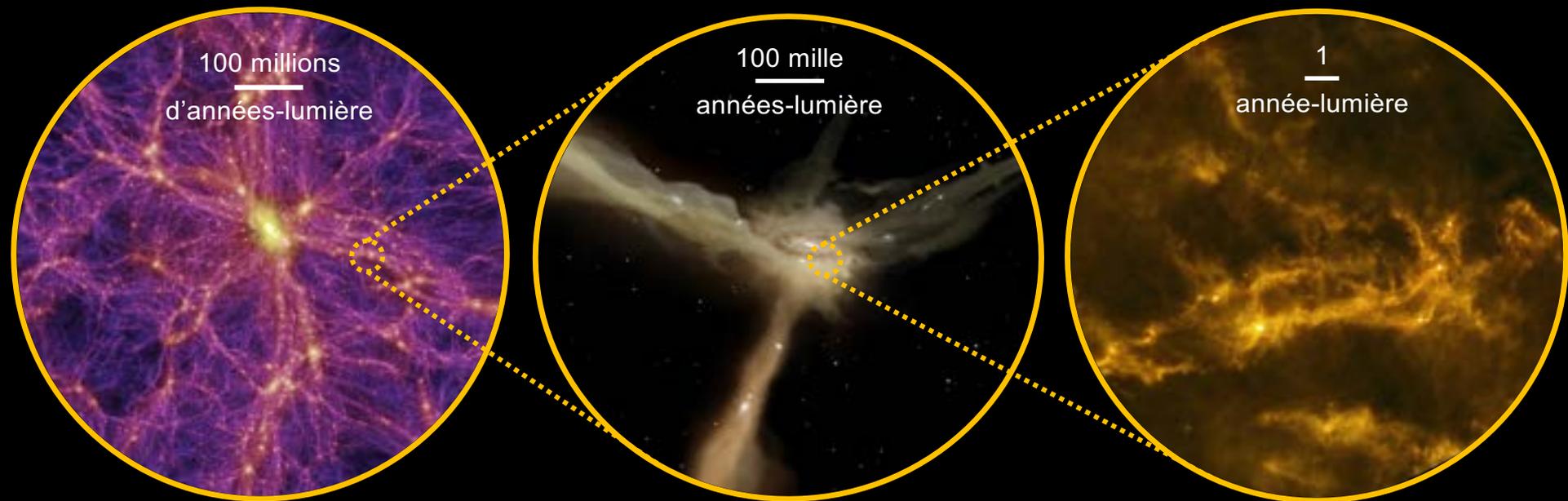
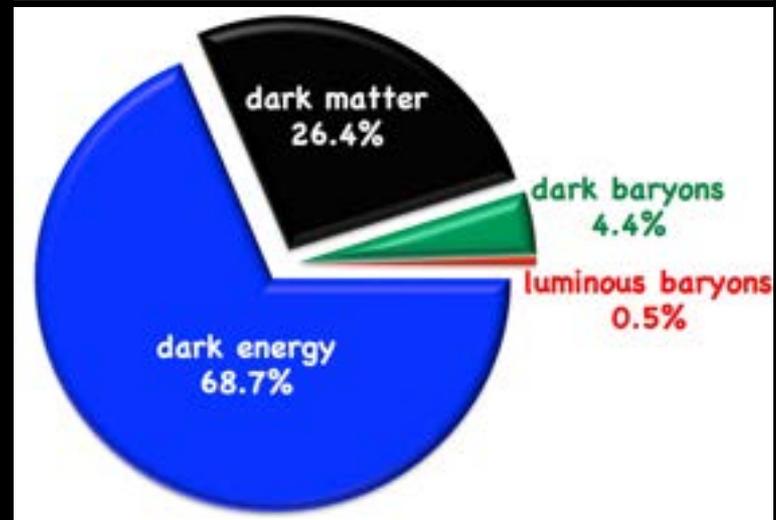
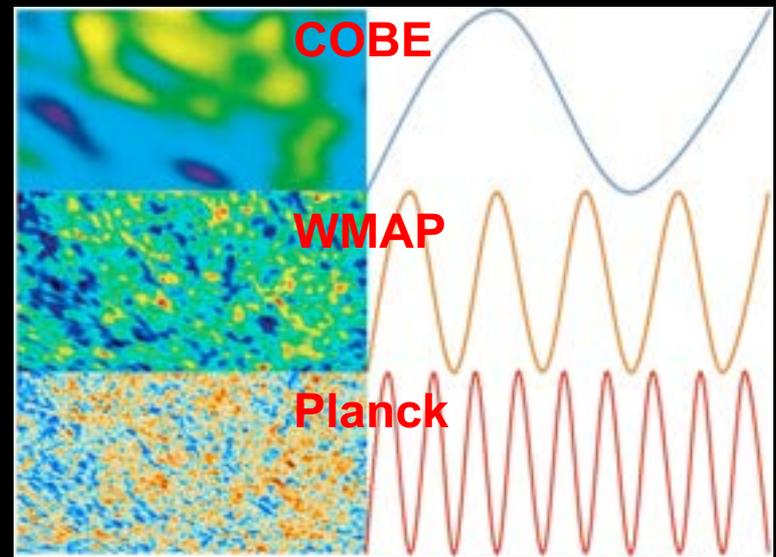
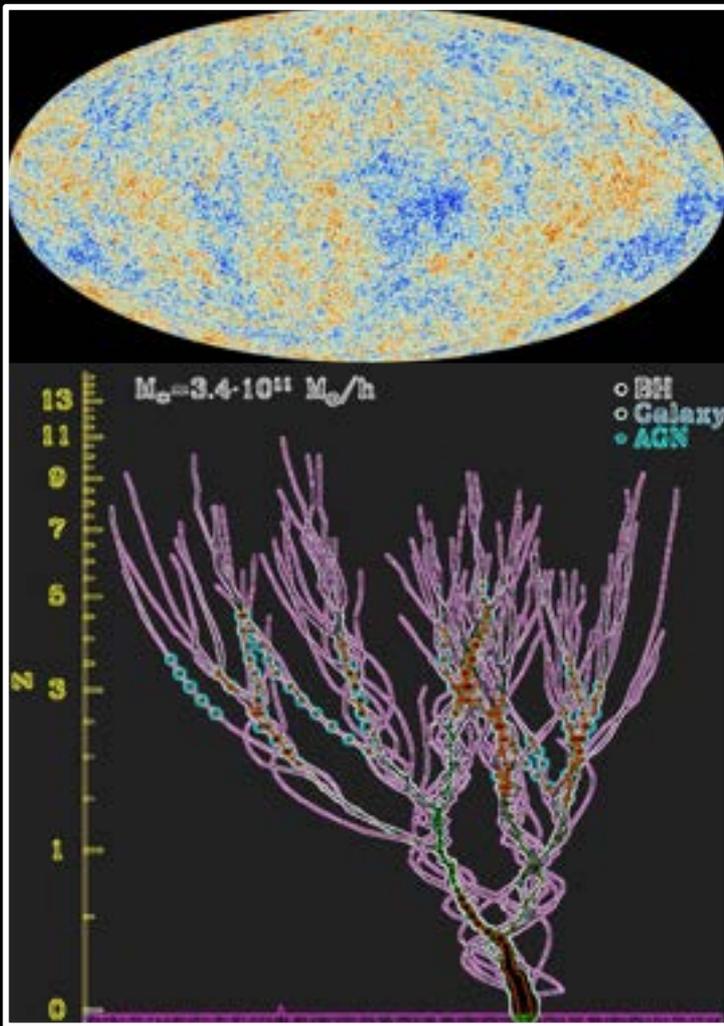


Formation des galaxies : *forces et faiblesses d'un nouveau paradigme*

David Elbaz – CEA Saclay



Le paradigme classique...



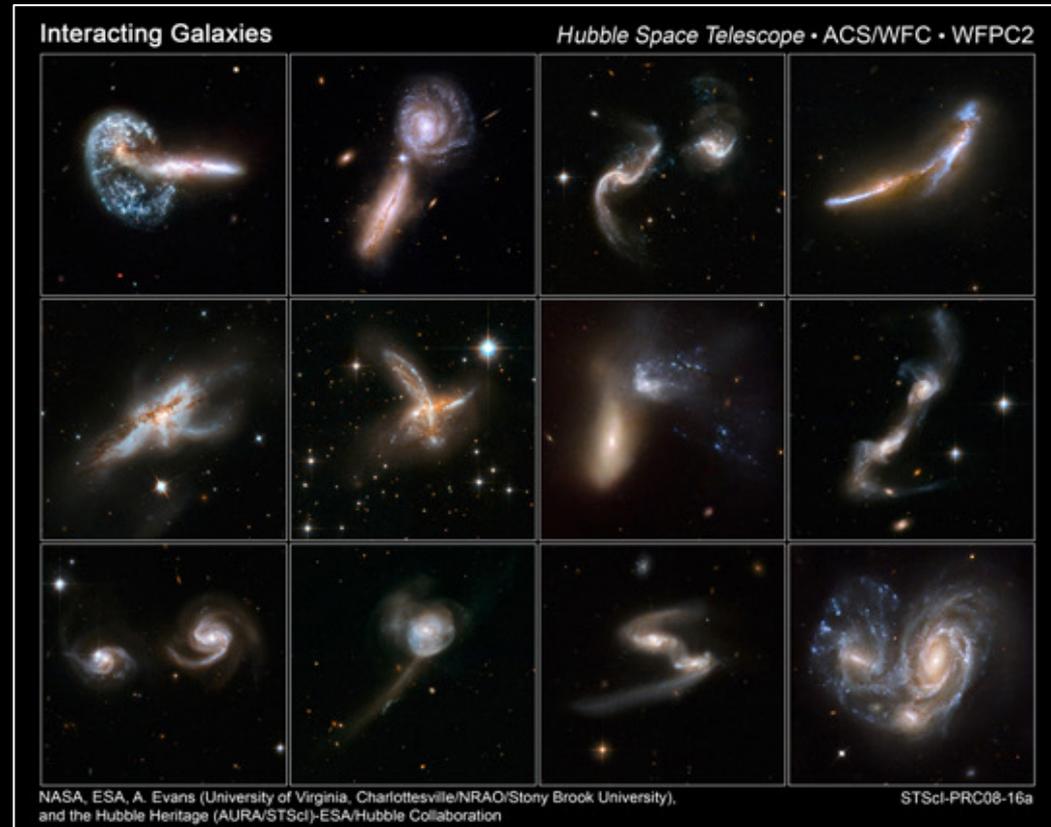
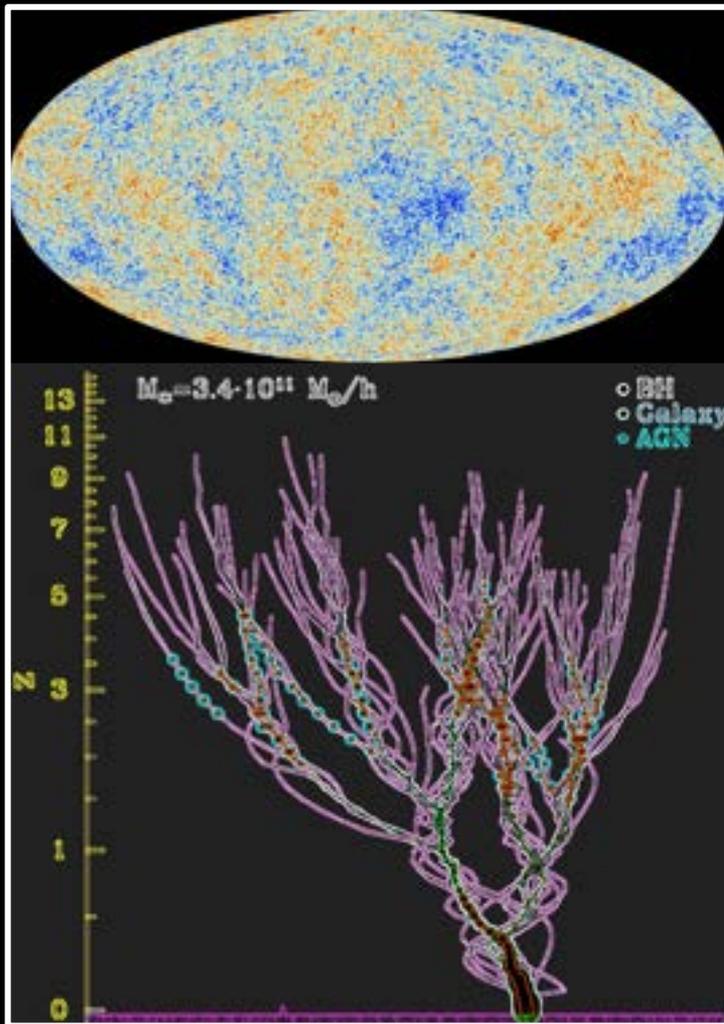
Paradigme de la formation hiérarchique des galaxies :

1981 : germes des galaxies / inflation (Guth)

1982-84 : matière noire = puits de gravité

Peebles ; Blumenthal, Faber, Primack, & Rees

Fusions galactiques et flambées d'étoiles



Paradigme de la formation hiérarchique des galaxies :

1981 : germes des galaxies / inflation (Guth)

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Peebles ; Blumenthal, Faber, Primack, & Rees

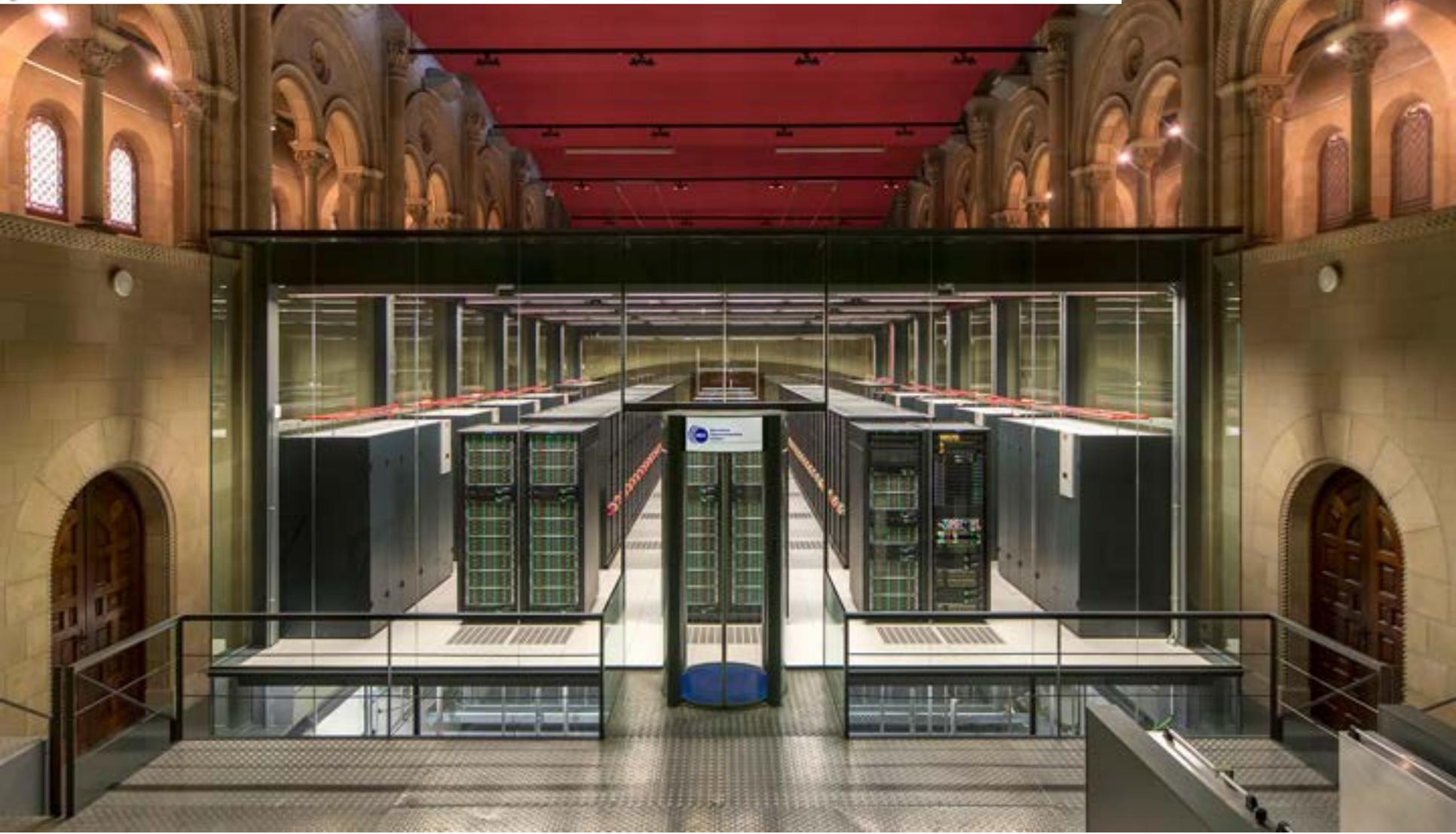
Le nouveau paradigme...

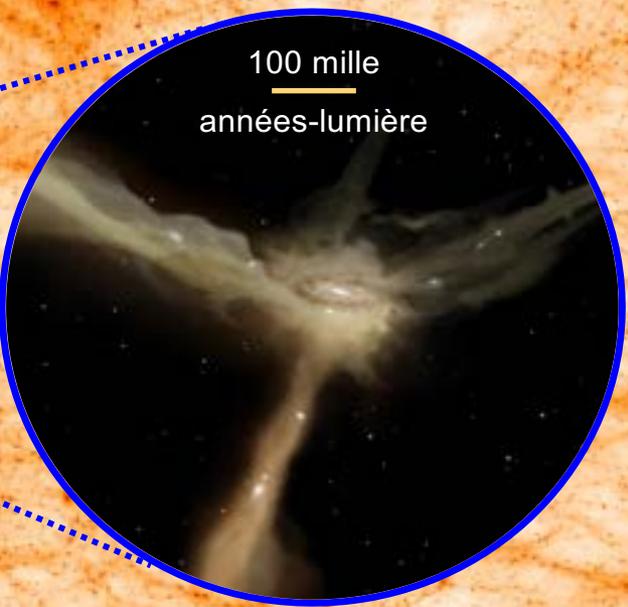
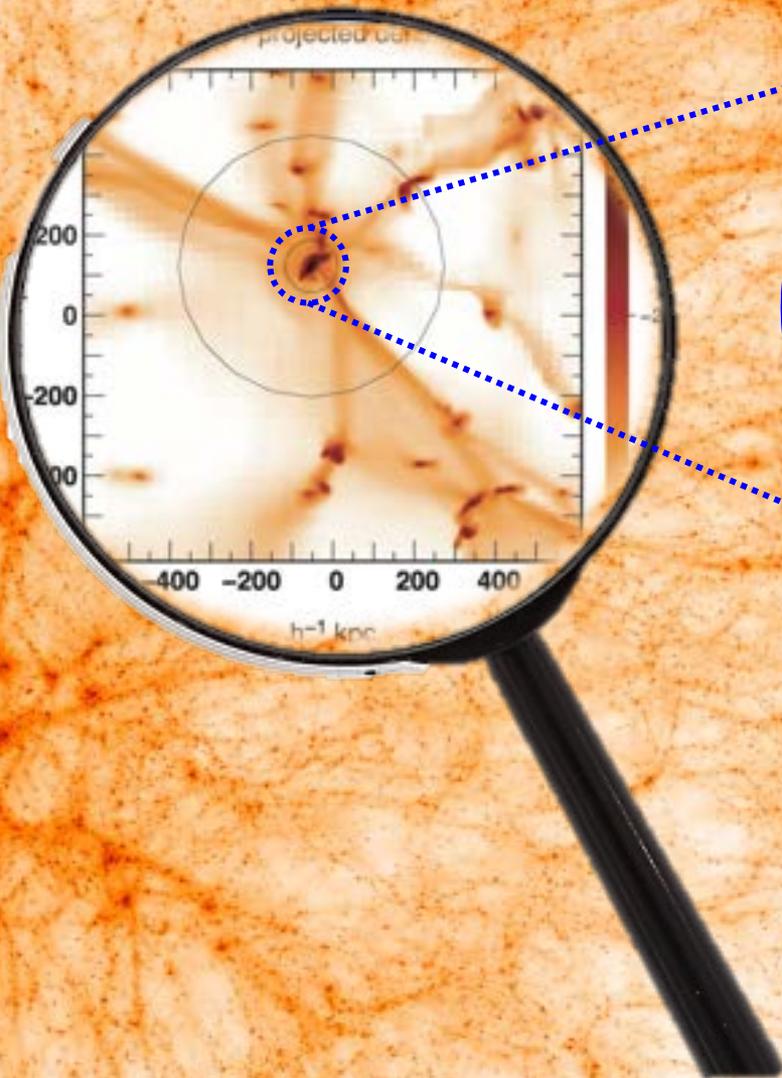


El superordenador más bonito del mundo está en una capilla de Barcelona

EL PAÍS

Realiza 13.700 billones de operaciones cada segundo y es utilizado por investigadores de toda Europa para, por ejemplo, diseñar tratamientos a medida para enfermedades como el cáncer





Cold streams in early massive hot haloes as the main mode of galaxy formation

Dekel et al. [Nature](#) volume 457, pages 451–454 (2009)

Les galaxies massives de l'Univers jeune, il y a dix milliards d'années, ont formé des étoiles à des intensités surprenantes.

Bien que cela soit **communément attribué à des fusions** violentes, les propriétés d'un grand nombre de ces galaxies sont **incompatibles avec de tels événements**, montrant des disques rotatifs étendus, riches en gaz...

Les trois quarts des galaxies formant des étoiles sont alimentées par des courants de gaz froid

Ce **scénario** de formation des disques et des sphéroïdes par les courants est une **alternative à celui des fusions**.



Comment valider le paradigme de formation des galaxies ?

1- Taille des galaxies :

devraient être plus petites dans le passé

2- Âge des galaxies (de leurs étoiles) :

les premières à naître possèdent les plus vieilles étoiles aujourd'hui

3- Croissance des galaxies :

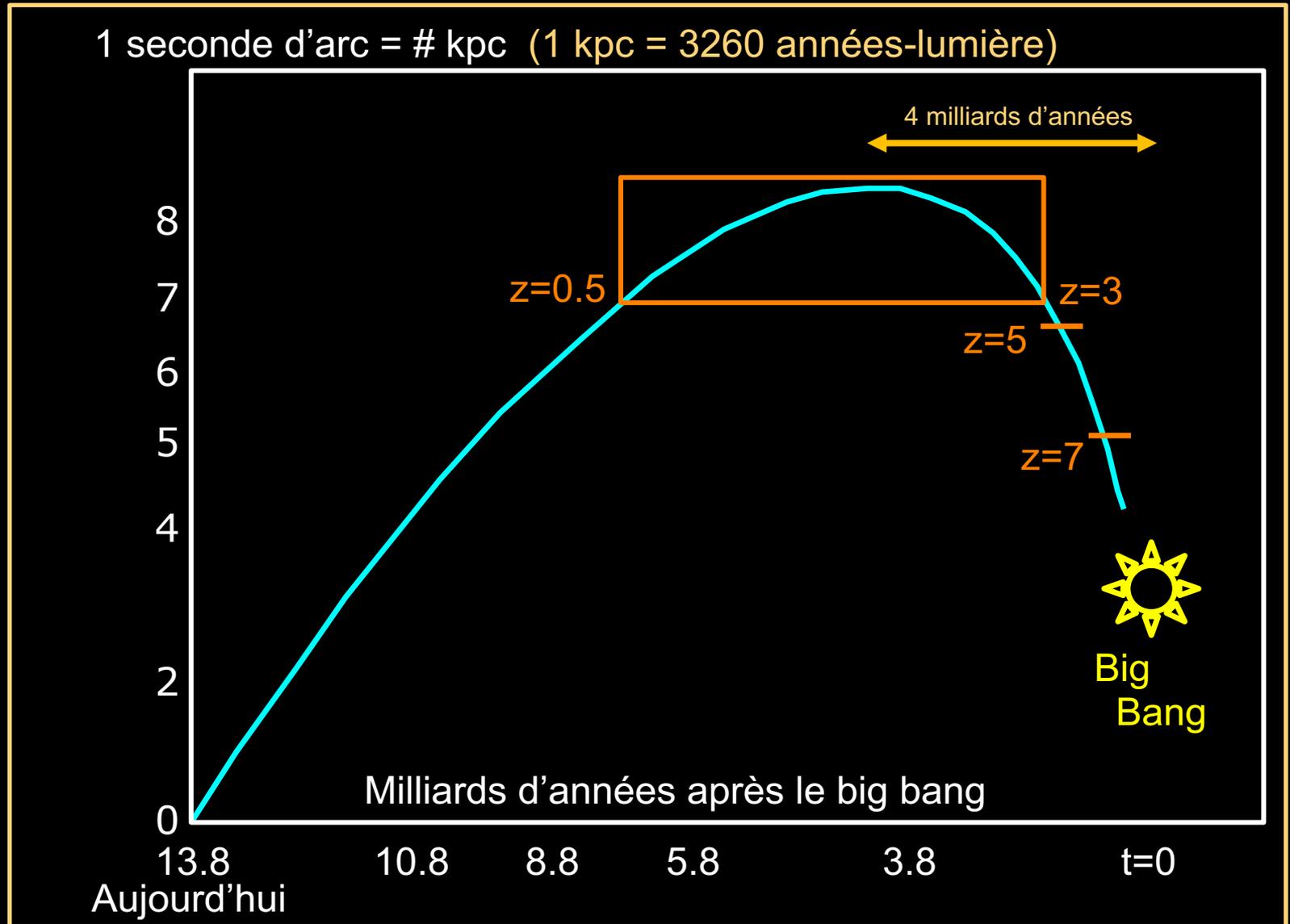
les plus lumineuses galaxies forment le plus d'étoiles

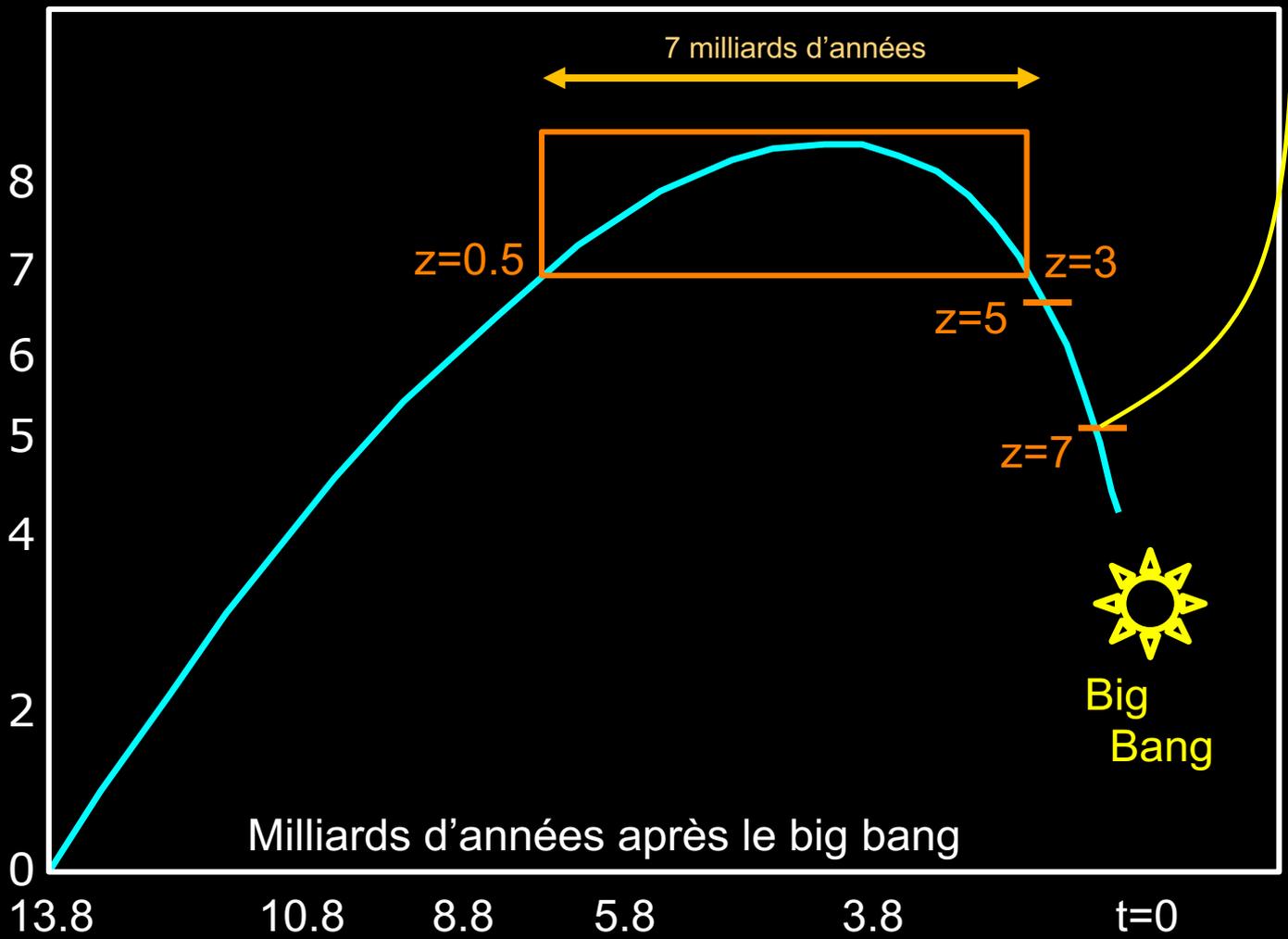
4- Potentiel de croissance des galaxies :

la matière diffuse interstellaire est le réservoir pour engendrer de nouvelles étoiles. Plus le réservoir est grand, plus une galaxie formera d'étoiles avec.

Taille des galaxies

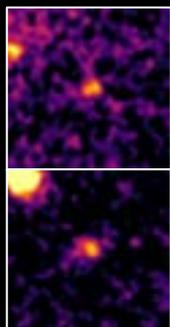
Taille des galaxies : devaient être plus petites dans le passé



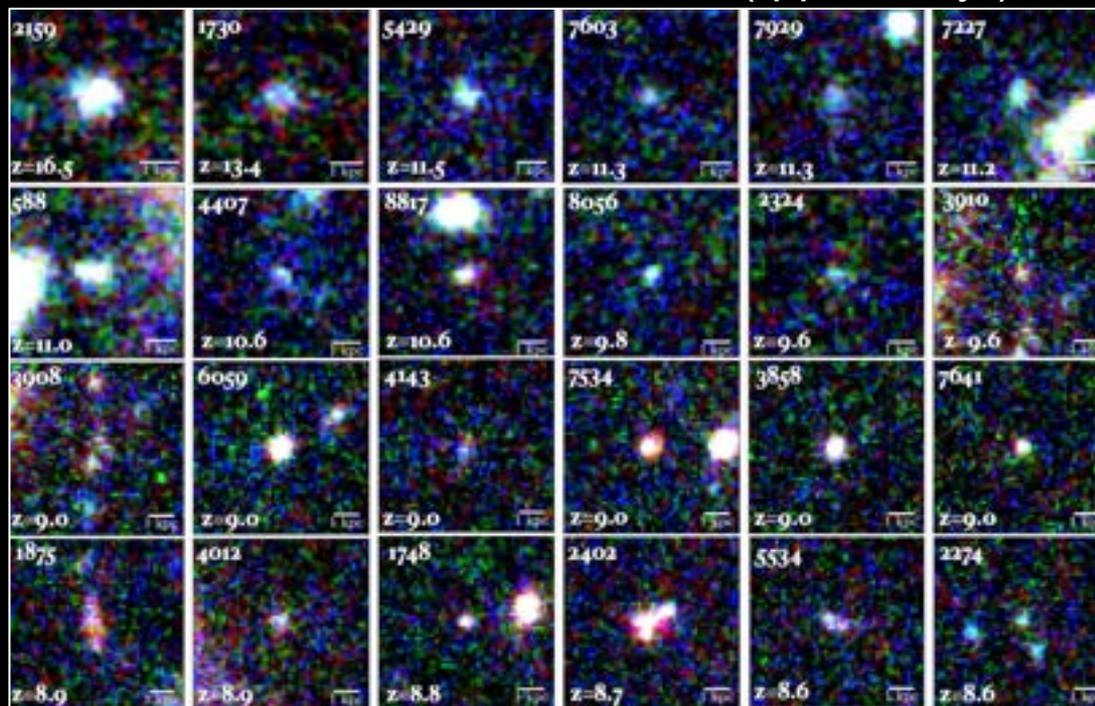




Galaxies à l'aube de l'univers (qq 100 Myr)



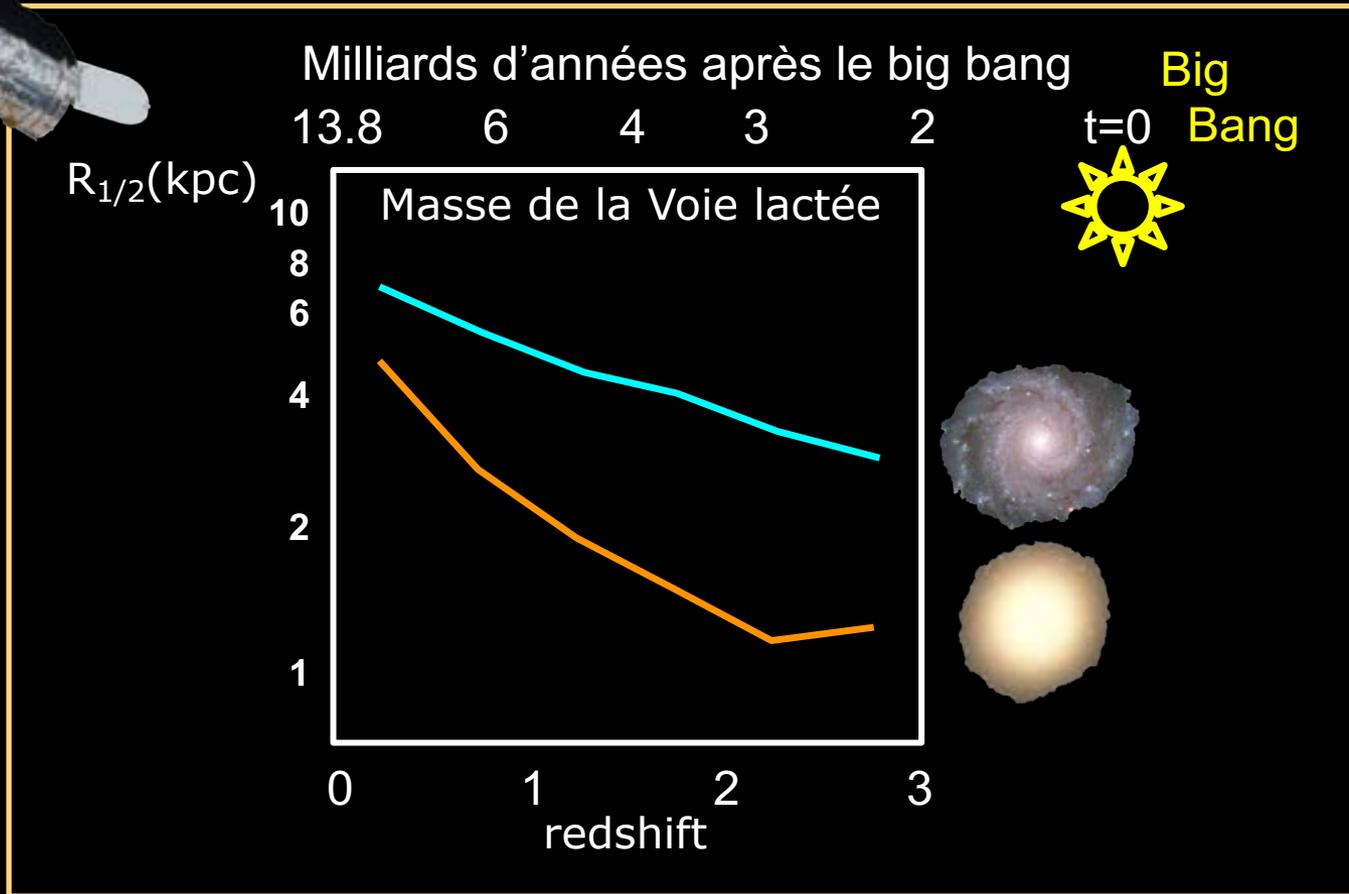
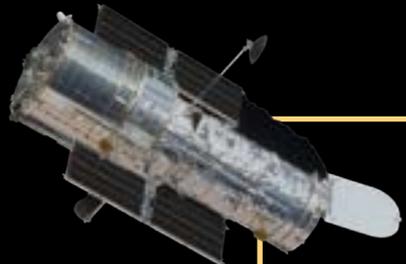
Atek +2022



Tailles ~ 0.1''

Finkelstein +2022

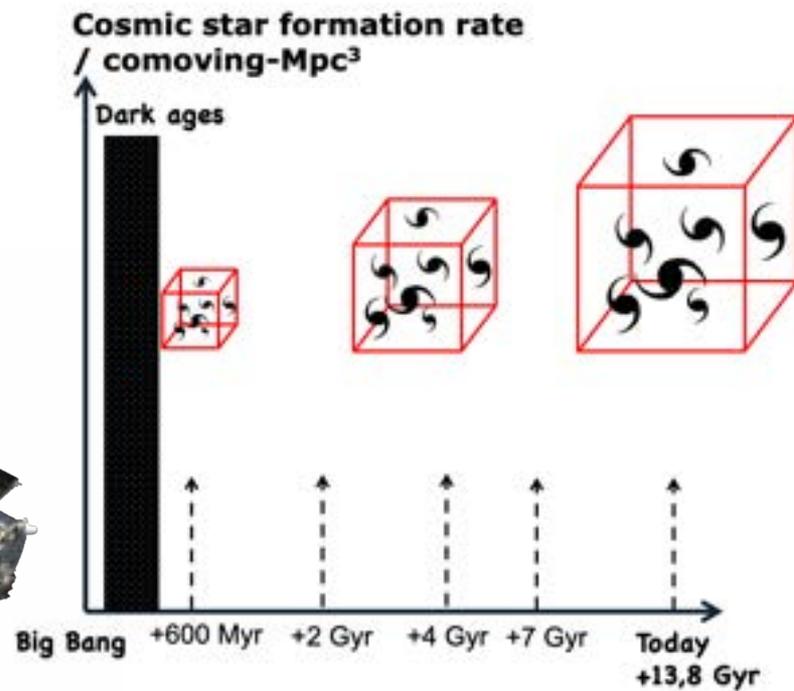
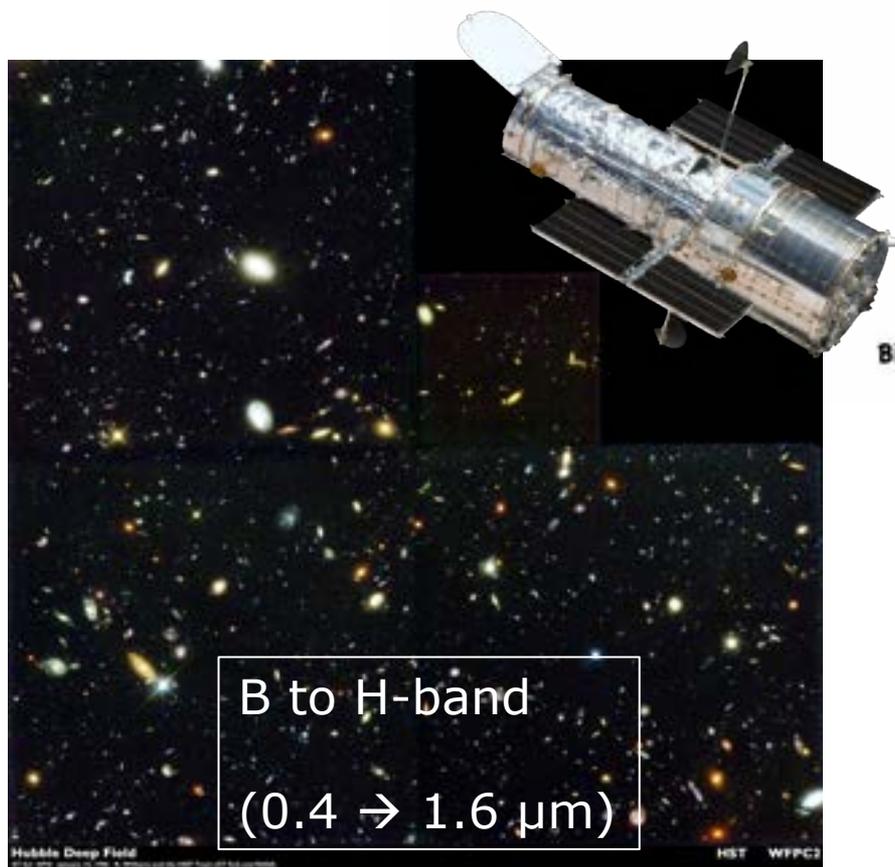
Taille des galaxies : devaient être plus petites dans le passé

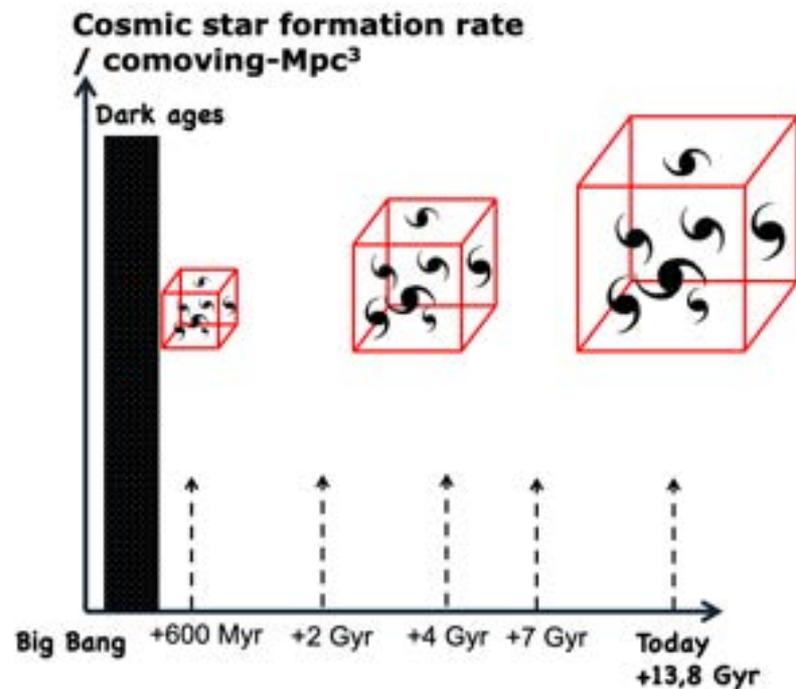
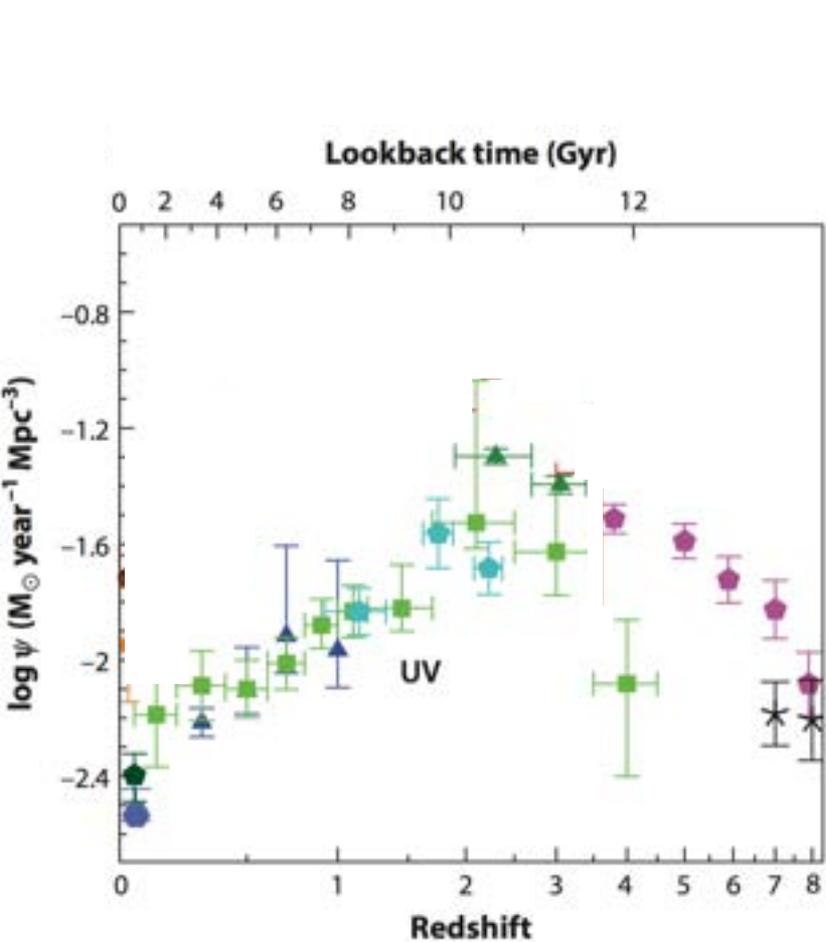


observations @ 5000Å $\text{Log}(M_{\star}/M_{\odot})=10.5-11$
(longueur d'onde visible dans le référentiel au repos)

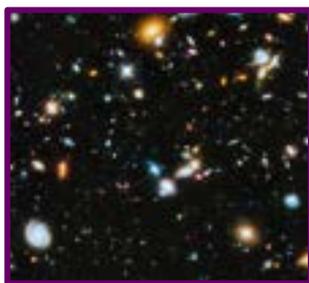
van der Wel +2014

Histoire visible et invisible de la formation d'étoiles

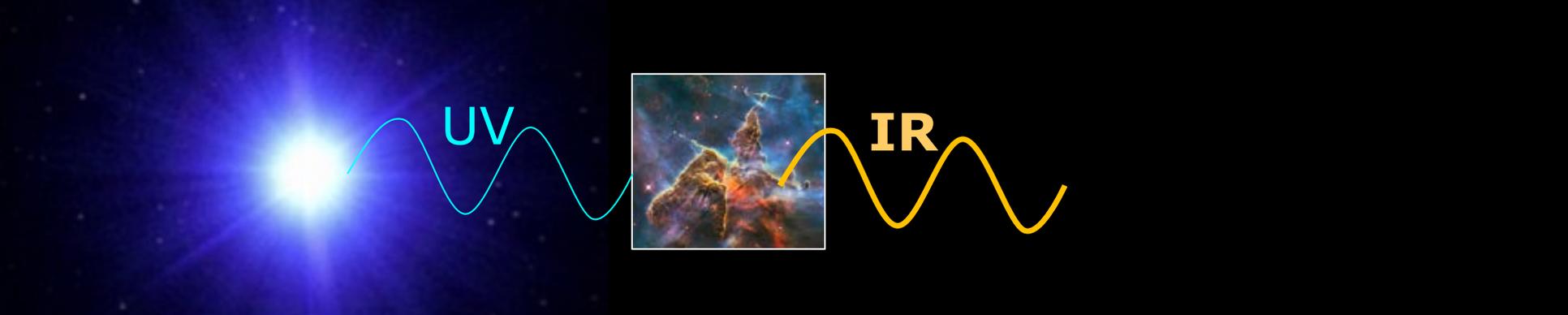




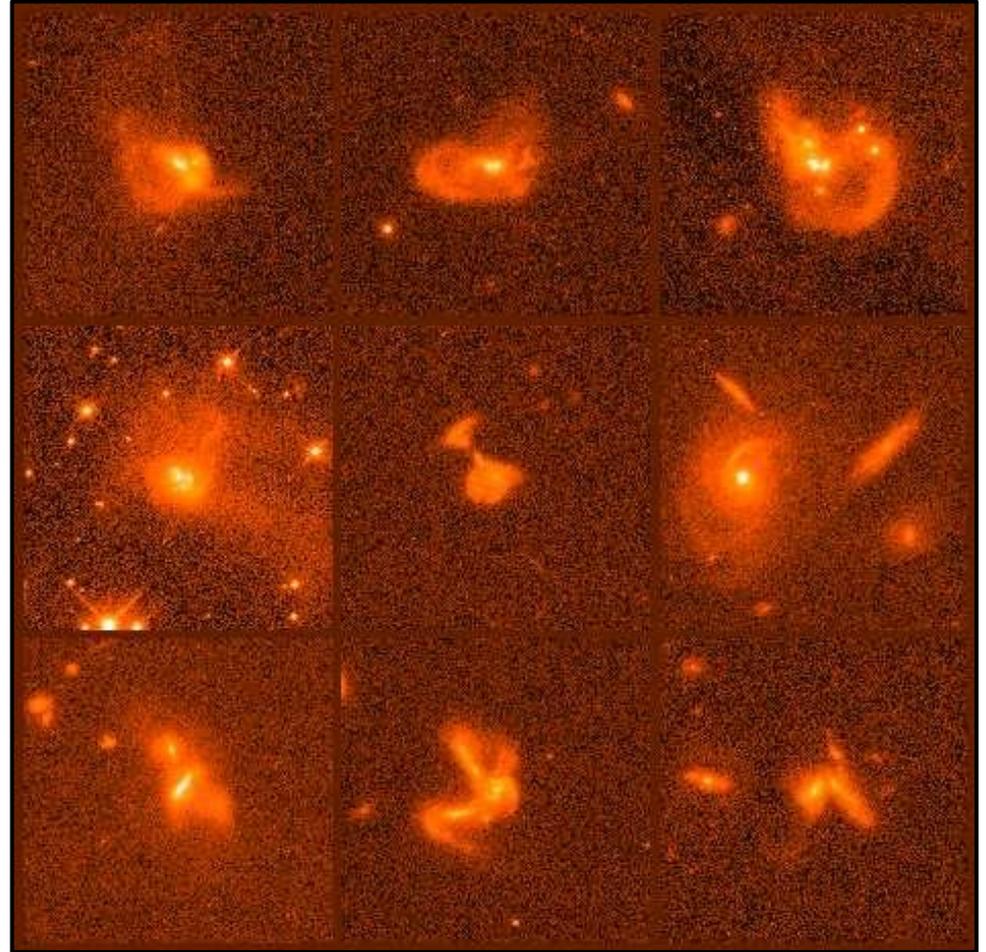
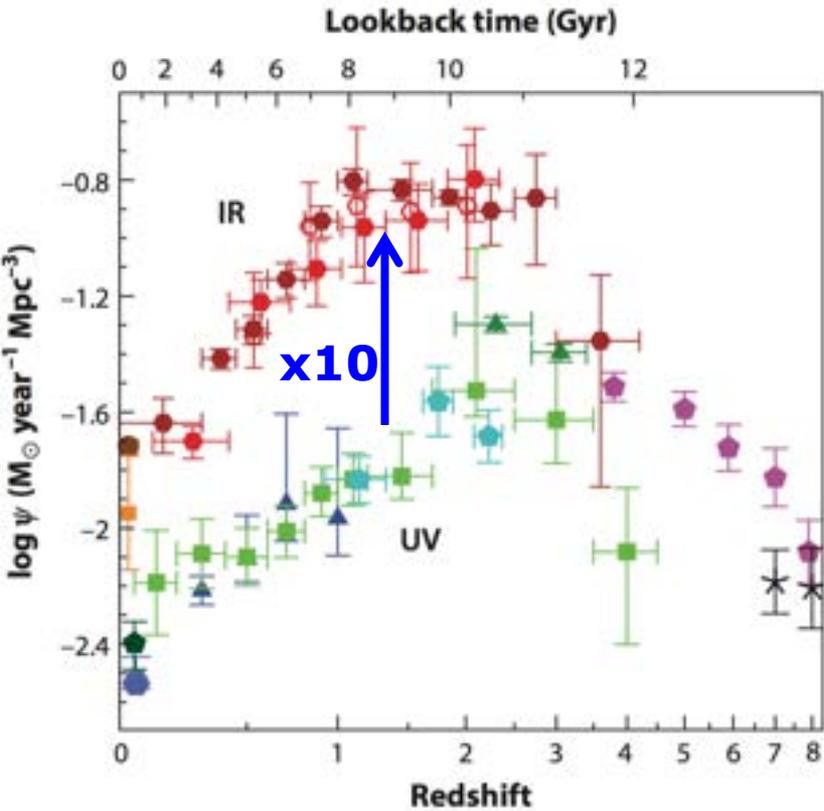
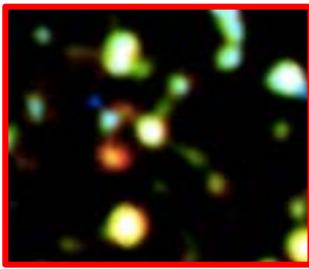
Visible side



Madau & Dickinson 2014, ARAA



Dust-obscured



Borne +2000

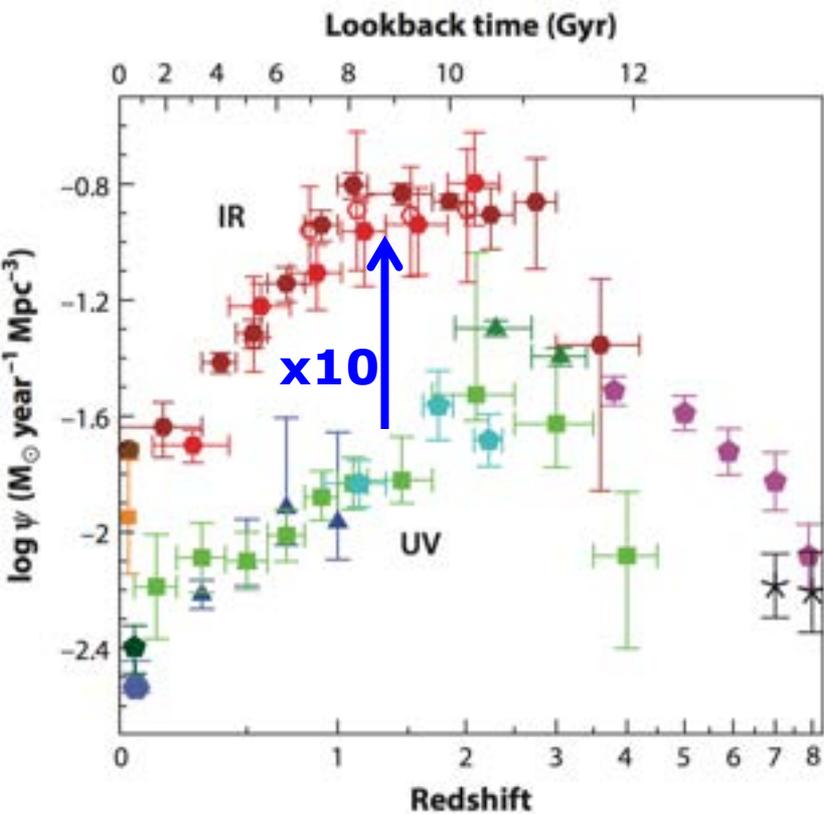
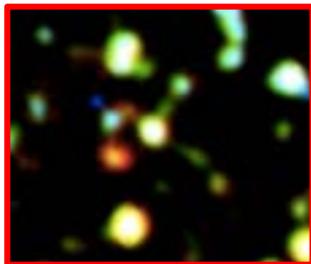
Madau &
Dickinson
2014, ARAA

Visible side

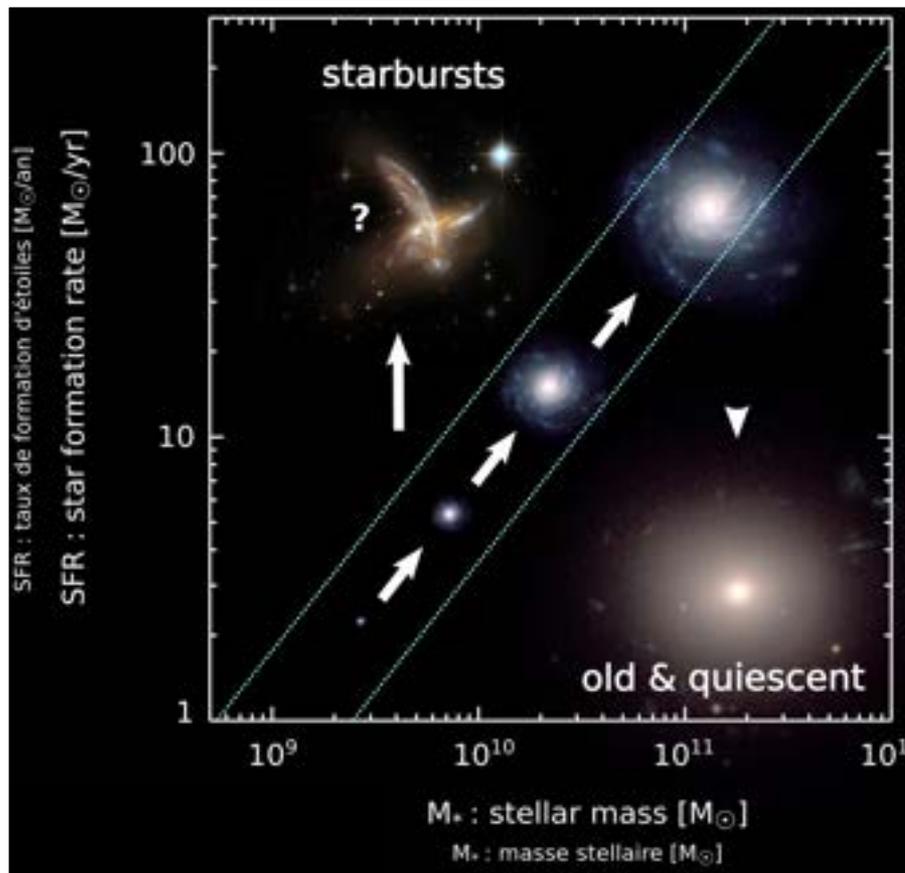


David Elbaz

Dust-obscured

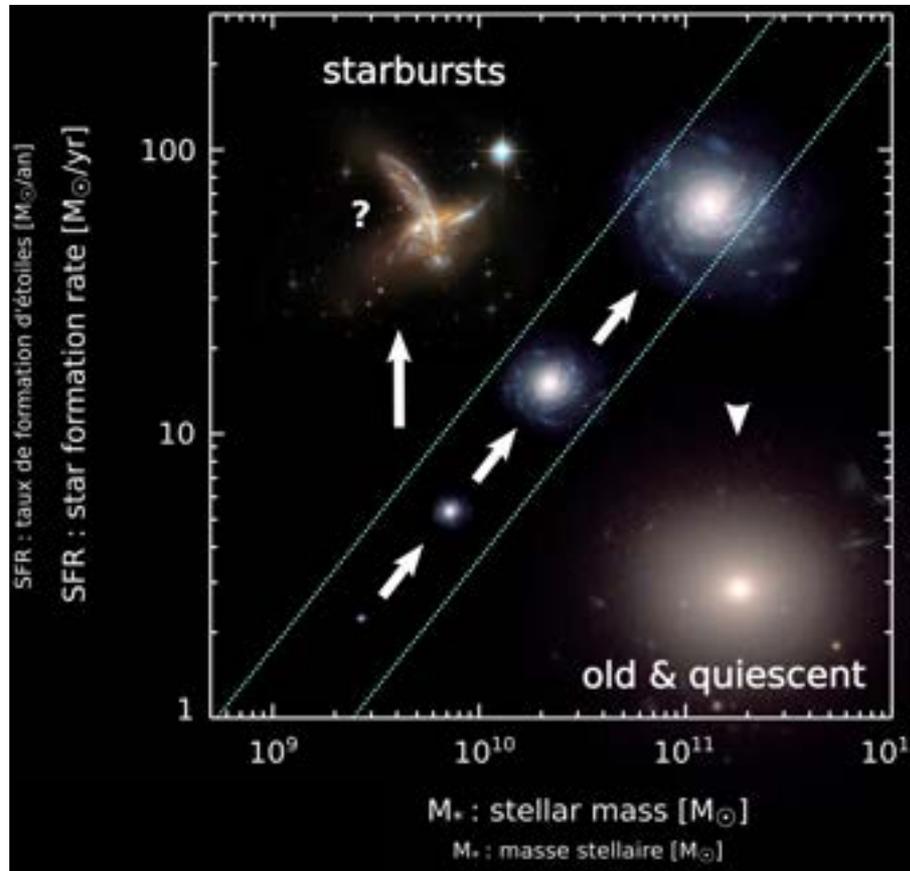


Visible side

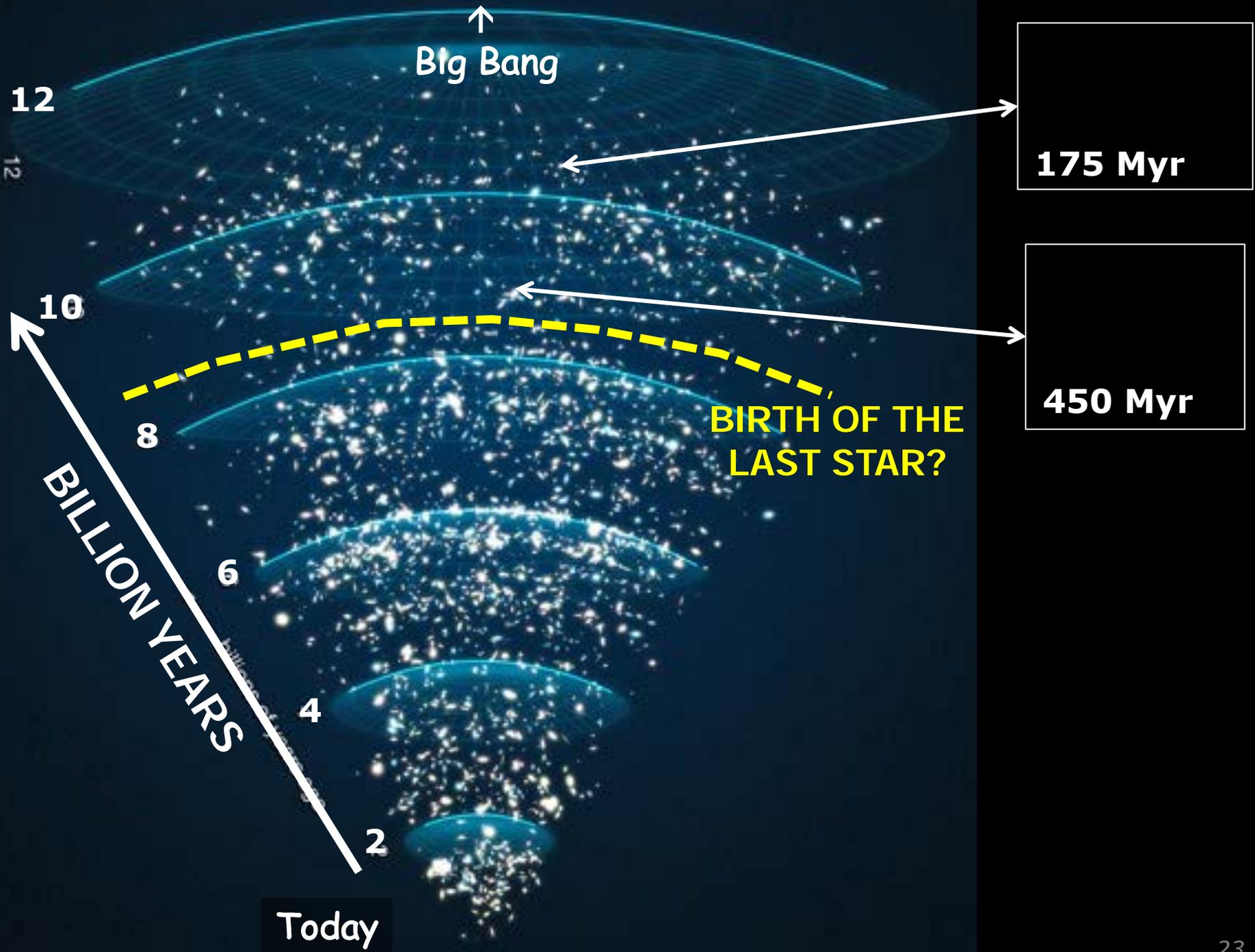


2 énigmes :

- 1- Réservoirs de matière suffisants pour former des étoiles pendant 600 millions d'années...
- 2- Un mécanisme régule la formation d'étoiles...



Elbaz +07,+11, Noeske +07; Daddi +07; Pannella +09; Schreiber +15



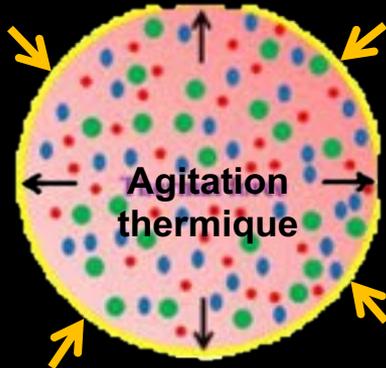
Morphogenèse galactique

la fourchette de

Edwin Hubble



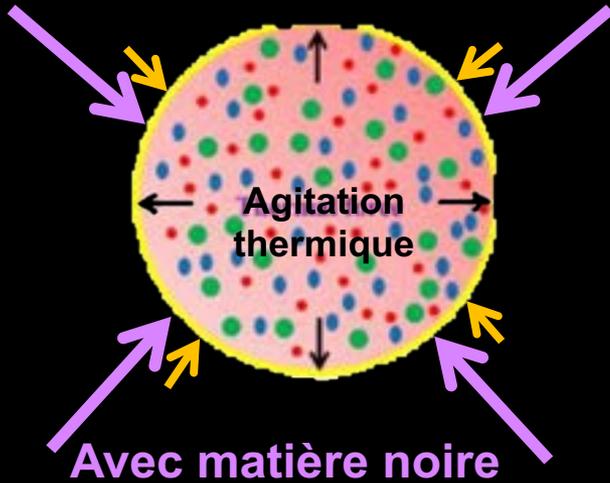
Effondrement gravitationnel



1929: Jeans gravitational instability

1933: matière noire / Zwicky

Effondrement gravitationnel

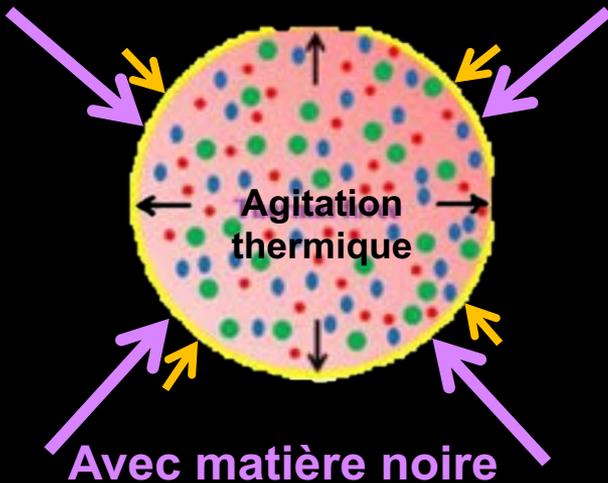


1929: Jeans gravitational instability

1933: matière noire / Zwicky

Densité/agitation > seuil
 $L > L_{\text{Jeans}} \text{ seuil} \Rightarrow \text{effondrement}$

Effondrement gravitationnel



Cas de la Voie Lactée:

- dispersion de vitesses des étoiles du disque : agitation $\sigma_v \sim 45 \text{ km/s}$
- densité d'étoiles: densité $\rho \sim 0.14 M_{\odot}/\text{pc}^3$

$\rightarrow L_{\text{Jeans}} \sim 1 \text{ kpc} = 3000 \text{ années-lumière} !$

$\rightarrow \text{Les dimensions} > 1 \text{ kpc} \text{ devraient s'êtr} \text{ effondrées} ! \dots$

1929: **Jeans gravitational instability**

1933: **matière noire / Zwicky**

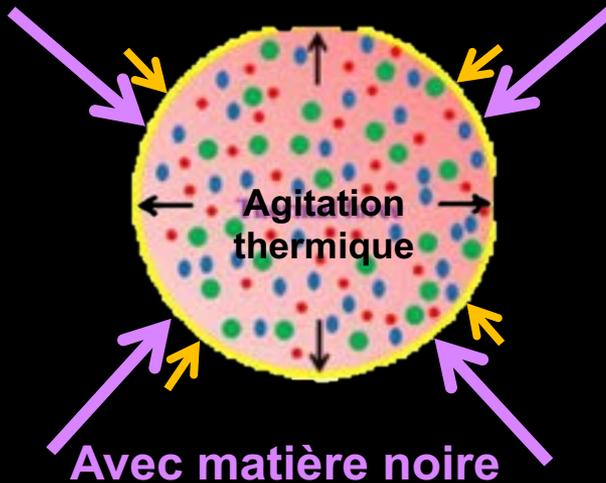
1964: **Rotation différentielle (critère de Toomre)**

$L > L_{\text{jeans}}$ seuil effondrement

Mais:

$L > L_{\text{rotation}} > L_{\text{jeans}}$ stabilisé par rotation

Effondrement gravitationnel



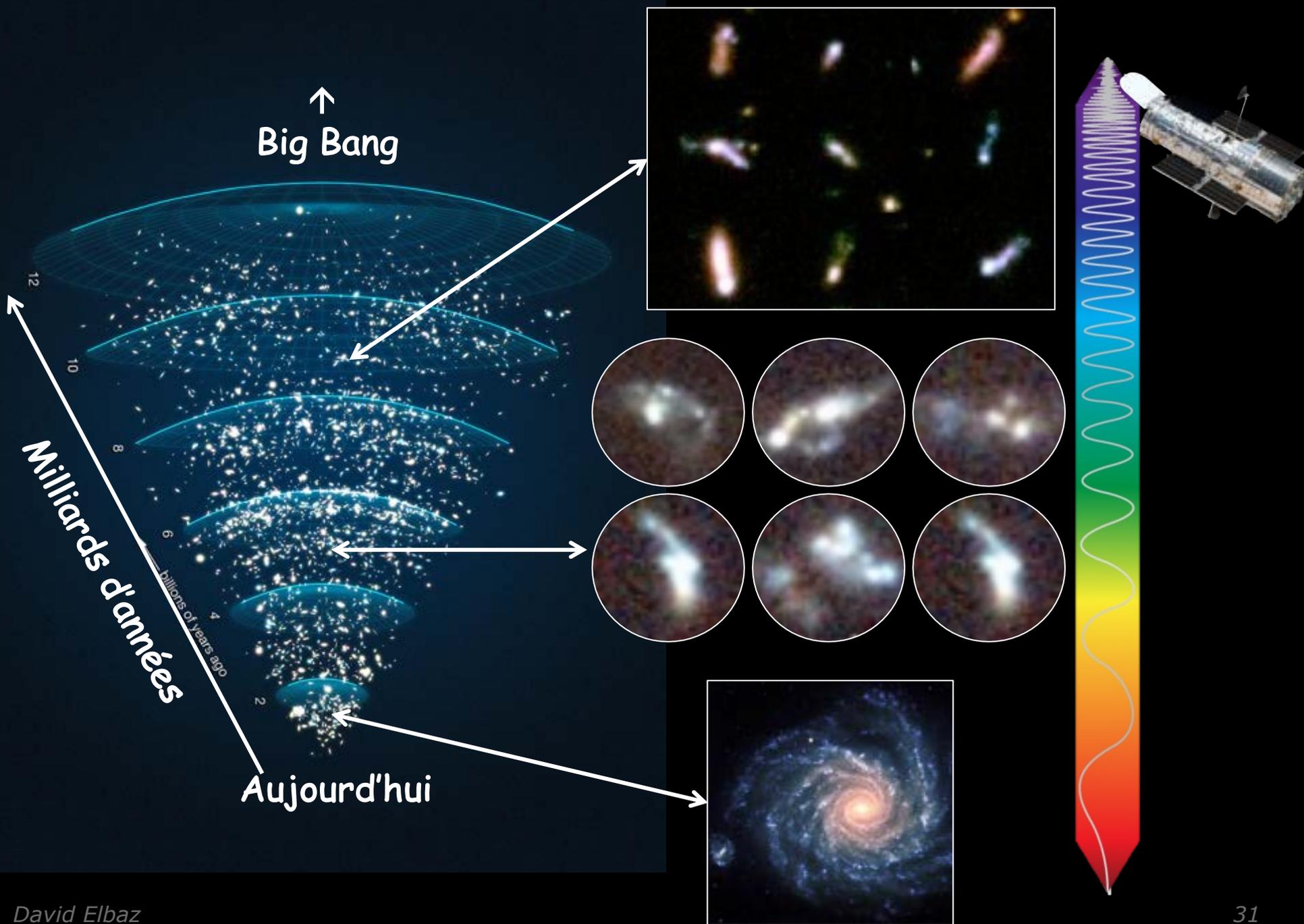
1929: Jeans gravitational instability

1933: matière noire / Zwicky

1964: Rotation différentielle (*critère de Toomre*)

1964: Théorie des ondes de densité (*Lin & Shu*)

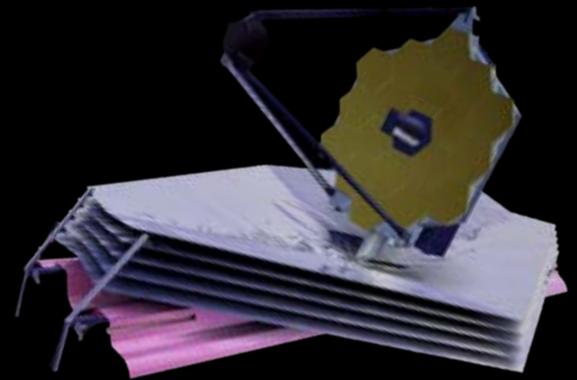


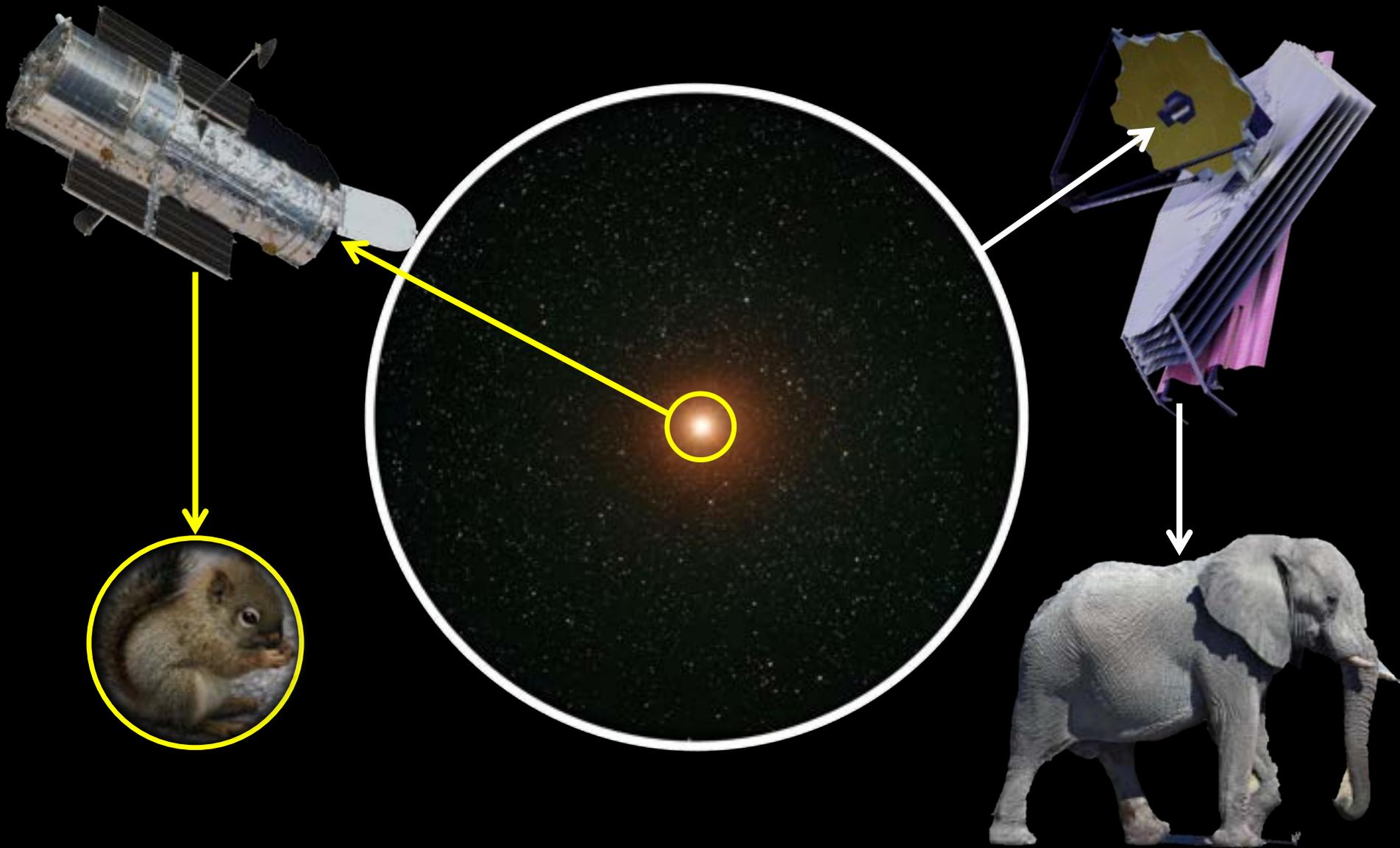


25 décembre 1995
le Hubble Deep Field
(>100h)



25 décembre 2021
SMACS0723
(12.5 heures)





NGC1376

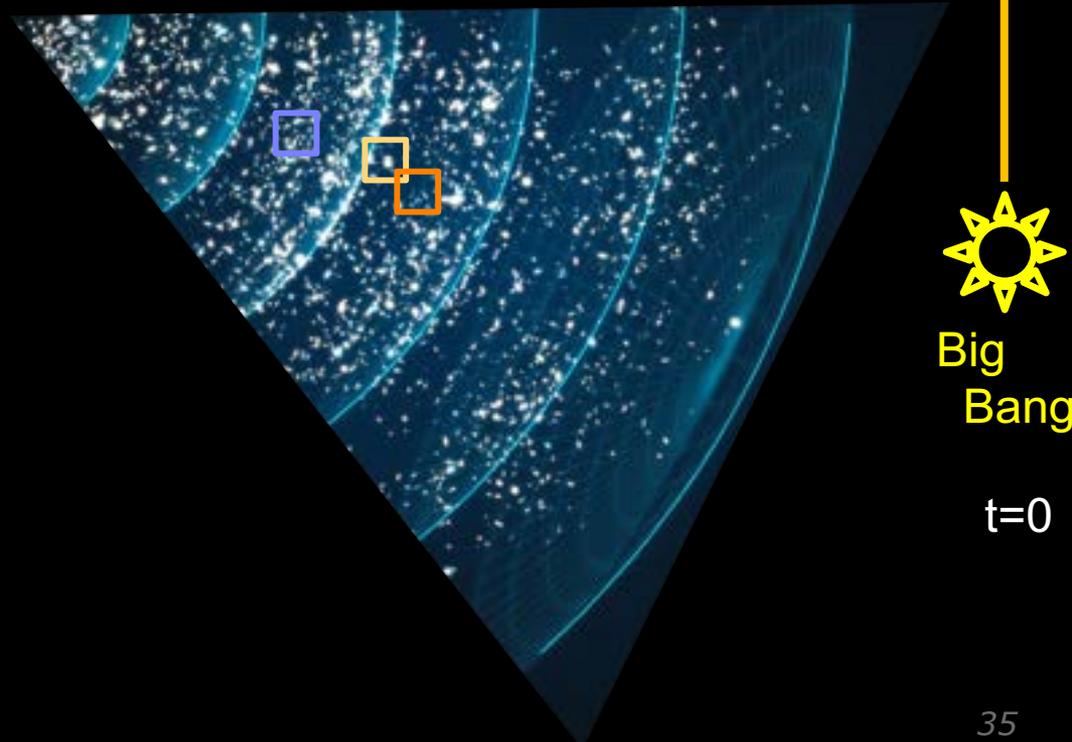
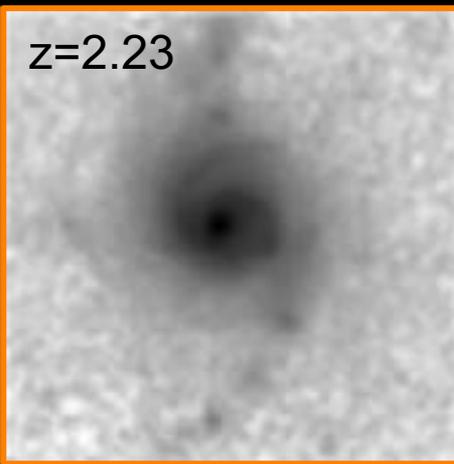
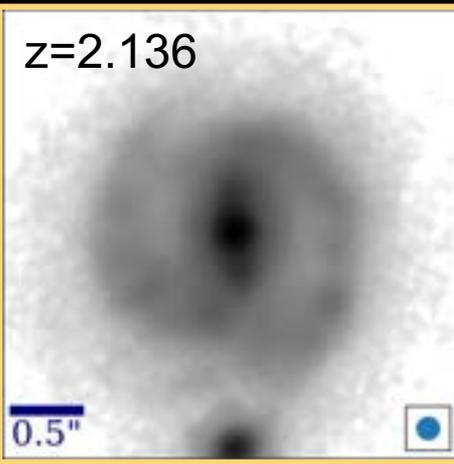
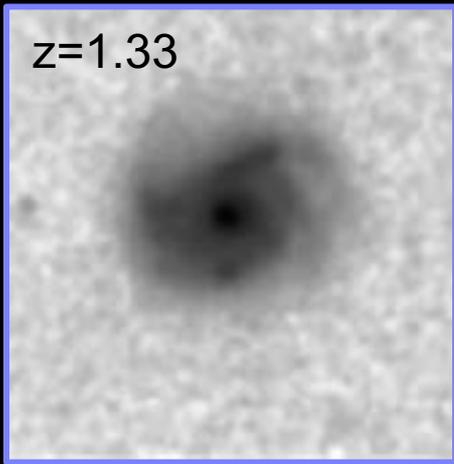
Aujourd'hui

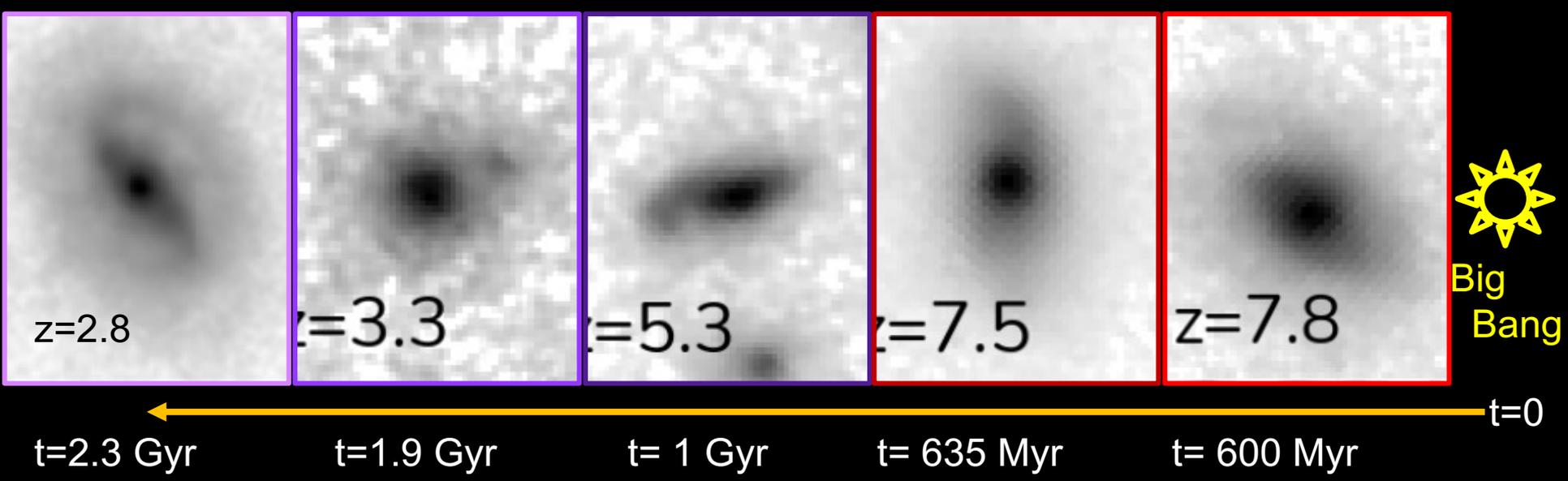
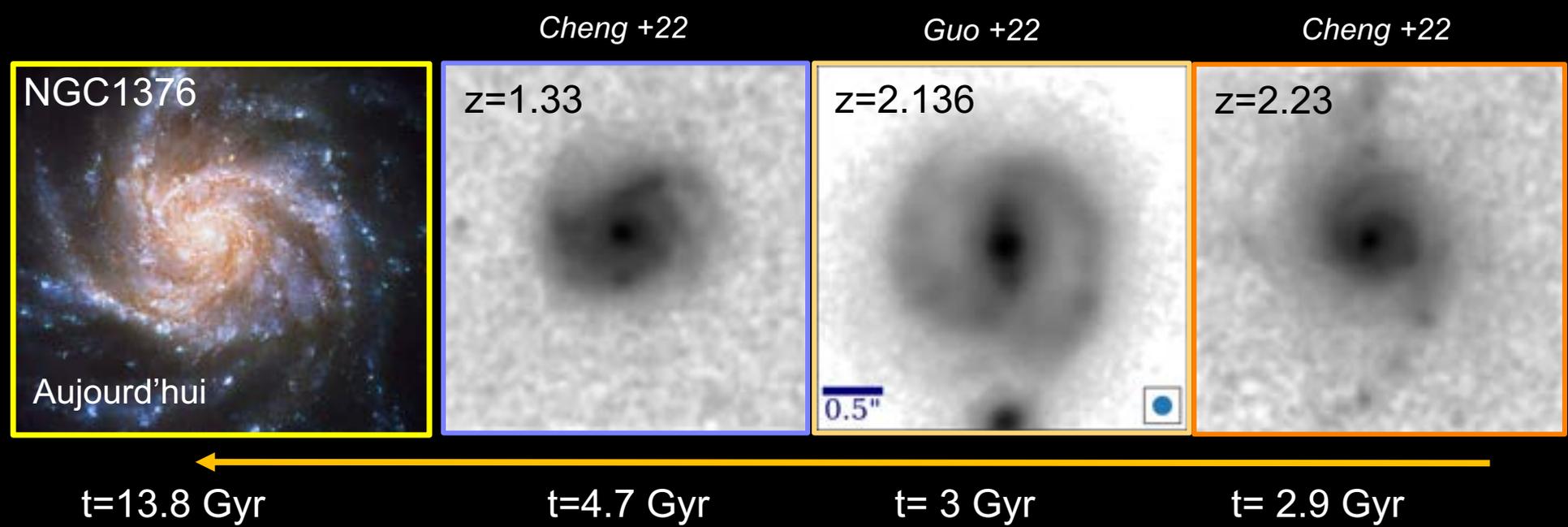
$t=13.8$ Gyr



Big
Bang

$t=0$





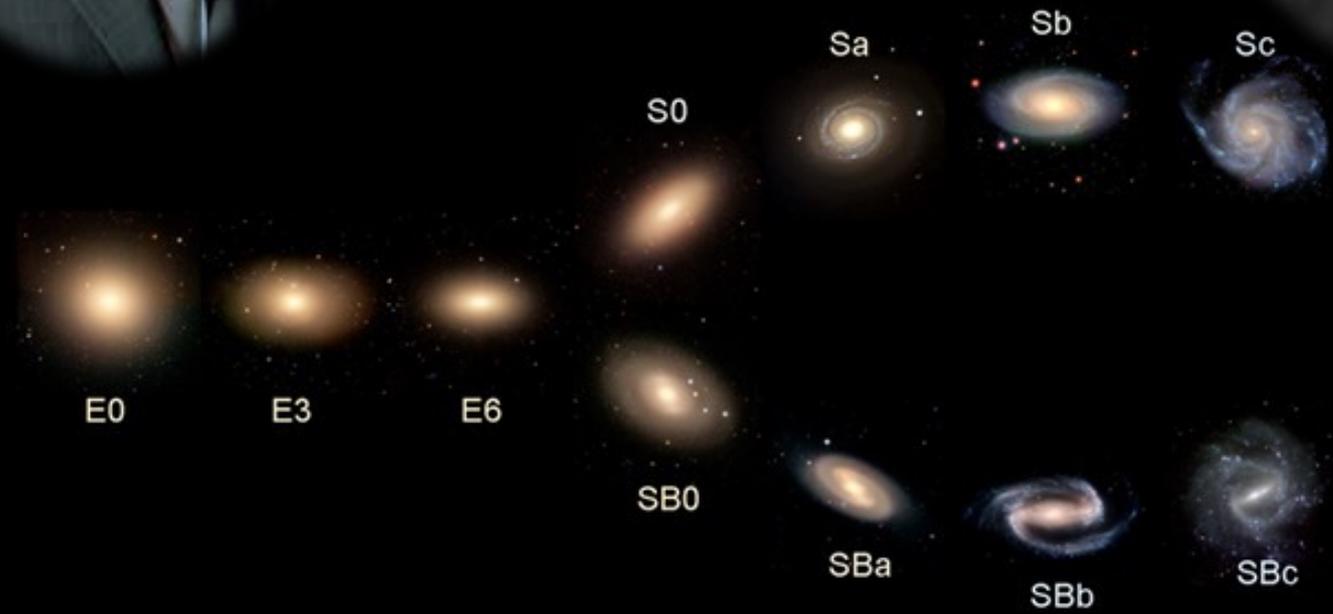


James Webb...

a repêché la fourchette de...



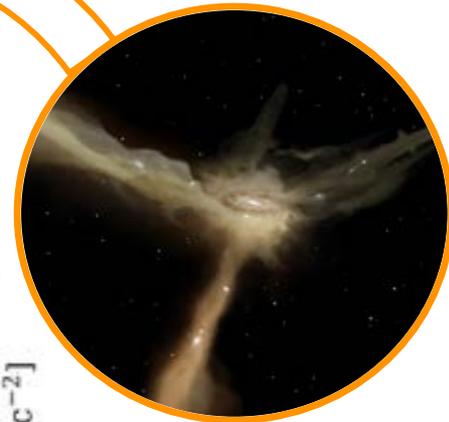
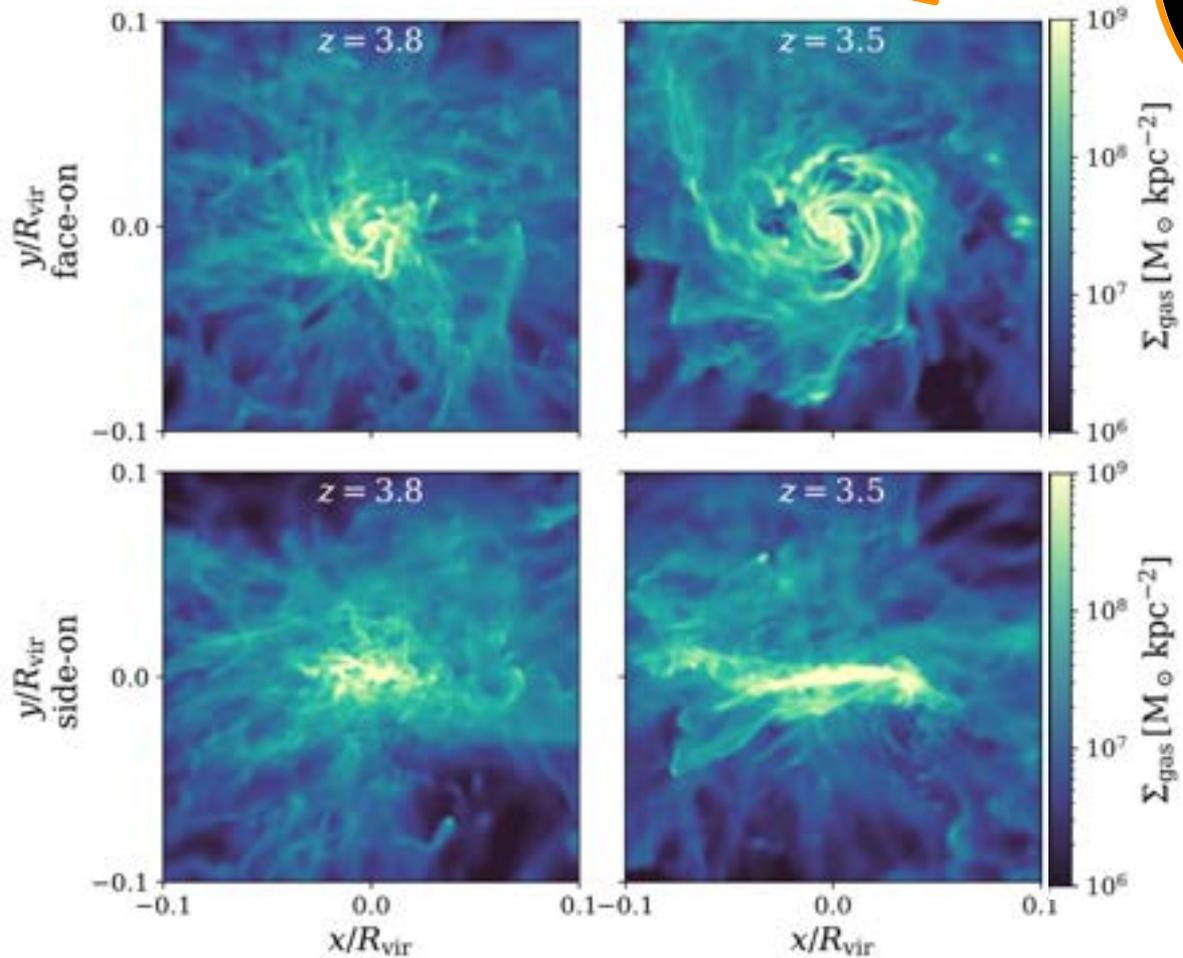
Edwin Hubble



Morphogenèse galactique :
qu'est-ce qui fait tourner les galaxies ?







Avant l'accrétion

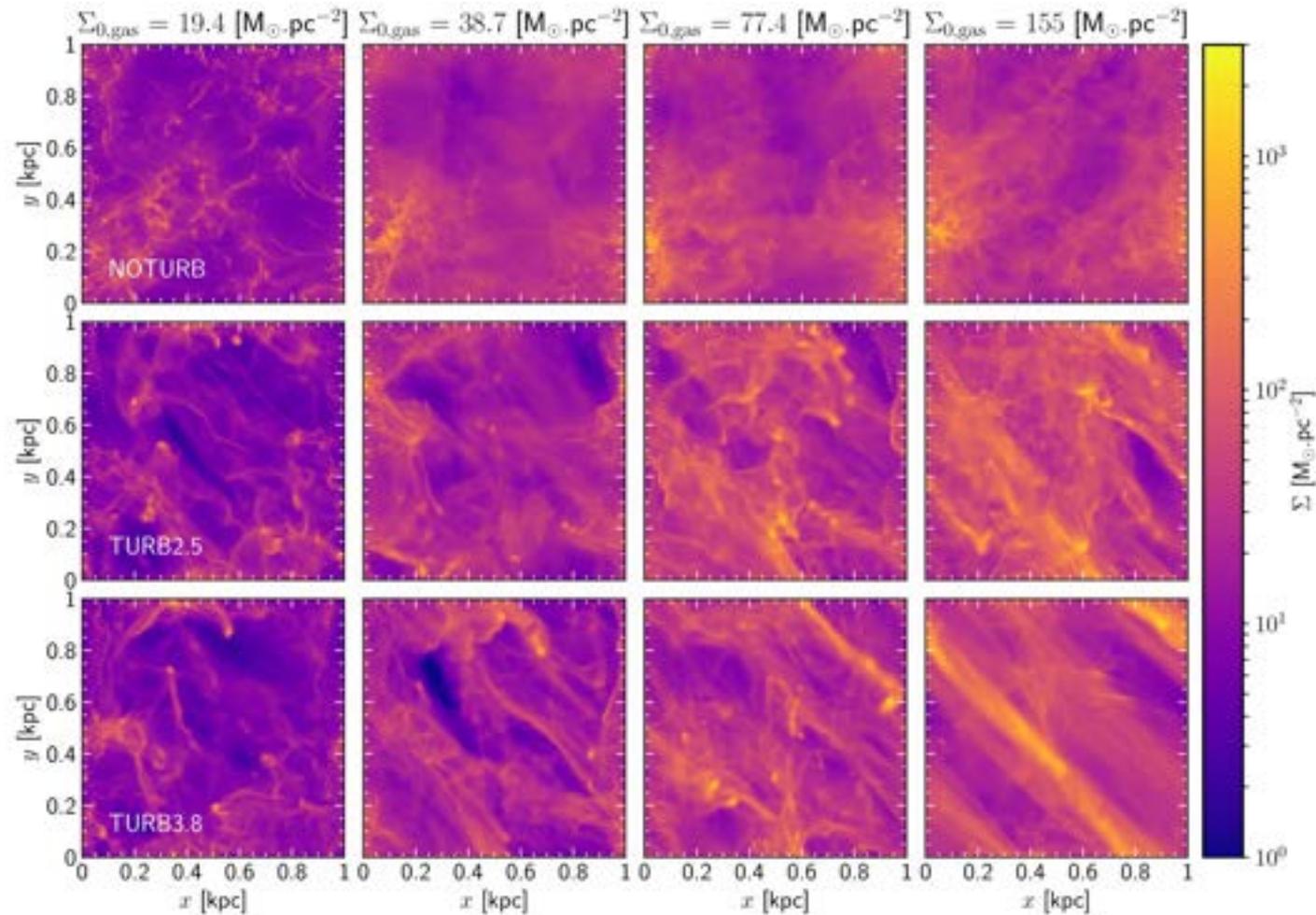
Pendant l'accrétion

Kretschmer+2021

Large-scale Turbulent Driving Regulates Star Formation in High-redshift Gas-rich Galaxies

THE ASTROPHYSICAL JOURNAL LETTERS, 896:L34 (8pp), 2020 June 20

Noé Bruy¹, Patrick Hennebelle², Frédéric Bournaud³, and Cédric Colling

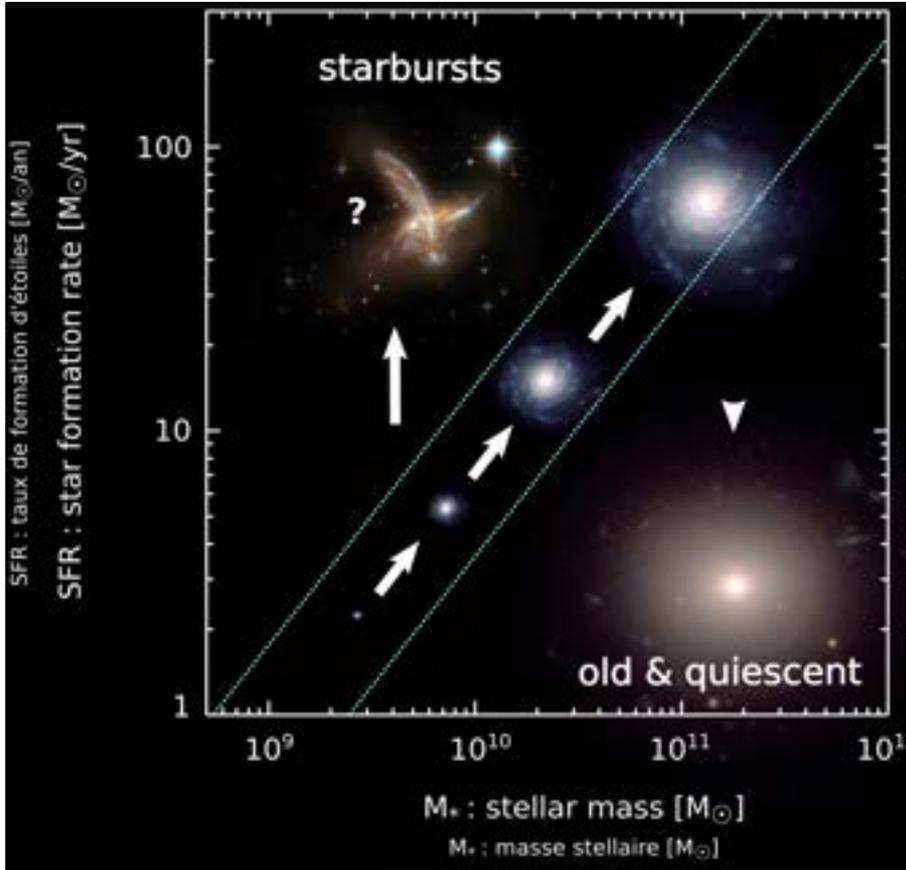
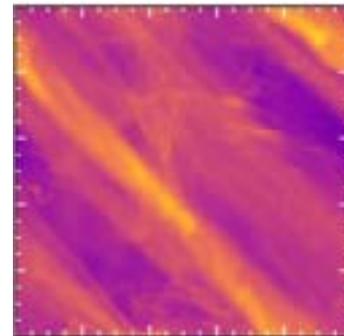


2 énigmes :

1- Réservoirs de matière suffisants pour former des étoiles pendant 600 millions d'années...



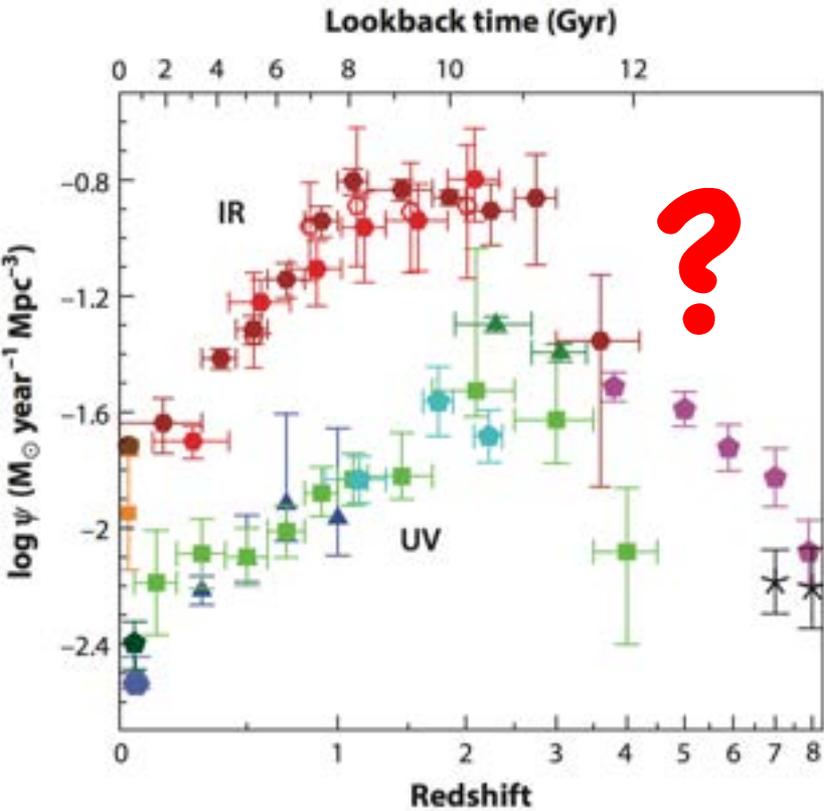
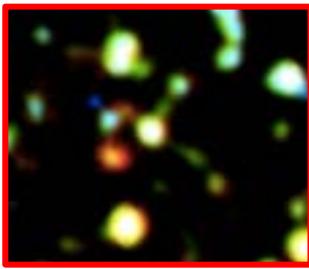
2- Un mécanisme régule la formation d'étoiles...



Elbaz +07,+11, Noeske +07; Daddi +07; Pannella +09; Schreiber +15

Les premiers milliards d'années de l'histoire...
...l'ère des dinosaures galactiques

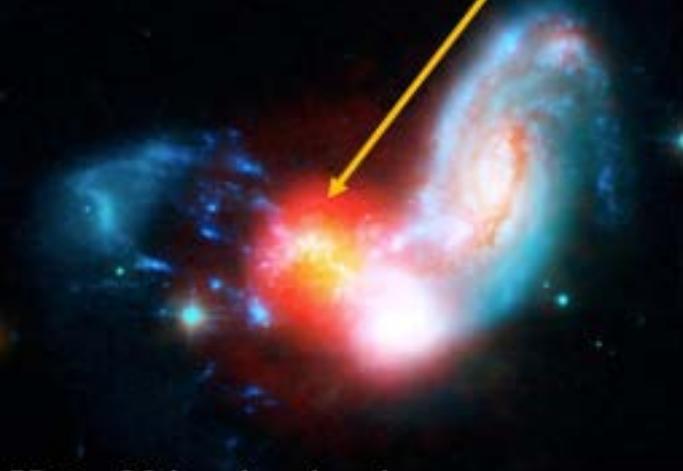
Dust-obscured



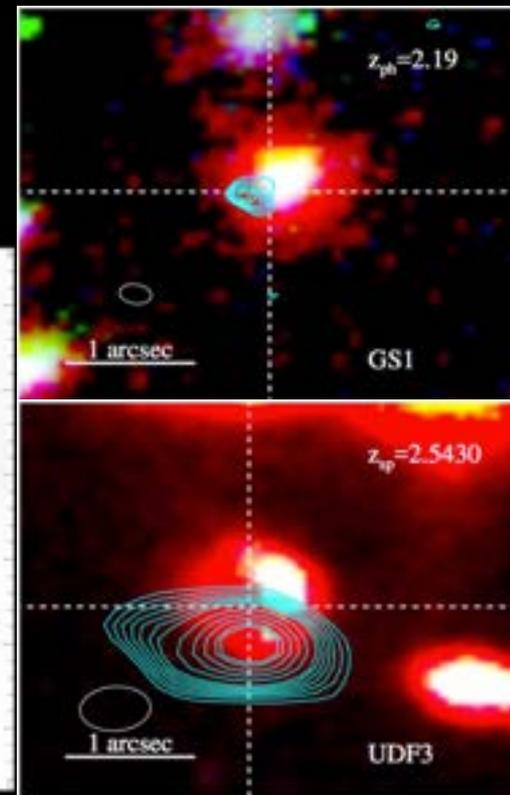
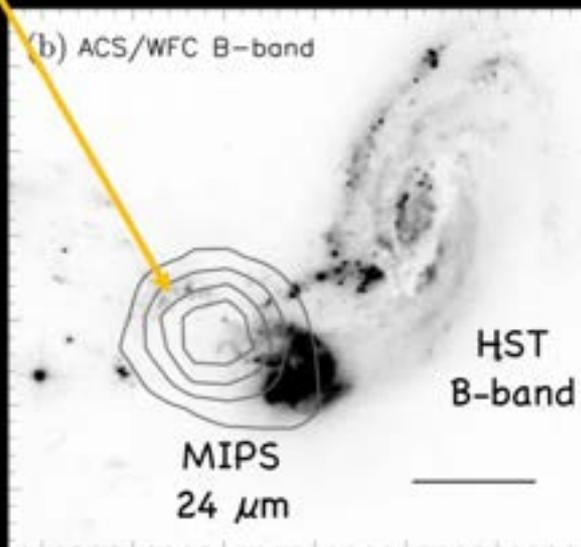
Visible side



Young stars
Hidden by dust



Inami +2010

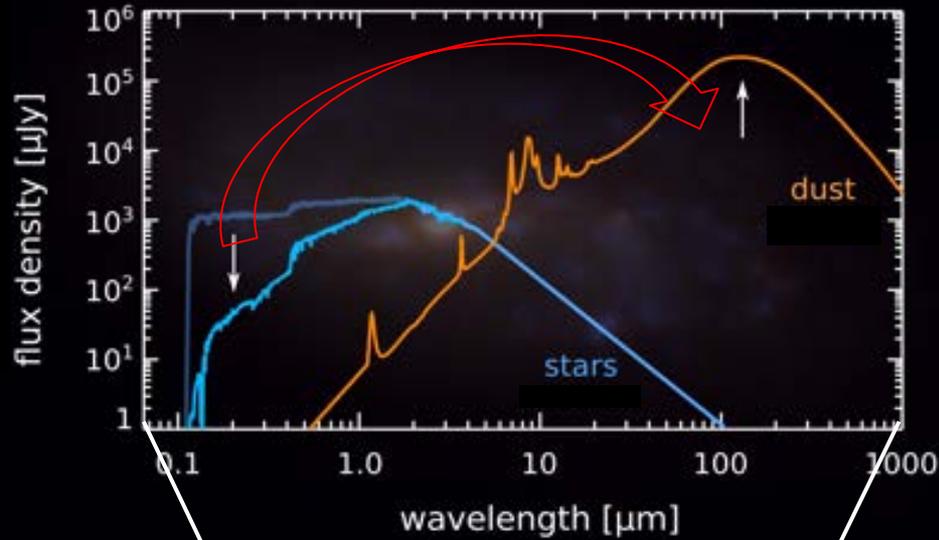


Elbaz +2008

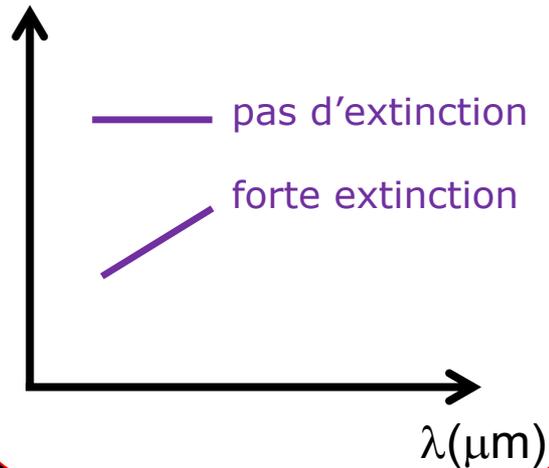
short-lived high-mass stars
radiate mostly in the UV
→ birthrate of stars

long-lived low-mass stars
radiate mostly in the NIR

most UV light is absorbed
by dust → radiates in the
far-infrared



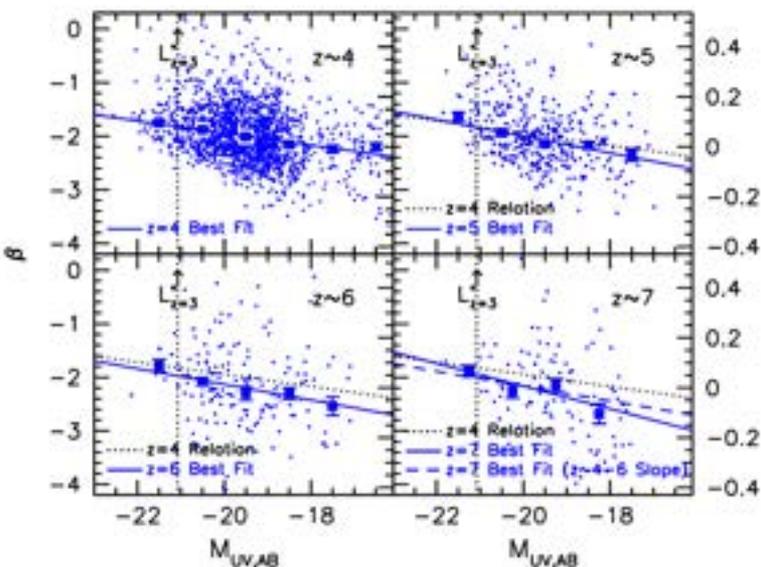
$$F_\nu = dF/d\nu \text{ (Wm}^{-2}\text{Hz}^{-1}\text{)}$$



UV-CONTINUUM SLOPES AT $z \sim 4-7$ FROM THE HUDF09+ERS+CANDELS OBSERVATIONS: DISCOVERY OF A WELL-DEFINED UV COLOR-MAGNITUDE RELATIONSHIP FOR $z \geq 4$ STAR-FORMING GALAXIES*

R. J. BOUWENS^{1,2}, G. D. ILLINGWORTH², P.A. OESCH^{2,6}, M. FRANX¹, I. LABBÉ¹, M. TRENTI³, P. VAN DOKKUM⁴,
C. M. CAROLLO⁵, V. GONZÁLEZ², R. SMIT¹, AND D. MAGEE²

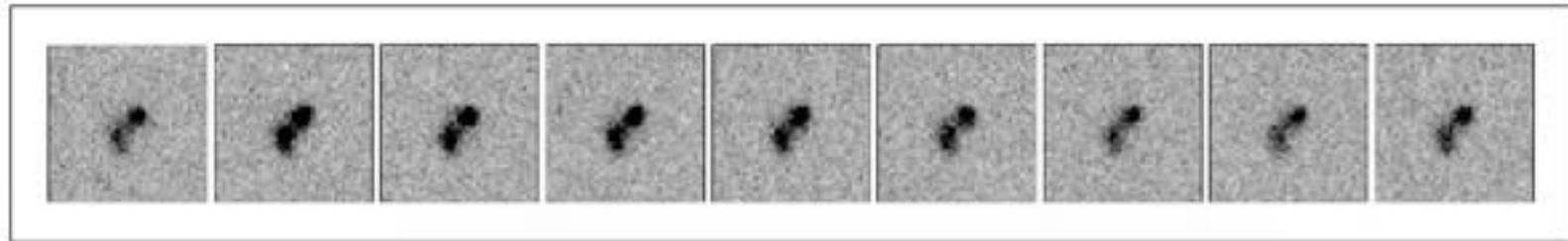
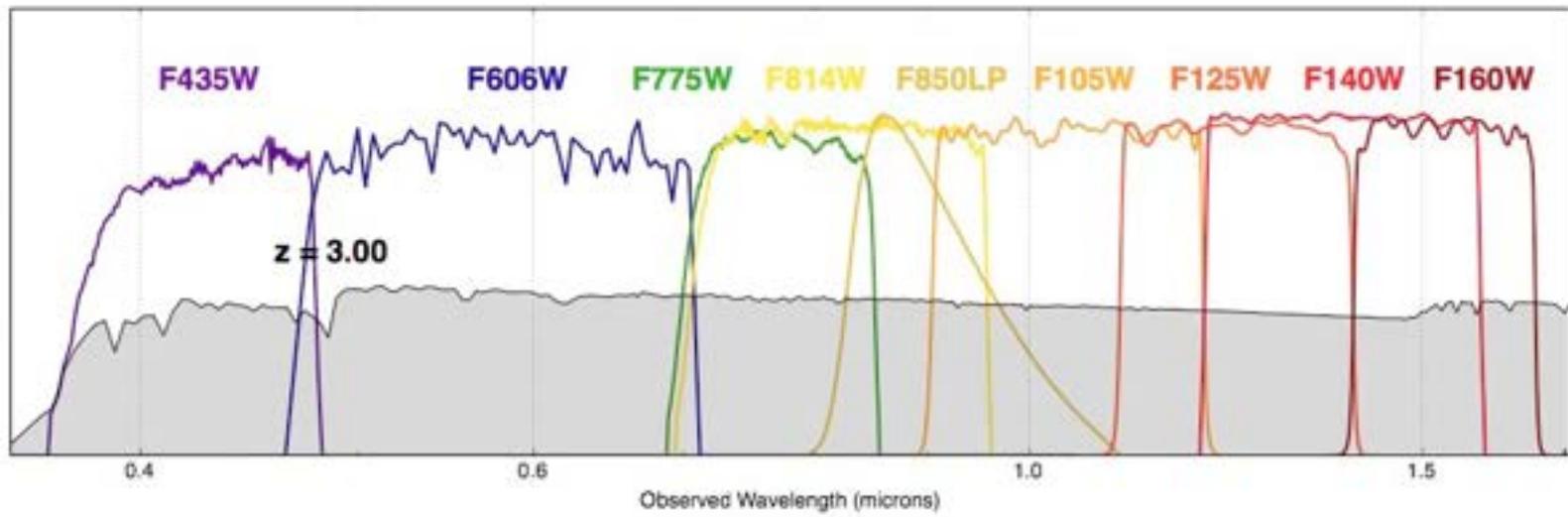
“These new larger β samples lead to improved dust extinction estimates at $z \sim 4-7$ and confirm that the extinction is essentially zero at low luminosities and high redshifts.”

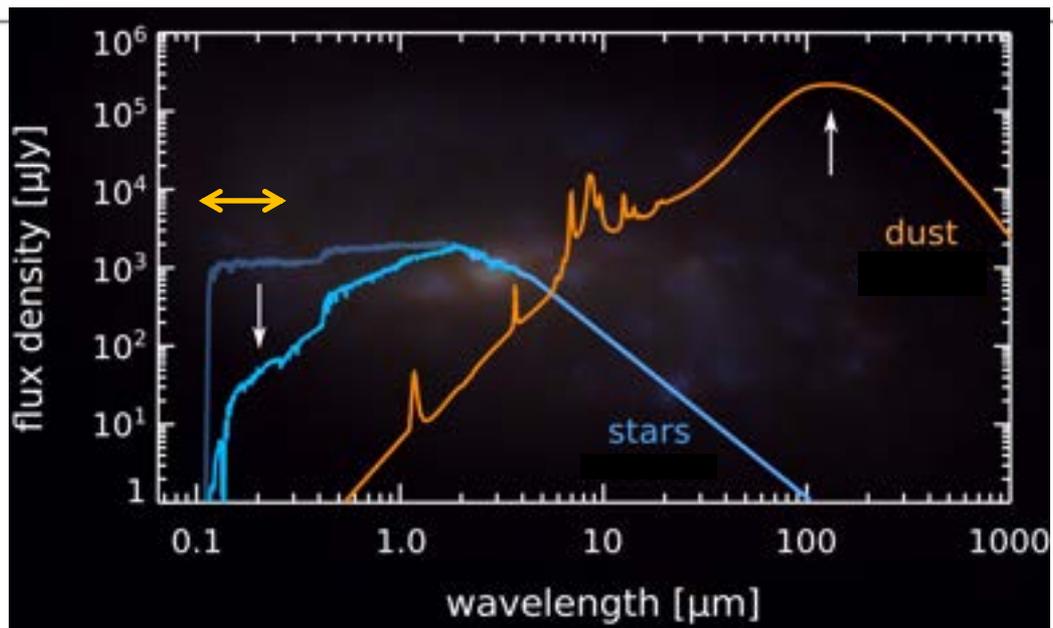
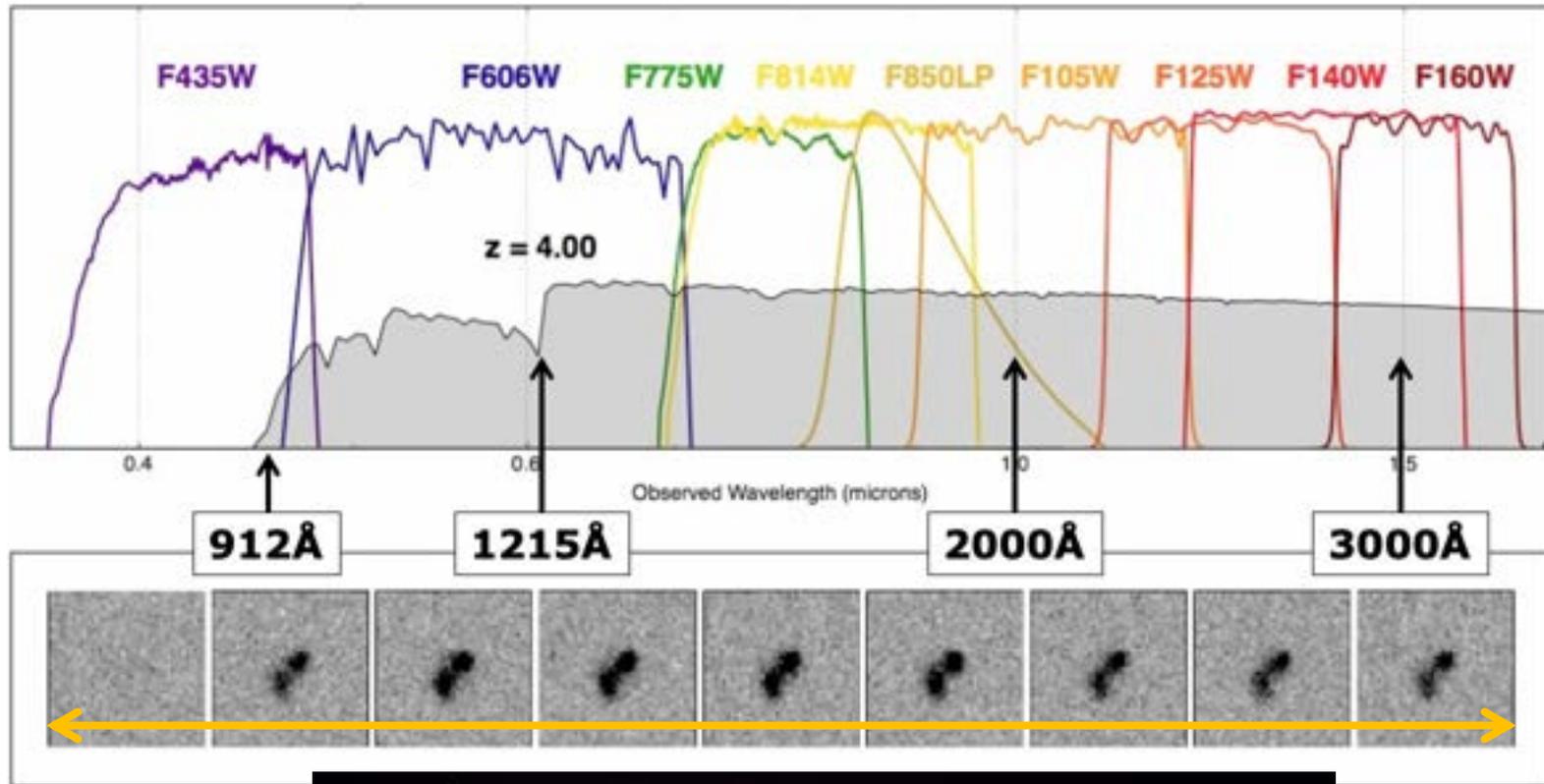


En 2012, Bouwens et al. mesurent la pente du spectre dans le domaine UV de galaxies qui remontent entre 12 et 13 milliards d'années :

Ils trouvent qu'elle est compatible avec aucune extinction par la poussière !

Mais leur étude souffre d'une faiblesse à laquelle ils n'ont pas pensé...





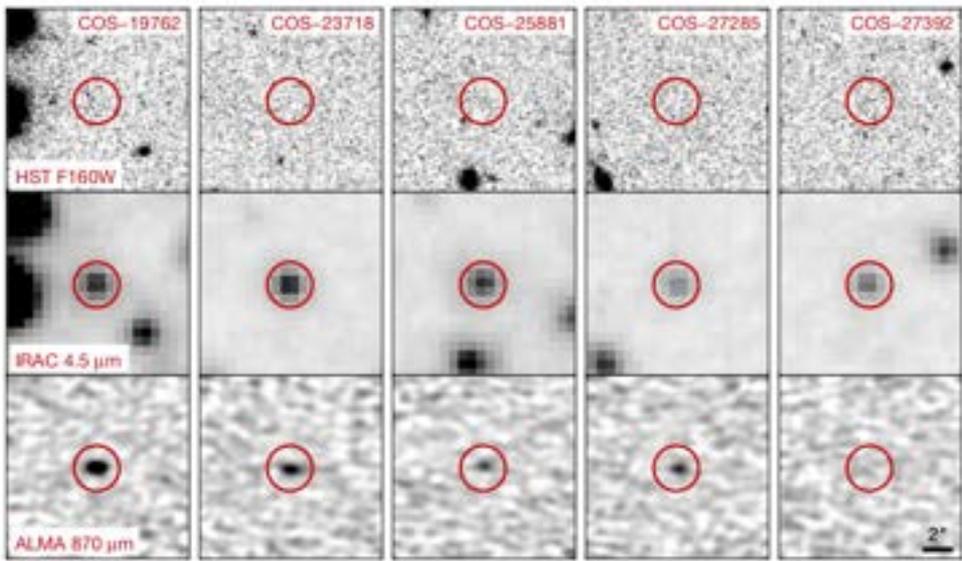
Wang, Schreiber, Elbaz et al.

A dominant population of optically invisible massive galaxies in the early Universe

T. Wang^{1,2,3*}, C. Schreiber^{2,4,5}, D. Elbaz², Y. Yoshimura¹, K. Kohno^{1,6}, X. Shu⁷, Y. Yamaguchi¹, M. Pannella⁸, M. Franco³, J. Huang⁹, C.-F. Lim^{10,11} & W.-H. Wang¹²



H-dropouts $H > 27$, $[4.5\mu\text{m}] < 24$

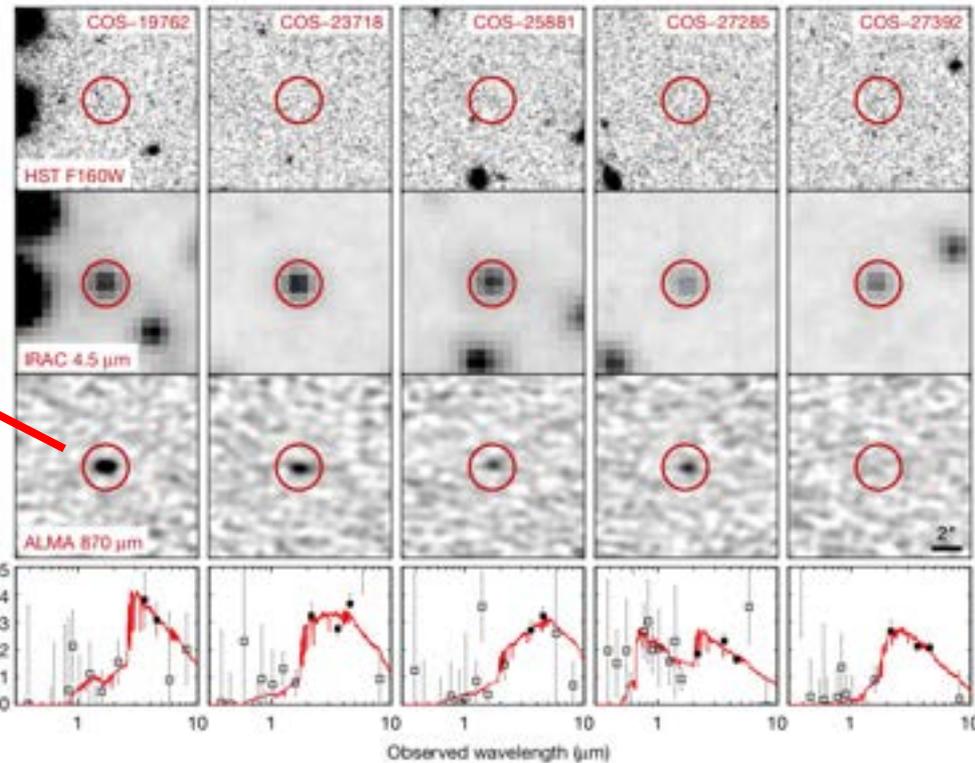
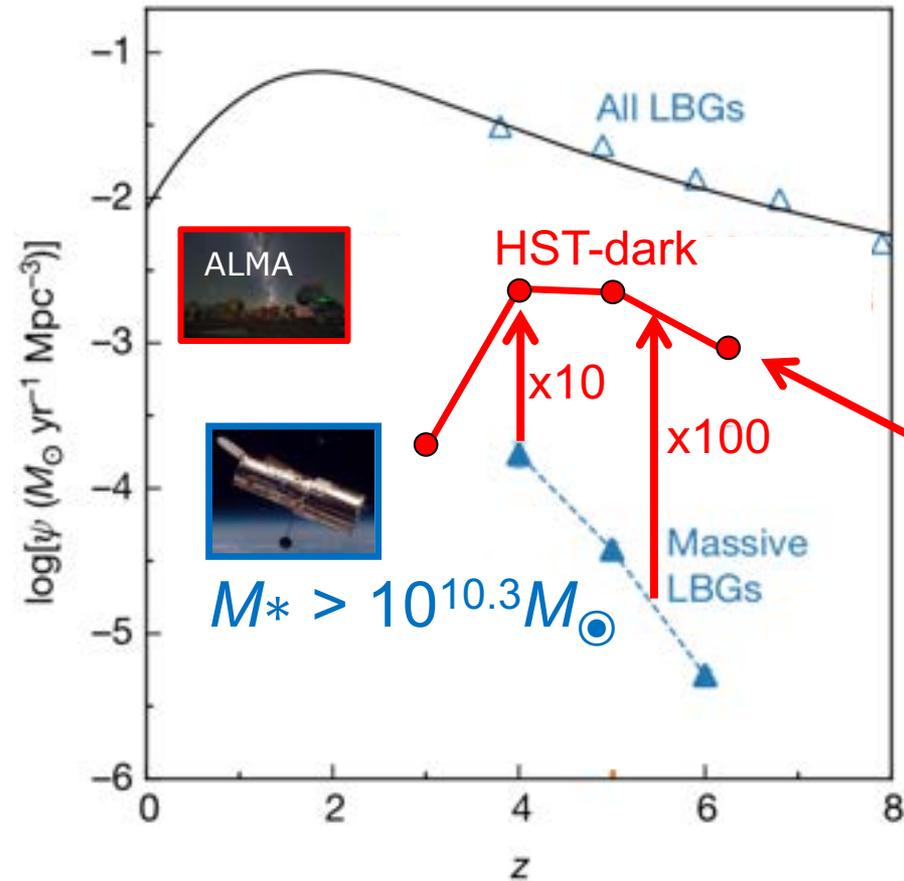


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H-dropouts H>27, [4.5μm]<24



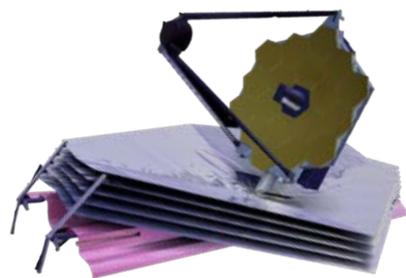
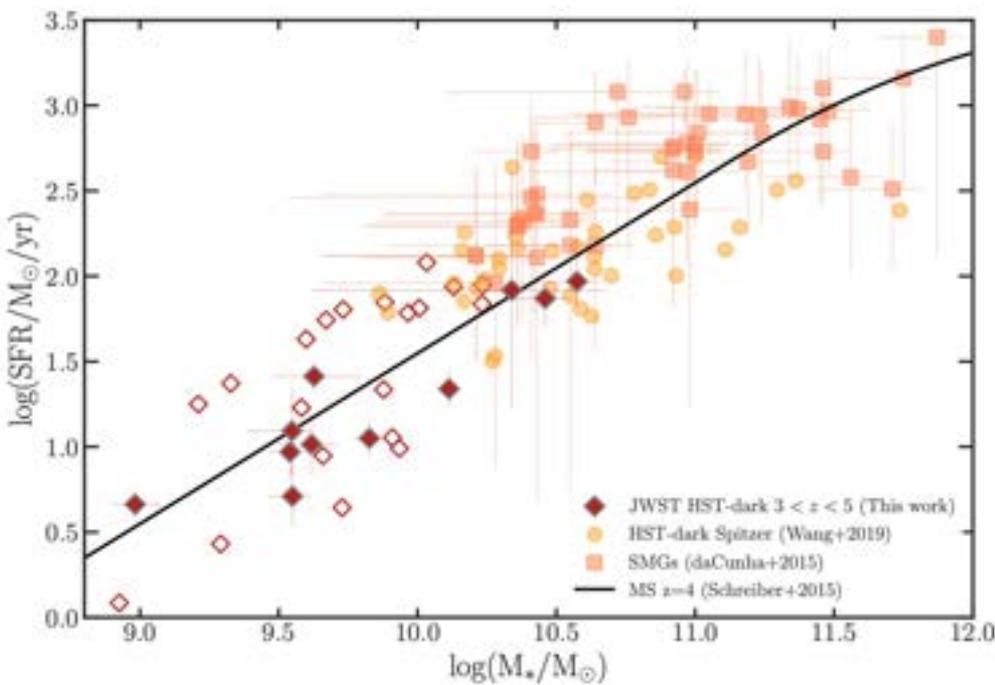
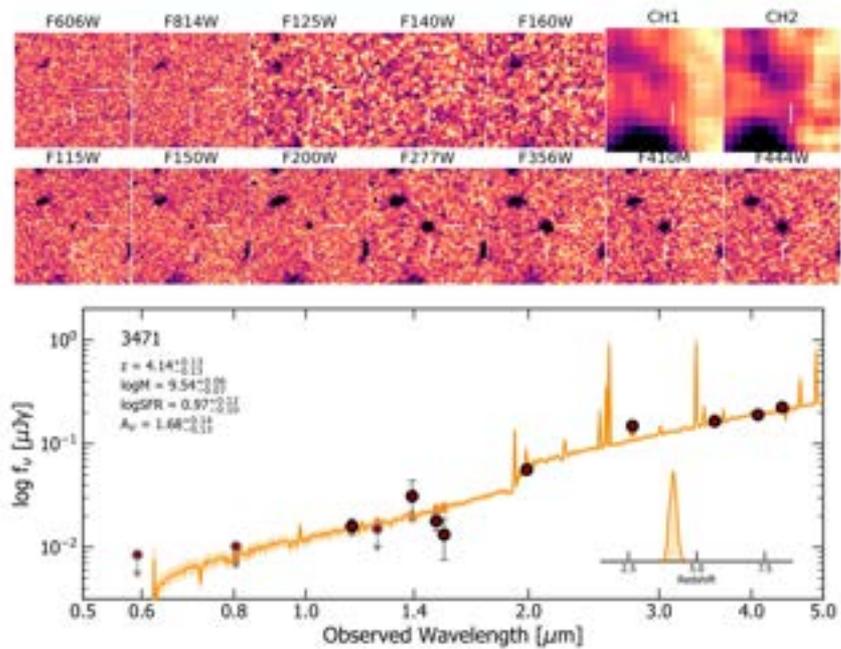
Que dit le James Webb sur les premières galaxies :

(1) les dinosaures galactiques

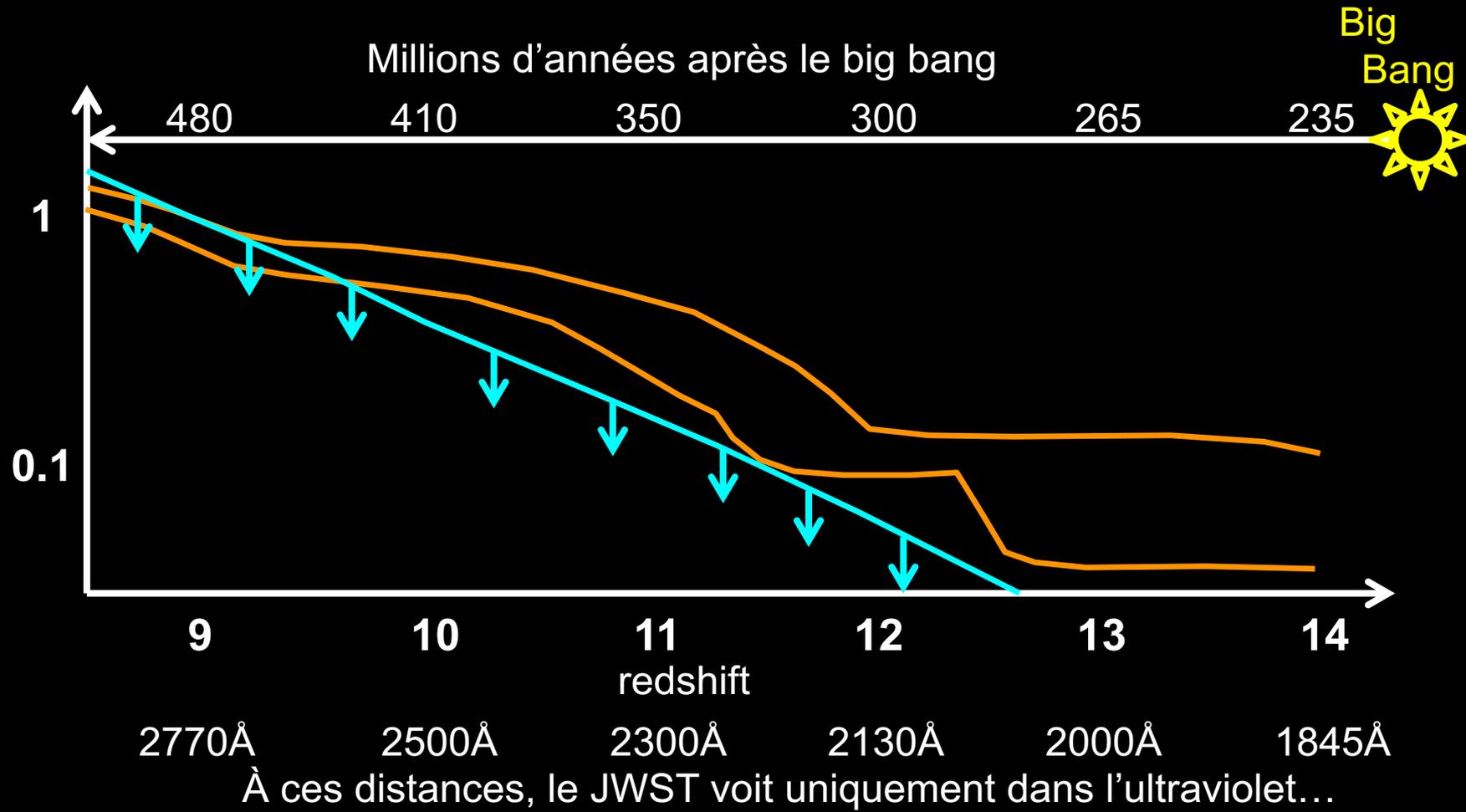
(2) leurs ancêtres...

Unveiling the Nature of Infrared Bright, Optically Dark Galaxies with Early JWST Data

L. Barrufet^{1*}, P. A. Oesch^{1,2}, A. Weibel¹, G. Brammer², R. Bezanson³, R. Bouwens⁴, Y. Fudamoto^{5,6},



Nombre de galaxies au-delà de z / arcmin²



Observé à 2.77 μ m

Finkelstein +2022

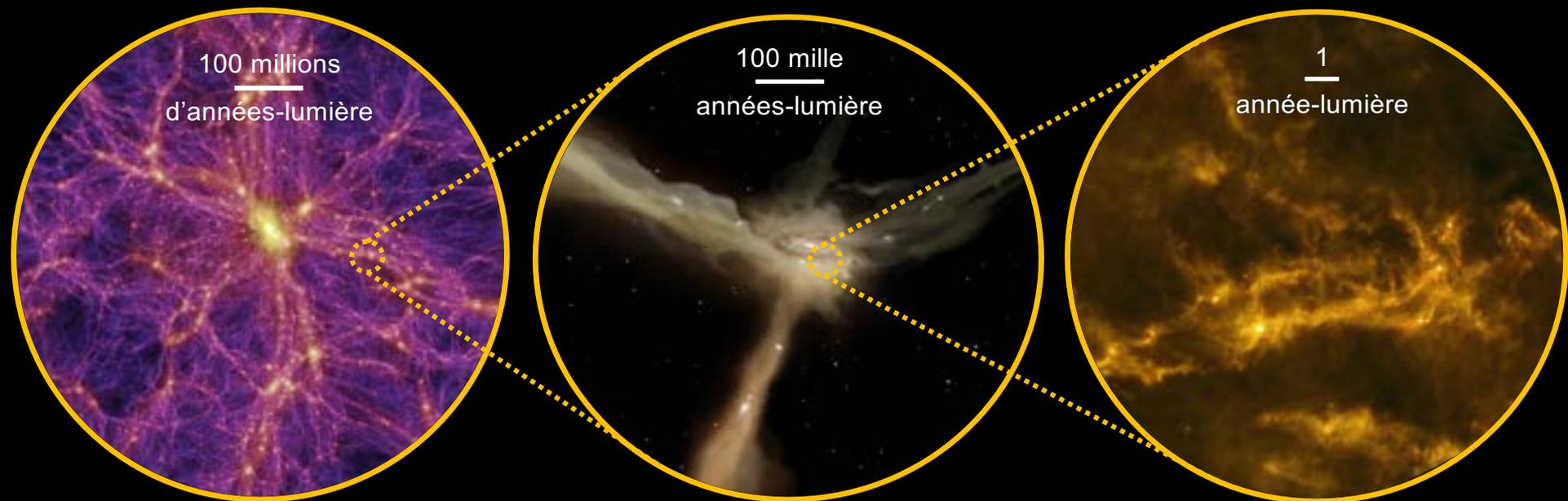
Formation des galaxies : nouveau paradigme

forces :

- *Nourrit la formation d'étoiles*
- *Participe à la formation des grands disques galactiques*
- *Engendre la turbulence qui régule la formation d'étoiles*

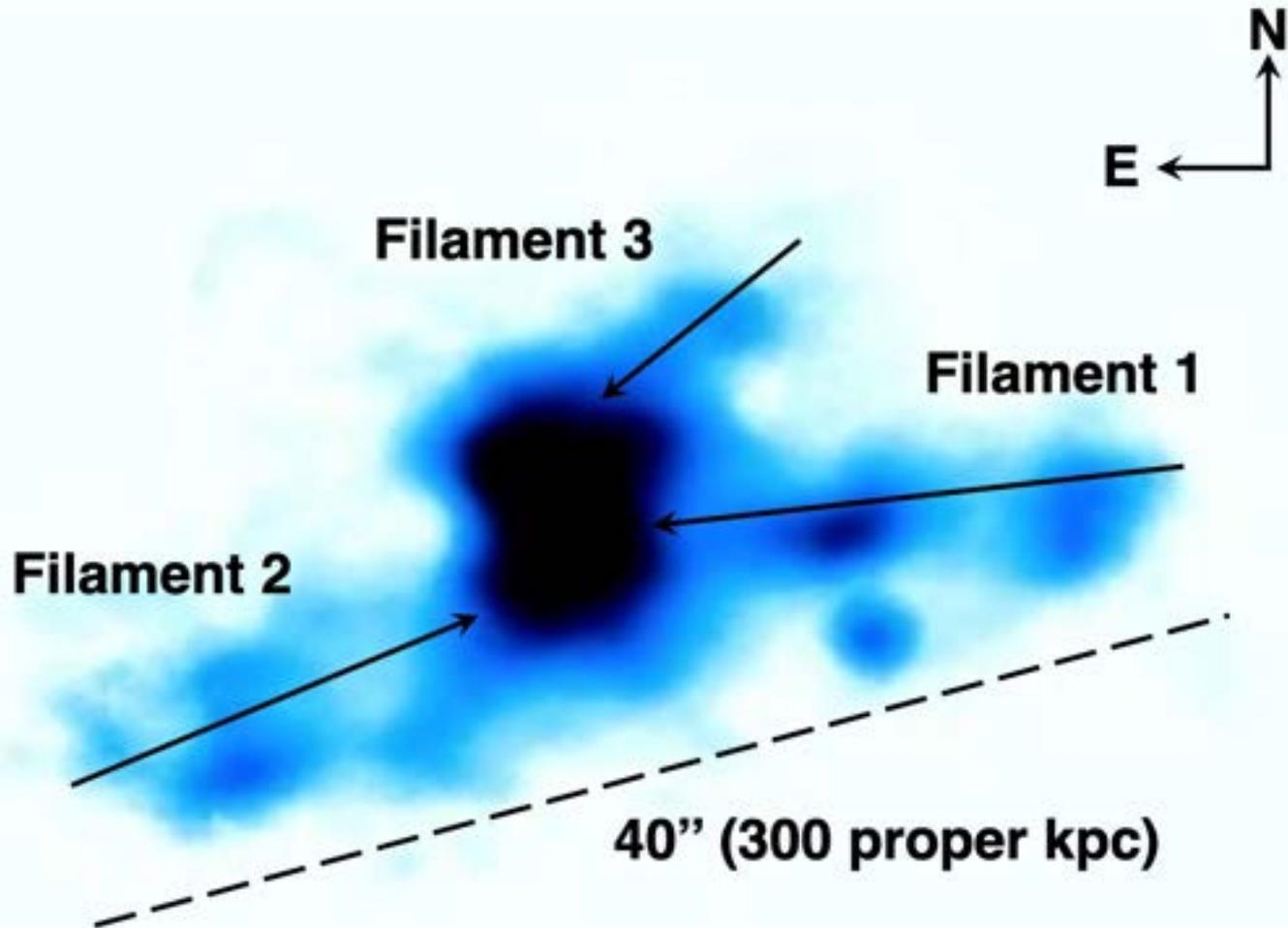
faiblesses :

- *On n'a pas de preuve irréfutable de l'existence de ces courants froids...*
- *On ne comprend pas pourquoi les galaxies primordiales sont si compactes -*



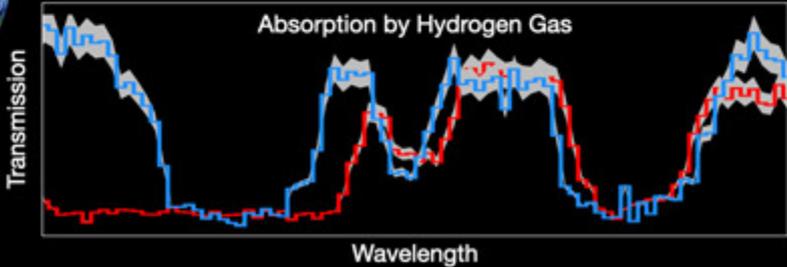
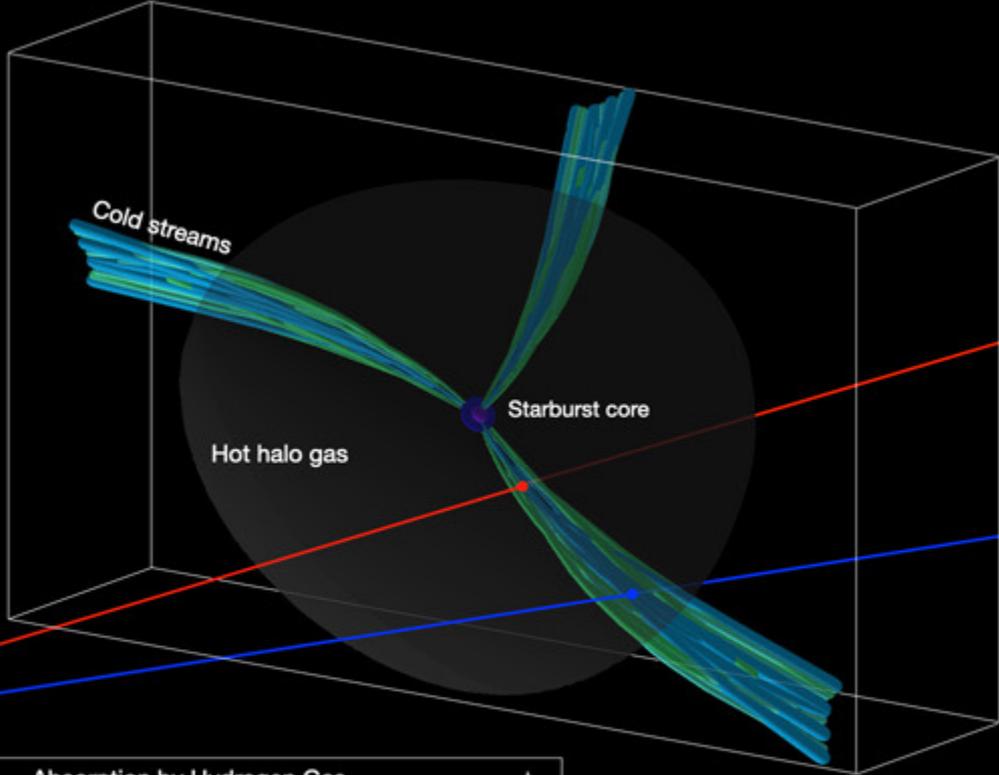
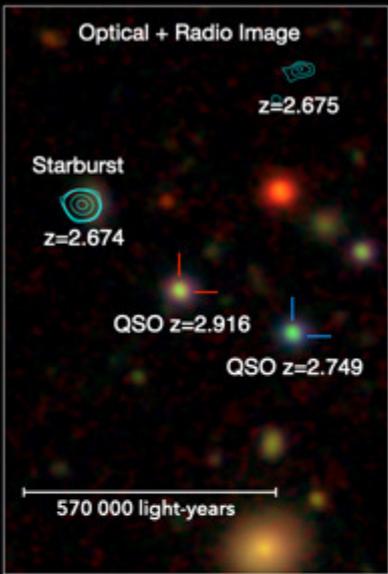
Three Lyman- α emitting filaments converging to a massive galaxy group at $z=2.91$: discussing the case for cold gas infall 2021

E. Daddi¹, F. Valentino^{2,3}, R. M. Rich⁴, J. D. Neill⁵, M. Gronke^{6*}, D. O'Sullivan⁵, D. Elbaz¹, F. Bournaud¹, A. Finoguenov⁷, A. Marchal⁸, I. Delvecchio^{1,9}, S. Jin^{10,11}, D. Liu¹², V. Strazzullo^{13,14,15}, A. Calabro¹⁶, R. Coogan¹⁷, C. D'Eugenio¹, R. Gobat¹⁸, B. S. Kalita¹, P. Laursen^{19,2}, D.C. Martin⁵, A. Puglisi²⁰, E. Schinnerer¹², and T. Wang²¹



Ly α image from KCWI





Detection of a Cold Gas Accretion Stream in Absorption

A Long Stream of Metal-poor Cool Gas around a Massive Starburst Galaxy at $z = 2.67$

Hai Fu^{1,2}, R. Xue^{1,3}, J. X. Prochaska⁴, A. Stockton², S. Ponnada^{1,5}, M. W. Lau⁶, A. Cooray⁷, and D. Narayanan⁸

24 février 2001