First Stars and Galaxies, The Roadmap Ahead: Observations

ELTs

With a photographic tour of Texas

JWST

SKA

Jonathan Gardner (GSFC)

WMAP Cosmological Parameters
Model: lcdm
Data: all

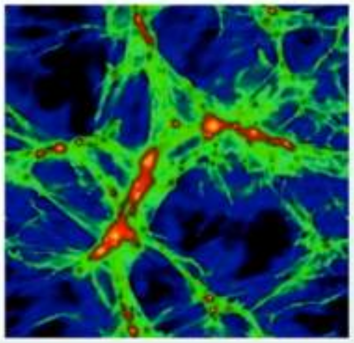
$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
A	=	$0.67^{+0.04}_{-0.05}$
$A_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10} \pm 1 \times 10^{-10}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24 \times 10^{-10}{}^{+1\times 10^{-10}}_{-2\times 10^{-10}}) \times 10^{-10}$
h	=	$0.71^{+0.01}_{-0.02}$
H_0	=	71^{+1}_{-2} km/s/Mpc
ℓ_A	=	$303.0^{+0.9}_{-1.3}$
n_s	=	$0.938^{+0.013}_{-0.018}$
$n_s(0.002)$	=	$0.938^{+0.012}_{-0.023}$
Ω_b	=	$0.044^{+0.002}_{-0.003}$
$\Omega_b h^2$	=	$0.0220^{+0.0006}_{-0.0008}$
Ω_c	=	$0.22^{+0.01}_{-0.02}$
Ω_Λ	=	0.74 ± 0.02
Ω_m	=	$0.26^{+0.01}_{-0.03}$
$\Omega_m h^2$	=	$0.131^{+0.004}_{-0.010}$
r_s	=	148^{+1}_{-2} Mpc
b_{SDSS}	=	$0.95^{+0.05}_{-0.06}$
σ_8	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8\Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
A_{SZ}	=	$0.78^{+0.23}_{-0.78}$
t_0	=	$13.8^{+0.1}_{-0.2}$ Gyr
τ	=	$0.069^{+0.026}_{-0.029}$
θ_A	=	0.594 ± 0.002 °
z_{eq}	=	3135^{+85}_{-159}
z_r	=	$9.3^{+2.8}_{-2.0}$

The initial conditions of the Universe can be summarized on a single sheet of paper, yet thousands of books cannot fully describe the complex structures we see today…

Avi Loeb

“Then the miracle goes away, which is sad, but that is science.”

-- Alexander Heger



Definitions

McKee & Tan (2008); O'Shea et al. (2008; First Stars III Conference Summary)

Population III

Stars having a metallicity so low ($Z<Z_{crit}$) it has no effect on their formation (i.e. negligible cooling) or their evolution.

Population III.1

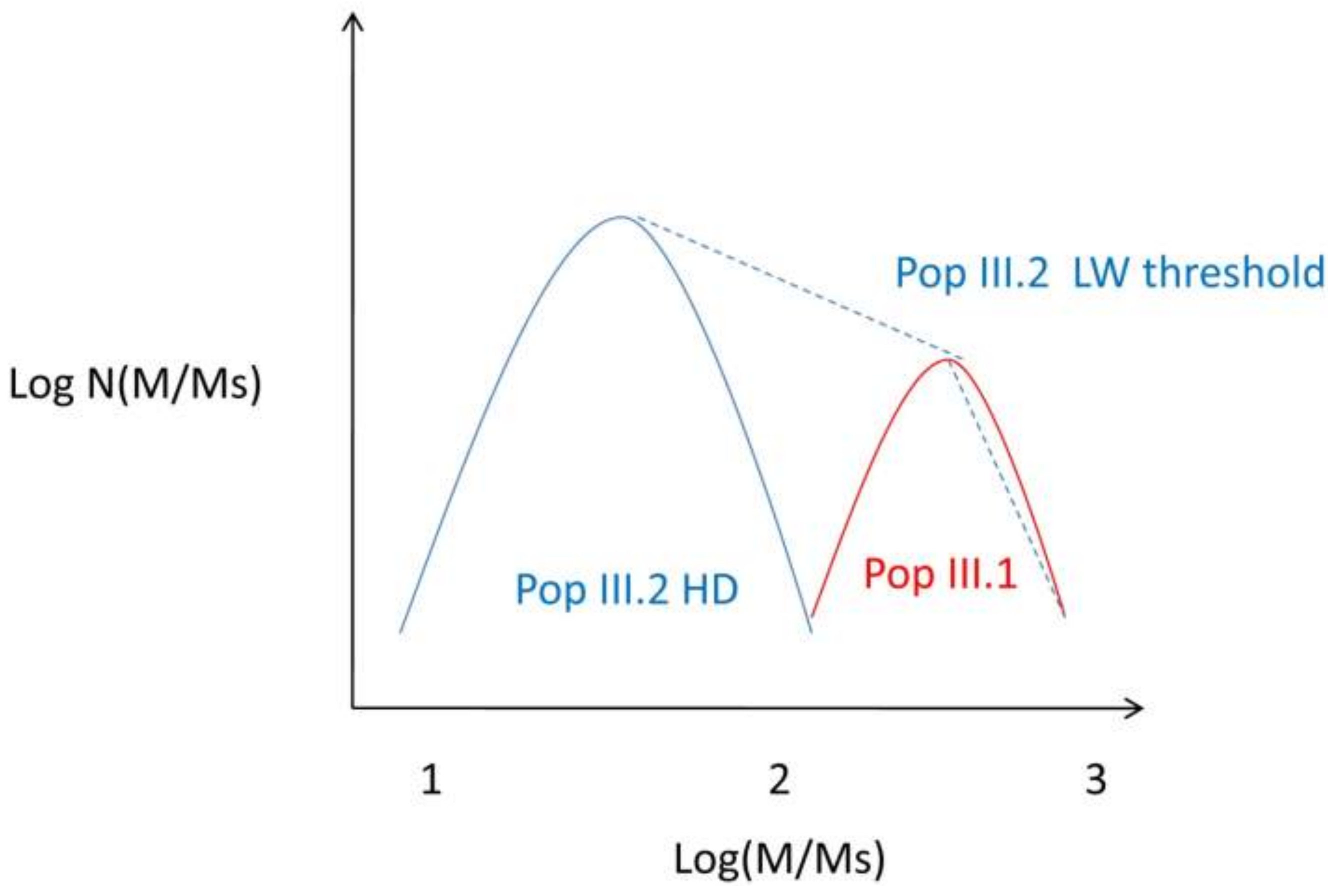
The initial conditions for the formation of Population III.1 stars (halos) are determined solely by cosmological fluctuations.

Population III.2

The initial conditions for the formation of Population III.2 stars (halos) are significantly affected by other astrophysical sources (external to their halo).

Jonathan Tan

Possible Evolution of Pop III IMF (very speculative!)



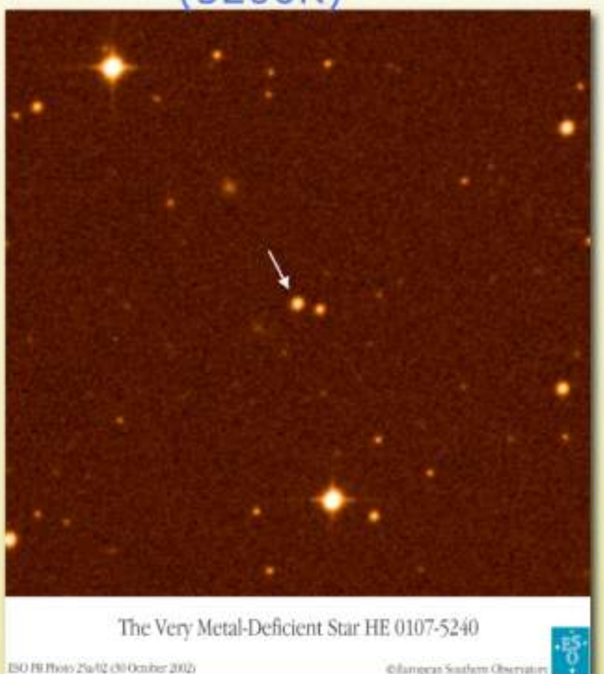
Mike Norman

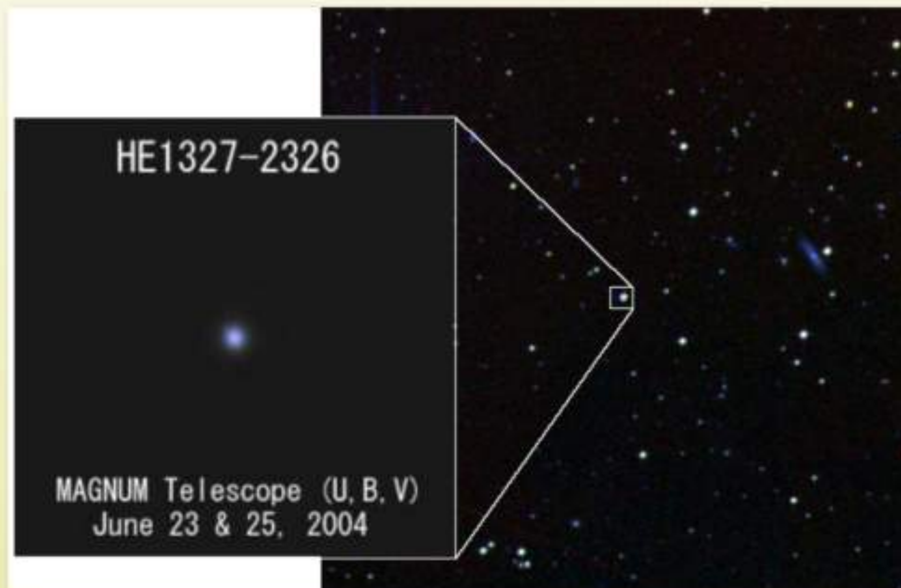
The most iron-deficient stars known

HE 0107-5240
Red giant
(5200K)

Masses: 0.6 - 0.8 $M_\odot$

HE 1327-2326
Subgiant
(6180K)





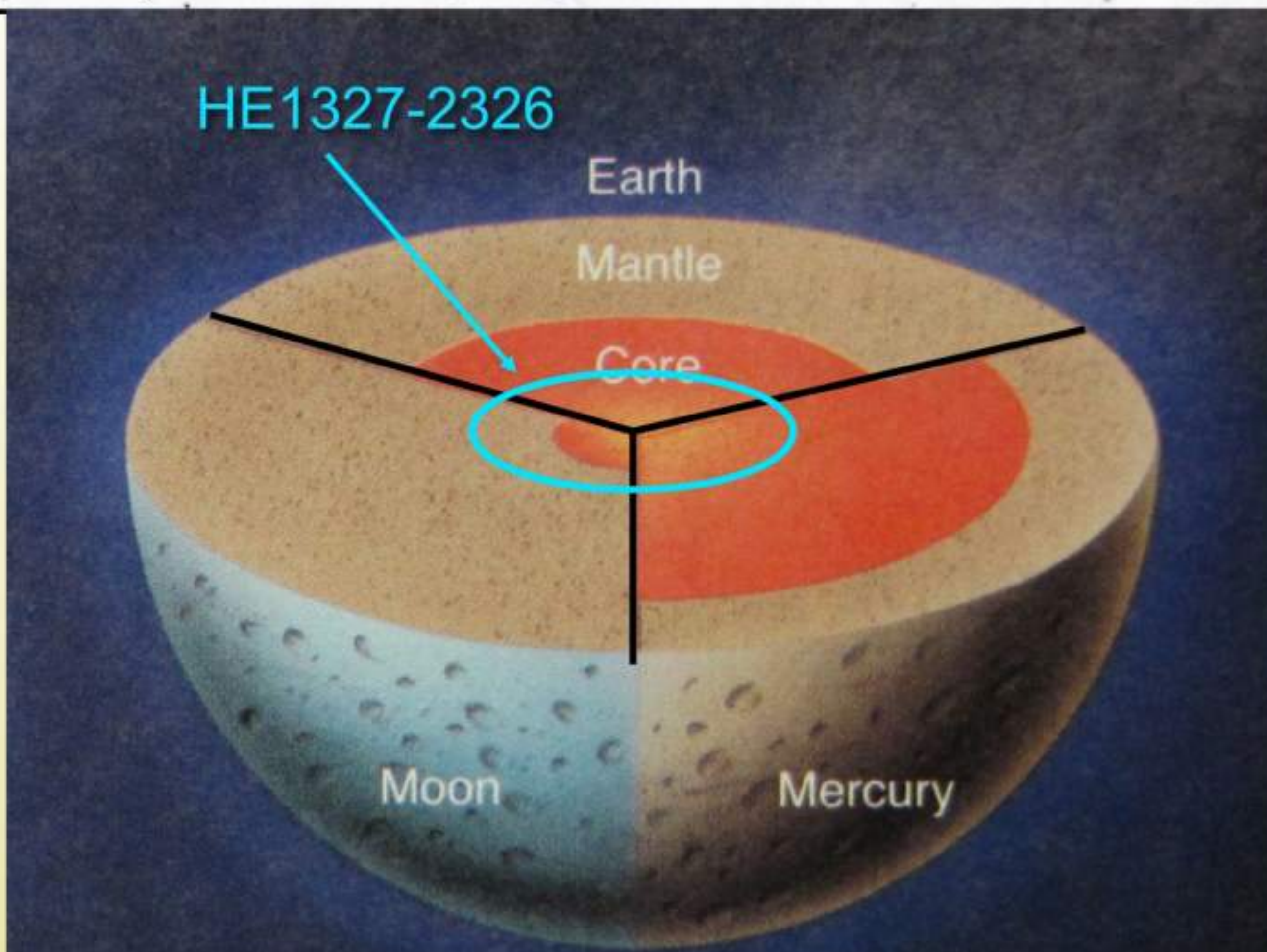
$[Fe/H]_{NLTE}$ = -5.2

Christlieb et al. (2002), Nature 419, 904
Christlieb et al. (2004), ApJ 603, 708
Bessell et al. (2004), ApJ 612, L61

$[Fe/H]_{NLTE}$ = -5.4

Frebel et al. 2005, Nature 434, 871
Frebel et al. 2006, ApJ 638, L17
Aoki, Frebel et al. 2006, ApJ 639, 897
Frebel et al. 2008, ApJ 684, 588i

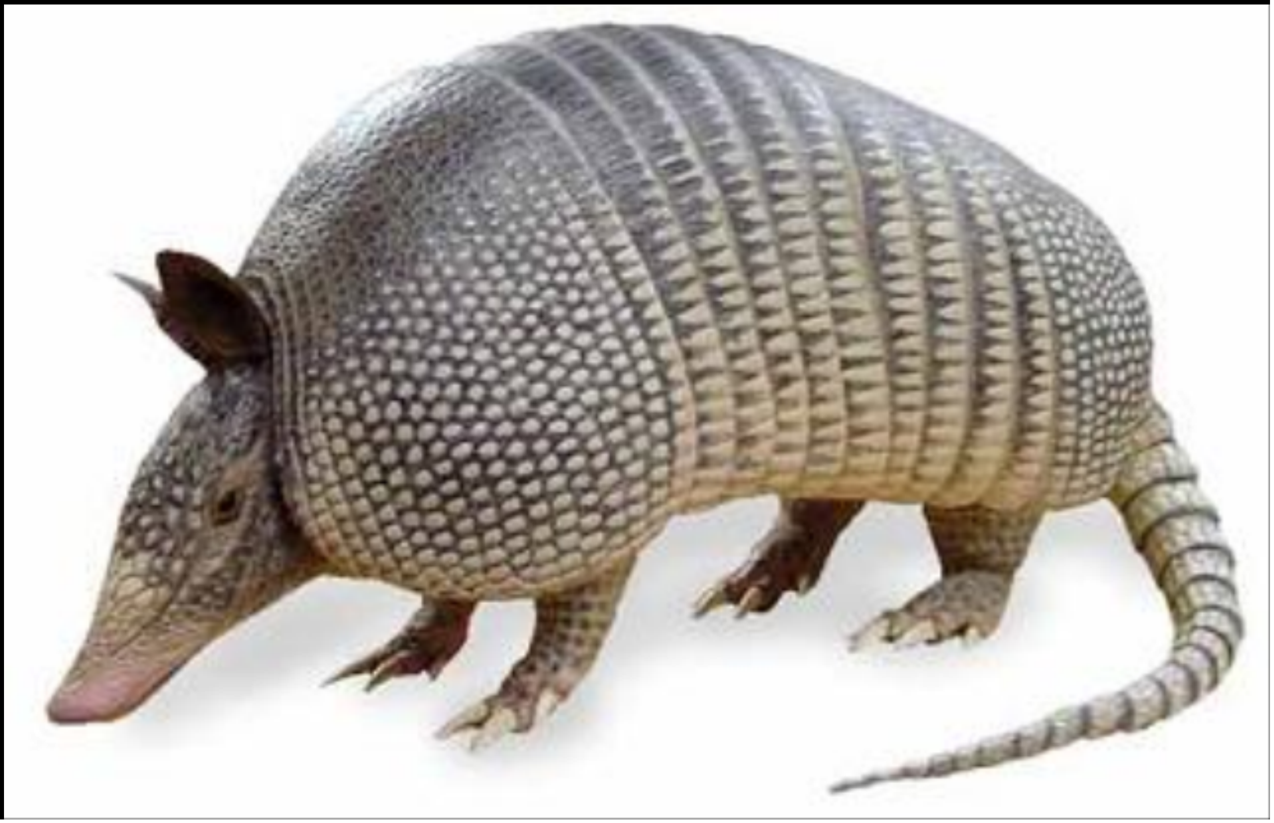
How much iron is in there?



Relative scales of Earth, Moon & Mercury to show size of Fe core

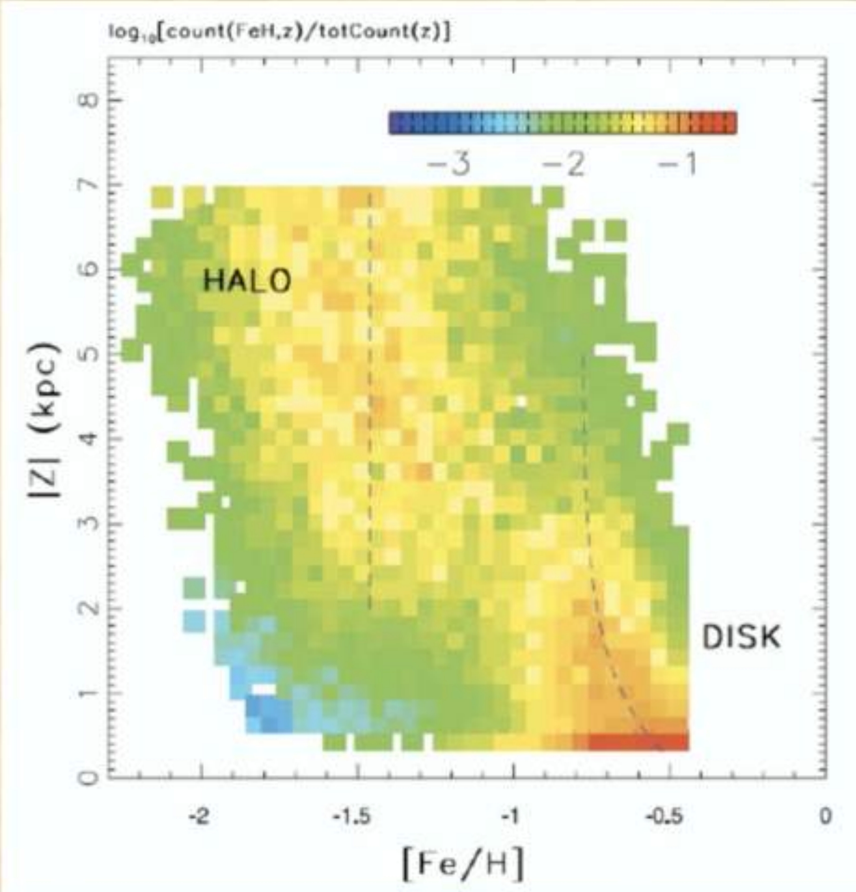
“Question: What is with the mayonnaise and paperclip?”
“Those are examples of metals in the local universe.”
-- Mark Dijkstra

“We can measure a lot of things with good data.”
-- Tim Beers

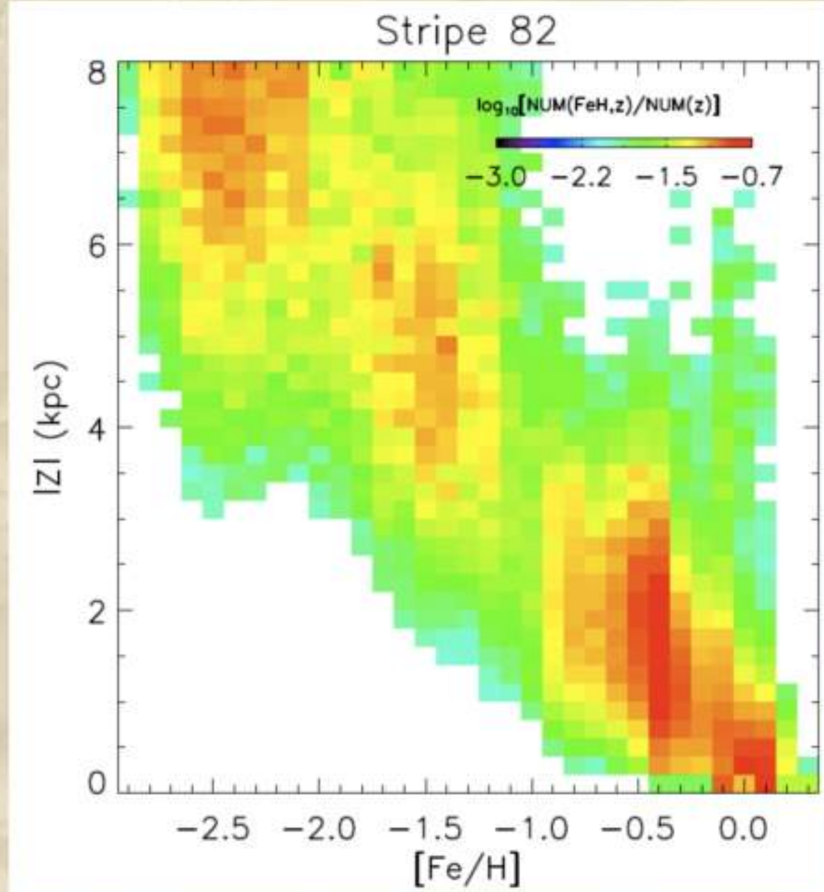


Metallicity Distribution

Preliminary



Ivezic et al. (2008)



Recalibrated isochrones

u g r i z

Tim Beers

u g r i z

The First Stars nomenclature

Pop III.1 : forms only under the effect of cosmology
Pop III.2 : formation affected by non cosmological effects
Pop III.2α : formation affected by cosmic rays
Pop III.2β : formation affected by electrons
Pop III.2γ : formation affected by radiation

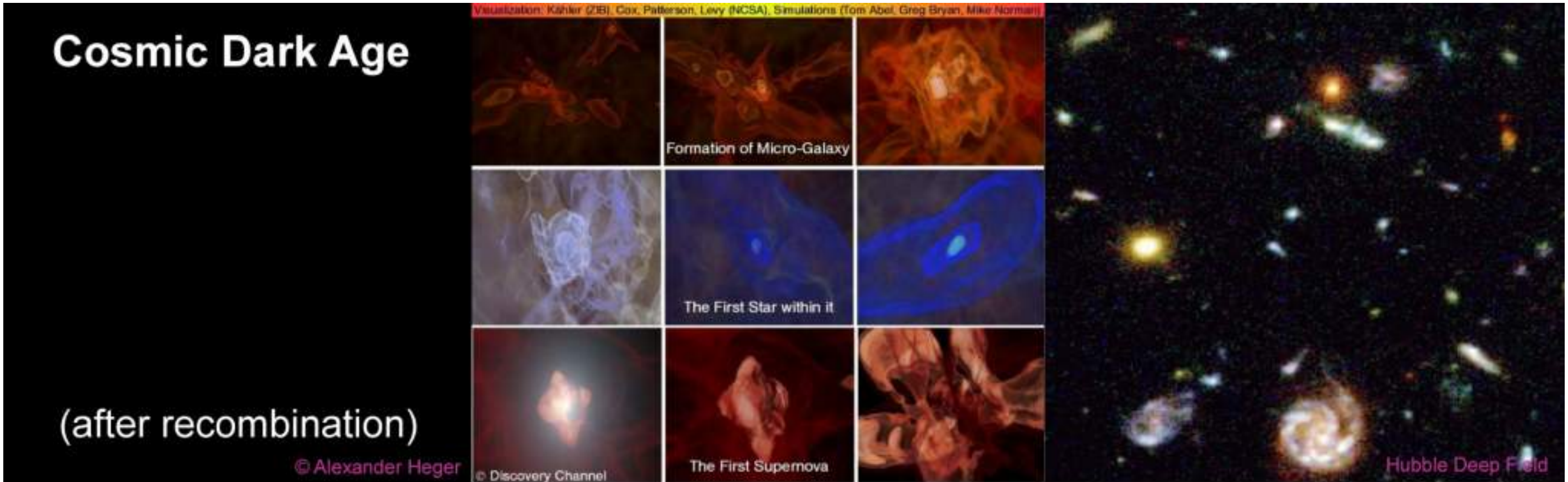
  Pop III.2γԱ : formation affected by Lyman-Werner
  Pop III.2γԲ : formation affected by ionizing radiation

Pop III.2♬ : formation affected by mechanical feedback
Pop III.2☹ : formation affected by magnetic fields
Pop III.2✂ : formation affected by loss of grant
Pop III.2♻ : formation affected by insufficient resolution

"The rule in the NSF is that if you have a very good idea they don't give you money."

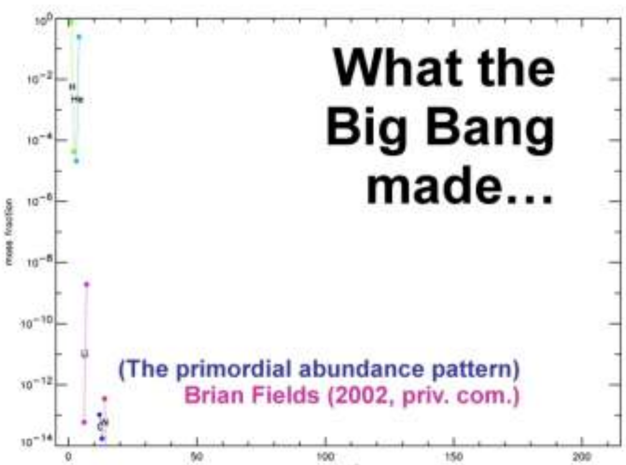
-- Shri Kulkarni

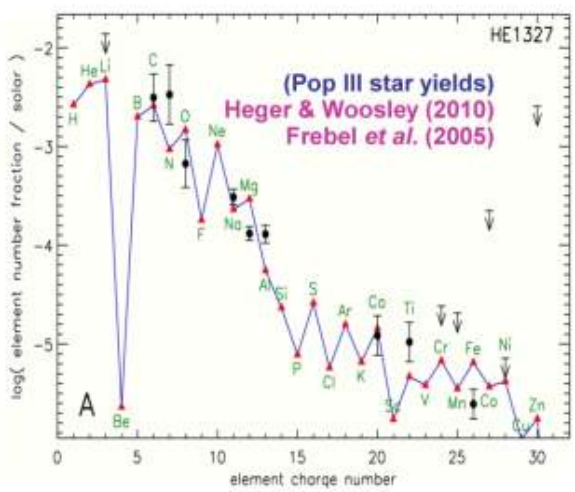
“We’ll have fun this morning blowing things up.”
-- Craig Wheeler

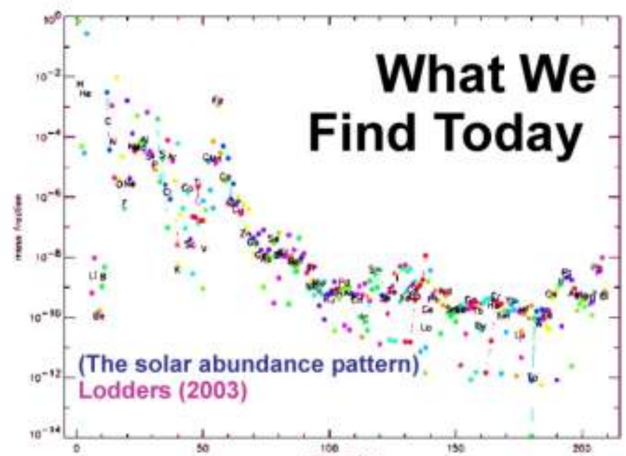


time

Alexander Heger

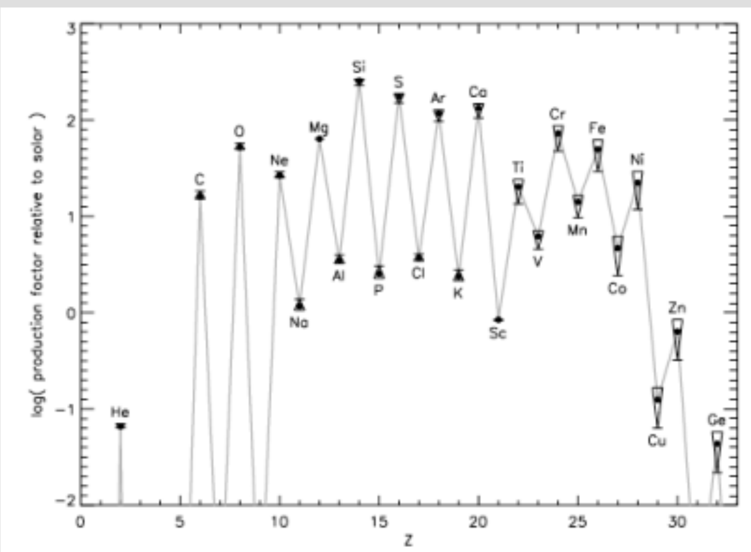






The First Stars - 1

* We expect Population III stars to form in mini-halos due to molecular Hydrogen cooling. Individual Pop III stars are too faint to be observed directly with JWST except when they explode as supernovae. We will discuss SNae separately.
* JWST might be able to identify spectroscopically the abundance pattern signatures of PISN enrichment.



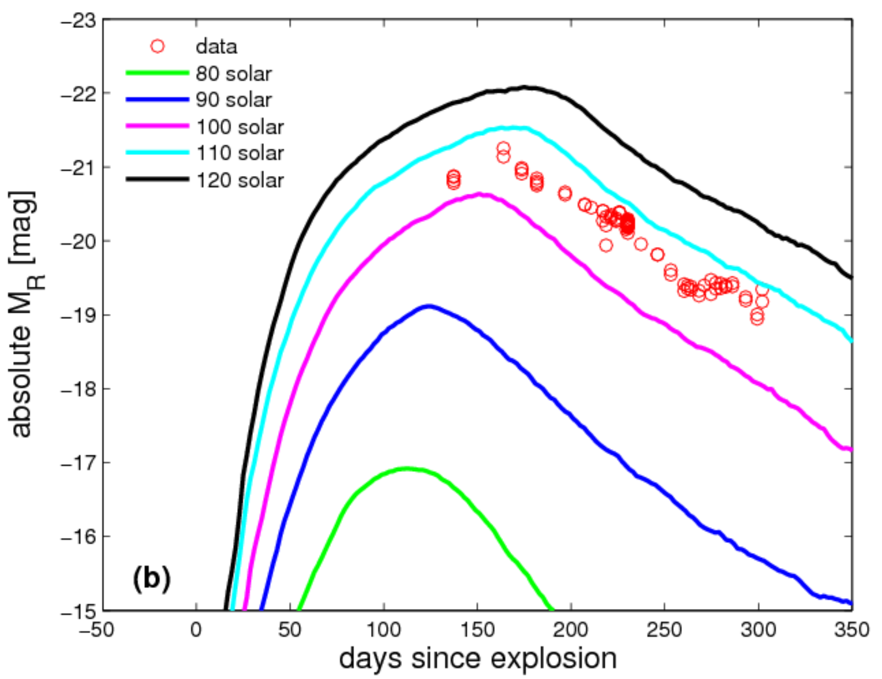
It would be useful to have a sample ready of z>7 QSOs for studying their LOS.

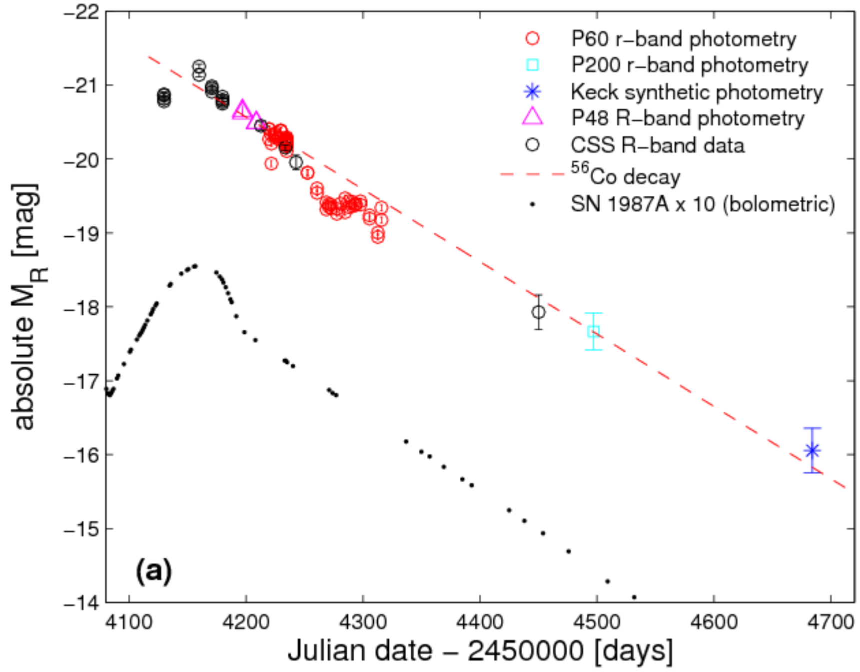
From Heger & Woosley 2002 for stars with mass 140-260 $M_\odot$.

Massimo Stiavelli

"We don't have a lot of observations of these events, so we can't see where the models are wrong. That makes for easy modeling." -- Daniel Kasen

SN 2007bi – *a Pair Instability Supernova in a Nearby Metal-Poor Dwarf Galaxy*





- Nickel mass of ~4-7$M_\odot$ (ejecta mass of 100 $M_\odot$); kinetic energy of ≈ 10^{53}ergs
- Dwarf galaxy at z=0.128 with M_B=-16.3 mag, and 12+[O/H]=8.25

Avi Loeb

Gal-Yam et al., Nature (arXiv:1001.1156)

Can JWST observe [dark star, PISNe, etc.]?

- We need to know three things:
  1. How bright?
  2. How common?
  3. How can we tell?
- Without both 1 & 2 we probably can't even search for candidates.

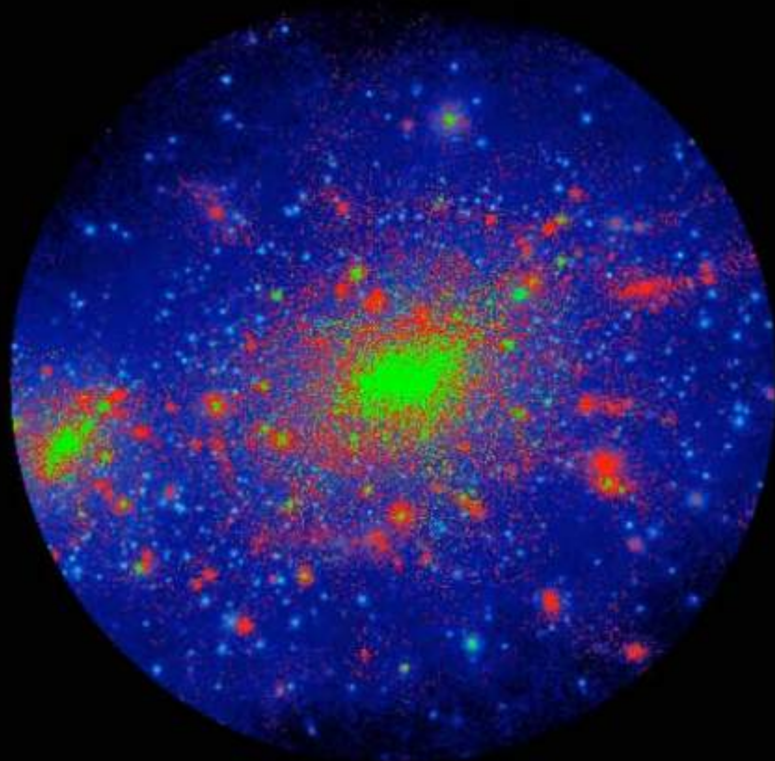
“The Universe is very big and radiation goes further than metals.”

-- Mike Norman

Third Big Idea: Where to Look for the First Second Stars

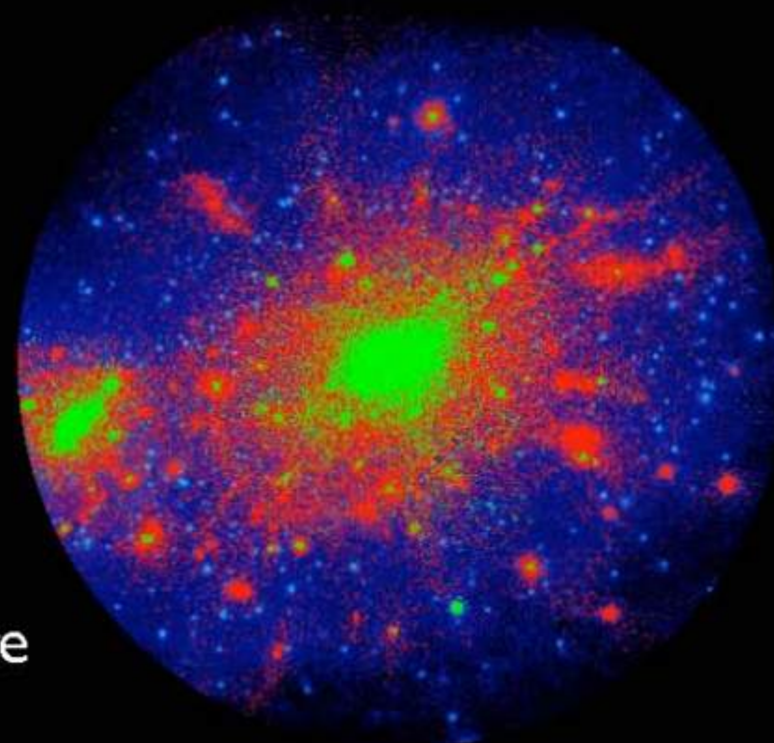
stars formed $z > 10$

stars formed at all z



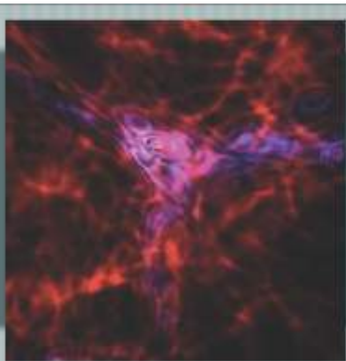
$[Fe/H] < -3.5$

$[Fe/H] < -2.0$



Chronologically older stars are more centrally concentrated.

Jason Tumlinson



Summary

- The first Gyr after the Big Bang is characterized by a complex interplay between metal free (first stars) and metal enriched (first galaxies) star formation
  - PopIII/PopII transition highly inhomogenous: at z~5 metal free gas pockets still exist, but very low number density
- Pair Instability SNe at z<6 best chance to witness PopIII stars - if IMF allows them
- Majority of EMP gas is produced at z<10
- Galactic archeology probes primarily "low" redshift PopIII/PopII transition, not PopIII formation in minihalos, nor PopIII.1

Michele Trenti

“This is not a relativistic calculation, so I can go faster than the speed of light.”

-- Chris Fryer

Why the Early Universe? Grand Questions

- **What** - reionized the universe and were star-forming galaxies the primary agents?
- **When** - did reionization occur? Was it a sudden, protracted or even two-stage process?
- **How** - did it proceed? What processes defined the emerging mass function of galaxies
- **Then What?** - Implications for the subsequent development of galaxies and the IGM

Mostly a review, but with some collaborative material from:

Brant Robertson (CIT), Dan Stark (IoA), Masami Ouchi (OCIW), Eiichi Egami (Arizona), Andy Bunker (Oxford), Jim Dunlop & Ross McLure (Edinburgh), Jean-Paul Kneib (Marseilles), Johan Richard (Durham),

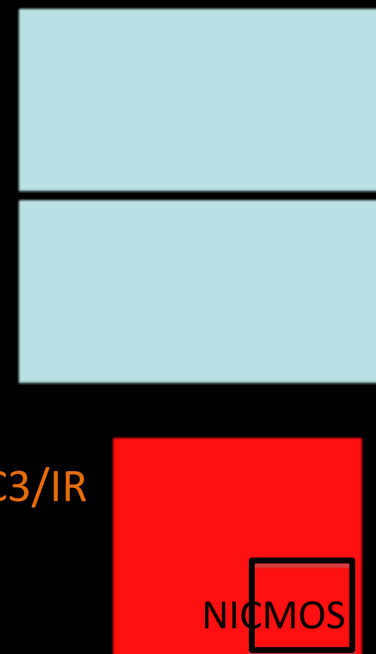
Richard Ellis

WFC3/IR *vs* NICMOS

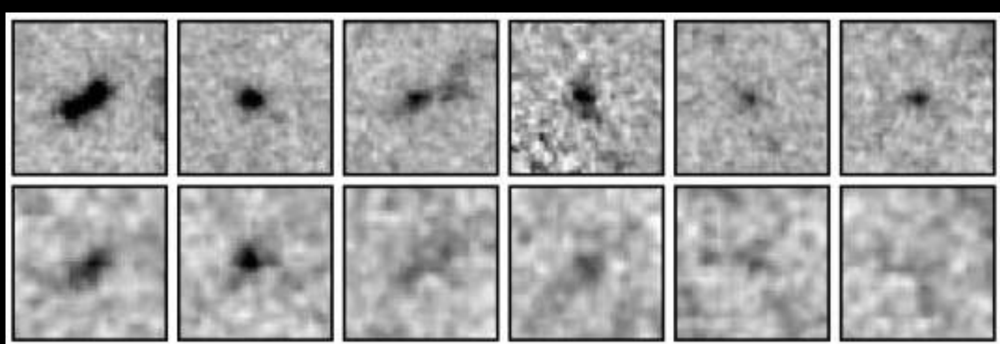
WFC3/IR is ~6X larger in area than NICMOS and much better matches ACS

to find a z~7 galaxy took ~100 orbits with NICMOS – with WFC3/IR it takes a few orbits

WFC3/IR has a discovery efficiency ~40X NICMOS



comparing the old and new Hubble infrared cameras



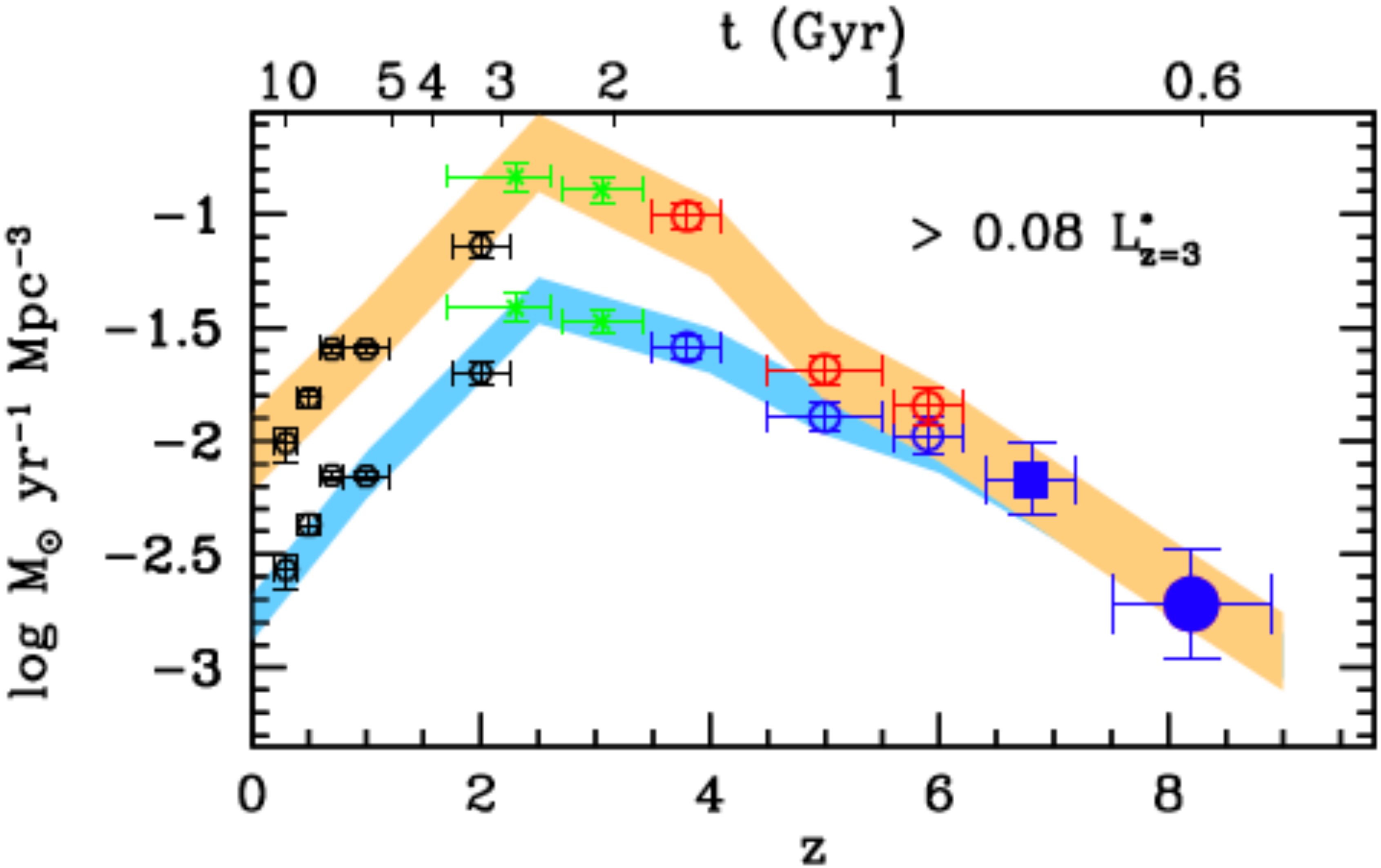
z~7 galaxies 2.2″ x 2.2″

Oesch et al

"I am humbled to be speaking after all this amazing WFC3 data, but I'm afraid we will have to return to theory land."

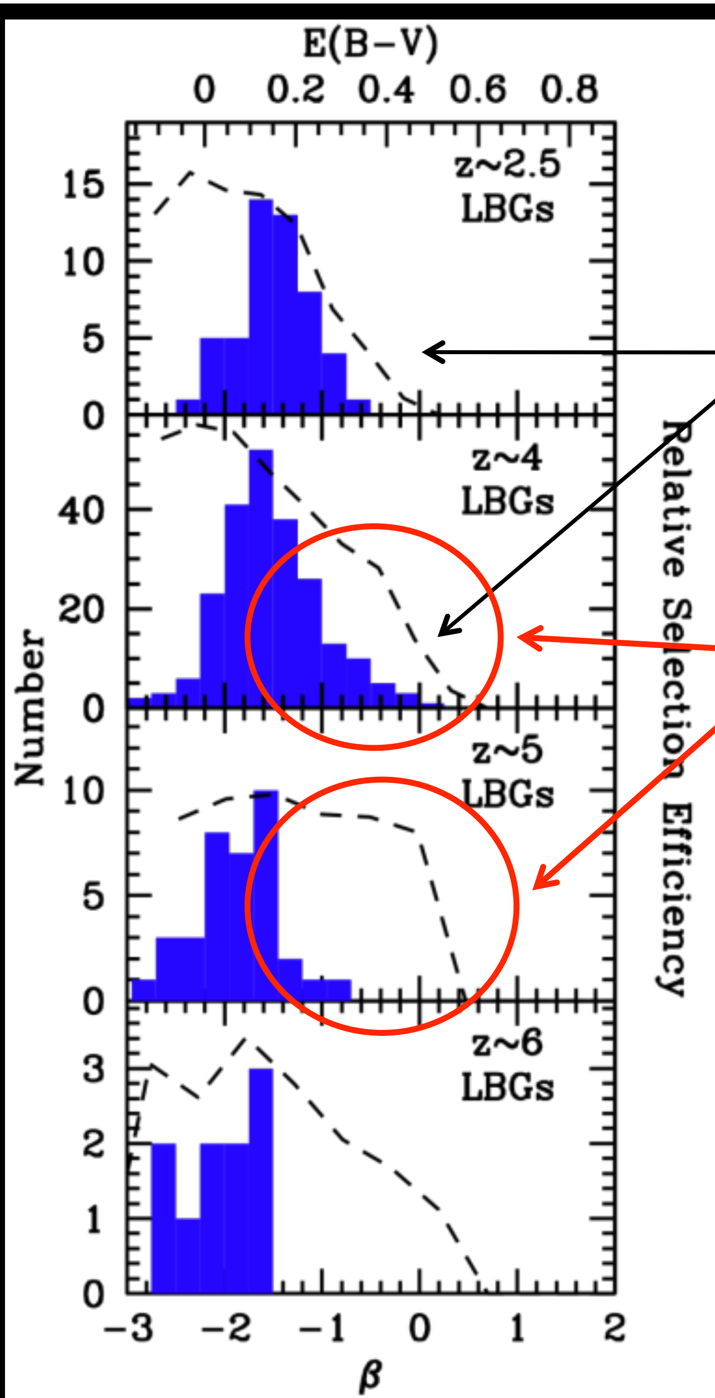
-- Zoltan Haiman

WFC3 Progress – I: Continued SF decline 3 < z < 8



Bouwens et al astro-ph/0909.1803

evolved galaxies not significant at z>4?



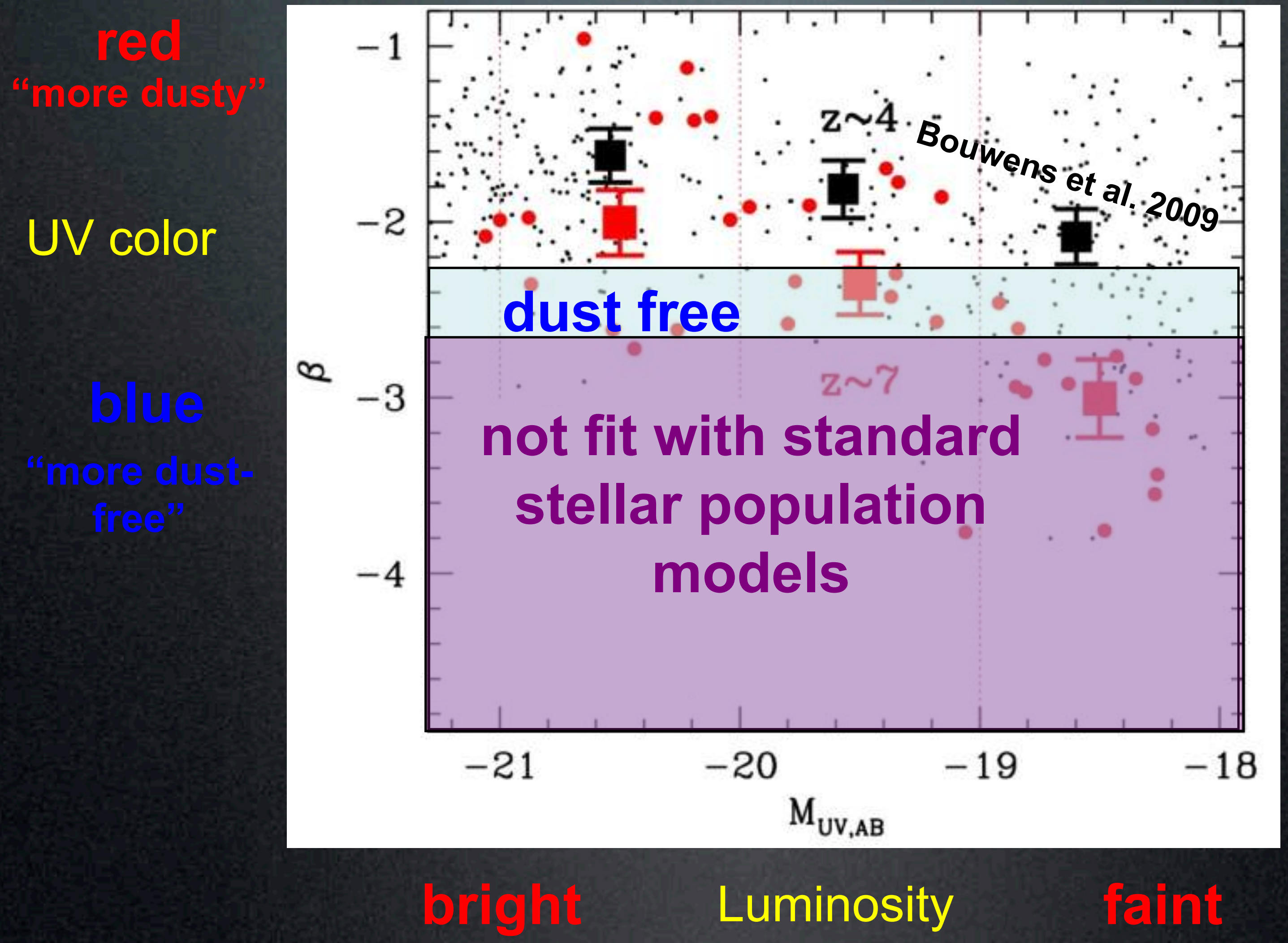
selection efficiency

“redder”, evolved sources could be detected in these ~0.1L* to ~2L* samples at z~4 and z~5+

there is *NOT* a continuum of UV slopes: => if there are evolved galaxies or dusty galaxies at z>4 they must have *distinctly* different UV properties or be quite rare

Garth Illingworth

z~7 galaxies from ultra-deep WFC3/IR observations of the HUDF: What about their UV colors?



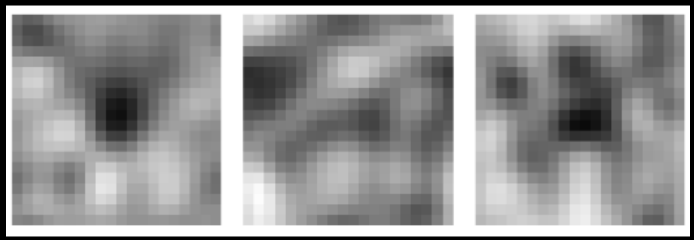
Bouwens et al. 2010

“We know where dust forms. Well, Eli knows anyway.”
-- Ranga-Ram Chary

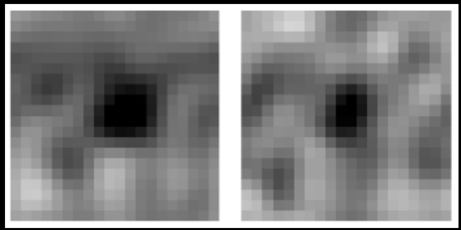
these galaxies probably formed stars much earlier

WFC3/IR Hubble and Spitzer results also combine to show us that z~8 galaxies could well have been forming stars two-three hundred million years earlier (at z>10-11)

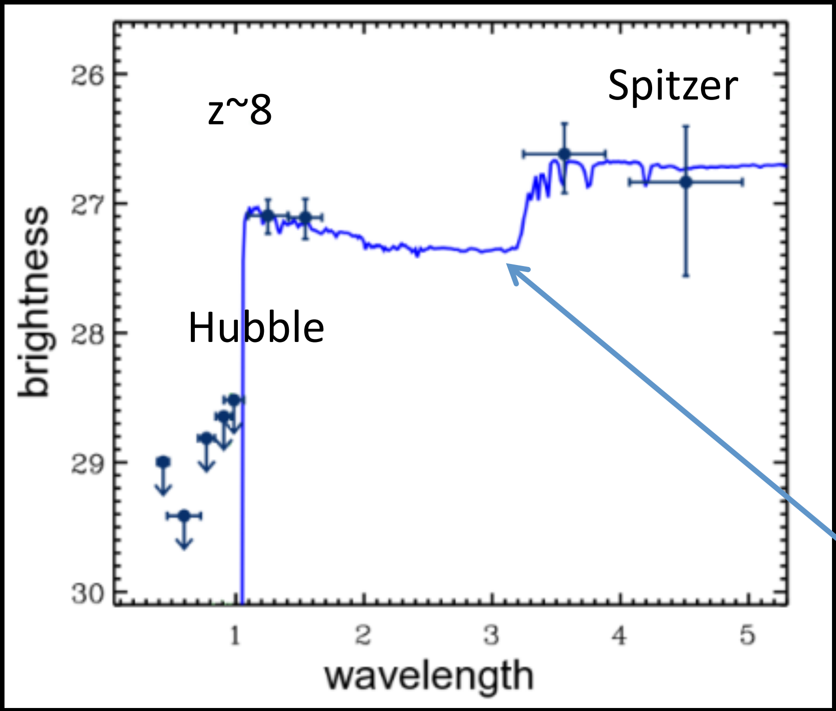
some individual z~8 Spitzer 3.6 µm images



z~8 summed Spitzer images



3.6 µm 4.5 µm

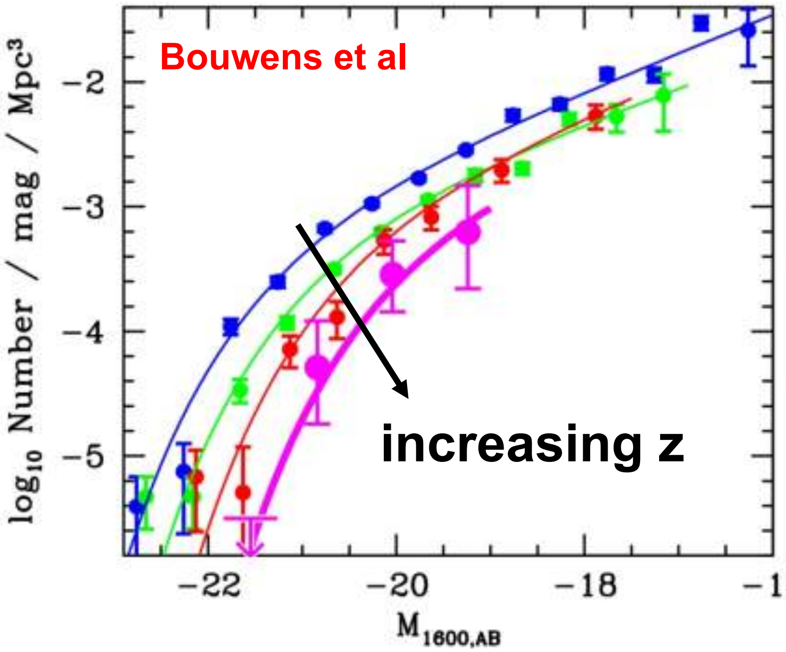


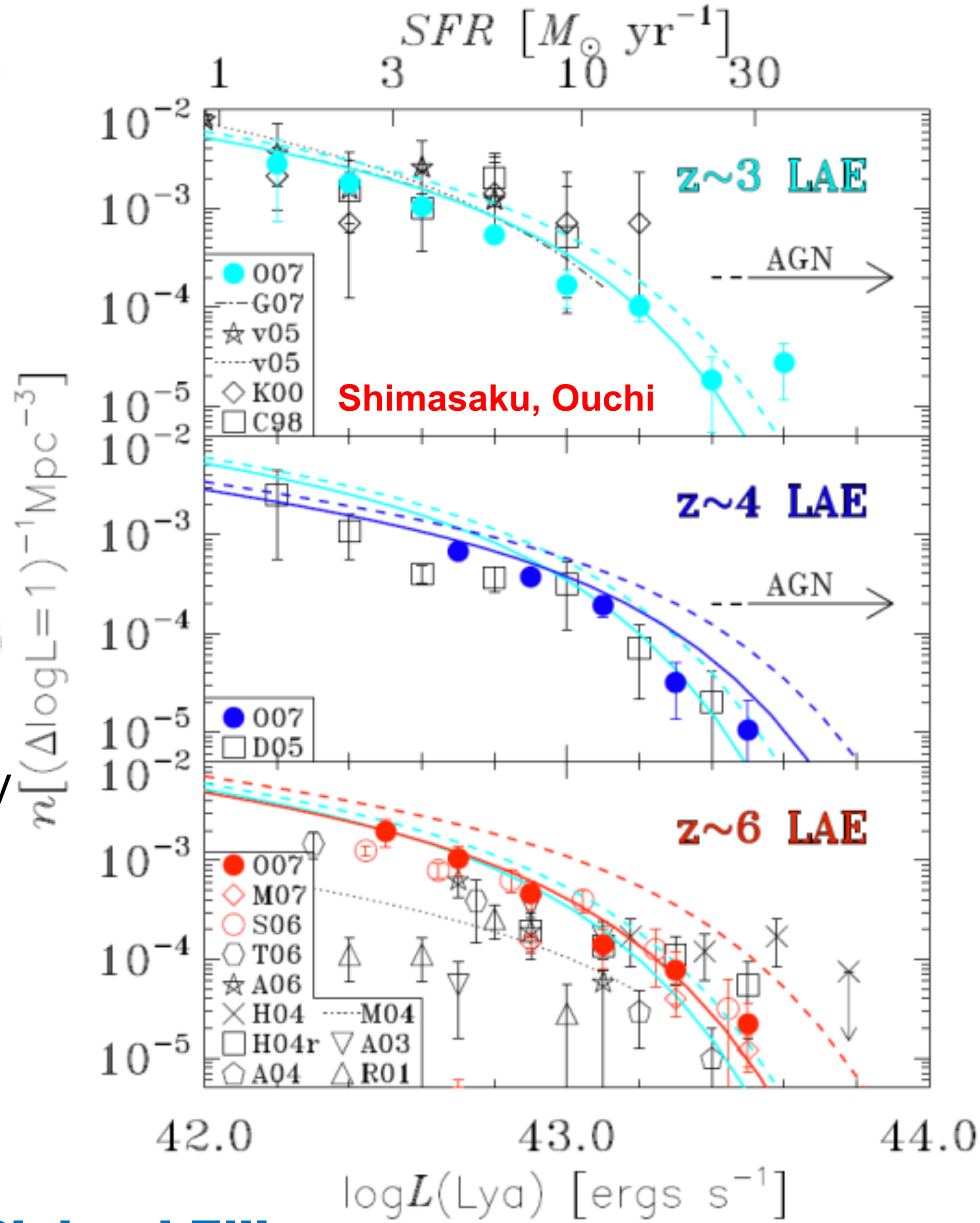
Labbé/Gonzalez et al

Model fit is BC03 CSF $0.2Z_{\odot}$ log M = 9.3
z~7.7 and 300 Myr (SFH weighted age = t/2)

Garth Illingworth

LBGs vs LAEs: Very Different Evolution





LBGs: Marked decline in UV luminosity density with redshift over 3<z<6

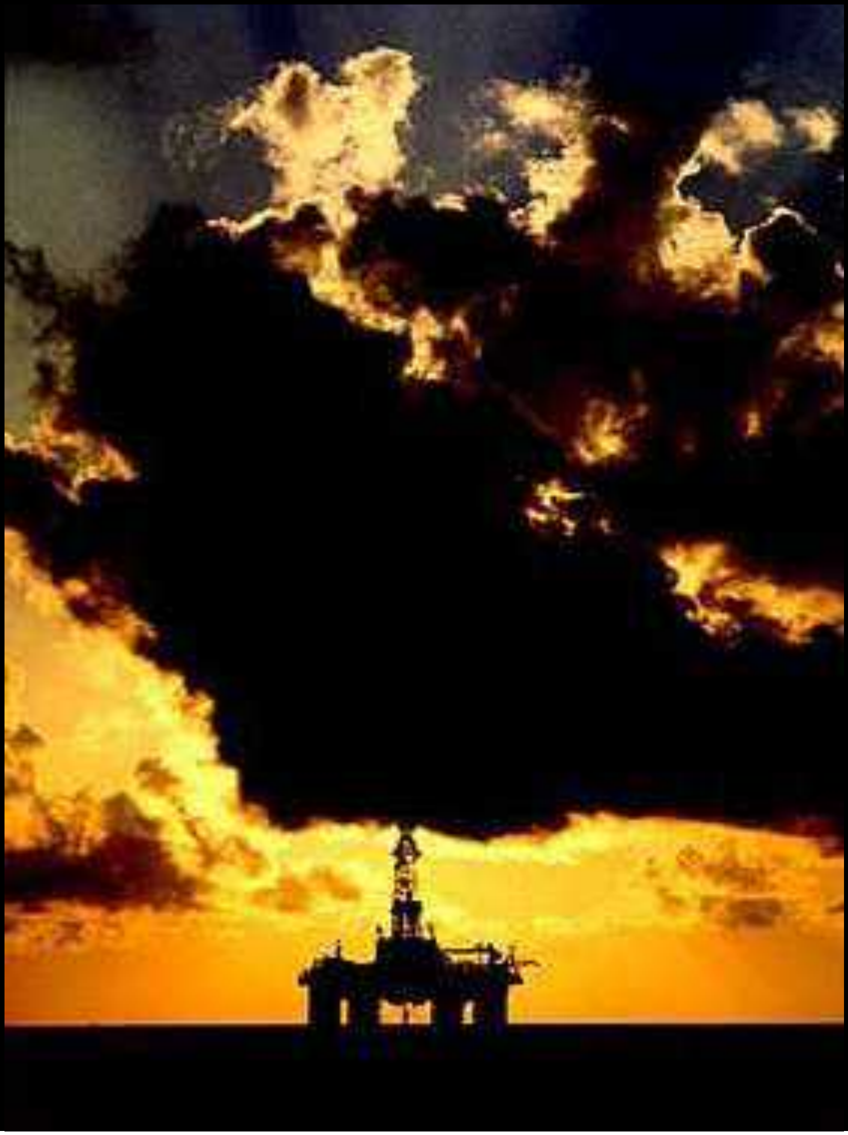
LAE: no evolution to z~5.7

Increasing dominance of Lyα emission at high z

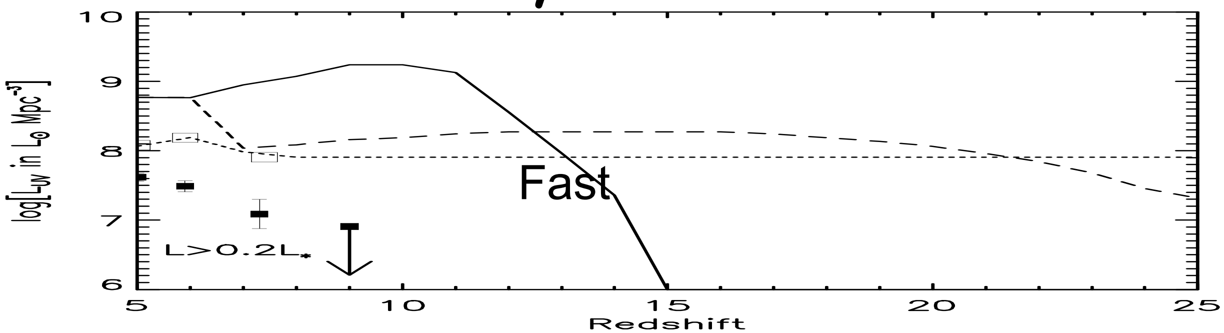
Reduced dust; HI covering fraction, faster duty-cycle of SF?

Richard Ellis

“Can we see galaxies at z=10?
-- An unequivocal maybe.”
-- Garth Illingworth



Minimum Required Evolution of UV Luminosity Density for Reionization



Ranga-Ram Chary

"We are at the start of a revolution."

-- Chris Carilli

“Stellar seed” *vs* “direct collapse”

- **STELLAR SEEDS**

  uninterrupted near-Eddington accretion

  - continuous gas supply
  - avoid radiative feedback depressing accretion rate
  - must avoid ejection from halos

- **DIRECT COLLAPSE**

  rapid formation of 10^5-10^6 $M_\odot$ black holes either by direct collapse of gas or super-Eddington accretion onto a lower-mass seed

  - gas must be driven in rapidly (deep potential)
  - must avoid fragmentation
  - transfer angular momentum

Conclusions

1. Explaining z=6 quasar SMBHs with $\sim 10^9 M_\odot$ is a challenge, requiring optimistic assumptions, unique to these objects

   (i) stellar seeds common, embedded in dense gas, can grow at Eddington rate without interruption, or

   (ii) rapid "direct collapse" in rare special environment in "second generation" halo with no metals or H_2, or

   (iii) global instabilities and supersonic turbulence (?)

2. Extra challenge: not to overproduce number of $\sim 10^{5\text{-}6} M_\odot$ SMBHs. (i) seed formation stops at ultra-high z~25 ?

   (ii) internal feedback always maintains M_{BH} - σ relation?

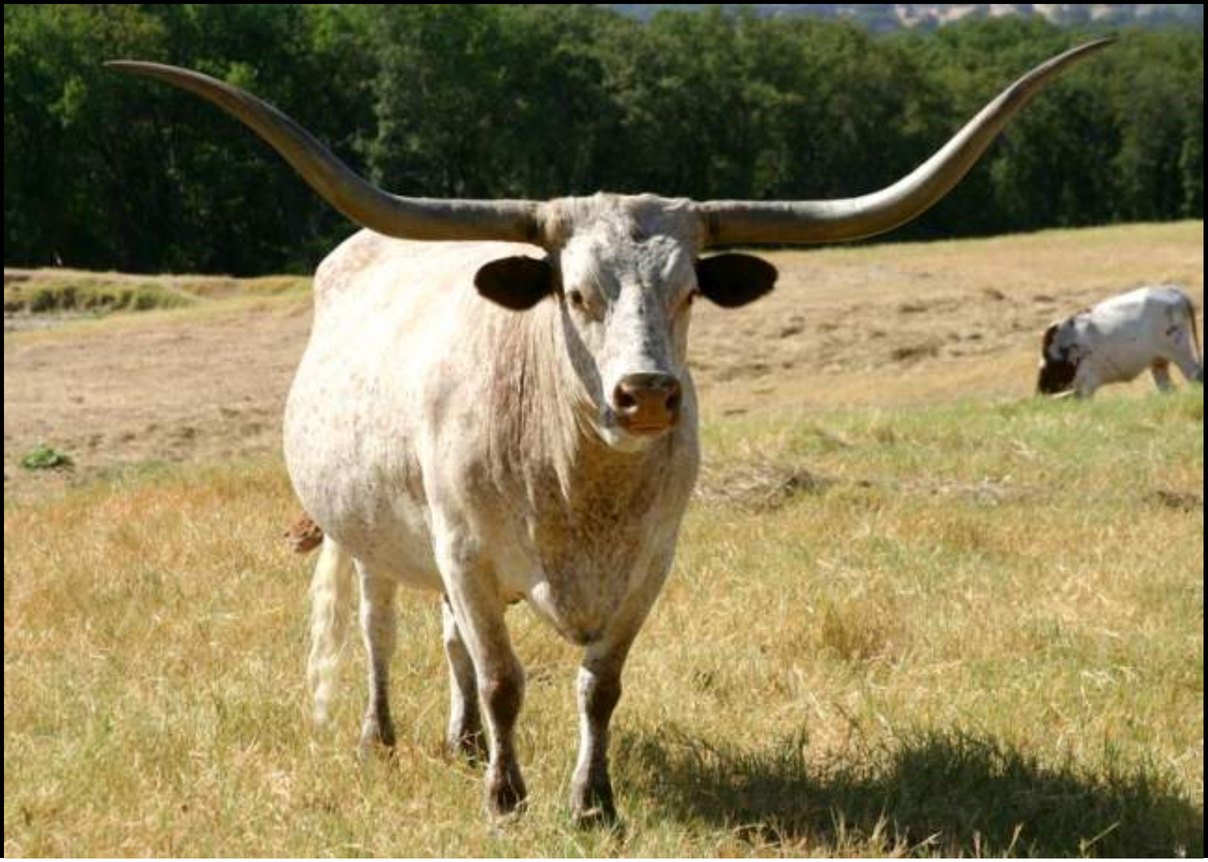
3. Direct detections (optical/radio/X-ray) down to $\sim 10^{5\text{-}6} M_\odot$ at $z=10$

   0-30 LISA merger events/yr + Indirect reionization signatures (21cm)

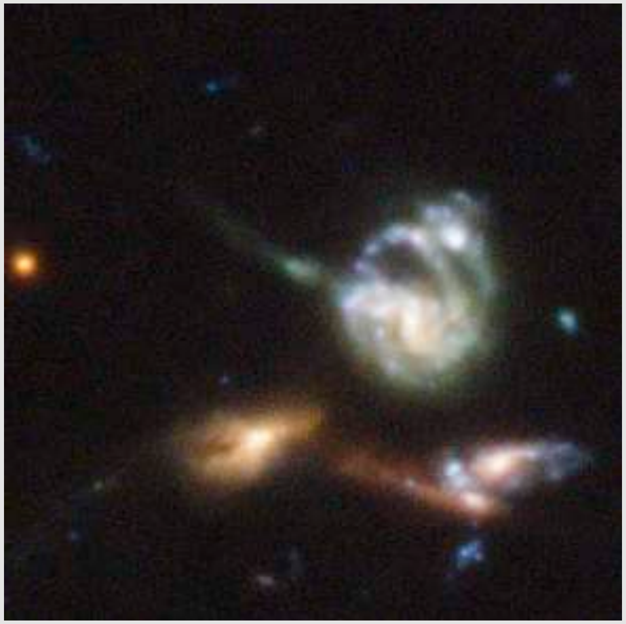
Zoltan Haiman

“I’ll follow the theme of the meeting and talk about our new favorite observatory.”

-- Jason Tumlinson

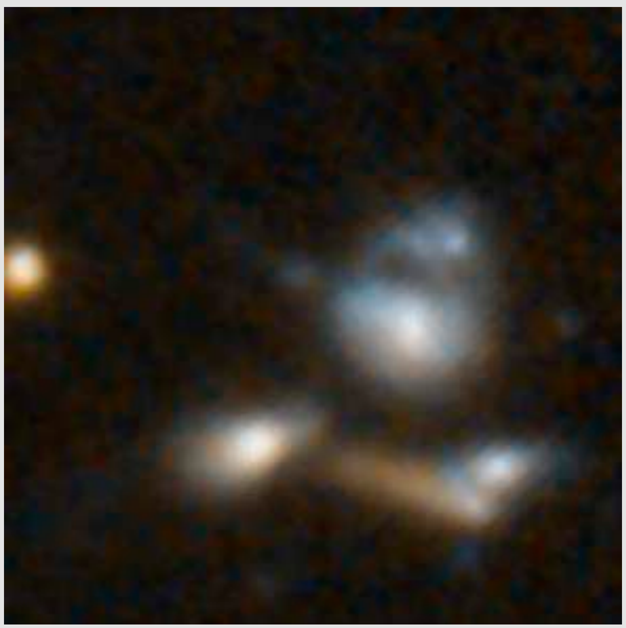


HST/ACS
Viz



JWST/NIRCam
Viz

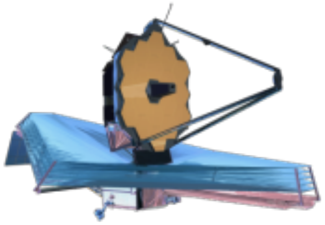
HST/NICMOS
J H



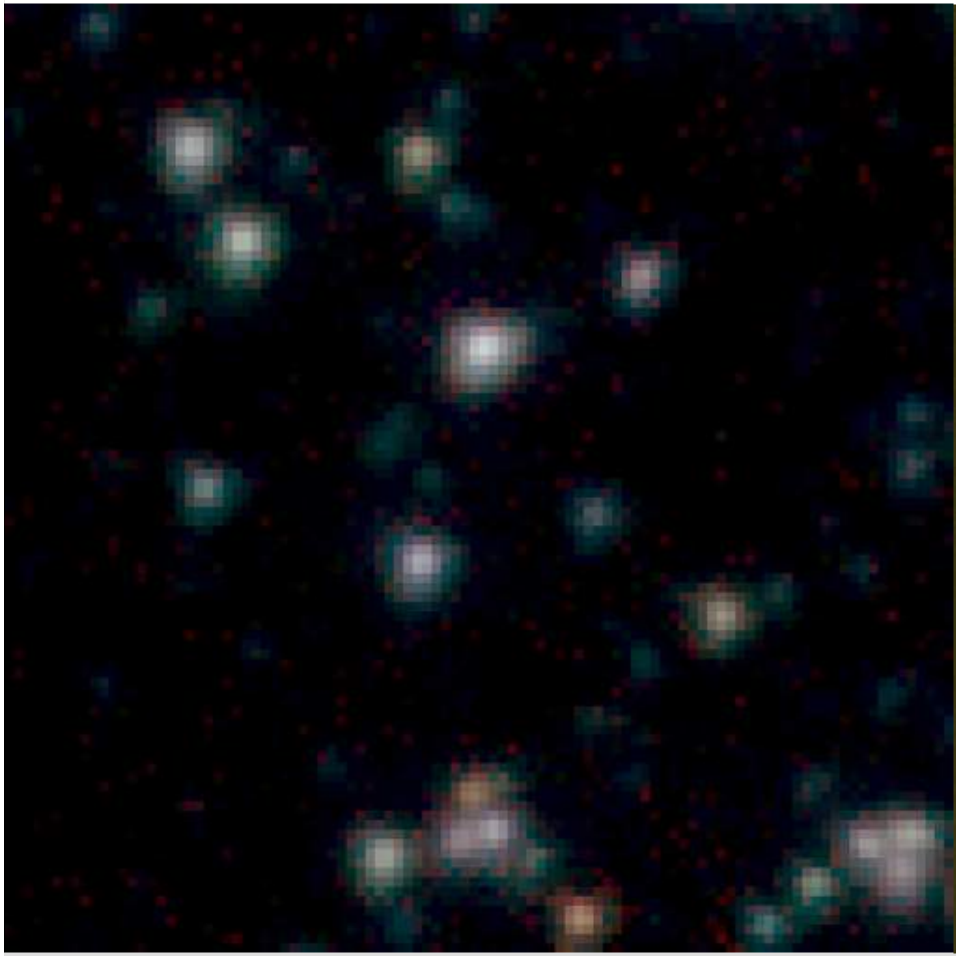
JWST/NIRCam
J H

Massimo Stiavelli

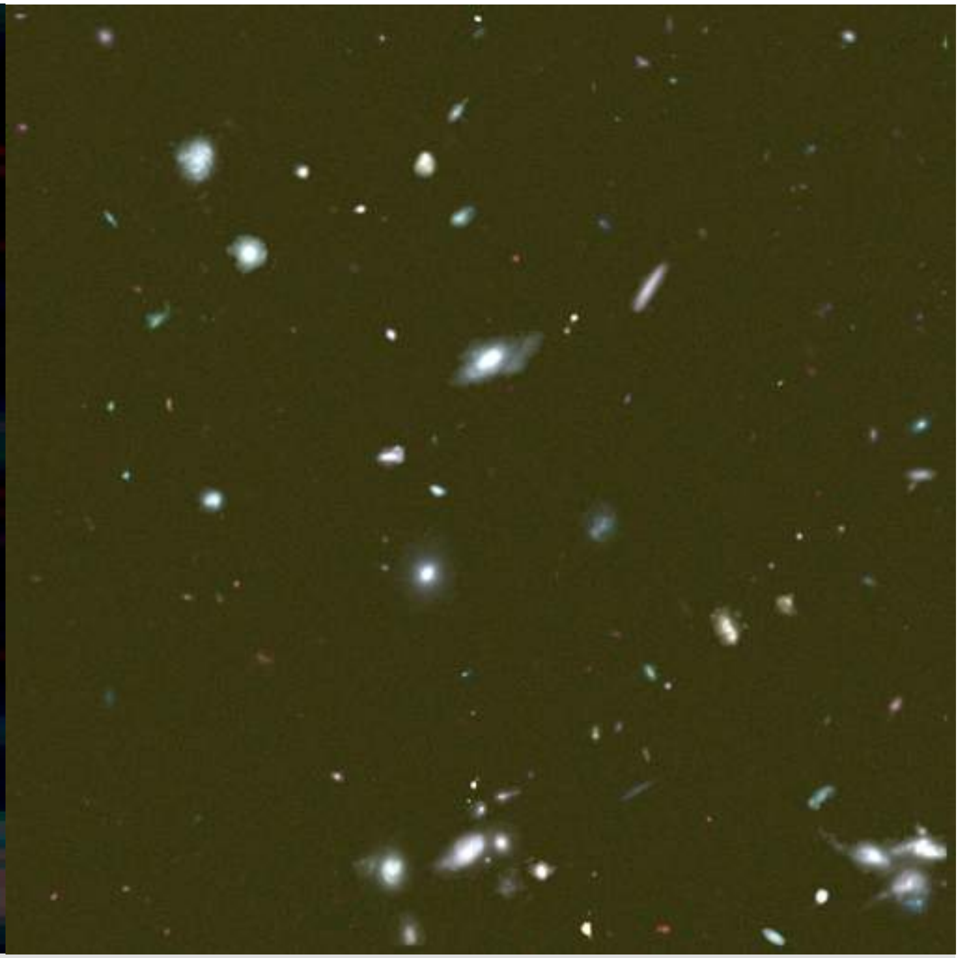
JWST-Spitzer image comparison



1'x1' region in the UDF – 3.5 to 5.8 μm



Spitzer, 25 hour per band (GOODS collaboration)



JWST, 1000s per band (simulated)

Massimo Stiavelli


Jason Tumlinson

Live update every 60 seconds http://www.jwst.nasa.gov/webcam.html.

Sneak preview: Astronomy Picture of the Day for tomorrow.

“Can you put error bars on the word ‘Reasonable’ and propagate them through your models?”

-- Daniel Wolf Slavin

First-light science in the era of large telescopes

Thirty Meter Telescope

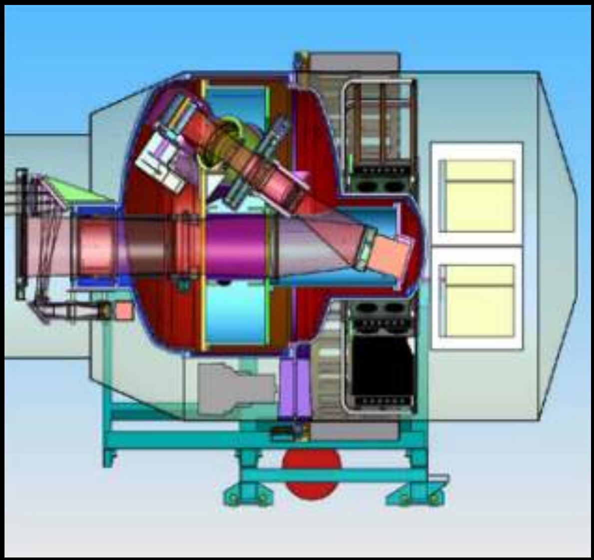
TMT first-light IR instruments that will tackle first light:

- **IRMS:** 2 arcminute field-of-view; can use for narrow-band imaging
- **IRIS:** 16-arcsecond fov DL imager/ 0.26-3.2 arcsecond IFU

Betsy Barton

IRMS: InfraRed Multi-object Spectrograph

- **Based on Keck/MOSFIRE**
- **0.95-2.45 μm**
- **All of Y, J, H, or K at once**
- **2 arcminute field of view**
- **46 reconfigurable cryogenic slits**
- **0.06-0.08 arcsecond sampling**
- **80% energy in 2x2 pixels**
- **R ~ 4660**



Betsy Barton

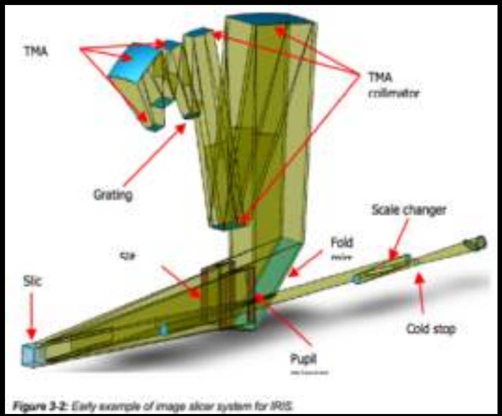
IRIS: InfraRed Imaging Spectrograph

IFU:

- 64 x 64 “pixel” IFU; up to 128 x 128 in some modes (?)
- 0.84-2.45 μm requirement
- 4 plate scales: 4, 9, 25, 50 mas
- 4 fields of view for IFU, at least: 0.26, 0.64, 1.60, 3.20 arcsec
- Full Y, J, H, or K coverage at once
- R ~ 4000
- Design currently lenslet AND image slicer

IMAGER:

- 16 arcsecond fov
- 4 mas sampling



(Taylor & Prieto)

Betsy Barton

“Follow the dust.”

-- Francoise Combes

ALMA Status

•Antennas, receivers, correlator in production: best submm receivers and antennas ever!

•Site construction well under way: Observation Support Facility, Array Operations Site, 3 Antenna interferometry at high site!

• Early science call Q1 2011

EVLA Status

•Antenna retrofits 70% complete (100% at $\nu \geq$ 18GHz).

•Early science in March 2010 using new correlator (2GHz)

•Full receiver complement completed 2012 + 8GHz

Chris Carilli

Capacities of ALMA

➔50 x 12m, bases from 200m to 14km, 3mm to 0.3mm
(factor ~6 in surface with respect to IRAM-PdB)
+ 4 antennae of 12m + 12 antennae of 7m ACA (Japan)
➔4 frequency bands at the beginning
84-116 GHz, 211-275 GHz, 275-370 GHz, 602-720 GHz
Large bandwidth of 8GHz/polar

Spatial resolution, up to 10mas,
Spectral resolution up to $R=10^8$
Dynamical range from 128x128 to 8192x8192 pixels

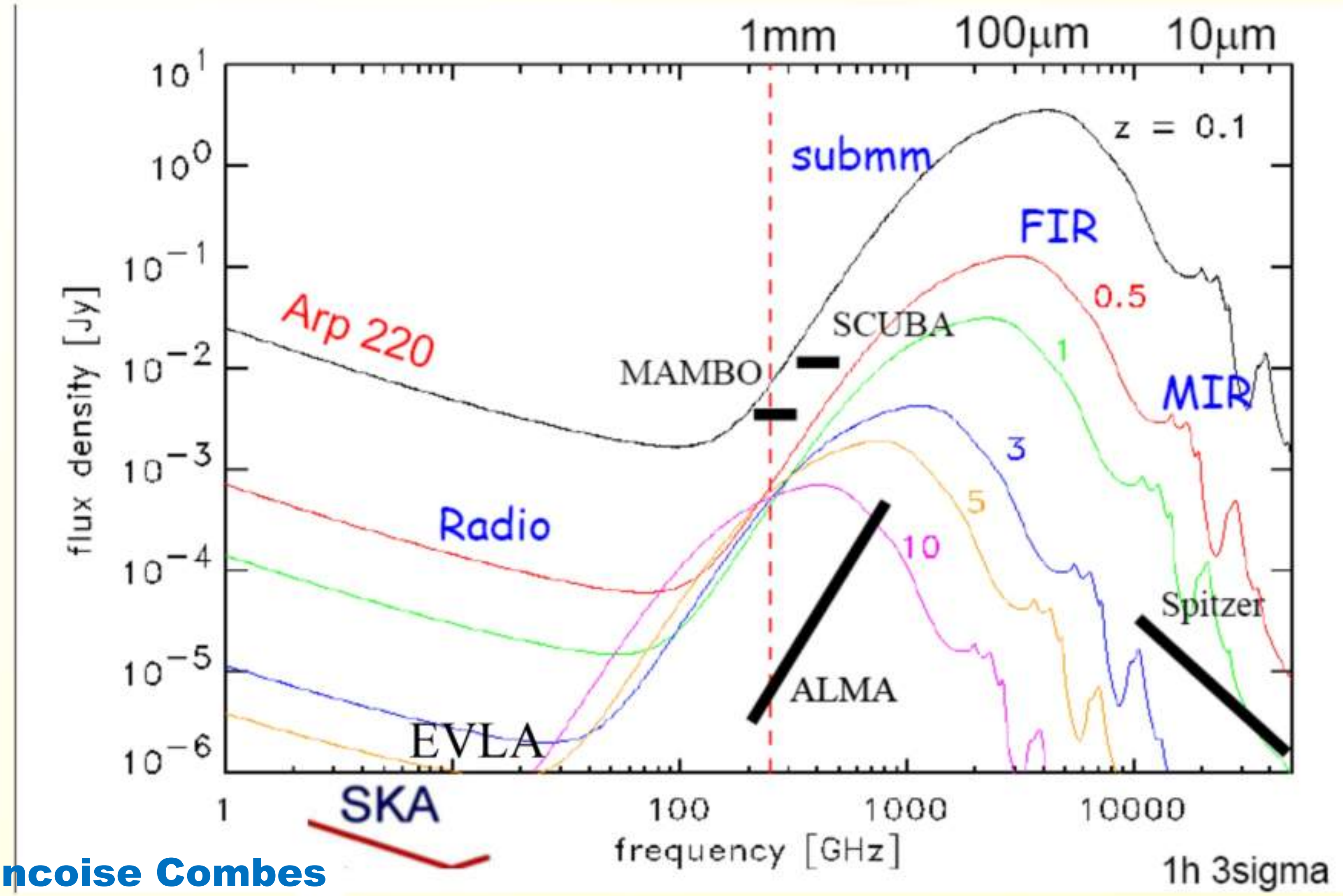
Small field of view: from 1arcmin (3mm) to 6 arsec (0.3mm)
Possibility of mosaics

Francoise Combes

Early Science 2011? **In 2012-3:** Full Operation

Main privilege of the mm/submm domain

Negative K-correction: example of Arp 220



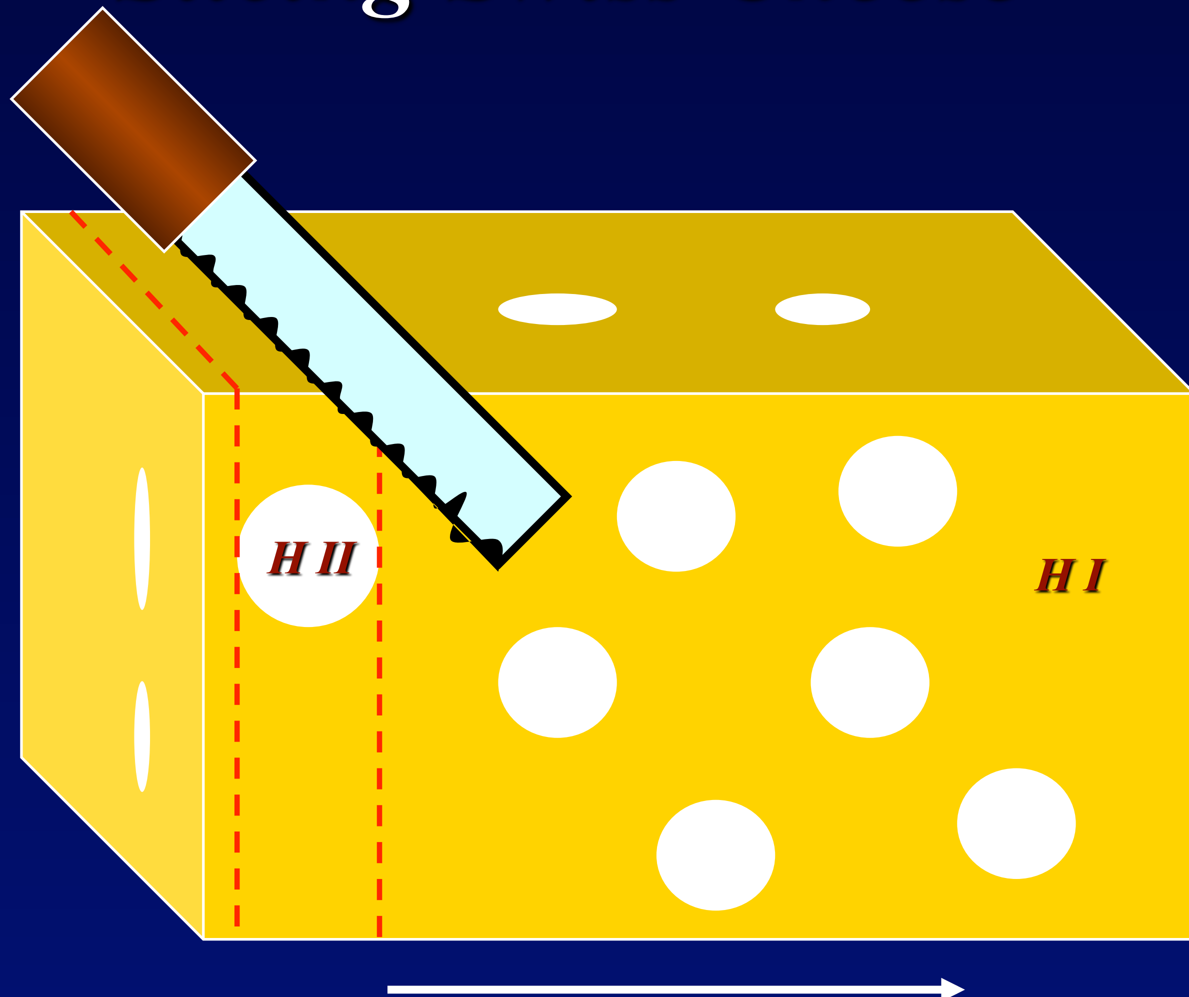
Francoise Combes

"My prediction is somewhere between 0 and 100%, inclusive."

-- Brian O'Shea

21cm Tomography of Ionized Bubbles During Reionization is like

Slicing Swiss Cheese



Observed wavelength ⇔ distance

21cm â (1 + z)

Avi Loeb

“If dark matter is not self-annihilating then everything I am saying is wrong. Maybe that is why they put me at the end.”

-- Fabio Iocco

I'd like to thank my collaborators:
Google images, and
You:

“Obesity was ubiquitous in the early Universe.”

-- Ranga-Ram Chary

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