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

Ocvirk+2018

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The Epoch of Reionization: the next frontier

21cm

SKA 2020+

JWST 2020

LSST 2022
The UV background as an external FB

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

Missing satellite problem/solution

- Semi-analytical models
- Satellite SF stops at $z_{reion}$
- $\Rightarrow$ sats = reionization fossils?
- $\Rightarrow$ local dwarf pop = local probe of the EoR?
Impact of radiative environment on Milky Way dwarf satellite population

Impact of radiative environment on Milky Way dwarf satellite population

=> 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) => $L \sim 10$ s Mpc

=> **COSMIC DAWN SIMULATIONS**
COSMIC DAWN (CODA) PROJECT

Collaborators


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)
- CODA II - 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

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

\[ T, x_{\text{HI}}, \Lambda \quad \uparrow \quad T, \rho, \text{stars} \]
TITAN at Oak Ridge National Laboratory

- 18,688 GPUs (world’s largest GPU accelerated supercomputer)
  - top 1 in 2013
  - now top 5
Setup: CoDall specs

- 16384 GPUs, 65536 CPUs
- 64 h⁻¹ Mpc side, 4096³ grid
- \( M_{\text{halo}} \sim 1 \times 10^8 \, M_\odot \)
- \( \Delta x \sim 22 \, \text{kpc} \) comoving (\(< 3.2 \, \text{kpc} \) physical)
- \( z_{\text{end}} = 5.8 \)
- \( \sim 6 \) days runtime, 2 PB data
- Planck 2013 cosmology
- New ICs: \( M_{\text{Virgo}} = 2.14 \times 10^8 \, M_\odot \)
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

- xHI neutral fraction
- xHII ionised fraction
- Ionising UV background flux
- Thomson optical depth
CoDall 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 UV Luminosity Function

$\log_{10}(\phi \text{ [N/Mpc$^3$/Magl]})$

$M_{AB1600}$
Cosmic star formation rate density

- Madau plot
- Kroupa binary vs Salpeter IMF: $-0.34$ dex
- CoDaII 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: $\text{SFR} \propto M^{1.4}$
- steeper at $M < 1.0 \times 10^9$
- Suppression:
  - $z \leq 6$: SFR drops at low M
  - High mass haloes unaffected
  - suppression less dramatic than CoDa I but still there!
- Important: removed T criterion in sub-grid SF recipe
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Suppression of star formation by UV ionising radiation

Star formation histories of z=5 haloes

- Auxiliary test boxes 8h^{-1}Mpc
- 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 CoDaII
SF suppression by radiative environment SFH vs \((z, \delta)\)

- 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 reionization
  - late suppression
- at \(z\sim6.2\): \(\text{SFR(underdense)} > \text{SFR(overdense)}\)
- at \(z\sim5.8\): SFRs converge?
SUMMARY

- **Cosmic Dawn simulations** are the largest GPU-driven Radiation-Hydrodynamics galaxy formation simulations ever made.

- Describes galaxy formation $\leftrightarrow$ reionization self-consistently.

- CoDa II matches well current observational constraints at $z>6$: global $z_{rei}$, $\tau$, 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 CoDall less strong than CoDal 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