
First Light and Faintest Dwarfs
Concluding Remarks
Richard Ellis (Caltech)
KITP February 17th 2012

Opening Remarks or Closing Remarks?

- TIWLTHMA — Things I would like to hear more about
- TIOTHLTBWRME — Things I ought to have listened to but was reading my email
- TITWIBIDRU — Things I thought were interesting but I didn't really understand
- TCTMTS — Things Carlos told me to say

The Important Role of Dwarf Galaxies

I: **Dwarf galaxies as probes of cosmic history**
- test of hierarchical assembly via Galactic archeology
- role of galaxies in cosmic reionization

II: **Dwarf galaxies as `dark matter laboratories'**
- fine structure in DM power spectrum
- interaction of DM with baryons
- key tests of standard CDM paradigm

- Meeting succeeded in bringing together two different astrophysical communities
- Not an easy task, organizers to be congratulated
- Some interesting sociological observations (personal view!)

Spot the Difference

Very high z observers



Very low z observers

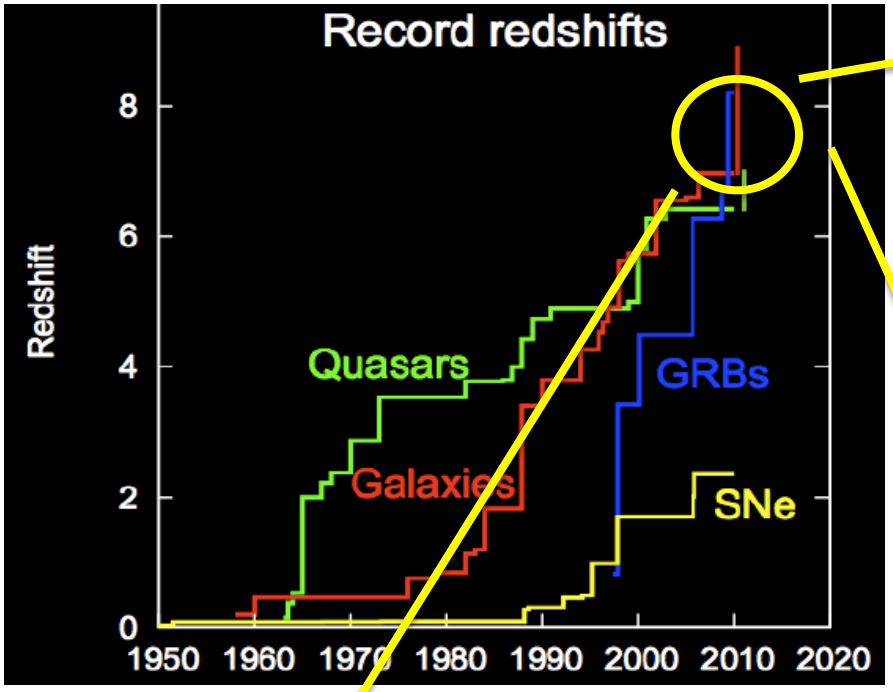


I: Dwarf Galaxies at Probes of Cosmic History: Connecting Very Low & Very High z

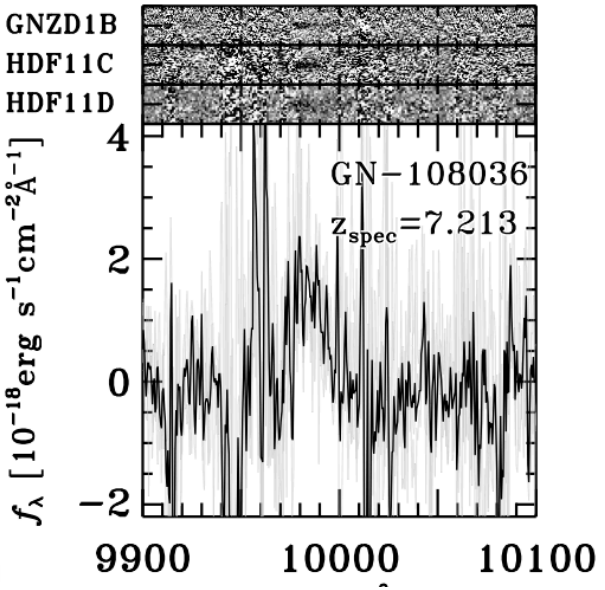
- Dwarf galaxies dominate the reionization process
- Metallicity in neutral hydrogen dominated DLAs
- Early supernovae may generate unique nuclear signatures

- Local Group dwarfs as fossils of hierarchical assembly
- Metal poor stars; nuclear signatures & chemical tagging
- Role of globular clusters?

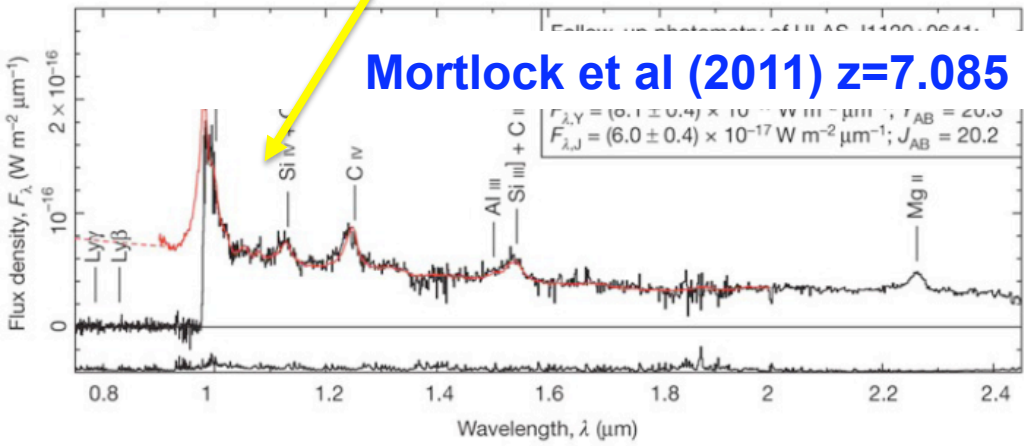
Great Progress in High Z Discoveries!



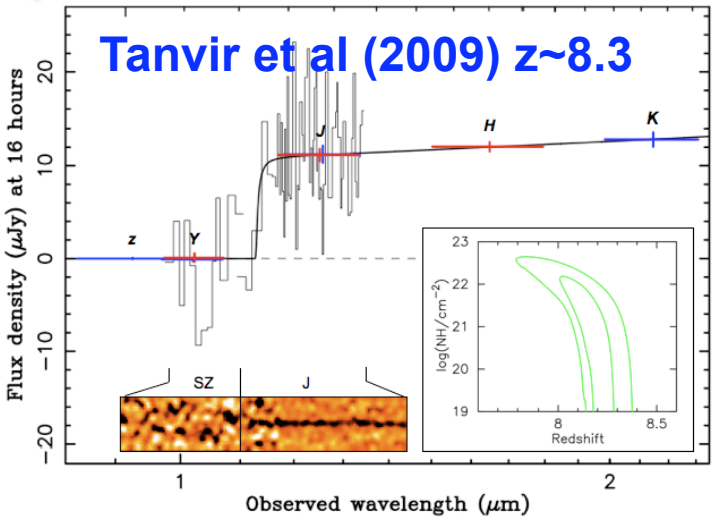
Ono et al (2012) z=7.213



Mortlock et al (2011) z=7.085

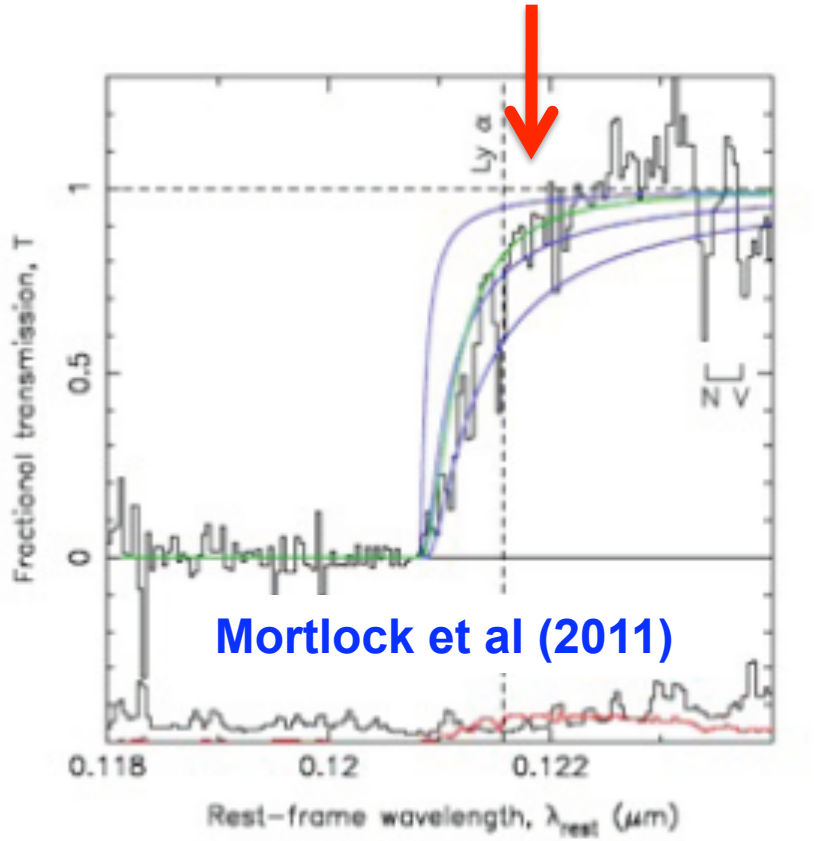


Tanvir et al (2009) z~8.3



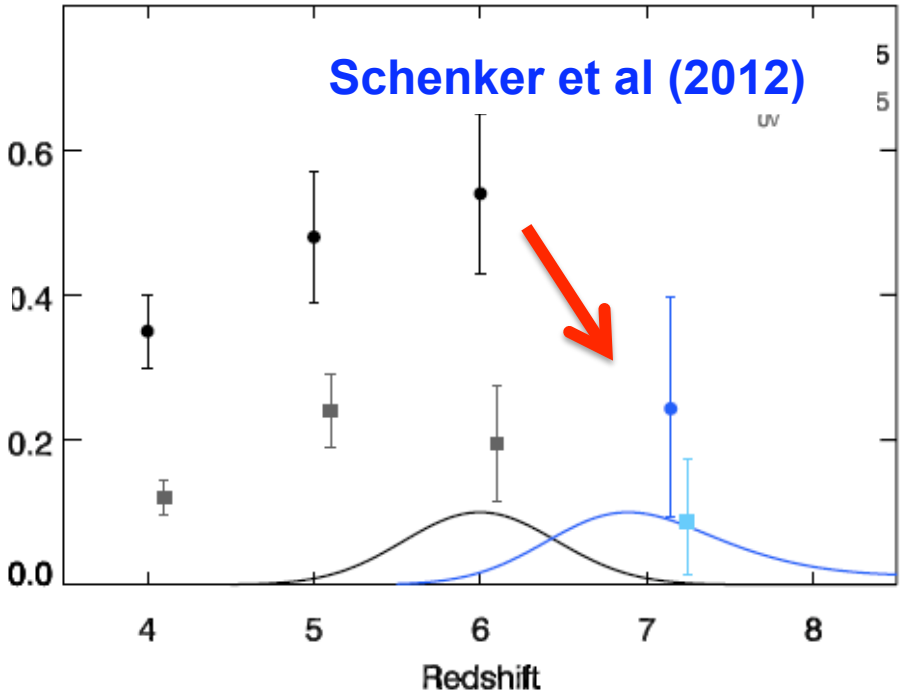
Does the Neutral Era Begin at z~7?

Rate of occurrence in Lyman α emission in WFC3/IR LBGs and red damping wing in z~7.085 QSO give tantalizing hints that we are entering the neutral era



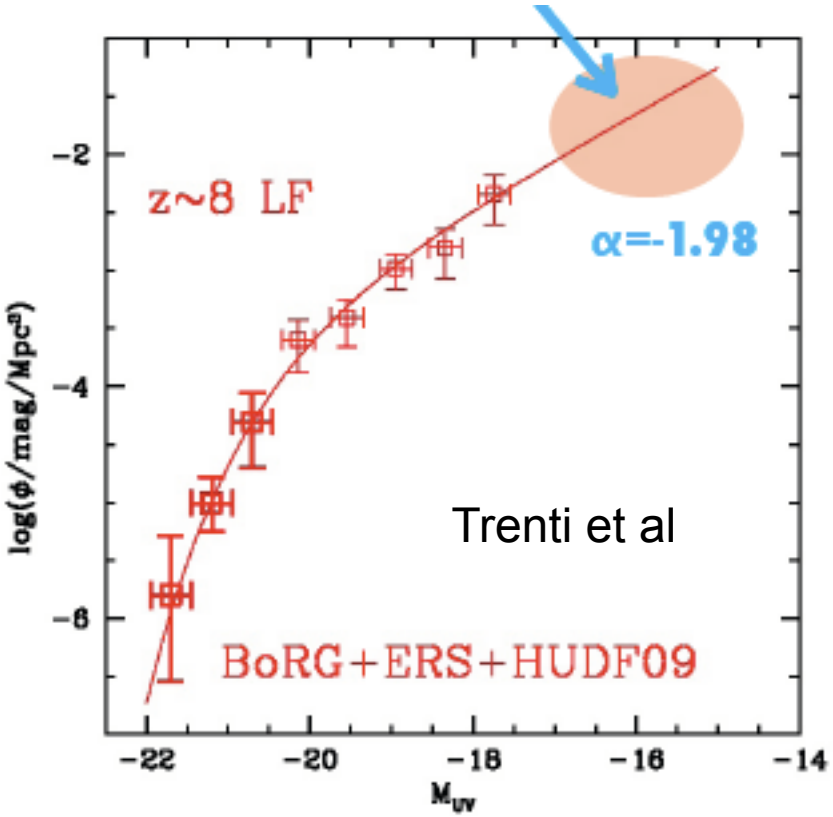
Mortlock et al (2011)

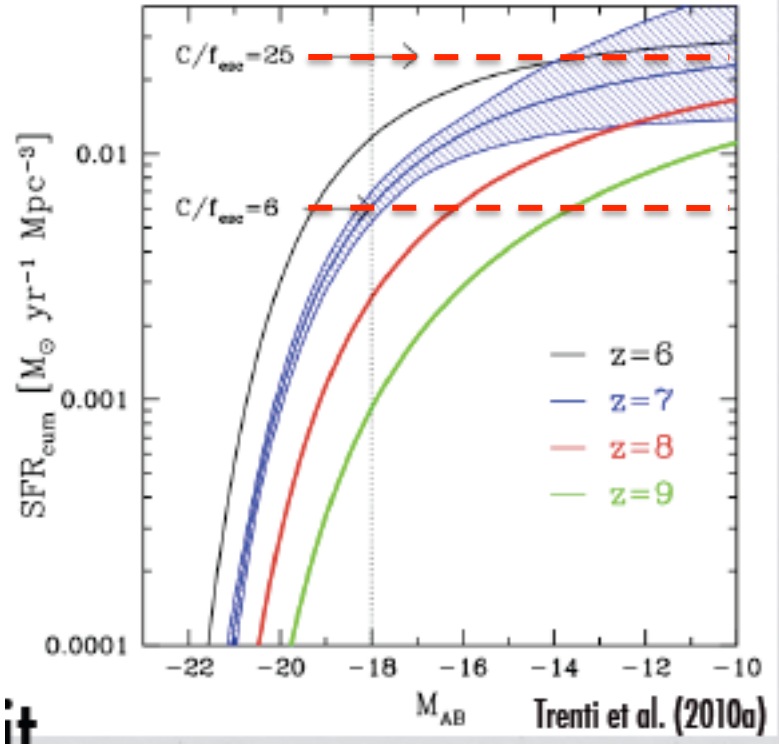
Fraction with Lyα



Expect rapid progress in this area with VISTA (more high z QSOs) and multi-slit IR spectrograps on Keck and VLT

Loads of Dwarfs at High Redshift?





f_{esc}
~10%
~50%

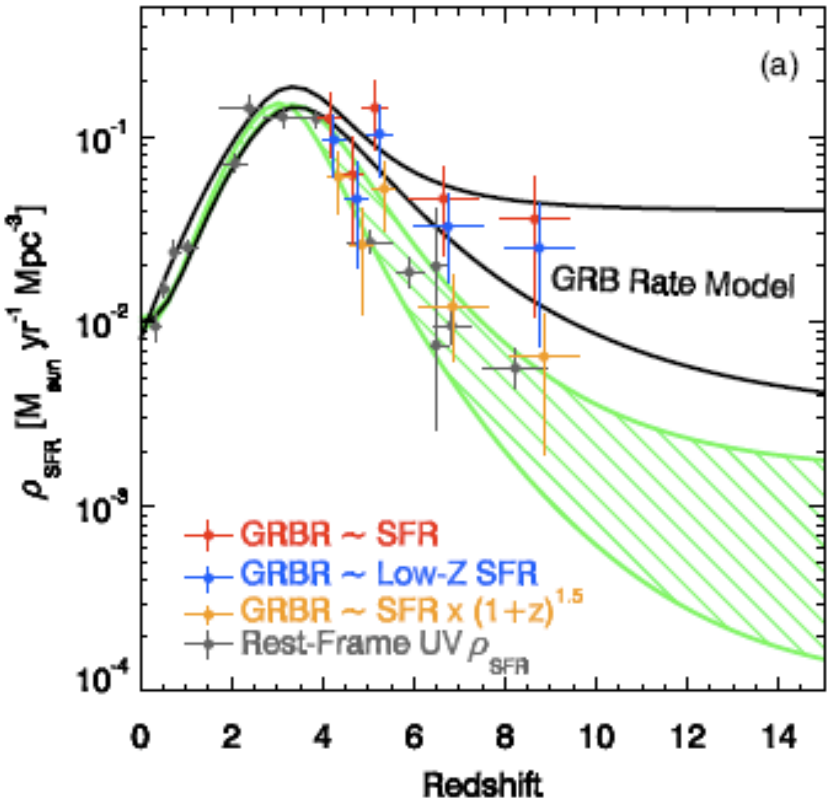
Combination of ultra-deep UDF09 data plus multi-pointing BORG survey of 250 arcmin^2 gives excellent constraints on z~8 LF to M_{UV}~-17 (NB: only L*+3!)

Steep faint end slope α~-2 suggests 75% of luminosity density from unobserved objects (e.g. to M_{UV}~-10!) – but is this deduction sound?

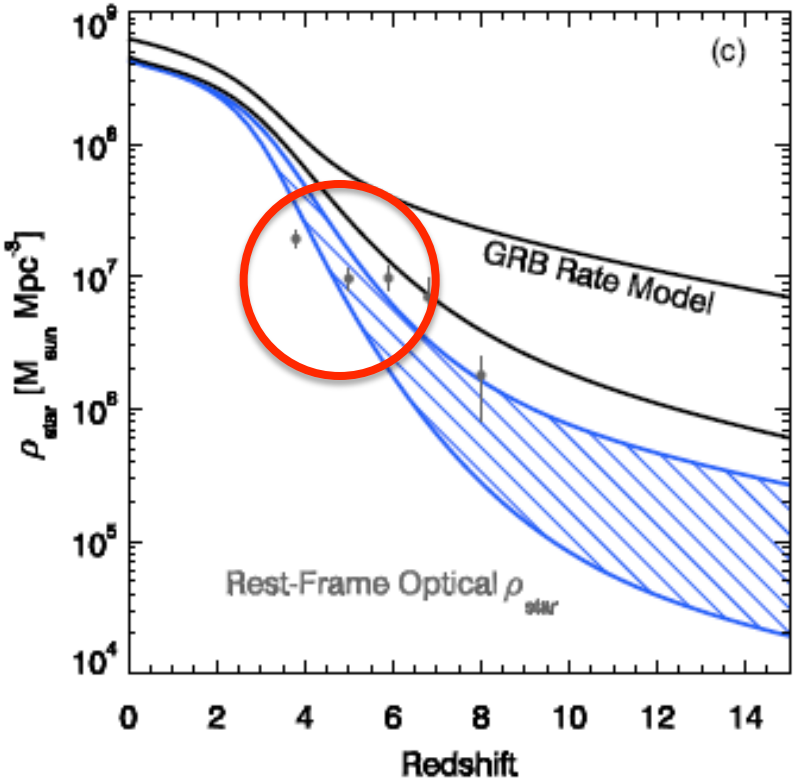
Loads of dwarfs are dearly needed to solve the reionization mystery!

Stellar Mass Constraints

Star Formation History

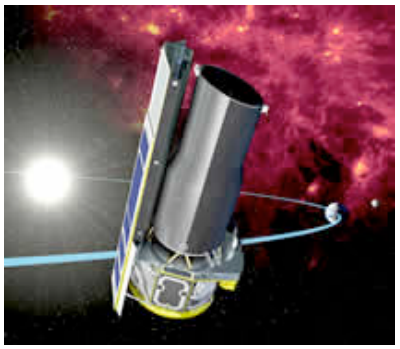


Stellar Mass Assembly



Extending observed LF to ultrafaint limits (so as to be consistent with GRB-derived star formation history) may violate the measured stellar mass density at z~4-6, particularly if those estimates are too high due to nebular emission

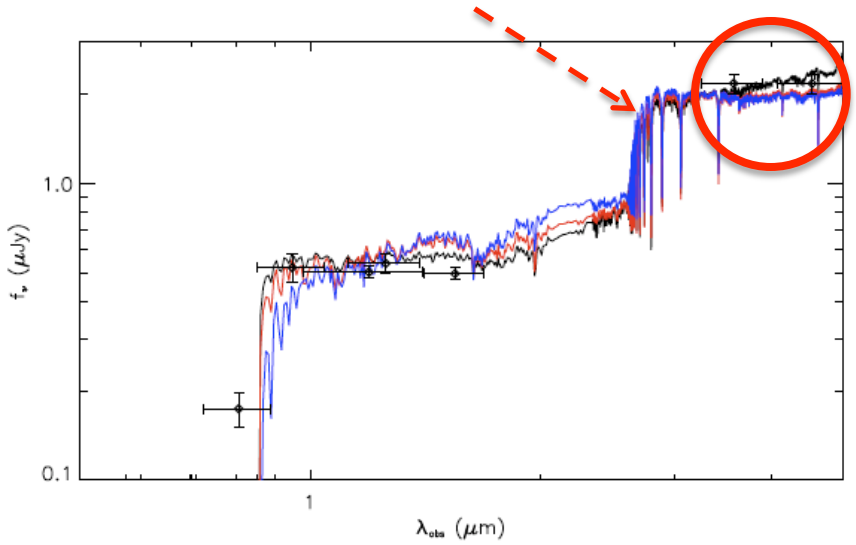
Robertson & Ellis (2012)



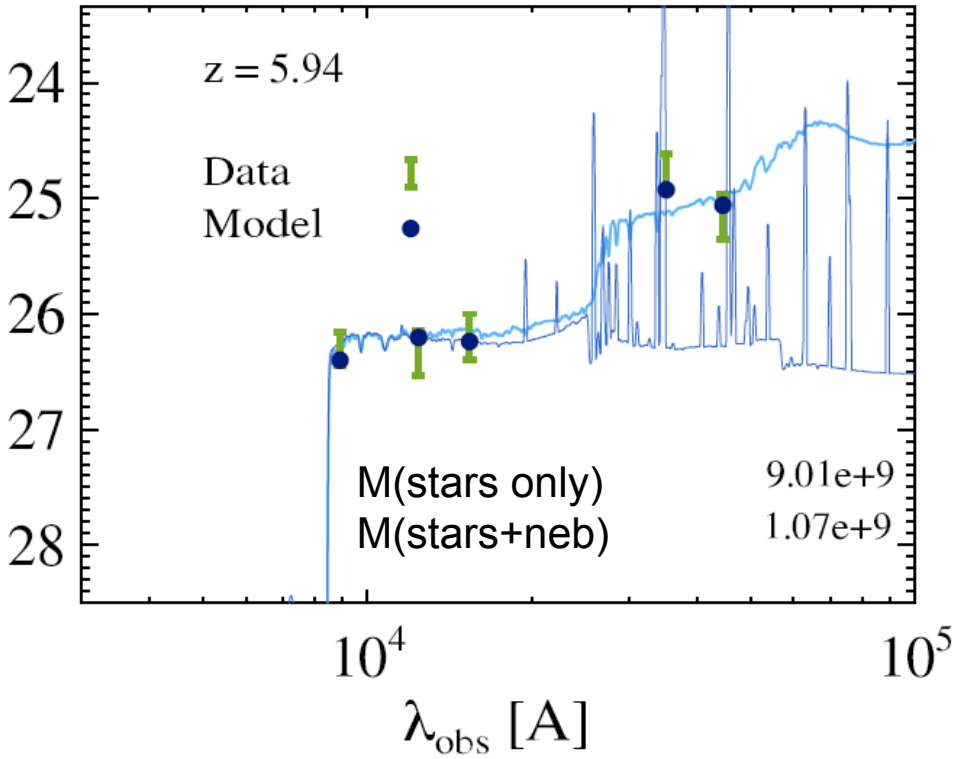
Role of Spitzer: Ages & Masses

Most likely z~6 stellar mass density over-estimated!

Massive and old at z~6??



Alternative fits: stars vs stars + nebular



For spectroscopically-confirmed galaxies we can determine in which IRAC bands nebular lines fall & estimate corrections to ages and stellar masses

Stark et al (2012)

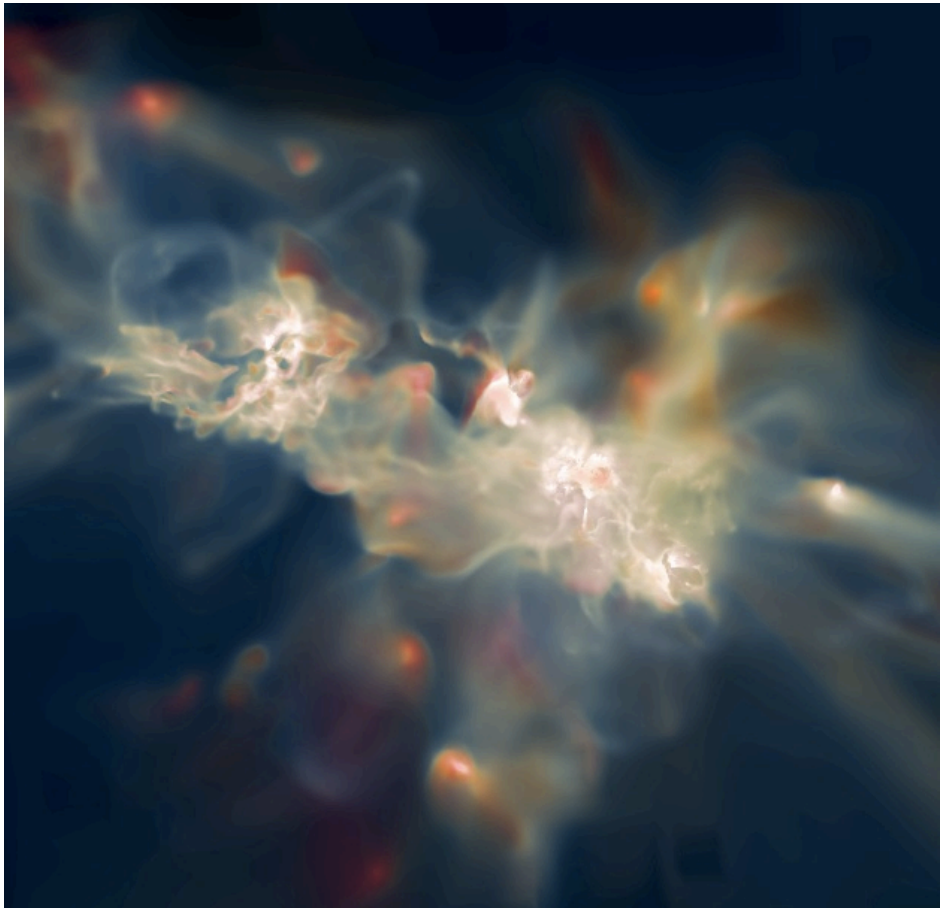
f_{esc}?

The most profound statement at the meeting:

"The escape fraction of ionizing photons lies between zero and one"

Radiation pressure leads to `cometary like' structures in simulated z~8 galaxies implying favorable geometries for escaping photons?

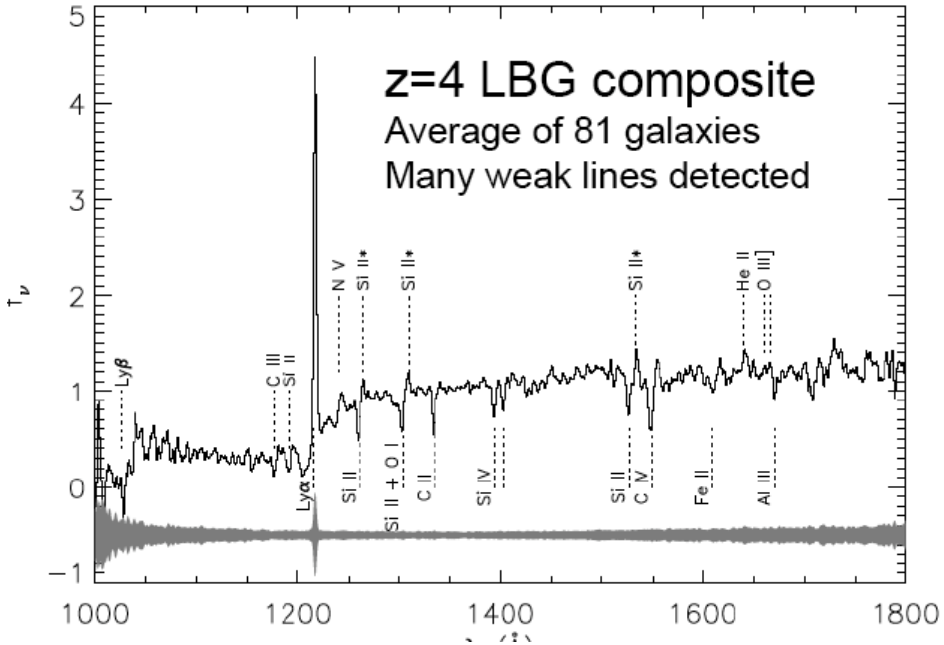
(J. Wise)

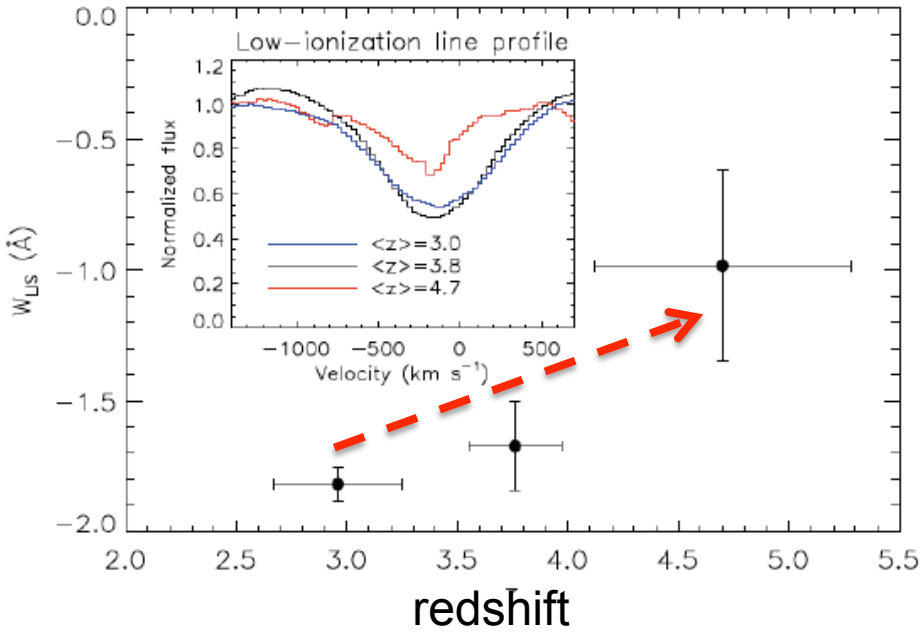


High z Observations Relating to f_{esc}!

Escape fraction inferred via covering fraction of neutral gas ($1-f_{esc}$)!

Traced by low ionization absorption lines in stacked 3<z<5 spectra

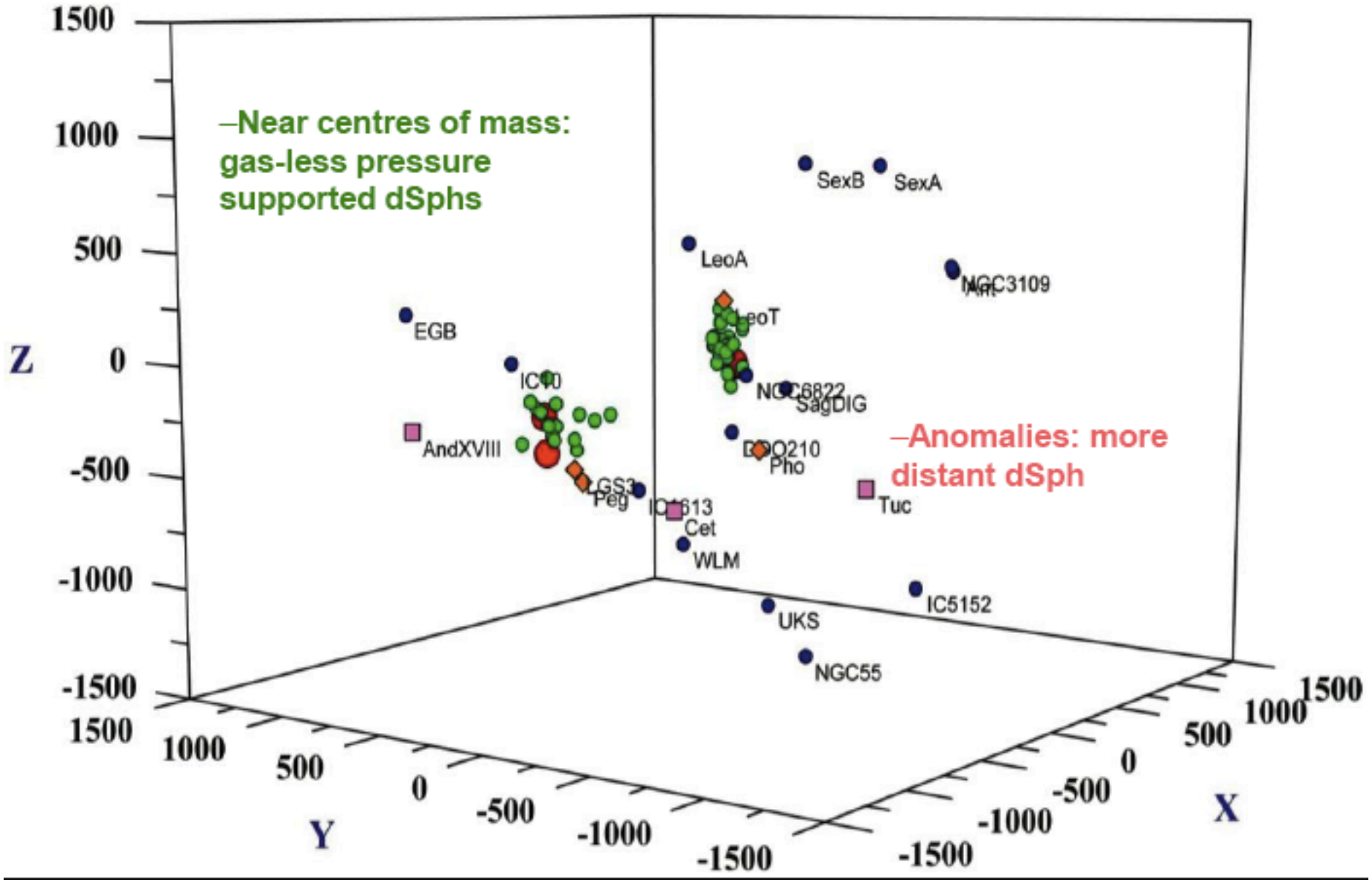




Systematic weakening with increasing redshift in low ionization species implying galaxies become more porous as we approach reionization era

Jones et al (astro-ph/1111.5102)

The Local Group Dwarfs

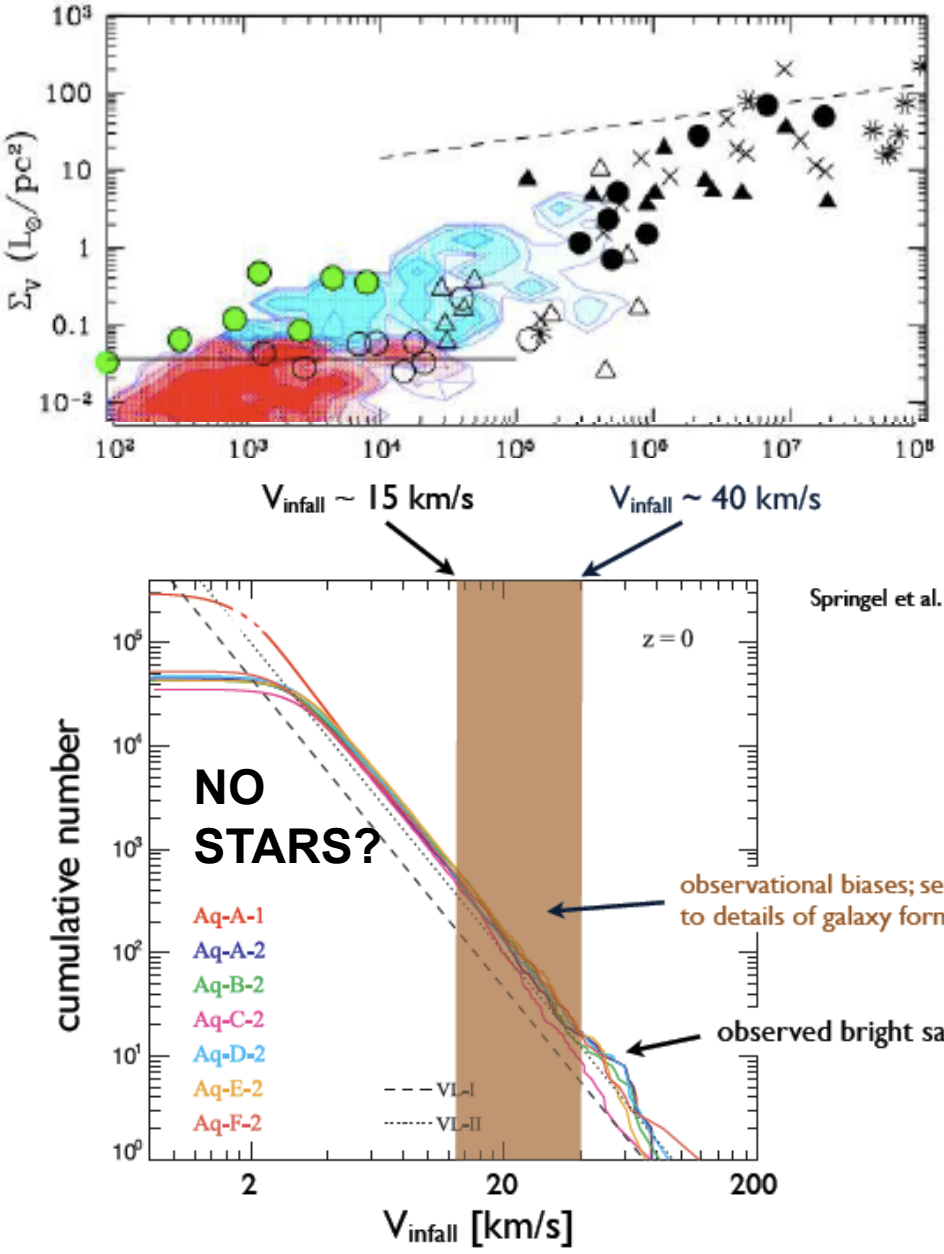


We Expect More Ultra-Faint Dwarfs

Current surveys are naturally limited in surface brightness and sampled volume. We expect many more ultrafaint dwarfs down to some limit where we expect only dark subhalos

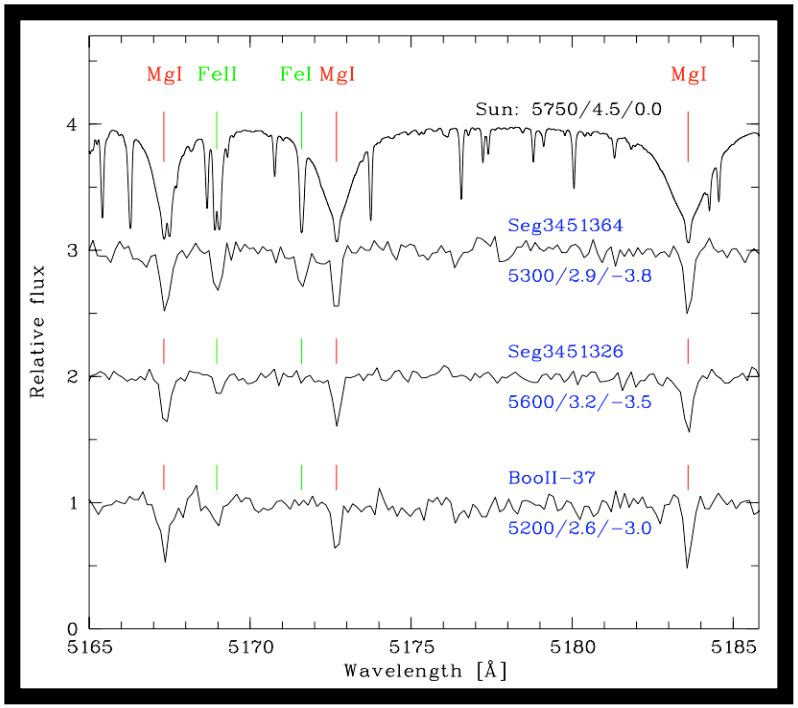
Challenge is to search for more metal-poor ultra-faint dwarfs in deeper sky survey data: prospects good with new deeper all-sky surveys

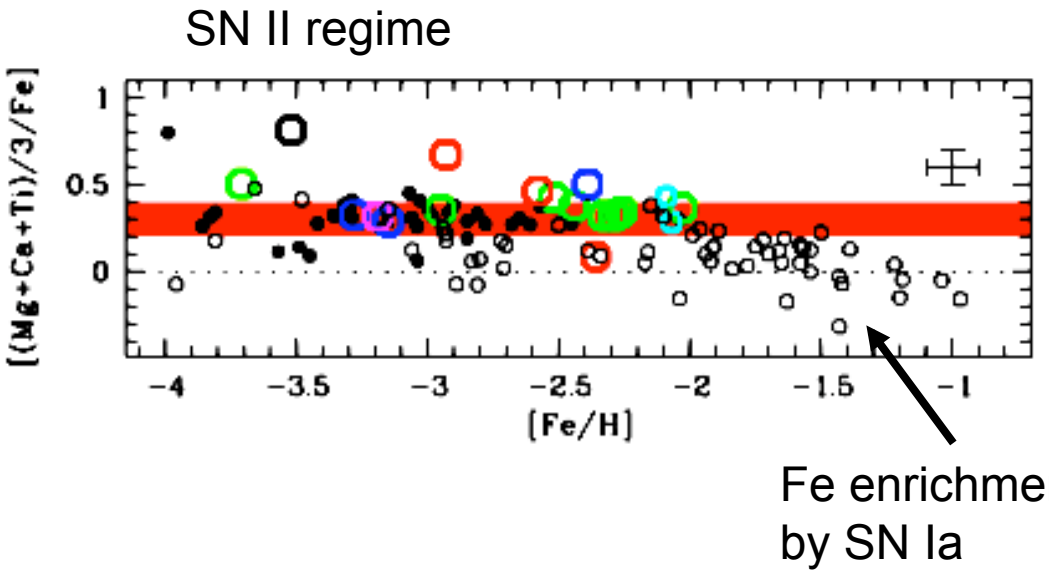
Springel et al (2008)
Tollerud et al (2008)
Bovill & Ricotti (2011)
Rashkov et al (2012)



Dwarfs as Fossils

Chemical Abundances are Best Probe!





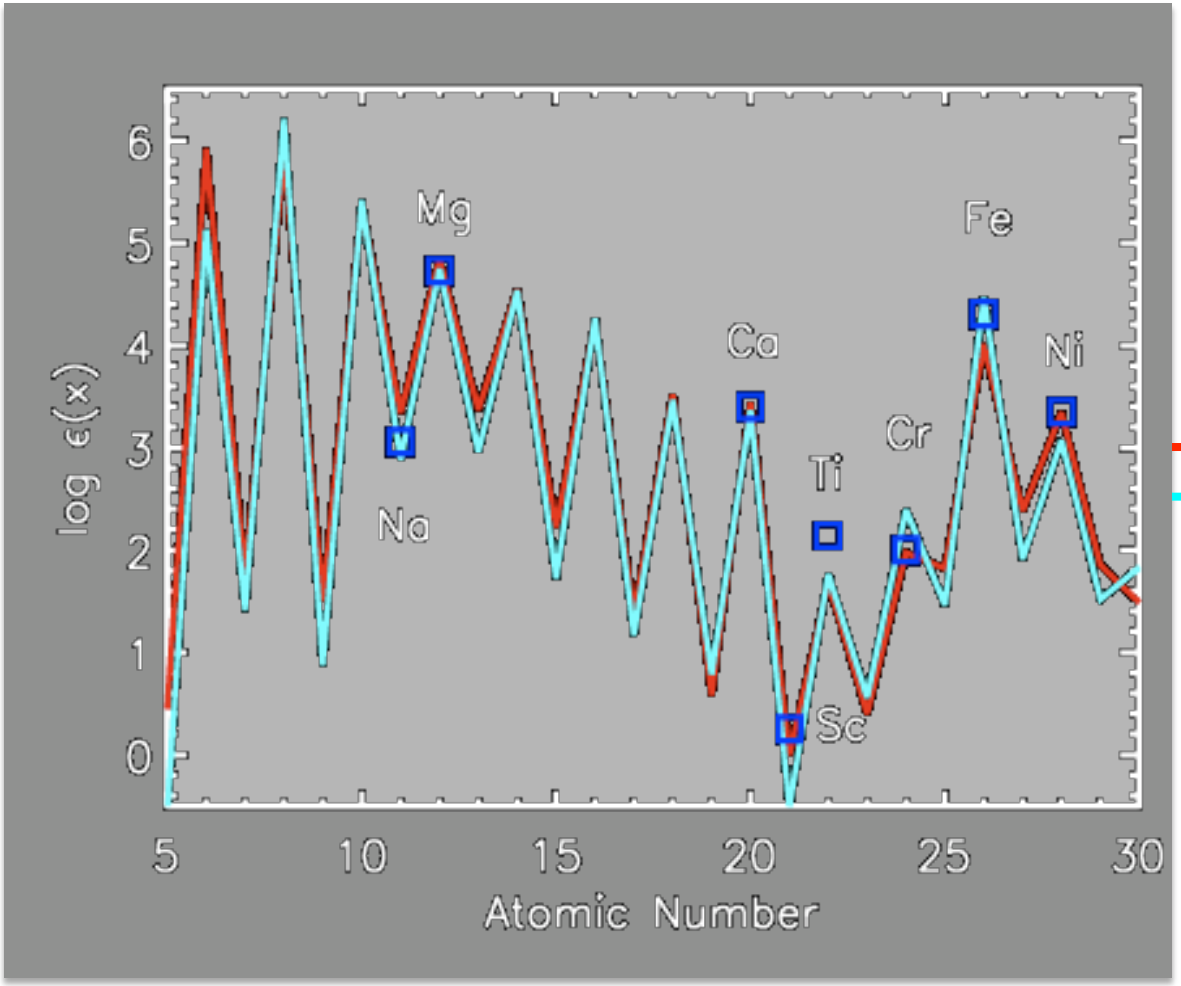
Composition of metal poor dwarf stars matches that in Milky Way halo suggesting they are surviving building blocks

For a genuine fossil, there should be no subsequent AGB or SN Ia enrichment

Frebel et al (2010,2011)

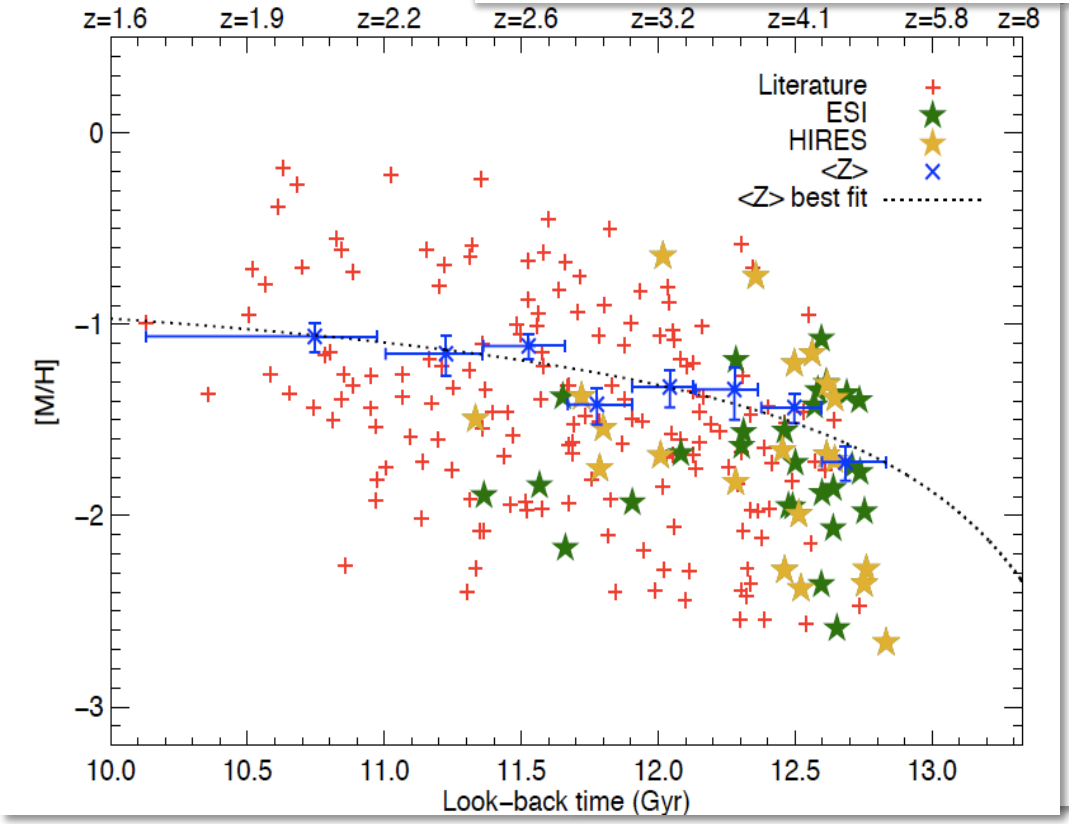
Can We Tie Nuclear Products to Early SNe?

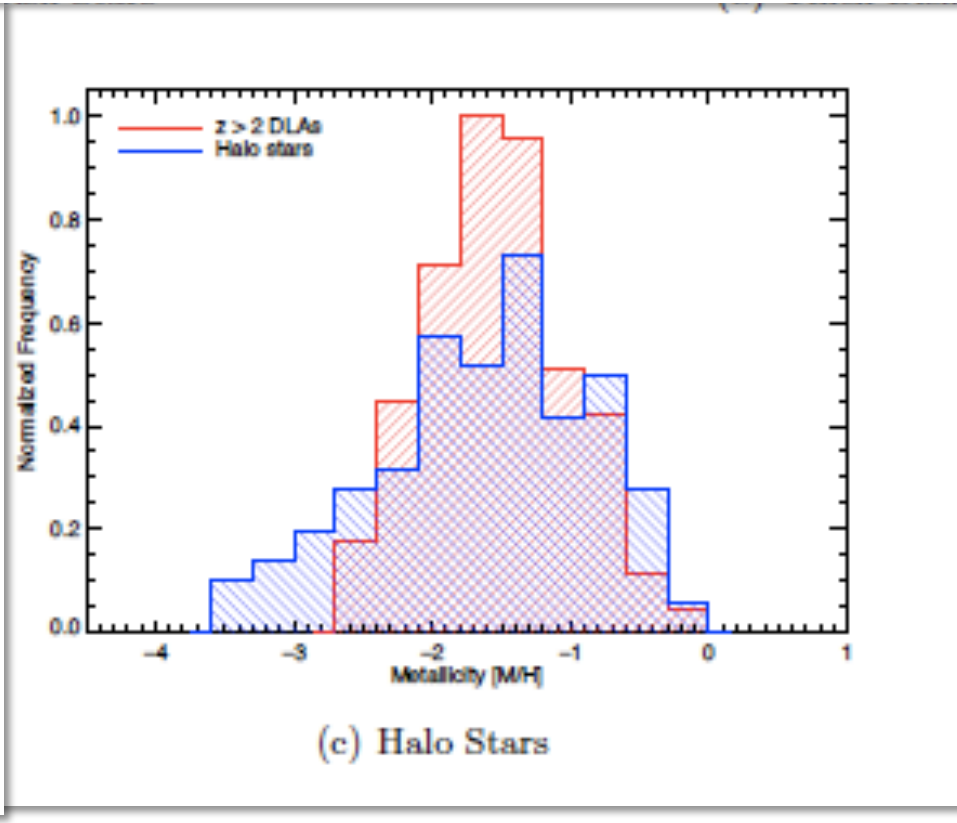
Leo IV abundances c.f. Pop III supernova models



Simon et al (2011)

High Z Chemical Analogs of Local Dwarfs?





High quality data on DLAs: the natural reservoir of neutral gas to z~5
At the highest redshift metal distribution most closely matches MW halo

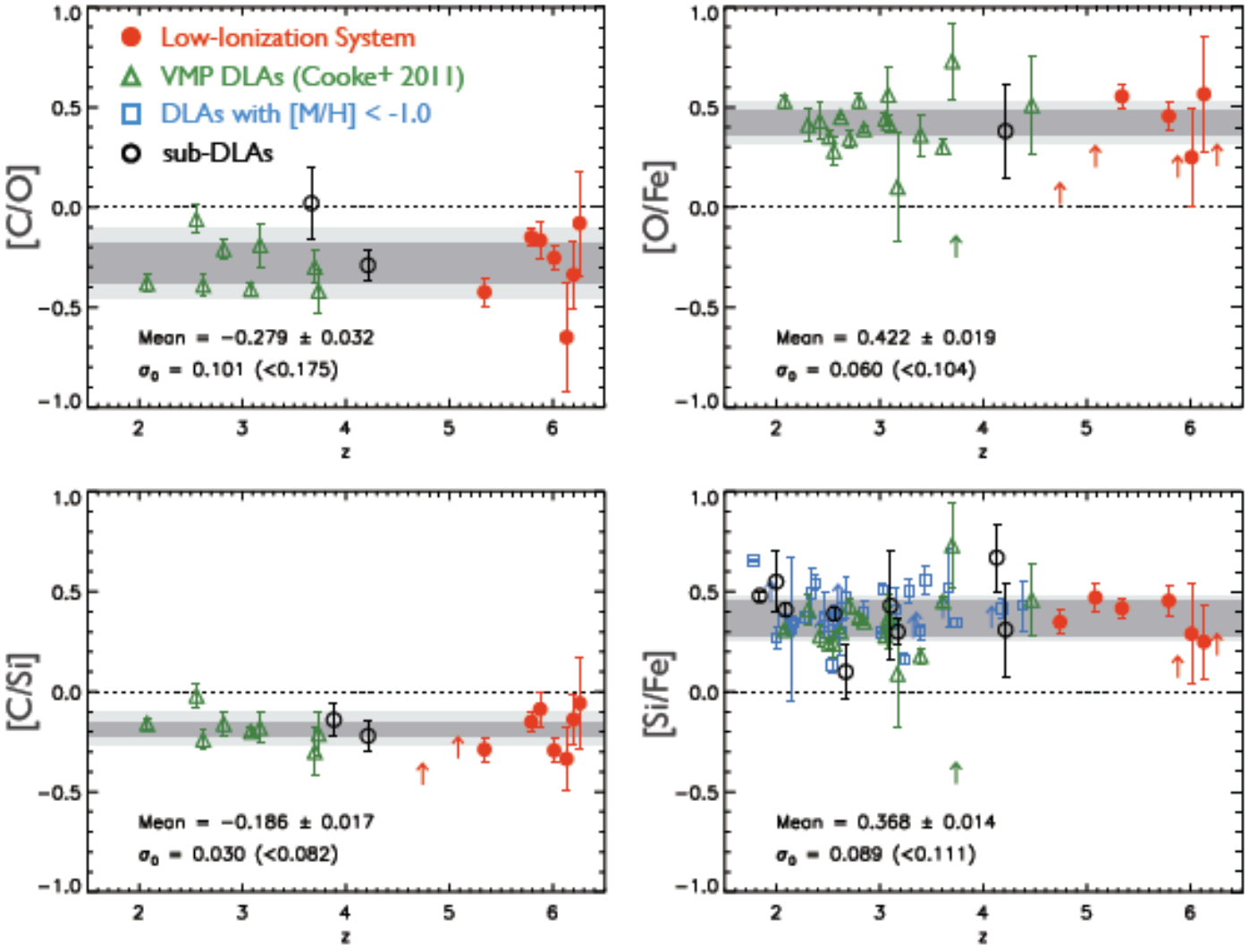
Artie Wolfe

More Detailed Abundances in DLAs

Relative abundances consistent with low z metal poor absorbers & metal poor halo stars

Small scatter suggests bulk of stars that enriched were Pop II

Implies: Pop III phase short

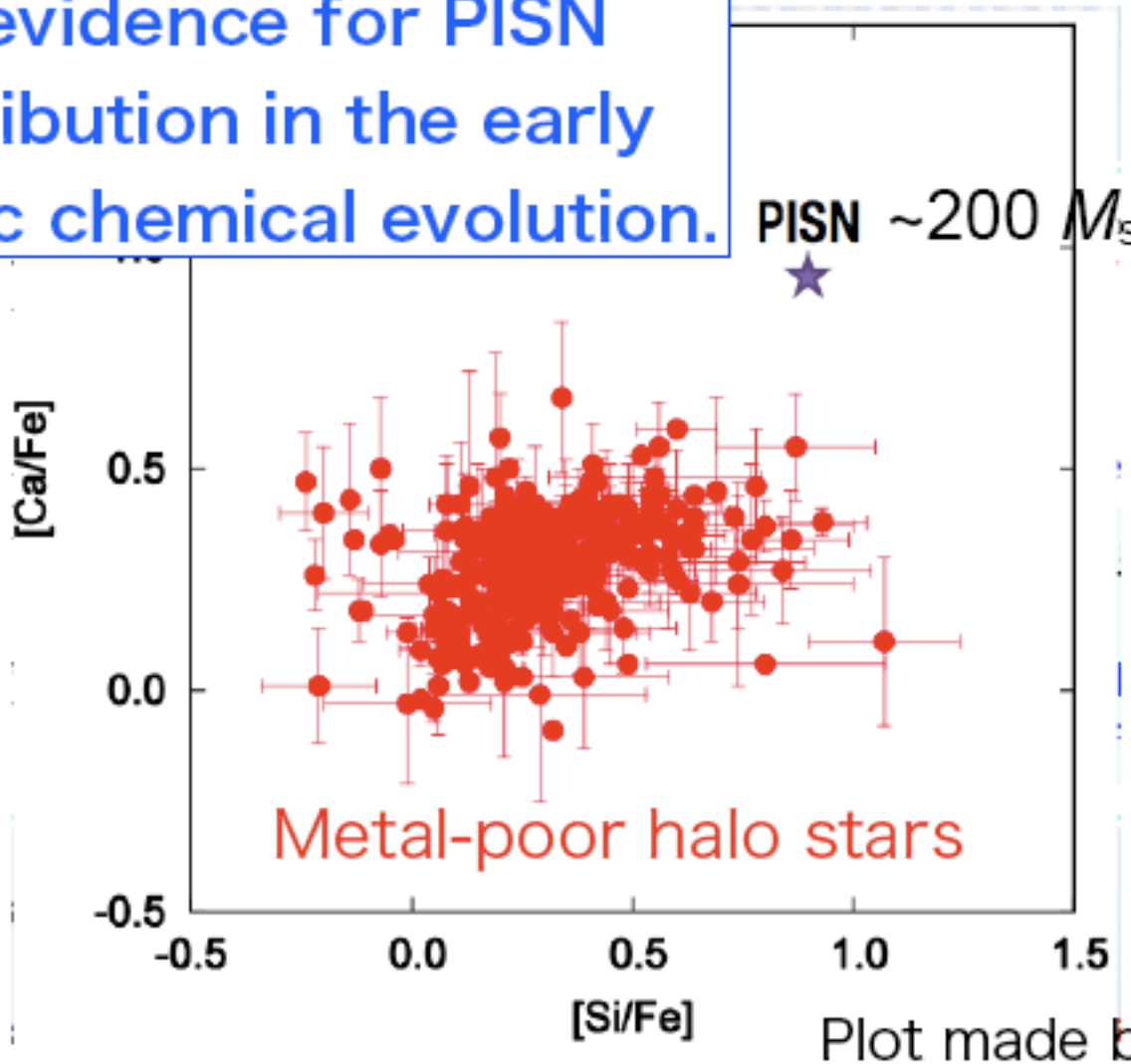


Becker et al (2011):

– Great opportunity! chemical tagging connection to MW halo (Johnston)?

No Evidence for Pair Instability SNe?

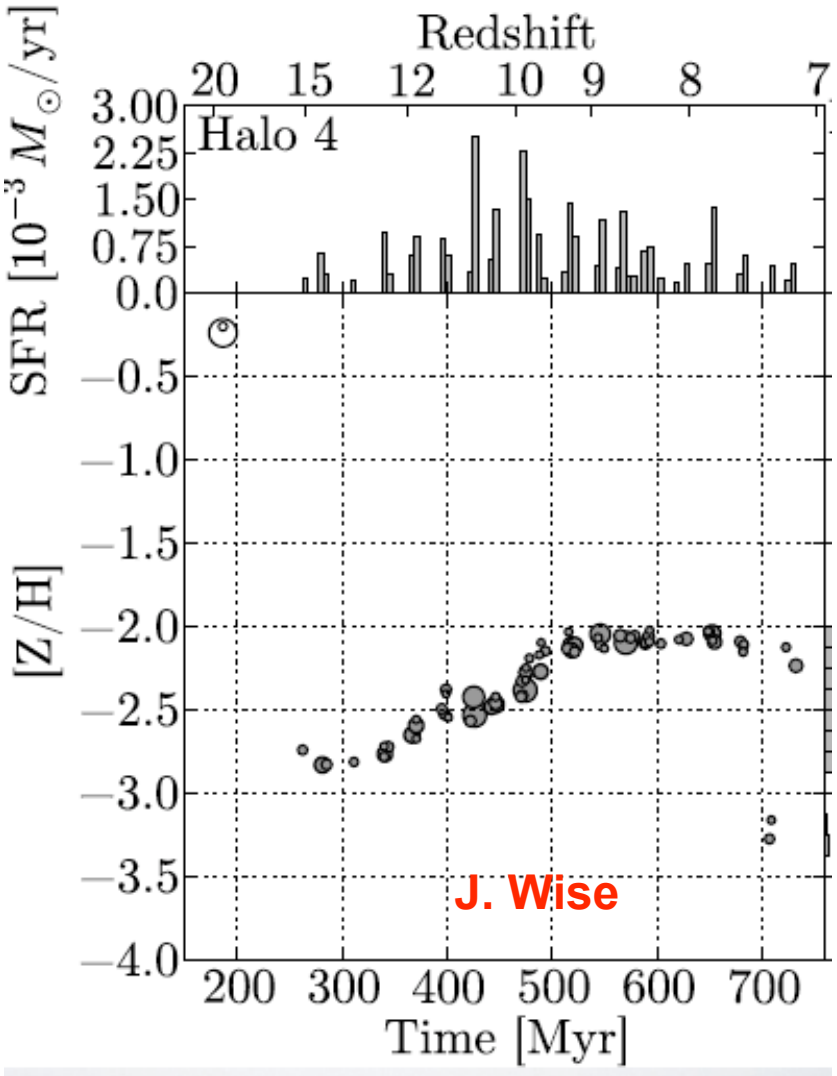
No evidence for PISN contribution in the early Galactic chemical evolution.

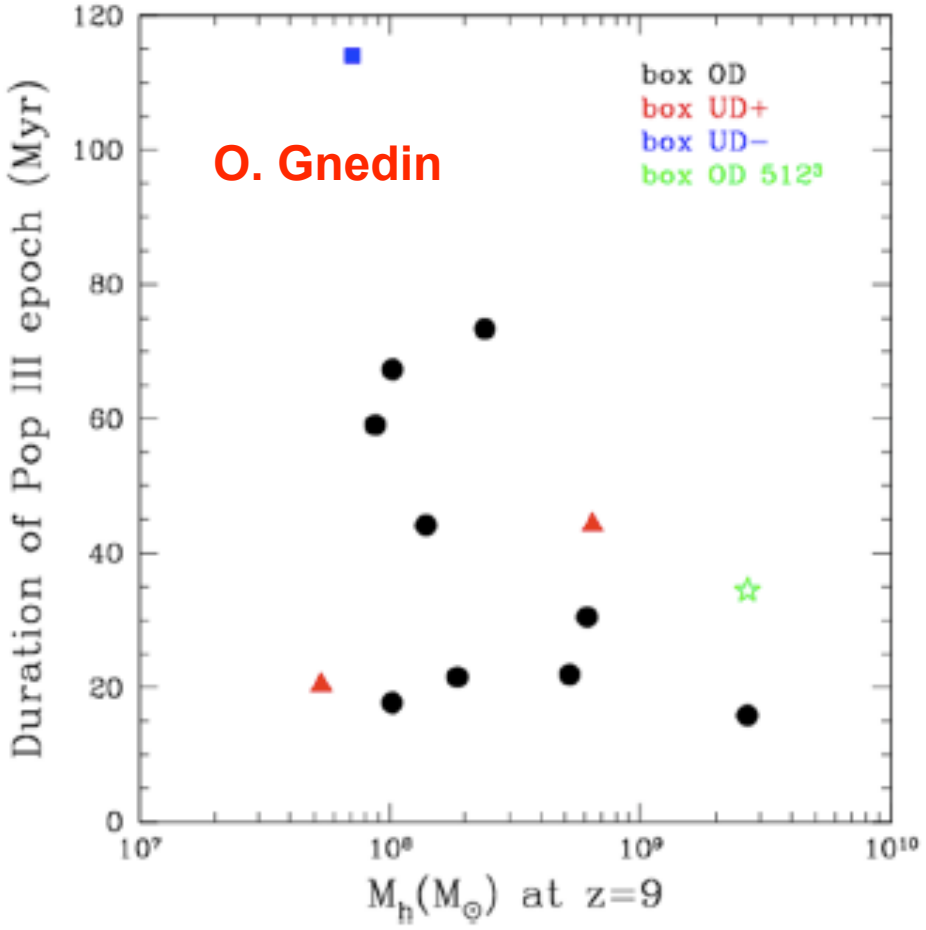


Plot made by N. Tominaga

N. Yoshida

Can We Forget About Pop III?





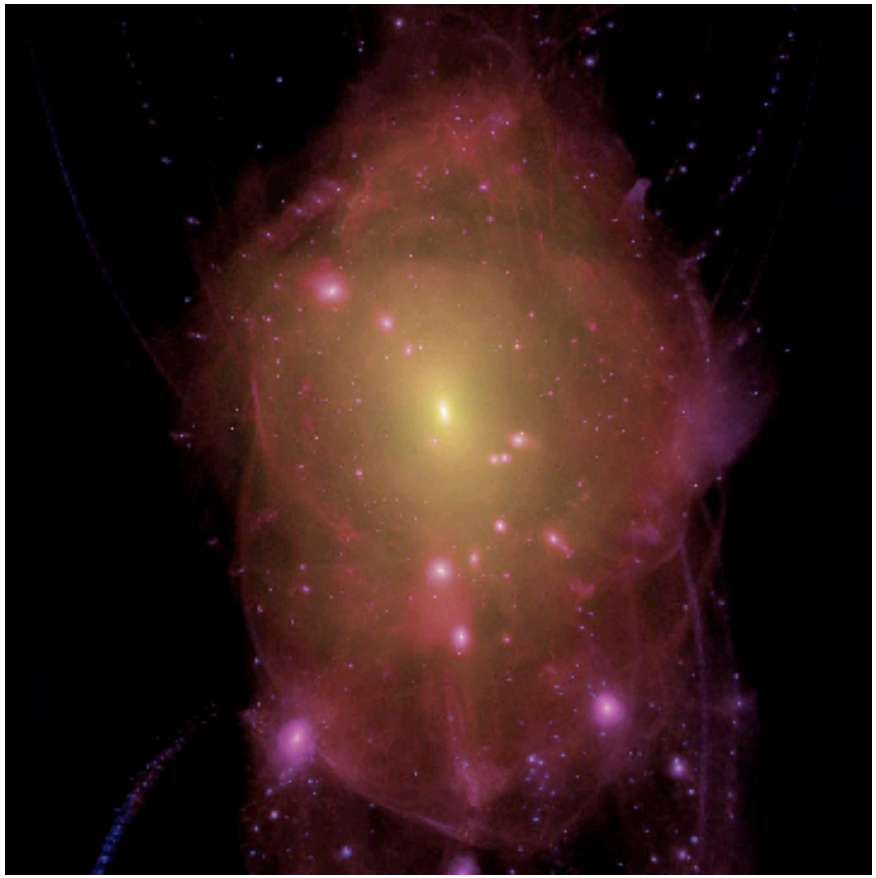
Metal enrichment is ~instantaneous on a cosmic timescale (20 Myr for JWST-accessible sources)

II: Dwarf Galaxies as DM Laboratories

A galactic halo (~10^{12} M_0)

cold dark matter

warm dark matter



The Three Big Issues

- **`Missing Satellite' Problem**
- **Core-Cusp Problem**
- **The `too big too fail' problem (`Boylan-Kolchin effect'?)**

Can rationalize solutions according to personal outlook

1. Revolutionary/anarchist: Problems are fundamental to cosmology: e.g. Warm Dark Matter

2. Interest in cooking: baryonic feedback (e.g. SNe outflows)

3. Pessimist: Nature is a bitch:

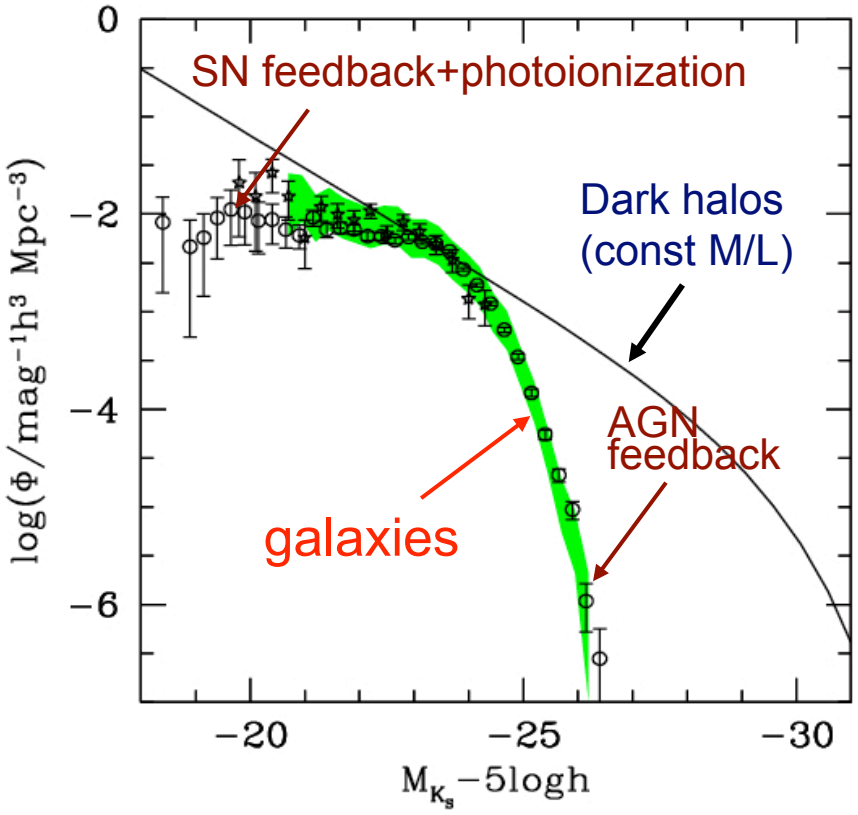
Milky Way is atypical (satellites)

data is suspect (core-cusp)

Missing Satellites?

Suppression of star formation due to reionization and SN feedback is a semi-analytic fit to the galaxy luminosity function: it is a hypothesis and not a proof

Thus, Carlos, we do have to find the dark satellites

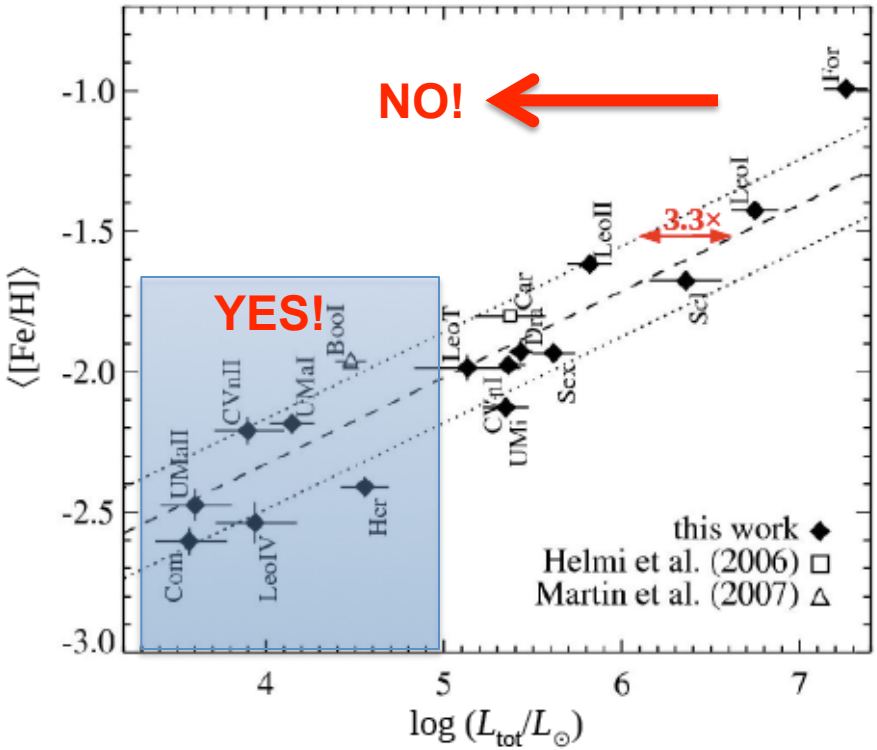


Substructure in MW Halo

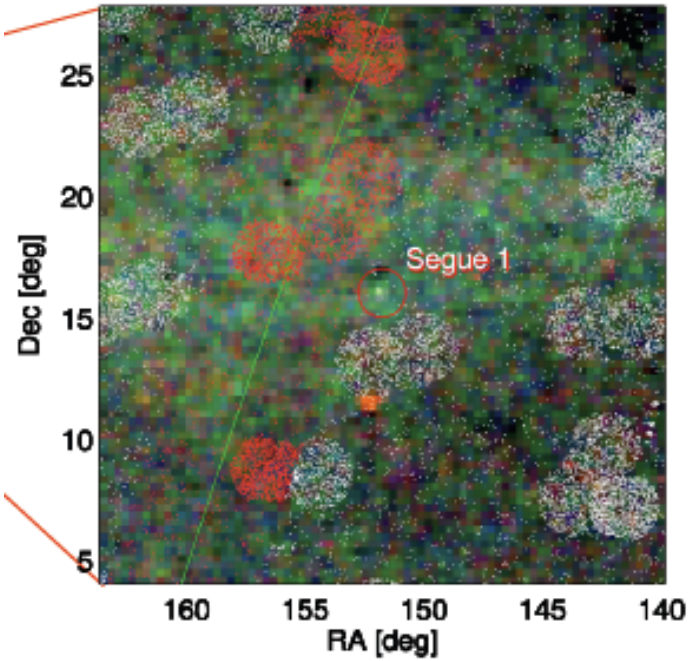
Can we deduce original abundance of subhalos through distortions and tidal debris?

Tight mass-metallicity relation precludes wholesale downsizing of classic dwarfs by loss of stars (but loss of enriched gas significant)

Association of most ultrafaint dwarfs with tidal streams suggests there were once many more: how many depends on their internal structure



Kirby et al (2011)



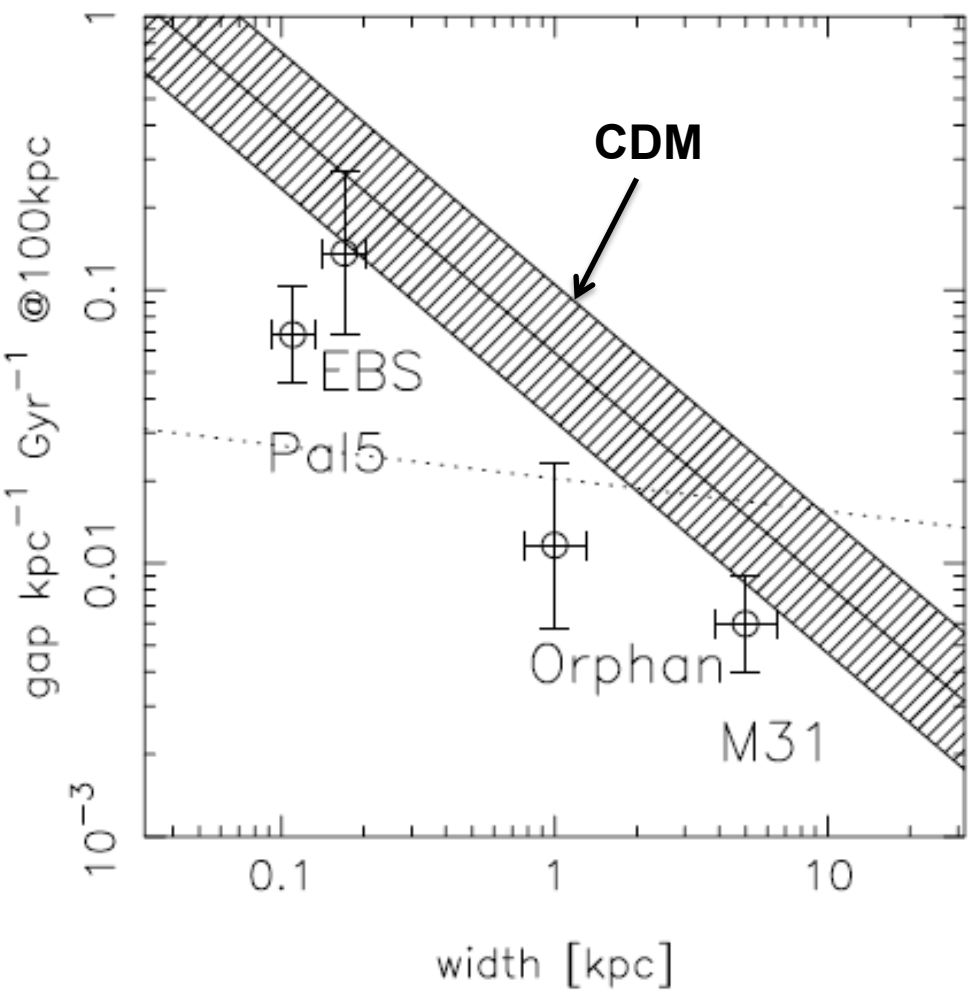
Belokurov (2012)

Gaps in the Streams

Structure in the streams is caused by DM sub-halos with masses > $10^8\,M_\odot$

The number density of gaps in well-studied streams can thus be used to quantify the abundance of dark sub-halos above this minimum mass.

With some uncertainty, the abundance of gaps scaled to 100 kpc distance is consistent with 10^5 halos above the detectable minimum mass.

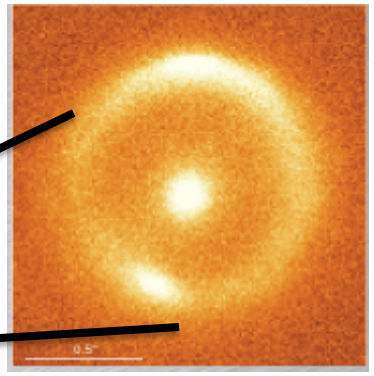


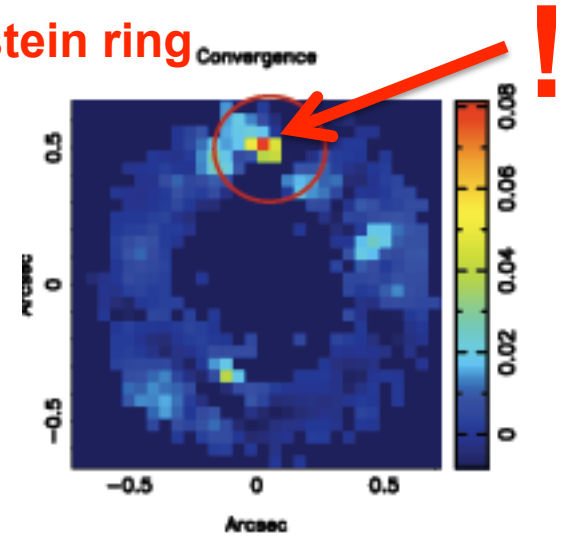
Carlberg (2012)

Highlight: the promise of strong lensing

Uncle Fritz was right!

B1938+666 Einstein ring





Techniques to detect substructures with M > 3.10^8 $M_\odot$ and hence DM fraction f and mass function slope α

$$dN/dm \propto m^{-\alpha}$$

$$f_{CDM} \approx 0.1\% \qquad \alpha_{CDM} = 1.9$$

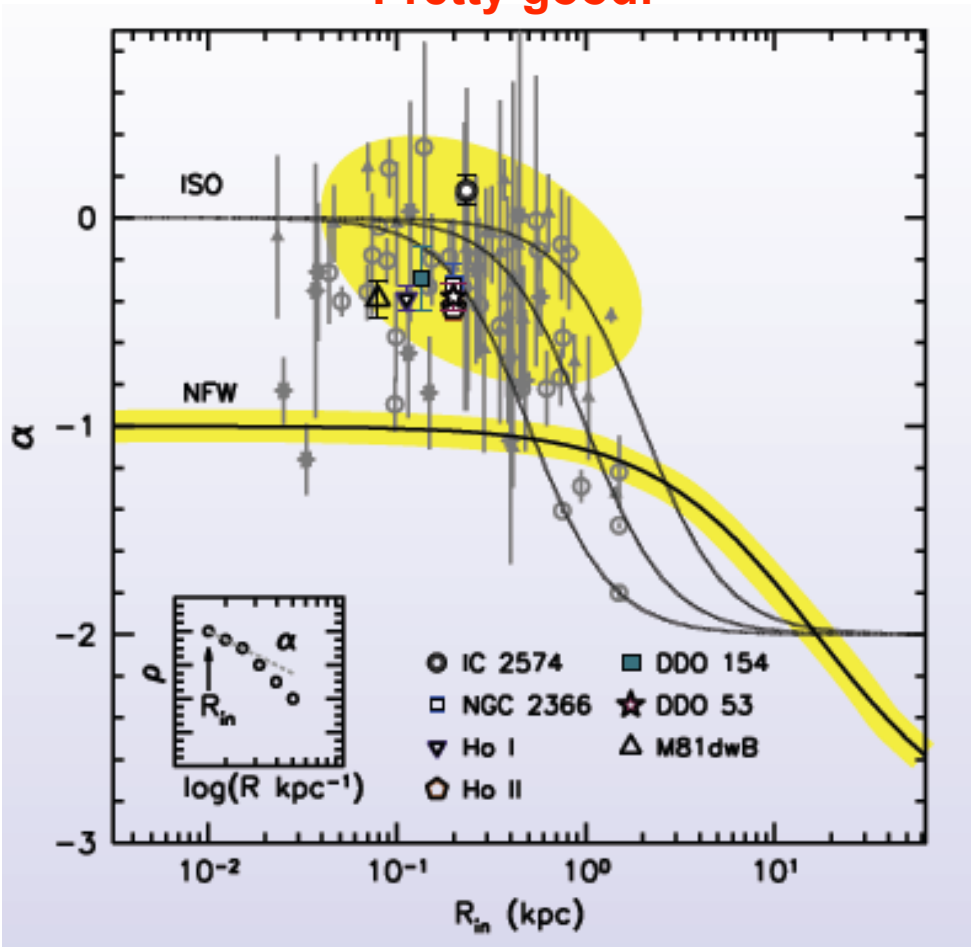
Need lots of lenses, accurate PSF

Limitations: 3-D position of substructure in host, los projection effects

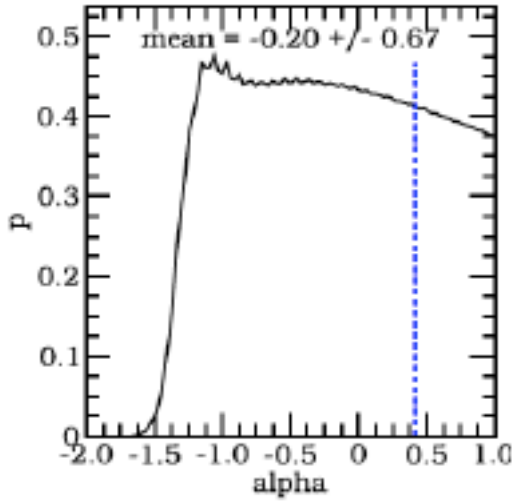
Vegetti et al – great talks also by Keeton, Treu

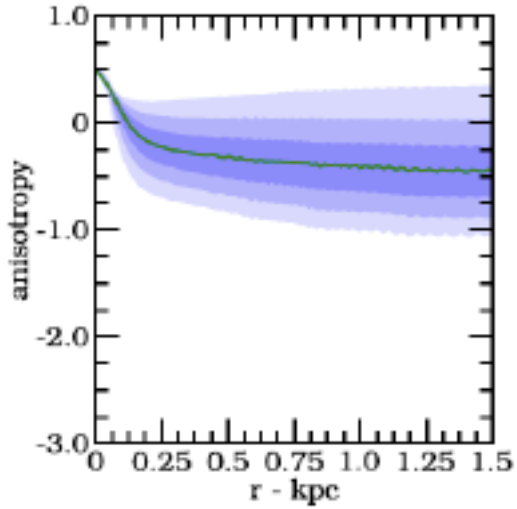
Core-Cusp Problem: How good is the data?

Pretty good!



Degeneracies

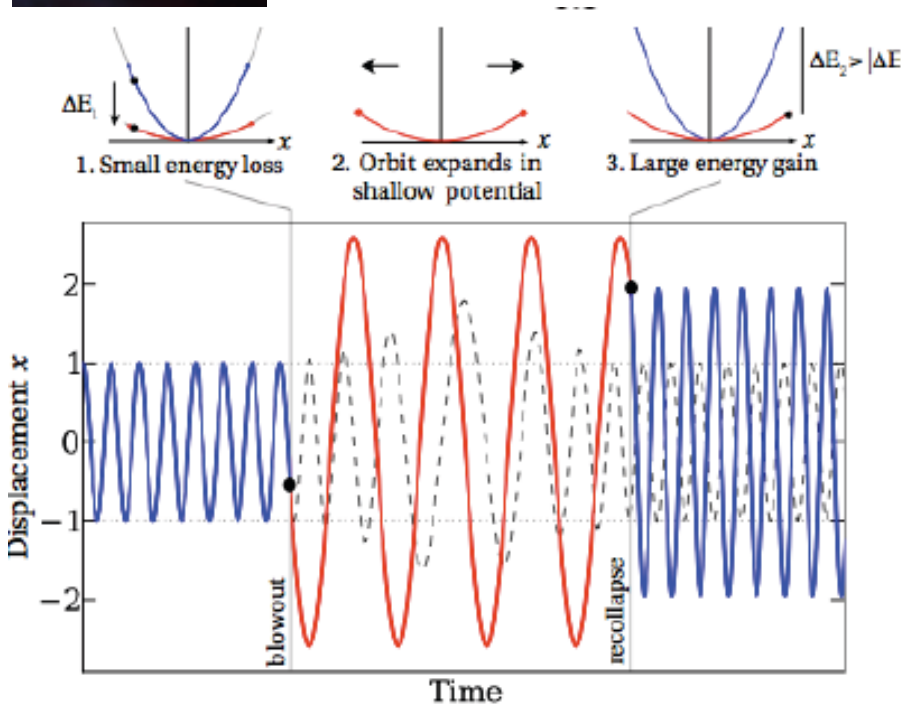


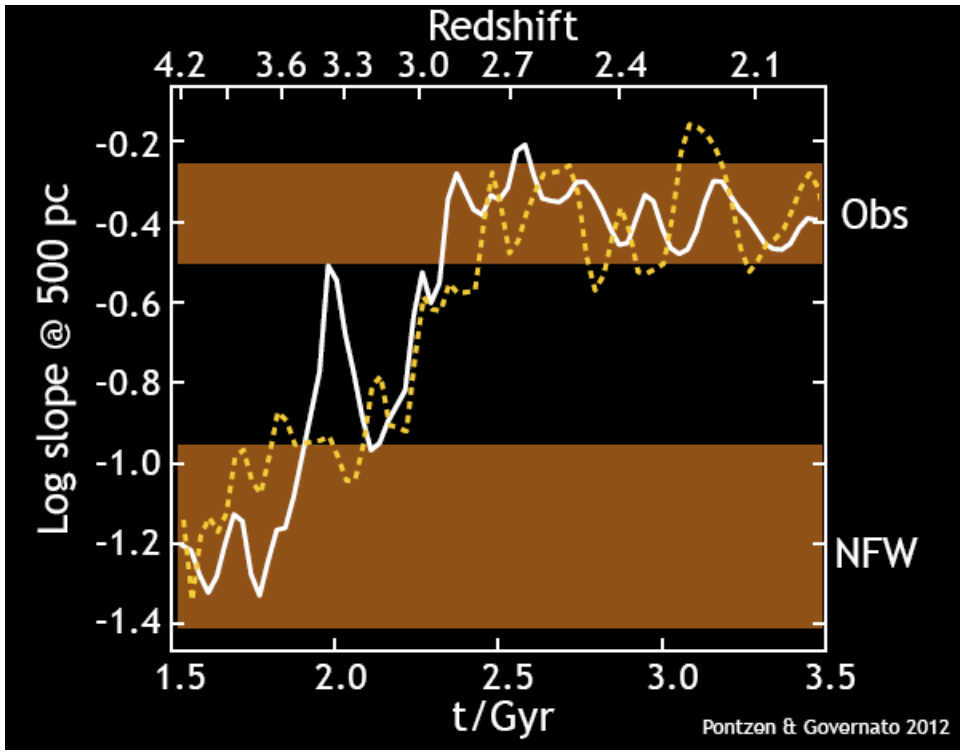


Field dwarfs: Oh et al (2011)

Sculptor dSph: Helmi, Breddels et al (2012)

Repeated SN Outflows Induce Core

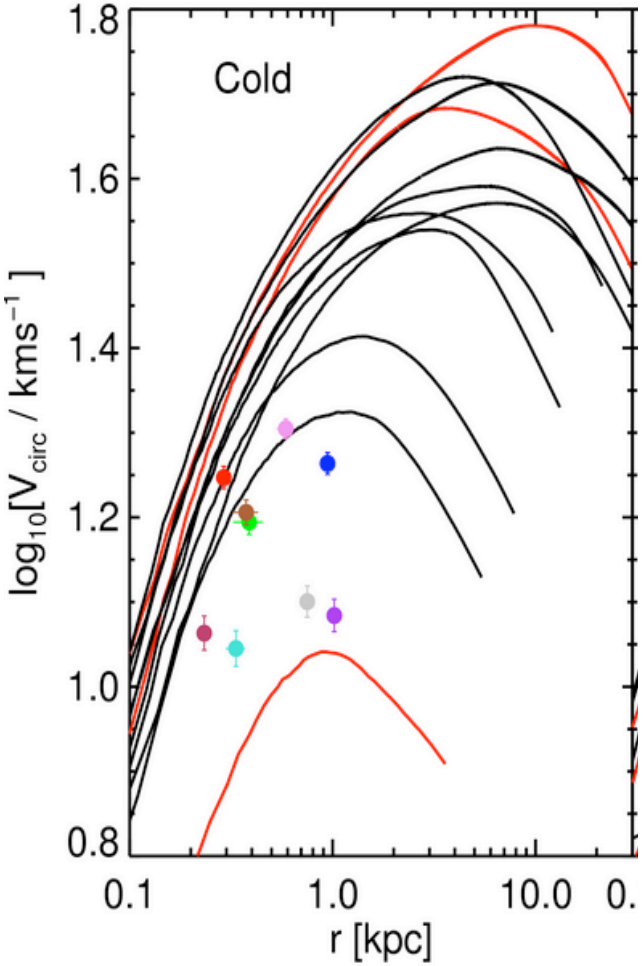




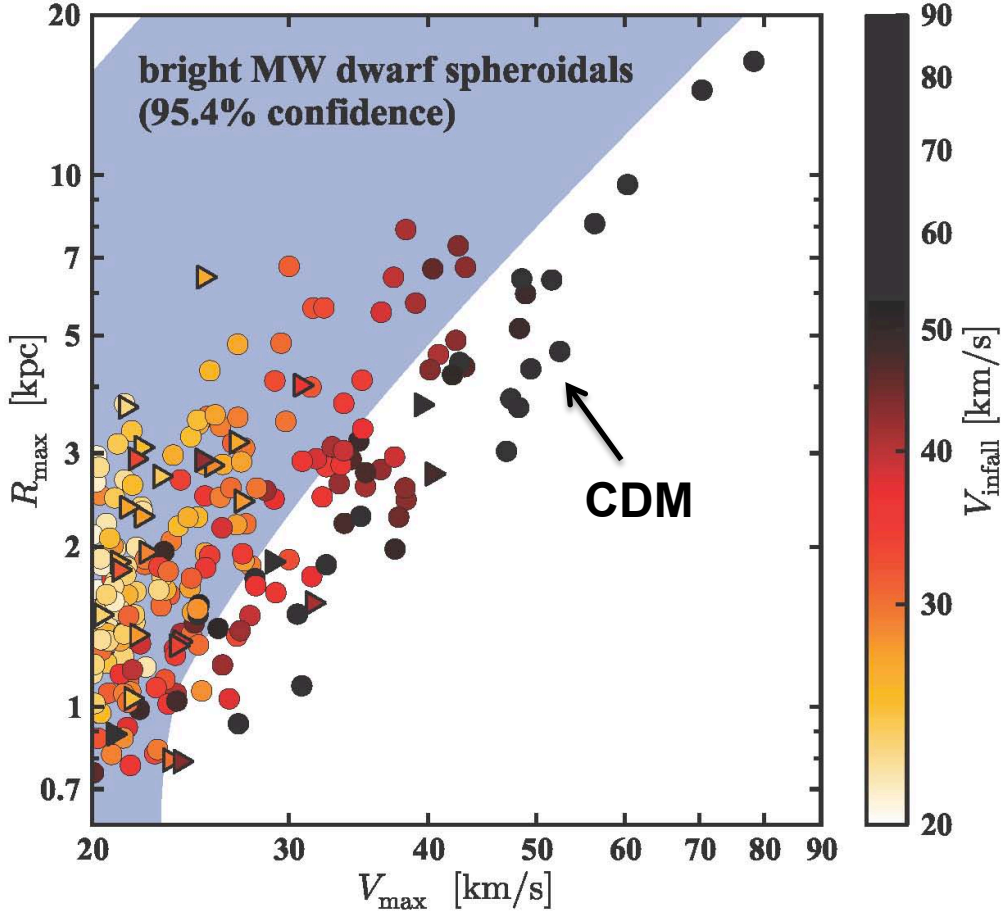
Pontzen & Governato (2012)

The `Too Big to Fail' Problem?

CDM puts the brightest satellites into halos more massive than observed

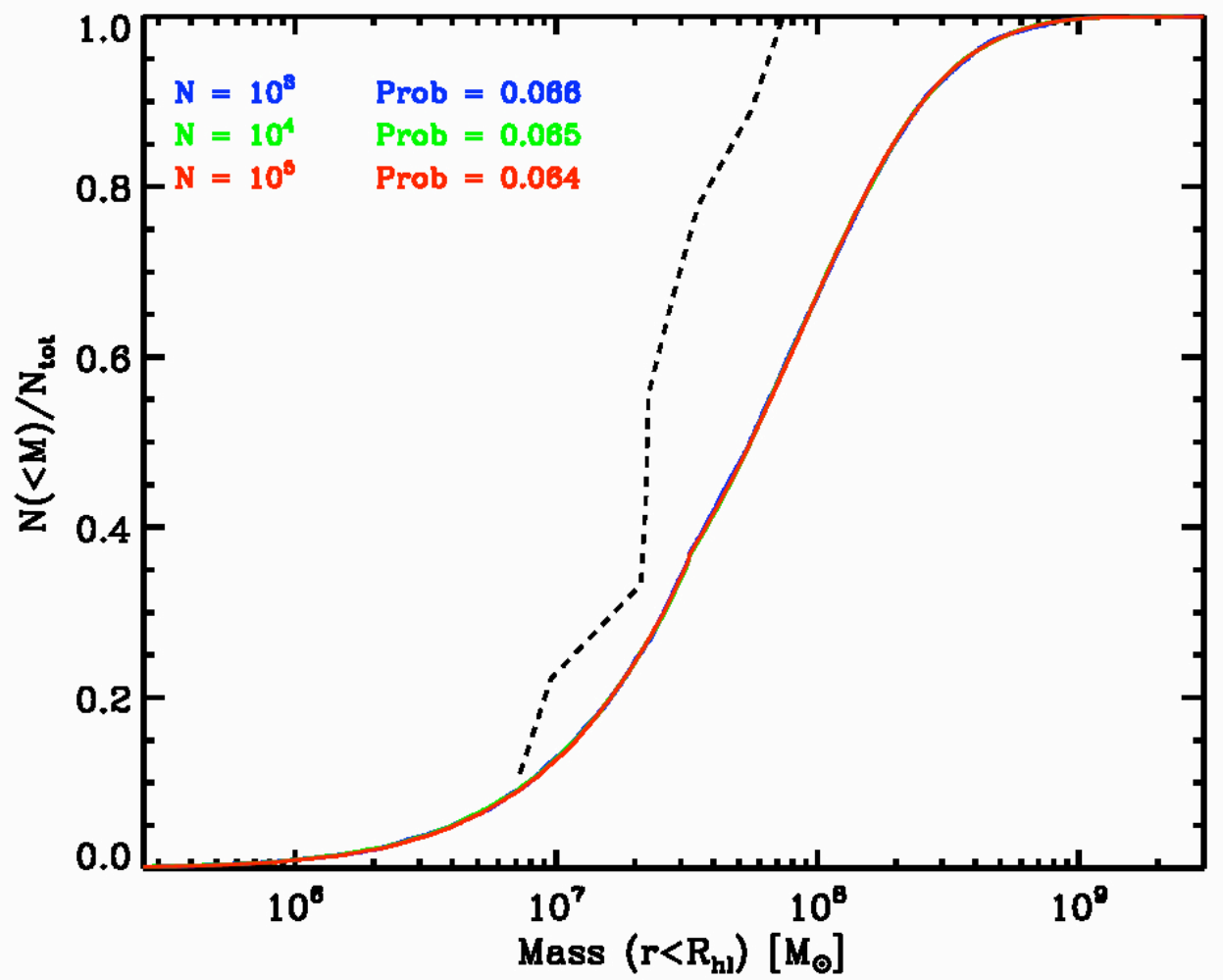


Lovell et al (2011)



Boylan-Kolchin et al (2011)

How Big A Deal Is the Discrepancy?



CDM rejected at 93.6% confidence level

Parry et al (2011)

The Irish Times - Thursday, September 15, 2011

Expert losing sleep over theory

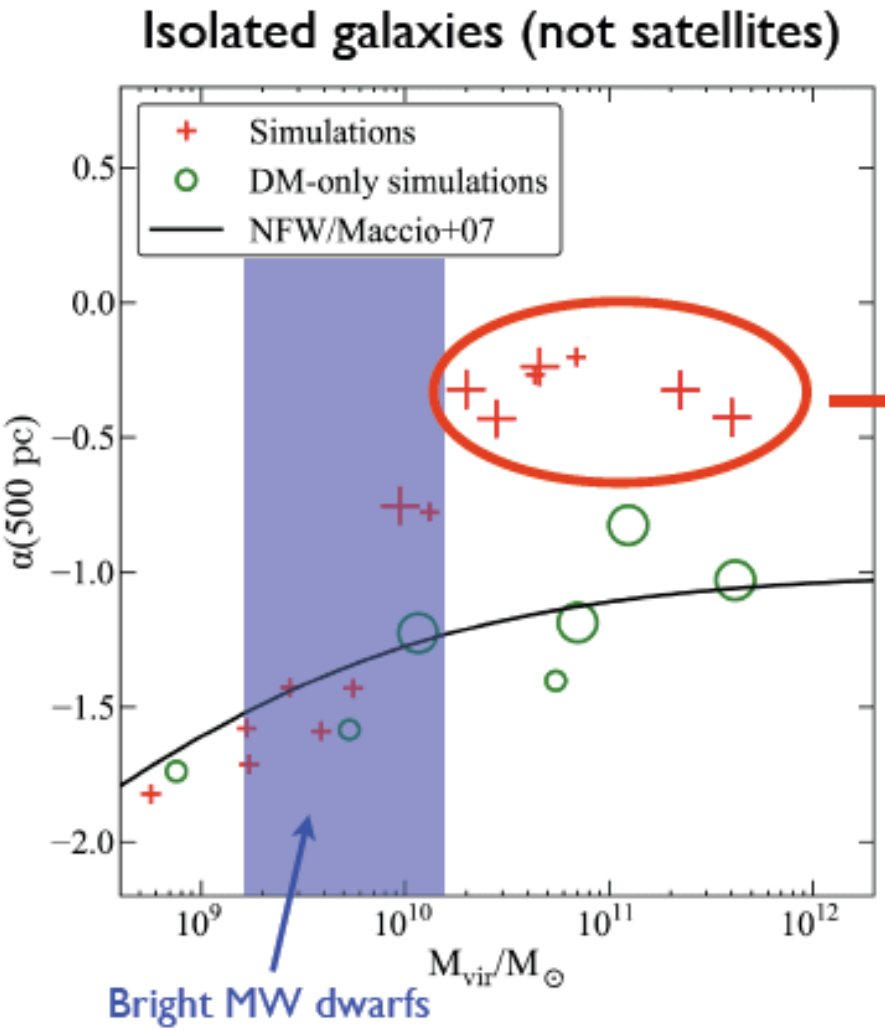
CREATION OF UNIVERSE: THE STANDARD theory on the creation of the universe is under threat, according to world leading cosmologist Prof Carlos Frenk.

At the British Science Association festival, Prof Frenk admitted he was losing sleep following the realisation that everything he had worked on for the last 35 years was based around an idea that was looking increasingly flawed. "I don't say this lightly," he said.

Baryonic Feedback?

Reduction in dark matter density from supernova feedback?

(e.g., Navarro et al. 1996; Read & Gilmore 2005; Governato et al. 2010; Pontzen & Governato 2012)

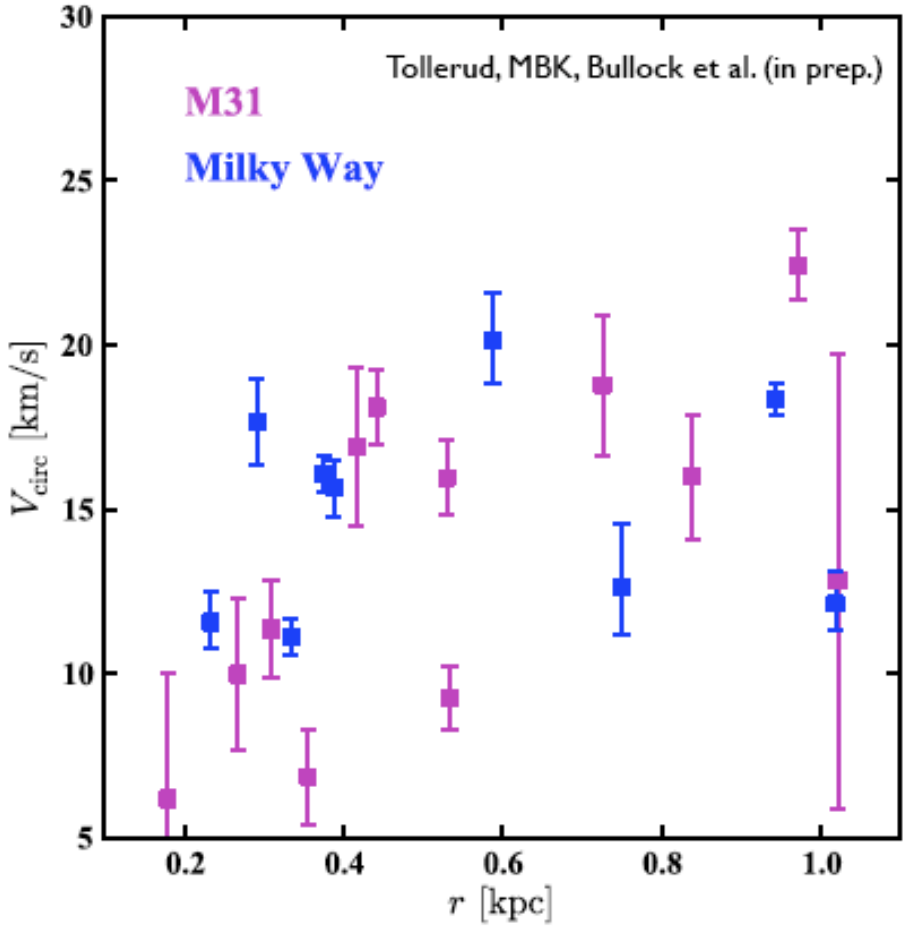


$M_\star > 10^8\, M_\odot$

dSphs : $M_\star \sim 10^6\, M_\odot$

Governato et al. 2012

Milky Way Doesn't Seem Anomalous?



M31 dwarf spheroidals

MW dwarf spheroidals

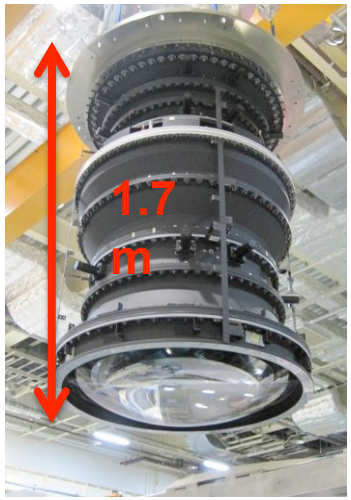
Abundance of satellites as bright as Fornax consistent between MW and SDSS averages
(Strigari & Wechsler 2012)

Preliminary; based on data on M31 from the SPLASH collaboration
(see also Collins et al. / PAndAS)

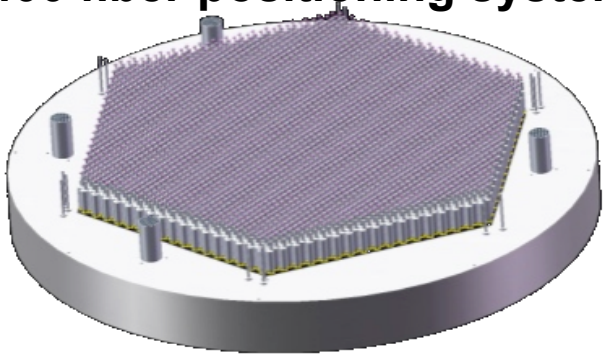
The Future is Bright

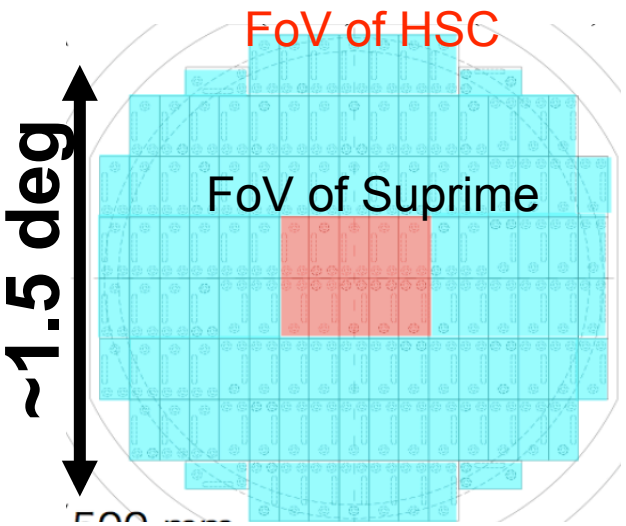
- Launch of GAIA – a revolution in the field
- Faint Imaging: WFC3/IR, DES, Skymapper, PanSTARRS, Subaru HSC
- Spectroscopy: MOSFIRE/KMOS, Ca K survey, Subaru PFS, 4MOST

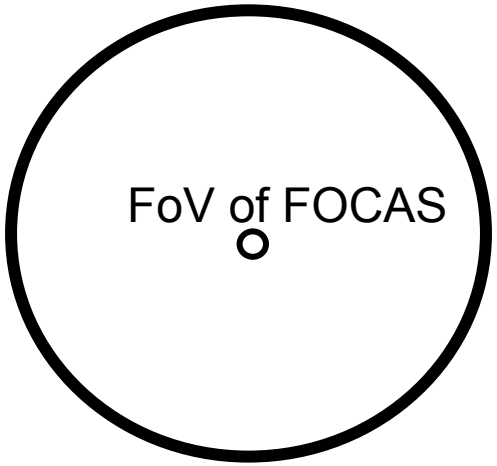
Subaru Wide Field 8m imager and matched spectrograph

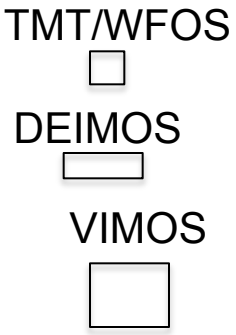


2400 fiber positioning system









Opening Remarks (redux)

TIWLTHMA

- DM detections from Fermi? NOT YET, PROMISING
- Flux anomalies – consistent with CDM? SO FAR
- Are Milky Way DGs typical? YES
- Can DGs Reionize the Universe? PROBABLY

Thanks to Nick, Risa and Léon!