ON THE EMERGENT STRUCTURES AT COSMIC DAWN

THE FIRST STARS AND GALAXIES IN THE UNIVERSE

Pre-defence seminar

Anton Vikaeus

15/6 2023

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Image credit: ESO / M. Kornmesser.

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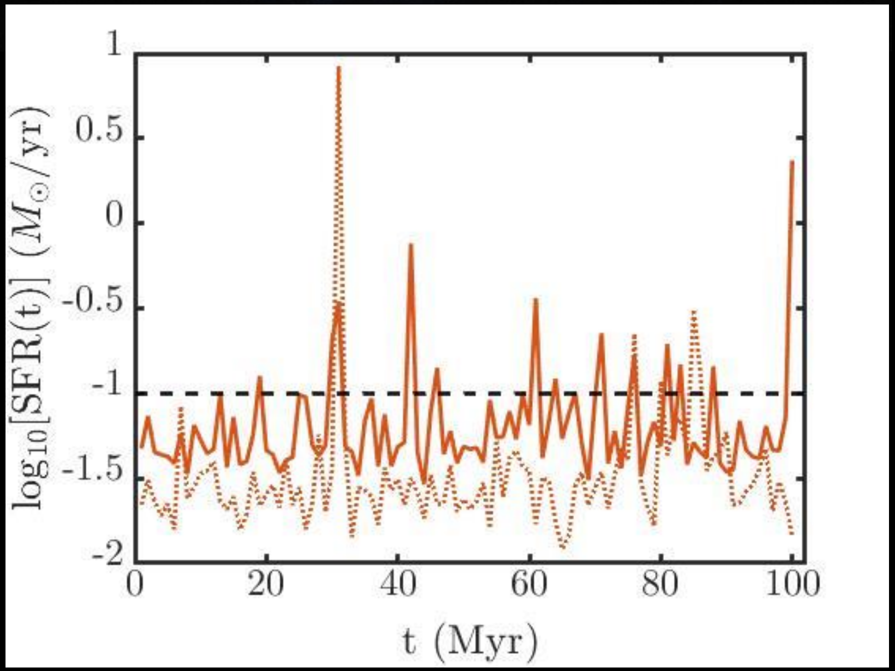

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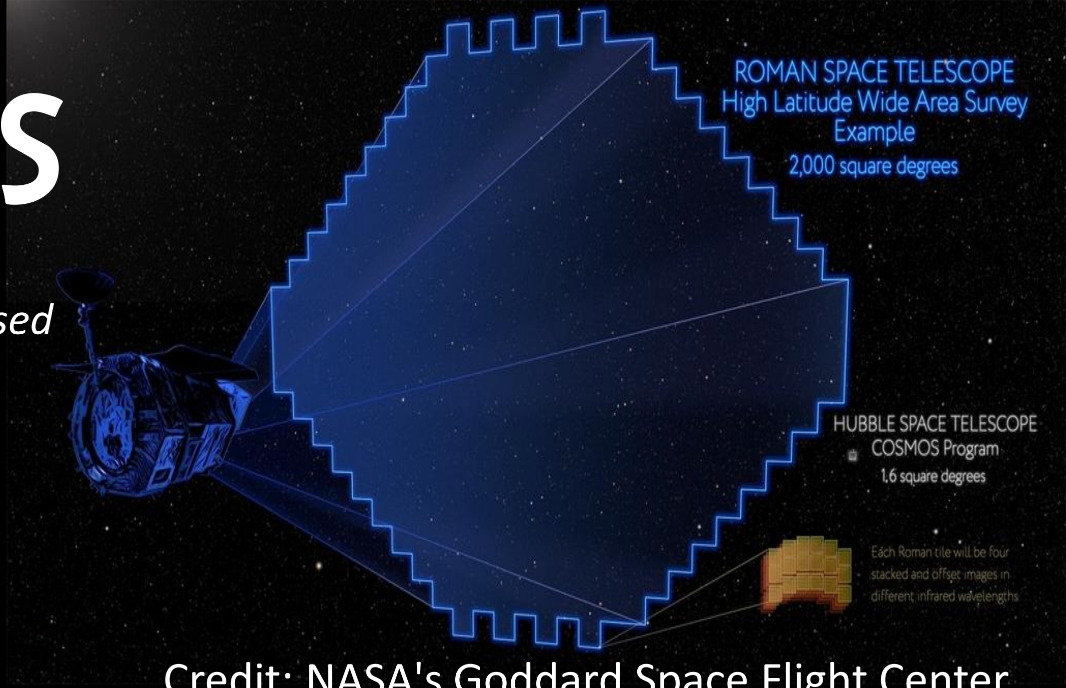

Credit: NASA's Goddard Space Flight Center

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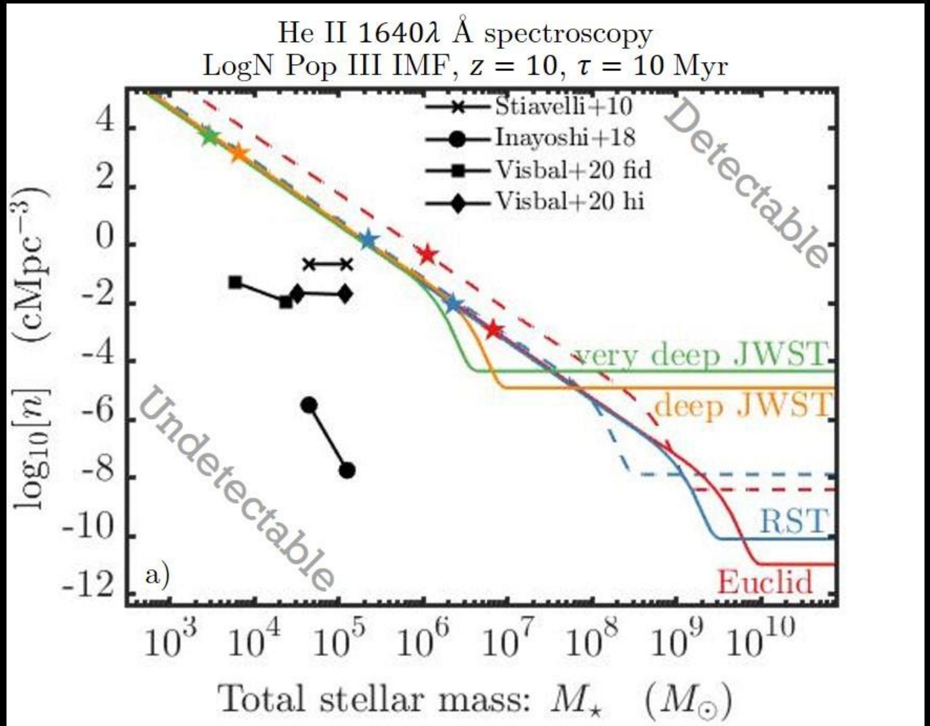

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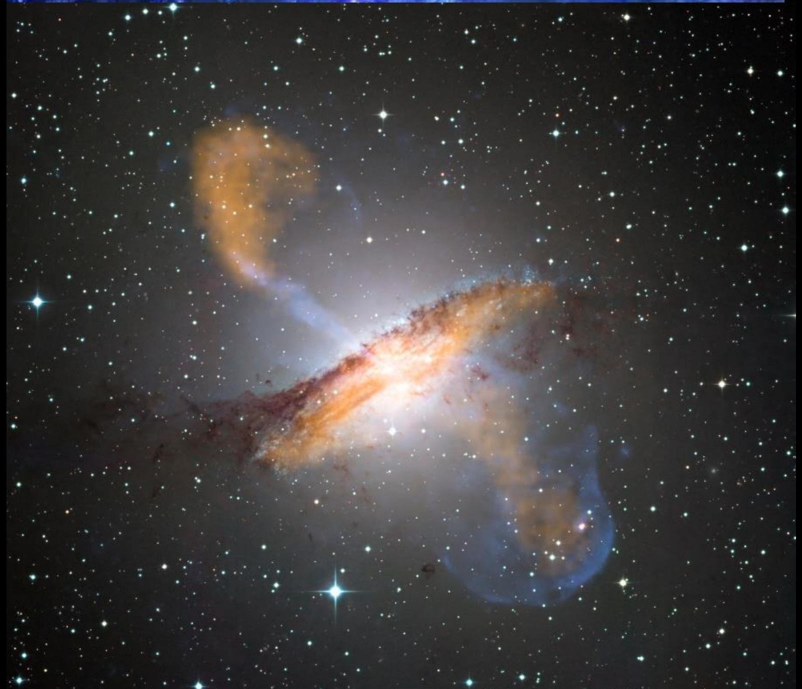

Image: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

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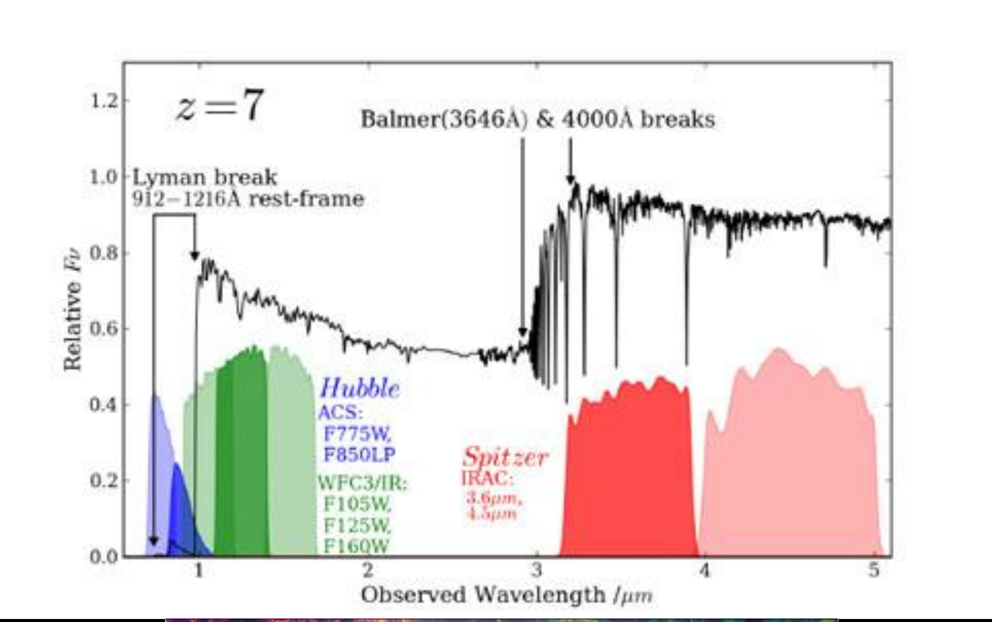

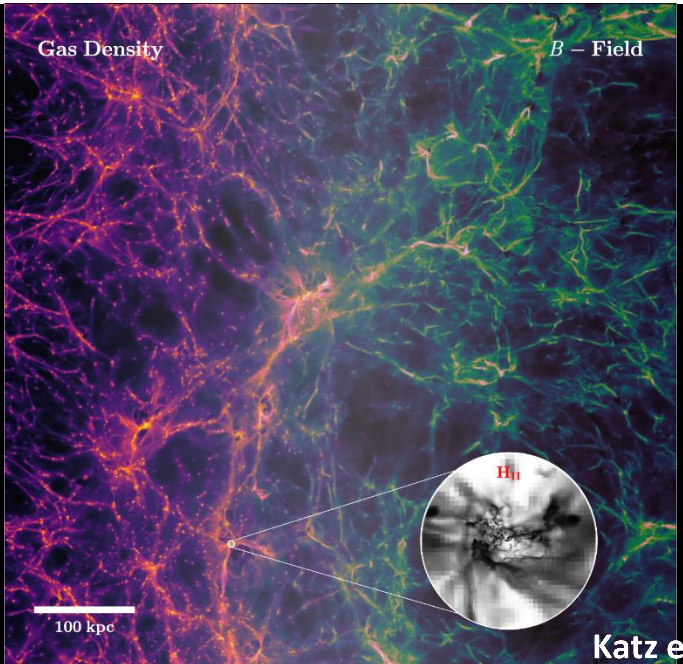

Katz et al 2022

PRELUDE

In a broader sense, there are two routes followed in the thesis:

Modeling the early Universe

- Abundance of star forming halos (minihalos, atomic cooling halos)
- Gas cooling (primordial gas) –> Star formation -> Feedback
- Gas enrichment (Pop III –> Pop I/II)
- Stellar initial mass functions (related to uniqueness of Pop III signatures etc)

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Observing the early Universe

- Identification of high redshift objects (SED-fitting, continuum features, emission lines) -> Observation signatures of Pop III etc.
- Gravitational lensing (cluster lensing, probability for lensing in blank fields)
- Infrared observations e.g., JWST, RST, ELT and many other present telescopes
- Mapping the Universe at high redshifts --> Closing the gap towards cosmic dawn

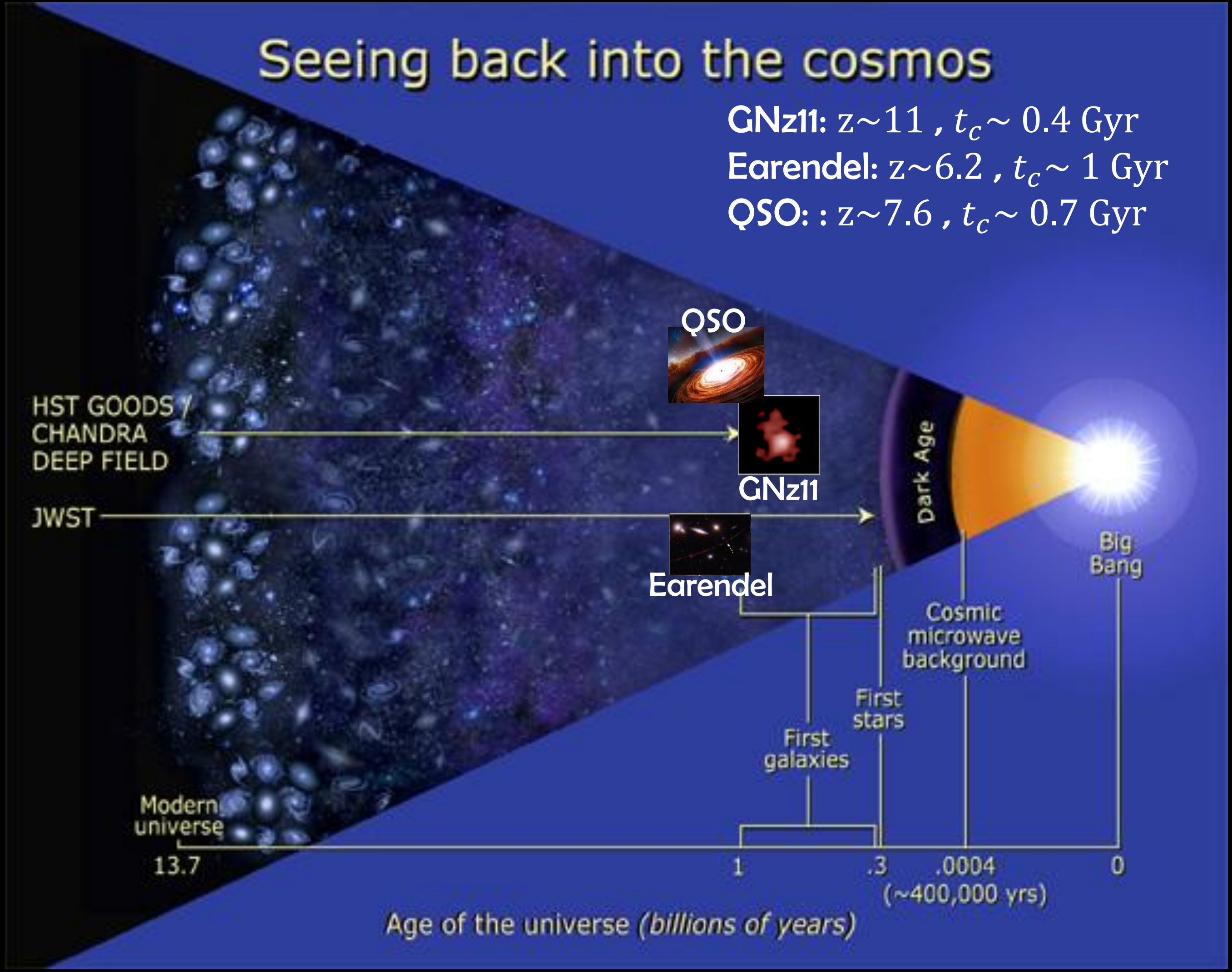
THE REDSHIFT FRONTIER

Hubble (and others) barely reaches the epoch where the first galaxies formed (GNz11, at z~11)

Detected the most distant star observed – Earendel at z~6.2 (possible binary!)

Detected quasars at extreme redshifts – QSO J0313–1806, at z~7.6

Acquired ~ $10^9\ M_\odot$ BH in ~ 0.7 Gyr of cosmic time



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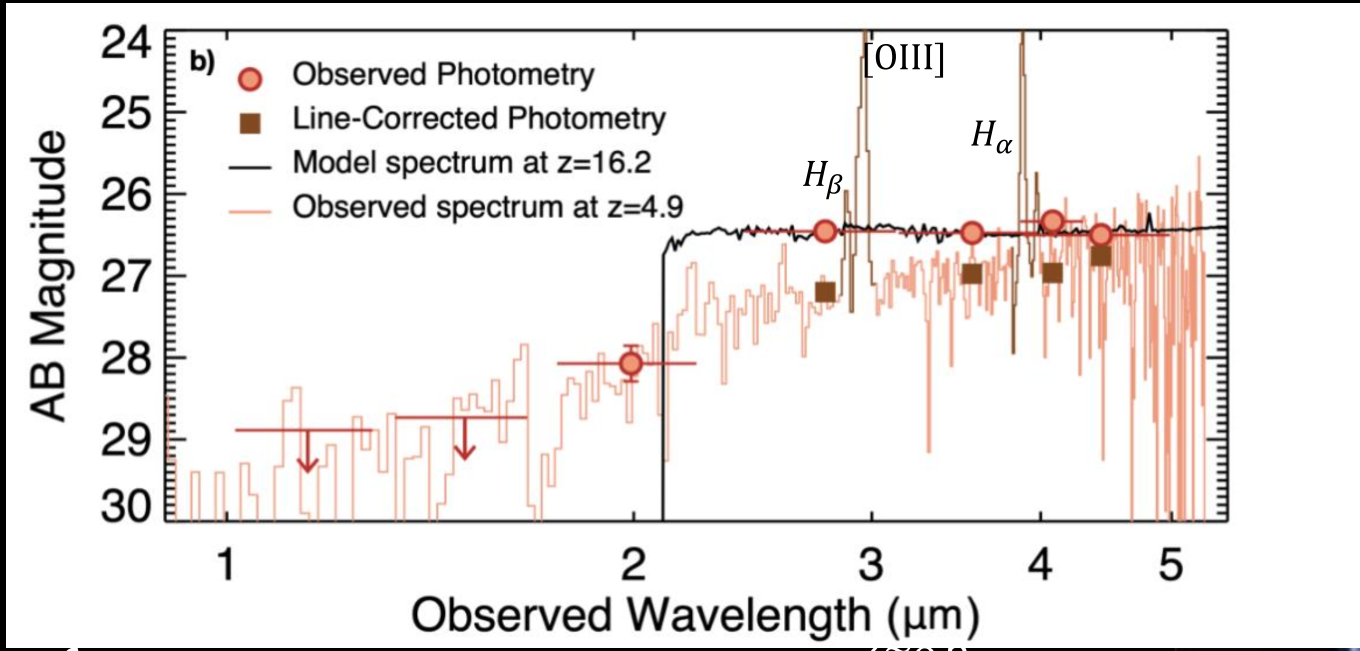
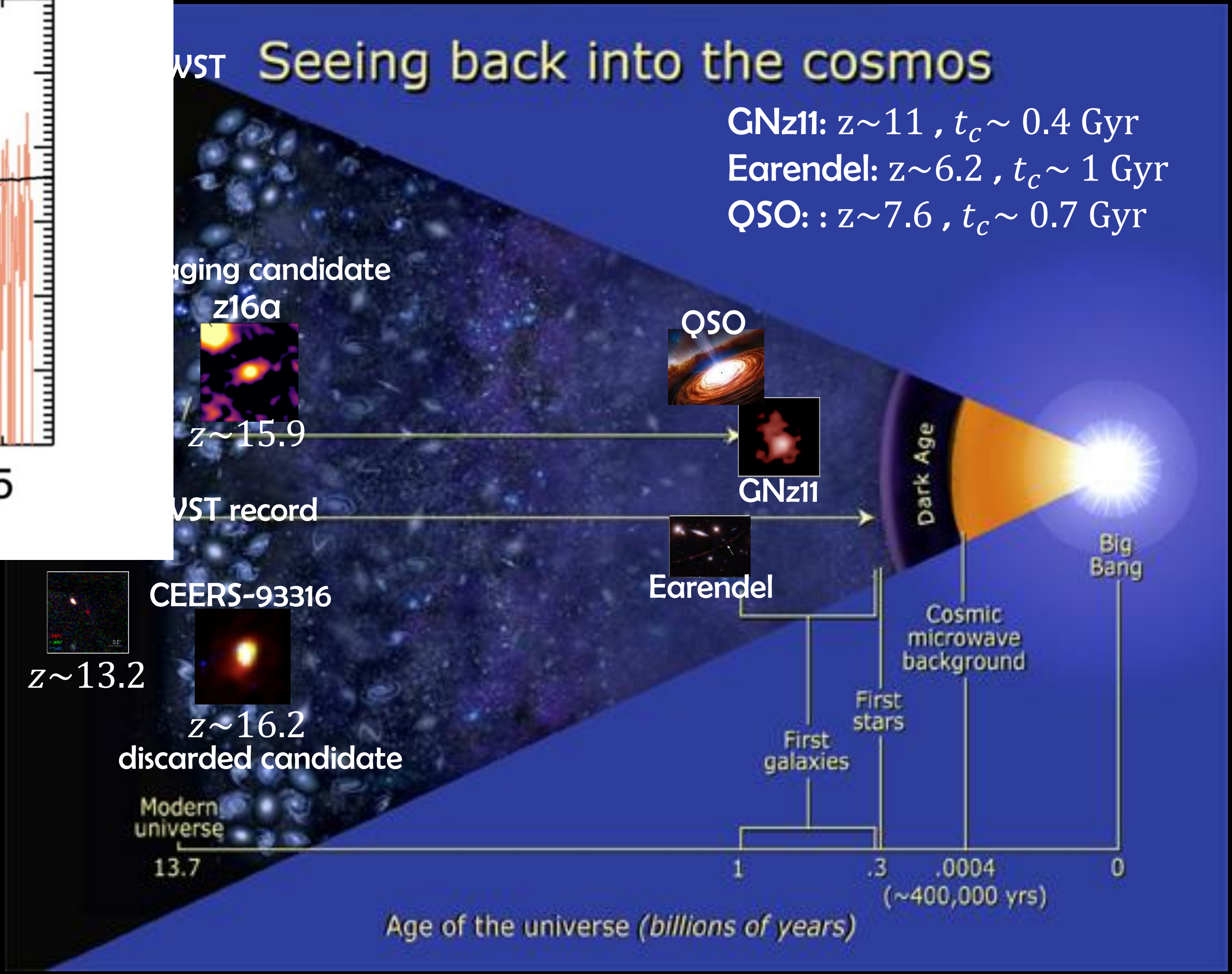


from spectrocopy



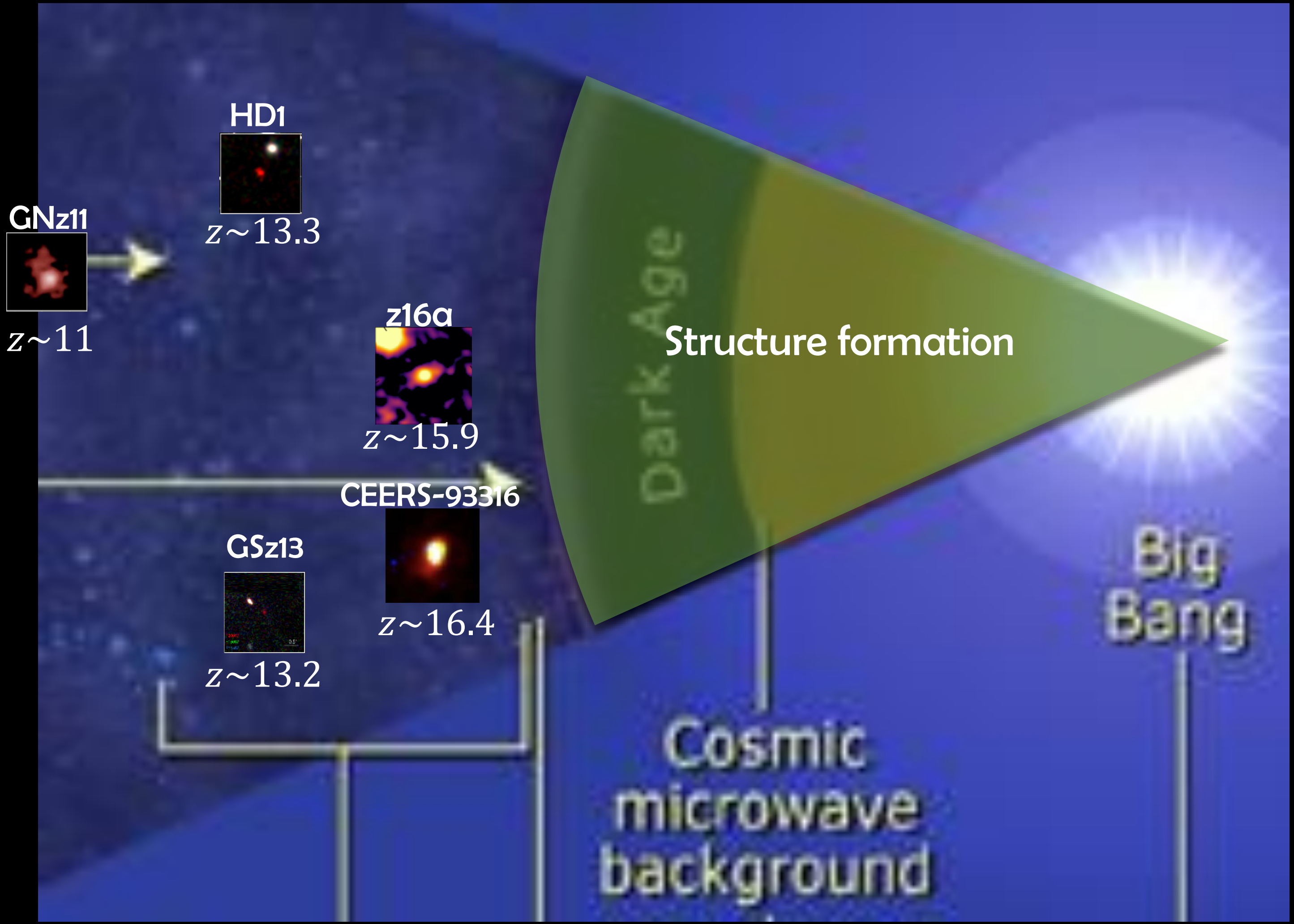
Possible quasar seed detected at z~8.6

in AGN CEERS 1019 (EGSY8p7)

~ $10^7\ M_\odot$ BH at ~ 0.6 Gyr of cosmic time

MODELING THE EARLY UNIVERSE

By honing in on the times preceding these detections we arive at the epoch where such structures begin to form



MODELING THE EARLY UNIVERSE

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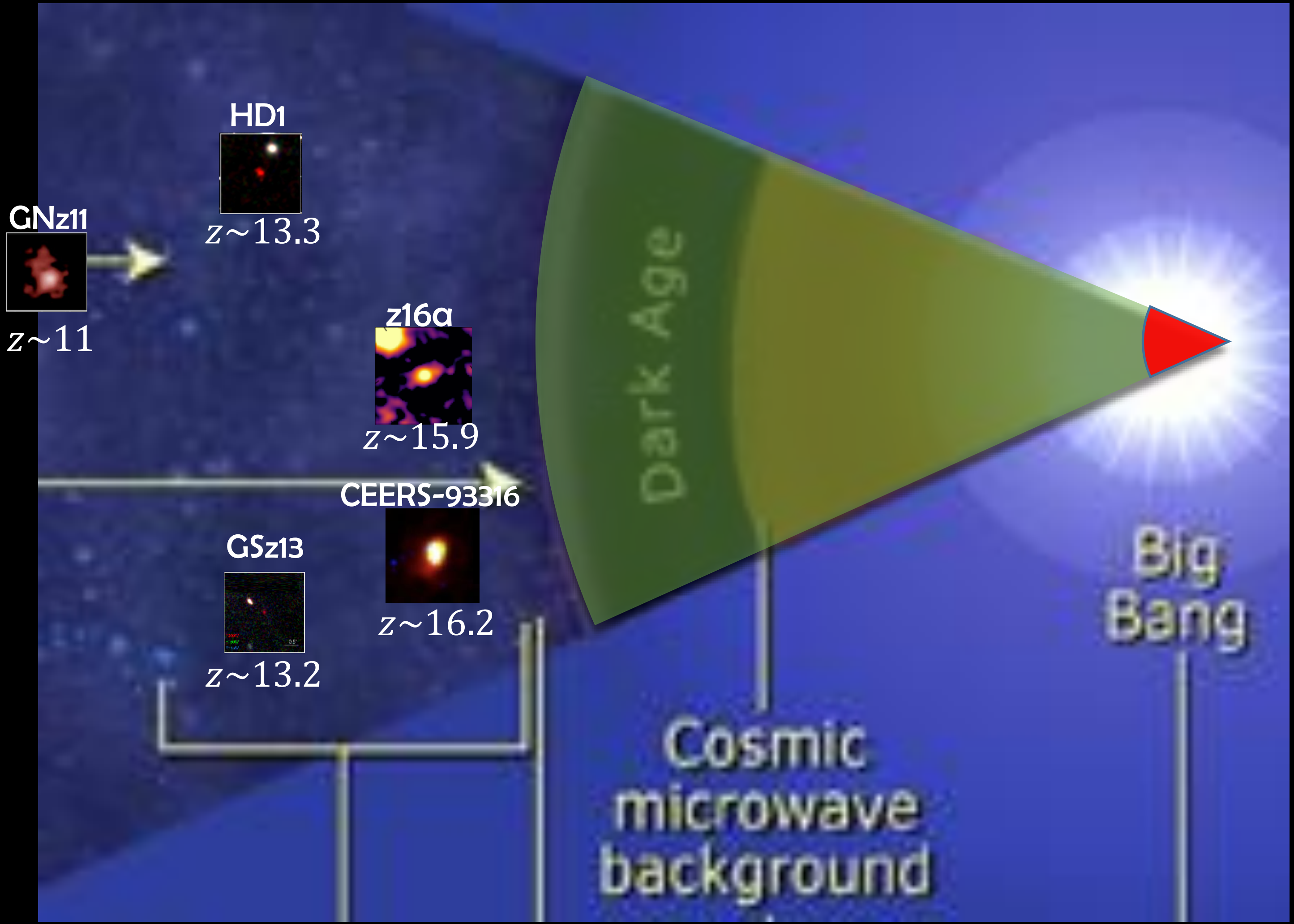
Fluctuations set during the inflationary epoch make up the primordial power spectrum (z~10^{28})

$$P_{\text{pri}}(k) \propto k^{n_s}$$

The favoured value of $n_s \approx 1$ implies similar fluctuations on all spatial scales



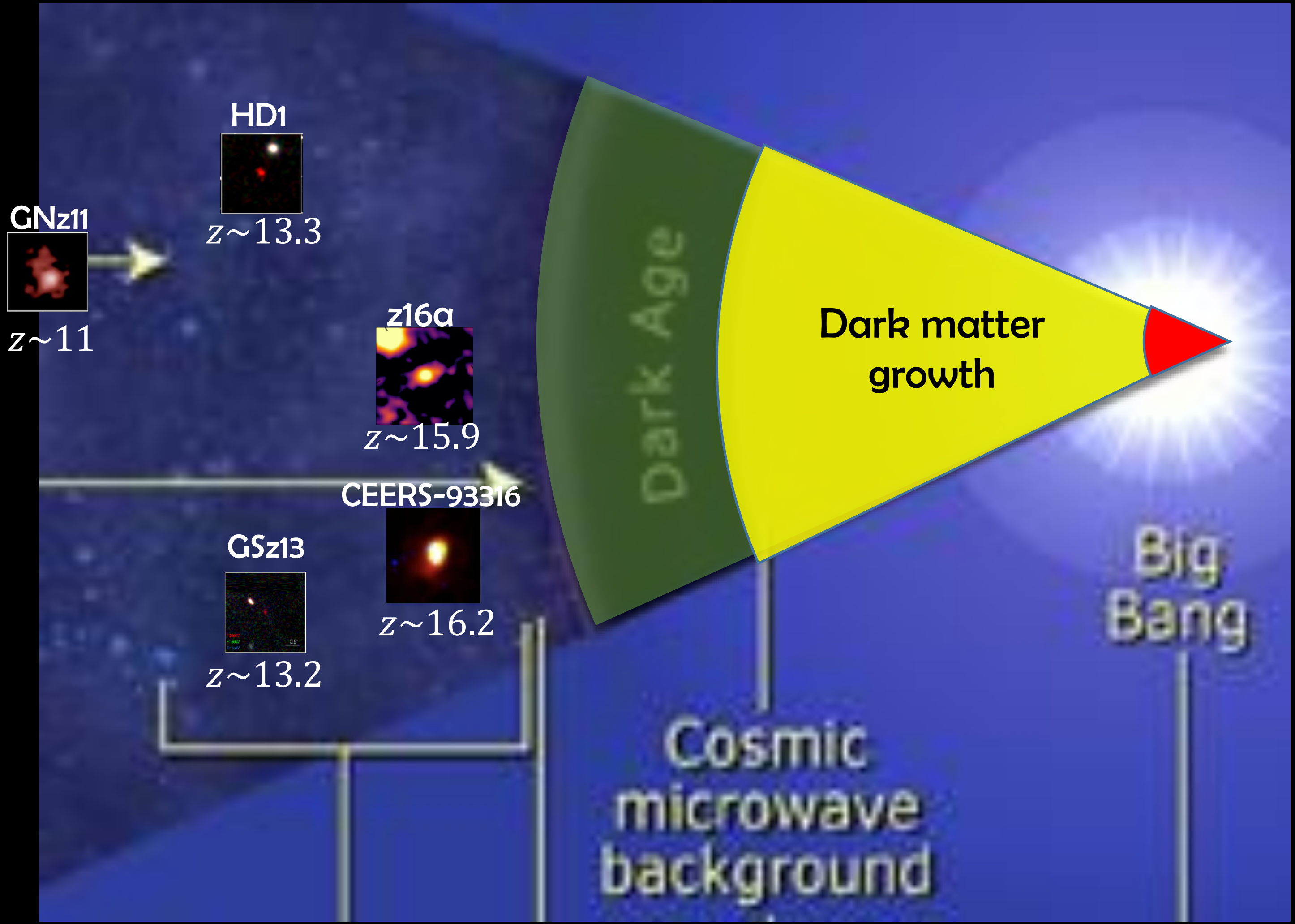
MODELING THE EARLY UNIVERSE

By honing in on the times preceding these detections we arive at the epoch where such structures begin to form

Dark matter halos grow and assemble in overdensities accordingly (z<3300)

$$P(t,k) \propto P_{\rm pri}(k)T(k)^2$$

Depending on cosmology the primordial fluctuations are now evolved away from the scale invariant spectrum



MODELING THE EARLY UNIVERSE

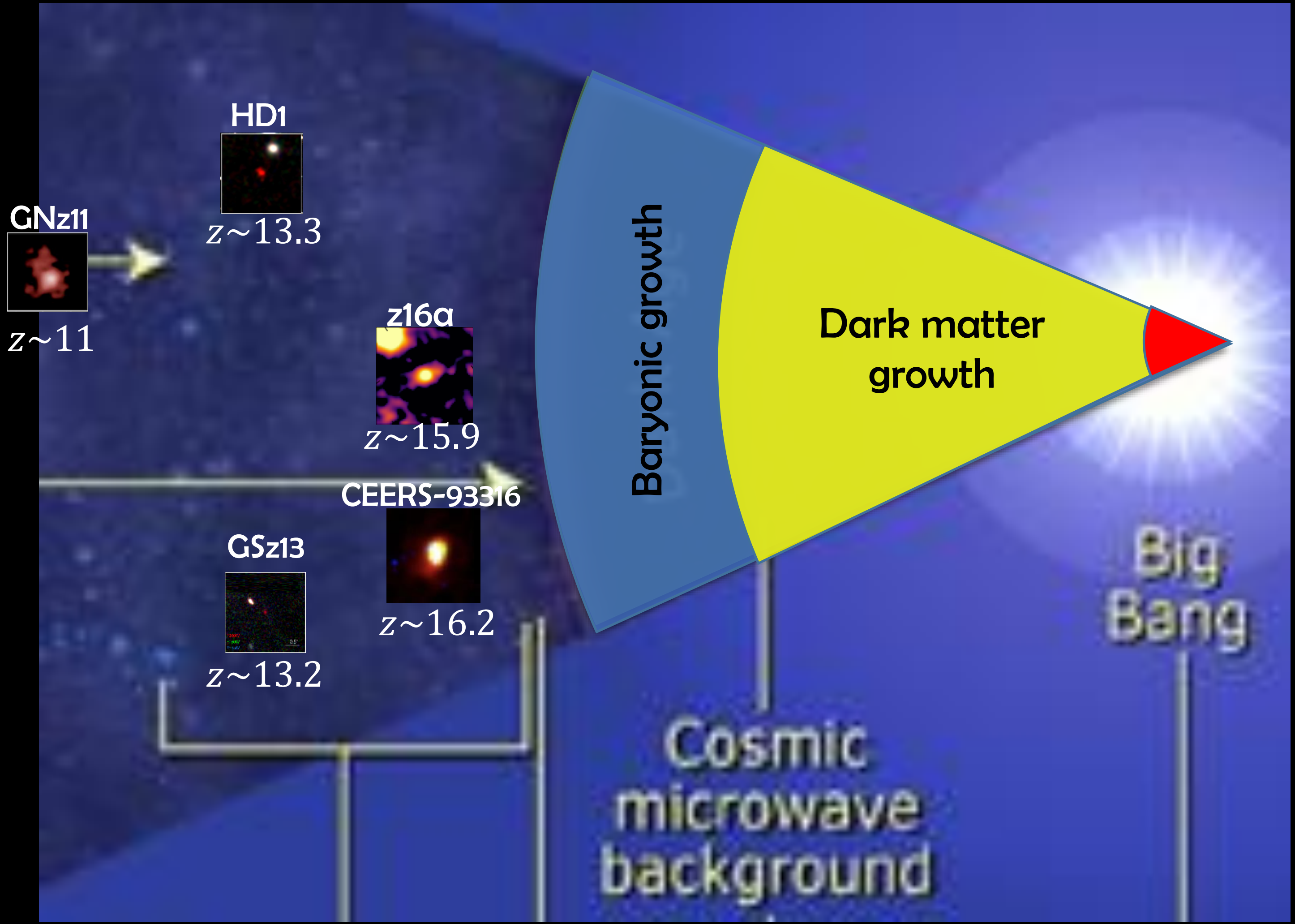
By honing in on the times preceding these detections we arive at the epoch where such structures begin to form

The overdensities act as sites for subsequent baryonic growth which becomes effective at decoupling (z<1100)

$$\delta(\boldsymbol{r}, t) = \frac{\rho(\boldsymbol{r},t)-\overline{\rho}(t)}{\overline{\rho}(t)}$$

the density contrast grows

$$\frac{\partial^2\delta}{\partial t^2} + 2H\frac{\partial\delta}{\partial t} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G\overline{\rho}\right)\delta = 0,$$

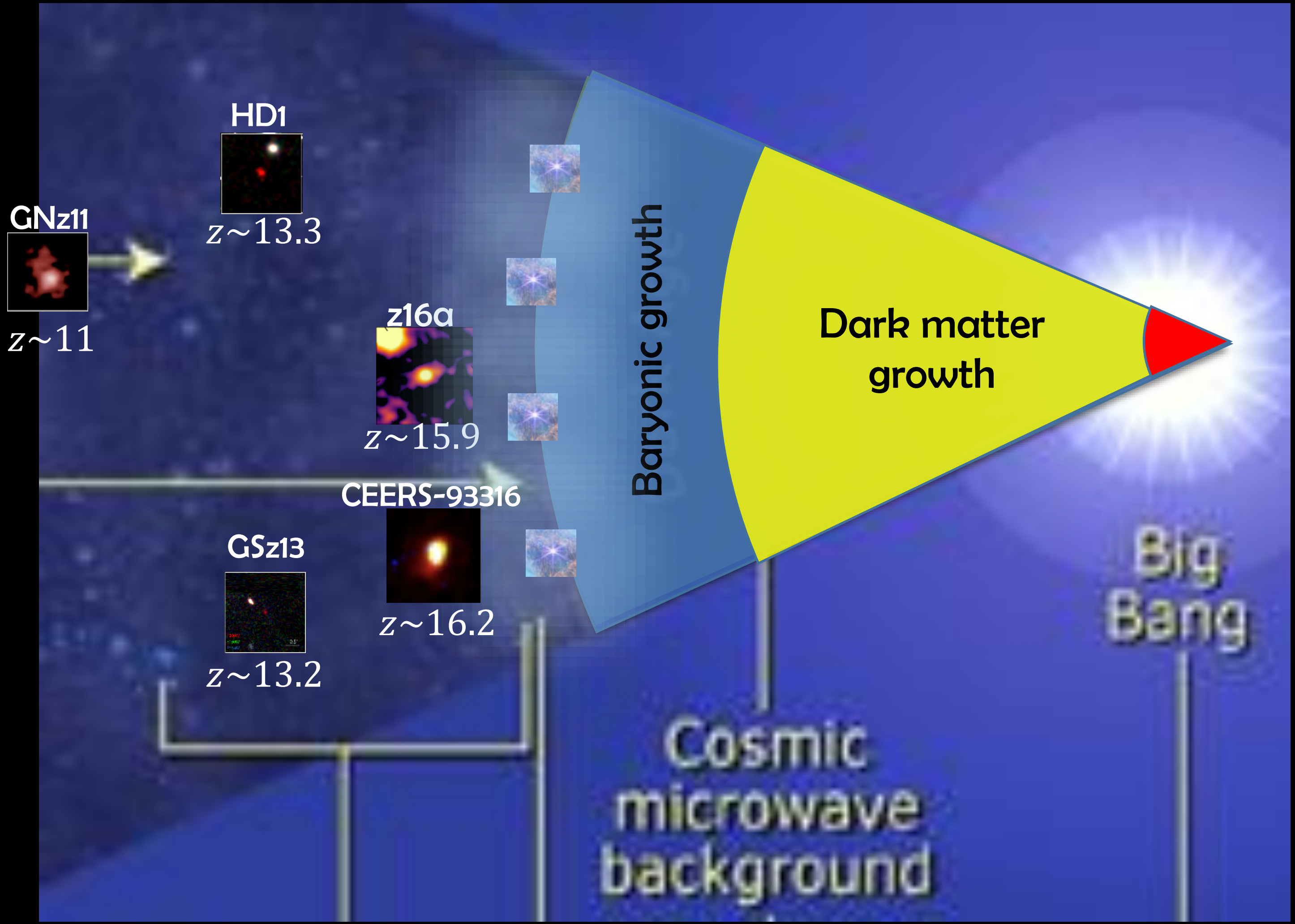


MODELING THE EARLY UNIVERSE

By honing in on the times preceding these detections we arive at the epoch where such structures begin to form

These assembies of overdensites subsequently cool down and form the first stars in the Universe at $z \sim 30$

Enter; *Cosmic Dawn*



STAR FORMATION

In order to form stars, gas must be cooled and condensed first!

Locally, we know quite well how star formation takes place in molecular clouds (nebulae)

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A condition for gravitational collapse is given by the Jeans mass:

$$M_J = 50\ M_{\odot}\ \mu^{-2}\ \left(\frac{n}{1cm^{-3}}\right)^{-1/2}\ \left(\frac{T}{1\ \mathrm{K}}\right)^{3/2}$$

$\mu = 1.32$ for primordial gas

Effective star formation -> Reduce T, and increase n

STAR FORMATION

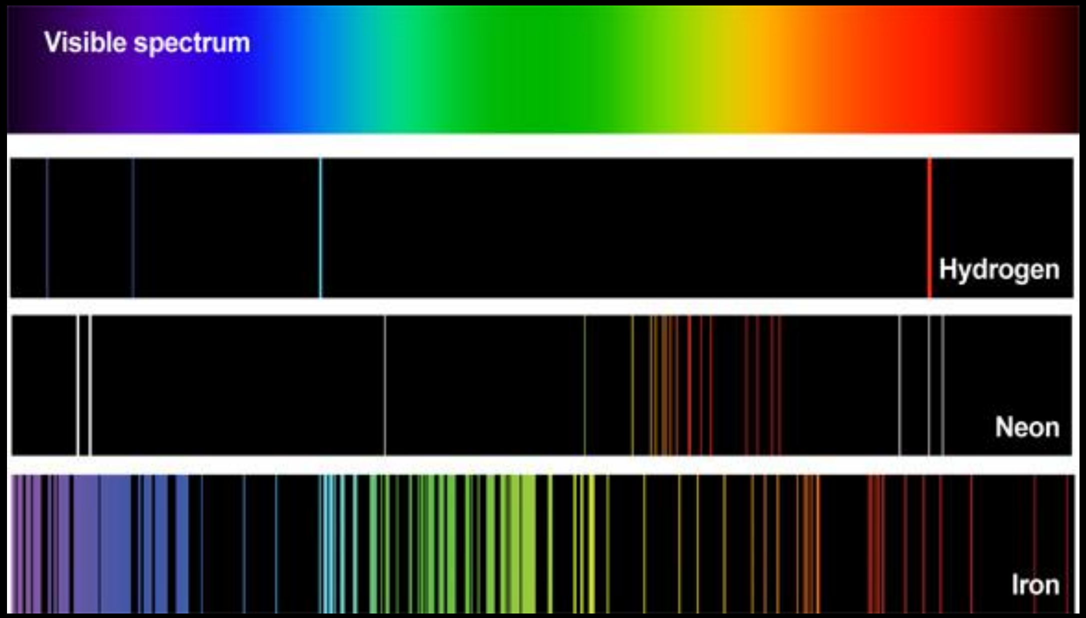
The highly metal enriched material generally available at lower redshifts fascilitates many efficient cooling mechanisms!

Nice exampel with iron

Very effective cooling tends to induce fragmentation – a hot topic when considering the Pop III IMF

Primordial gas contains no such metals --> inefficient at cooling

High levels of fragmentation has recently been argued though – advocating a less top-heavy Pop III IMF



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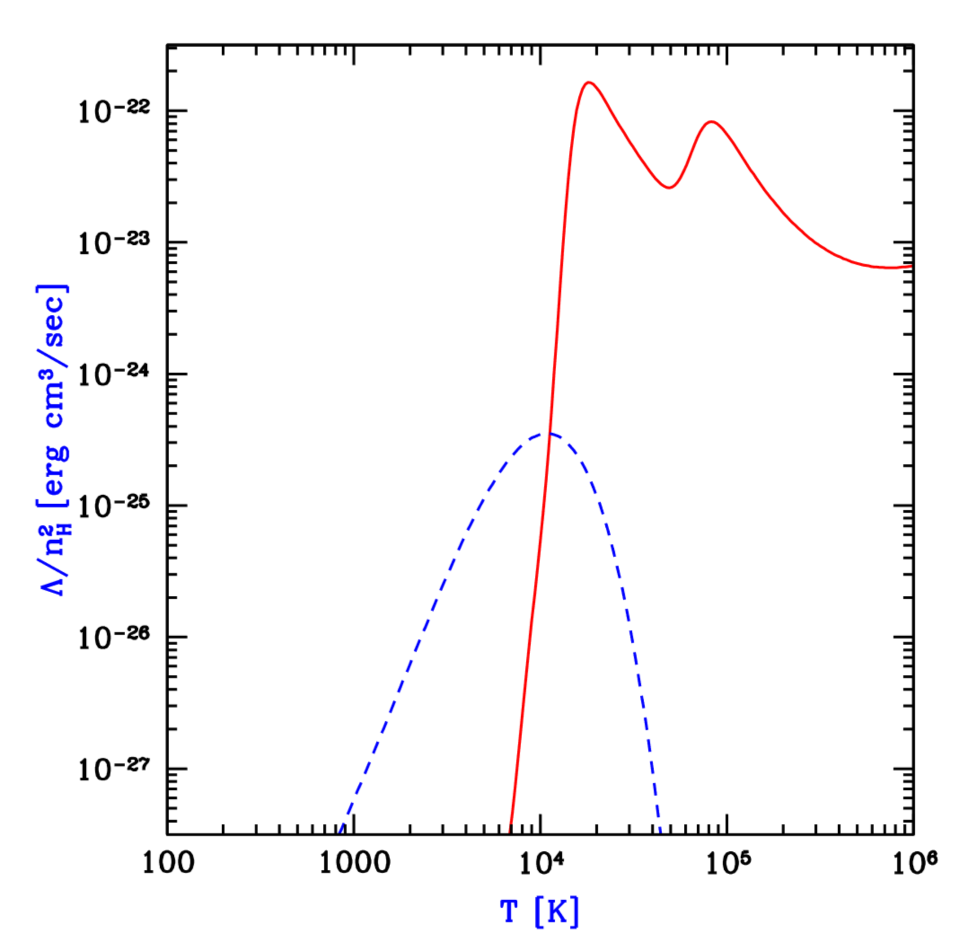
STAR FORMATION

There are two important temperature thresholds particularly relevant for Pop III star formation

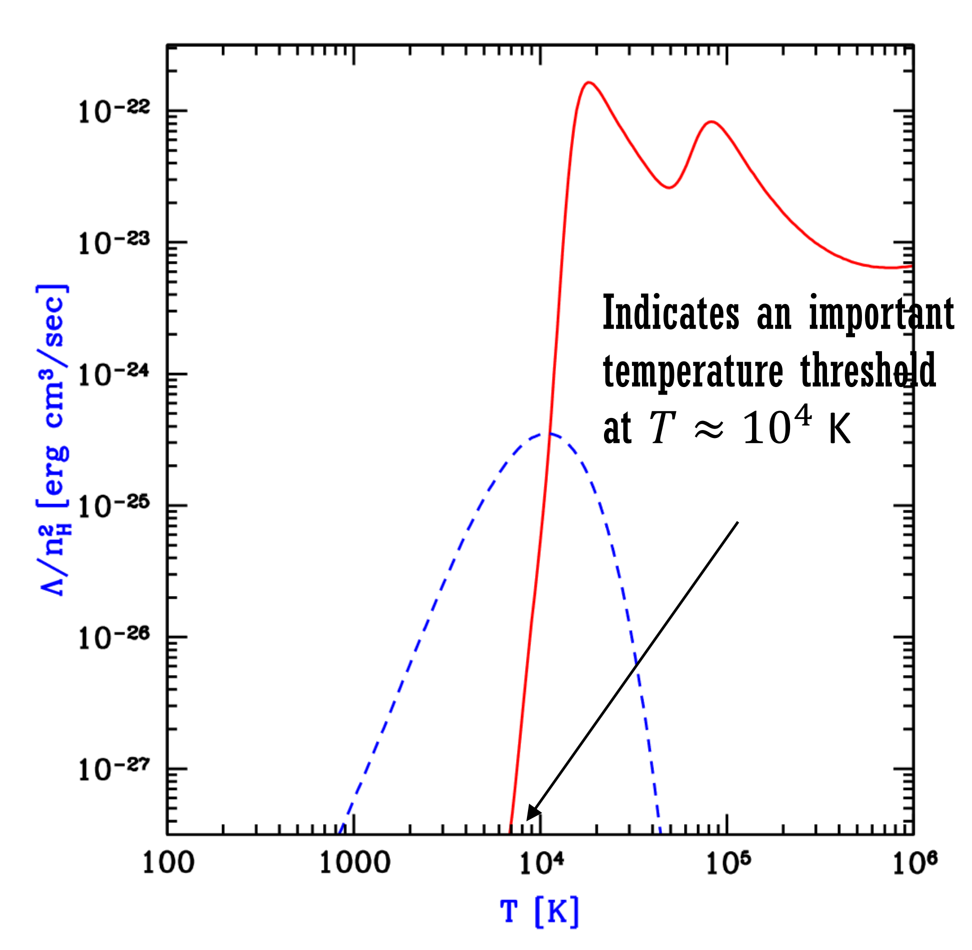


The cooling functions for primordial gas. Red solid line: atomic hydrogen and helium gas. Blue dashed line: $\frac{n_{H_2}}{n_H} = 10^{-3}$. Adapted from Barkana & Loeb 2001.

STAR FORMATION

There are two important temperature thresholds particularly relevant for Pop III star formation

Atomic cooling halo: $T_{\rm vir} = 10^4$ K



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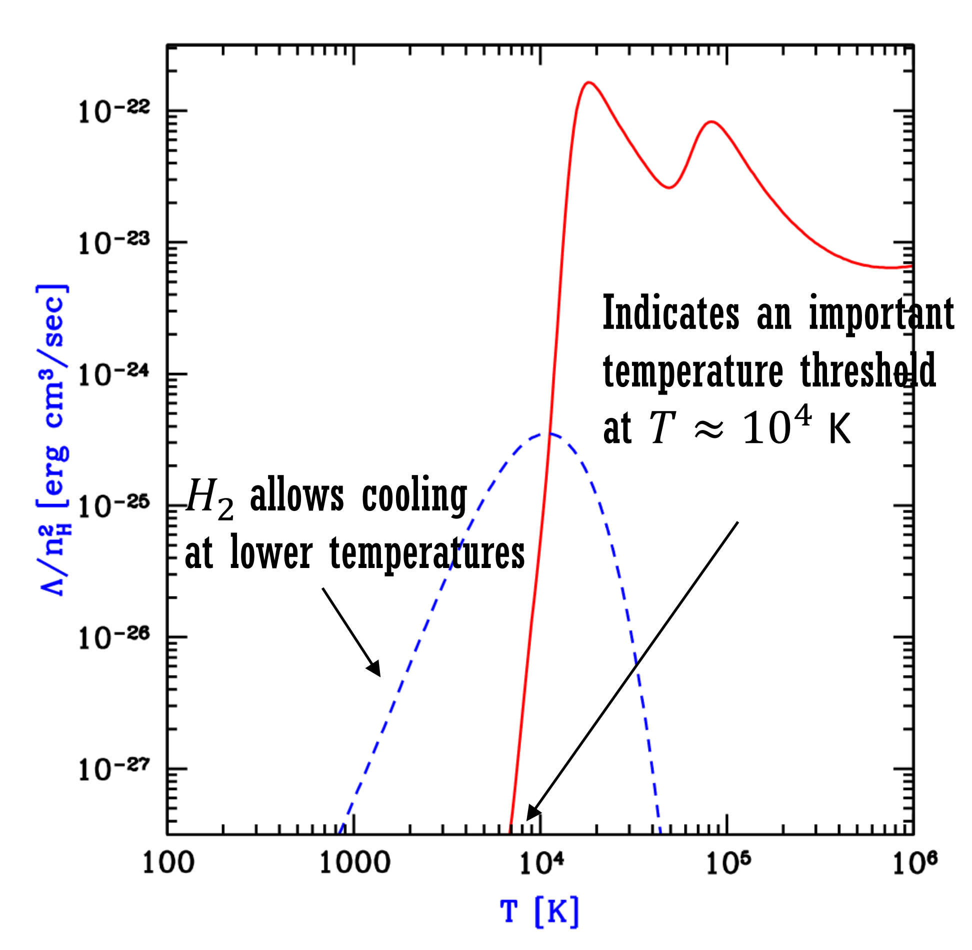
Minihalos: $T_{\rm vir} \approx 10^3$ K (also lower if including HD etc)



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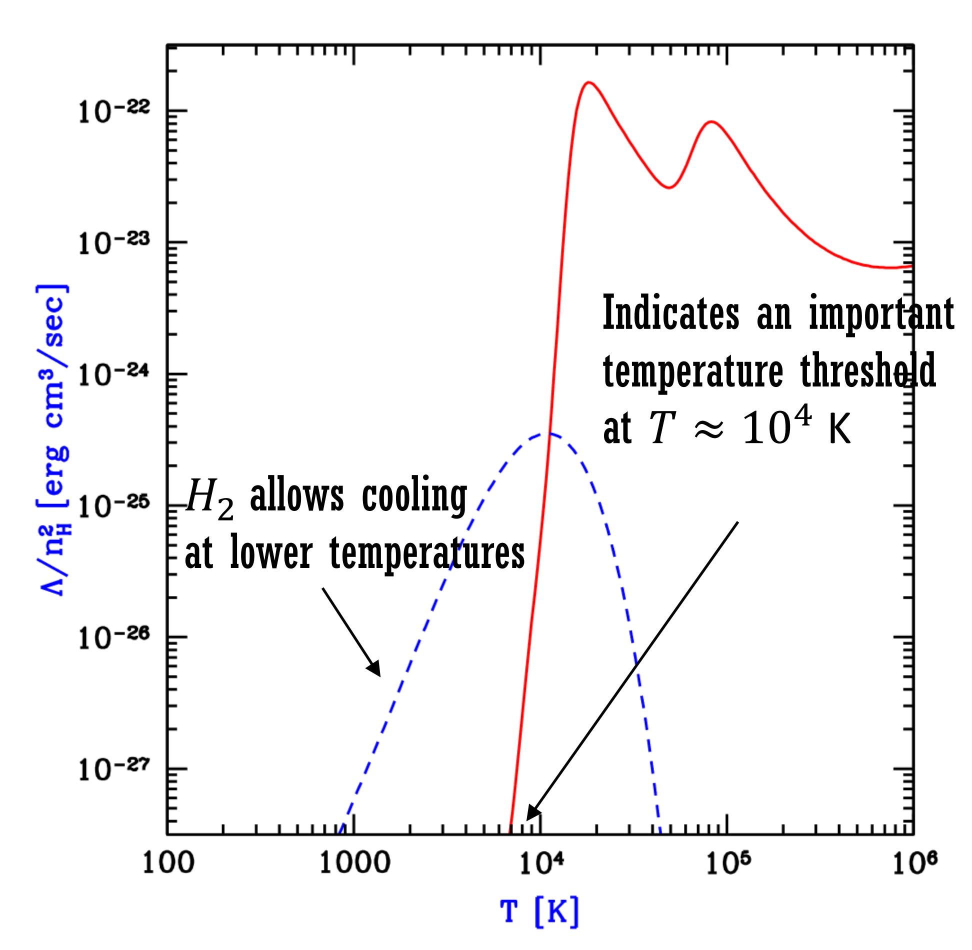
There are two important temperature thresholds particularly relevant for Pop III star formation

Atomic cooling halo: $T_{\rm vir} = 10^4$ K

Minihalos: $T_{\rm vir} \approx 10^3$ K (also lower if including HD etc)

The virial temperature is linked to the mass of the halo:

$$T_{\rm vir} \approx 0.1 \times M_{\rm vir}^{2/3} \frac{1+z}{10}$$



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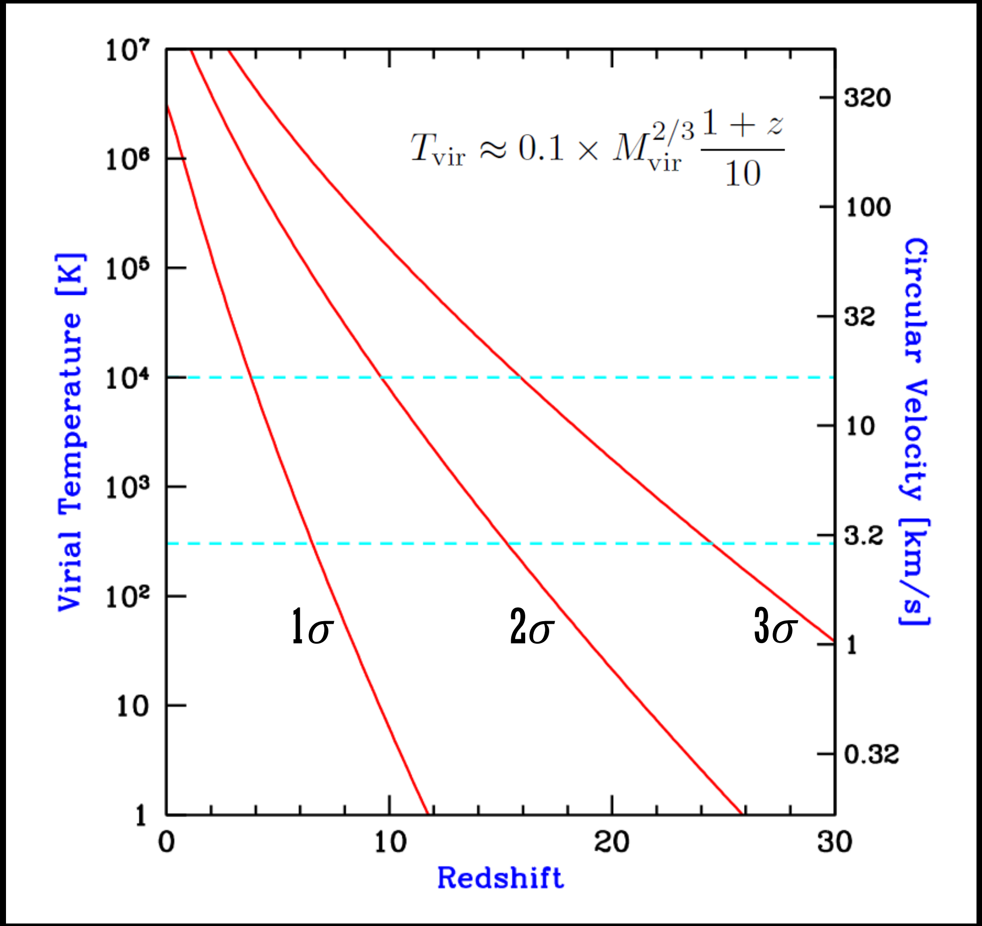
STAR FORMATION

The mass of the dark matter halo is directly linked to the virial temperature of the baryons that virializes in the halo

As just argued, the temperature of the gas is decicively important if cooling is even to commence!

Structure formation allows us to predict the number of halos with given masses that collapse (virialize) at high redshifts

Smaller halos collapse (virialize first)



The virial temperature of collapsing halos. The red solid lines correspond to 1σ, 2σ and 3σ fluctuations. Dotted lines are atomic cooling halos of $T_{\rm vir} = 10^4$ K or molecular cooling halos (minihalos) with $T_{\rm vir} = 300$ K.

MINIHALO

- A minihalo is a dark matter halo that has a virial temperature of $T_{\text{vir}} \sim 1000$ K, sufficient for molecular hydrogen cooling.
- Corresponds to a total halo mass $M \sim 2 \times 10^5\ M_{\odot}$, at redshift $z = 30$.
- Relies on the existence of H_2
- Dark matter minihalos are the formation sites of the first stars in the Universe!
- Sensitive to feedback. Star formation quenched after initial burst! (No prolonged star formation, i.e., not a galaxy)

ATOMIC COOLING HALO

- Atomic cooling halo: A virialized dark matter halo with a virial temperature $T_{\mathrm{vir}} \sim 10^4$ K, leading to a total halo mass $M \sim 2 \times 10^7\ M_\odot$, at redshift $z = 15$.
- Capable of cooling through atomic line emission, do not rely on the existence of H_2
- Formation sites for the first galaxies in the Universe
- Usually contains stars already formed in the minihalo substructure of this bigger halo

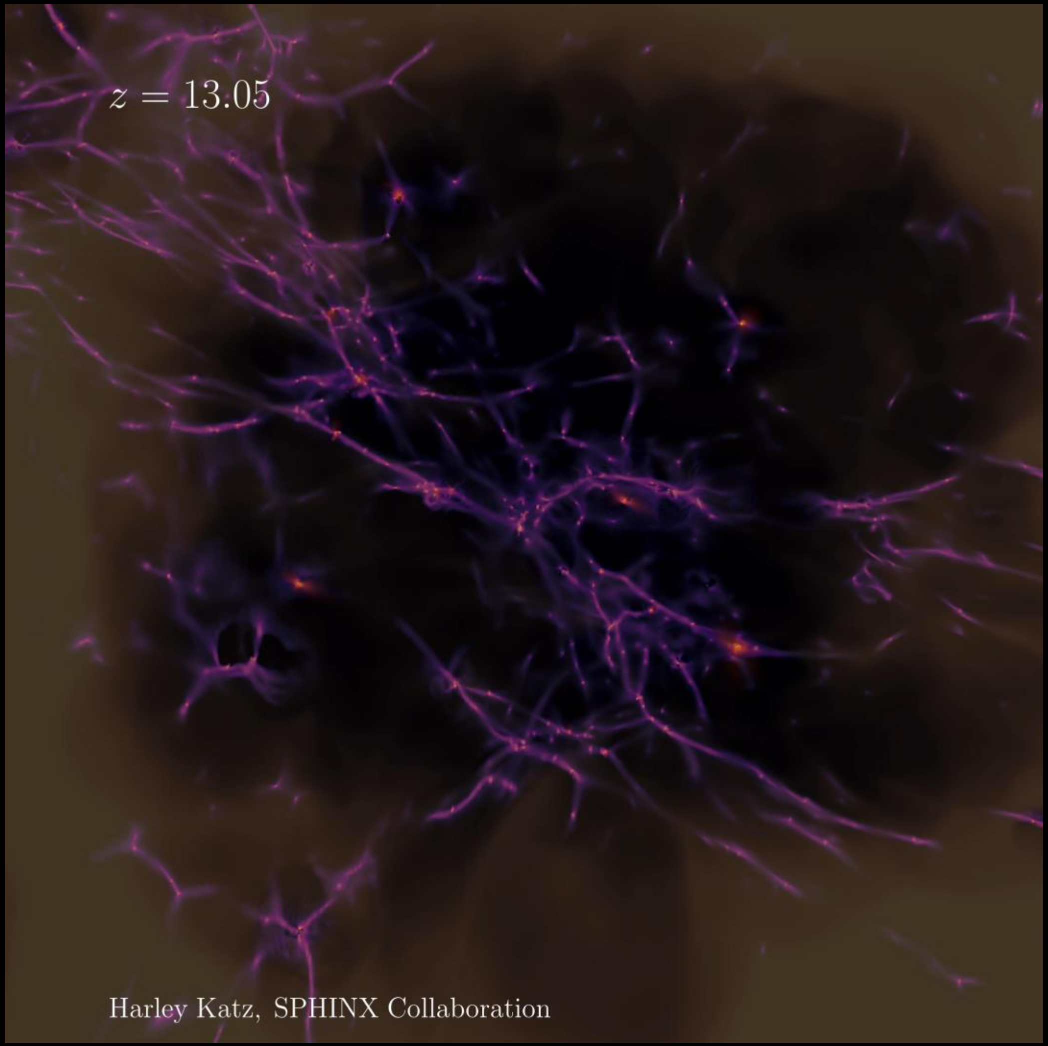
DELAYING STAR FORMATION

When it comes to the detectability of pure Pop III galaxies – we require that star formation is delayed in minihalos

Metals formed through stellar evolution and supernovae otherwize quickly pollute the galaxy

A flux of Lyman-Werner radiation (11.2 eV – 13.6 eV) from other adjacent halos dissociate the molecular hydrogen

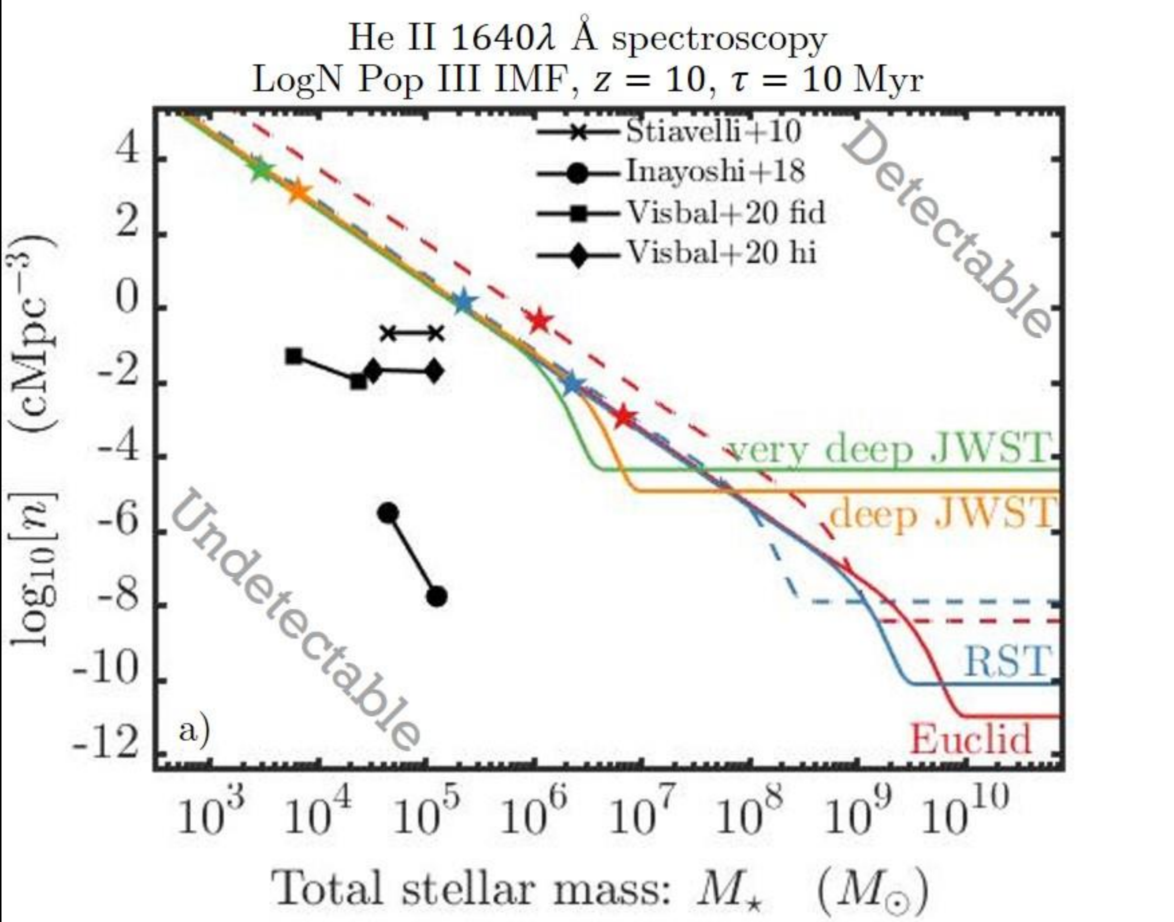
Star formation then first commences when the atomic cooling threshold has been reached



DETECTION

In paper III we investigate how such delayed star formation could produce pure Pop III galaxies that can be detected with gravitational lensing

The number density of such galaxies and the likelihood of sufficient gravitational lensing combines to reveal the prospects!



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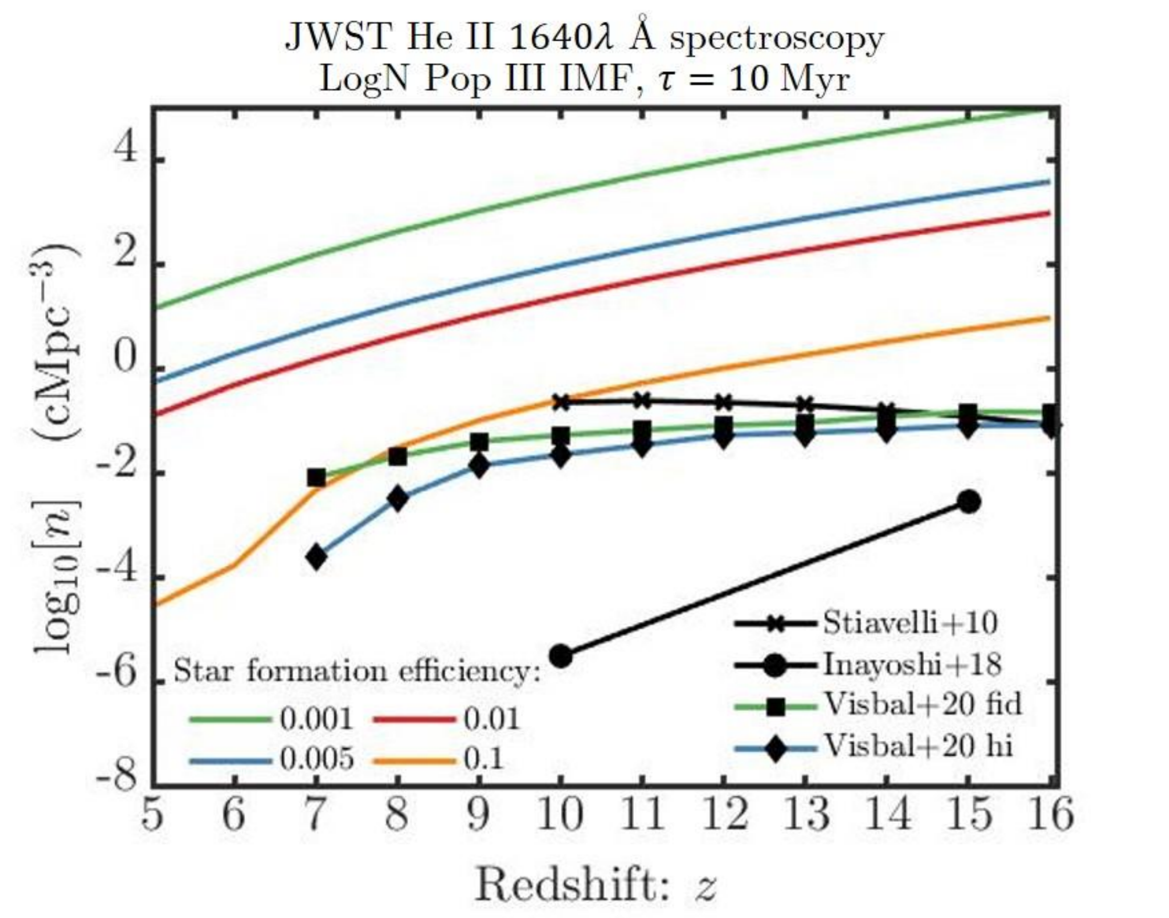
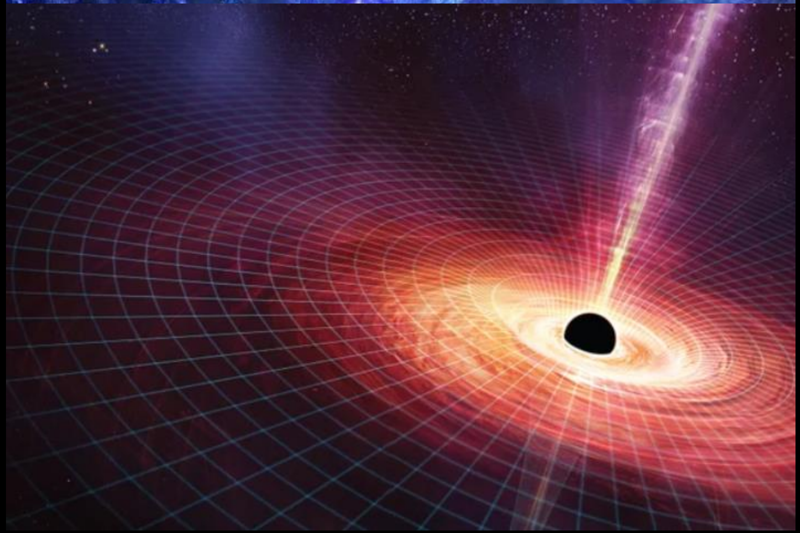
We also looked for the most promising redshifts for detection



DETECTION

Similar scenarios with high LW flux and supressed cooling mechanisms make up ideal environments for the formation of supermassive stars and direct collapse black holes



DETECTION

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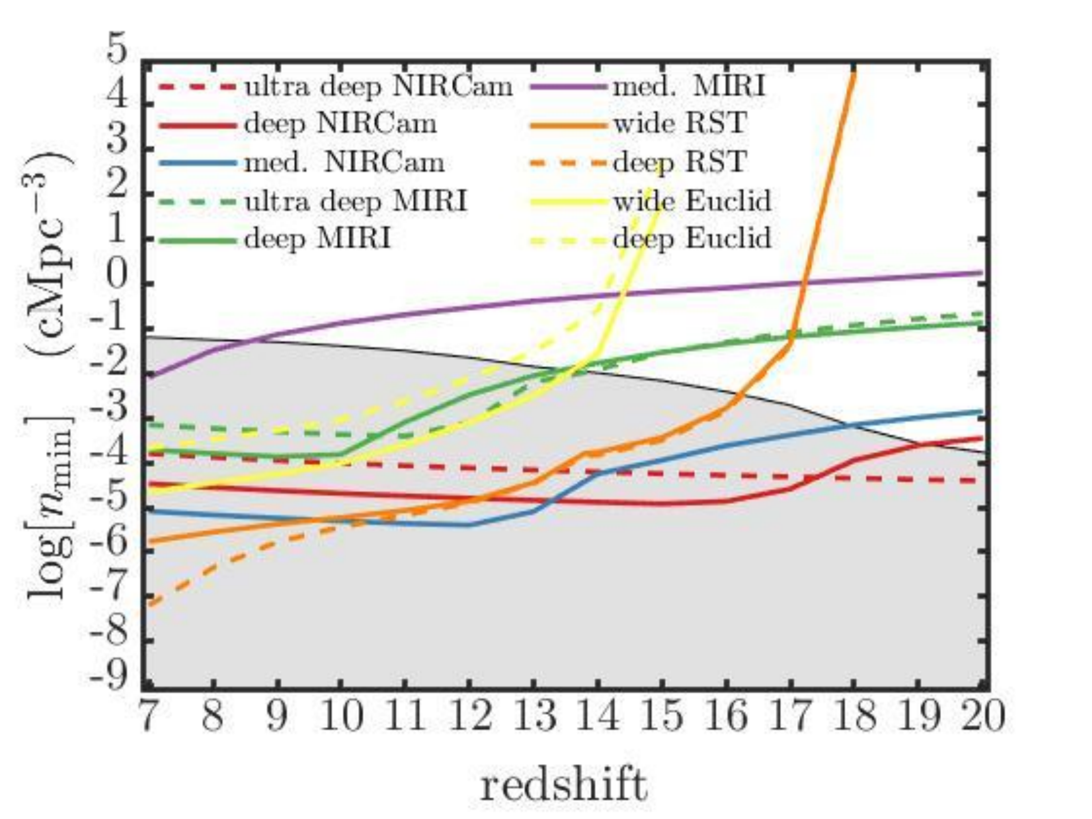
In paper IV we did similar estimates for the detection of direct collapse black holes

The predicted number densites of such objects vary so much that conclusions on detectability are speculative!



TO INFINITY – AND BEYOND

- Buzz Lightyear

Thank you for your time!