Molecular Hydrogen for RAMSES

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Carina Nebula, Credit: NASA, ESA, N. Smith, and The Hubble Heritage Team

Outline

1. An introduction to H_2
2. Ramses-RT with H_2
3. Full galaxy simulation

Carina Nebula, Credit: NASA, ESA, N. Smith, and The Hubble Heritage Team

H_2 in Galaxies

- Most common molecule in the Universe
- Important to cooling the interstellar medium
- No dipole moment and is light, leading to high emission temperature
- Difficult to detect directly, usually inferred from CO by conversion factor
- Dense, cold molecular clouds are linked to star formation

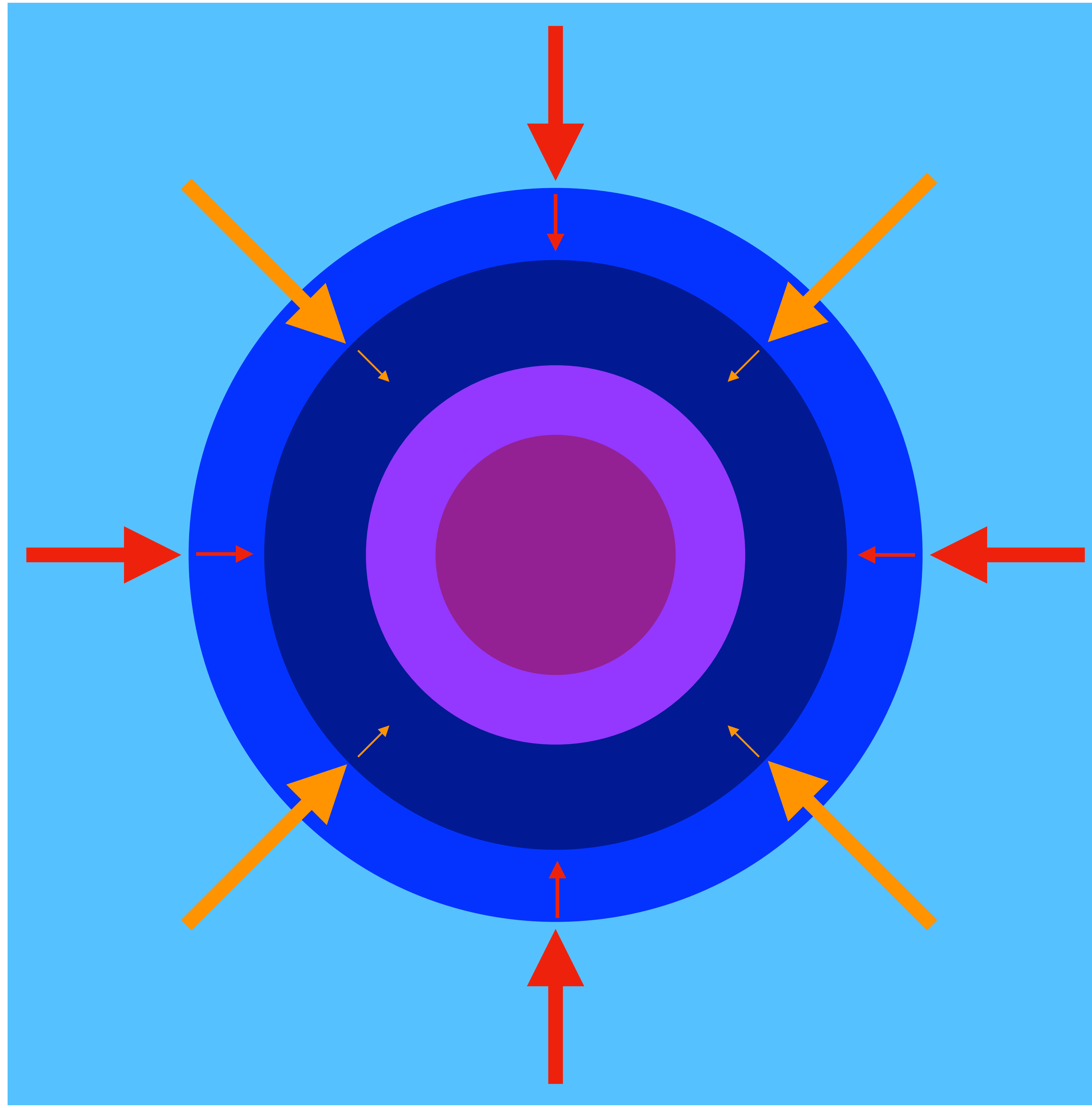
Molecular Cloud Schematics

Lyman Werner radiation
(11.20-13.60 eV)

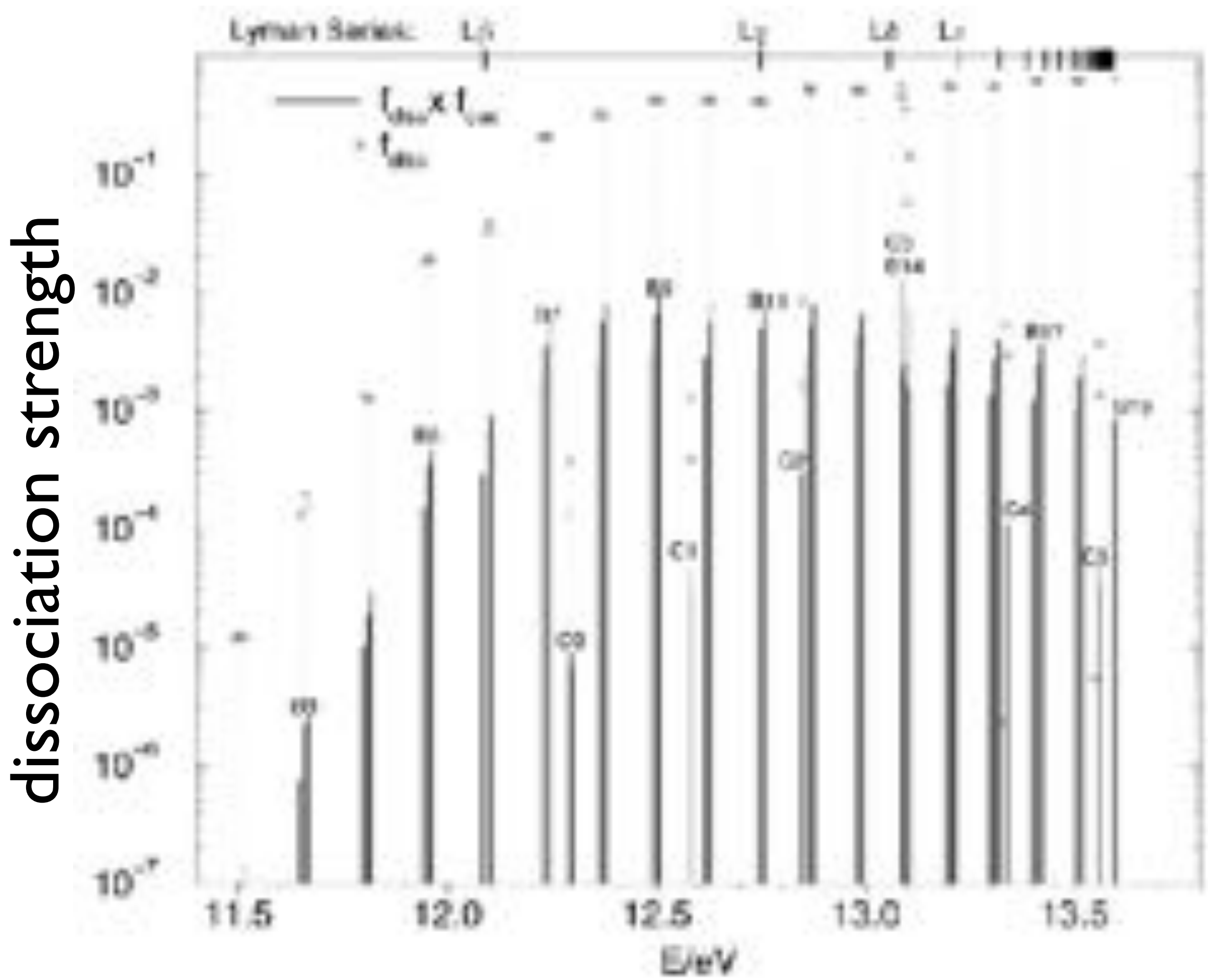
Ionizing radiation
(≥13.60 eV for HI, ≥15.42 eV for H_2)

easily observable?

hot	diffuse	✔	HII gas
		✔	HI gas
		✘	H_2 gas
		✔	CO gas
cold	dense	✔	HCN gas



H_2 Self-Shielding



wavelength

Source: Haiman et al. 2000

- Not every absorption of a Lyman-Werner photon (11.2 to 13.6 eV) leads to dissociation
- Different lines of Lyman-Werner photons dissociate H_2 at different rates
- Stronger lines absorbed at cloud surface, weaker lines sneak deeper
- Heisenberg uncertainty means that finite molecular excitation time leads to natural line width
- The strong lines interfere with the weak lines
- Deeper into H_2 cloud, absorption becomes harder

Ramses-RT

- Rosdahl et al. 2013
- Moment-based radiative transfer scheme for RAMSES
- Computation independent of source number
- Non-equilibrium chemistry of HI, HII, HeI, HeII, and HeIII coupled to ionising photon groups and thermal state of gas

Adding H_2 to RAMSES-RT

$$\dot{n}_{\mathrm{H_2}} = \alpha^{\mathrm{Z}}_{\mathrm{H_2}}(T) Z f_{\mathrm{d}} n_{\mathrm{H}} n_{\mathrm{H\,I}} + \alpha^{\mathrm{GP}}_{\mathrm{H_2}}(T) n_{\mathrm{H\,I}} n_{\mathrm{e}} + \beta_{\mathrm{3B}}(T) n^2_{\mathrm{H\,I}} (n_{\mathrm{H\,I}} + n_{\mathrm{H_2}}/8) - \beta_{\mathrm{H_2 H\,I}}(T) n_{\mathrm{H\,I}} n_{\mathrm{H_2}} - \beta_{\mathrm{H_2 H_2}}(T) n^2_{\mathrm{H_2}} - \Gamma^{\mathrm{LW}}_{\mathrm{H_2}}(N_{\mathrm{H_2}}) n_{\mathrm{H_2}} - \Gamma^{+}_{\mathrm{H_2}}(N_{\mathrm{H\,I}}) n_{\mathrm{H_2}} - \xi_{\mathrm{H_2}} n_{\mathrm{H_2}}$$

- Formation on dust (Hollenbach & McKee 1979; Jura 1974; Gry et al. 2002; Habart et al. 2004)
- Gas-phase formation (McKee & Krumholz (2012)
- Formation by three-body collisions (Forrey 2013; Palla et al. 1983)
- Collisional destruction with HI (Dove & Mandy 1986)
- Collisional destruction with itself (Martin et al.1998)
- Photodissociation by Lyman-Werner photons (Sternberg et al. 2014)
- Photoionisation by ionising photons (Abel et al. 1997)
- Cosmic ray ionisation (Indriolo & McCall 2012; Gong et al. 2017; Glassgold & Langer 1974)

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Additional Thermal Processes

$$\mathcal{H} = \sum_{j}^{\mathrm{H_2,HI,HeI,HeII}} n_j \sum_{i=1}^{M} c_i N_i (\bar{\epsilon}_i \sigma_{ij}^E - \epsilon_j \sigma_{ij}^N)$$
(heating)

$$+\mathcal{H}_{\mathrm{PE}}(T) + \mathcal{H}_{\mathrm{UVP}}(T) + \mathcal{H}_{\mathrm{H_2}}(T) + \mathcal{H}_{\mathrm{CR}}(T)$$

$$\mathcal{L} = [\zeta_{\mathrm{HI}}(T) + \psi_{\mathrm{HI}}(T)]\, n_e\, n_{\mathrm{HI}}$$
(cooling)

$$+ \zeta_{\mathrm{HeI}}(T)\, n_e\, n_{\mathrm{HeI}}$$
$$+ [\zeta_{\mathrm{HeII}}(T) + \psi_{\mathrm{HeII}}(T) + \eta^{\mathrm{A}}_{\mathrm{HeII}}(T)$$
$$+ \omega_{\mathrm{HeII}}(T)] n_e n_{\mathrm{HeII}}$$
$$+ \eta^{\mathrm{A}}_{\mathrm{HII}}(T)\, n_e\, n_{\mathrm{HII}}$$
$$+ \eta^{\mathrm{A}}_{\mathrm{HeIII}}(T)\, n_e\, n_{\mathrm{HeIII}}$$
$$+ \theta(T)\, n_e (n_{\mathrm{HII}} + n_{\mathrm{HeII}} + 4 n_{\mathrm{HeIII}})$$
$$+ \varpi(T)\, n_e$$
$$+ \Lambda_Z(T)$$
$$+ \Lambda_{\mathrm{H_2}}(T)$$

- Photoelectric effect heating (Bakes & Tielens 1994, Wolfire et al. 2003)
- Heat from UV pumping (Baczynski 2015, Draine & Bertoldi 1996, Burton et al. 1990)
- H_2 formation heating (Hollenbach & McKee, Omukair 2000)
- Cosmic ray ionization heating (Glassgold et al. 2012)
- H2 collisional destruction cooling (Halle & Combes 2013, Hollenbach & McKee 1979)

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Previous Self-Shielding Models

- Galaxy simulations use the Draine and Bertoldi 1996 self-shielding as a function of column density
- Decreases H_2 destruction
- Problems: simulations use volume density and ray tracing is expensive for galaxies with multiple sources
- Many approximations to convert column density to volume density, local and non-local

$$f_{\mathrm{shield}}(N_2) = \frac{0.965}{(1 + x/b_5)^2} + \frac{0.035}{(1 + x)^{0.5}} \times \exp\left[-8.5 \times 10^{-4}(1 + x)^{0.5}\right]$$

$x = N_2/10^{14}$

b is a constant

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Our Self-Shielding Model

- Takes advantage of moment-based radiative transfer that treats photons like a fluid
- Instead of decreasing H_2 destruction, we enhance Lyman-Werner destruction
- Use a constant factor, S; calibrated with Bialy et al. 2016 HI-H_2 transition depth
- Cumulative destruction of LW photons while they travel through each cell is similar

$$D_{LW} = c\sigma_{LW} n_{H2} \rightarrow S c\sigma_{LW} n_{H2}$$

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Molecular Strömgren Sphere

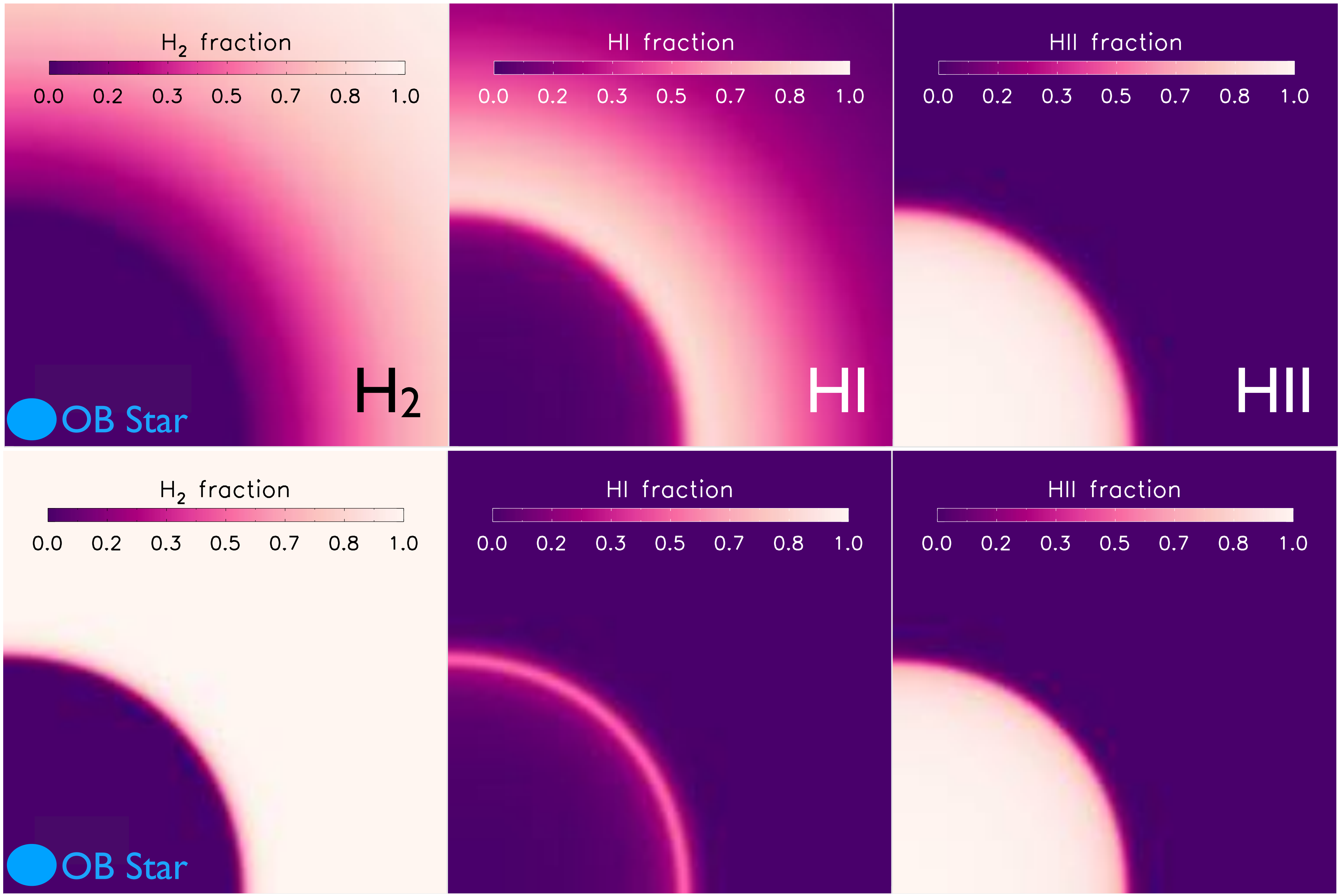
Originally describes radiation from an OB star ionising an atomic medium

We describe ionizing and dissociating radiation in an atomic and molecular medium

Molecular and atomic fronts grow according to analytical expressions

No self-shielding

With self-shielding



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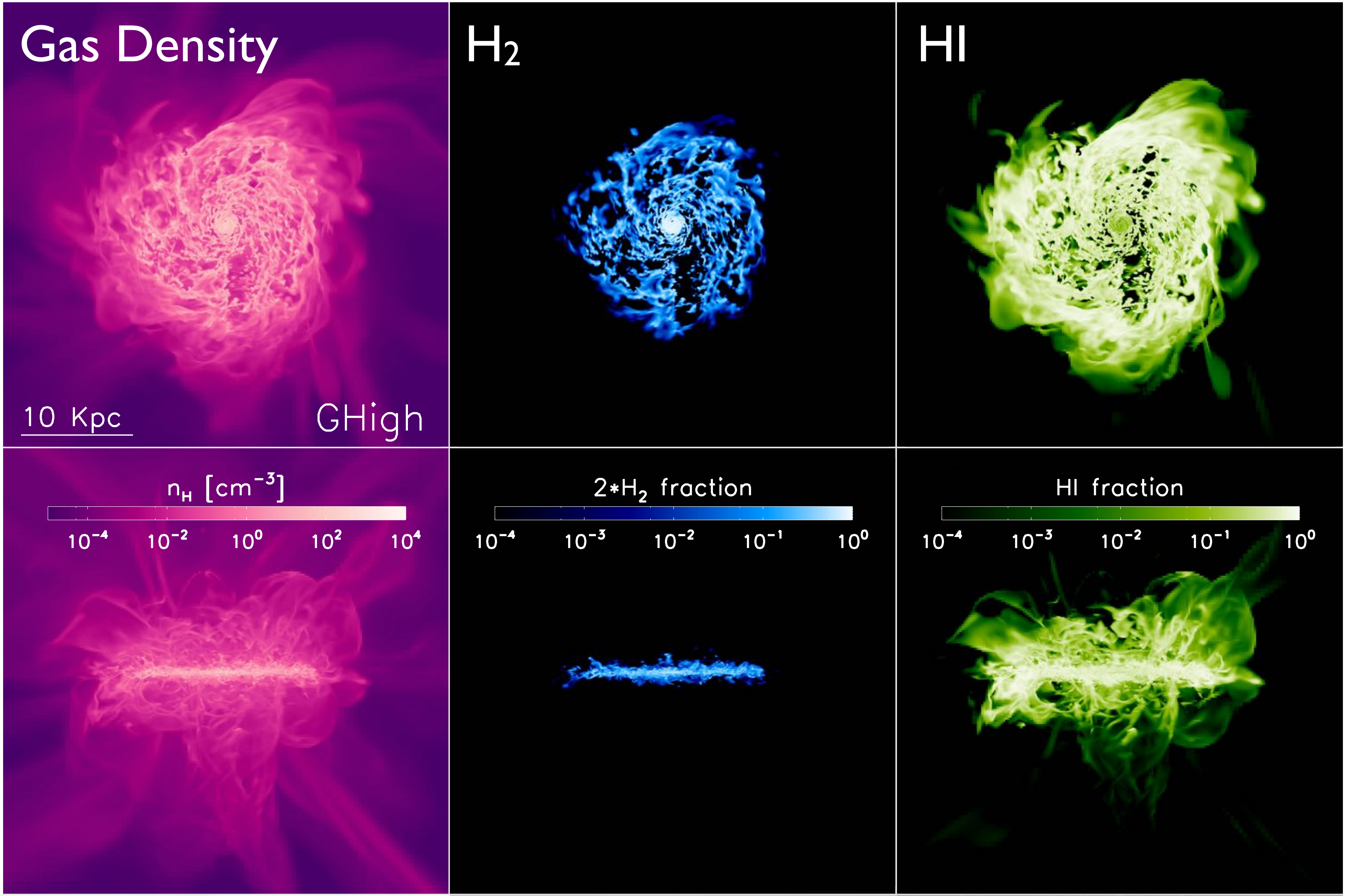
Galaxy!

Milky Way-like, isolated disc galaxy (from the AGORA project, Kim et al. 2016)
Resolution 6 pc, 400 kpc box
Star formation recipe independent of H_2, is total gas density-based (Rasera & Teyssier 2006)
Delayed cooling thermal feedback for supernovae (Teyssier et al. 2013)



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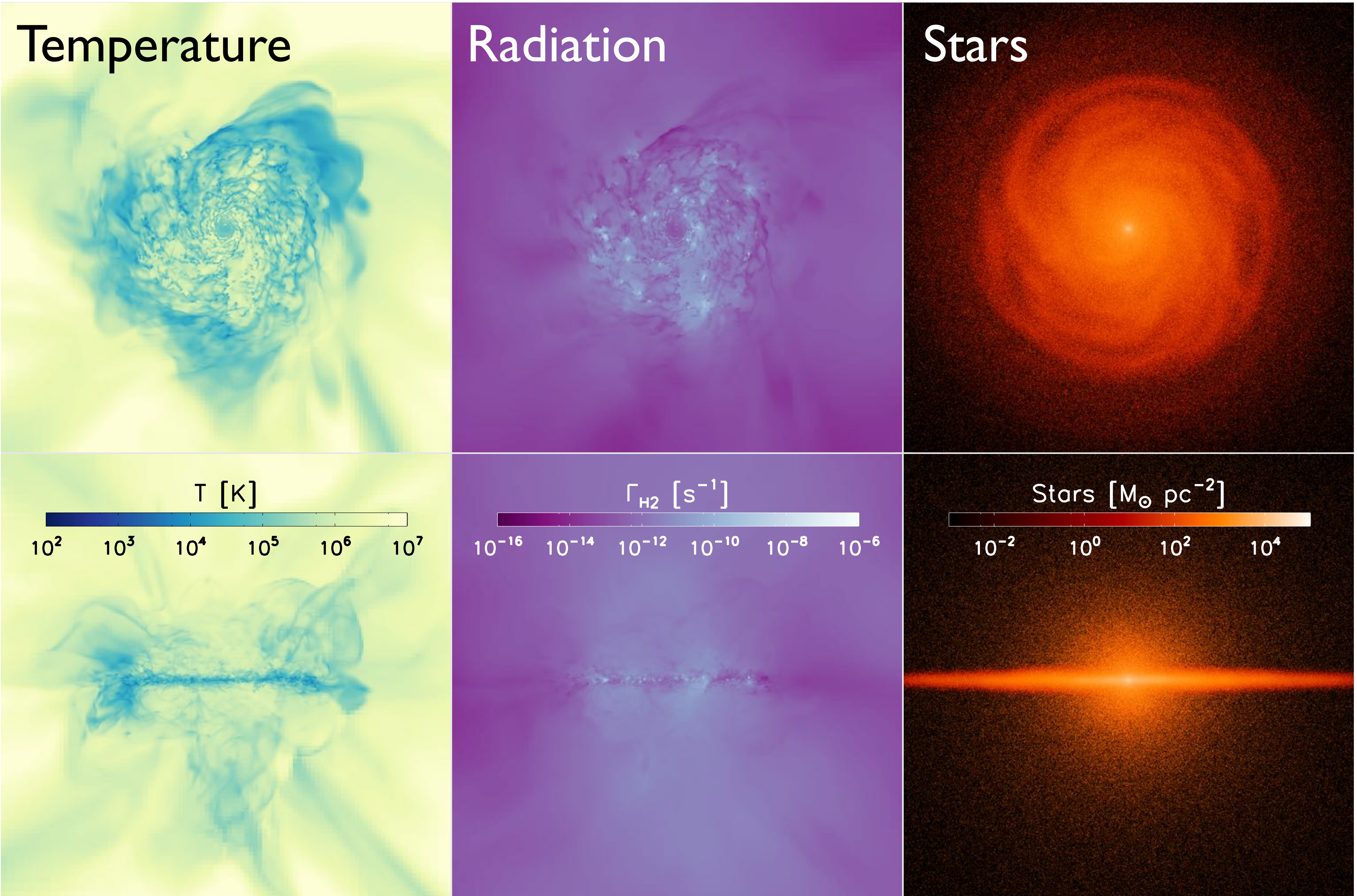

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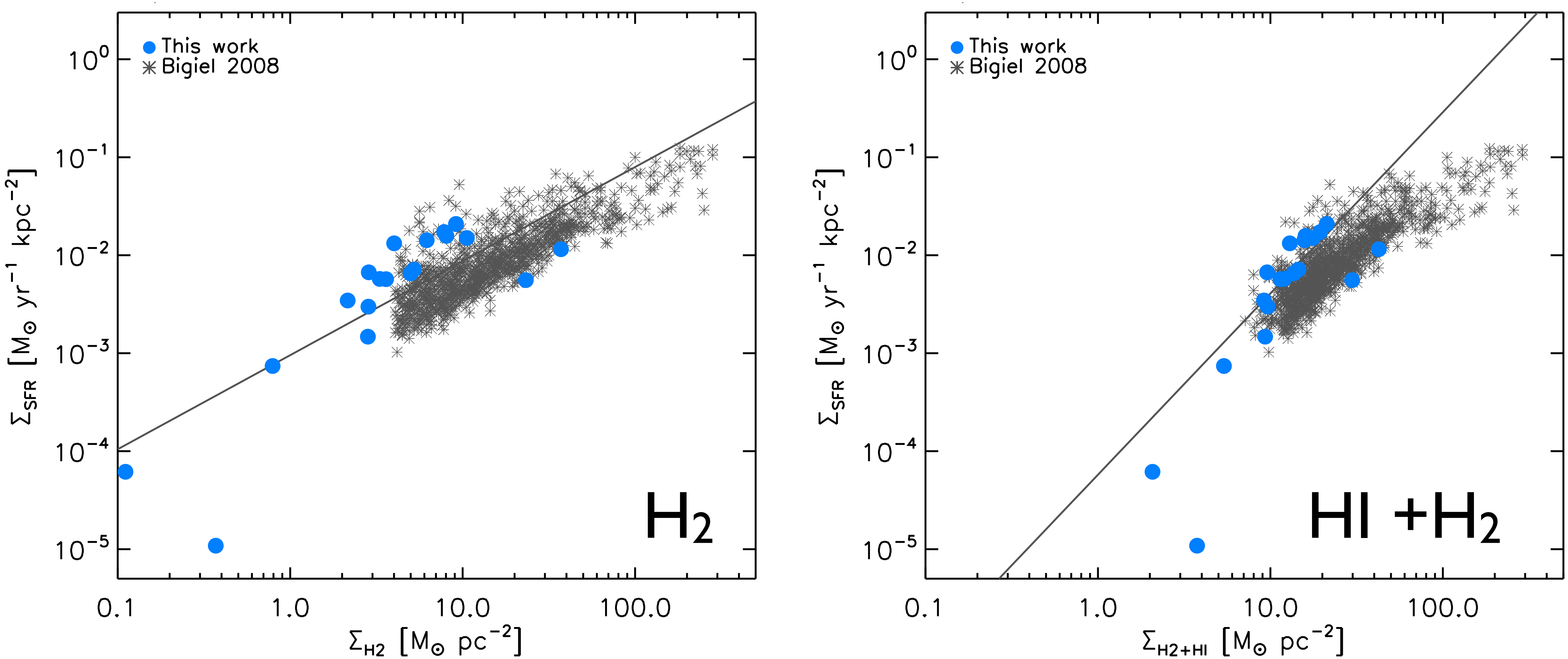
Kenincutt-Schmidt

- Established, observed relation between neutral gas and SFR (Schmidt (1959) and Kennicutt (1998))
- More recently discovered relation between H_2 and SFR (e.g. Bigiel et al. 2008)
- We match both, aside from quenched central points
- Scruba 2011 extend this relation to lower densities, and we match fall in HI-H_2 relation



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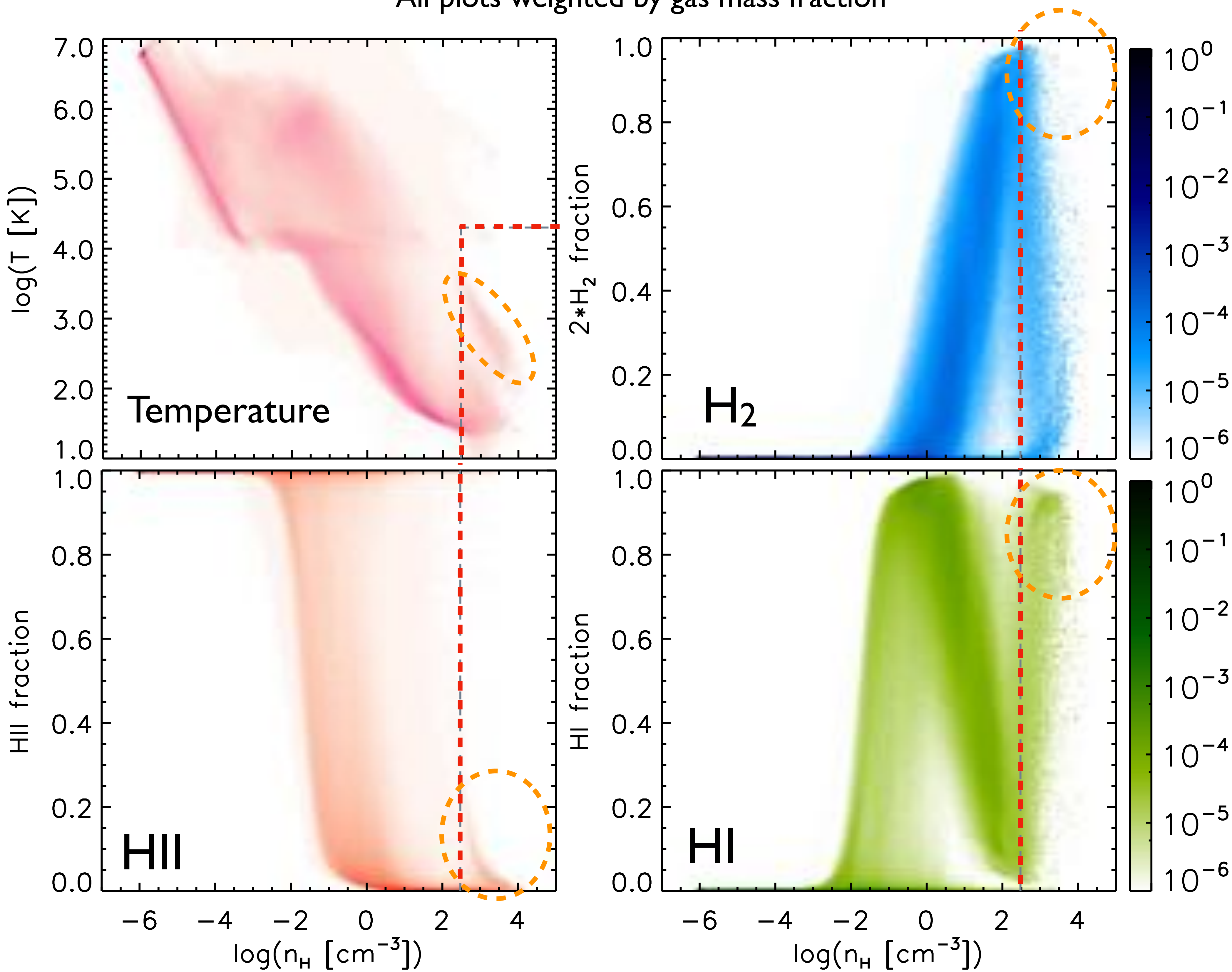
Phase Diagrams

All plots weighted by gas mass fraction

Unresolved HII regions

Star formation threshold



HII sparse, hot gas

H_2 cold, dense gas

HI in between

Cannot resolve 100% molecular regions or HII regions around young stars

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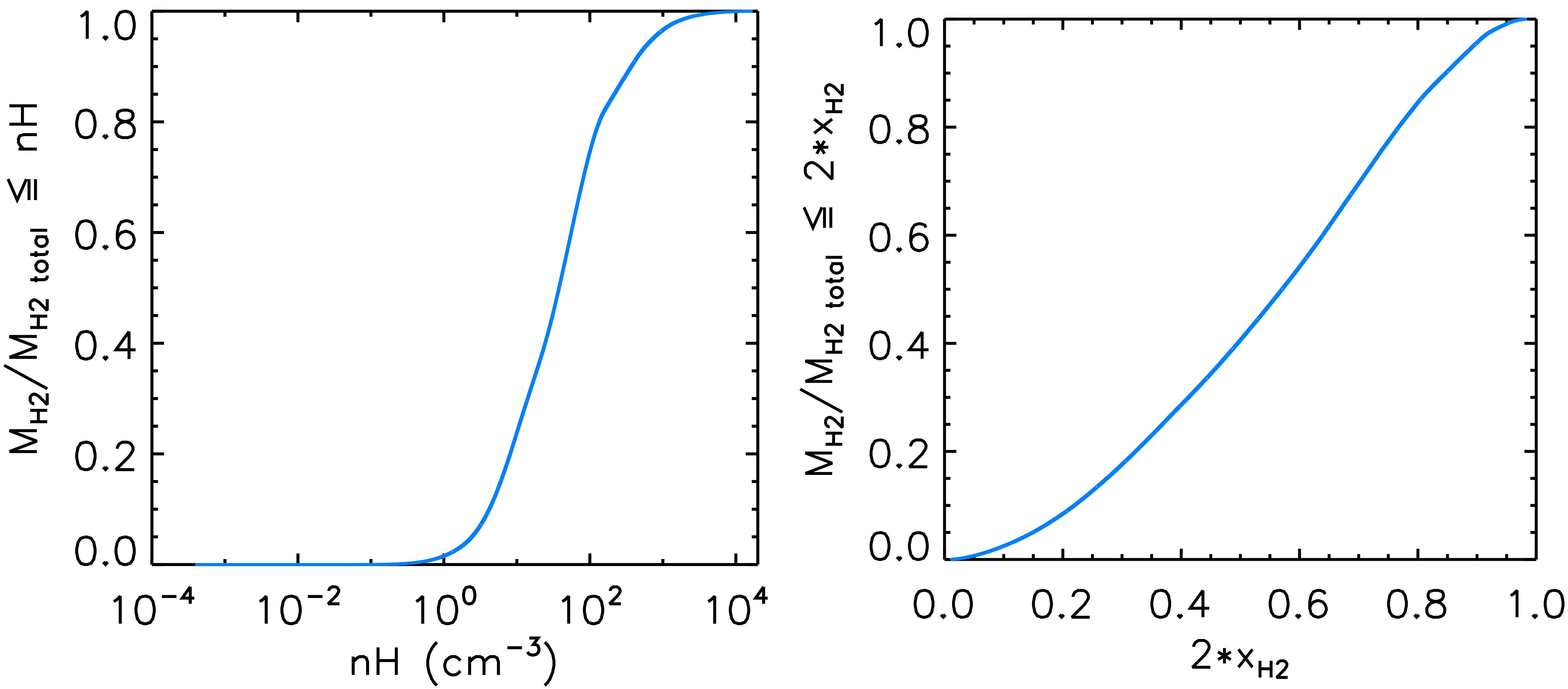
Where is the H_2?



- 50% of H_2 is at densities 37.8 cm^{-3} and lower
- 50% of H_2 is at fractions 0.57 and lower

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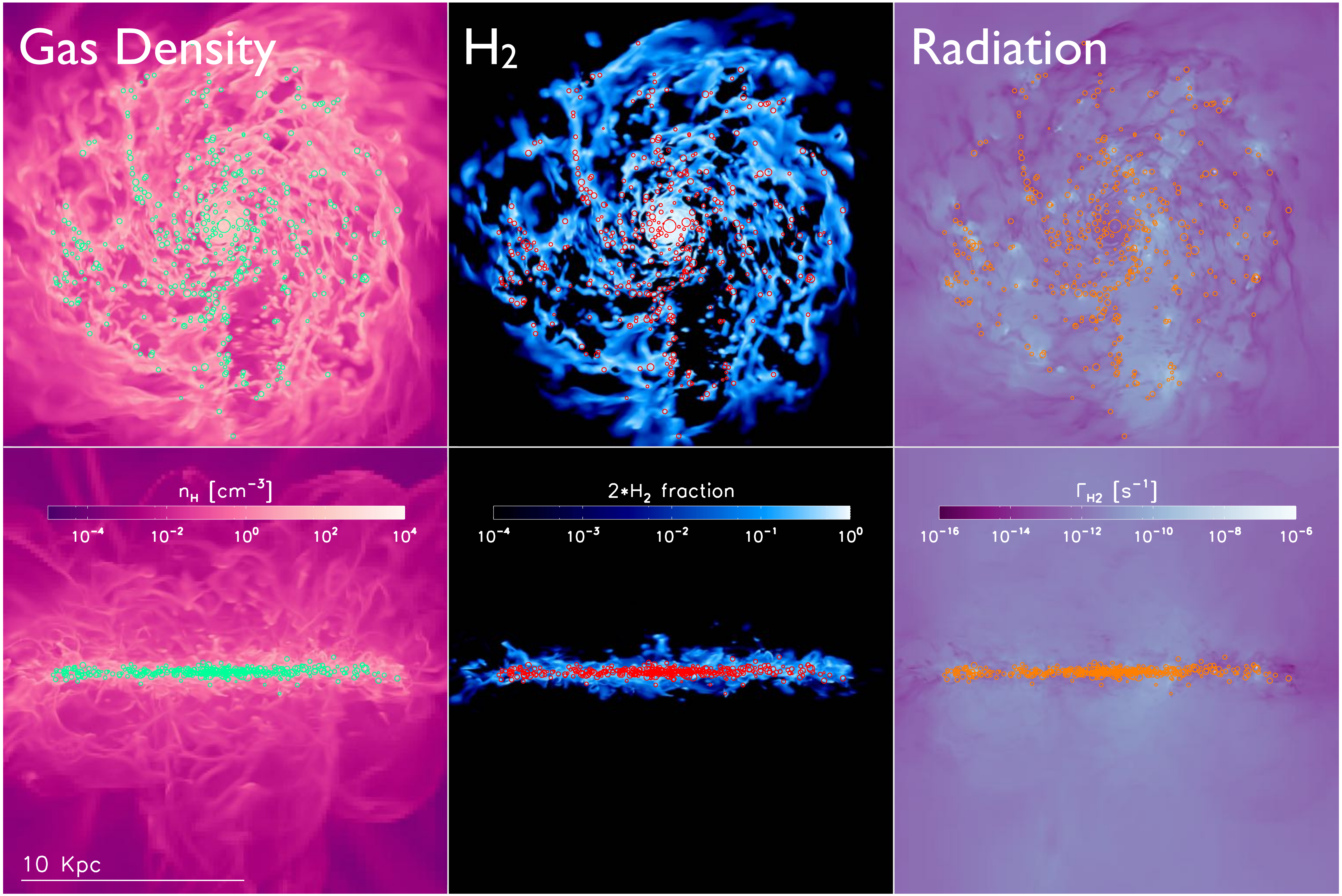
Clump Finding With PHEW



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Conclusions

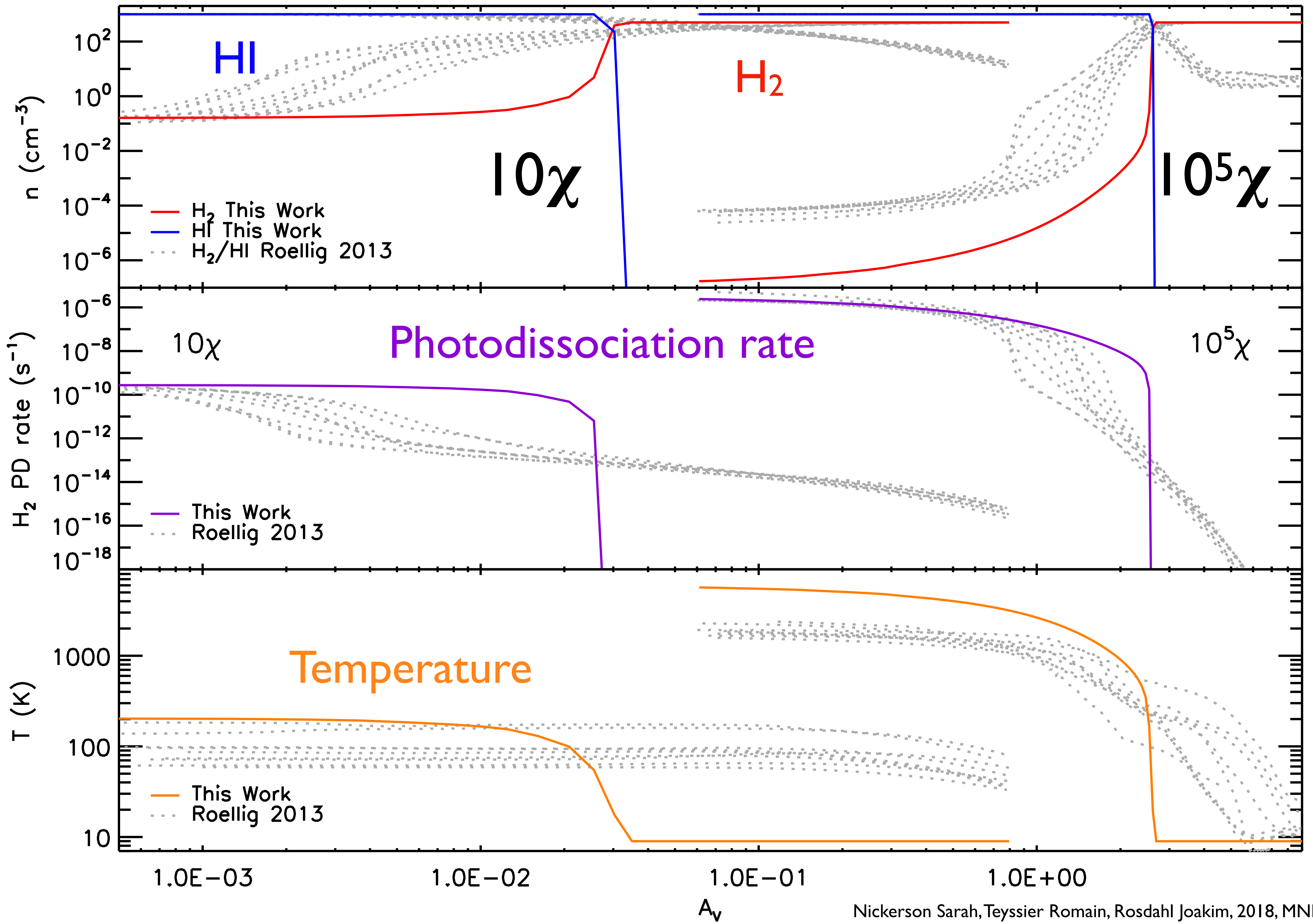
- Successfully modelled non-equilibrium H_2 chemistry using local methods with Ramses-RT
- Introduced new radiative transfer-based self-shielding model for galaxy simulations
- Tested model in idealised situations against benchmark models to demonstrate robustness
- Realistic galaxy
- Much of the H_2 gas is diffuse and mixed with HI
- In progress: CO chemistry to investigate the CO-H_2 conversion factor and the existence of a "CO-dark" H_2 component of the ISM

Chemistry: Nickerson Sarah, Teyssier Romain, Rosdahl Joakim, 2018, MNRAS, 479, 3206
Galaxy: Nickerson Sarah, Teyssier Romain, Rosdahl Joakim, 2018, arXiv:1809.01657, submitted to MNRAS

Carina Nebula, Credit: NASA, ESA, N. Smith, and The Hubble Heritage Team

PDR Code Comparison

- Photodissociation regions (PDRs) UV dominated (6 to 13.2 eV) and host most galactic atomic and molecular gas
- Roellig 2013 benchmark comparison of 10 PDR codes
- PDR codes are 1D so can treat self-shielding exactly
- We reproduce transition point, but not shape



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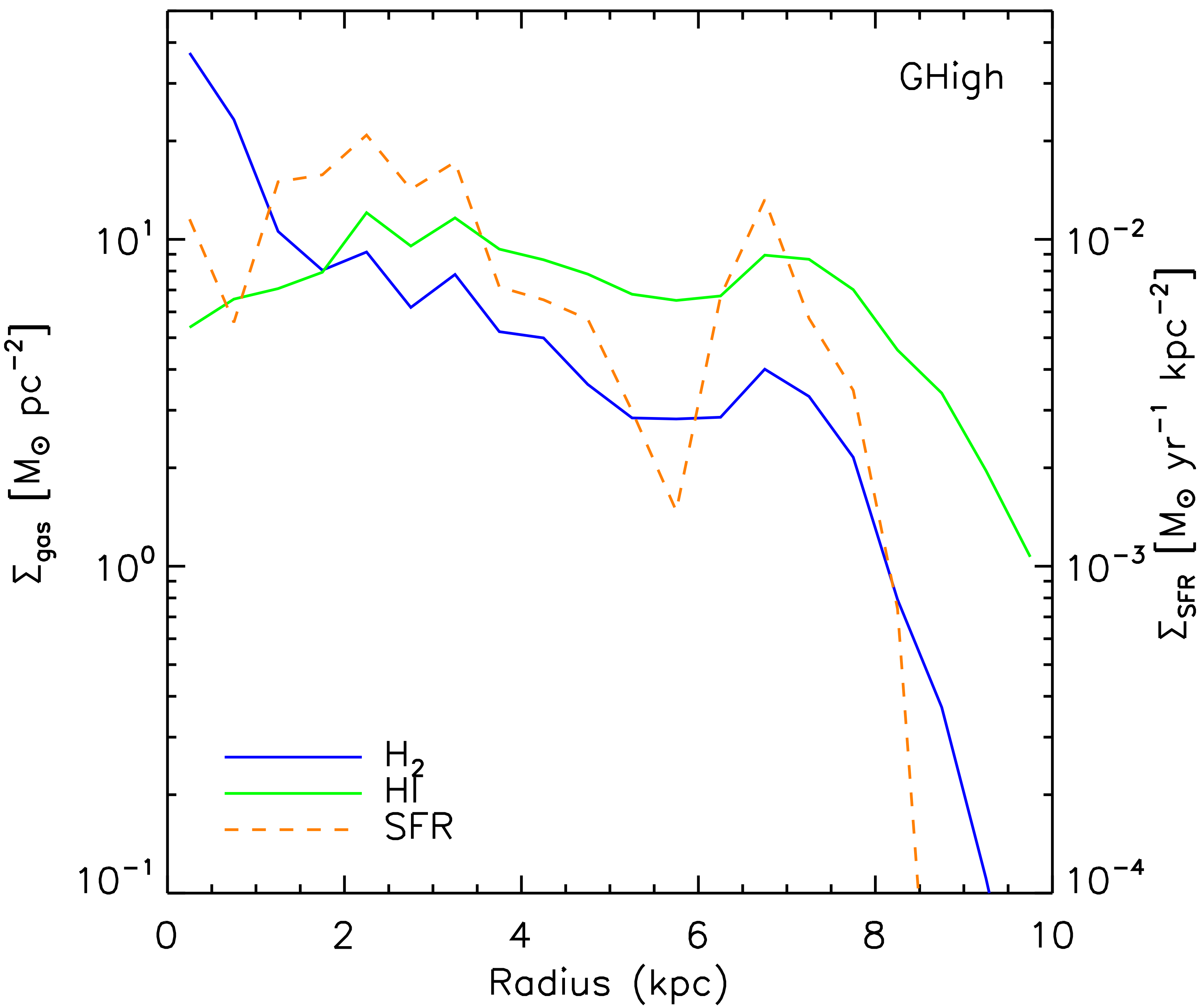
Radial Profile

Reproduce central H_2 spike and flat HI profile

SFR trends mimic H_2 trends, except for galactic centre

Central bulge may cause morphological quenching

Surface density and SFR numbers are similar to observed galaxies around Milky Way mass



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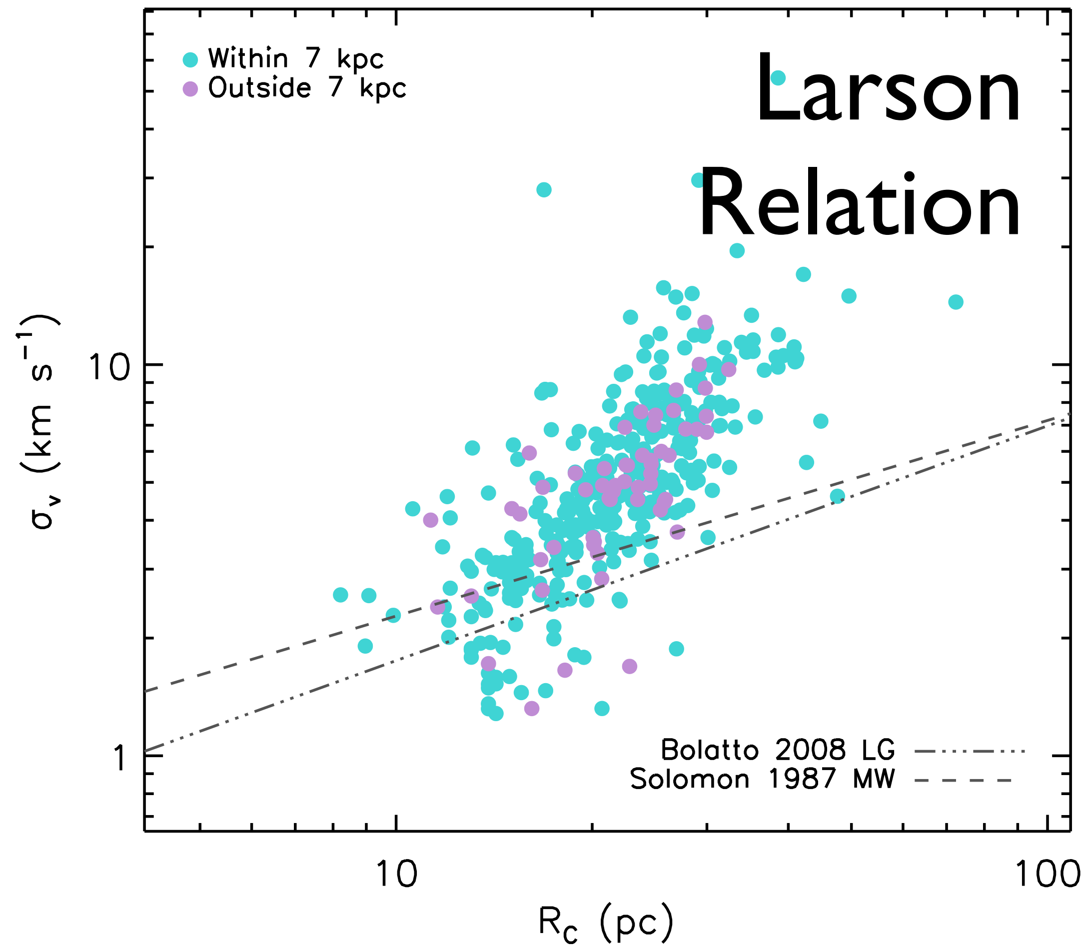
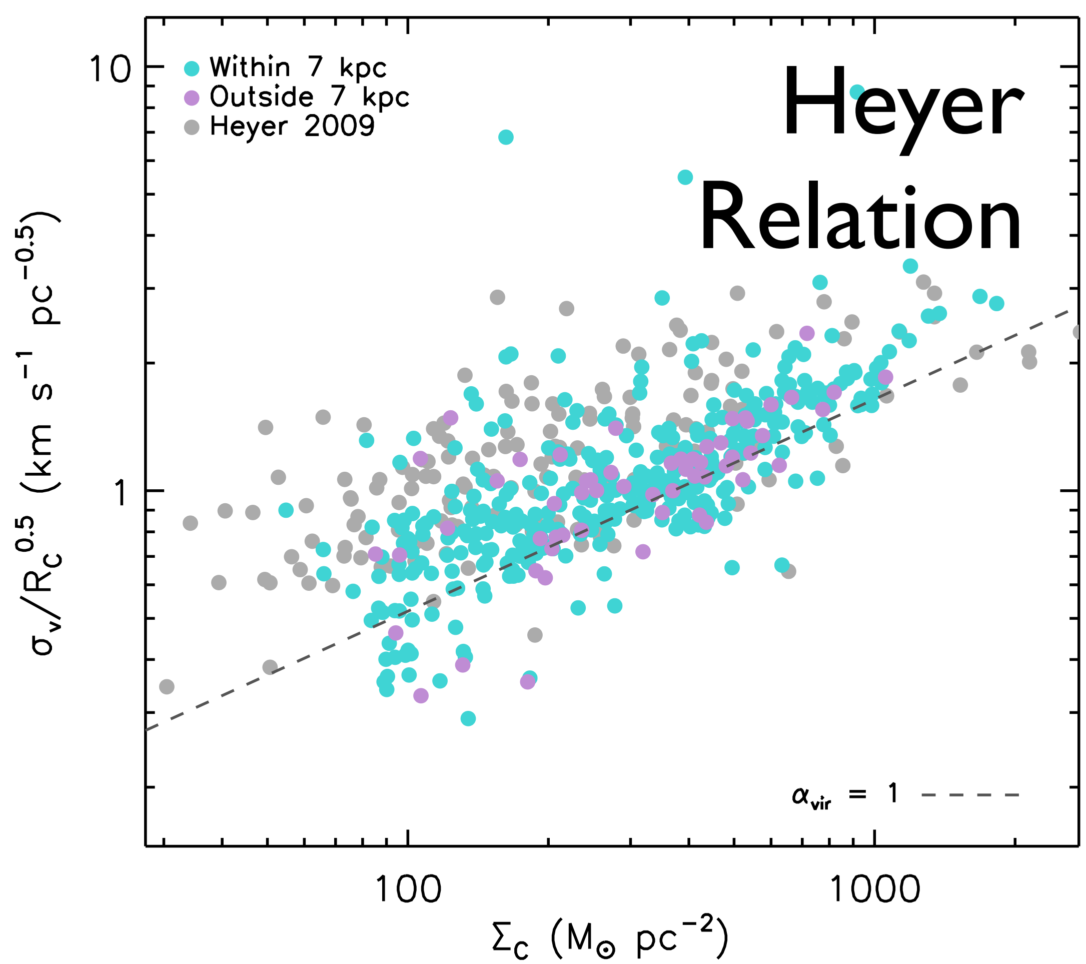
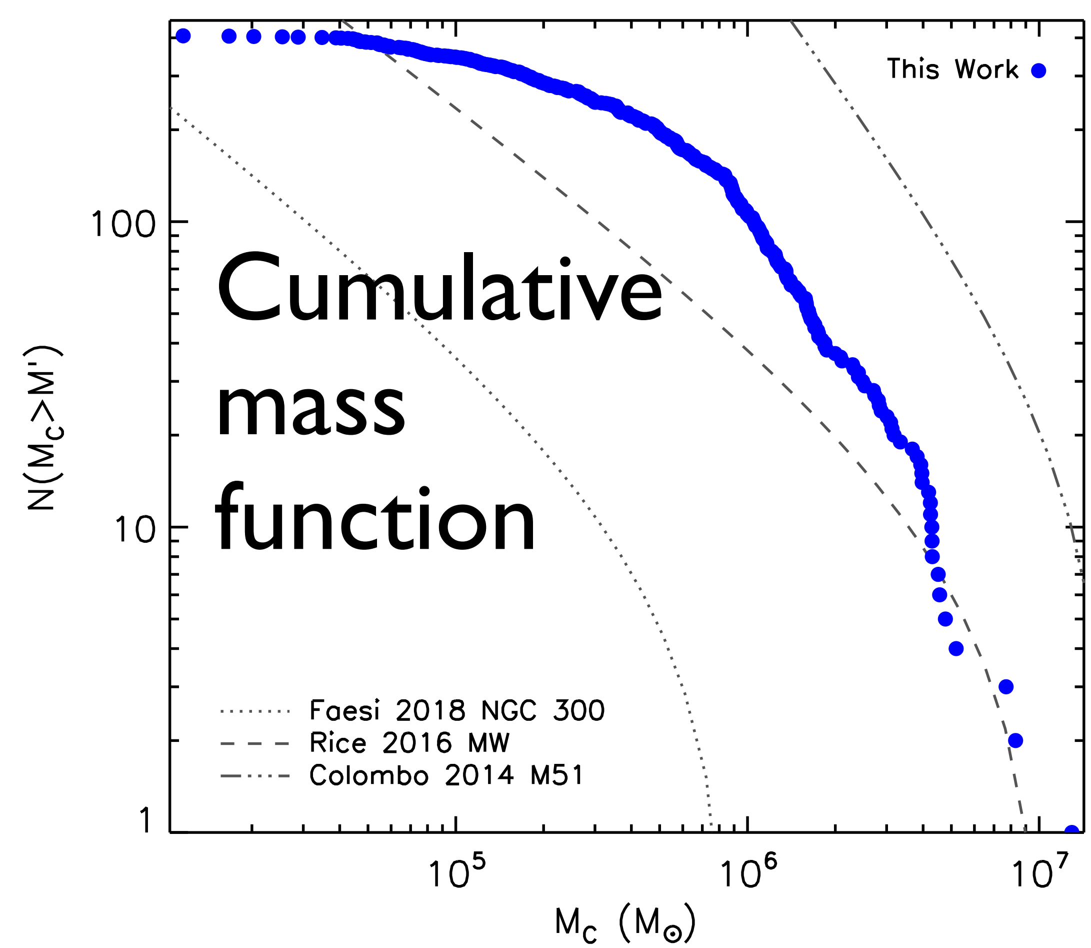


- Clouds are 96% molecular
- Slightly more at medium masses than Milky Way, fewer low mass clouds
- Inner and outer galaxy cloud populations show no difference
- Do no follow traditional Larson relation (1981), but do with newer Heyer relation (2009)





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