The Role of Dwarf Galaxies in Cosmic Reionization

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- Mike Shull (CU-Boulder)
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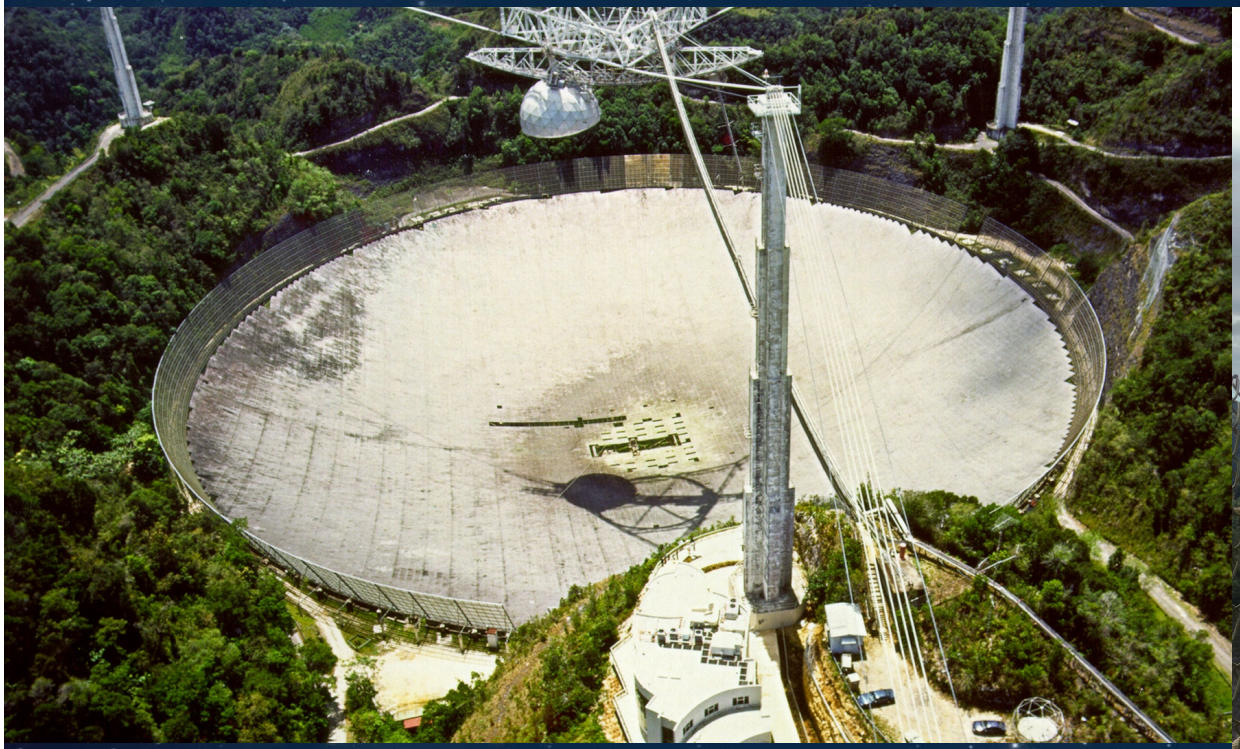
The 99 percent…

- Could these systems have hosted the first stars, and be cosmological survivors of galaxy assembly and reionization?

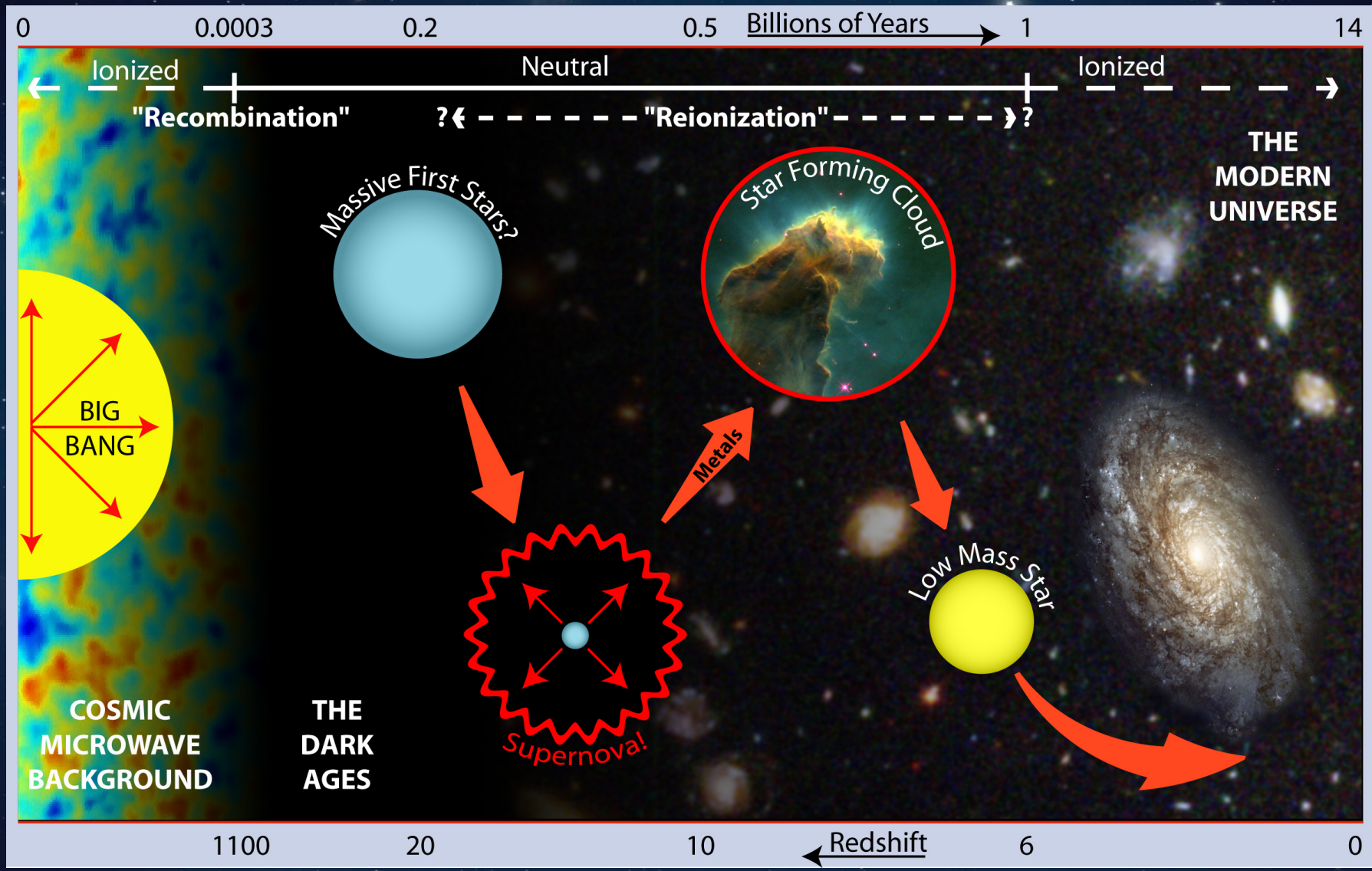
No animals or galaxies harmed in creating this talk

- How important were they for reionization, and cosmic metal enrichment? What are the observed patterns relative to other local universe systems?

Examine this through theory, UV/optical data and also 21 cm studies (ALFALFA)

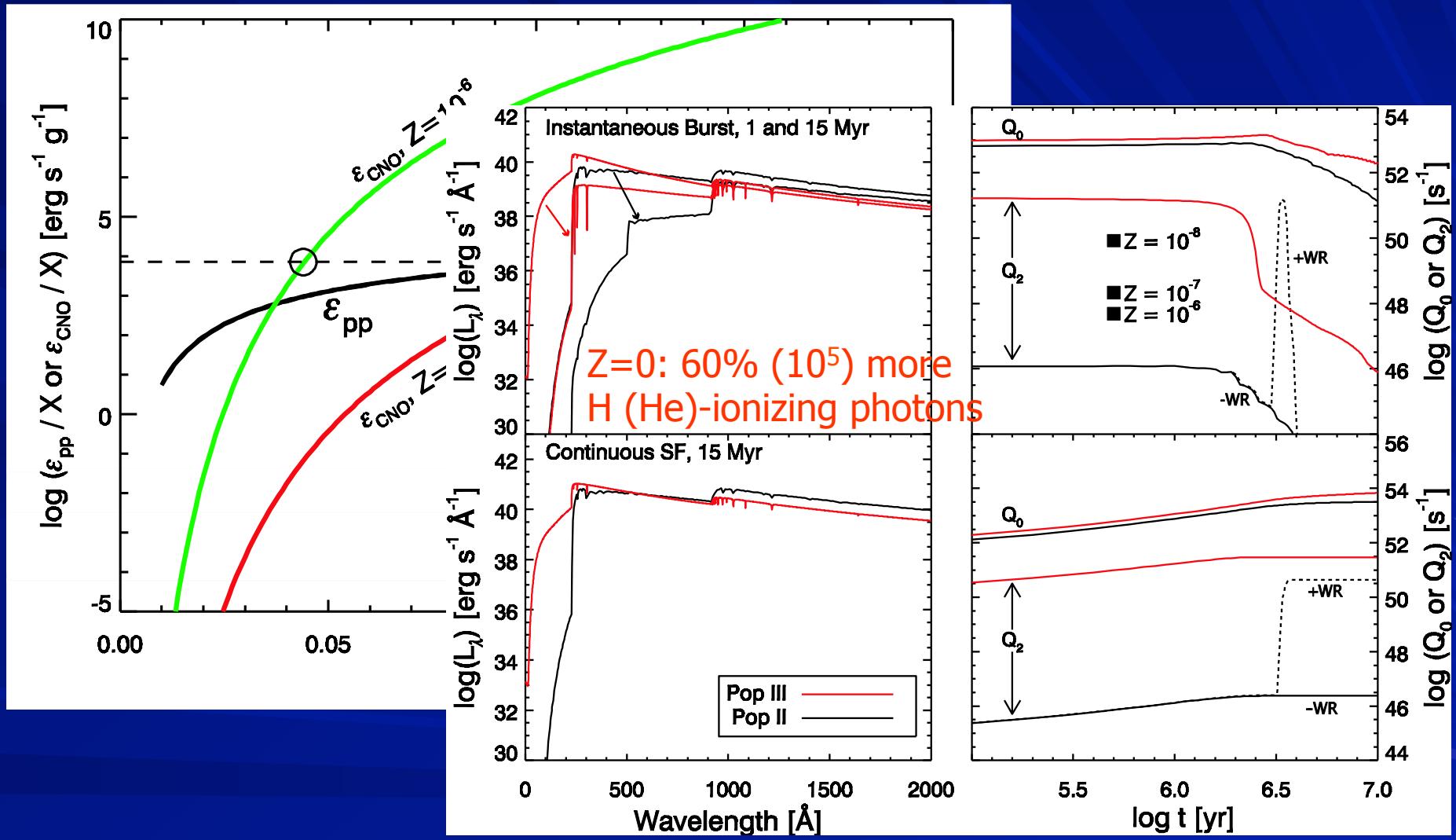


Almost all ALFALFA galaxies found at 21 cm (HI) have stars, and are dIrrs.



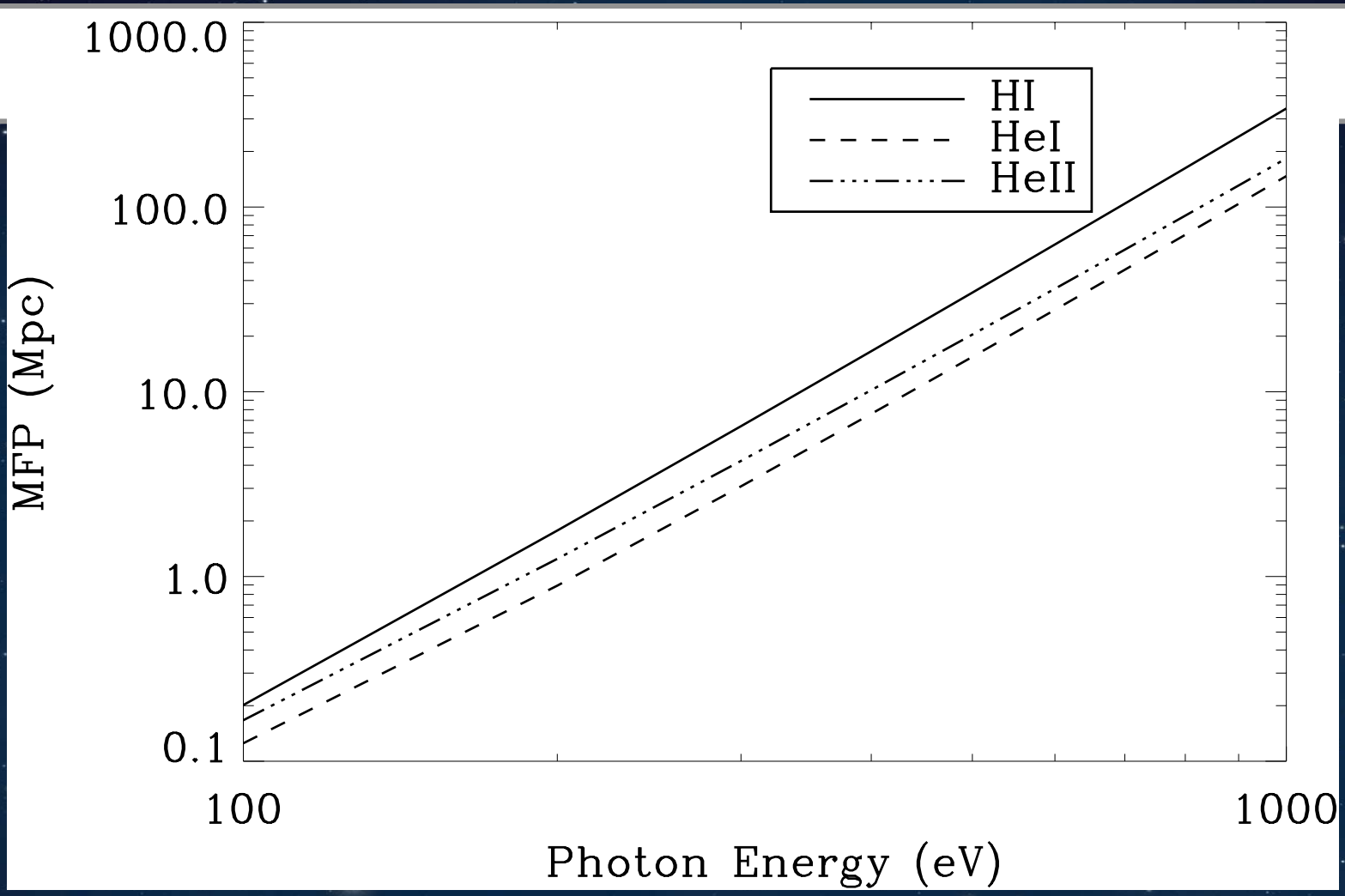
From Tumlinson, Venkatesan & Shull 2004, as featured in Sky and Telescope

From Venkatesan, Tumlinson & Shull 2003; see also Schaerer 2002, Bromm, Kudritzki & Loeb 2001



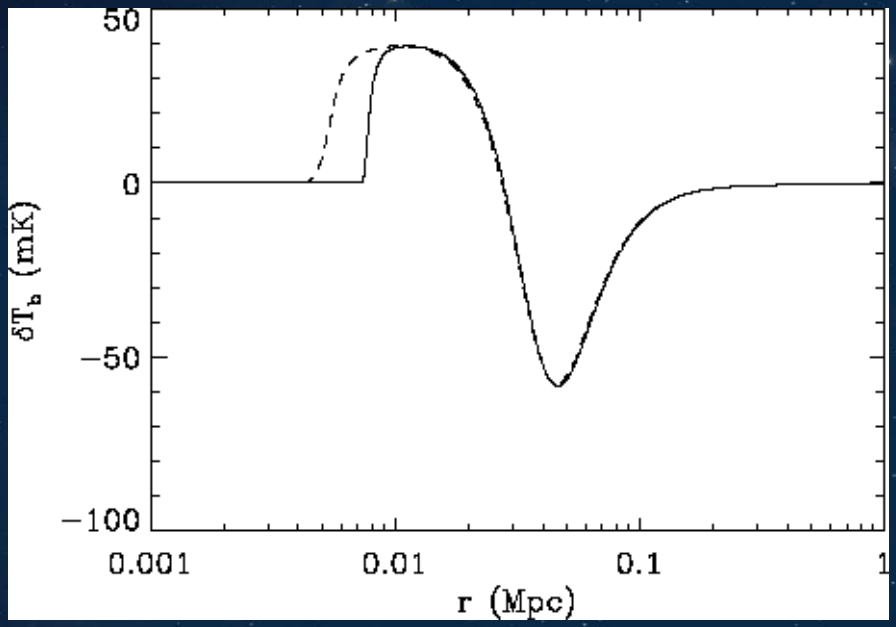
Why are X-rays interesting?

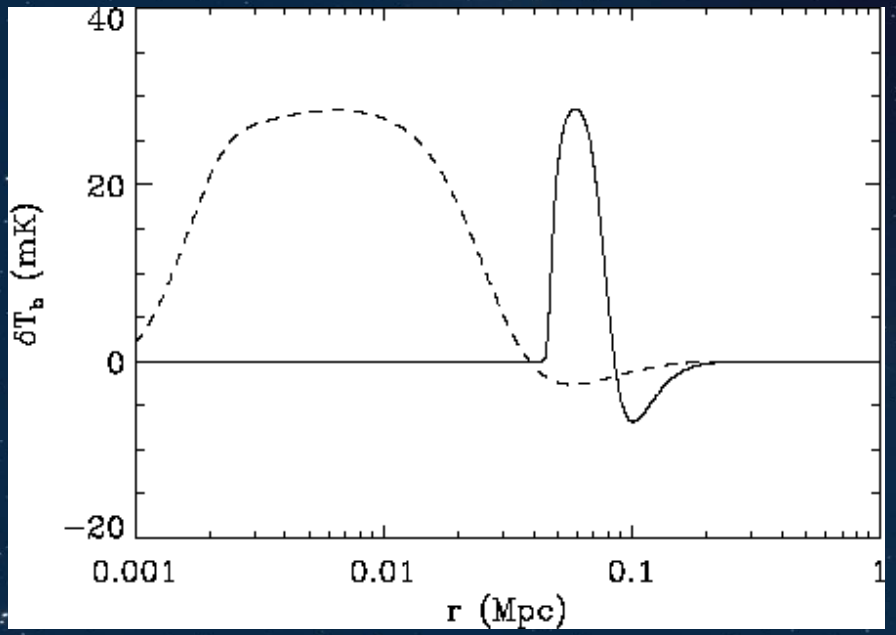
- X-rays have more penetrating power than UV radiation, seeding more (partial) IGM ionization/heating at early times
- X-rays ionize He I → photoelectrons → secondary ionizations of H I. This becomes important at early times and the EARLY stages of IGM ionization *(Shull & van Steenberg 1985, Venkatesan, Giroux & Shull 2001, Oh 2001, Ricotti & Ostriker 2004, 2005 papers and others)*, effectively coupling X-ray and He ionization from early sources of hard ionizing radiation
- Joint effects of X-rays and He-ionizing radiation has important consequences for topology of reionization (workshop topic of outside in or inside out reionization)
- Affects thermal/reionization history of IGM, "visibility" of z>6 universe, and CMB/radio signals from first galaxies/QSOs *(Chen & Miralda-Escude 2008, Bolton et al. 2009, Pritchard & Furlanetto 2007, and many others)*



- MFP in Mpc, at $z=10$, for 0.1-1 keV photons.
- Note the ranking of species (the X-ray "bottleneck" of He I), i.e., He I "sees" the X-rays first

21 cm radio signal from X-rays

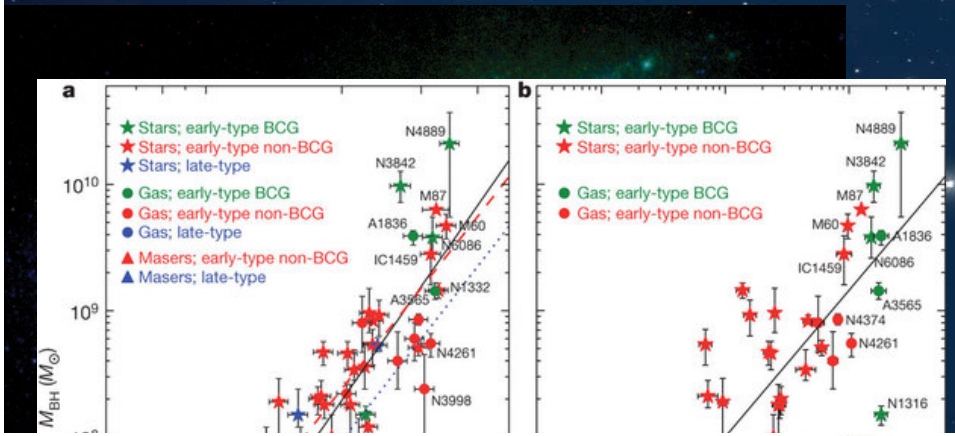


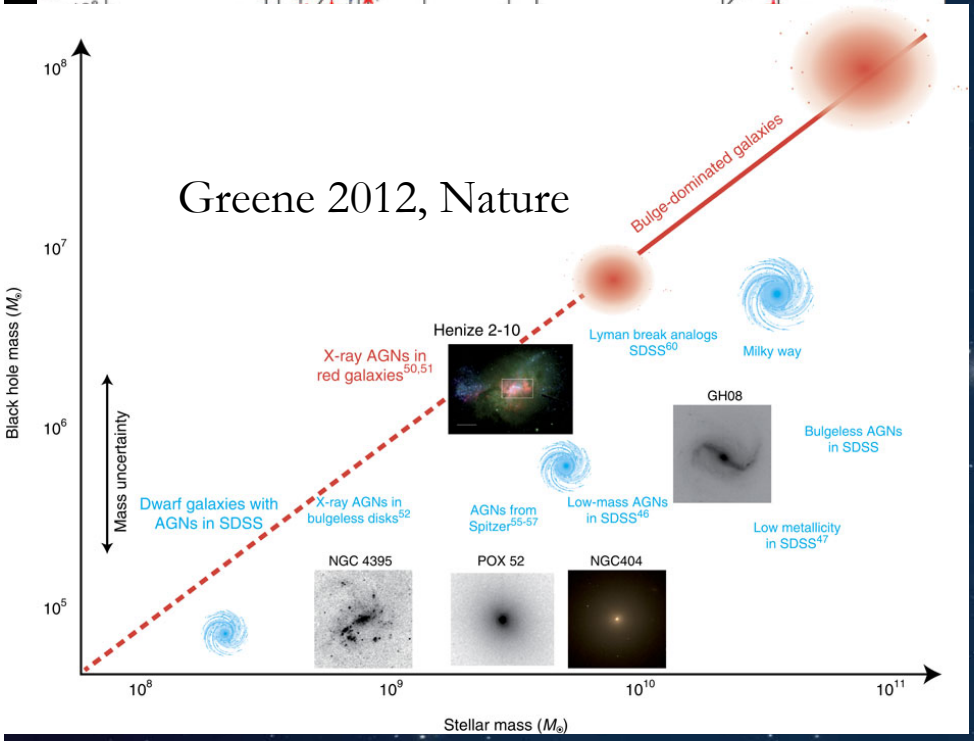


- 21 cm Brightness Temperature shown
- **Solid**: full spectrum, **Dashed:** Xrays only – note distinct signature spatially
- LEFT: 10^5 M_{sun} stars, 10^6 M_{sun} BH at t = 0.1 Myr, at z=20
- RIGHT: 10^6 M_{sun} stars ONLY at t = 1 Myr, at z=10

(Venkatesan & Benson 2011)

Central Black Holes in Dwarf Galaxies

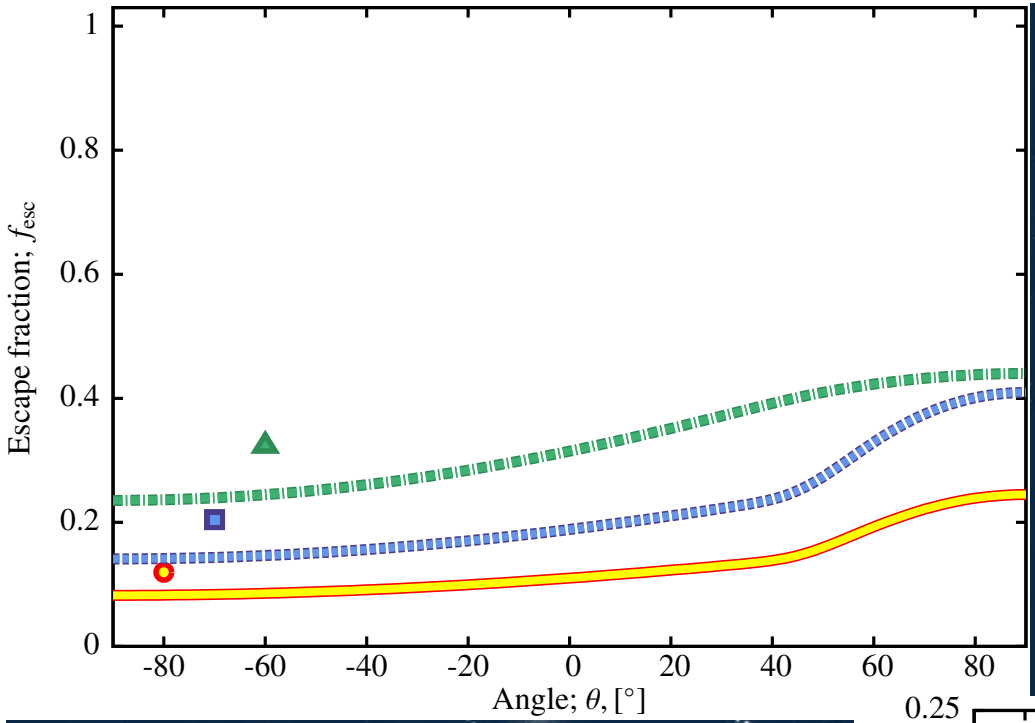




- Reines et al. 2011 report an active acrreting BH (~10^6 M_{sun}) in the center of Henize2-10.
- Reines, Greene & Geha 2013 have assembled the largest sample to date of nearby dwarf galaxies (151) with active massive BHs (10^5-10^6 M_{sun}).
- Connection to AGN feedback, to testing DM annihilation in cores

Escape fraction from dwarf galaxies

- The escape fraction of ionizing radiation f_{esc} is a critical parameter in cosmological studies, theoretical and observational
- Determines the reionization/thermal history of universe (IGM and CMB), and affects the viability of detecting high-z sources
- Observational measurements of low-z galaxies indicate an escape fraction of H-ionizing radiation f_{esc} (H) ~ 1—10%. For sources at z~3, this can be higher (LBGs or otherwise). No measurements of f_{esc} (He) to date, or any data for dwarf galaxies.
- Theoretical calculations have ranged from < 1% to 100%, with strong variations with galaxy or source properties, and higher values coming from numerical simulations of dwarf galaxies.



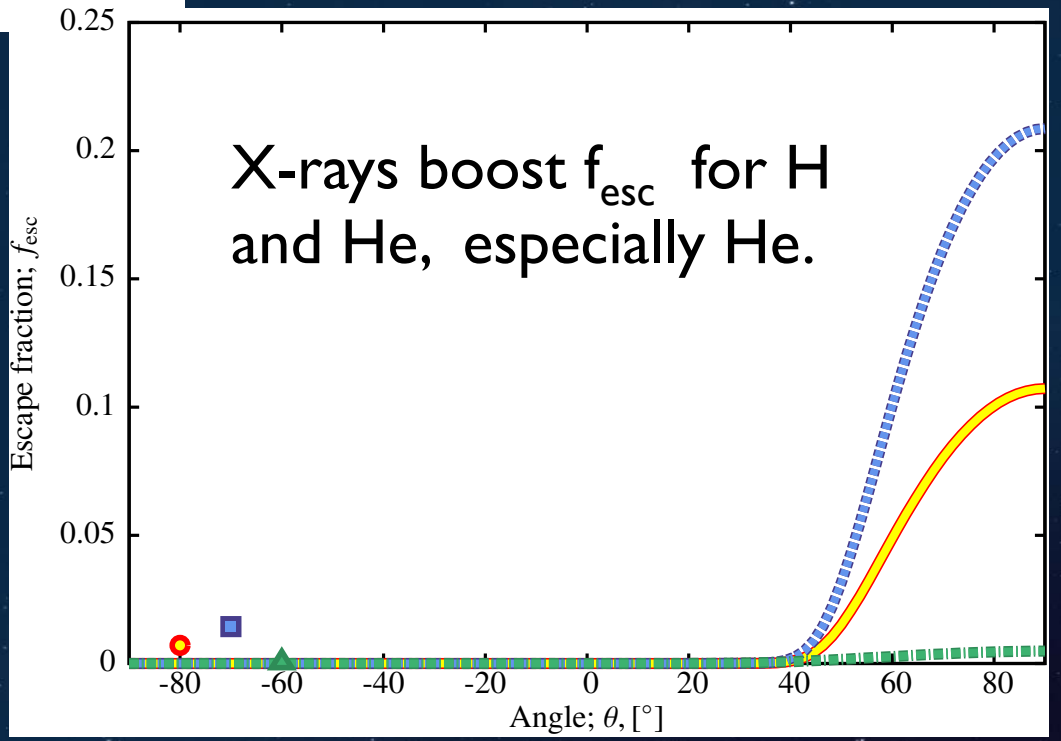
Benson, Venkatesan & Shull 2013

Impact of X-rays on f_{esc}
First calculation of f_{esc} for He

YELLOW: H I
BLUE: He I ; GREEN: He II
Averaged over all realizations

Beta gas density profile within
NFW 10^8 Msun halo at z=10
Virial radius ~ 1.4 kpc
10^4 AGN off center by 100 pc

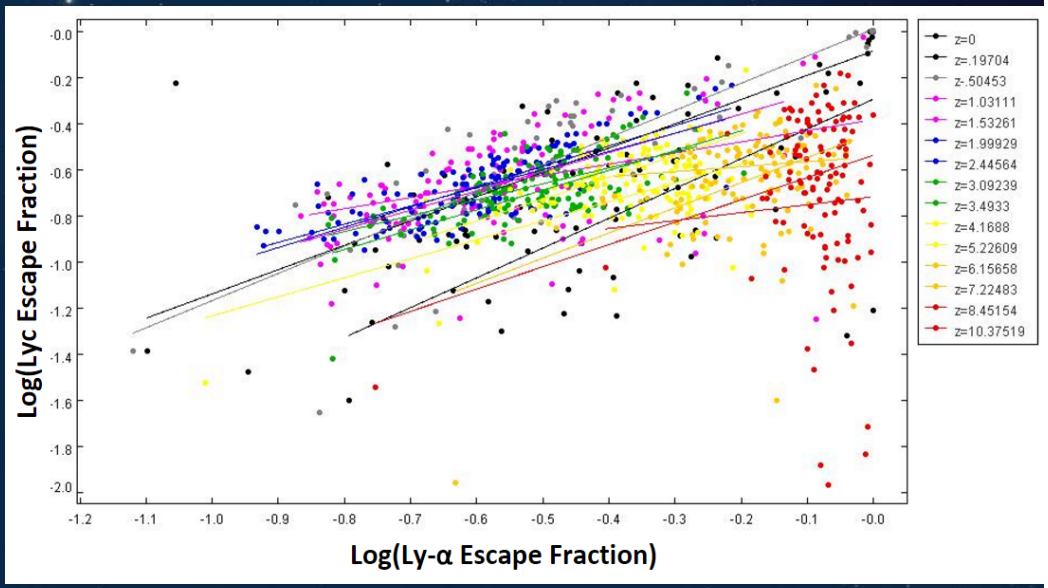
CLUMPING:
Cloud overdensity 10,
filling factor 20%, size 30 pc
WITH X-RAYS (TOP)
NO X-RAYS (BOTTOM)

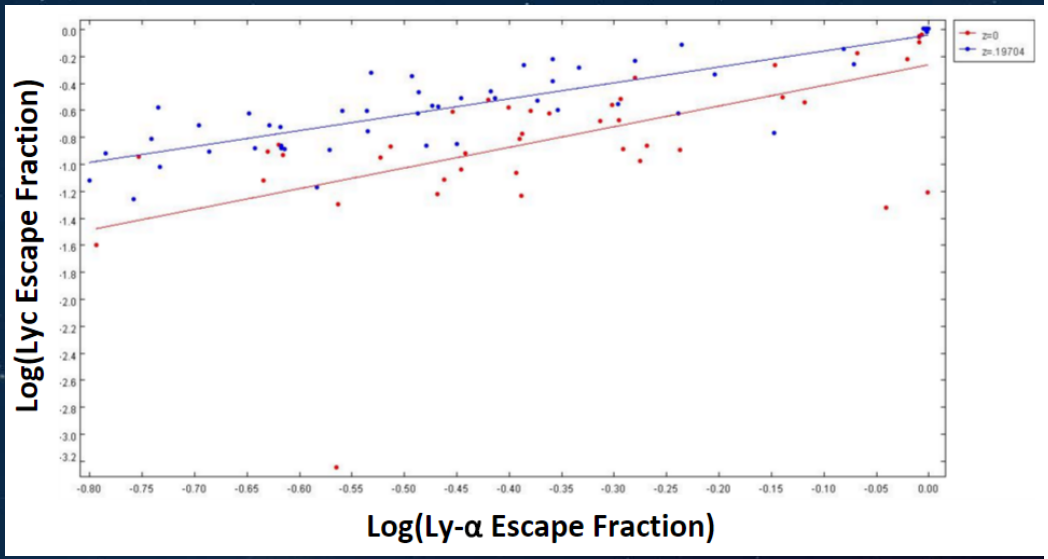


X-rays boost f_{esc} for H and He, especially He.

Escape Fractions for 18 Local Low-Mass Galaxies

- Sample: 18 star-forming galaxies (12 from the Lyman-Alpha Reference Sample, Rivera-Thorsen et al. 2015; 6 from the KISS sample, Salzer et al. 2001). All were observed in the FUV with HST/COS to derive limits on their escaping Lyman-alpha radiation (Wofford et al. 2013).
- Use simulations + radiative transfer model of Yajima et al. (2014) to derive f_{esc}(Ly-continuum) from f_{esc}(Ly-alpha). *Caveat:* their derived relations are for a MW-like galaxy.

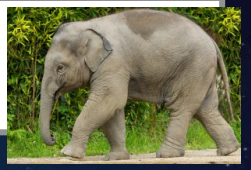




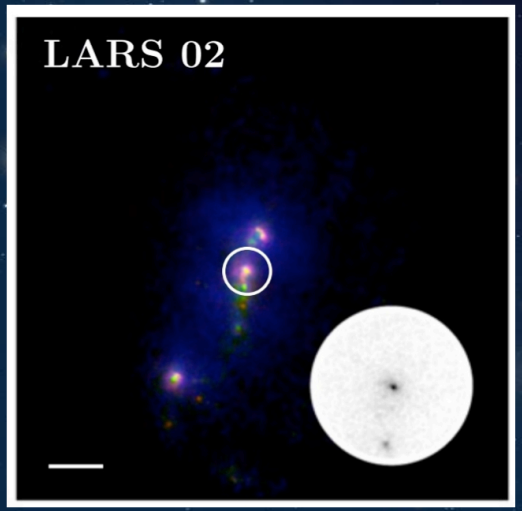
The LARS and KISSR Galaxy Sample

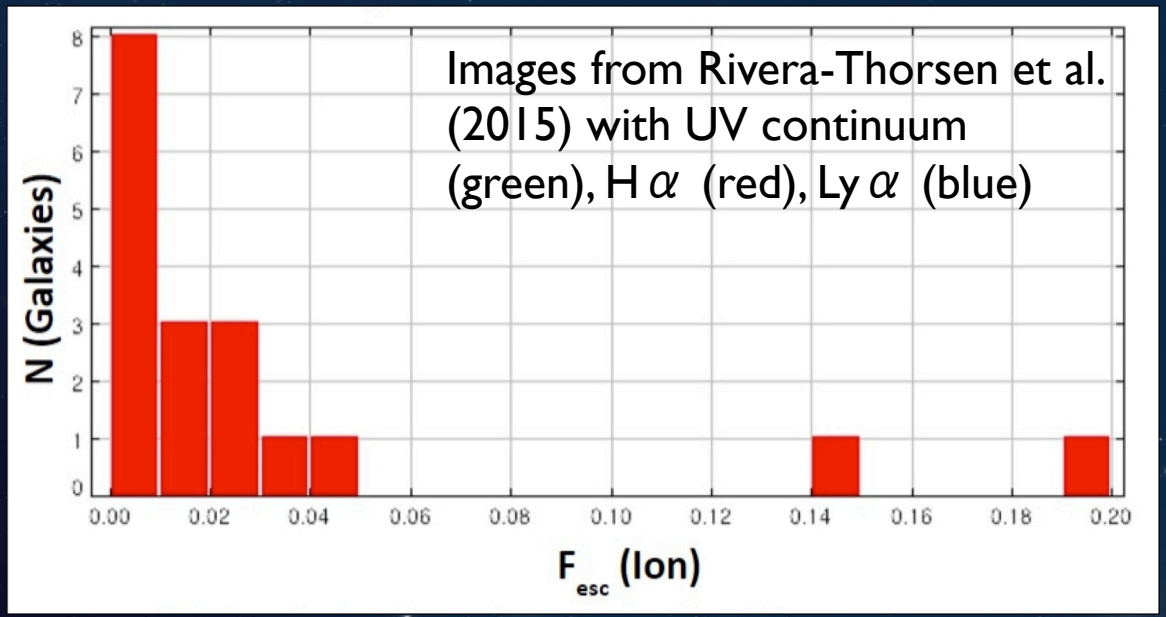
- Galaxies were selected from the LARS (Rivera-Thorsen et al. 2015) and KISSR (Salzer et al. 2001) surveys
- The surveys select star-forming galaxies in the local universe
- Galaxies are nearby ($z<0.2$), mostly low mass ($\log M/M_\odot < 10.8$ for all but 2 systems, 10 systems with $M_{star} < 5 \times 10^9$ M_{sun}), and star-forming.
- Two highest mass systems have $\log M/M_\odot = 11.0$ and 11.1
- Galaxies have existing Ly-α measurements from HST/COS
- These galaxies are unusual, they are detected in Ly-α
- These galaxies are thought to be local analogs to high-redshift systems that might have reionized the universe

Escape Fractions for Sample

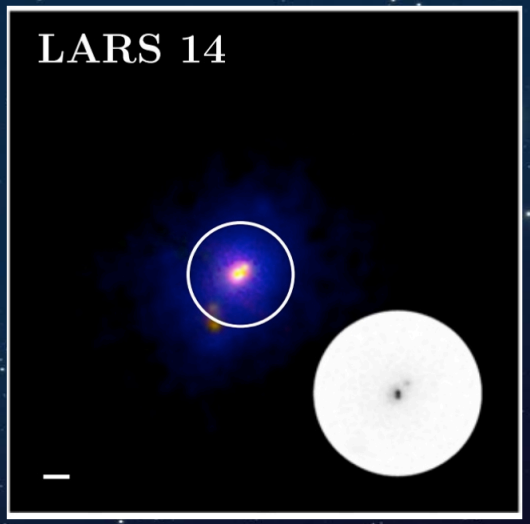


- f_{esc} < 5% for all but 2 extreme cases where f_{esc} > 14%.
- Sample averaged f_{esc} insufficent for reionization BUT the two outliers are two of the lowest mass systems from the LARS sample which is intriguing.





Images from Rivera-Thorsen et al. (2015) with UV continuum (green), H α (red), Ly α (blue)



LARS02 and LARS14

- These 2 galaxies have continuum escape fractions several times larger than other galaxies in the sample

LARS 14 ($z = 0.180691 \pm 5.6 \times 10^{-5}$)

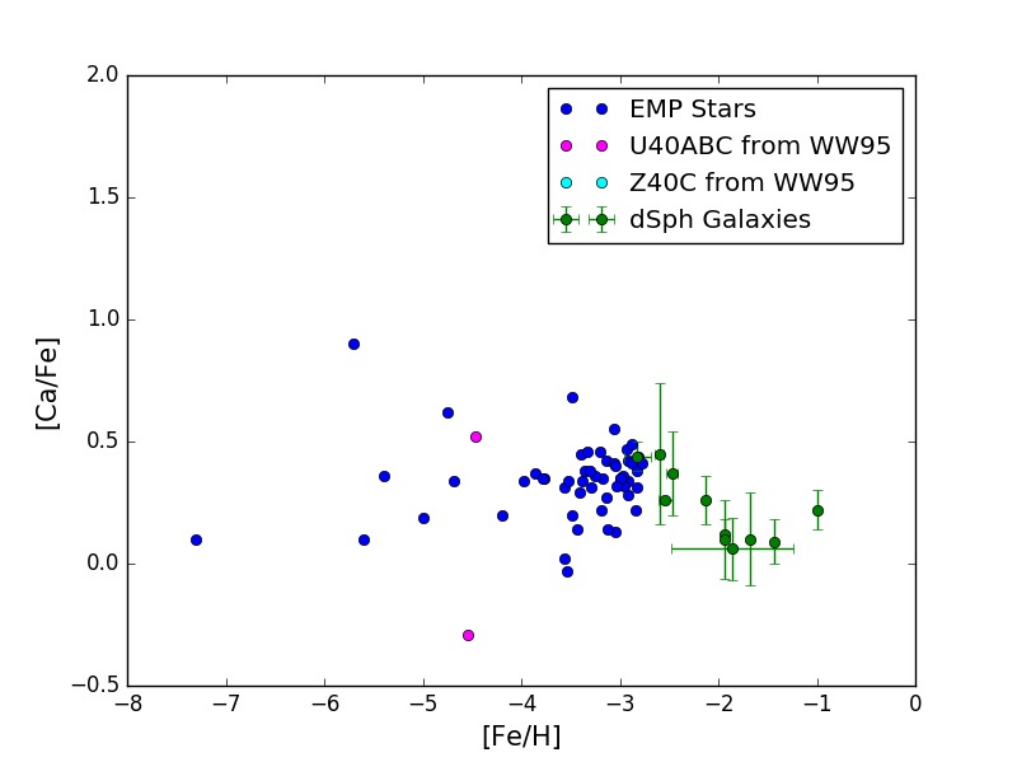
- Age: 3.21 Myr (youngest) , Mass: 1.75 x 10^9 $M_\odot$ (lowest), Low Metallicity (12 + log(O/H) = 7.8 from electron temperature method)
- Compact, hot galaxy with low neutral gas column density ('Green Pea' type galaxy).
- Double-peak emission profile, many absorption anomalies, fragmented neutral medium.

LARS 02 ($z = 0.029836 \pm 1.8 \times 10^{-5}$)

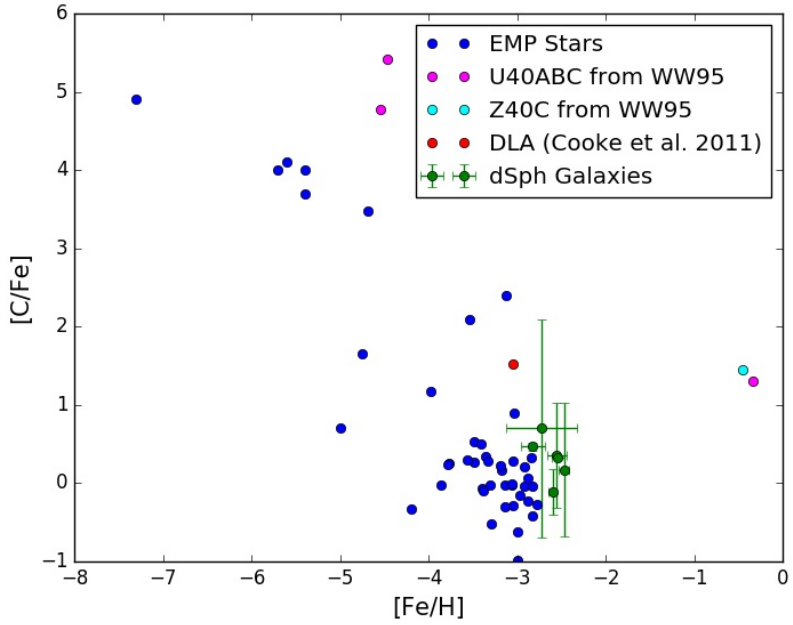
- Age: 7.95 Myr (median), Mass: 2.35 x 10^9 $M_\odot$ (second lowest), Metallicity 0.25 $Z_\odot$ (similar to LARS 01)
- Has a high infrared metal line covering fraction and low-outflow velocity, which normally quench Ly-α escape.
- Low dust content would facilitate Ly-α escape, but not enough to explain extremely high Ly-α escape fraction

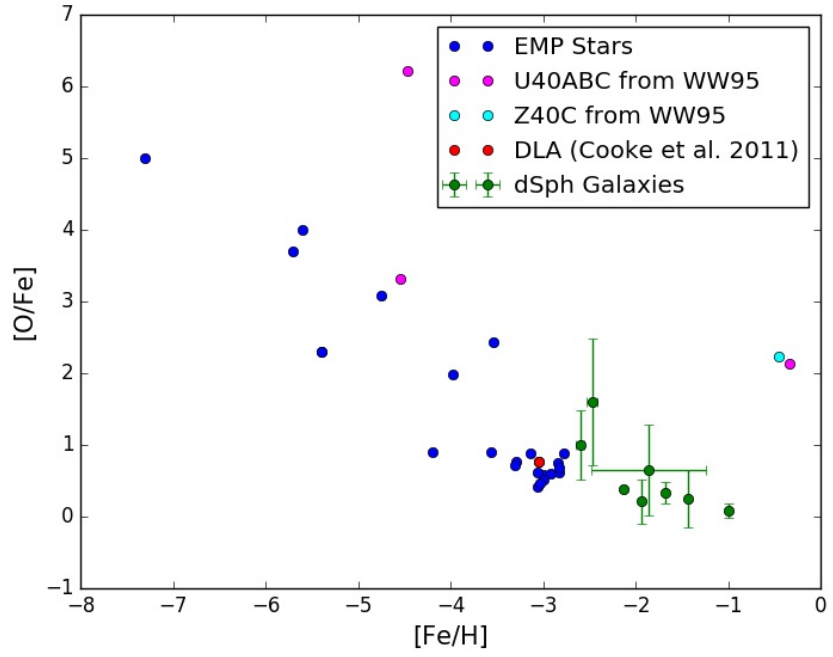
Metal abundance trends in dwarfs:

- Increasingly clear that local gas-poor dSph systems, many of them very old, have similar relative metal abundance patterns to those in very metal-poor Galactic halo stars (Frebel 2012, Brown et al. 2012, and others). Note addition of most iron-poor stars known to date (Keller+ 2014, Komiya+ 2016):



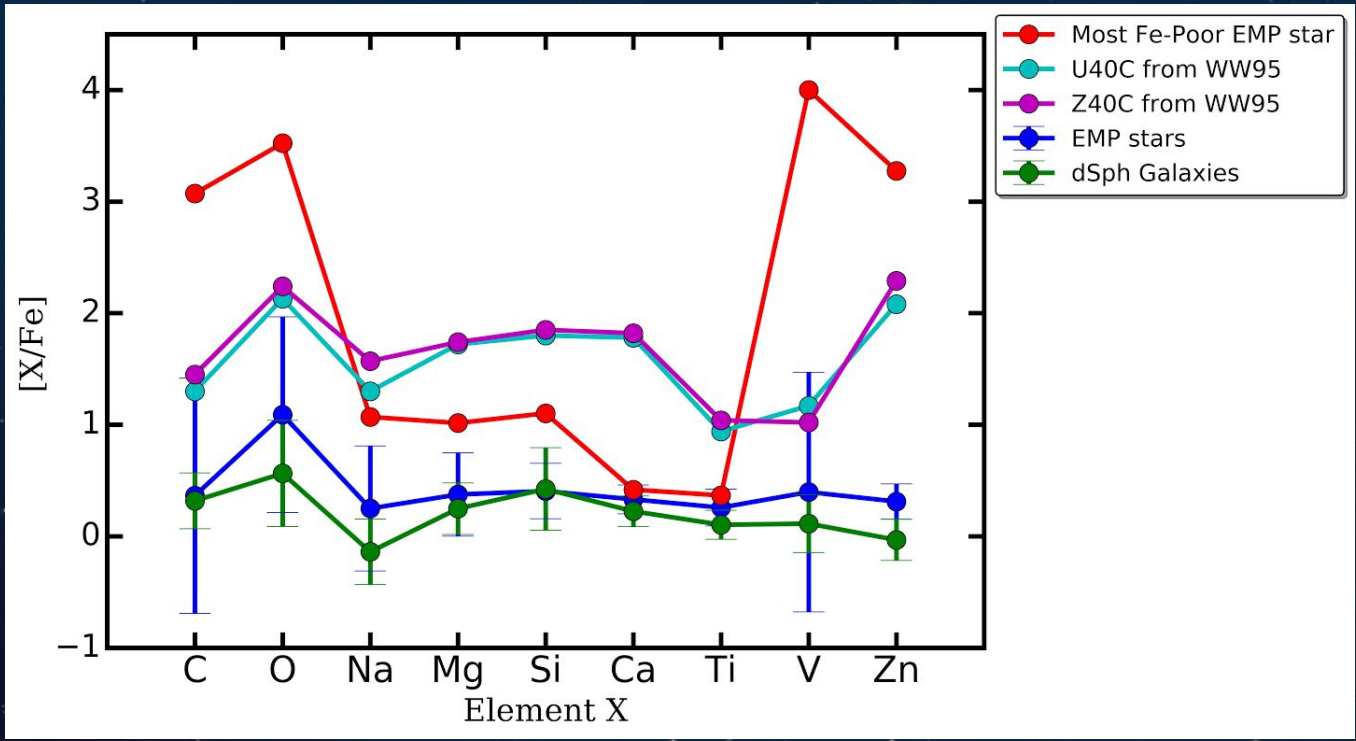
[C/Fe] and [O/Fe]


EMP Stars
U40ABC from WW95
Z40C from WW95
DLA (Cooke et al. 2011)
dSph Galaxies
[C/Fe]
[Fe/H]


EMP Stars
U40ABC from WW95
Z40C from WW95
DLA (Cooke et al. 2011)
dSph Galaxies
[O/Fe]
[Fe/H]

A comparison of dwarf galaxies and EMP stars amongst 9 common elements

- Many local dSph galaxies show similar abundance trends as the EMP halo stars, and strikingly close mean values for many commonly measured elements between the two datasets.



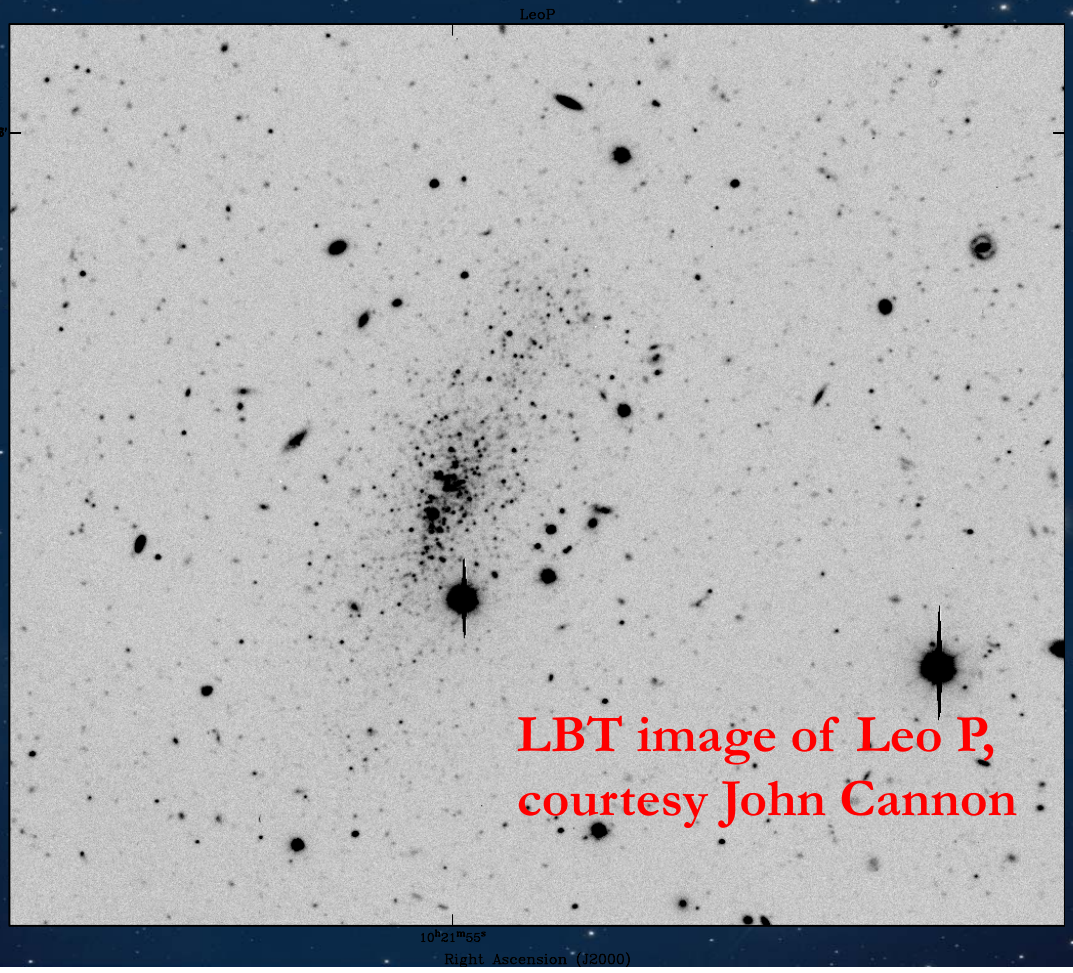
Metal abundances in these two distinct systems are closely correlated, and within 1 std-dev for nearly all elements!

Bringing ALFALFA into this:

Team Motto: having more fun than human beings should be allowed to have!

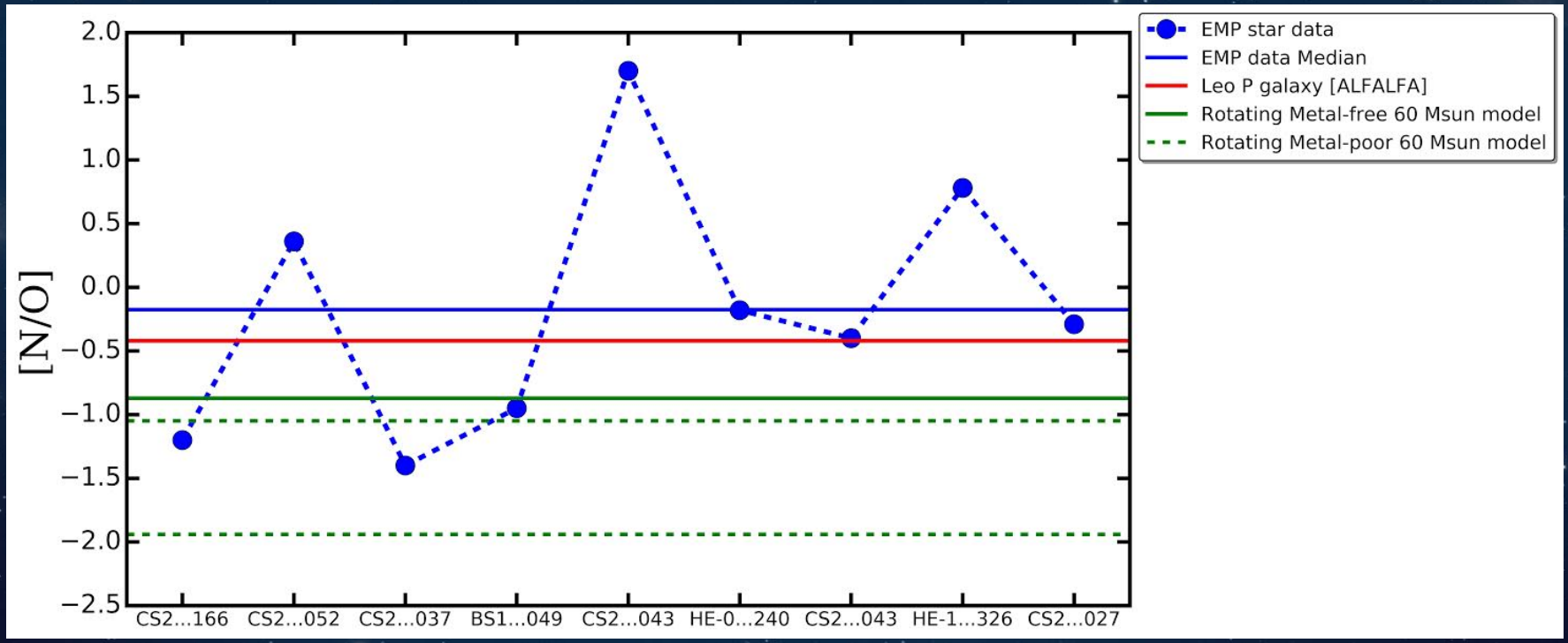
With ALFALFA data:

- Recent discovery of very metal-poor gas-rich dwarf irregular galaxy Leo P with followup spectroscopy on KPNO and LBT/ MODS (Skillman et al. 2013)



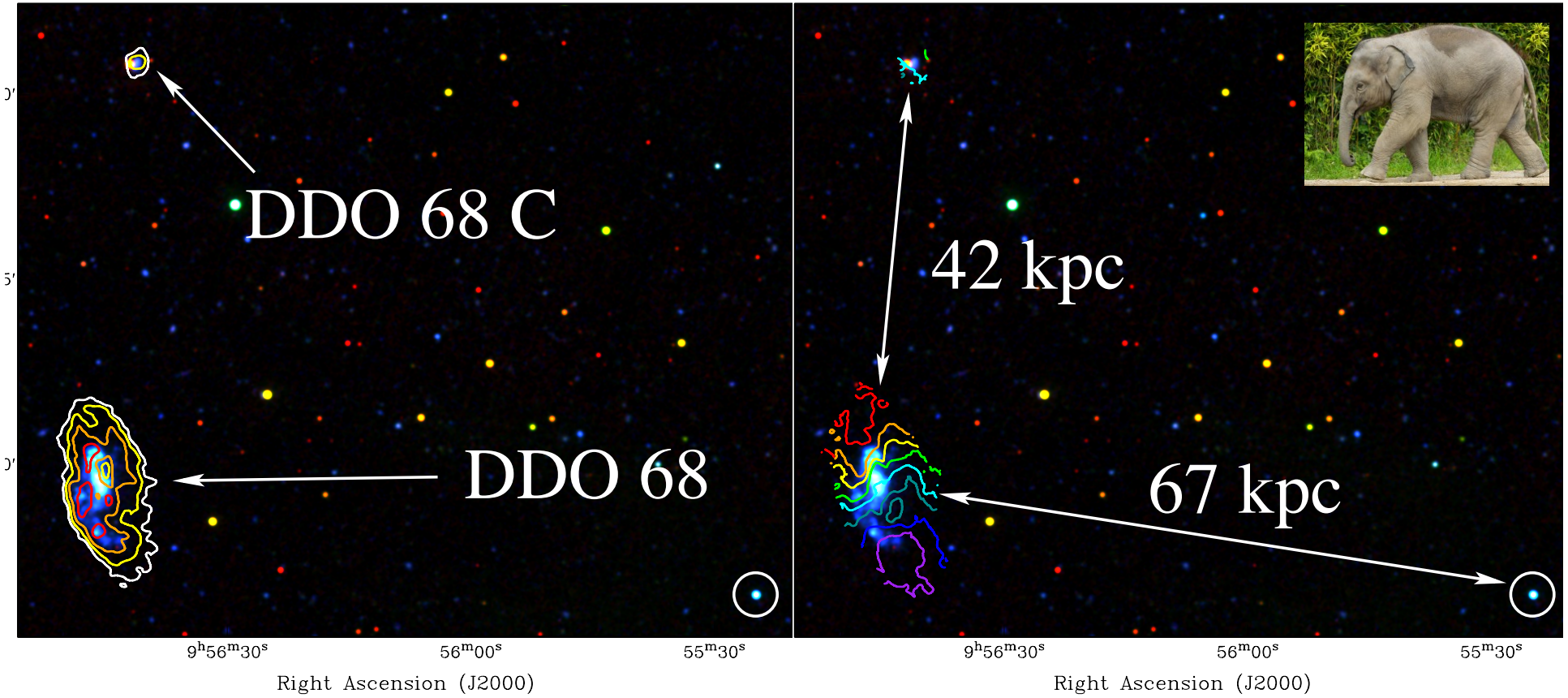
LBT image of Leo P, courtesy John Cannon

- A close match in [N/O] values between Leo P and the median EMP star data (*caveat:* nebular vs stellar metal abundances)
- We see this for [Ne/O] as well.
- What does this say about the connection between dIrrs, dSphs and EMP halo stars in galaxy assembly, and shared star formation/metal synthesis histories?



Role of Cold Gas Accretion

- From Cannon,… Venkatesan et al. 2014: Discovery of a gas-rich low-mass companion to the relatively massive galaxy DDO 68 with a nebular O abundance of 3% solar (like IZw 18, one of the the most metal-deficient galaxies known in the local volume)



Summary

- Dwarf galaxies dominate by number at early times and must play some role in reionization.
- Gas-rich low-mass systems in the local universe that have survived reionization are more accessible observationally, and provide an important cross-check with models of the host galaxies of first-light ionizing sources.
- We need more constraints on f_{esc} in low mass galaxies, and ways to relate f_{esc} (LyC) to f_{esc} (Ly-alpha) and other more readily observed quantities. Preliminary (very simple) work with LARS and KISSR galaxies, we find f_{esc} < 5% in all but two extreme cases where f_{esc} >14%. Our sample-averaged f_{esc} is perhaps insufficient for what reionization requires, although our values are likely to be lower limits and the two outliers are two of the lowest-mass systems in our sample.
- The role of central BHs in dwarf galaxies cannot be underestimated, from a number of aspects. X-rays from such BHs or early X-ray binaries could boost f_{esc} for H and He. This can be impt. for early IGM thermal/ionization history, and 21 cm signals.

Looking Ahead

- More realistic models for the diversity of dwarf galaxies that we observe, and understanding the role of accretion in their SFn and metal buildup history
- More data on gas-rich local dwarfs like Leo P, plus age determinations and SFn histories of such galaxies
- Direct f_{esc} measurements through UV followup, or archival data: we really need data on f_{esc} for dwarf galaxies. Escape fractions (and also: the assumed MFP of photons from early halos) seem critical inputs for many people's work at this meeting: worth a targeted effort both observationally and theoretically, esp. under the conditions of the early universe

- All this will help us utilize dwarf galaxies as a wonderful lab for near-field cosmology