Simulations of the Epoch of reionization with RAMSES-CUDATON

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Collaborators

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- **I. Iliev, D. Sullivan**, P. Thomas (University of Sussex) (sci. exp., AHF)
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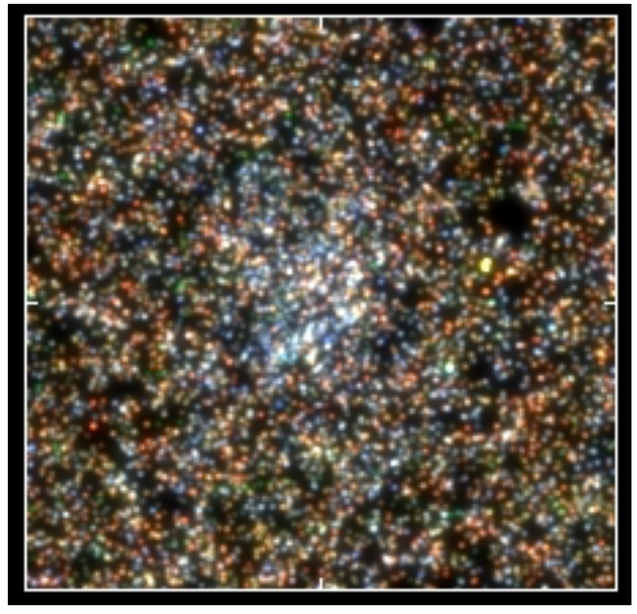
- **Y. Hoffmann** (Hebrew University of Jerusalem) (ICs)
- F. Roy, Y. Rasera (Observatoire de Paris) (pfof)
- Y. Dubois (IAP) (SN feedback)

Reionization & the Milky Way

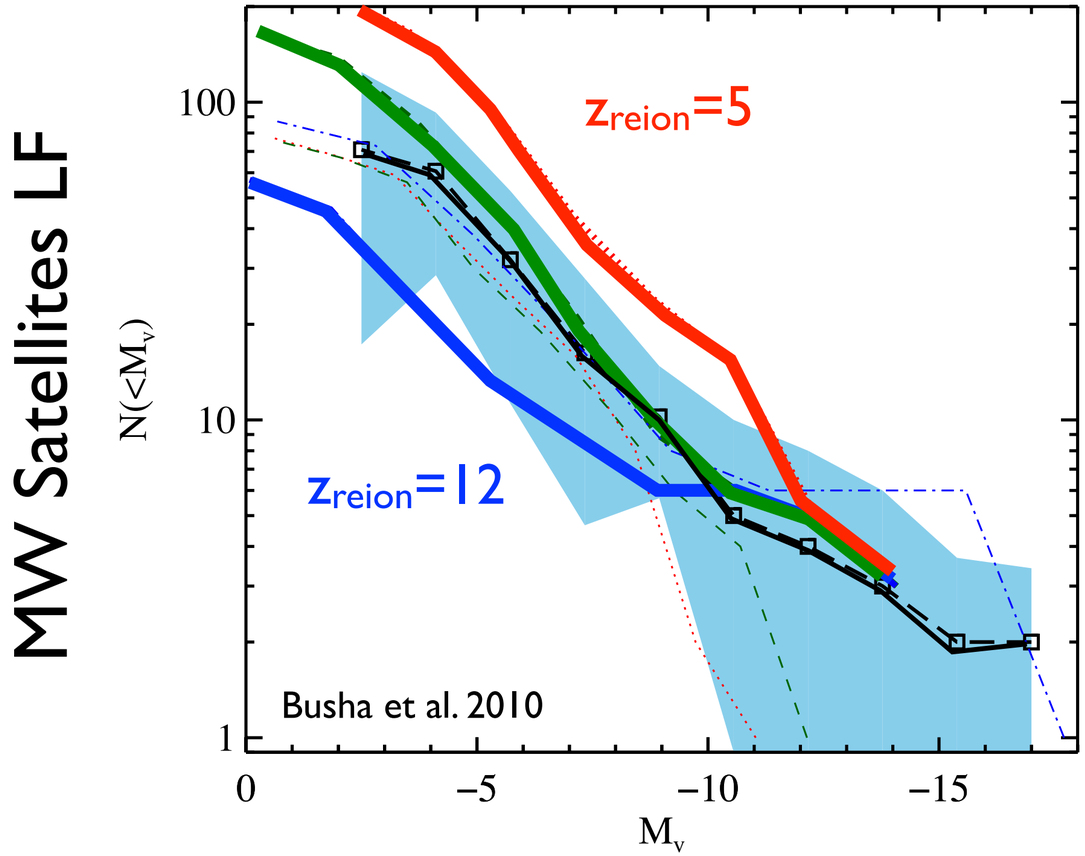
Solution to <u>missing satellite problem</u>?

- UV background
- => gas photo-evaporation
- => SF suppression low-mass galaxies
- => satellite galaxies, ultra-faint dwarfs



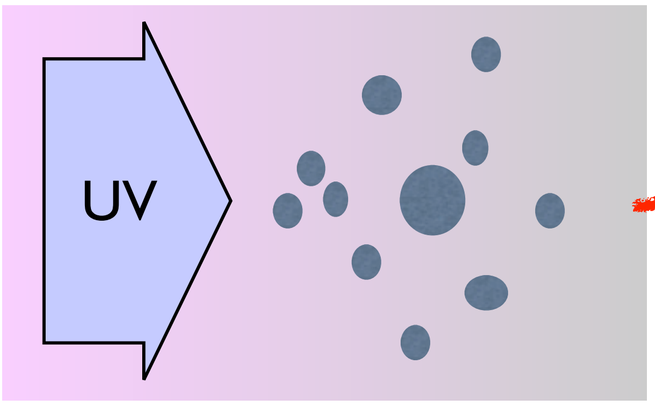
Bootes
D = 60 kpc
r_h = 220 pc
M_v = -5.8 mag

Courtesy V. Belokurov and SDSS collaboration

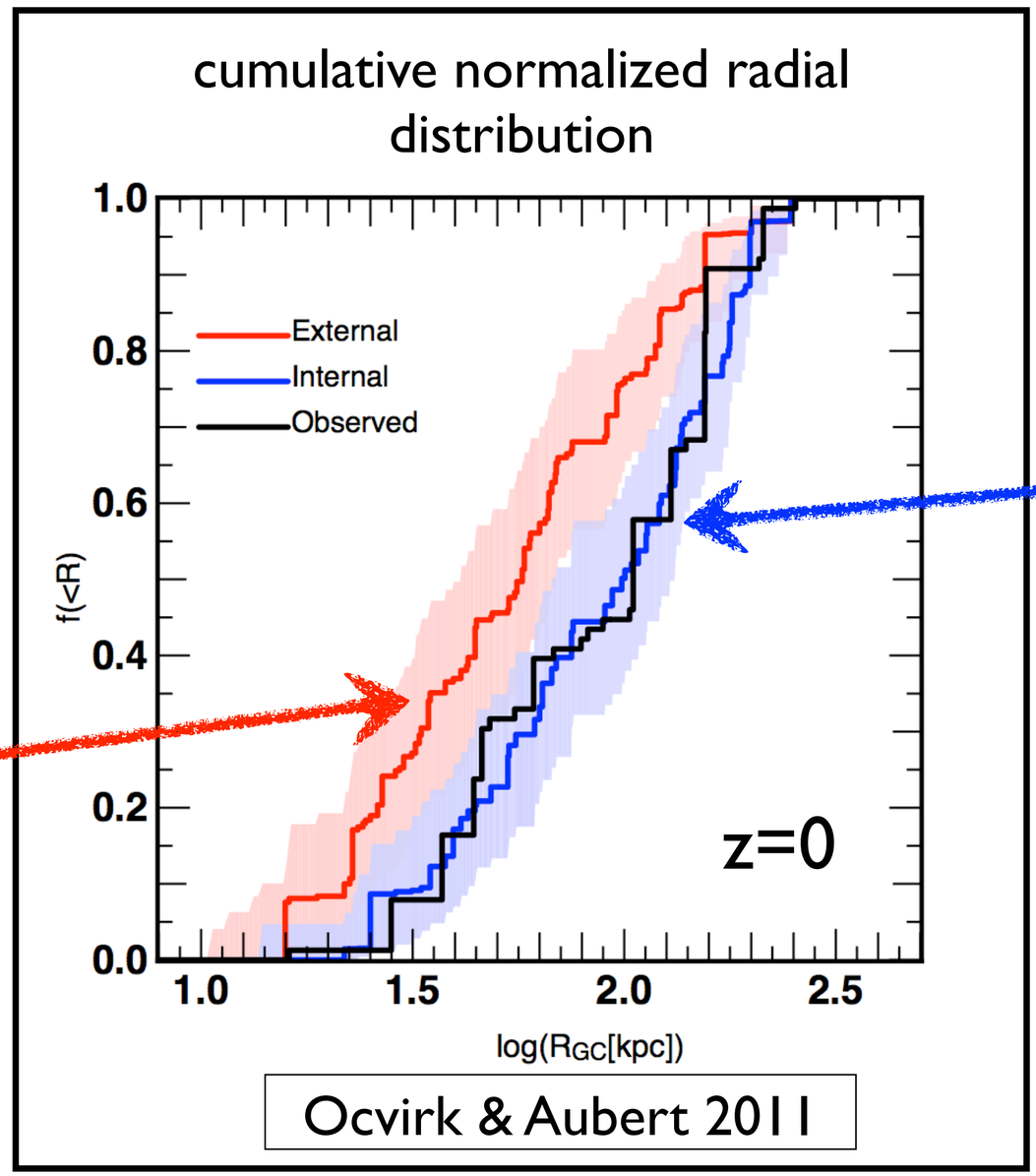


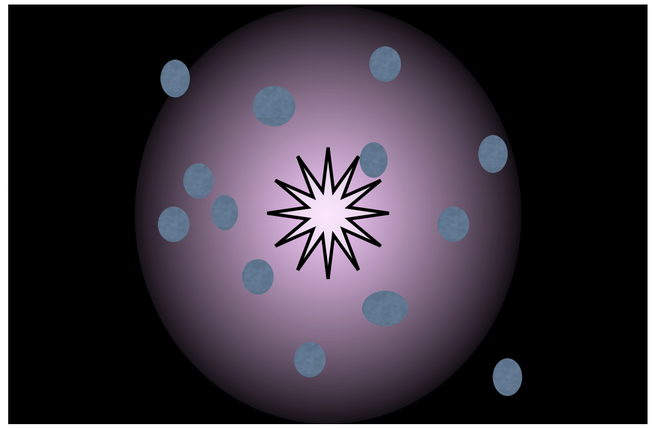
- Semi-analytical models
- Satellite SF stops at z_{reion}
- => sats = reionization fossils
- simplistic assumption:reionization uniform & instantaneous

Impact of local structure of UV field at reionization on MW satellite pop



External, uniform BG

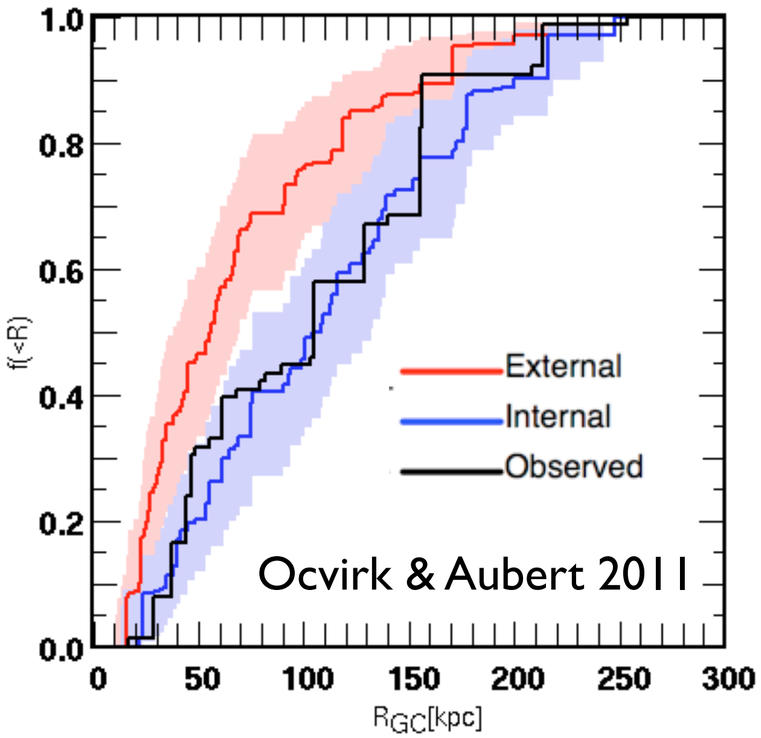




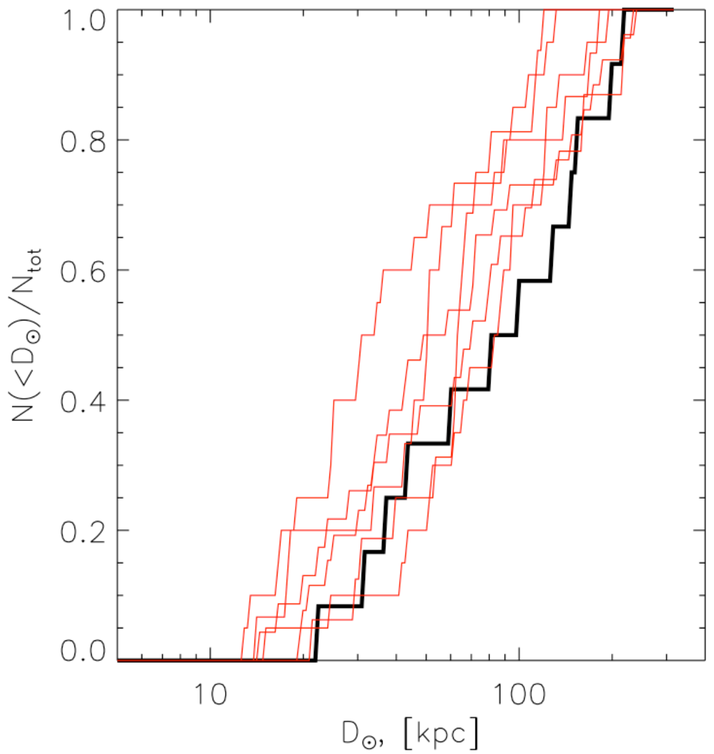
Internal, inside-out reionization

=> Signature of reionization geometry survives down to z=0

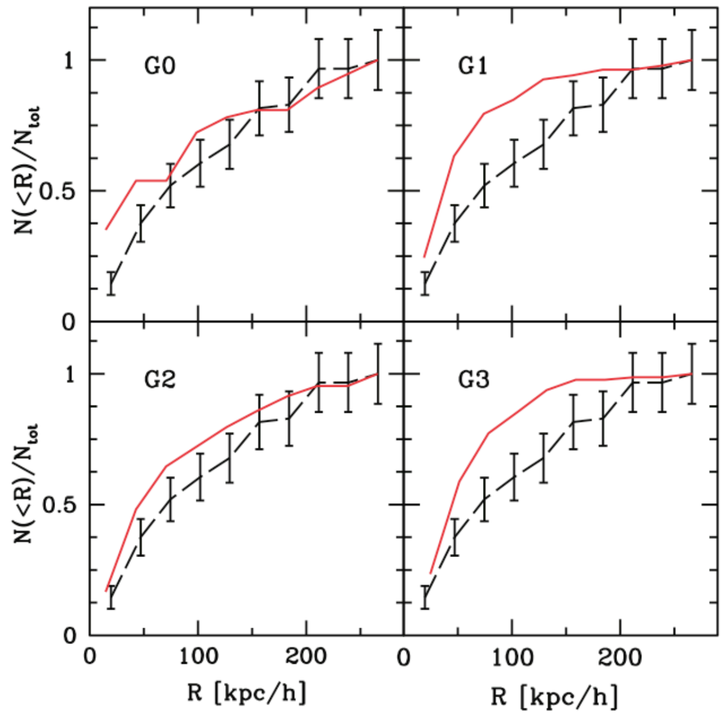
Comparing with literature



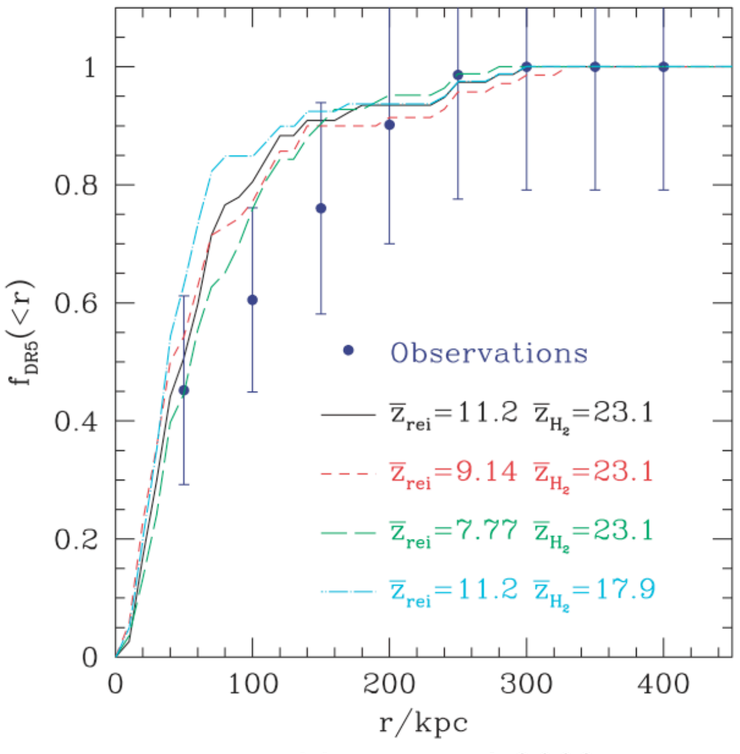
Ocvirk & Aubert 2011



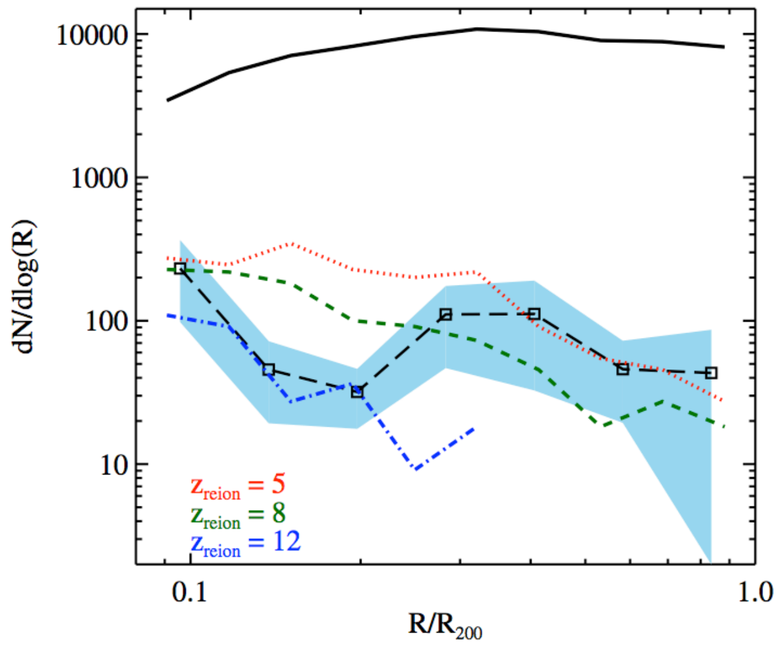
Koposov et al. 2009



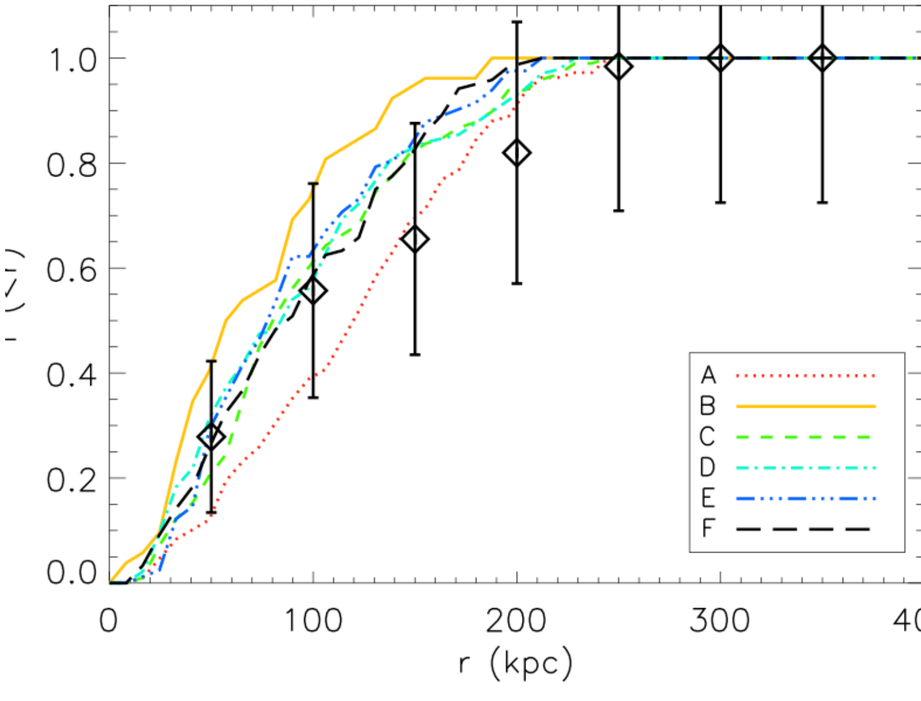
Maccio et al. 2010



Munoz et al. 2009



Busha et al. 2010



Lunnan et al. 2011, "self-consistent" reionisation

Beyond current crude SAMs

- Modelling assumptions: source multiplicity + geometry?
- Feedback on sources?
  - Inside haloes: self-regulation?
  - On halo environment: filaments / cold accretion ?
- Enough photons to reionize the whole Universe?
- Influence of environment?
  - Next big galaxy M31?
  - Other nearby massive gals? (ex. council of giants)
  - Nearby galaxy cluster? (ex.Virgo)

Improvement requires numerical simulations

- **coupled hydro-radiative galaxy formation code**
- **External radiative feedback => c = 1 !**
- **High mass resolution (to resolve all sources down to 10^7 $M_\odot$ haloes)**
- **High spatial resolution (LG gals progenitors) => dx~10-20 h^{-1} kpc**
- **Large volume (galaxy cluster + many LG examples) => L~ x10s Mpc**

=> big simulation

RAMSES-CUDATON

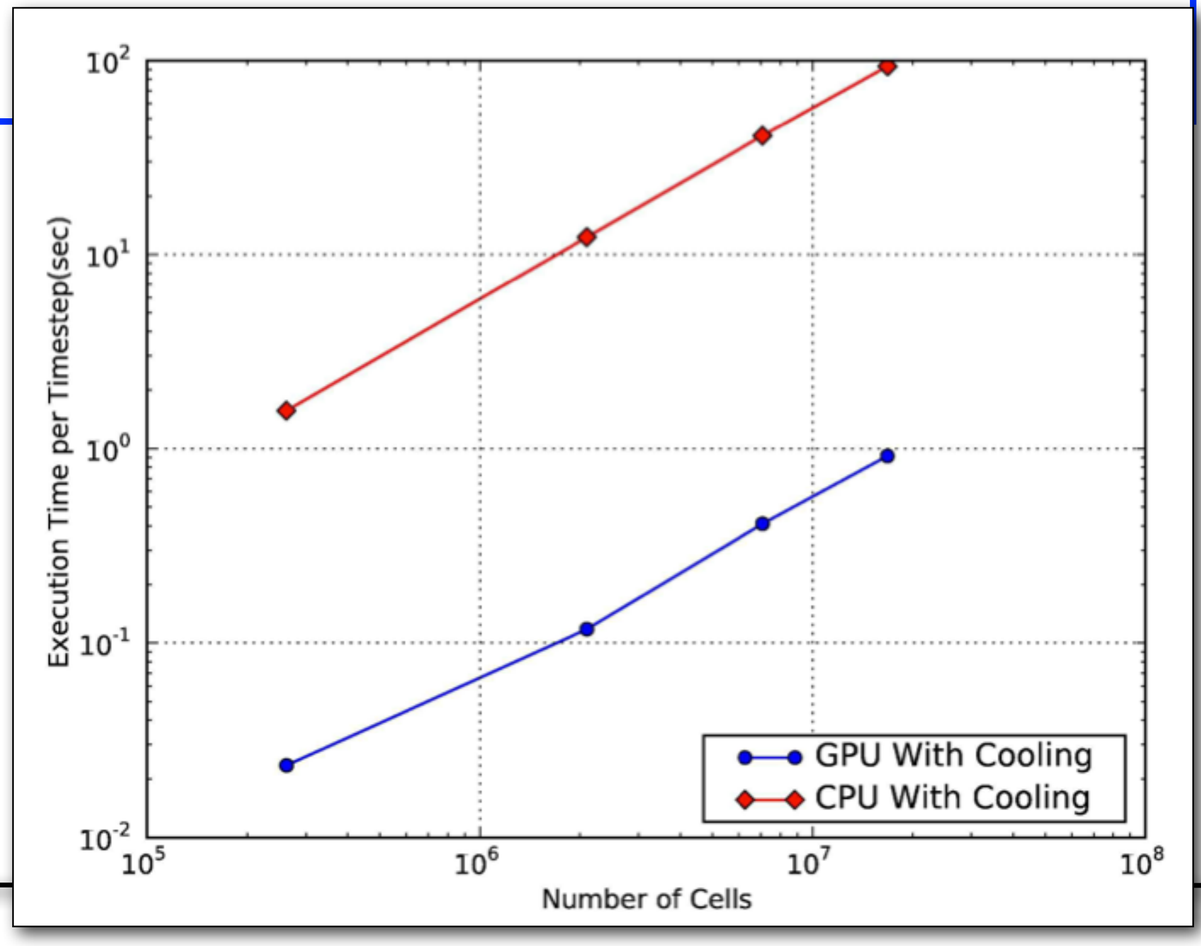
- RAMSES + ATON + CUDA
- **RAMSES** (Teyssier 2002): CPU
  - gravity (PM) + hydrodynamics
  - star formation + SN thermal + kinetic feedback
- **ATON** (Aubert 2008): UV Radiative Transfer, H only, 1 freq.
  - Radiative transfer on a grid
  - “photon soup” approximation (!= ray-tracing)
  - cpu cost INDEPENDENT of number of sources !!!
  - => excellent scalability
- **CUDATON** (T. Stranex, D. Aubert, R. Teyssier): ATON on GPU
  - speedup x80 :-)
  - c=1 :-)
  - but no AMR => unigrid :-(

RAMSES-**CUDA**TON

- For photons or gas flows on grid, max timestep is set by the Courant stability condition: $\Delta t < c\ \Delta x$
- => $\Delta t_{rad} \sim 0.01 - 0.001\ \Delta t_{hydro}$
- => node hours(RHD) ~ 100-1000 node hours (hydro) !!!
- 3 solutions:
  - slow light (c = c/100): not suitable for reionization studies
  - $\Delta x_{rad} \sim 10\ \Delta x_{hydro}$: proscribed (lose low mass sources + FB)
  - **GPU: x 80 speedup**

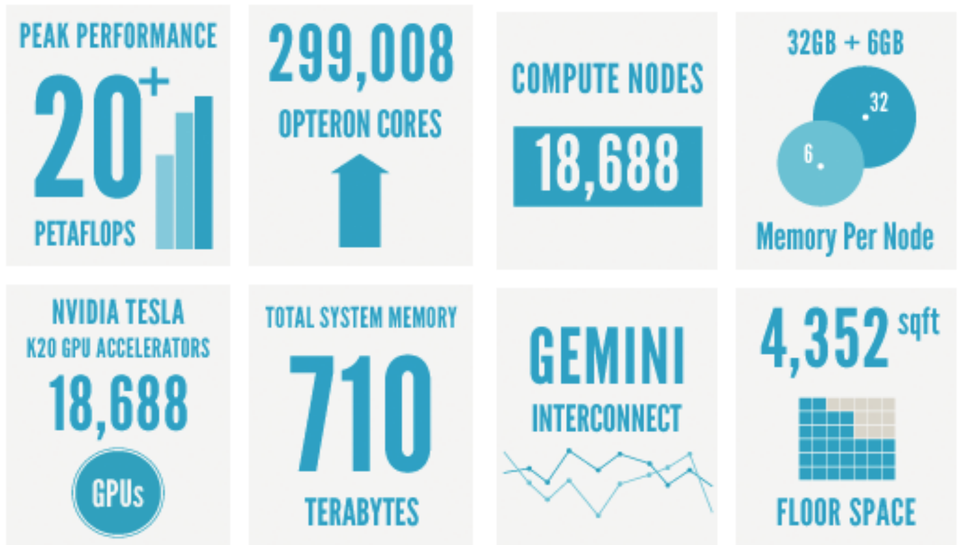
why x 80?

- CPU: 16 cores x 3 GHz = $24 . 10^9$ cycles/s
- GPU: 2000 cores x 1 GHz = $2000 . 10^9$ cycles/s

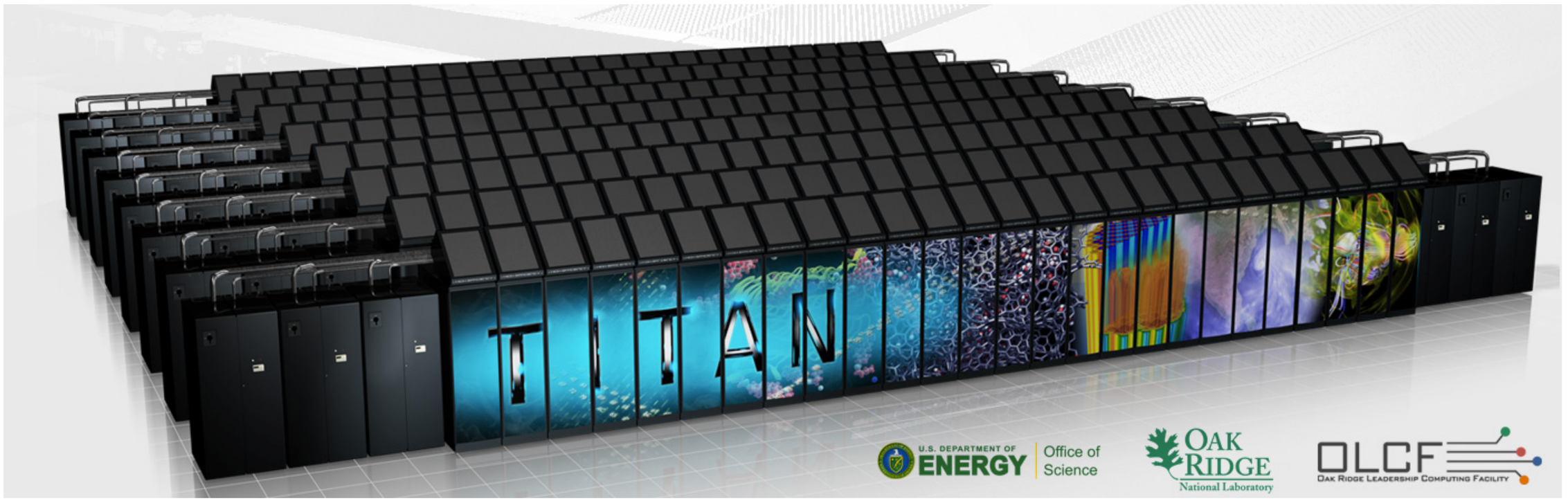


Aubert & Teyssier 2010

TITAN at Oak Ridge National Laboratory

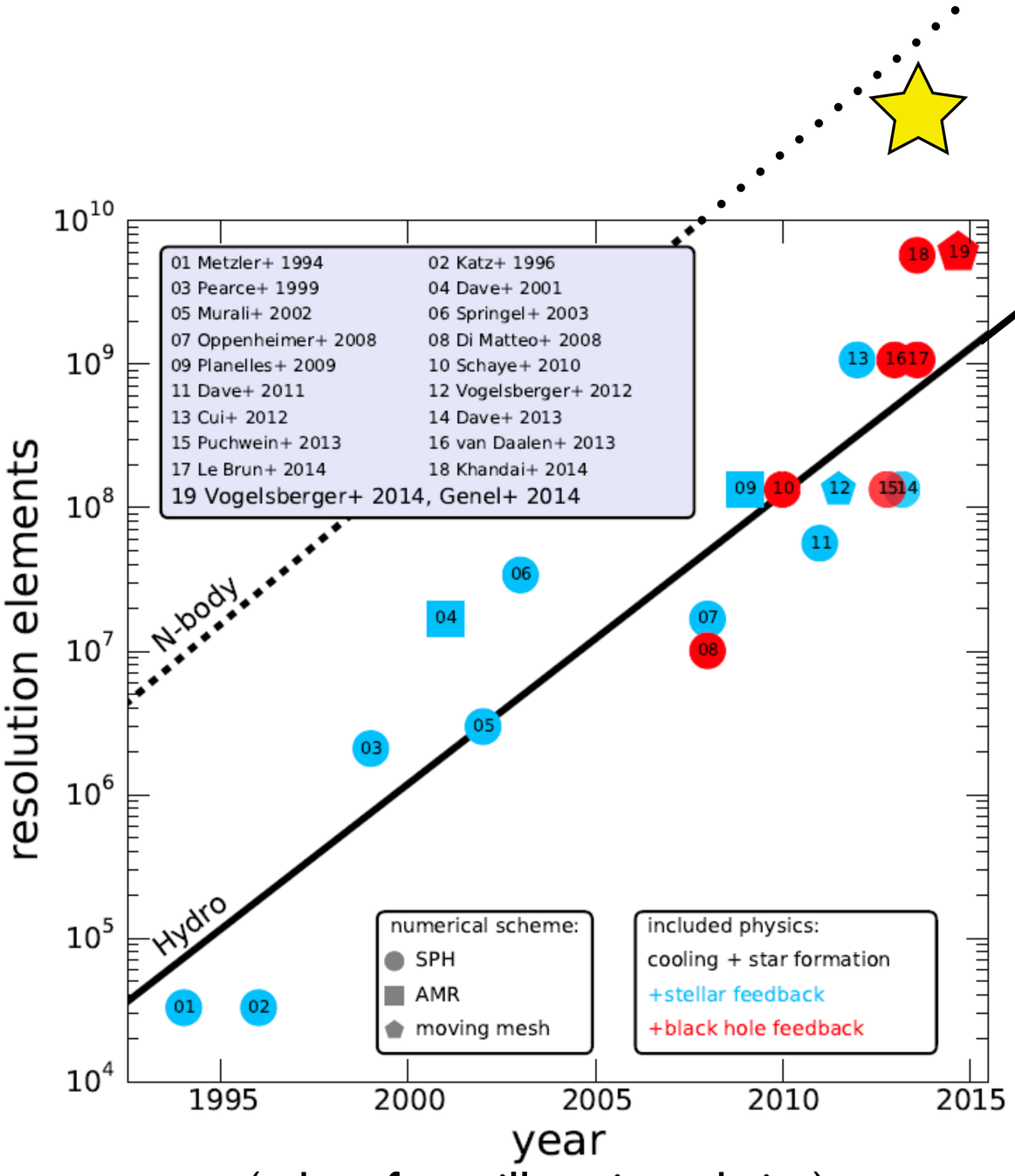


- 30-35 PB filesystem
- top 1 in 2013
- now top 2 (Tianhe - 2 is top 1)



The TITAN RAMSES-CUDATON simulation

- 64 h^{-1} Mpc side, 4096^3 grid, 4096^3 DM parts ($Mdm=3.5 \times 10^5 M_\odot$)
- => $\Delta x \sim 15\ h^{-1}$ kpc comoving, $\Delta x < 3$ kpc physical
- each domain is 128x256x256 cells (maxed out)
- => 8192 titan nodes (16 CPU + 1GPU per node)
- from z=300 to z=4.2, WMAP5 ICs provided by CLUES project[1]
- ~ 11 days => 2.15 million node hours, 2000 (+800 000) timesteps
- 138 snapshots (every 10 million years)
- 2 PB data=> reduced dataset: 100 TB
  - (cutouts HR + fullbox LR + halo fof catalogs, 13 million haloes, >200 million stars)



(taken from illustris website)

- ~60 LG analogs
- 100s of L* galaxies
- several groups, 1 galaxy cluster (Virgo analog)

4 h^{-1} Mpc

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- 100s of L* galaxies
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4 h^{-1} Mpc

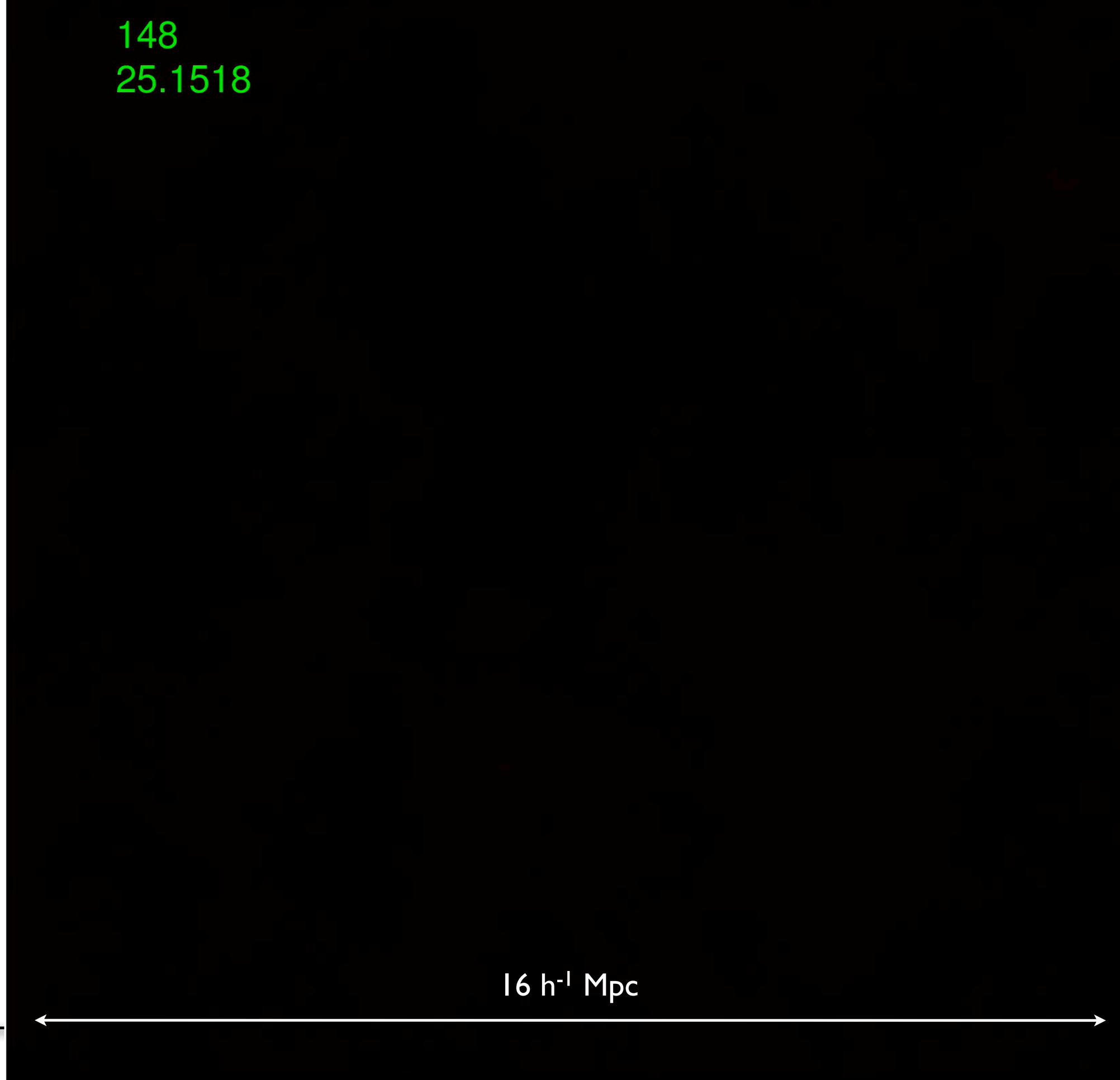
Temperature
6 Mpc thick slice

2
143.076

2 h^{-1} Mpc

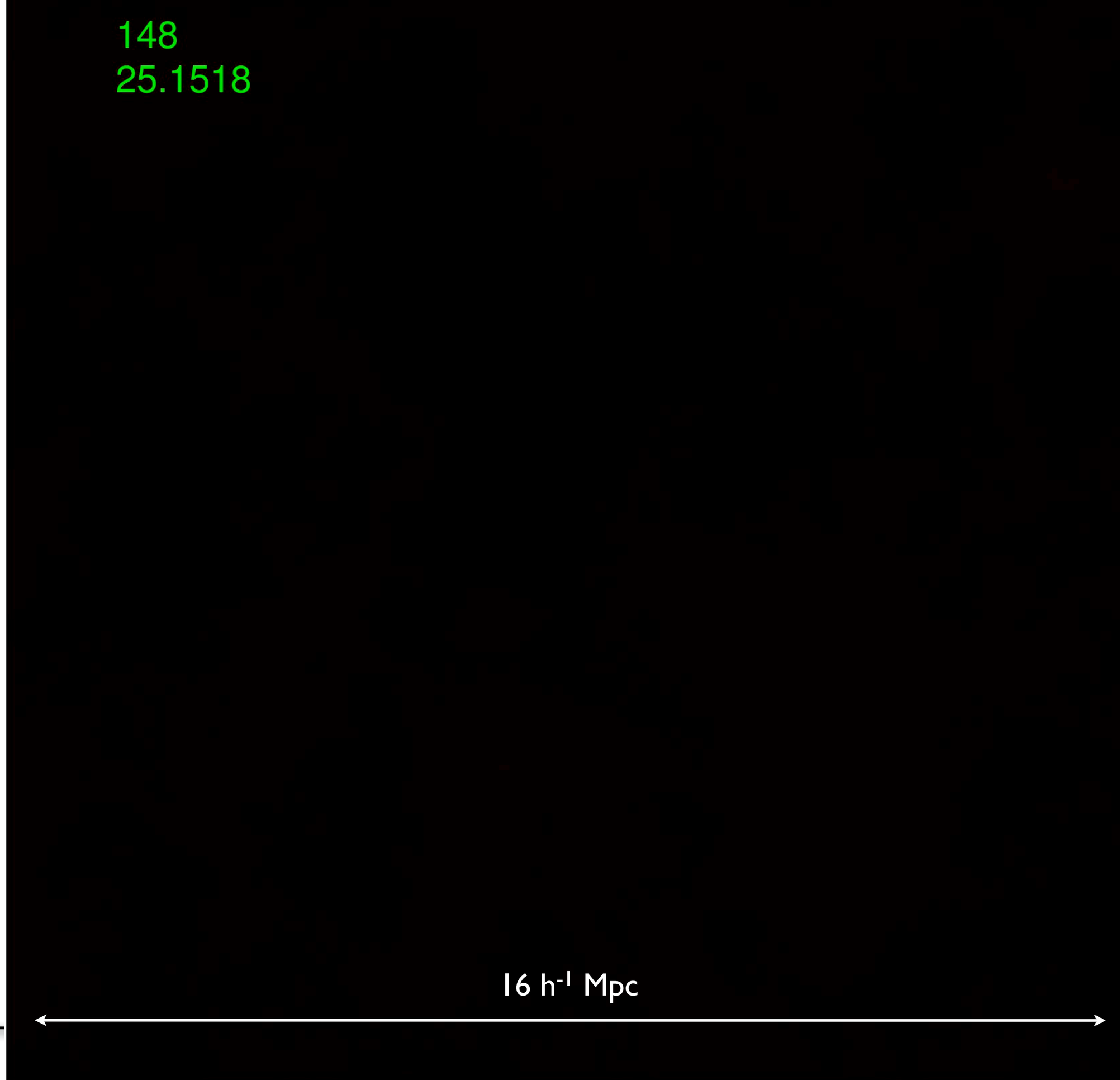
16 h^{-1} Mpc

UV photon density
6 Mpc thick slice



2 h^{-1} Mpc

UV photon density
6 Mpc thick slice



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UV photon density
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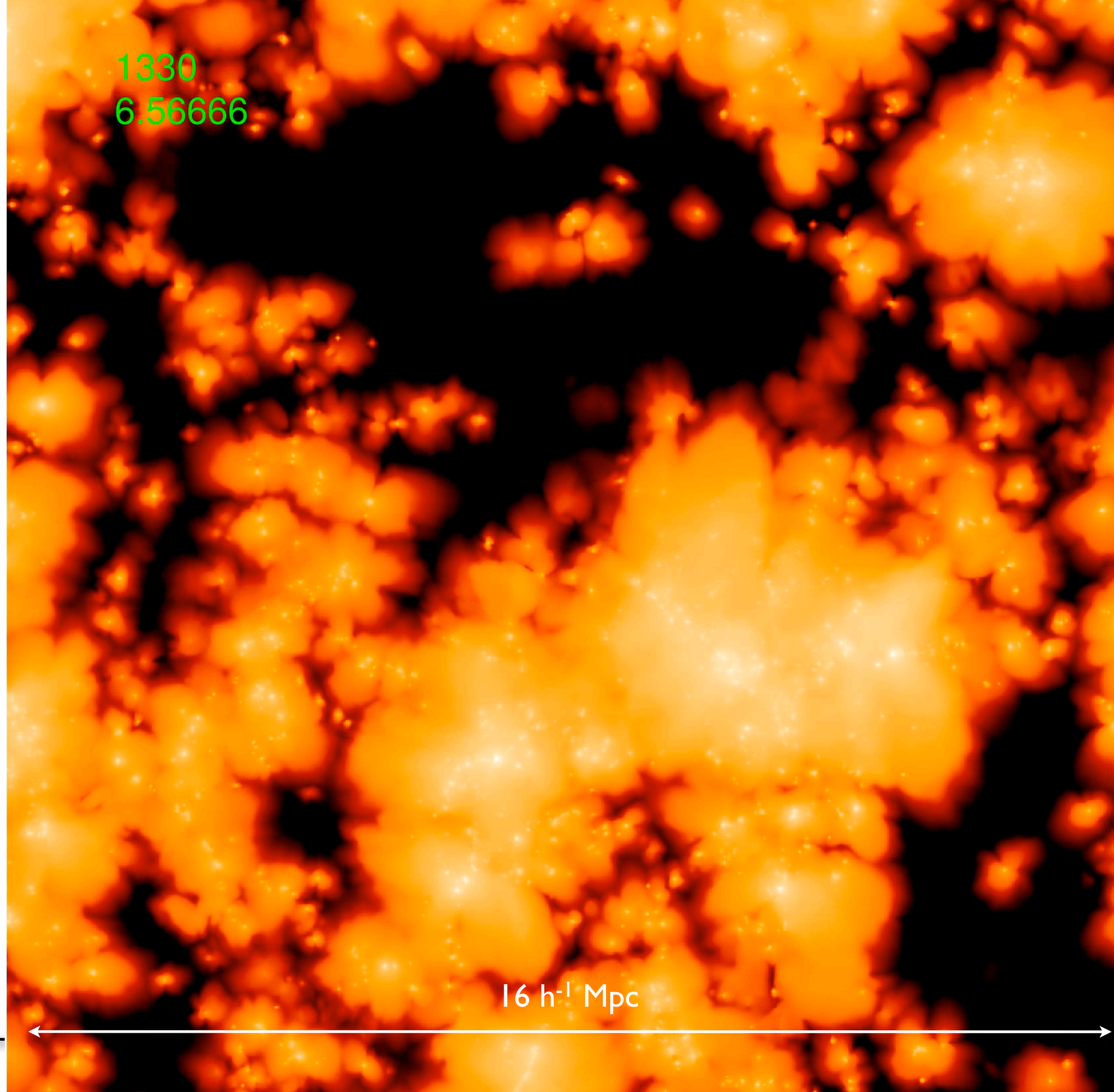

2 h^{-1} Mpc

Preliminary Conclusions I: Radiation and satellite populations

- $10^{8\text{-}9}$ $M_\odot$ haloes at z=3 will be ~$10^{8.5\text{-}9.5}$ $M_\odot$ at z_{acc} = 1
- SF suppressed at z_{reion}, result of UV radiation - matter coupling
- Lots of dark satellites: only 20% of 10^8 $M_\odot$ haloes have stars at z=4
- => very low stellar content ($10^{3\text{-}5}$ $M_\odot$), old stellar populations, high M/L,
- => good candidate progenitors for ultra-faint dwarfs and dark sats
- => Towards realistic satellite populations? => Missing satellites no more?
- Caveat: spatial resolution? cf. David Sullivan's talk

About the data

- original dataset: 64 h^{-1} Mpc side, 4096^3 grid, 4096^3 DM parts ($M_{dm}=3.5 \times 10^5 M_\odot$), 2PB, 138 snaps, >13 Million haloes at z=4.2
- => $\Delta x \sim 15\ h^{-1}$ kpc comoving, $\Delta x < 3$ kpc physical
- reduced dataset:
  - fullbox: rhogas, rhodm, rhophot, T, xion, vxyz on 2048 grid
  - fullbox: fof halo cats, all star particles (xyz,mass,age)
  - cutouts (493): 4 Mpc regions
    - same as fullbox but at full res (4096) + all DM particles
  - at OLCF: ~100 PB
- Transferred datasets:
  - TACC (Texas): everything
  - Potsdam (geras/erebos): ~ 2/3 of dataset, transfer finished
  - Strasbourg (buffy): ~2/3 of dataset, still copying
- Discussion for projects open within CLUES

Project status

- First INCITE Simulation finished in late 2013
- Processing on OLCF clusters still ongoing (re-running FOFs)
- (will require update of the datasets at TACC, Potsdam, Strasbourg)
- processing allocation until august 31st, extended to november 1st
- After that, data-only access
- Archiving of the reduced dataset at OLCF.
- new INCITE proposal submitted for a run in 2015 with:
  - RAMSES-CUDATON updated physics (e.g. chemical enrichment)
  - EMMA (Aubert et al. 2014, in prep)
- PRACE runs with RAMSES-CUDATON and RAMSES-RT (cf David Sullivan & Ilian Iliev).