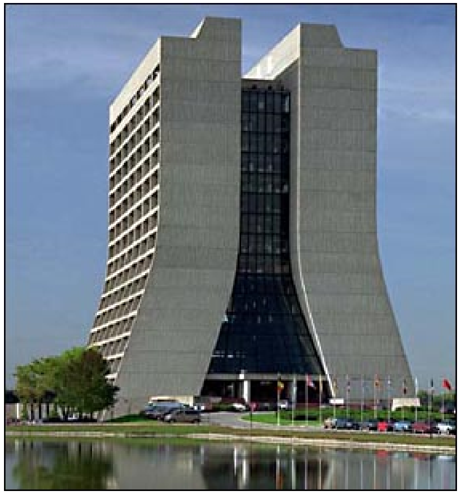
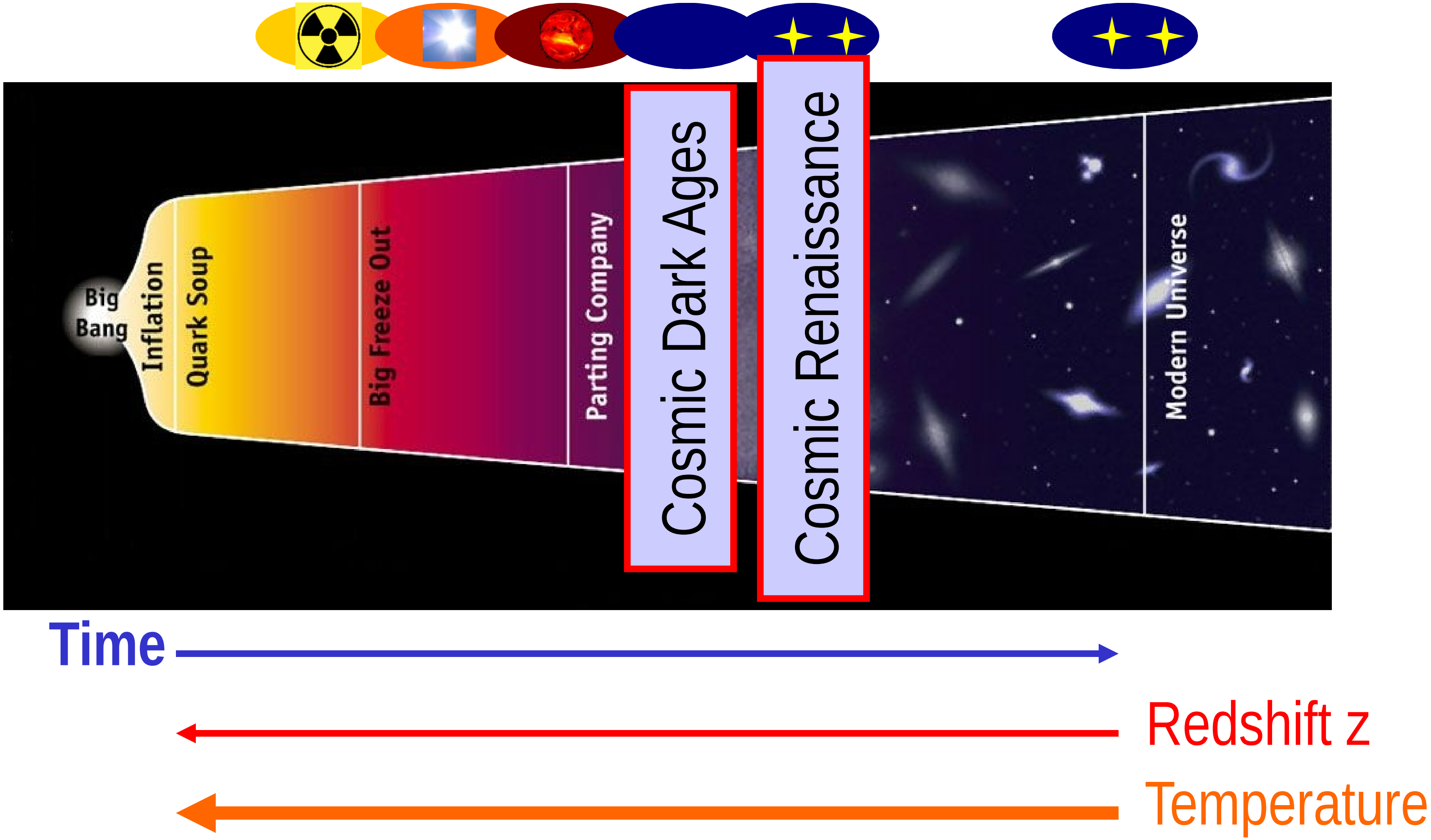
The End of the Dark Ages

Nick Gnedin



Fermilab
THE UNIVERSITY OF CHICAGO

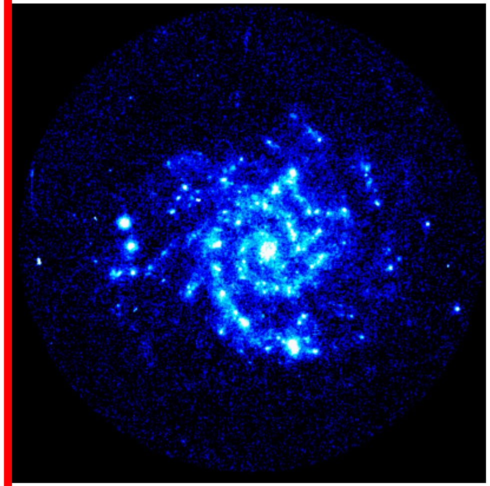
The Brief History of Time



What You See Is Not What You Get

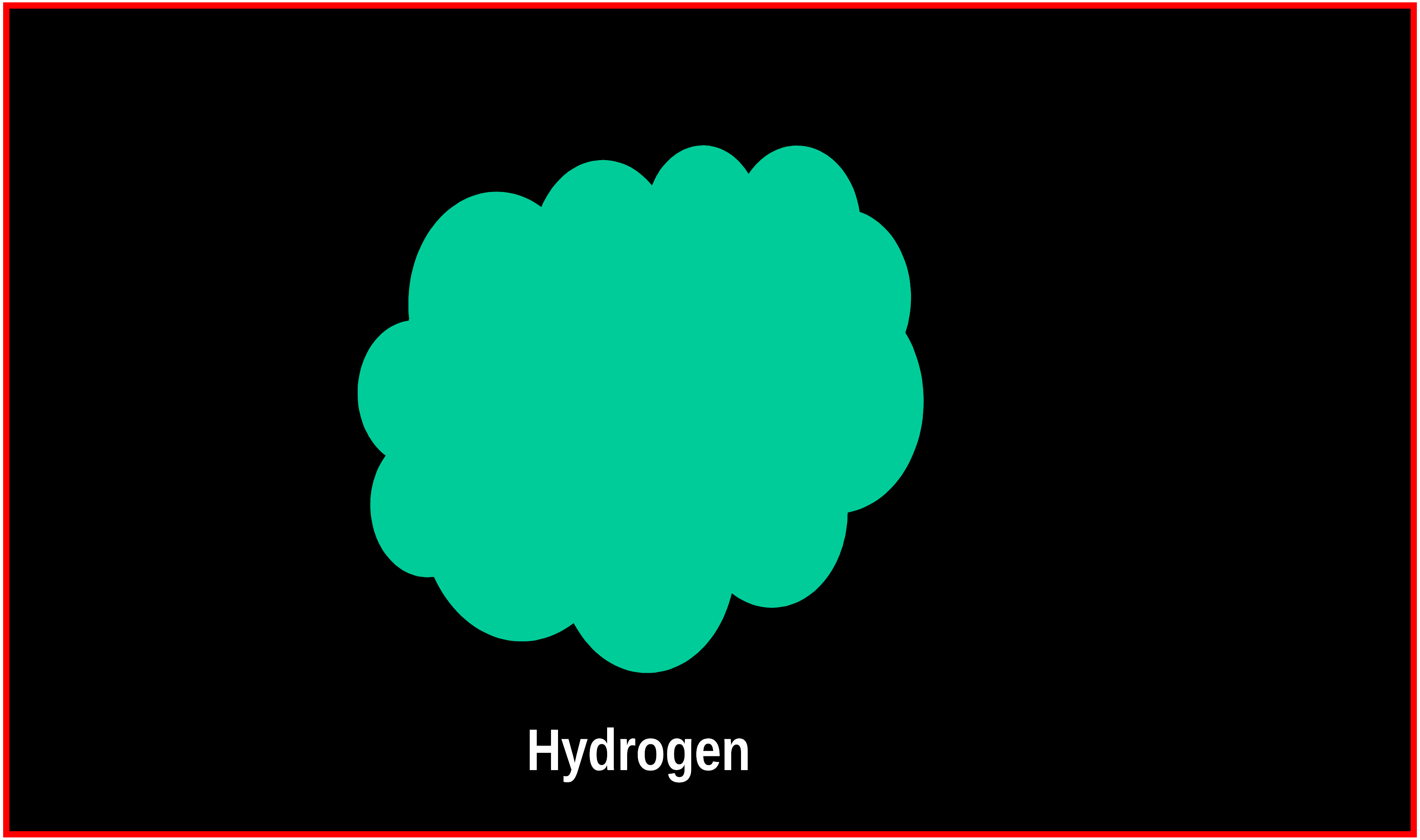
Infra-Red (IR) | Visible | Ultra-Violet (UV)

Now

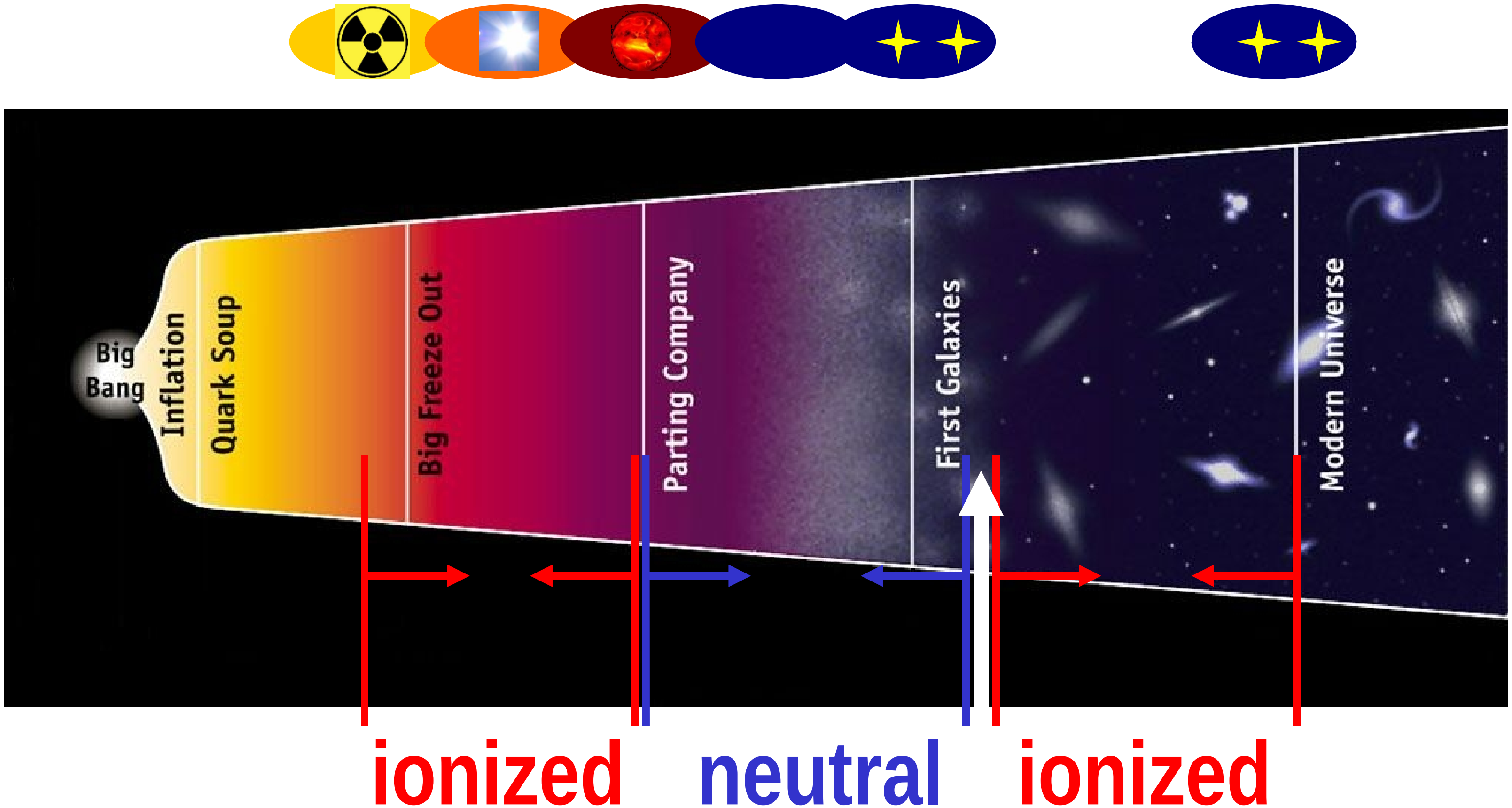


High z

Transparent & Opaque

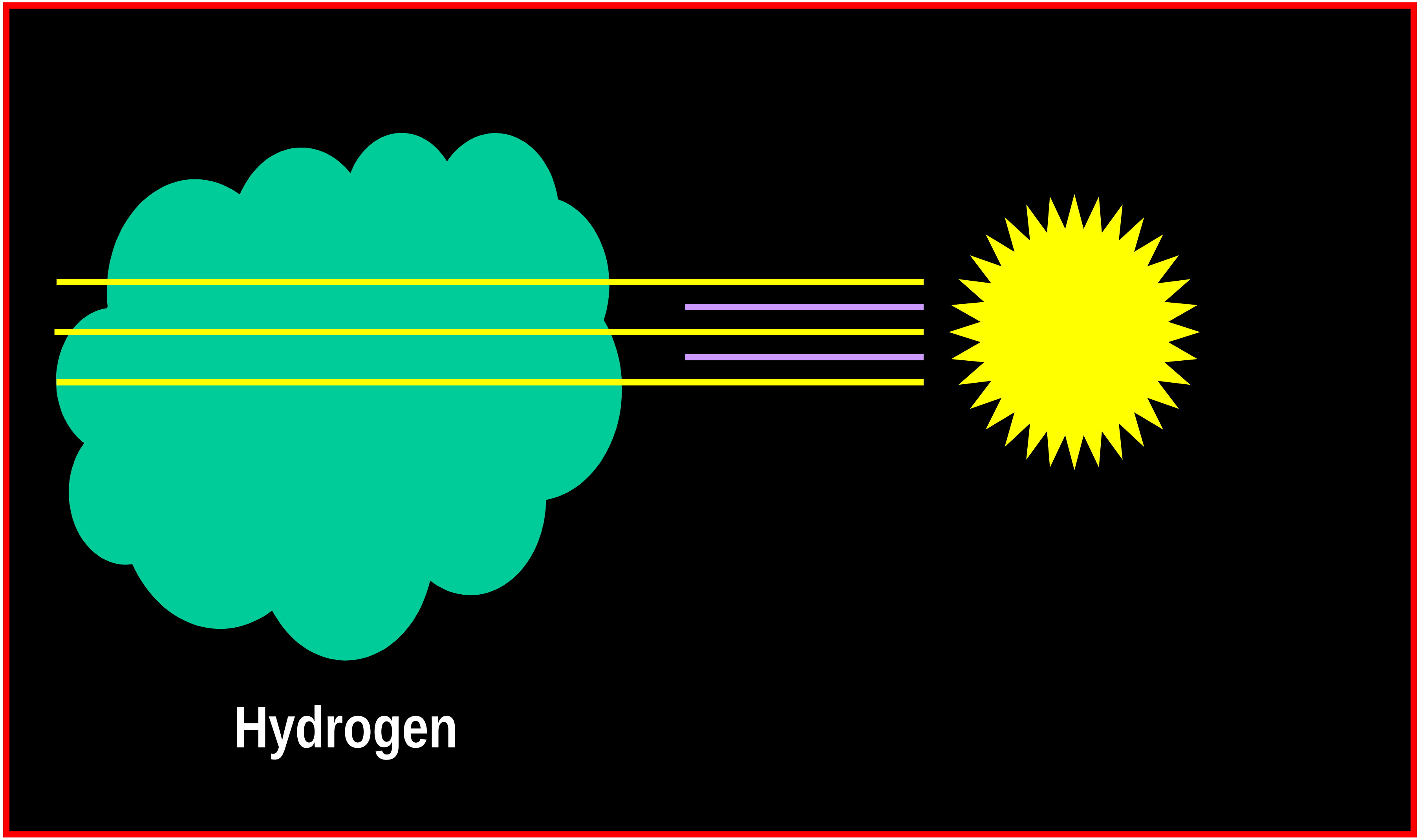


The Brief History of Hydrogen



RE-IONIZATION

The End of the "Dark Ages"

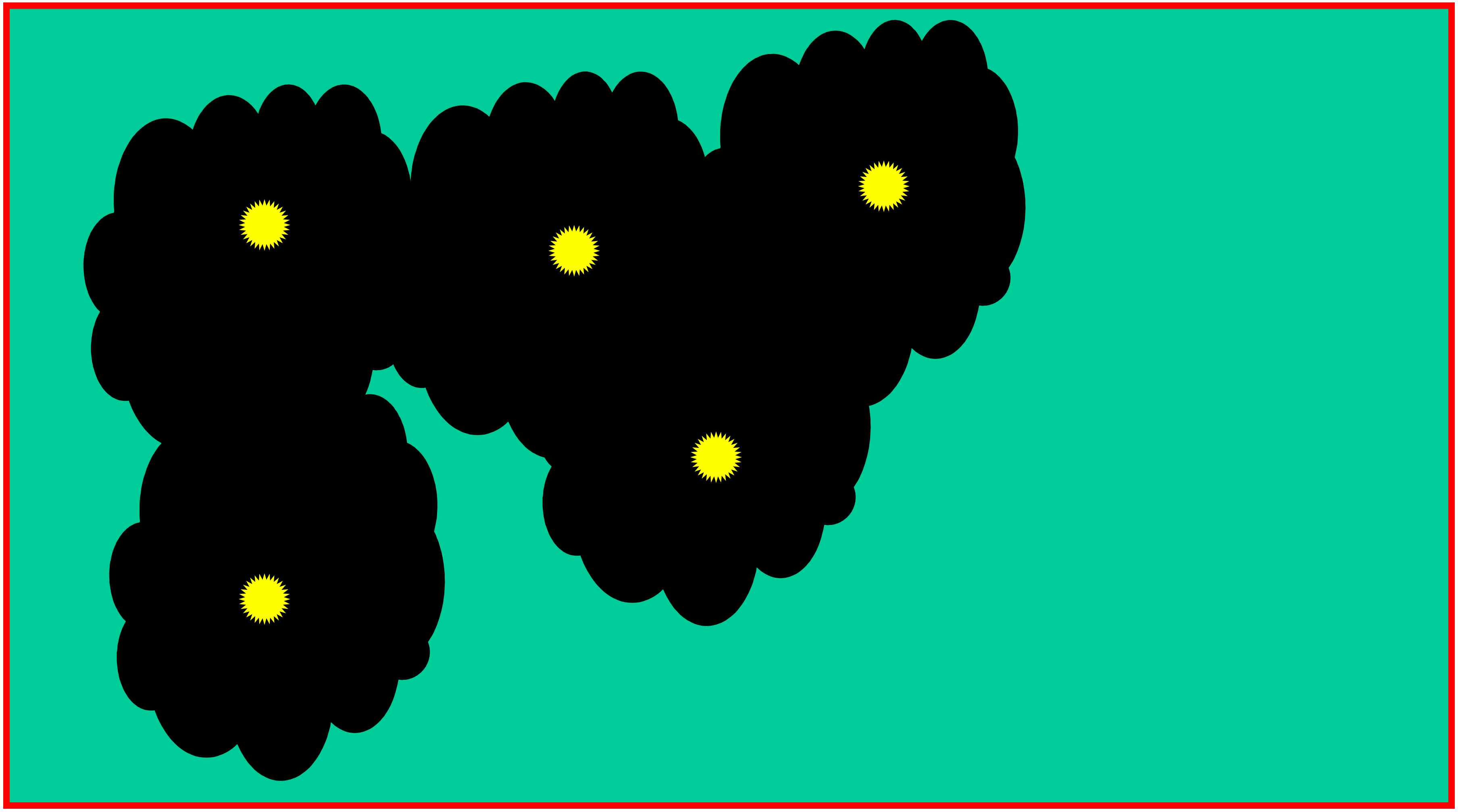


The End of the “Dark Ages”

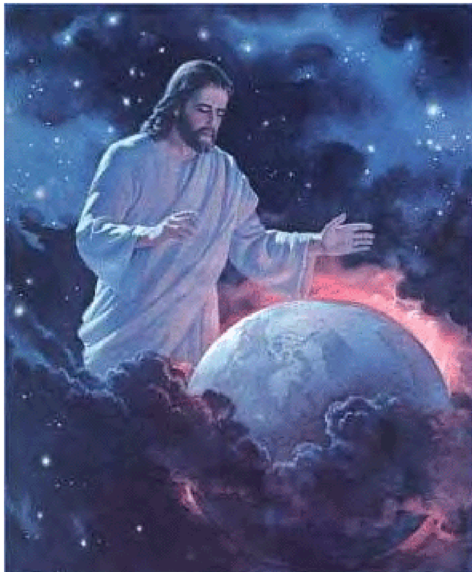
IS

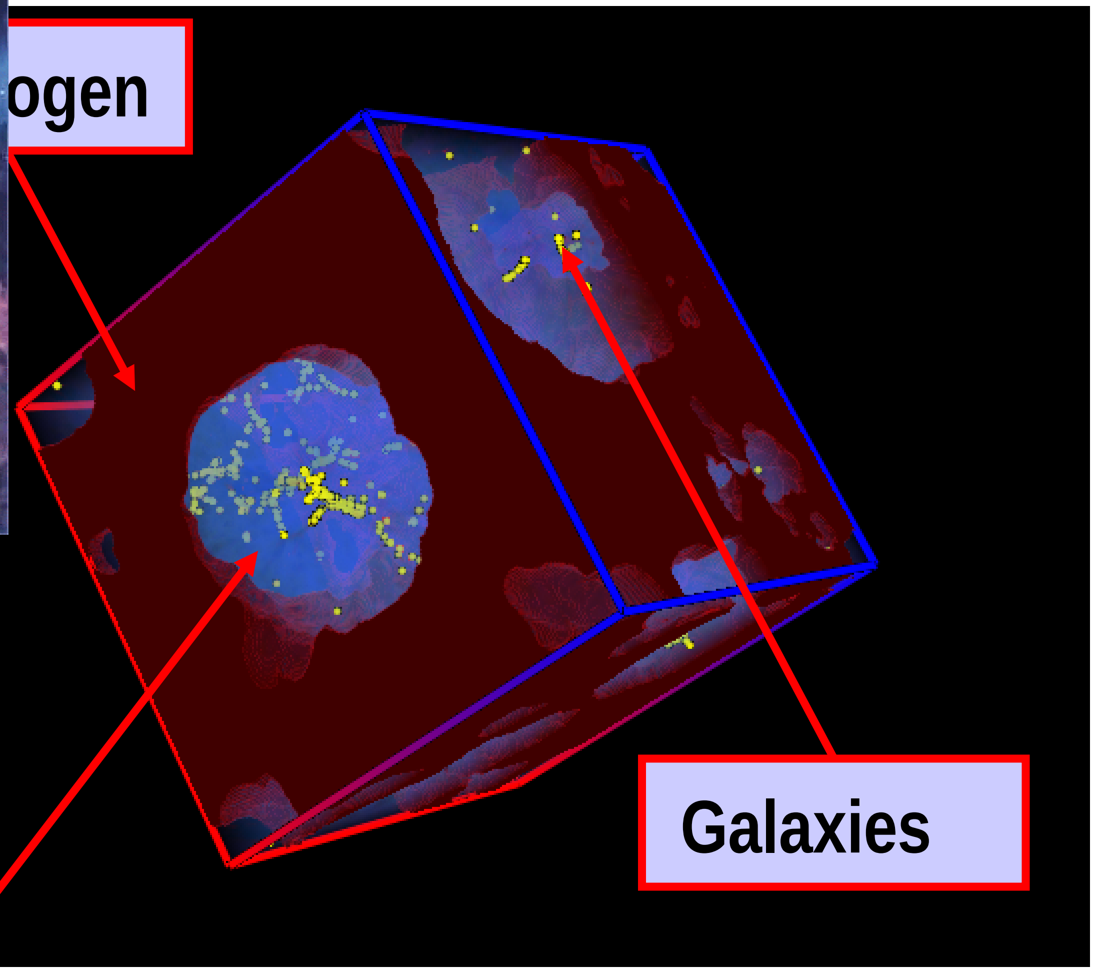
Re-ionization

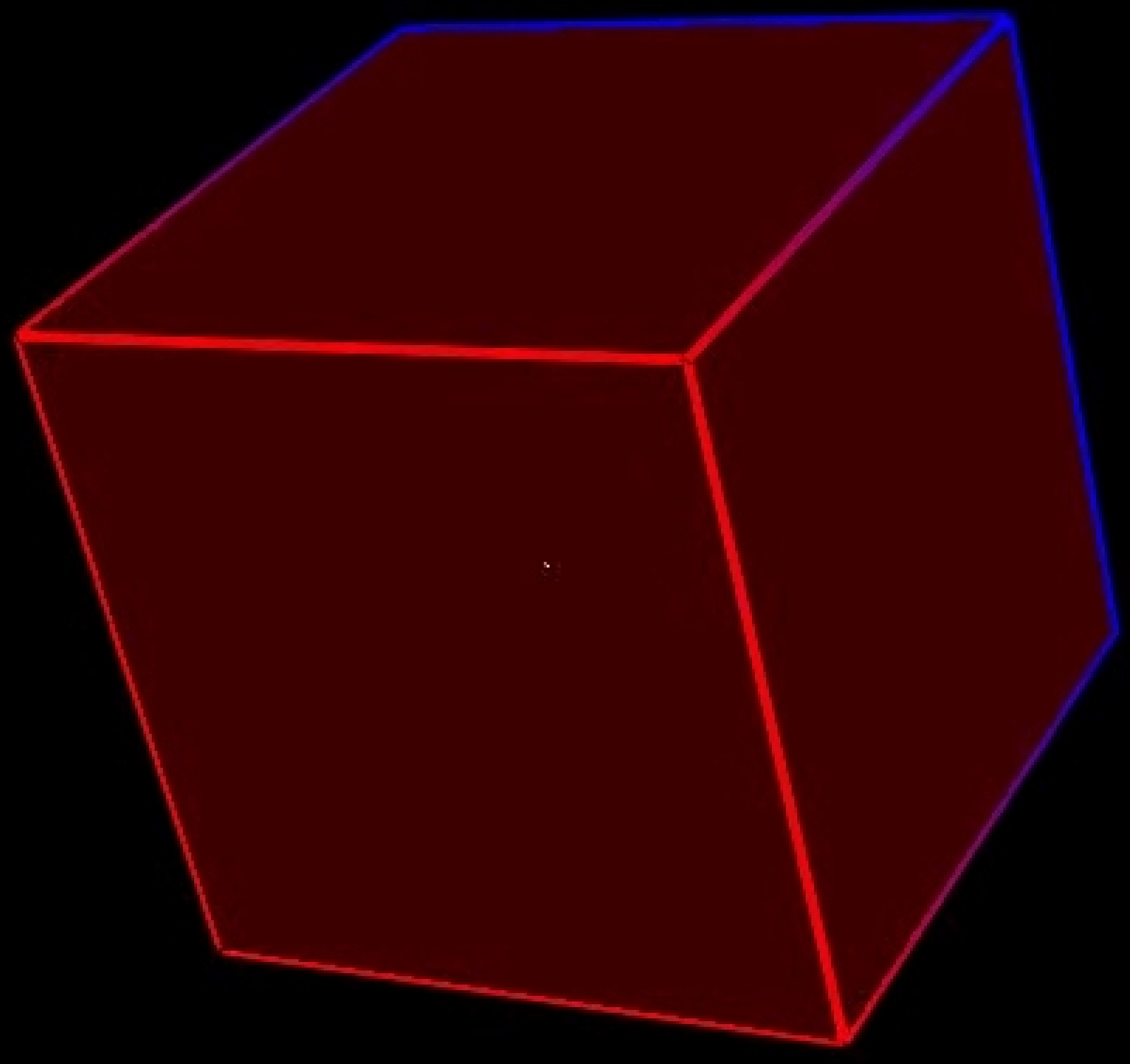
Bubbly Story



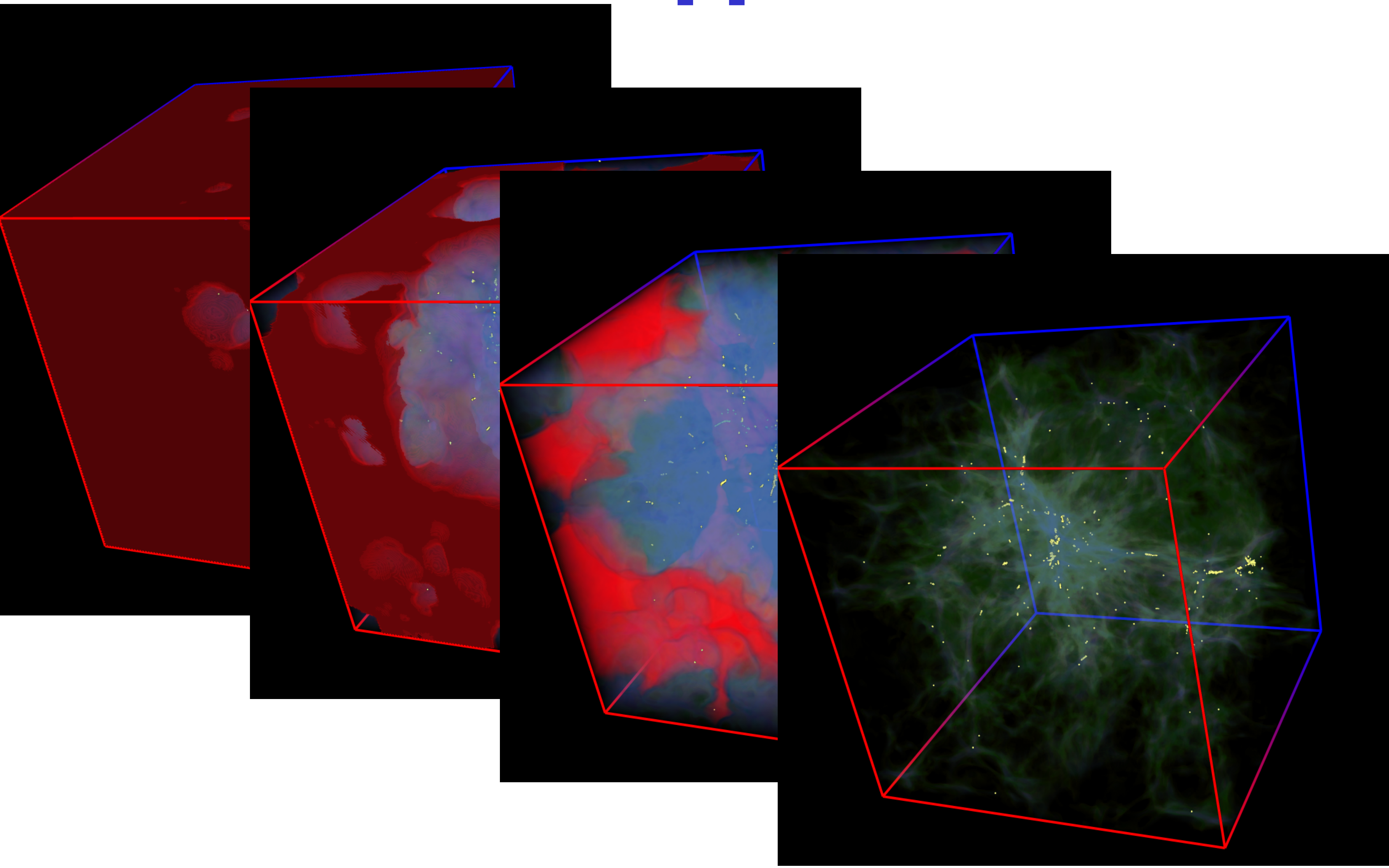
Let Us Be Gods...







How It All Happens...

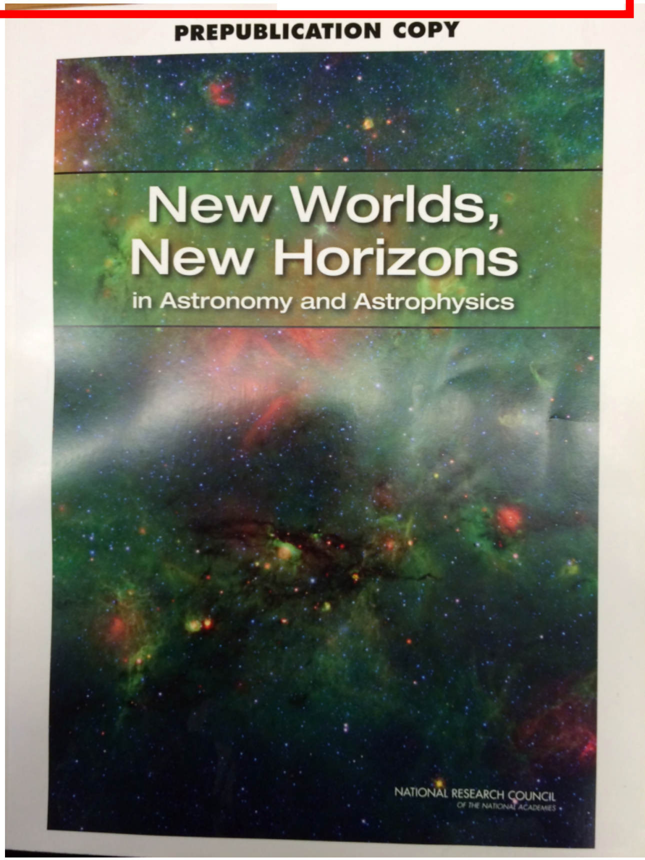


Not Just Fun: Priority Science

- Astro2010:

The priority science objectives chosen by the survey committee for the decade 2012-2021 are searching for the first stars, galaxies, and black holes;

- Also identified as a likely discovery area.

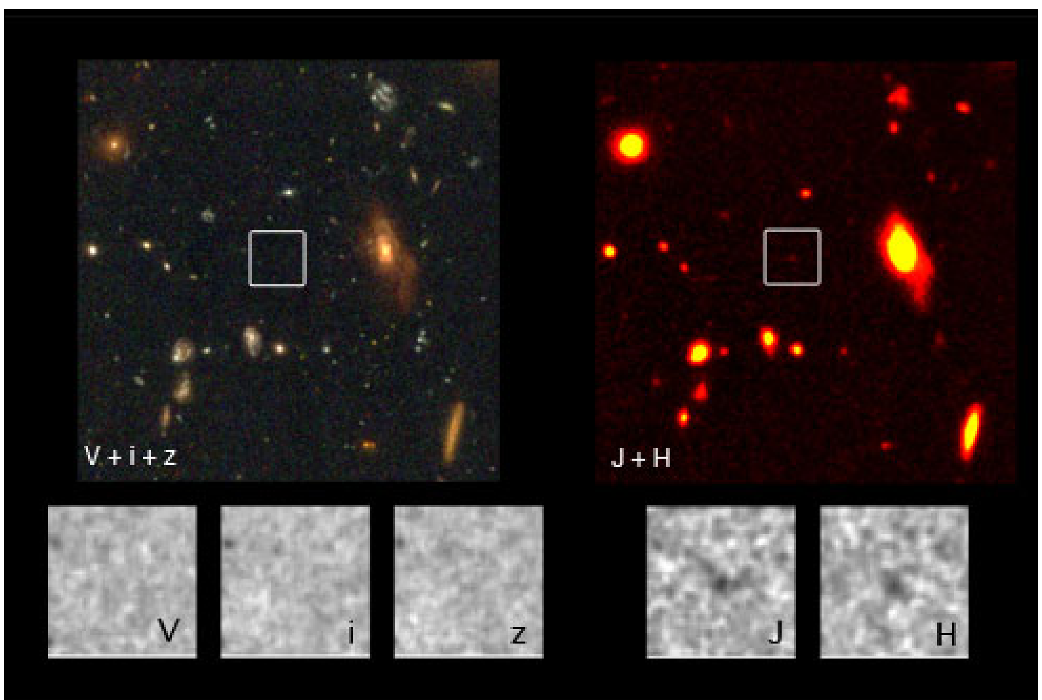


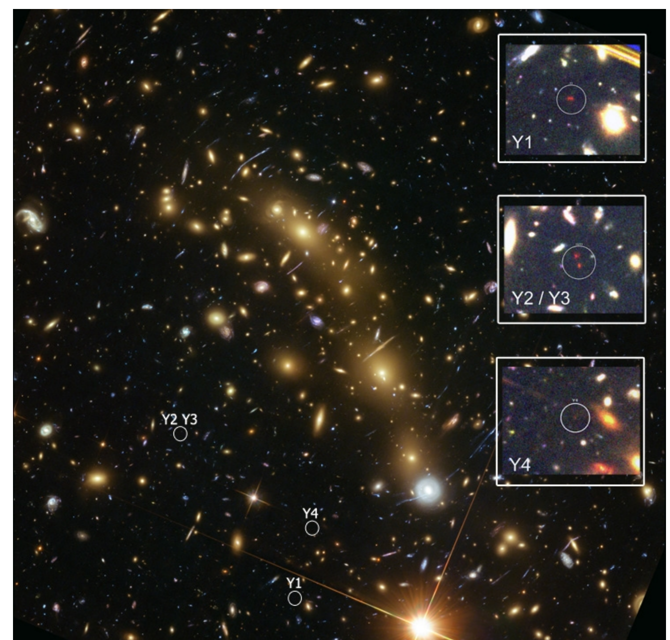
The Flood Is Coming

- Atacama Large Millimeter Array (ALMA) 2017+
- James Webb Space Telescope (JWST) 2021?
- Hydrogen Epoch of Reionization Array (HERA) 2021-22?
- Next generation optical telescopes 2021-25? (GMT, TMT, E-ELT)

What We Know Now: Galaxy Luminosity Functions

- High redshift galaxies are not particularly glaring.
- The faintest ones are detected with the help of gravitational lensing in HST *Frontier Fields.*

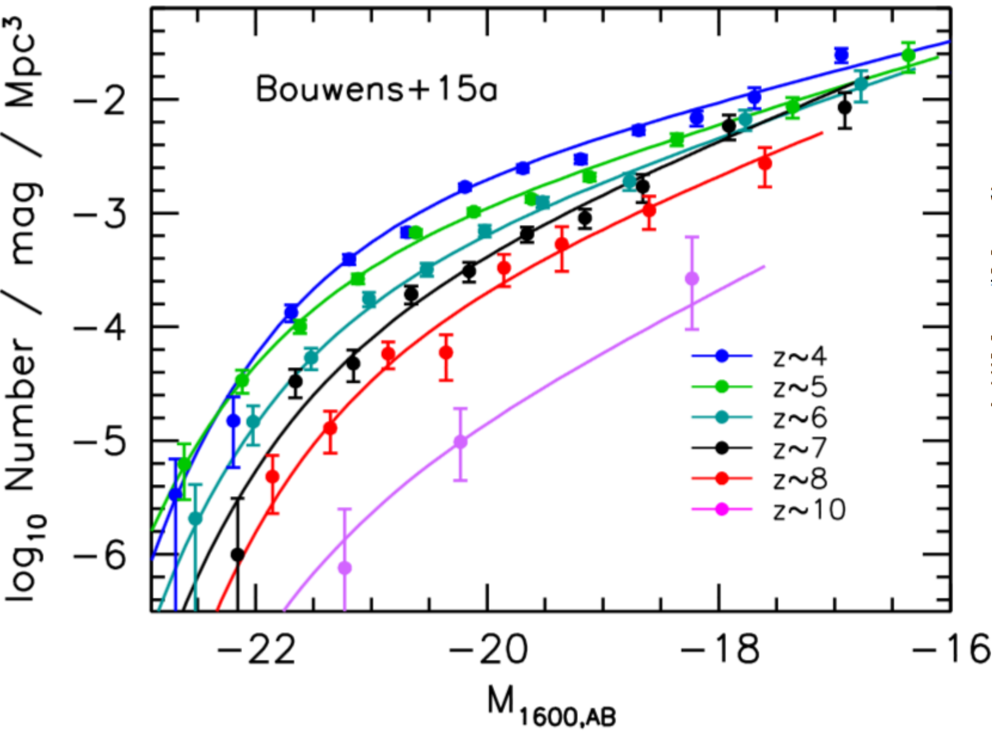




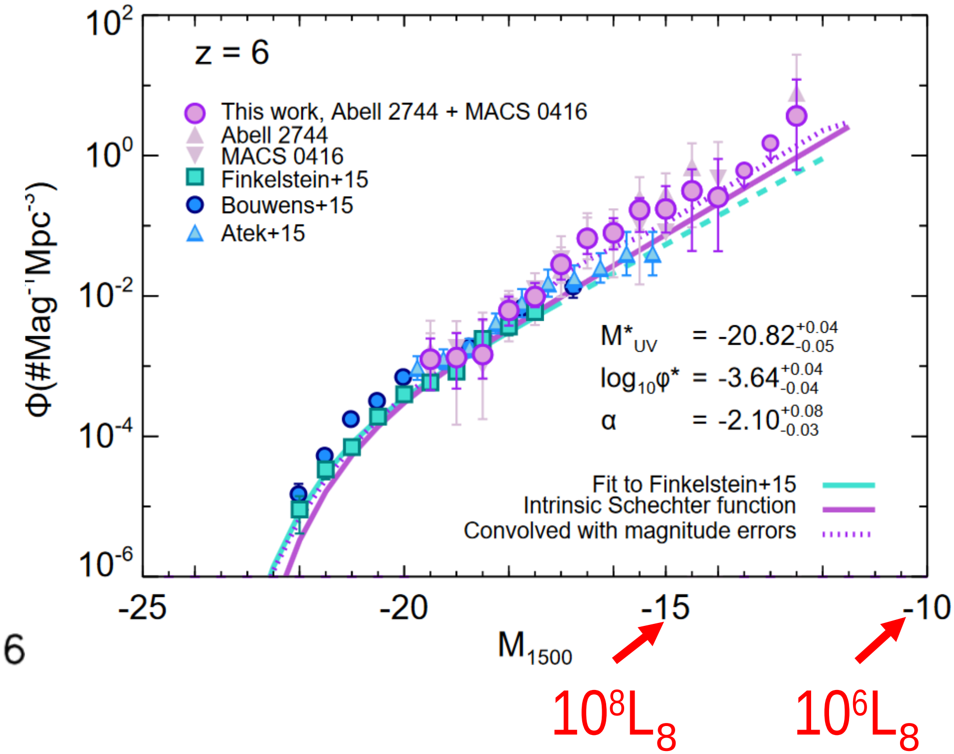
Redshift ~ 8 candidates in Frontier Field cluster MACS J0416.1-2403 (Laporte et al. 2015)

What We Know Now: Galaxy Luminosity Functions

- Data (may) exist all the way to z=10 and M_{UV}=-13.



Bouwens+2015



Livermore+ 2016

About "Magnitudes"

- Astronomers use magnitudes to maintain self-esteem. Without them astrophysics is too easy.

Particle Physics

1 $$L = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
2 $$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$
3 $$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
4 $$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
5 $$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

About "Magnitudes"

- Astronomers use magnitudes to maintain self-esteem. Without them astrophysics is too easy.

General Relativity

$$\frac{1}{2}g^{rs}\left(-\frac{\partial^2 g_{ij}}{\partial x^r \partial x^s}+\frac{\partial^2 g_{is}}{\partial x^r \partial x^j}+\frac{\partial^2 g_{rj}}{\partial x^i \partial x^s}-\frac{\partial^2 g_{rs}}{\partial x^i \partial x^j}\right)+\frac{1}{4}g^{qp}\left(-\frac{\partial g_{is}}{\partial x^p}+\frac{\partial g_{pi}}{\partial x^s}+\right.$$

$$\left.\frac{\partial g_{ps}}{\partial x^i}\right)\times\left(\frac{\partial g_{qj}}{\partial x^r}+\frac{\partial g_{qr}}{\partial x^j}-\frac{\partial g_{rj}}{\partial x^q}\right)-\frac{1}{4}g^{qp}\left(-\frac{\partial g_{ij}}{\partial x^p}+\frac{\partial g_{pi}}{\partial x^j}+\frac{\partial g_{pj}}{\partial x^i}\right)\left(\frac{\partial g_{qr}}{\partial x^s}+\right.$$

$$\left.\frac{\partial g_{qs}}{\partial x^r}-\frac{\partial g_{rs}}{\partial x^q}\right)-\frac{1}{4}g_{ij}g^{rs}g^{uv}\left(-\frac{\partial^2 g_{rs}}{\partial x^u \partial x^v}+\frac{\partial^2 g_{rv}}{\partial x^u \partial x^s}+\frac{\partial^2 g_{us}}{\partial x^r \partial x^v}-\frac{\partial^2 g_{uv}}{\partial x^r \partial x^s}\right)+$$

$$\frac{1}{8}g_{ij}g^{rs}g^{uv}g^{qp}\left(\frac{\partial g_{qr}}{\partial x^v}+\frac{\partial g_{qv}}{\partial x^r}-\frac{\partial g_{rv}}{\partial x^q}\right)\left(\frac{\partial g_{ps}}{\partial x^u}+\frac{\partial g_{pu}}{\partial x^s}-\frac{\partial g_{us}}{\partial x^p}\right)-$$

$$\frac{1}{8}g_{ij}g^{rs}g^{uv}g^{qp}\left(\frac{\partial g_{qr}}{\partial x^s}+\frac{\partial g_{qs}}{\partial x^r}-\frac{\partial g_{rs}}{\partial x^q}\right)\left(\frac{\partial g_{pu}}{\partial x^v}+\frac{\partial g_{pv}}{\partial x^u}-\frac{\partial g_{uv}}{\partial x^p}\right)=\frac{8\pi G}{c^4}T_{ij}.$$

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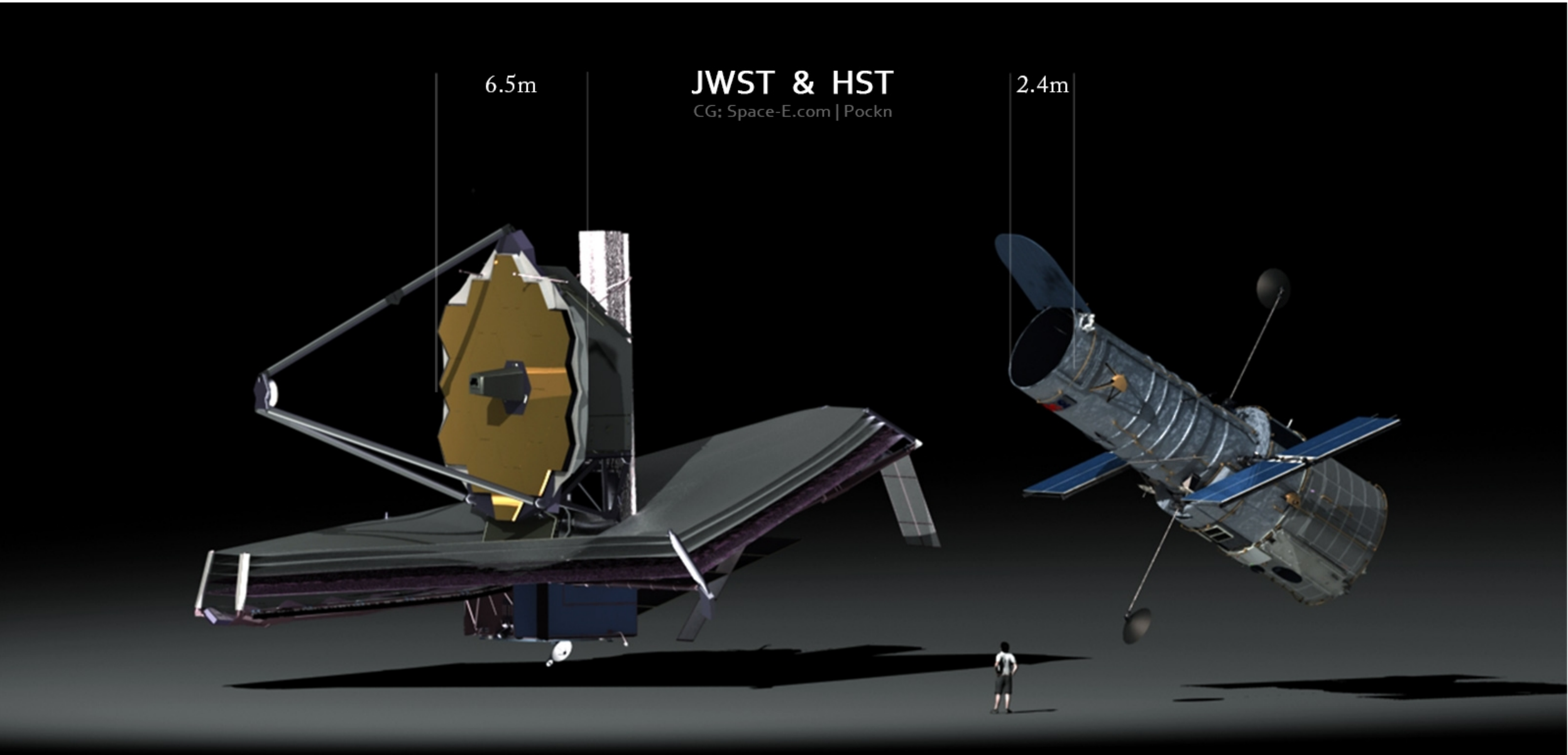
Astrophysics

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\frac{\partial f}{\partial \vec{x}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = C[f]$$

The Flood Is Coming: JWST

- James Webb Space Telescope (JWST) is the primary NASA mission for the next decade.



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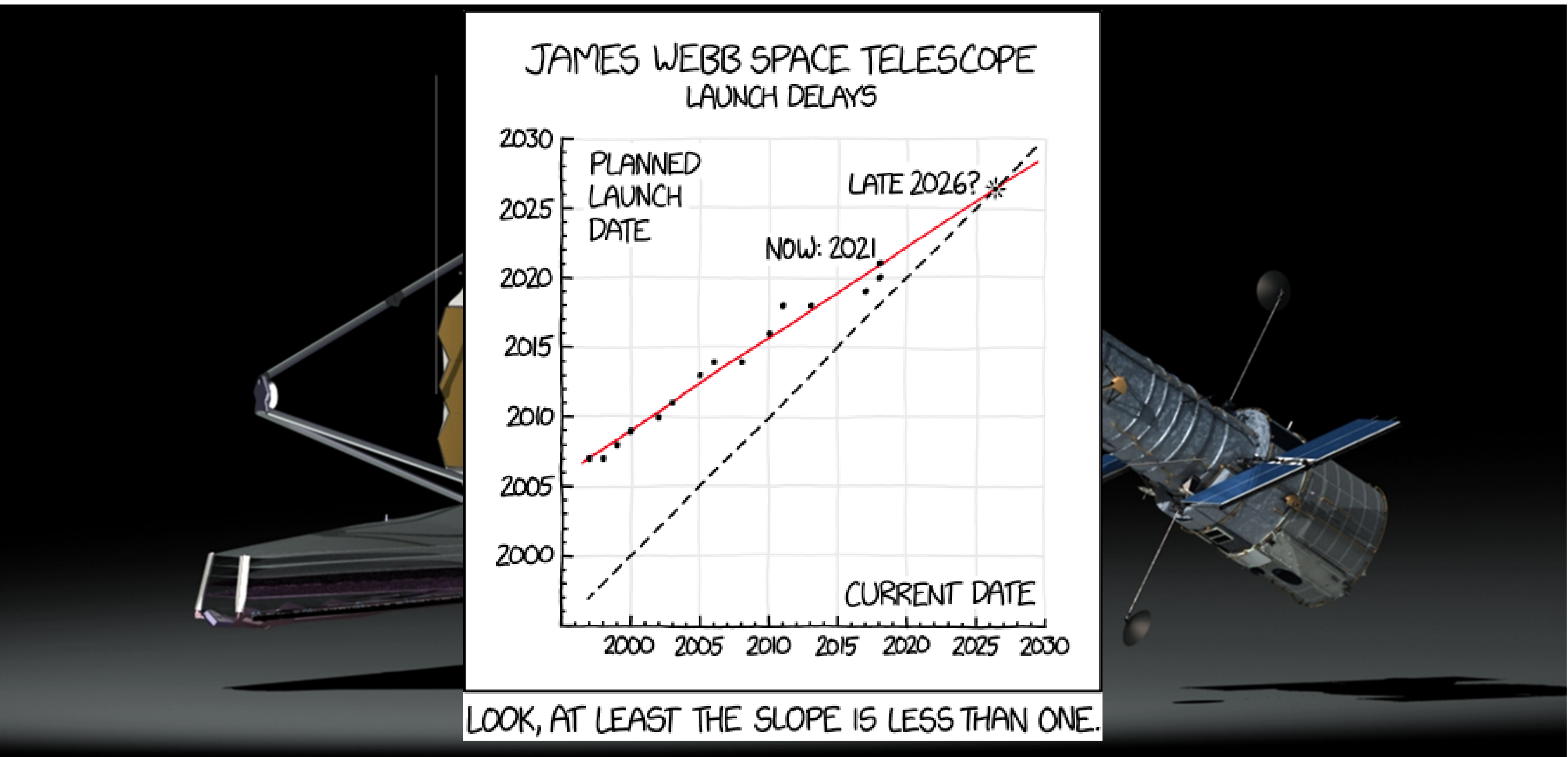
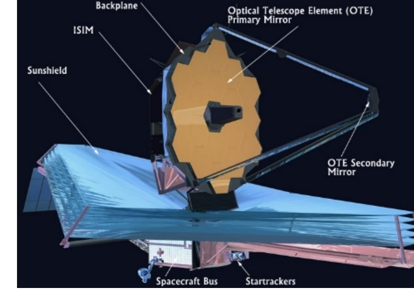
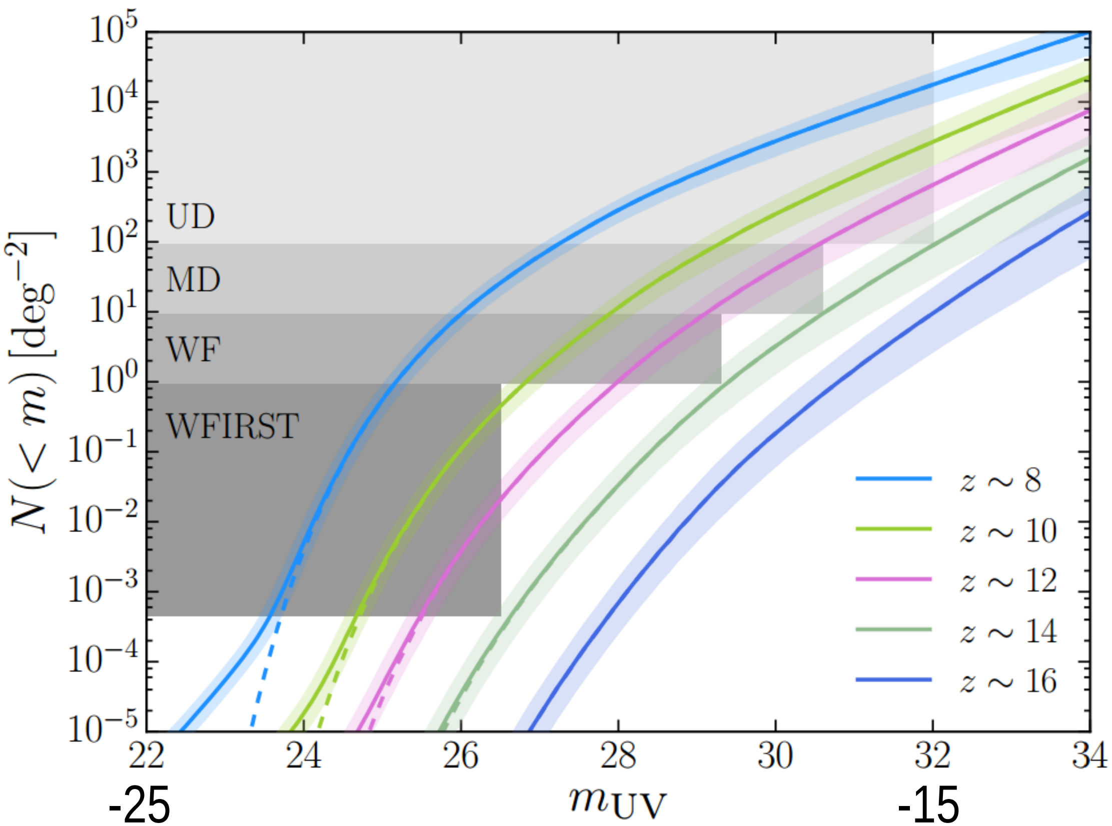


The Flood Is Coming: JWST



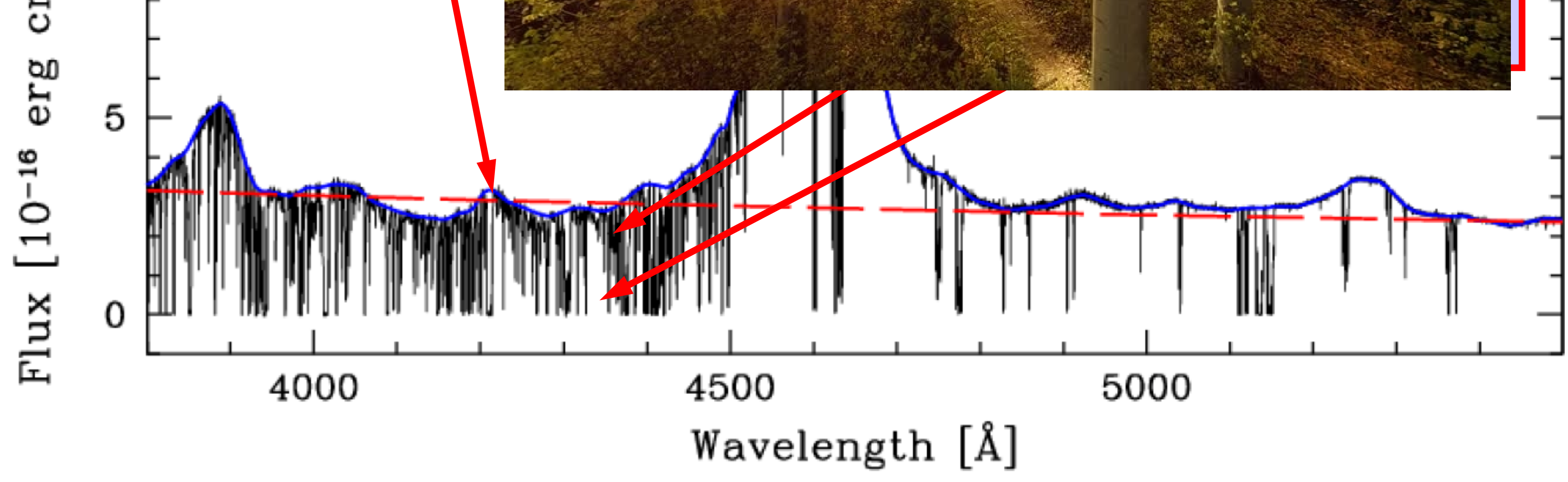
- Studying reionization sources is the primary science goal of JWST.



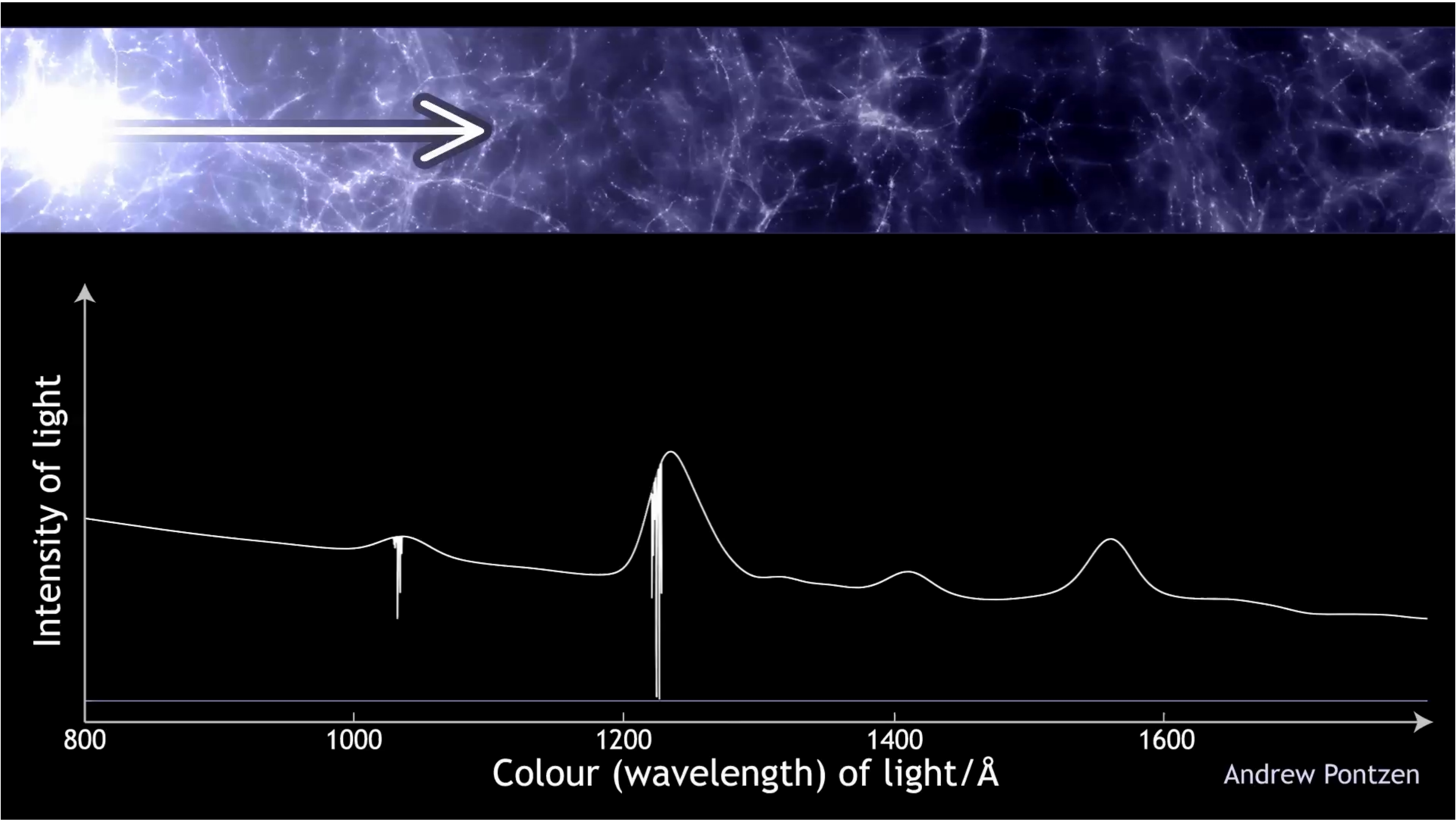
Mason+ 2015

- It will perform a range of surveys of varying depth, greatly improving precision of luminosity functions, as well as studying individual galaxies.

Intro: Ly-α Forest

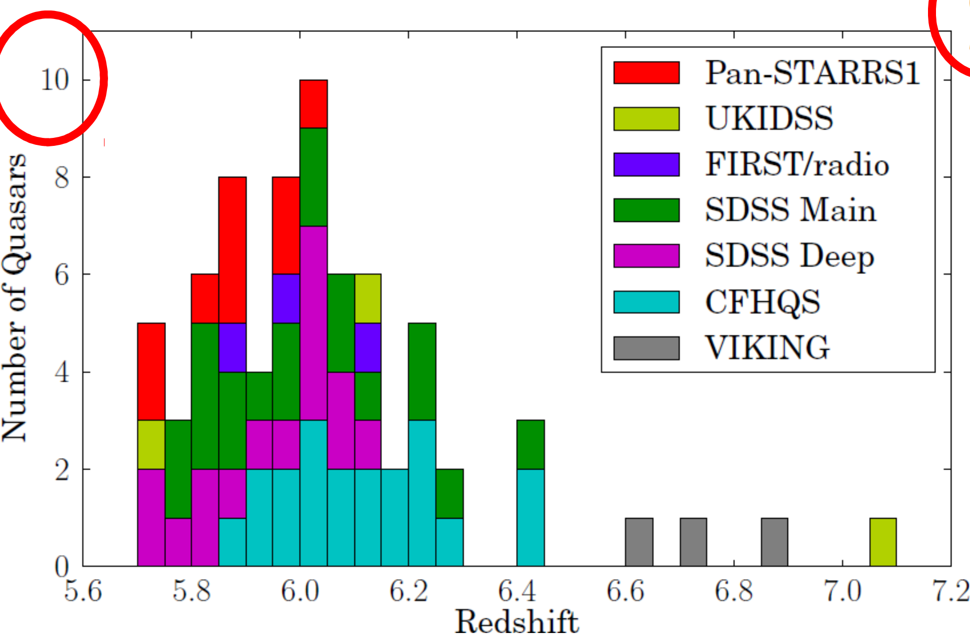


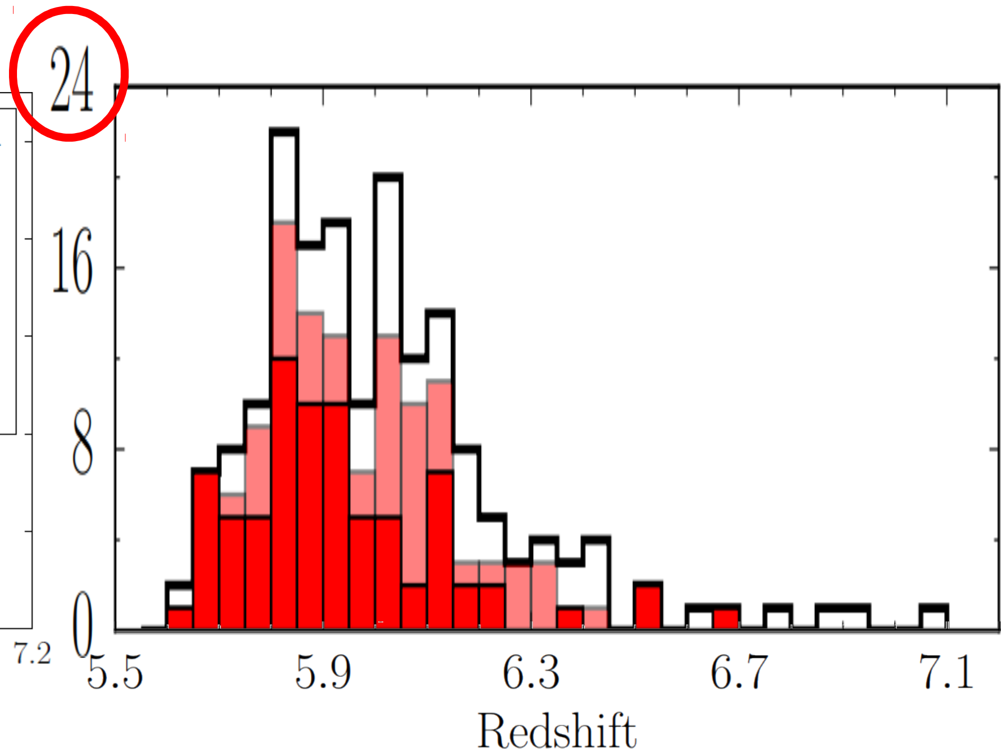
Intro: Ly-α Forest



What We Know Now: Post-reionization IGM

- High-z QSOs appear as mushrooms after a rain, and data become extremely constraining.





Banados+ 2014

Banados+ 2016

What We Know Now: Post-reionization IGM

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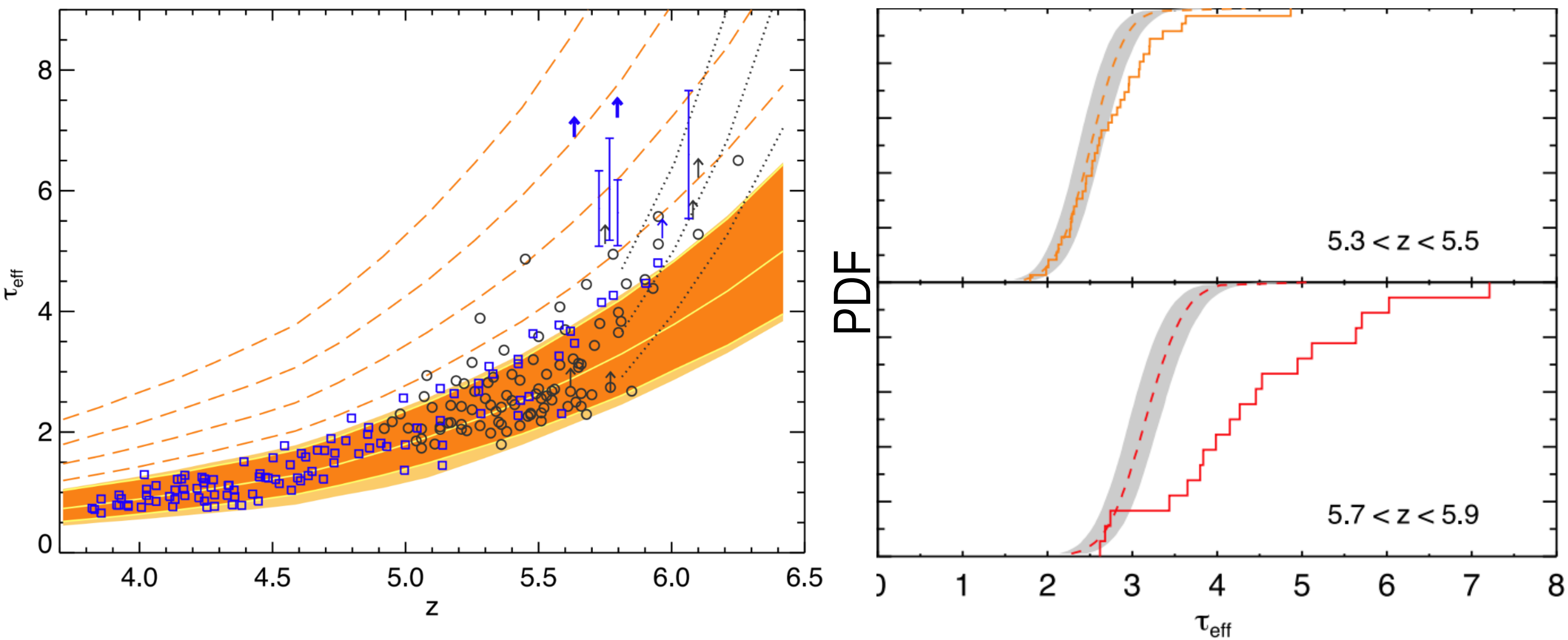
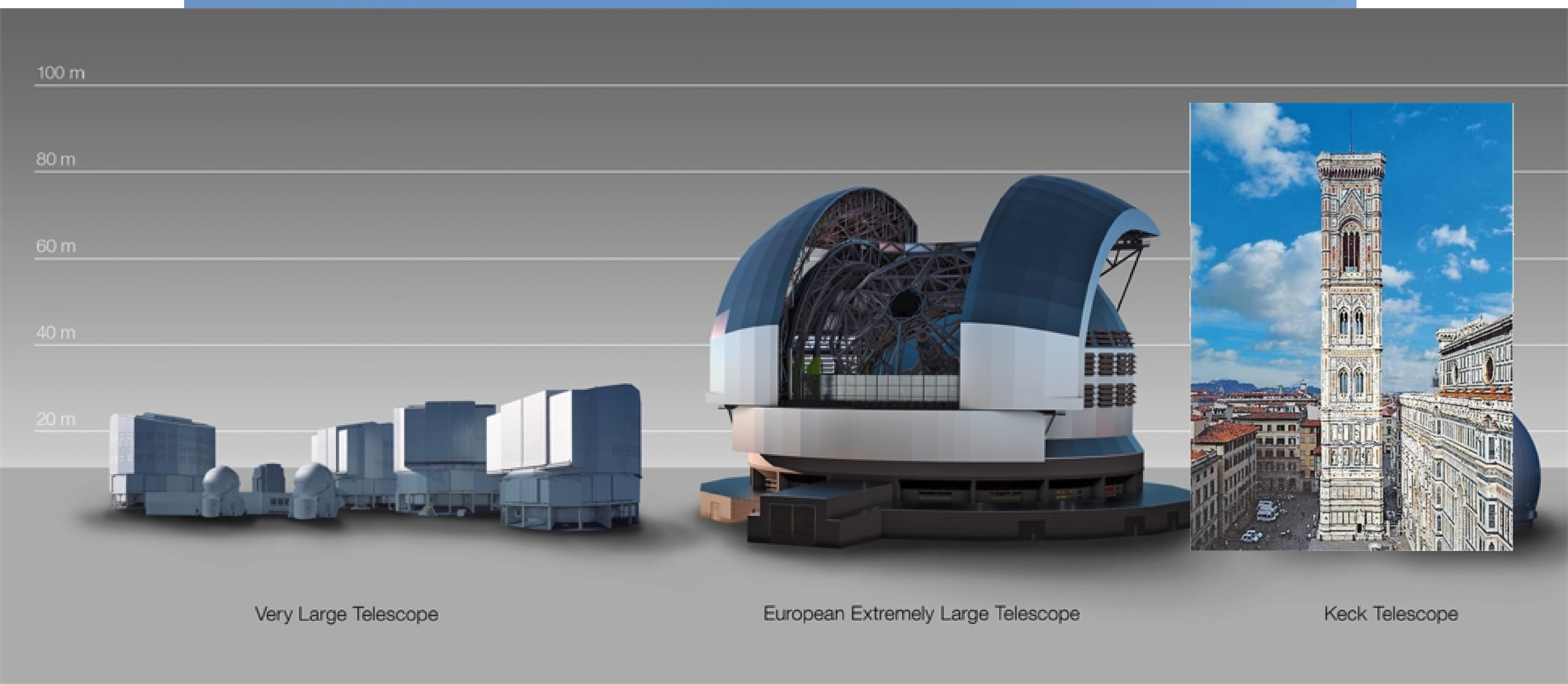


Becker+ 2015

The Flood Is Coming: GMT,TMT,E-ELT

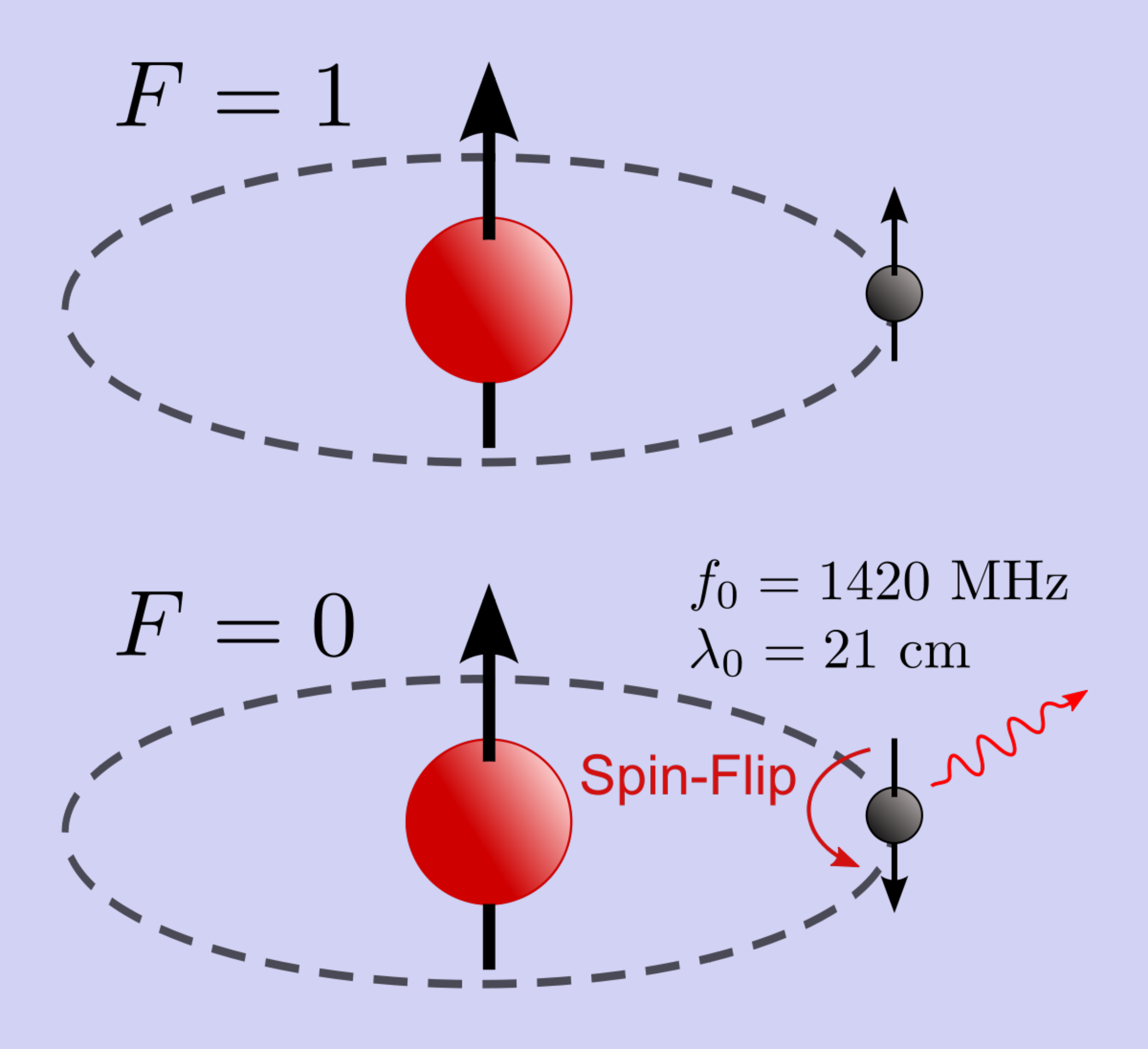
- Large optical telescopes will increase high-redshift quasar samples ~ 100-fold.

E-ELT: 42m



What We Know Now: Redshifted 21cm Emission

- Neutral hydrog
  structure line.
- During reioniz
  neutral, that e
- Epoch of
  reionization (E
  is far away, th
- Foregrounds (
  galactic) are ~
  times stronger
  the cosmic sig

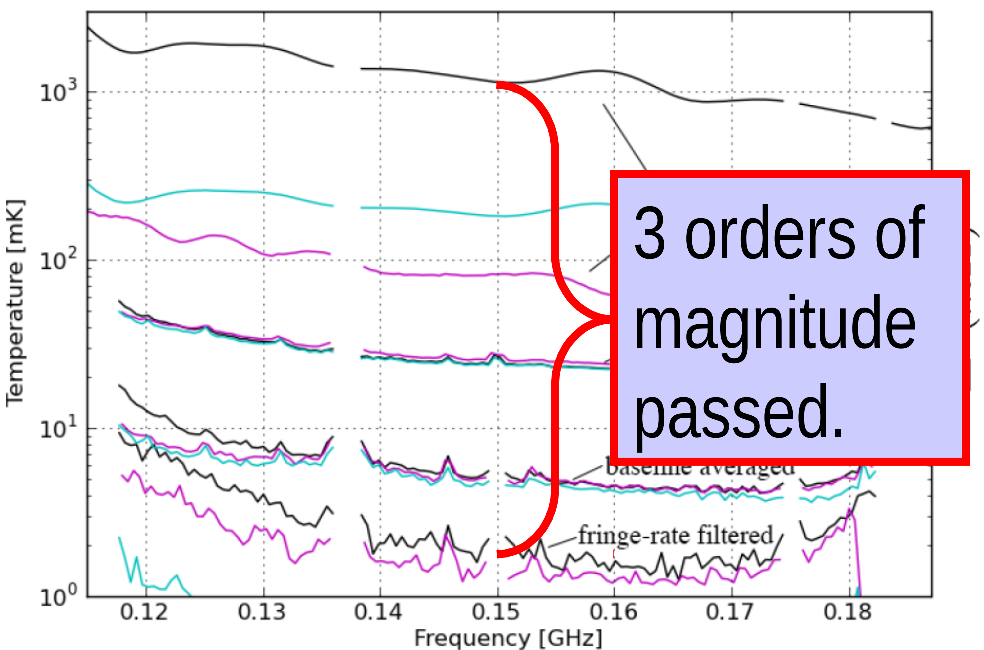


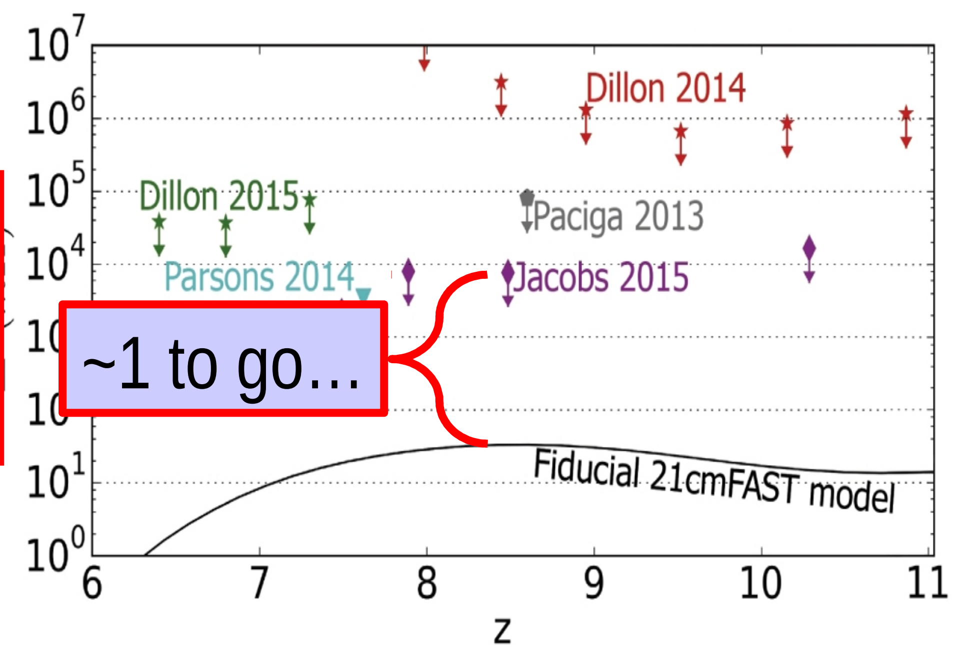
What We Know Now: Redshifted 21cm Emission

- Current experiments:
  - Precision Array for Probing the Epoch of Reionization (PAPER), South Africa, finished
  - Murchison Widefield Array (MWA), western Australia, finished
  - Low Frequency Array (LOFAR), *Netherlands*

What We Know Now: Redshifted 21cm Emission

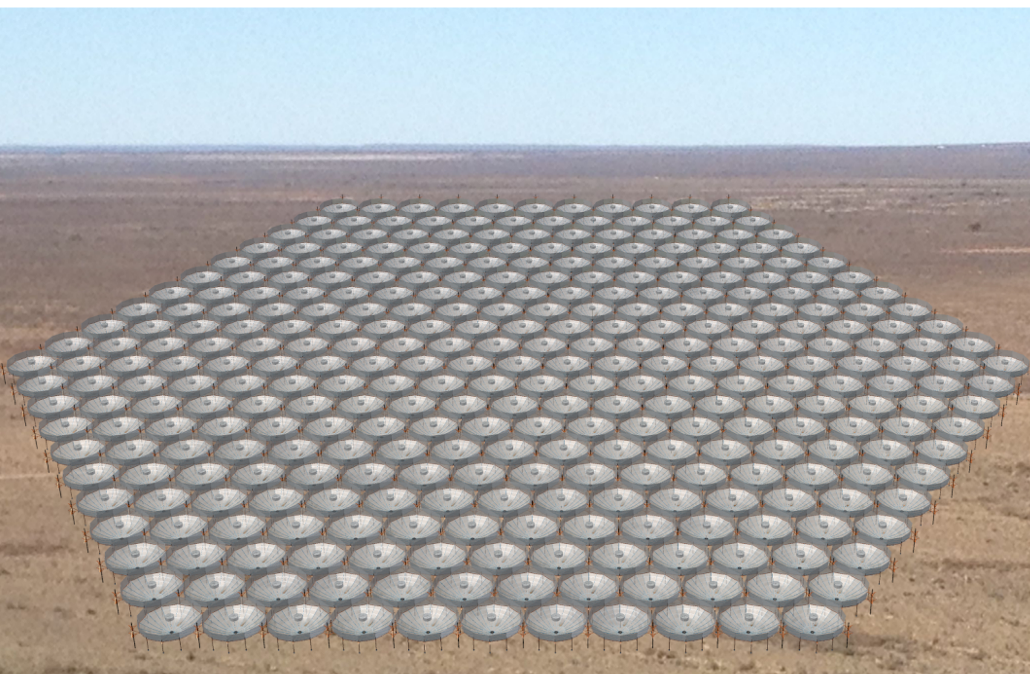
- No measurement yet.
- PAPER and MWA have placed the upper limits so far, the LOFAR limit is forthcoming.
- They are within a factor of ~10…



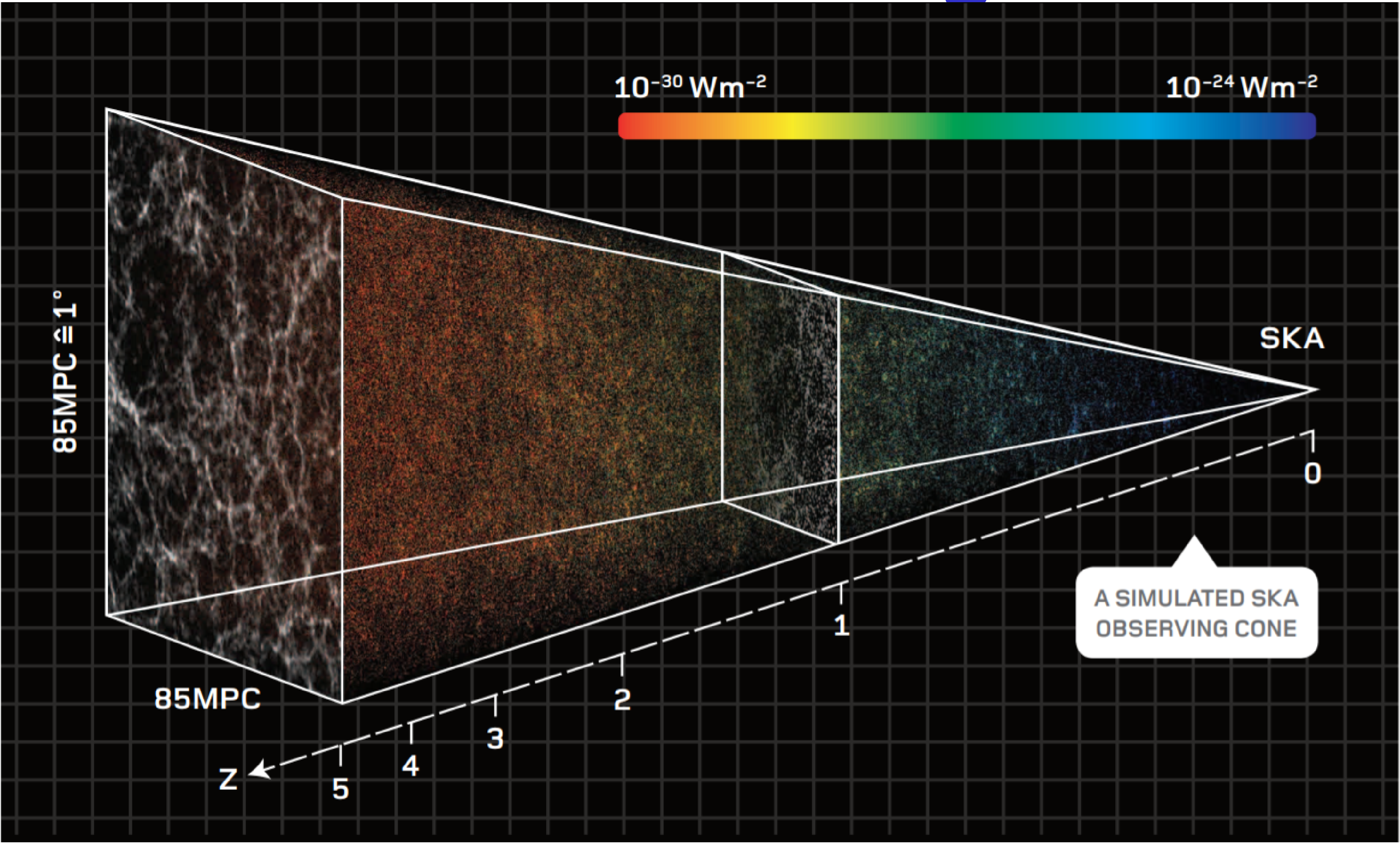


The Flood Is Coming: Redshifted 21cm Signal

- Despite 1st generation experiments not detecting any signal, NSF+MF already fully funded the 2nd generation experiment:
  Hydrogen Epoch of Reionization Array (HERA).



The Flood Is Coming: Redshifted 21cm Signal



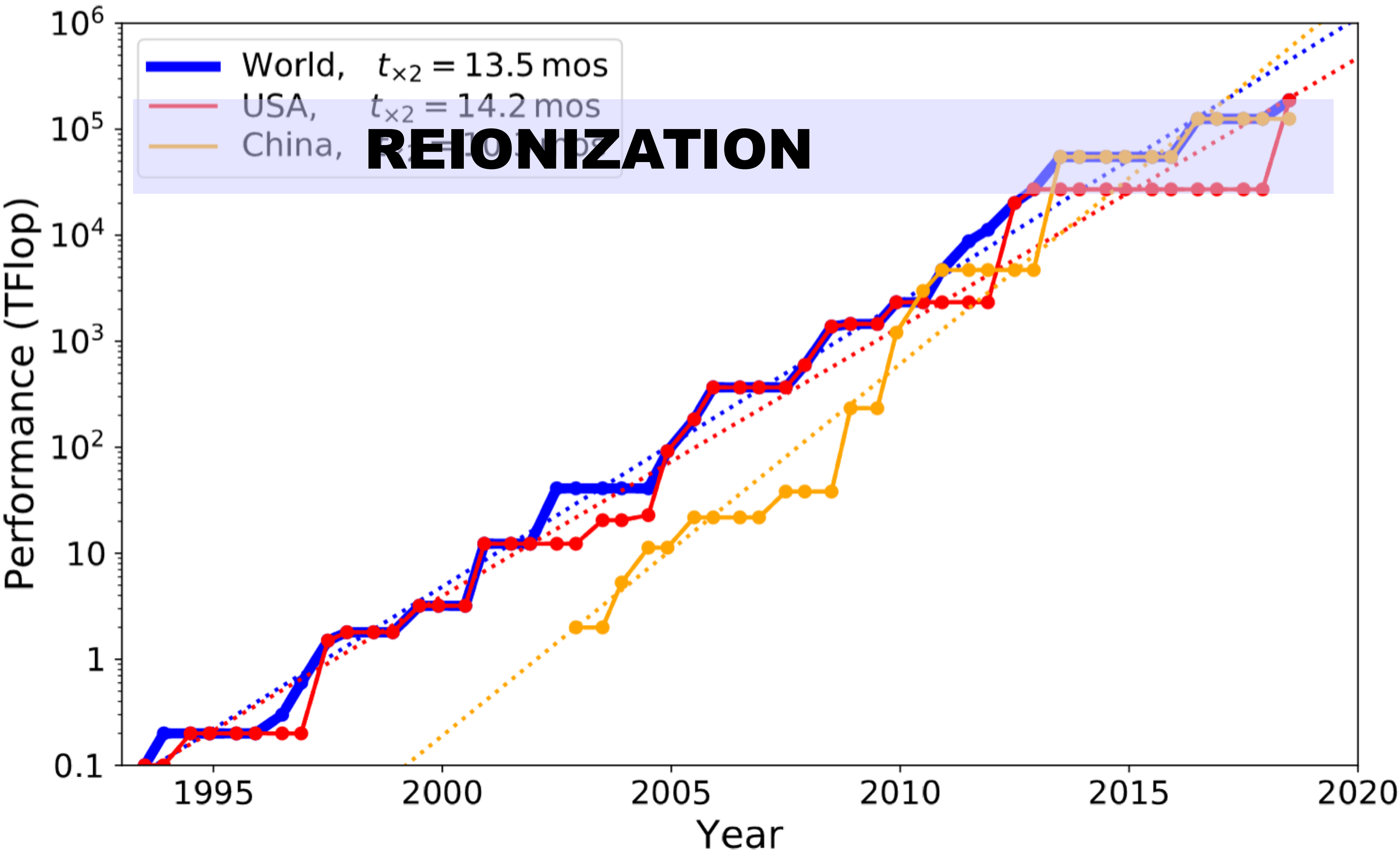
What Will We Learn From All That Data?

- Actually, not much, unless…
- …we get equally precise theory.

The Flood Is Coming

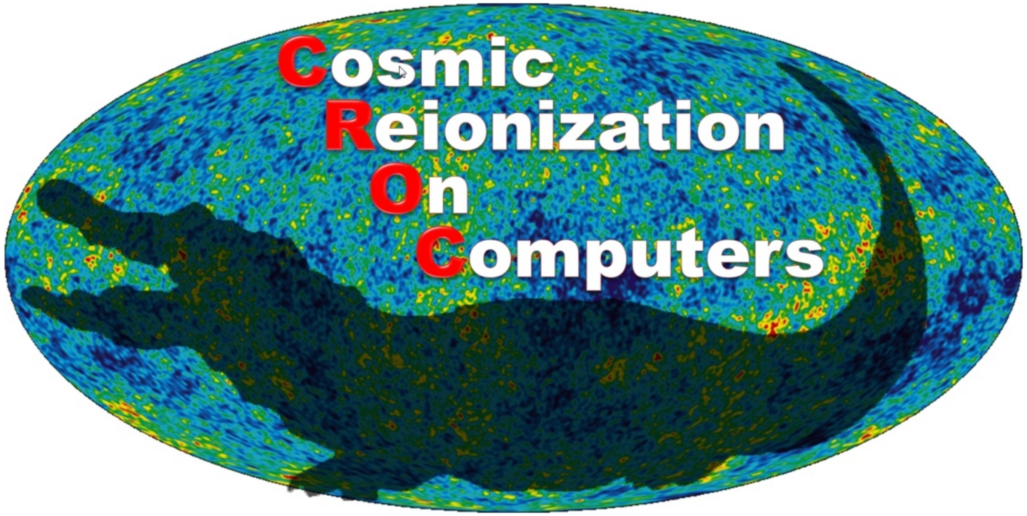
- Existing observations already make many models obsolete; forthcoming observations will make obsolete **all** of them.
- Hence, theorists' task is not to make more models now, but rather to develop new modeling technology.
- And it is happening:
  - *Aurora*
  - *Cosmic Dawn*
  - *CRASH*
  - *CROC*
  - *DRAGONS*
  - *Emma*
  - *Renaissance Simulations*
  - *SPHINX*

Moore's Law


World, $t_{\times 2} = 13.5$ mos
USA, $t_{\times 2} = 14.2$ mos
China,
REIONIZATION
Performance (TFlop)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
1995
2000
2005
2010
2015
2020
Year

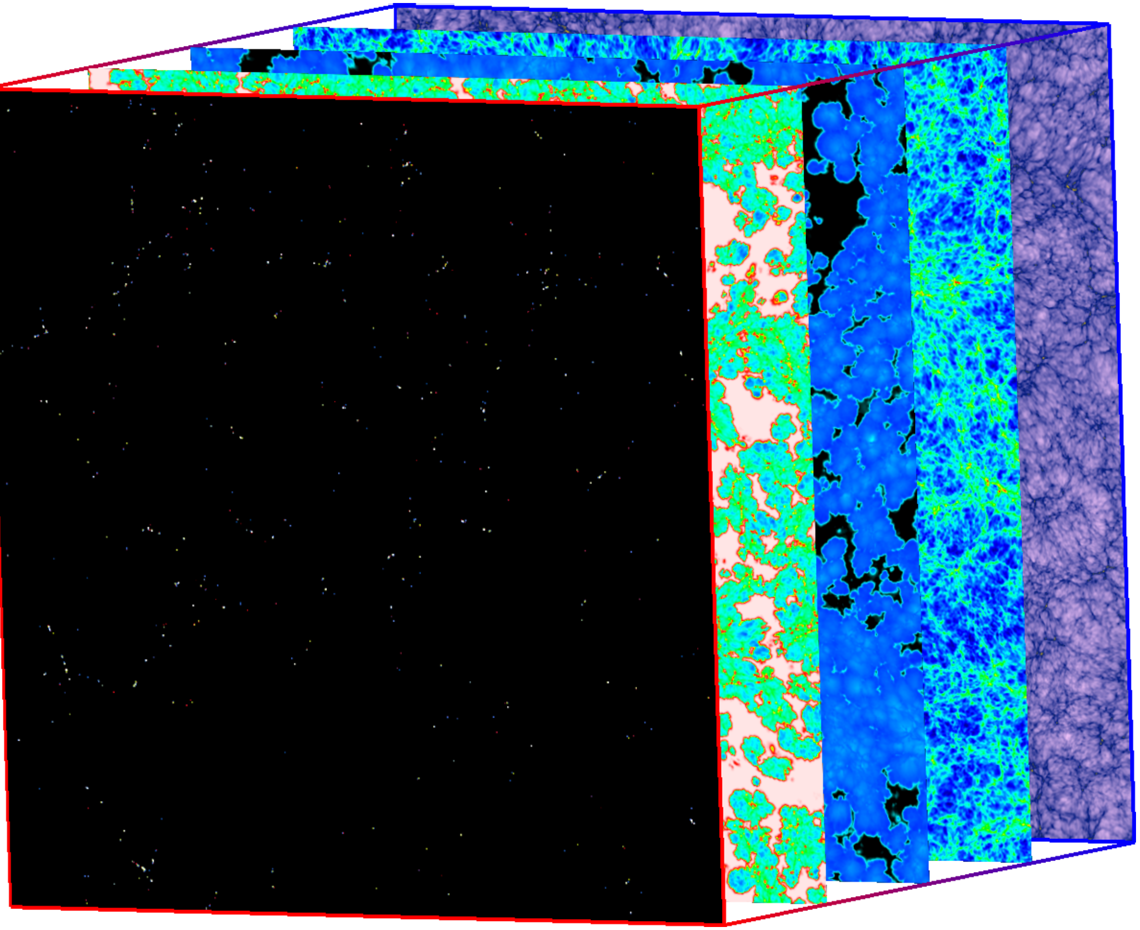
The Flood Is Coming

- One (typical) example in action:



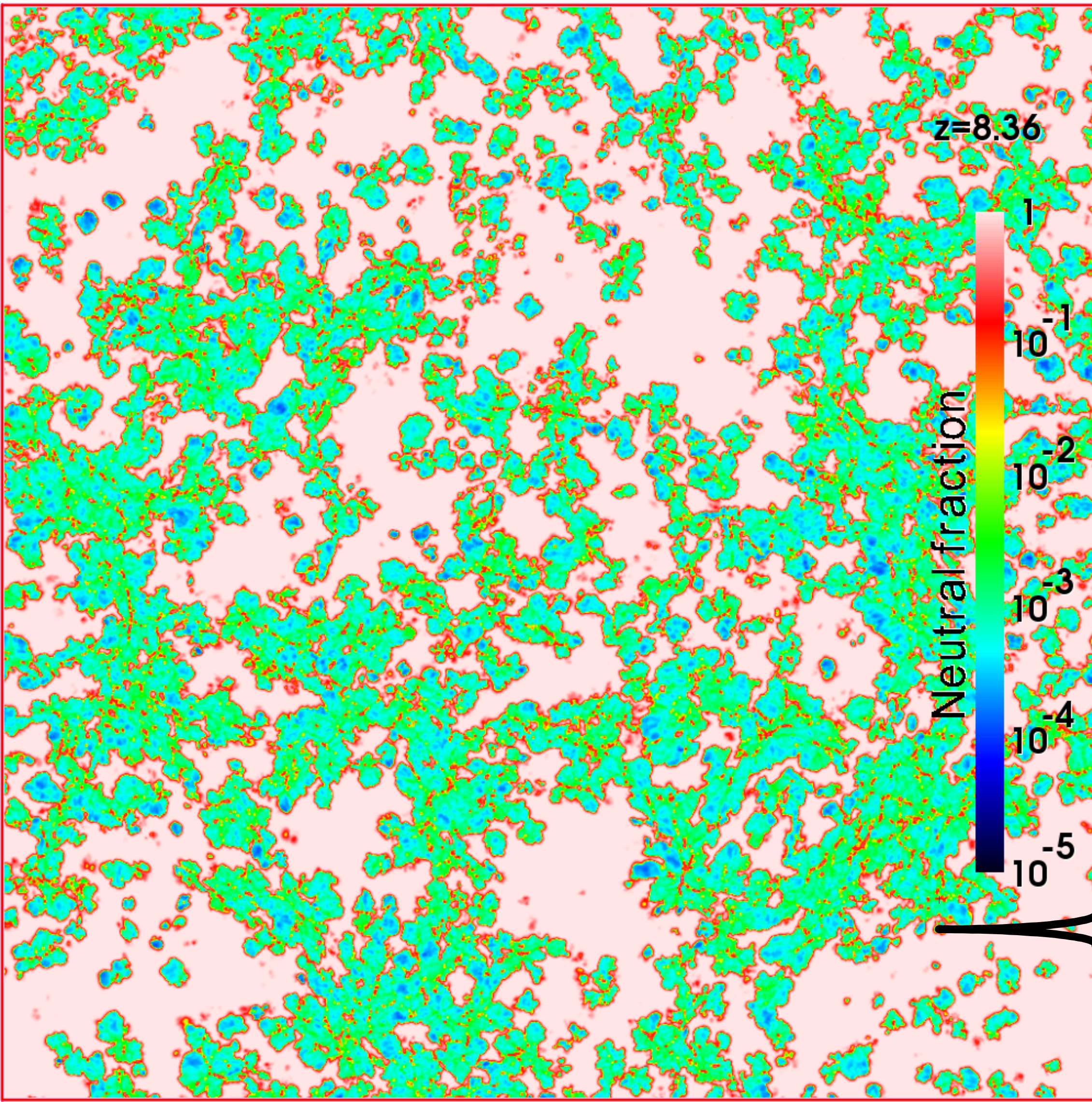
- Disclaimer: *other projects/efforts are achieving similar overall levels of computational scale, agreement with data, etc.*

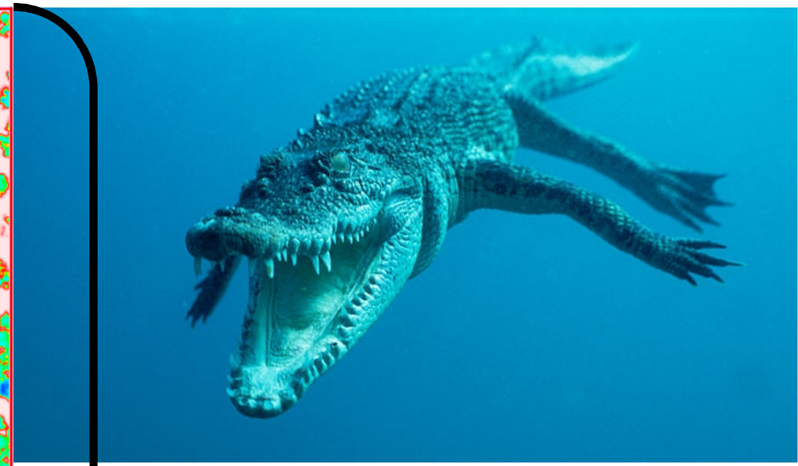
Simulating Reionization: Physics



- Dark matter
- Gas dynamics
- Atomic processes
- Radiative transfer
- Star formation & stellar feedback

Simulating Reionization: CROC on Blue Waters

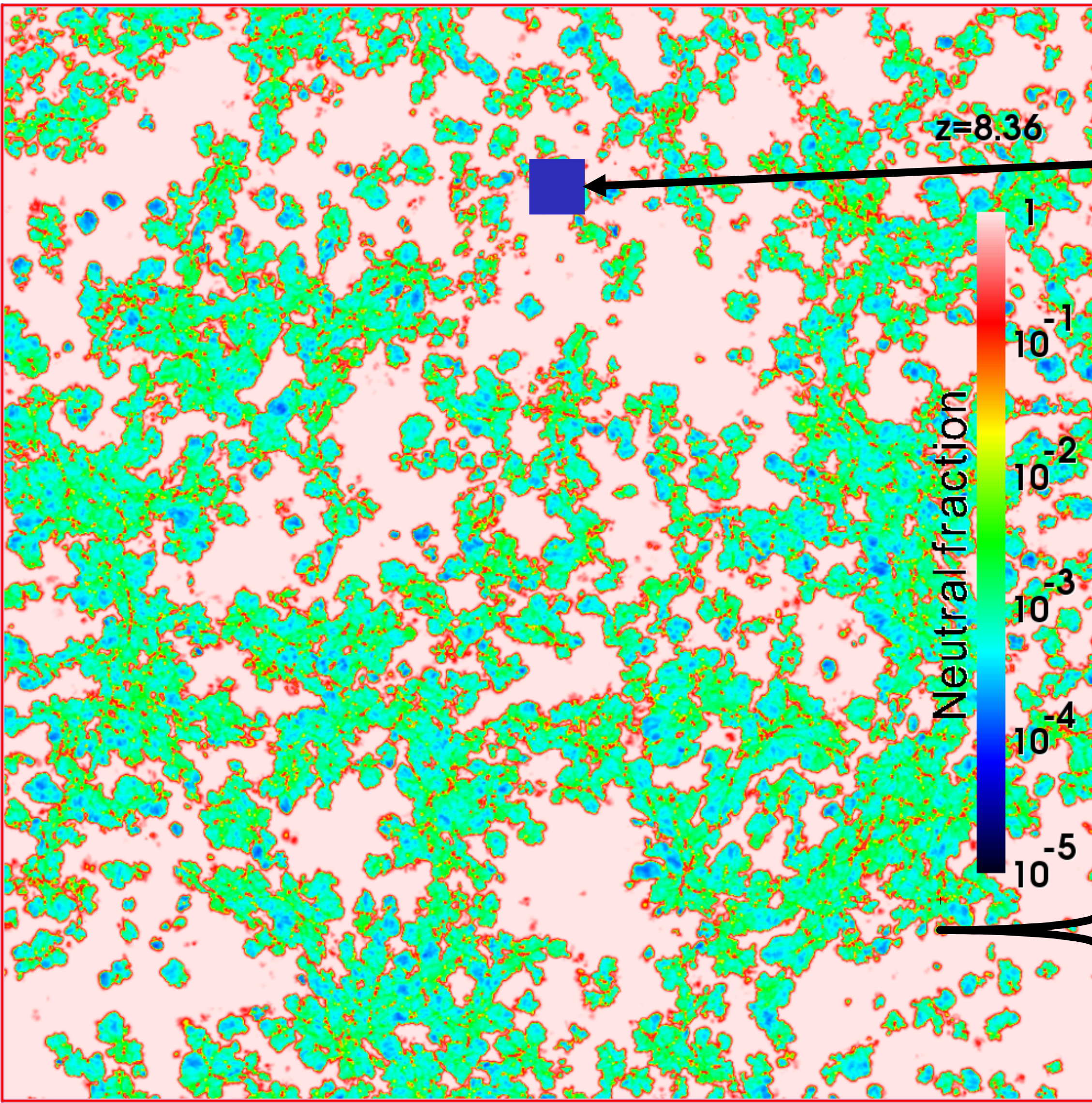




Box size: 120 Mpc

Resolution: 100 pc

Simulating Reionization: CROC on Blue Waters



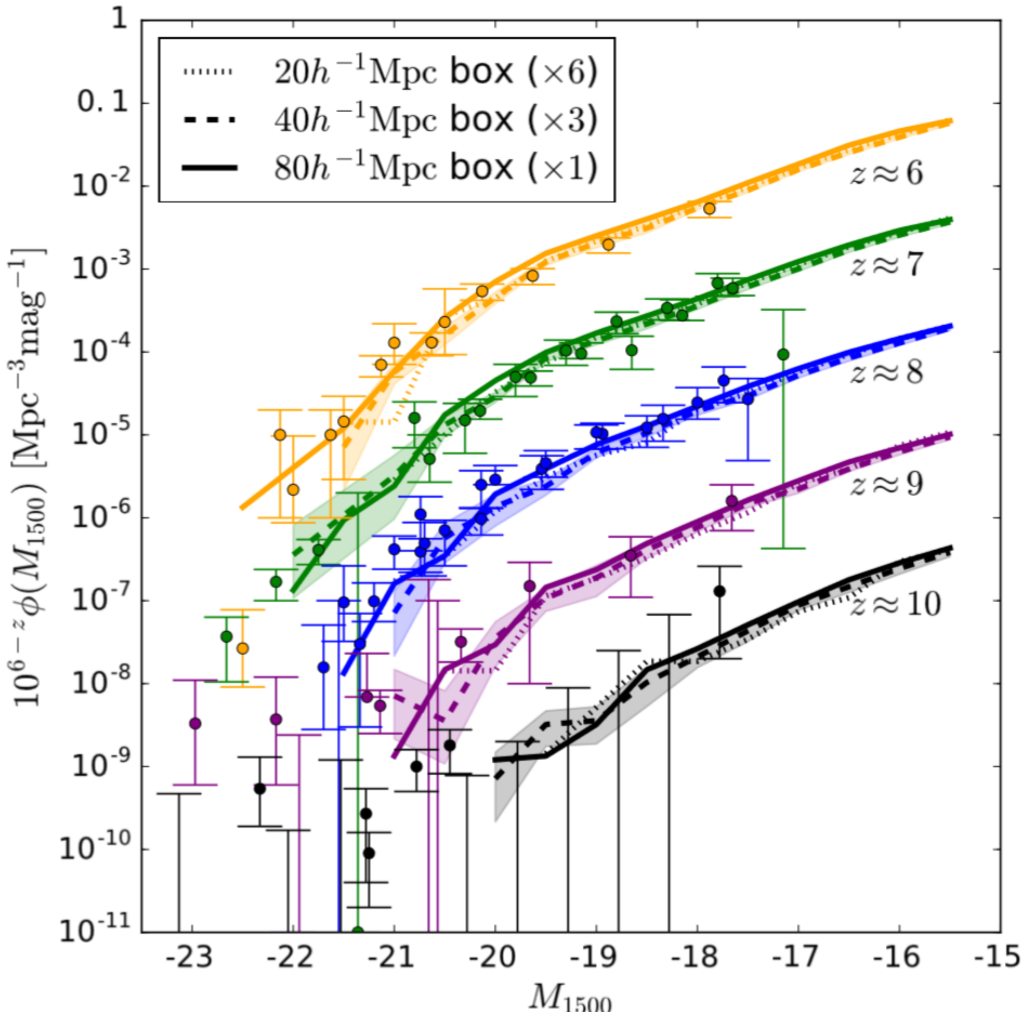
Box from the movie

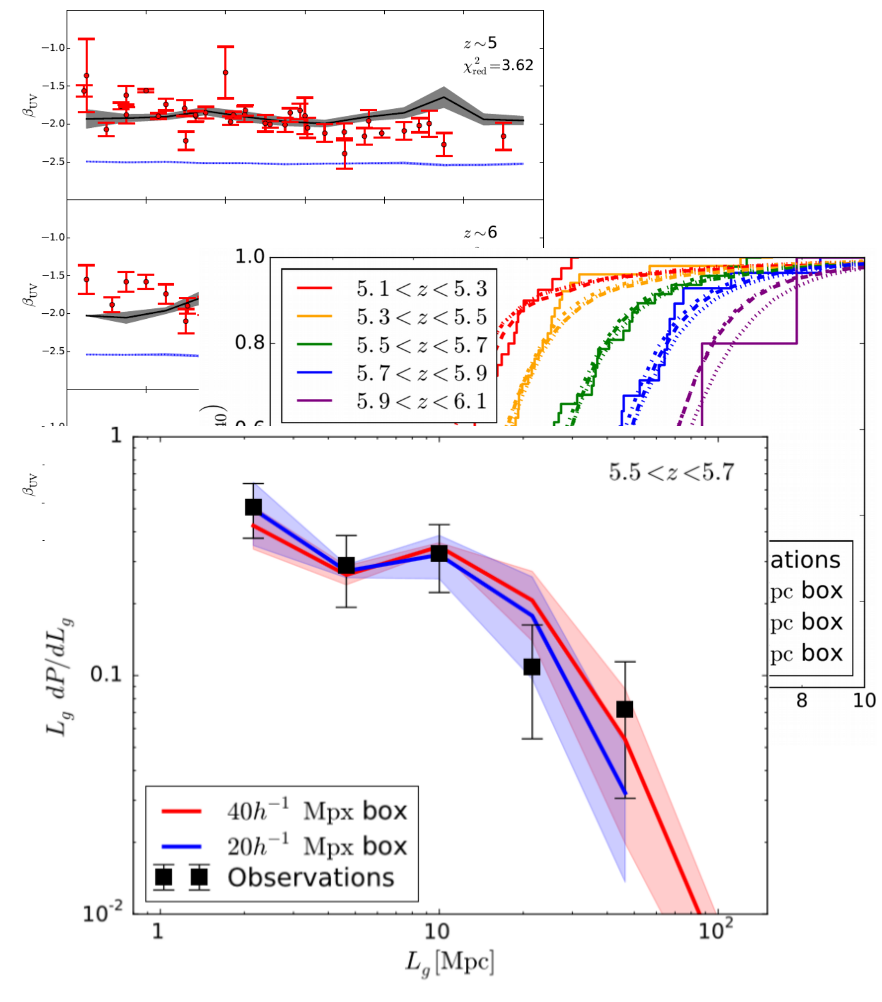
Box size: 120 Mpc

Resolution: 100 pc

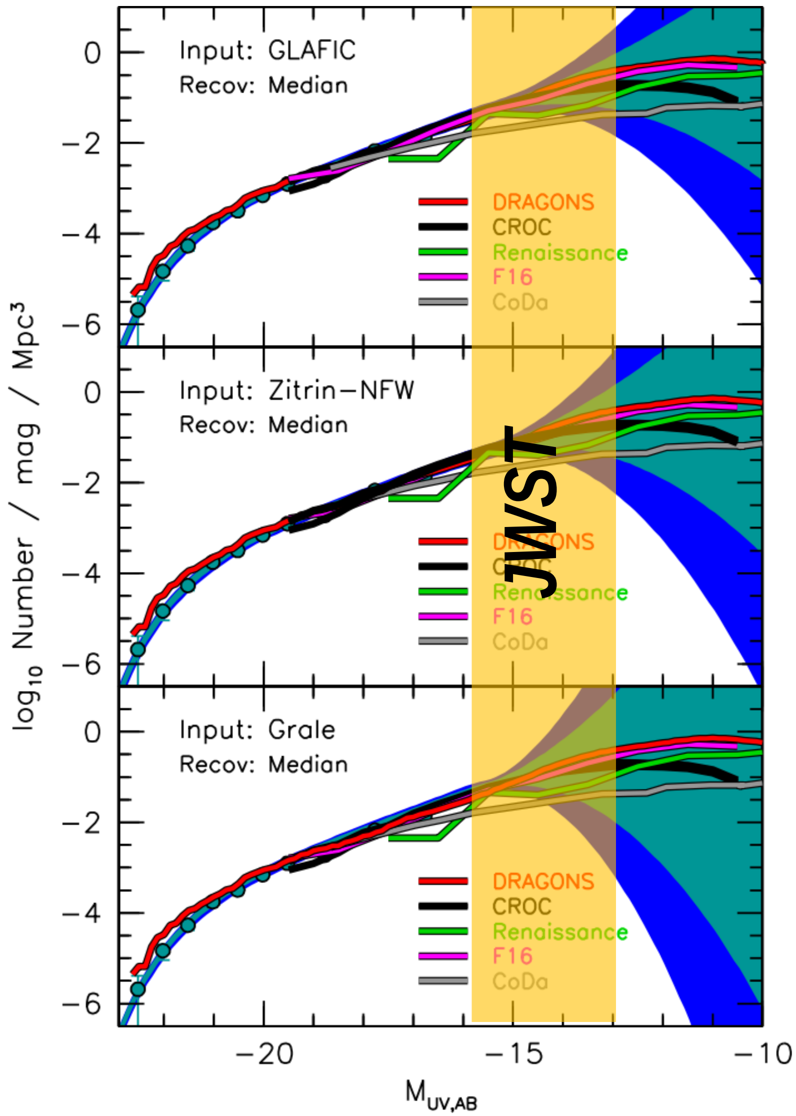
The CROC Project: Success

- Galaxies (and many other things) are ok!





The Role of JWST: There Will Be Blood!

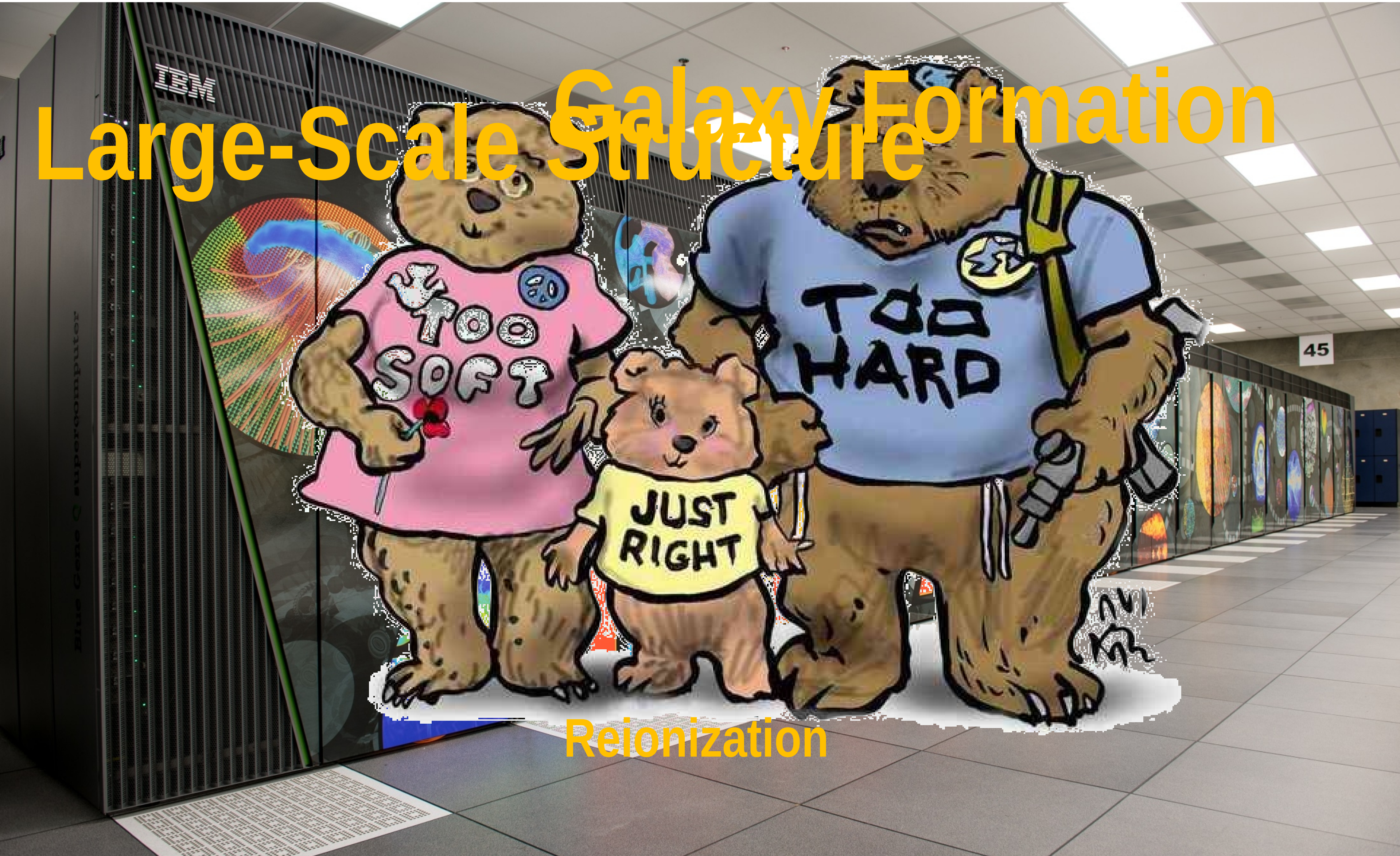


- All simulation agree with the data where the data exist.
- They all disagree (for a good reason!) strongly in the regime that JWST will probe.
- JWST will kill most (or all) existing models.

Conclusions

- We are entering a golden age of reionization studies, with observations increasing the data volume ~100-fold and opening new subfields of astronomy.
- Theory is finally maturing to the level of theoretical uncertainties approaching observational ones, and Moore’s law ensures that it will only get better.
- Lots of fun ahead…

The End


Galaxy Formation
Large-Scale Structure
IBM
TOO SOFT
TOO HARD
JUST RIGHT
45
Reionization