Dust-UV offsets in the Cosmic Dawn III simulation
-
RT beyond M1

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https://coda-simulation.github.io/
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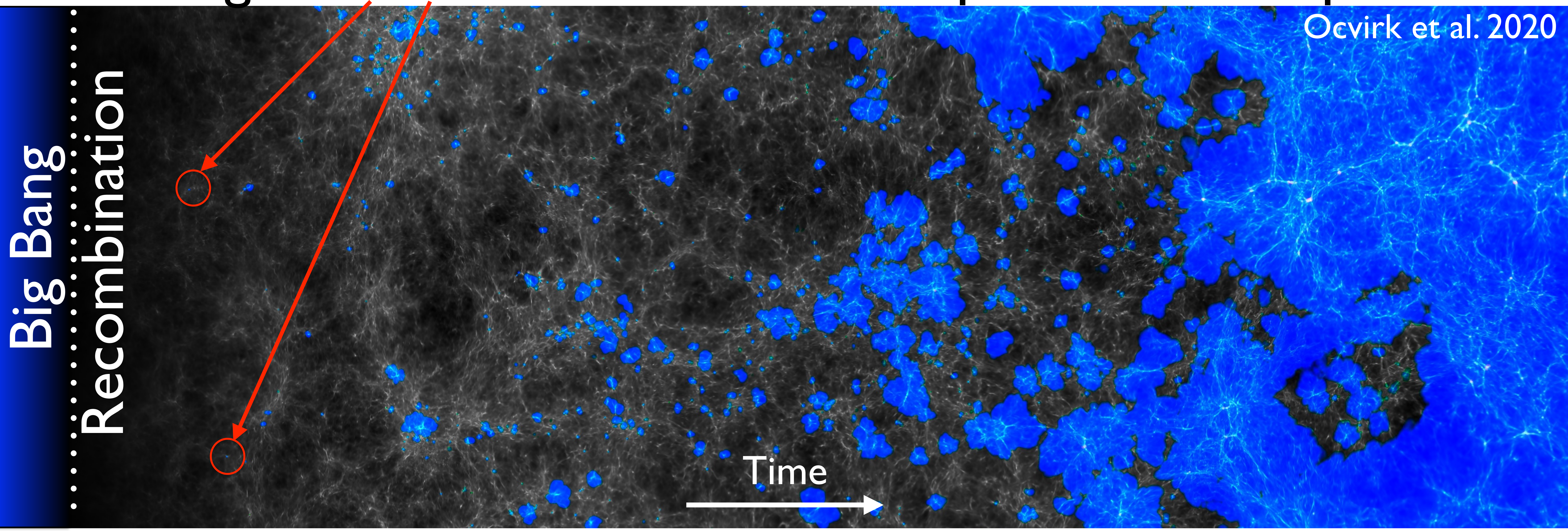
de Strasbourg

Plan

1. Context: the Epoch of Reionization (EoR)
2. Cosmic Dawn III simulation
3. Dust-UV offsets in Cosmic Dawn III
4. Pn: a « new » RT method for next-gen astrophysical simulations

I - The Epoch of Reionization

Dark ages First stars Partial overlap Overlap



z=1100 z=7 z=6

z=30-15?

Neutral 50% ionised Ionized

Dark ages / EoR open questions

- When did dark ages / reionization start / finish?
- Ionising sources? Galaxies (high/low mass?) / BHs (stellar / supermassive)
- Ionising UV Escape fraction? Impact of dust?
- Radiative feedback on early galaxies? mass limit for star formation?
- => Impact on reionization history?

Addressing these questions numerically is extremely challenging:

- **COUPLED** radiation hydrodynamics galaxy formation code, costly
- High mass resolution (to account for all sources down to at least $10^8 M_\odot$ haloes)
- Large volume (bright-end galaxy MF, galaxy clusters) => L~ 100 Mpc

I - Fully coupled Radiation-hydro with RAMSES-CUDATON (Ocvirk+2016)

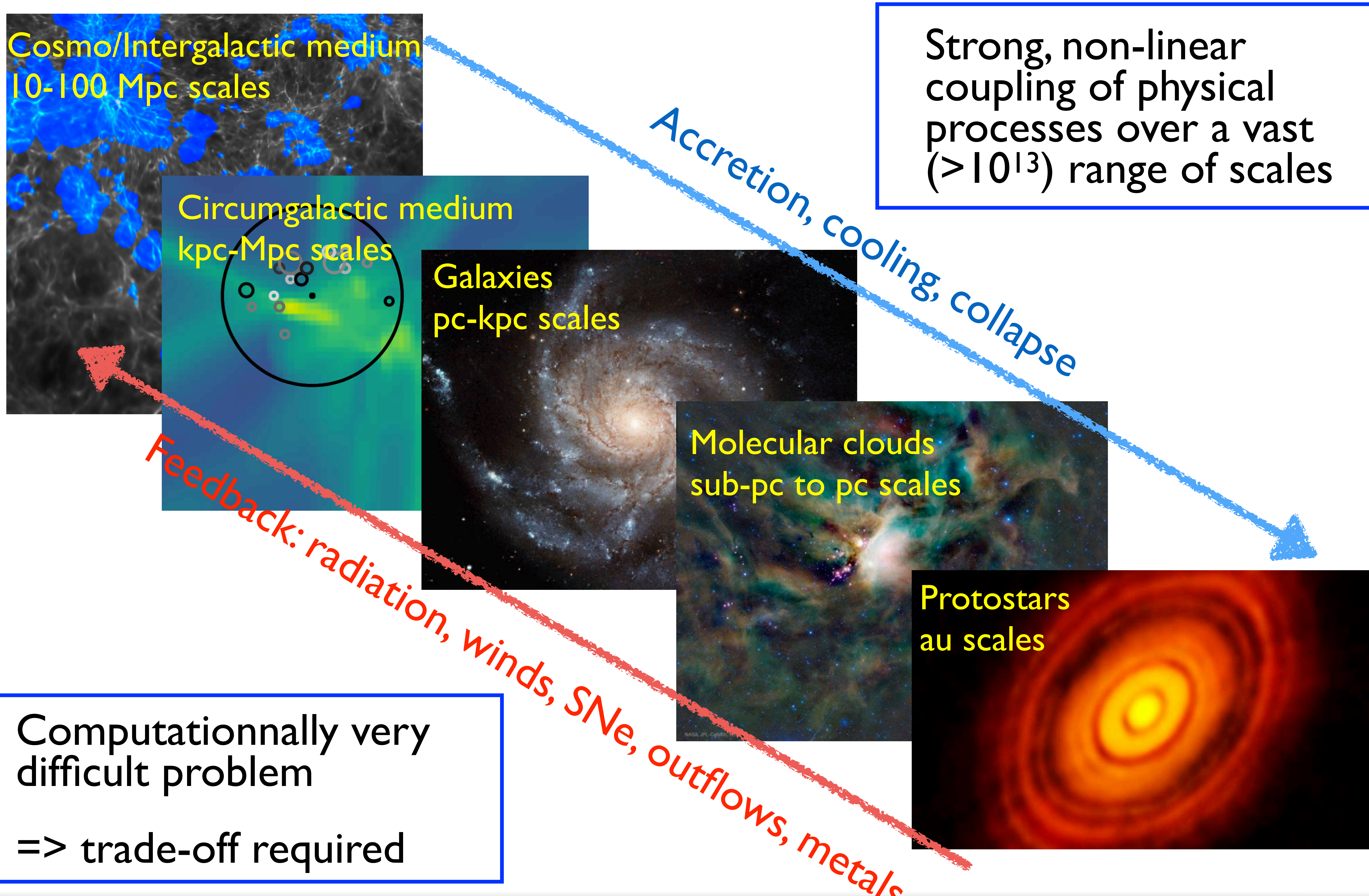
- **RAMSES** (Teyssier 2002): **CPU**
  - gravity (PM) + hydrodynamics
  - star formation + SN thermal + kinetic feedback
  - chemical enrichment, dust production + destruction (Lewis+2022)

T, x_{HI} ↑ ↓ T, ρ_{HI}, stars, ρ_{dust}

- **ATON** (Aubert 2008): UV Radiative Transfer,
  - photon propagation, H ionization
  - H Photo-heating + cooling
  - dust absorption

II - The tyranny of scales

Strong, non-linear coupling of physical processes over a vast (>10^{13}) range of scales



Computationnally very difficult problem

=> trade-off required

(Inspired from J. Rosdahl's slide)

II - Cosmic Dawn III setup

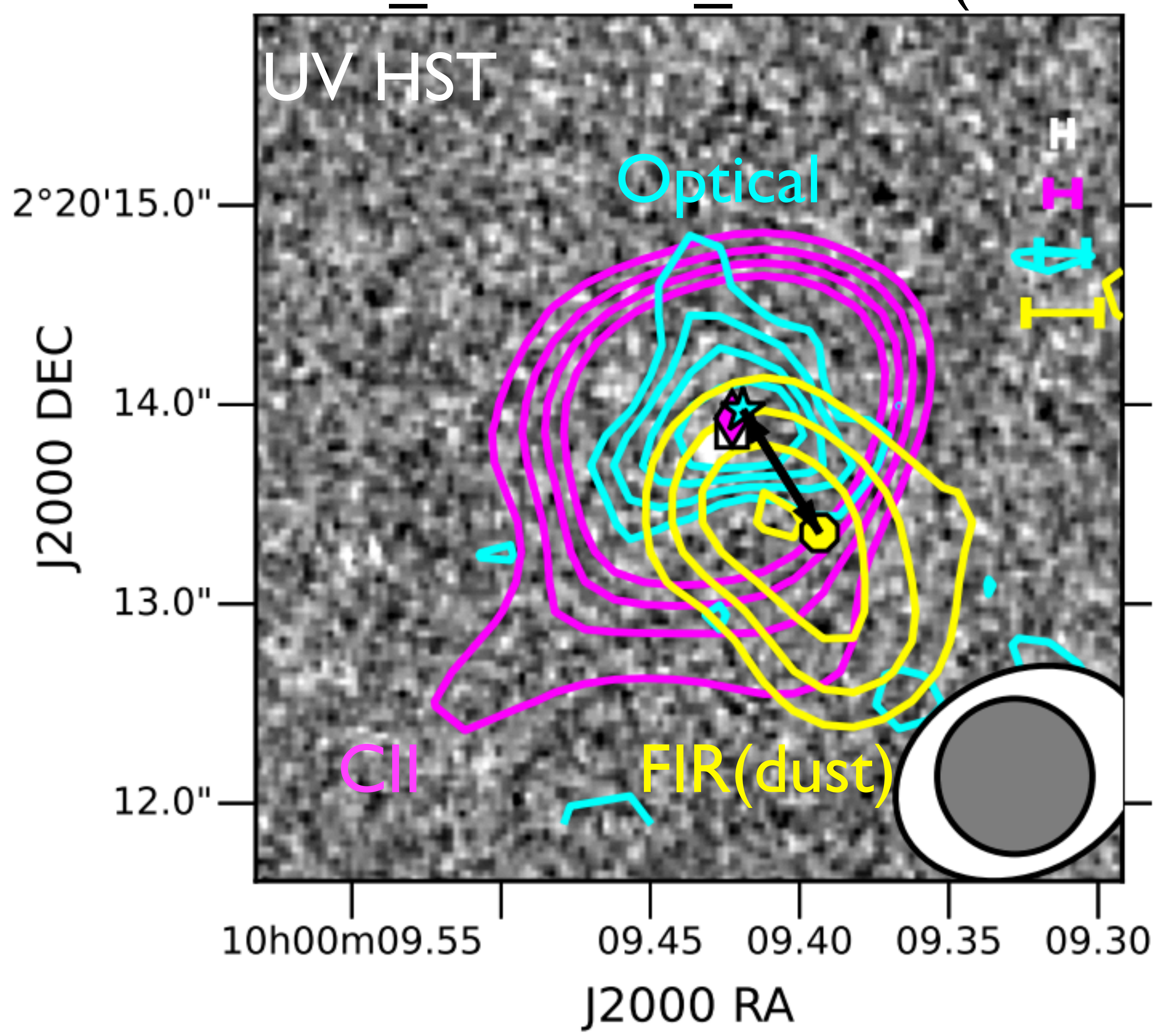
Run parameters					
Domain	Box size (h^{-3} cMpc^3)	64^3	**Ionizing radiation**	Emissivity (ph/s/)	BPASSv2.2.1
	Grid size	8192^3		Lifetime (Myr)	
	Cell size dx(z=6)	1.65 pkpc		sub-grid f_{esc}	**1**
Mass resolution (M_{sun})	DM particle mass	5 x 10^4	**Setup**	Computer	Summit
	Stellar particle mass	~10^4		Number of nodes	4096
	Minimum halo mass	3.10^7		Number of CPUs	131 072
Star formation	Density threshold (rho/rho_average)	50		Number of GPUs	24 576
	Efficiency	0.03		Total data	20 PetaBytes
	Temperature threshold	2×10^4 K		End redshift	4.6

- Main improvement in spatial and mass resolution (x2 and x8)
  - => improved description of galaxies and sinks
- > 1 trillion particles+cells
- Huge parallelism
- Updated physics: BPASS, metals & dust (Lewis+ 2022), SF T threshold

Observed UV-FIR offsets

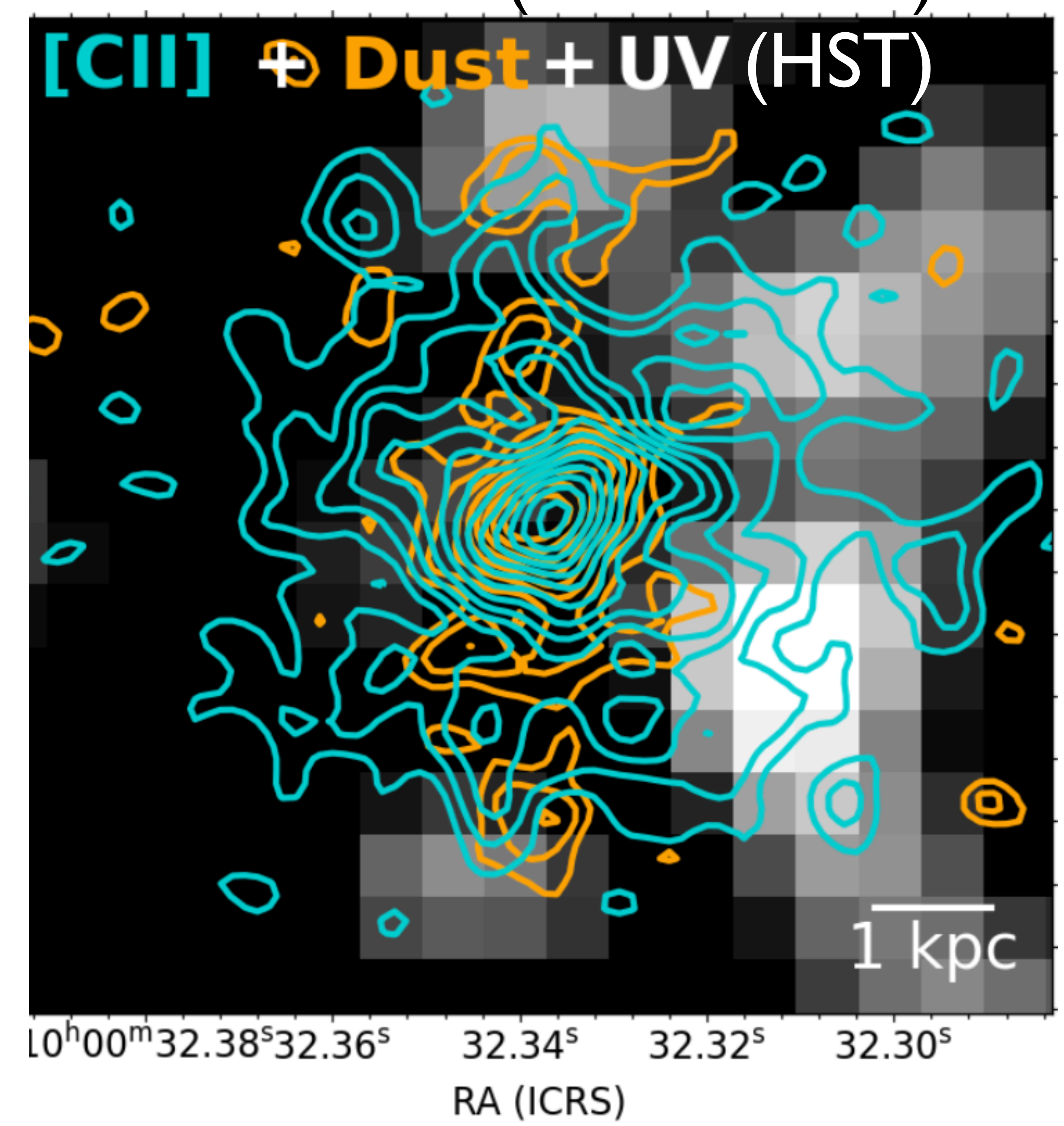
ALPINE

DEIMOS_COSMOS_683613 (Killi+24)



REBELS

REBELS-25 (Rowland+24)



- Significant offsets between UV (HST) and dust (ALMA) emission distributions
- z=4-7
- Up to several pkpc
- Multiplicity(?) of UV counterpart

Dust-UV offsets, open questions

- Astrometric calibration?
- Genuine misalignment between bulk stellar mass and ISM?
- Complex morphology/merger?
- Dust obscuration effects?
- Impact on stellar mass / SFR measurements?

Cosmic Dawn III as an investigation ground

- $\sim 100^3$ Mpc^3 box (=> handful of very massive (10^{12} $M_\odot$ haloes)
- Reasonably good calibration (IGM reionization, galaxy UV LF)
- End redshift z_{end}=4.7

Cosmic Dawn III dust model

- early version of Dubois+24.
- Dust production:
  - SN condensate
  - Grain growth
- Dust destruction:
  - SN:
  - thermal sputtering:
- Coupled to ionizing UV RT to investigate impact on rei history
- But no impact on e.g. cooling
- Implemented by J. Lewis into RAMSES-CUDATON during PhD.

1 grain size $0.1\mu m$

$$\mathrm{M_{dust} = M_{ejecta} f_{cond}}$$

$$\dot{\mathrm{M}}_\mathrm{d} = \left(1 - \frac{\mathrm{M_d}}{\mathrm{M_{metal}}}\right)\frac{\mathrm{M_d}}{\mathrm{t_{growth}}} \,,$$

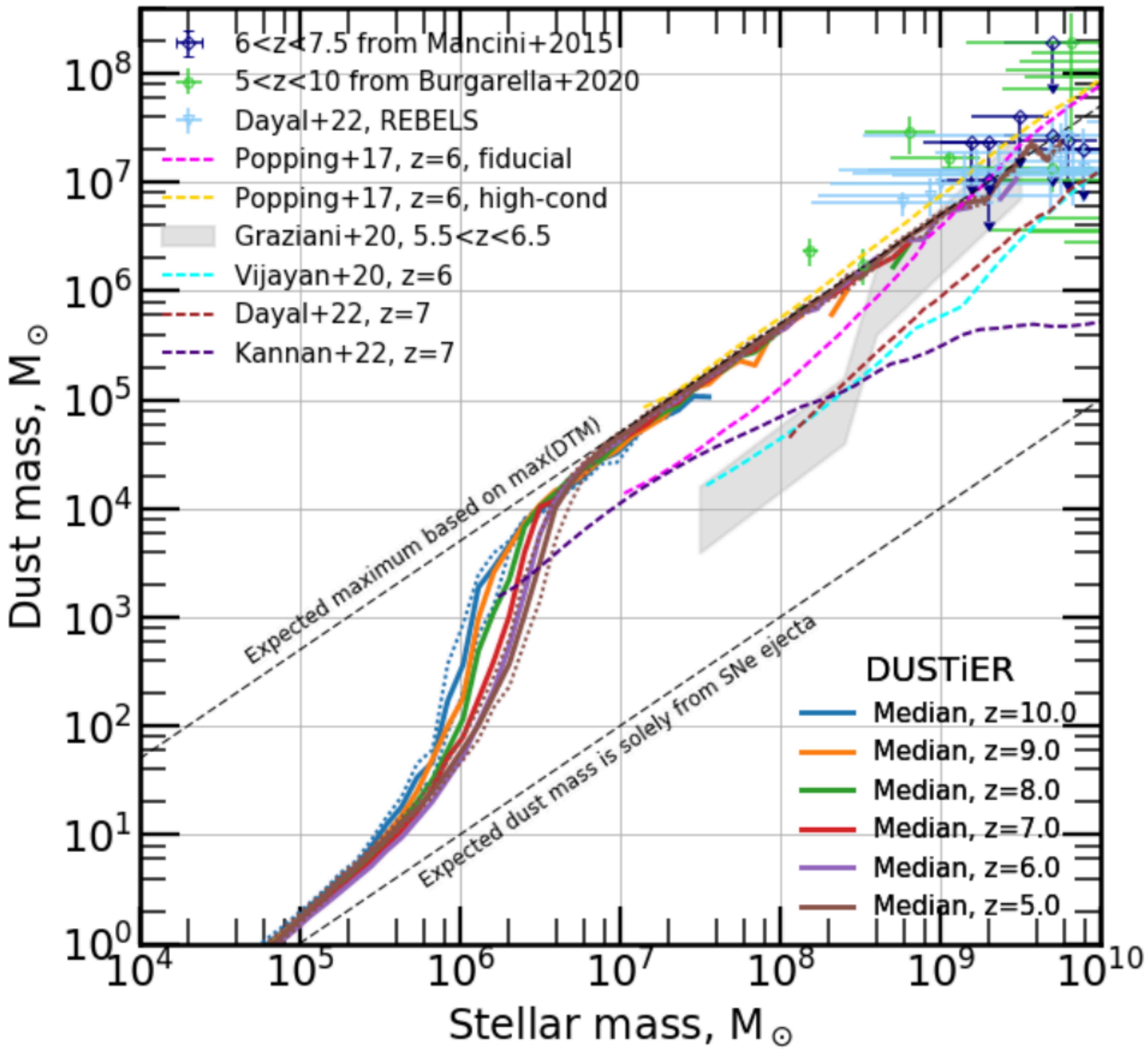
$$\mathrm{t_{growth}} = 100\,\alpha^{-1}(\mathrm{T})\,\mathrm{a_{0.1}}\,\mathrm{n_{gas}^{-1}}\left(\frac{\mathrm{T}}{20\mathrm{K}}\right)^{-0.5}\mathrm{Myr}$$

$$\Delta\mathrm{M_{dest,SN}} = 0.3\frac{\mathrm{M_{s,100}}}{\mathrm{M_g}}\mathrm{M_d}\,\mathrm{M_\odot}$$

$$\mathrm{t_{dest,sput}} = 0.1\,\mathrm{a_{0.1}}\,\mathrm{n_{gas}^{-1}}\left(1 + \left(\frac{10^6\mathrm{K}}{\mathrm{T}}\right)^3\right)\mathrm{Myr}$$

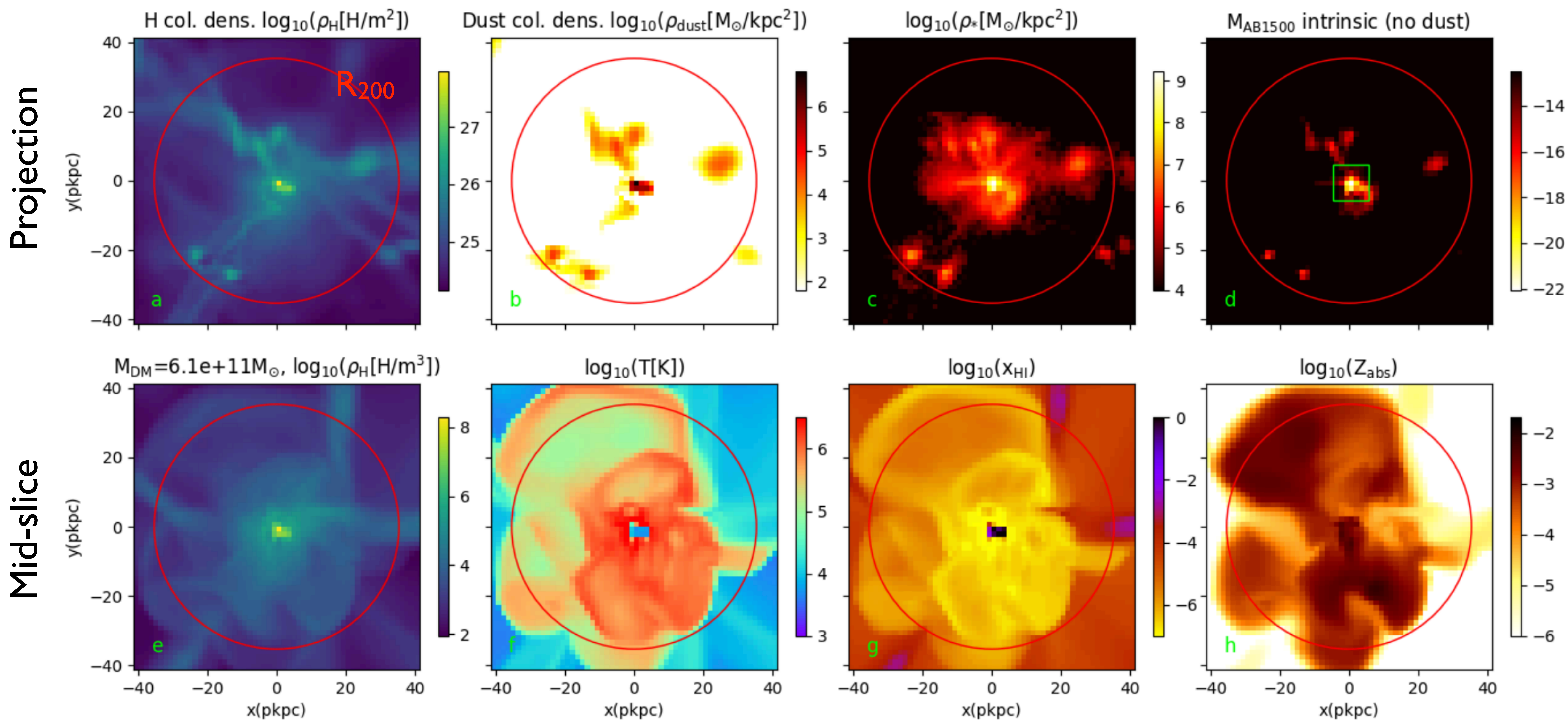
Cosmic Dawn III dust model

Lewis et al. 2023



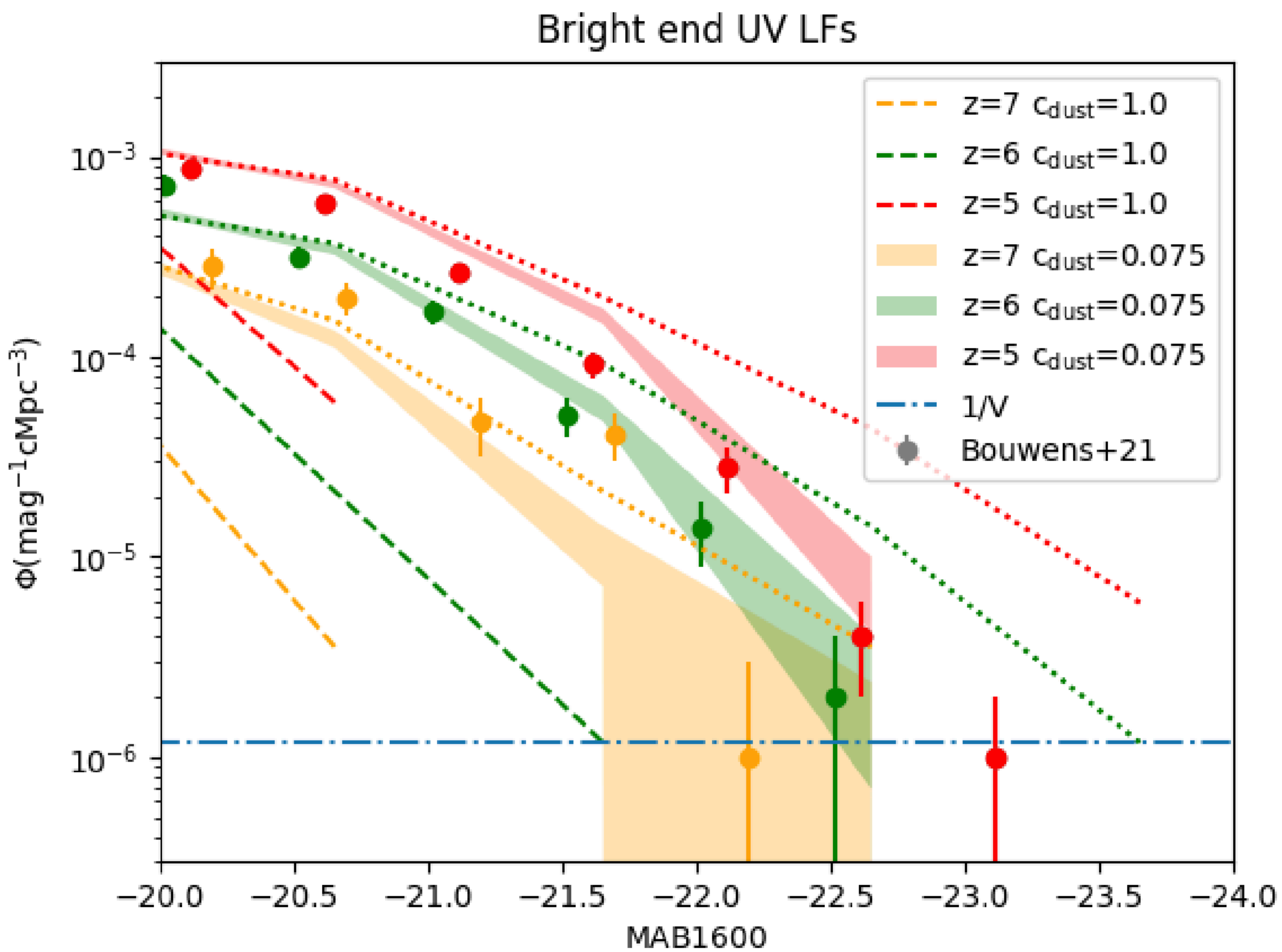
- Obs. constraints at $M_* > 10^8\ M_\odot$
- good match at massive end
- No constraints at lower mass
- Saturated behaviour due to:
  - fairly low dust condensation from SN
  - fast increase through grain growth
  - inefficient destruction
- Max(DTM)=0.5 hard threshold

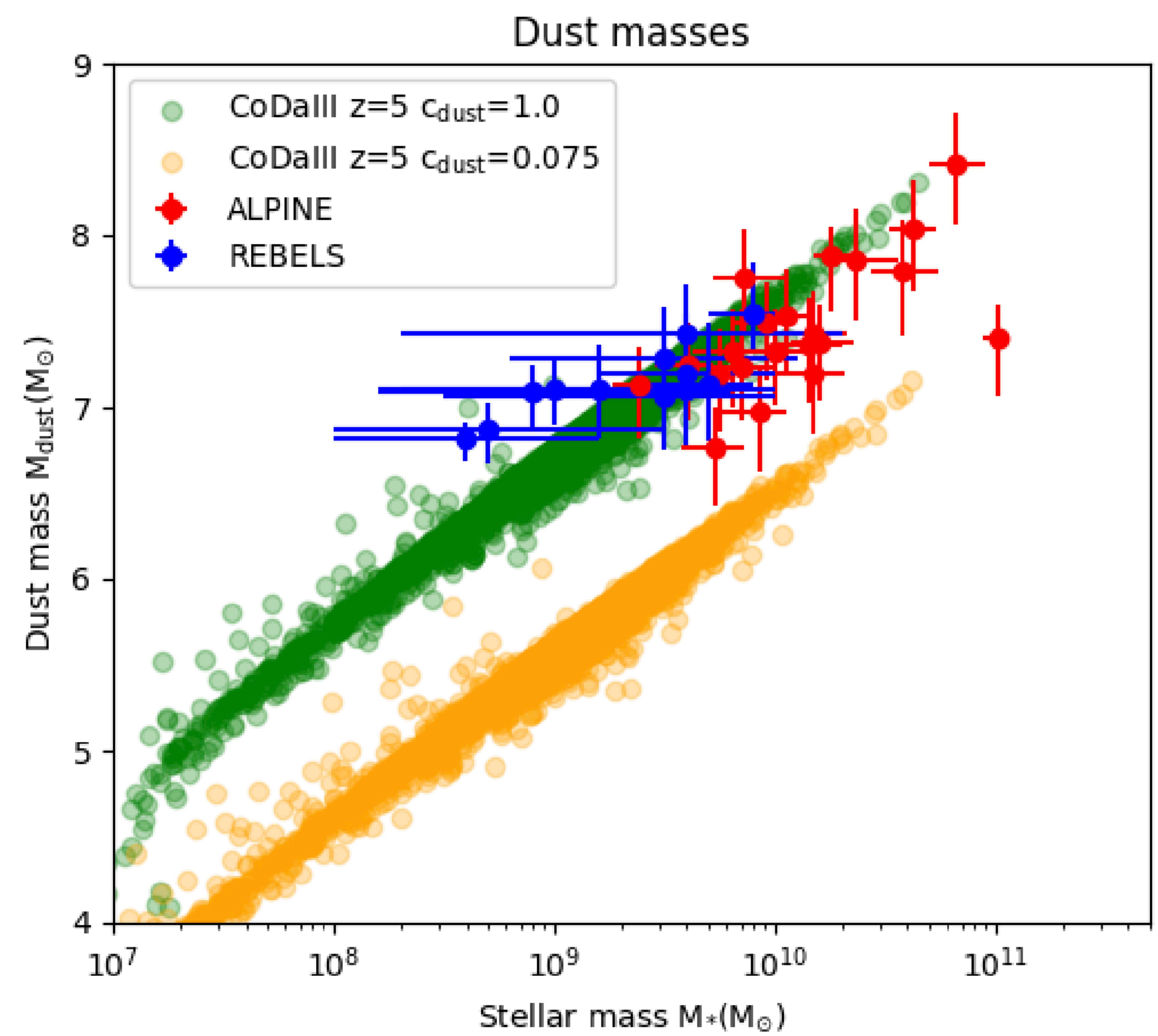
A massive z=7 halo in Cosmic Dawn III



- $M_{DM}=6x10^{11}$ $M_{\odot}$
- Typical filamentary accretion
- Strong SN shocks & winds
- Significant sub-structure
- Distinct cool, neutral center

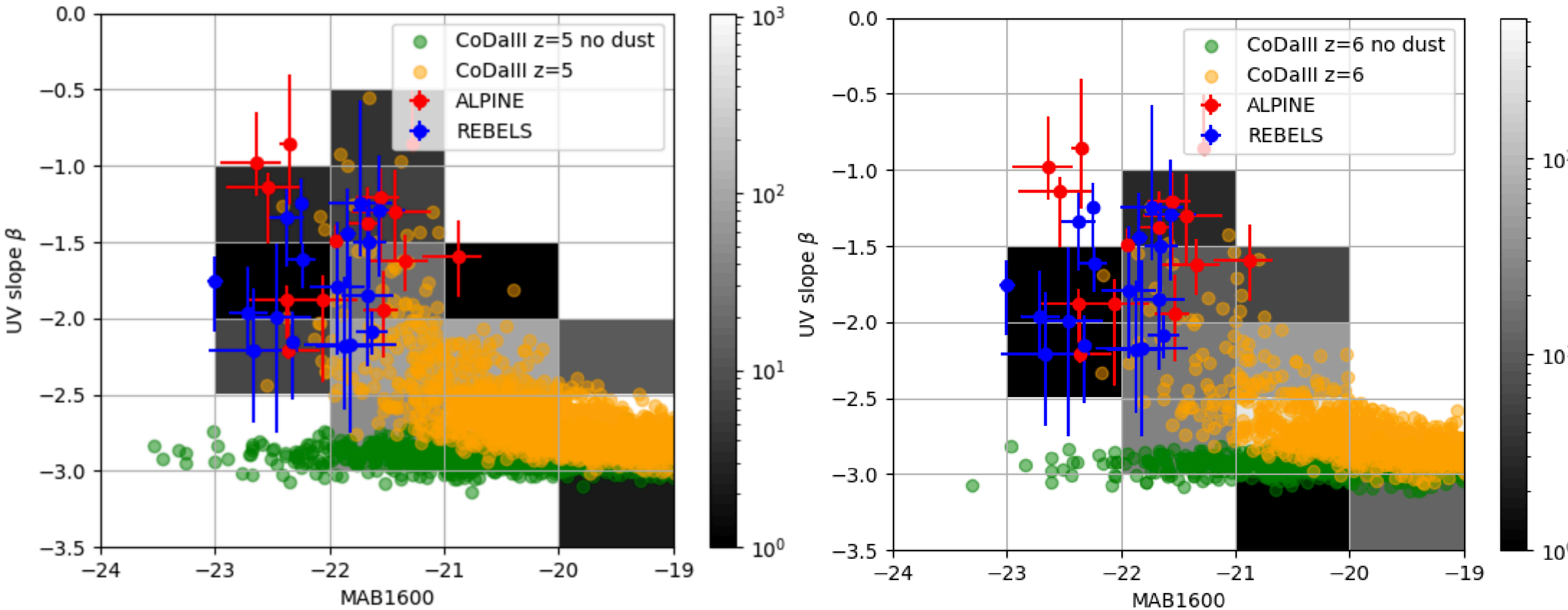
Dust recalibration





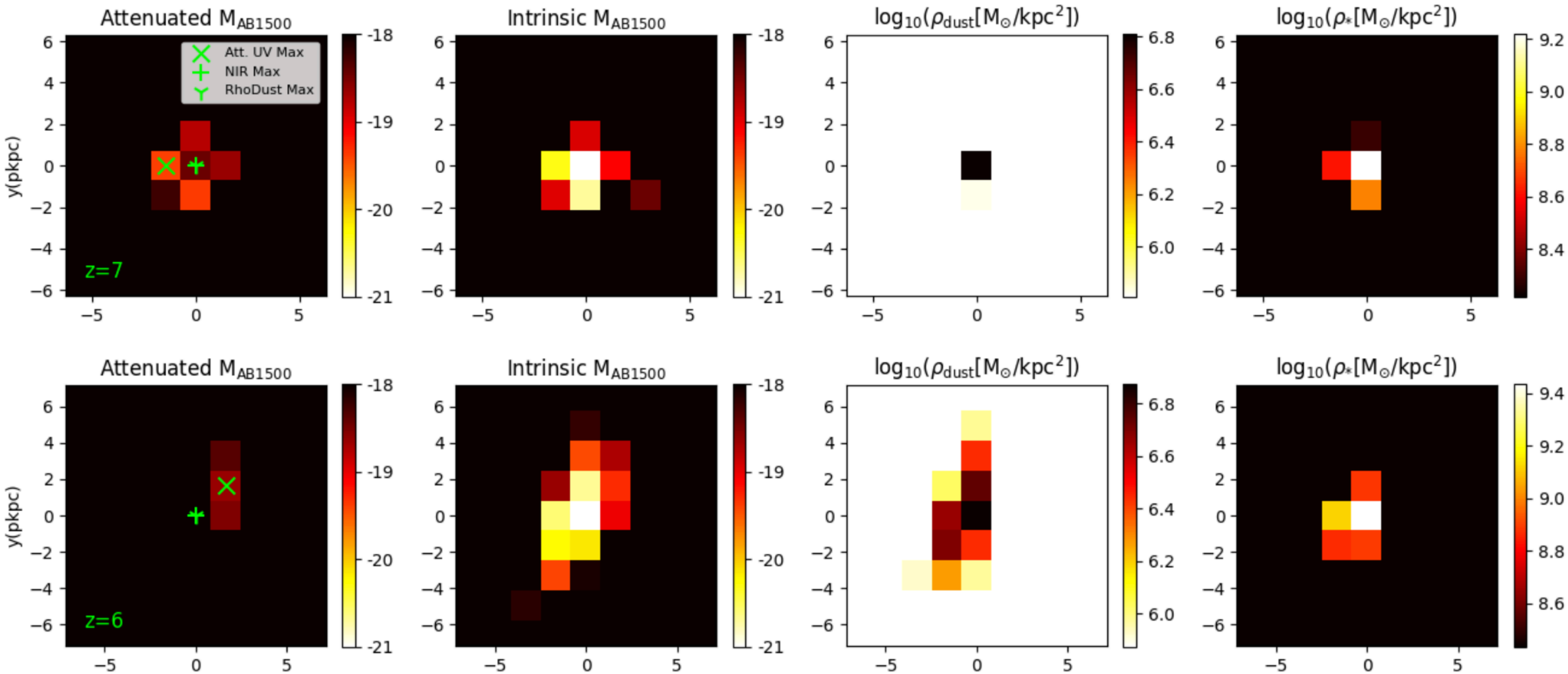
- Galaxy absolute mags computed using simple 1d dusty RT.
- Full CoDaIII dust content undershoots UVLF
- No dust overshoots UVLF
- Agreement for 7.5% of CoDaIII dust mass => undershoots observed M_{dust}
- Discrepancy alleviated if grain size > $0.1\mu m$? Draine & Li SMC?

Dust recalibration



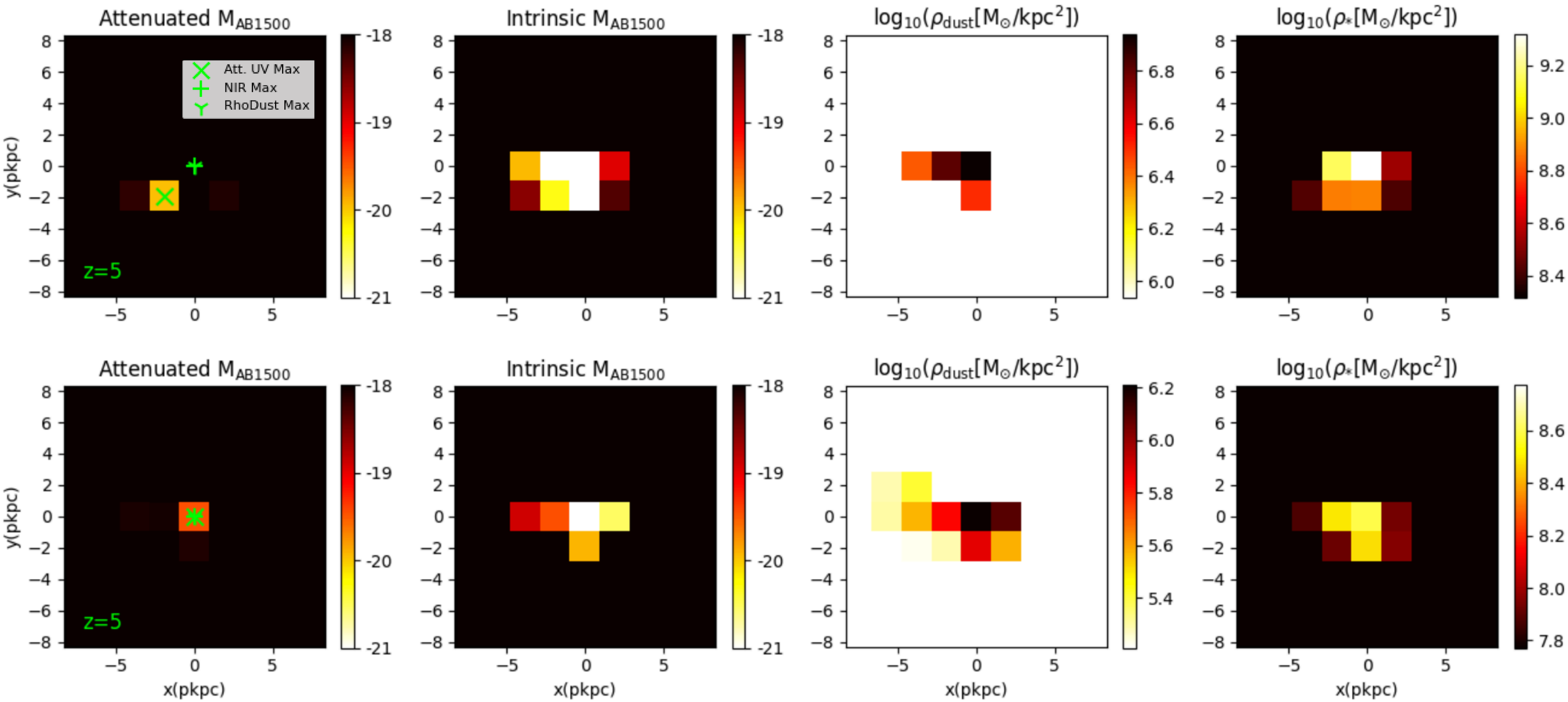
- Agreement obtained using only 7.5% of CoDaIII dust mass….
- Under this assumption, sample overlaps in UV slope and mags with ALPINE+REBELS
- Difficult to do quantitatively because of obs. selection functions.

Massive galaxies in Cosmic Dawn III



- 1d RT of UV photons through dust (no IR RT)
- Intrinsic UV, dust (Y) and stellar mass (+) are well-aligned
- Heavy dust attenuation results in offset transmitted UV (X) …
- …but not always

Massive galaxies in Cosmic Dawn III



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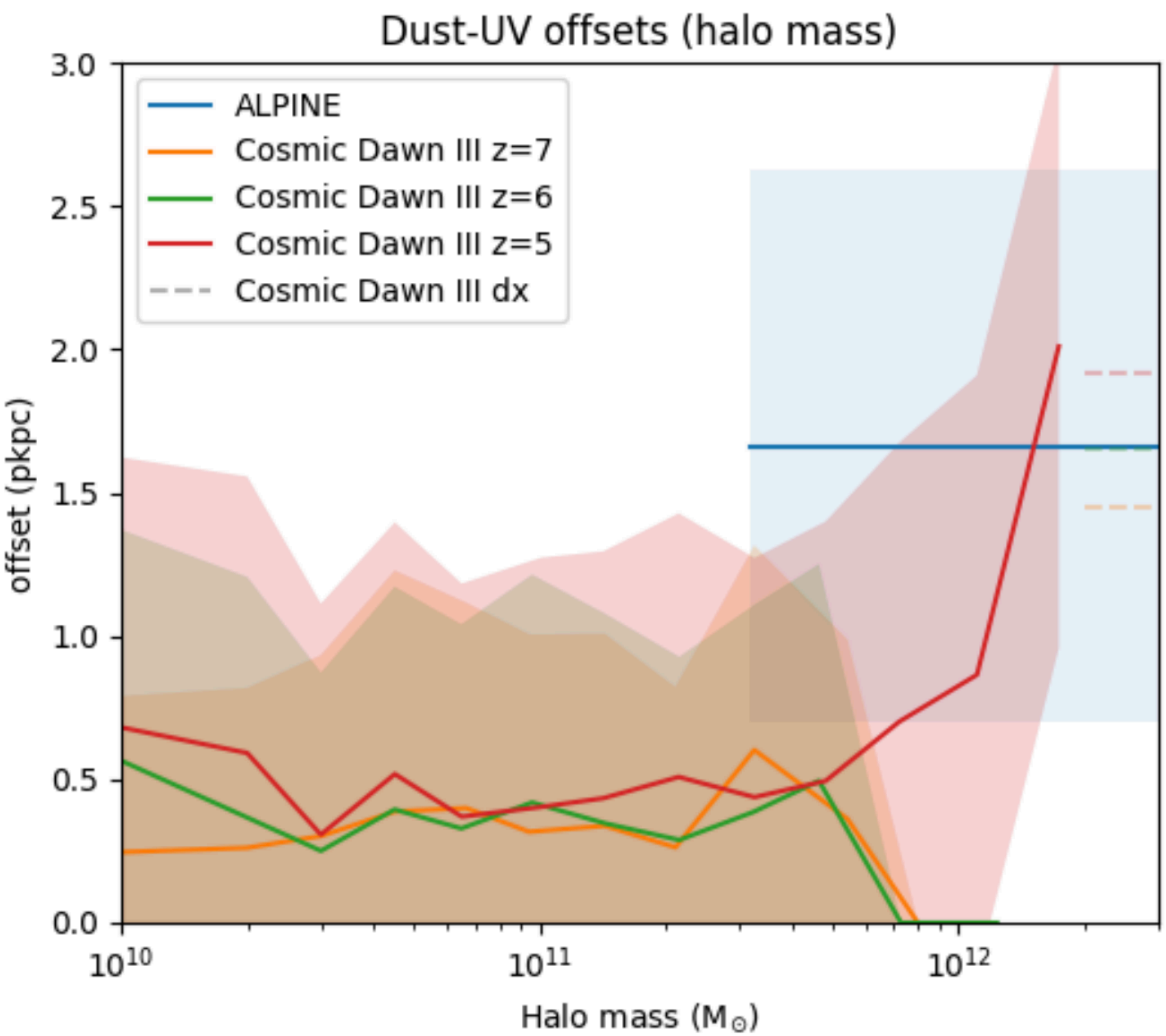
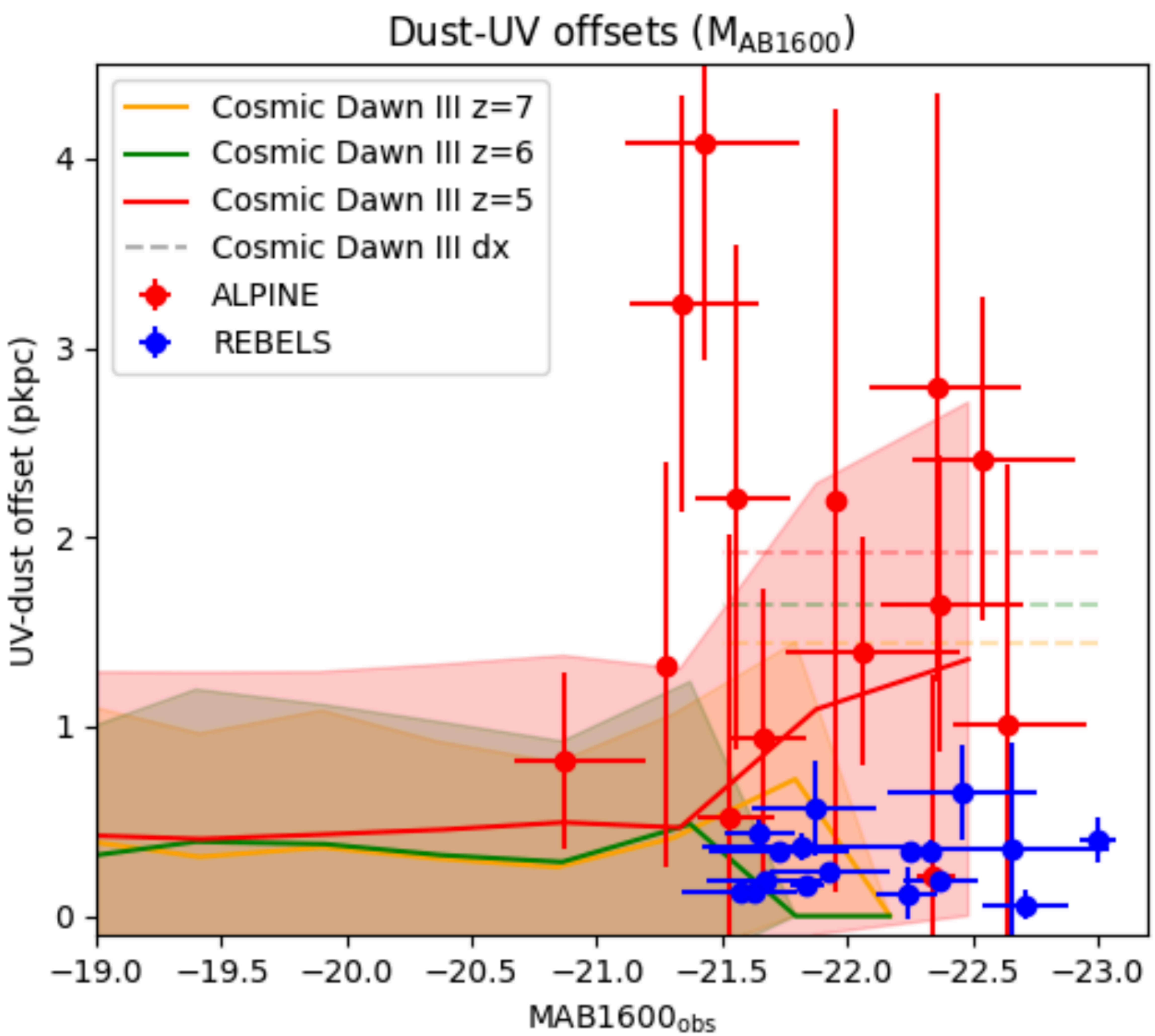
Dust-UV offsets = f(halo mass)



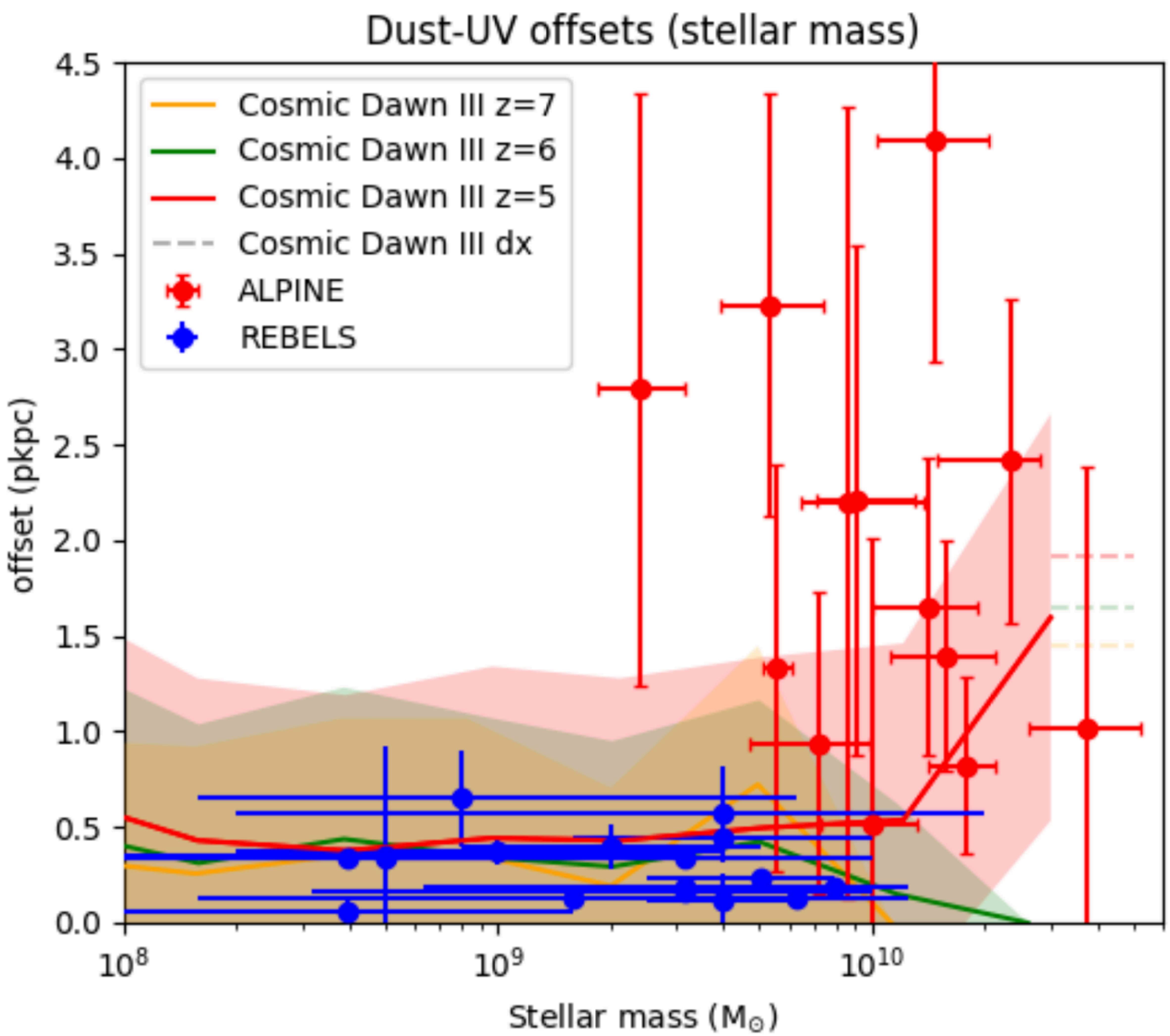
- Offset increases with M_{DM}
- Wide spread
- No redshift trend
- At 10^{12} $M_\odot$, offset comparable with ALPINE+REBELS
- Average offset ~ cell size
- => high mass offsets are at the resolution limit of the simulation
- Smaller offsets at lower masses not ruled out

Dust-UV offsets = f(M_{AB1500})



- Offset increases with galaxy UV luminosity
- Wide spread
- No clear redshift trend
- ALPINE and REBELS samples seem to describe 2 different regimes
- Same range of magnitudes but very different offsets.

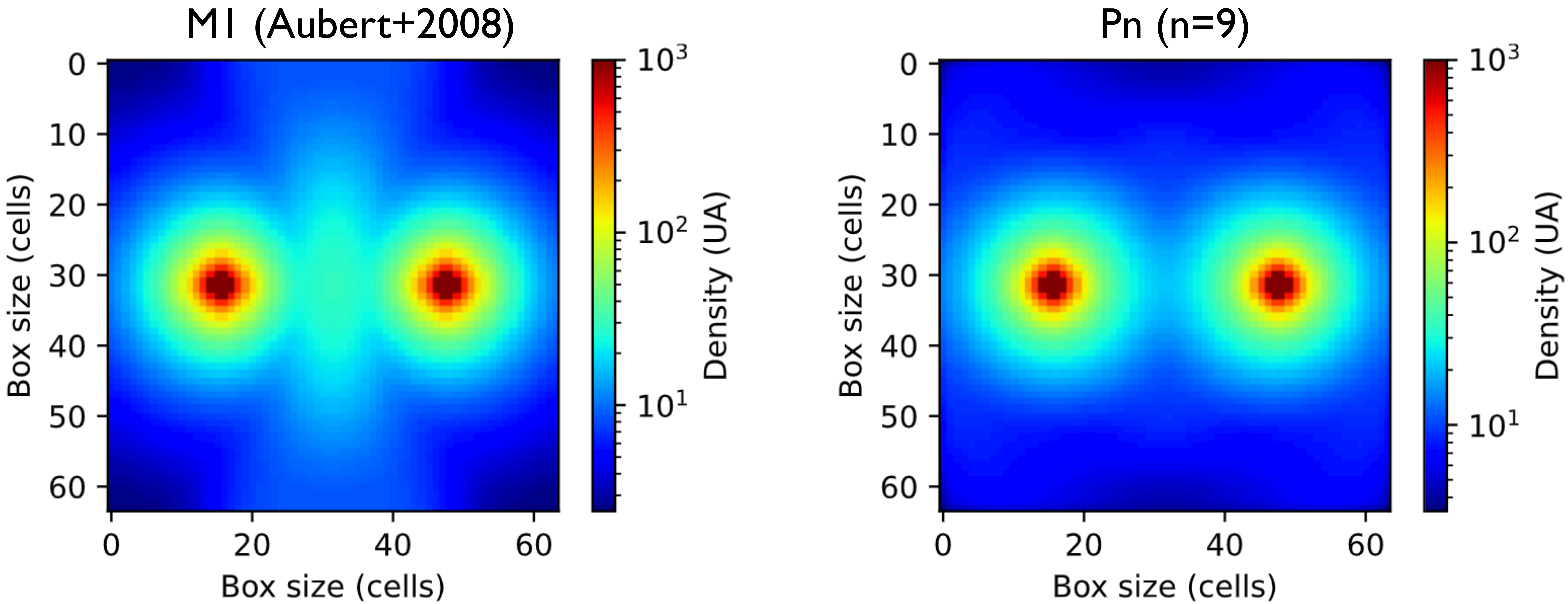
Dust-UV offsets = f(M_{star})



- Offset increases with galaxy stellar mass
- Wide spread
- No clear redshift trend
- High stellar mass mass galaxy sample comparable with ALPINE
- Low stellar mass (<$10^{10}M_\odot$) comparable to REBELS sample

4 - Pn: a « new » RT method for astrophysical simulations

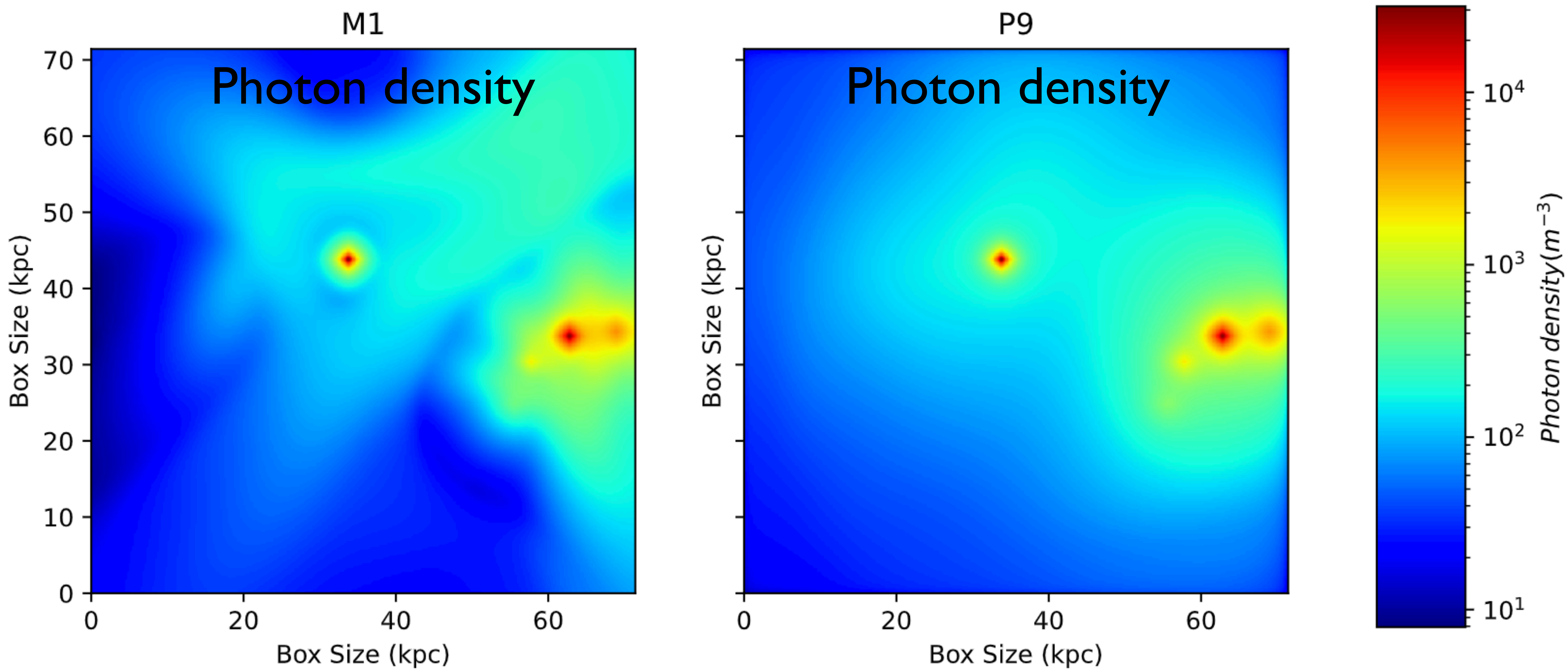
Artefacts of M1 RT model



- 2 isotropic continous sources
- Collisional behaviour of M1 produces spurious pseudo-sources and anisotropy.
- Pn (n=9 here) is free of such artefacts.

Palanque+2025, arxiv:2508.02453

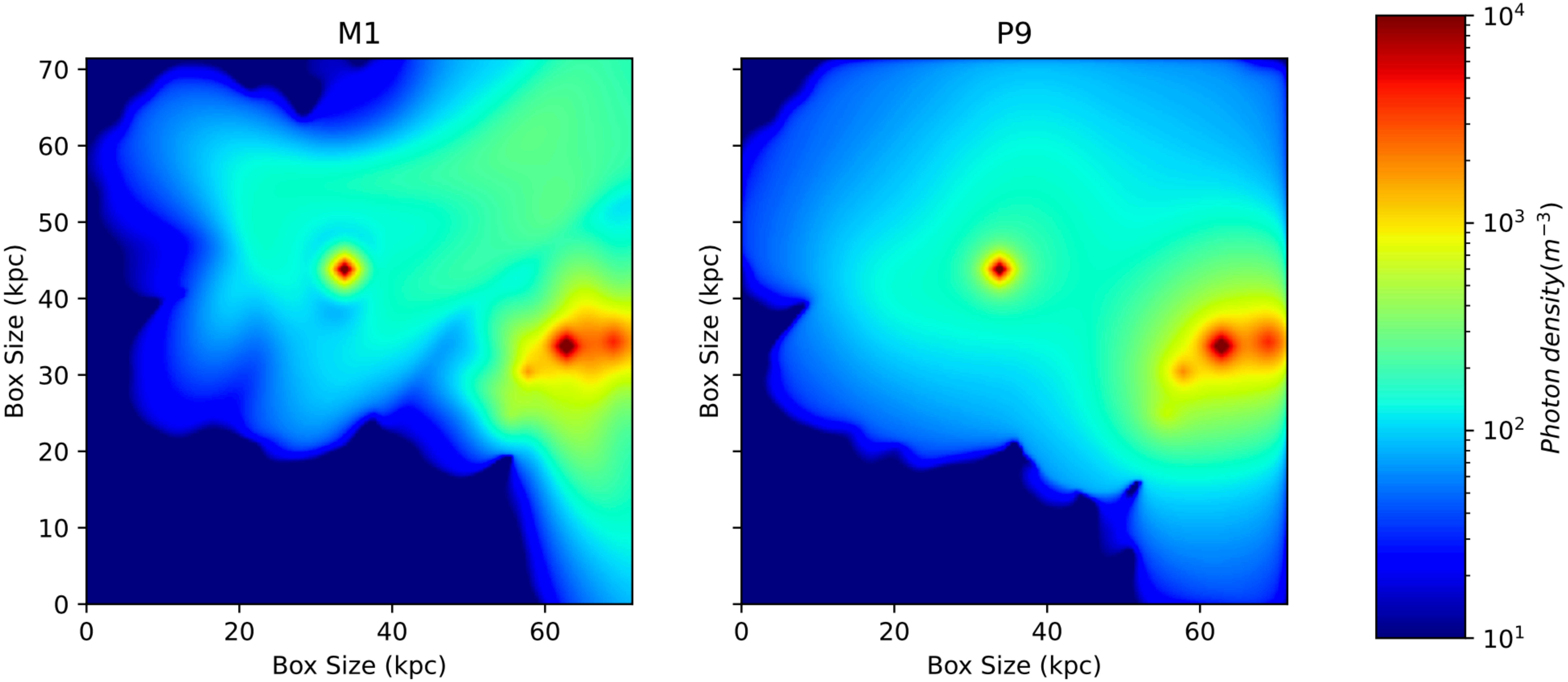
Artefacts of M1 RT model



- Iliev 2006 test 4 (multiple sources in a cosmo density field) at t=4Myr
- In this regime, any deviation from spherical symmetry is an artefact
- Multiple artefacts in M1, including a dark sombrero
- P9 is 25 times more expensive than M1 in CPU and RAM

Palanque+2025, arxiv:2508.02453

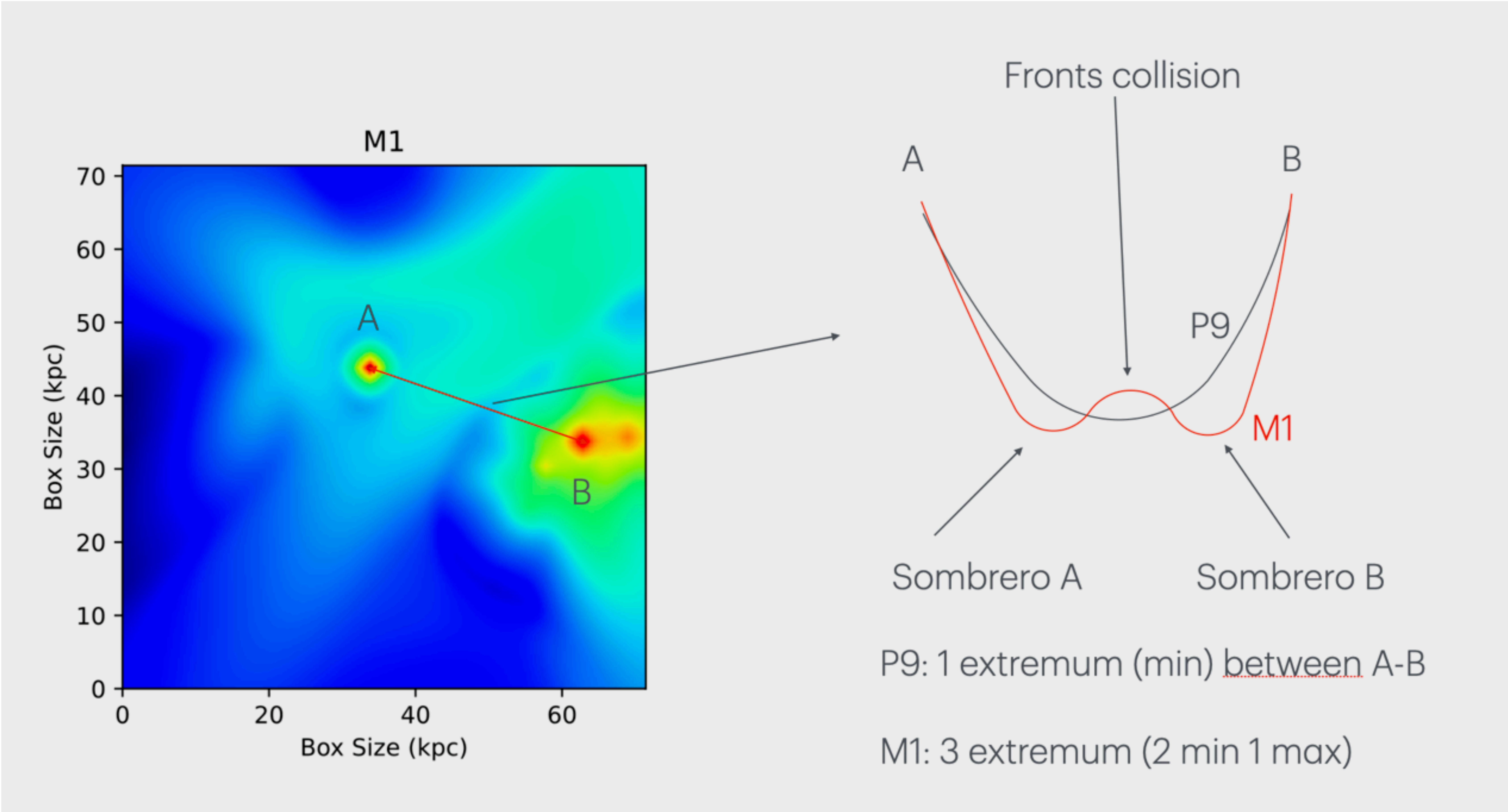
Artefacts of M1 RT model



- Iliev 2006 test 4 (multiple sources in a cosmo density field) at t=0.4Myr
- Box is ~70% ionized
- Artefacts and sombrero still visible

Palanque+2025, arxiv:2508.02453

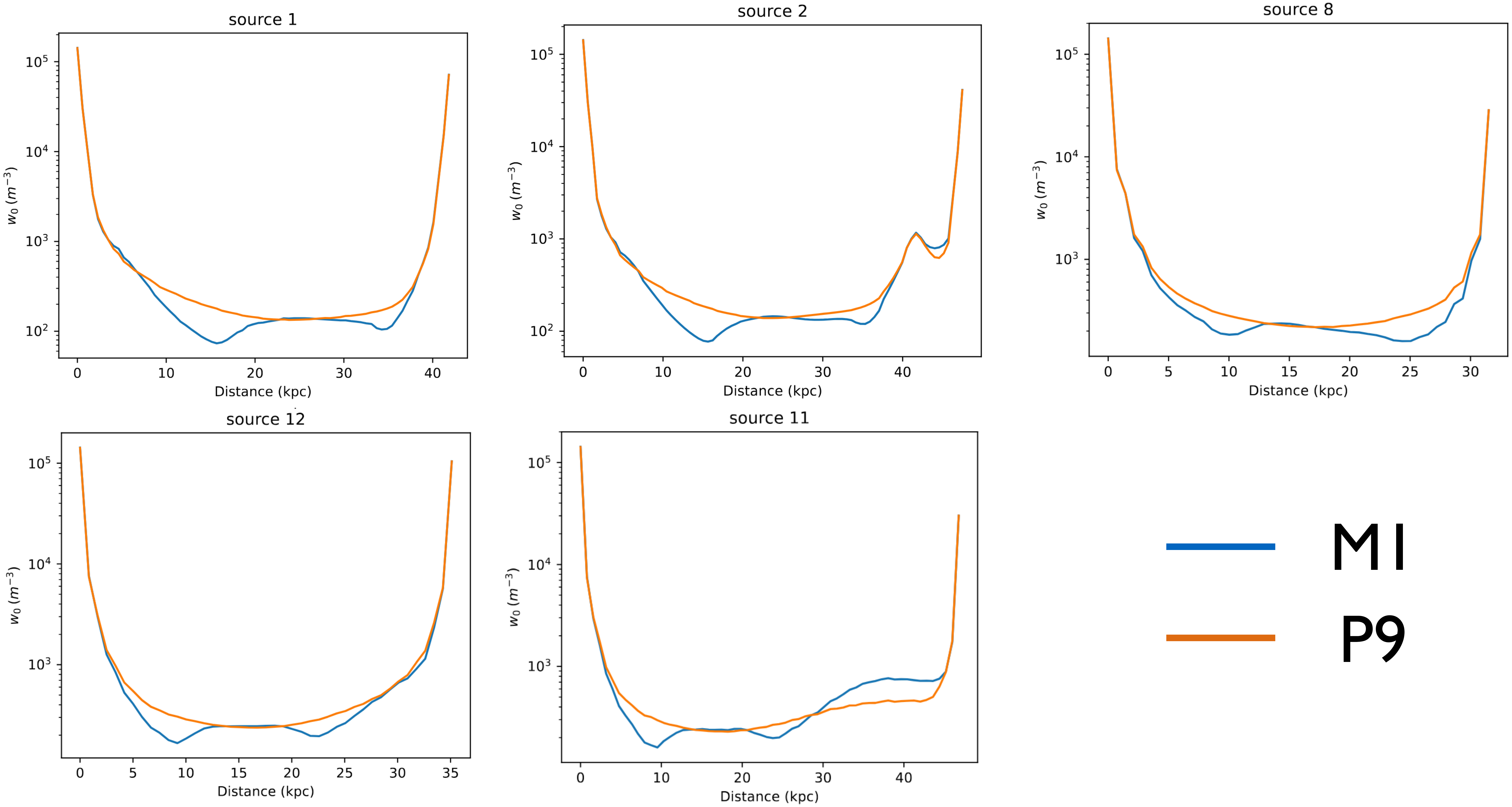
Artefacts of M1 RT model



- Dark Sombrero emerges as a negative 'compensation' for the photon overdensity building up where fronts collide.
- => should be everywhere

Palanque+2025, arxiv:2508.02453

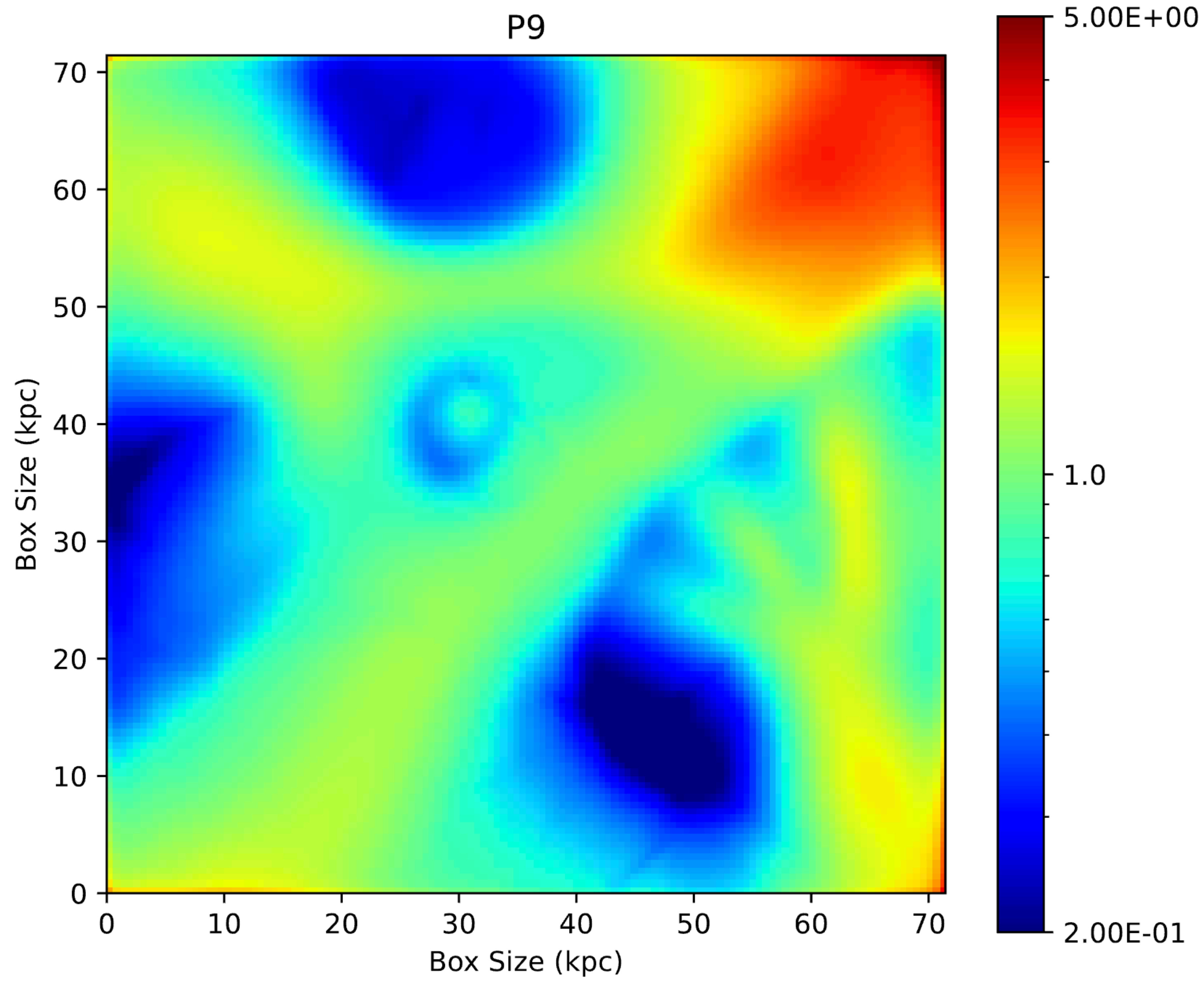
Dark sombreros everywhere

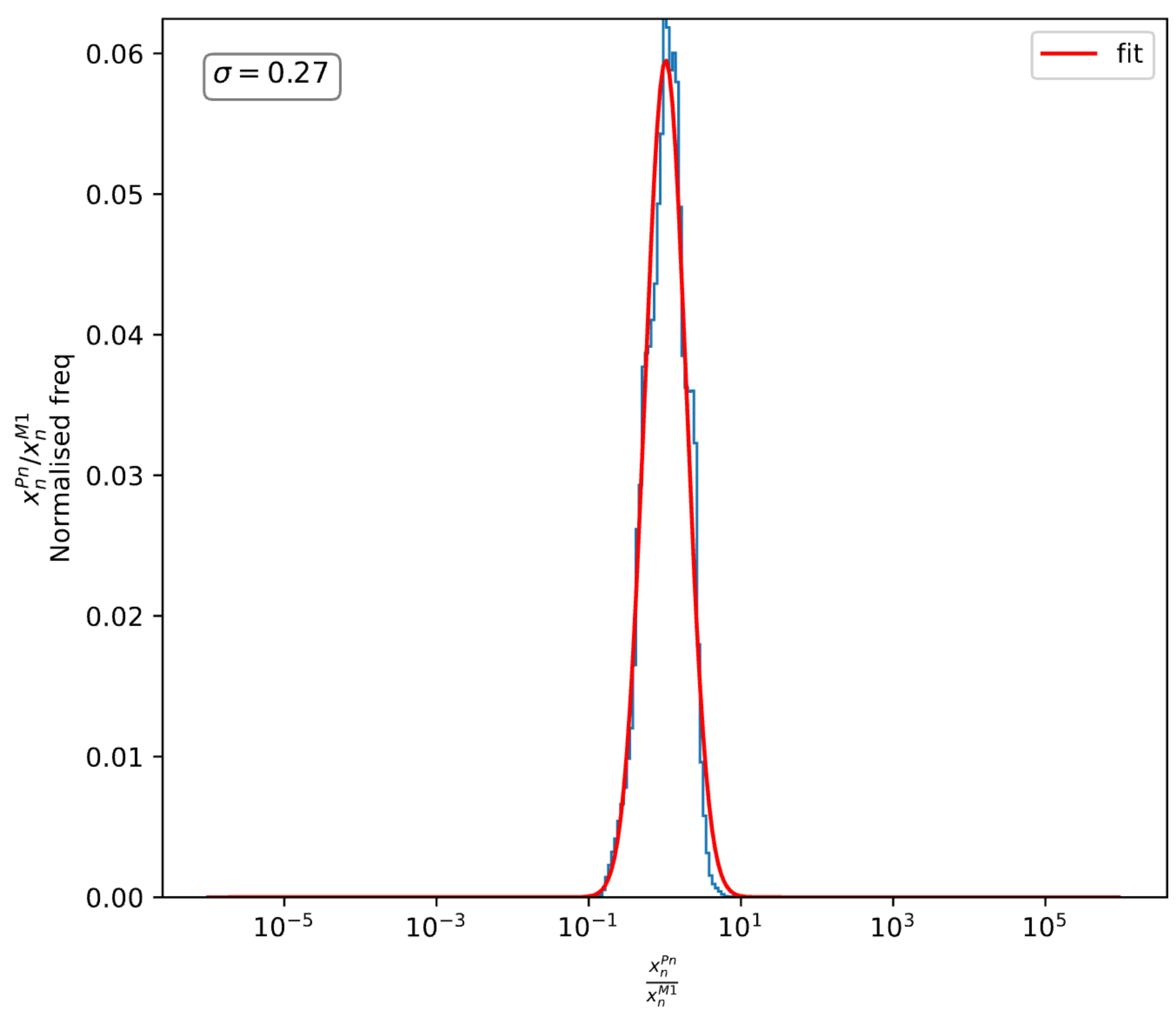


- Plotting photon density along a line between 2 sources in the volume
- Dark sombreros are ubiquitous, sometimes less obvious due to complex geometry

Palanque+2025, arxiv:2508.02453

Impact on HI neutral fraction x_{HI}

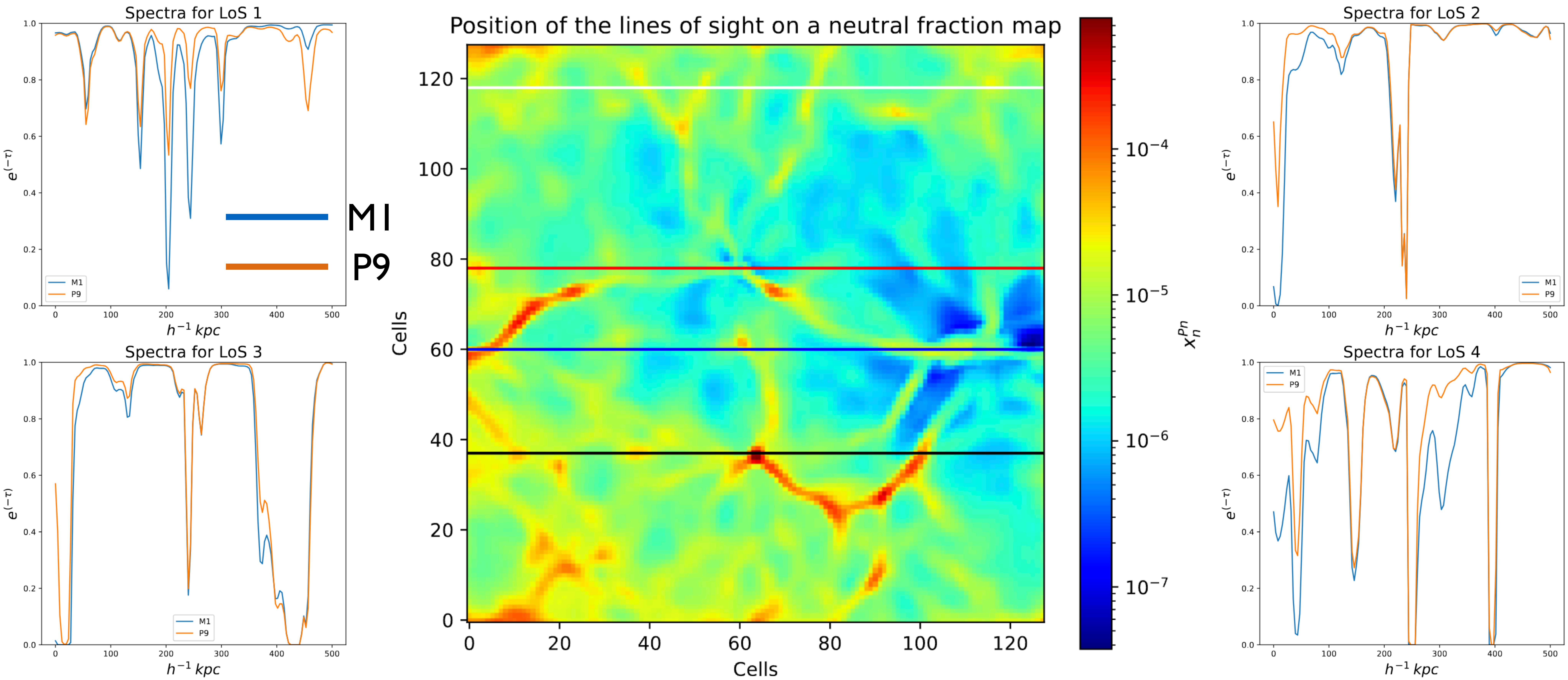




- Map of relative neutral fraction error: $x_{HI}(P9)/x_{HI}(M1)$
- Artefacts and dark sombrero are visible
- Distribution of error ~ Gaussian, rms=0.27 dex (i.e. ~2 or 0.5)

Palanque+2025, arxiv:2508.02453

Impact on Lyman alpha forest



- Lyman-alpha QSO pseudo-spectra for 4 LoS
- Marked differences are visible, M1 more opaque but not always
- Ideally, need to run a large reionization sim with P9 => port to Dyablo?

Palanque+2025, arxiv:2508.02453

Summary

- Dust-UV offsets naturally occur in massive Cosmic Dawn III galaxies due to severe dust attenuation in galaxy centers
- Offsets increase with halo mass / galaxy luminosity / stellar mass
- No clear redshift trend between z=5-7
- Average offset is 1-2 pkpc at $M_{DM}=10^{12}$ $M_{\odot}$ / M_{AB1500}=[-21,-20]
- Compatible with ALPINE + REBELS samples
- Ideally, revisit with high-res sims such as OBELISK, NewCluser?

- Numerical schemes matter: (Palanque+25)
  - M1 (dark sombreros, collisional behaviour) results in systematic relative errors on photon density, xHI of a factor 2 in rms in cosmo RT test
  - P9 more accurate but 25x more expensive than M1 in mem and cpu
- However, current tests are idealised, what about full physics sims?
- Improving physics, resolution, volume requires exascale computing power
- => ideally, implement P9 in dyablo / Shamrock / mini-ramses / ramses

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