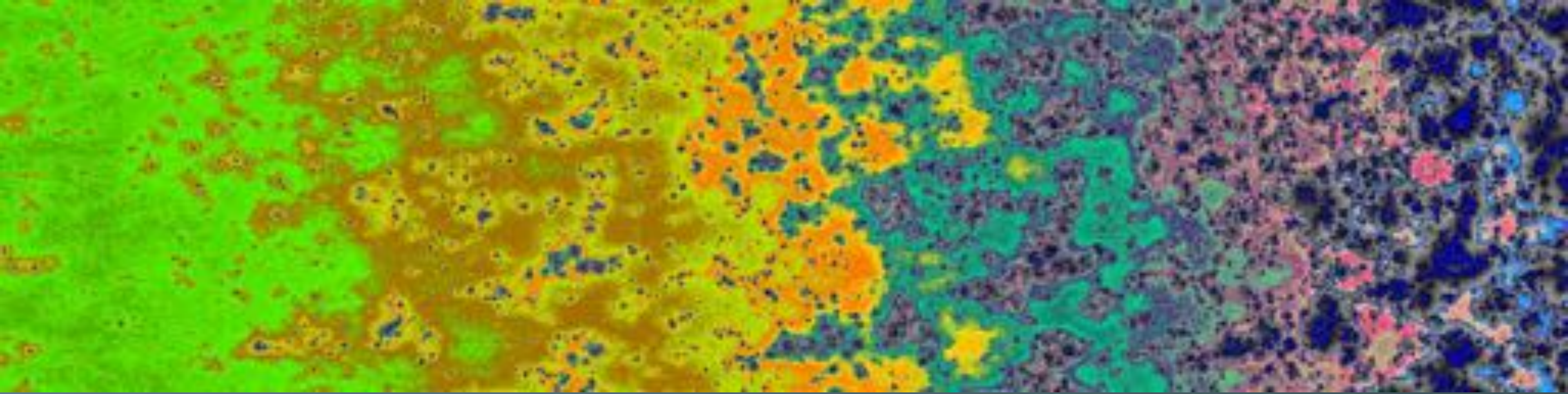


Peering into the Cosmic Dawn with the SKA

Benoît Semelin (SU - Observatoire de Paris)
contributions from H. Shimabukuro et A. Doussot

SF2A, Jully 2018

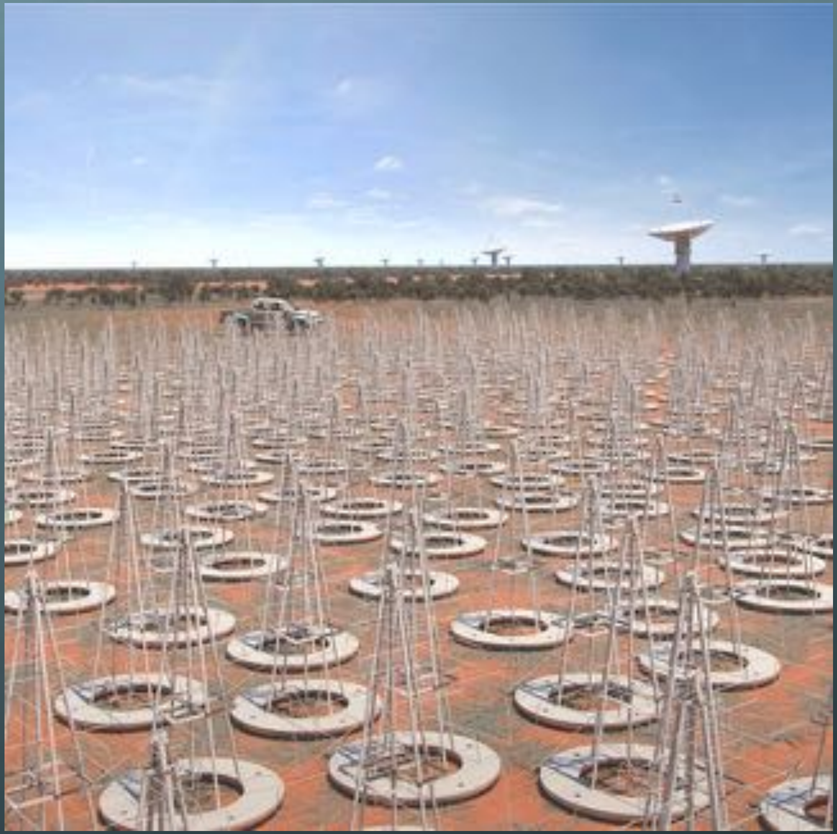
One of the main science goals of the SKA

From the SKA science book:

- The Cradle of life
- Fundamental Physics with Pulsars
- Magnetism
- The Hydrogen Universe
- The Transient Universe
- The Continuum Universe
- Cosmology
- Epoch of Reionization (EoR)

Observe the redshifted 21cm signal from the neutral IGM during the EoR: 50 - 200 MHz

=> SKA-Low



SKA –Low

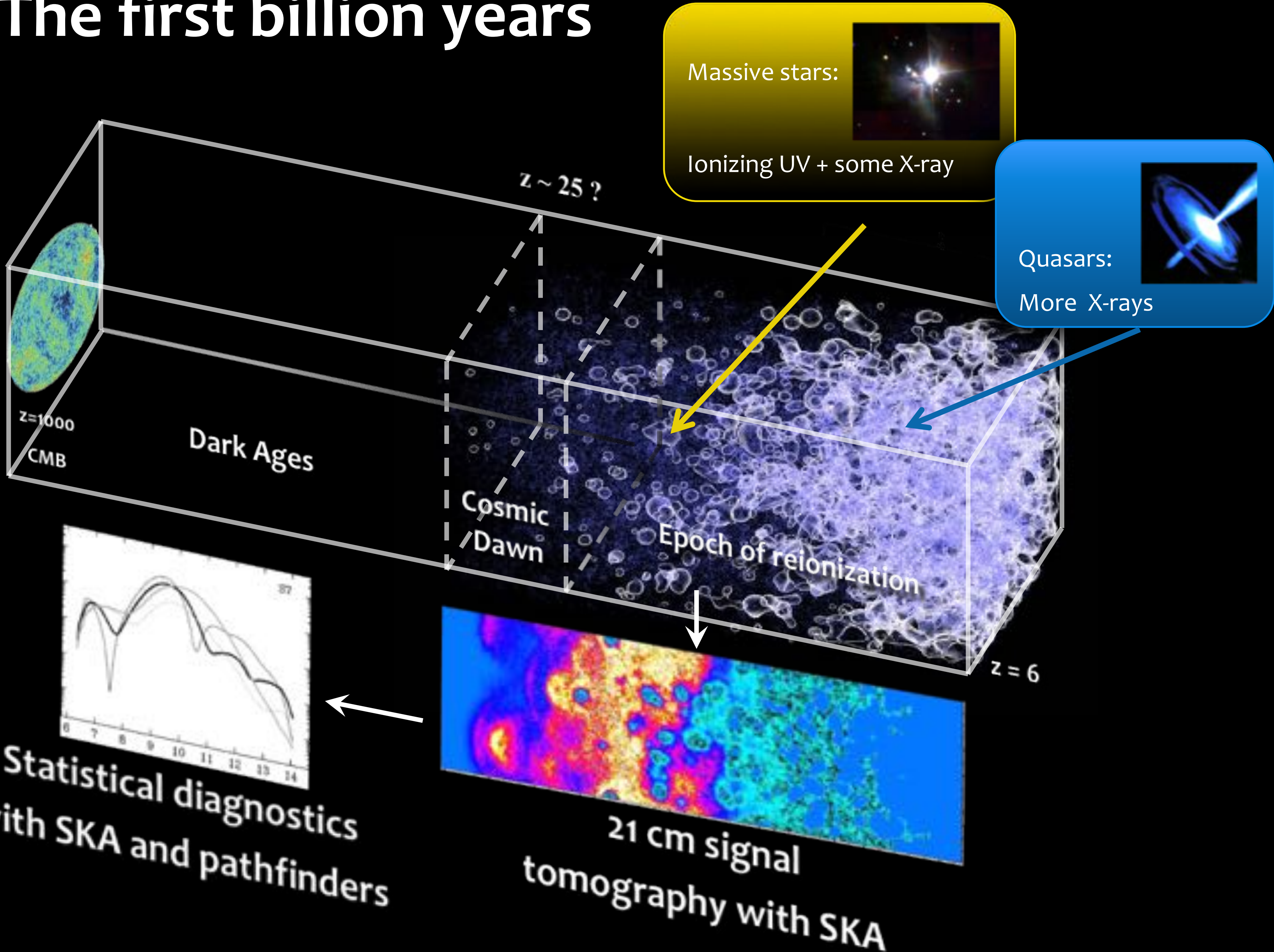
Western Australia

130 000 dipoles

Bandwidth 50-350 MHz

Sensitivity: 500 m^2/K at 110 MHz

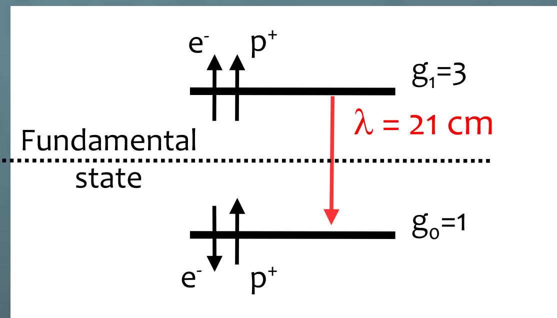
The first billion years



The 21 cm signal

Fondamental process:

Hyperfine transition

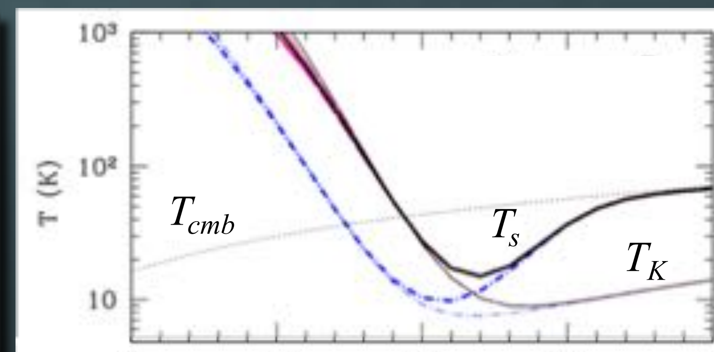


Level populations:

- ⇔ Spin temperature
- ⇔ emission proba

$$\frac{n_1}{n_0} \propto \exp\left(-\frac{h\nu_{21}}{k_B T_s}\right)$$

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_K^{-1} + x_{col} T_K^{-1}}{1 + x_\alpha + x_{col}}$$



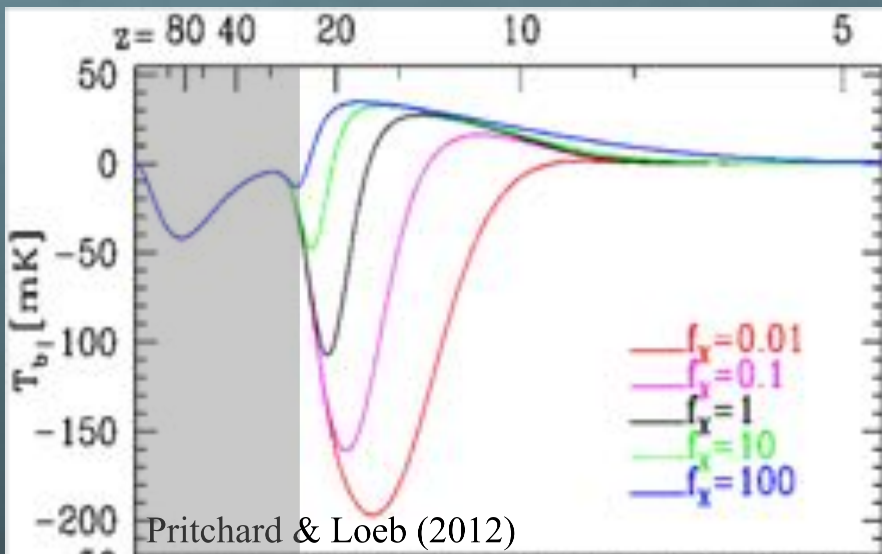
Furlanetto et al. (2006)

Observed intensity:

$$\delta T_B \propto 28\,\mathrm{mK}\ \overbrace{(1+\delta)\,x_{HI}}^{\text{Nb of emitting atoms}}\ \underbrace{\overbrace{\left(\frac{T_S - T_{CMB}}{T_S}\right)}^{\text{intensity per atom}}}_{\text{astro}} \left(1+\underbrace{\frac{1}{H}\frac{dv}{dr}}_{\text{cosmo}}\right)^{-1}$$

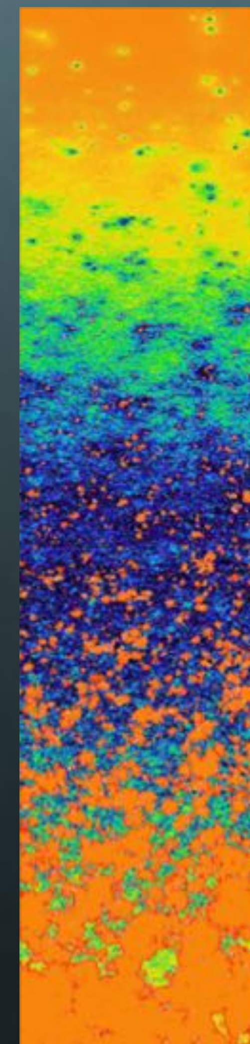
21 cm signal observables

Integral signal: $\langle \delta T_B \rangle_{sky}(z) \propto \langle x_{HI} \rangle_{sky} \langle 1 - T_{cmb}/T_s \rangle_{sky}$



EDGES
SARAS
LEDA
SCI-HI
PRIZM
NCLE
...

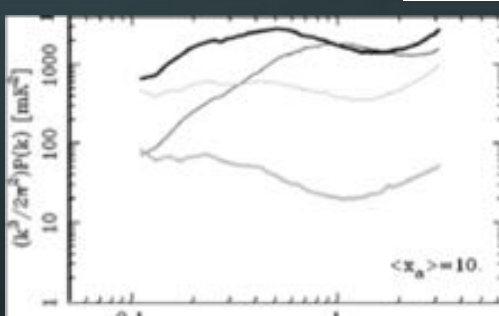
Imaging: $\delta T_B(\mathbf{x}, z)$



SKA

All information + random phases

3D power spectrum: $P_{\delta T_B}(k, z)$



LOFAR
PAPER -> HERA
MWA
GMRT
NENUFAR

Upper limits by SKA pathfinders/precursors

PAPER (S. Africa)

(22 mK)^2 at z = 8.4

several 100h integration

(Ali et al. 2015)

MWA (Australia)

(164 mK)^2 at z~7

32h hours (Beardsley et al. 2016)

(qq 10 K)^2 at z ~16

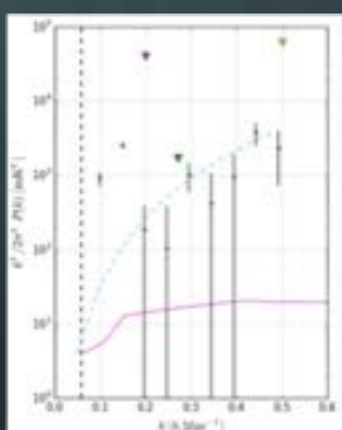
4 hours (Ewall-Wice et al. 2016)

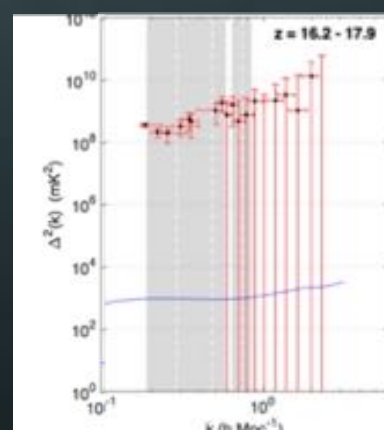
LOFAR (NL)

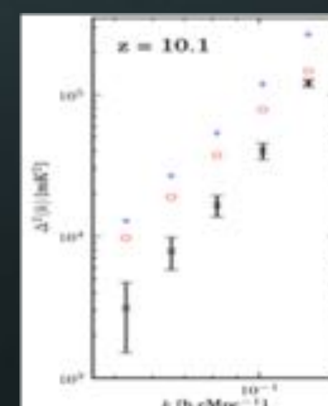
(56 mK)^2 at z~ 10

with only 13h integration

(Patil et al. 2017)







The EDGES « detection » (Bowman et al. 2018)

EDGES:

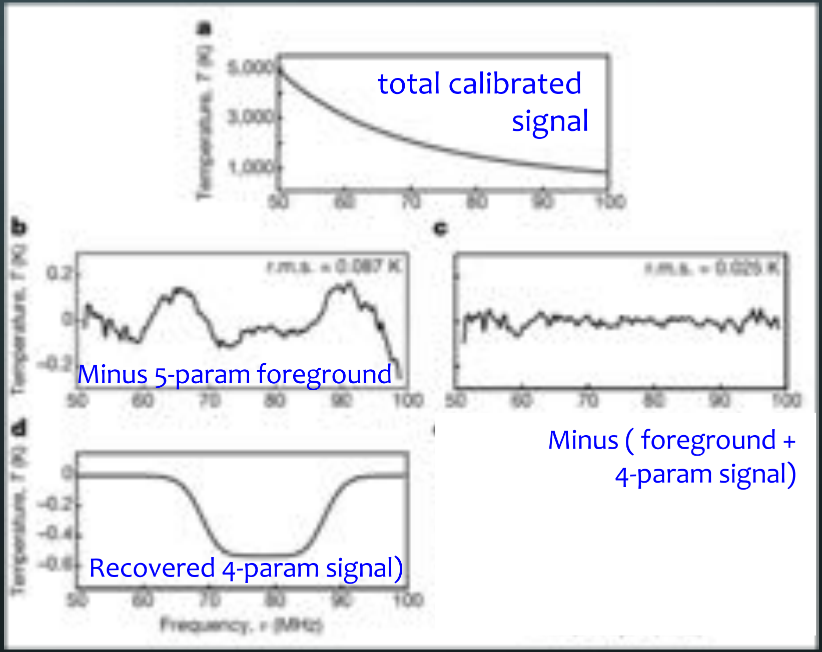
- single dipole experiment
- At future SKA site, Australia
- Lowband (50-100 MHz) antena
- Highband (90-200 MHz) antena
- > 100 h integration

Validations tests:

- 6 hardwares configs (ground plane, orientation, etc.)
- 18 processing configs (time of obs, temp, beam, calib solution, foreground, …)

Caveat: Hills et al. (2018)

Some serious questions about foreground modeling



The EDGES « detection »: implications

More than 50 papers triggered by EDGES results in 2 month! Even more now…

« Standard model »

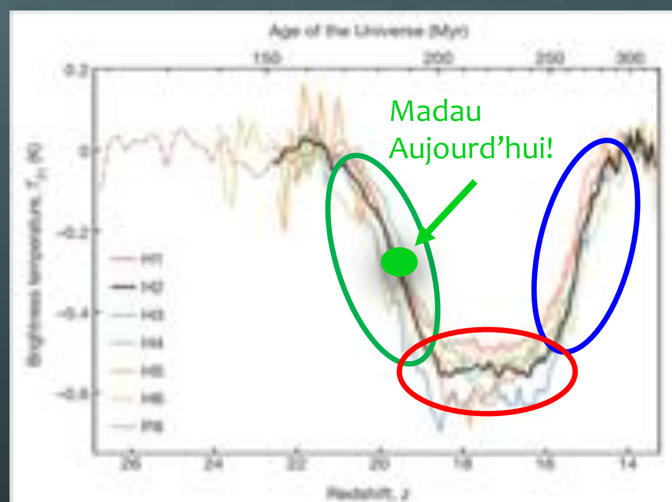
- If no heating: $T_K \approx 400 \left(\frac{1+z}{151}\right)^2 \approx 6\ \mathrm{K}$
- At z=17 : $\langle \delta T_b \rangle \approx 26 \sqrt{\frac{1+z}{10}} \left\langle - \frac{T_{CMB}}{T_K} \right\rangle \approx \mathbf{-220\ mK}$

Early Ly-α production:

-> Constraints on first stars formation (tension with lower z LF)

-> Constraint on WDM particle mass

Very sudden!



Heating of the gas:

-> Constraints on DM annihilation

-> Constraints on primordial BH populations

Very sudden heating…

Strength of absorption feature:

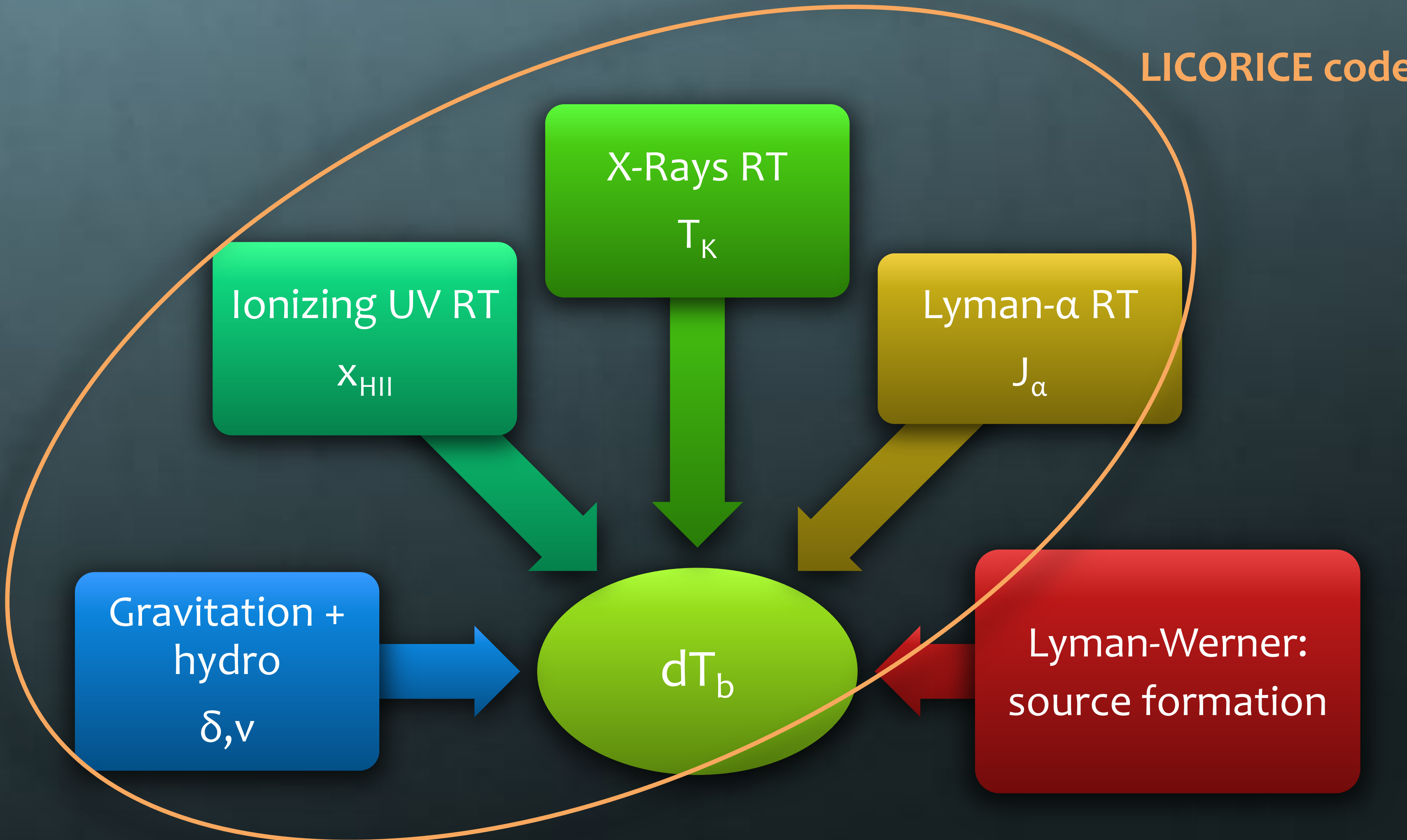
-> Colder gas, new physics (DM-baryon interaction, new DE)

-> Stronger radio background (QSOs, new DM -> stronger radio CMB,
axions -> macro quark nuggets -> radio emission)

Modelling the signal

$$\delta T_B = 28\,(1+\delta)\; x_{HI} \left(\frac{T_S - T_{CMB}}{T_S}\right) \left(1 + \frac{1}{H}\frac{dv}{dr}\right)^{-1} mK$$

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_c T_K^{-1} + x_\alpha T_K^{-1}}{1 + x_c + x_\alpha}$$



The 21SSD database

(Semelin et al. 2017)

<u>State-of-the-art set of templates:</u>

- 1024^3 radiative-hydro simulations in 300 Mpc box.
- 45 models covering part of the parameter space (mainly CD)
- δT_b lightcones, power spectra, PDFs, thermal noise

<u>Access:</u>

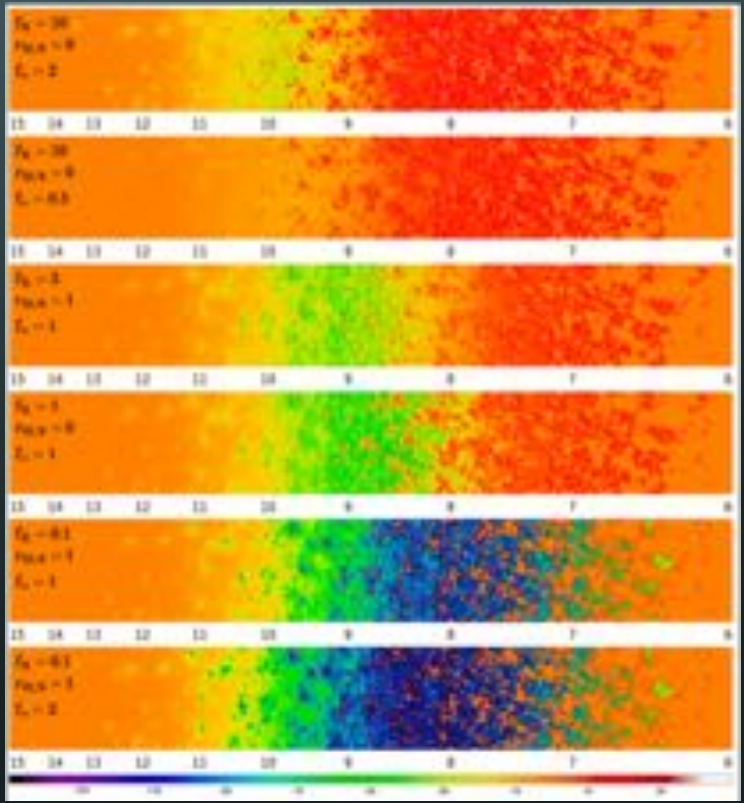
- Free access to the data at https://21ssd.obspm.fr
- Crashed, being rebuilt…barebone is running

<u>Limitations:</u>

- Modest FoV: 1.8°x1.8°
- Limited set of parameters… etc!

<u>What for?</u>

- End-to-end simulation
- Parameter constraint derivation (NN, MCMC, etc..)

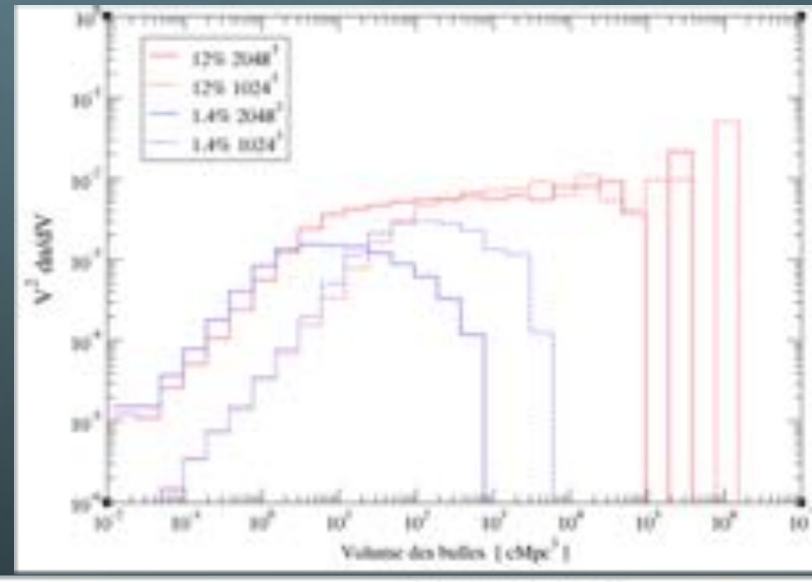


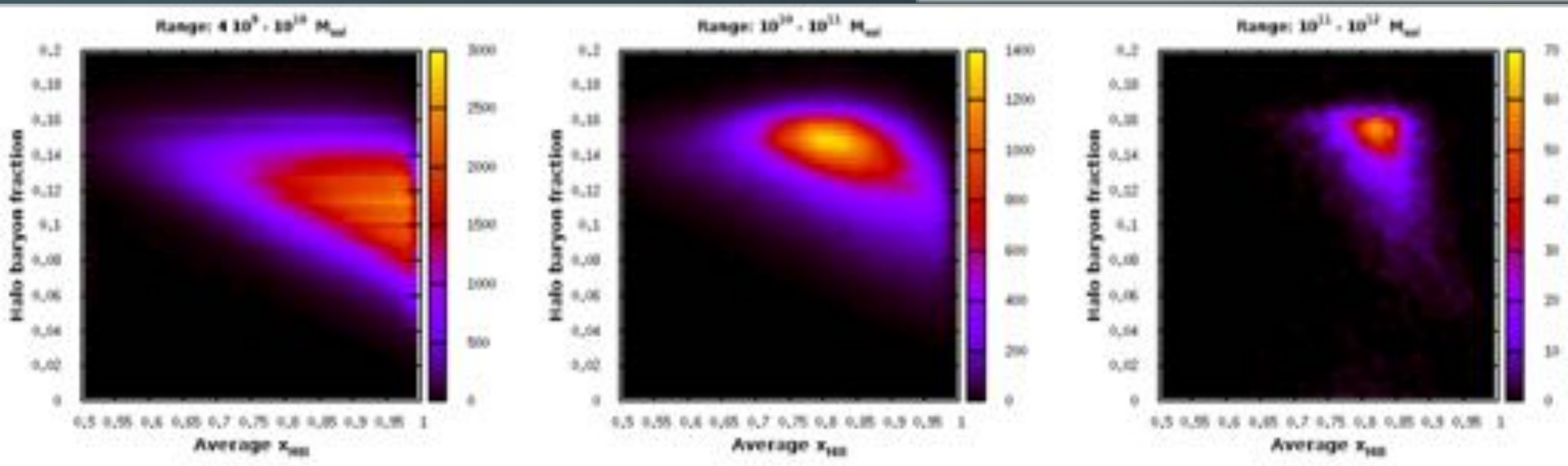
21SSD: a resolution study? (preliminary)

A GENCI « grand challenge » simulation:

- 300 Mpc box.
- 2048^3 particles, ~ 10^9 $M_\odot$ halos, ~ 3 kpc res.
- UV + hard X (XRB) + soft X (AGN) + Ly-band WF
- About 5 Mh CPU. 4096 Mpi domains, 16384 cores.

Effect of/on small halos (in a 300^3 Mpc^3 volume!)





The Wouthuysen-Field coupling

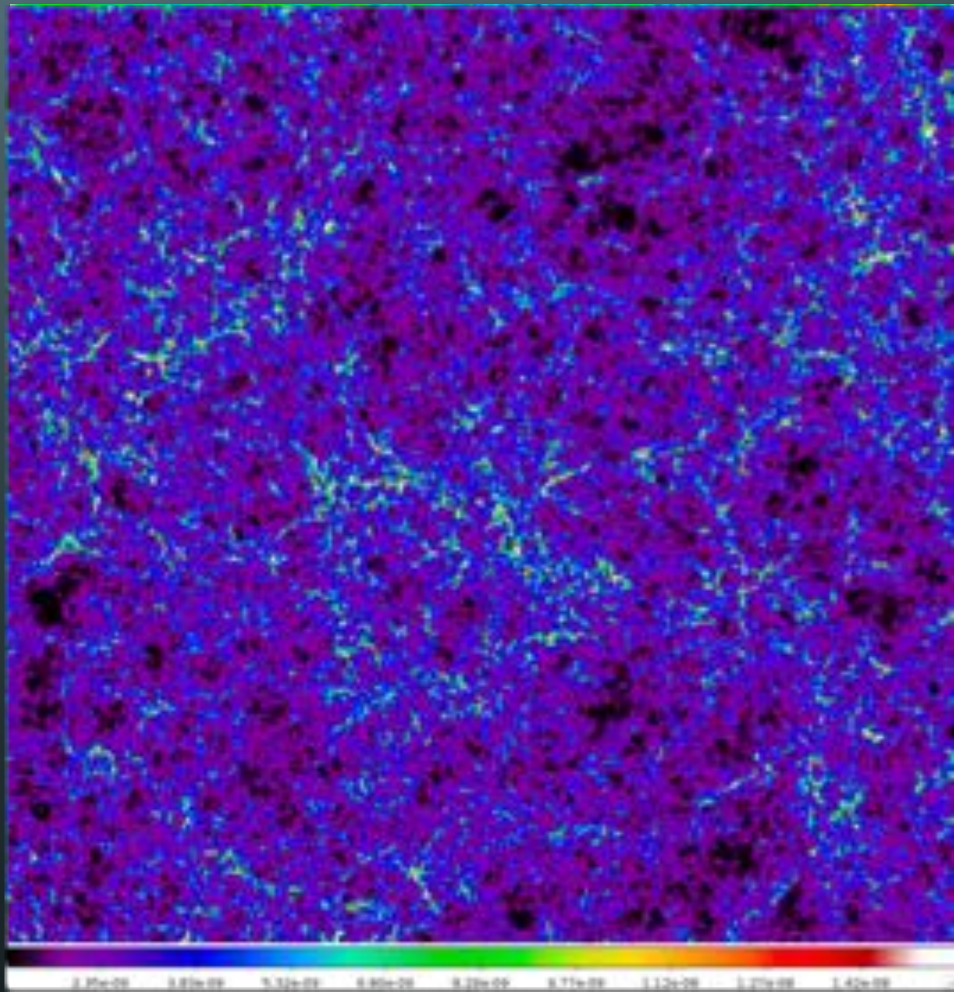
LICORICE: Monte Carlo RT transfert of Lyman continuum in post-processing

Poisson noise < 10% on a 1024^3 grid :

=> ~2. 10^{11} « instantaneous photons »

=> ~4. 10^{12} photons in total

=> ~ 10^6 CPU hours



$1/r^2$ flux only a rough approximation

Self shielding (also in Semelin 2016 in 50 Mpc/h)

ρ and x_α partially anticorrelated !

A factor of 2 on x_α

21-cm maps

The first 21cm maps are there!

Comparison with 21ssd not so simple:

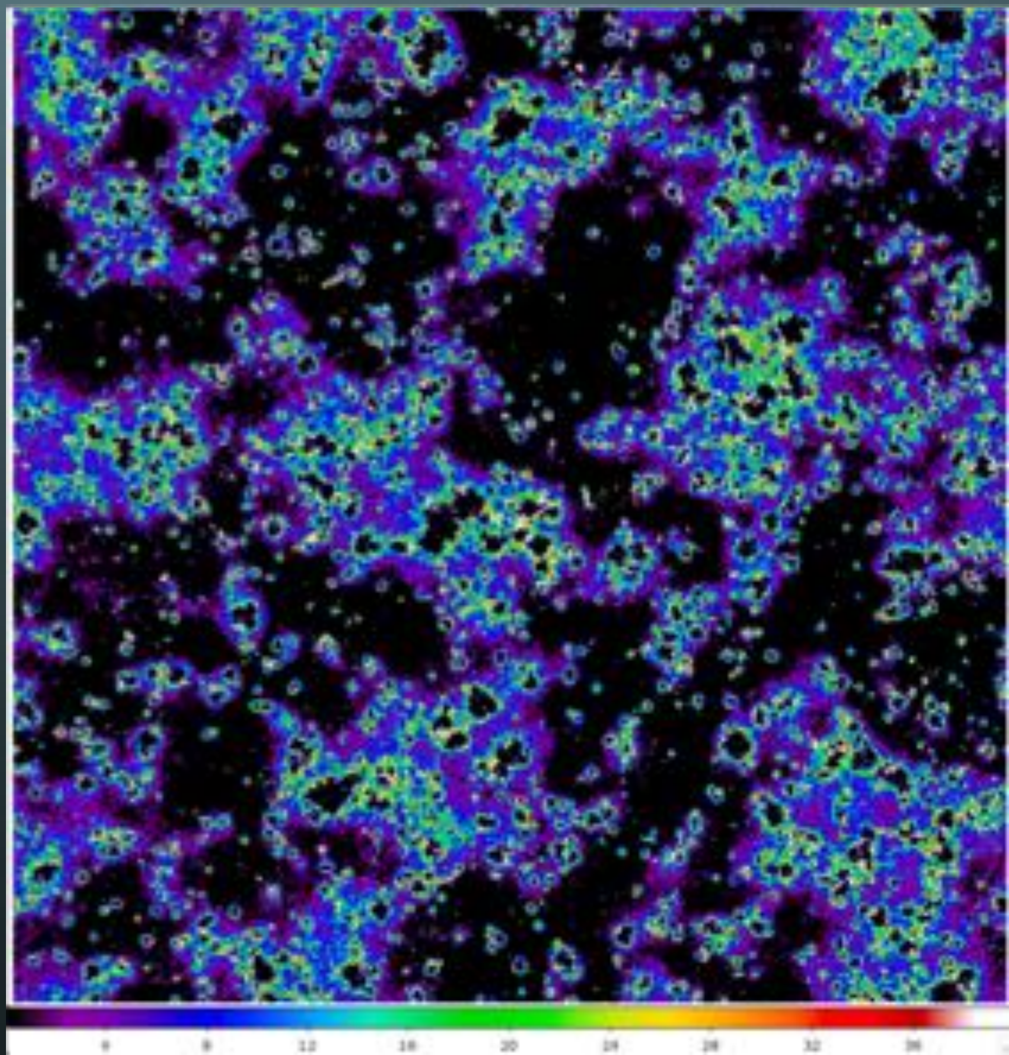
- Same $\langle x_{HII} \rangle$?
- Same z ?
- Same total star mass ?

Check different resolution effects:

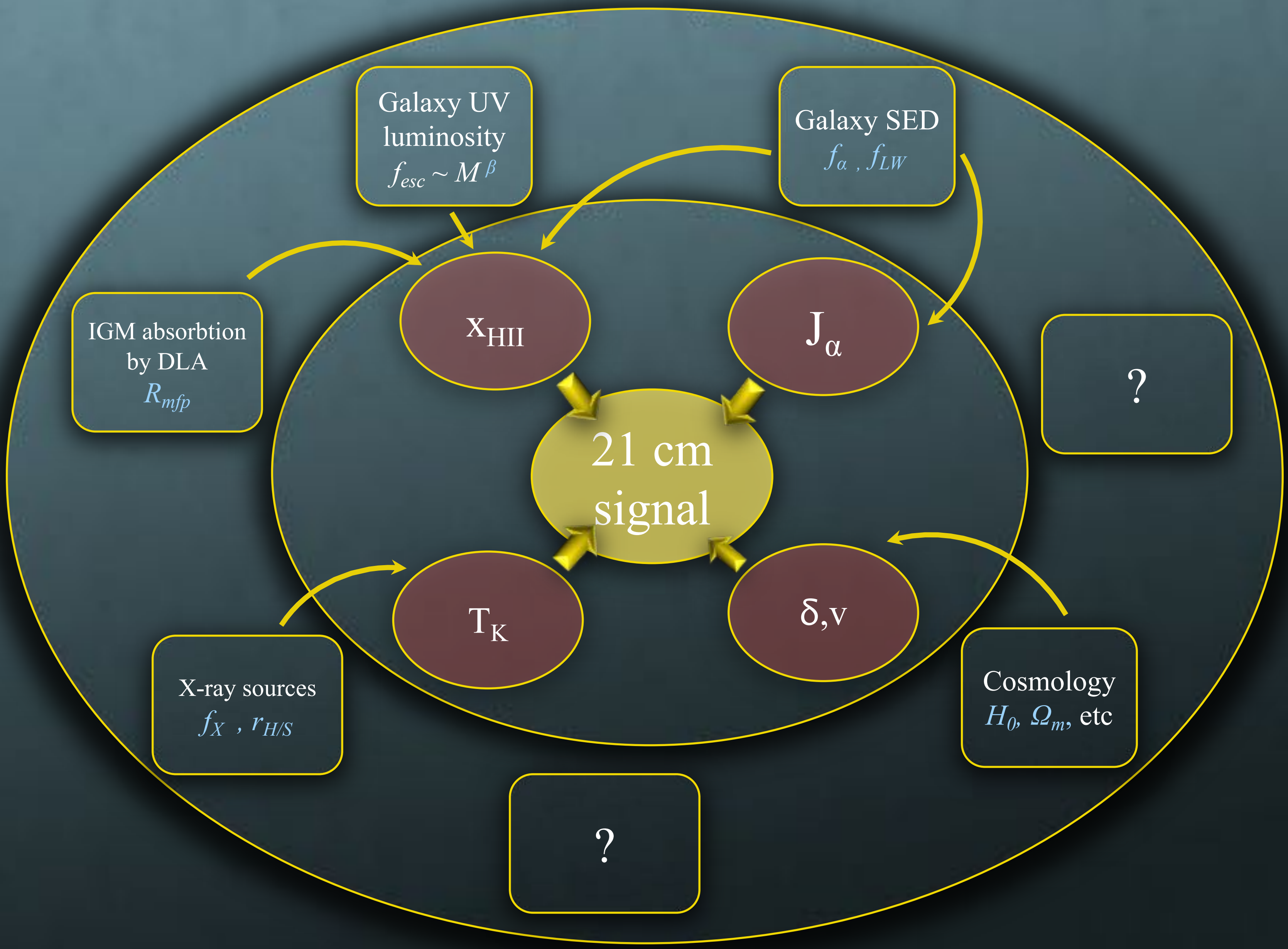
- w/wo small halos

- $\langle T_b \rangle_{SKA}$ vs $T_b(\langle \rho \rangle_{SKA}, \langle T_s \rangle_{SKA}, \langle x_{HI} \rangle_{SKA})$

- …

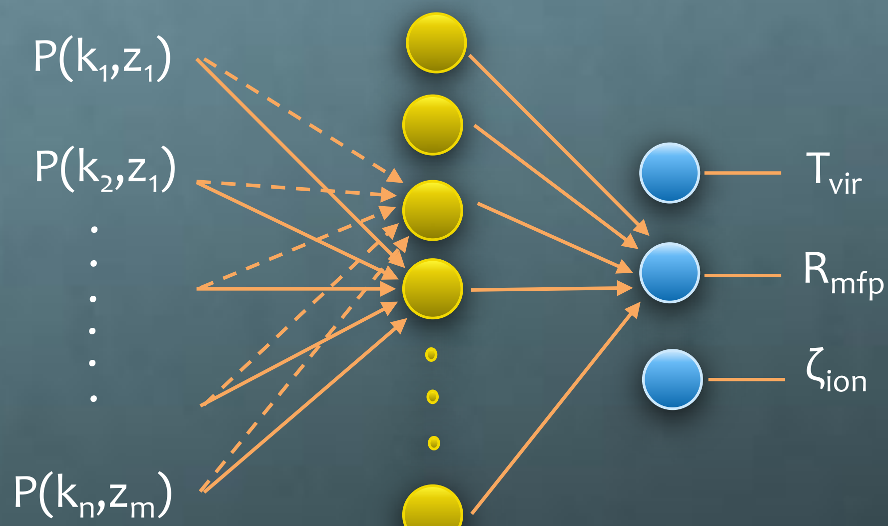


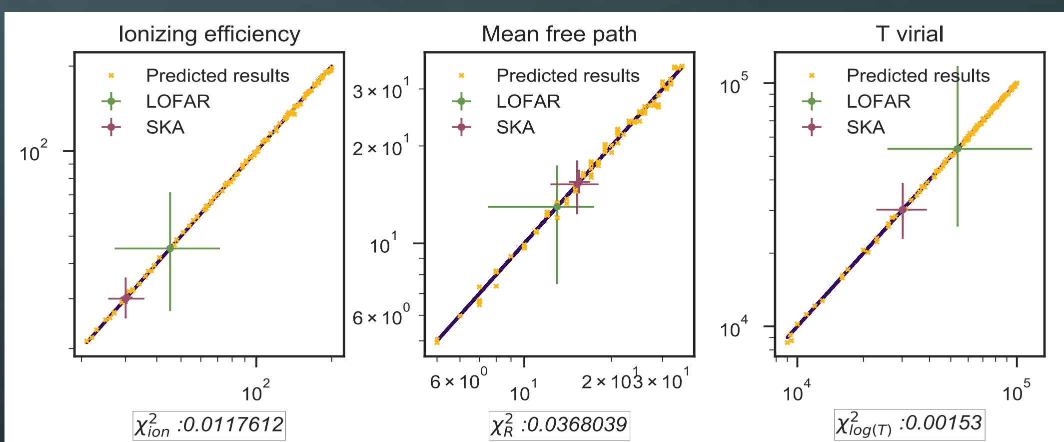
Parameterizing the EoR



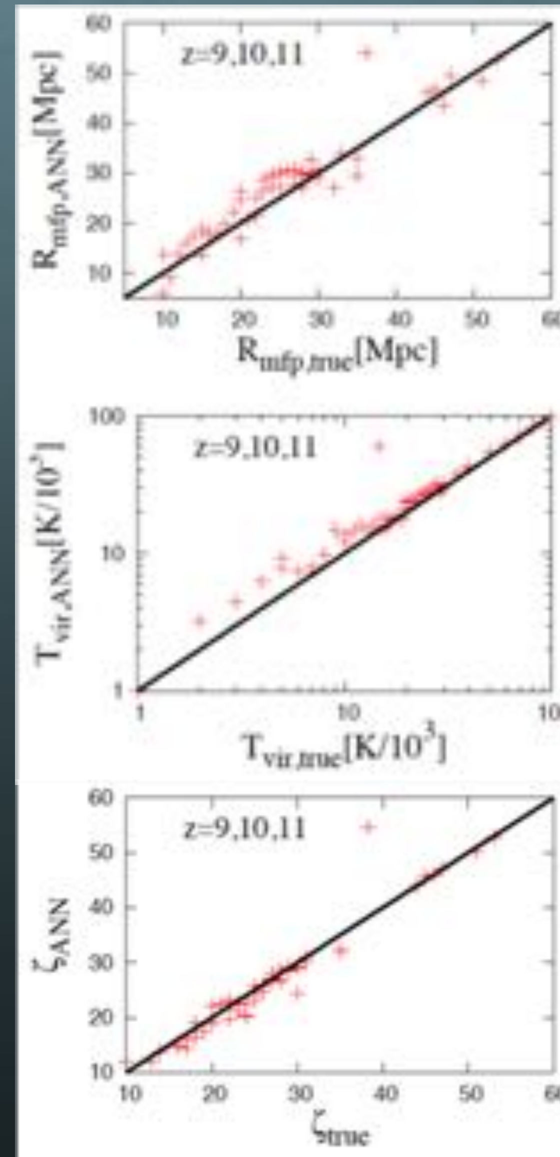
Parameter reconstruction with neural networks

An alternative to Bayesian MCMC approach.





Doussot et al. (2018, in prep), larger learning sample.



Neural network reconstruction
Shimabukoro & Semelin (2017)

Conclusions

- The 21cm signal may have an impact on astrophysics similar to the CMB.

- Numerical simulations are the key to extracting knowledge from upcoming observations.

- New “inversion” algorithms will have to be explored.