* C^2-Ray: Helium Extension & QSO H II Regions

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Contents

* The C^2-Ray concept
* Including helium
* Photo-ionization heating
* Application to QSO HII region during reionization

* Driver: enable time steps >> ionization time step.
* Especially useful in combination with hydrodynamics.
* Achieved using analytical solution of linearized photo-ionization equations.
* Independent of ray tracing algorithm.

* C^2-Ray Concept

* Photo-Ionization Chemistry

$$\frac{\partial n(H^+)}{\partial t} = (\,n - n(H^+))\Gamma - n(H^+)n_e\alpha(T) + (\,n - n(H^+))n_e C(T)$$

Photo-ionization

Recombinations

Collisional Ionization

$$\Gamma = \frac{1}{4\pi r^2}\int_{\nu_0}^{\infty}\frac{L_\nu}{h\nu}a_\nu e^{-\tau_\nu(r)}\mathrm{d}\nu$$

Photo-Ionization rate

Solution of the radiative transfer equation

$$\tau_\nu(r) = \int_0^r a_\nu n(H^0)\mathrm{d}r$$

Optical depth between source and position *r*

Non-local connection!

Time-dependent!

* C²-Ray photo-ionization rate:

$$\Gamma_{\rm HI} = \int_{\nu_{th}}^{\infty} \frac{L_\nu e^{-\langle\tau_\nu\rangle}}{h\nu} \frac{1-e^{-\langle\Delta\tau_\nu\rangle}}{\langle n_{\rm H\mathit{I}}\rangle V_{\rm shell}} {\rm d}\nu$$

with

$$\langle\Delta\tau_\nu\rangle = a_\nu \Delta r \left(1 - x_{\rm eq} + (x_{\rm eq} - x_0)(1 - e^{-\Delta t/t_{\rm i}})\frac{t_{\rm i}}{\Delta t}\right)$$

Time-averaged optical depth

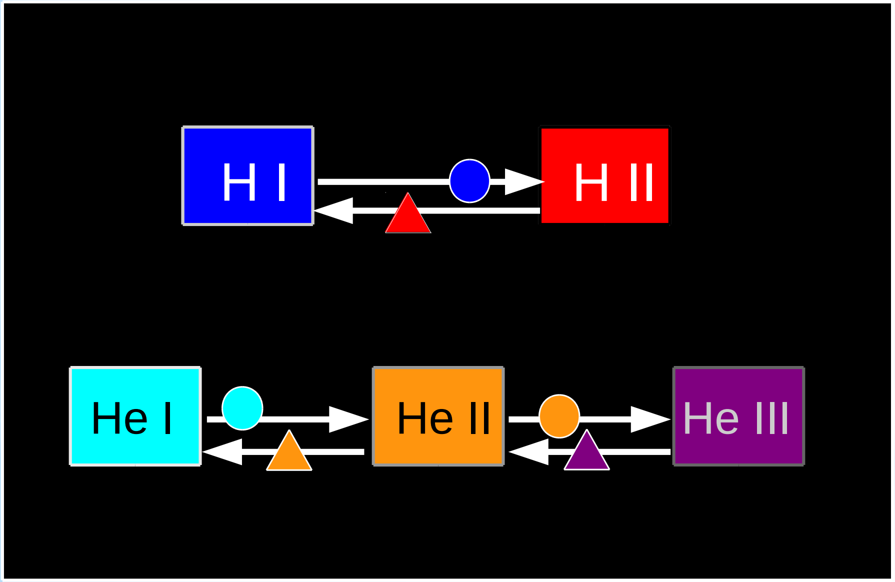
* C²-Ray rate

* Derive time-averaged optical depths for H and He.
* Include On-The-Spot approximation
* Include secondary ionizations
* Multi-frequency approach
* Friedrich et al. (2012), MNRAS 421, 2232

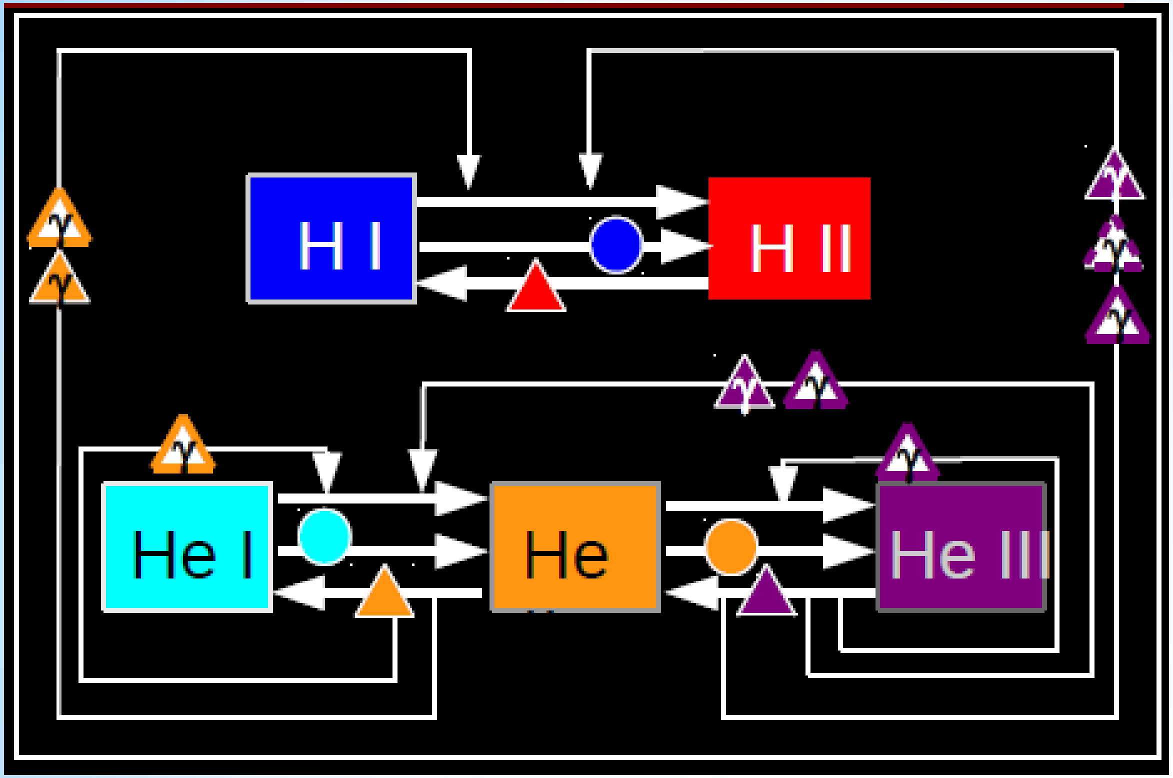
* Adding Helium

* Time-averaged optical depths are calculated from solution of linearized equations.

* When adding helium (without OTS) these equations were solved by Altay et al. (2008).



* Optical Depths



* Recombinations to the ground states
* Recombinations HeIII → HeII n=2
* Deexcitations from HeII n≥2 to ground state (2 photon decay + HeII Lyα)

*OTS Approximation

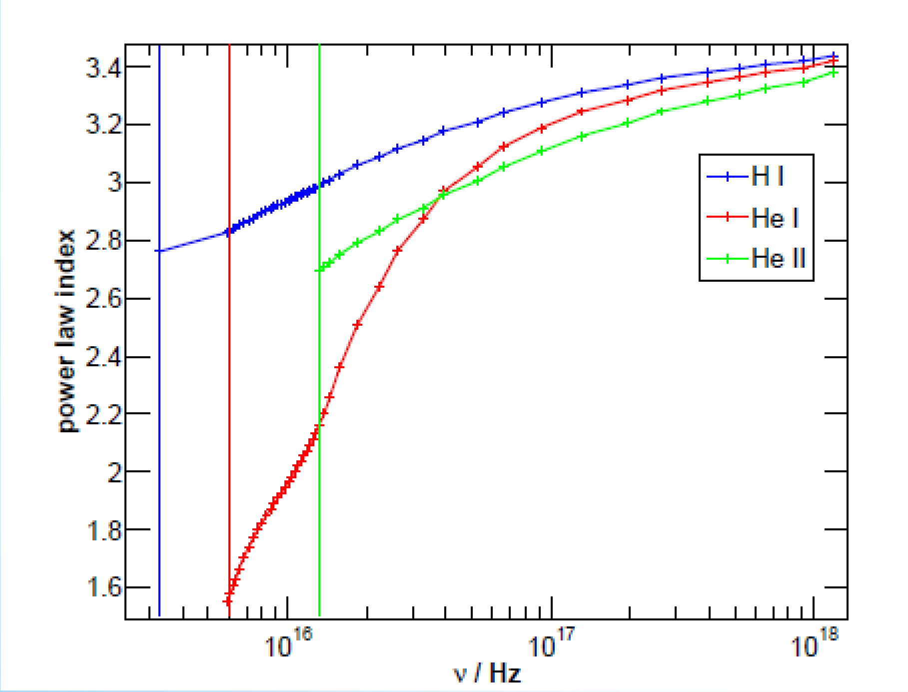
* Excess energy $h\Delta\nu = h(\nu-\nu_{th})$:
  * Heating
  * If $h\Delta\nu > h\nu_{th}$: may produce additional ionization(s).
* Depends on $h\Delta\nu$ and ionization fractions x.
* We use separable relations from Ricotti et al. (2002).

* Most works assume x(HII)=x(HeII) and neglect production of HeIII.

*Secondary Ionizations

* Photo-ionization integrals can be tabulated.
* Function of τ(HI), τ(HeI), τ(HeII) → 3D table!
* Solution: use total τ → 1D table!
* Complication: ν-dependence of τ's

Verner et al. (1996)



* Solution: frequency bins.
* Minimum 3, for ~1% errors
  1 + 10 + 11 = 22

* Multi-frequency approach

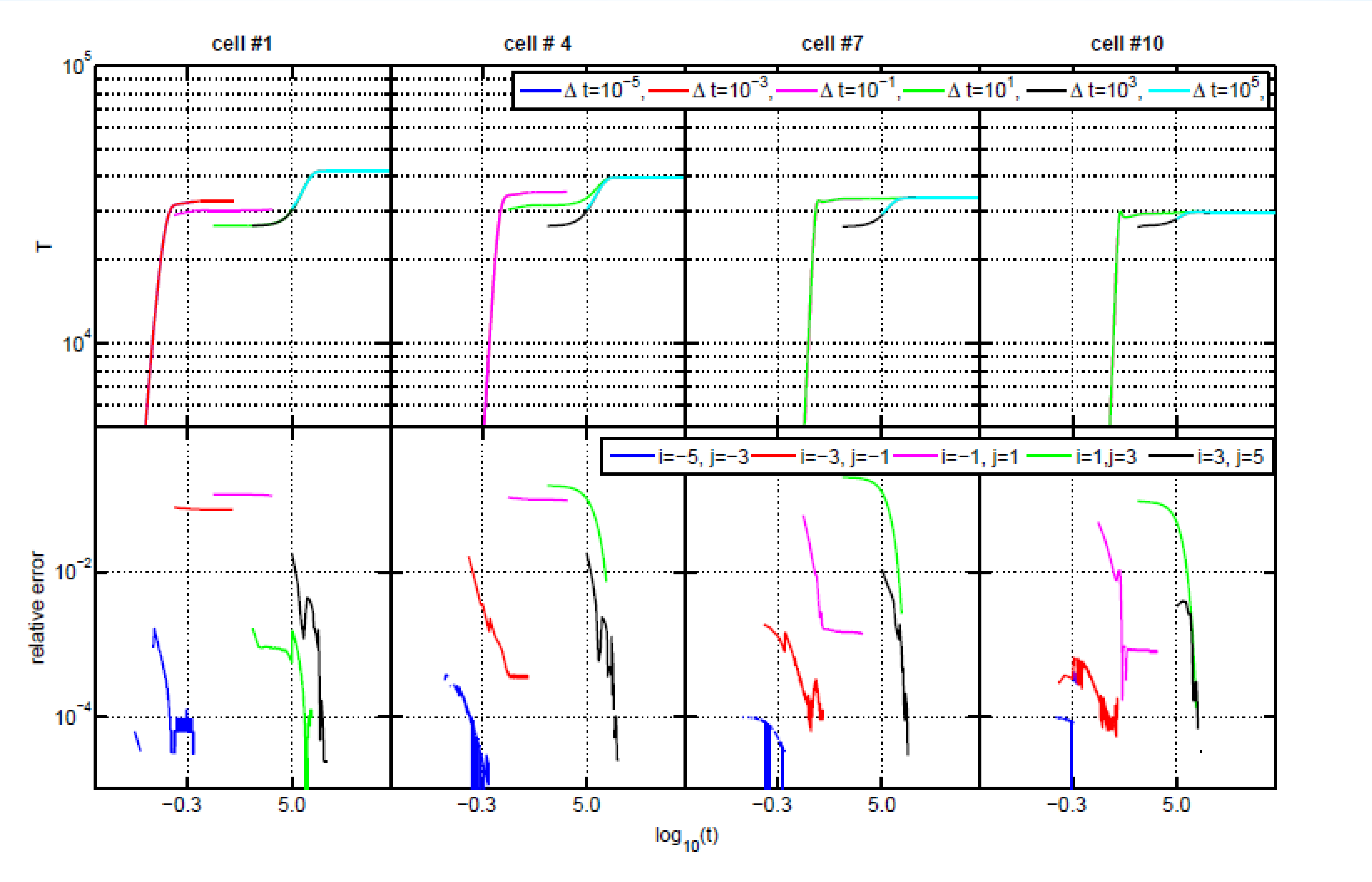
Heating

* Same principle as for photo-ionization.
* But: heating/photon depends on optical depth!
* Optically thin versus optically thick.

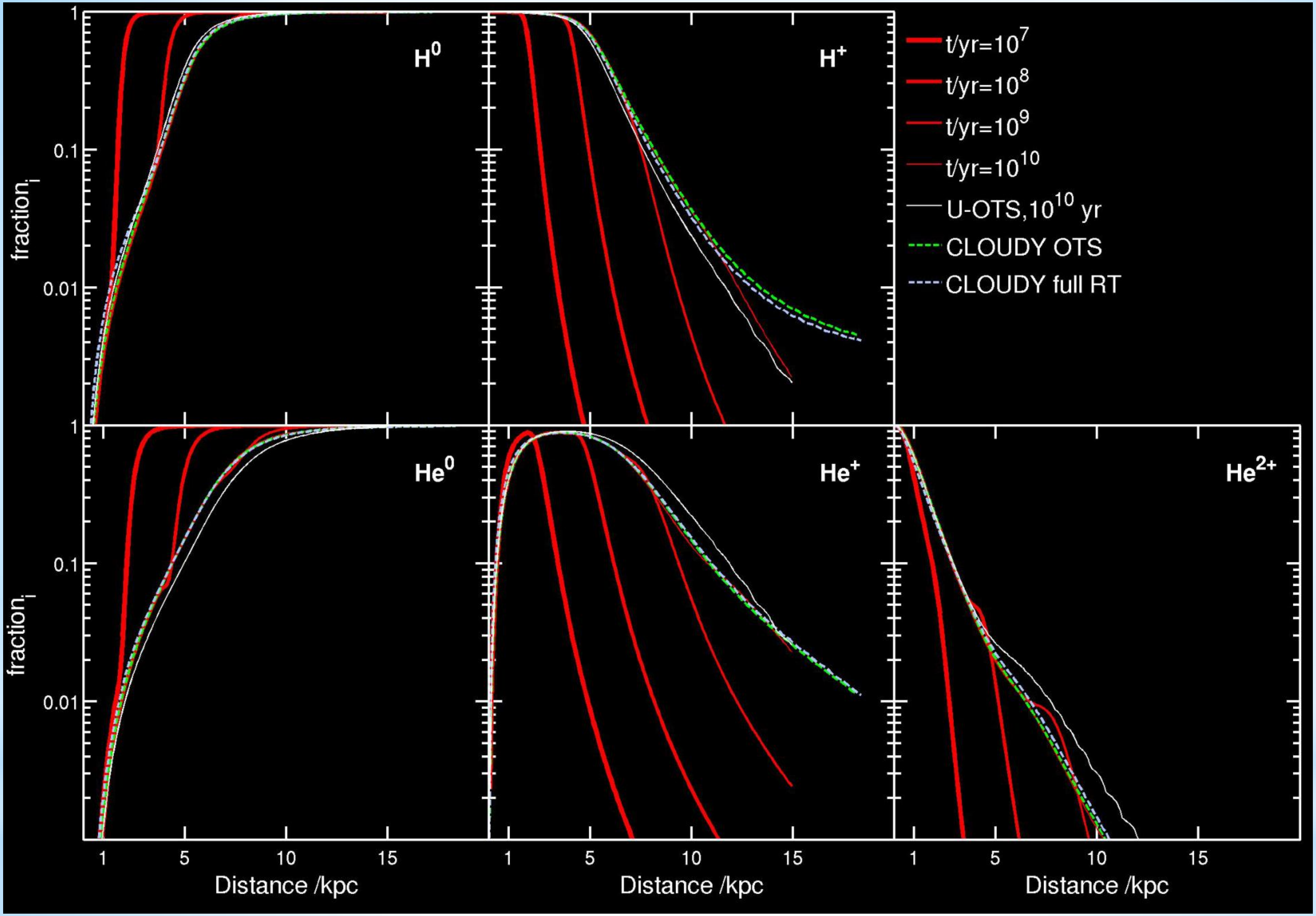
* Accurate heating $\leftrightarrow$ accurate optical depth history: non-local effect!
* Imposes time step constraints... (Kai Yan Lee).

$$\mathcal{H}(i) = \int_{\nu(\mathrm{sub-bin})} \frac{h(\nu - \nu_{\mathrm{th}}(i)) L_\nu e^{-\langle\tau_\nu\rangle}}{h\nu} \frac{1 - e^{-\langle\Delta\tau_\nu\rangle}}{V_{\mathrm{shell}}} \mathrm{d}\nu$$

$$\mathcal{H}(\langle\tau\rangle_{\Delta t}) \leq \frac{\int_0^{\Delta t} \mathcal{H}\left(\tau(t')\right) dt'}{\Delta t},$$



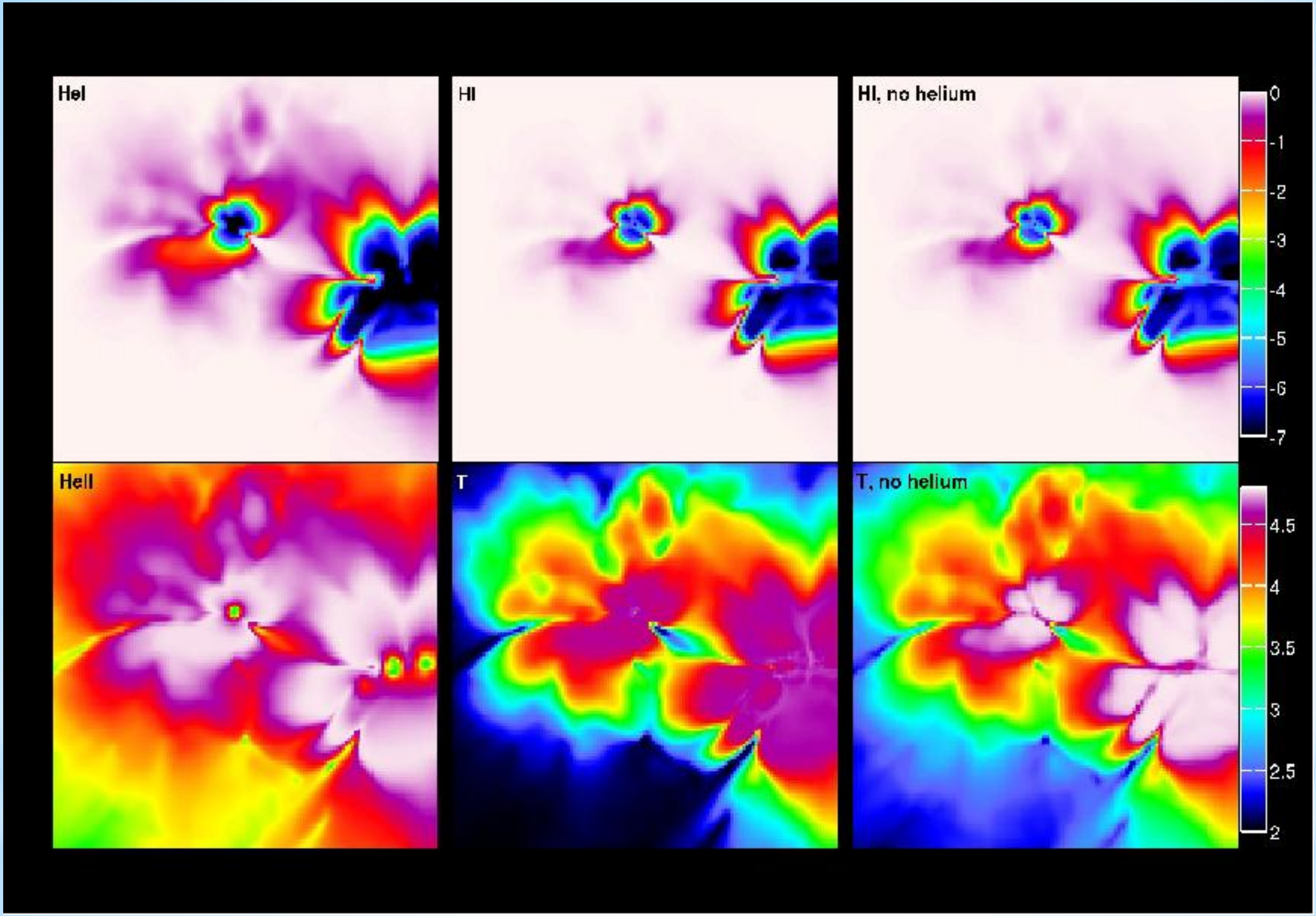
cell #1
cell # 4
cell #7
cell #10
10^5
10^4
T
Δ t=10^-5, Δ t=10^-3, Δ t=10^-1, Δ t=10^1, Δ t=10^3, Δ t=10^5,
i=−5, j=−3 i=−3, j=−1 i=−1, j=1 i=1,j=3 i=3, j=5
relative error
10^{-2}
10^{-4}
−0.3
5.0
−0.3
5.0
−0.3
5.0
−0.3
5.0
$\log_{10}(t)$



*Tests

"Test 2", but isothermal

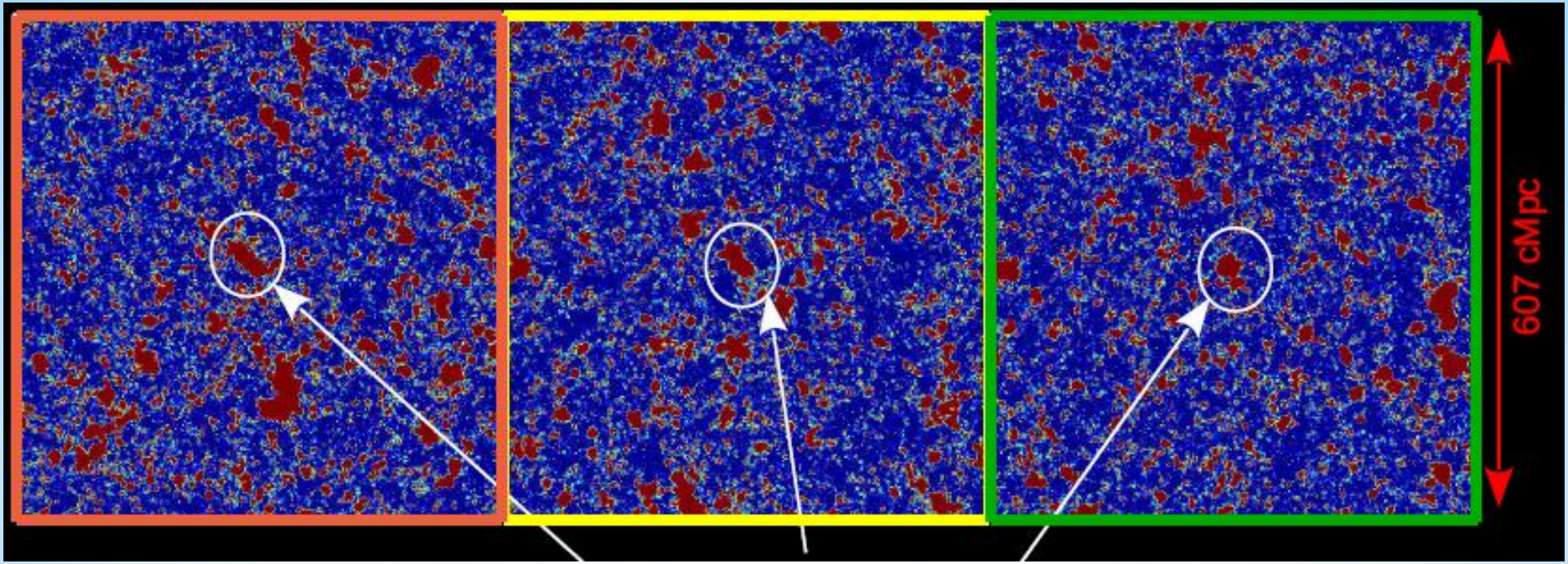
*Tests



"Test 4"

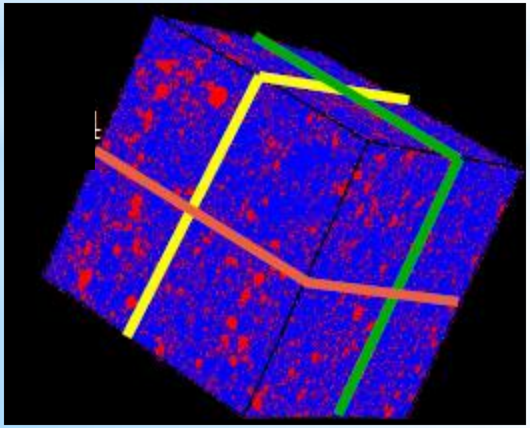
*Impact of QSO

* QSOs are powerful sources of ionizing photons.
* But: most massive QSOs form in very biased regions.
* How large an impact has the QSO on the ionization structure?
* Datta et al. (2012), MNRAS 424, 1877

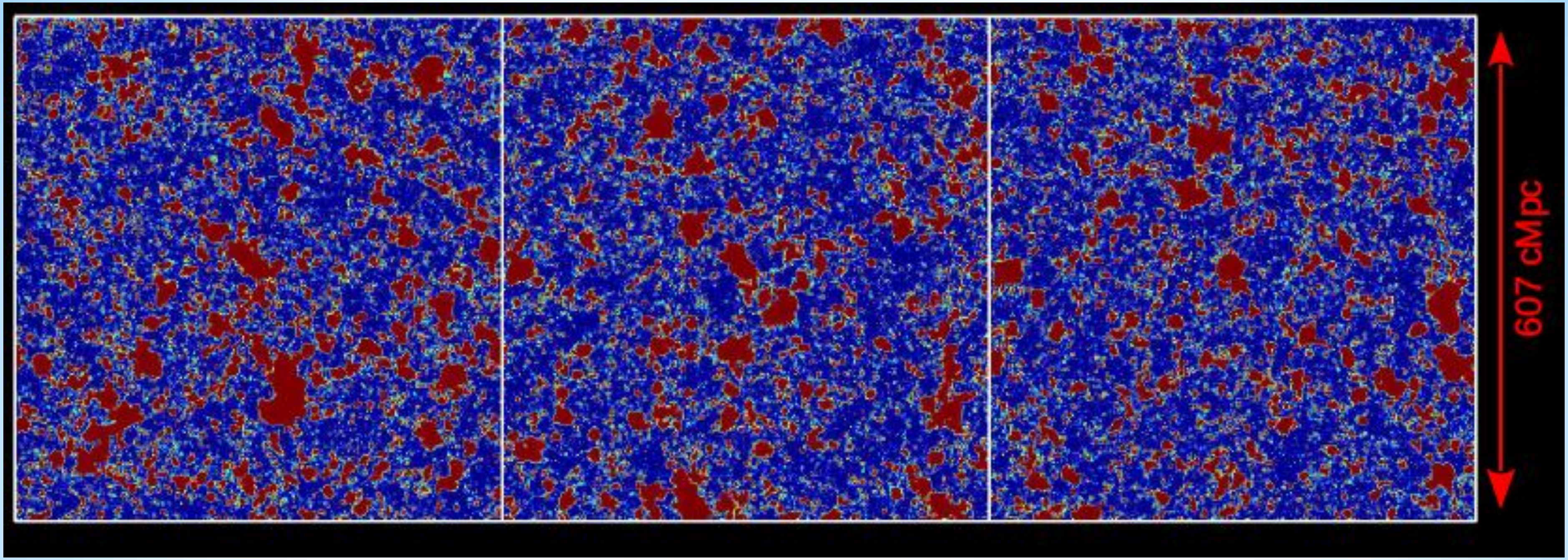


* z=7.76
  * Most massive halo: $M = 1.2 \times 10^{12}\ M_\odot$
  * Mass ~50% ionized, reionization completes by z~6.5.

*Before the QSO

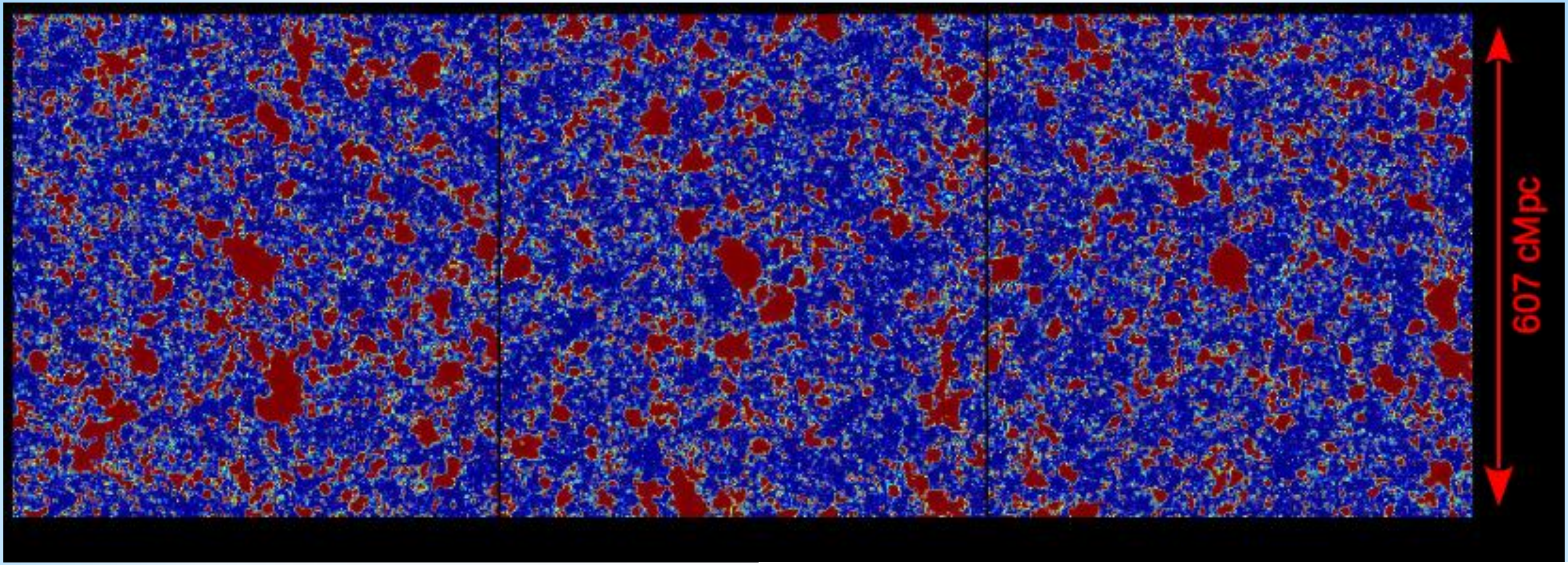


Ionization fraction field, 3 cuts



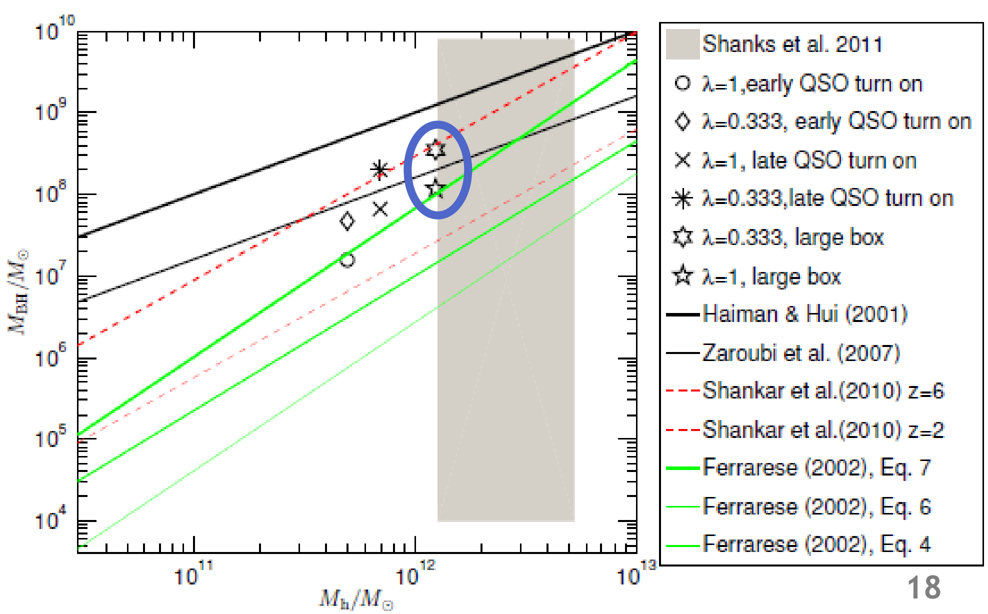
* z=7.57 (23 Myr later)

* No QSO

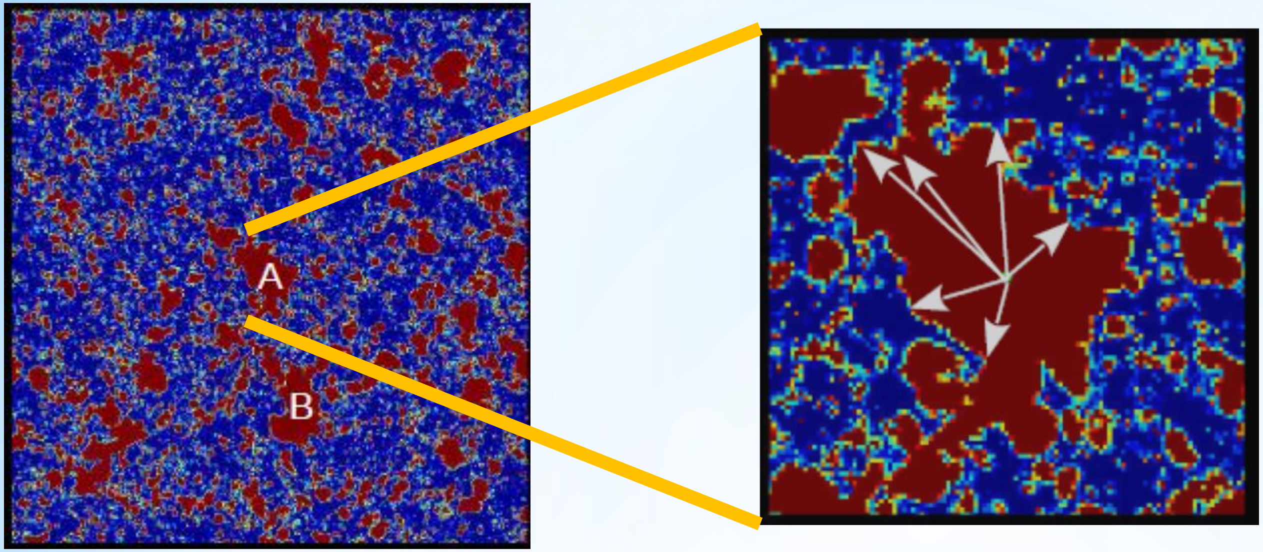


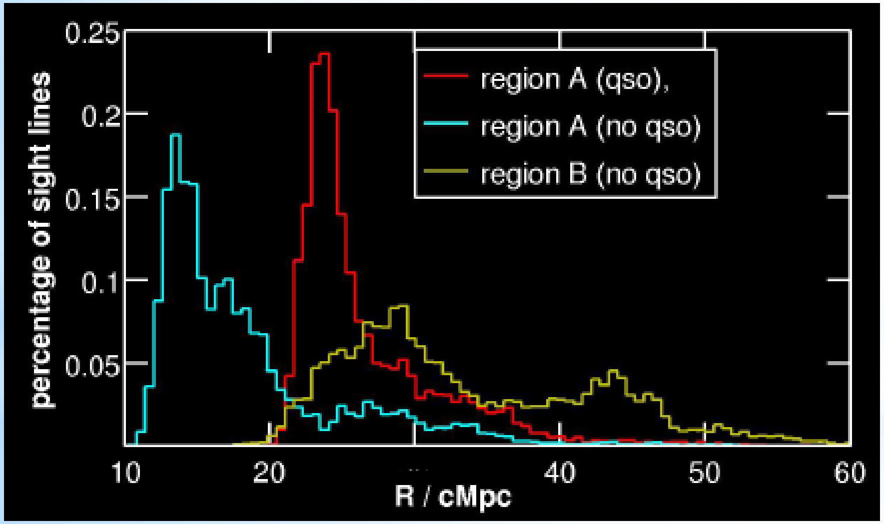
* z=7.57 (23 Myr later)

$$L_{\rm QSO} = \lambda L_{\rm Edd} = \lambda \frac{4\pi M_{\rm BH} m_{\rm p} c}{\sigma_{\rm T}} \approx \lambda\, 1.3 \times 10^{31} \frac{M_{\rm BH}}{M_\odot} {\rm W}\,.$$



* With QSO





*Can we recognize a QSO HII region?

Photon Budgets

* Total number of ionizing photons during QSO on-time:
  * $N_\gamma(QSO) = 1.7 \times 10^{71}$ (2.4×10^{56} s^{-1})
  * $N_\gamma(stars) = 3.1 \times 10^{70}$ (4.3×10^{55} s^{-1})

* Total number of ionizing photons during entire history of region:
  * $N_\gamma(QSO) = 1.7 \times 10^{71}$
  * $N_\gamma(stars) = 2.2 \times 10^{71}$

* C^2-Ray algorithm successfully extended to include helium.
* Comparison for hydrogen + helium photo-ionization needed.
* Accurate photo-heating imposes stricter time step constraints.

* Bright QSO may have observable impact but hard to dominate over stars.

*Conclusions

Photo-Evaporation in Astrophysical Systems

Program
3—28 June 2013

Coordinators: Garrelt Mellema, Barbara Ercolano, Andreas Burkert

This programme brings together astrophysical theoreticians and simulators interested in radiative feedback, specifically the dynamical effects of radiative heating of dense gaseous structures, a process known as photo-evaporation, which occurs in regions of intense star formation, in the dense planet forming discs around young stars, in massive planets orbiting close to their parent star and even in the earliest phases of galaxy formation in the Universe. As part of the programme a 5-day workshop will address the latest observational and theoretical results.

*Nordita Programme

Lyman Alpha as an Astrophysical Tool

Program
2—27 September 2013

Coordinators: Göran Östlin, Matthew Hayes, Garrelt Mellema

This program is about the Ly α transition in Hydrogen and its astrophysical applications. Young stellar populations are dominated by massive, hot and short-lived stars that ionize their surroundings, which is hence a powerful, but complicated, probe of star forming and high redshift galaxies. This programs aims to bring together experts in modeling Ly αradiative transfer and galaxy formation, and observations of Ly α in local galaxies and the distant universe.

*Another Nordita Programme!