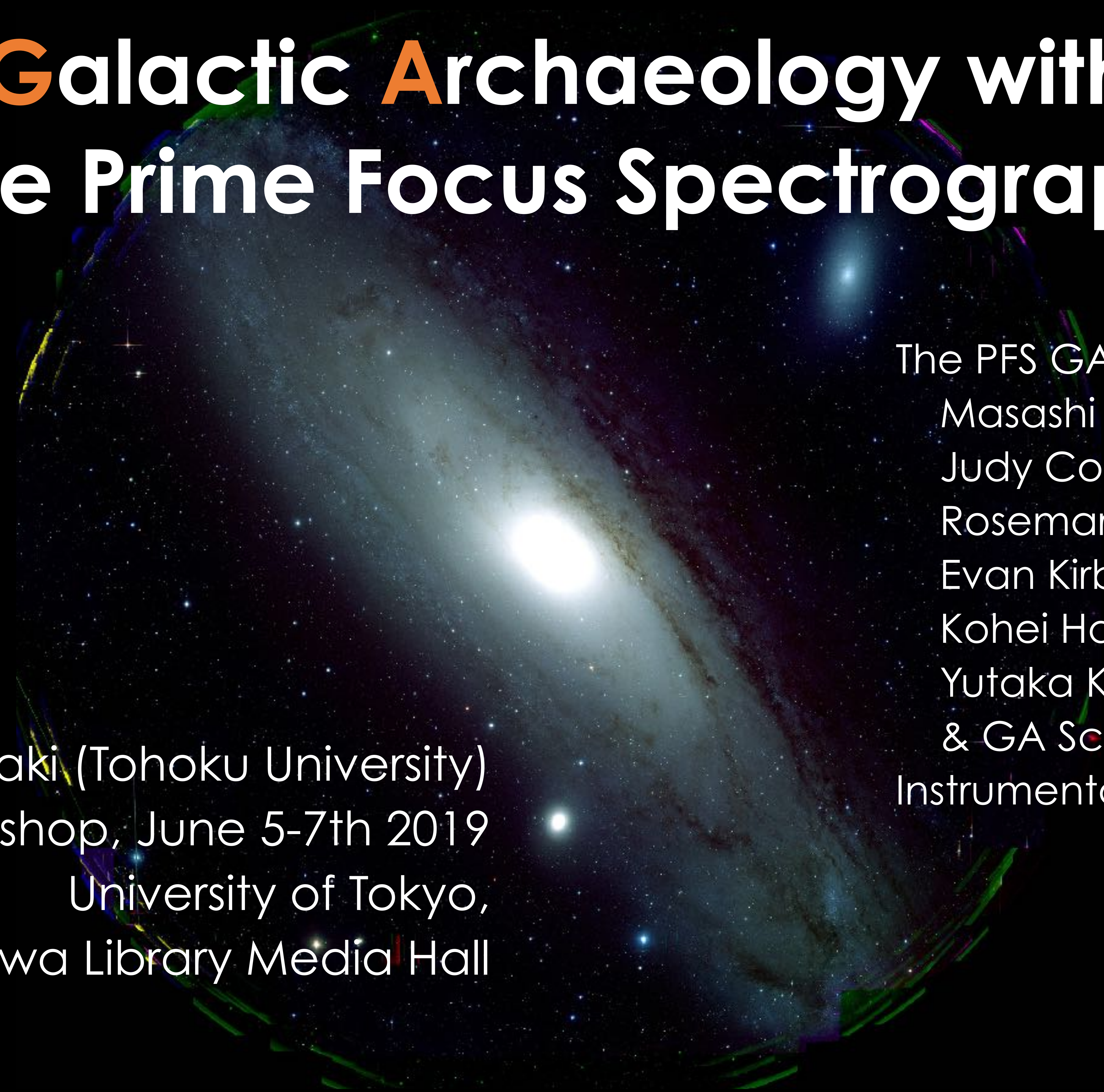
Credit: Subaru Telescope

Galactic Archaeology with the Prime Focus Spectrograph



Miho N. Ishigaki (Tohoku University)
Galaxy Evolution workshop, June 5-7th 2019
University of Tokyo,
Kashiwa Library Media Hall

The PFS GA team
- Masashi Chiba (PI, Tohoku University)
- Judy Cohen (Caltech)
- Rosemary Wyse (John Hopkins University)
- Evan Kirby (Caltech)
- Kohei Hayashi (ICRR)
- Yutaka Komiyama (NAOJ)
- & GA Science working group

Instrumentation & Software teams

Special thanks to inspiring discussions/conversation with theorists and observers

Outstanding questions in galaxy evolution

- Beginning
  - Formation and physical properties of the very first galaxies
- Growth
  - Merging history of large spiral galaxies like the Milky Way and the M31
- Present
  - Distribution of dark and luminous matter in galaxies
- Chemical evolution
  - Production of metals by supernovae of various generations of stars

This talk: How GA help answering these questions, Why PFS is useful

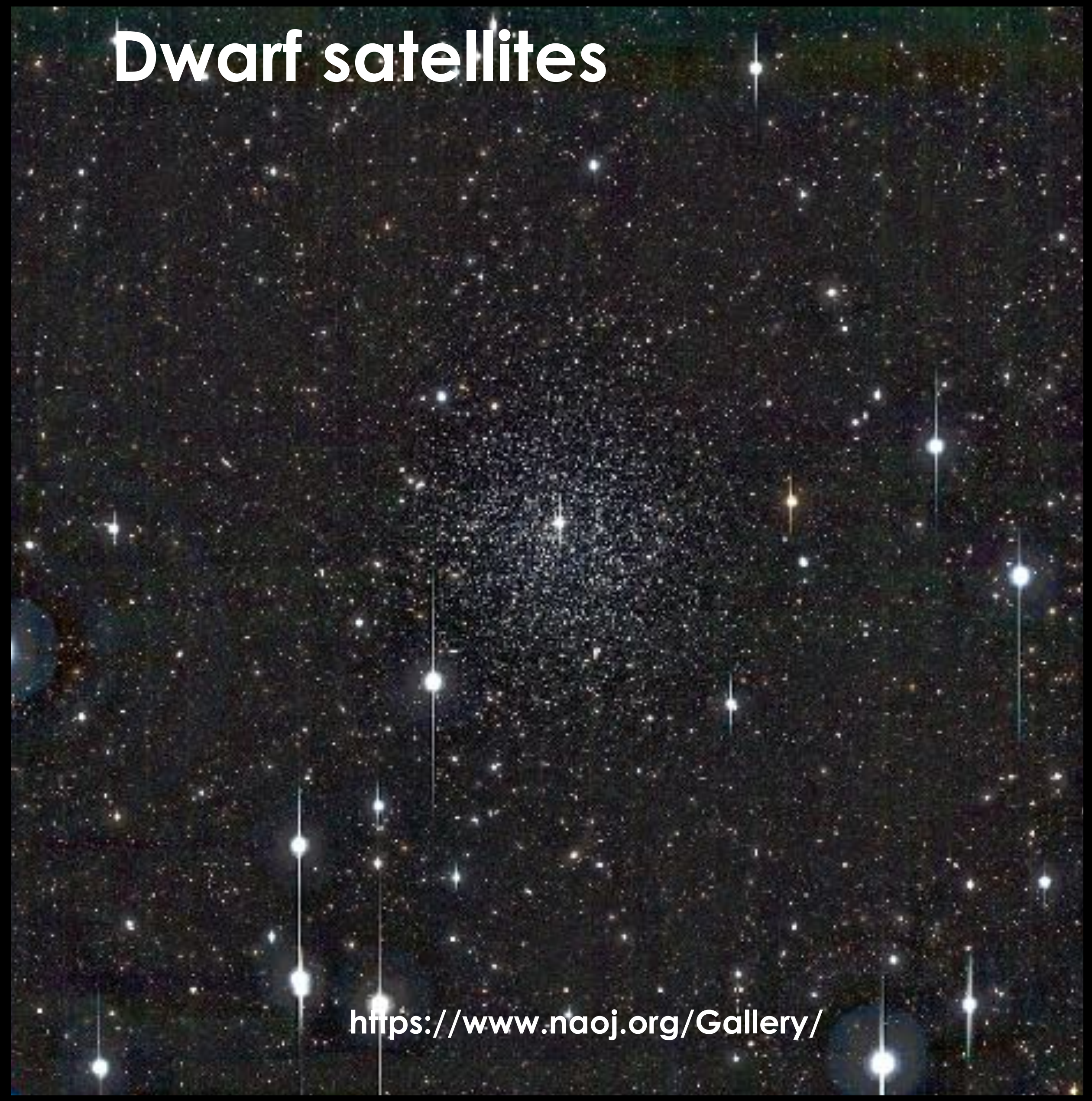
What makes PFS unique?

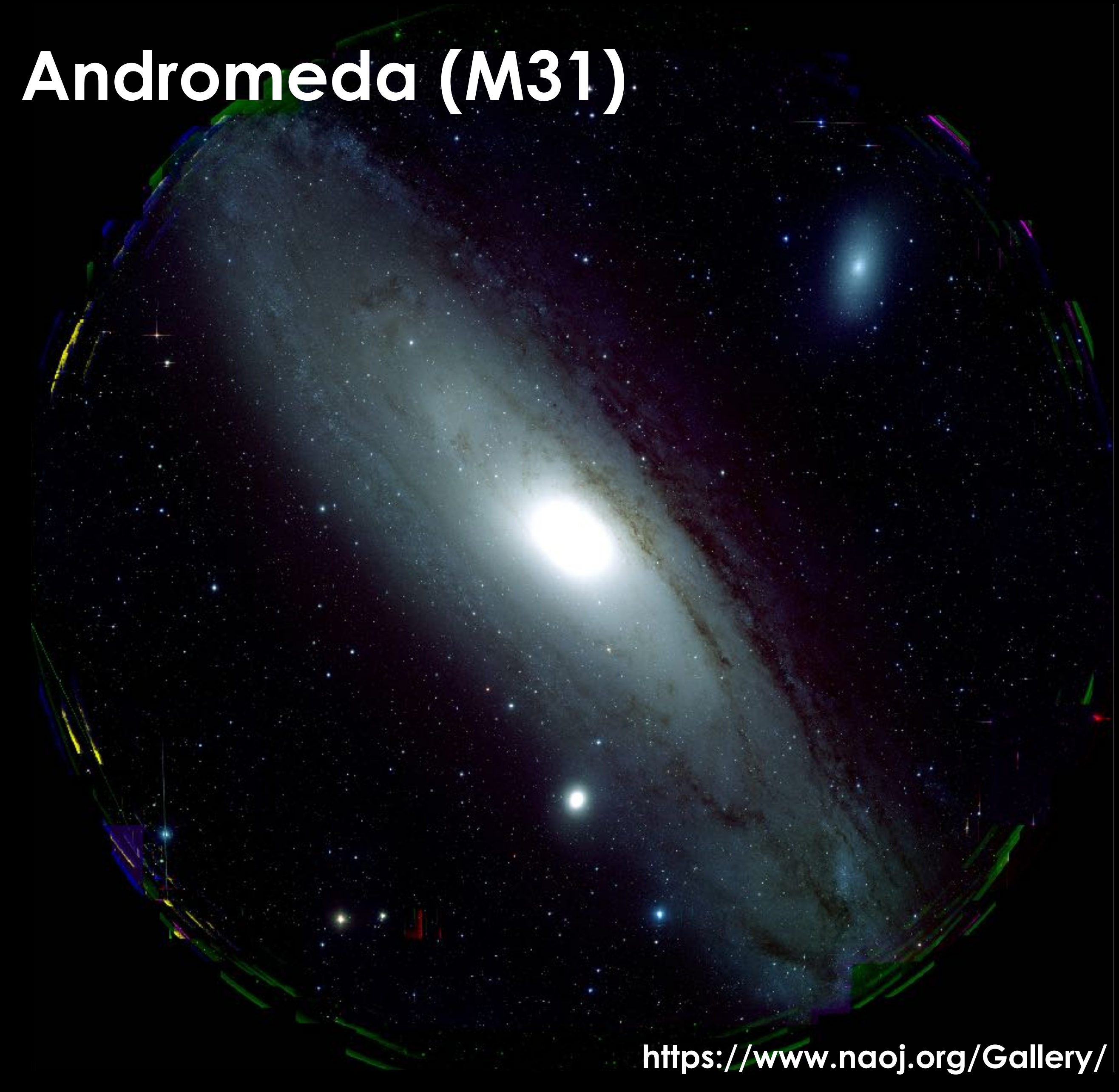
Subaru telescope (8.2 m)

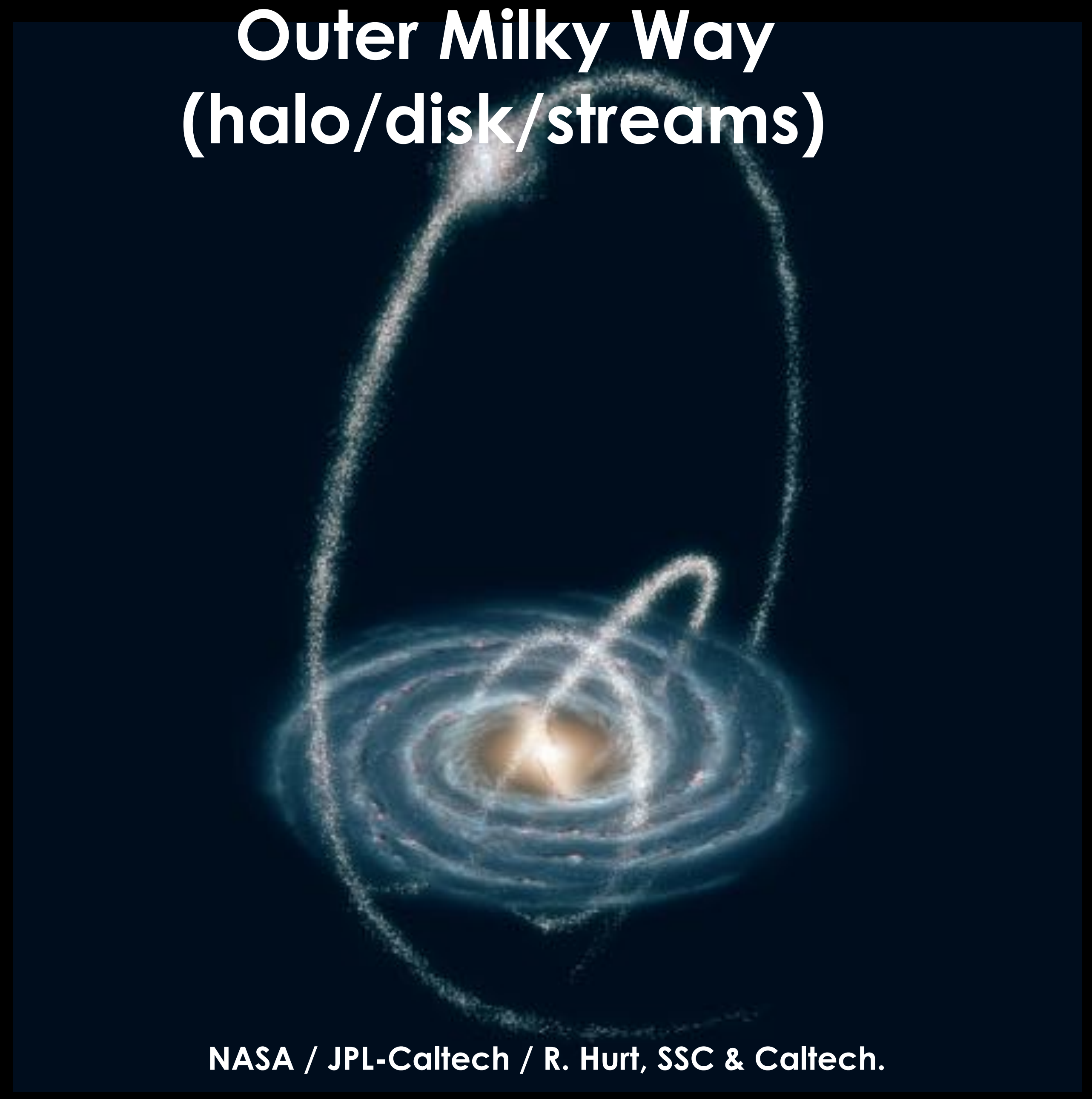
+

Moderately wide field of view (1.3 deg^2)

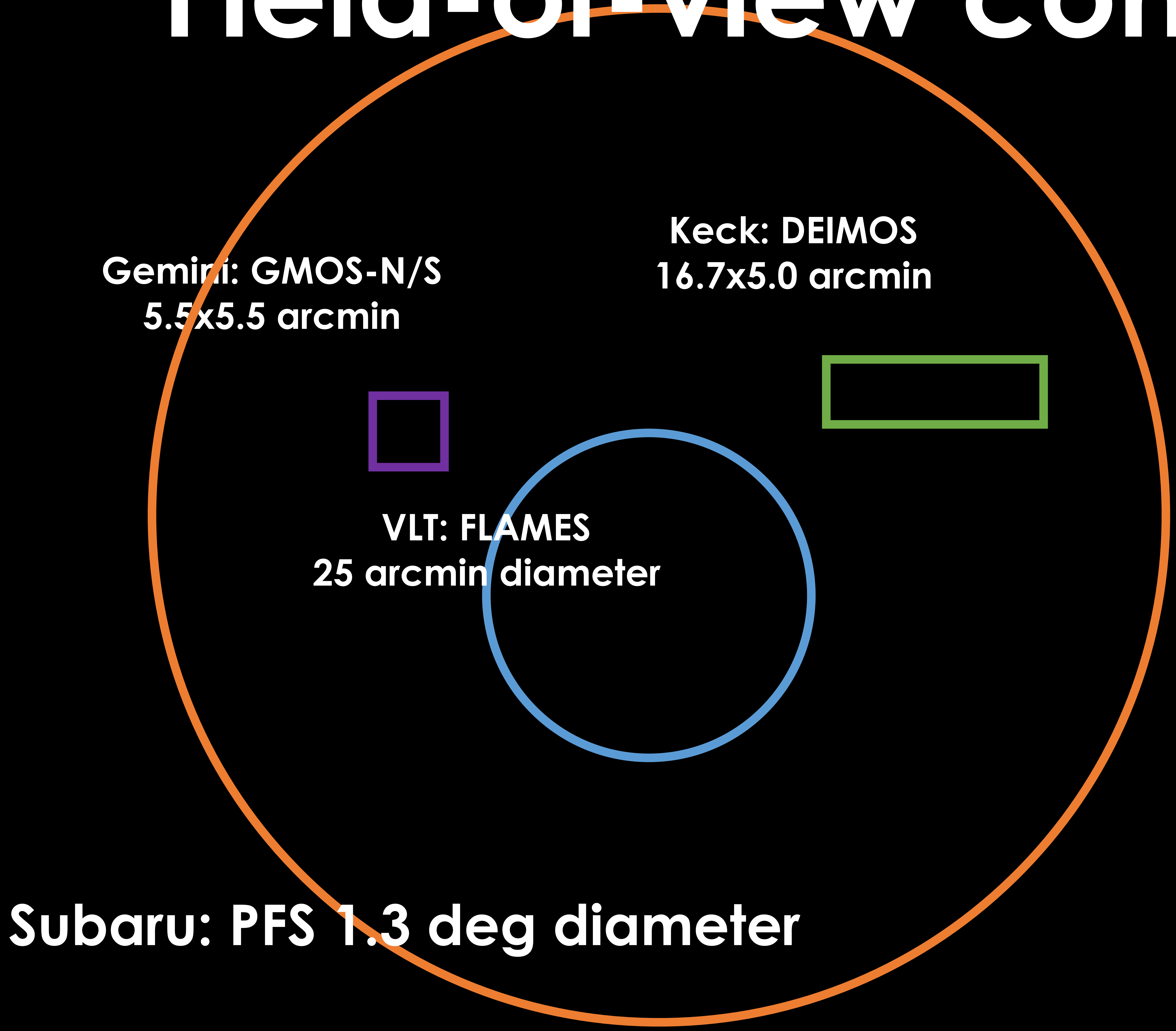
➡ Faint and distant stellar populations (i<22)







Field-of-view comparison

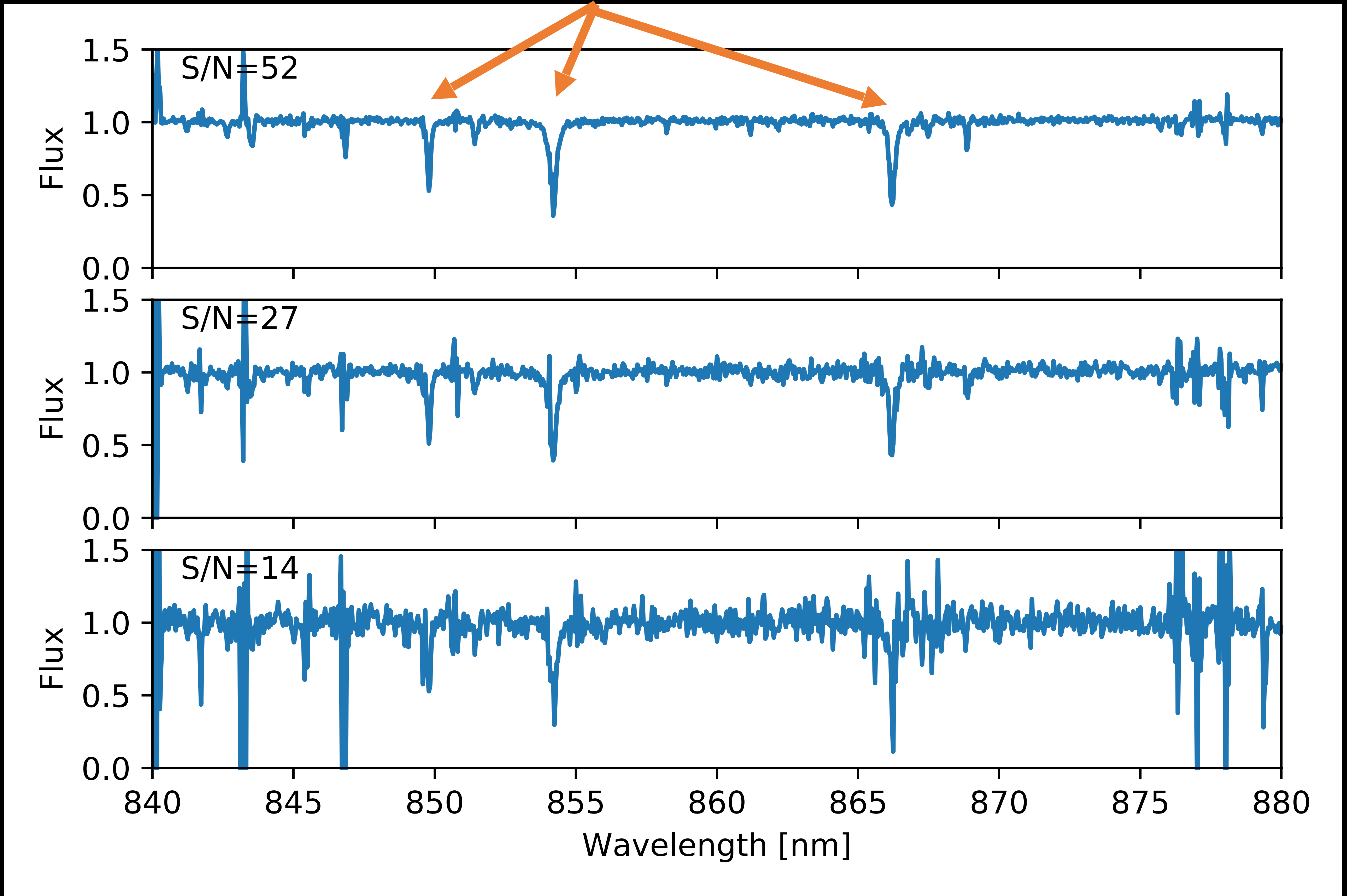


- The widest FoV among optical multi-object spectrographs at 8-10m telescopes
- Complementary to the 4m projects
  - 4MOST: 4deg^2
  - WEAVE: 3deg^2
  - DESI: 7deg^2

Mock PFS spectra for a red-giant star

PFS simulator (K. Yabe, C. Hirata et al.) for gmag=20, 21, 22 stars, Exposure time = 3hours

Absorption lines produced by singly ionized calcium



σ_{Vlos} ~ 1km/s

σ_{Vlos} ~ 2km/s

σ_{Vlos} ~ 5km/s

+ measurement of elemental abundances of Fe, Mg, Si, Ca, and Ti

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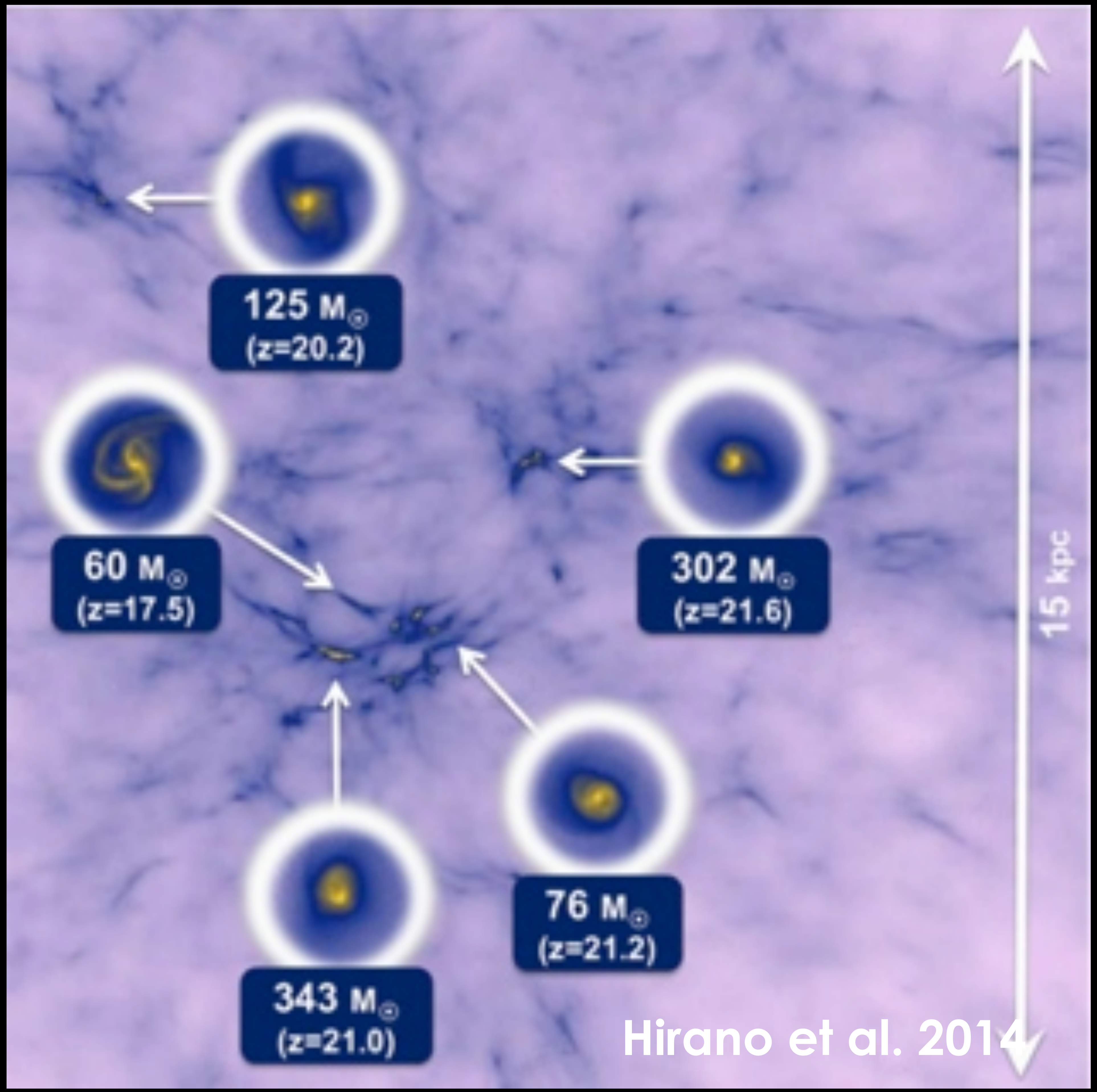
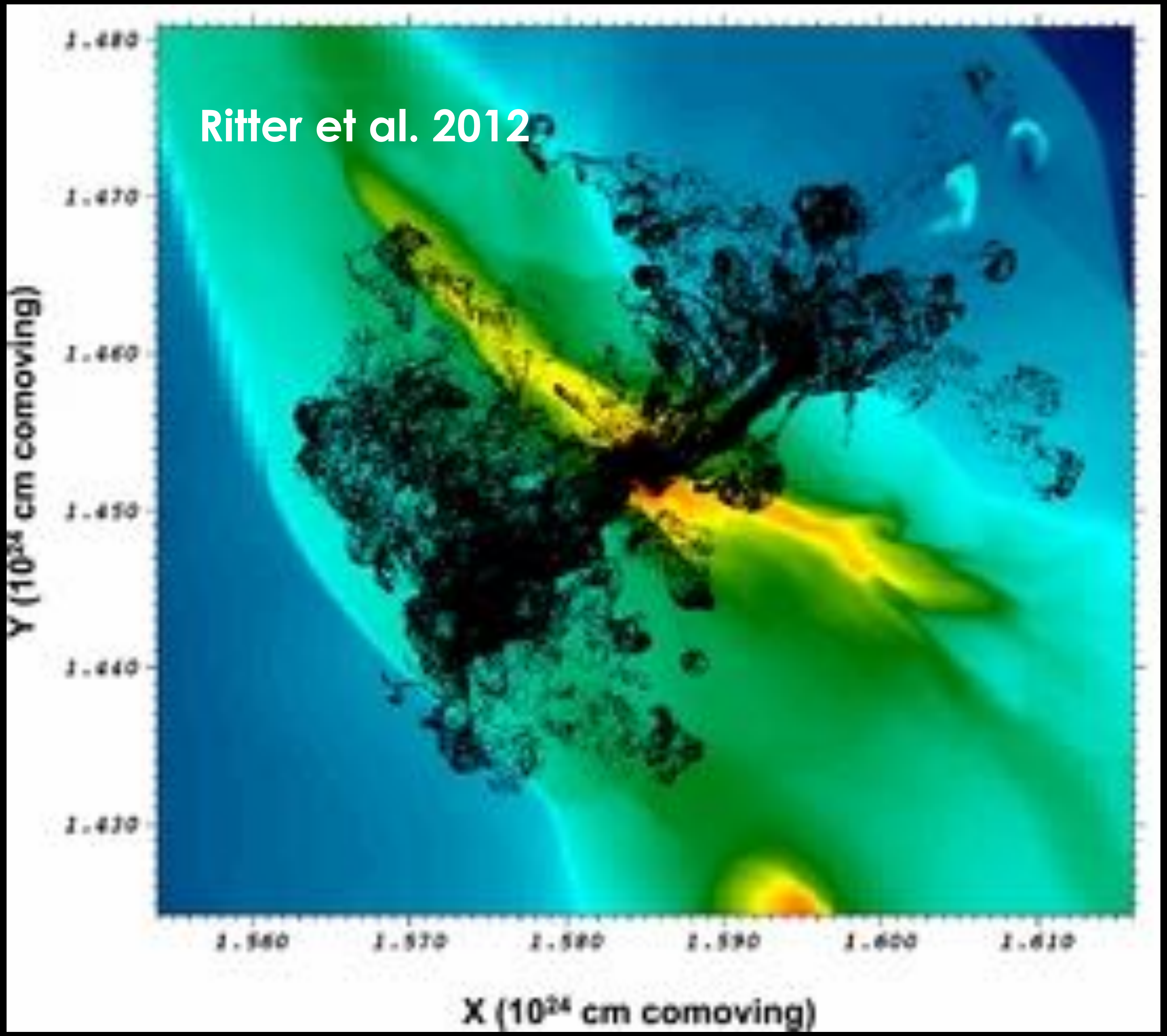
The beginning of galaxy formation

Formation of the first (PopIII) stars at z>15



Supernovae of the first stars ejecting metals



Open questions

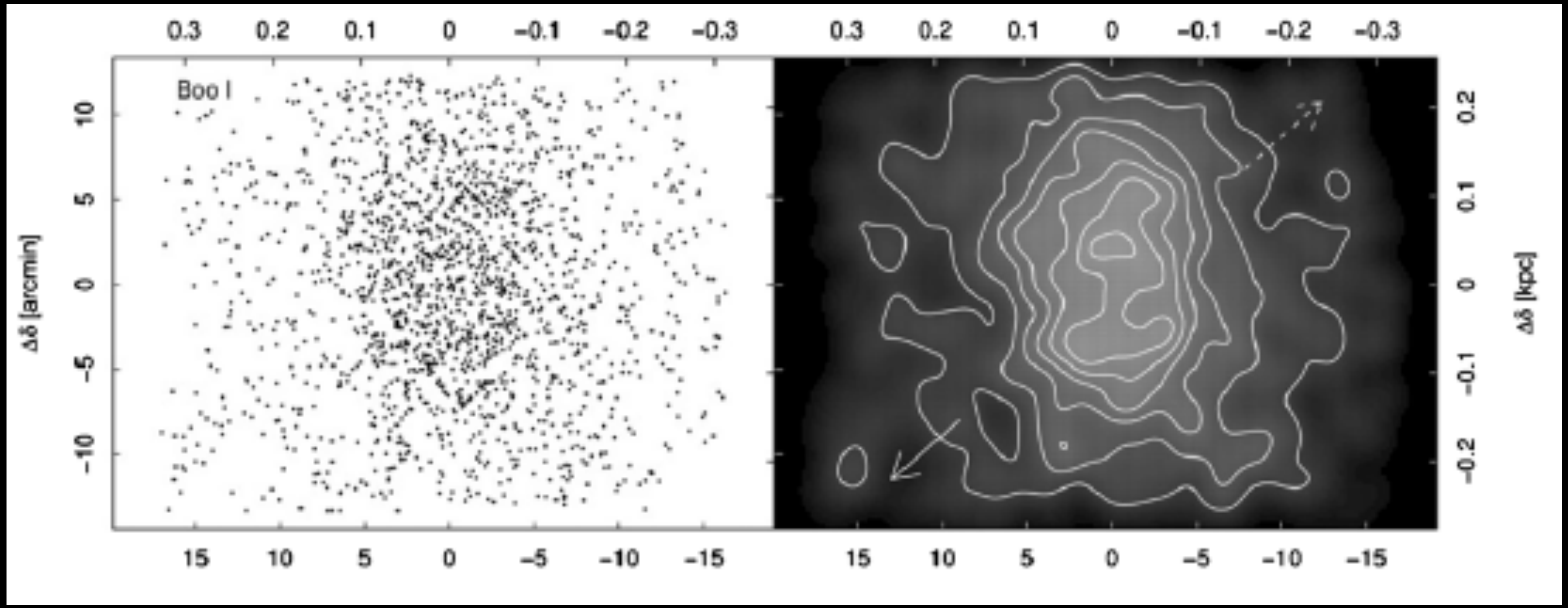
- How massive the first stars were?
- How does their supernovae impact to the IGM?
- How did the ejected metals mix with IGM?
- When did the first galaxies form?

Direct observations are not feasible

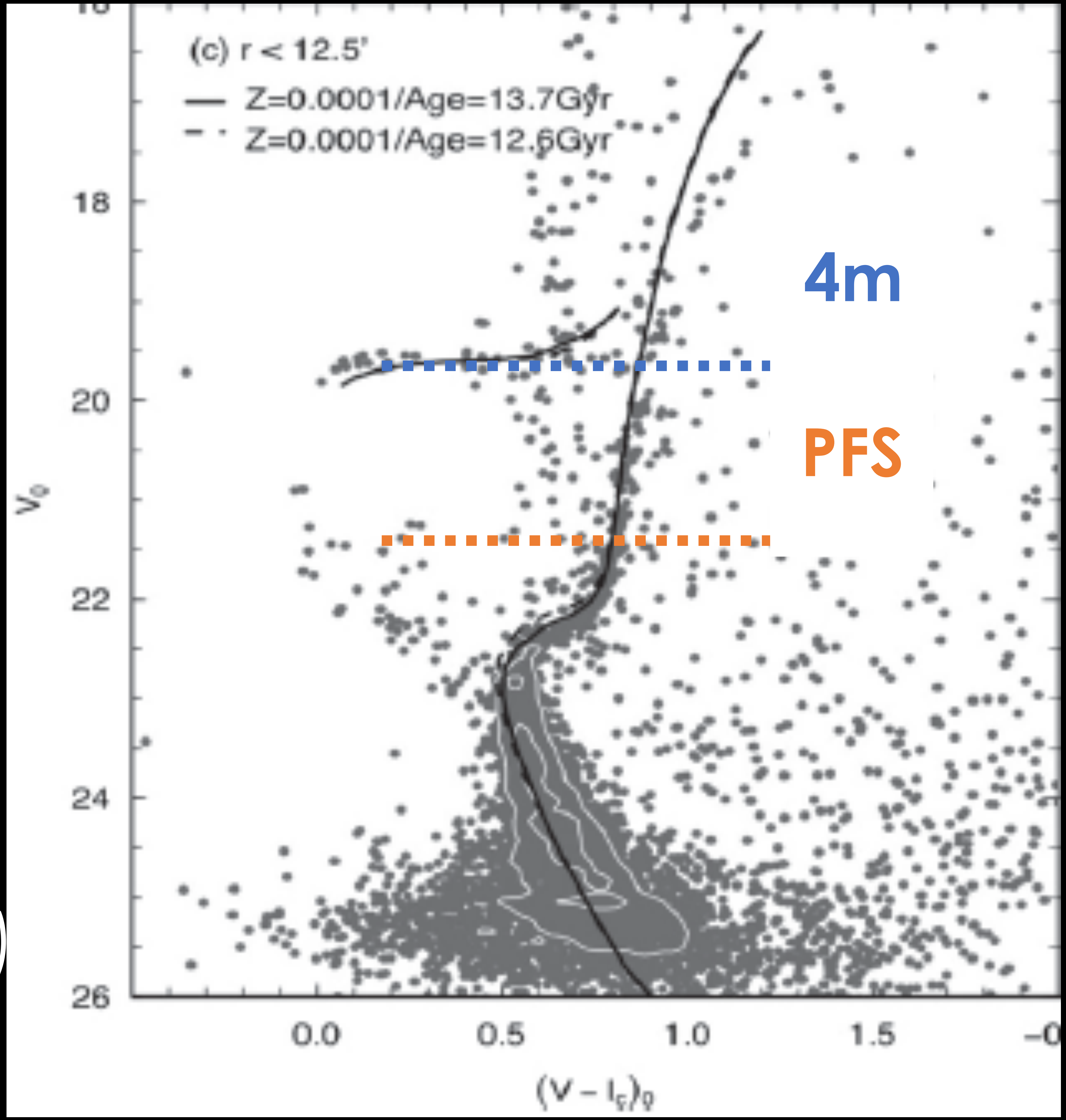
➡ Galactic Archaeology is the key

Ultra-faint dwarf galaxies as a fossil of the first galaxies

Bootes I Ultra-faint dwarf galaxy



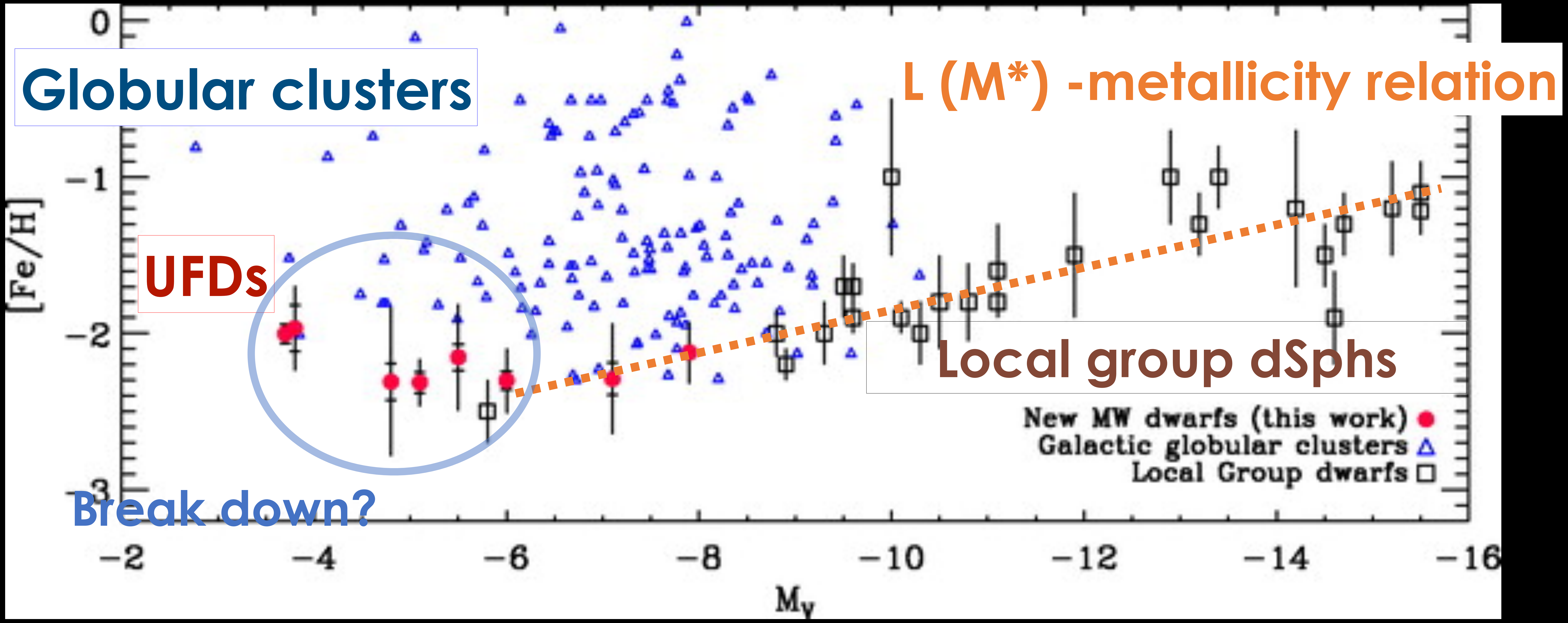
Okamoto et al. 2012



- Very faint M_V~-5.8, Dynamical mass ~ $10^6 M_\odot$
- Age greater than 13 Gyrs, spread < 1 Gyr
- Velocity and chemical analysis with PFS (1 pointing) will reveal its full chemodynamical evolution

Metallicity of the faint dSphs hint at stochastic chemical enrichments

Simon & Geha 2007



Hint at stochastic chemical enrichments by the first generations of stars in the early Universe

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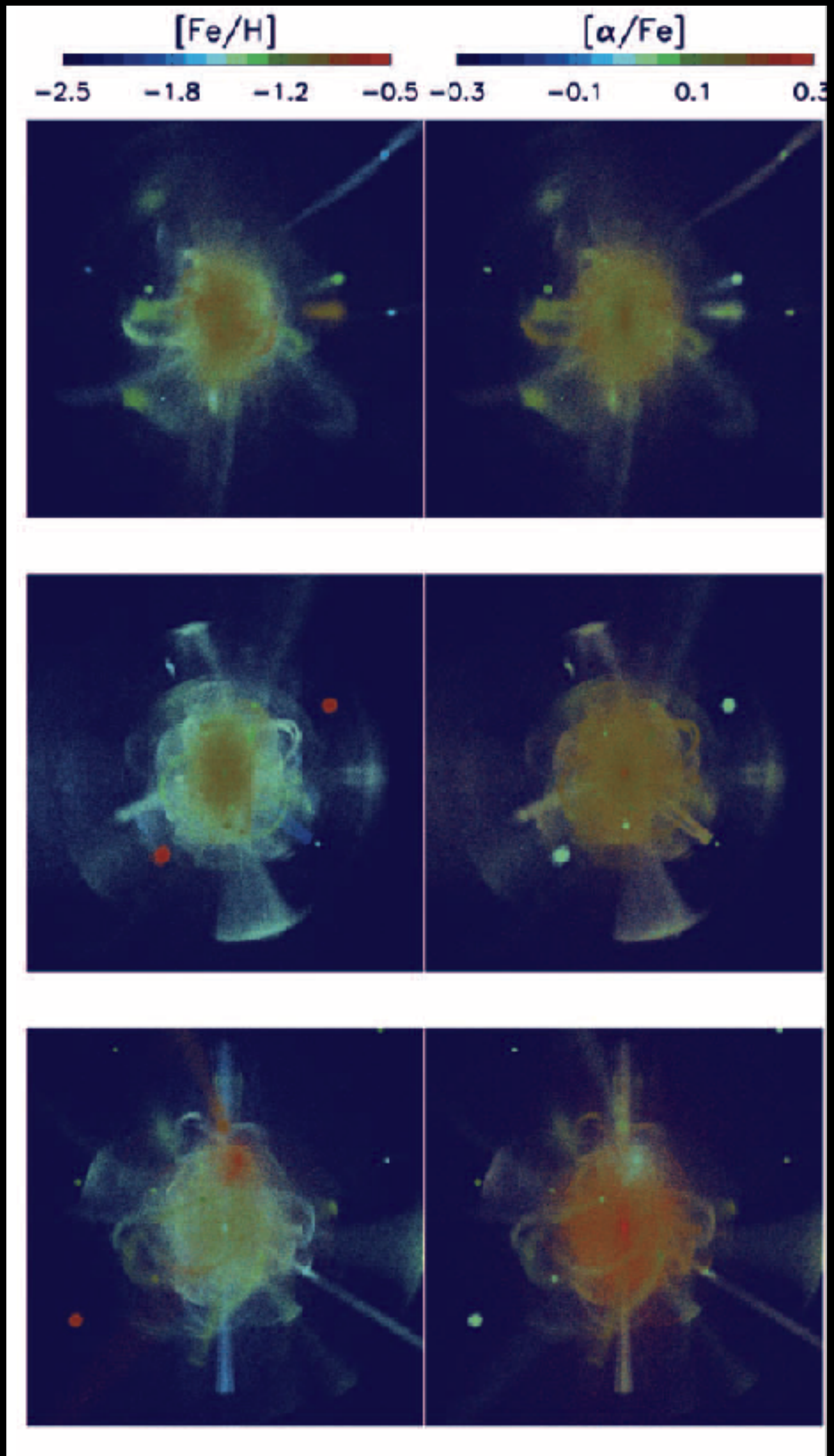
Growth of large spiral galaxies

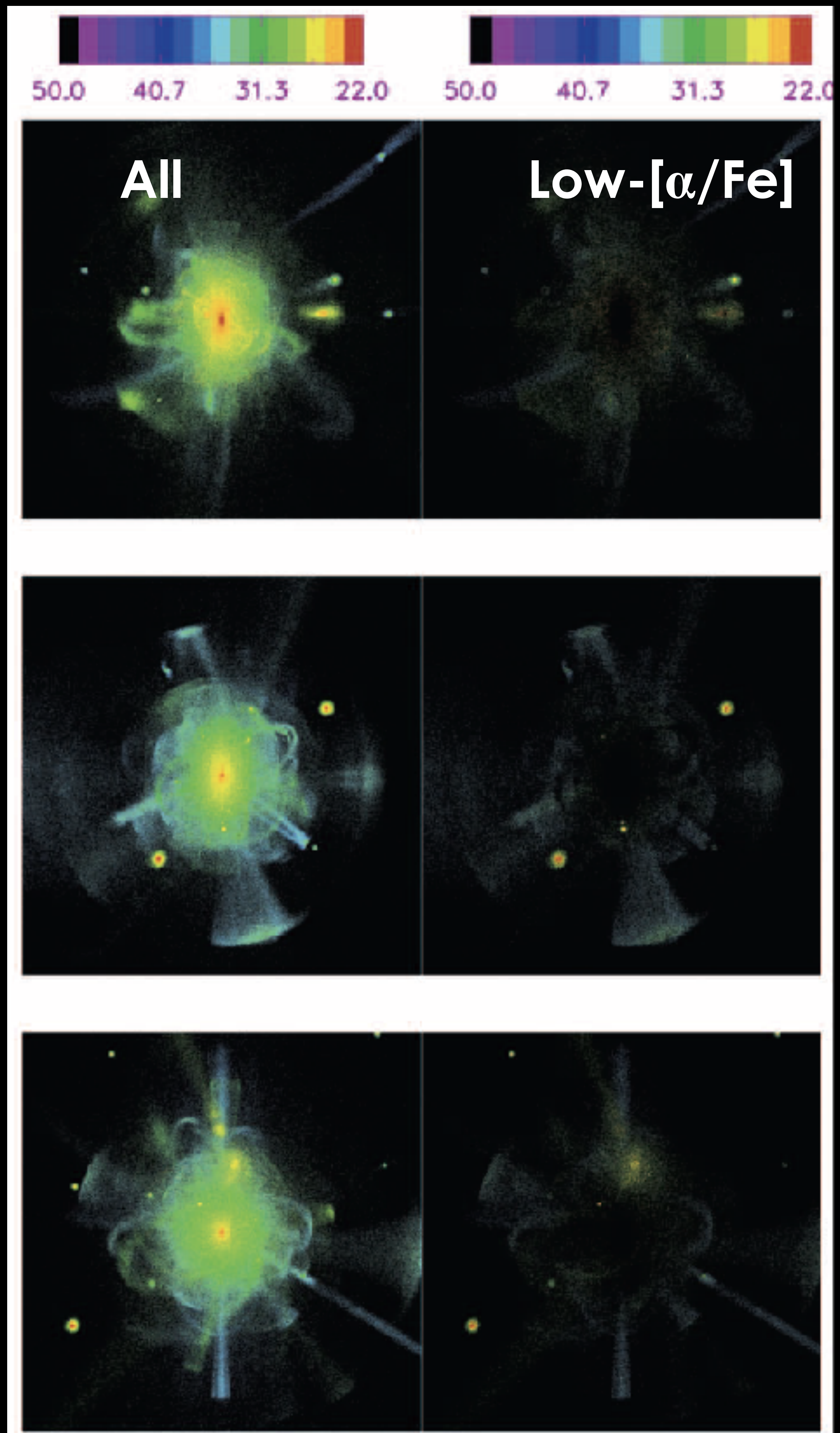
Font et al. 2006



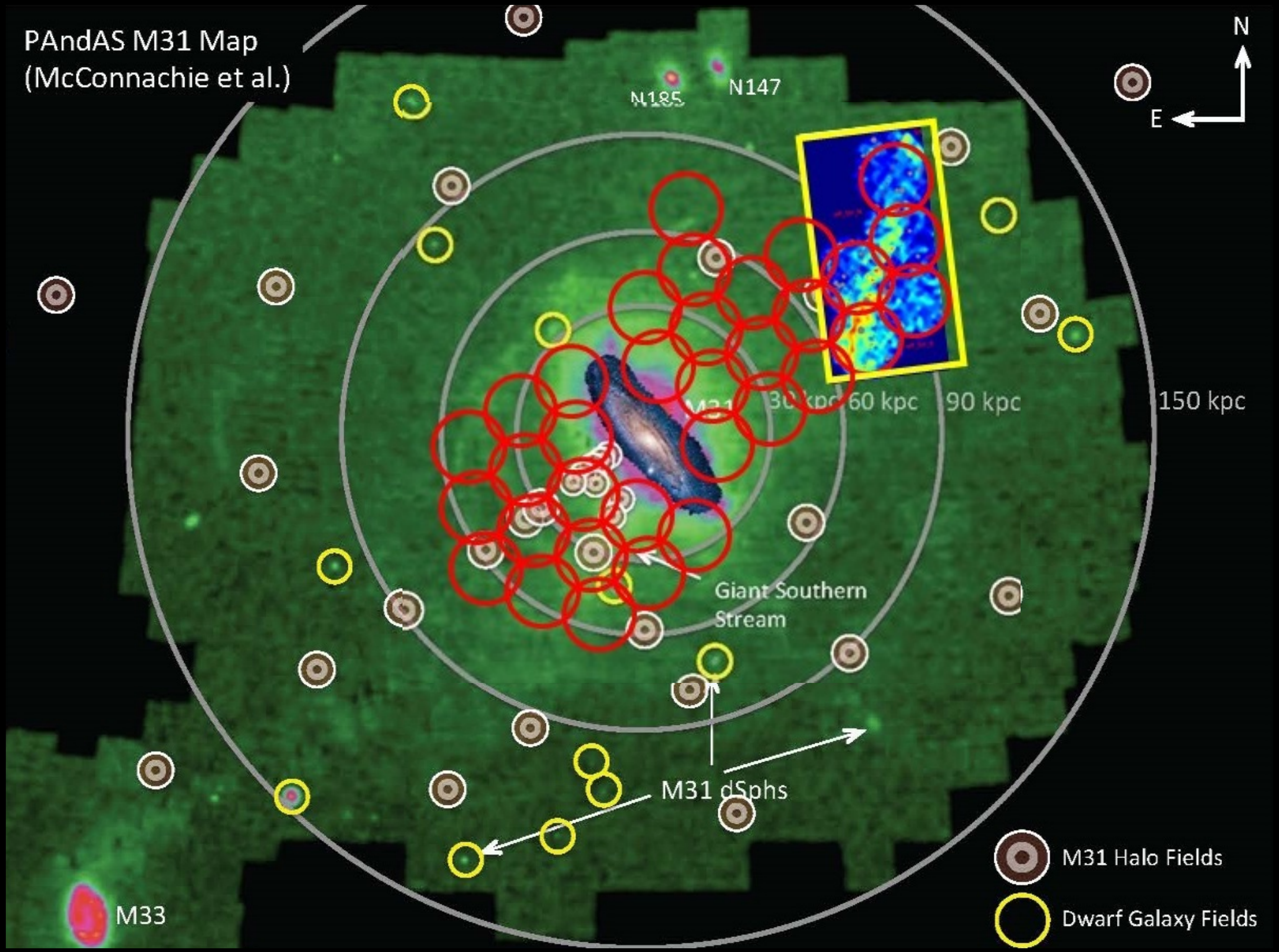
Merging history is encoded in spatial, kinematic and chemical distributions of old stars

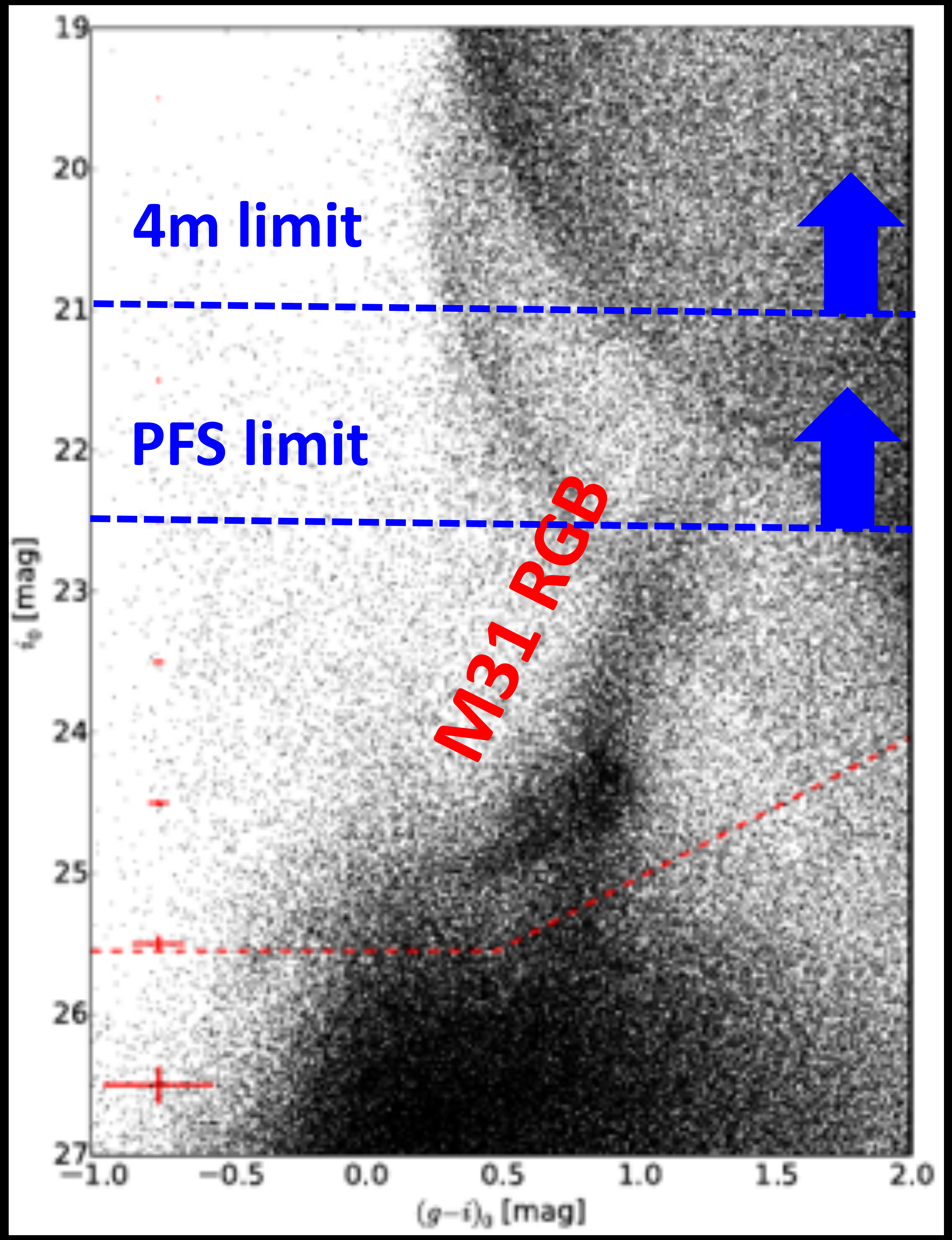
Outer halo of the Milky Way and M31 are particularly important

Substructures associated with the cosmological merging events



Wide-field spectroscopic surveys of M31

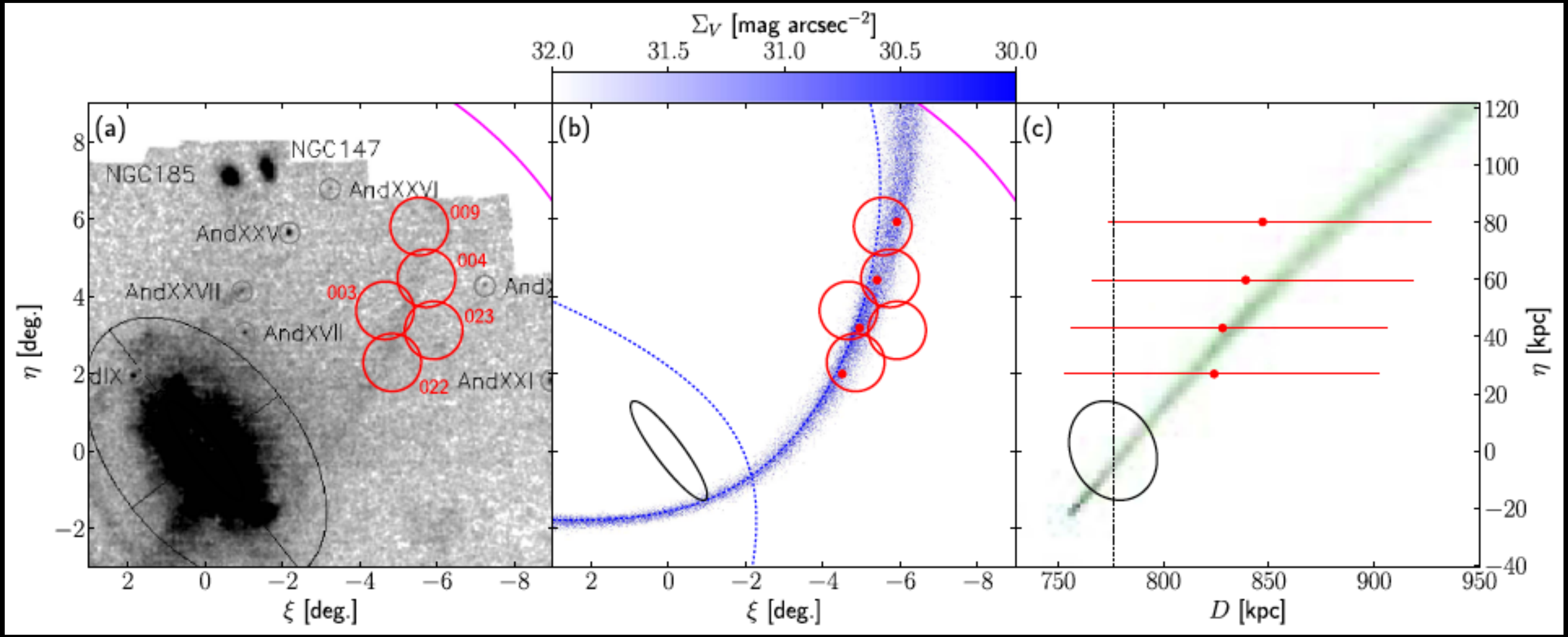




Merging history of M31

When did the accretion occur?, how massive the accreted galaxy was?

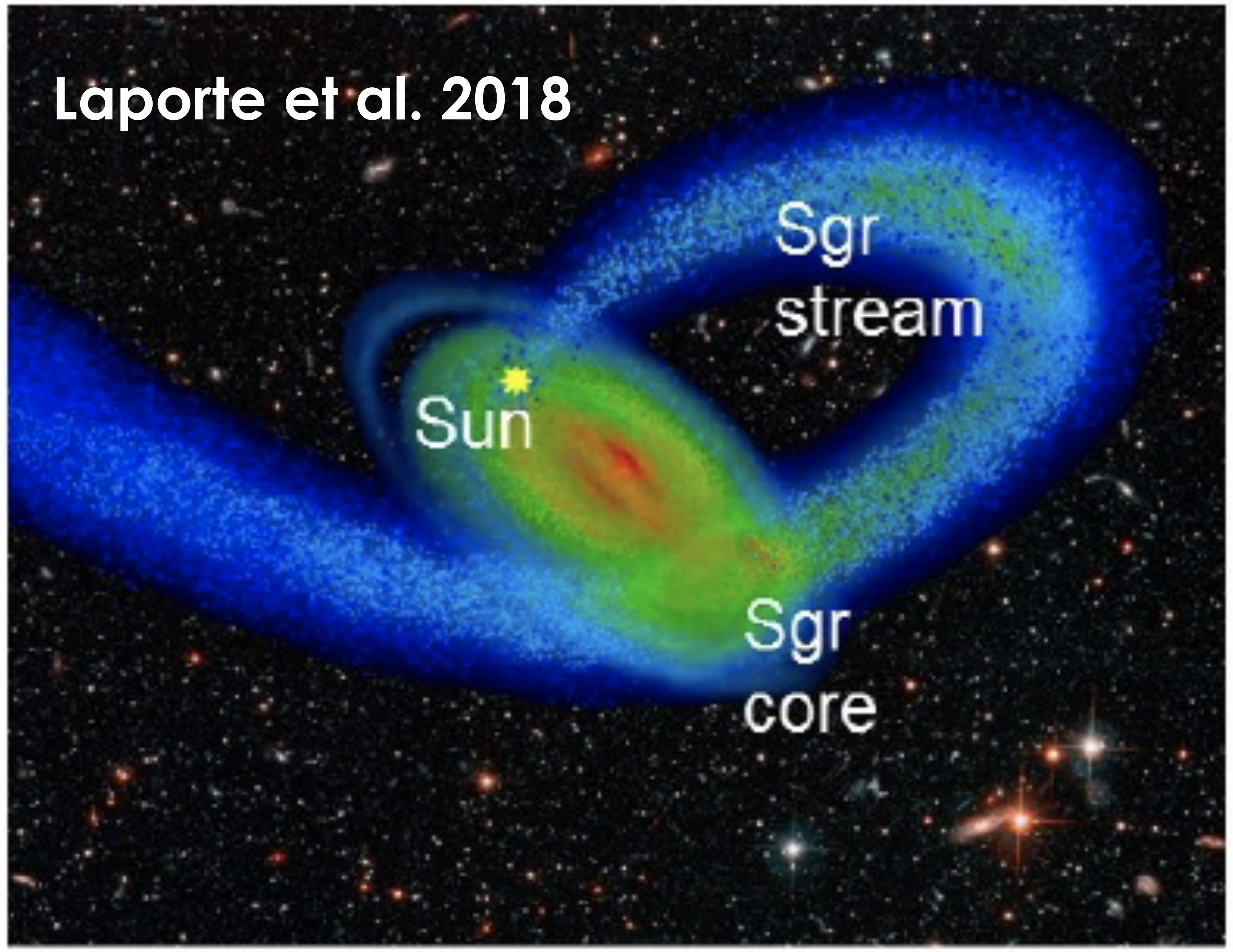
➡ Line-of-sight velocity and metal abundance ([Fe/H], [alpha/Fe]) are the keys

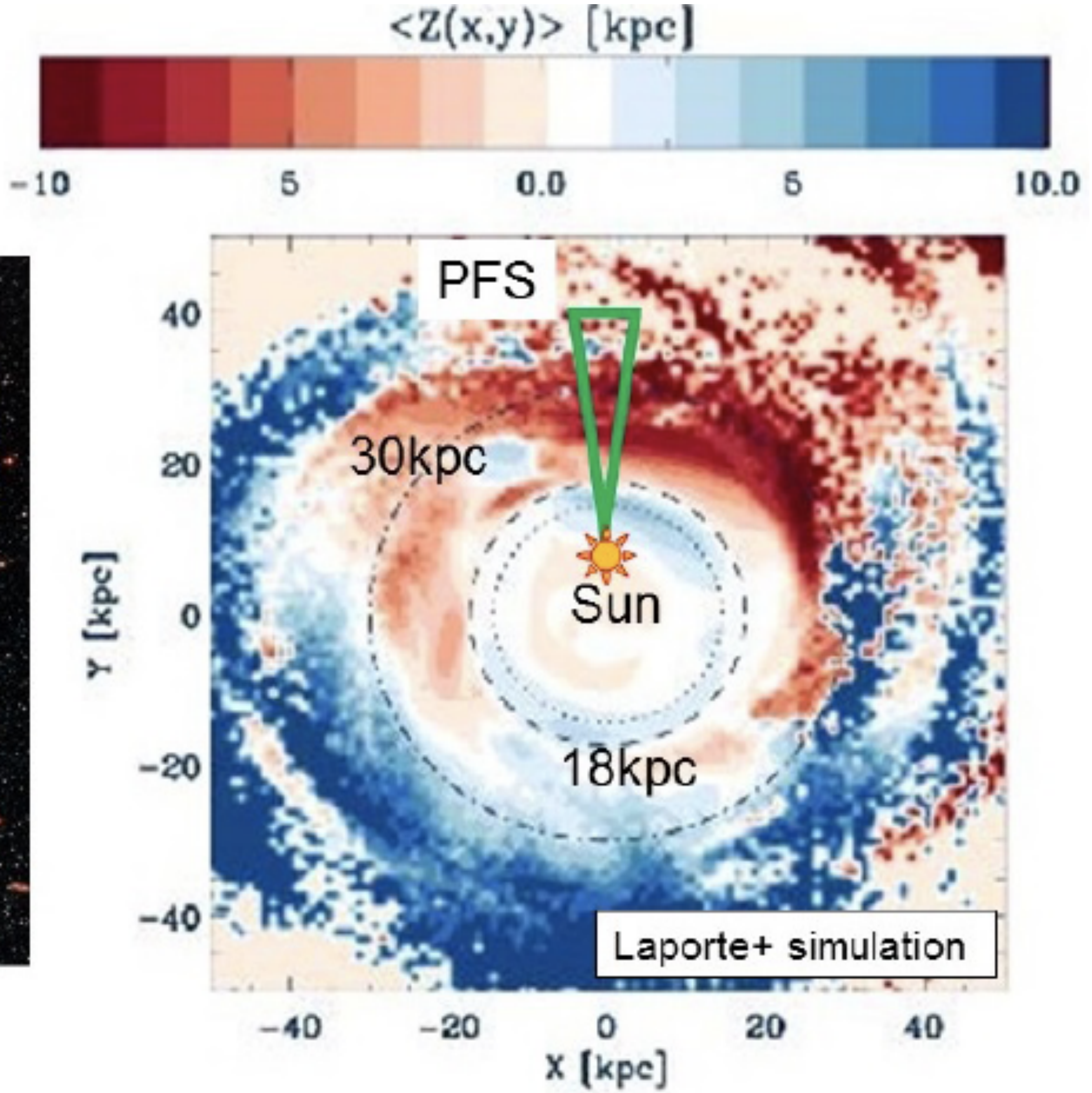


Komiyama et al. 2018

The mechanism of galaxy mergers probed by Sgr

Chiba-san's slide
(the PFS collaboration meeting 2018)





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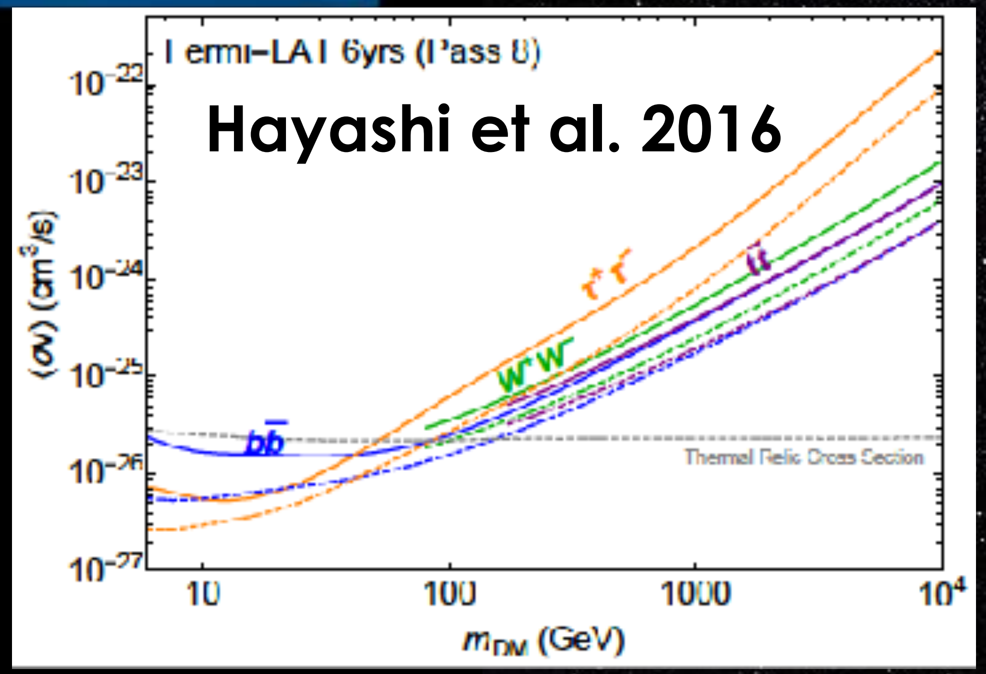
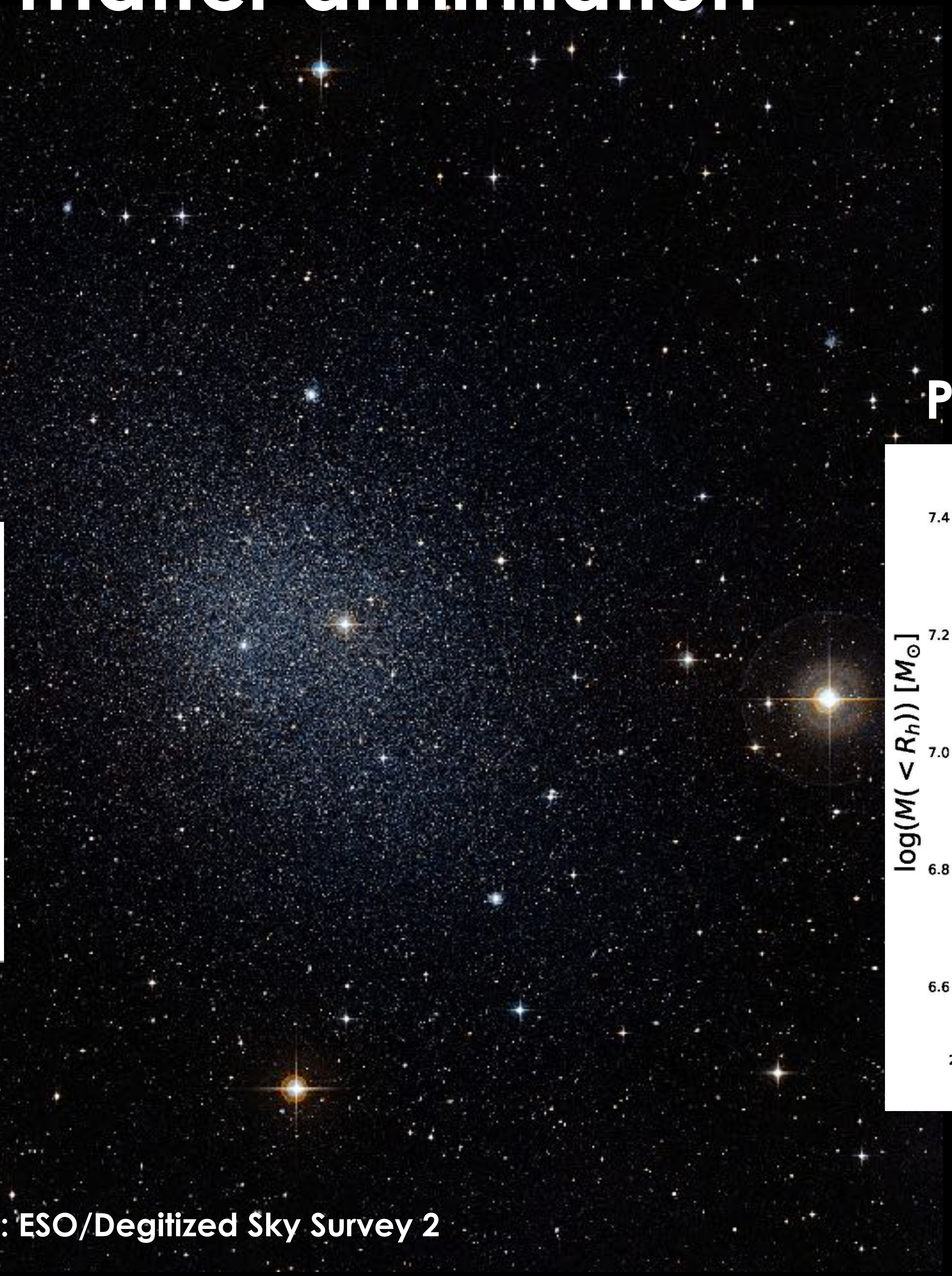
Particle nature of dark matter

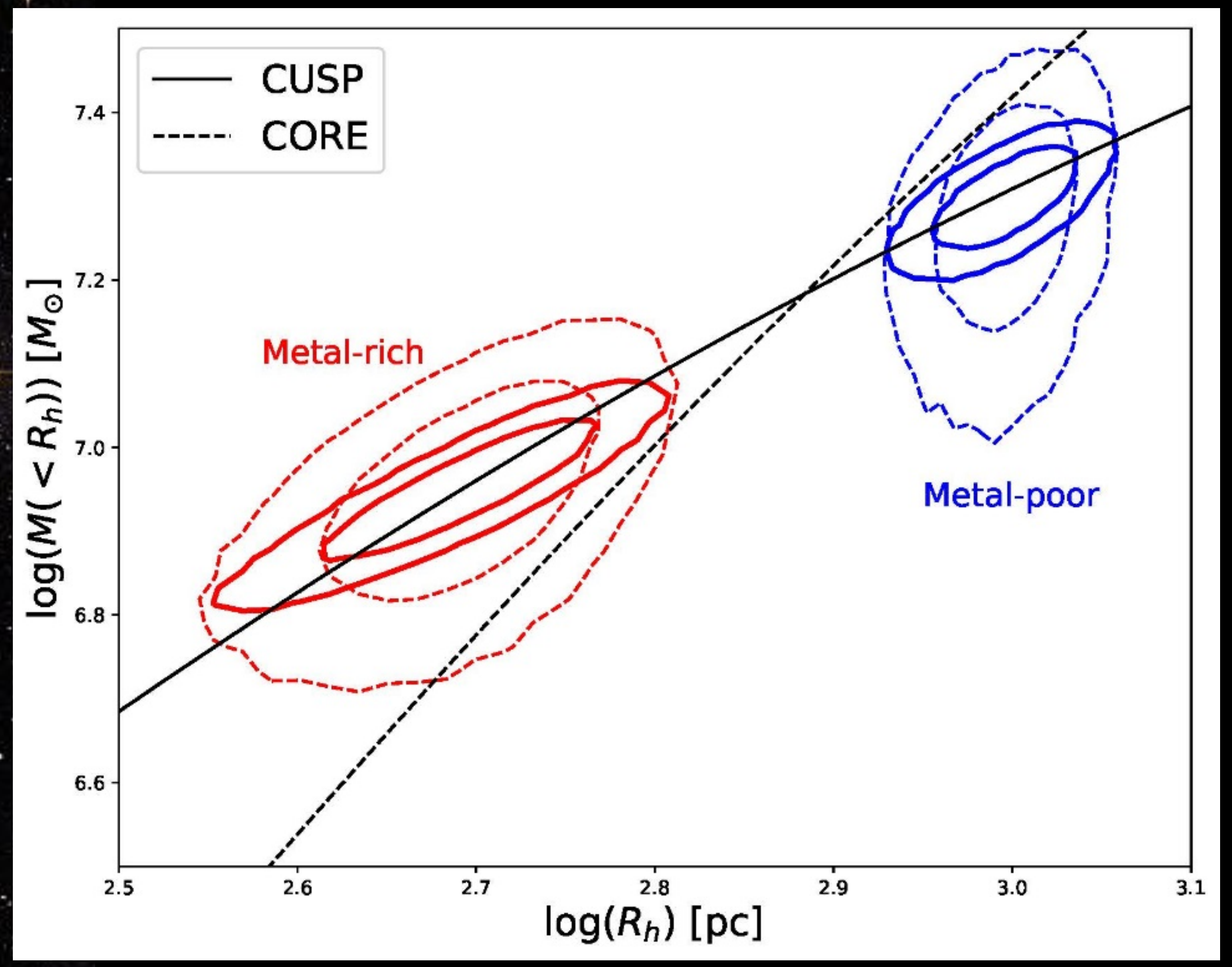
Searches for γ-rays from dark matter annihilation



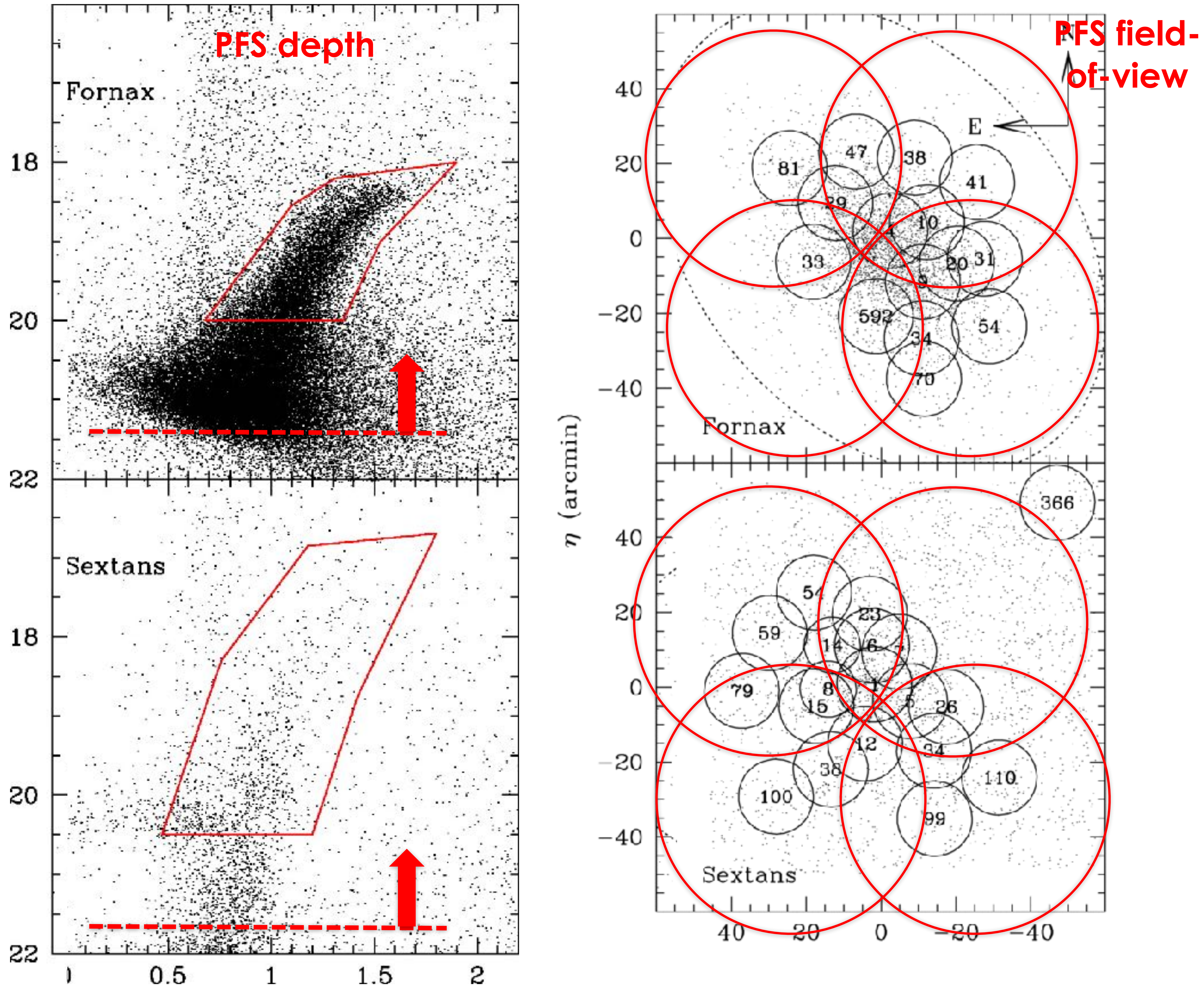


Fornax dwarf galaxy, Credit: ESO/Degitized Sky Survey 2

Plot by Hayashi & Chiba



Dwarf satellites stellar sample will be increased

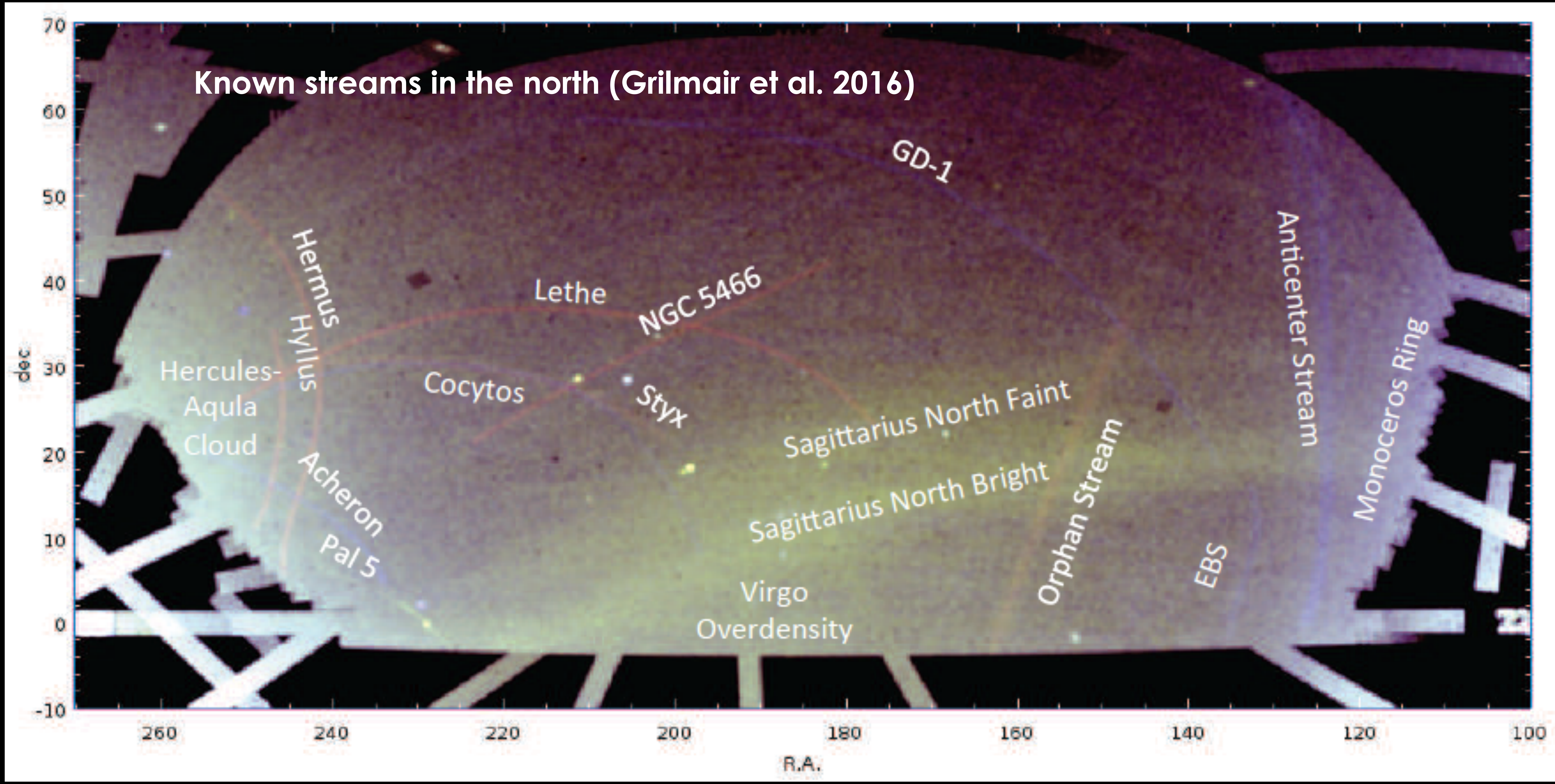


PFS-GA-plan (@12/2018):

Sculptor
Fornax
Draco
BootesI
Ursa Minor
Sextans

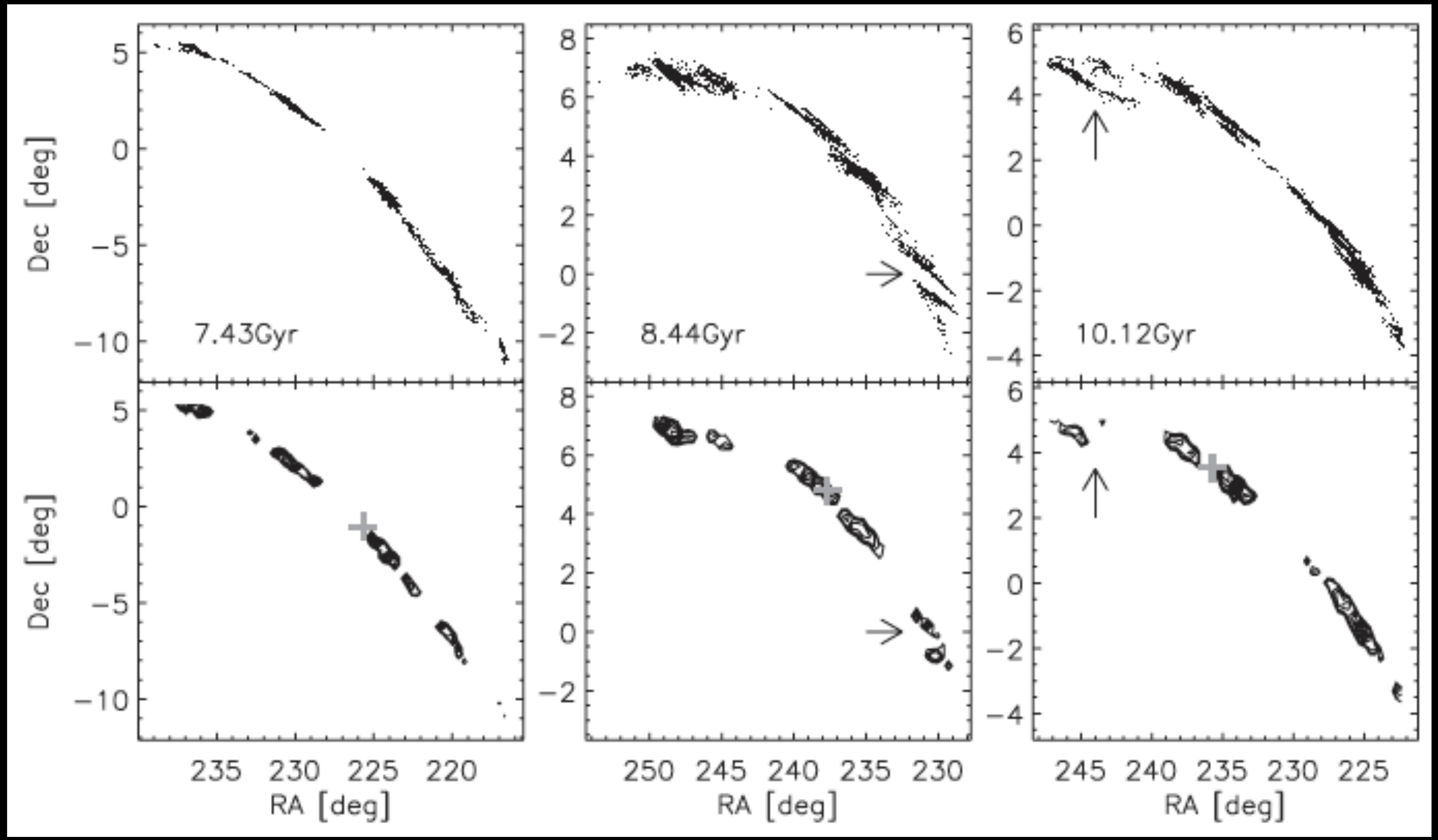
Stellar streams

Tracer of the gravitational potential of the Milky Way's dark matter halo



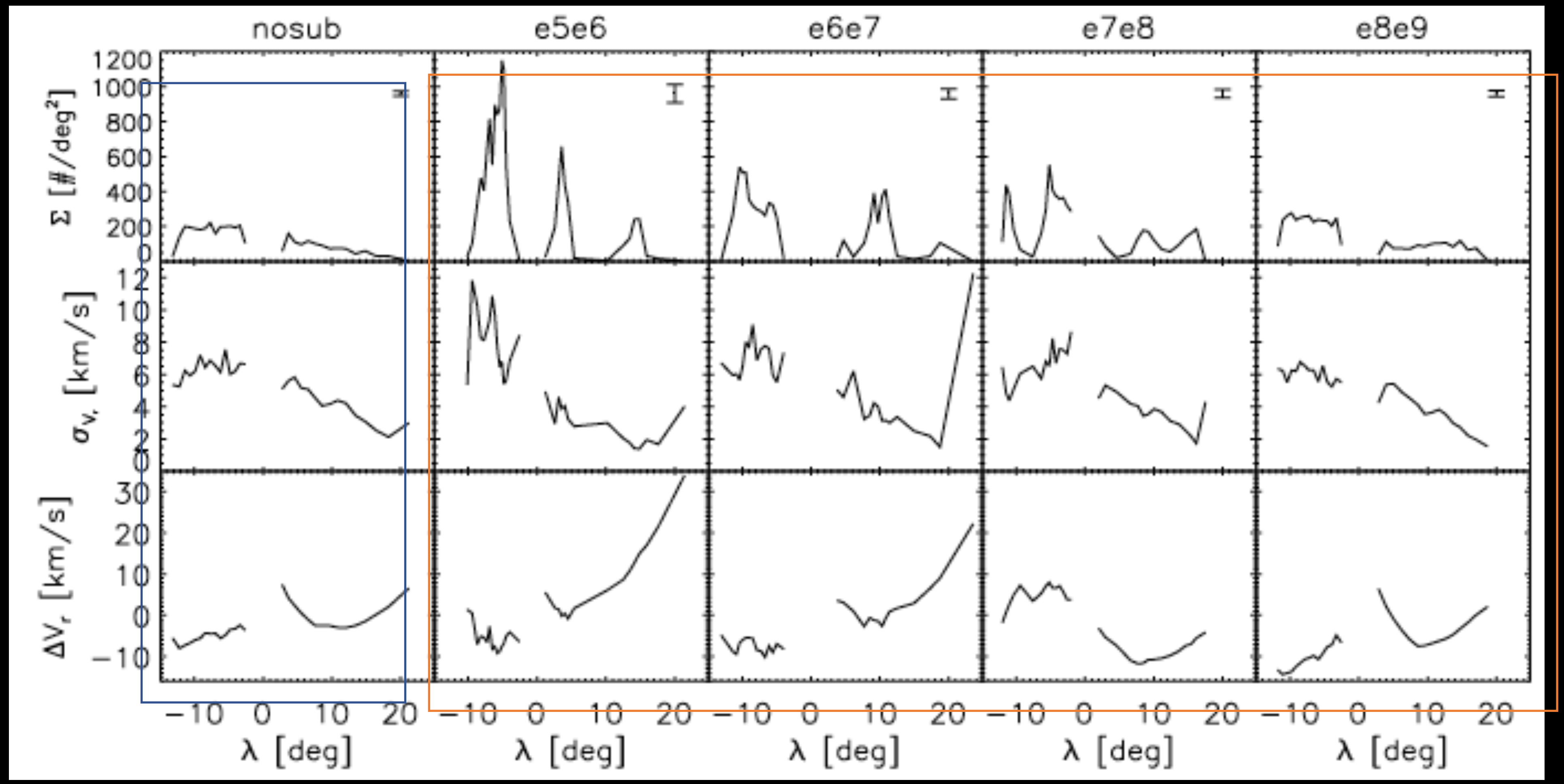
Stellar stream gaps as probes of missing satellites

Yoon et al. 2011



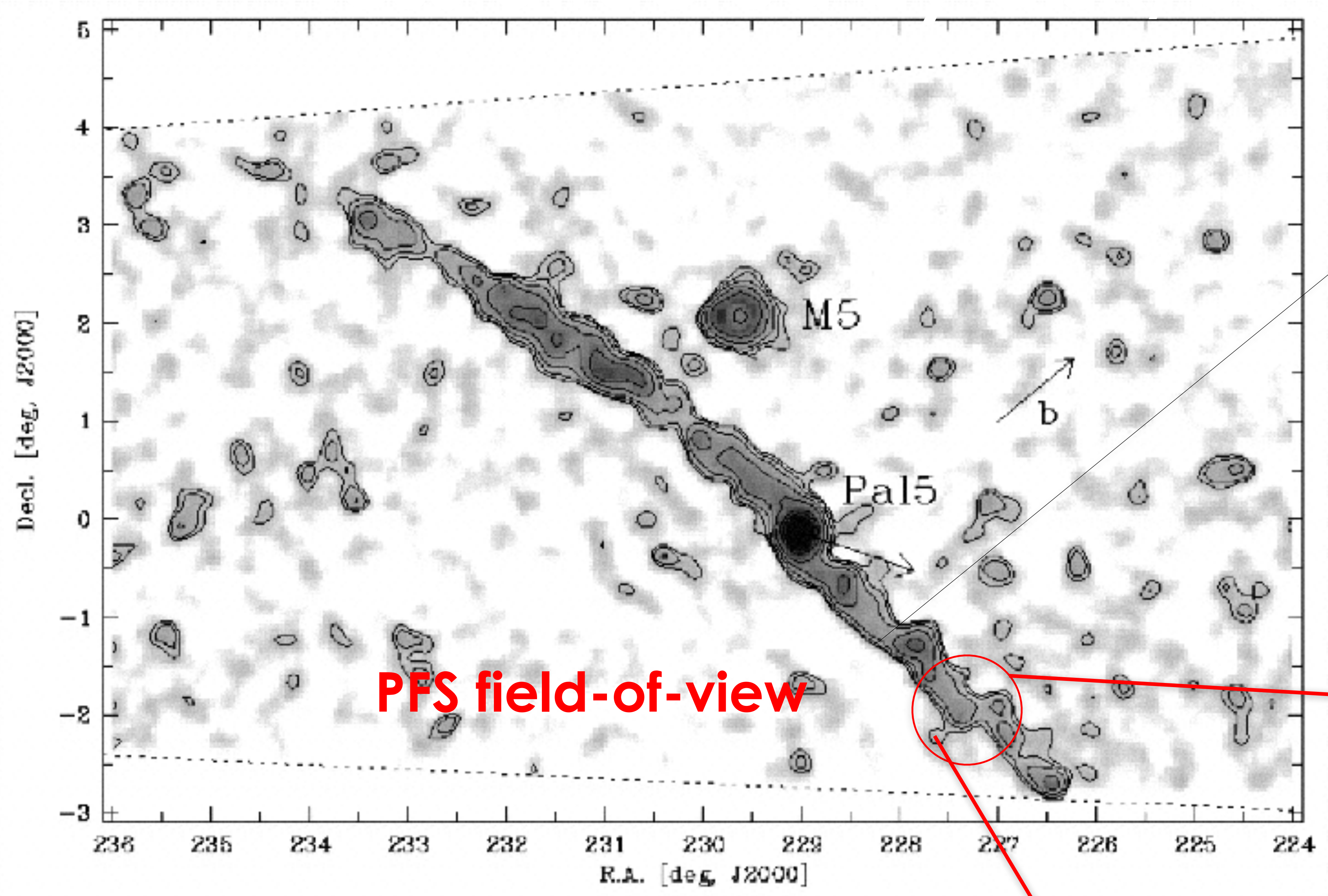
Gaps in a simulated stellar stream orbiting in a host halo with the dark matter subhalo mass distribution consistent with the ΛCDM prediction

No subhalos Subhalos with different masses



Top: stellar density, middle: line-of-sight velocity dispersion, bottom: line-of-sight velocity

Distant streams by PFS



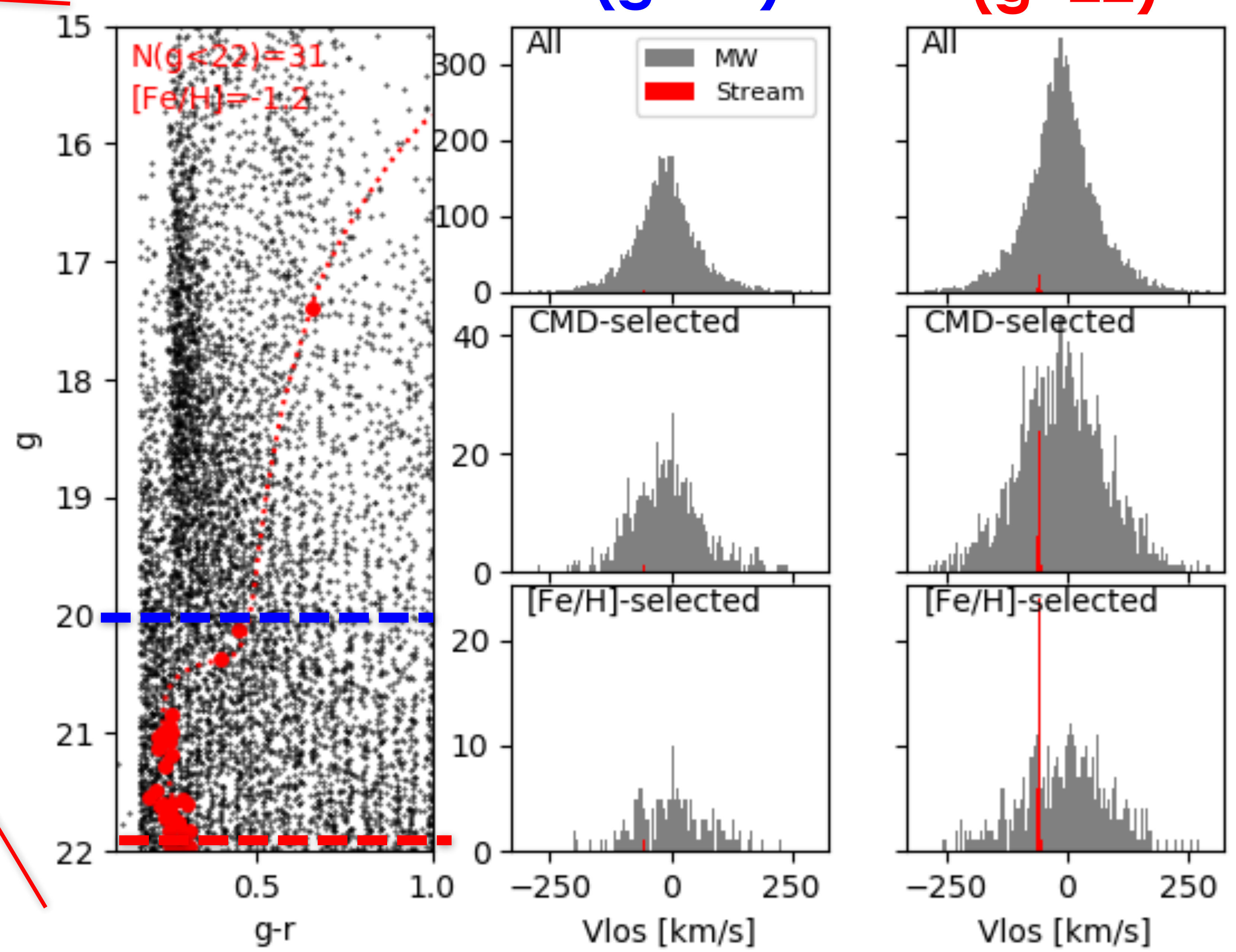
Diffuse

➡ e.g. ~ 10-30 stars/deg^2 (g<22)

Mock CMD for Pal5 stream

Shallow (g<20)

Deep (g<22)



Deeper than MSTO

➡ Clear separation of the stream stars from contaminating field stars based on [Fe/H]

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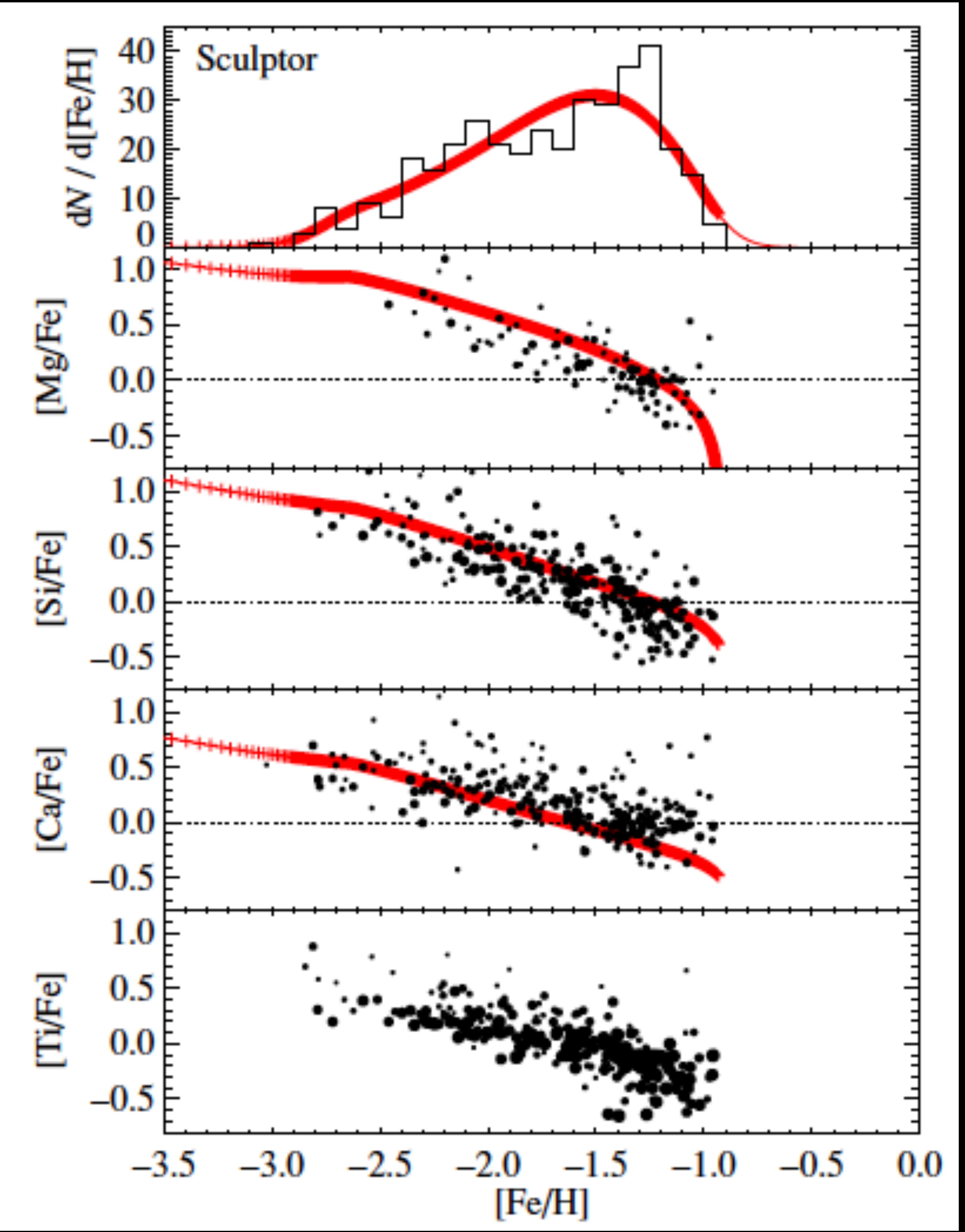
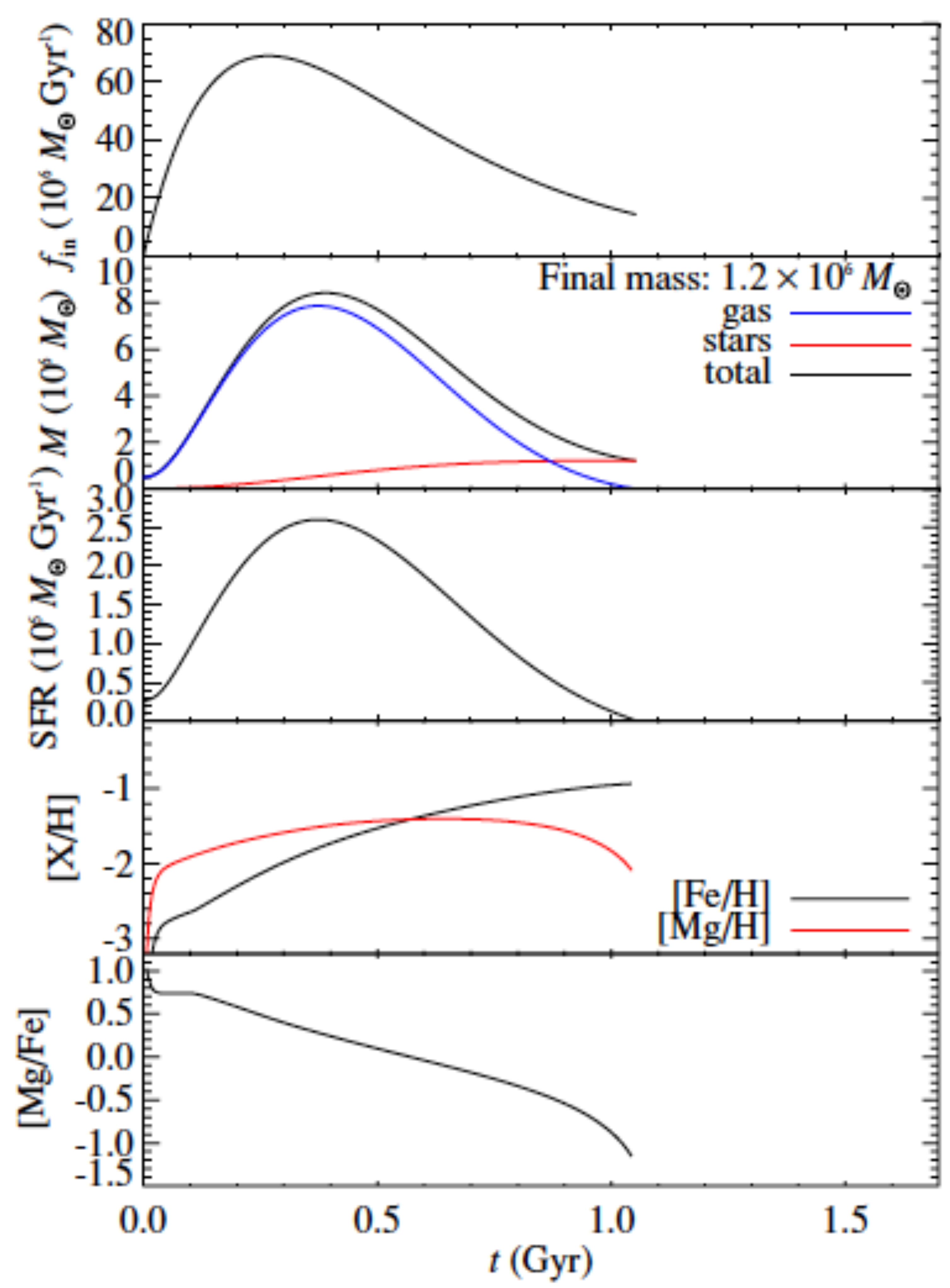
Chemical abundance ratios

Kirby et al. 2011

Observed chemical abundances



Chemical evolution model



Core-collapse supernovae

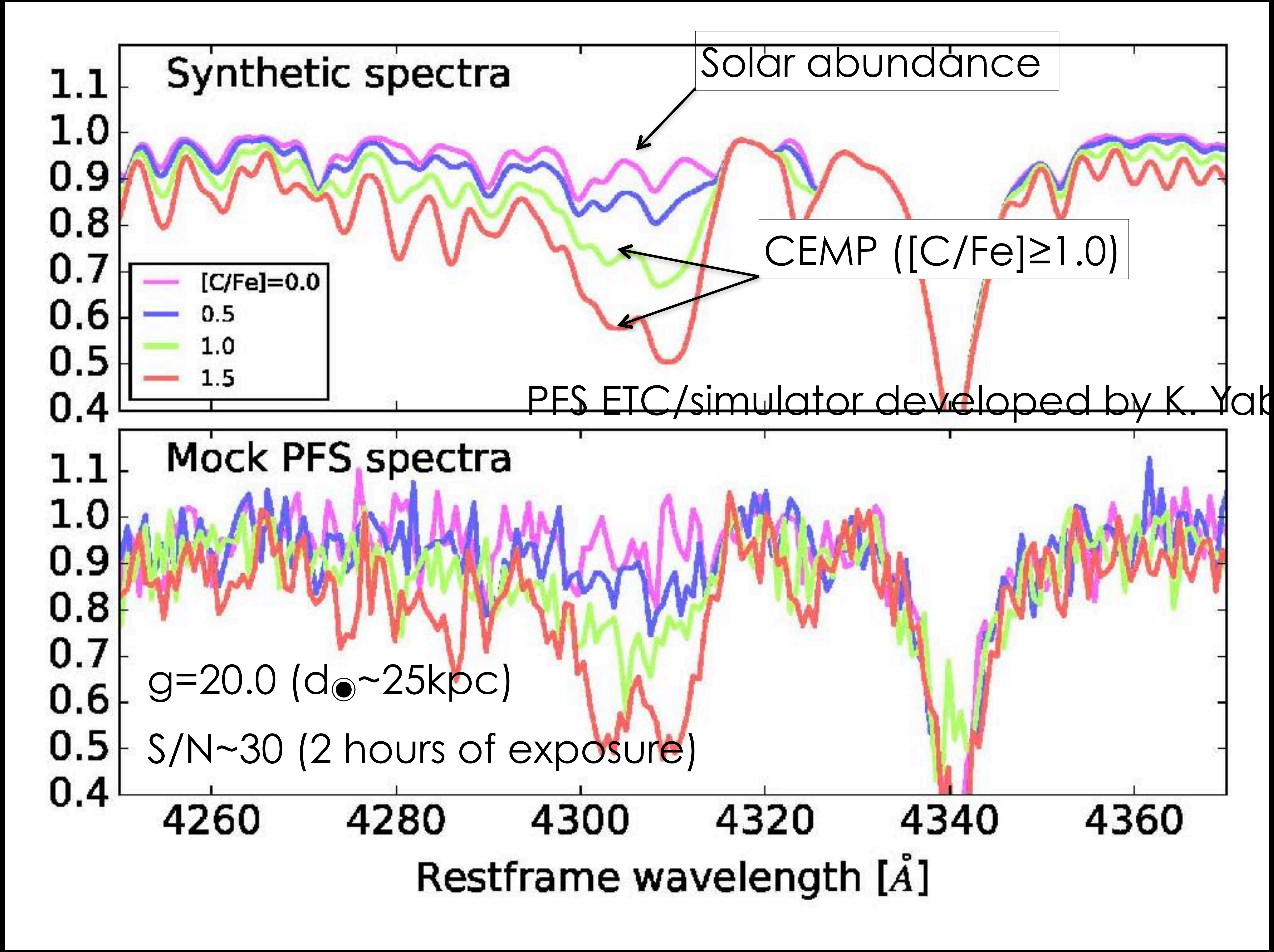
Core-collapse supernovae

Core-collapse + Type Ia supernovae

Core-collapse + Type Ia supernovae

Measuring C in PFS spectra

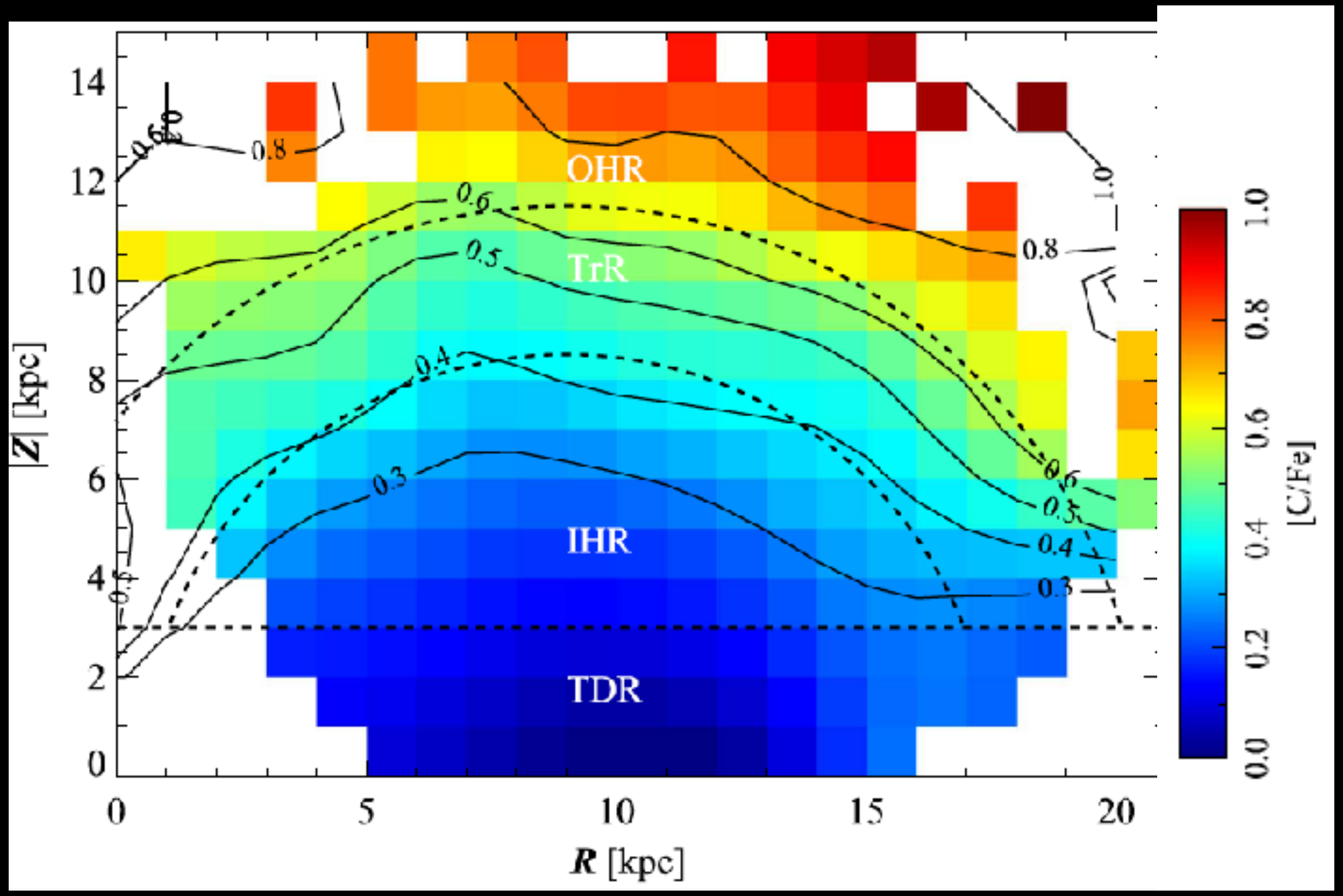
Synthetic spectra for a typical halo subgiant; T_{eff}=5800K, log*g*=3.5, [Fe/H]=-2
(Calculated by the code developed by W. Aoki-san; Kurucz model + VALD line list)

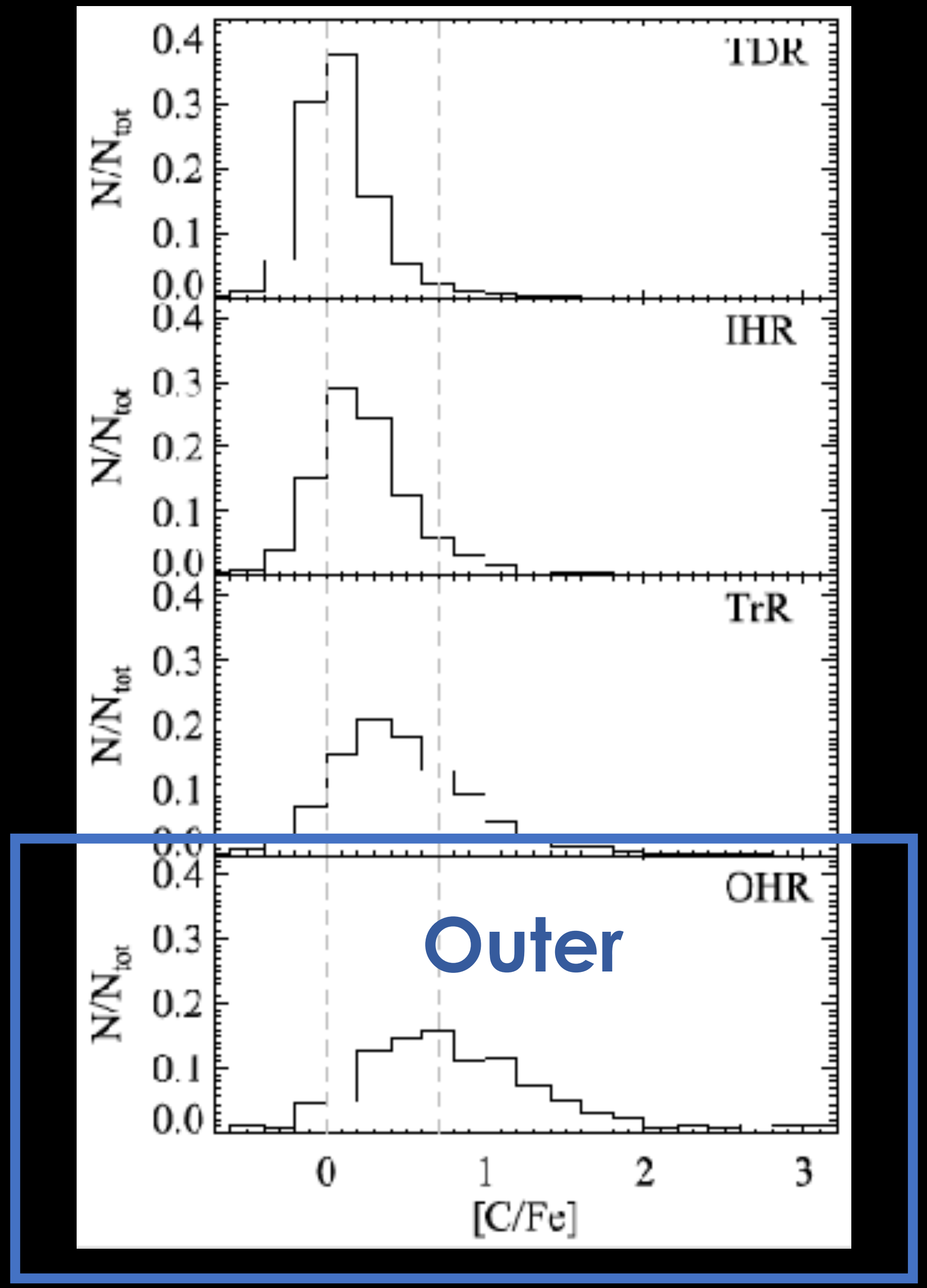


Searches for stars with pristine chemistry in the outer Milky Way halo

Carbonicity ([C/Fe]) map from the SDSS/SEGUE survey (Lee et al. 2017)

High [C/Fe] ratios may be originated from supernovae of the Pop III stars





- Chemistry ([Fe/H], [α/Fe], and [C/Fe]) in the outer stellar halo hints at nucleosynthesis in the early Universe
- Making constraints on surviving (low-mass) Pop III stars (Ishiyama et al. 2016; Hartwig et al. 2016)

Revised PFS/GA Survey (as of 12/12, 2018)

Survey	Mode	Mag. Range (mag)	Exp. (sec)	No. Fields	Survey (nights)	Comments
MW dSph	MR+ LR(blue)	g < 22	10800	14 x 2 →16x2	11.3 →12.1	Boo I, Fnx, Scl, UMi & Dra
MW dSph	MR+ LR(blue)	g < 22	10800	7 x 2	5.3	Sextans
MW dIrr	LR	g < 22.5 (i < 21)	14400	1 x 2	1	NGC6822
MW halo	MR+ LR(blue)	g < 22	10800	14 →12	5.3 →4.5	Halo: b=60, l=90 & 270
MW outer disk	MR+ LR(blue)	g < 22	10800	44	16.5	Outer disk: l=180
MW streams	MR+ LR(blue)	g < 22	10800	24	9	'Field of Streams'
M31 halo	MR	i < 22.3	18000	34	21.6	HSC sample
Total					70	

Created by M. Chiba

PFS GA summary

- Beginning
  - Faint dwarf satellite galaxies, which are the potential candidate of surviving first galaxies, provide a unique opportunity to observational probe the cosmic dark ages
- Growth
  - Kinematics and chemistry of substructures/streams in the outer stellar halos of the Milky Way and M31 allow for reconstructing the merging history of large spiral galaxies
- Present
  - Present-day distribution of dark matter in dwarf satellites puts stringiest constraints on the nature of dark matter
- Chemical evolution
  - Detailed chemical abundances in dSphs are powerful in constraining formation history of these galaxies. Chemistry in the outer MW stellar halos can be used as a signature of nucleosynthesis by the progenitor Pop III stars.

PFS has an advantage in all of these science cases because of its large FoV and faint limiting magnitudes

SUBARU TELESCOPE 20TH ANNIVERSARY

Registration, Abstract Submission

Wide-field-surveys of the Local Group and Nearby Galaxies

Parallel Science Sessions -
Local Group & Nearby Galaxies

b/g image: M81 through Hyper Suprime-Cam, prime-focus camera (S Okamoto et al. 2015)

Subaru 20th anniversary conference
November 17-22 @Waikoloa Beach, Hawaii

https://www.subarutelescope.org/subaru20anniv/index.html
Abstract submission deadline: June 15th

There will also be the "PFS session"!

Keynote & Invited Speaker
Vasily Belokurov (U. of Cambridge)
Brent R. Tully (UH-IfA)
Eric Peng (PKU-KIAA)
Karoline Gilbert (STScI)
Kim Venn (U. of Victoria)
Laura Ferrarese (CNRC-NRC)
Masashi Chiba (Tohoku U.)
Michael Rich (UCLA)