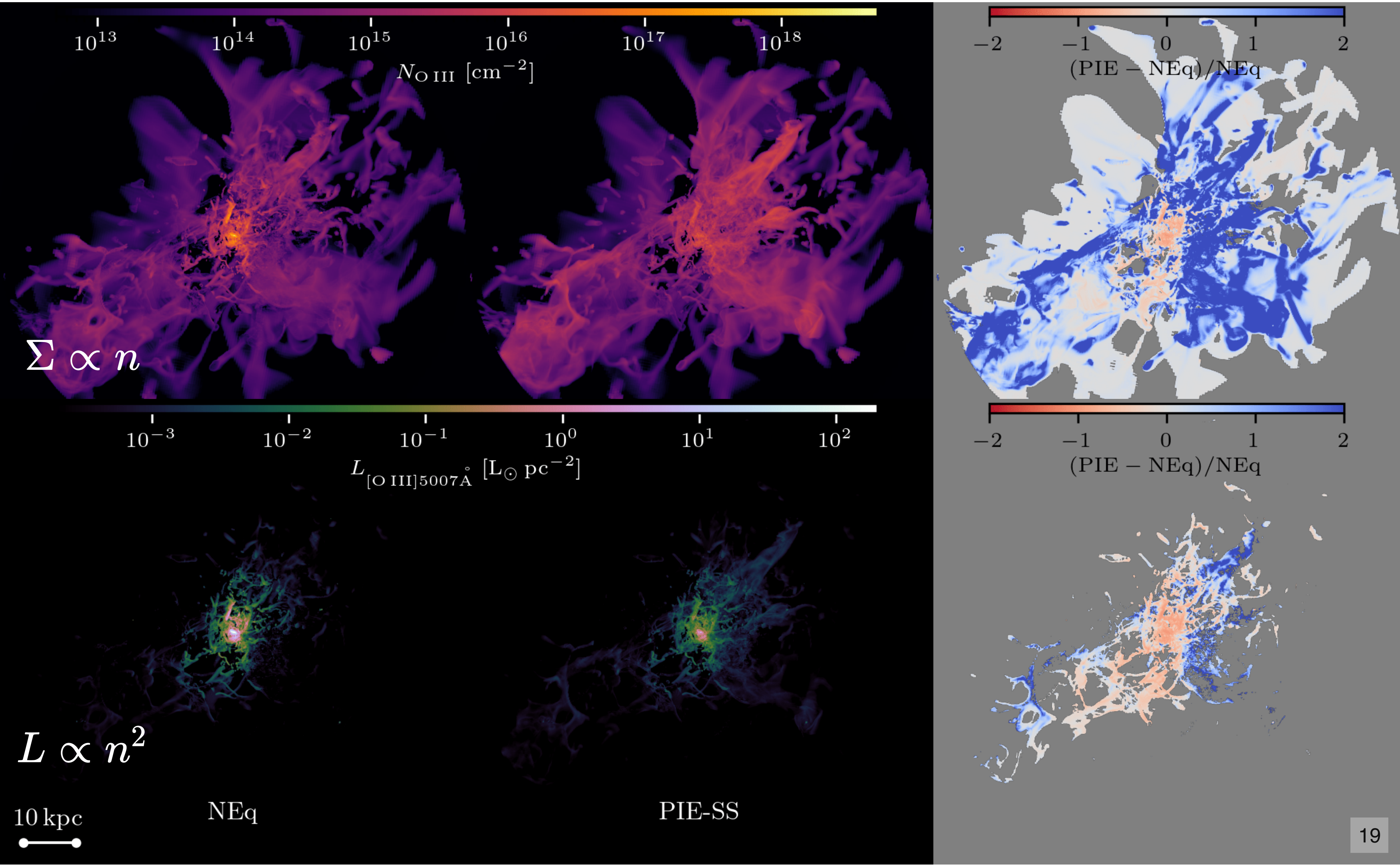
Relax to photo-ionisation equilibrium (PIE)

No local radiation field, no time-dependence, assume n_e

dominated by primordial species, self-shielding

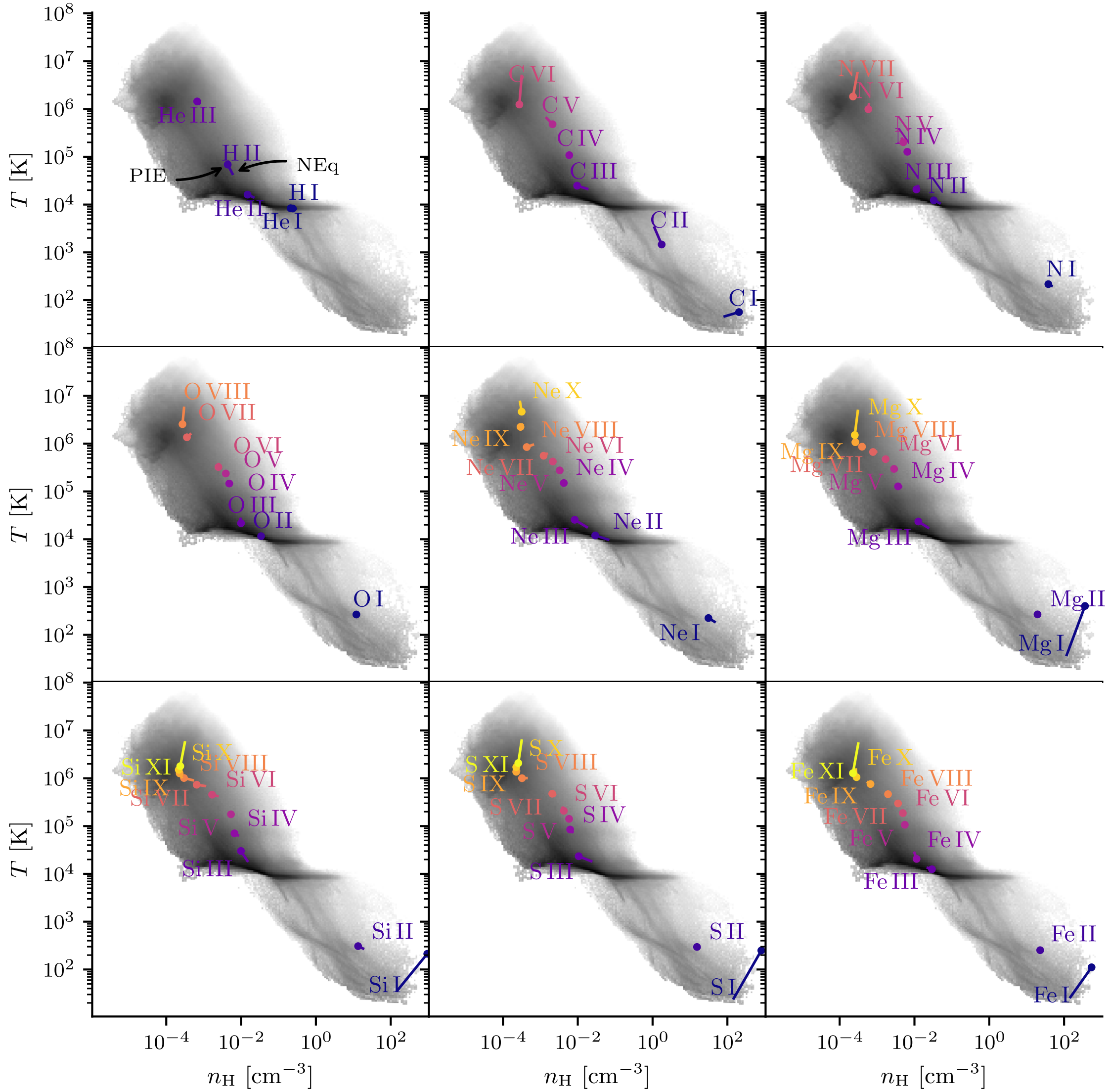
CGM at $z \approx 3 - 4$

Is the CGM in equilibrium?



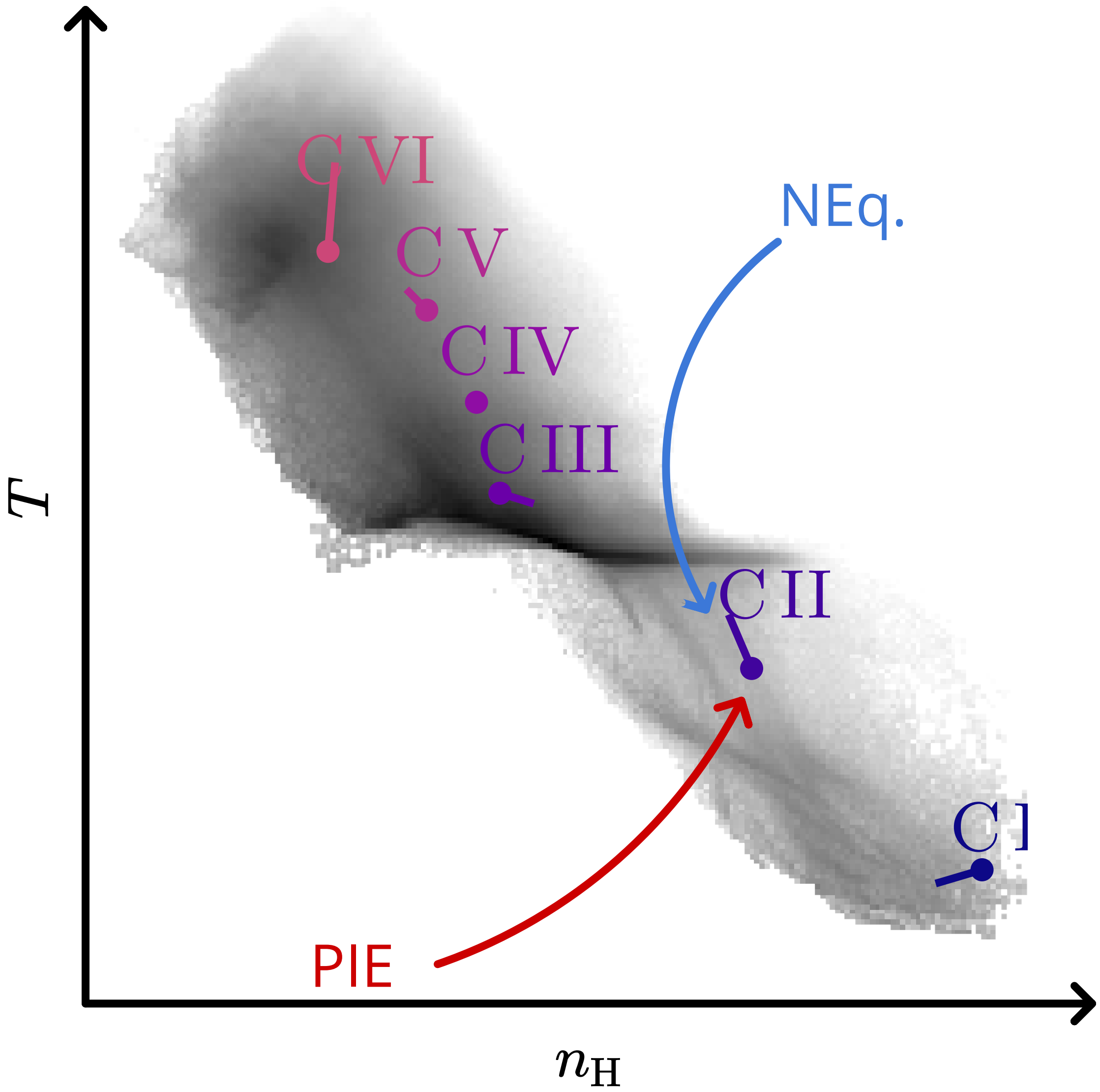
CGM at $z \approx 3-4$

Is the CGM in equilibrium?



CGM at $z \approx 3 - 4$

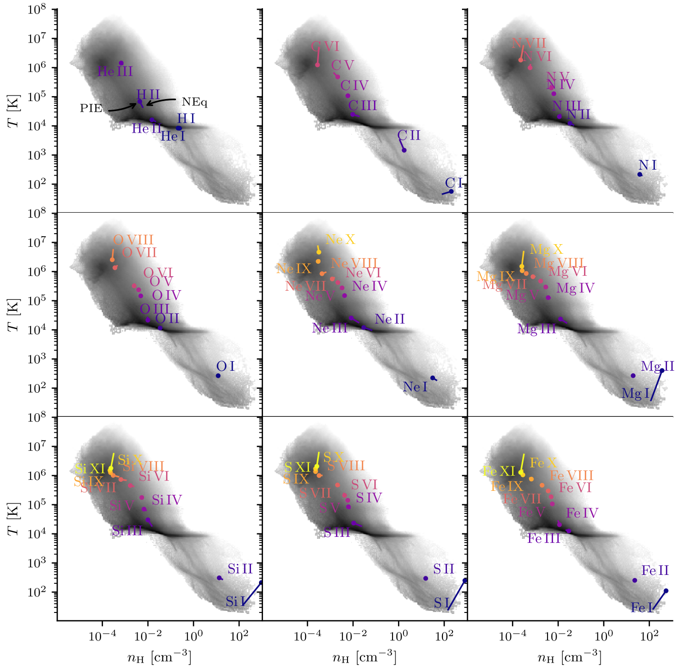
Is the CGM in equilibrium?

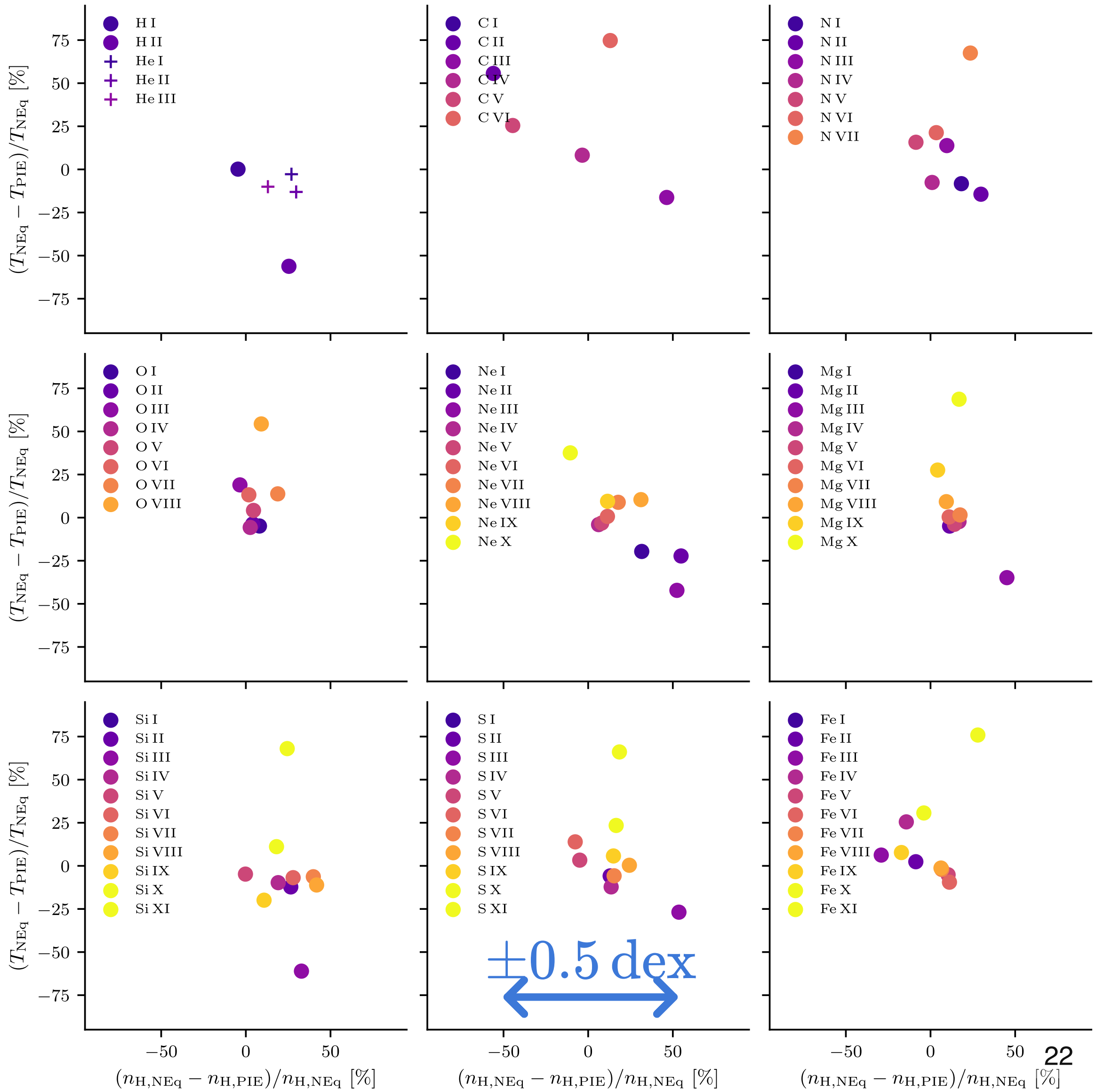


Assuming PIE ⇒ biased towards colder/denser gas

CGM at $z \approx 3 - 4$

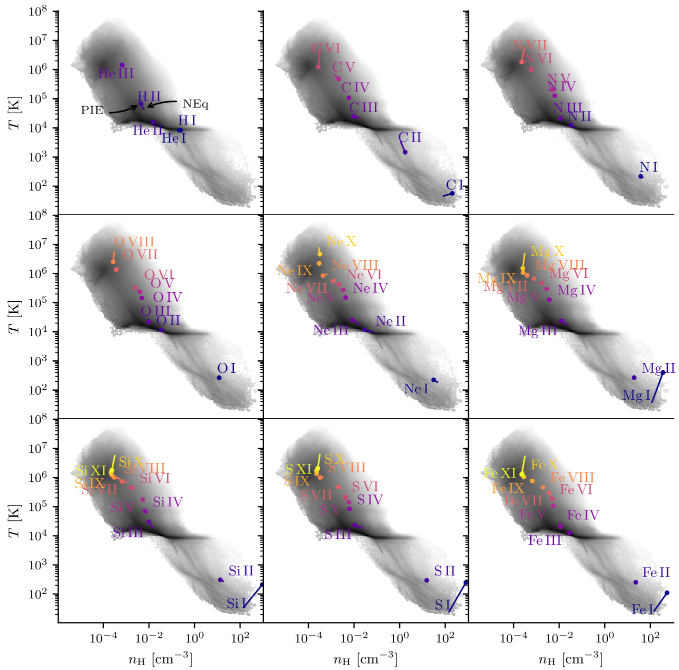
Is the CGM in equilibrium?

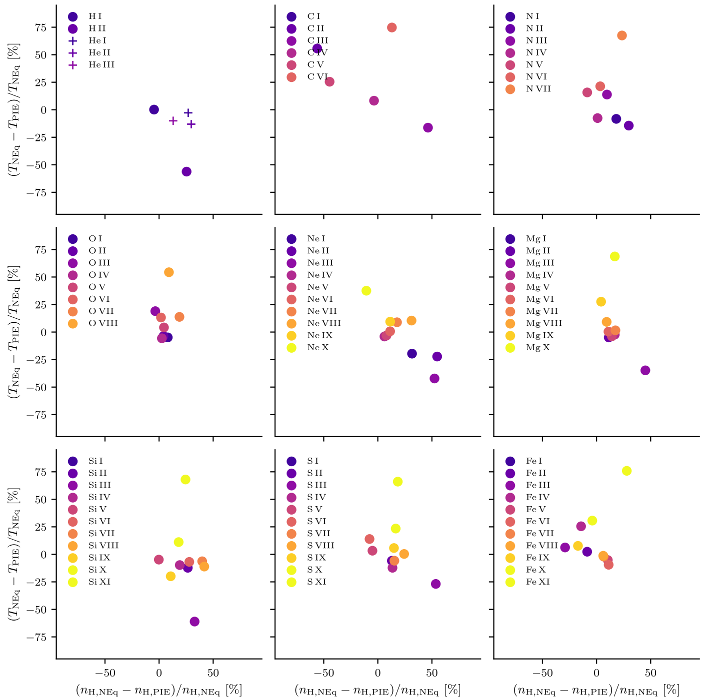




CGM at $z \approx 3 - 4$

Is the CGM in equilibrium?



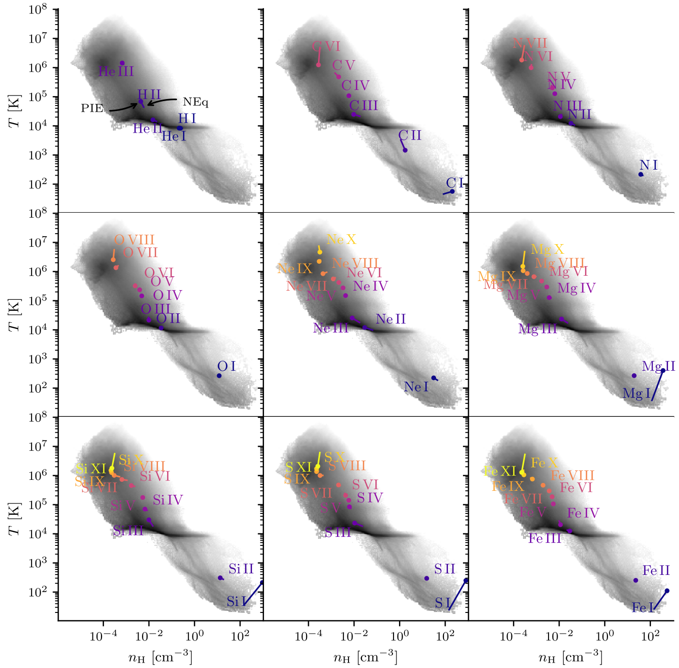


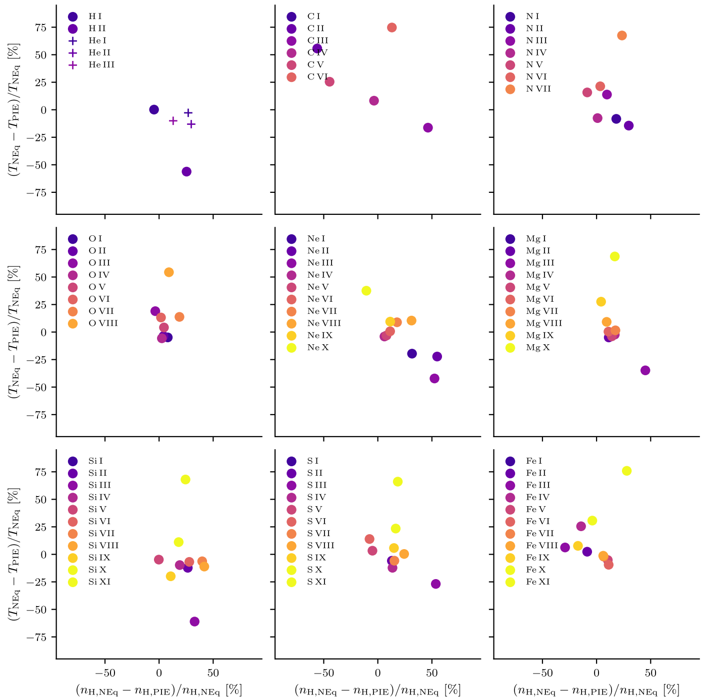
Non-equilibrium effects:

$$\Delta(T, n_{\rm H}) \sim 0.2 - 0.5\,{\rm dex}$$

CGM at $z \approx 3 - 4$

Is the CGM in equilibrium?





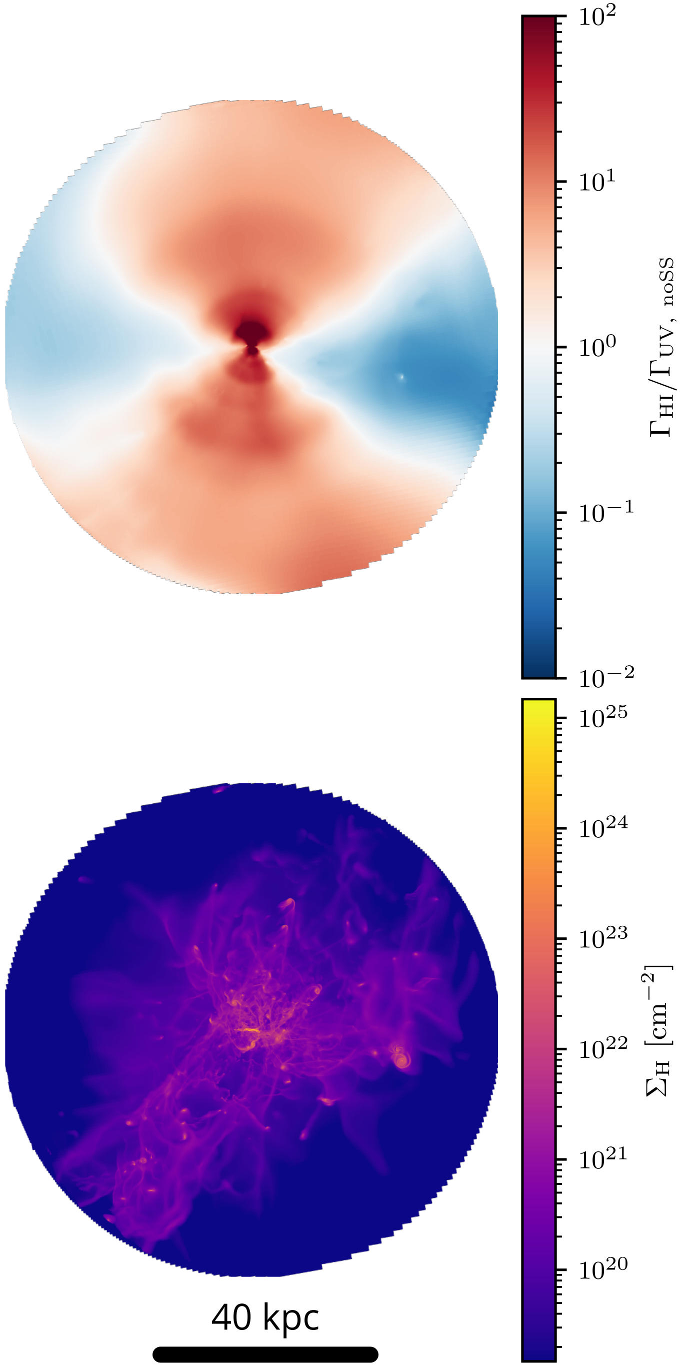
Non-equilibrium effects:

$\Delta(T, n_{\rm H}) \sim 0.2 - 0.5\,\mathrm{dex}$

$\Rightarrow \Delta L \sim 1\,\mathrm{dex}$

for some lines

CGM at $z \approx 3 - 4$



CGM out of equilibrium: why?

1. Local radiation dominate locally over UVB

   Anisotropic effects

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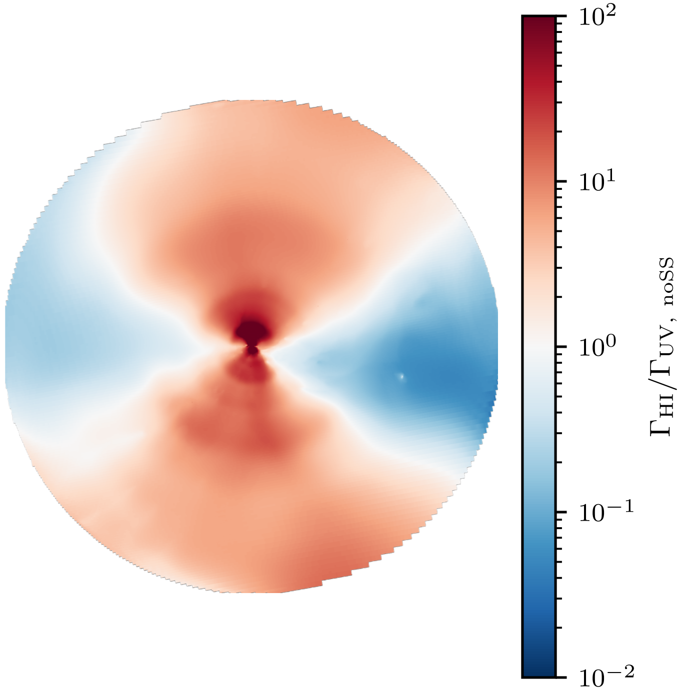

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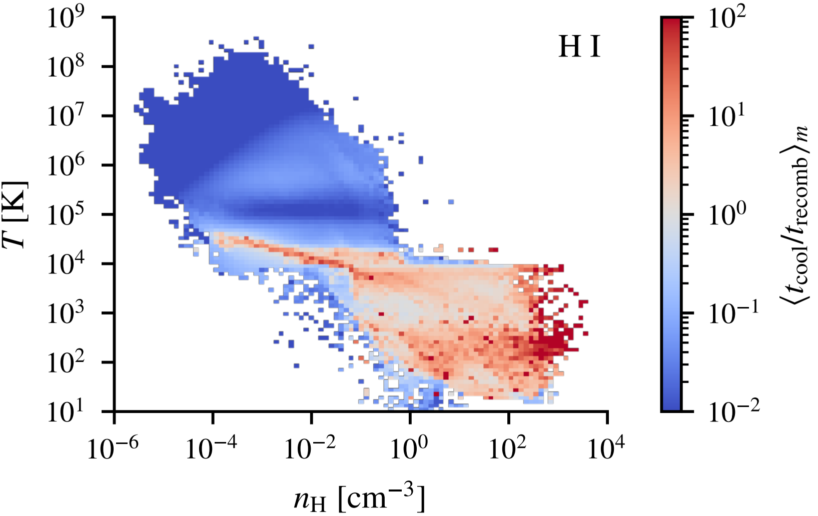
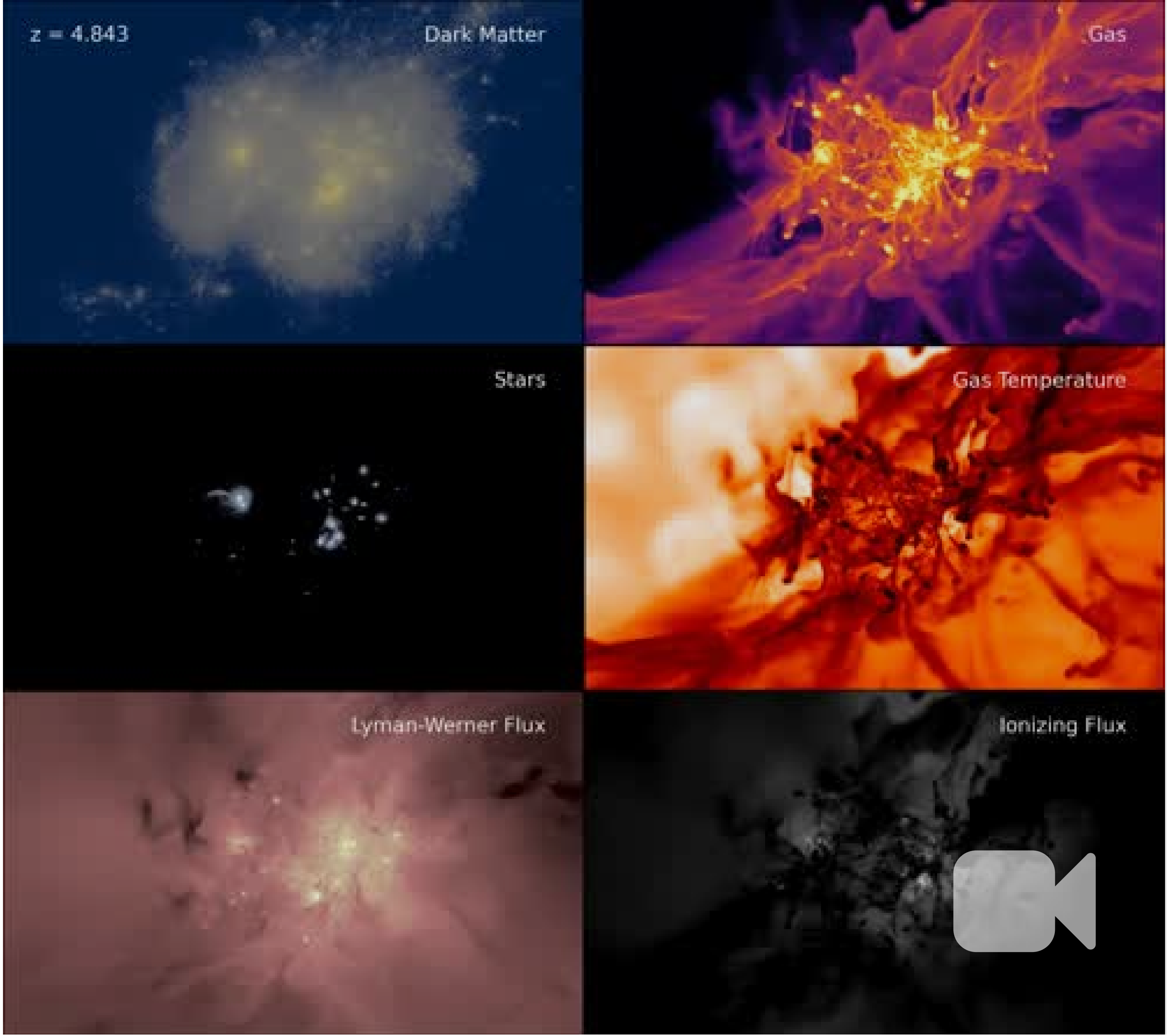


2. Recombination lag
   $t_{\rm cool} \ll t_{\rm rec}$, *worse at low* z


z = 4.843
Dark Matter
Gas
Stars
Gas Temperature
Lyman-Werner Flux
Ionizing Flux

Upcoming:
MEGATRON data release

Data viewer

Requirements:

- ✔ interactive,
- ✔ handles raw data
  (RAMSES outputs, catalogues, spectra)
- ✔ everything local — except data.
  → run Python+yt in your browser 🙃

3D viewer

Requirements:

- ✔ interaction-before-accuracy,
- ✔ GPU-accelerated,
- ✔ up to **millions** of AMR cells,
- pre-extracted lightweight cutouts

Take-home messages

Take-home messages

- Megatron simulation suite

  200,000+ spectra in 4 “ISM” runs ($z \gtrsim 8$) ⇒ Katz, **CC**+25

  3+1 “CGM” runs ($z \gtrsim 3.5$) ⇒ **CC**+25

  Link to low-z UFDs ⇒ Rey, ..., **CC**+25

  Properties of Pop. III stars ⇒ Storck, ..., **CC**+25

  Sensitivity of line diagnostics to subgrids ⇒ Choustikov, ..., **CC**+25

  Origin of steep β slopes ⇒ Katz, **CC+** **(in prep)**

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  Assuming PIE leads to 0.5 dex (median), and factors of
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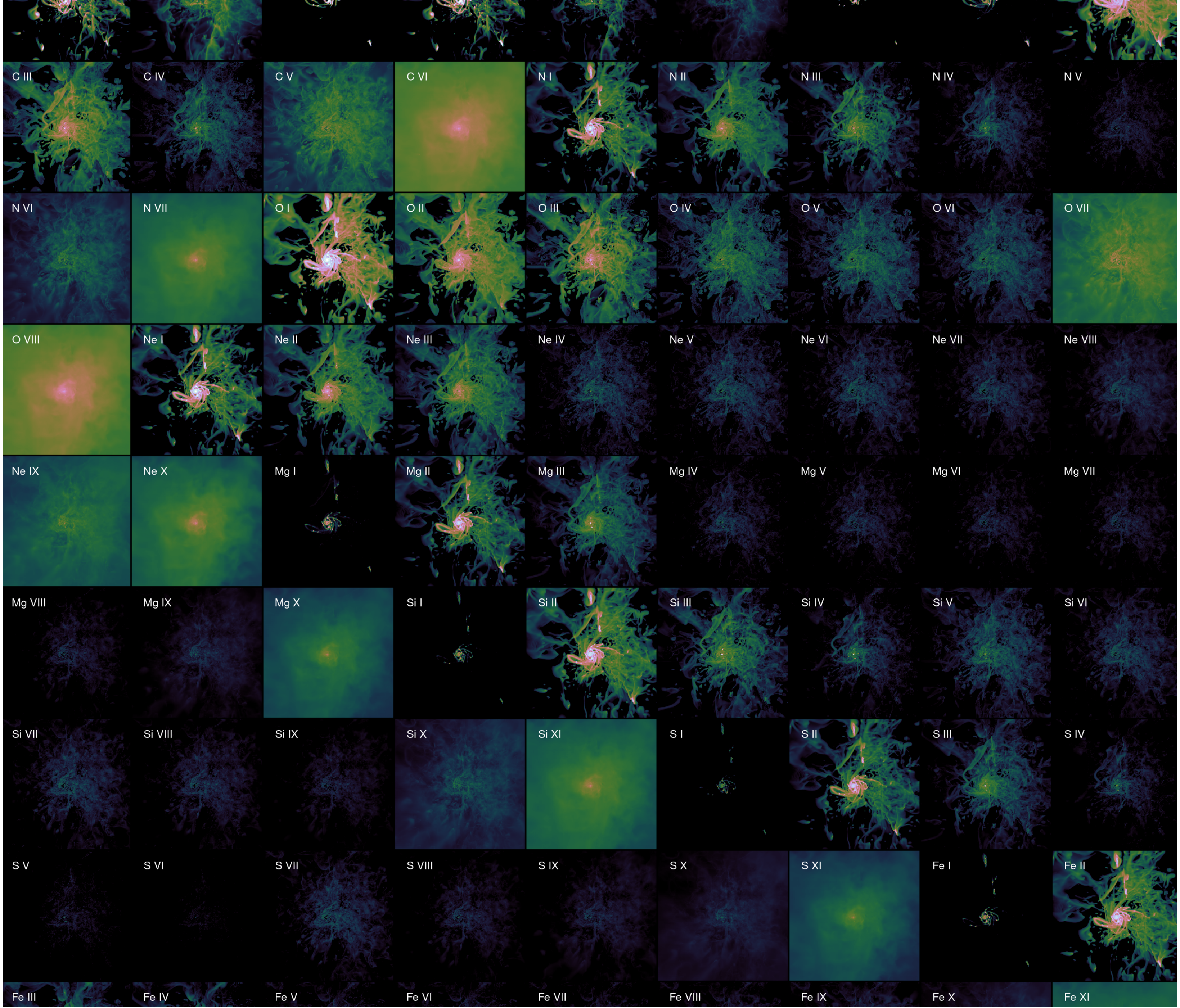
  Assuming PIE leads to 0.5 dex (median), and factors of
  2-3× on individual line of sight

- Data release **⇒ CC+** **(in prep)**
  ✔ Pre-computed spectra, halo catalogues, cut-outs
  ✔-ish data viewer + 3D viewer
  🚧 JWST images, ALMA Cubes, RASCAS post-processing ($f_{\rm esc}$, $L_{\rm Mg\,II}$, ...)


C III
C IV
C V
C VI
N I
N II
N III
N IV
N V
N VI
N VII
O I
O II
O III
O IV
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O VI
O VII
O VIII
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Mg VII
Mg VIII
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S VIII
S IX
S X
S XI
Fe I
Fe II
Fe III
Fe IV
Fe V
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Fe VII
Fe VIII
Fe IX
Fe X
Fe XI