Semi-numerical simulations of Reionization and the Cosmic Dawn

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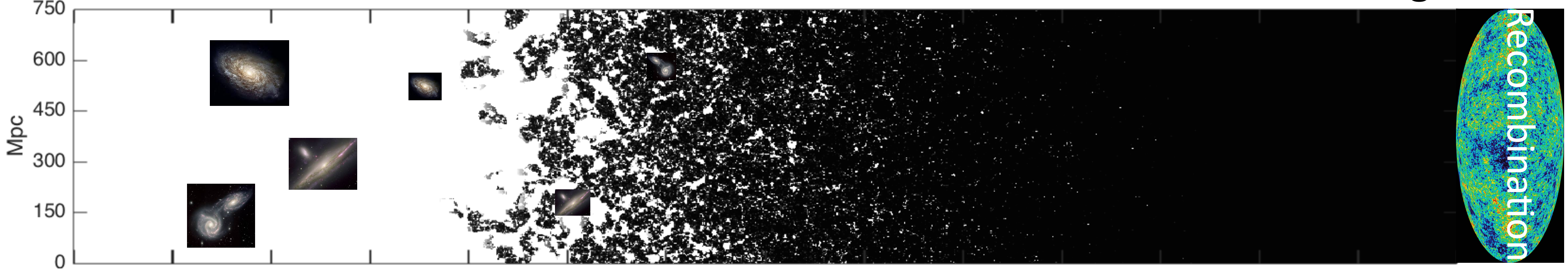
European Research Council

Why Reionization/CD?



Potentially some <u>fundamental</u> questions: *When did the first generations of galaxies form? What were their properties? How did they interact with each other and the intergalactic medium? What is the structure of the intergalactic medium? What is the thermal and ionization history of the baryons?*

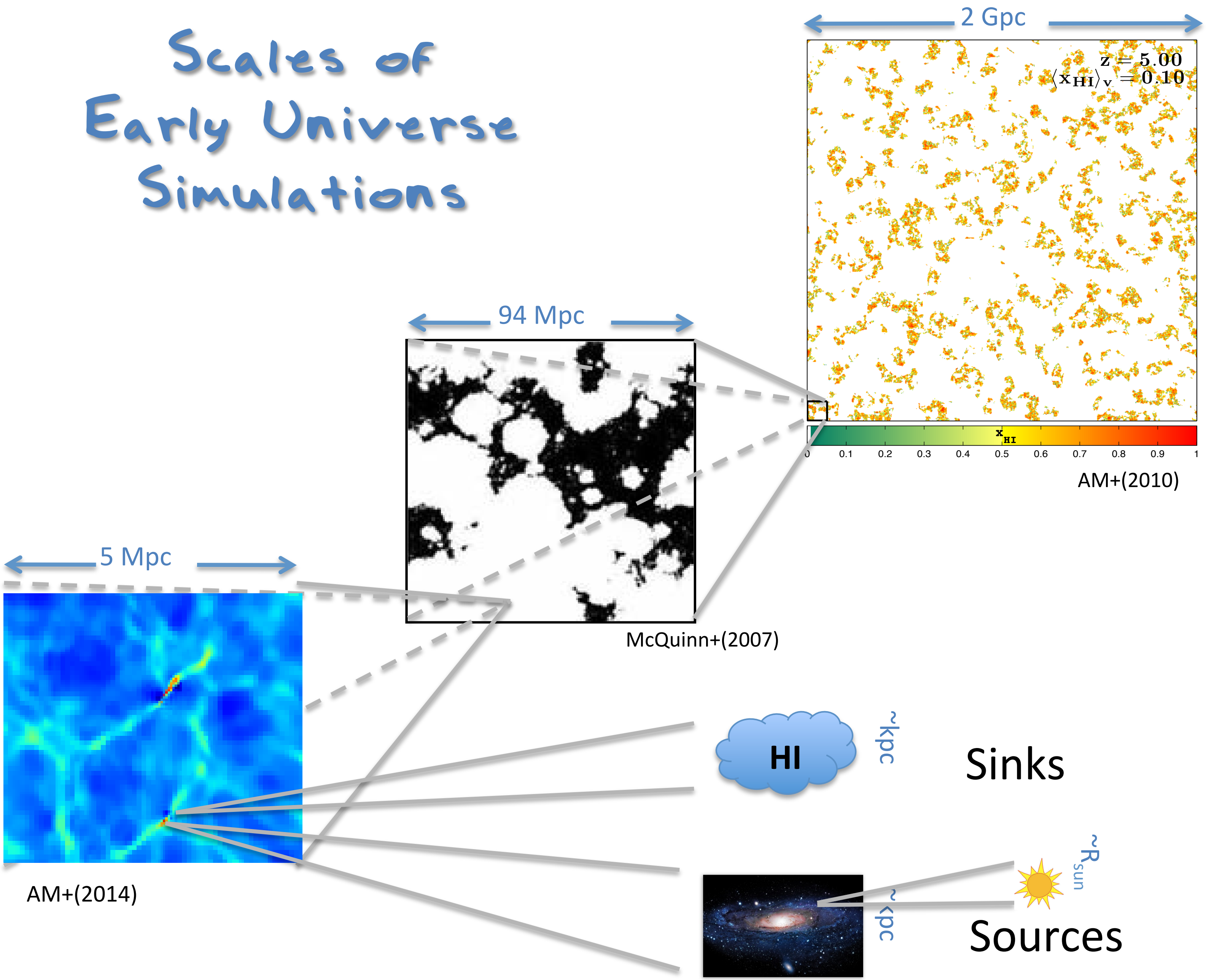
<u>*Robust* conclusions require</u>:

- accurate models
- statistics
- exploration of astrophysical parameter space

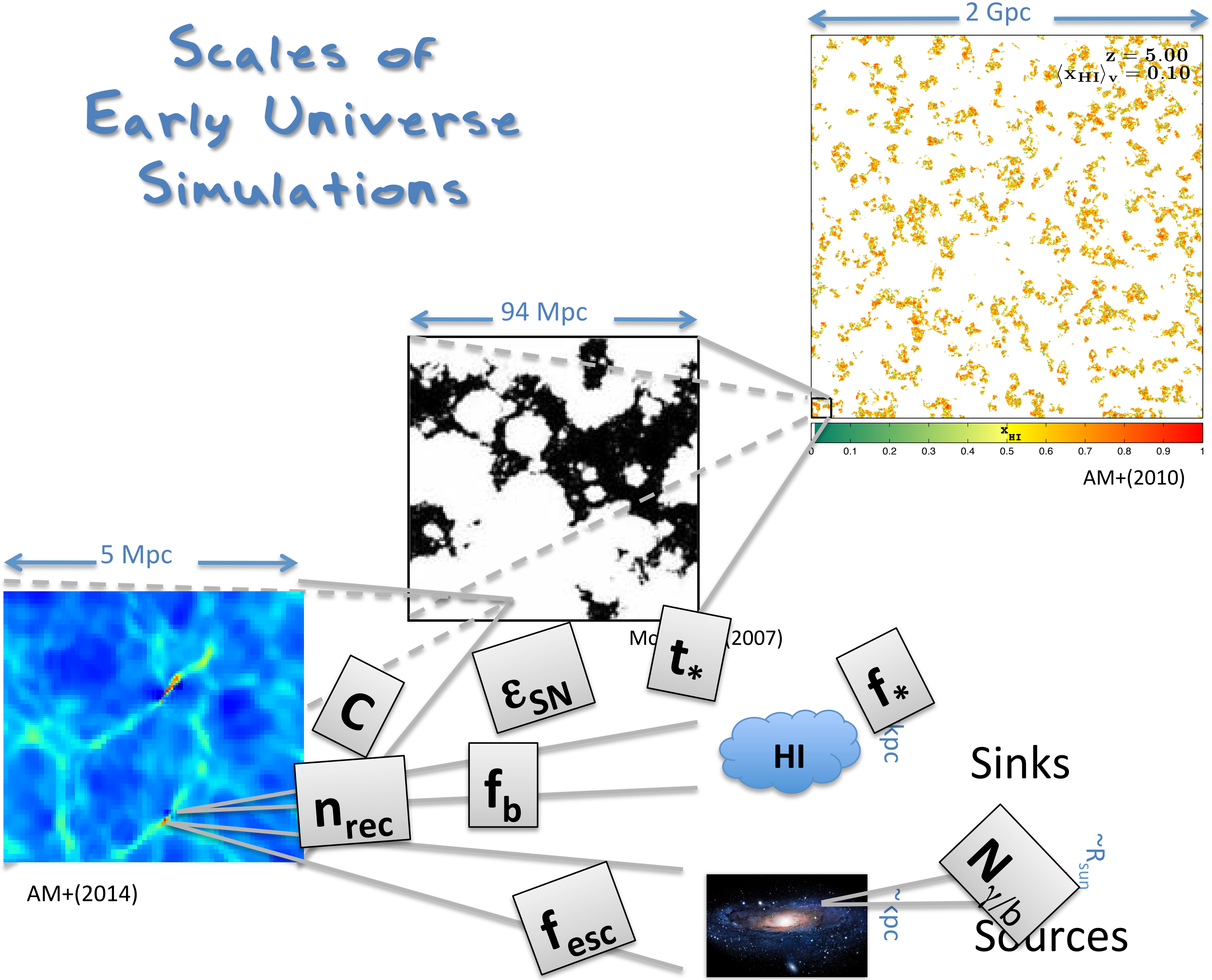
Outline

- Motivation for ‘non-standard’ approaches
  1. dynamic range
  2. range of uncertainties
- Historical development of ‘semi-numerics’
- Avenues for the future
  1. Sub-grid physics (numerical/semi-numerical)
  2. Statistical analysis (semi-numerical/empirical)
  3. Analysis pipelines (instrument + semi-numerical)
  4. Testing and calibration (numerical→semi-num)

Scales of Early Universe Simulations



Astrophysical (known) unknowns



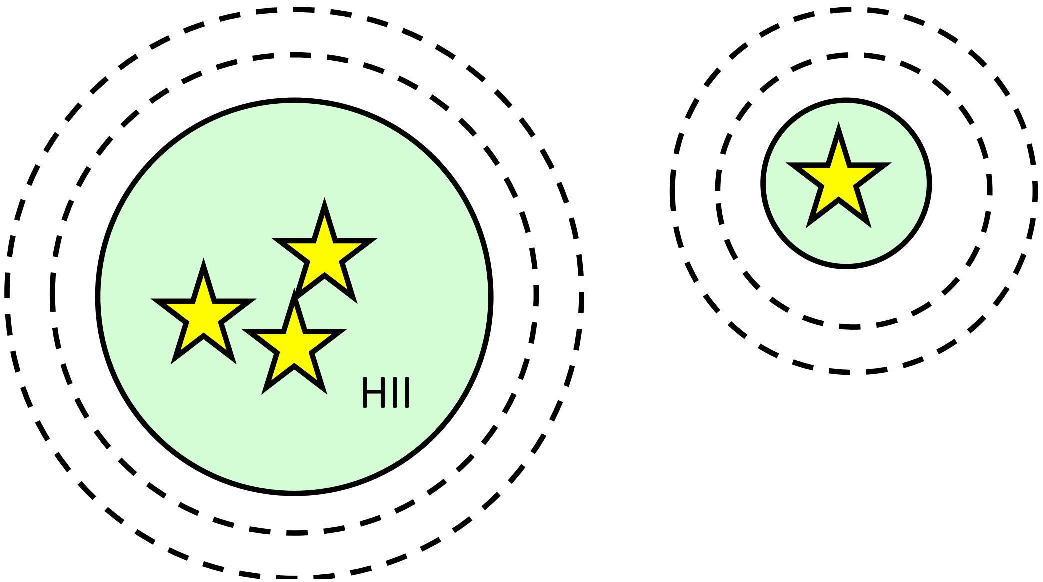
Impossible to explore the full range of **scales** and **uncertainties**,
without ‘**approximations**’

Analytic methods for patchy reionization

Clustering of sources governs reionization (i.e. reionization is inside-out on large scales)

We have tools to estimate the halo abundance on large-scales (bias, excursion-set formalism)

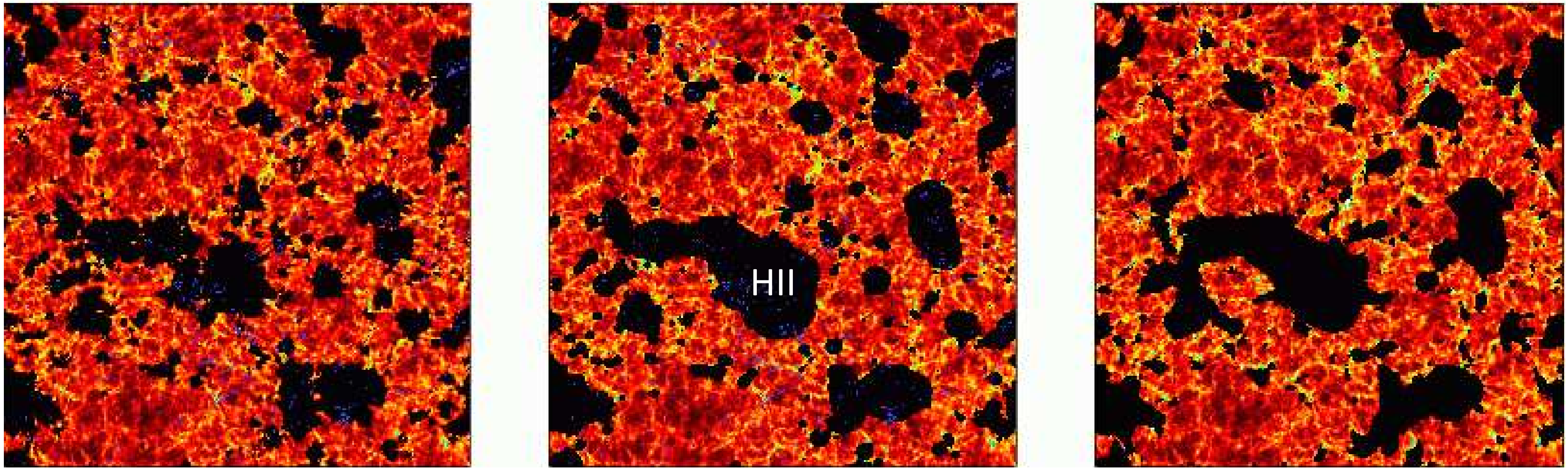
Analogous to the excursion-set formalism, can construct random-walks from large to small scales, comparing N_γ to N_b



$$f_{\rm coll}(\mathbf{x_1}, M, z) \geq \zeta^{-1}$$

Furlanetto+ (2004)

Application to 3D boxes



N-body sources + RT

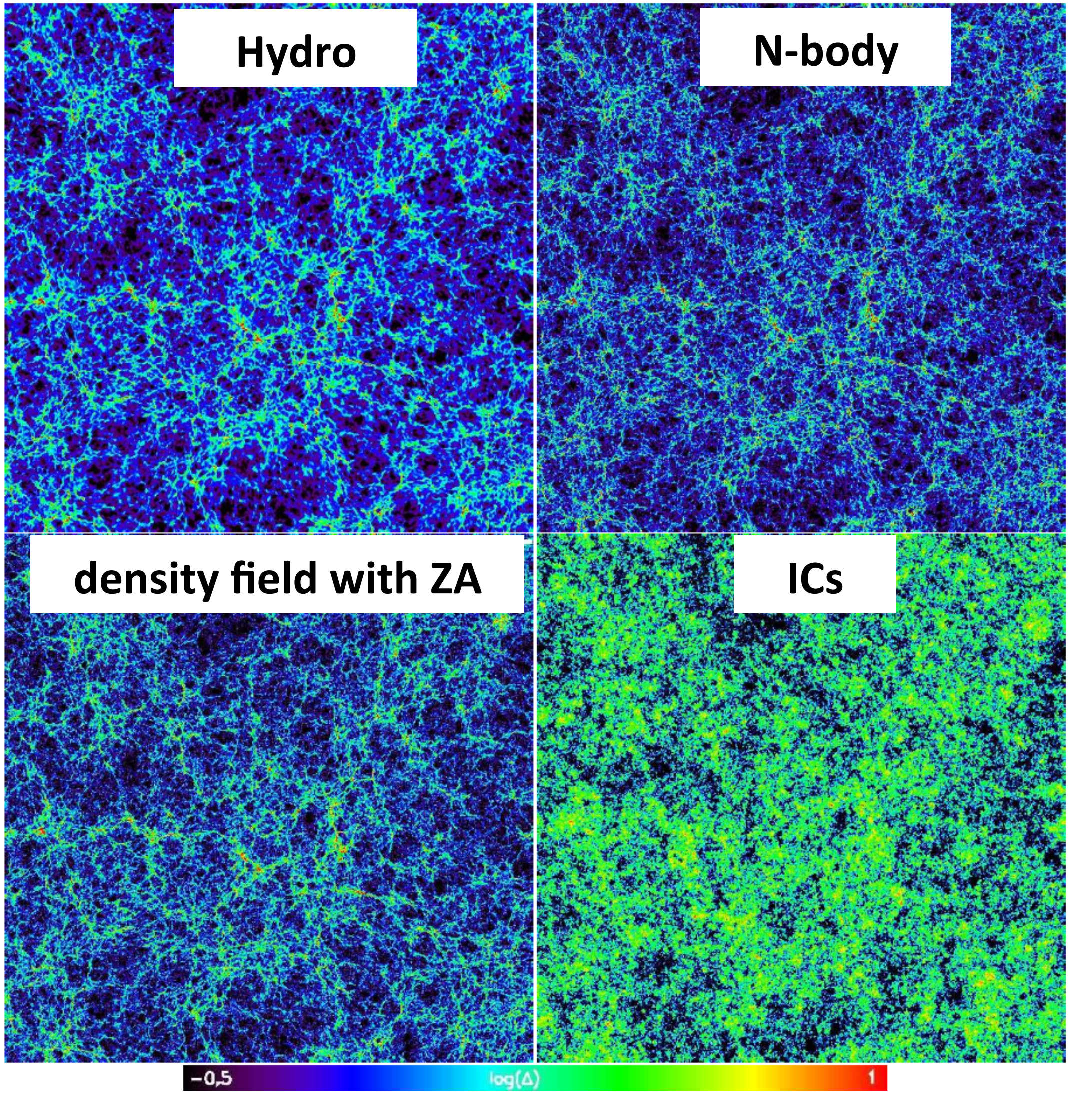
N-body sources + excursion set

Gaussian IC + excursion set (density from N-body)

Zahn+ (2007)

3D boxes without N-body

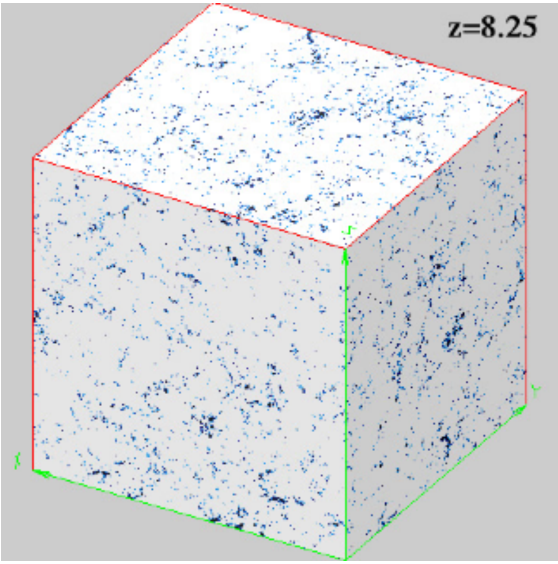
Density fields (ZA)



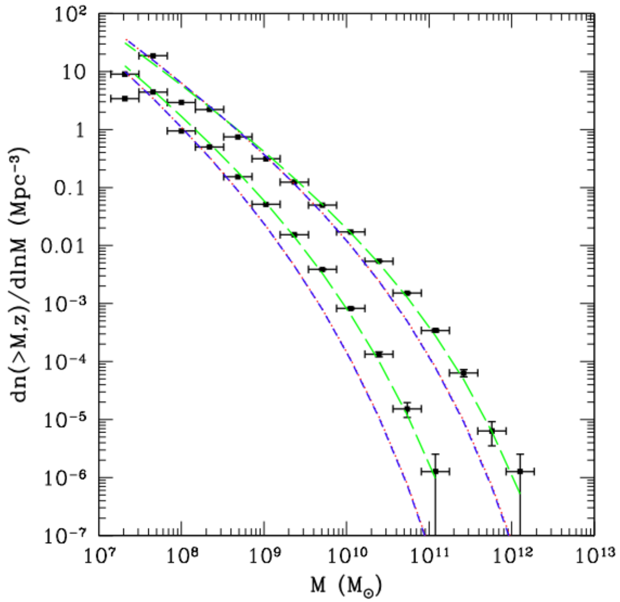
AM & Furlanetto (2007)

3D boxes without N-body

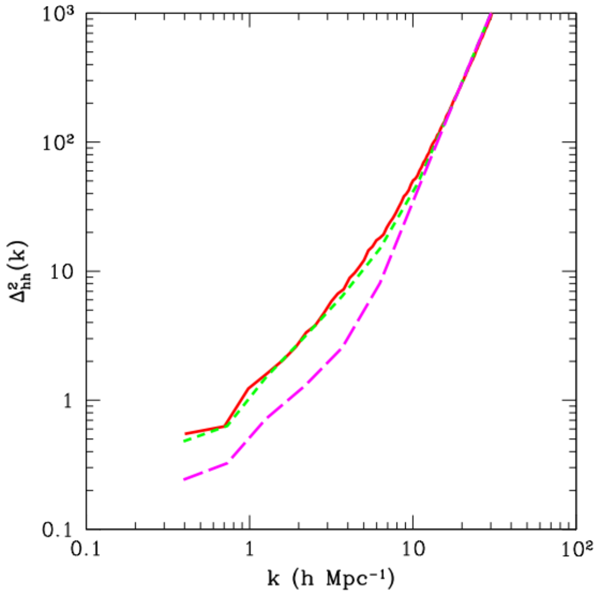
Density fields
(excursion set + ZA)



Halo maps



Halo mass functions



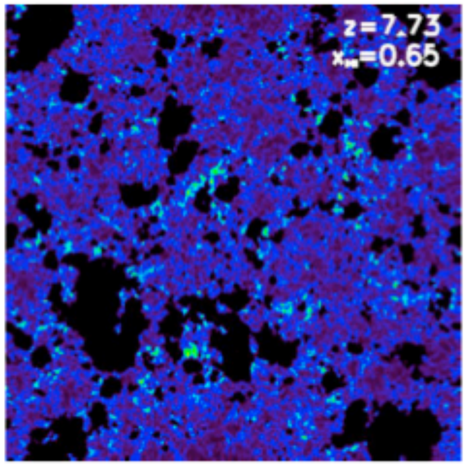
Halo power spectra

AM & Furlanetto
(2007)

3D boxes without (discrete) halos
21cmFAST

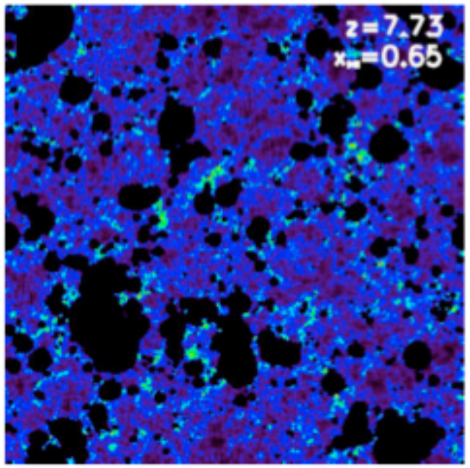
- apply conditional excursion–set to evolved density fields

hydro + N-body + RT

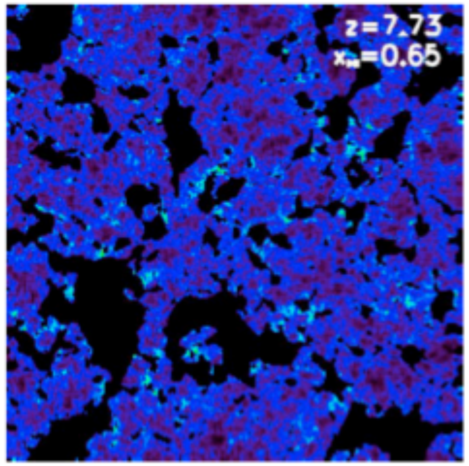


~ few days on 1536 cores

DexM (with halos)



21cmFAST (without halos)

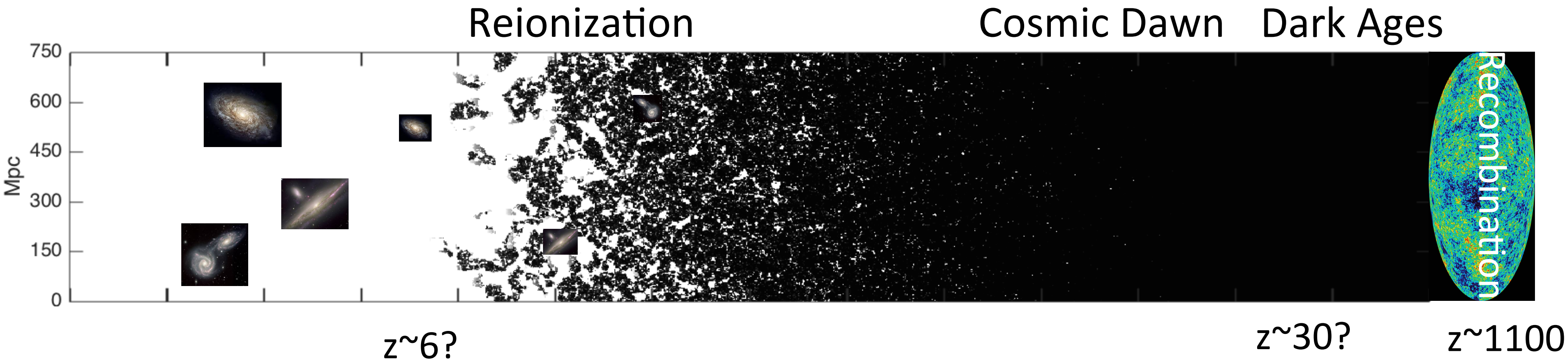


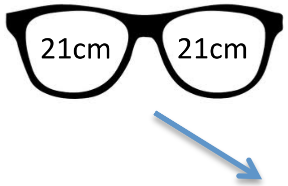
~ few min on 1 core

143 Mpc, 756^3

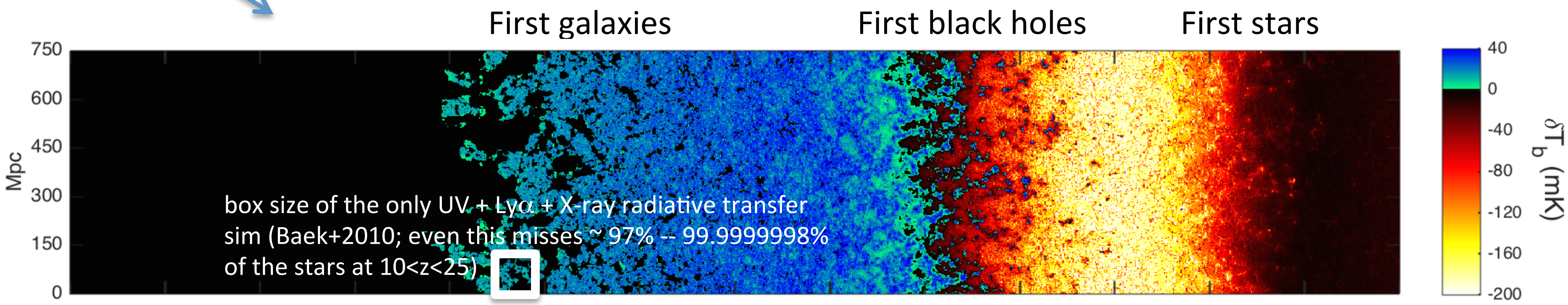
AM+ (2011)

Extension to Cosmic Dawn





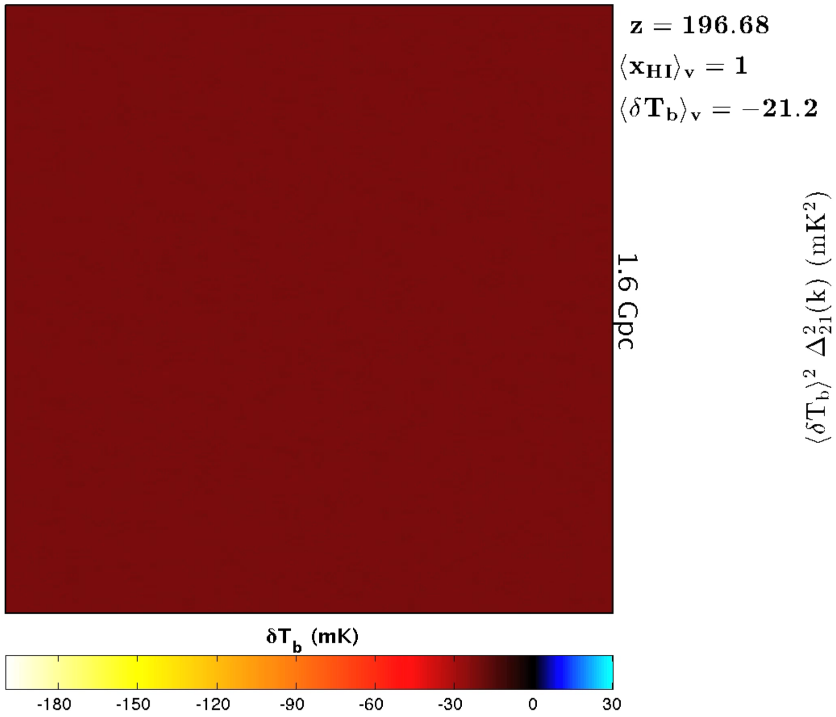
$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

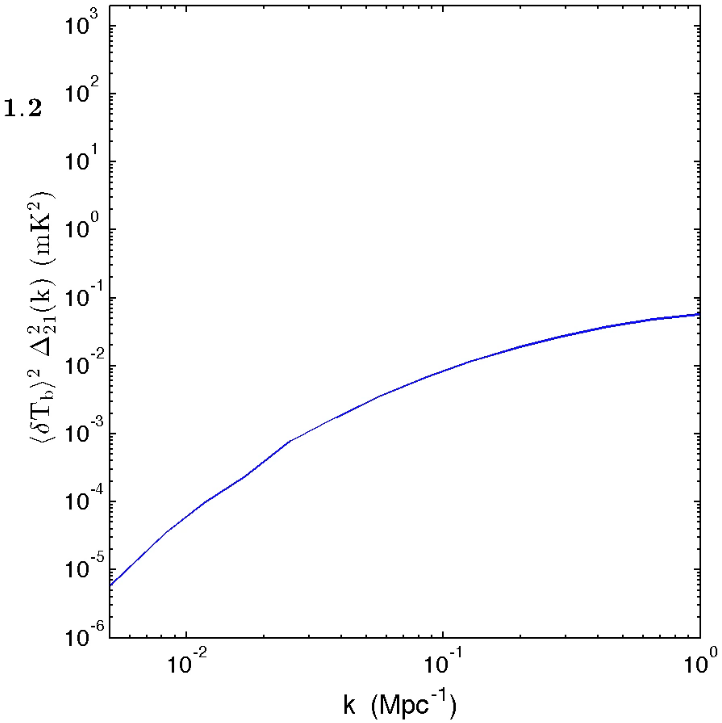


CD fluctuations: Pritchard & Furlanetto 2007; Santos+ (2010); Baek+ (2010); AM+ (2011)

Cosmic Dawn in 21cm

Analytic: Madau+ (2004); Furlanetto (2006); Pritchard & Furlanetto (2007)
Semi-numeric: Santos+ (2010); AM+(2011); Thomas & Zaroubi (2011)
Numeric: Baek+ *(2010)*





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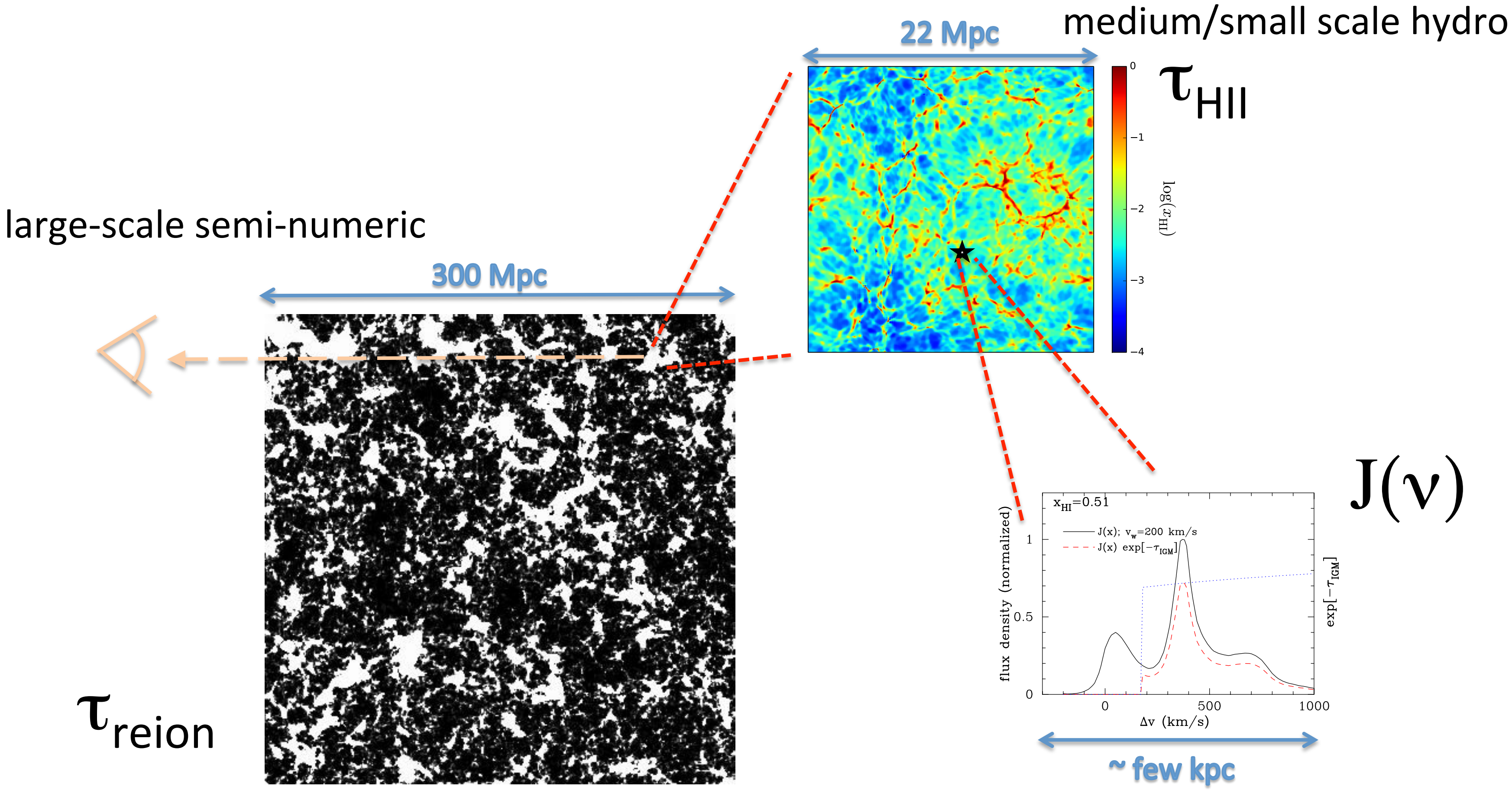
Reionization   Cosmic Dawn

Hybrid techniques

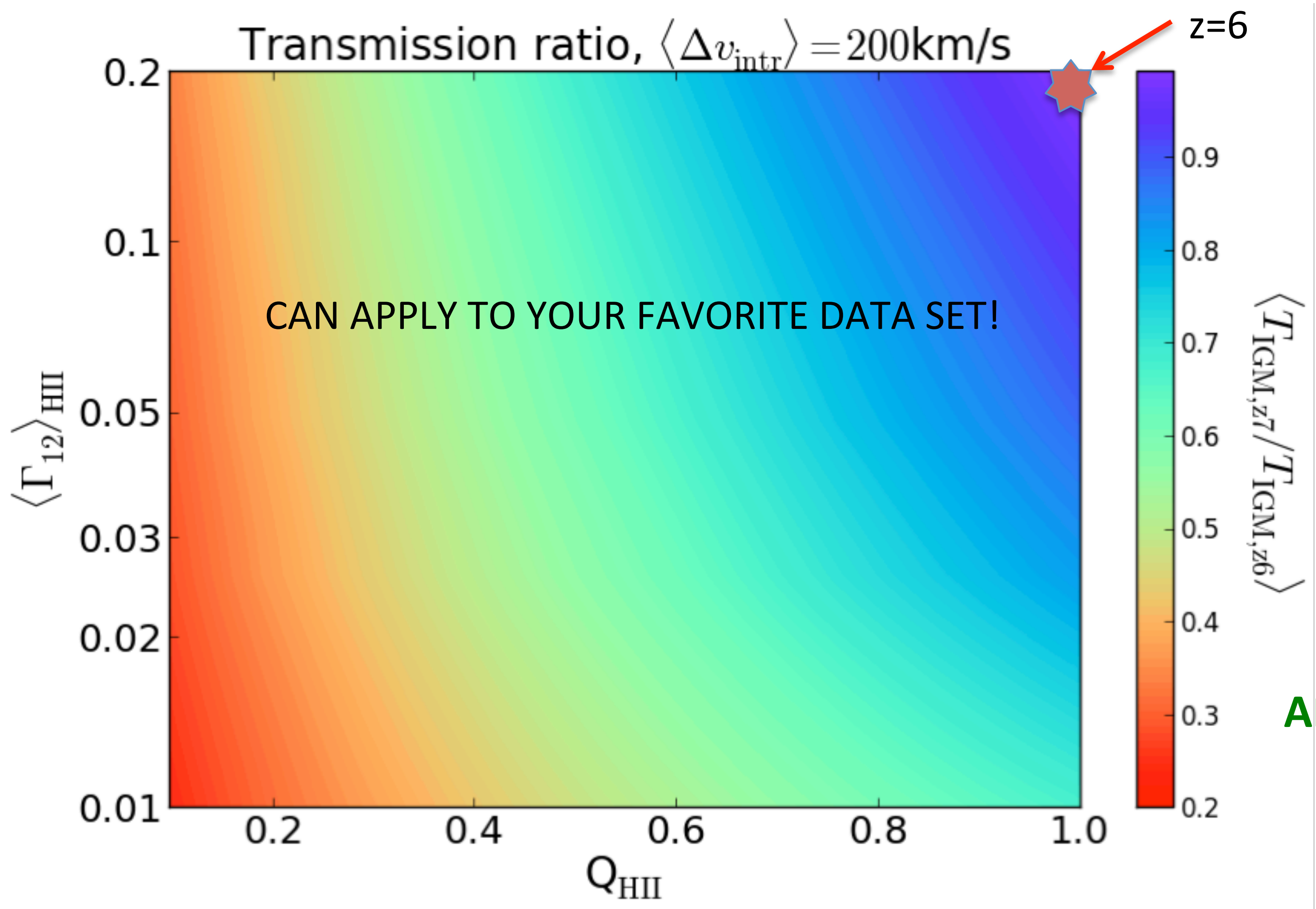


Multi-scale approach

$$T_{\rm IGM} = \int d\nu J(\nu) \exp[-\tau_{\rm reion}(\nu) - \tau_{\rm HII}(\nu)]$$

AM+2015
(see also Choudhury+2015)

Semi-numerics in hybrid techniques: ***parameter space exploration***



AM+2015

marginalizing over Γ, we get **$Q_{HII,z7} < 0.6$ (68% C.L.),**
from Schenker+2014 sample

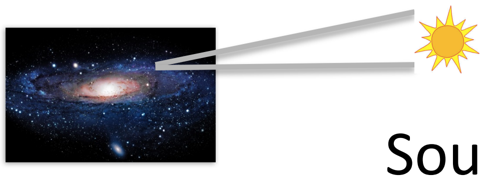
Future….

1) create the most realistic, physically-motivated ‘best-guess’ simulations:

SUB-GRID modeling

1) Sub-grid modeling

Sinks



Sources

Improved treatment of **SOURCES and SINKS**

- combine with SAMs (e.g. DRAGONS project)
- couple to photo-heating feedback
- inhomogeneous, unresolved recombinations

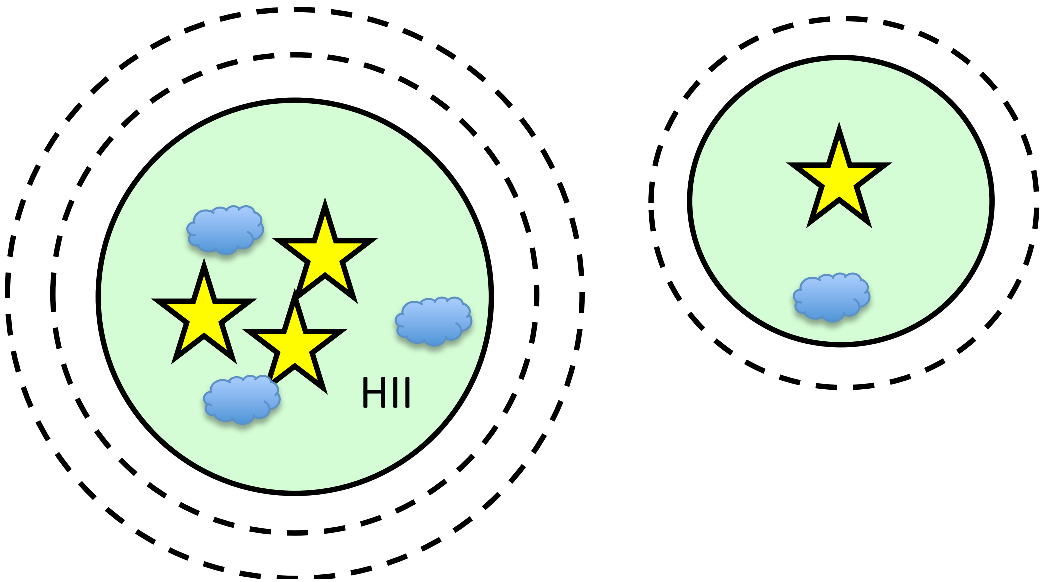
example

Sub-grid recombinations/limited mfp

- Clustering of sources AND sinks governs reionization

$$\xi f_{\rm coll}(\mathbf{x}, z, R, \bar{M}_{\rm min}) \geq 1 + \bar{n}_{\rm rec}(\mathbf{x}, z, R)$$

$$\frac{dn_{\rm rec}}{dt}(\mathbf{x}, z) = \int_0^{+\infty} P_{\rm V}(\Delta, z)\, \Delta \bar{n}_{\rm H} \alpha_{\rm B} \left[1 - x_{\rm HI}(\Delta)\right]^2 d\Delta$$



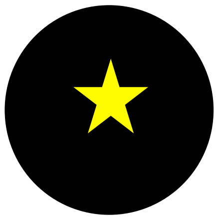
Sobacchi & AM (2014)

Simple picture

As time passes and an HII region grows

- only very massive halos host stars (high M_{crit}).
- many photons are lost to balance recombinations (high n_{rec}).

Simple picture



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$$t_{\rm rec} \sim 40\,{\rm Myr}\,\Delta^{-1}(1-x_{\rm HI})^{-1}[(1+z)/20]^{-3}$$

Simple picture

As time passes and an HII region grows

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recombinations AND photo-heating feedback drain photon budget

Simple picture

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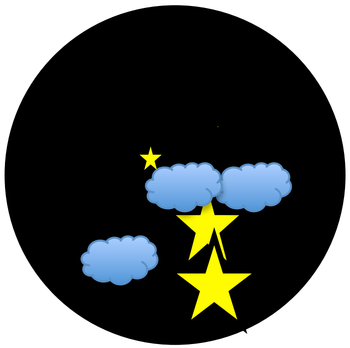

approaches recombination limited growth (e.g. Furlanetto & Oh 2005)

Simple picture

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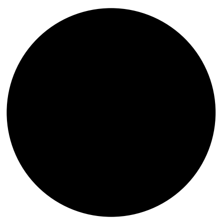
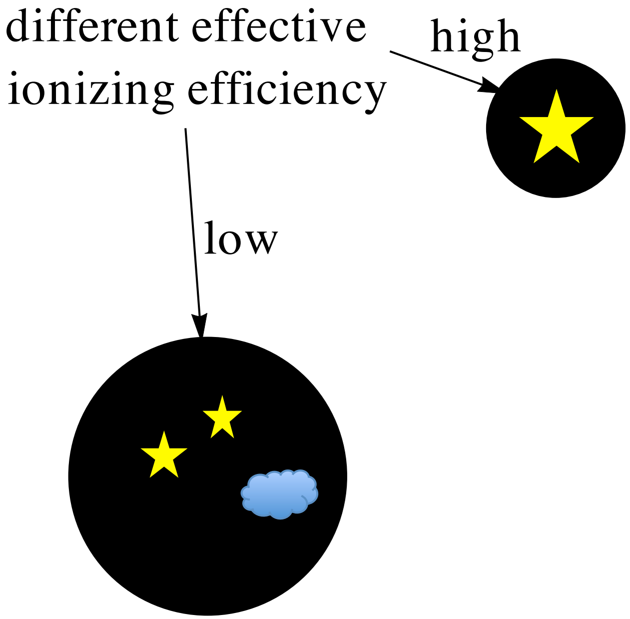


Simple picture



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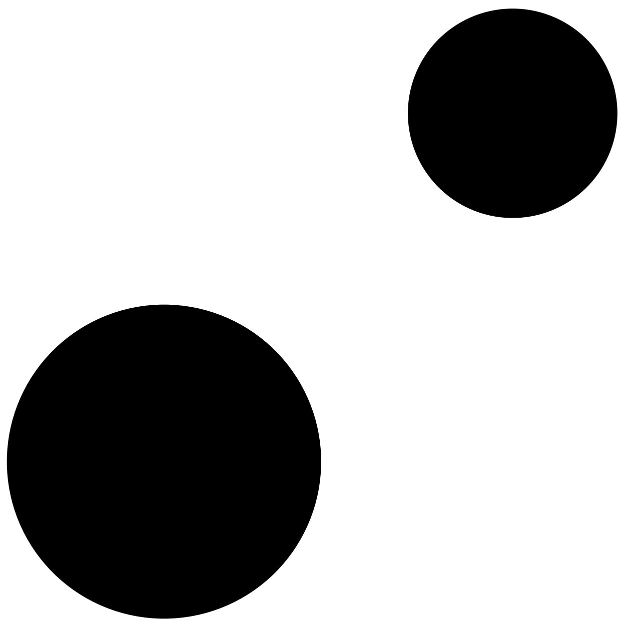

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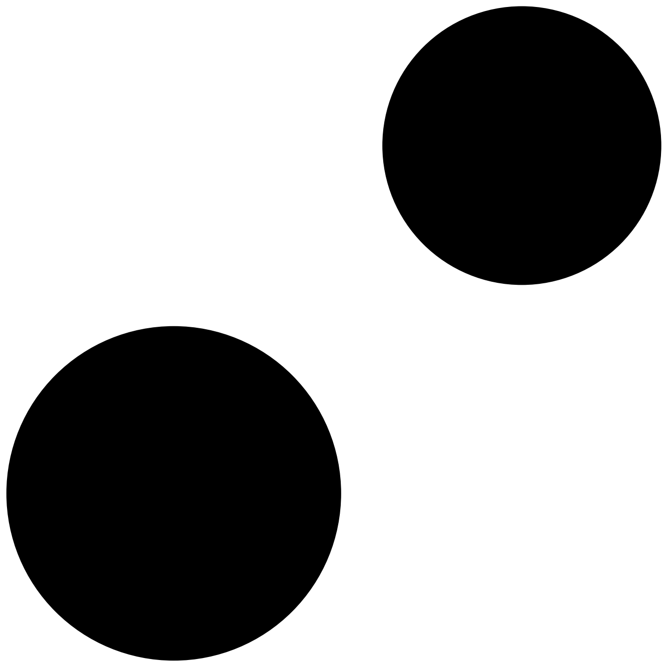

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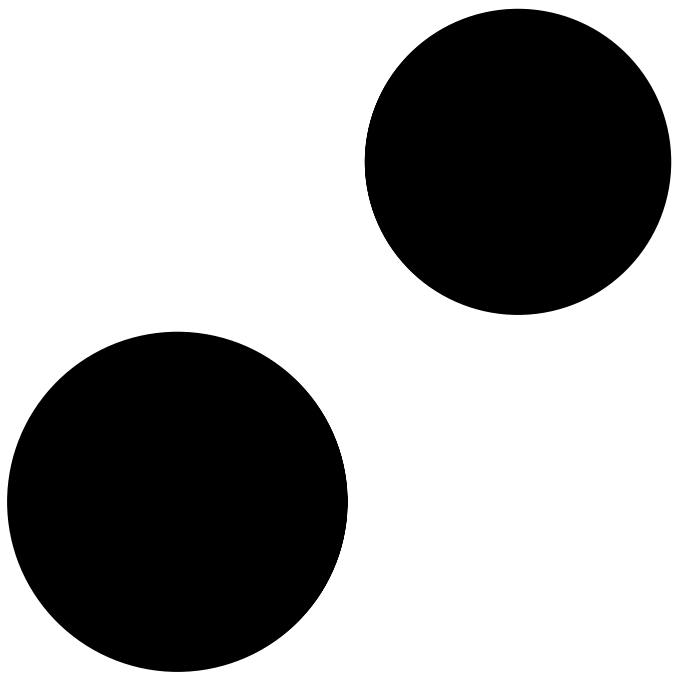

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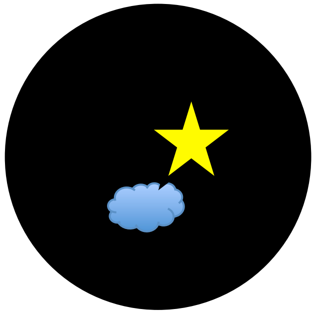

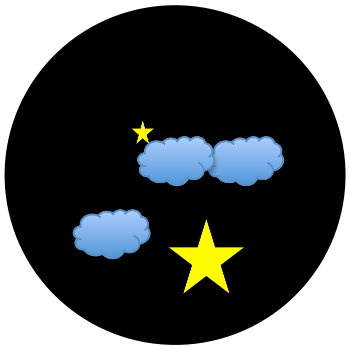

As time passes and an HII region grows

- only very massive halos host stars (high $M_{\rm crit}$).
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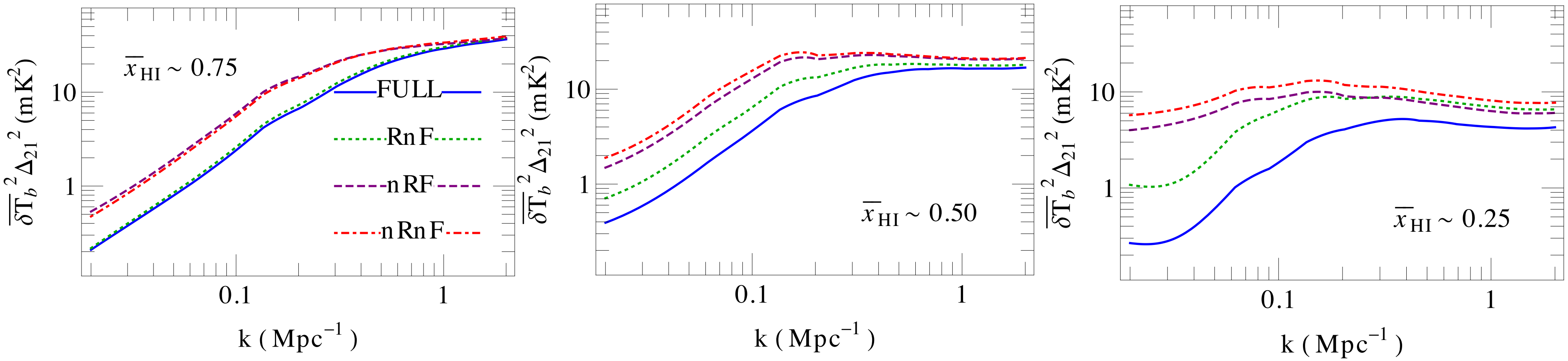
- **Delay** end stages
- **Suppress HII regions** $\gtrsim$ 10 Mpc.

This means the 21cm signal is smaller than expected!



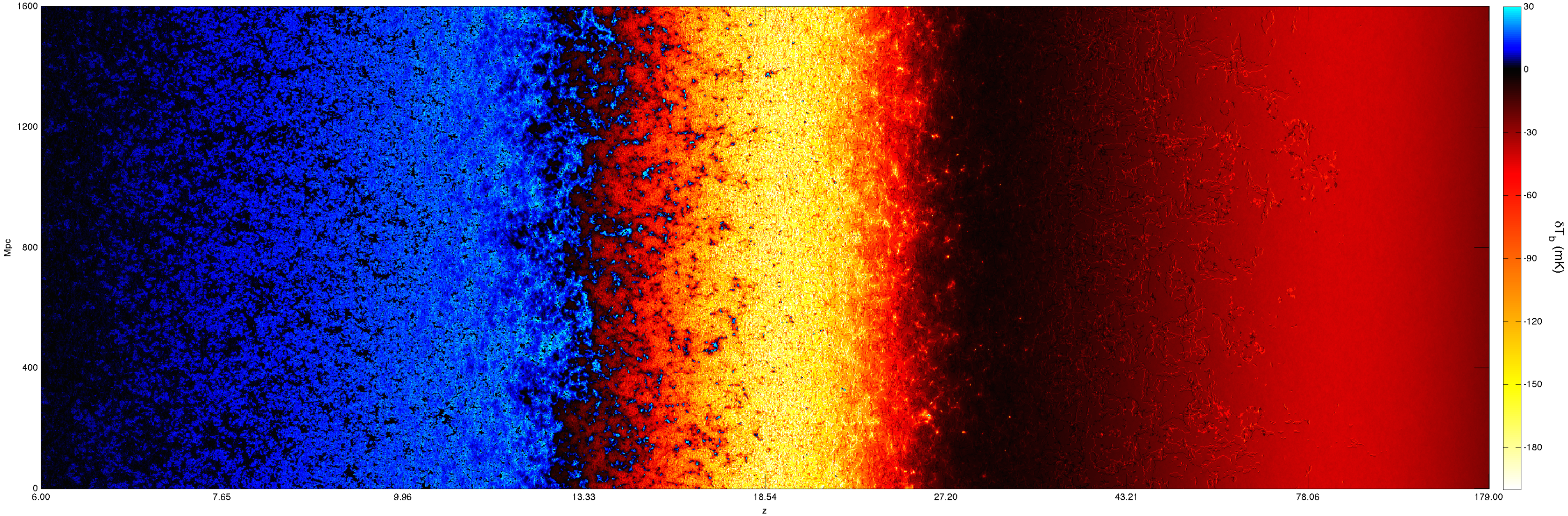
Patchy recombinations and photo-heating feedback on gas accretion have an additive impact

Suppression of large-scale 21cm power by factors of >3 throughout reionization, and a steeper spectrum. Quantitative impact depends on the duration of reionization.

Sobacchi & AM (2014)

Evolution Of 21cm Structure

- periodic, public releases of the latest, large-scale 21cm sims (~current 'best-guess')

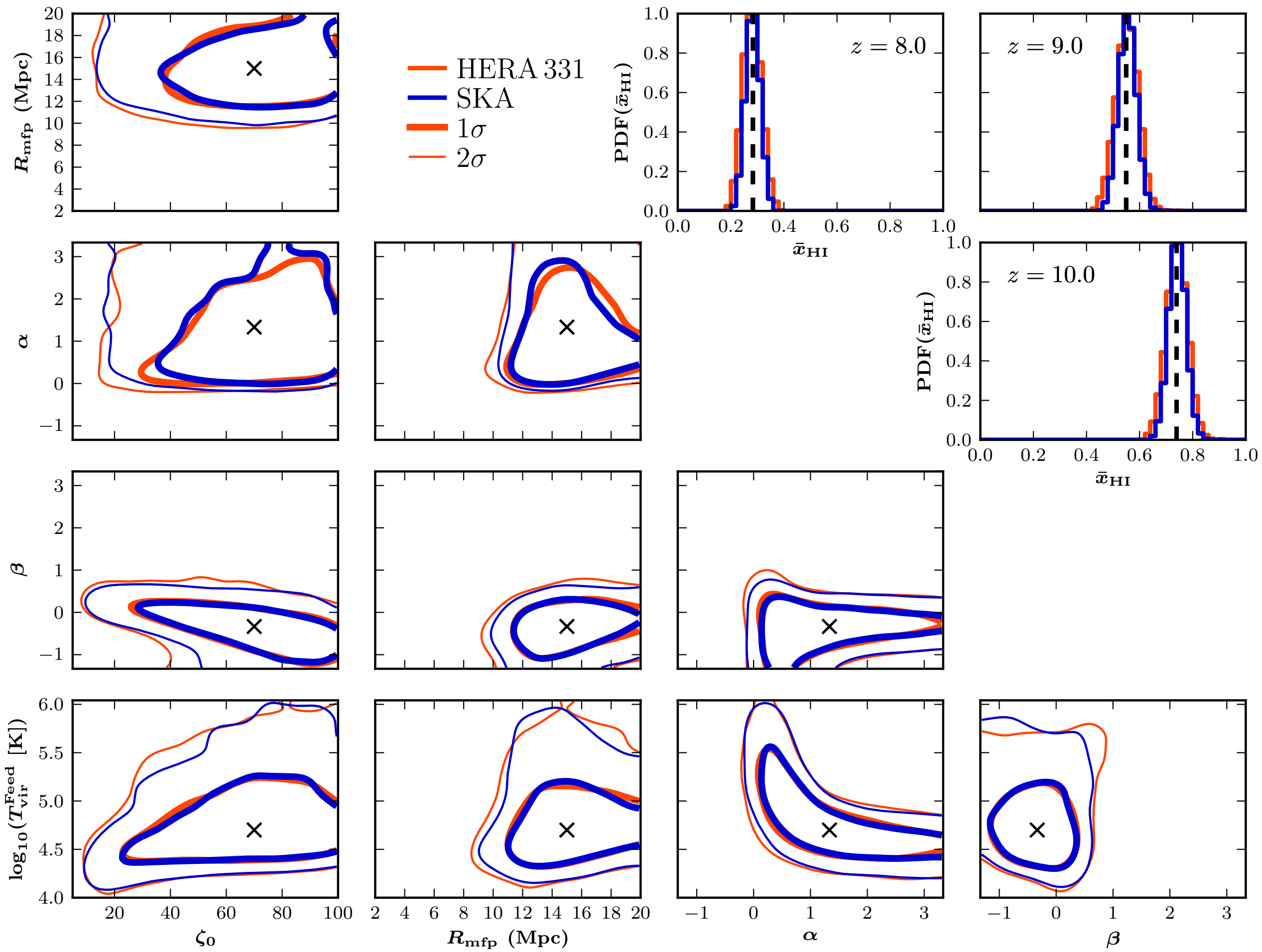


1.6 Gpc, 1024^3

http://homepage.sns.it/mesinger/EOS.html

2) ultra-fast, models with flexible parametrizations:

Bayesian constraints on EoR astrophysics



~10^5 **21CMFAST** realizations with **21CMMC**

(impossible with numerics)

Greig & AM (2015)

(see Brad's talk)

3) instrument pipelines

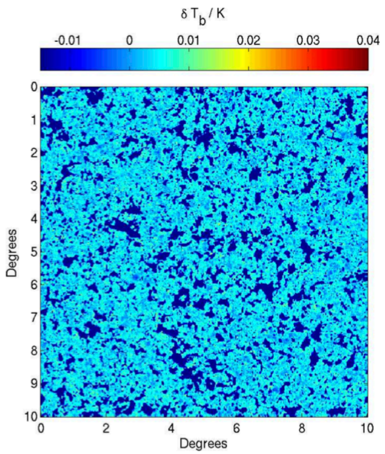
Instrument pipelines

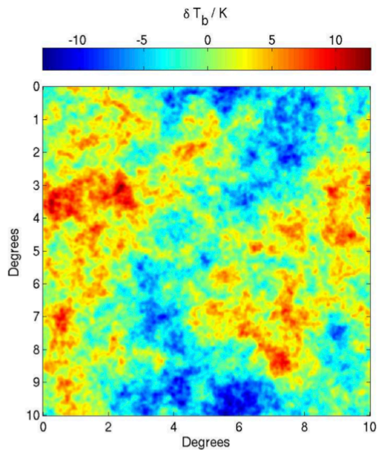
cosmic signal
21cmFAST

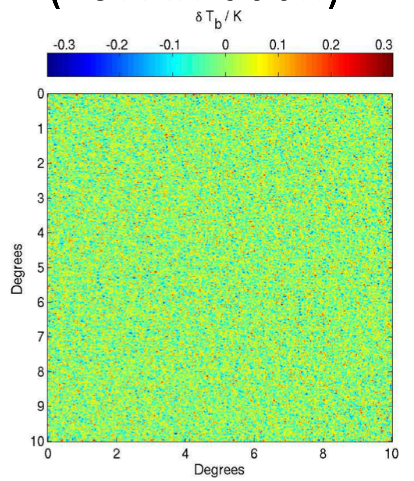
foregrounds (FG)
(e.g. Jelic+2010)

instrument noise
(*LOFAR* 600h)

DATA=

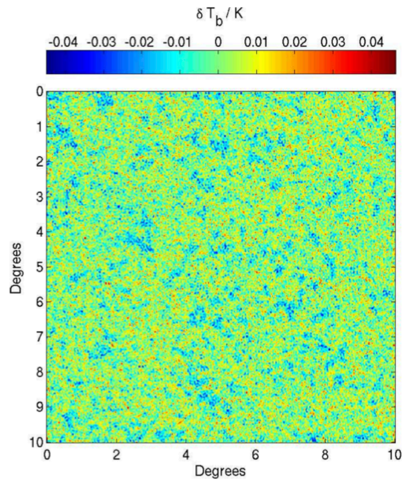






reconstructed signal =

DATA − FG removal − noise =

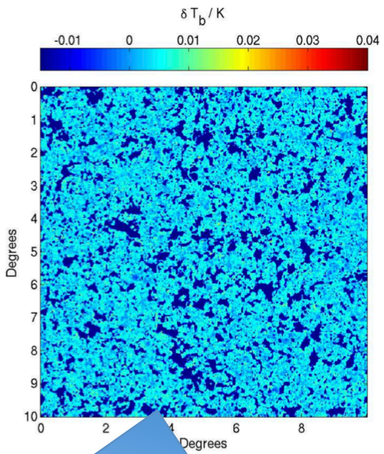


Chapman+ 2012

Instrument pipelines

DATA=

cosmic signal
21cmFAST



foregrounds (FG)
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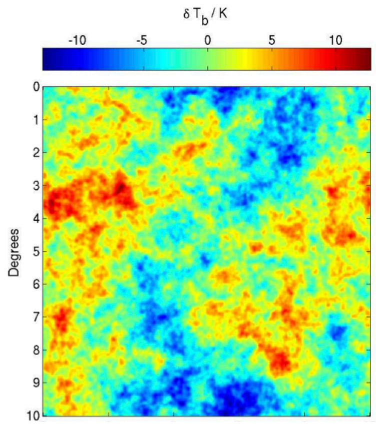
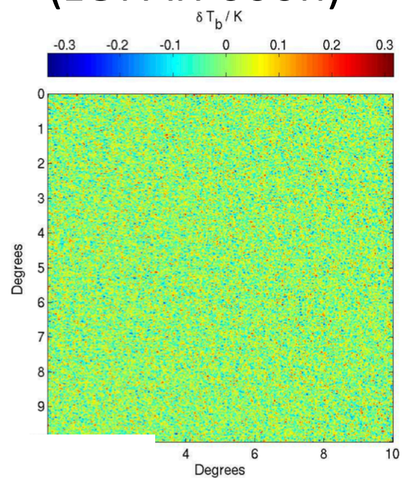
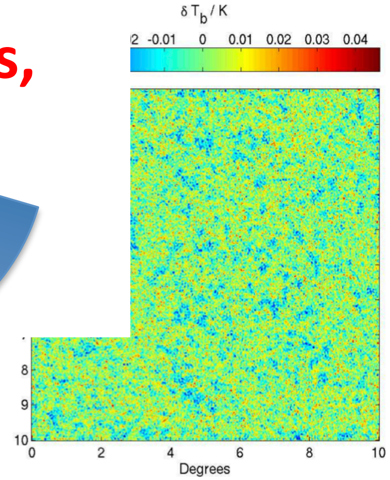


instrument noise
(*LOFAR* 600h)



- *statistical comparison*
- **do we recover EoR physics, e.g. with 21CMMC???**
- **try different cleaning/ different EoR!**

reconstructed signal = **DATA**

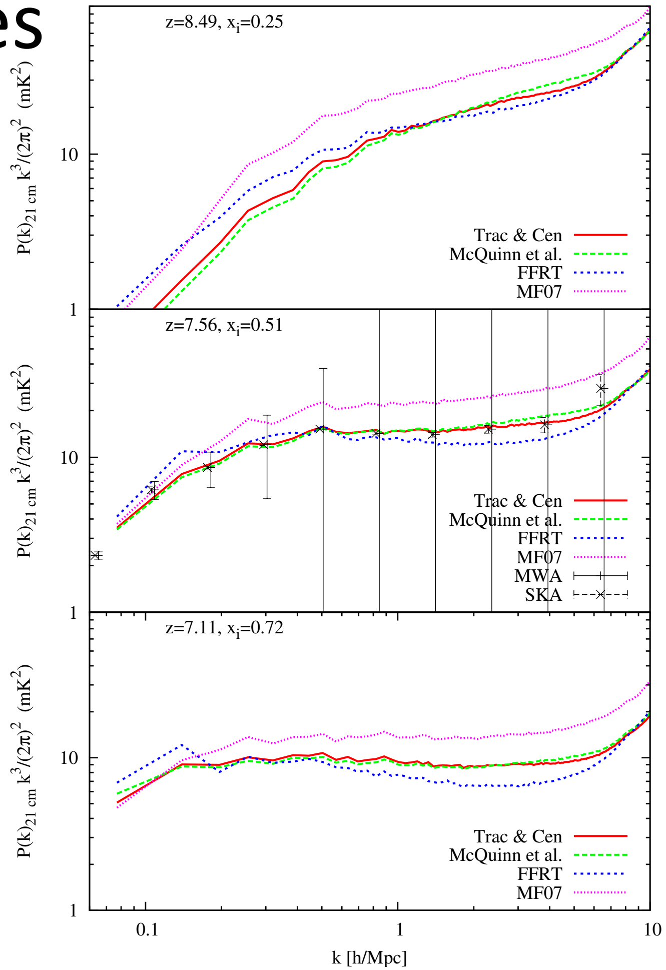


Chapman+ 2012

4) testing and calibration

Testing against large-scale RT

- Agreement w/RT is ~30% over the relevant scales



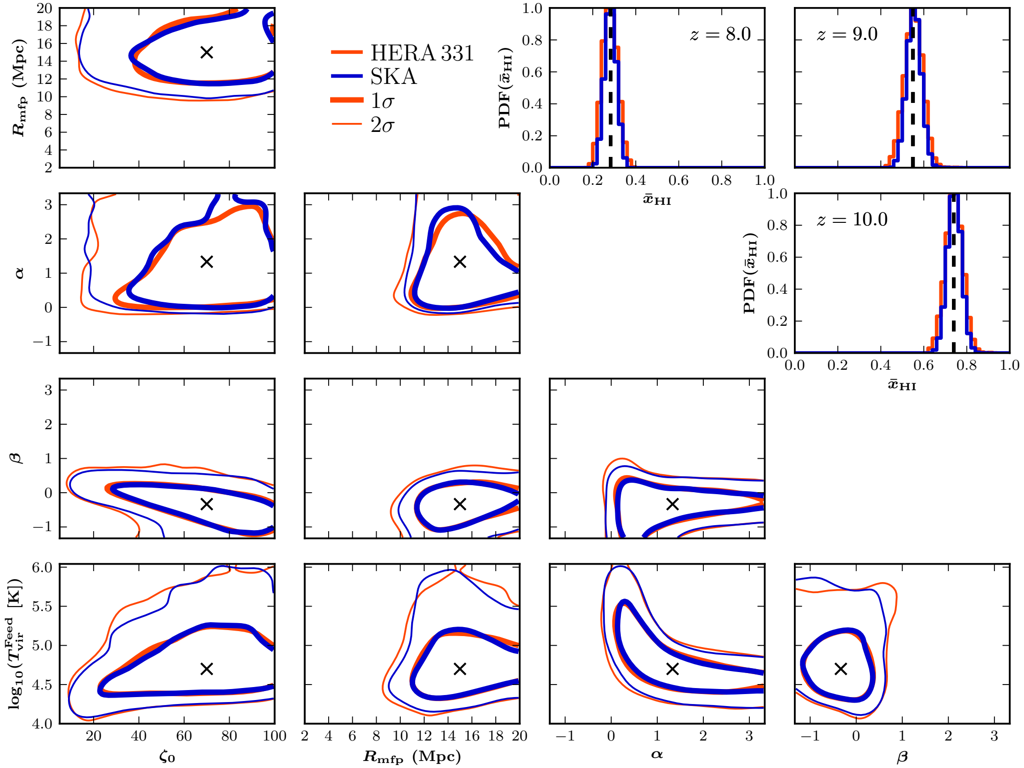
Zahn, AM+ (2011)

see also AM+(2011); Majumdar+(2014)

Testing against large-scale RT

- Agreement w/RT is ~30% over the relevant scales, **BUT** comparisons have only been made for very simple models
  - what about Ts, sub-grid, various source prescriptions?
  - comparisons can be used to **quantify biases and errors**, which can be folded-into statistical analysis (e.g. 21CMMC)

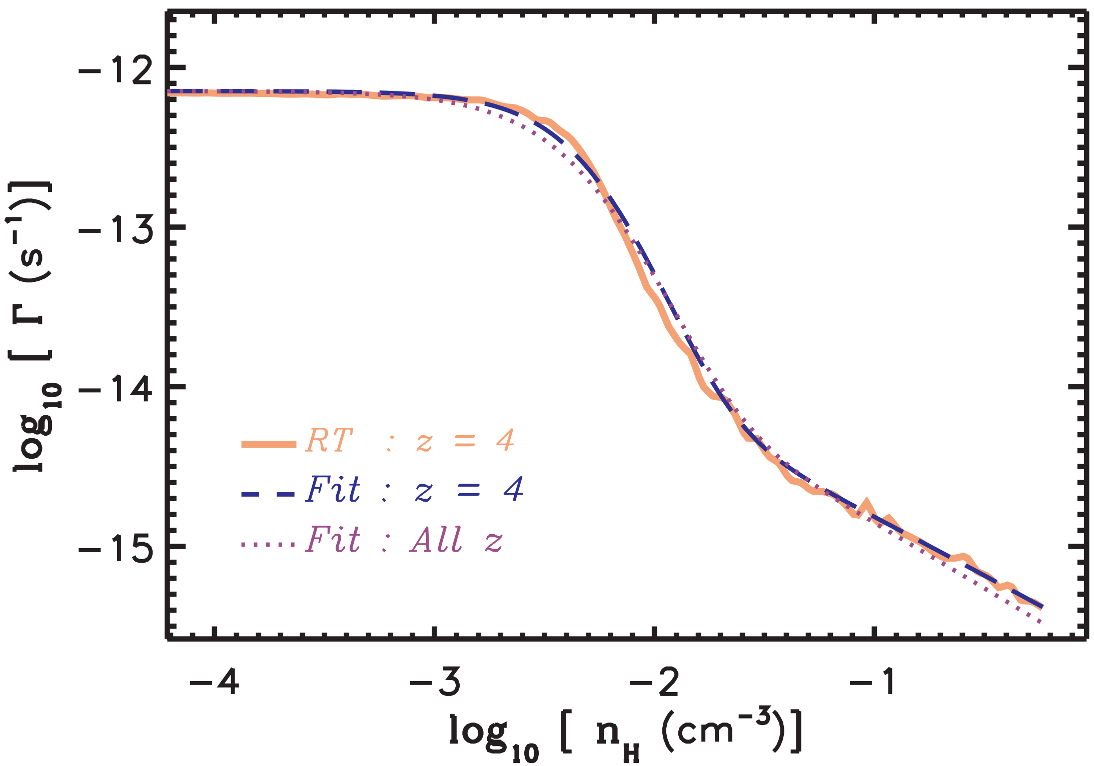
Testi … RT



- Agreement … nt scales, **BUT** … made for very sim…
  - what abou… prescriptic…
  - comparisons can be used to **quantify biases and errors**, which can be folded-into statistical analysis (e.g. 21CMMC)

Calibrating to small-scale sims

- feedback, self-shielding, gas dynamics, etc. require **systematic** studies using small-scale, physics-rich simulations. These can then be used to **empirically calibrate** sub-grid physics for large-scale semi-numerical sims (e.g. Sobacchi & AM 2013, 2014)



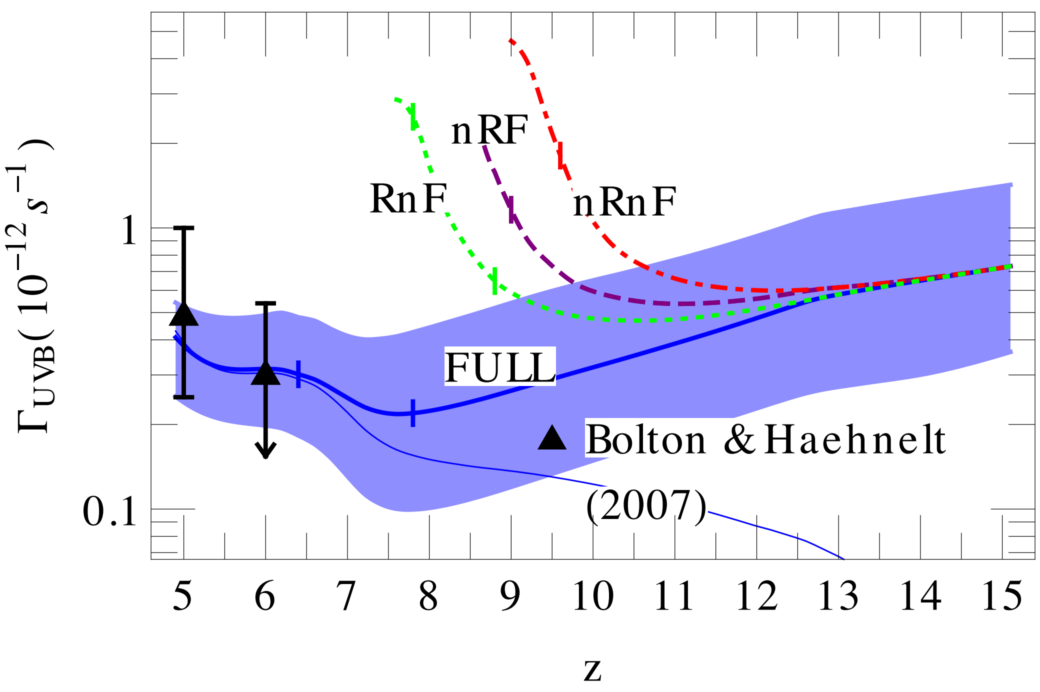
e.g. self-shielding of a UVB

Rahmati+ (2012)

Conclusions

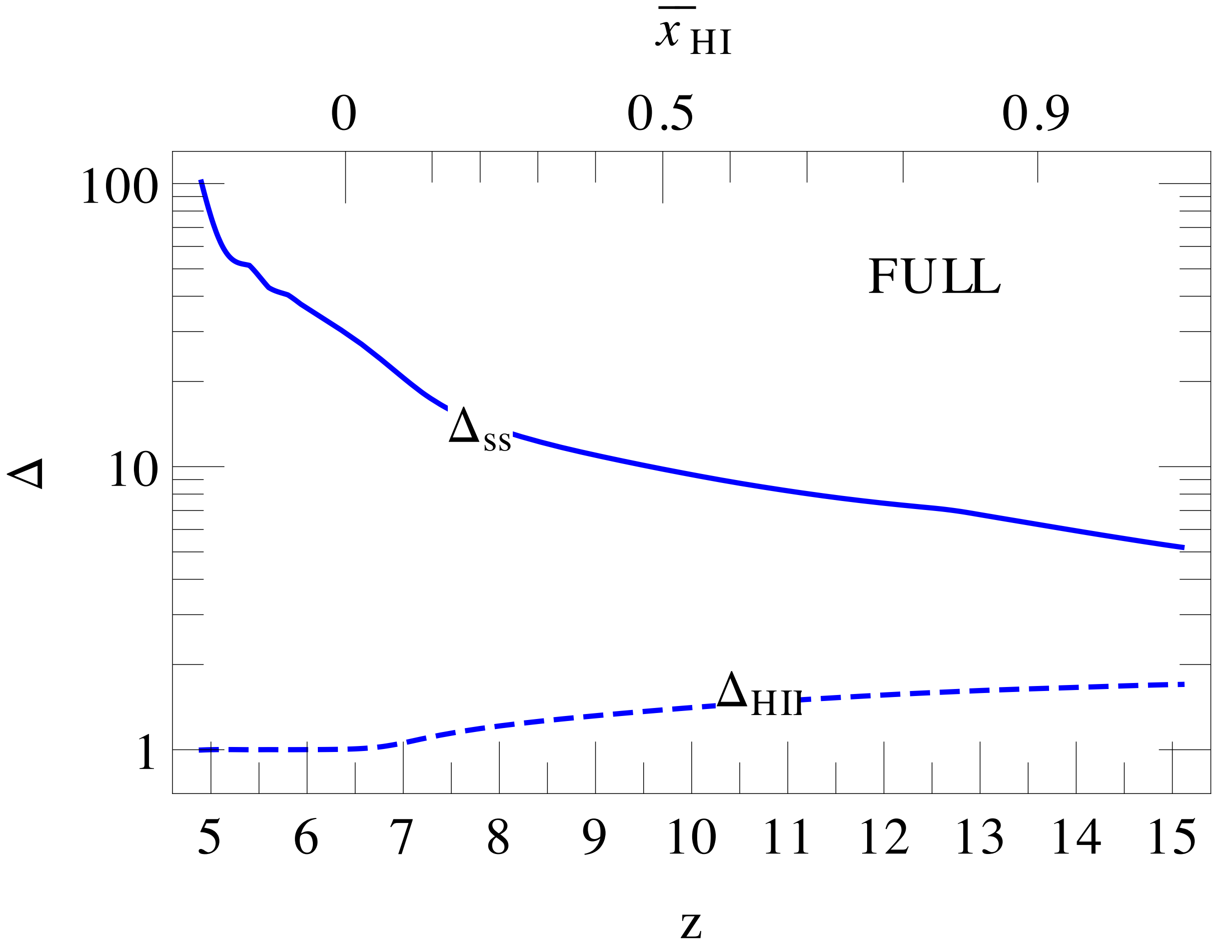
- Semi-numerical simulations offer a cheap alternative to RT+N-body, at a ‘modest’ cost in accuracy
- They are here to stay!
  - fast enough to be used for EoR astrophysical parameter exploration
  - allow for flexible parameterizations (physical and empirical)
  - test-bed for sub-grid models
  - can be calibrated in a bottom-up fashion to physics-rich simulations on small scales

Gammas



nRF
RnF
nRnF
FULL
Bolton & Haehnelt
(2007)
$\Gamma_{UVB}(10^{-12}s^{-1})$
1
0.1
5
6
7
8
9
10
11
12
13
14
15
z

Deltas



$\overline{x}_{HI}$
0
0.5
0.9
100
10
1
Δ
FULL
Δ_{ss}
Δ_{HII}
5
6
7
8
9
10
11
12
13
14
15
z