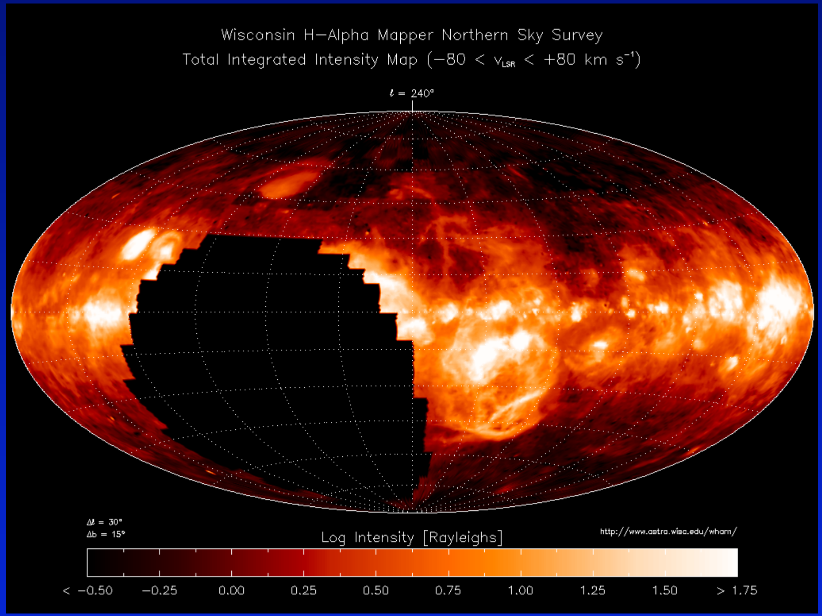
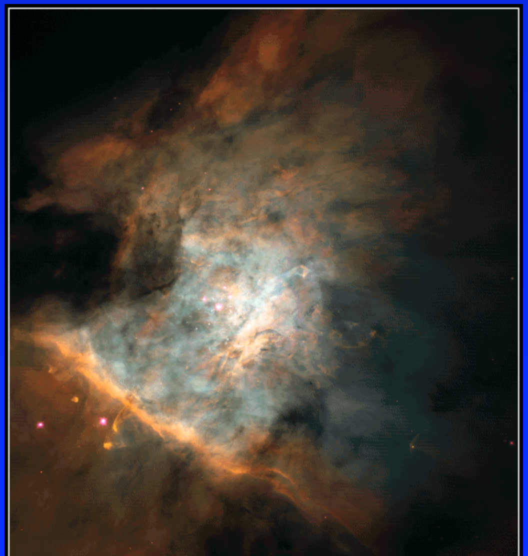
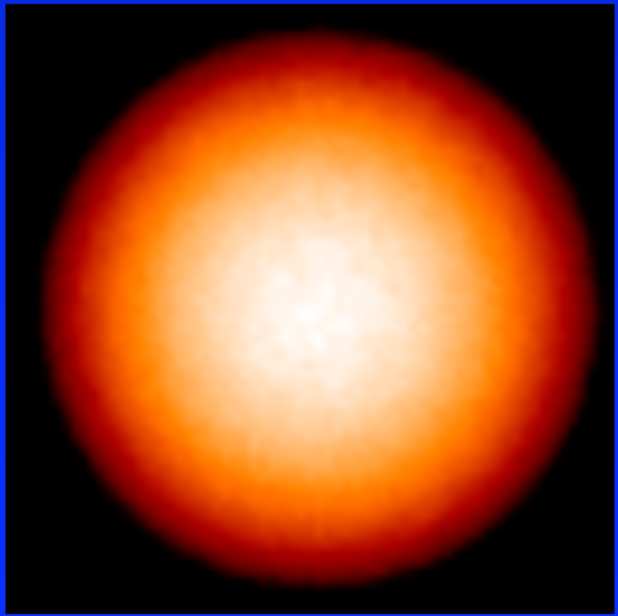
A Monte Carlo Photoionization Code for H II Regions

Kenneth Wood, John Mathis, & Barbara Ercolano





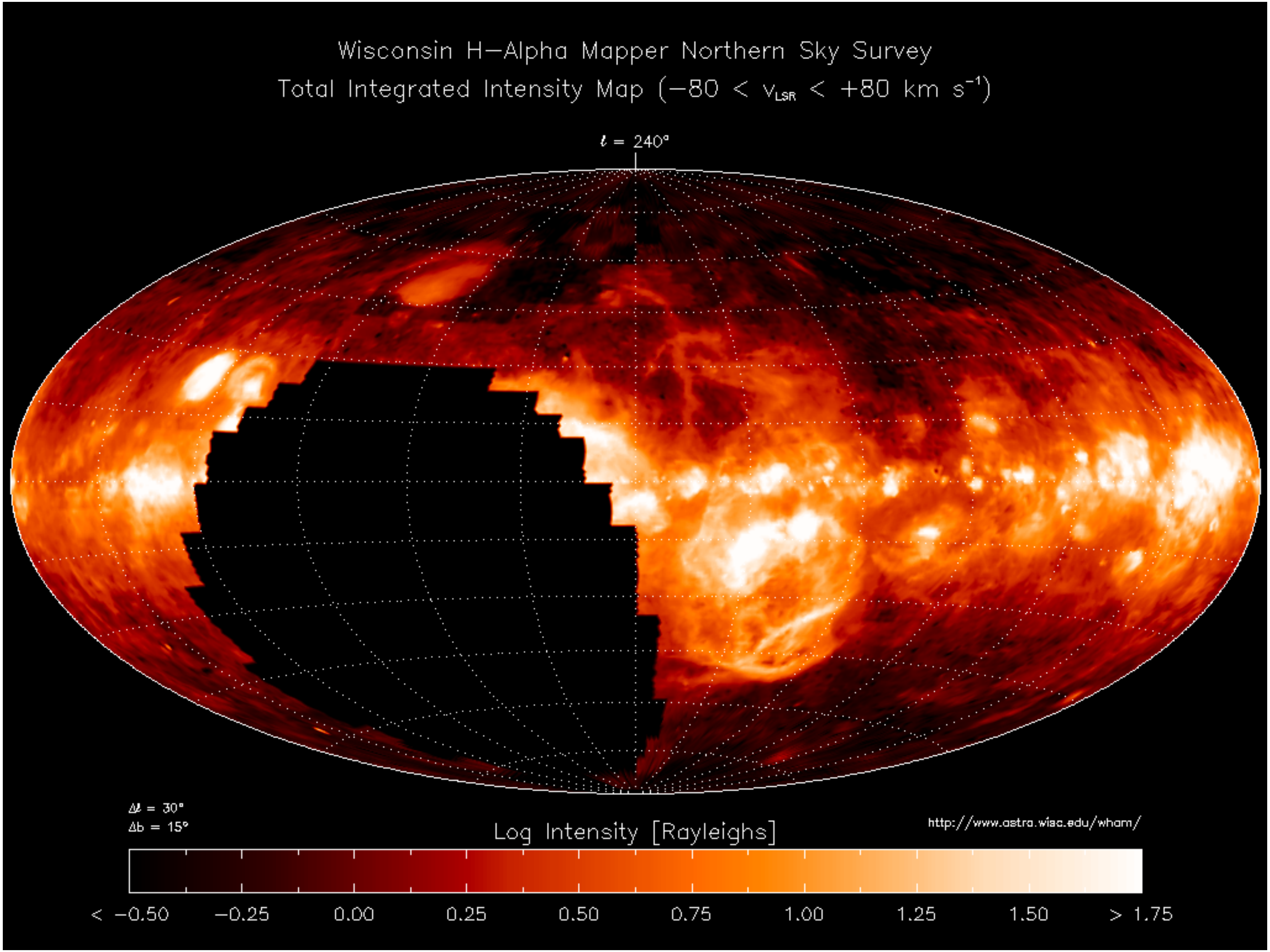
Orion Nebula Mosaic HST · WFPC2
PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA



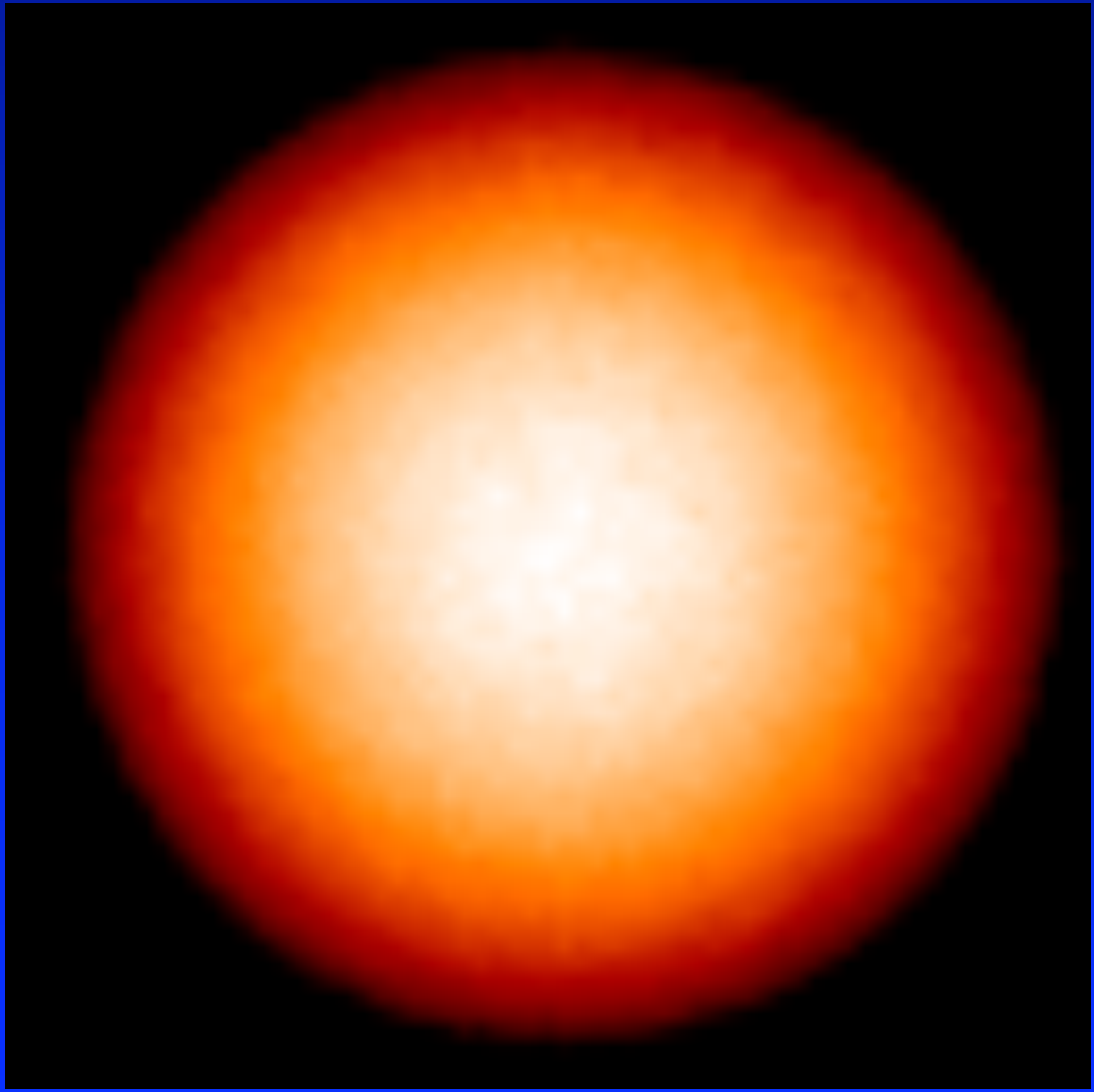
Orion Nebula

Orion Nebula Mosaic HST • WFPC2
PRC95-45a • ST ScI OPO • November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

Tarantula Nebula


Wisconsin H-Alpha Mapper Northern Sky Survey
Total Integrated Intensity Map (−80 < v_LSR < +80 km s⁻¹)
ℓ = 240°
Δℓ = 30°
Δb = 15°
Log Intensity [Rayleighs]
http://www.astro.wisc.edu/wham/
< −0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
> 1.75

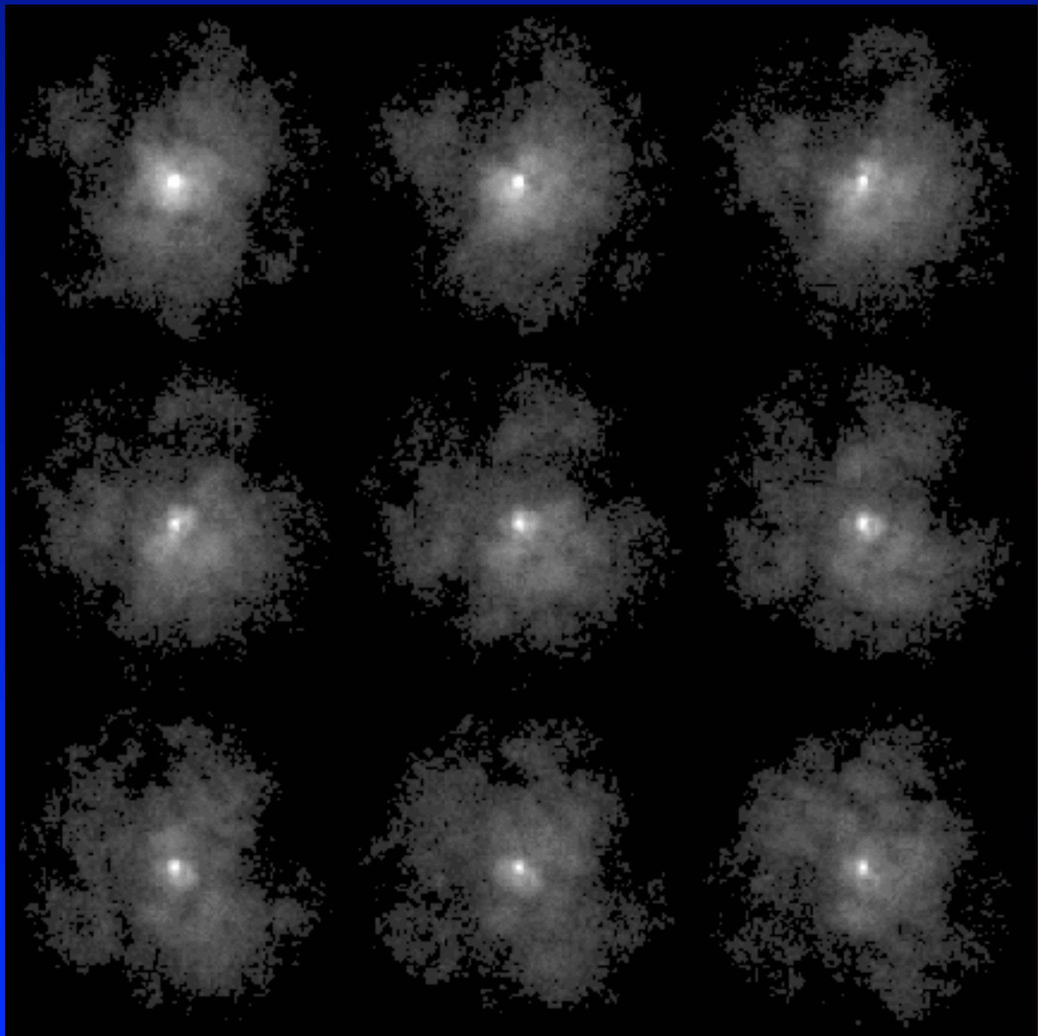
H II Region Model: Hα



H II Regions

- Use line ratios to determine nebular density, temperature, & abundances
- 3D effects on temperature & ionization?
- How do line strengths & ratios from 3D models differ from smooth models?
- Big effects, cf dusty reflection nebulae?

Dust in Reflection Nebulae



NGC 7023

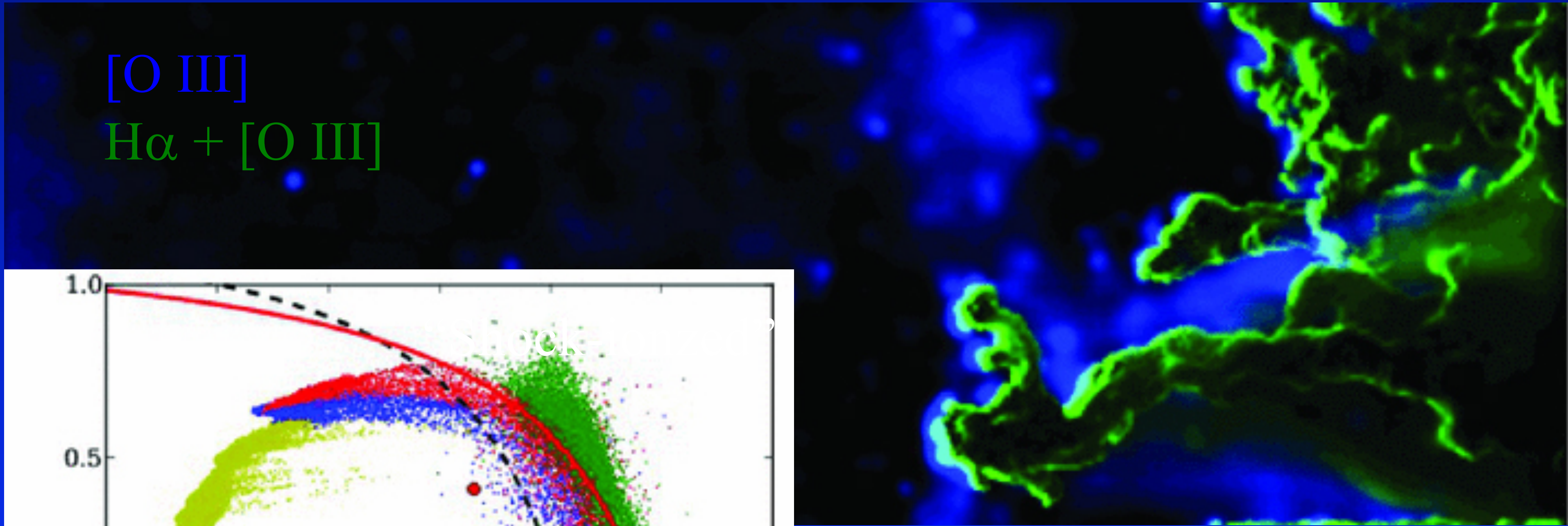
Mathis, Whitney & Wood (2002)

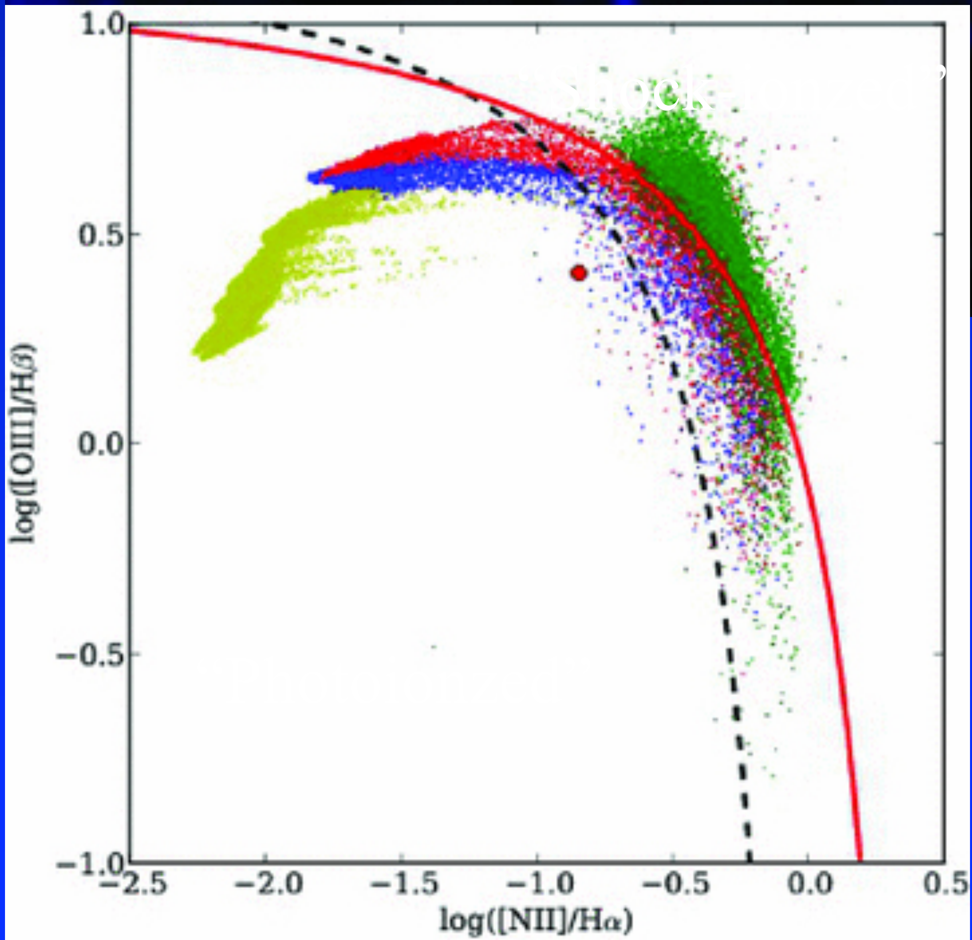
Cannot determine dust properties (albedo, phase function) from analysis of scattered light images

Monte Carlo Photoionization

- 3D density structure and radiation transfer
- Input: ionizing spectrum from source(s)
- Output: 3D temperature & ionization structure
- Use temperature & ionization structure to get line emissivities, make emission line maps and line ratios

Photo- or shock- ionization?





Ercolano et al. (2012)

Assumptions for H II Regions

- Monte Carlo RT for packets with $h\nu > 13.6$eV
- All ions in ground state: *nebular approximation*
- No collisions, so $n < 10^3$ cm^{-3}: OK for H II regions
- No He^{+2}: no packets with $h\nu > 54.4$eV
- Opacity from H^0 and He^0: ignore dust (easy to include) and heavier elements with low abundances
- He I Lyman α heats and ionizes "on-the-spot"
- Ions: $H^0 - H^+$, $He^0 - He^+$, $N^0 - N^{+3}$, $C^+ - C^{+3}$, $O^0 - O^{+3}$, $Ne^0 - Ne^{+3}$, $S^+ - S^{+3}$
- Heating: photoionization of H and He
- Cooling: recombination of H & He, free-free radiation, collisionally excited lines of C, N, O, Ne, S

Monte Carlo Radiation Transfer

1. Choose random frequency from ionizing spectrum
2. Emit packets isotropically from point source(s)
3. Find where packet is absorbed: photoionization event occurs
4. If recombination then re-emit packet at new (ionizing) frequency
5. Repeat 3 & 4 until packet exits simulation
6. Emit new source packet: do all source packets
7. Update temperature & ionization structure: new opacity grid
8. Iterate until temperature & ionization converges

Photon Packets

- Radiative equilibrium Monte Carlo codes use photon ENERGY packets:

$$\varepsilon = L\,\Delta t \,/\, N \qquad\qquad n = \varepsilon \,/\, h\nu$$

- We use PHOTON packets:

$$\varepsilon = Q\,h\nu\,\Delta t \,/\, N$$

- Can easily use atomic probabilities for photon interactions

Sampling from Probability Functions

Probability of event, *P(x)*: form *cumulative distribution function*

$$C(x) = \text{Area under PDF} = \int_a^x P(x')\,\mathrm{d}x' \Big/ \int_a^b P(x')\,\mathrm{d}x'$$

Want to randomly choose τ, θ, ν, … so that PDF is reproduced

$$\xi = \int_a^X P(x)\,\mathrm{d}x \Big/ \int_a^b P(x)\,\mathrm{d}x \Rightarrow X$$

ξ is a random number uniformly chosen in range [0,1]

Packet Frequencies

Sample from *photon* luminosity. Pre-tabulate $C(\nu_i)$:

$$\xi = C(\nu_i) = \int_{\nu_H}^{\nu_i} L(\nu)/h\nu \, \mathrm{d}\nu \Big/ \int_{\nu_H}^{\infty} L(\nu)/h\nu \, \mathrm{d}\nu \Rightarrow \nu_i$$

Isotropic Emission

Initial direction for random walk:

$$\theta = \cos^{-1}(2\xi - 1)$$

$$\phi = 2\pi\,\xi$$

Choosing a Random Optical Depth

$P(\tau) =$ exp(-τ): packet travels τ before interaction:

$$\tau = -\log \xi$$

Physical distance, *S*, that the packet has traveled:

$$\tau_\nu = \int_0^S n\, a_\nu\, \mathrm{d}s$$

$$n\, a_\nu = n(\mathrm{H}^0)\; a_\nu(\mathrm{H}^0) + n(\mathrm{He}^0)\; a_\nu(\mathrm{He}^0)$$

Photoionization/Recombination

- Probability of being absorbed by H:

$$P(\mathrm{H}) = \frac{n(\mathrm{H}^0)\ a_\nu(\mathrm{H}^0)}{n(\mathrm{H}^0)\ a_\nu(\mathrm{H}^0) + n(\mathrm{He}^0)\ a_\nu(\mathrm{He}^0)}$$

- If $\xi < P(H)$: packet reprocessed into H I spectrum
- If $\xi > P(H)$: packet reprocessed into He I spectrum

H I: Ionizing & Non Ionizing

- Lyman continuum, $h\nu > 13.6$ eV
- Probability of emission: $$P_{\text{Ly-c}} = \alpha_1 / \alpha_A$$
- Recombination coefficients: $\alpha(T)$
- If $\xi < P_{\text{Ly-c}}$: sample ν from Ly-c emissivity, re-emit isotropically
- If $\xi > P_{\text{Ly-c}}$: $h\nu < 13.6$ eV, non-ionizing line + continuum spectrum, terminate packet as it cannot ionize, nebula optically thin so photon escapes

He Recombination

- Only four end states: 1^1S, 2^1P, 2^3S, 2^1S
- These metastable levels yield H-ionizing photons

- Direct to 1^1S, Ly-c ($h\nu > 24.6$eV): $P_{\text{Ly-c}} = \alpha_1 / \alpha_A$
- Lyα (21.2eV) $2^1P - 1^1S$: $P_{\text{Ly}\alpha} = \alpha^{eff}_{2^1P} / \alpha_A$
- $2^3S - 1^1S$ (19.8eV): $P_{19.8} = \alpha^{eff}_{2^3S} / \alpha_A$
- Two photon continuum $2^1S - 1^1S$: $P_{2q} = \alpha^{eff}_{2^1S} / \alpha_A$
- All ways of populating given level: α^{eff}

Photoionization

$$n(\mathrm{H}^0)\int_{\nu_H}^{\infty}\frac{4\pi J_\nu}{h\nu}a_\nu(\mathrm{H}^0)\,\mathrm{d}\nu = n(\mathrm{H}^+)\,n_\mathrm{e}\,\alpha(\mathrm{H}^0,T)$$

\# photoionizations/sec \# recombinations/sec

Need to know mean intensity throughout grid. Lucy (1999):

$$4\pi J_\nu\,\mathrm{d}\nu = \sum \varepsilon_\nu\, l/(\Delta t\,\Delta V)$$

$$\varepsilon_\nu = Q\,h\nu\,\Delta t/N$$

Sum (l a) in each cell for each element. At end of iteration have:

$$\int_{\nu_H}^{\infty}\frac{4\pi J_\nu}{h\nu}a_\nu(\mathrm{H}^0)\,\mathrm{d}\nu = Q/(N\,\Delta V)\sum l\,a_\nu(\mathrm{H}^0)$$

Photoionization Heating

Electron kinetic energy due to excess above H-threshold. Form counters analagous to photoionization:

$$G(\mathrm{H}^0) = \int_{\nu_H}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\mathrm{H}^0)\, h(\nu - \nu_H)\, \mathrm{d}\nu$$

$$= Q / N \sum l\, a_\nu(\mathrm{H}^0)\, h(\nu - \nu_H)$$

Cooling

- Recombination of H and He:

$$L(\mathrm{H}^0) = 8.7 \times 10^{-27}\, n(\mathrm{H}^+)\, n_\mathrm{e} \frac{\sqrt{T}\,(T/10^3)^{-0.2}}{1+(T/10^6)^{0.7}}$$

- Free-Free radiation:

$$L(\mathrm{ff}) = 1.42 \times 10^{-27}\, [n(\mathrm{H}^+) + n(\mathrm{He}^+)]\, n_\mathrm{e} \frac{\sqrt{T}\,(T/10^3)^{-0.2}}{1+(T/10^6)^{0.7}}$$

- Collisionally excited lines of C, N, O, Ne, S:

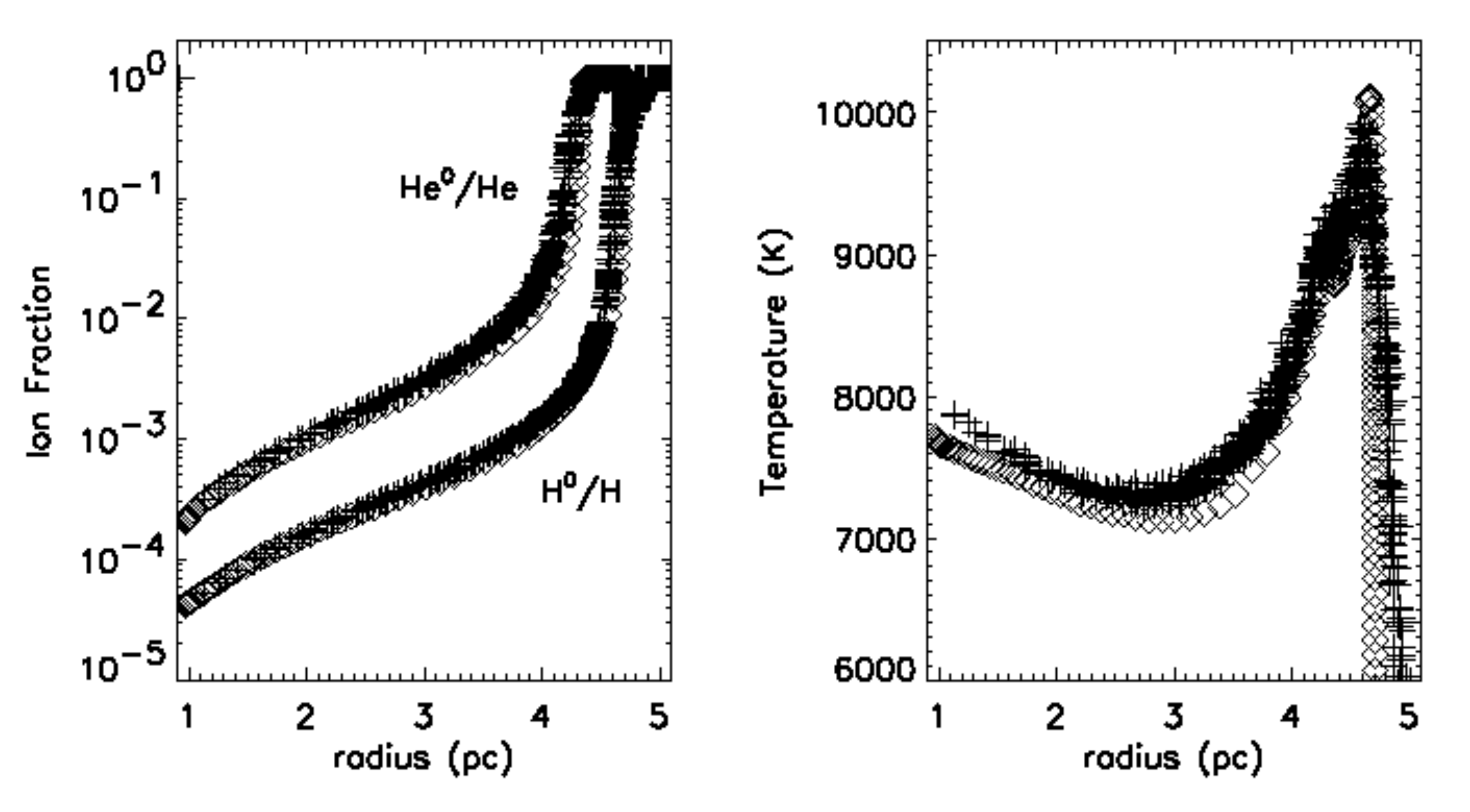
linecool.f : John Mathis

He I Lyman Lines

- Optically thick resonance lines
- Scattered *locally* many times, degrade to low energies and Ly α
- Ly α absorbed by H^0 close to emission location – "On the Spot" approximation
- Every Ly α packet generated ($\xi < P_{\mathrm{Ly}\,\alpha}$) is absorbed and reprocessed into H I spectrum

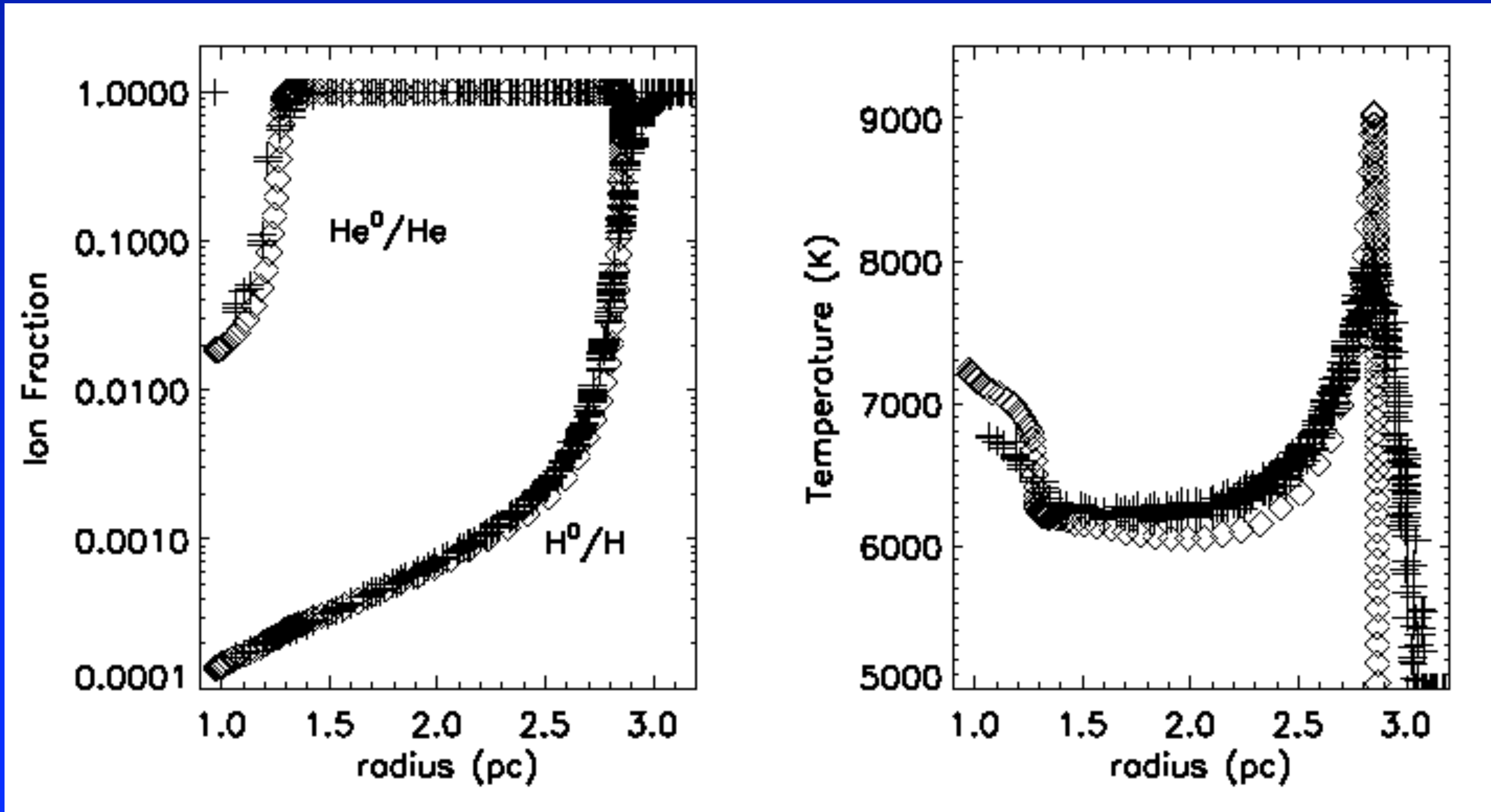
Lexington H II Benchmarks

- $T_* = 40000K$, $Q(H) = 4.26E49\ s^{-1}$, $n(H) = 100\ cm^{-3}$



Lexington H II Benchmarks

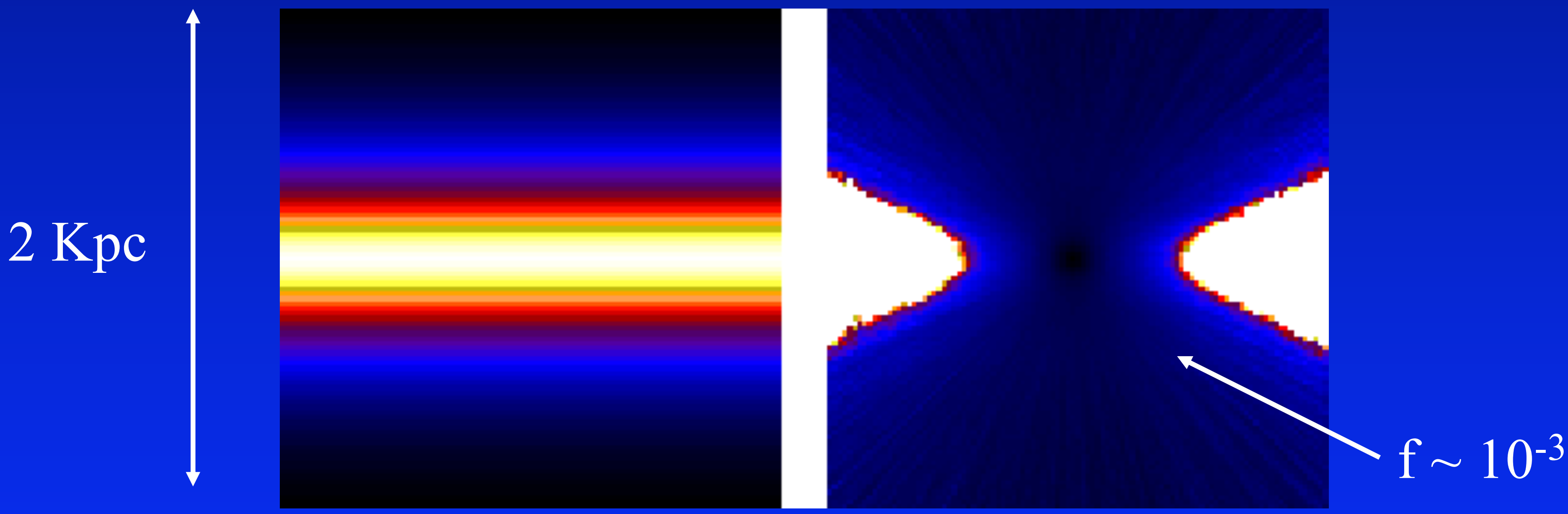
- $T_* = 20000K$, $Q(H) = 1.E49\ s^{-1}$, $n(H) = 100\ cm^{-3}$



Photoionization code

- Three page instruction manual
- Calculates ionization fractions of H, He, C, N, O, Ne, S.
- Opacity only from H and He.
- input.params – set number of MC photons, ionizing luminosity, grid size, abundances, ionizing spectrum, etc
- gridset.f, density.f – set up density grid
- sources.f, sources.txt – set up locations and relative luminosities of point sources

Strongren Volume in a Dickey-Lockman Disk

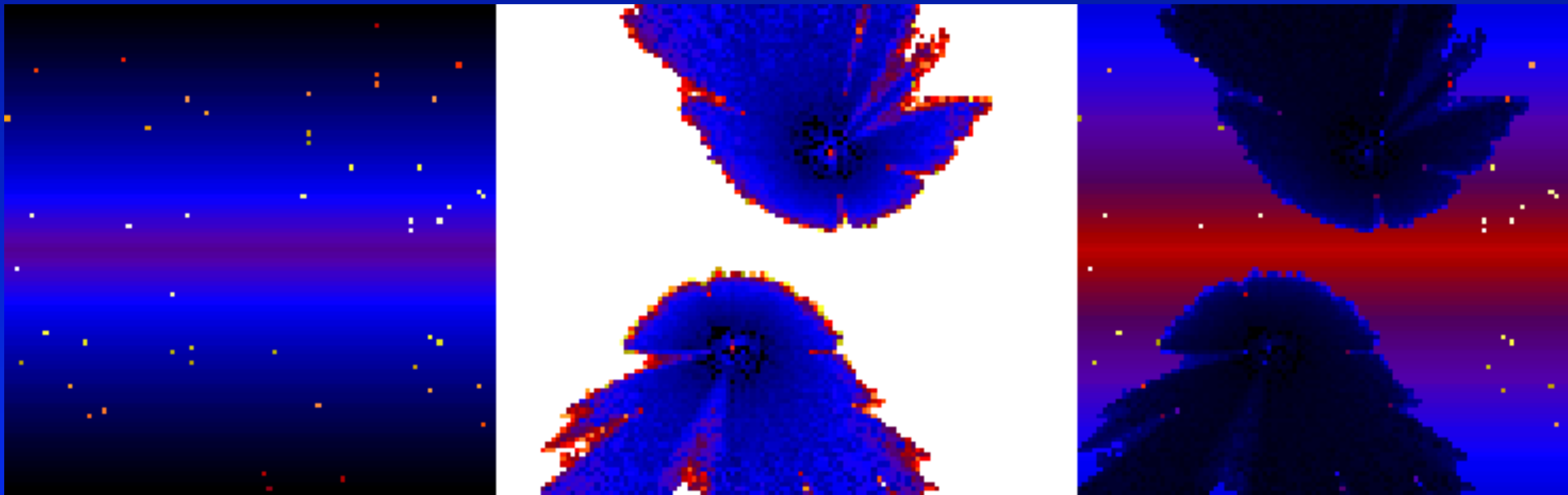


$n(H^0)$ Ionization fraction

$Q(H^0) = 2\ 10^{50}\ s^{-1}$: Escape fraction = 22%

Ionization of HVCs, Magellanic Stream, IGM…

3D Stromgren Volumes



$n(H^0)$ (before) Ionization fraction $n(H^0)$ (after)

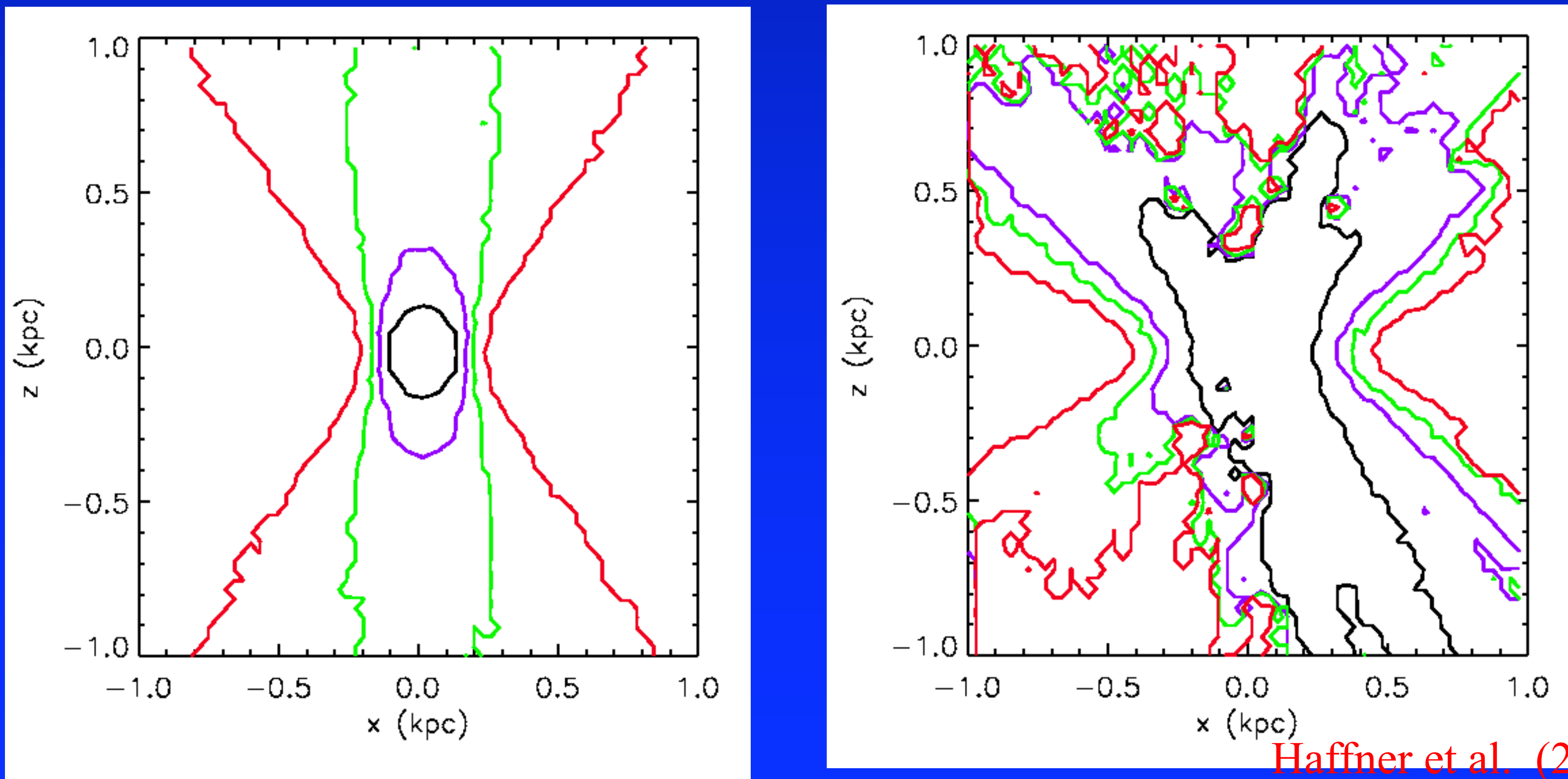
Clumpy density; 2 sources with $Q(H^0) = 2\ 10^{50}\ s^{-1}$

3D ionization structure, shadow regions

3D modeling of WHAM data

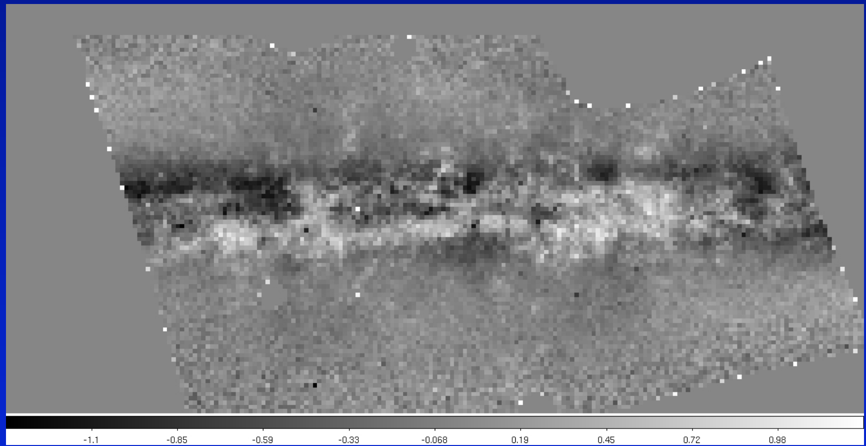
Ionizing a Smooth and Fractal ISM

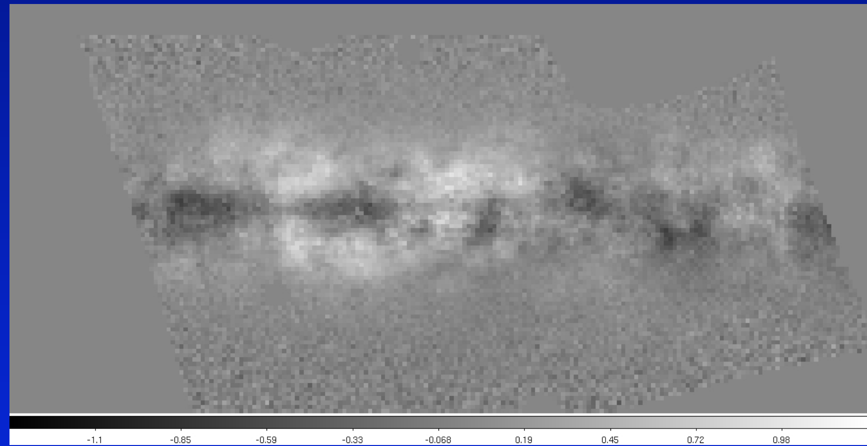
- Initial H^0: Dickey-Lockman disk + Reynolds layer
- Fractal algorithm: Elmegreen (1997)
- Source: $Q(H^0)$ = 1.e49, 3.e49, 5.e49, 1.e50 s^{-1}
- Contours: slices showing edge of H^+ volume
- Hα from smooth component and also cloud faces

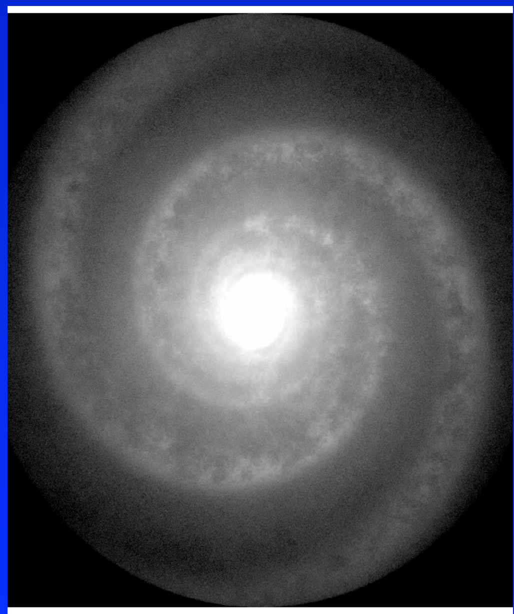


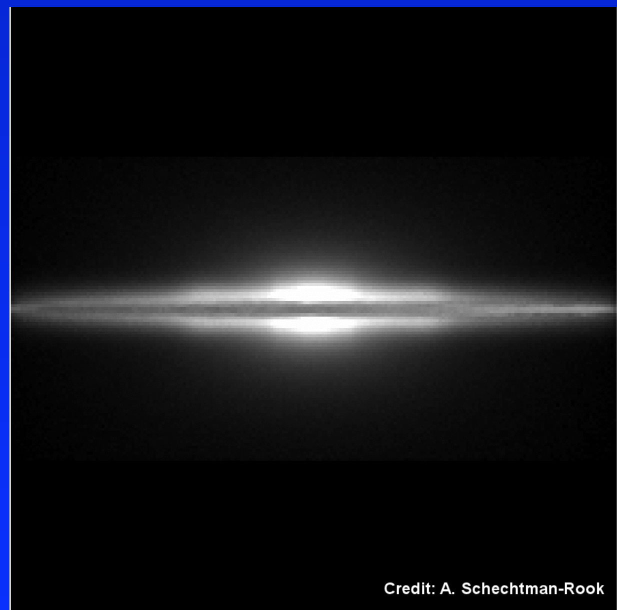
Haffner et al. (2009)

3D Models: NGC891 & M51





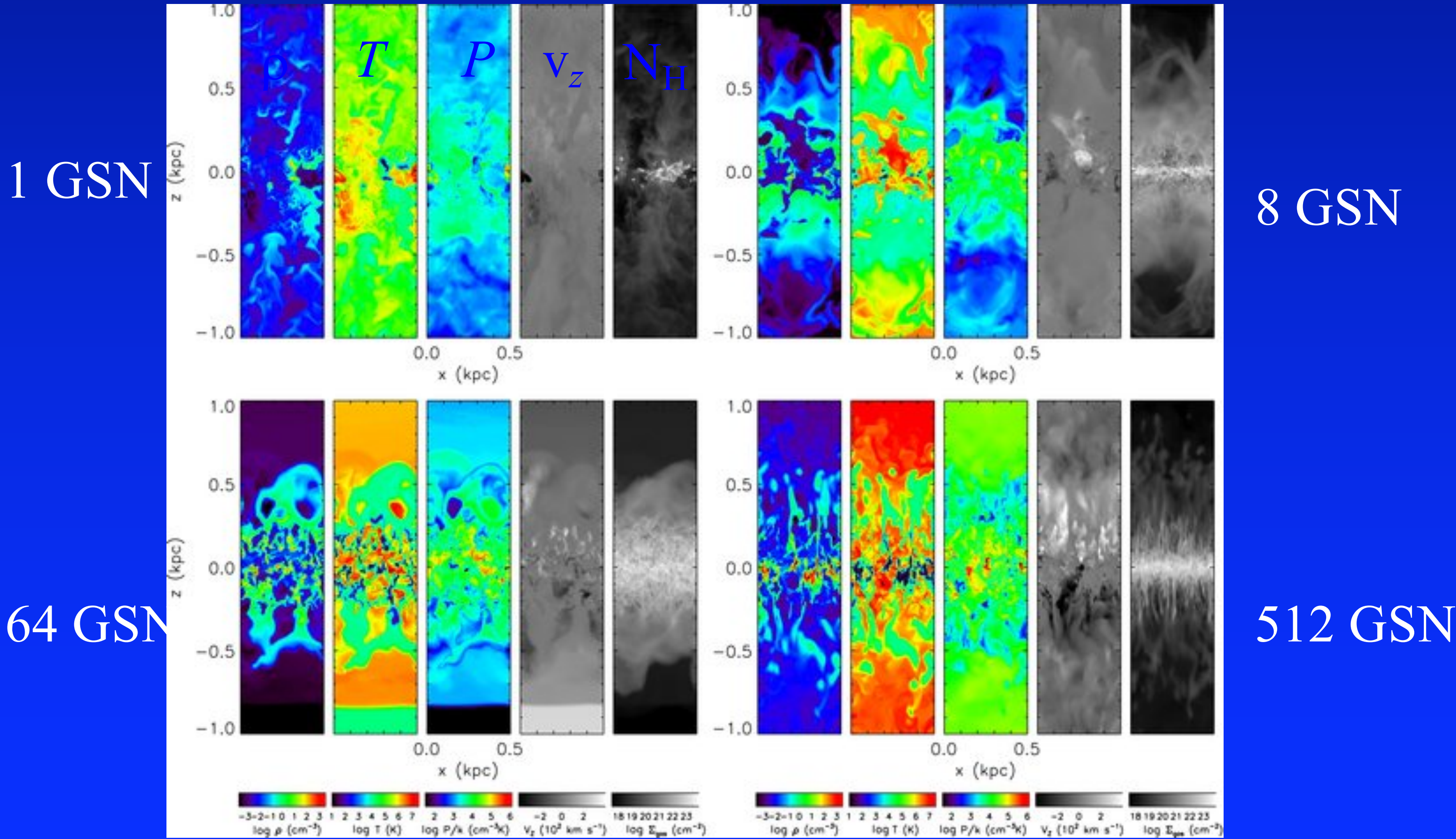




Schechtman-Rook, Bershady, & Wood (2011)

Need 3D dynamical simulations of ISM…

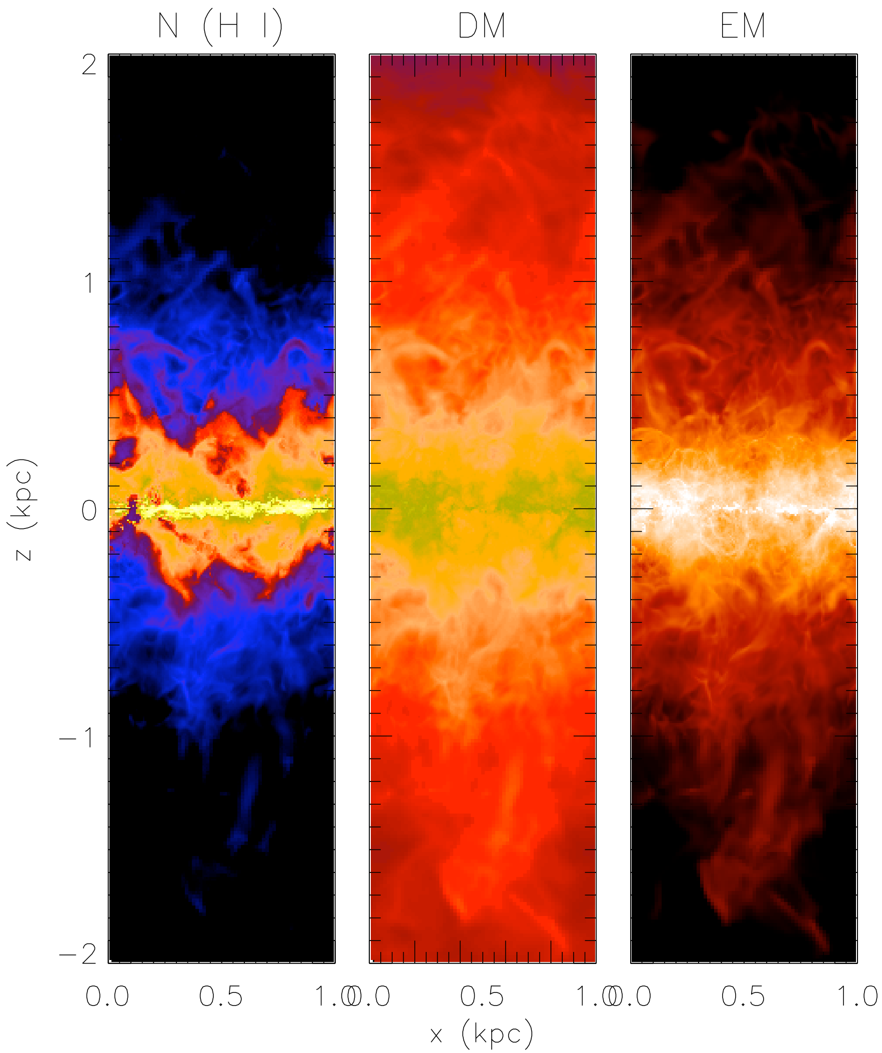
Supernovae Driven Turbulent ISM

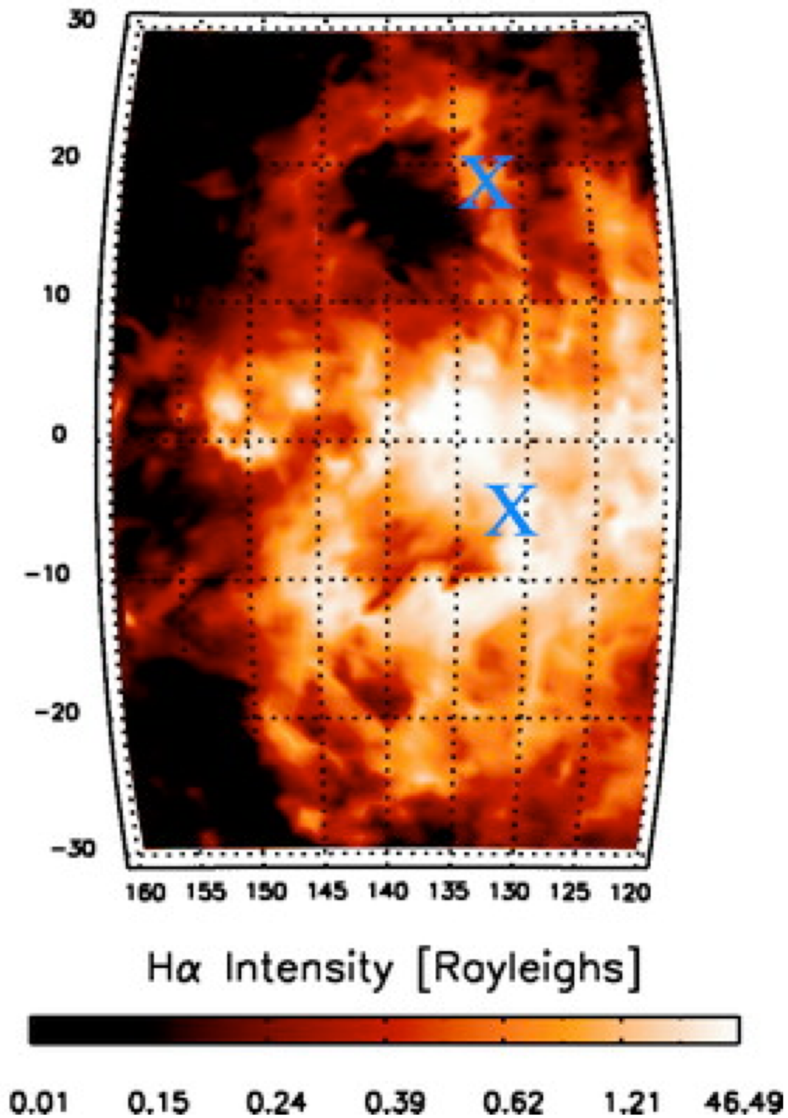


GSN = Galactic supernova rate = 258 SNe Myr^{-1} kpc^{-3}

Joung et al. (2009)

Photoionize MHD snapshots

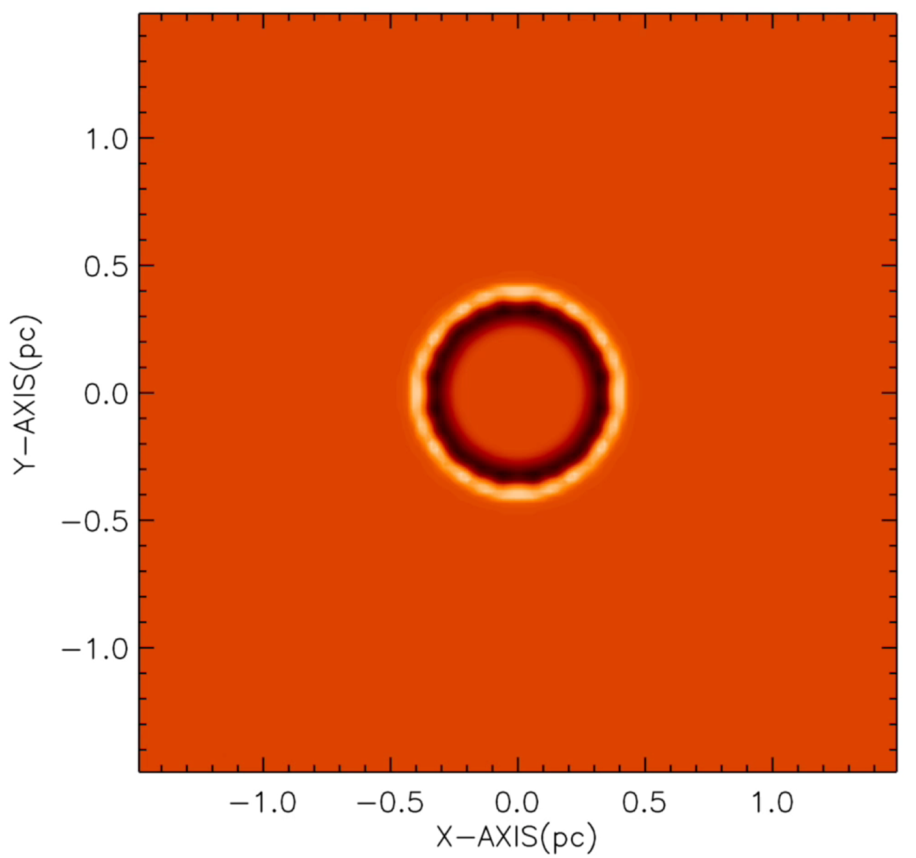


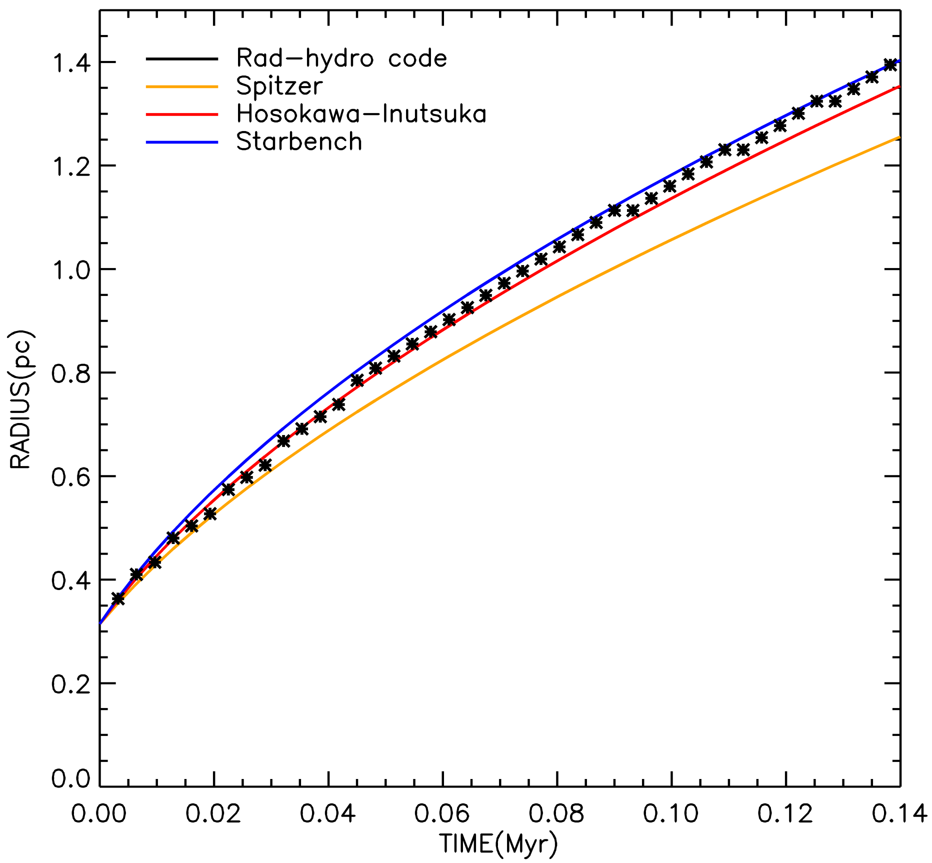


Naturally produce concentrated layer of H^0 and extended H^+

Hill et al. (2012), Barnes et al. (2014)

Monte Carlo Radiation Transfer + MHD

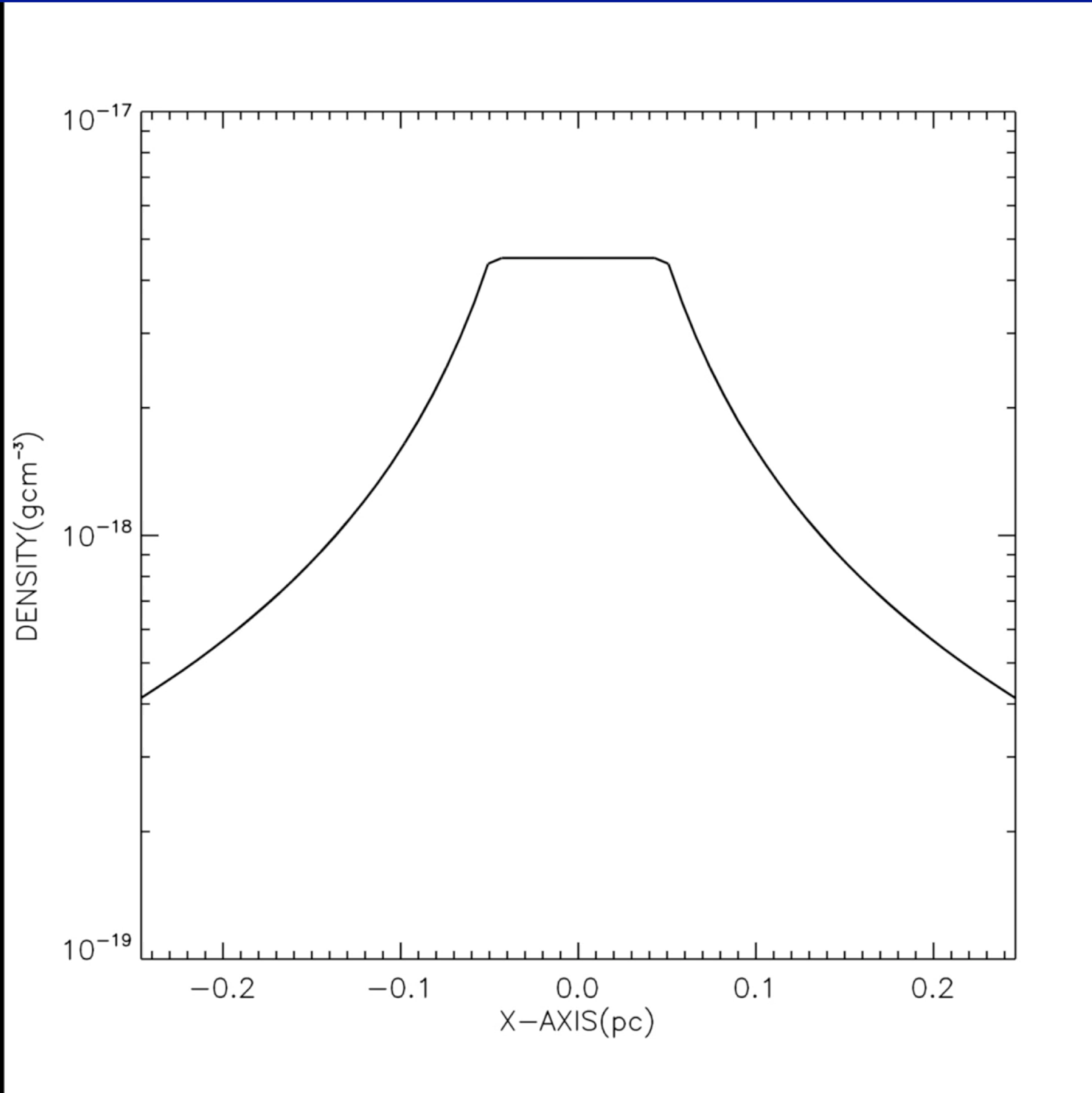




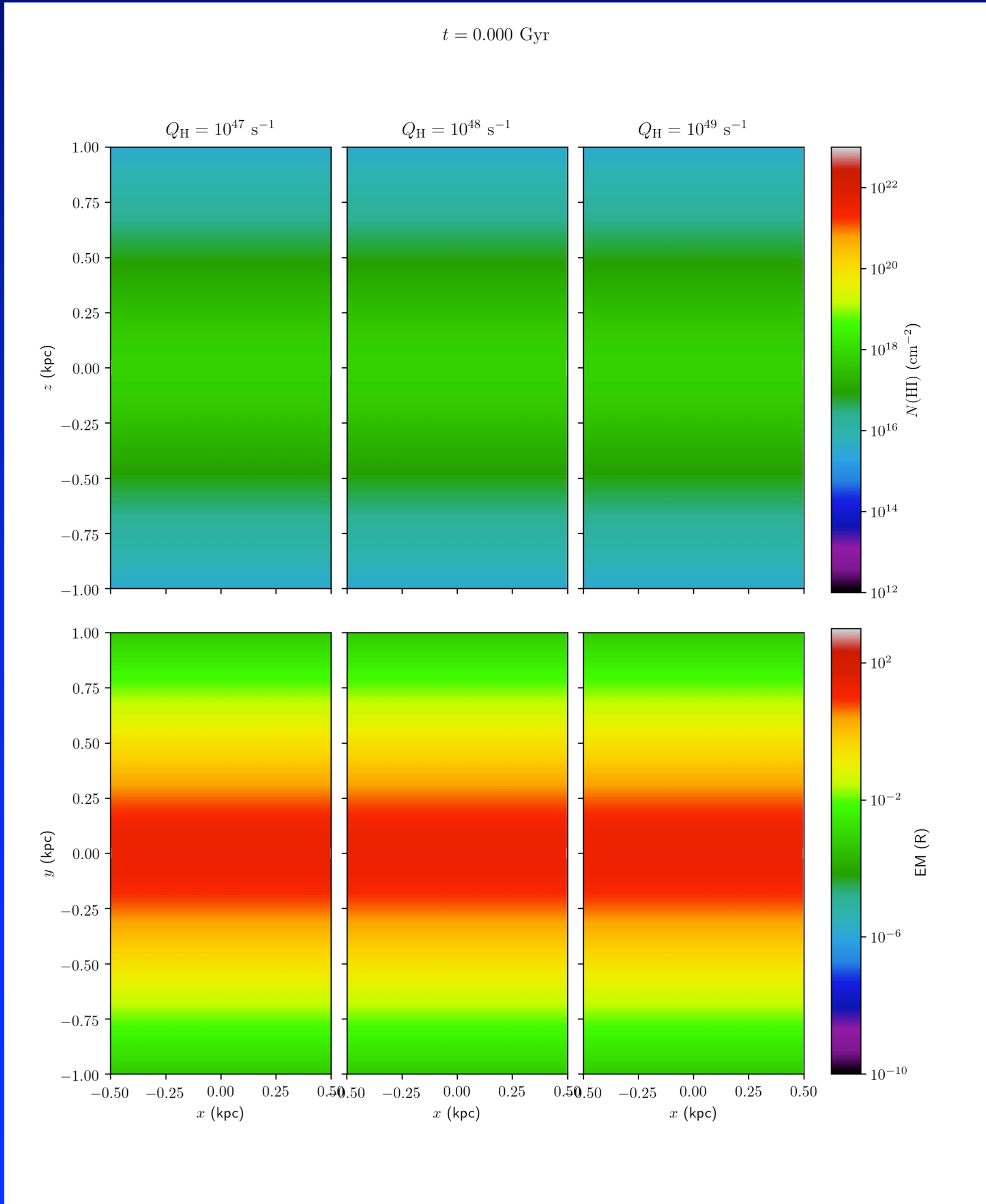
Code reproduces STARBENCH D-type ionization fronts

Lund, Barnes, Goncalves, Sartorio, Vandenbroucke, Wood (2017)

Gravitationally trapped HII region



Lund et al. (2019), Vandenbroucke et al. (2019)



Radiation Hydrodynamics

Photoionisation feedback in the interstellar medium

Vandenbroucke & Wood (2019)