Cosmic Dawn (CoDa): Radiation-hydrodynamics of galaxy formation during the EoR

Ocvirk+2015: arxiv:1511.00011

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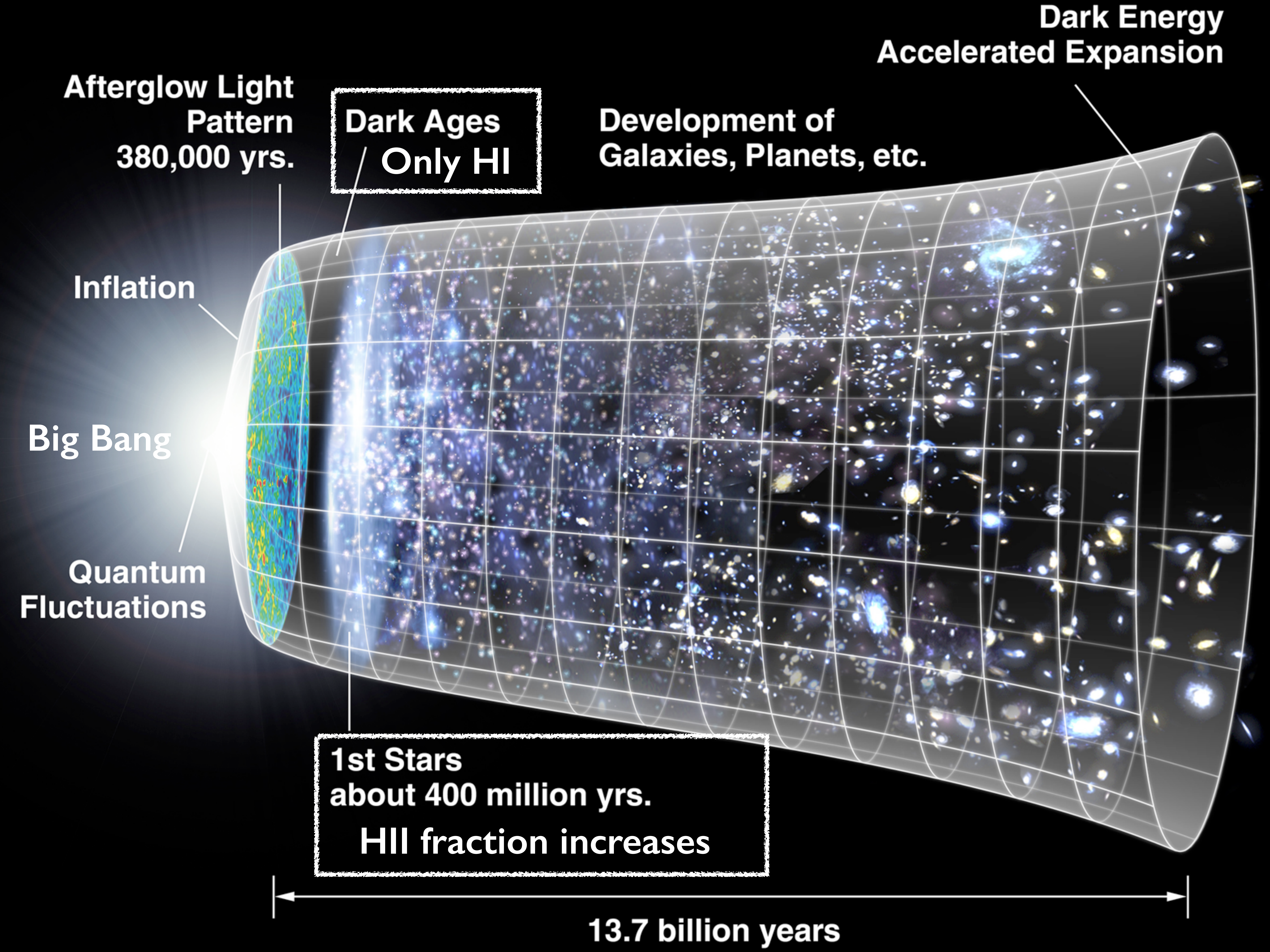
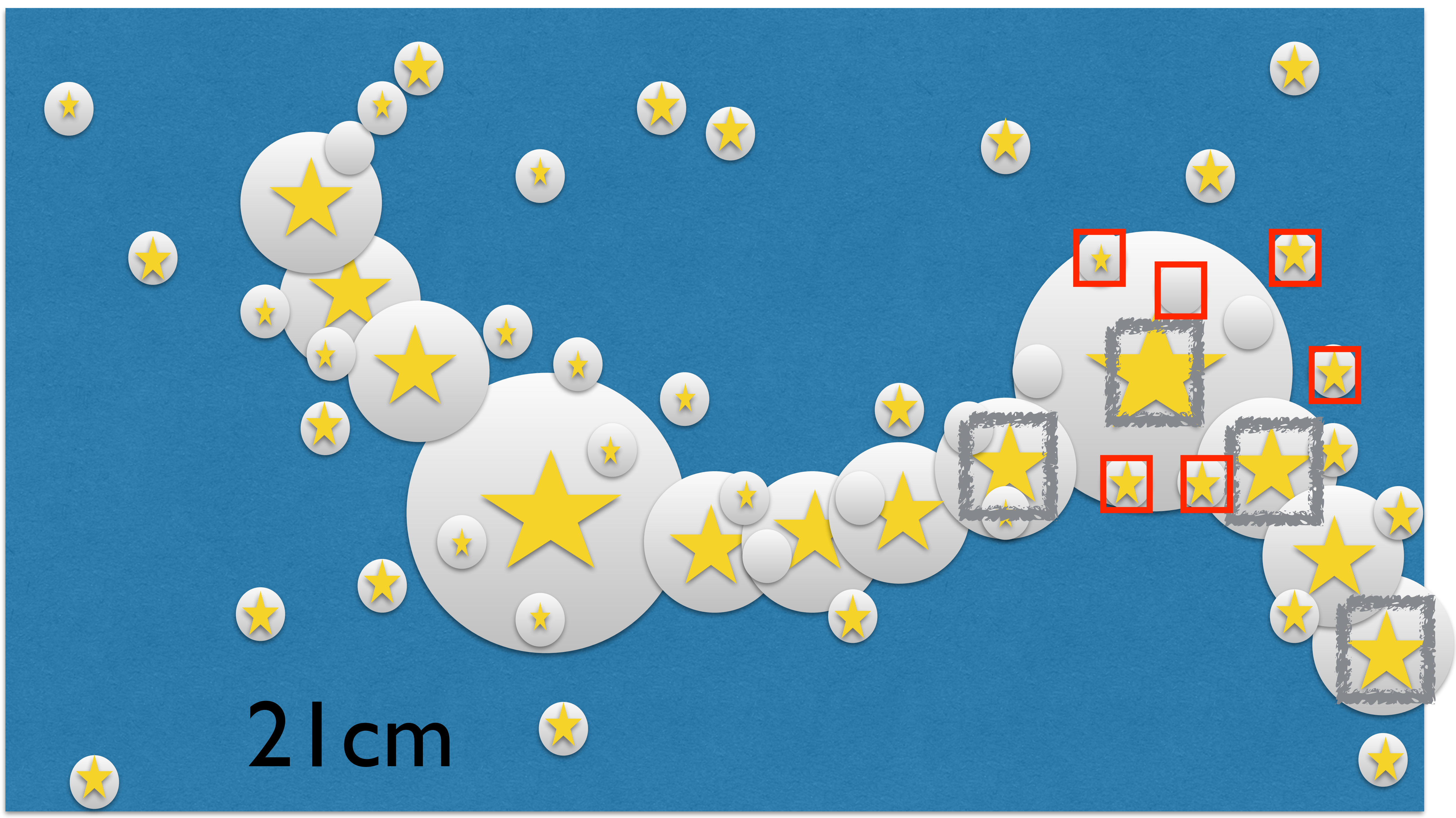
cnrs



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Only HI
Development of
Galaxies, Planets, etc.
Inflation
Big Bang
Quantum
Fluctuations
1st Stars
about 400 million yrs.
HII fraction increases
13.7 billion years

The Epoch of Reionization: the next frontier

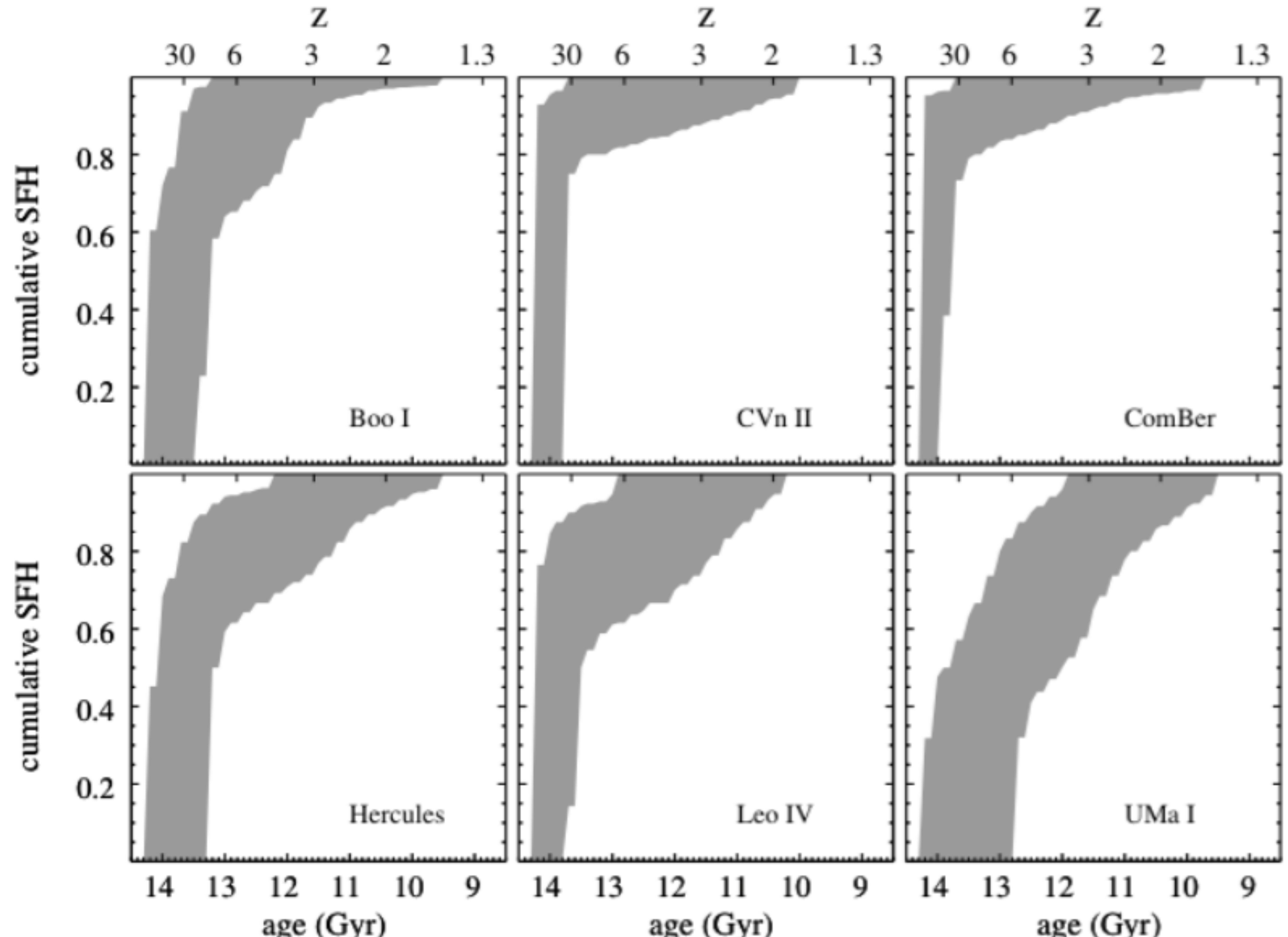


LSST
2019

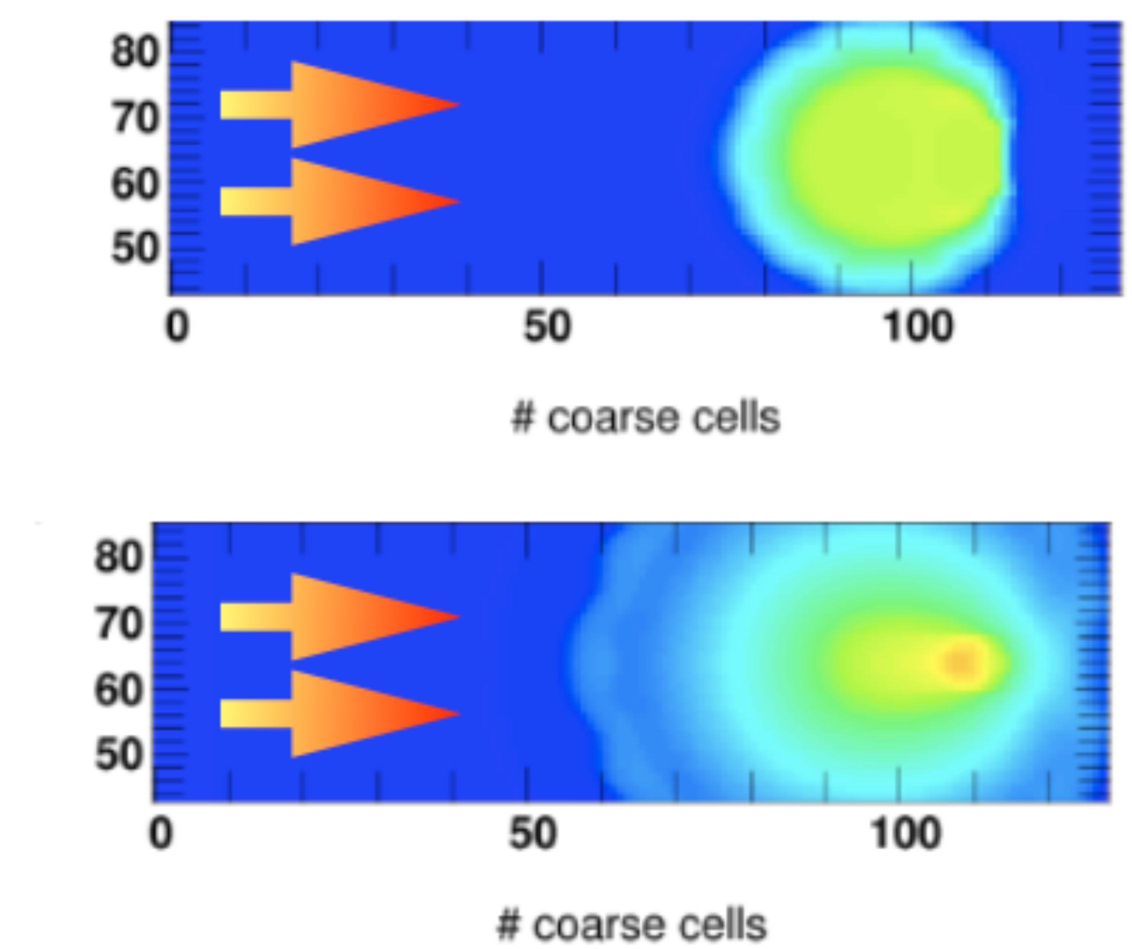
SKA
2020+

JWST
2018

The UV background as an external FB-I



Brown et al. 2014



Aubert et al., 2015

- The majority of stars are formed at z>6 (before reionization ends)
- => Catastrophic photo-evaporation of low mass haloes ($M<10^8\ M_\odot$)
- => UV background impacts star formation efficiency

Cosmic Dawn (CoDa) goals: Reionization and its feedback

- RADIATIVE FEEDBACK on sources?
  - INTERNAL (inside haloes): self-regulation?
  - On IGM: filaments / cold accretion ?
  - EXTERNAL/Environment effect?
    - Nearby large galaxy?
    - Other nearby massive gals? (ex. council of giants)
    - Nearby galaxy cluster?
- Connexion to low mass satellites properties? (missing sats, planes of sats?)

COUPLED RADIATION-HYDRODYNAMICS

HIGH MASS RESOLUTION

LARGE VOLUME

Coupled Radiation-hydro with RAMSES-CUDATON

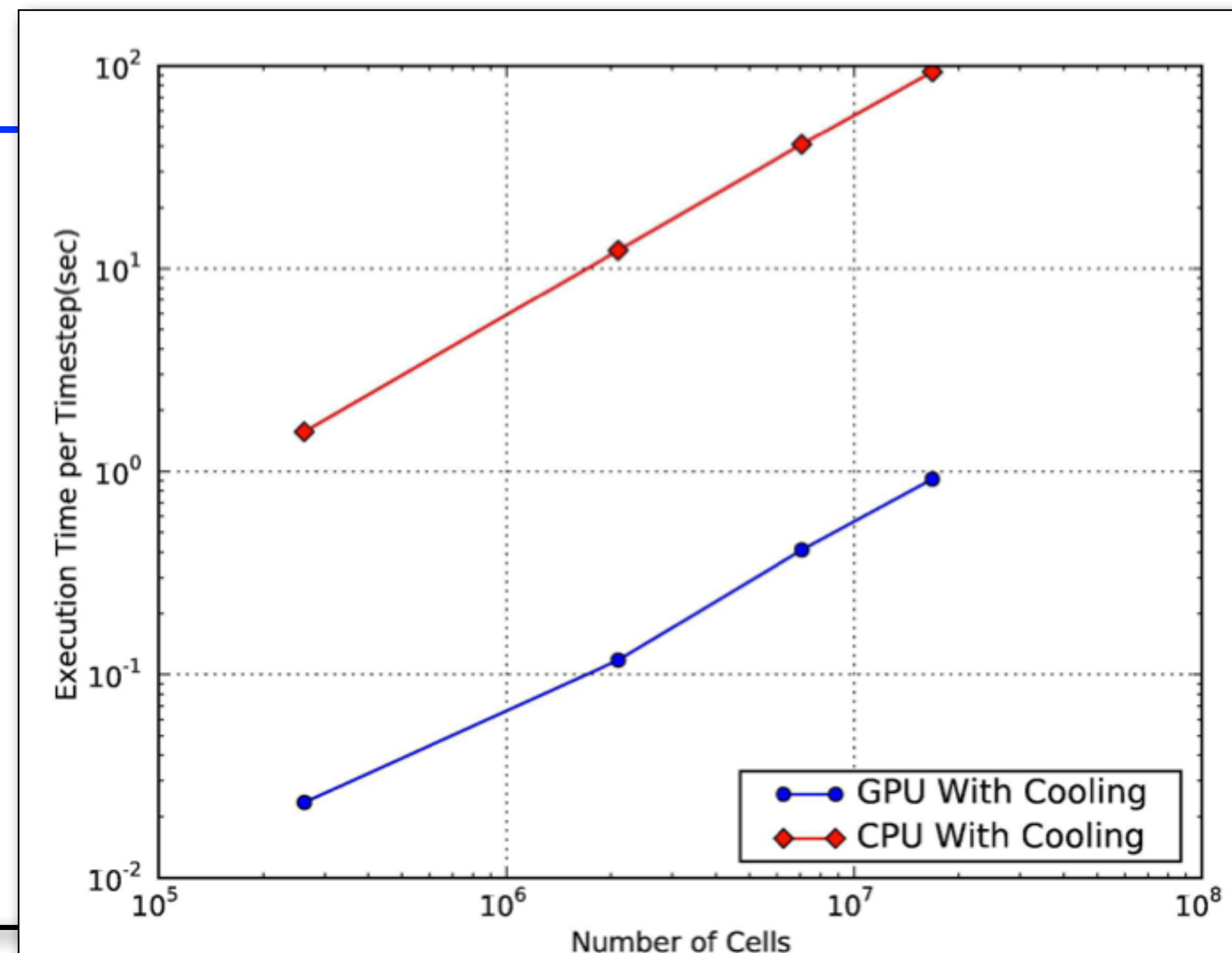
- **RAMSES** (Teyssier 2002): **CPU**
  - gravity (PM) + hydrodynamics (
  - star formation + SN thermal + kinetic feedback

T, x_{HI}, Λ ↑   ↓ T, ρ, stars

- **ATON** (Aubert 2008): UV Radiative Transfer,
  - UV photons propagation
  - Hydrogen ionization
  - Photo-heating + cooling

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**



Aubert & Teyssier 2010

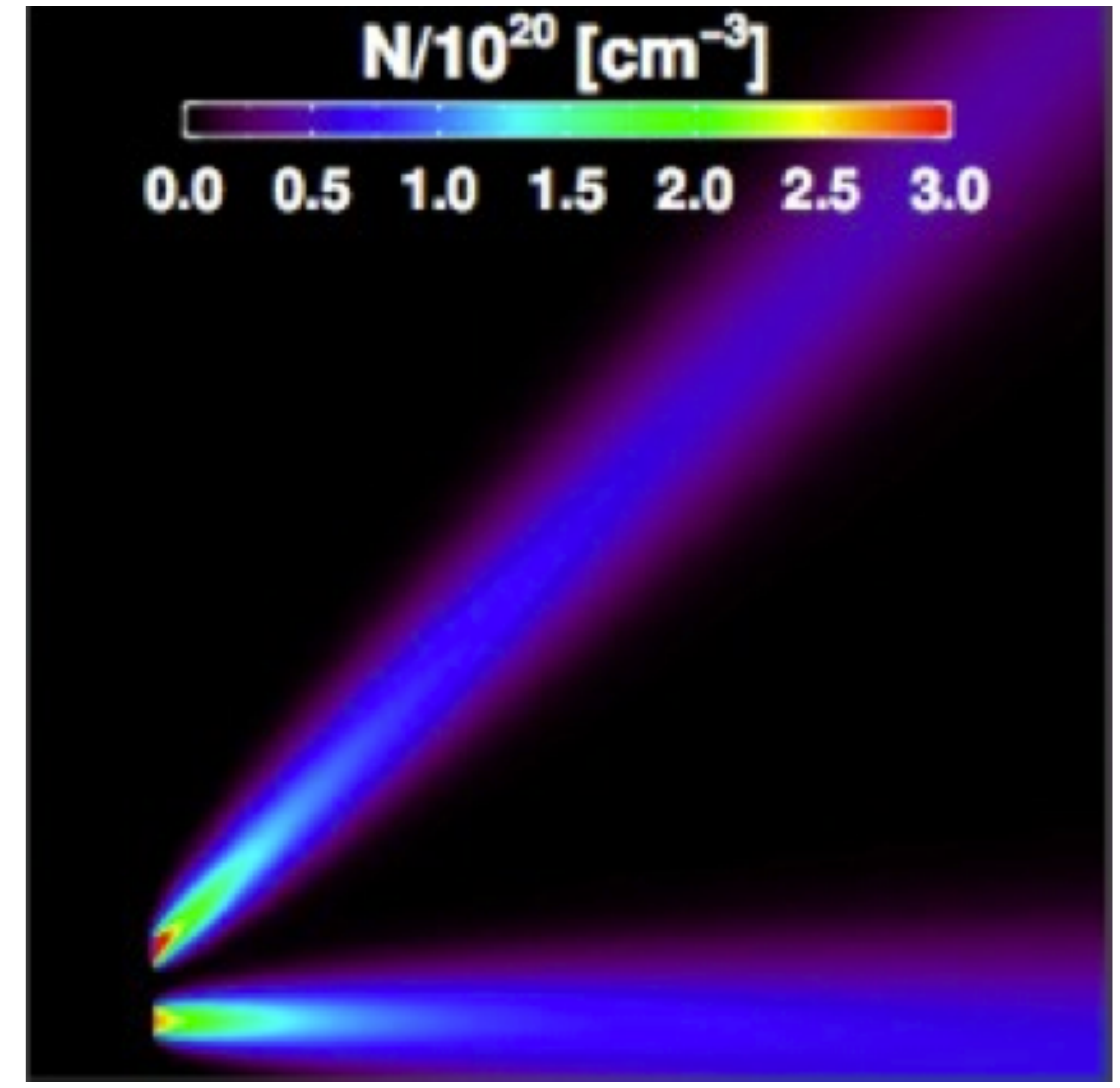
RAMSES-CUD**ATON**

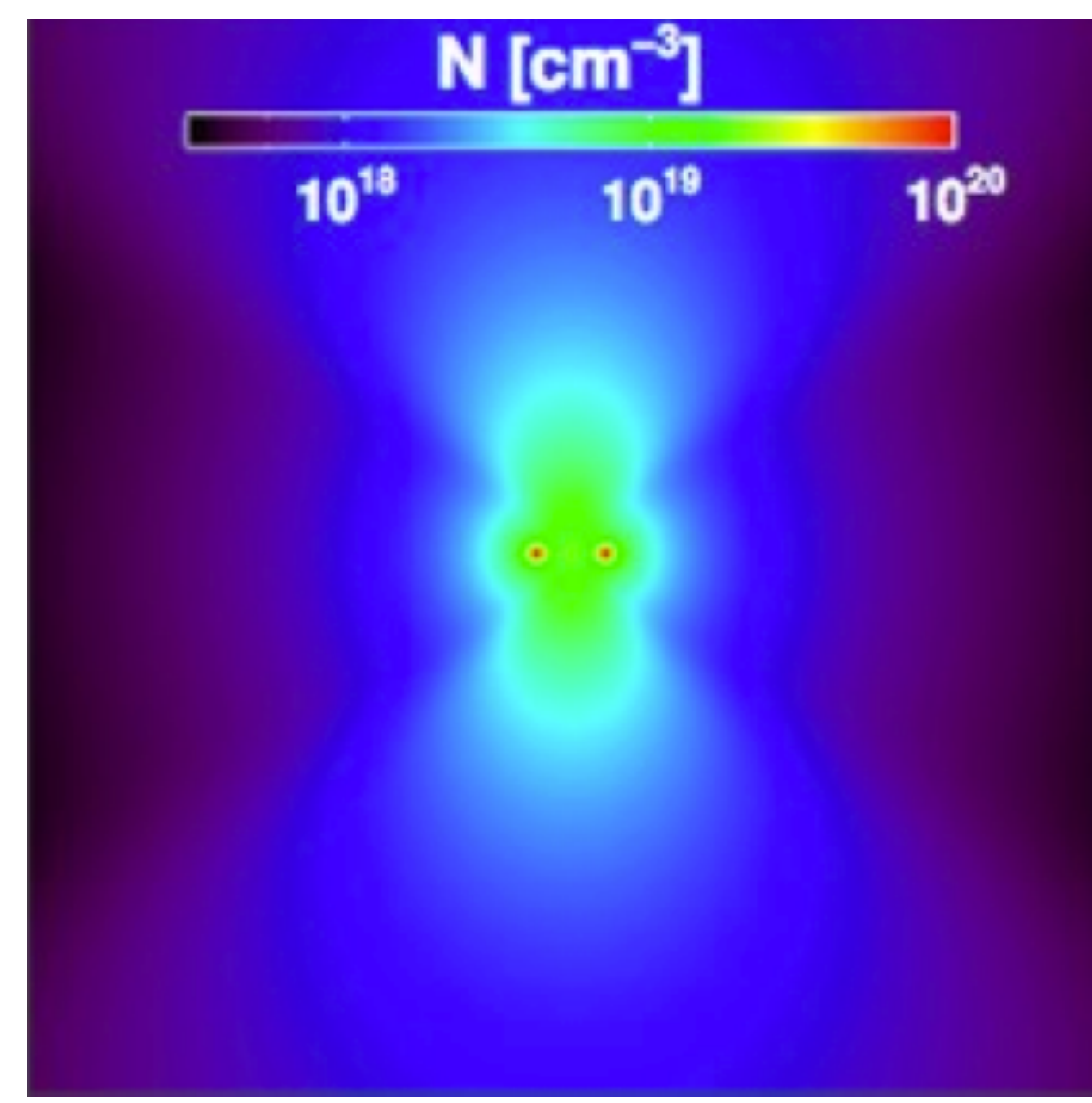
- ATON (Aubert & Teyssier 2008)
- Radiative transfer on a grid
- != ray-tracing
- “photon soup” approximation
- M1 closure relation (Levermore 1984) sets diffusiveness vs directionality

CON:
- in general, diffusive scheme
- photons interact / can not cross

PRO:
- 100% local (unlike ray-tracing)
- arbitrary number of sources
- Easy management of boundary conditions

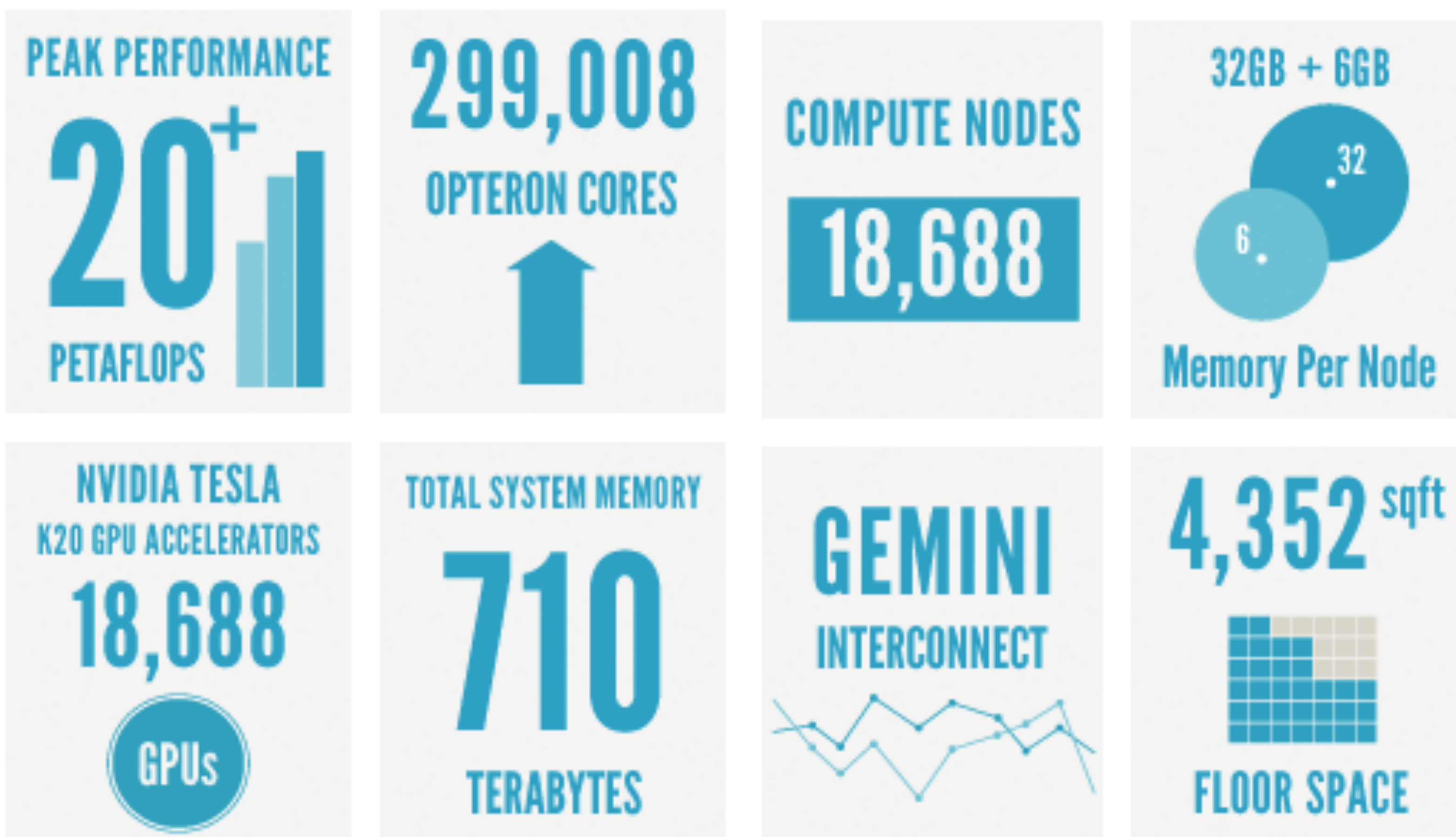
=> Excellent parallelism / scalability



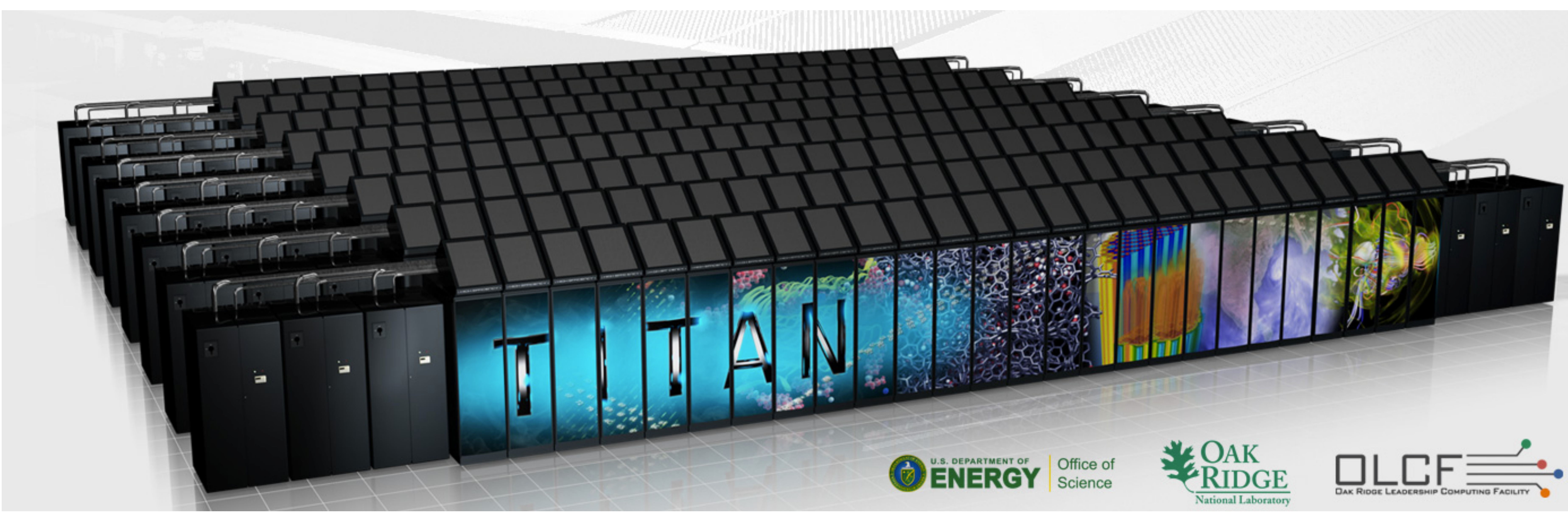


Rosdahl et al. 2013

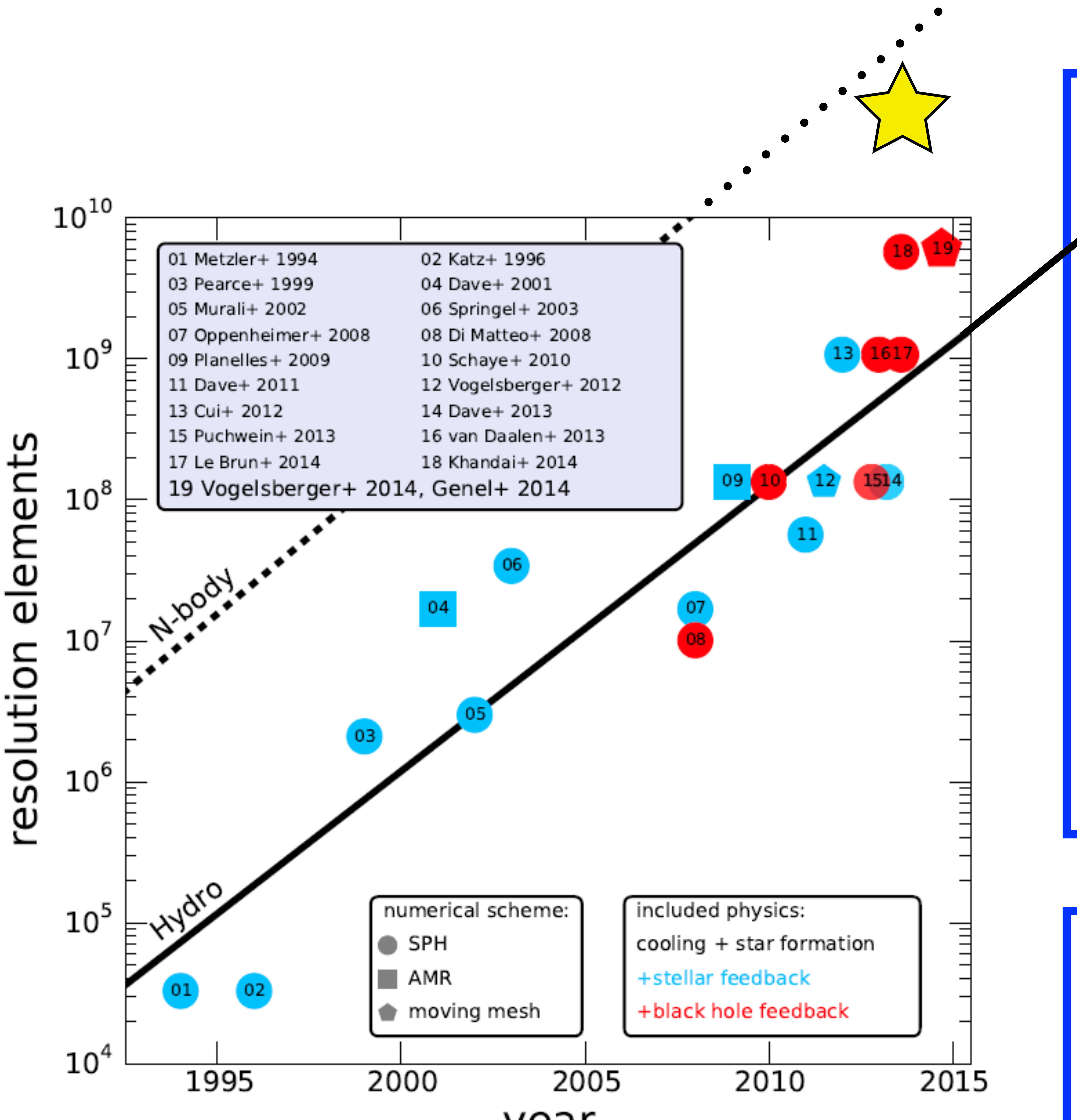
TITAN at Oak Ridge National Laboratory



- 18,688 GPUs
- 30-35 PB filesystem
- top 2 (top 1 = Tianhe)



Setup: Cosmic Dawn specs



(taken from illustris website)

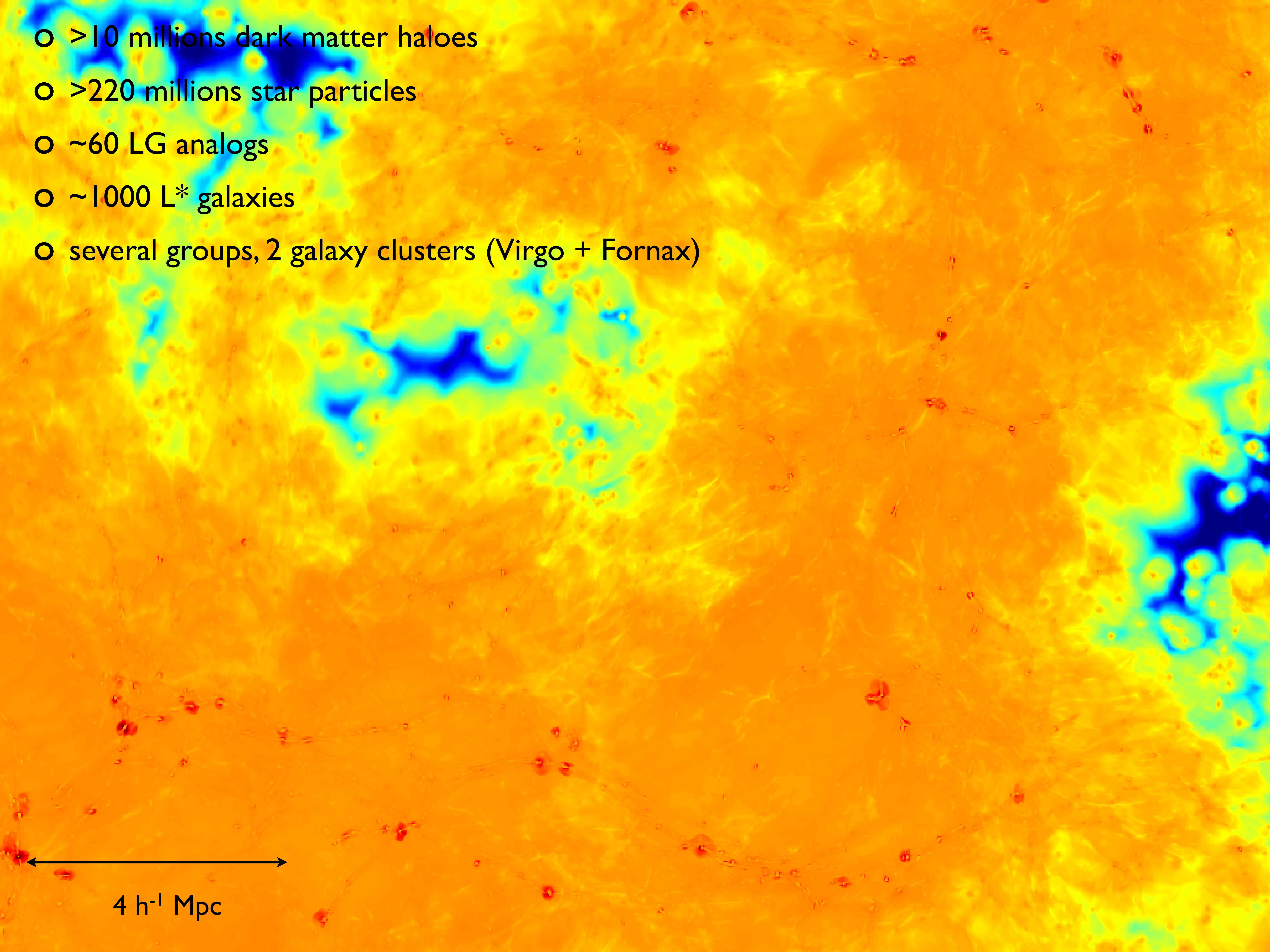
- 8192 GPUs
- 64 h^{-1} Mpc side, 4096^3 grid
- $Mhalo_{min} \sim 1 \times 10^8 M_\odot$
- $\Delta x \sim 15\ h^{-1}$ kpc comoving (< 3 kpc physical)
- $z_{end}=4.2$
- ~ 11 days runtime, 2 PB data

- => CoDa intermediate between large, low res (Iliev et al.) and small, very high res (Wise, Trebitsch, Rosdahl)

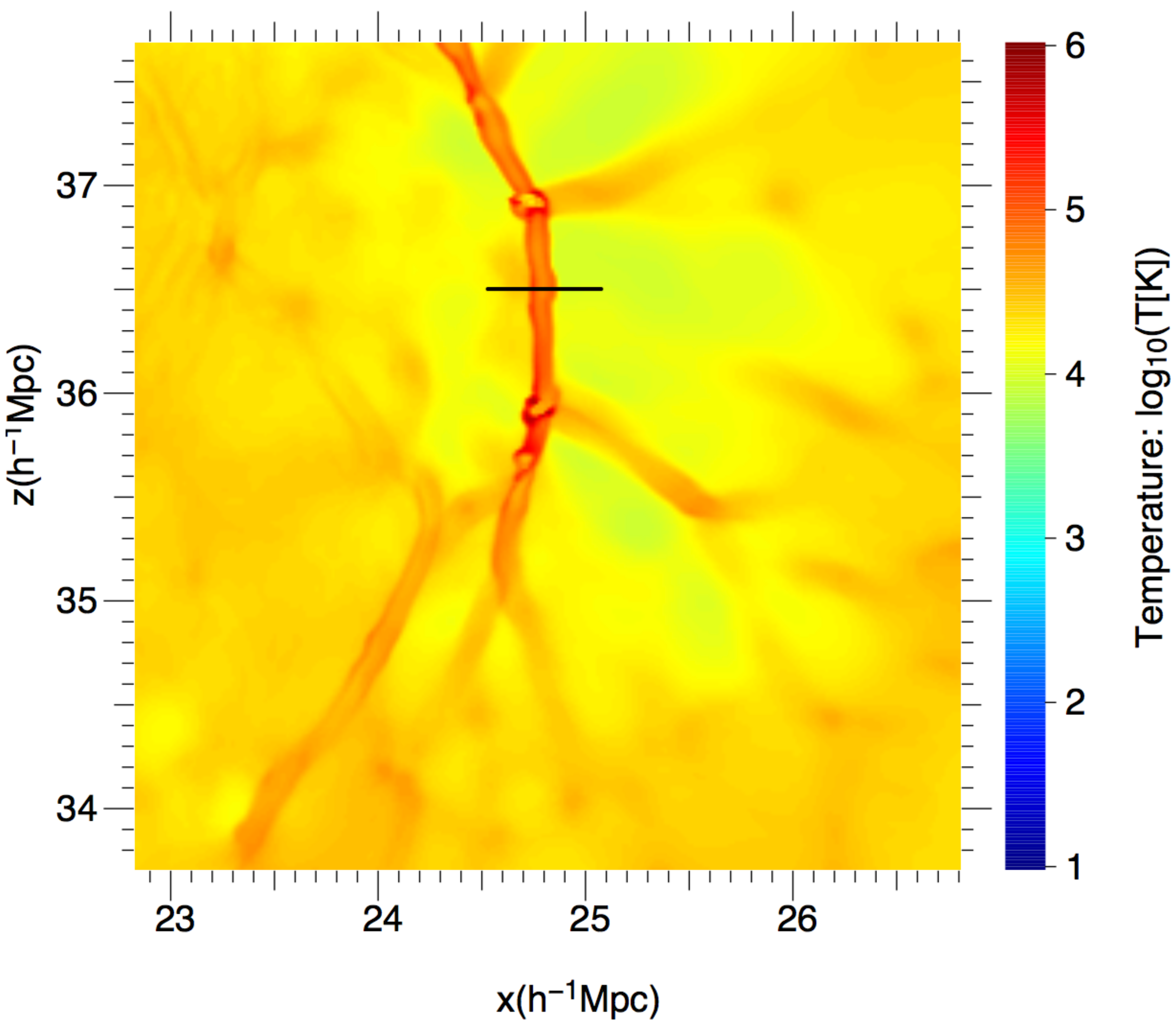
Technical aspects

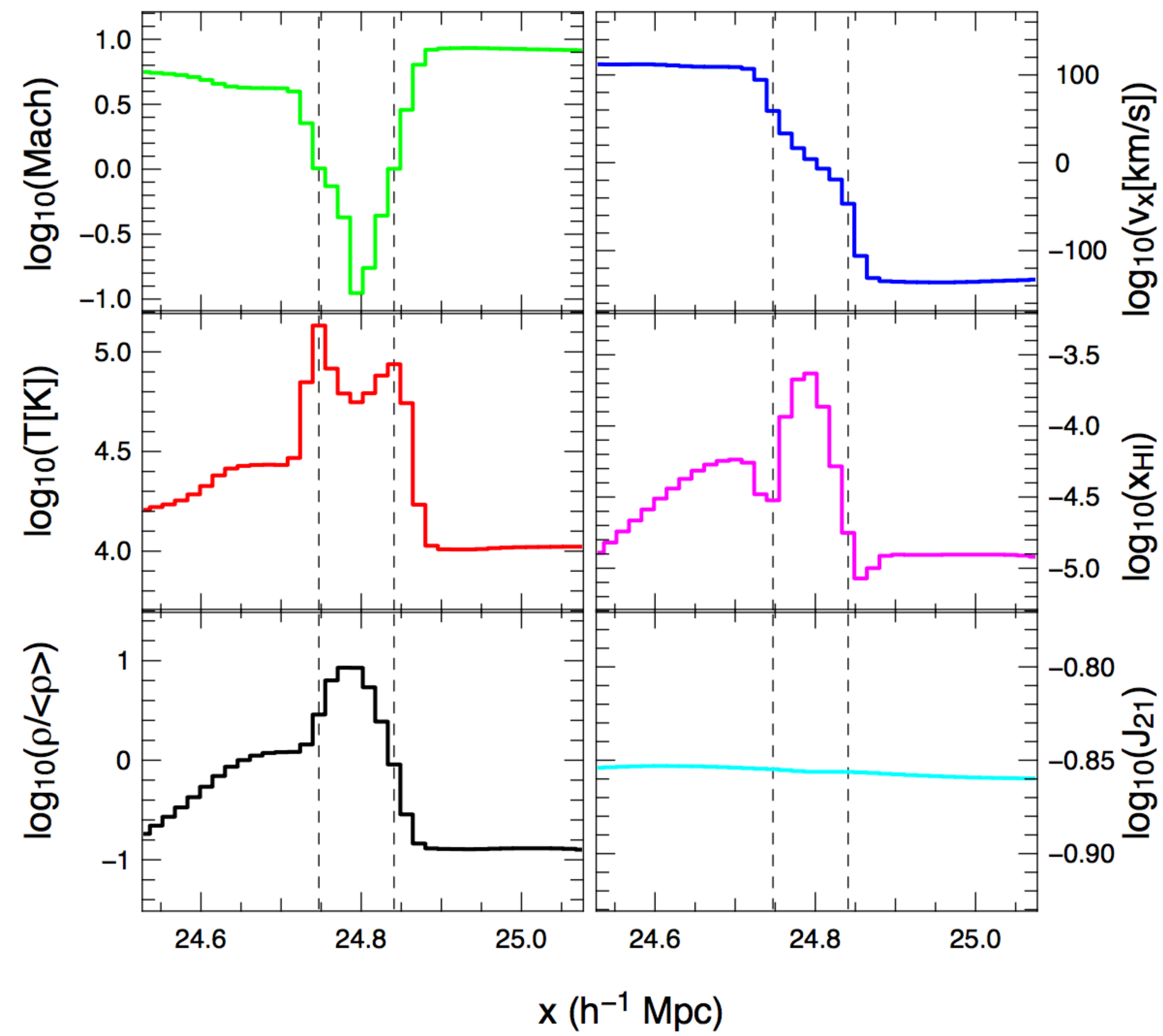
- GPUs are awesome for brute force computations
- but not very flexible (yet) (=>AMR loss)
- Load balancing still a problem
- Output very large (138 snaps = 2PB) => reduced data
- Basic analysis/processing requires ~ 10 % of allocated time
  - => auxiliary clusters (2x~500 nodes (16 cores))
  - ON SITE
- Analysis at home institute also requires development of dedicated tools e.g. DM halo <=> stars association

- >10 millions dark matter haloes
- >220 millions star particles
- ~60 LG analogs
- ~1000 L* galaxies
- several groups, 2 galaxy clusters (Virgo + Fornax)



Accretion shocks on filaments

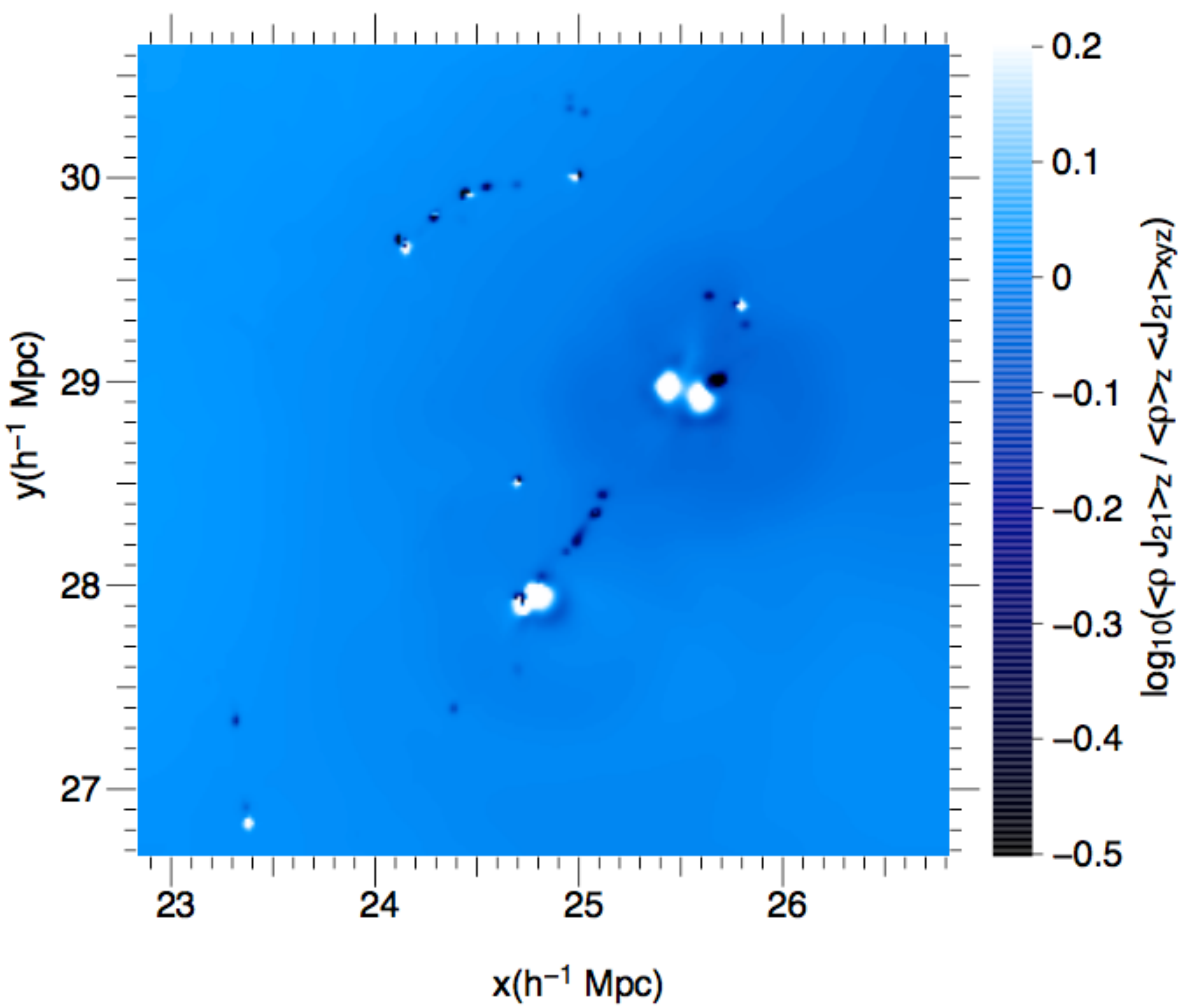


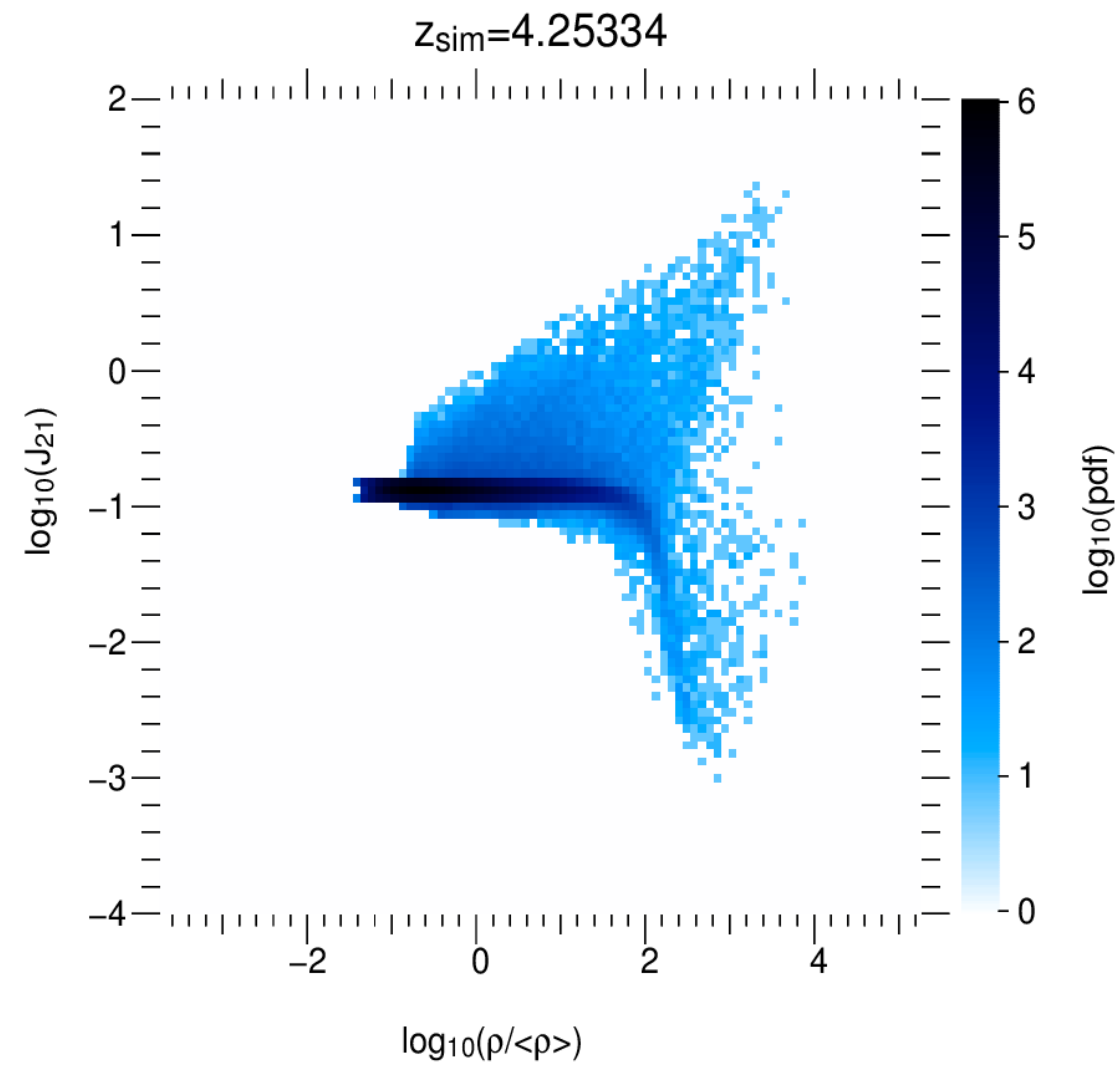


- Double-peaked, tube-like temperature profile of gas filaments
- Supersonic => subsonic deceleration
- => Signature of accretion shock (cf Ocvirk et al. 2008, Dekel et al.)

Radiative self-shielding

UV photon density

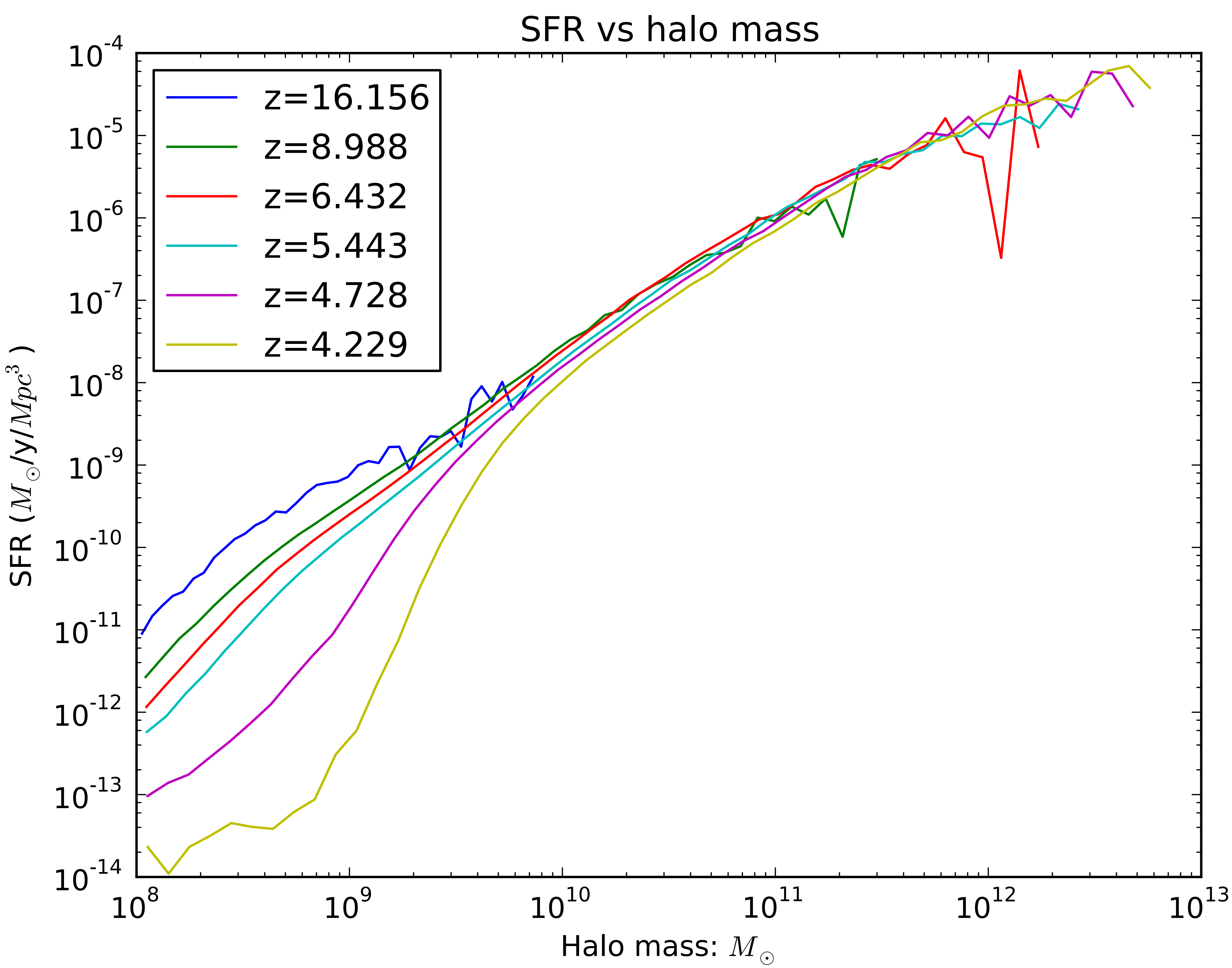




- Quasi-uniform UV background after reionization for $\rho/\langle\rho\rangle < 100$
- Branching at high density (haloes):
- Shielded vs nearby source, fast switching between states

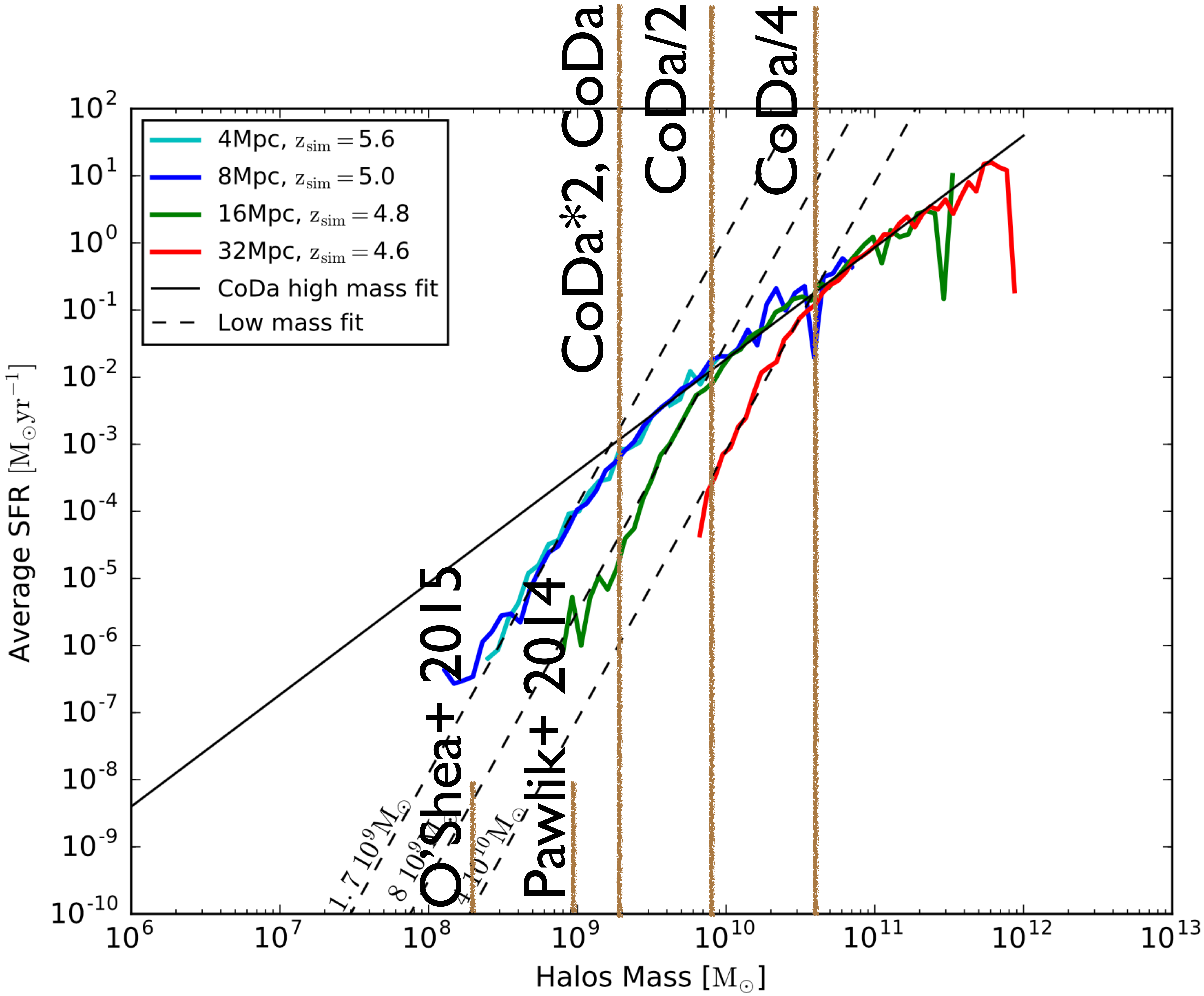
UV photon density
6 Mpc thick slice

Cosmic Dawn
Global SFR vs (M,z)



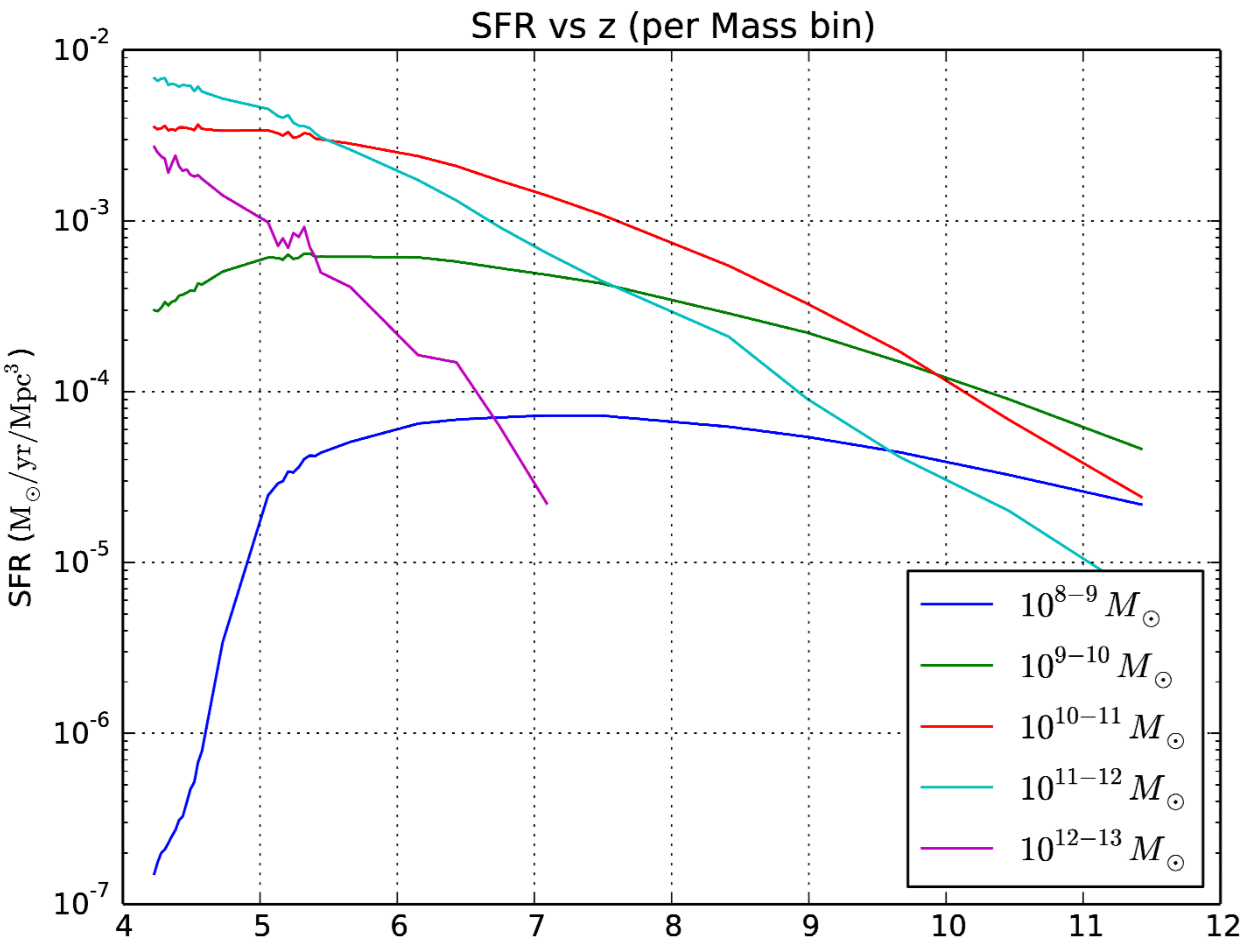
- SFR α $M^{5/3}$
- slow decrease at intermediate mass
- at z~5-4: SFR drops at low M: radiative feedback
- High mass haloes unaffected
- transition is smooth

Suppression mass and resolution



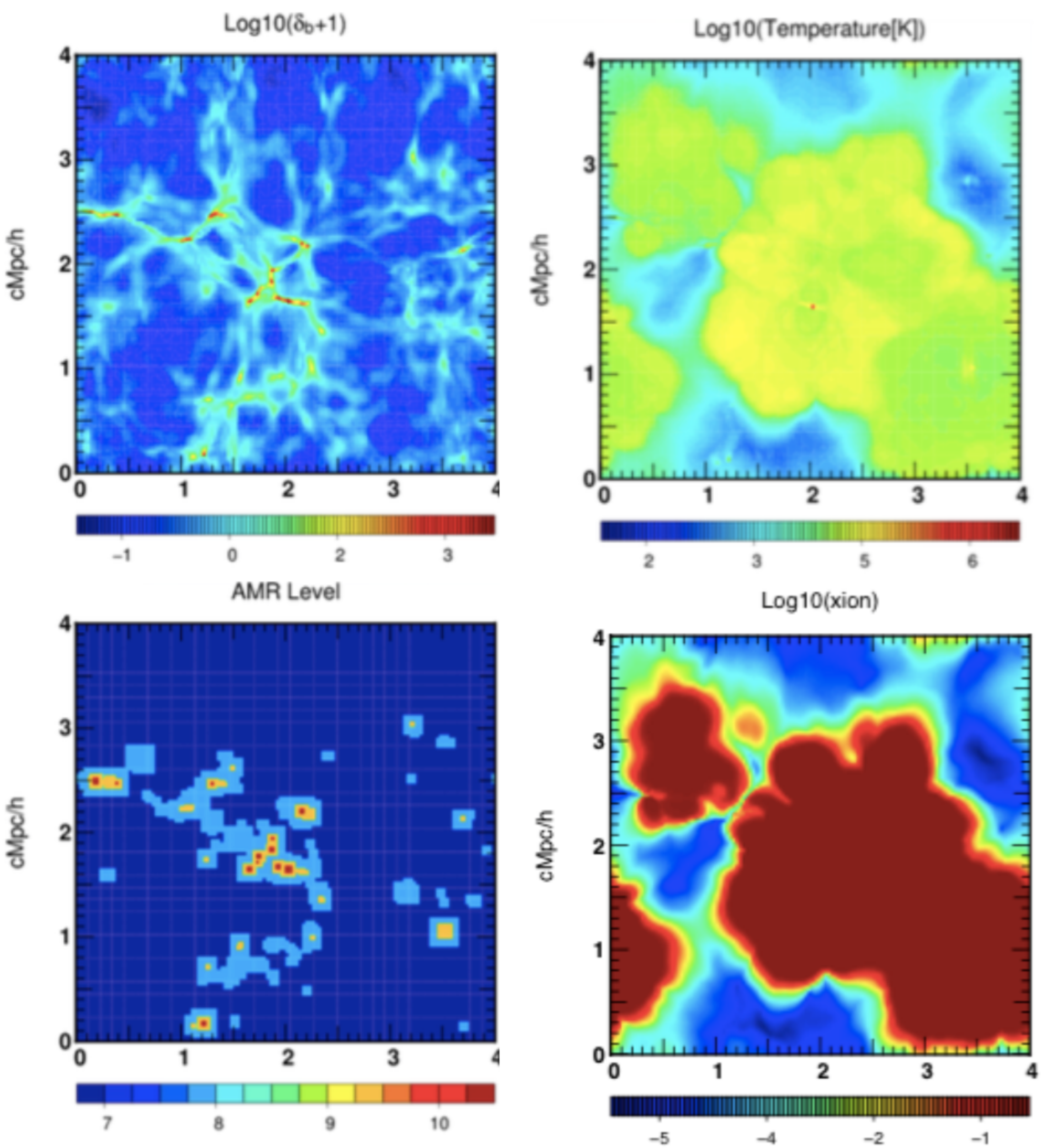
- Suppression mass increases when degrading resolution.
- But increasing CoDa res by 2 has no impact.
- O'Shea 2015: very HR
- Pawlik 2014: R~CoDa
- Gnedin?
- But completely different numerical methods / physics: metals, dust, UV +LW background, H_2 cooling

Cosmic Dawn Contribution to global SFR



- Low mass haloes never dominate
- very high mass haloes ramp up quickly but appear late
- $10^{10}\,M_\odot$ haloes dominate
- but what about f_{esc} ?

AMR Cosmological RT with **EMMA**

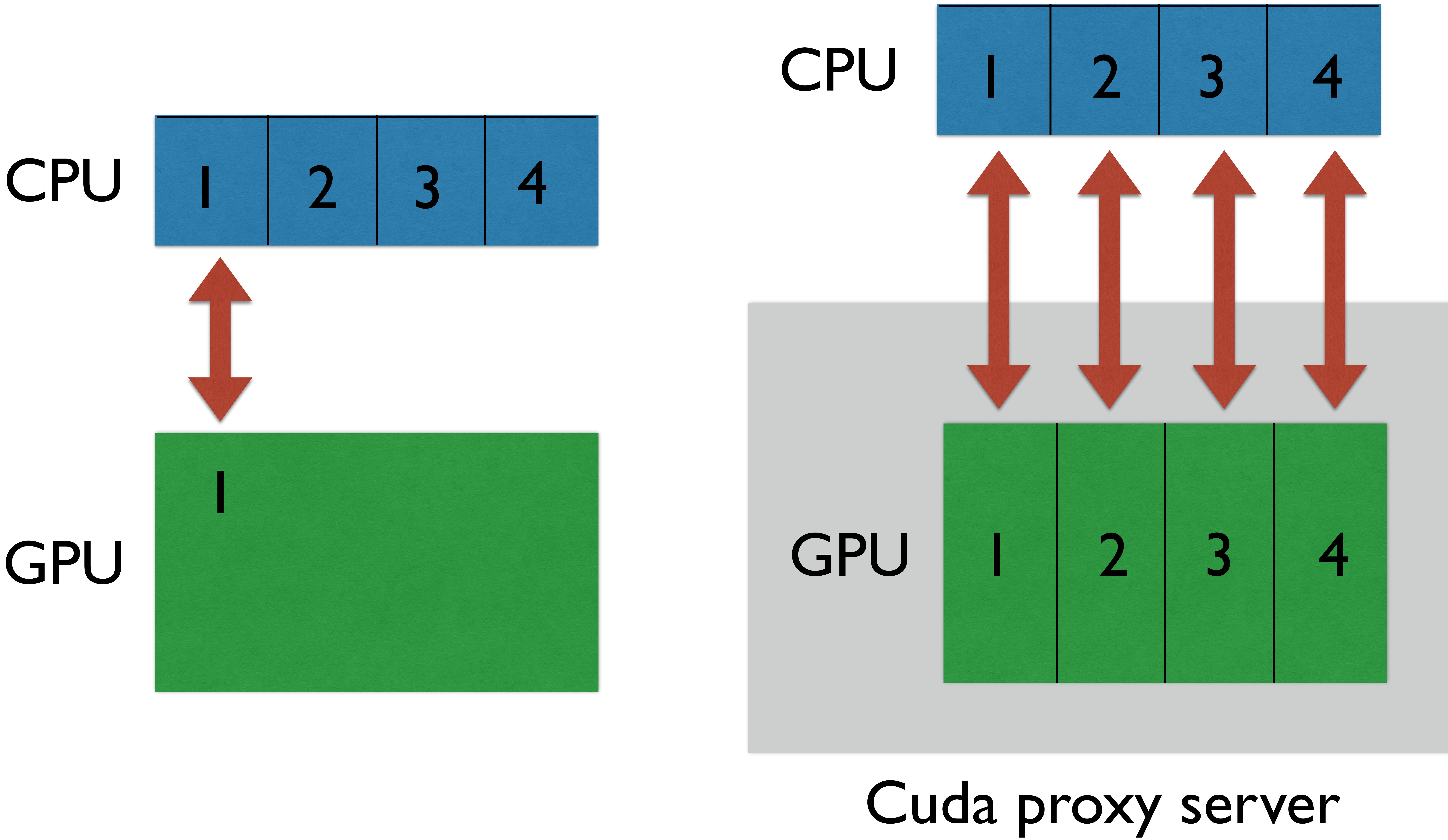


4 Mpc - 128^3 + 5 AMR levels

- **E**lectromagnétisme et **M**écanique sur **M**aille **A**daptative
- Full **standalone** cosmological code
- Collisionless Dynamics (PM)+ Hydro (MUSCL) +RT(M1)
- Full **AMR** radiative transport (like e.g. Ramses-RT (Rosdahl et al. 2013)) or restricted to the Coarse grid with thermo-chemistry on refined levels
- Star Formation + SN Feedback
- C+MPI Parallelisation (scales up to 2048 cores and 1024^3 coarse cells)
- **Optional GPU** (CUDA) acceleration for the Poisson , Hydro and RT solver

Aubert, Deparis & Ocvirk, MNRAS 2015 (in press), arXiv 1508.07888

Cuda proxy server



SUMMARY

- **Cosmic Dawn (CoDa)** is the largest GPU-driven self-consistent simulation of the EoR ever made.
- CoDa reproduces current observational constraints at z>6: x_{HI}, J_{21}, SFR, τ_{CMB}, UV LF, reasonable UV escape fractions
- Radiative feedback?
  - CoDa: M <10^9 $M_\odot$ haloes have suppressed SF
  - but no convergence between groups: resolution, physics?

- Future work: CoDa II: improve physics: chemical enrichment + dust, AGNs?
- EMMA (Aubert+2015) => CoDa with AMR (N. Deparis' talk)
- Taking advantage of the Cuda Proxy Server => more efficient