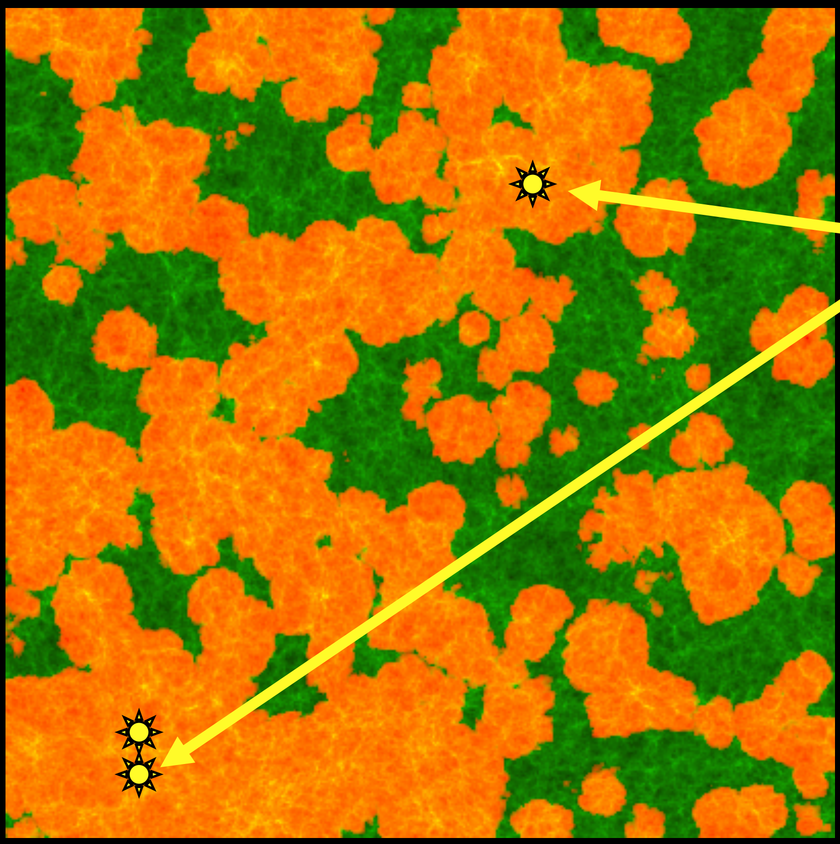
Exploring observational parameter space at very high redshifts

Betsy Barton

(UC Irvine)

J-D Smith (Toledo), Romeel Davé (Arizona), Casey Papovich (Texas A&M), Joe Jensen (Utah Valley College), Jeff Cooke (Caltech)

Early, ionizaing seed galaxies and reionization



First-light galaxies (and causes of reionization) that we can see in Lyα?

(Iliev et al. http://www.cita.utoronto.ca/~iliev/dokuwiki/doku.php?id=reionization_sims**)**

How do we guess what is out there?

- Theory tells us about
  - dark matter halo sizes (S/M/L?)
  - the IGM (neutral to "mixed" to ionized)
  - the very first stars (e.g., very big and hot?)
  - the possible progress of ionization (e.g., starts outside dense regions, then the bubbles coalesce?)

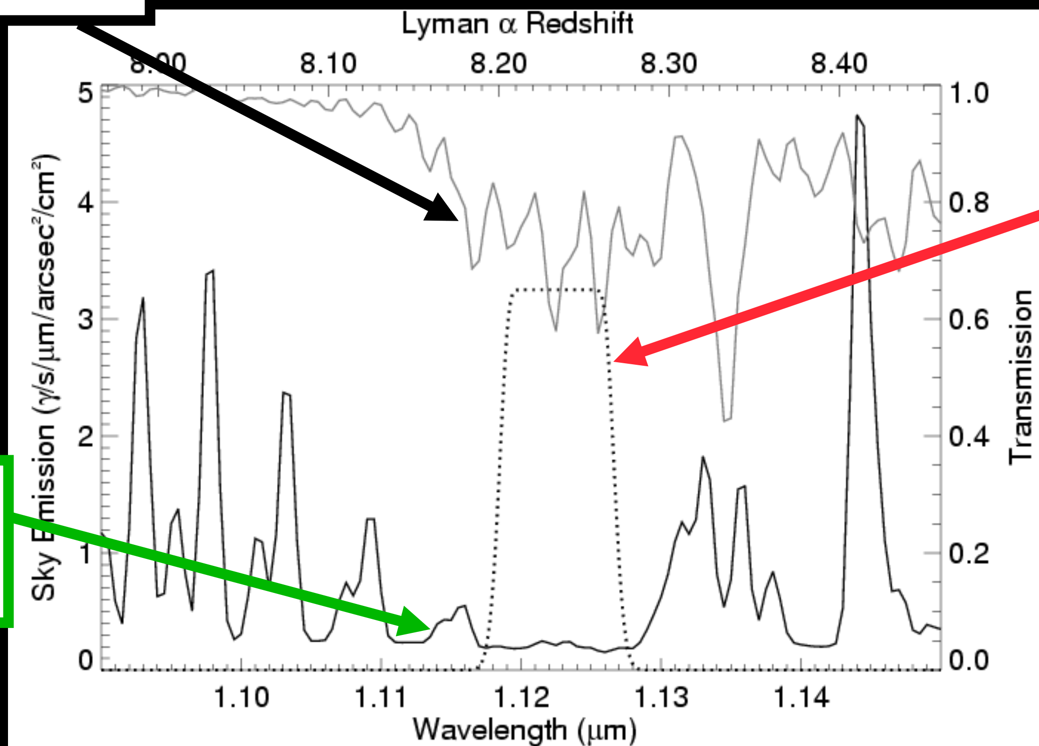
Theory tells us *less* about the baryonic properties of first-light sources

How do we figure out where to look in order to definitively find out what is out there (in Lyα)?

- Extrapolate from "low" redshift ($z < 6$)
  - Very (overly?) conservative about SFR vs. Lyα flus
  - Optimistic regarding the IGM
  - Problem is that we are searching for the epoch when things change dramatically to metal-free star formation and when the IGM is known to change dramatically
- Try to parameterize high-z galaxies with a few parameters and see what you predict
  - Very sensitive to what you choose
- Just do a thorough exploration of parameter space
  - Eventually, it should work
  - Expensive, and you don't know when it will work

First generation experiment: Window at z=8.227 w/ Gemini/NIRI

transmission



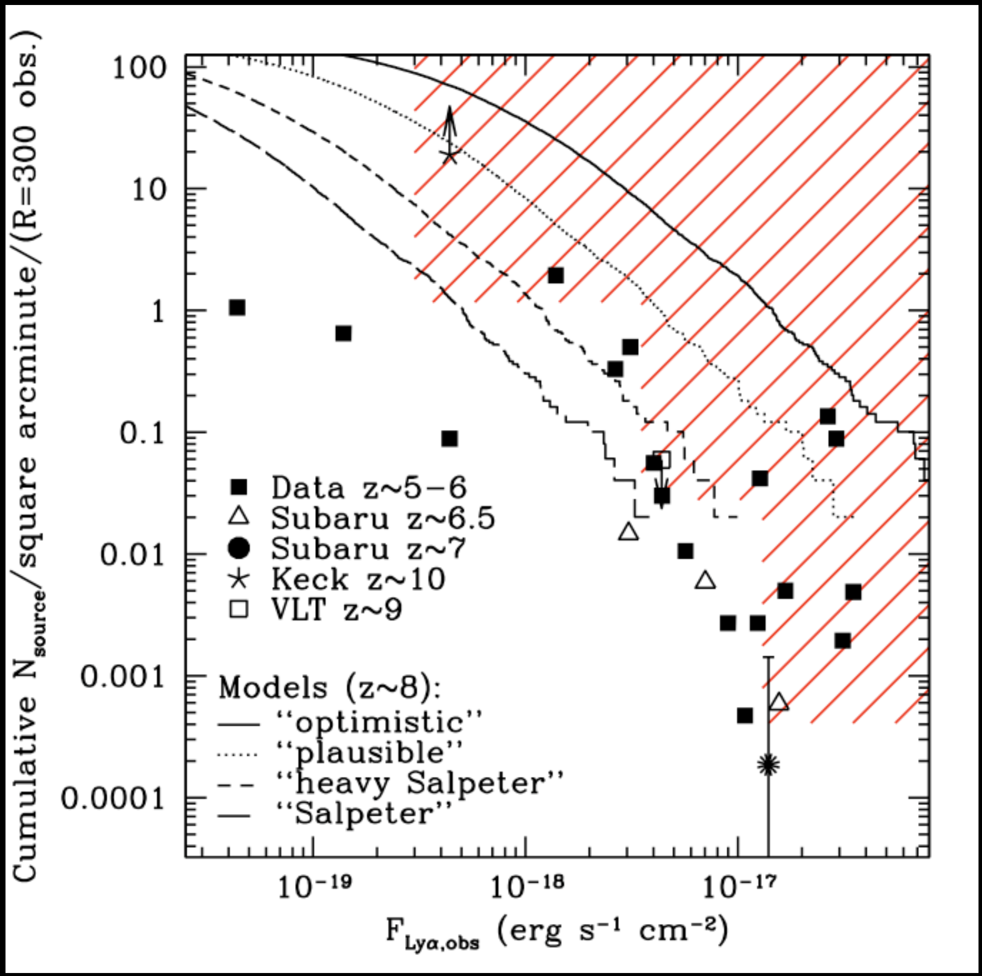
sky emission

Narrow-band filter (R=125)

Noise down by factor of >10 from other Gemini/NIRI narrow-band filters

(Barton et al. 2004)

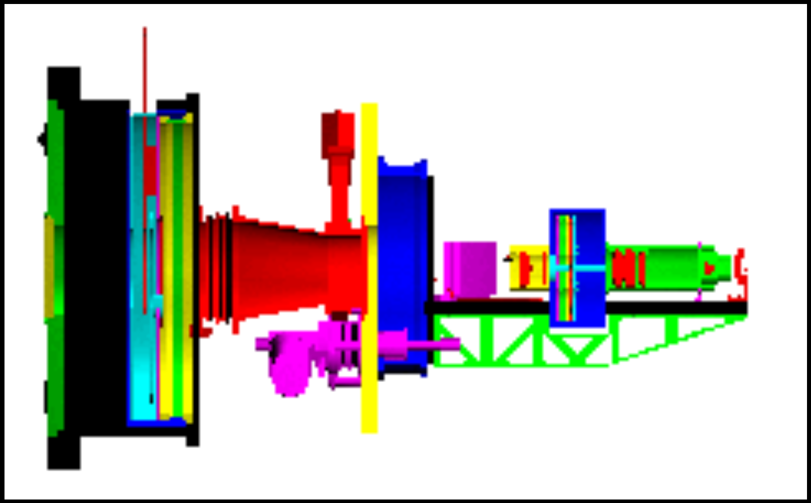
What do we know now?



Definite sources and likely/possible candidates at z=5-10

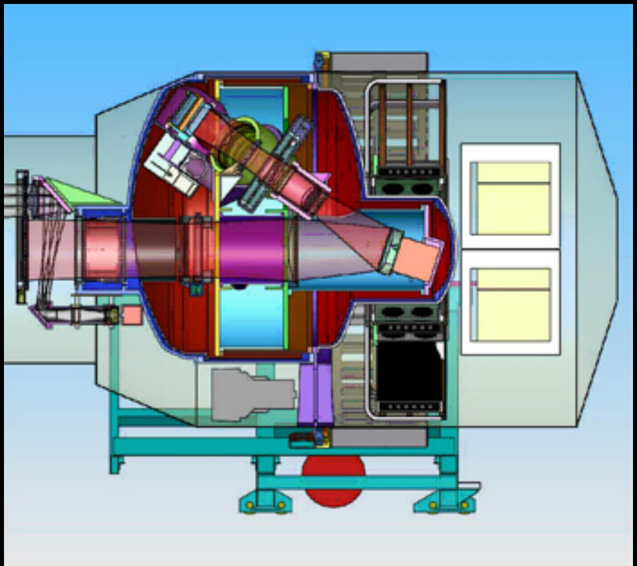
Fluxes shifted to common luminosity distance at z=7.7

The Next Steps for the US: FLAMINGOS 2 and MOSFIRE



Gemini-South FLAMINGOS 2:

6.1' FOV



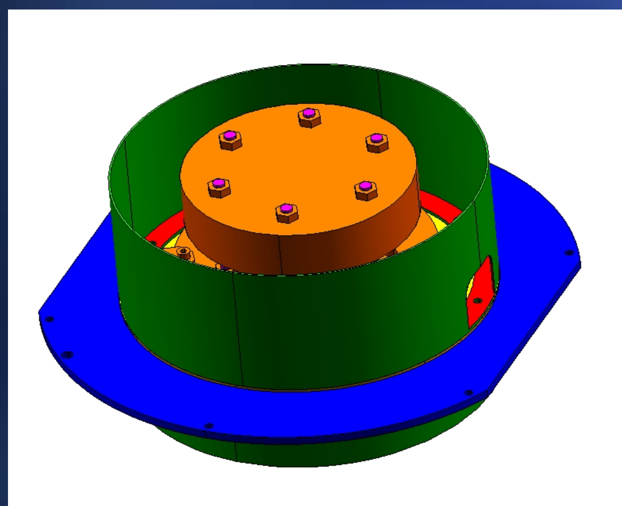
Keck MOSFIRE:

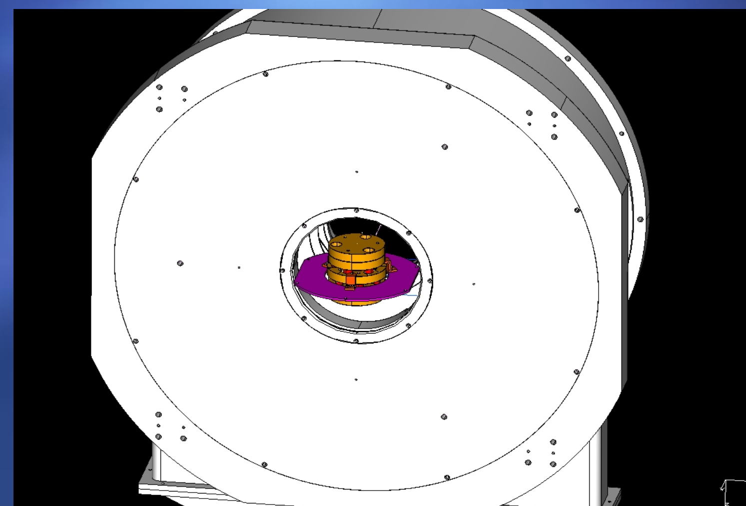
6.2' FOV

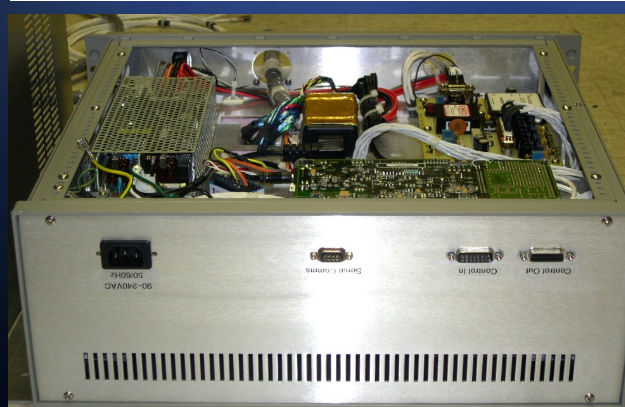
DAZLE on VLT already in operation

F2T2

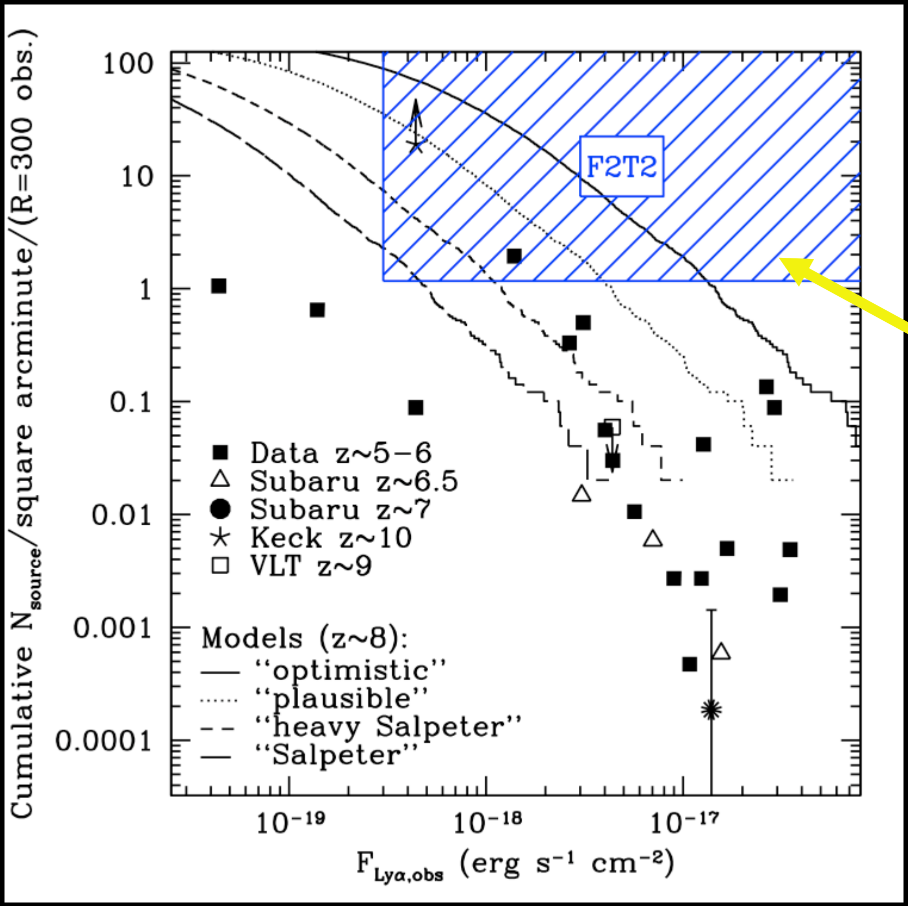
An engineering prototype for the JWST Tunable Filter Imager…
F2T2 will be fed by a multi-conjugate adaptive optics system
and be a facility-class instrument on Gemini <u>next year</u>.







A lensed cluster survey on Gemini with AO (F2T2)



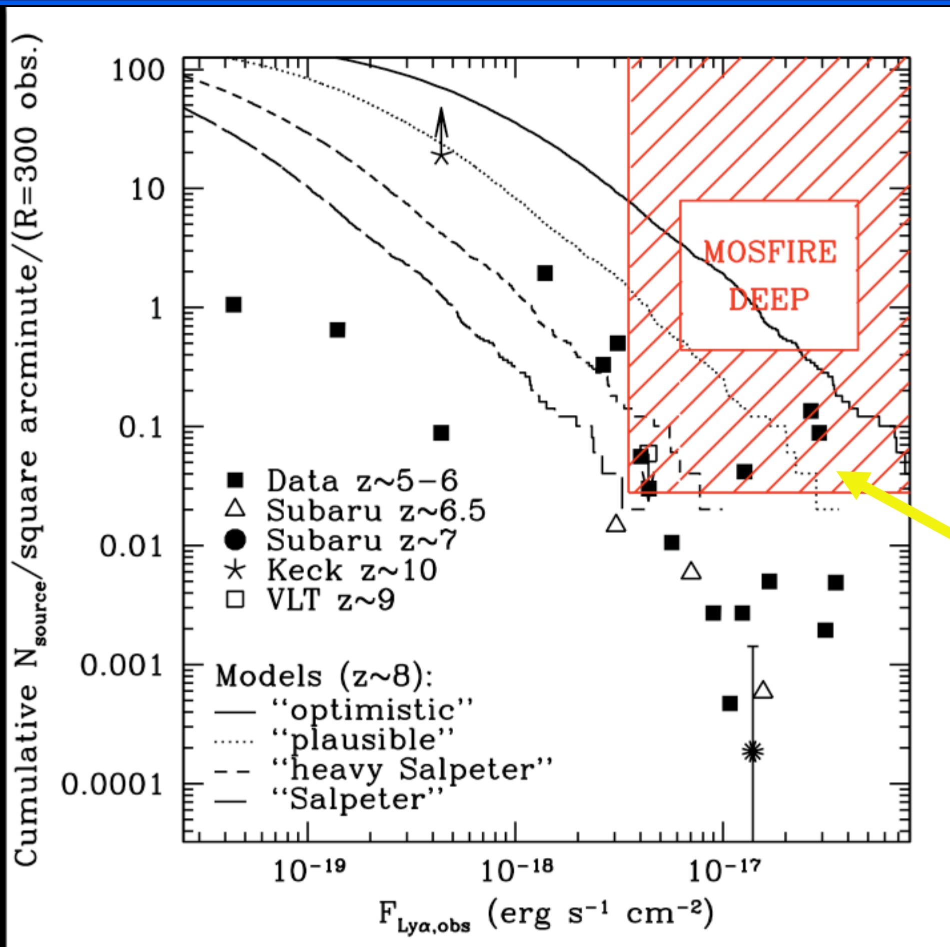
z=7.2-10

Approx. 20 nights with F2T2

Region of parameter space where expectation value of detected sources is >= 1

(Models from Barton et al. 2004)

A Single-field Deep (Unlensed) Survey

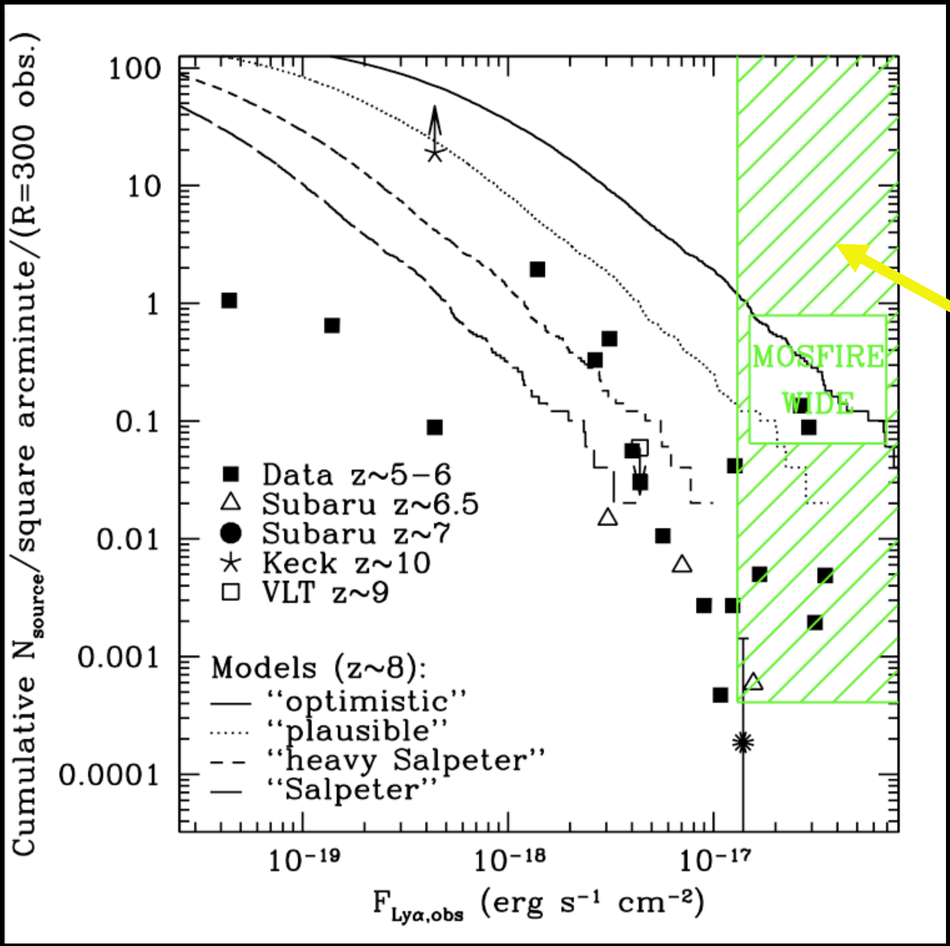


z=7.7
Approx. 13 hours with Keck/MOSFIRE

Region of parameter space where expectation value of detected sources is >= 1

Related science on VLT (DAZLE); planned for FLAMINGOS2

A Wide-field (Unlensed) Survey

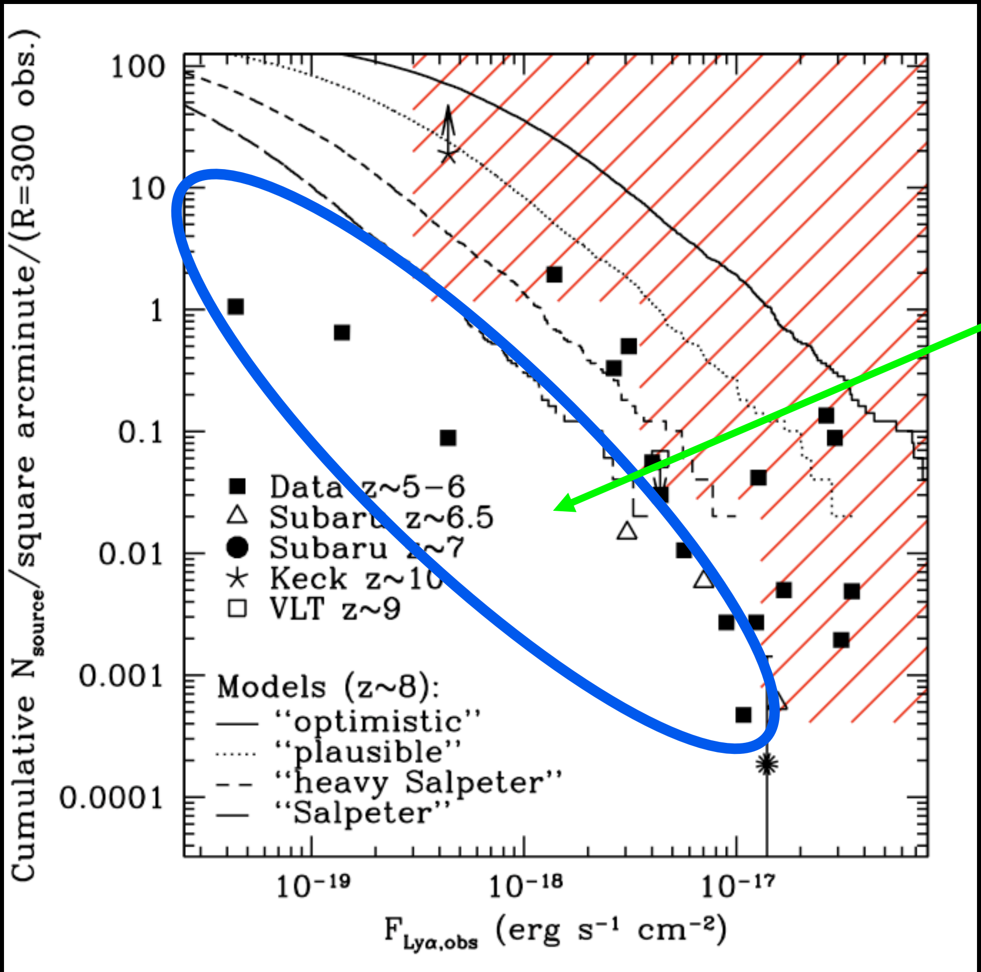


z=7.7
Approx. 50 hours with Keck/MOSFIRE

Region of parameter space where expectation value of detected sources is >= 1

Related science on VLT (DAZLE); SUBARU; planned for Gemini/ FLAMINGOS2

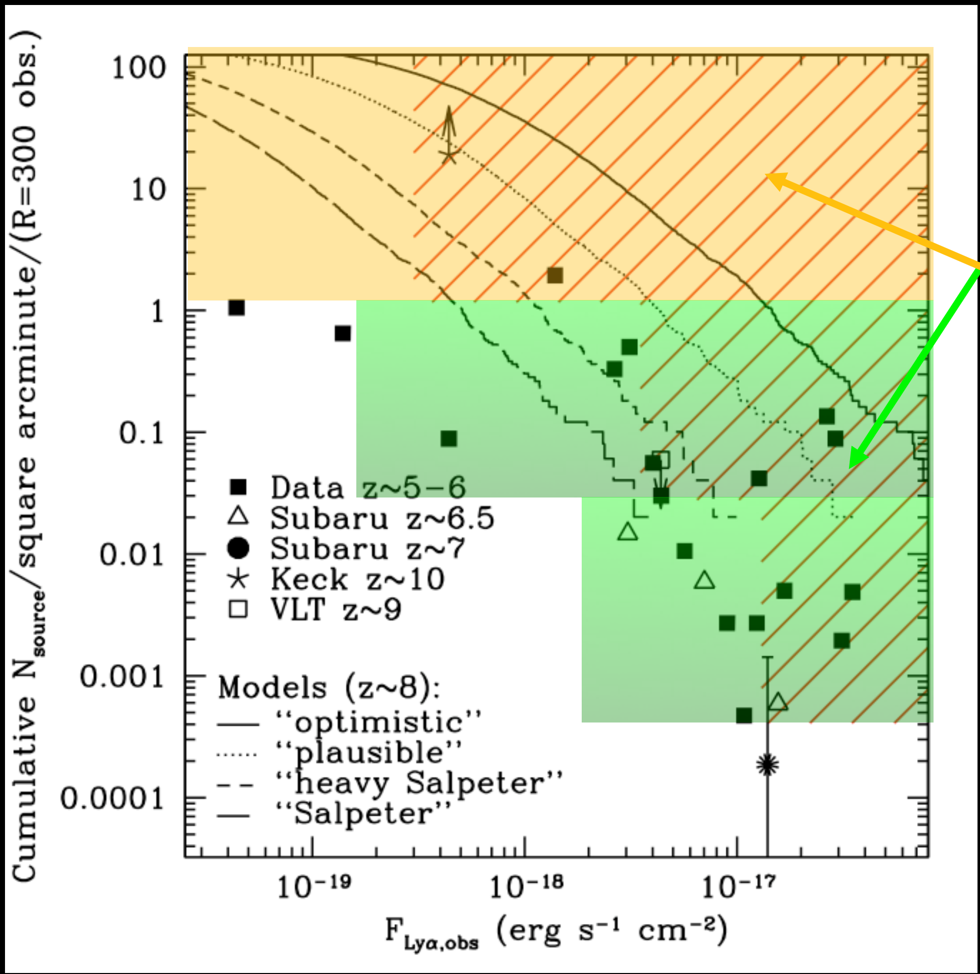
What might we know by 2018?



Difficult/impossible to explore with 8-10-m class telescopes at z > 7

z beyond ~8-10 essentially impossible

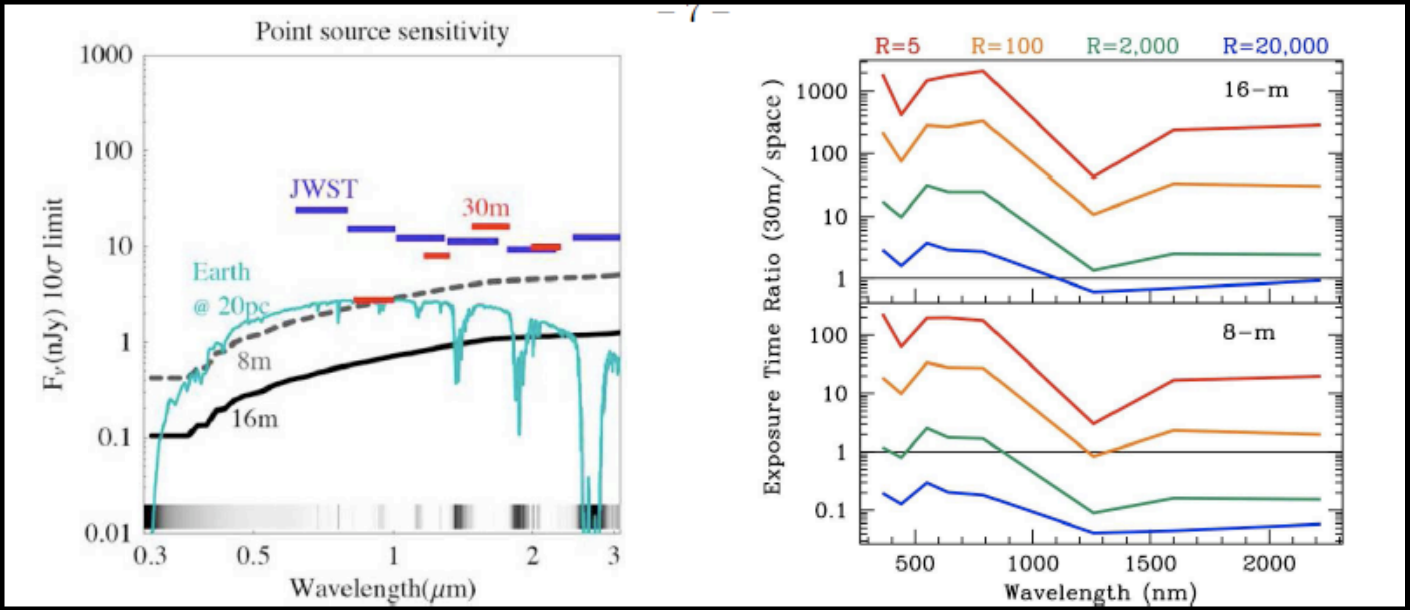
Changes in the ELT Era



Blind surveys in the 10^{-19} regime; lensed surveys in the 10^{-20} regime

We won't be doing luminosity function science any more; we can be more clever

Ground vs. space



(Matt Mountain et al. 2009; Astro2010 white paper; arXiv: 0909.4503)

- JWST and 30-meter not so far apart in broad-band NIR
- In NIR, TMT beats even 8-m in space at R >> 100
- TMT likely will beat JWST for R~100; JWST will have full λ coverage, win at longer wavelengths

First-light science in the era of large telescopes

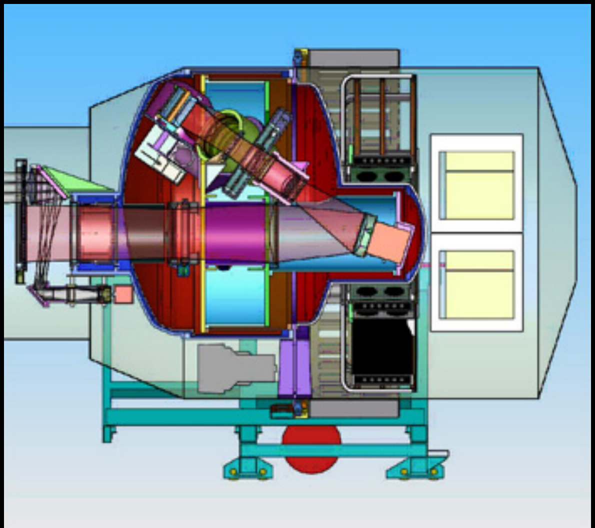
Thirty Meter Telescope

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

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**



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

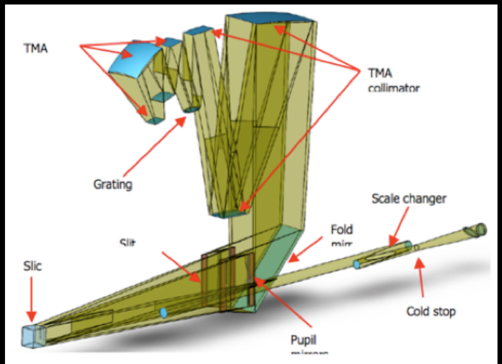


Figure 3-2: Early example of image slicer system for IRIS.

(Taylor & Prieto)

Can we benefit from adaptive optics for first-light Lyman α science?

- Early galaxies are predicted to be smaller than the seeing limit
  - (if the IGM around them is neutral, forget about it)
  - empirical best-guess scaling suggests candidate high-z galaxies are the right size for IRMS/coarse IRIS modes
- Tiny, luminous star clusters in formation are not beyond the reach of ELTs
  - Nominal star formation rate of unresolved 1 solar mass per year yields detectability well beyond z=10 (right size for IRIS)

What can we hope to understand with ELTs and AO?

- When did galaxies assemble and "turn on"?
  - Luminosity functions to z=20 and even beyond (JWST + Lyman α searches with ELTs?)
  - Keys are sensitivity and wide field

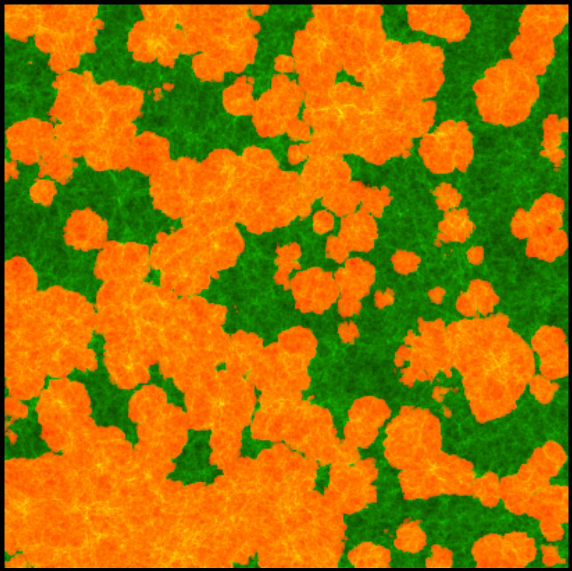
- How did reionization proceed? (Topology, rate, effects.)
  - Maps for Mpc-scale clustering (e.g., Mesinger & Furlanetto 2007; ELTs?)
  - Keys are sensitivity and wide field

- When did Population III (metal-free or at least low-metallicity) stars form?
  - Other spectral features like HeII with ELTs
  - Key is extreme sensitivity

How did reionization proceed?

Approach 1:

- **"Brute force" IRMS wide-field survey for clustering of fainter sources (same survey 4-night baseline above)**
- **Clustering tells about ionized bubble sizes/fraction (e.g., Mesinger & Furlanetto 2007)**



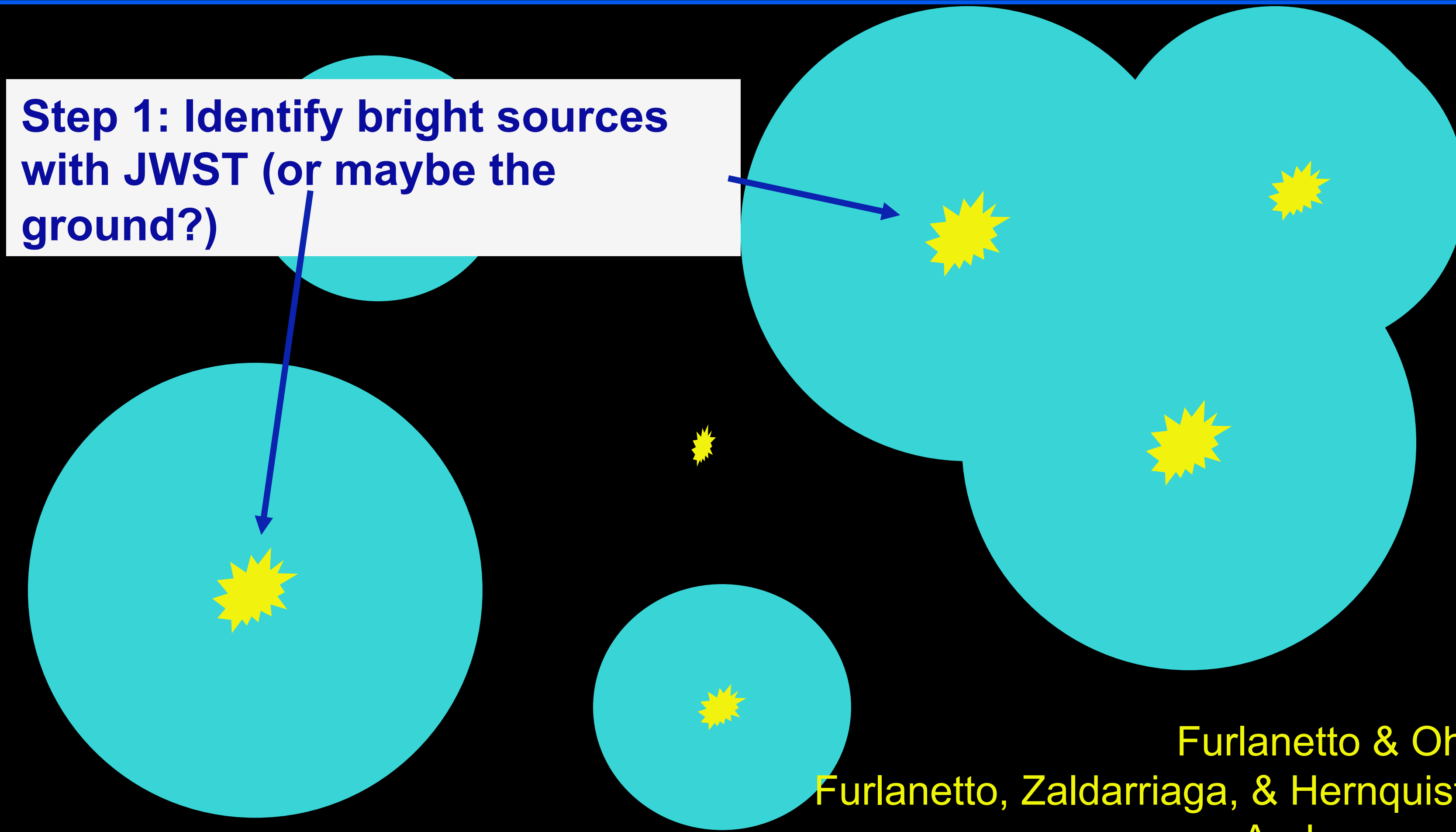
(Iliev et al.)

How did reionization proceed?

Approach 2:

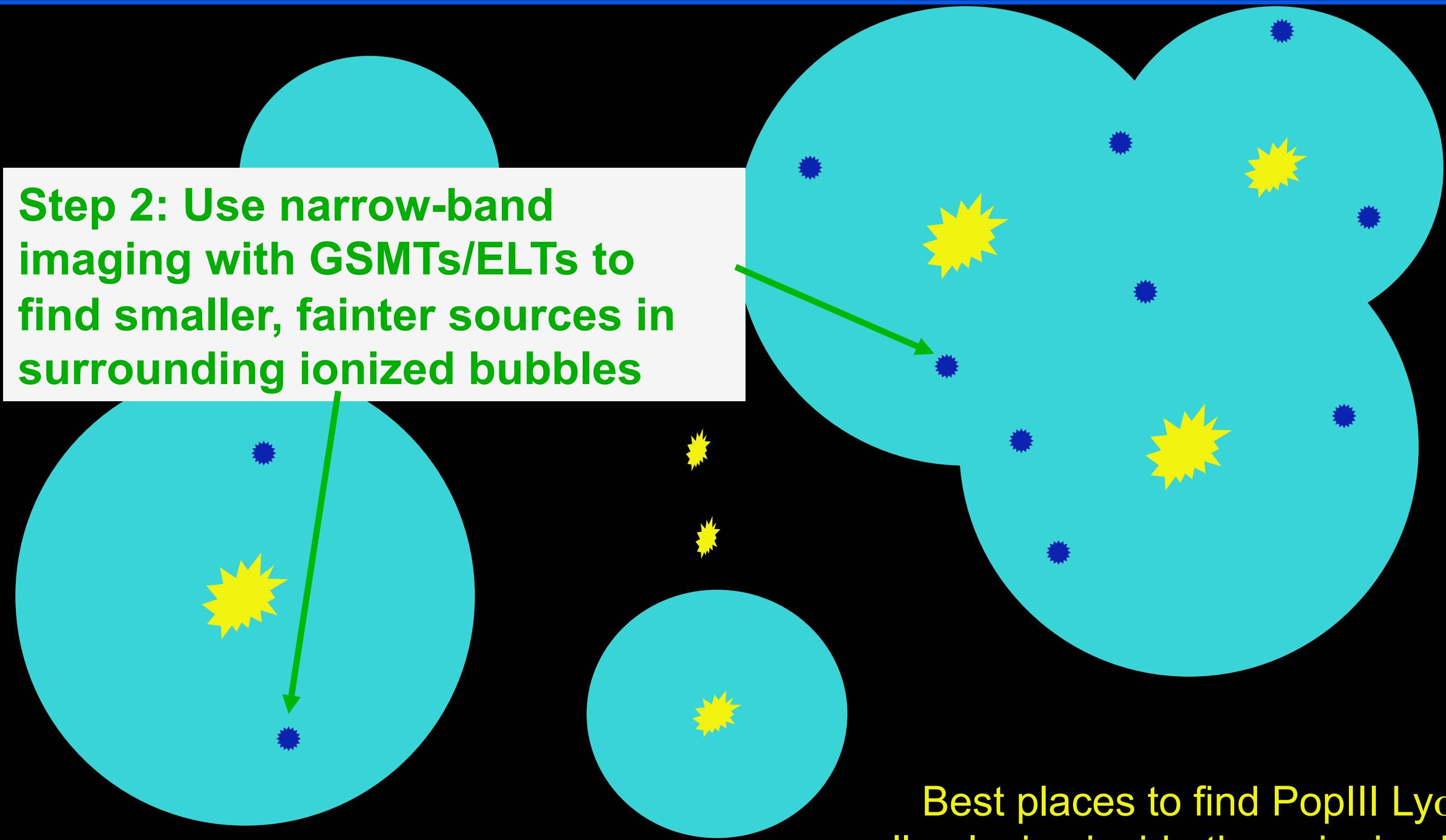
- **Find target sources in continuum (e.g., JWST legacy surveys)**
- **Search around for "ionized bubbles" by finding surrounding fainter Ly α sources**
  - **Specific bubble mapping: 1 IRMS field ~ 5 Mpc comoving**
  - **Simple surveys in narrow-band filters for Lyα or even HeII**

Topology of Reionization: Penetrating the IGM with ionized bubbles



Furlanetto & Oh (2005)
Furlanetto, Zaldarriaga, & Hernquist (2004)
And many others…

Penetrating the IGM with ionized bubbles

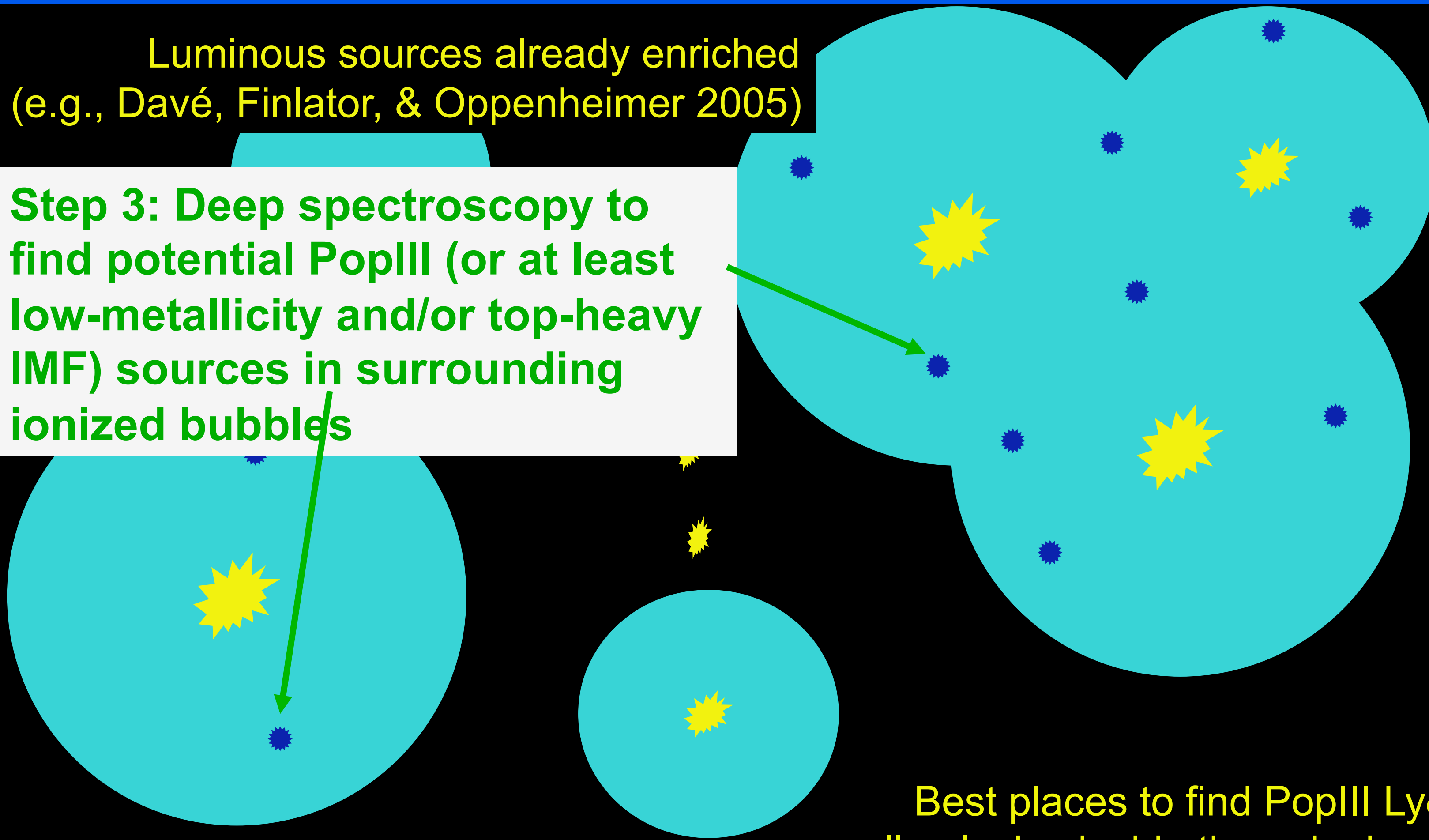


Best places to find PopIII Lyα may be small galaxies inside these ionized bubbles

When did Population III (metal-free) stars form?

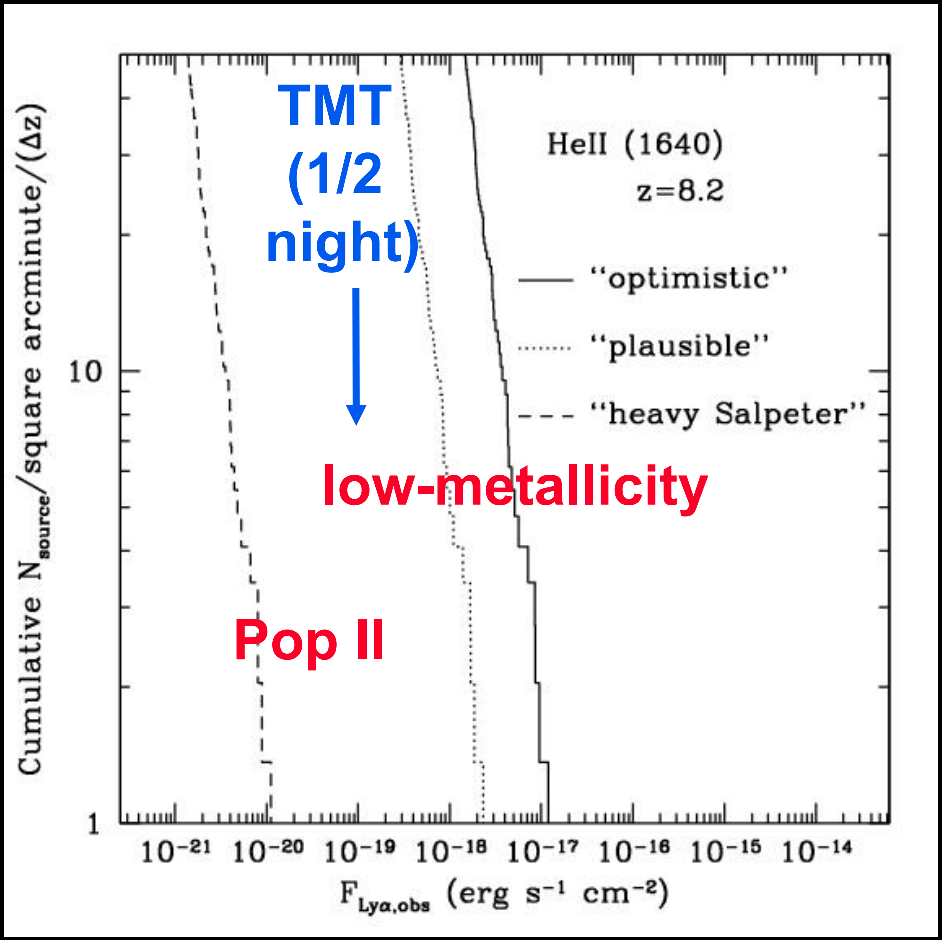
Luminous sources already enriched
(e.g., Davé, Finlator, & Oppenheimer 2005)

Step 3: Deep spectroscopy to find potential PopIII (or at least low-metallicity and/or top-heavy IMF) sources in surrounding ionized bubbles



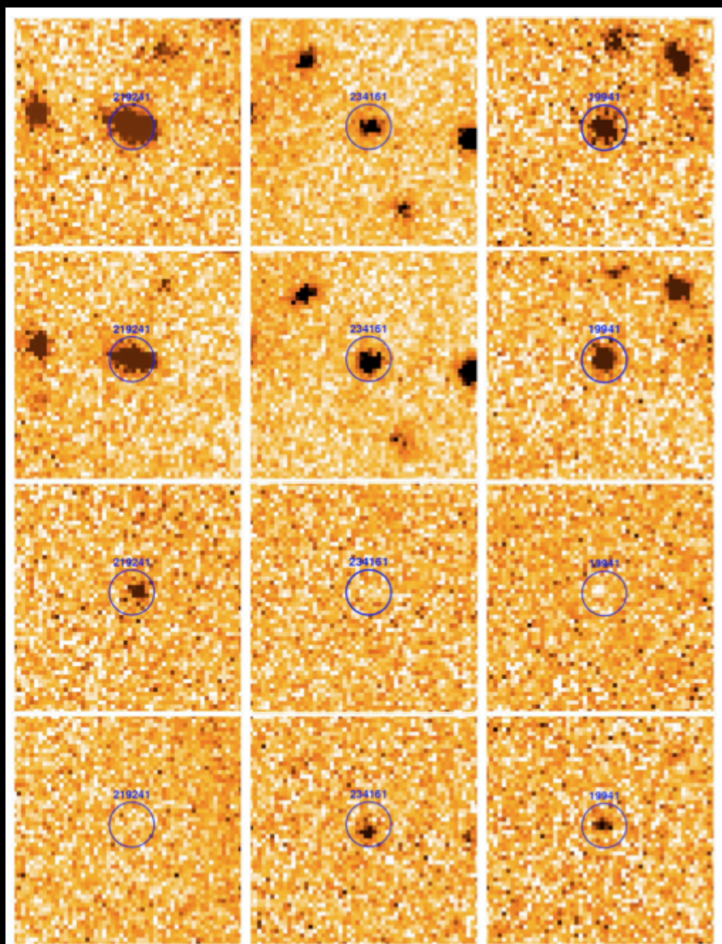
Best places to find PopIII Lyα may be
small galaxies inside these ionized bubbles

HeII (1640): signature of low-metallicity star formation



- Only low-metallicity or top-heavy IMF pops have detectable HeII (1640) emission
- Schaerer (2003) predicts high (>~ 20 Angstrom) equivalent widths for young, zero-metal bursts

A new technique for finding early supernovae



Type IIn SNe:
•UV luminous
•slowly evolving; long-lived emission lines
•very massive stars (analogs to what we will find at higher redshifts)

<u>SN distance record holders</u>

SN234161	**z = 2.013**
SN58360	**z = 2.187**
SN23222	**z = 2.231**
SN19941	**z = 2.357**
SN165699	**z = 2.364**
SN57260	**z = 3.028(?)**

(Cooke, Sullivan, Barton, Bullock, Carlberg, Gal-Yam, & Tollerud, Nature, 2009)

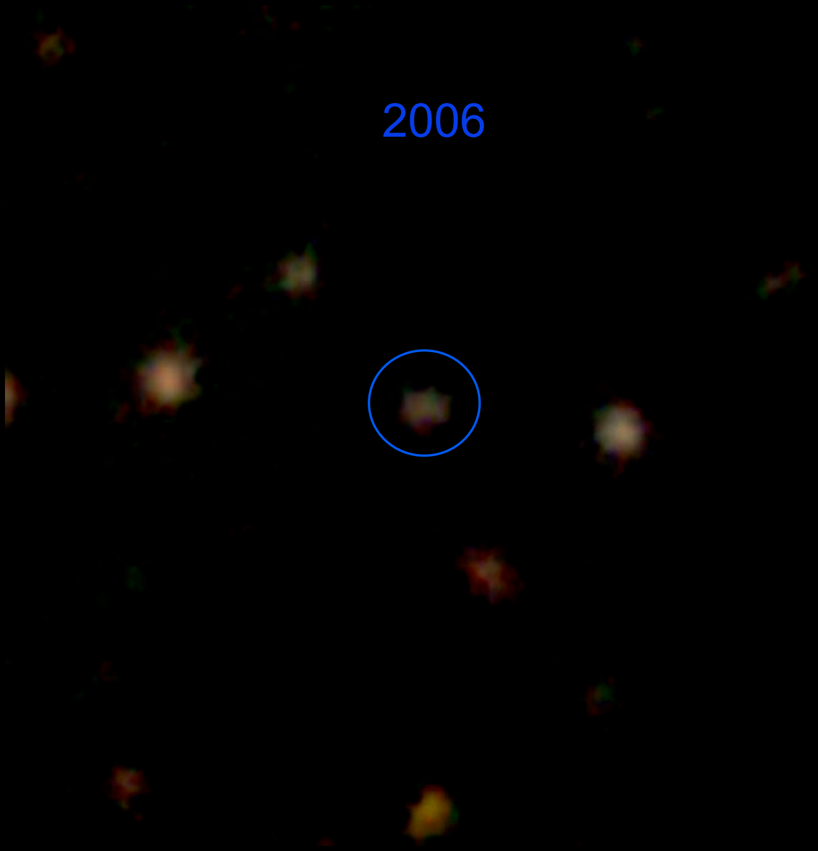
A new technique for finding early IIn supernovae

(Cooke 2008)

Object: 234161

<u>Host galaxy</u>

$m_r = 24.9 \pm 0.07$



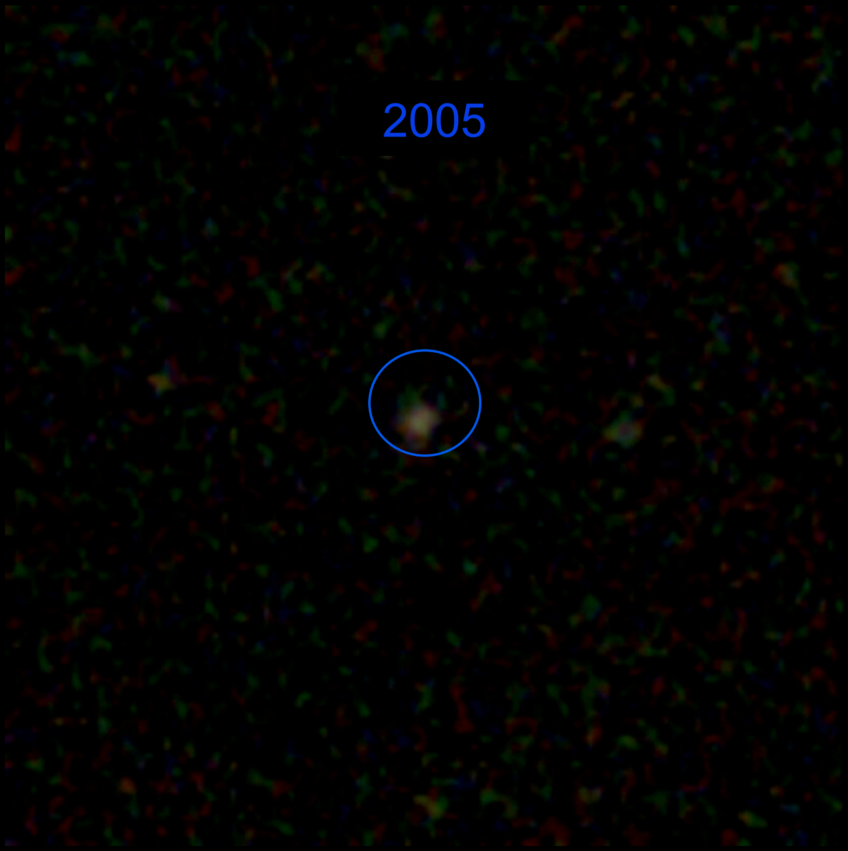
g′ r′ i′ filters

A new technique for finding early supernovae

Object: 234161

Host galaxy
m_r = 24.9 ± 0.07

SN event
m_r = 26.3 ± 0.14
Magnitude integrated over the full season

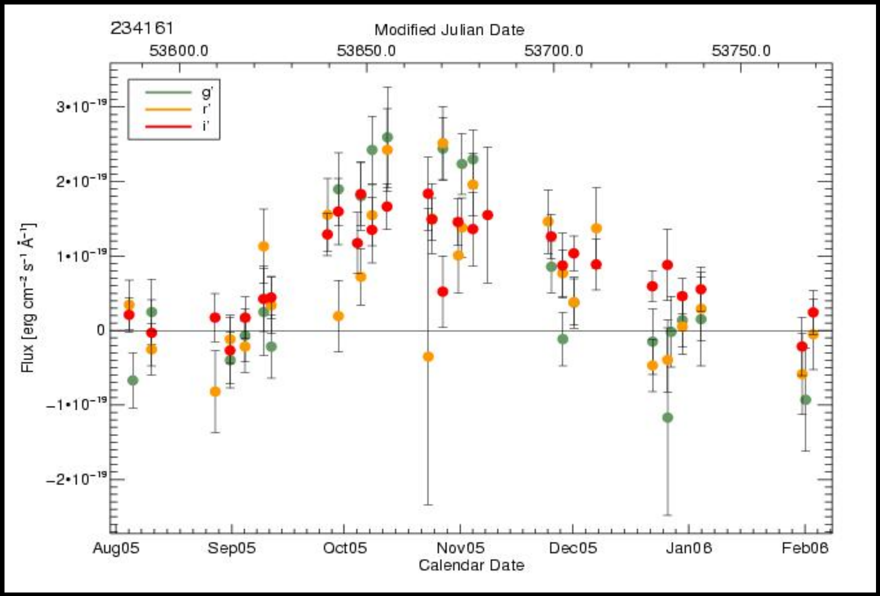


g′ r′ i′ filters

Image subtraction

SN is offset from host centroid by 2.8 ± 0.6 kpc (physical)

Type IIn supernovae at high redshift

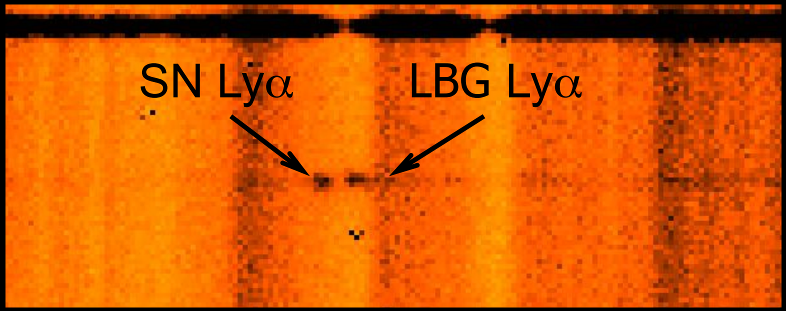


Time-dilation: ~2 week rise time and ~1 month decline

(decline rate differs per filter – reflective of a cooling BB)

g_{max}= 25.7
r_{max}= 25.2
i_{max}= 25.1

Optical filters correspond to rest-frame ultraviolet (~1500 - 2500Å)



Lyα emission from LBG host and supernova

(IIn typically have blue-shifted peaks)

Future search for SN Lyα decay and/or disappearance

Summary

By 2018, z > 7 sources may become routine with 8-10-meter class telescopes and wide-field OR AO imagers

- JWST + TMT and AO future will include
  - luminosity functions even to z=20; from ground, will be largely narrow-band imaging (unless OH suppression makes broad-band approaches more competitive with space)
  - topology of reionization
  - searches for PopIII (metal-free or low-metallicity) star formation, or “the first stars”
- TMT + LSST will enable routine detection of thousands of high-z Type IIn supernovae:
  - SN IIn 2006gy (closest to PISNe?) would be 27th mag AB at z~6 (See Cooke et al. 2009 Astro2010 white paper; on astro-ph)