The Cosmic Dawn simulation project
Galaxy formation during the Epoch of Reionization

Ocvirk+2018

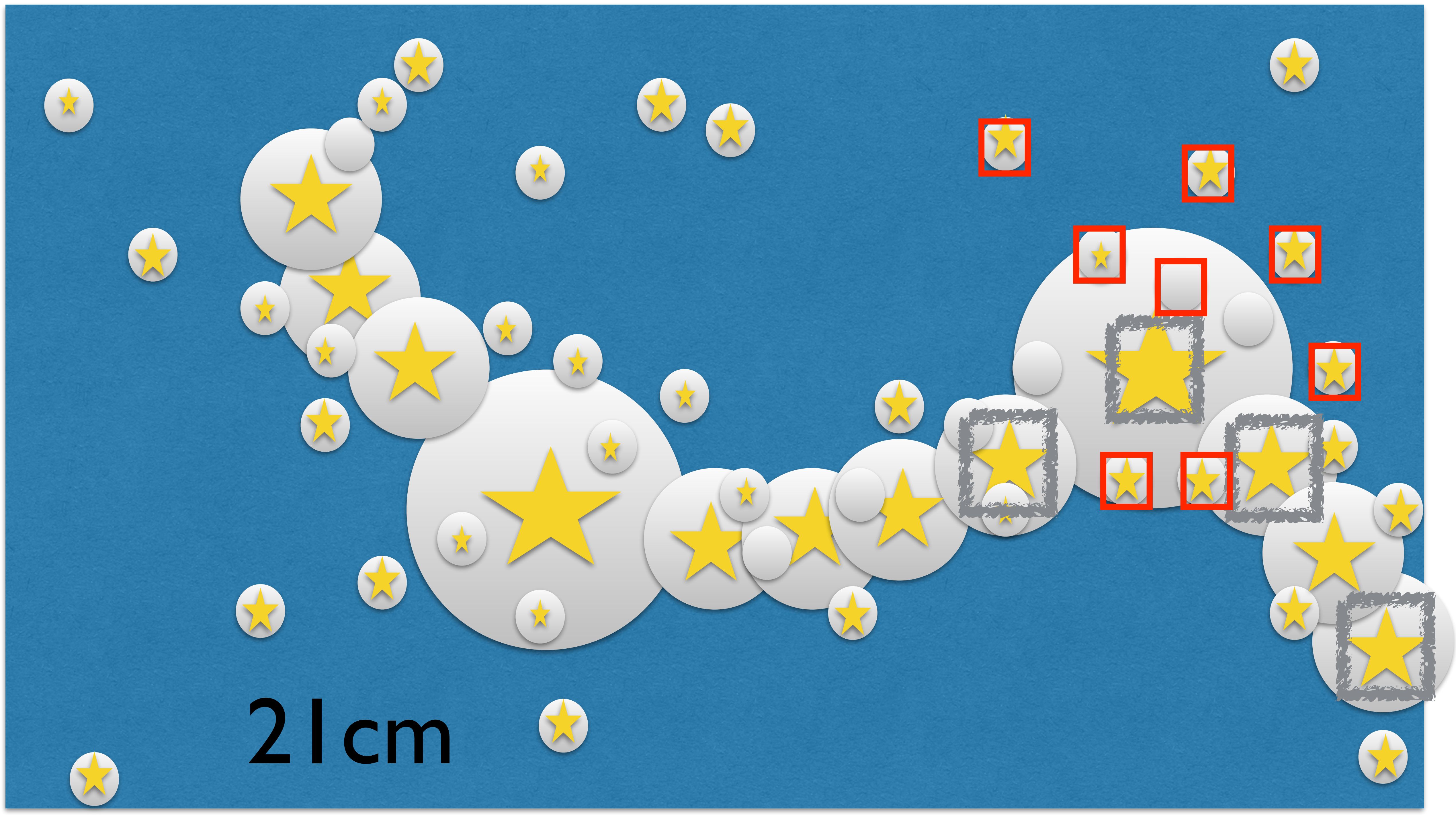
P. Ocvirk and CoDa collaboration
Observatoire astronomique de Strasbourg
Universite de Strasbourg

Agence Nationale de la Recherche ANR

Observatoire astronomique de Strasbourg

cnrs

The Epoch of Reionization: the next frontier



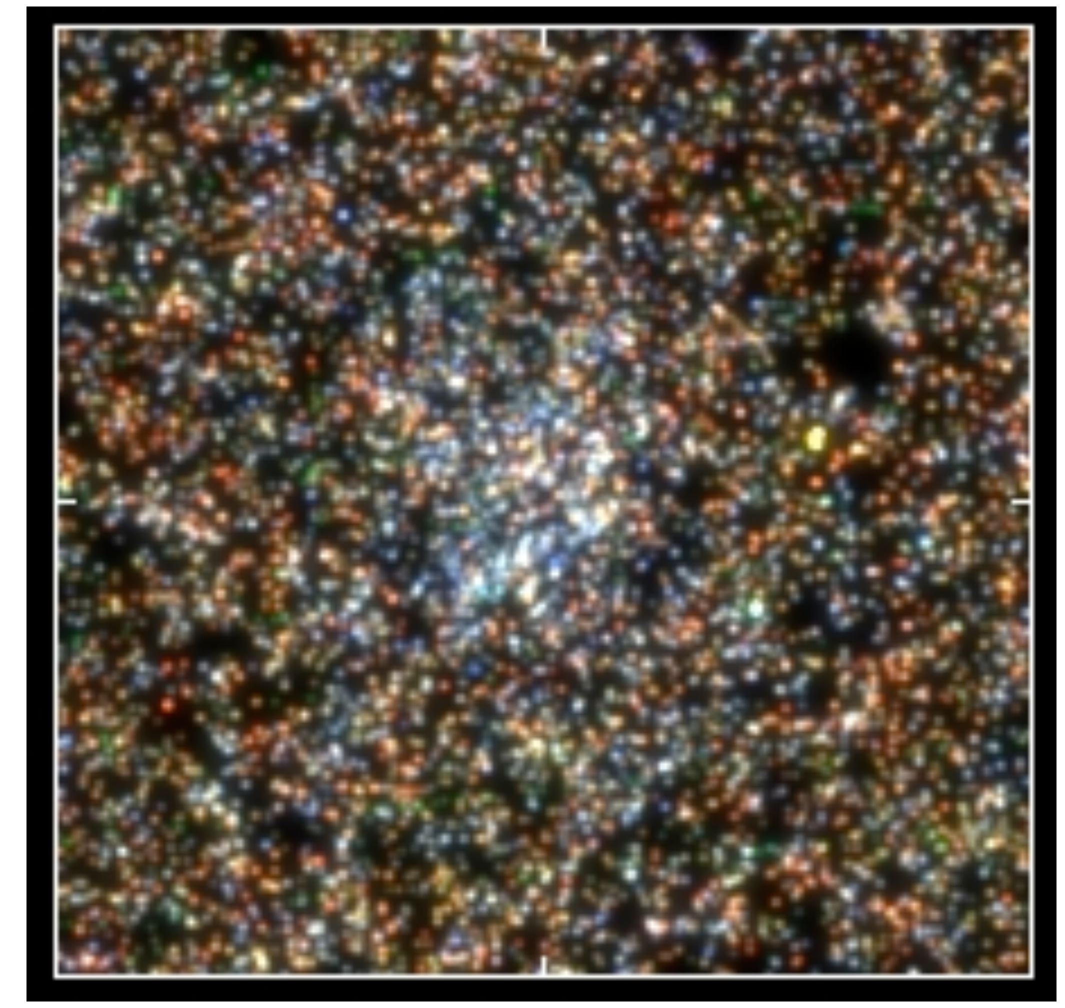
LSST 2022

SKA 2020+

JWST 2020

The UV background as an external FB

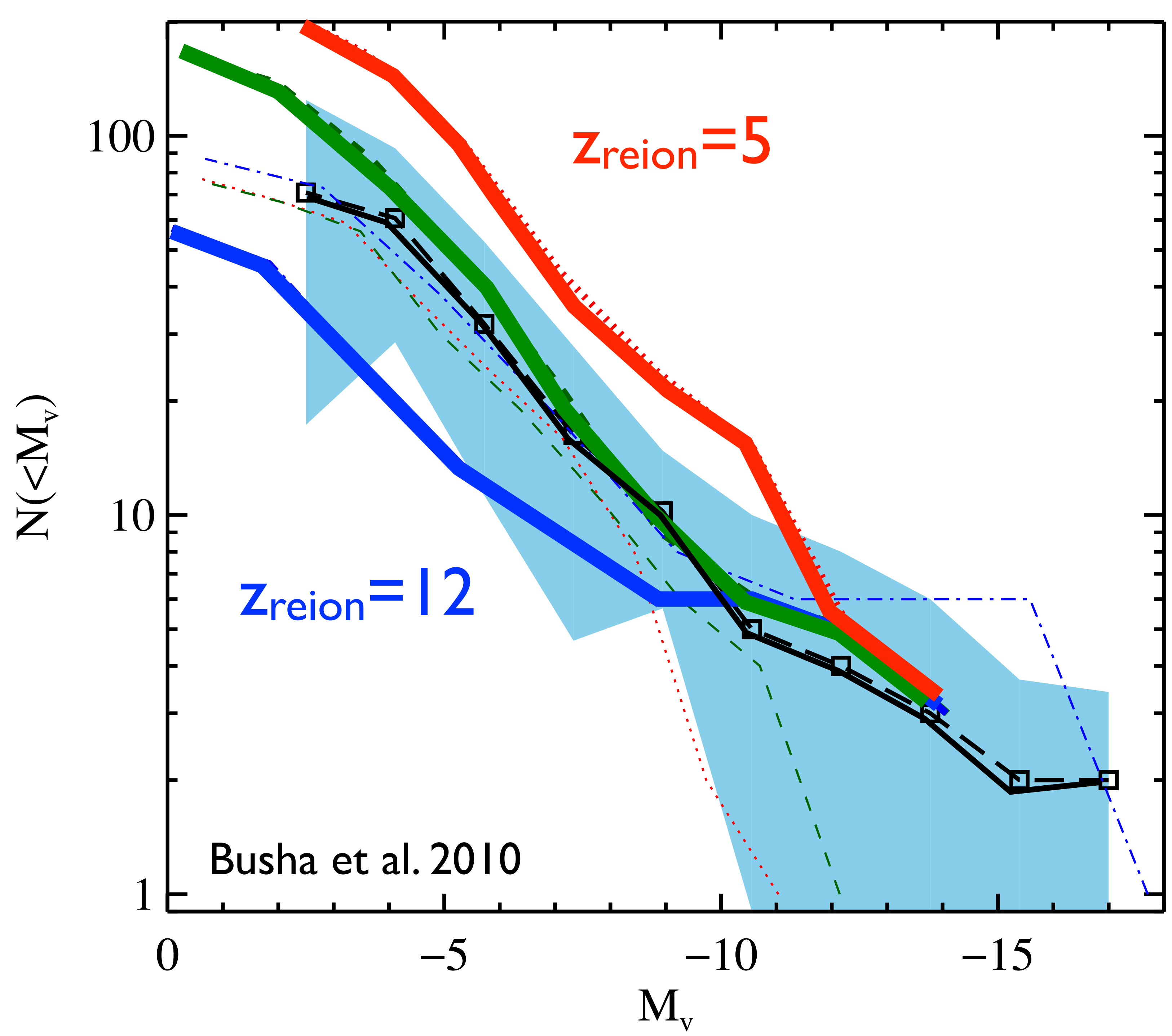
- UV background=> ionization + heat
- => gas photo-evaporation
- => SF suppression low-mass galaxies?
- => satellite galaxies, ultra-faint dwarfs



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

Courtesy V. Belokurov
and SDSS collaboration

MW Satellites LF

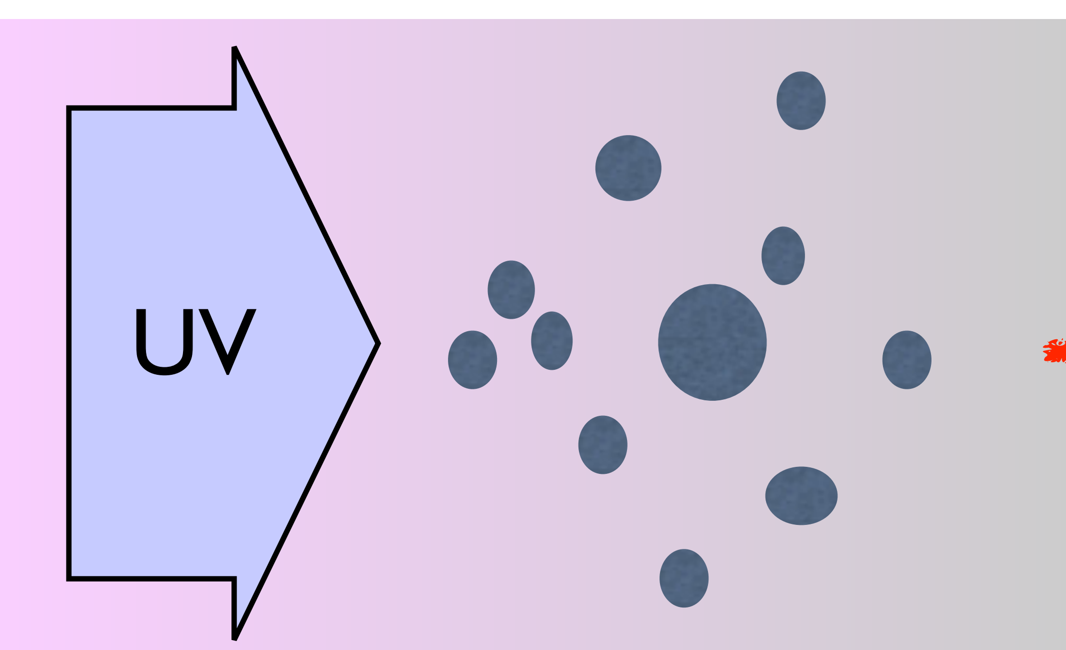


Missing satellite problem/solution

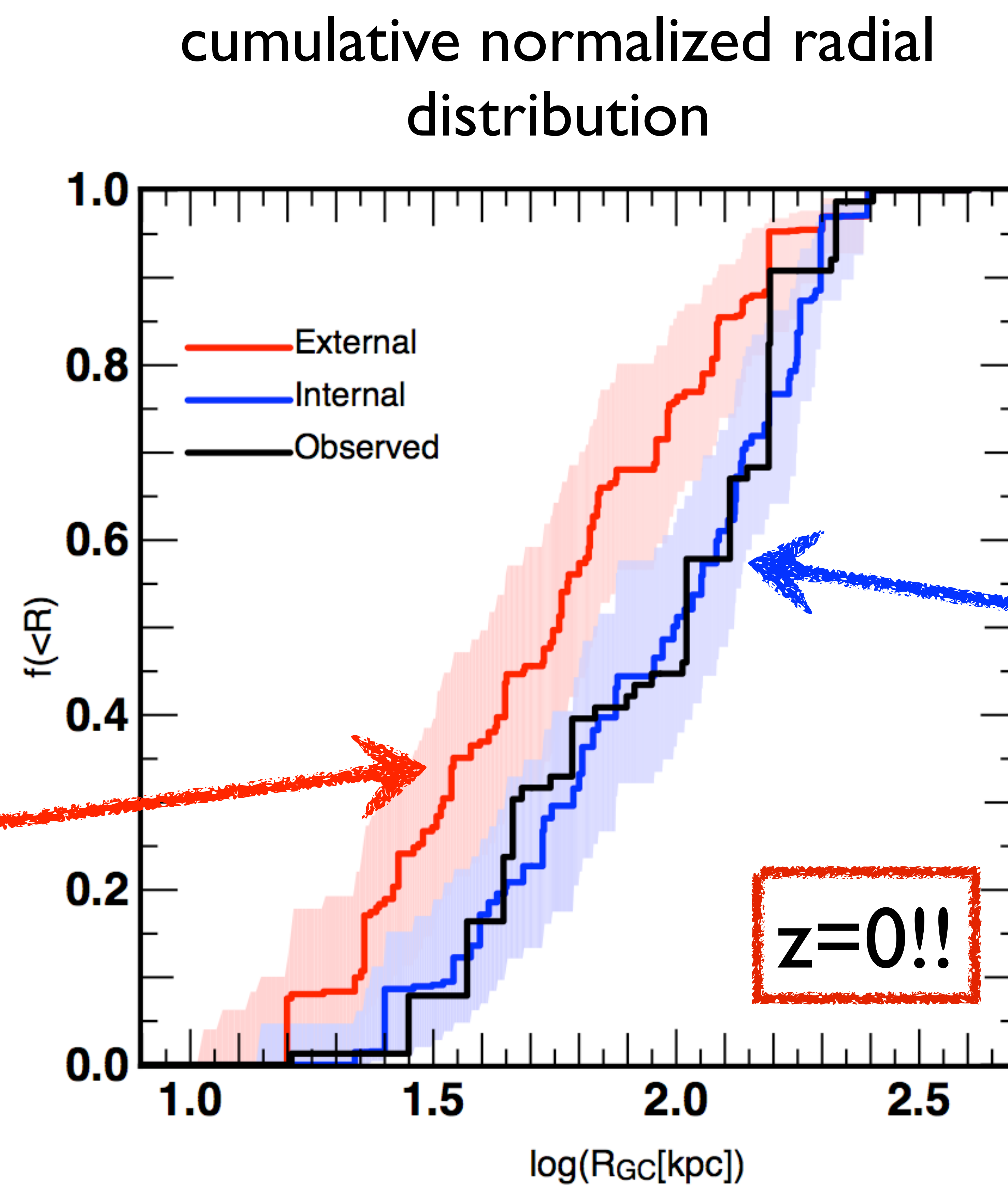
- Semi-analytical models
- Satellite SF stops at z_{reion}
- => sats = reionization fossils?
- => local dwarf pop = local probe of the EoR?

Impact of radiative environment on Milky Way dwarf satellite population

External
Uniform BG

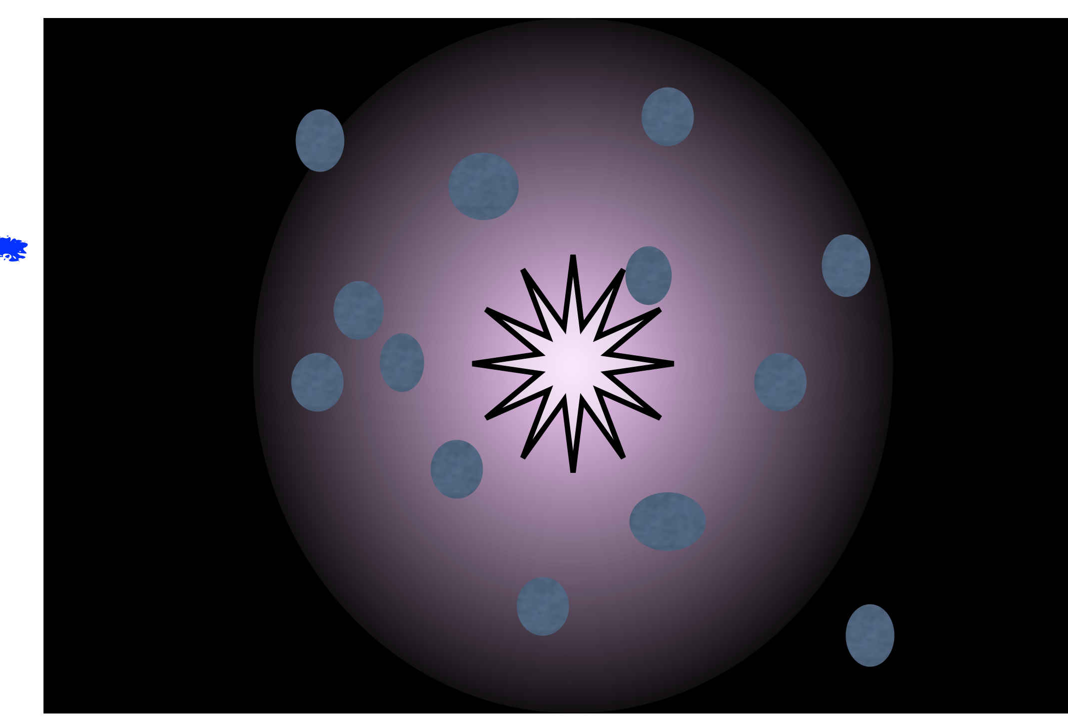


(e.g. from Virgo)



Ocvirk & Aubert 2011

Internal
inside-out
reionization



Powered by in situ sources

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

=> Can we check this in full RHD simulations?

EoR open questions

- Ionising sources? Galaxies (high/low mass?) / BHs (stellar / supermassive)
- Ionising UV Escape fraction?
- **Radiative feedback on early galaxies? mass limit for star formation?**
- Signatures of reionization in z=0 galaxies / satellites?

Addressing these questions numerically is extremely challenging:

- **COUPLED** hydro-radiative galaxy formation code
- High mass resolution (to resolve all sources down to 10^8 M$\odot$ haloes)
- Large volume (galaxy clusters) => L~ x10s Mpc

=> **COSMIC DAWN SIMULATIONS**

COSMIC DAWN (CODA) PROJECT

Collaborators

D. Aubert, P.R. Shapiro, N. Deparis, J. Sorce, J. Lewis, R. Teyssier, T. Stranex, Y. Dubois, J.-H. Choi, I. Iliev, D. Sullivan, S. Gottloeber, G. Yepes, Y. Hoffmann, F. Roy, Y. Rasera, K. Ahn, H. Park

- First run in 2013-14:
  - CODA I RAMSES-CUDATON (Ocvirk+16), late rei, restrictive SF recipe
- Second run in 2016-17:
  - CODA I - AMR: EMMA (Aubert+18)
  - CODAII - RAMSES-CUDATON, more permissive SF recipe
- => sample different numerical methods, calibrations and sub-grid recipes, CoDaI-II limiting cases in SF sub-grid physics
- CLUES ICs (CoDaI: G. Yepes, CoDa II: J. Sorce)

Fully coupled Radiation-hydro with RAMSES-CUDATON

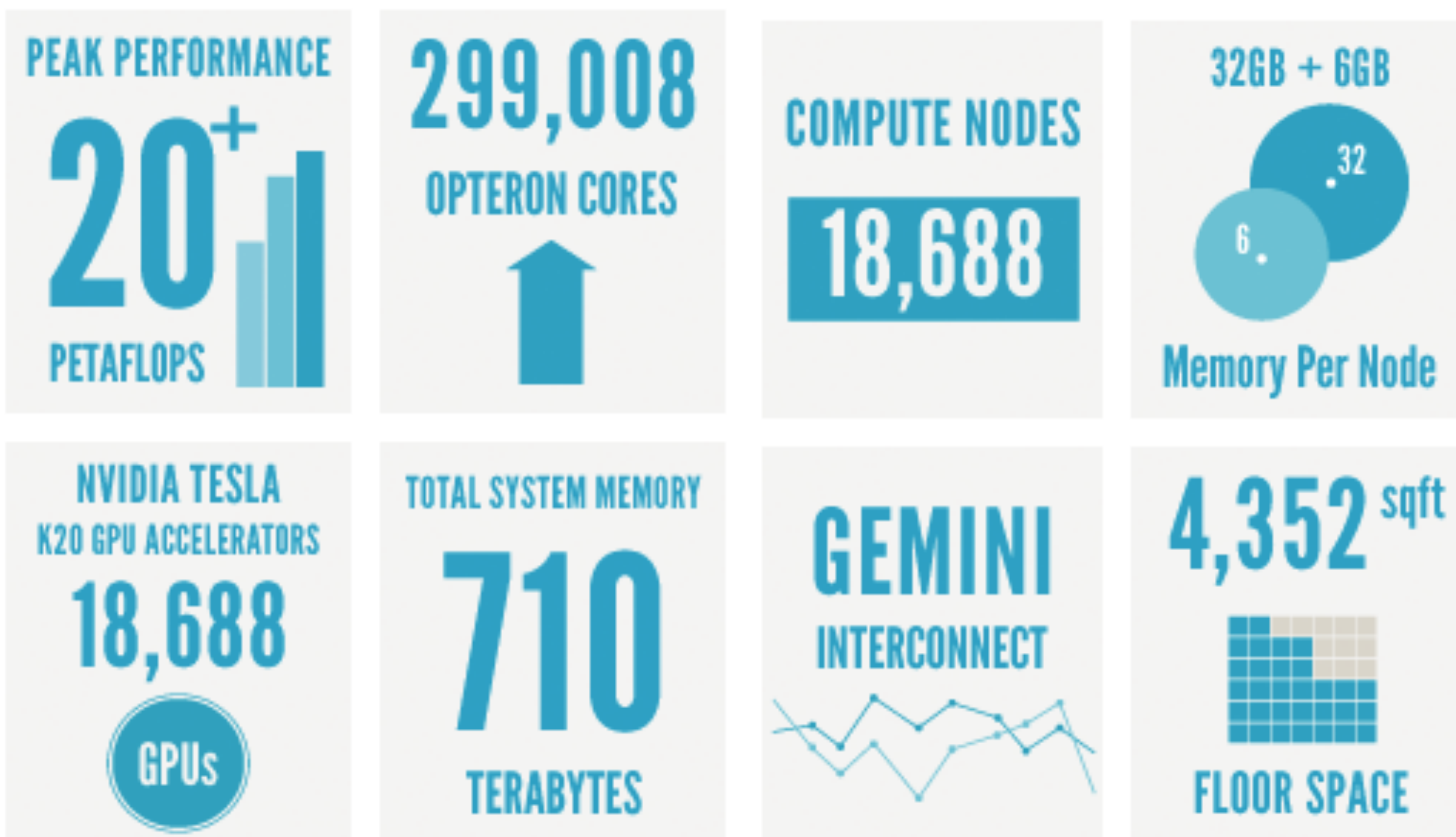
- **RAMSES** (Teyssier 2002): **CPU**
  - gravity (PM) + hydrodynamics
  - star formation + SN thermal + kinetic feedback

T, x_{HI}, Λ ↑

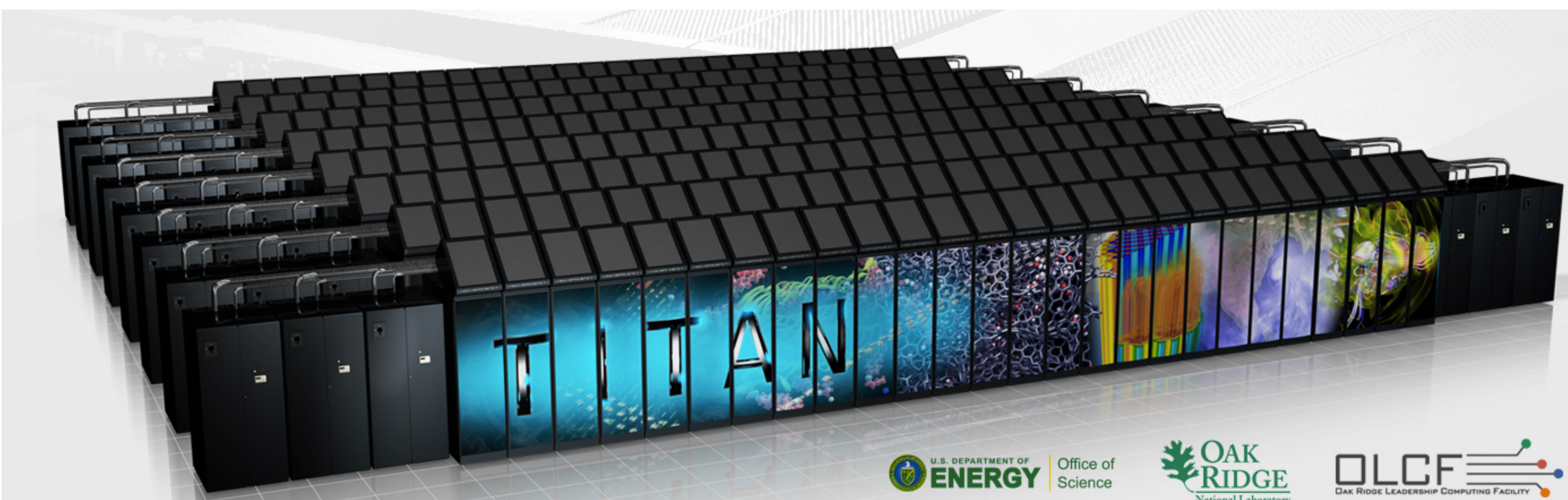
↓ T, ρ, stars

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

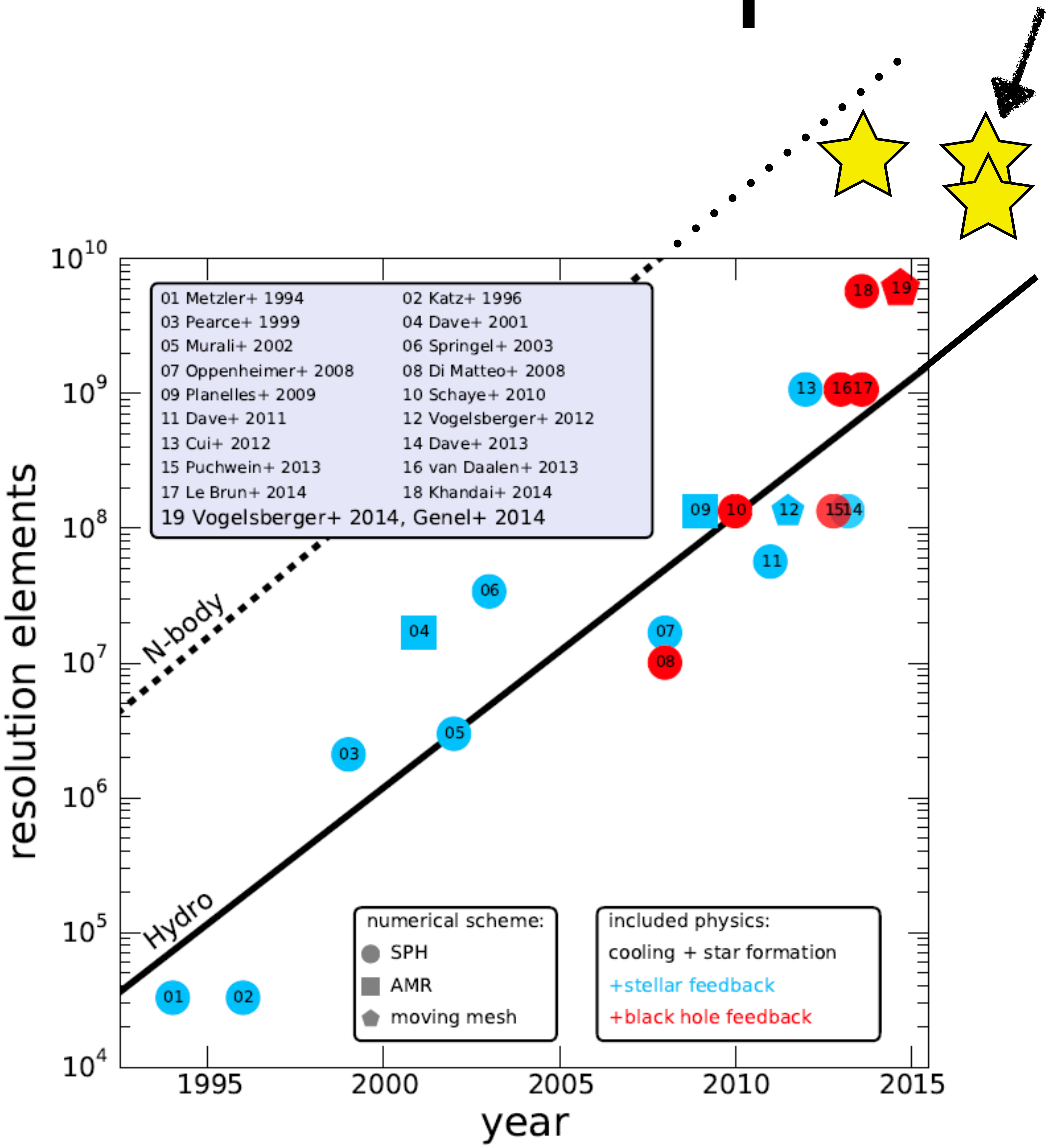
TITAN at Oak Ridge National Laboratory



- **18,688 GPUs (world's largest GPU accelerated supercomputer)**
- top 1 in 2013
- now top 5

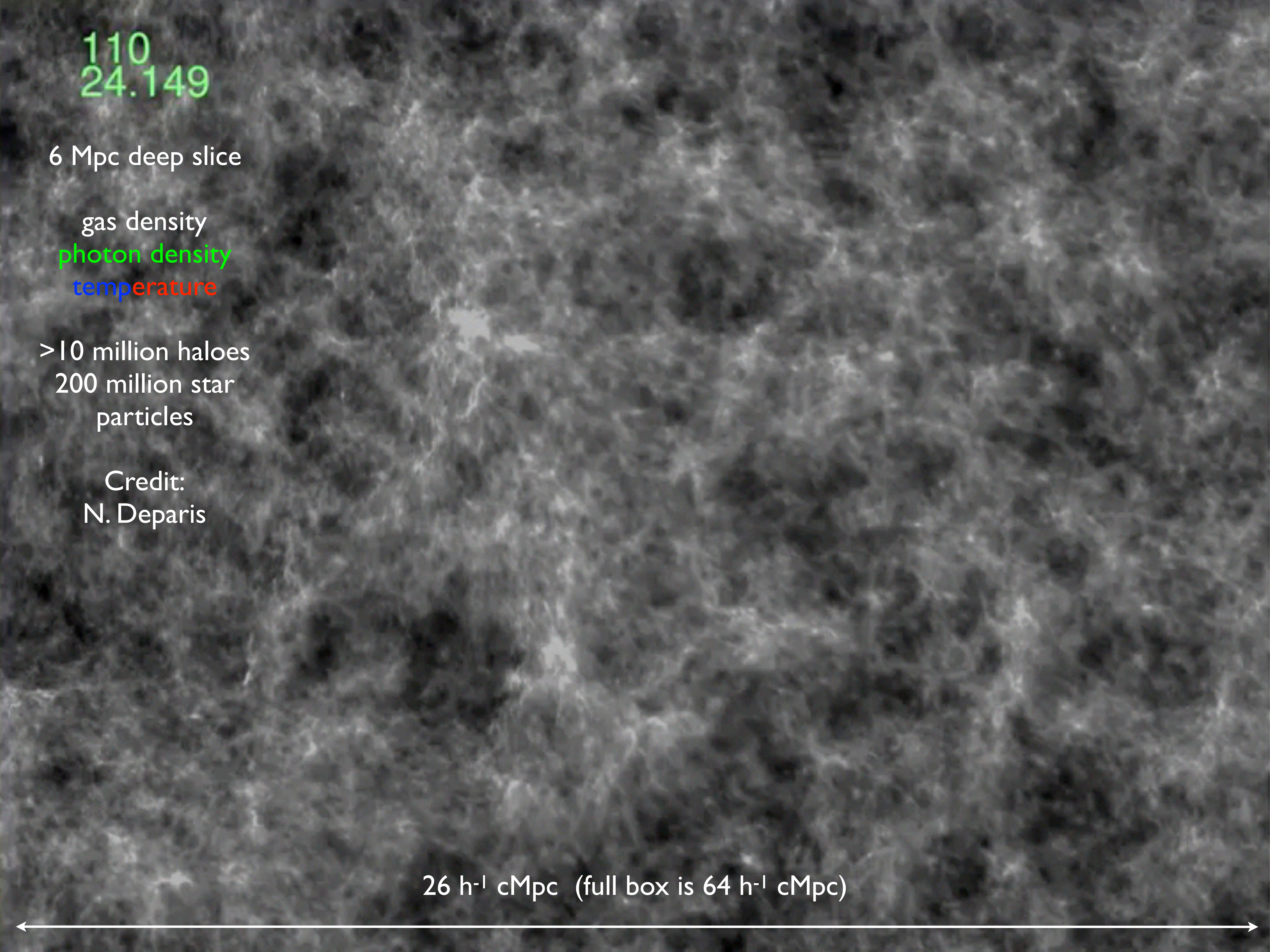


Setup: CoDaII specs



(taken from illustris website)

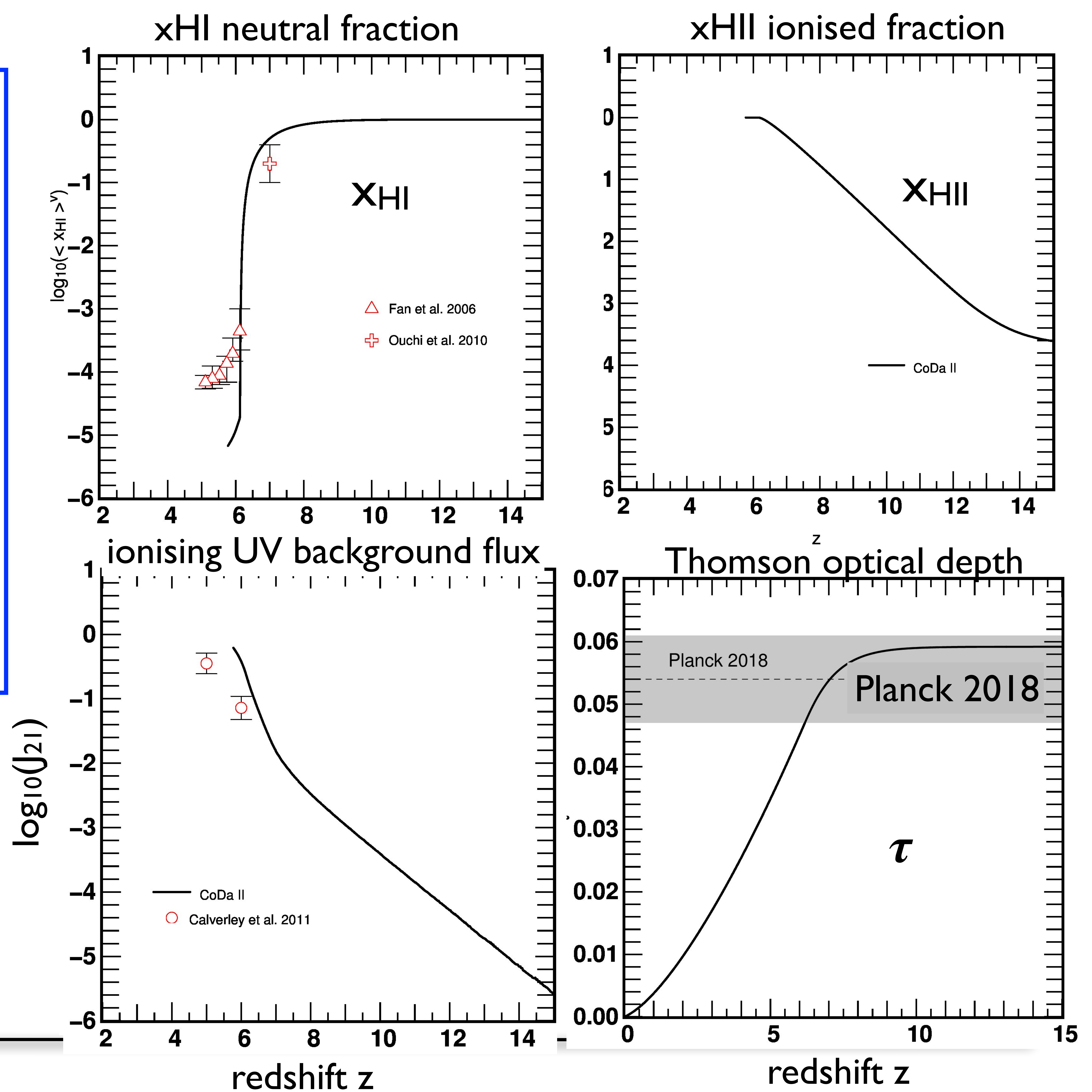
- 16384 GPUs, 65536 CPUs
- 64 h^{-1} Mpc side, 4096^3 grid
- $Mhalo_{min}$ ~1 x 10^8 M⊙
- Δx ~ 22 kpc comoving (< 3.2 kpc physical)
- z_{end}=5.8
- ~ 6 days runtime, 2 PB data
- Planck 2013 cosmology
- New ICs: M_{Virgo} = 2.e14 Msun


110
24.149
6 Mpc deep slice
gas density
photon density
temperature
>10 million haloes
200 million star particles
Credit:
N. Deparis
26 h^{-1} cMpc (full box is 64 h^{-1} cMpc)

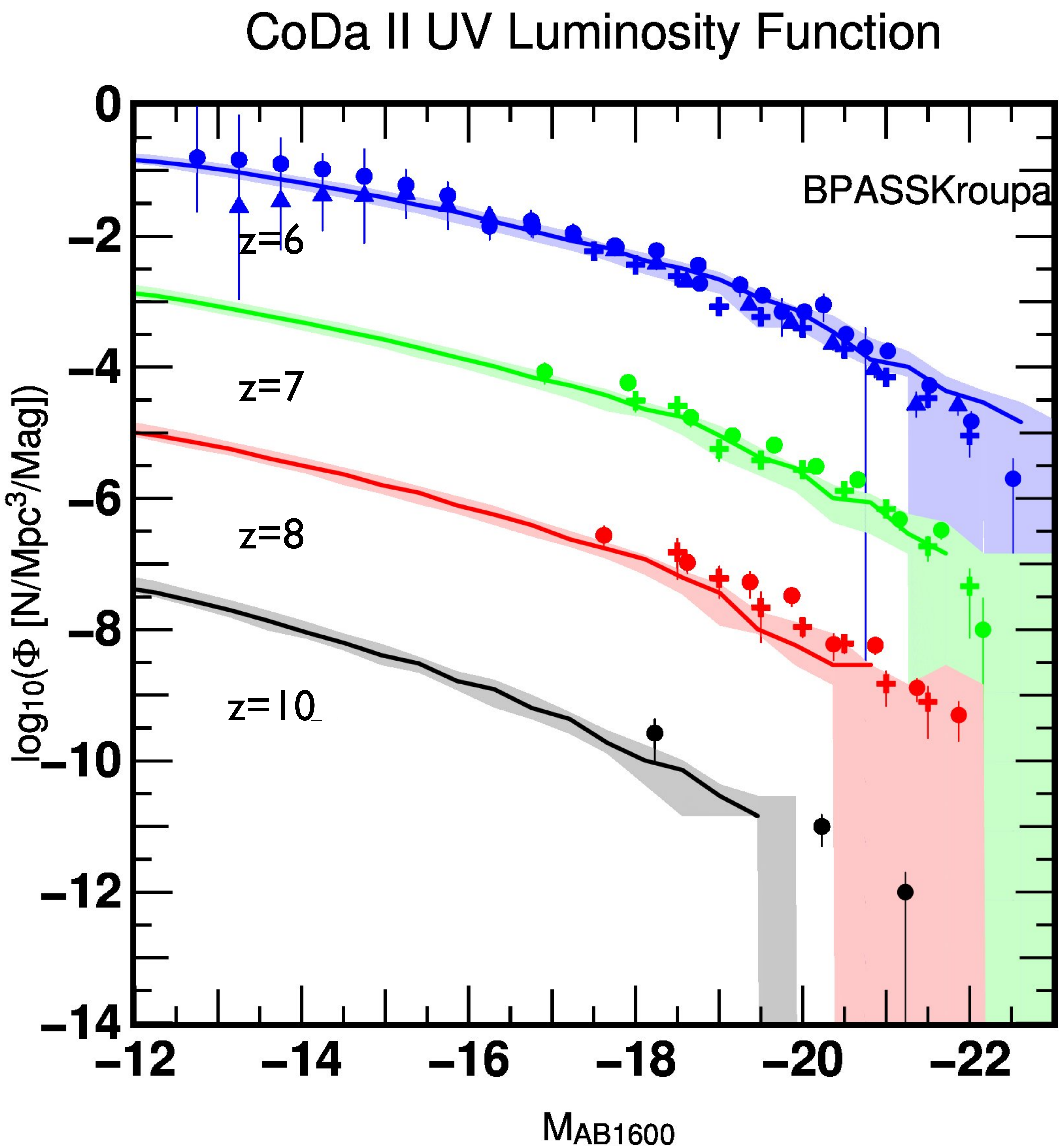
Cosmic Dawn II global properties

- Good general agreement, however:
- xHI too low, J21 too high
- => too many photons, or not enough recombinations?
- => gas clumping / absorbers missing at small scales?

CoDa II ——



CoDaII UV Luminosity Function



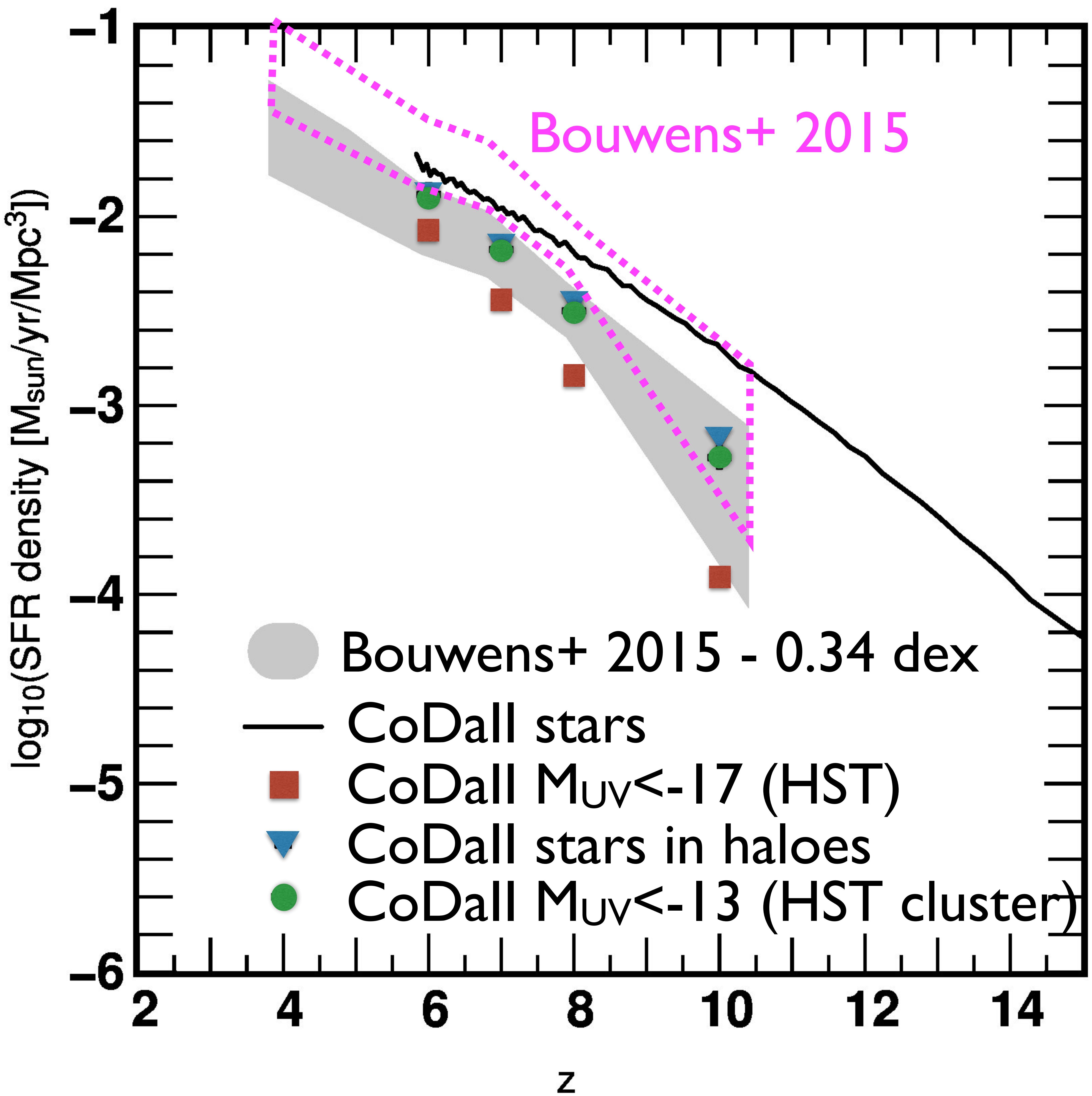
- BPASS Kroupa IMF
- Good agreement over ~10 mags
- slight overproduction at bright end but large dispersion
- increasing offset with z?

- No Fe/H evolution
- No evolving dust content

Bouwens+2016
Atek+2018

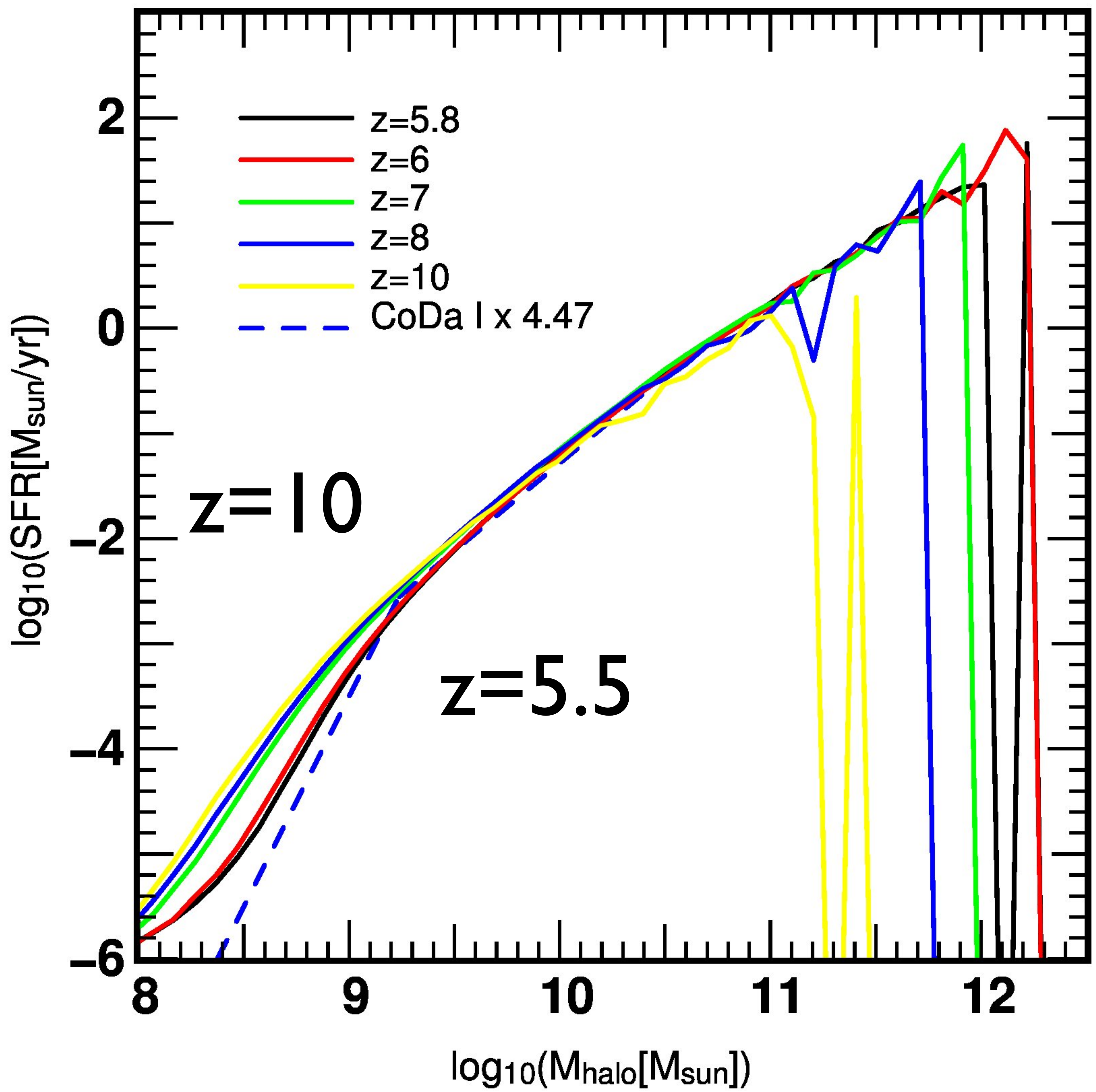
CoDa II

Cosmic star formation rate density



- Madau plot
- Kroupa binary vs Salpeter IMF=> -0.34 dex
- CoDall total SFR overshoots observations, but not realistic
- Good agreement when using realistic magnitude constraints (<-17)
- Box total SFR density overestimates "observable" SFR density by x2-3 at z<6
- Surveys down to -17 miss a significant fraction of SFR

Cosmic Dawn II: SFR vs (M,z)



- high M: SFR α $M^{1.4}$
- steeper at M<1.e9
- Suppression:
  - z<=6: SFR drops at low M
  - High mass haloes unaffected
  - suppression less dramatic than CoDaI but still there!
  - Important: removed T criterion in sub-grid SF recipe

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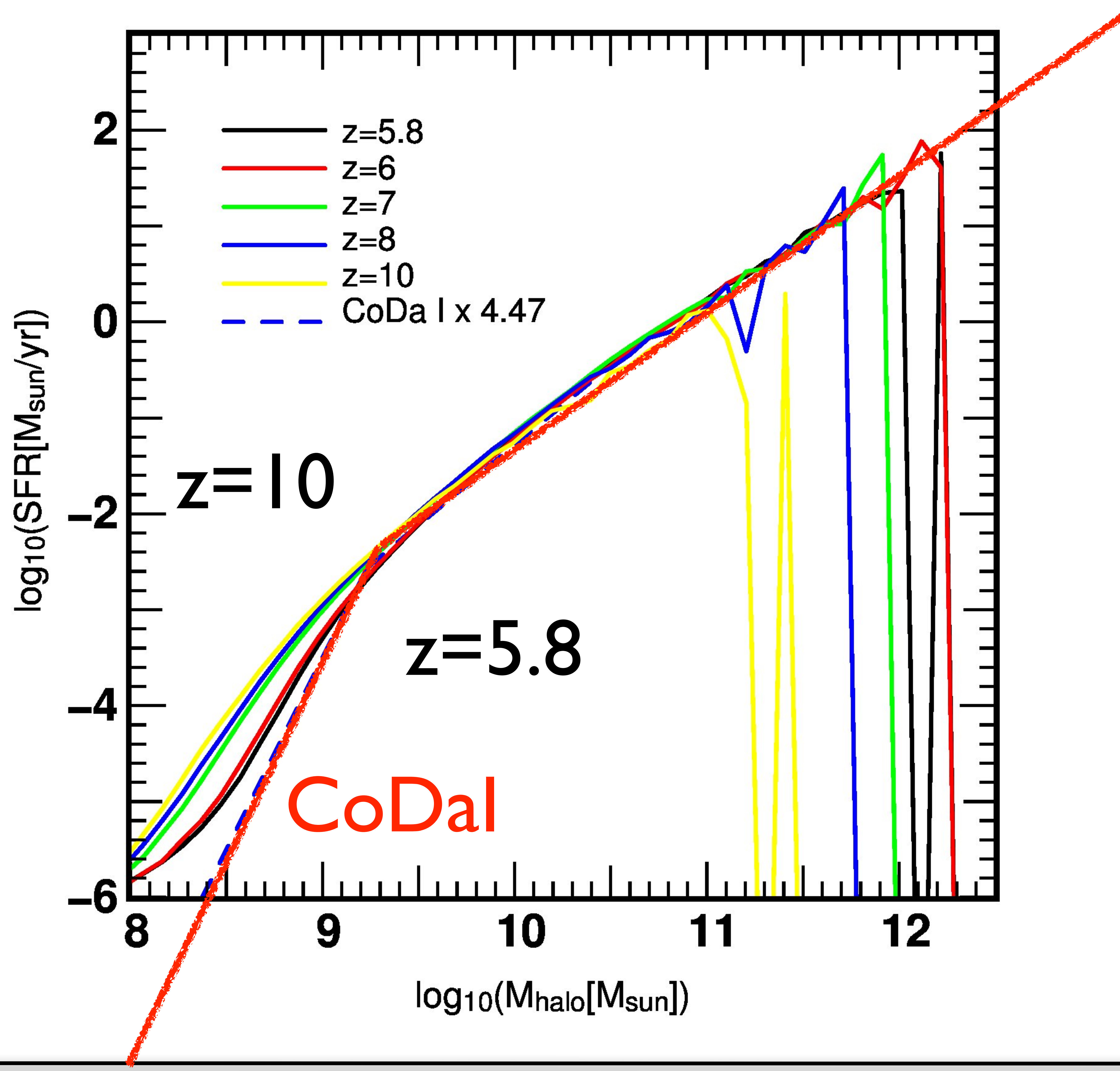

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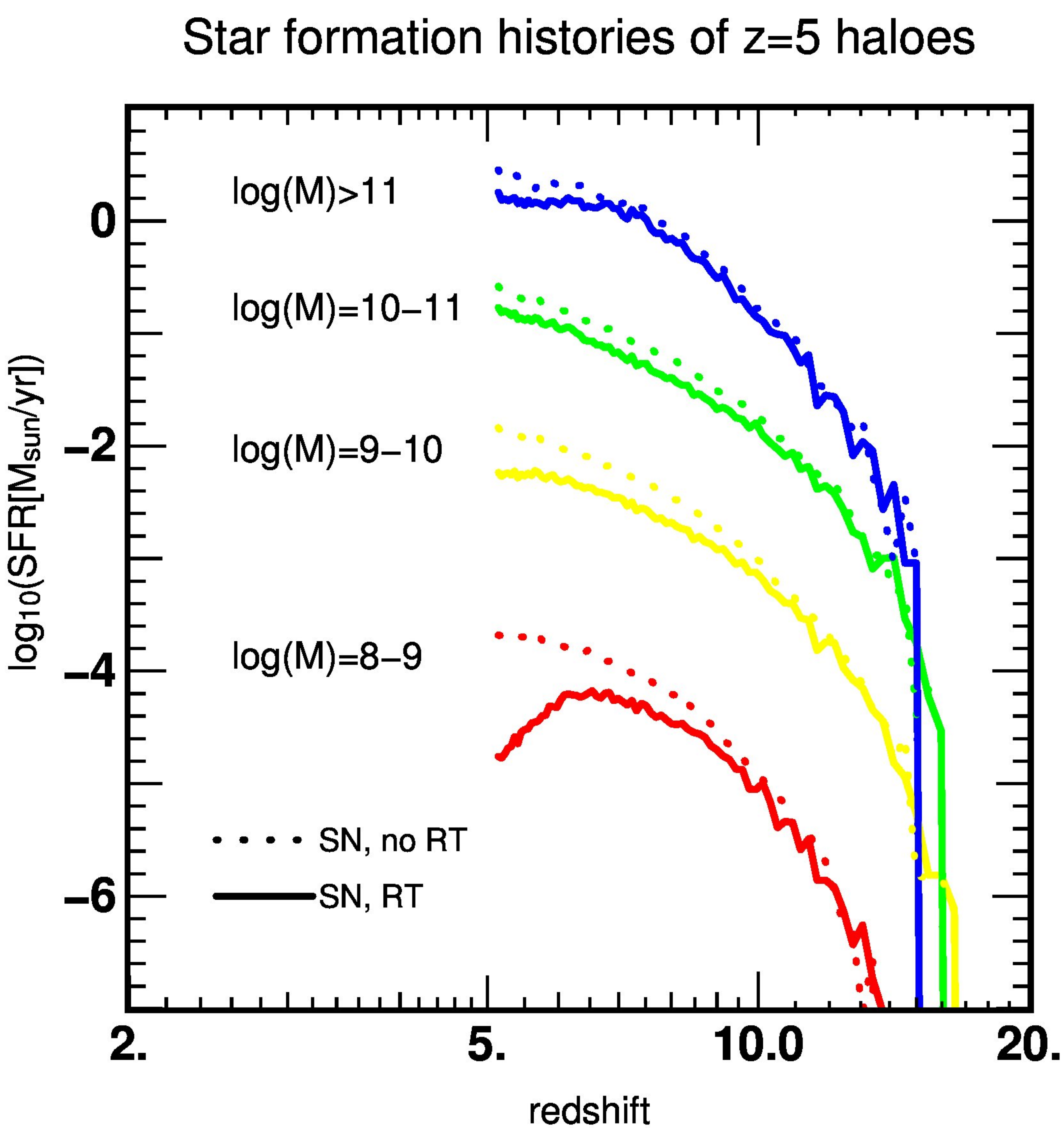
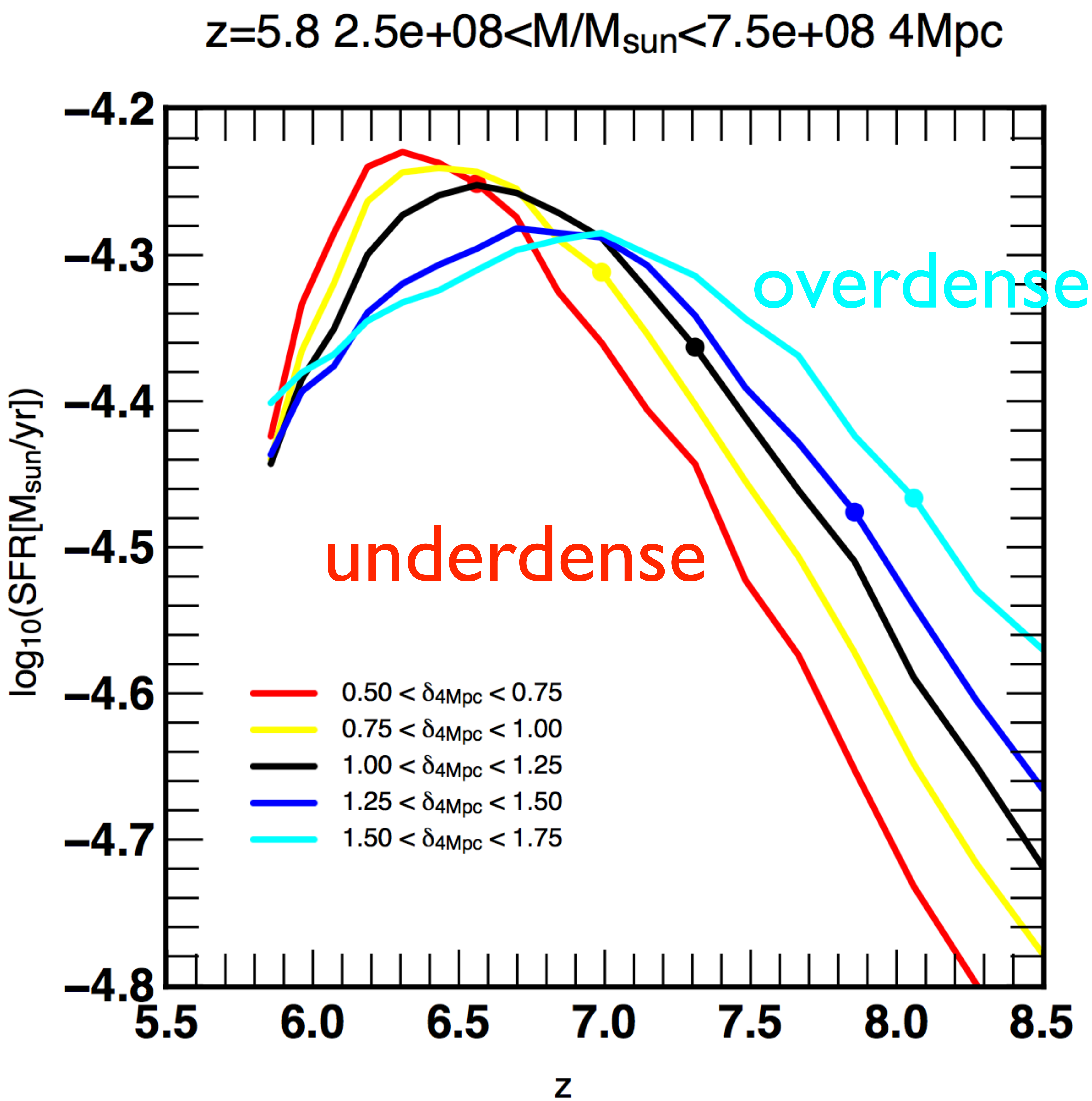
Suppression of star formation by UV ionising radiation



- Auxiliary test boxes 8h-1Mpc
- Same setup as CoDaII
- 2 sets of physics:
    - SN, no RT
    - SN, RT
- Low mass bin SFR decreases at z<6
- Small or no effect on higher mass bins.
- Suppression less strong than CoDaI

SF suppression by radiative environment SFH vs (z,δ)



- SFHs of haloes selected at z=5.8
- Overdensity at 4Mpc scale
- Rise and fall, max at z=6.5-7
- Overdense:
  - early reionization
  - early suppression
- Underdense:
  - late reionisation
  - late suppression
- at z~6.2: SFR(underdense)>SFR(overdense)
- at z~5.8: SFRs converge?

SUMMARY

- **Cosmic Dawn simulations** are the largest GPU-driven Radiation-Hydrodynamics galaxy formation simulations ever made.
- Describes galaxy formation <=> reionization self-consistently.
- CoDa II matches well current observational constraints at z>6: global z_{rei}, τ, UV LF down to M_{1600}=-13, while x_{HII}, J_{21} at z<6 are too high
- Comparing observed vs simulated cosmic SFRD requires accounting for:
  - Stellar pop models (IMF, binary vs single etc…)
  - Observational depth limit
- SF suppression in CoDaII less strong than CoDaI due to different sub-grid models
- Dwarf galaxies SFHs are affected by local reionisation history.

Further analysis and future work

- CODA II:
  - photon budget of galaxies during the EoR (J. Lewis)
  - Reionization of local group simulacra (J. Sorce) (also, Aubert + 2018)
  - LAEs LF Lyman alpha intensity mapping (K. Ahn)

- CODA III (prop. submitted in June 2018)
  - improve physics: chemical enrichment+ stellar pops + dust
  - SUMMIT (Titan successor) => 8192^3

- Euro-HPC: Big HPC (1 GEuro) initiative for 1-2 sub-exa european machines
  - Ambition = top 1 in 2023 => GPUs or Xeon Phi
  - My guess = GPUs
  - => CoDa IV and beyond