Challenges in extragalactic astronomy in the ‘40

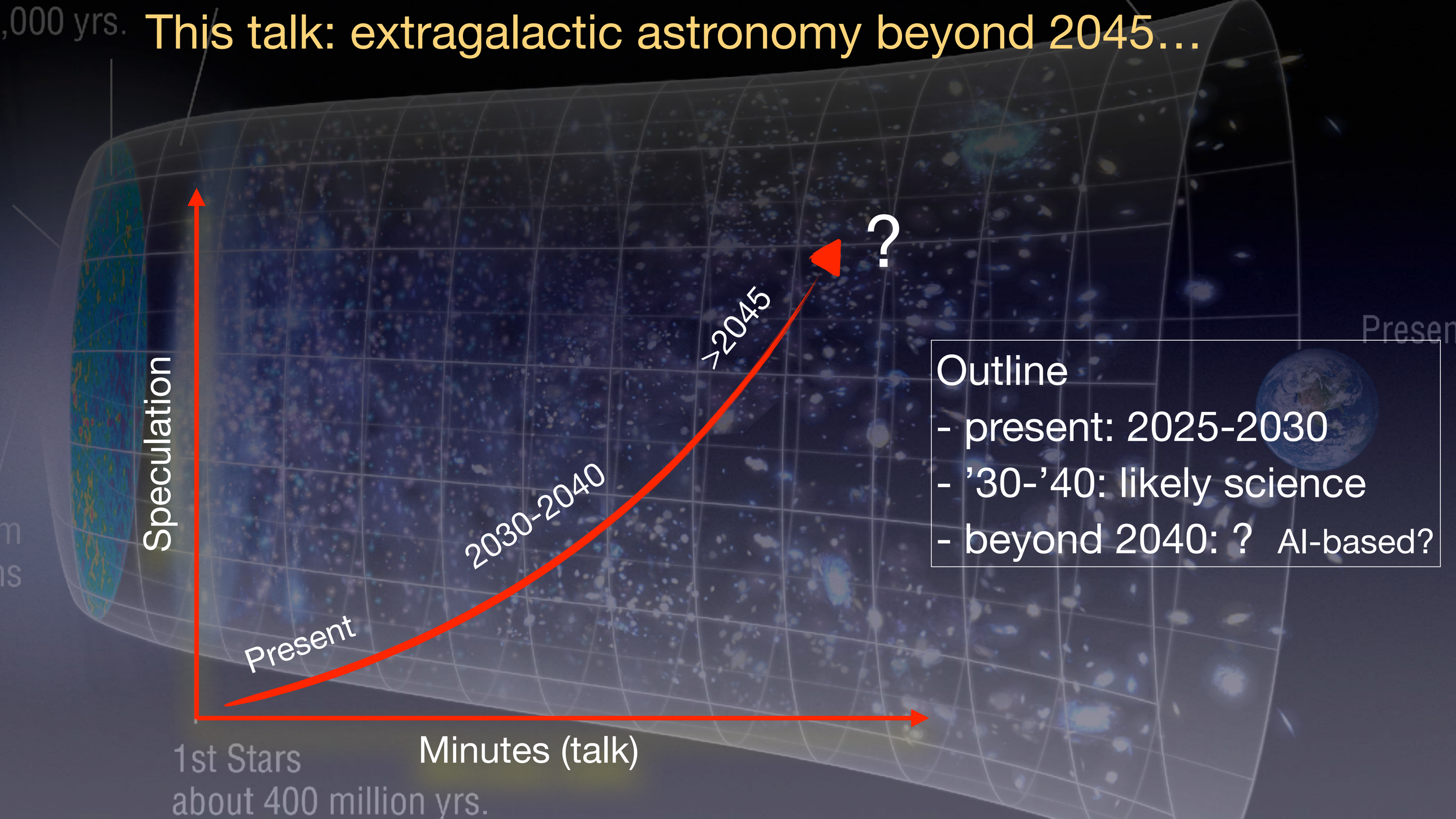
Eros Vanzella — INAF OAS

Expanding Horizons in Italy

Questions:

- What will be the strategic observational needs from the **ground** that will be possible only with the construction of a new European facility?
- How do the different options already circulated in the European context, such as WST and others, compare with each other?
- What technological development can be credible and realistic in the time scale of this project?
- What are the directions, even multiple, in which our community, and INAF in particular, want to push.

This talk: extragalactic astronomy beyond 2045…



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- present: 2025-2030
- ’30-’40: likely science
- beyond 2040: ? AI-based?

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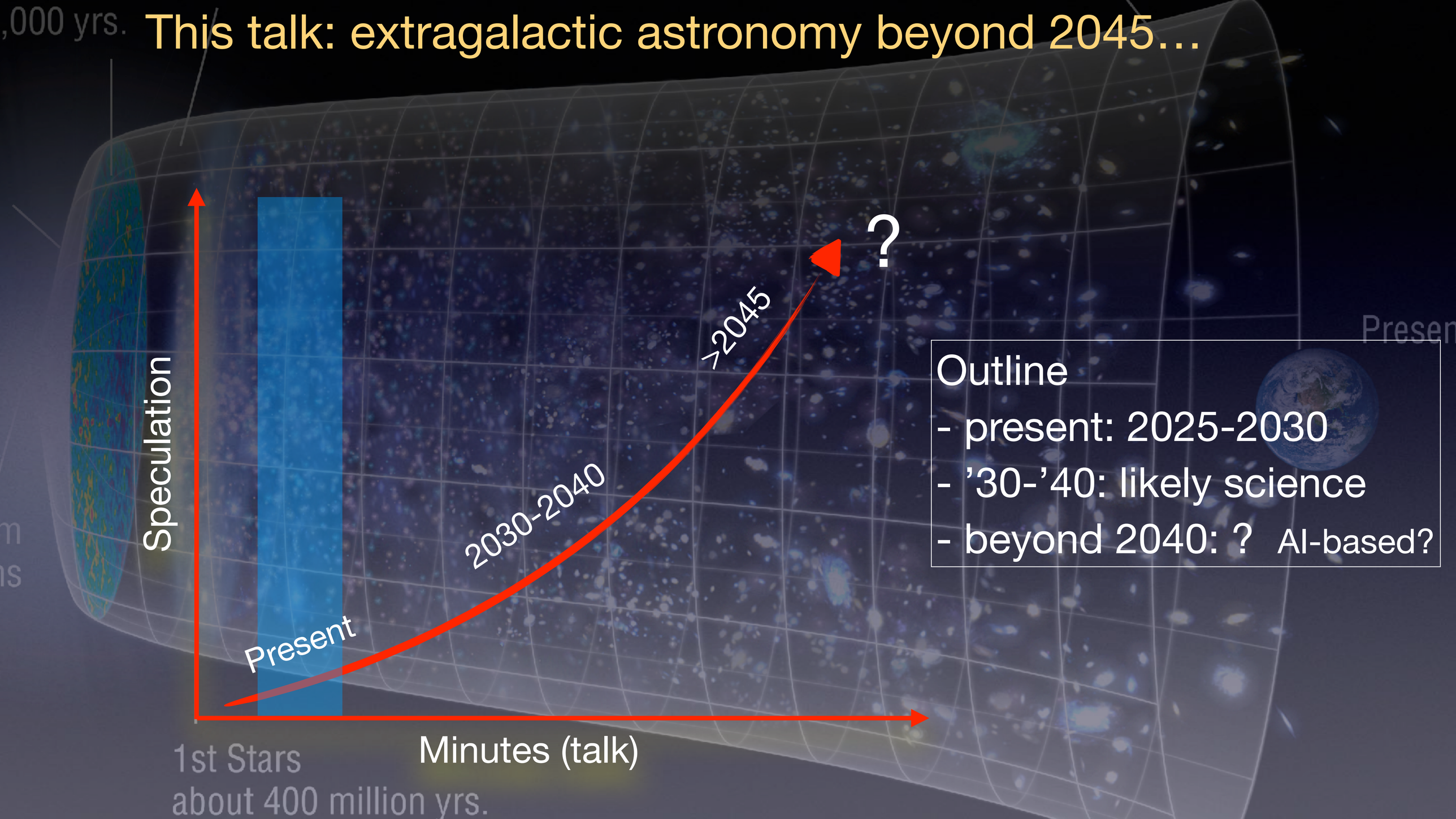

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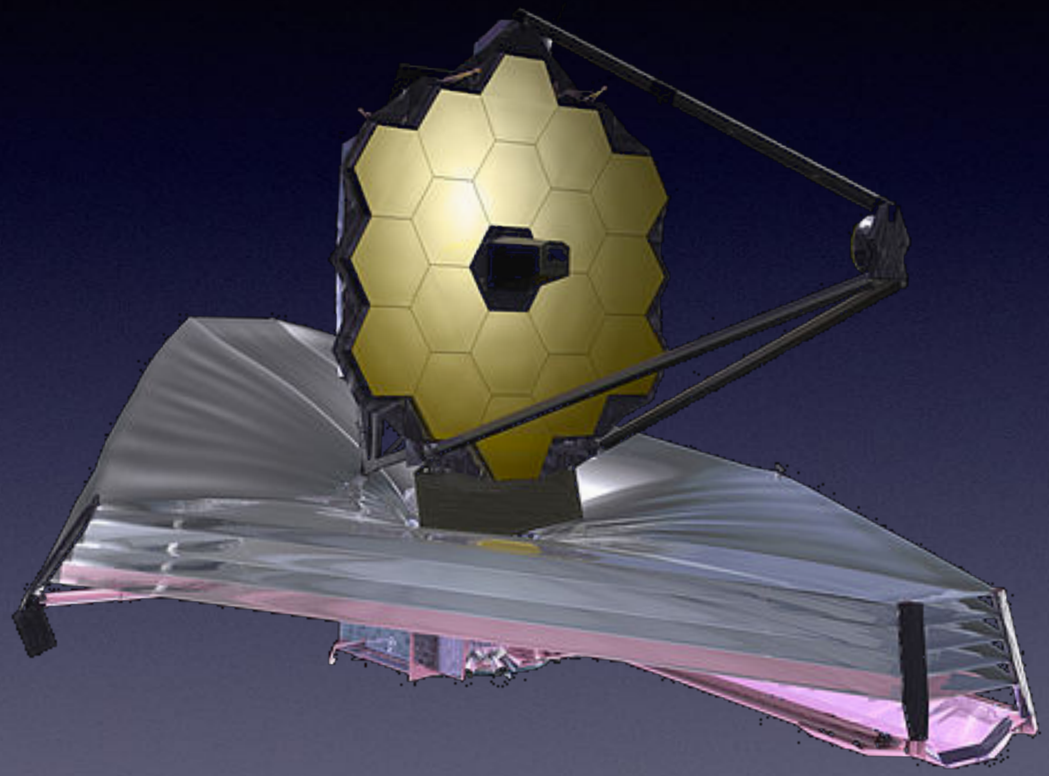
- Diffraction limited PSF in the NIR J,H,K bands (**50-60 mas**)
- Imaging: ~30 (AB) at 5 sigma; Spec: ~ x(1e-19) cgs in 5h ;



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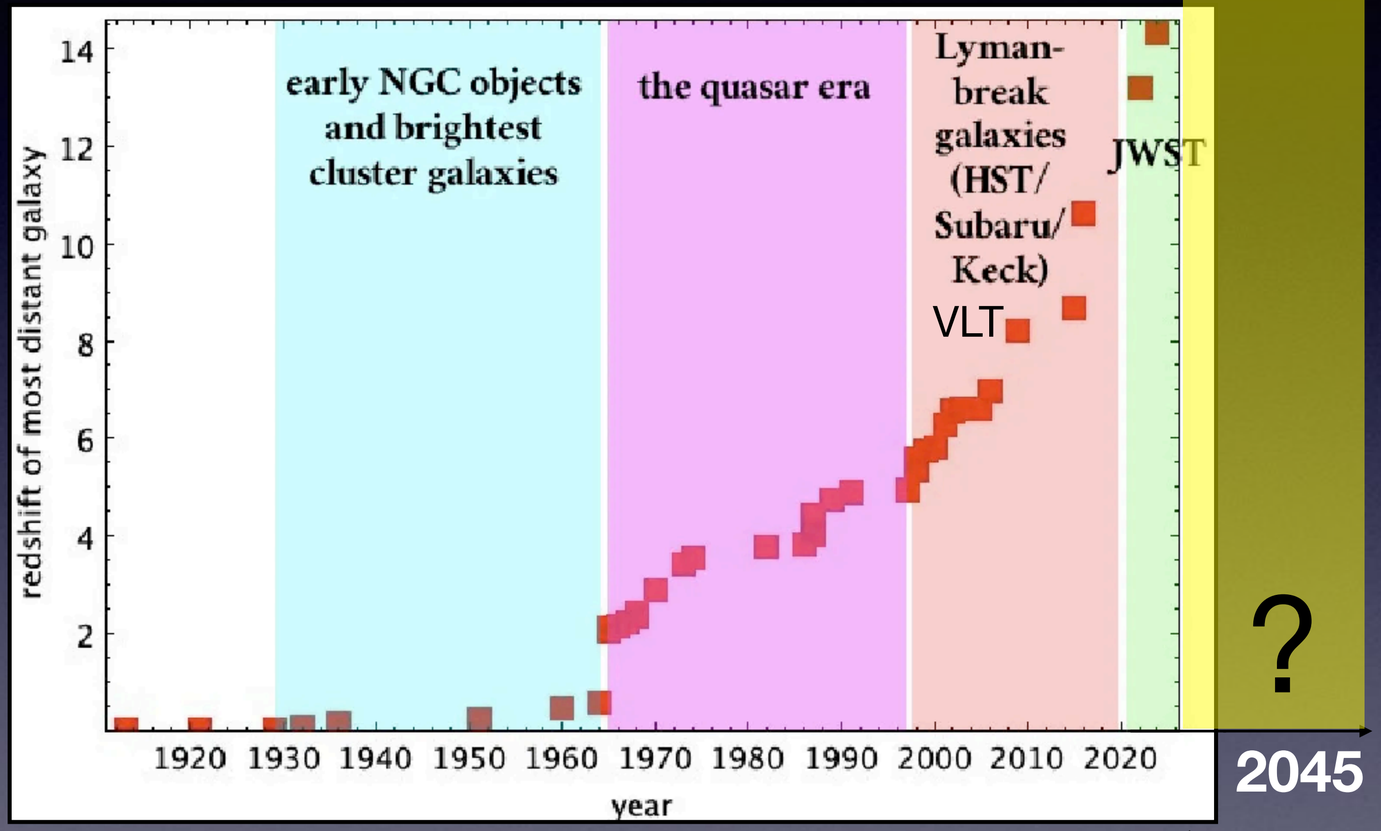

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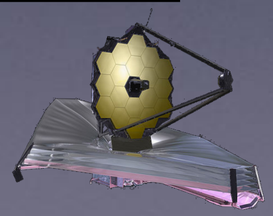
2045

Difficult to access redshifts of candidates z~**17** and **20**, **even with JWST**



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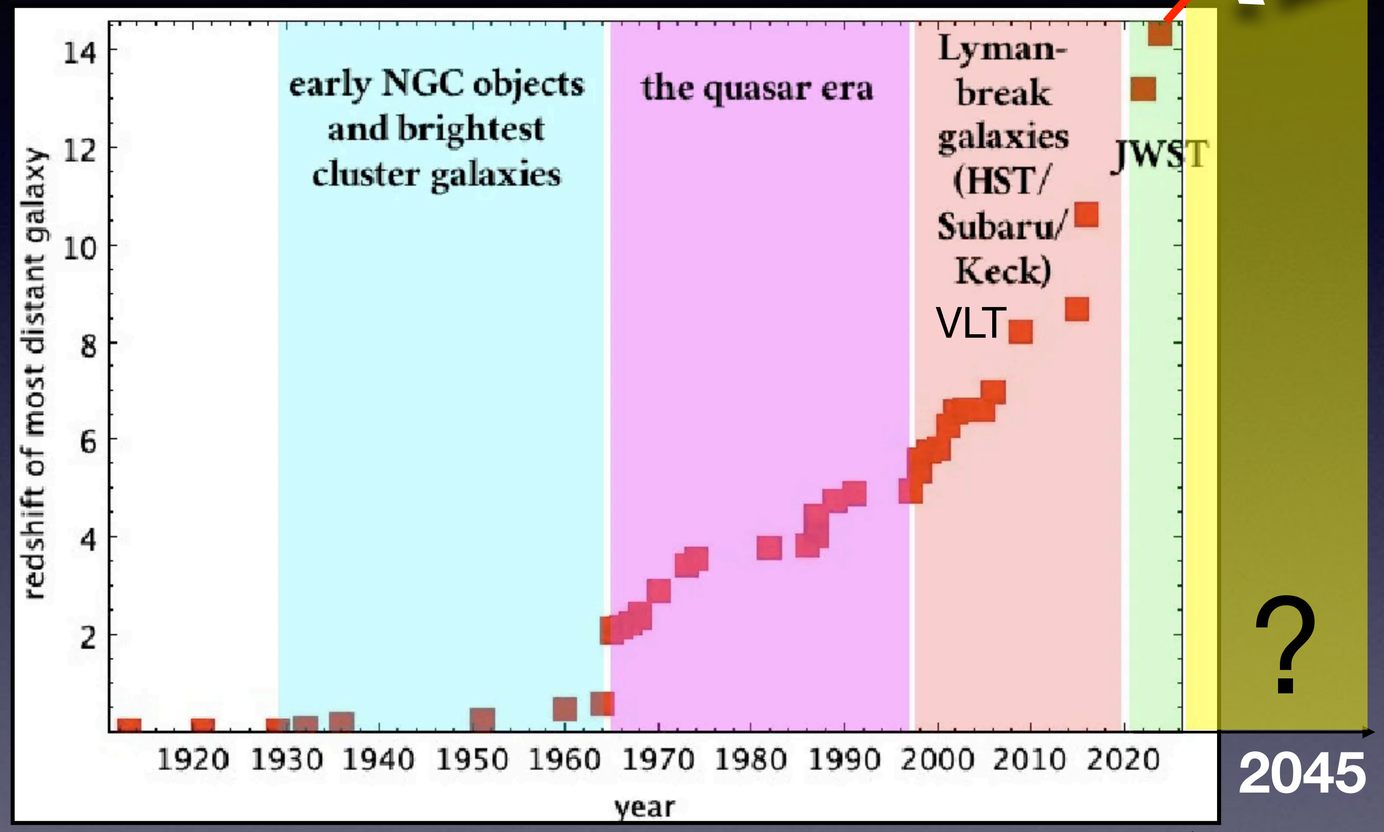

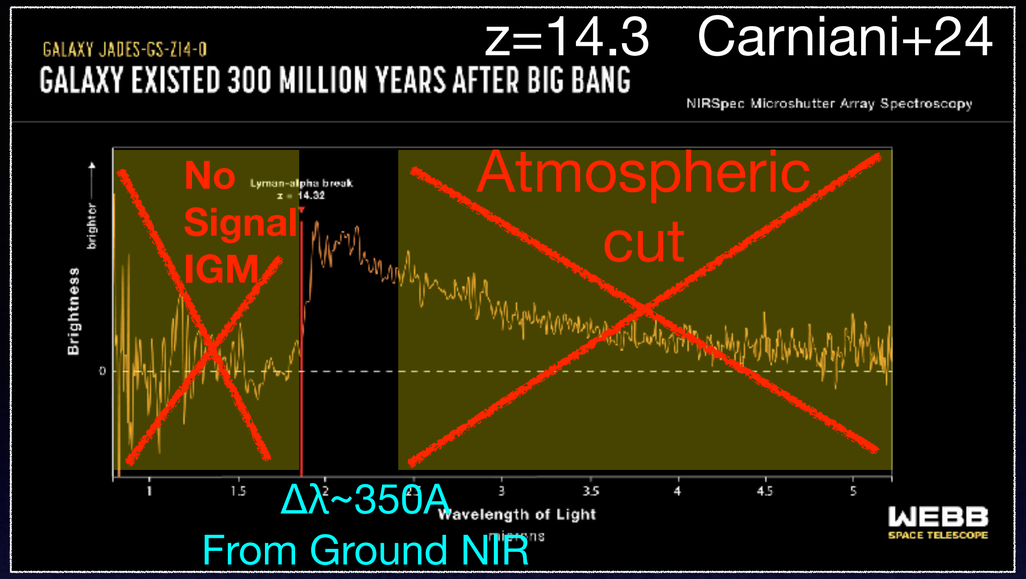

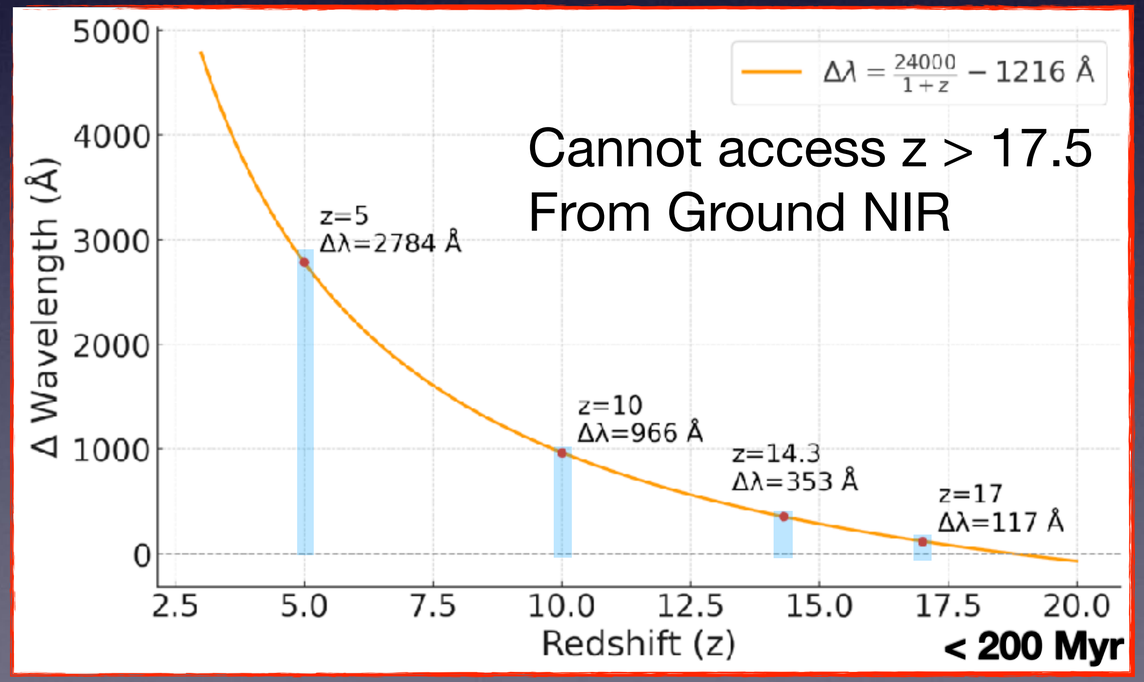

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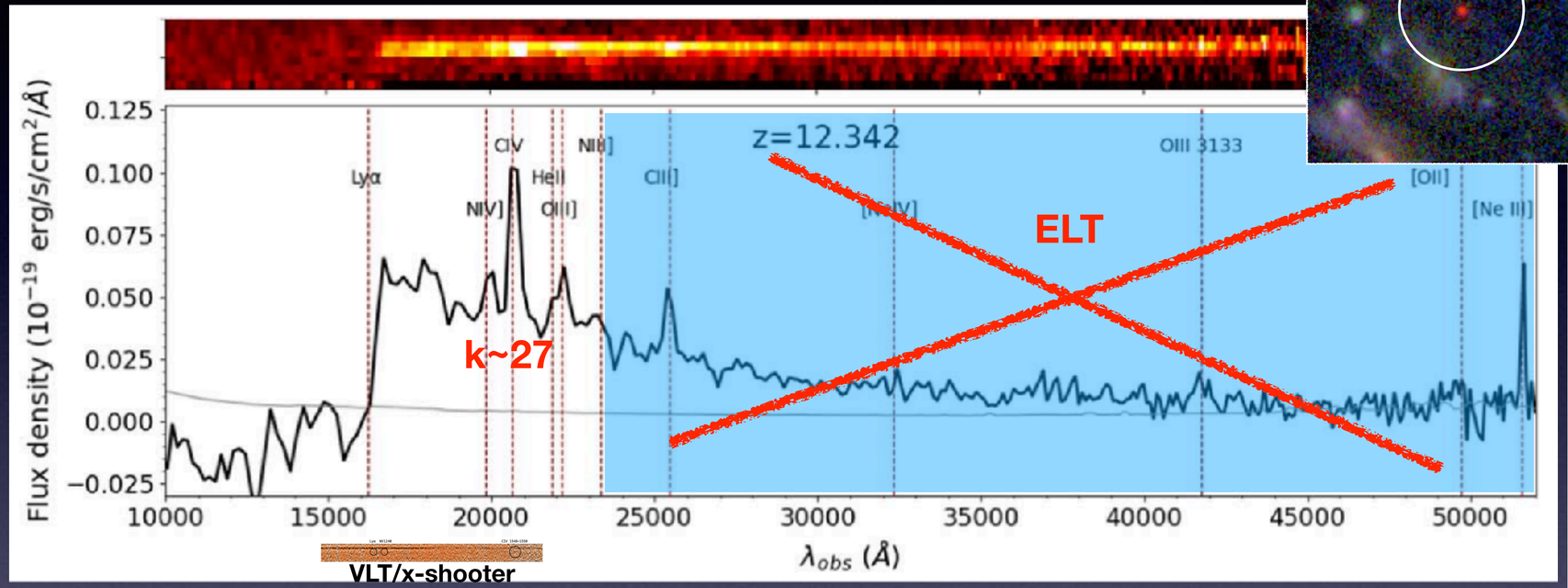
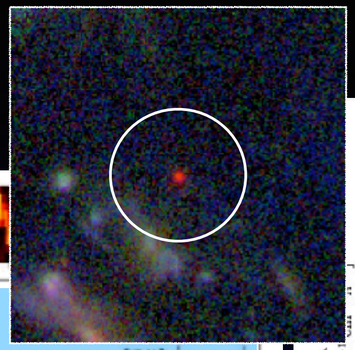
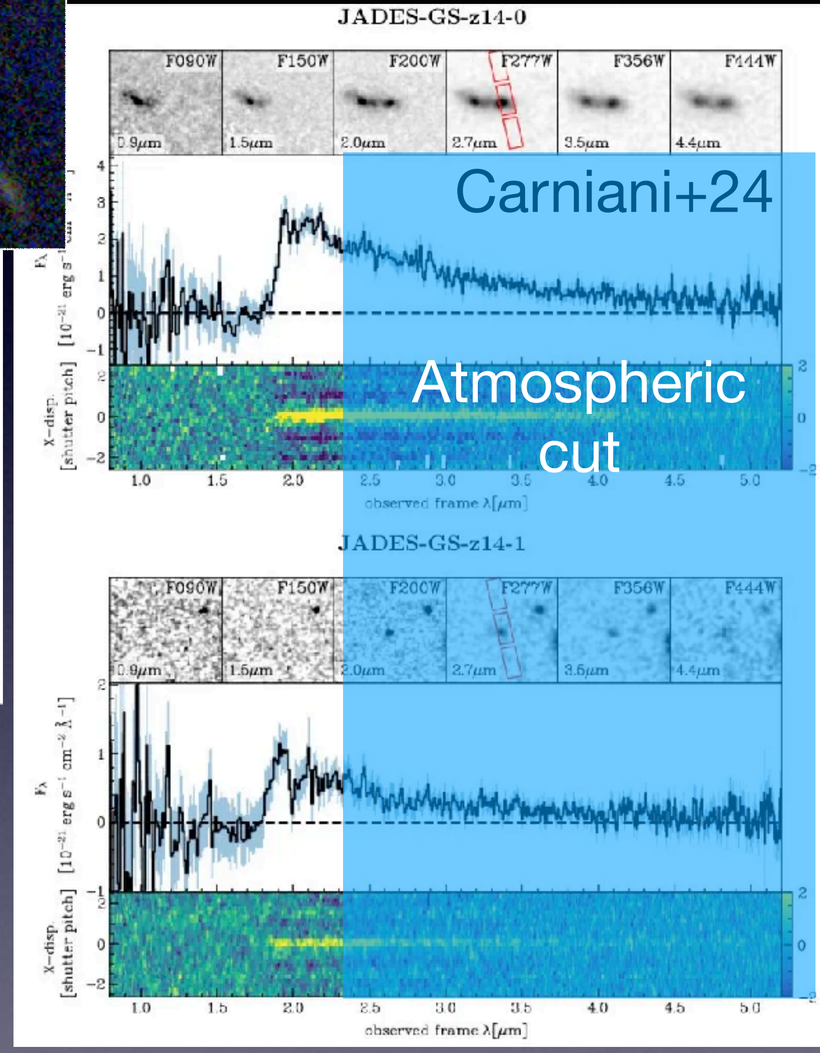
JWST confirms z=12.34 bright (barely resolved) object

Castellano+24 - **JWST/NIRSpec - prism**







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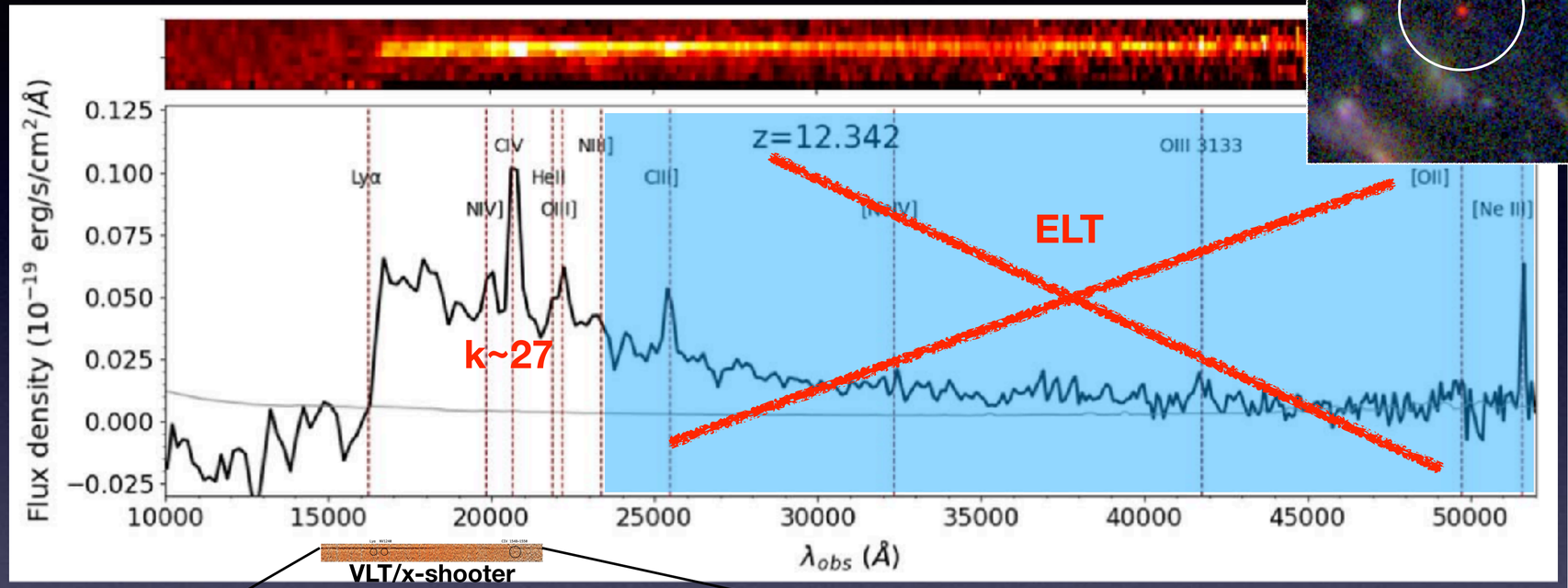

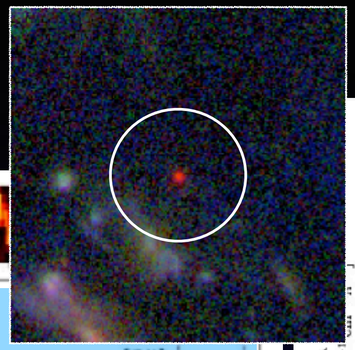

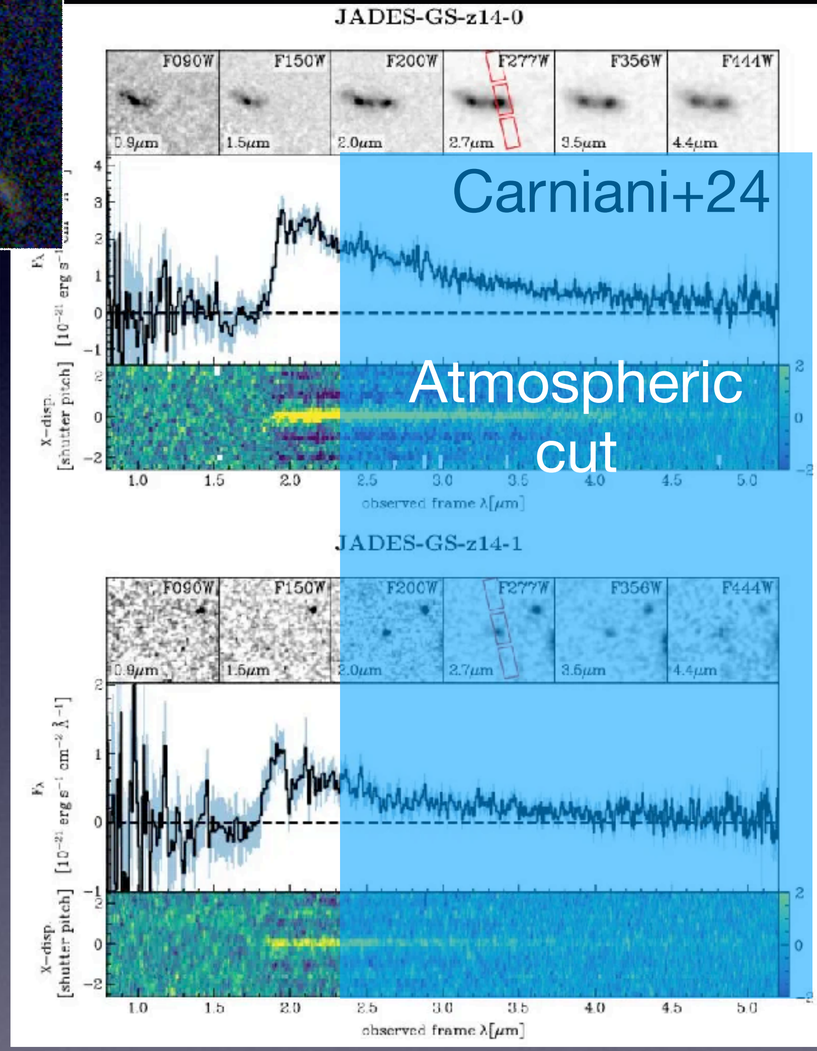

VLT/X-Shooter (30h, PI Vanzella)

The deepest and highest redshift spectrum from ground-based telescope in the NIR

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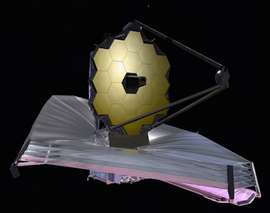
James Webb Space Telescope is revolutionizing our understanding of the high-redshift Universe



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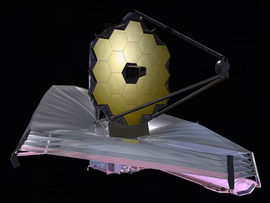

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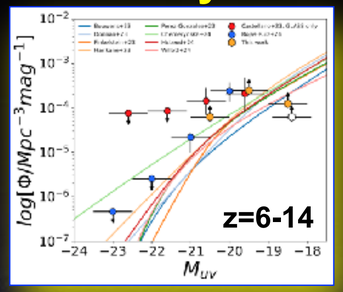

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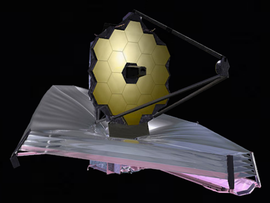

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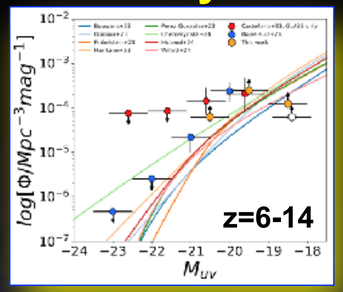

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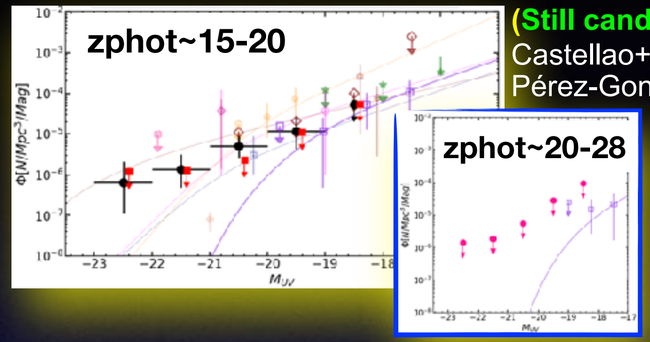

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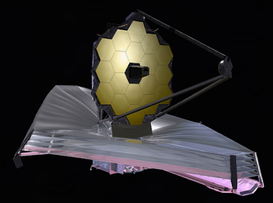

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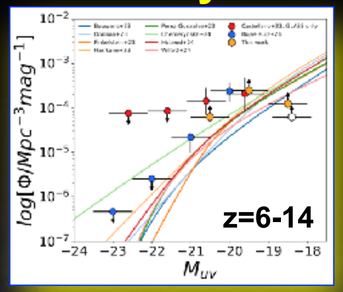

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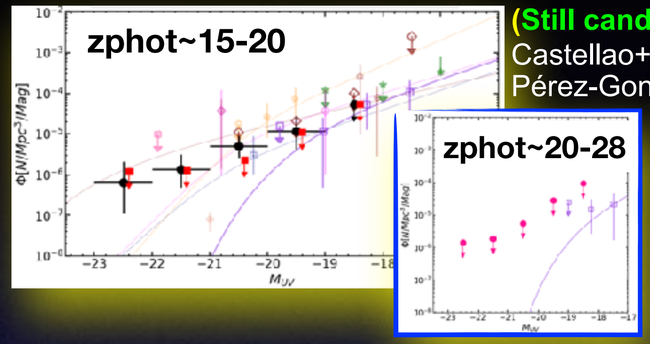

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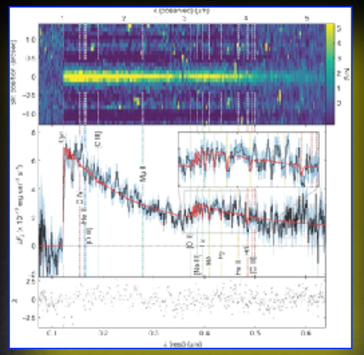

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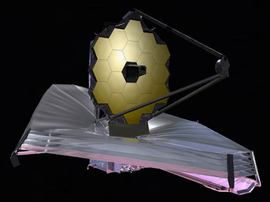

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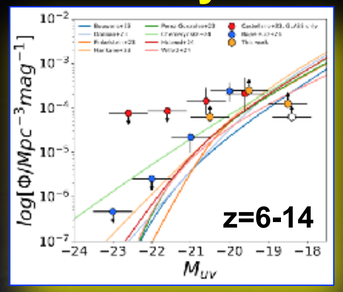

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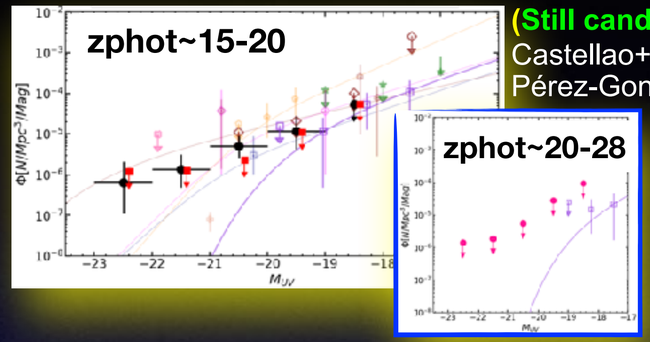

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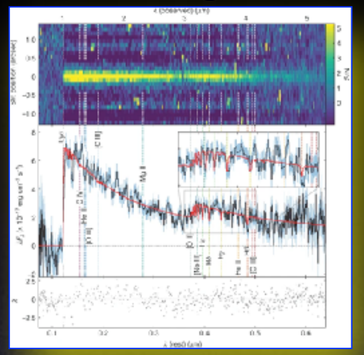

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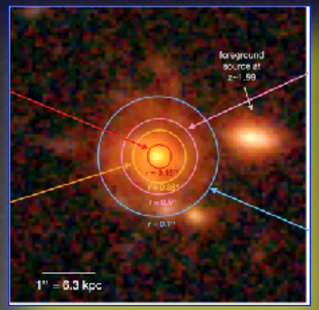

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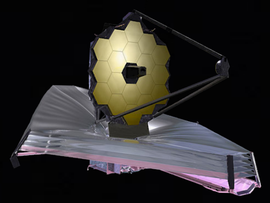

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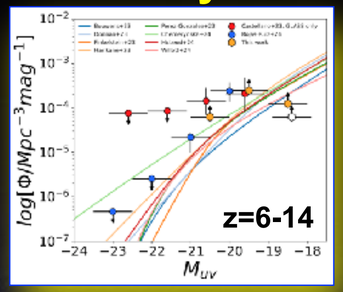

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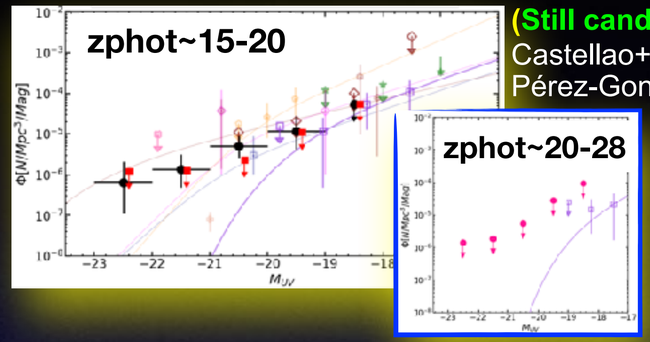

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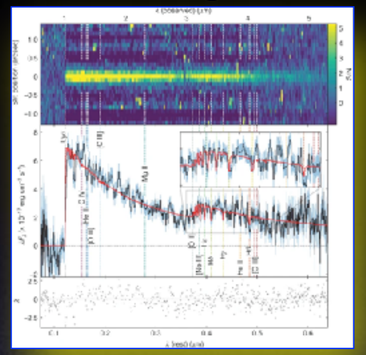

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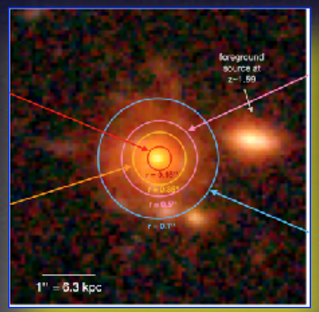

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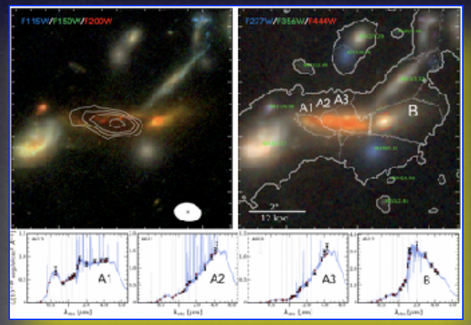

***JWST* Insights Into *HST*-dark Galaxies and the Quiescent Companions at *z*=2.58**
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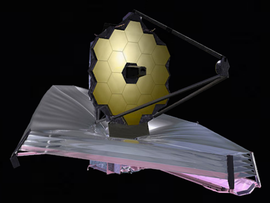

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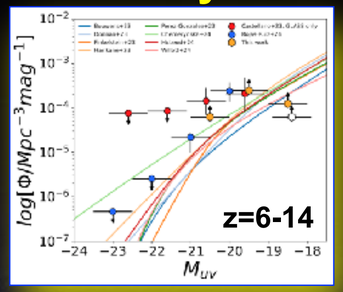

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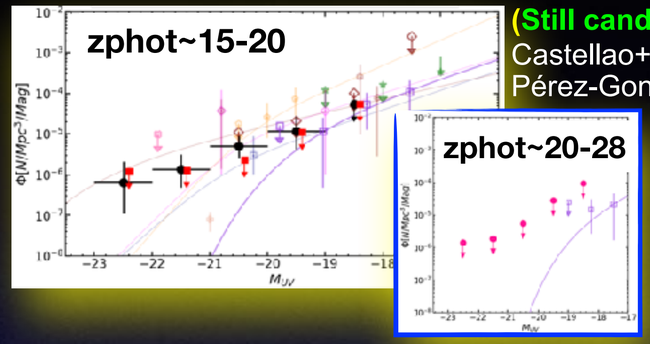

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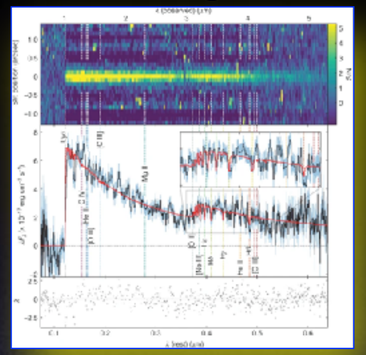

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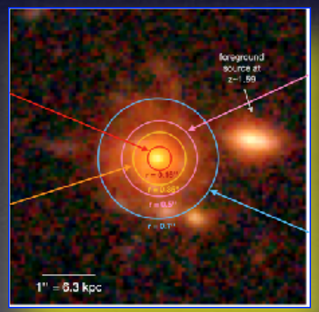

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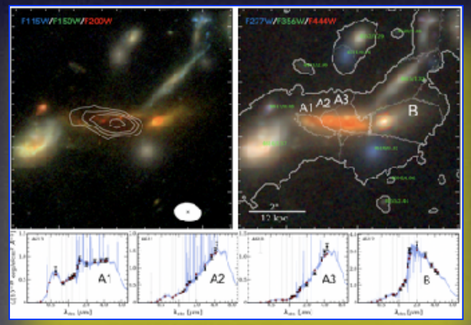

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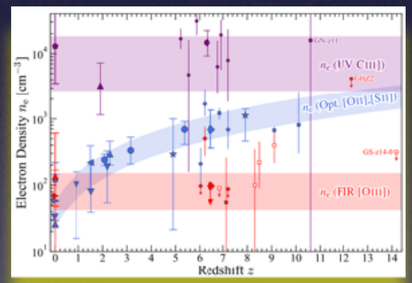
Electron density/temperature evolution JWST + ALMA



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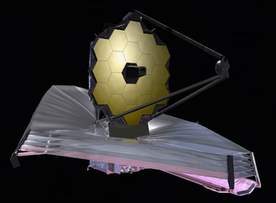

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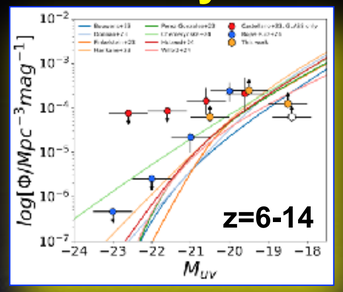

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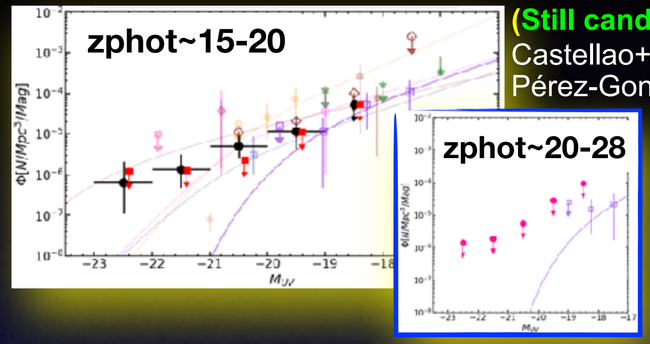

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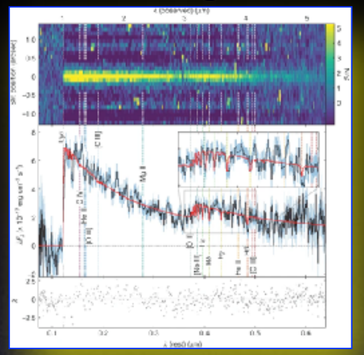

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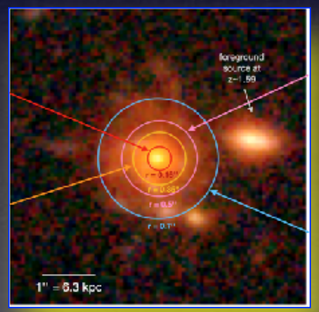

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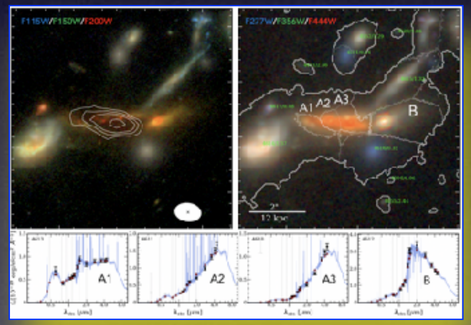

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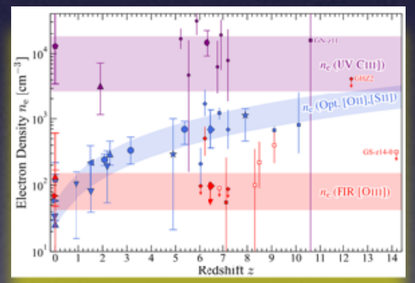

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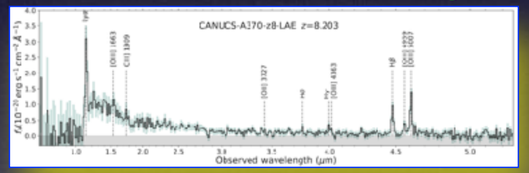

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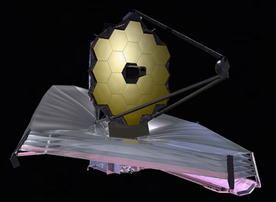

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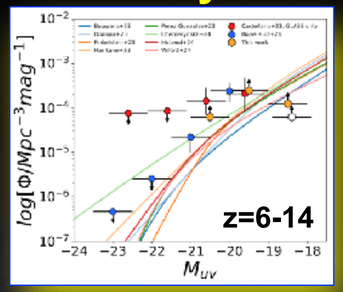

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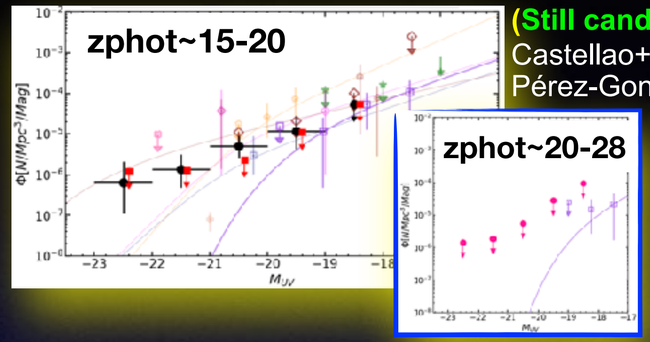

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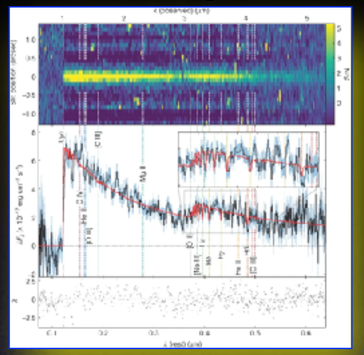

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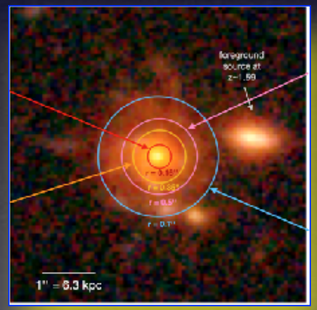

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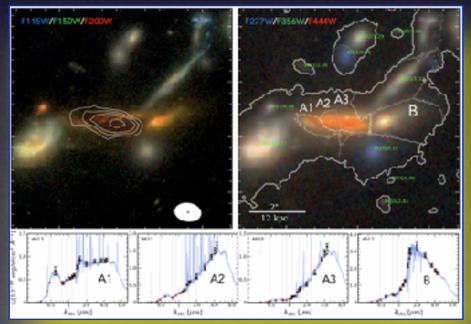

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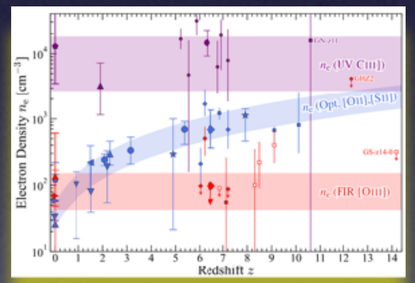

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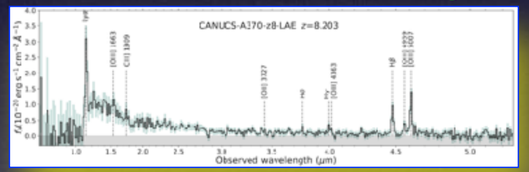

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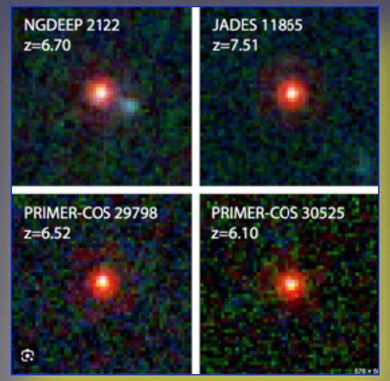

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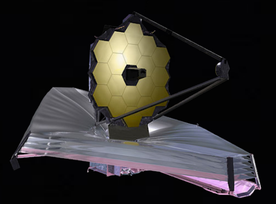

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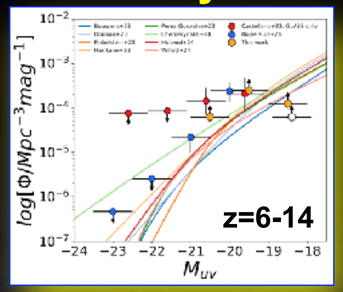

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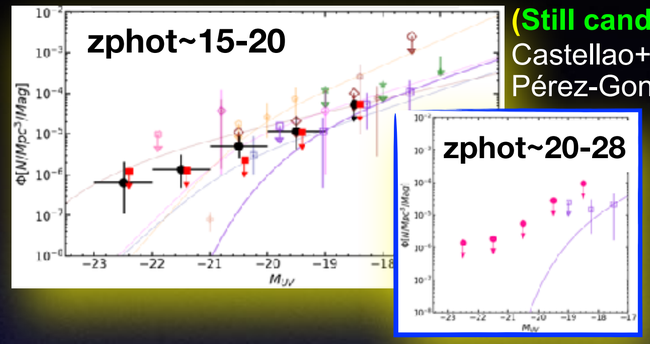

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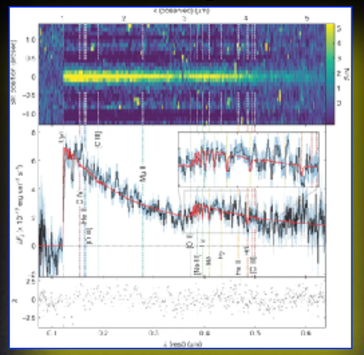

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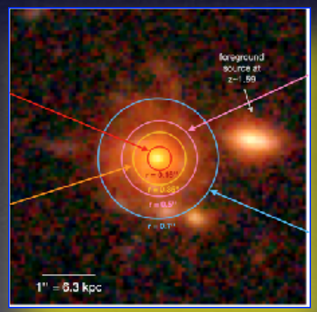

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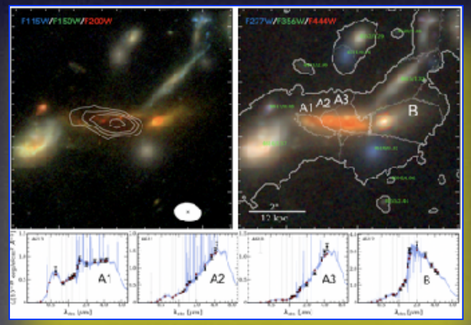

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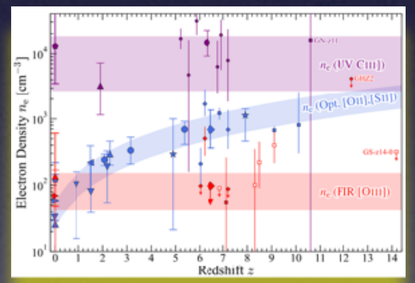

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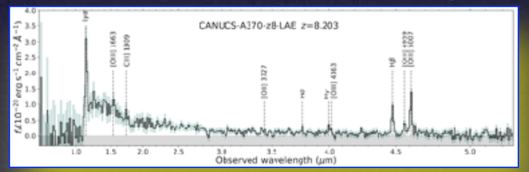

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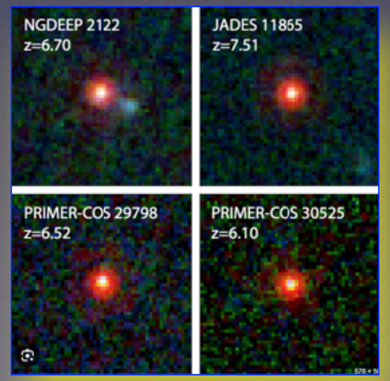

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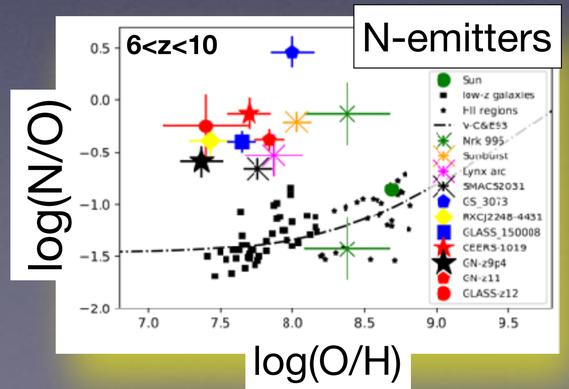

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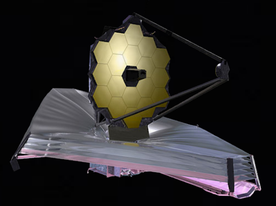

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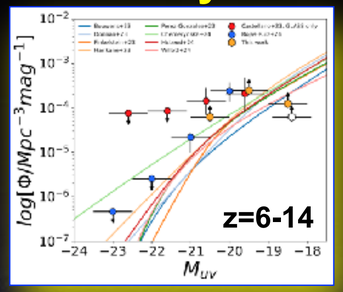

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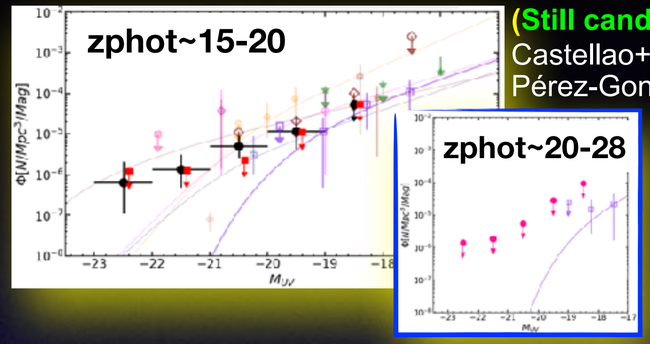

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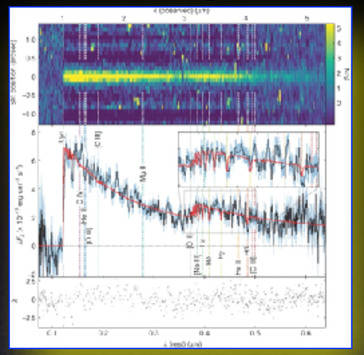

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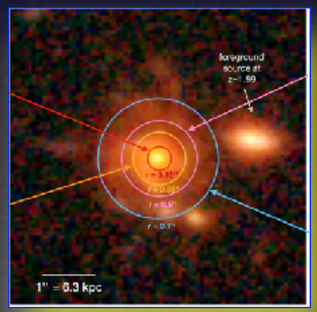

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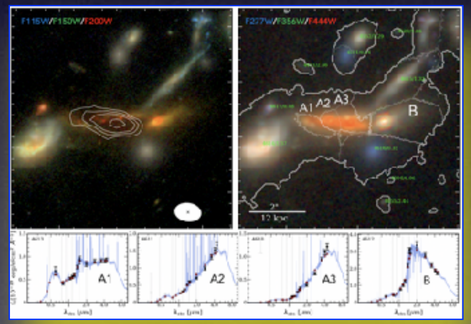

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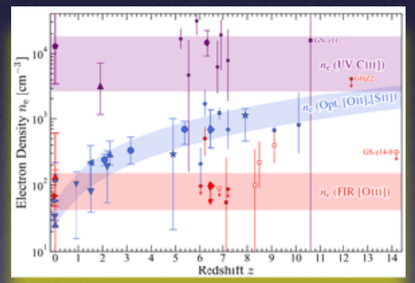

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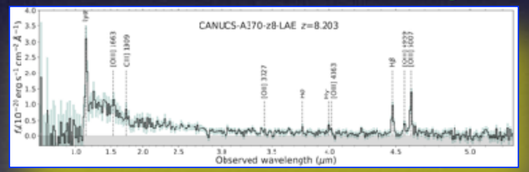

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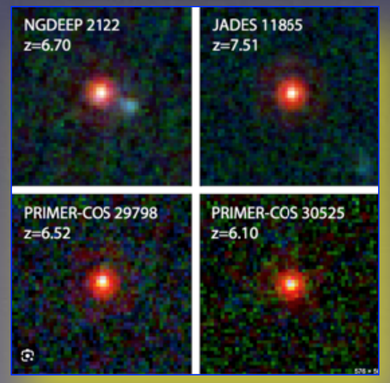

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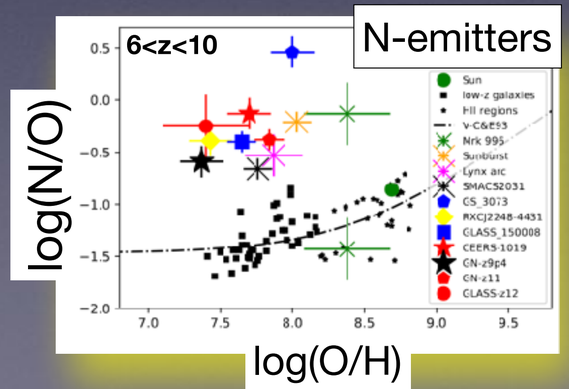

Gravitational lensing (star clusters)

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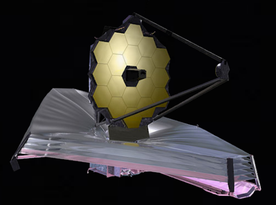

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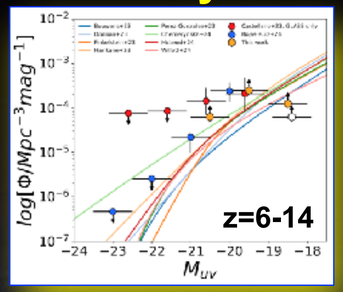

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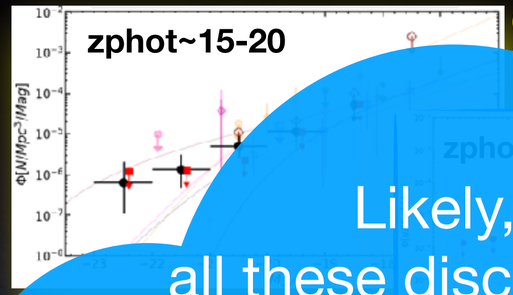

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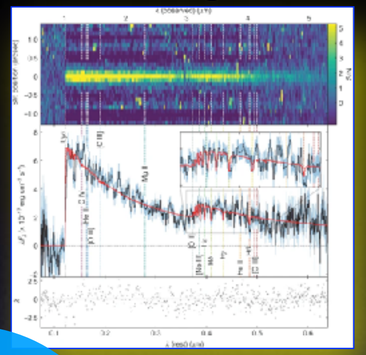

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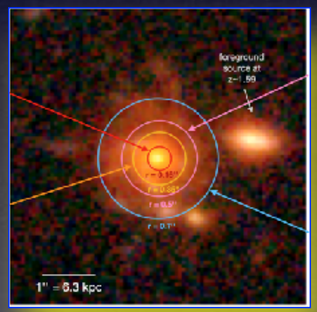

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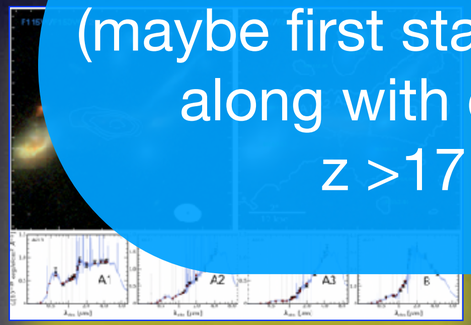

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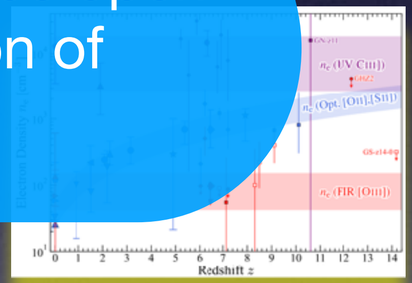

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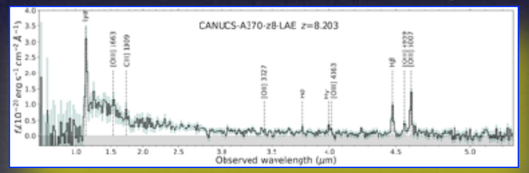

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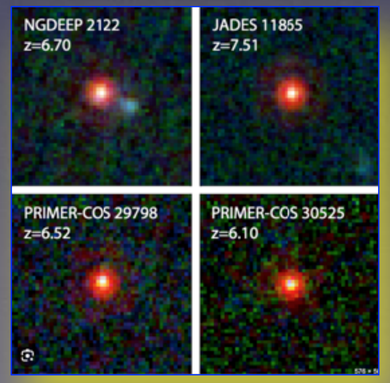

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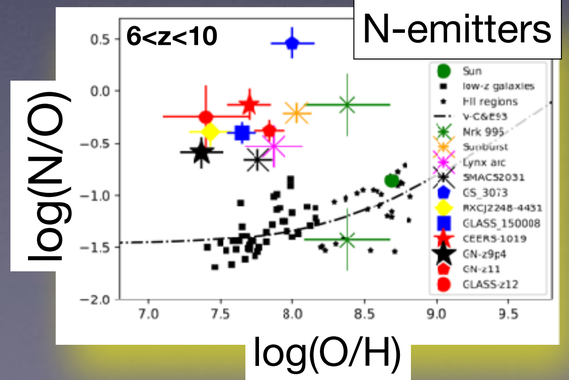

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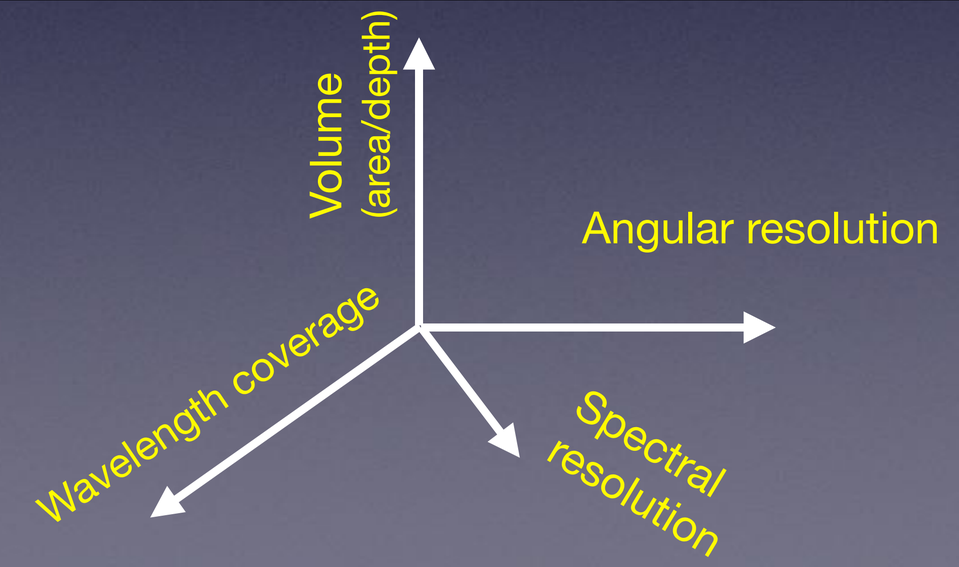
'Unpacking' high-z **galaxies into bound star clusters in the reionization epoch, Messa+25;Adamo+24; Vanzella+**

A ‘personal’ view of ground-based extragalactic astronomy/galaxy formation in the ’30-40

European Southern Observatory

ELT+VLT+ALMA + new gen. instruments
See also the other contributions.

- MAVIS ~ ‘30
- Blue MUSE ~ ‘30
- CUBES ~ ‘30
- (MOONS, ERIS…)



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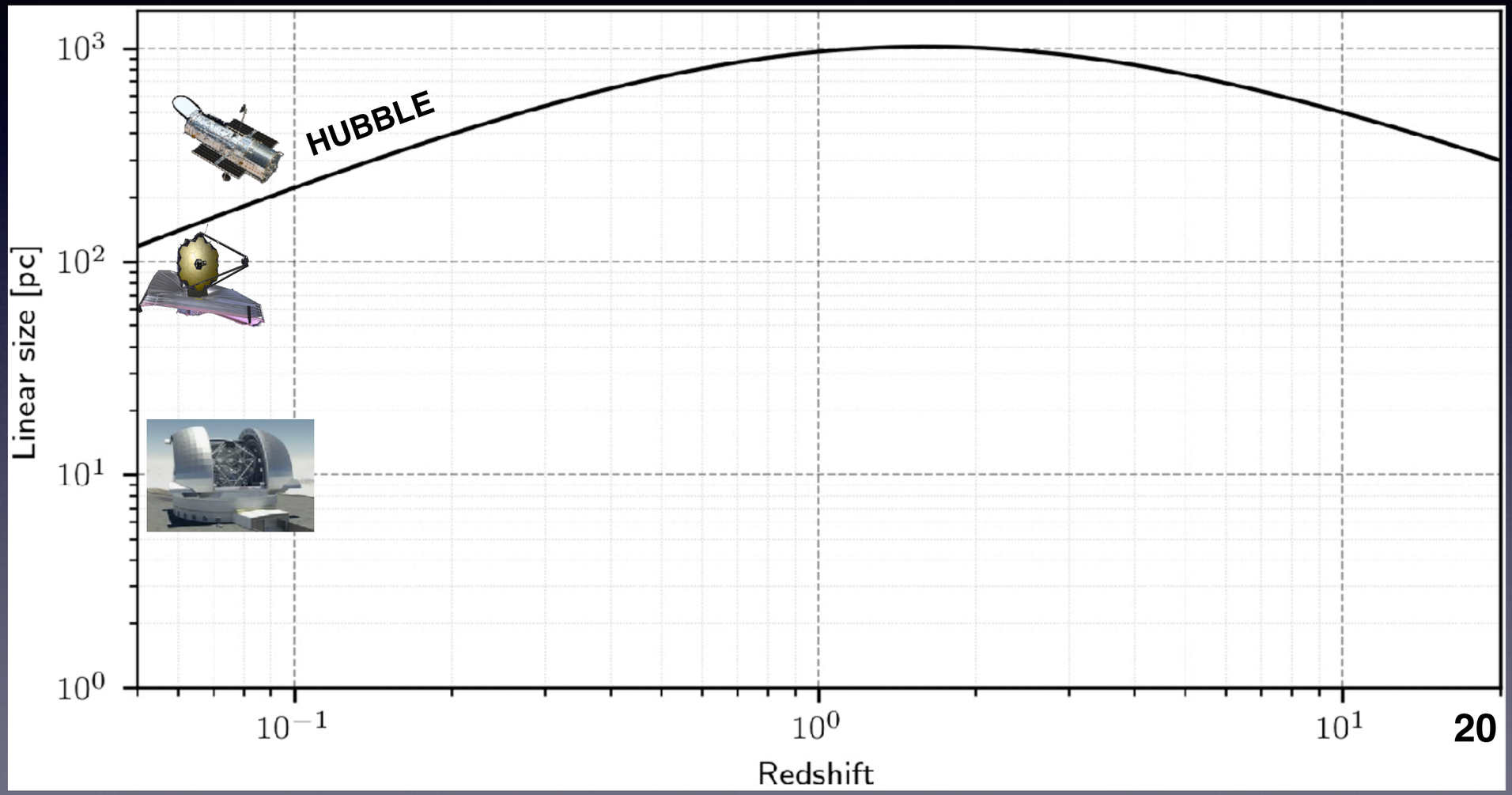
Glance to the future: ELT will probe < 100 parsec scale at any redshift (z<17) , not a survey machine

(Extragalactic Astronomy 2032-2040 with AO)

Hubble: ~120 mas (F814W)

JWST: ~70 mas (F200W)

ELT/MORFEO-MICADO: 12 mas (H-band) >2030



MORFEO AO module @ ELT (Ciliegi+21) - MICADO (Davies+21)

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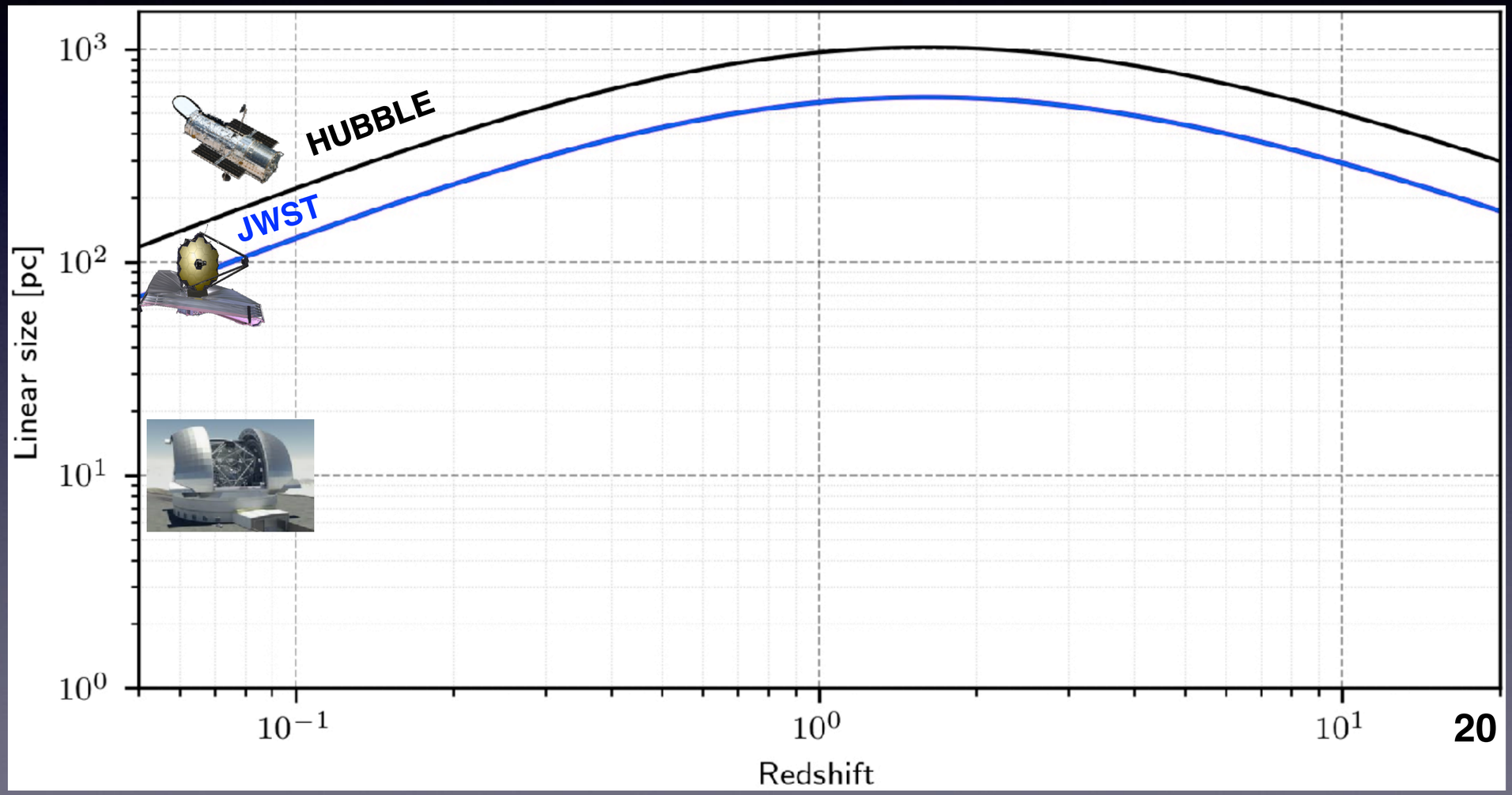

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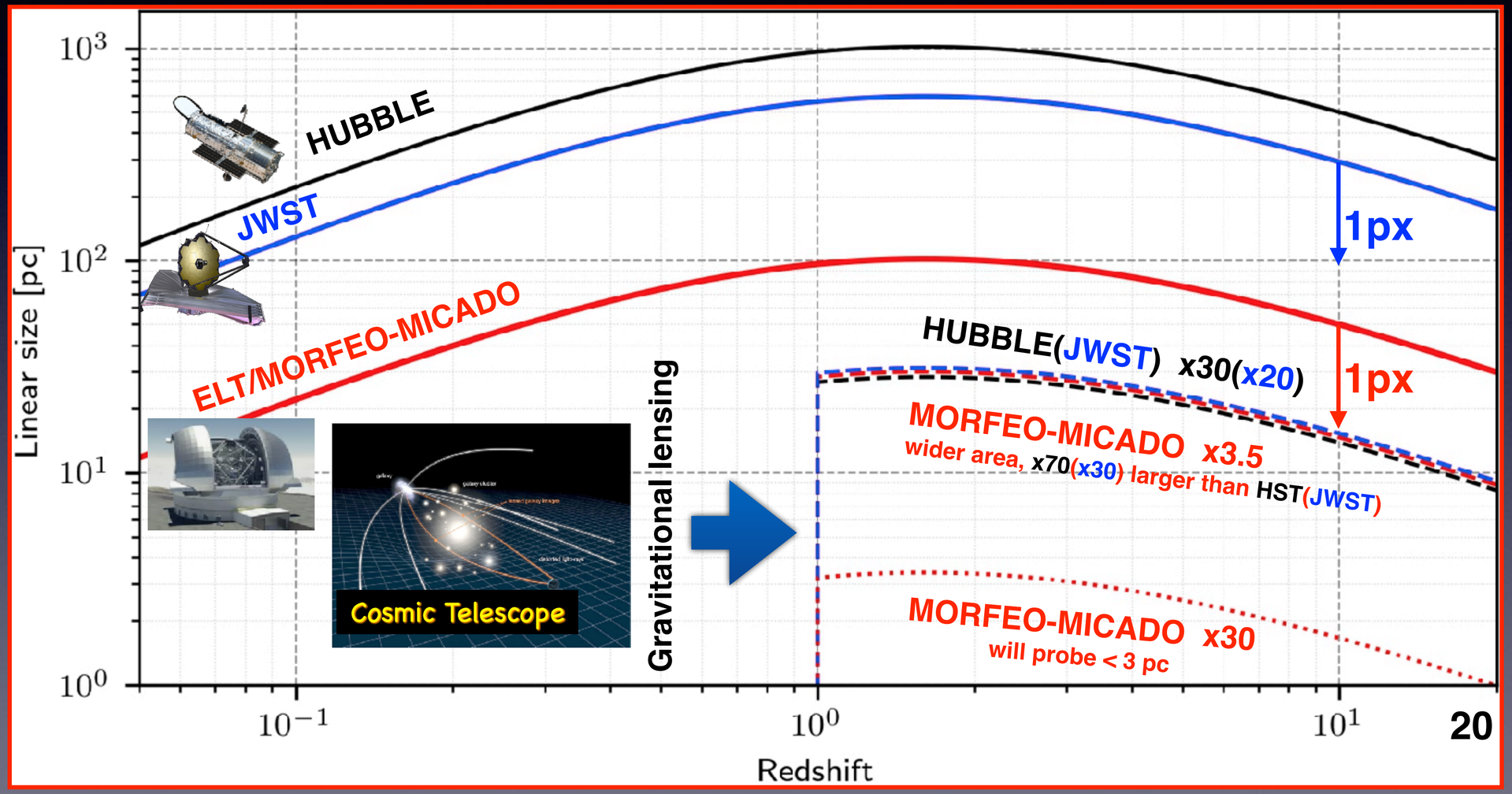


Sub-kpc clumps

SF complex

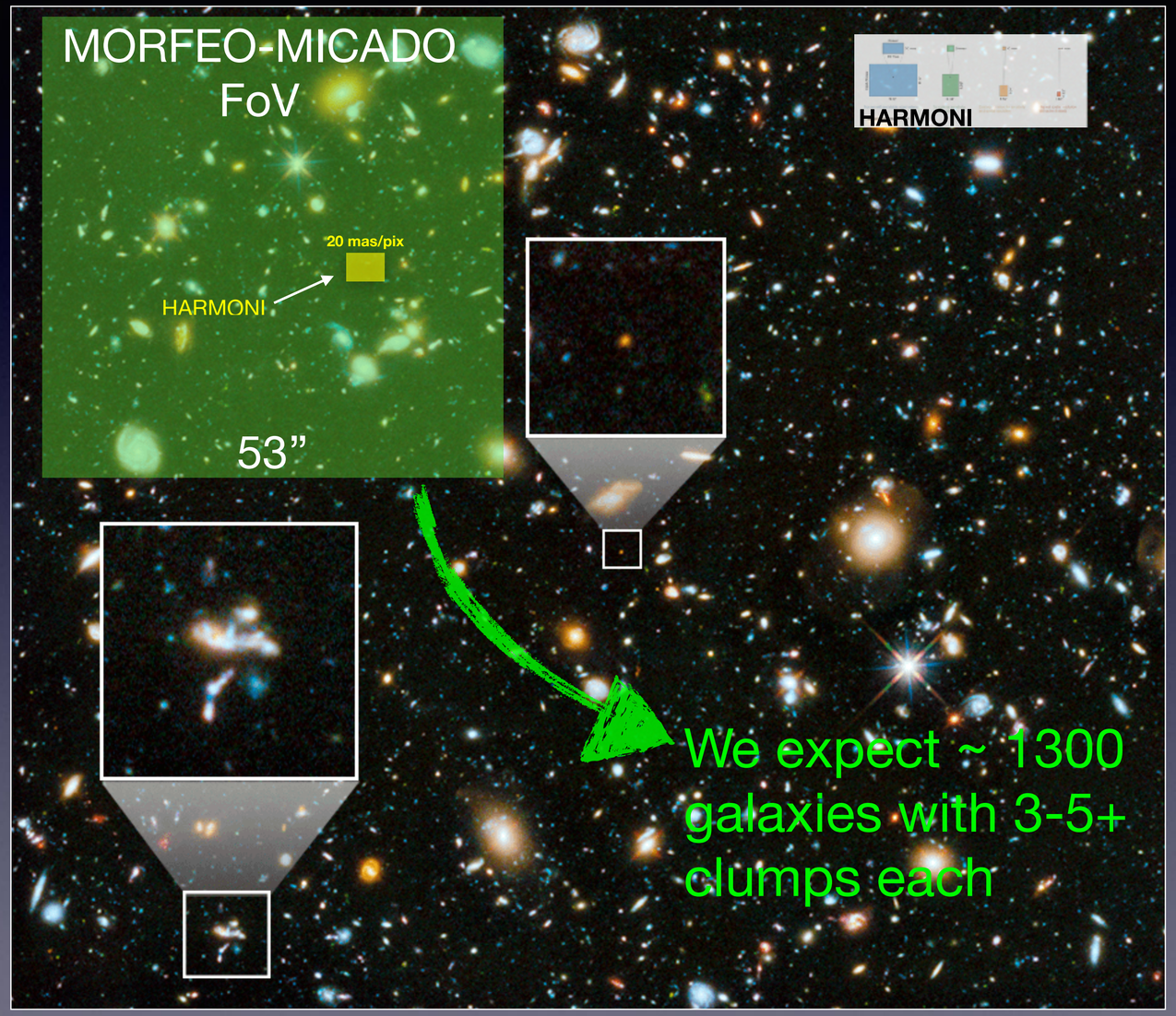
Star clusters

MORFEO AO module @ ELT (Ciliegi+21) - MICADO (Davies+21)

An example:
Extragalactic Astronomy 2032-2040 with ELT/VLT XAO

Imaging	~3,000-10,000 clumps in a single MORFEO-MICADO FoV probed at ~ 8-12 mas, <70-100 pc, z<17; H~29.6, 5h
Spectro	Target-oriented HARMONI: IFU on single/multiple source; MICADO long slit Very poor spectroscopic multiplex @ tens mas (!)

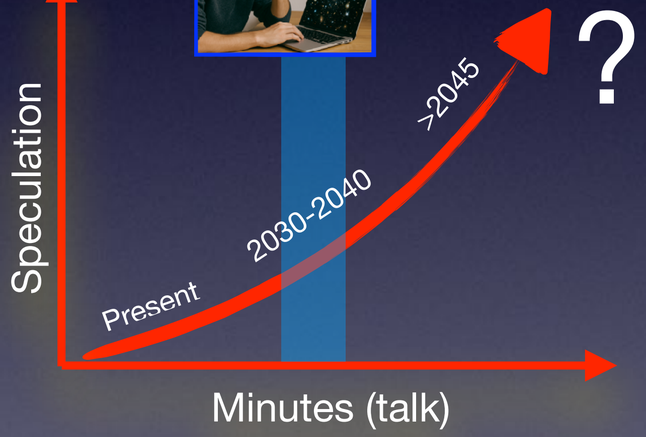
Hubble Ultra Deep Field => 10,000 galaxies to m ~ 29.5

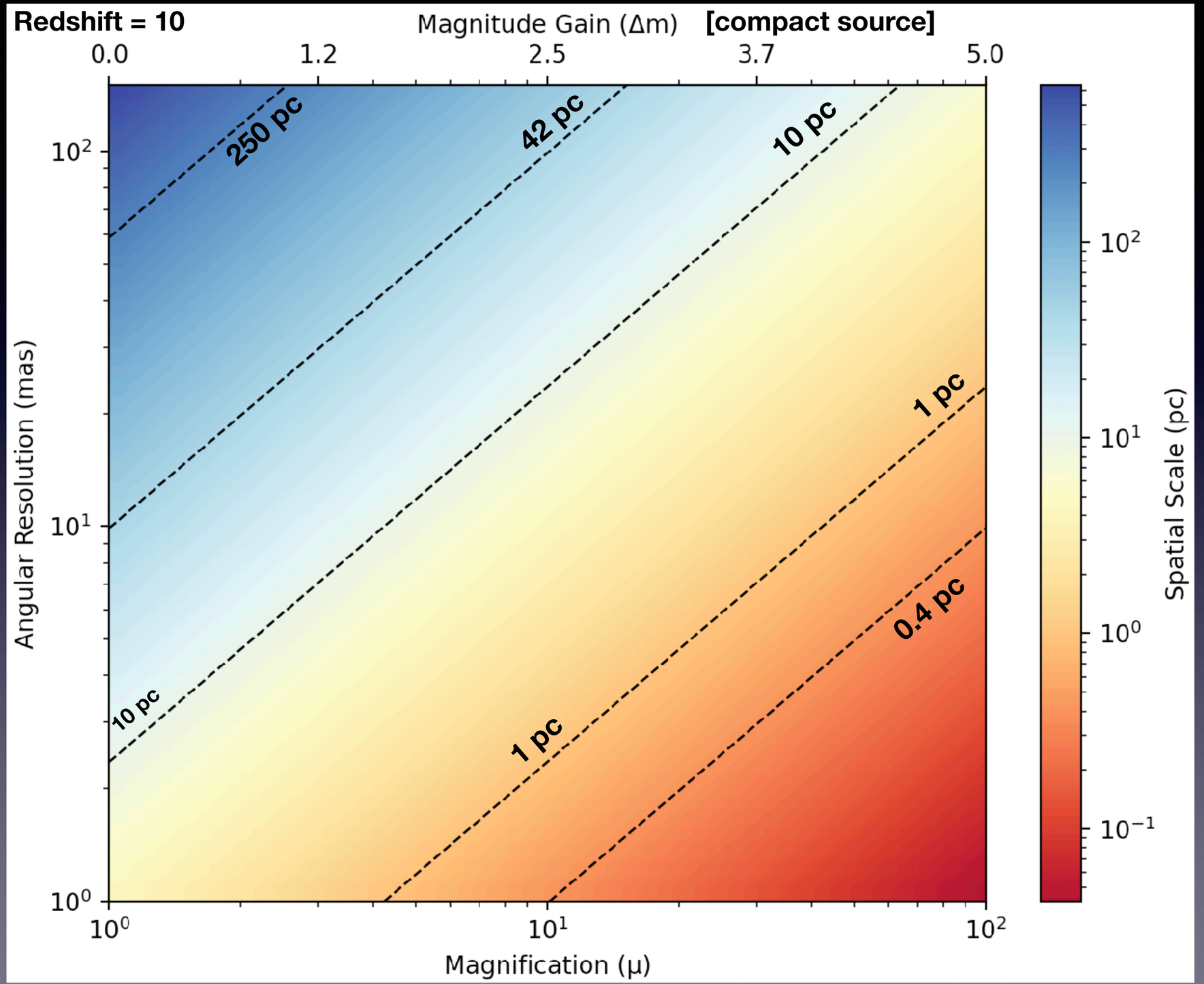


2.4 arcmin

Extragalactic Astronomy 2032-2040 with ELT Adding Gravitational lensing

Mimicking 100m - 1000m Class telescopes





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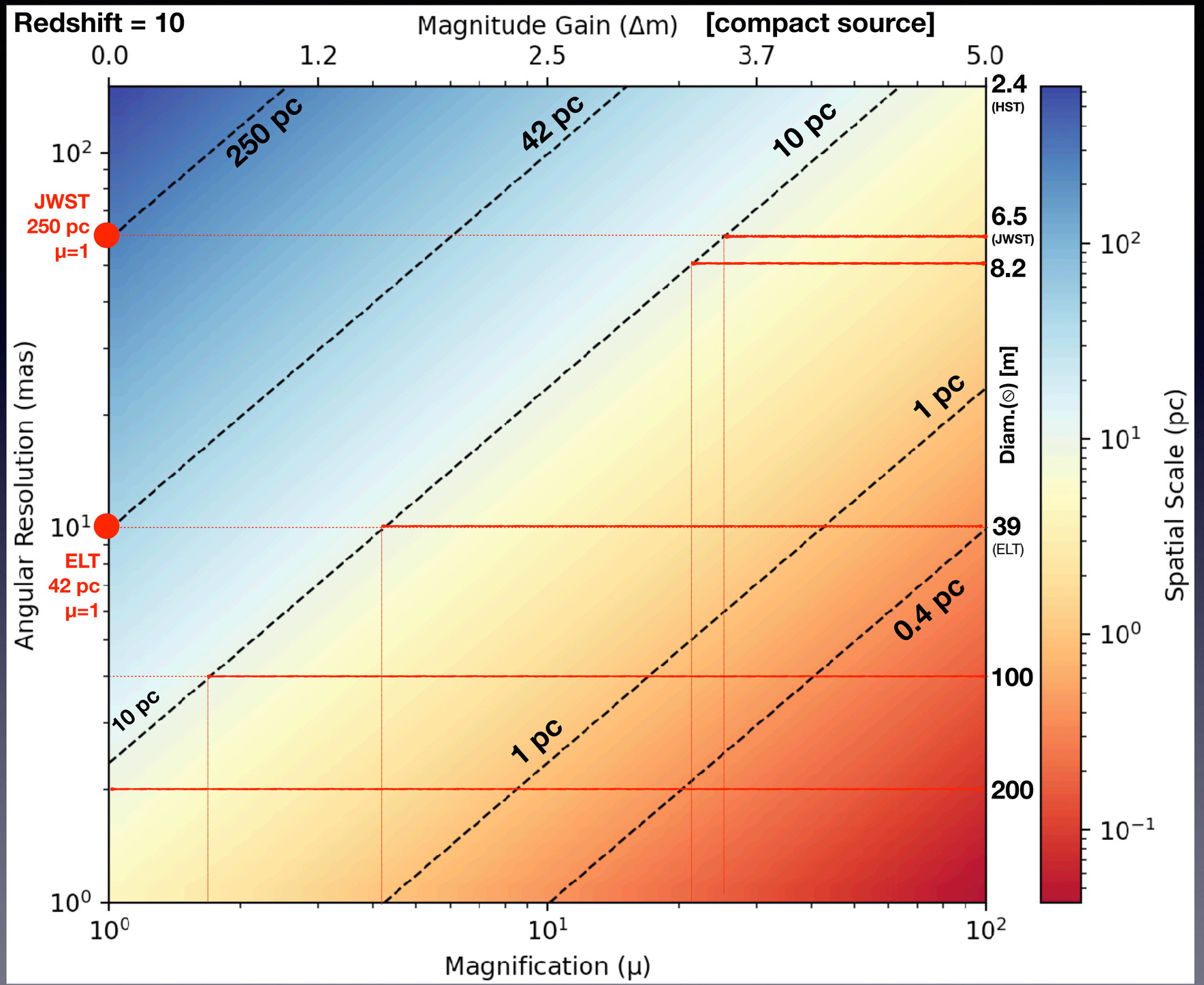

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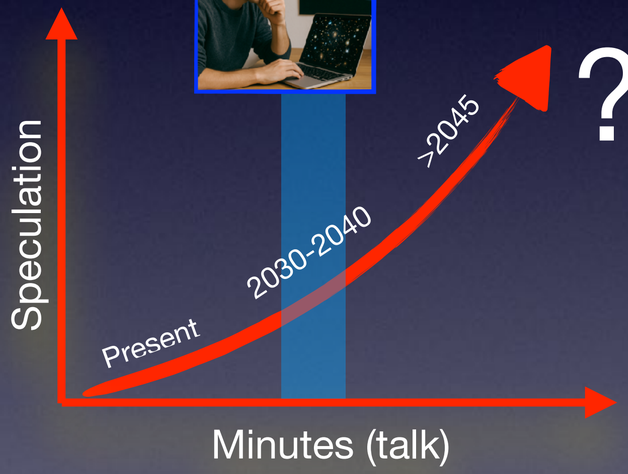

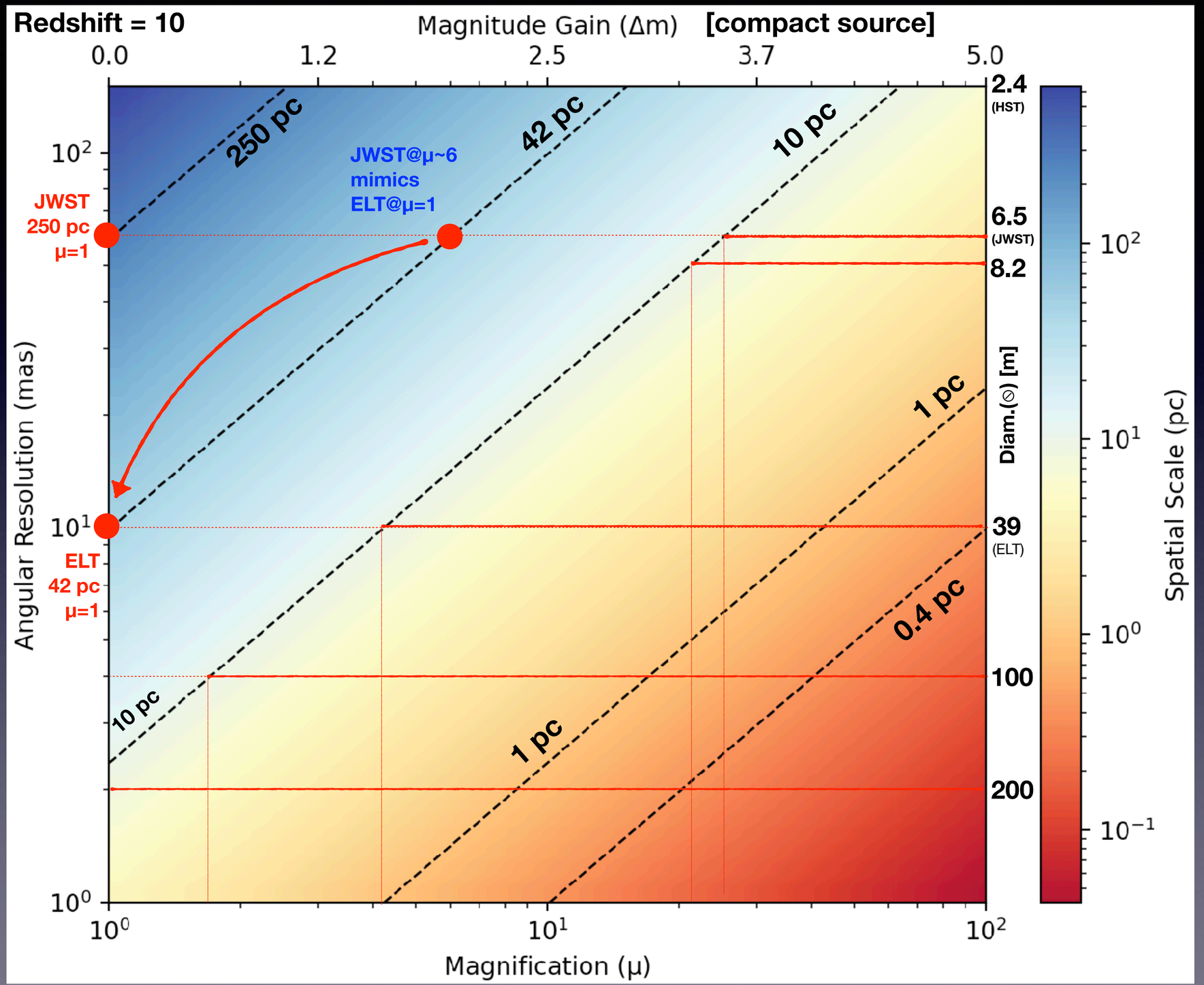

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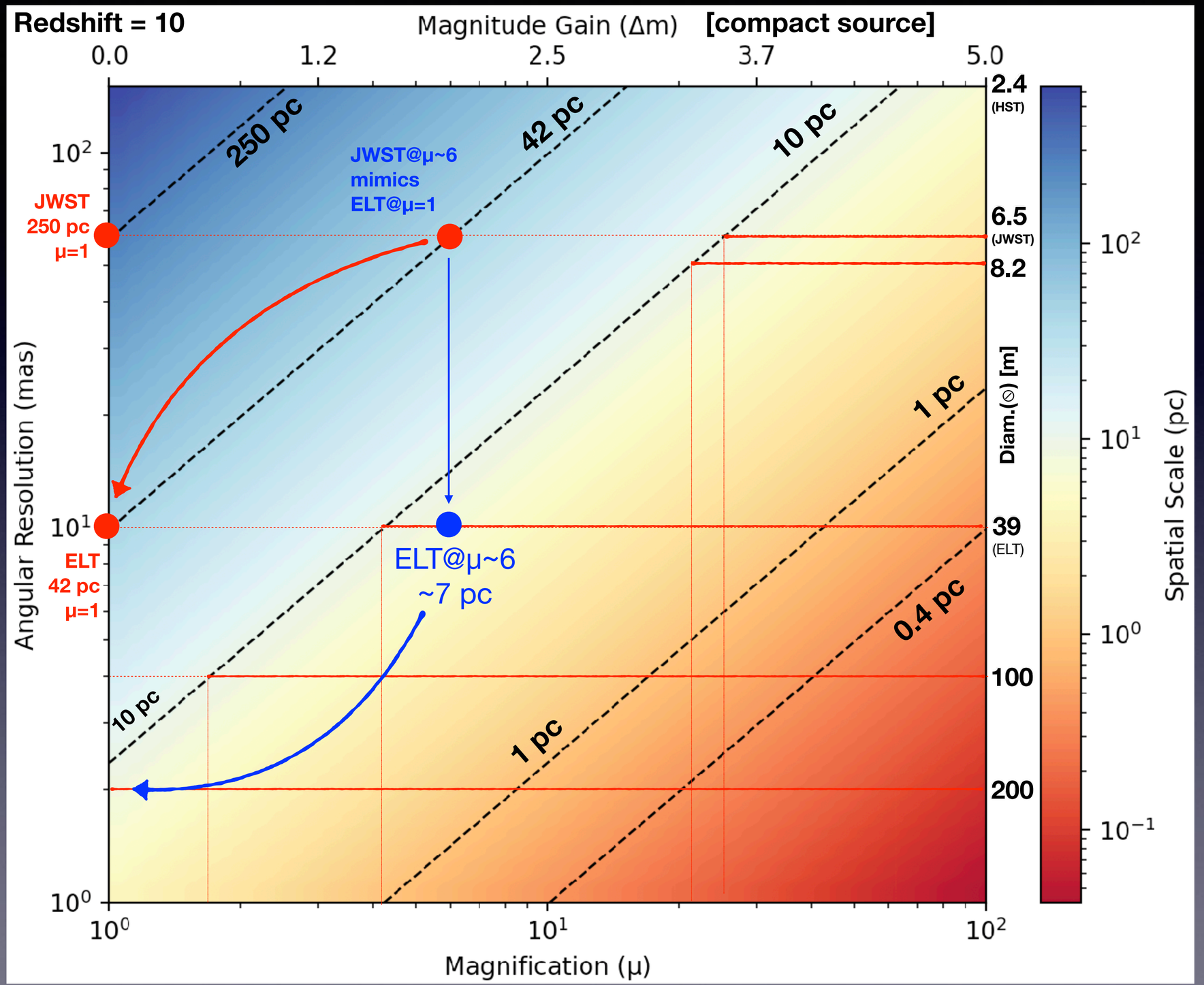

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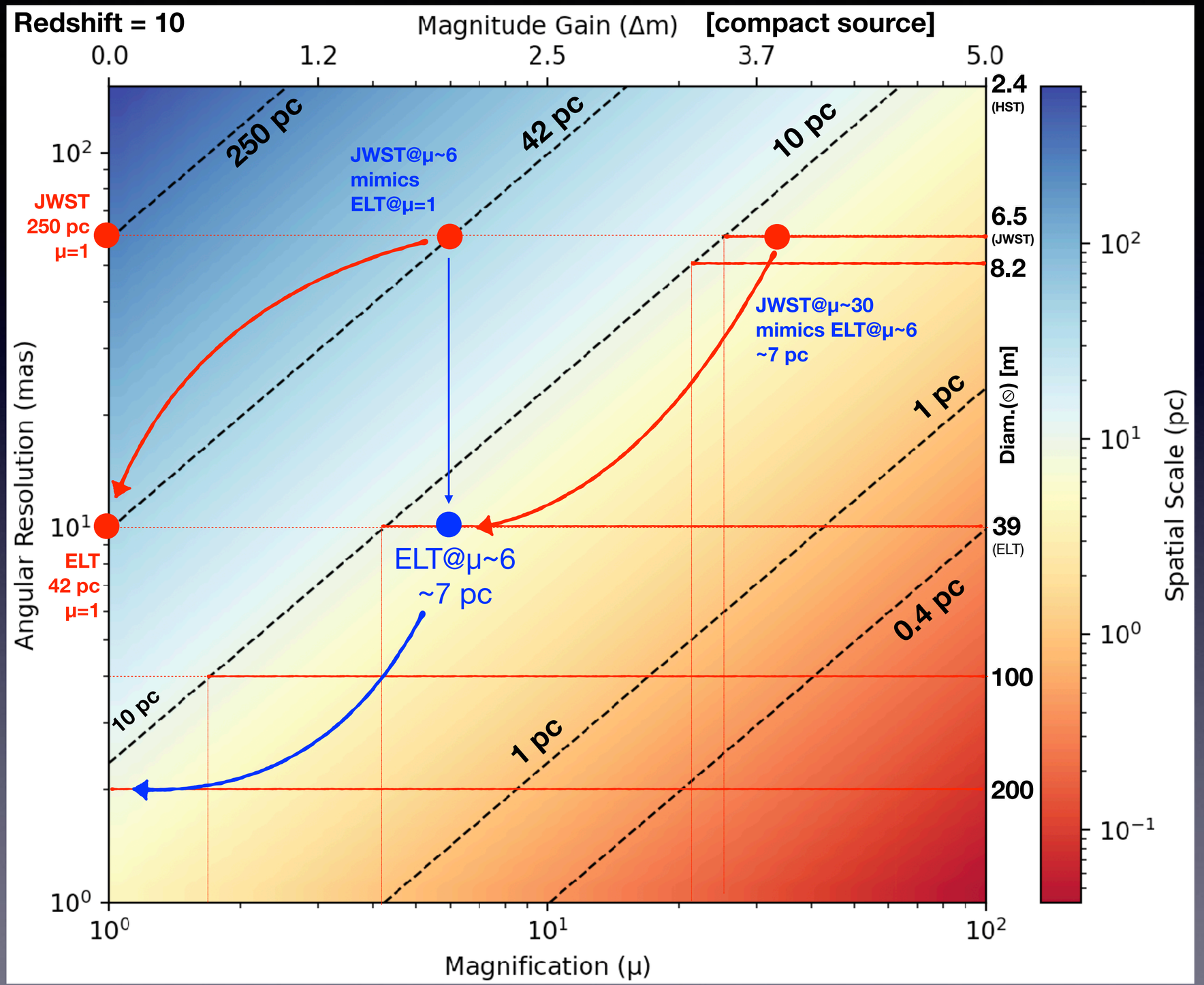

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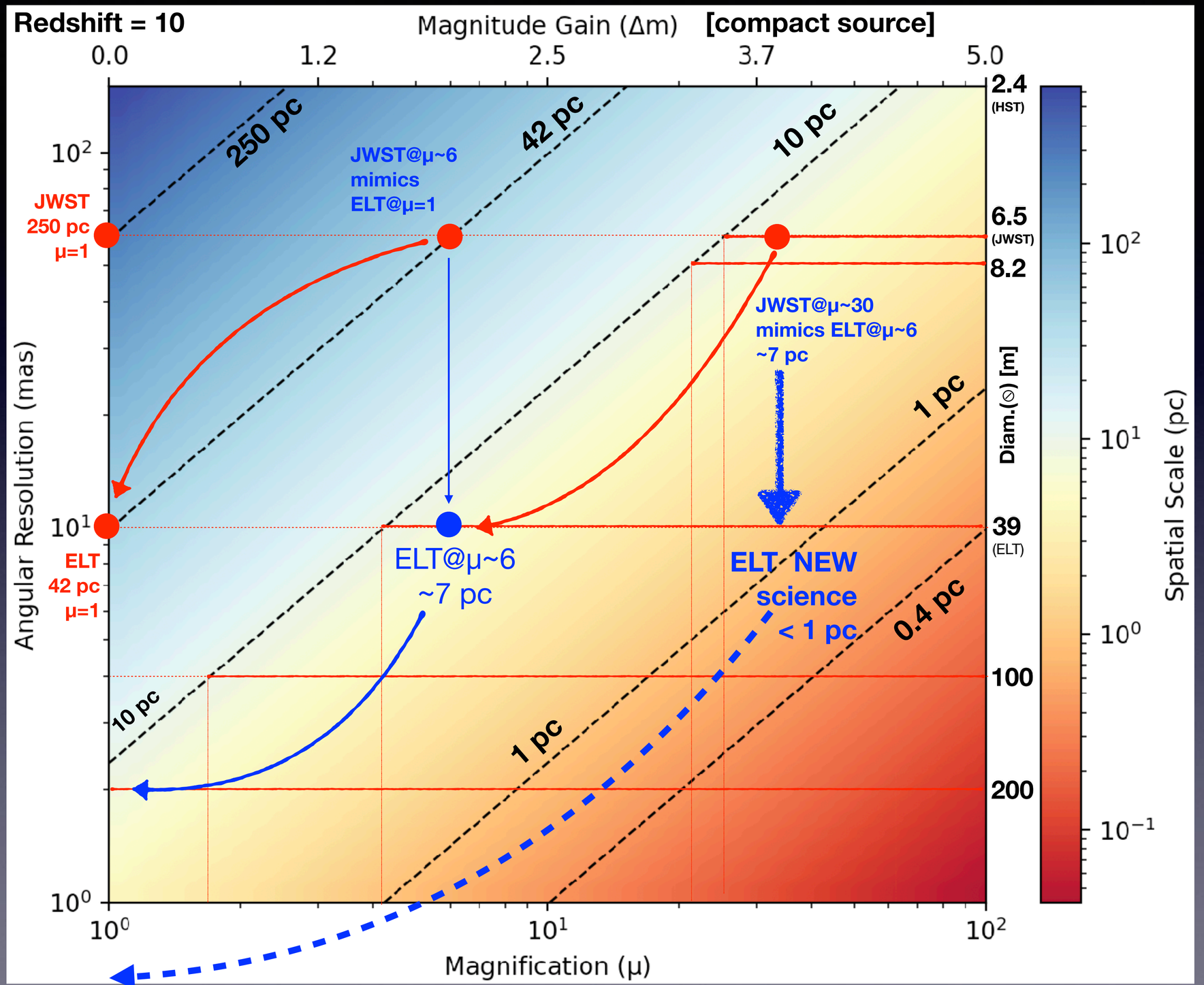

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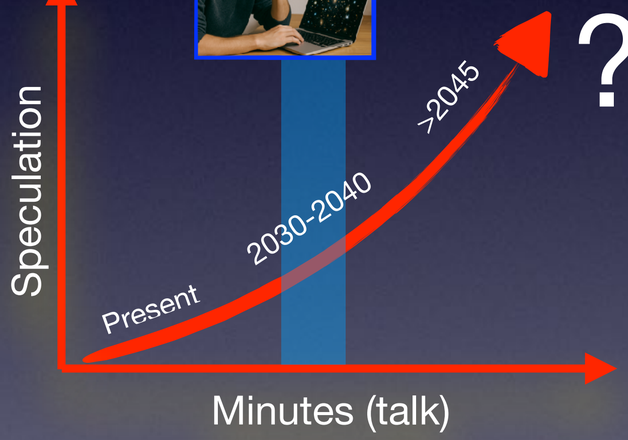

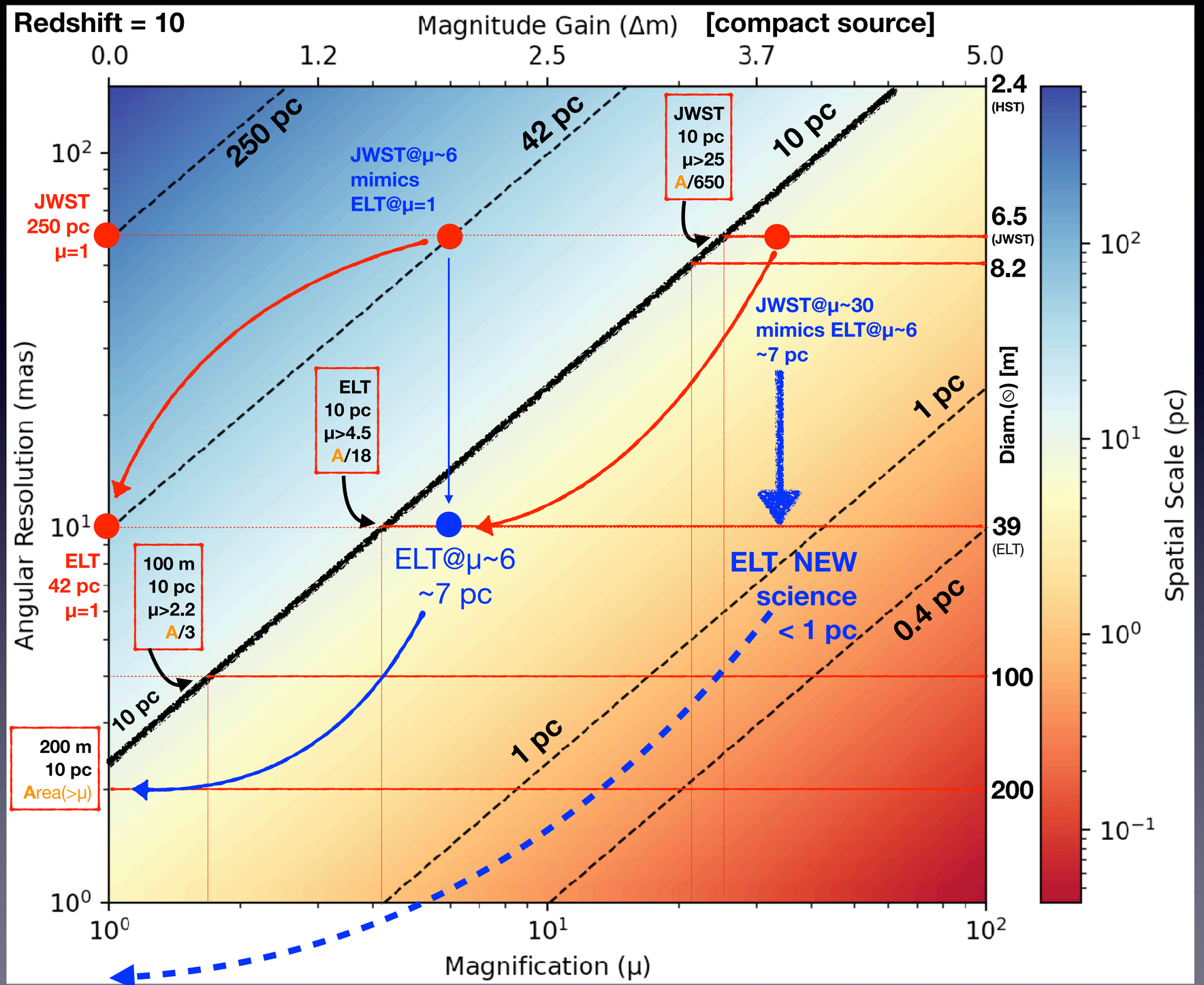

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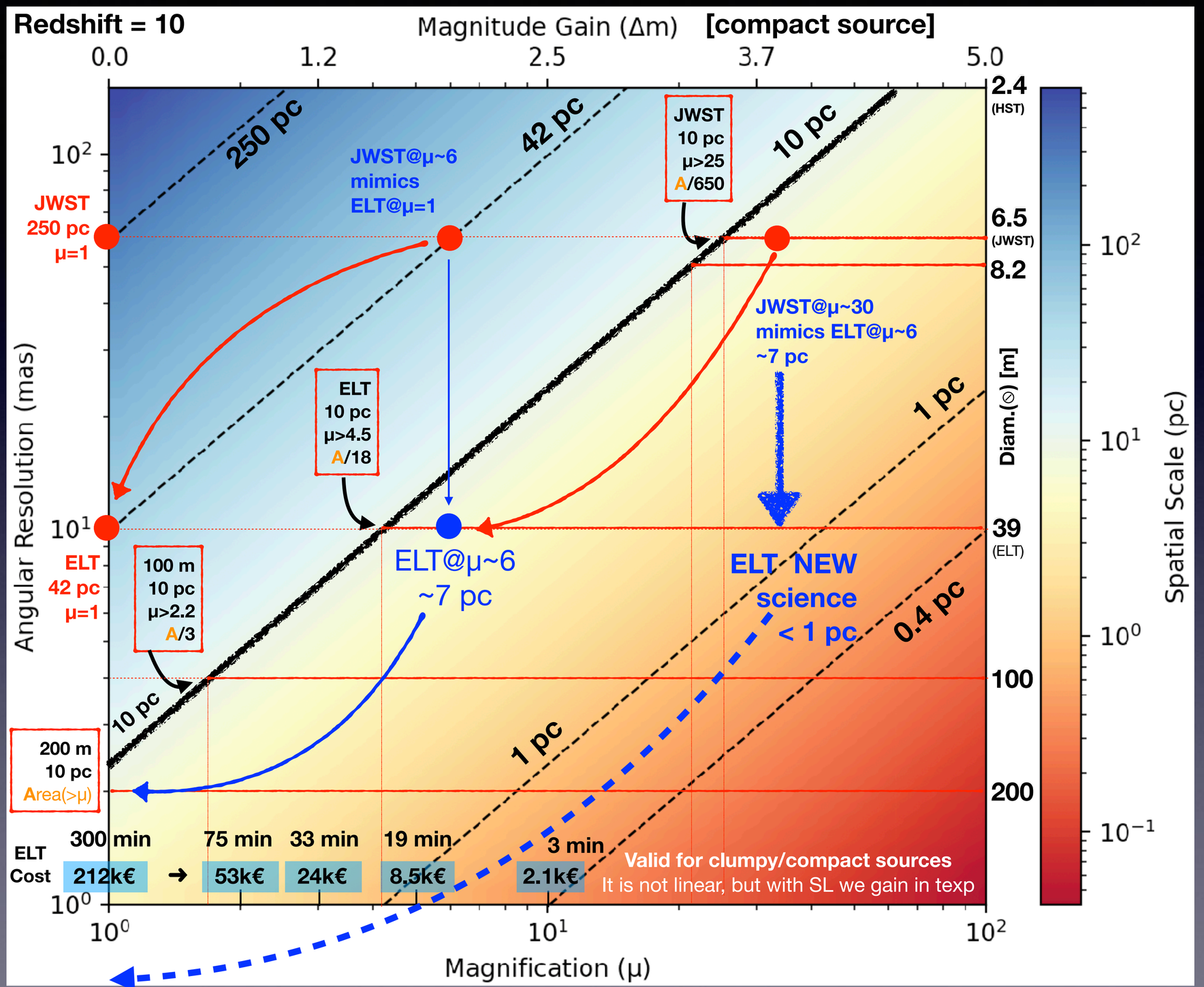
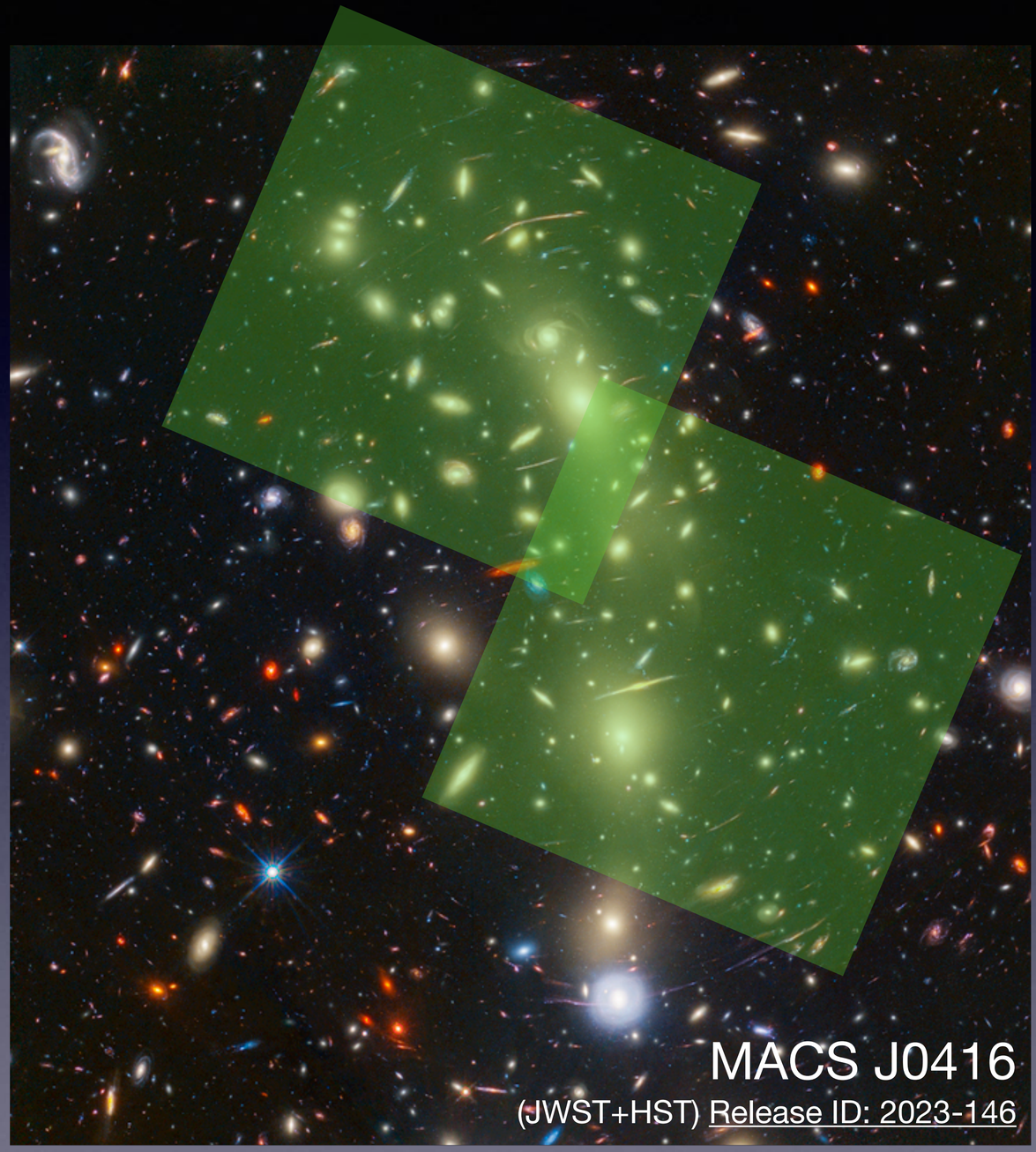


Glance to the future ’32-40: with moderate lensing amplification ELT will probe < 10 parsec scale



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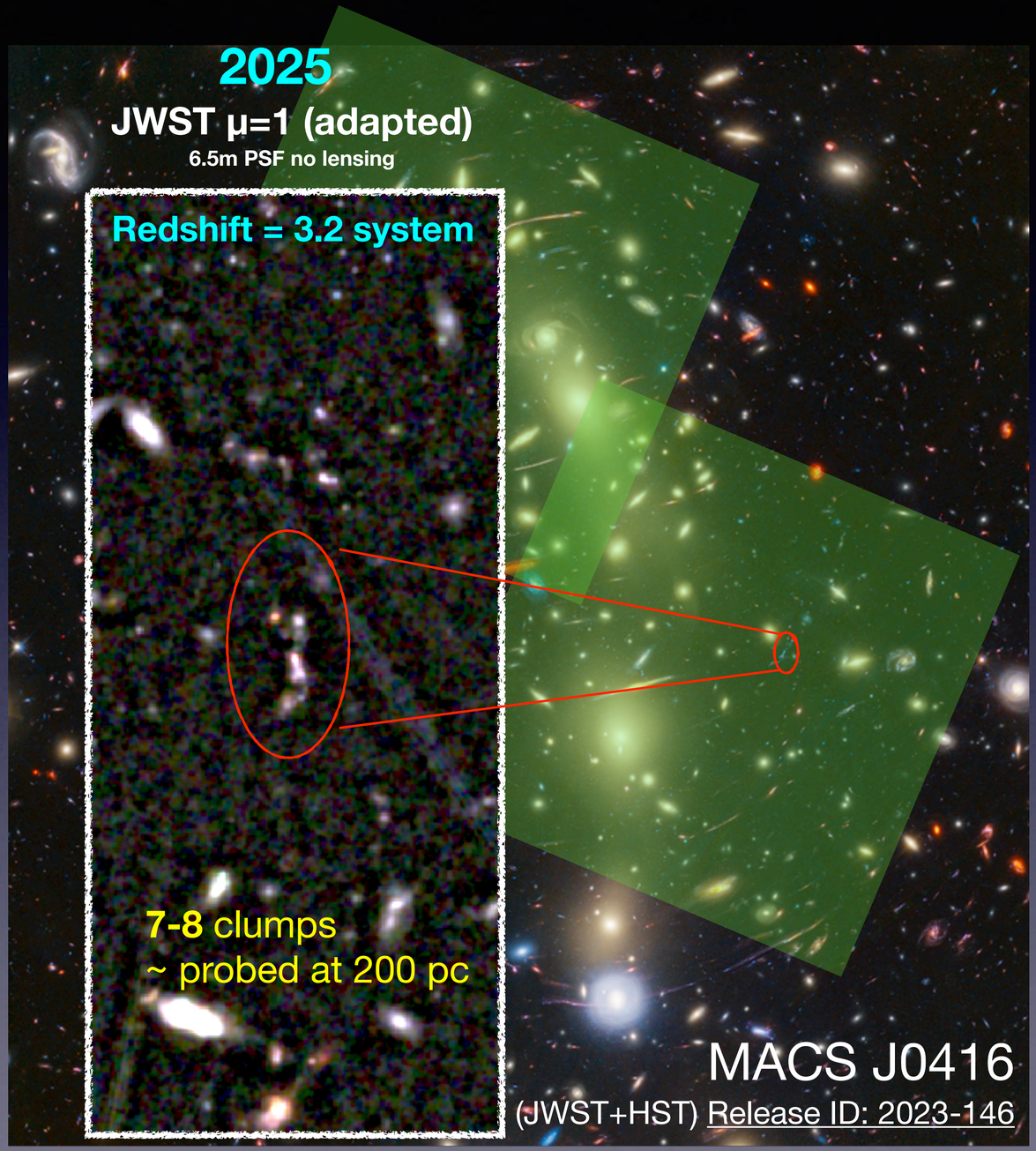

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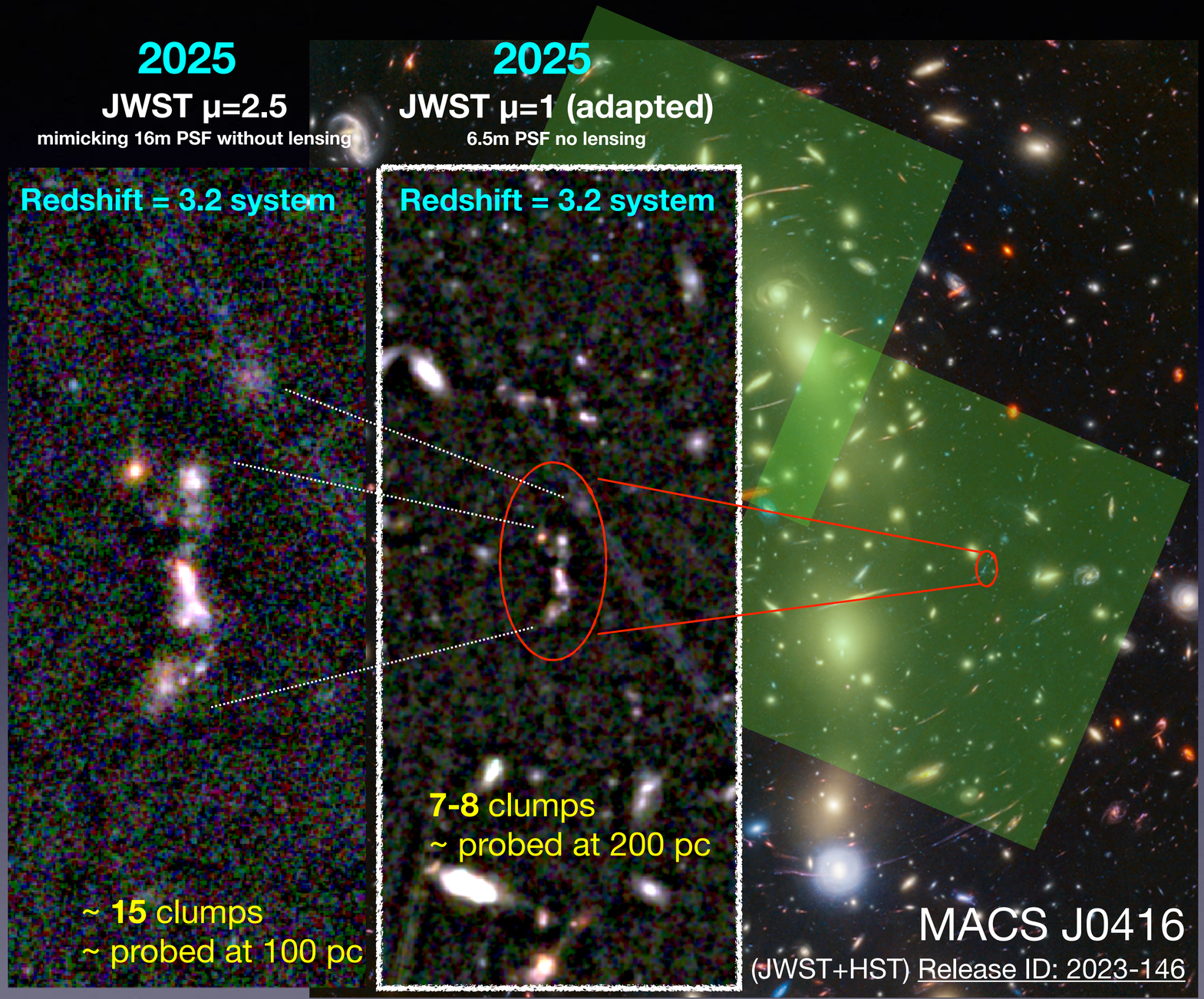

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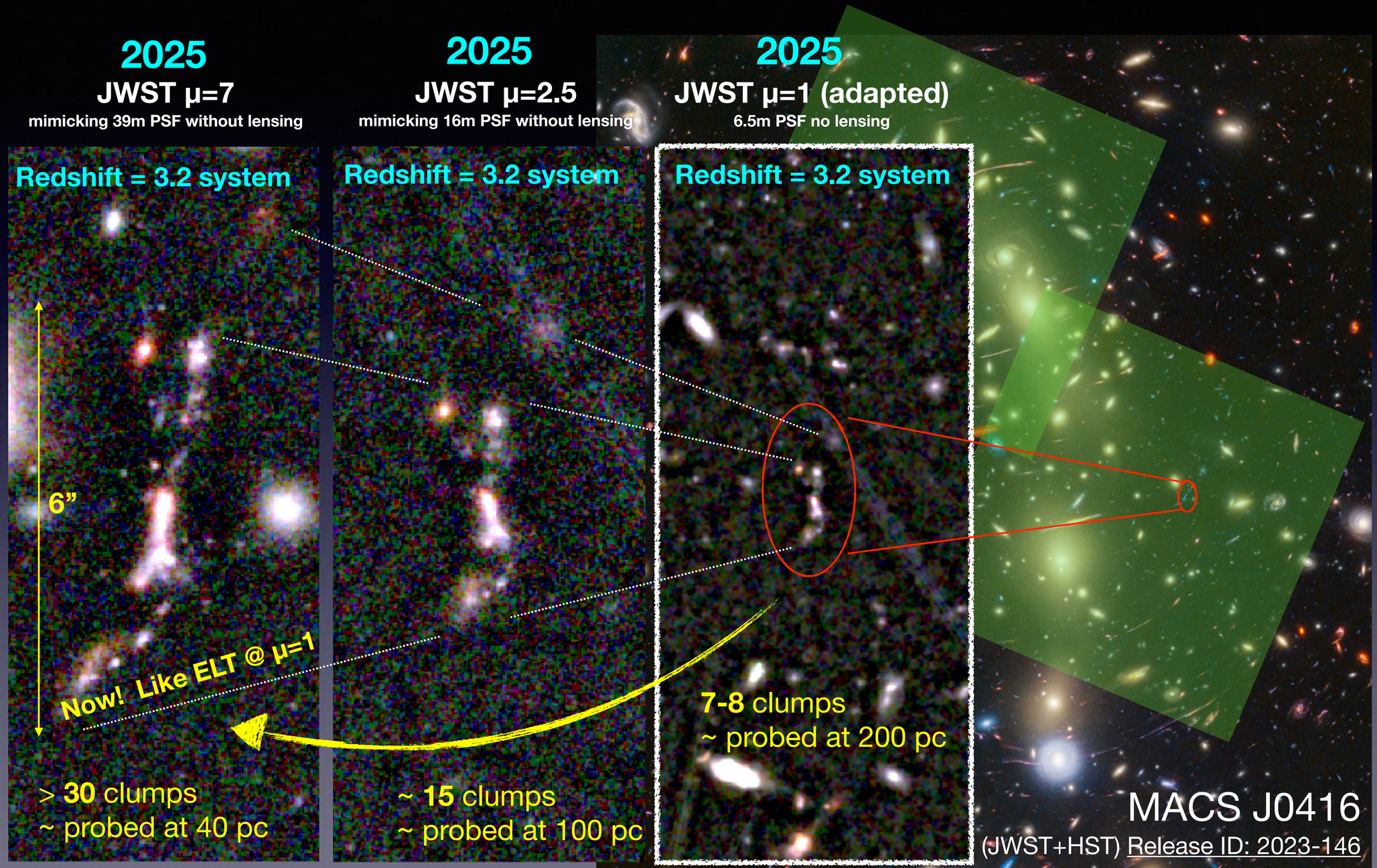

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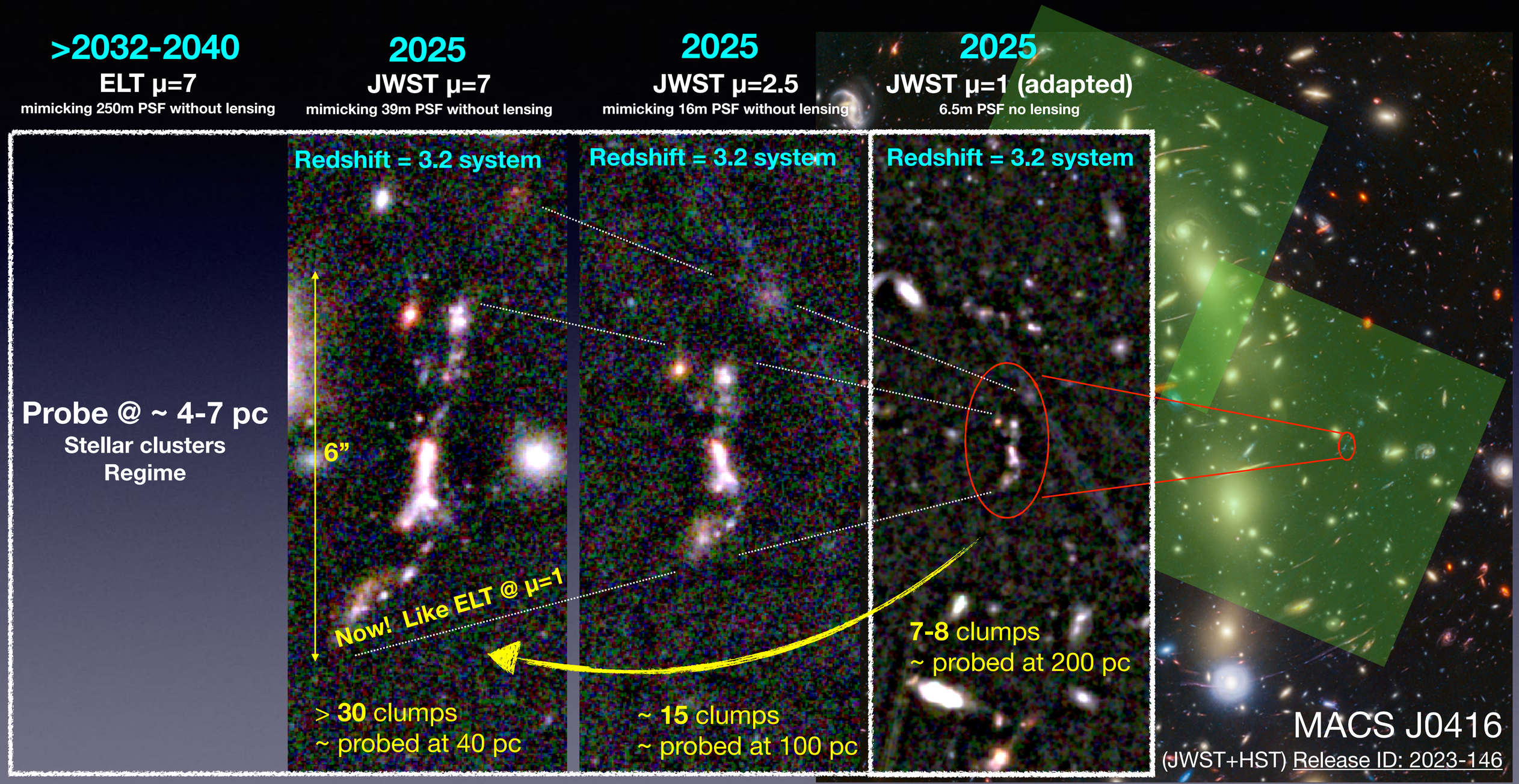
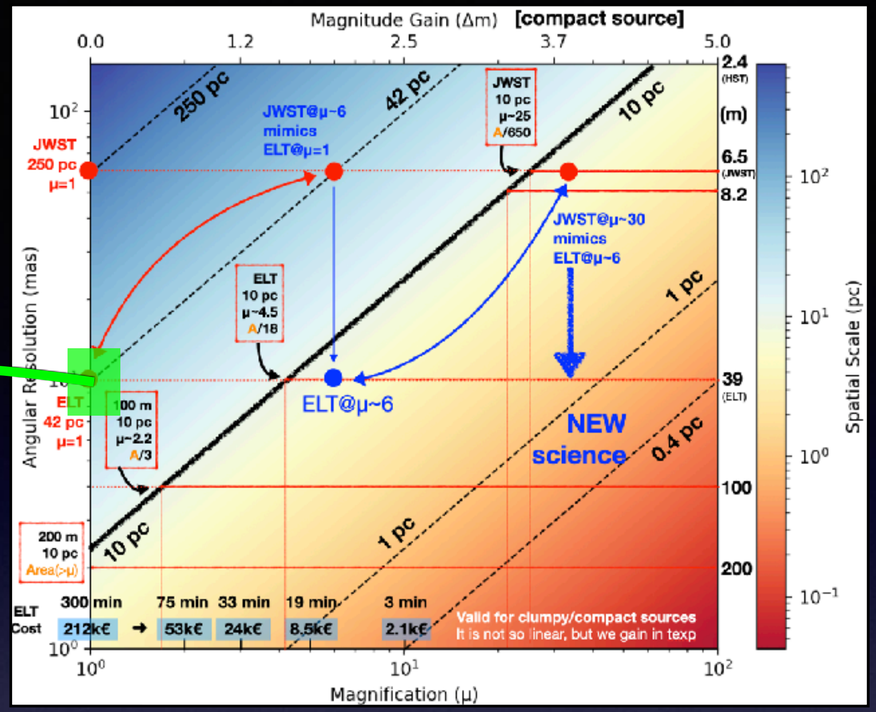
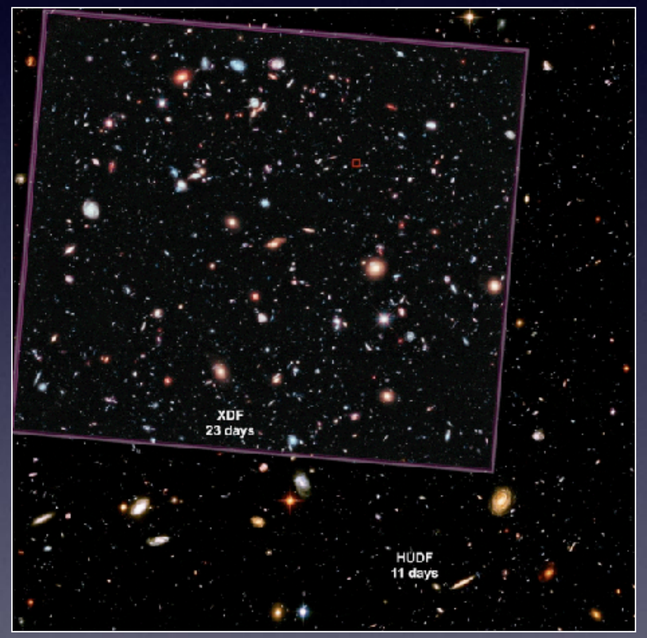


Extragalactic Astronomy 2032-2040: massive use of eXtreme AO (+ SL) Redshift < 17





Example 1: blank fields => clumps

Thousands of clumps , PSF <100 pc

Larger volume (statistics)

will probe 40-100 pc scale (z<17)

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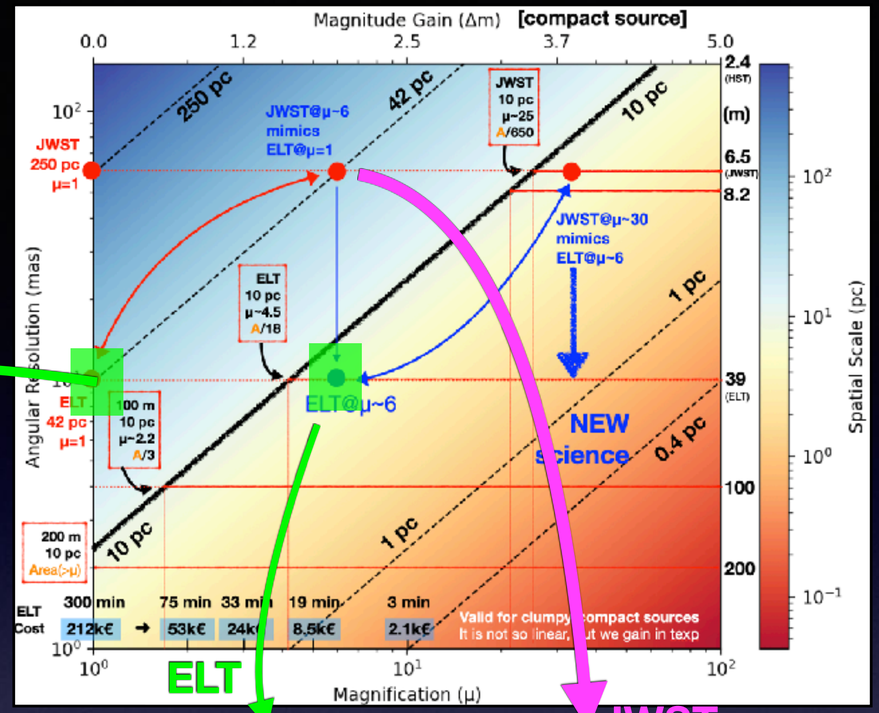

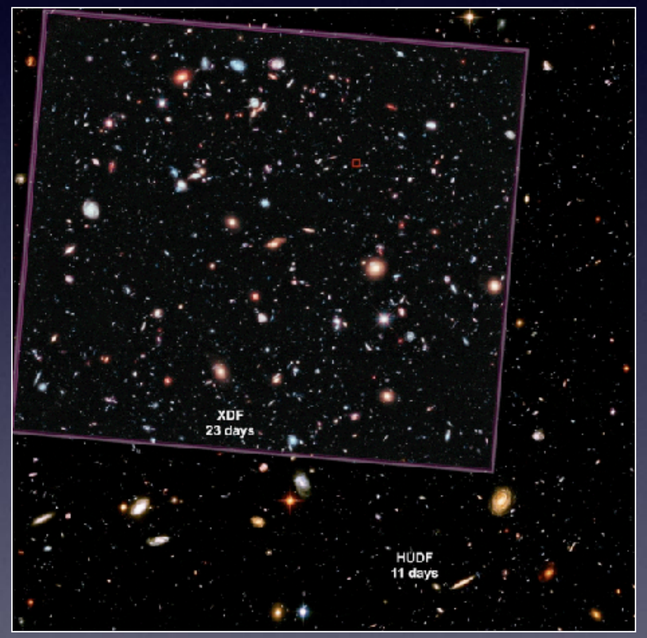

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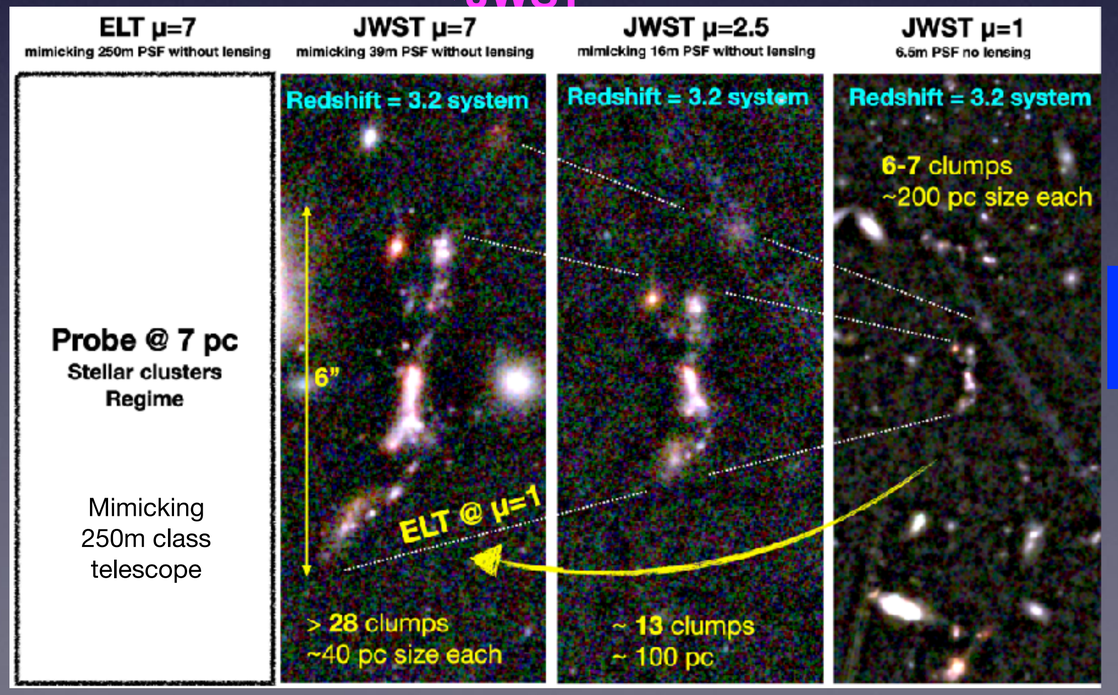

Example 2: Modest magnif
Star cluster regime

Relaxing magnification:
- Robust lens model
- Less distortion
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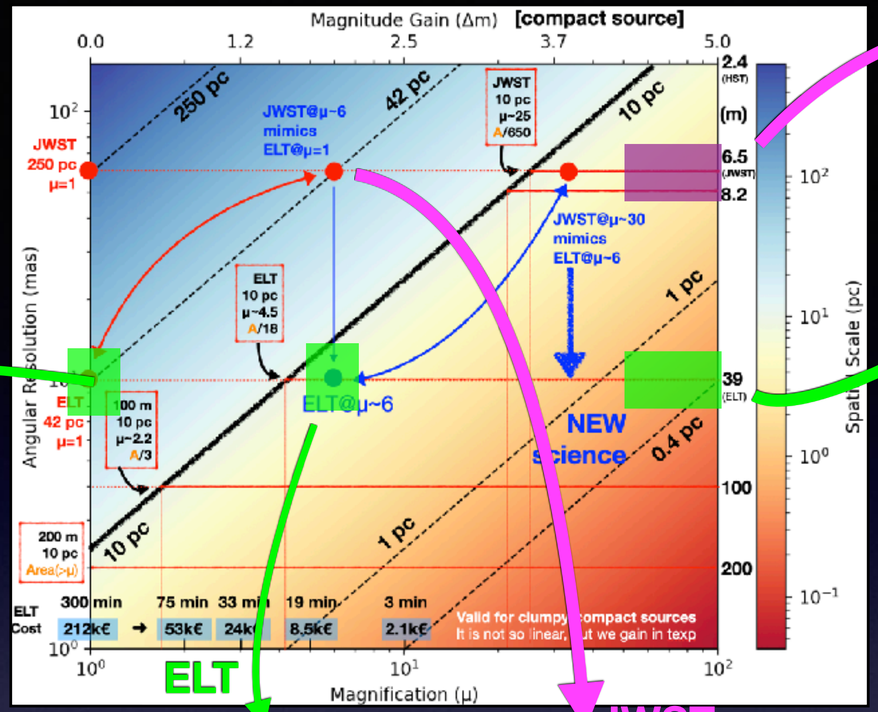

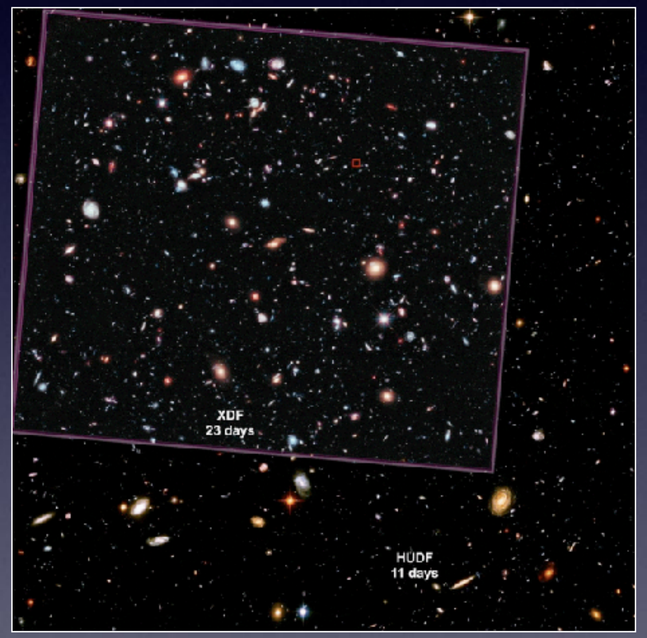

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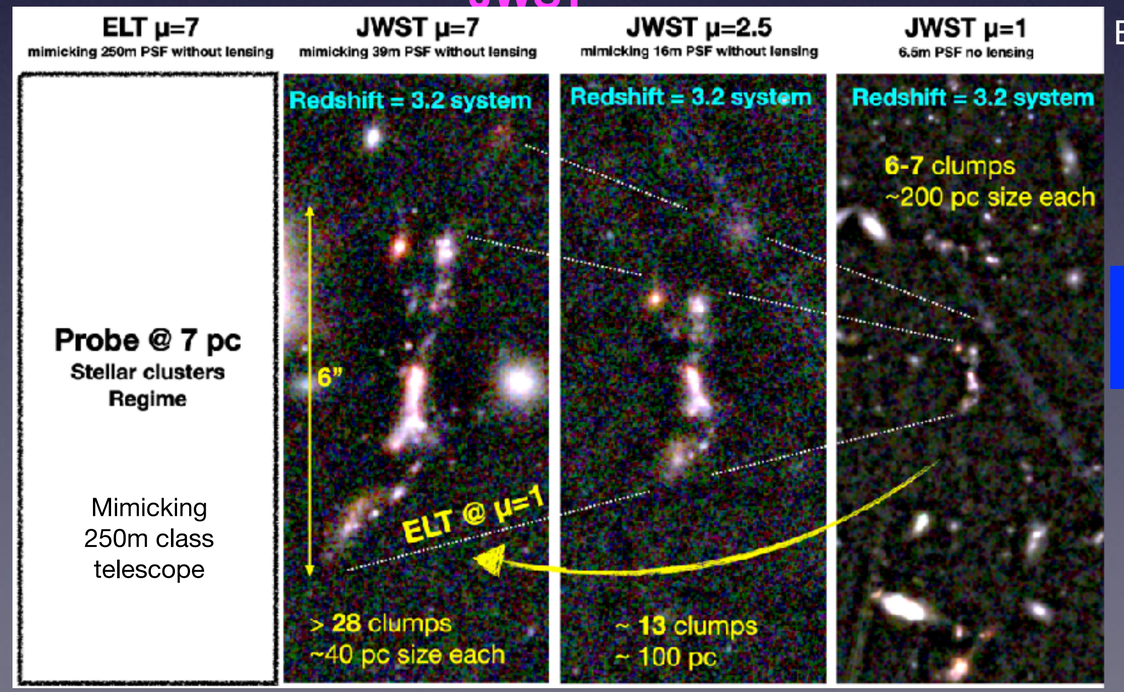
JWST

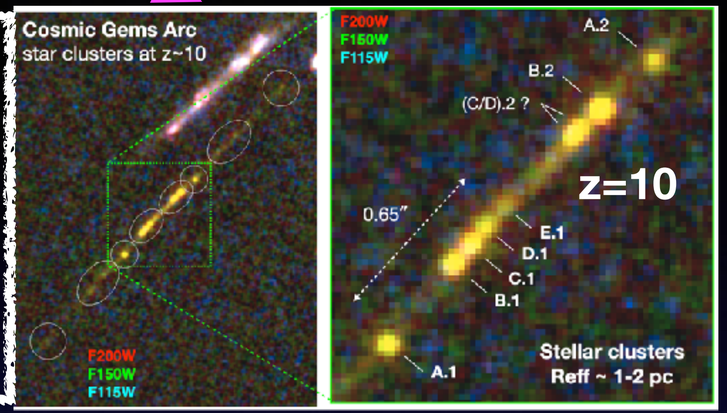


JWST

Example 3: Large magnif sub-parsec

ELT@10 mas
0.1-0.5 pc

ELT



VERY HIGH AMPLIFICATION REGIME, sub-pc at z=10
Will sample light profiles sub-pc scale: "New Science"
MORFEO/MICADO can **reach ~50 uas**
JWST(55mas) **'equivalent' to 400-800 m (⌀)**
ELT(10mas) **'equivalent' to 2000-4000 m (⌀)**

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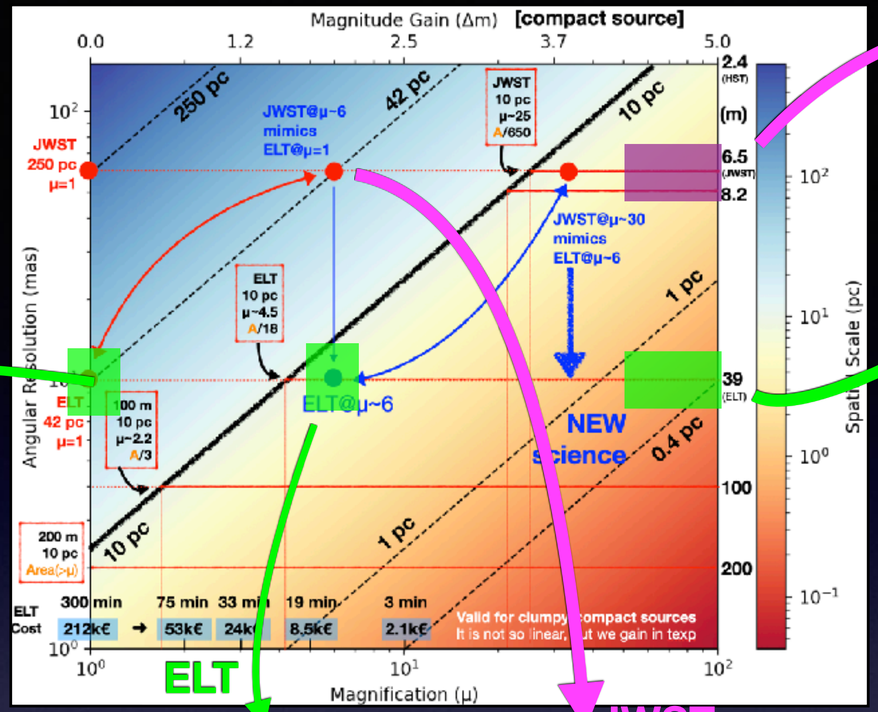

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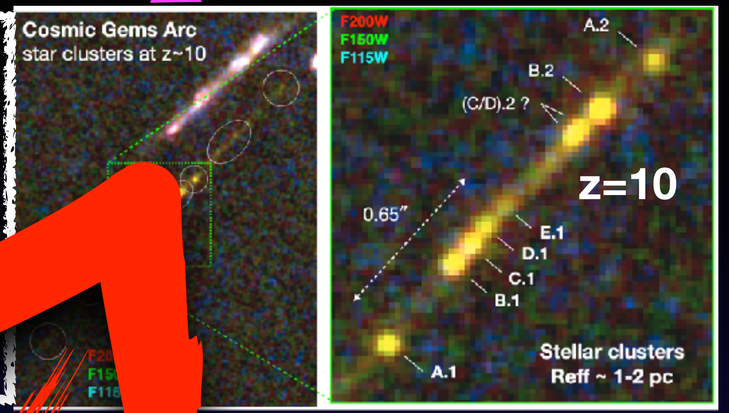

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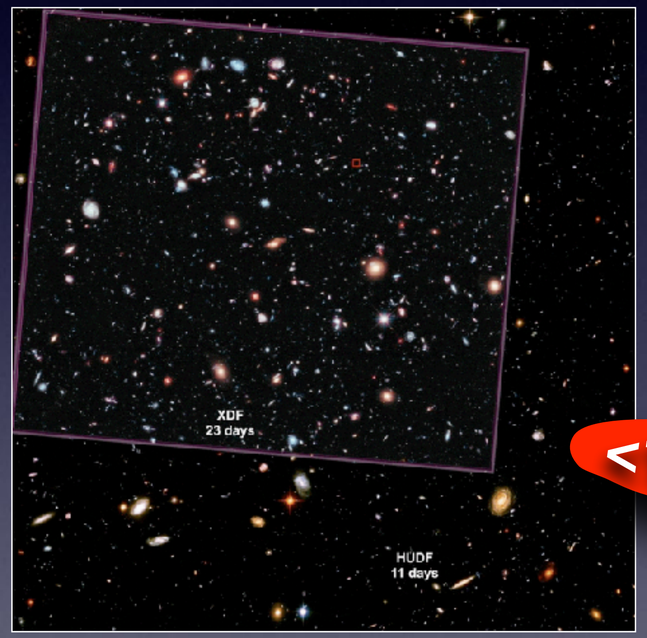

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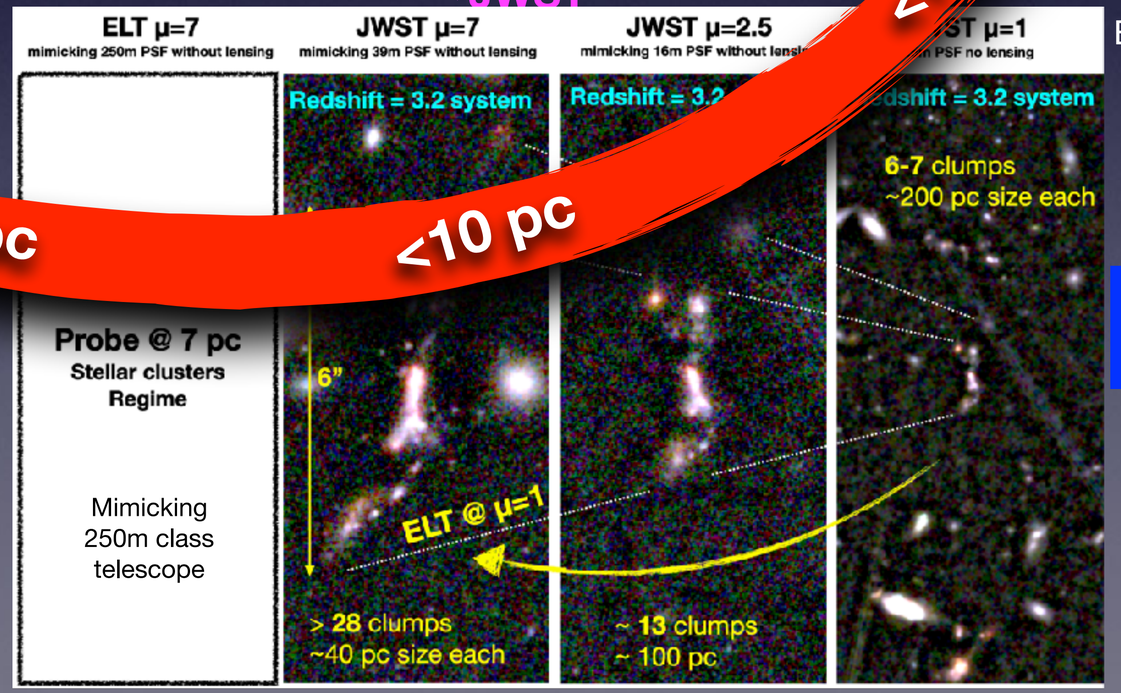

<100 pc
<10 pc
<1 pc

Example 2: Modest magnif Star cluster regime

Relaxing magnification:
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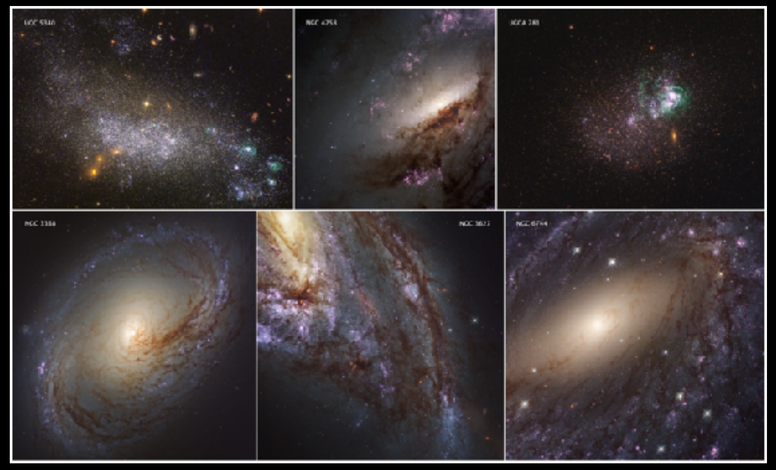
Sub-galactic scales at high-z: SF modes at star cluster scale; in the ’40 this will be the routine

Last few years

LEGUS, 50 galaxies *(Calzetti+15)*



+ e.g., GOALS (Armus+09), Hi-PEEC (Adamo+20),
+ PHANGS-HST (Lee+22),
+ PHAT/PHATTER (Dalcanton+12, Williams+21), …
+ FEAST (JWST-based) — Knutas+25, …

=

Hundreds of galaxies
Tens of thousands of clusters

but all at $z<0.01$

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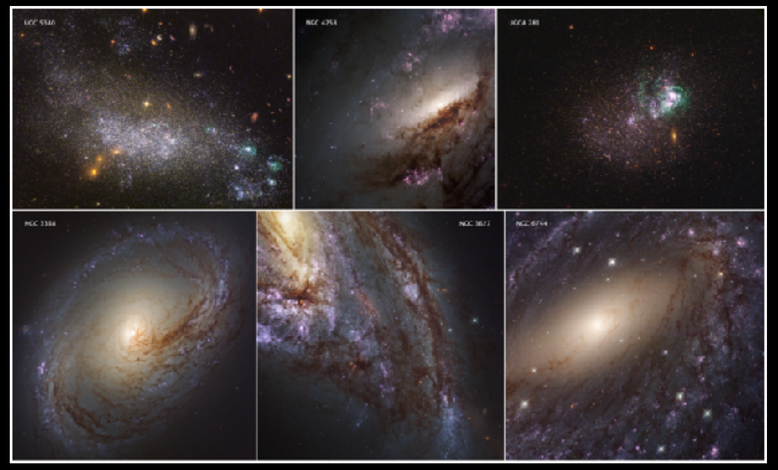

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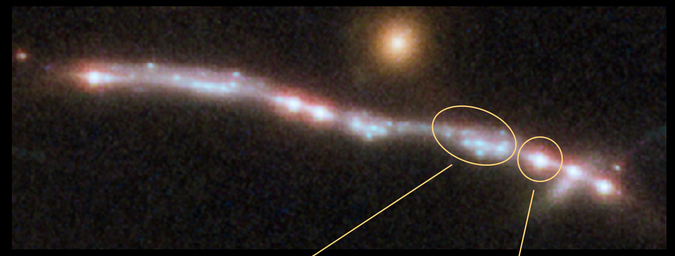
Strong gravitational lensing (examples)

Sunburst Arc *(e.g. Rivera-Thorsen+24; EV+22)*

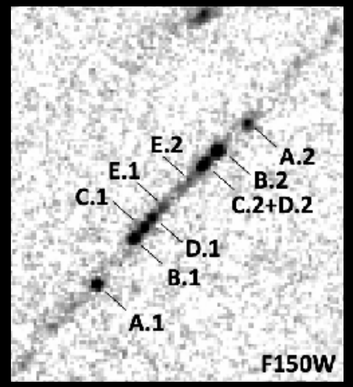


~10 clusters with $R_{eff} = 3 - 20$ pc

1 cluster with $R_{eff} \sim 8$ pc
Ly-C leaker !

@ z=2.4

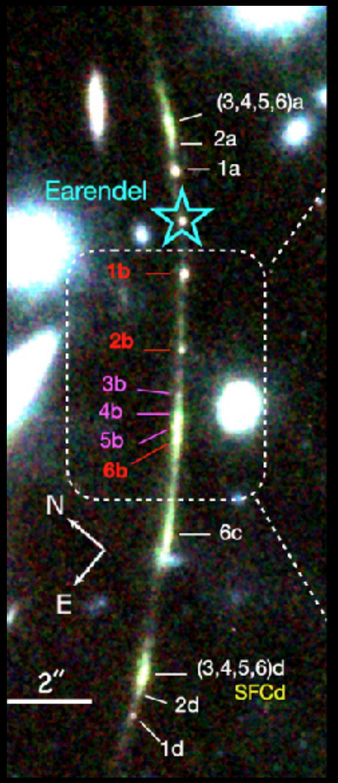
Cosmic Gems *(Adamo+24; Bradley+24; Messa+ in prep.)*



5 clusters in <70 pc region
$R_{eff} \leq 1$ pc
$M = 10^6\ M_\odot$

@ z=9.625

Sunrise Arc *(e.g. EV+23)*



6 clusters with
$R_{eff} = 1 - 10$ pc
$M = 10^6\ M_\odot$

@ z=5.93

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Last few years

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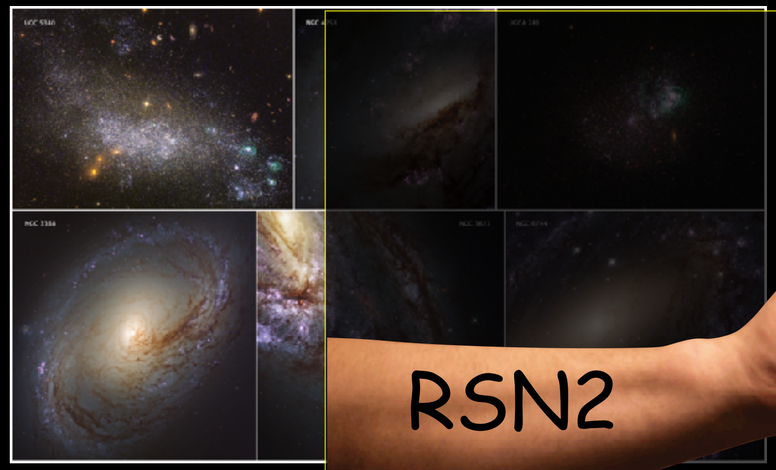

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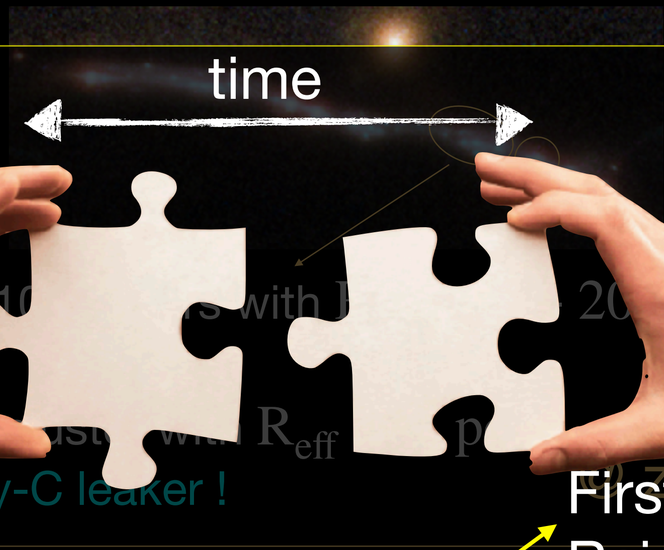

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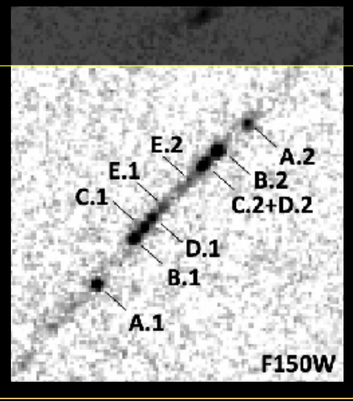
Stellar clusters relevant for (e.g.)

- First stars
- Reionization
- Galaxy growth
- GC formation

Cosmic Gems *(Adamo+24; Bradley+24; …)*



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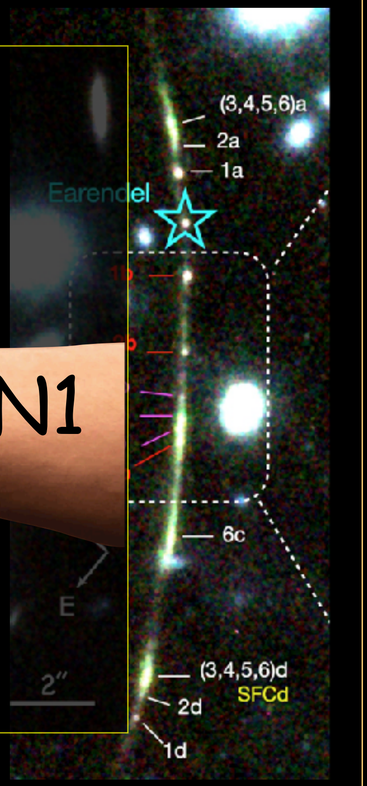
$R_{eff} \leq 1$ pc

$M = 10^6\ M_\odot$

@ z=9.625

Sunrise Arc *(e.g. EV+23)*



6 clusters with

$R_{eff} = 1 - 10$ pc

$M = 10^6\ M_\odot$

@ z=5.93

The targets: the key role of AO and JWST wavelength coverage in the ’30-40

bound young stellar clusters and **Globular Cluster Precursors** at cosmological distances

The dynamical age Π

Age/Tcr = Π , if Π>1 grav. bound

$$T_{cr} \equiv 10 \left(\frac{R_{eff}^3}{GM} \right)^{1/2}$$

Stellar agglomerates for which the age of the stars exceeds the crossing time are bound

Gieles+11, Ryon+17, e.g., LEGUS (Calzetti+15)

Tiny **sizes** (<10 pc) will need extreme Adaptive Optics, like ELT / MAVIS + modest strong lensing

Age & **stellar mass** (& **view of the host galaxy**)
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The best high-z targets for AO facilities will be the JWST ones

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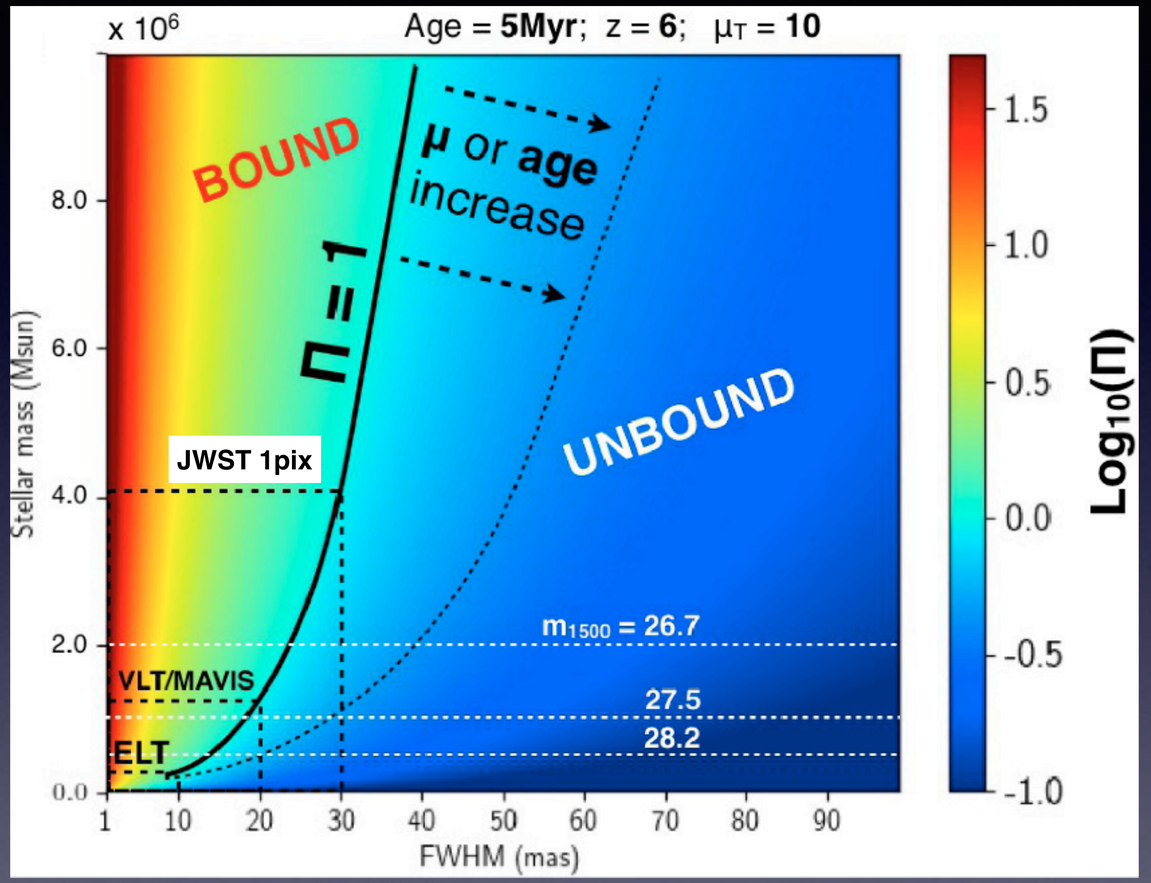
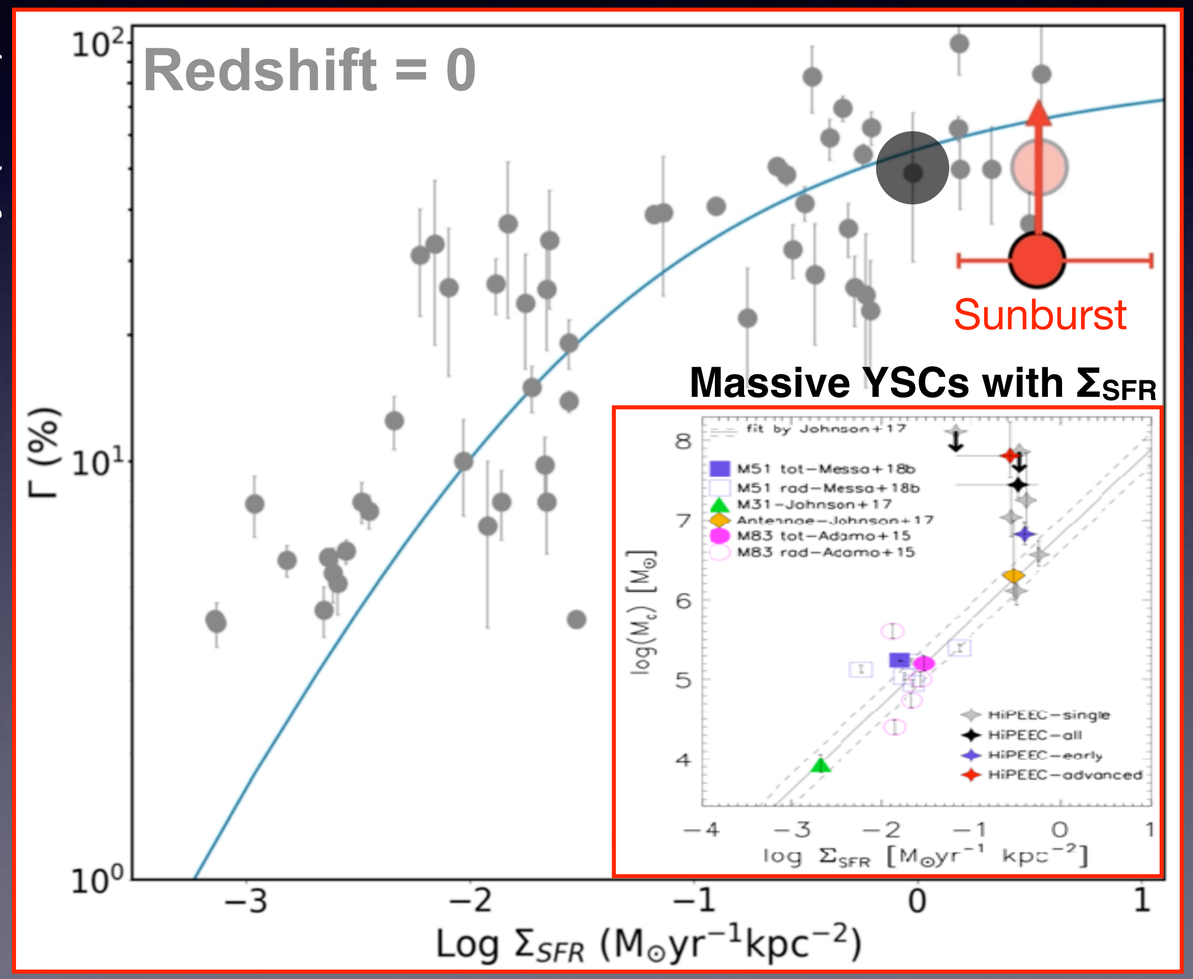


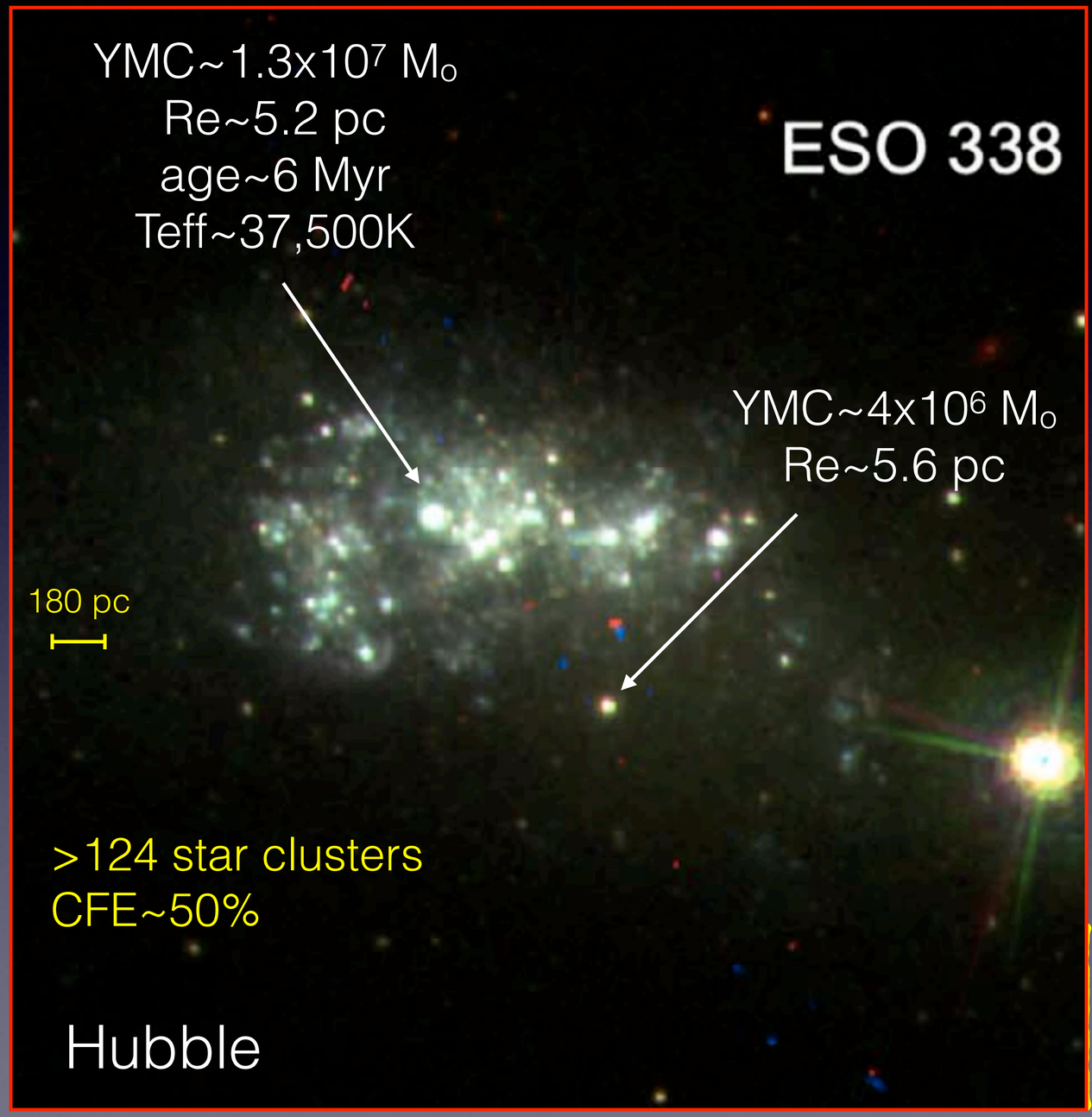
EV21

The best high-z targets for AO facilities will be the JWST ones

An example of extragalactic result in 2035-2040: hierarchical nature of SF and star clusters

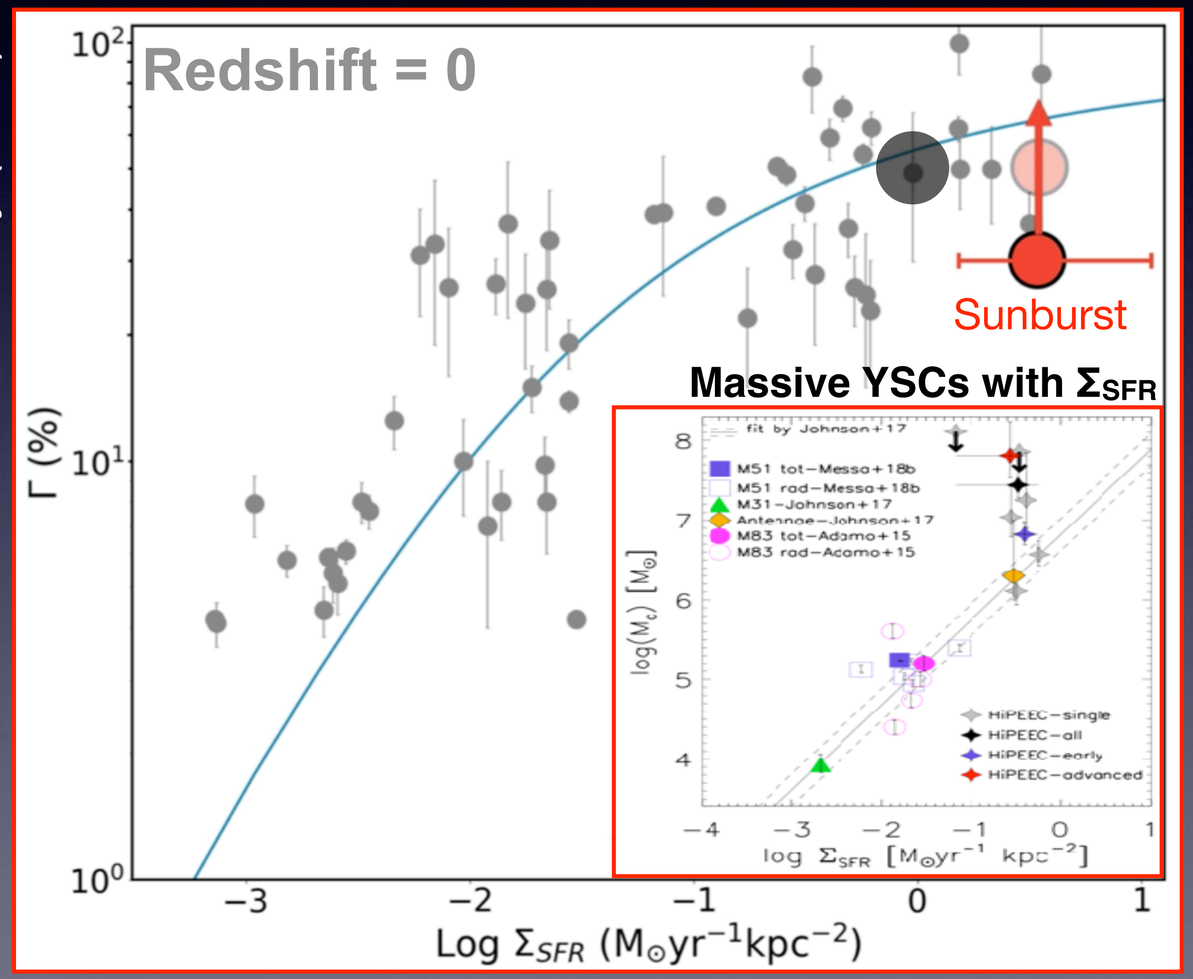


Adamo+2017, 2020 — CFE Sunburst (EV22)



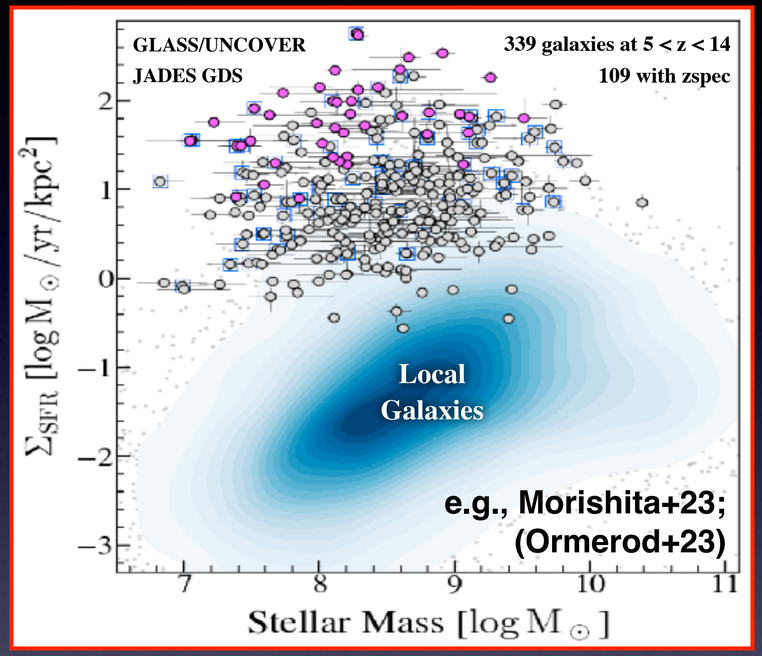
An example of extragalactic result in 2035-2040: hierarchical nature of SF and star clusters

Star cluster formation efficiency (**CFE**)



Adamo+2017, 2020 — CFE Sunburst (EV22)

High redshift galaxies are dense



Dense ISM conditions at high-z promote star cluster formation (e.g., Kruijssen+25)

Relevant for
- **Globular cluster formation**
- **Rionization**
- **Galaxy build-up**

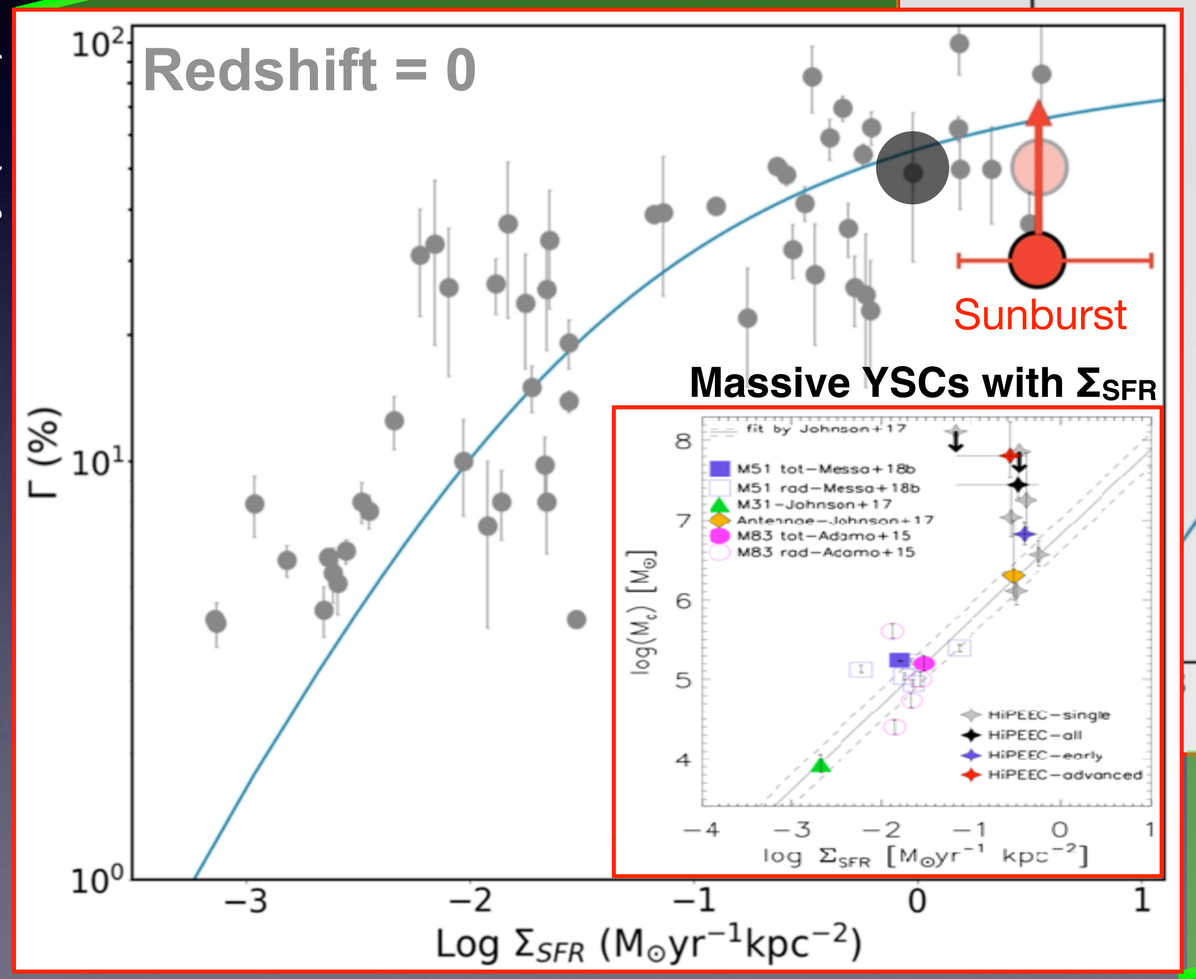
An example of extragalactic result in 2035-2040: hierarchical nature of SF and star clusters

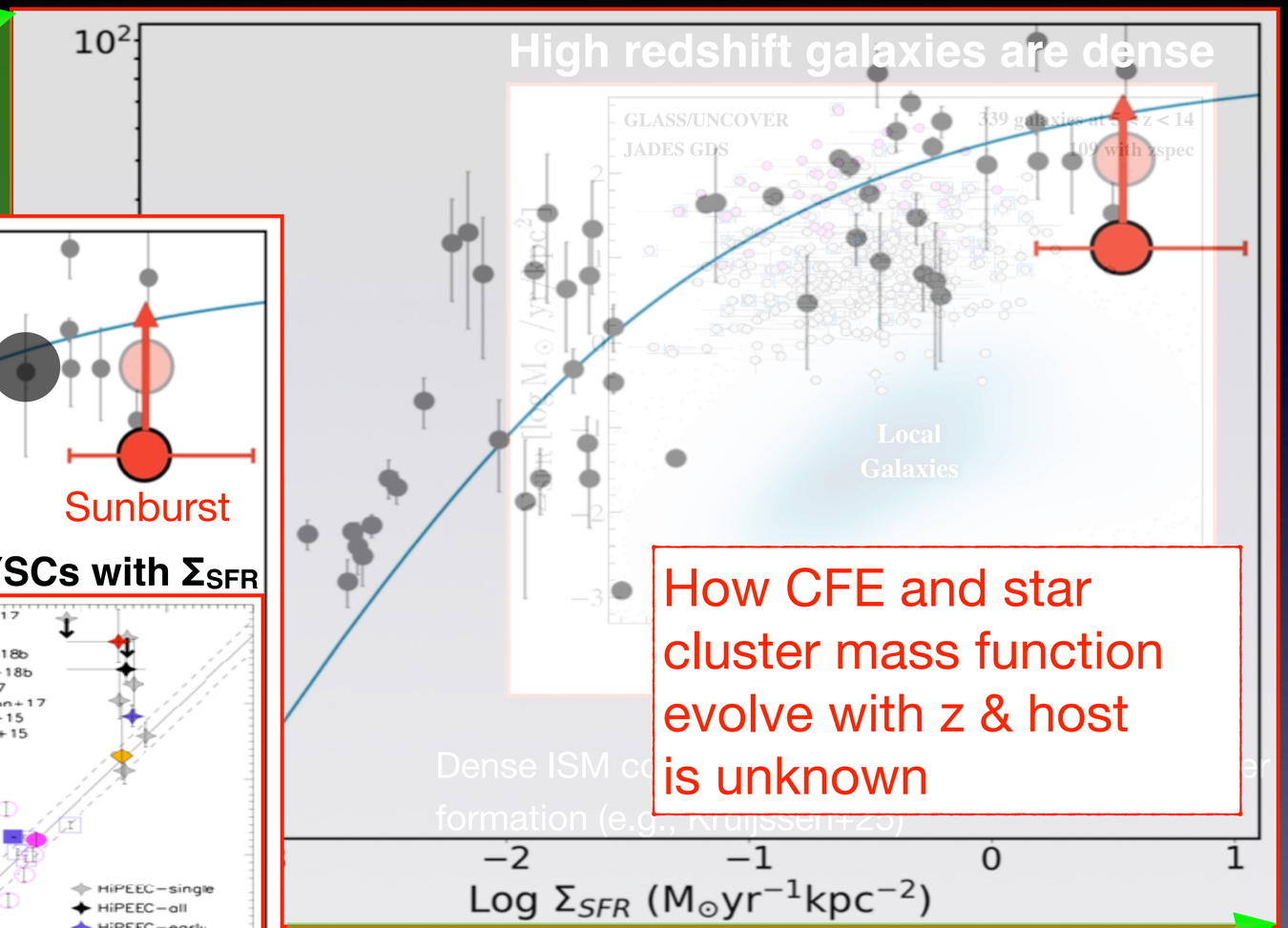
redshift 0-10+

Only with AO + SL (eg. ELT, MAVIS)

Picture of the CFE evolution with cosmic time

Star cluster formation efficiency (**CFE**)





How CFE and star cluster mass function evolve with z & host is unknown

redshift

Relevant for
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- **Rionization**
- **Galaxy build-up**

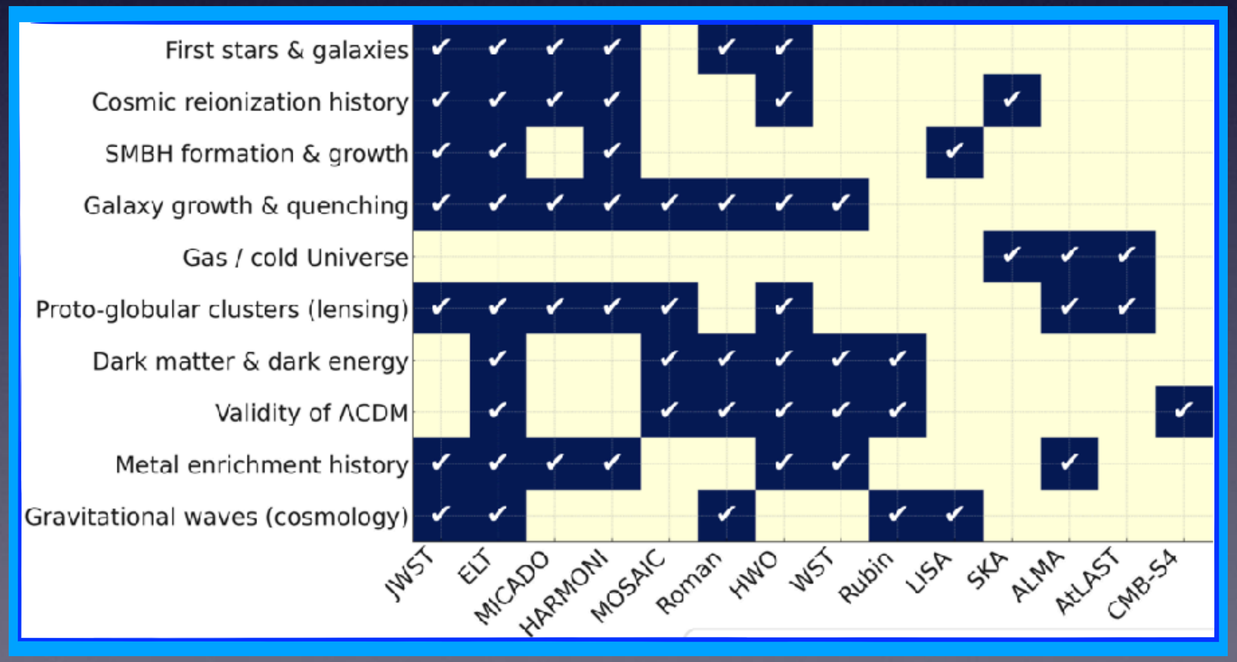
Adamo+2017, 2020 — CFE Sunburst (EV22)

Challenges in extragalactic astronomy in the > ’40 - 45

Asking chatGPT 4.5 o3 with advance reasoning

> *Which questions on extragalactic and high-redshfit astronomy will have an answer (will be solved) in the 2040-2045 ?*

Missions/instruments Addressing Extragalactic Questions (~2045 horizon)



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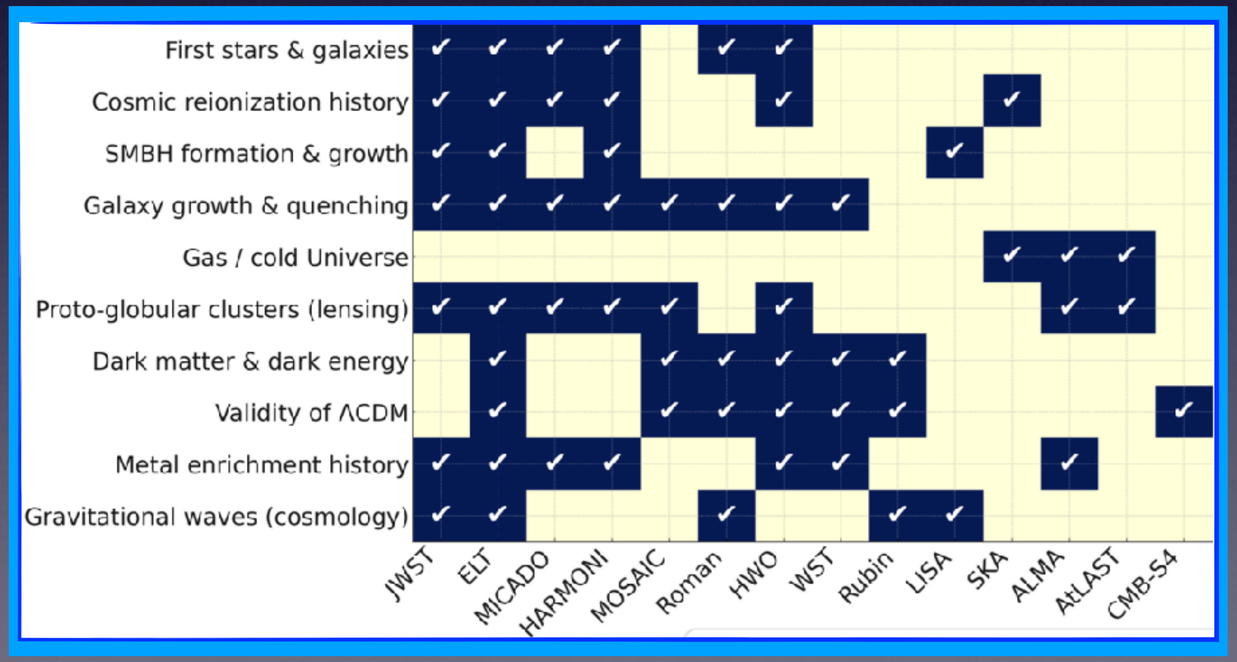
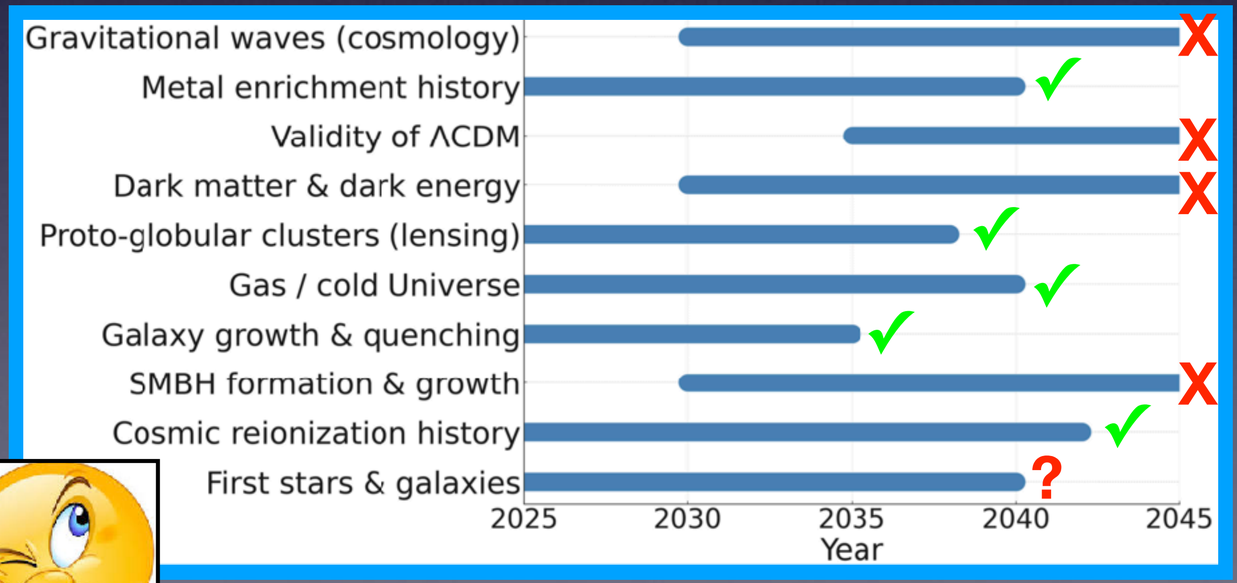
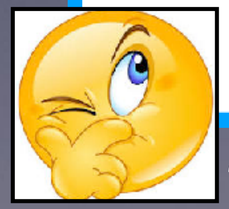


Roadmap to Solving Key Extragalactic Questions (~2045+)

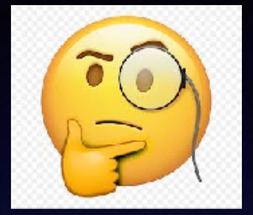


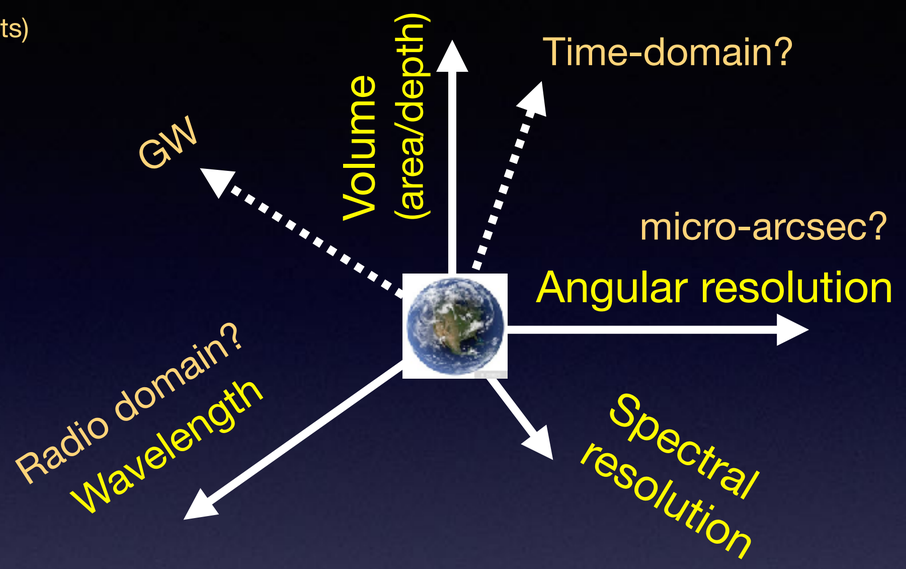


? Not fully sure…

> *And finally, knowing which are the future and current facilities, the key questions and the roadmap, tell me which questions will still be open after 2045 ? And if you have an idea about new ones?*

- Emerging Frontiers (Dark-Sector Structures, Extragalactic Planet Formation, Feedback from Pop III Gamma-Ray Bursts)
- The Very First Luminous Objects, PopIII (z ≳ 20) - first 200 Myr
- Dark Matter on Sub-galactic Scales
- Dark Energy Beyond Simple w(z)
- Primordial Gravitational-Wave Background
- Cosmic Dust & Chemistry at z > 10
- Cosmic Magnetism & Missing Baryons
- …





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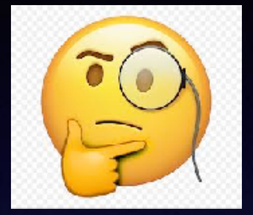
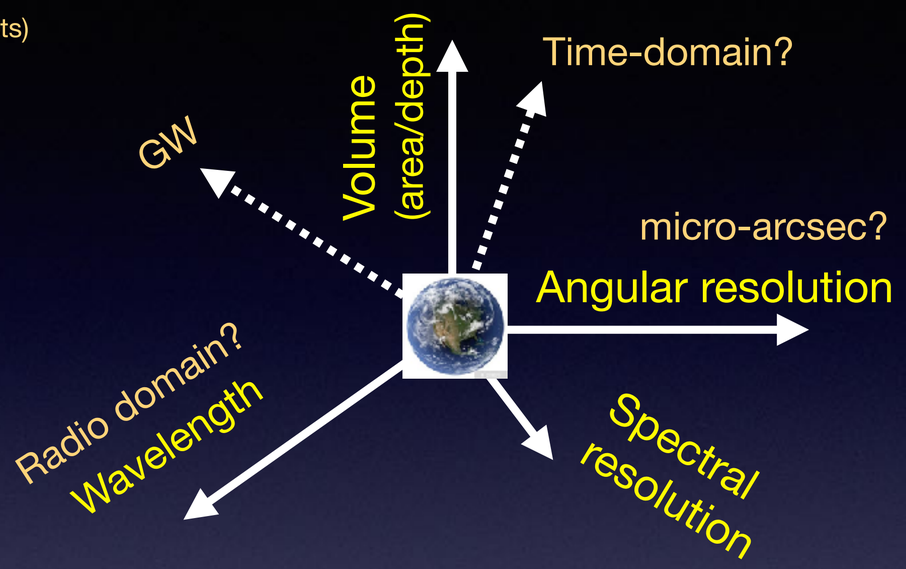
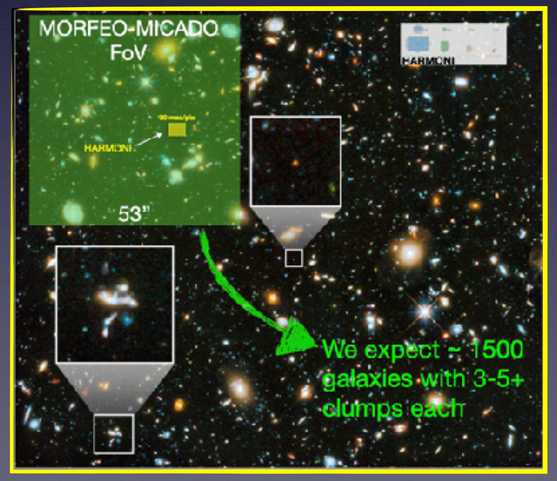




“Staying grounded” , ELT-related:

Critical fact: by 2042 we will image the faint & “tiny” Universe faster than we can *spectroscopically* characterise it. This is valid also for non-survey machines, like ELT.



2042+

still massive use of AO, likely on JWST fields w/o Strong lensing

Expected several millions clumps & hundred thousands star clusters at **~1 < z < 17** after several years of MORFEO-MICADO use, emerging from thousands of galaxies, all of them probed at <100 pc (10-12 mas)

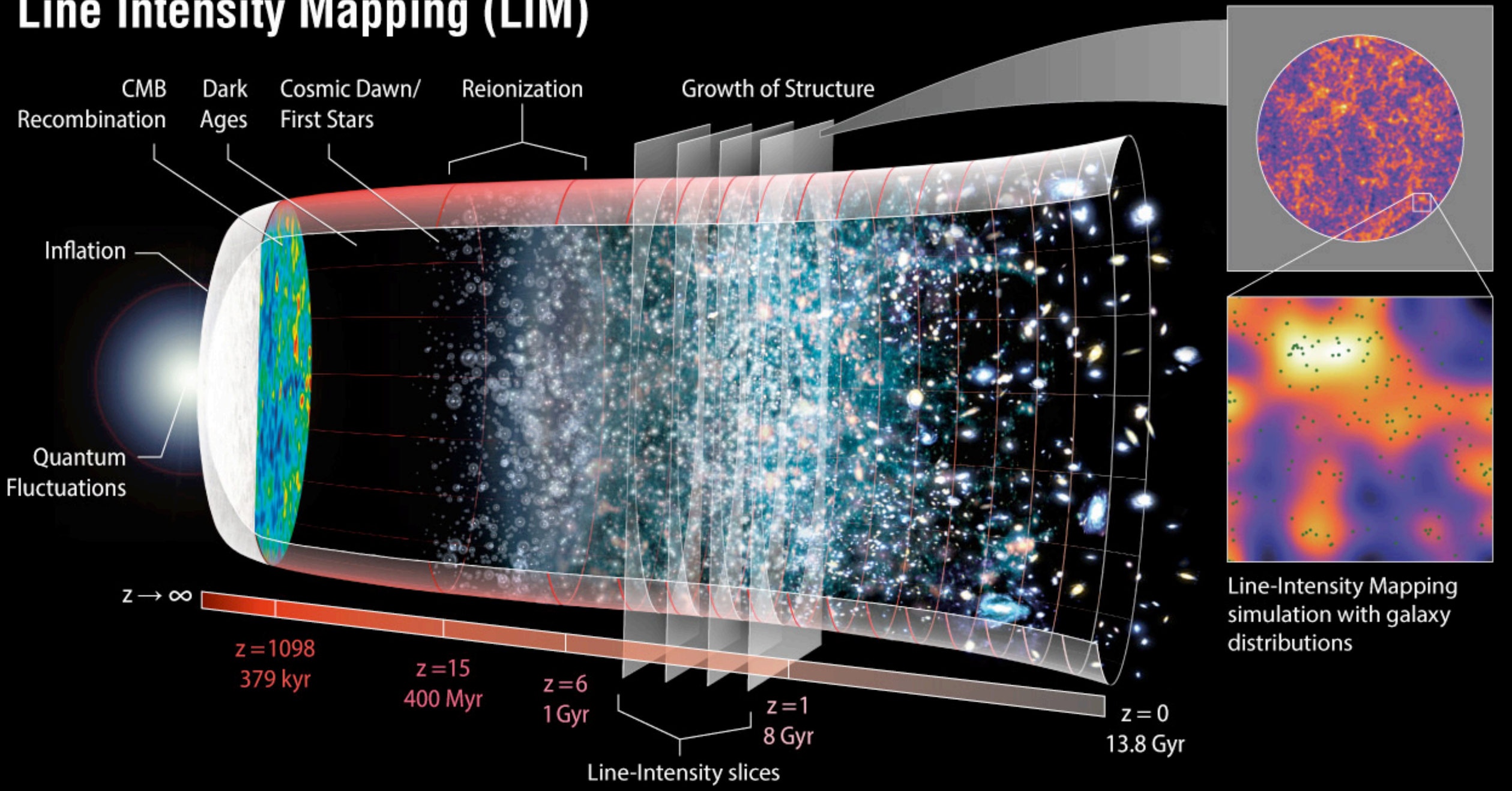
Critical fact: how can we perform efficient/reasonable spectroscopic follow-up in the NIR of such a big amount — at tens mas — MORFEO-MICADO clumps ?

An option: a significant UPGRADE of ELT ?

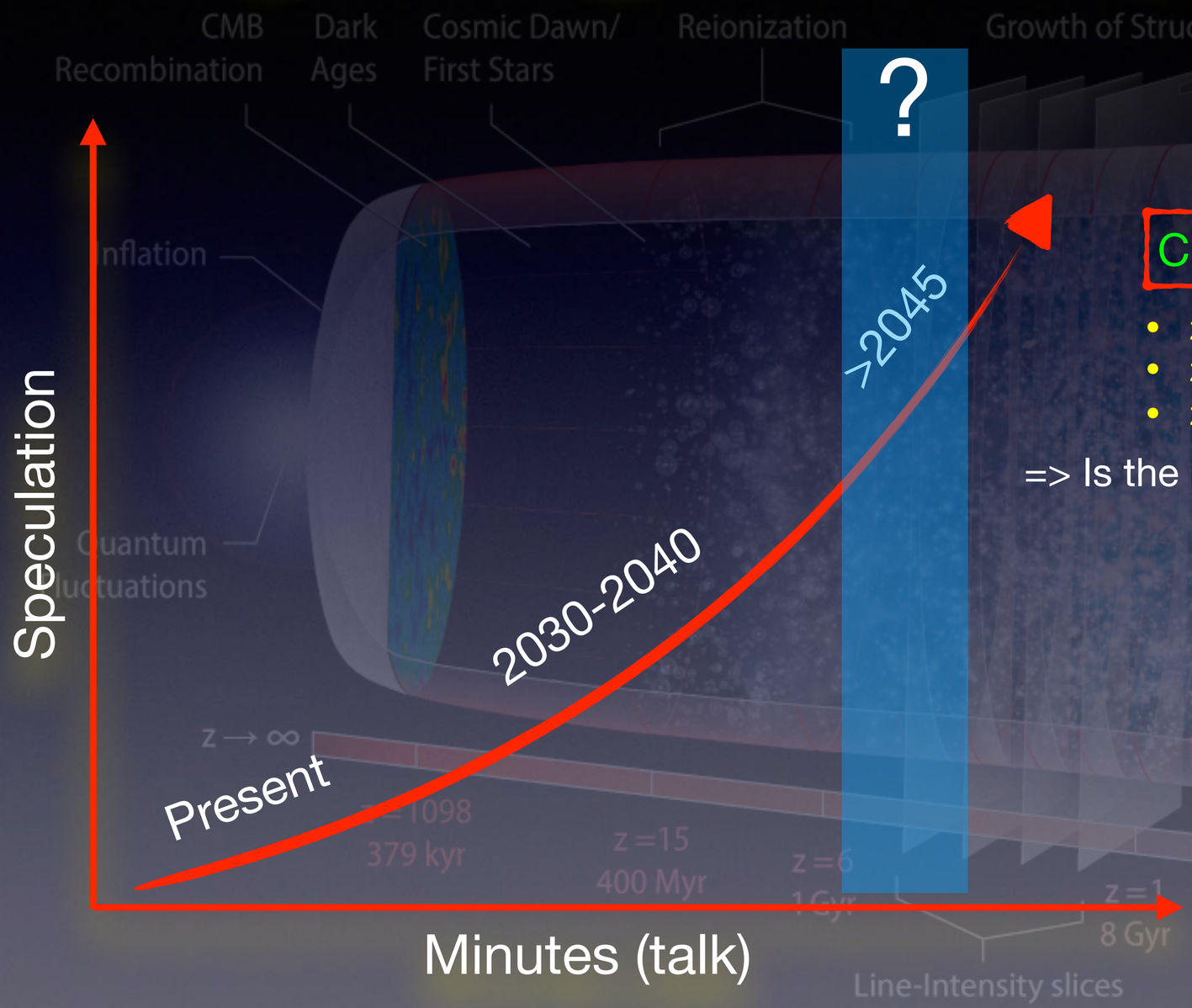
(e.g., post-HARMONI after 2045? ☞ super-HARMONI with x10-20 current FoV, at least.. ?)

Thanks

Line Intensity Mapping (LIM)



Challenges in Extragalactic Astronomy in the ’40…



Challenges >2045 (or just after JWST will die?)

- z>4: We will miss the optical rest-frame (img + spec)
- z≳17: We cannot explore the first **200** Myr from ground (NIR)
- z≫17: We cannot address the very first sources z>20-30

=> Is the radio domain the only option from ground for z>17?