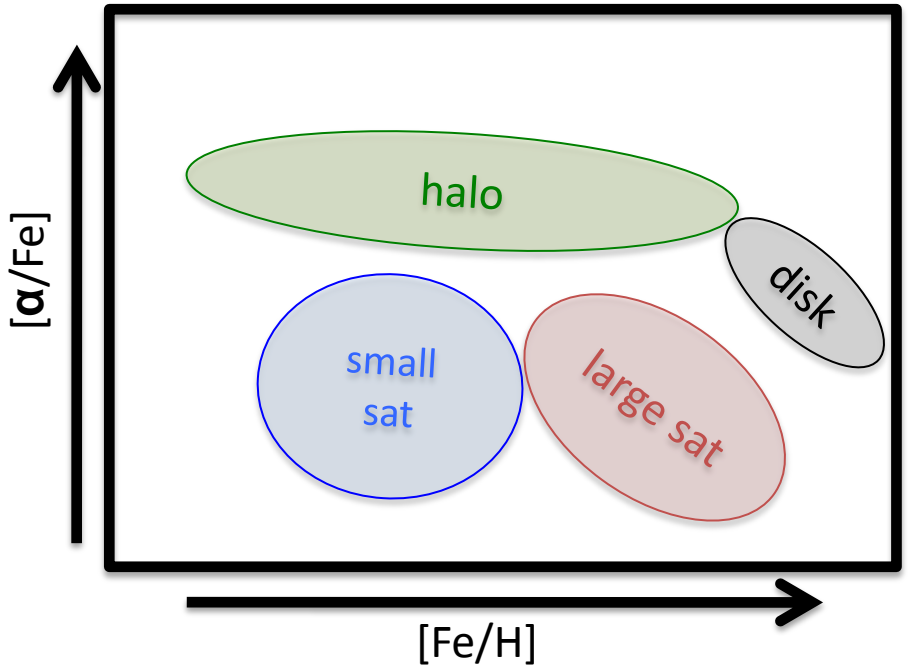
Supported by the National Science Foundation



Kathryn V Johnston
Columbia University
Astronomy Department

Reading the elements.....

.... to understand rain from stellar clouds .....

... and forecast results from direct dark matter detection experiments

(e.g. Kuhlen et al, astro-ph 1202.0007)

Reading the Elements: stars remember where they were born!

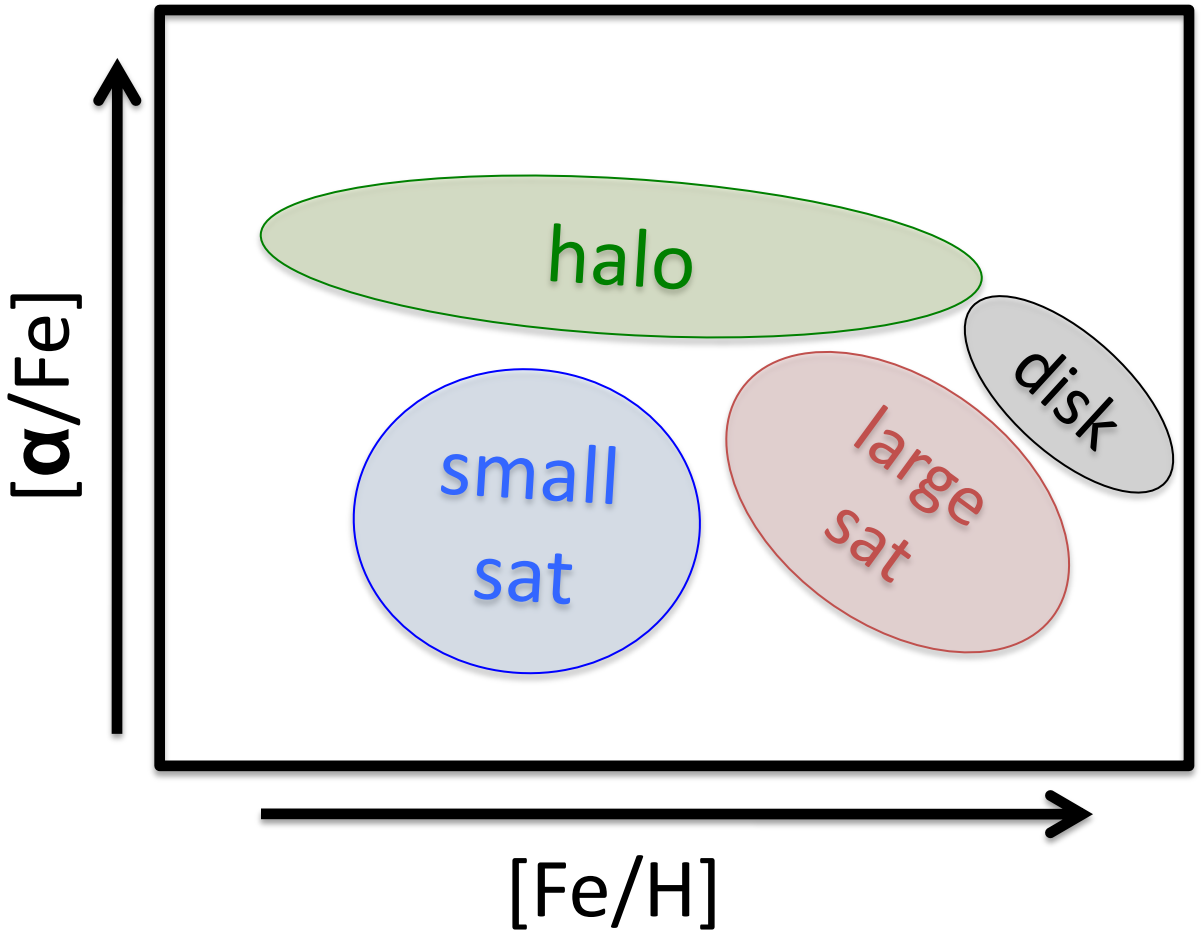
- Tracers of baryonic physics of galaxy formation
  - Evan Kirby (talk); Duane Lee (poster)

- "Chemical Tagging" (Freeman & Bland-Hawthorn, 2002)
  - Josh Simon, Anna Frebel (talks); Torgny Karlsson (poster)

"Statistical Chemical Tagging"

(e.g. Schlaufman et al, astro-ph 1202.2360)

[α/Fe] *vs* [Fe/H] ⇔ original host type

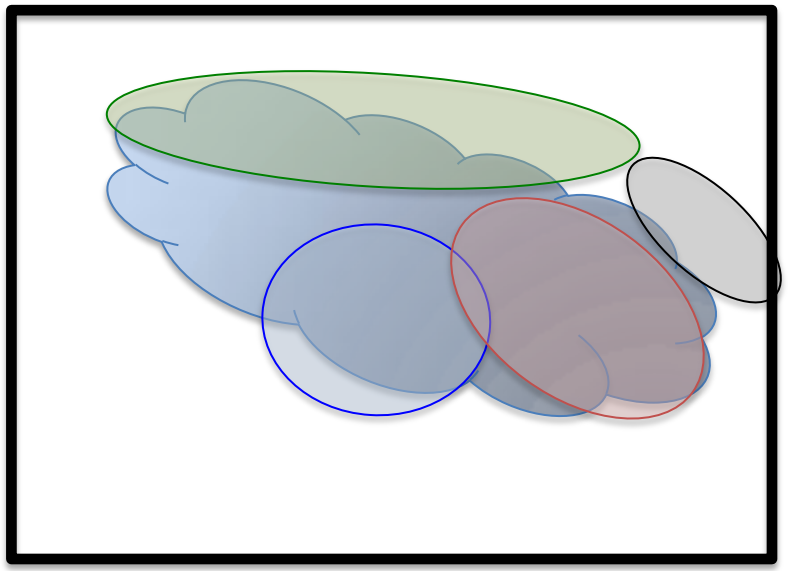


Chemical tags ➔ Galactic Accretion History?

(see also: Unavane et al 1996; Prantzos 2008)

1. f = observed distribution in [α/Fe] *vs* [Fe/H]
2. f_i = template distributions
3. find A_i such that

$$f = \Sigma_i A_i f_i$$

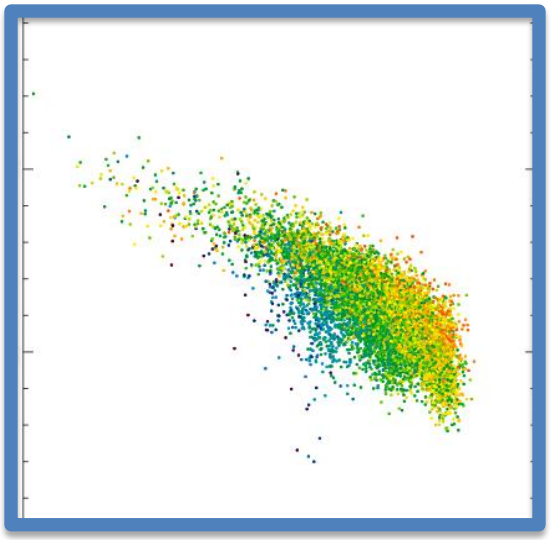


e.g. f = stellar halo distribution

- f_i of halo progenitors, (M_*, t_{acc})
- A_i = accretion history!

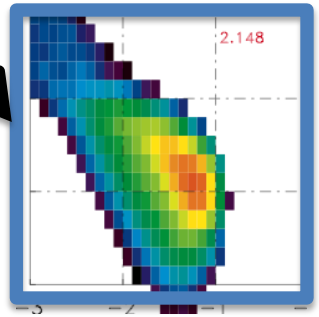
Accretion history in abundance space?

Duane Lee et al (2012)

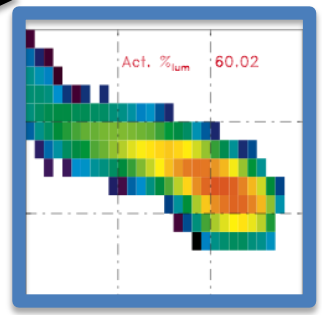


- f = "observations" of 11 model stellar halos
  (Bullock/Johnston/Robertson/Font)
- f_i = 5x5 grid in (M_*,t_{acc}) accreting satellites
- expectation-maximization ➔ A_i

$$f = \Sigma_i A_i f_i$$



e.g. low mass, late accretor

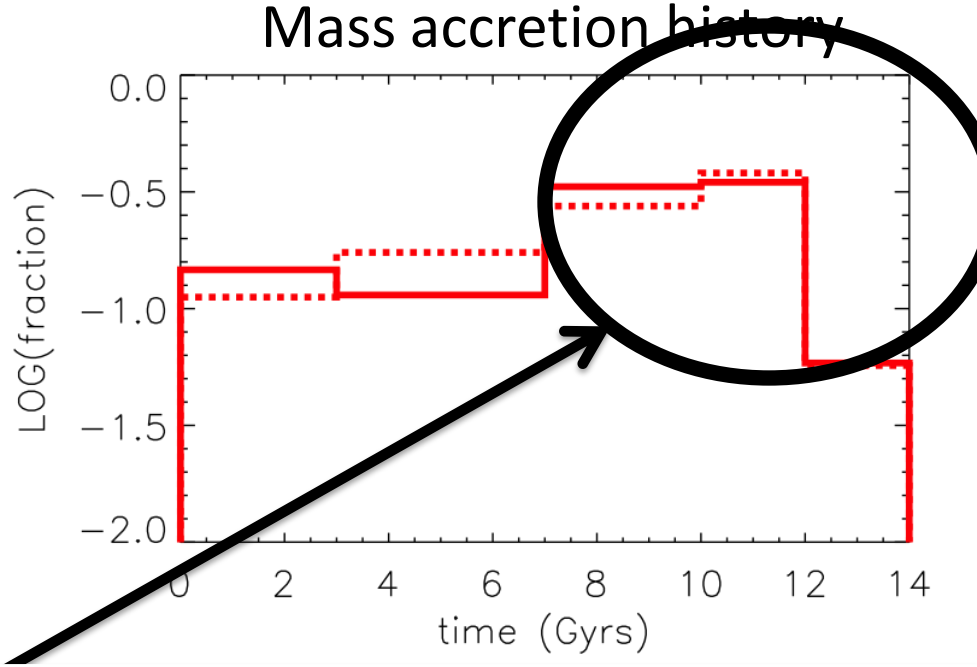


e.g. high mass, early accretor

Results:

dotted = input

solid = recovered

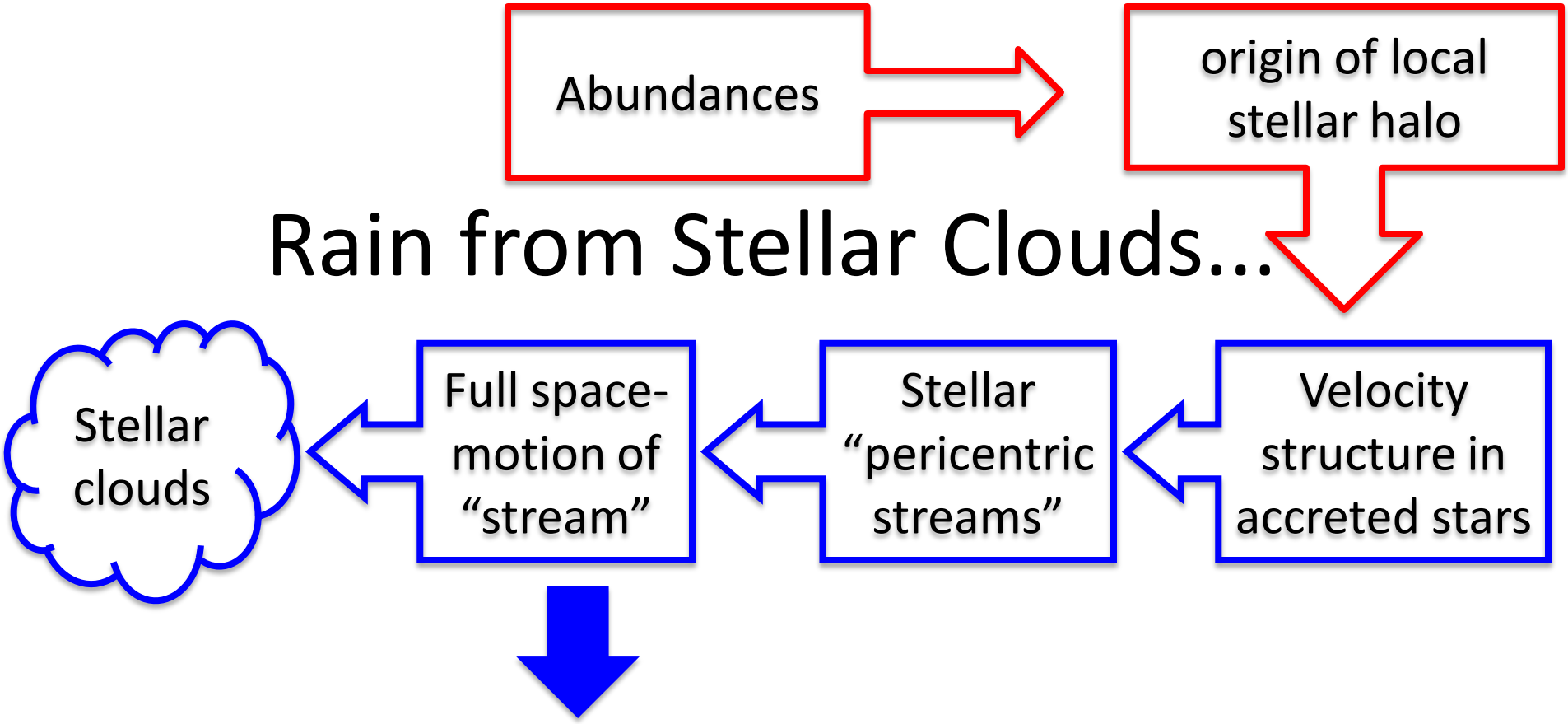


Conclusion

abundances ➔

- early accretion epoch
- low mass end of luminosity function

Reading the Elements....



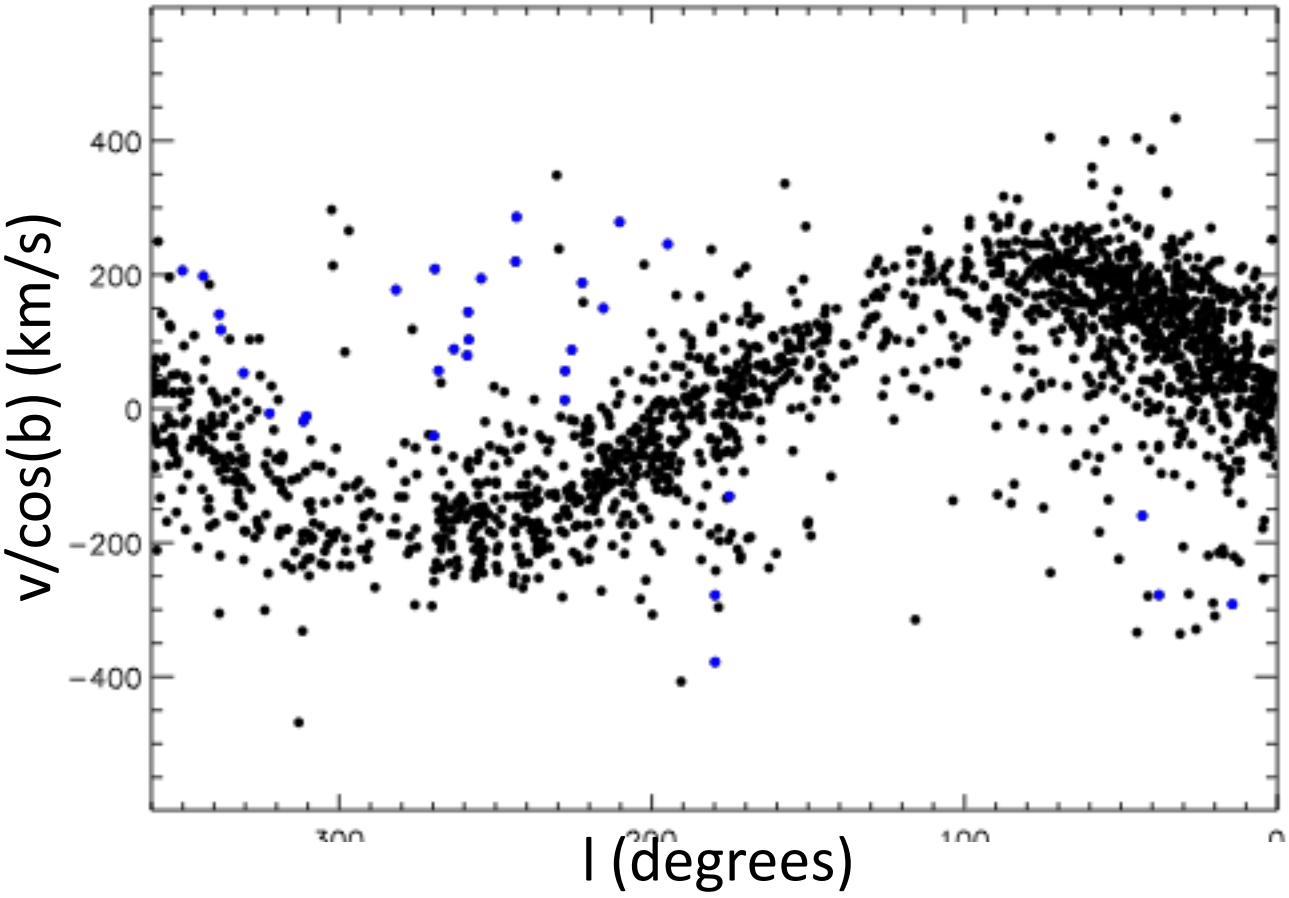
Forecasts for Direct Dark Matter Detection Experiments...

Allyson Sheffield et al, 2012
Johnston et al, 2012
(Majewski, Cunha, Smith, Sharma)

Medium-res spectra of 1799 M giant stars

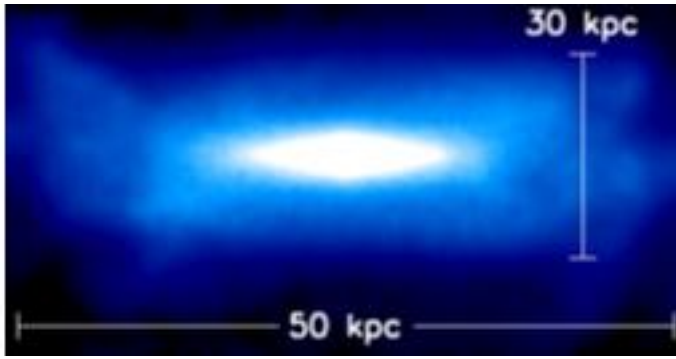
- from 2MASS
- 30 < |b| < 60
- < 10kpc of Sun

<u>34 high-res spectra of RV-outliers</u>



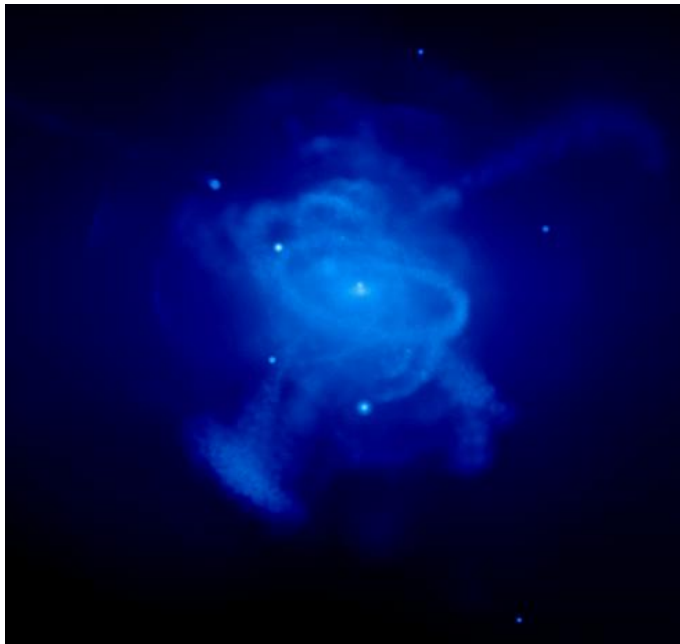
Chemical Tags → origin of stellar halo?

- ☐ "*in situ*" formation
  - Eggen, Lynden-Bell & Sandage (1962), Samland & Gerhard (2003)



- ☐ "*kicked out*" from disk
  - Purcell et al (2010), Zolotov et al (2009), McCarthy et al (2011)

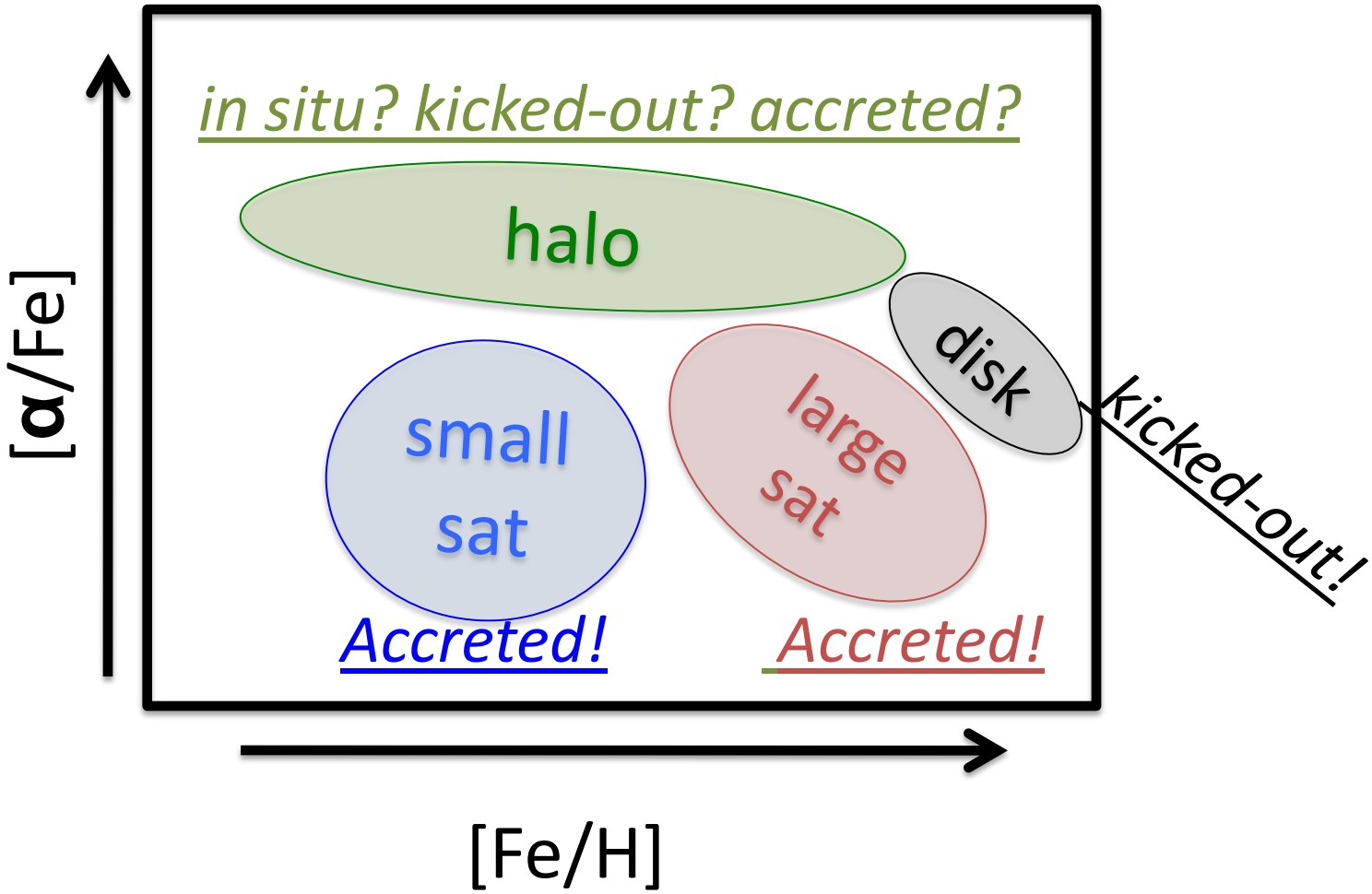
- ☐ "*accreted*" from other galaxies
  - Searle & Zinn (1972), Bullock & Johnston (2005), Cooper et al (2010)



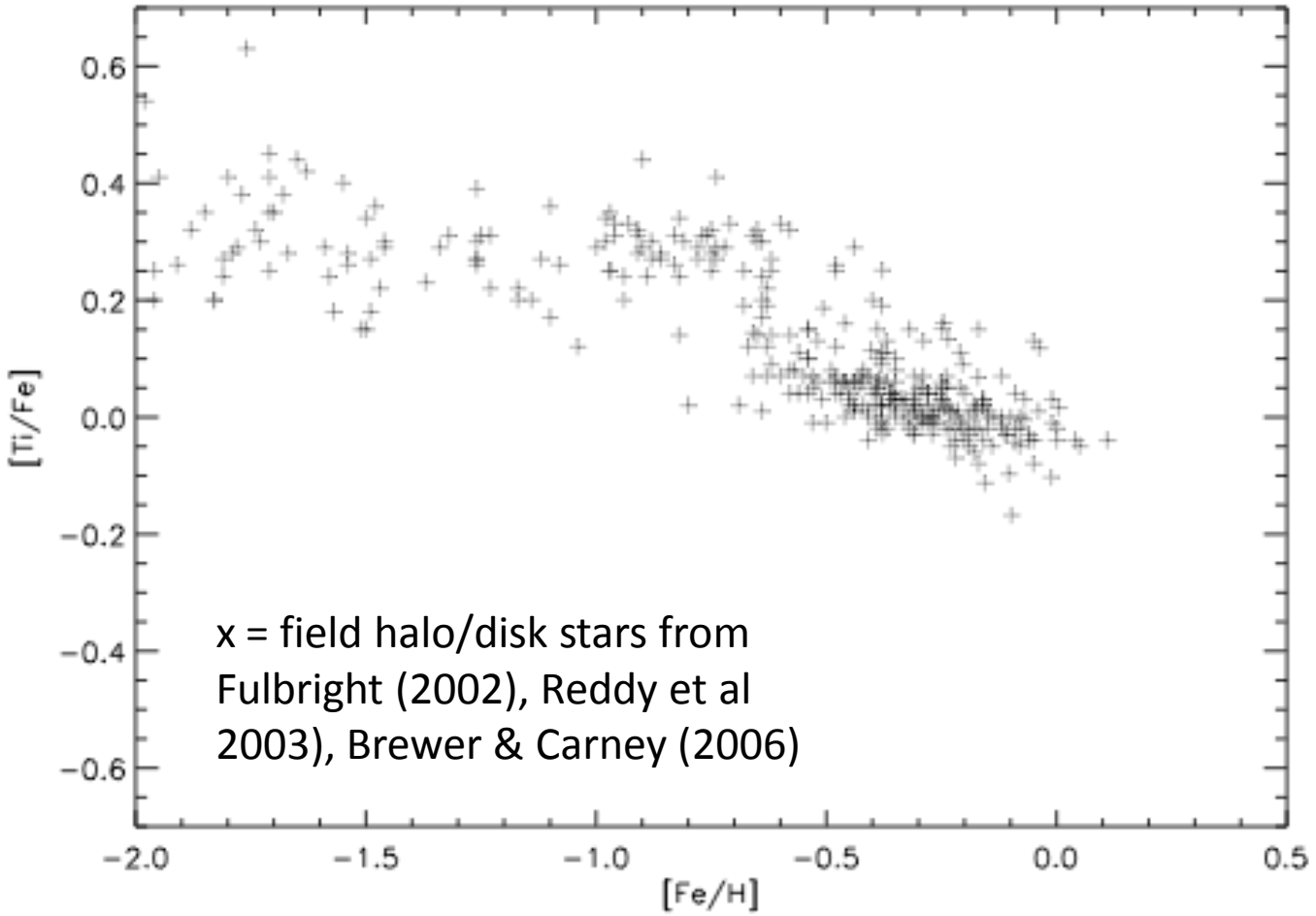
Chemical tags

➔ origin of stellar halo ?

(inspired by Zolotov et al, 2010)



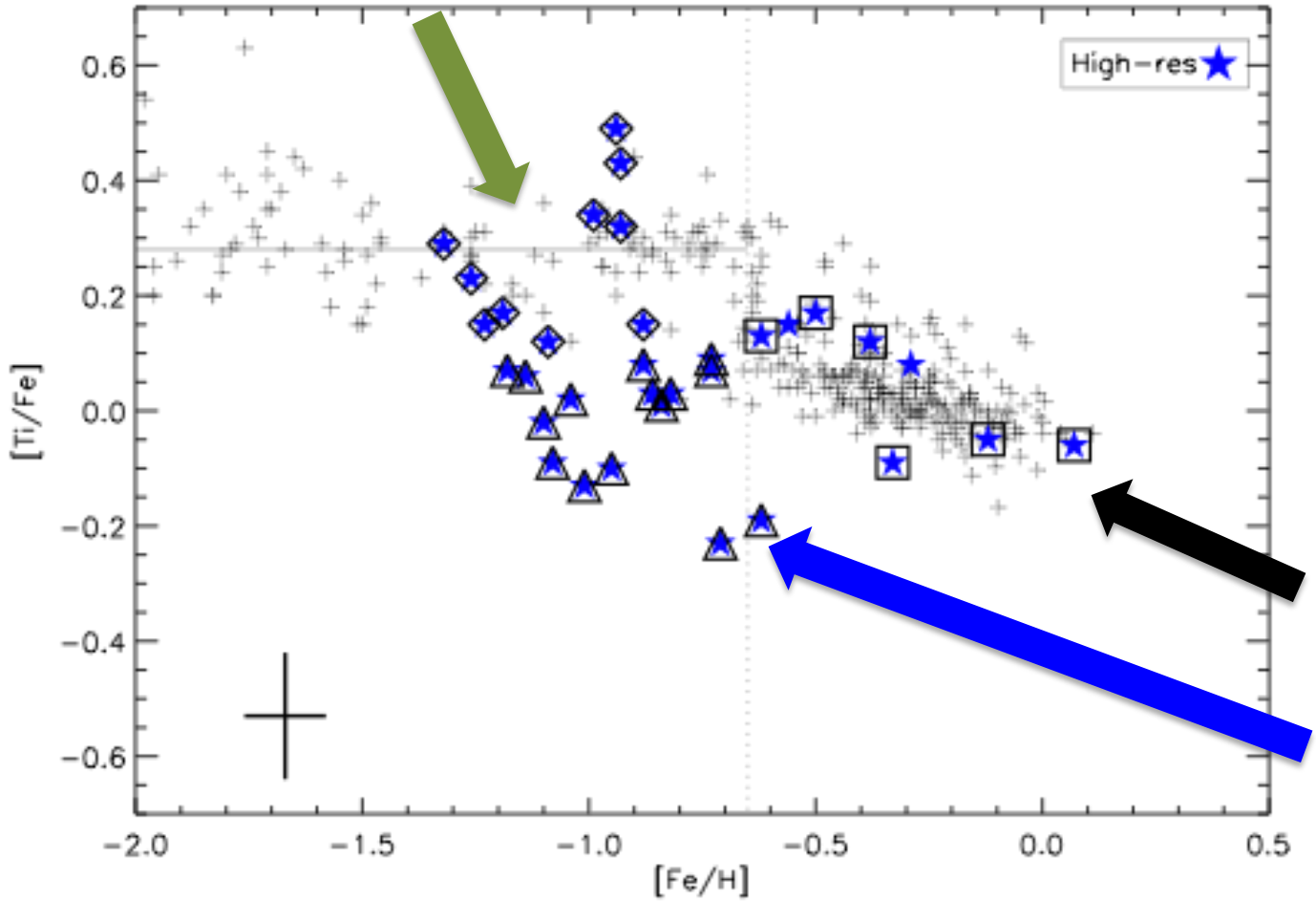
Chemical tags
➔ origin of stellar halo ?



Chemical tags

→ conclusion: multiple origins for stellar halo?

10 *In situ/kicked-out/accreted*



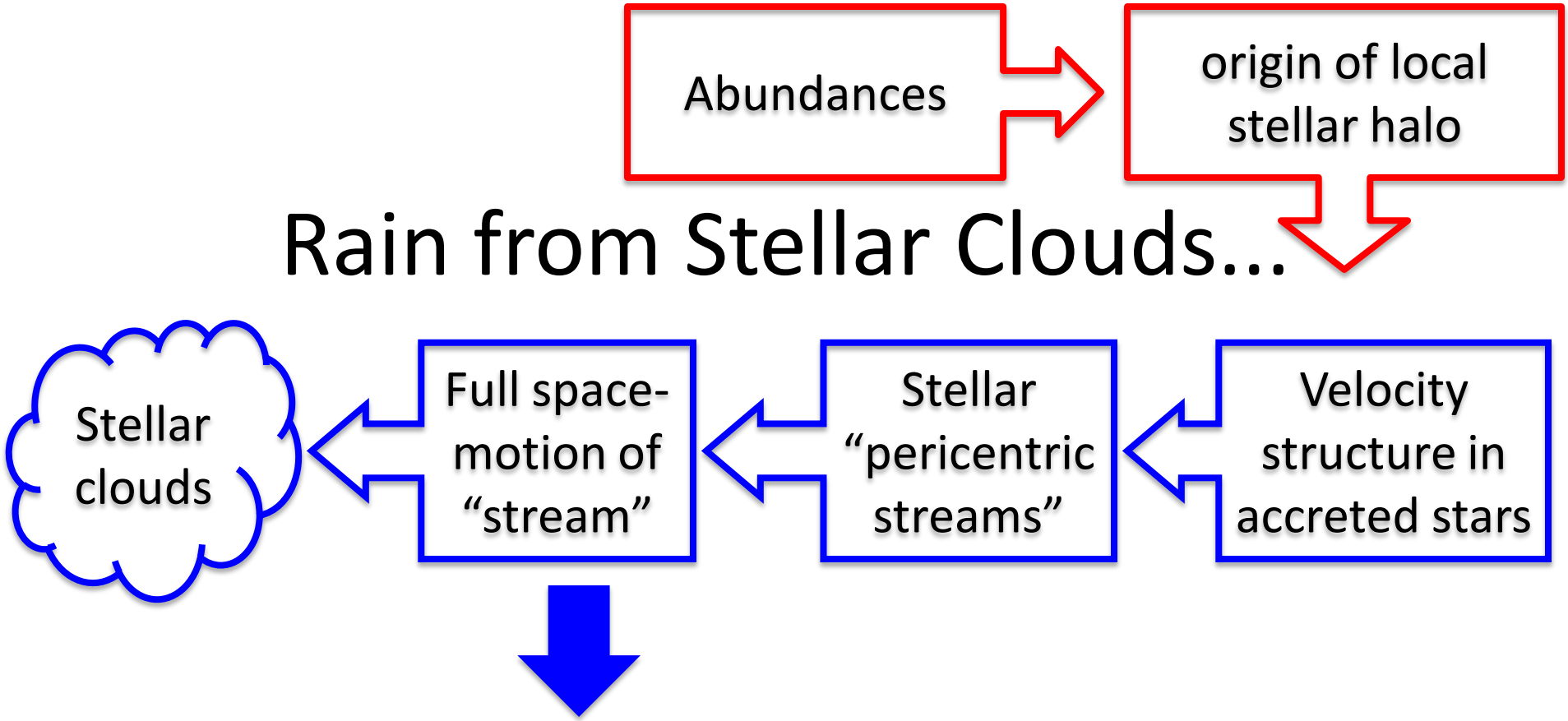
See also:

- Nissen & Schuster, 2010, 2011
- Lee et al, 2008
- Carollo et al 2012

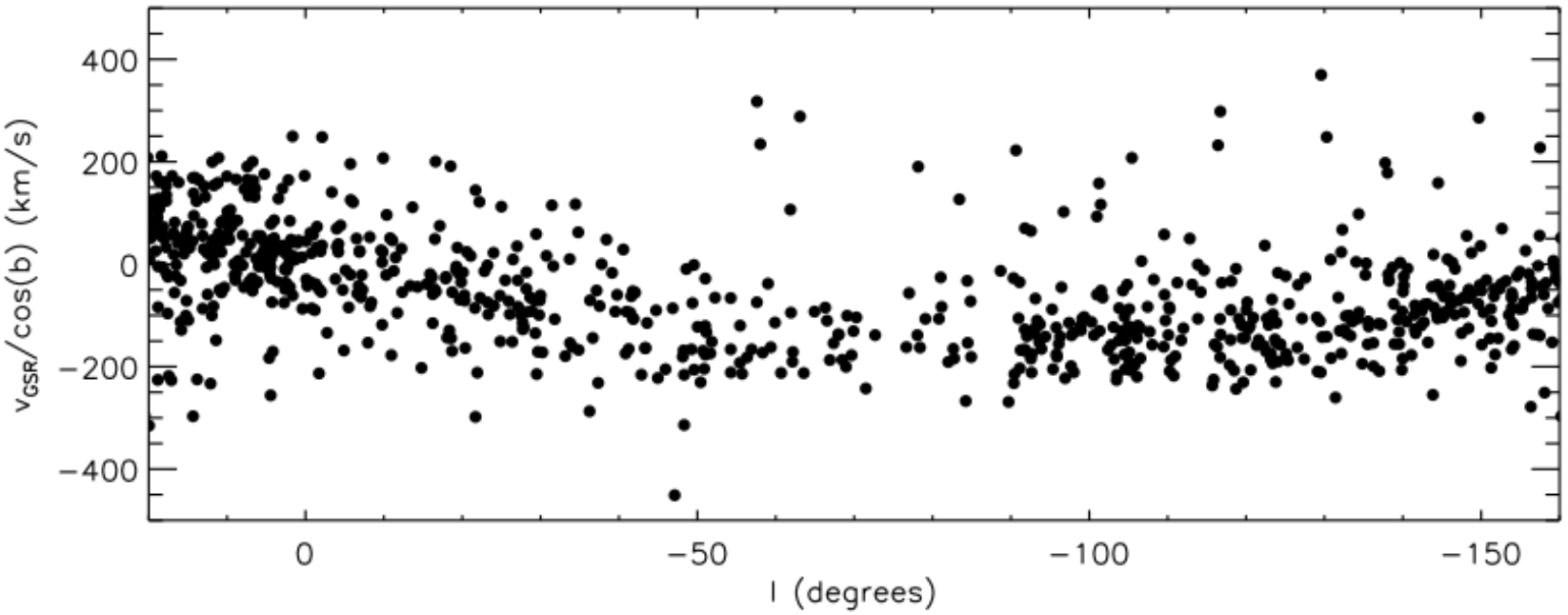
8 *kicked-out*?

16 *accreted*

Reading the Elements....



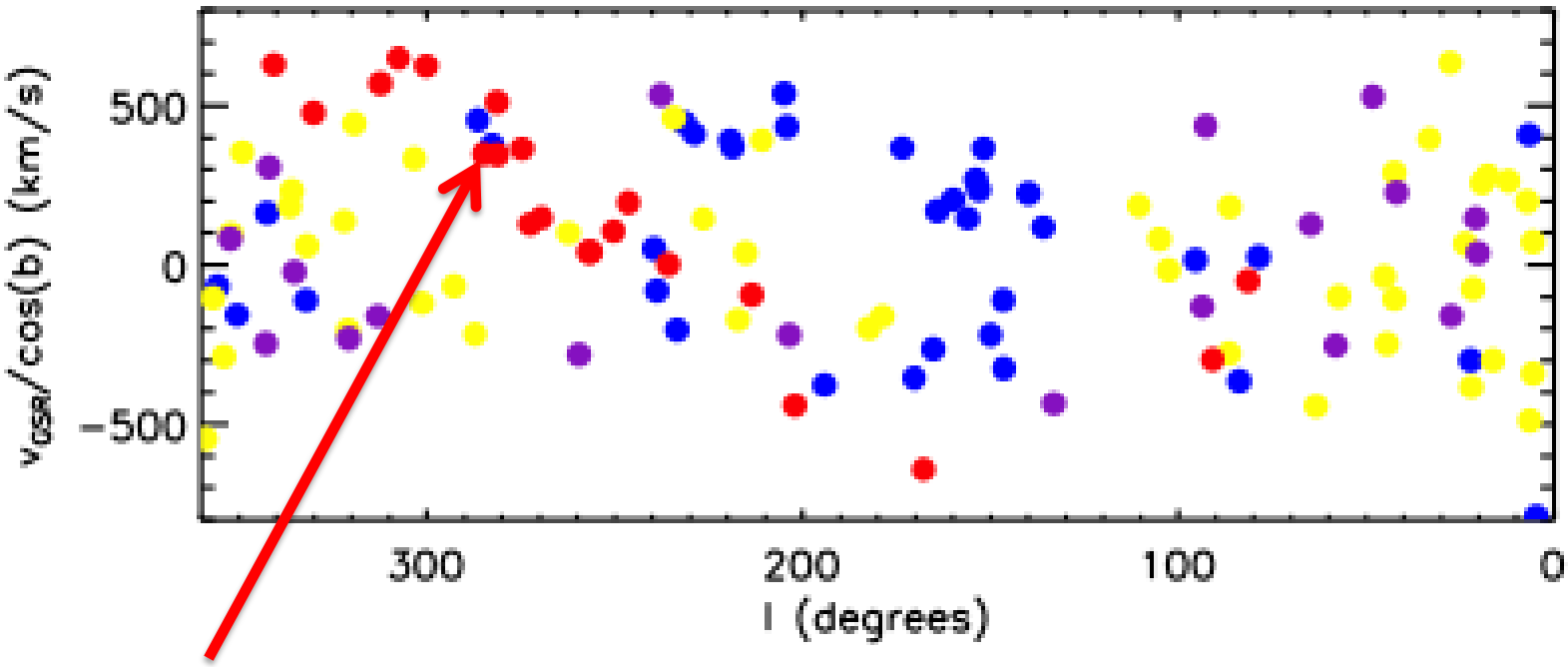
Forecasts for Direct Dark Matter Detection Experiments...


400
200
0
−200
−400
$v_{GSR}/\cos(b)$ (km/s)
0
−50
−100
−150
l (degrees)

Synthetic M-giant survey of simulations of accreted stellar halo

(using "galaxia" – Sharma et al 2011)

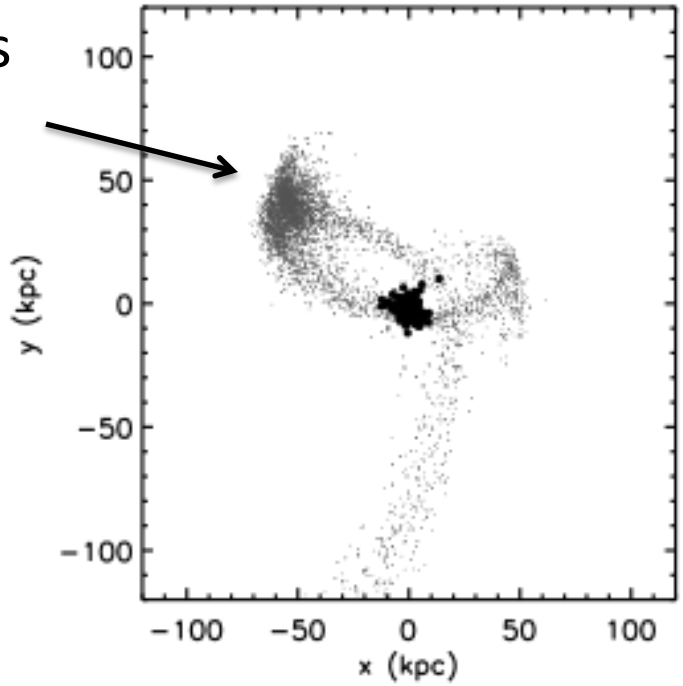
colors ⇔ progenitor satellites

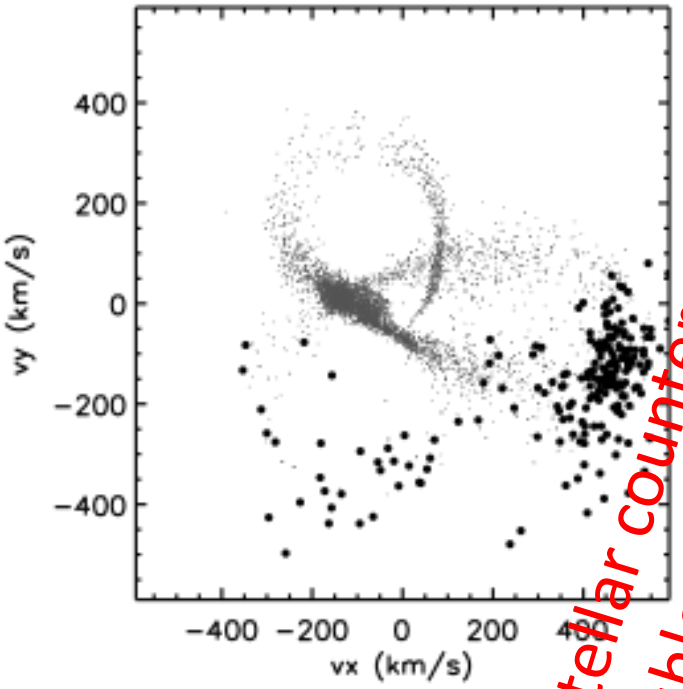


What's this red structure?

Stellar "pericentric stream"

Apocenter: "debris cloud"



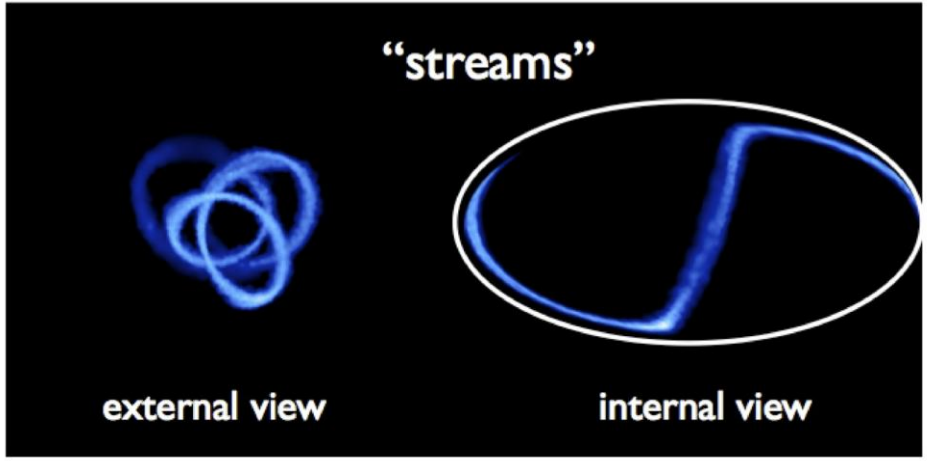


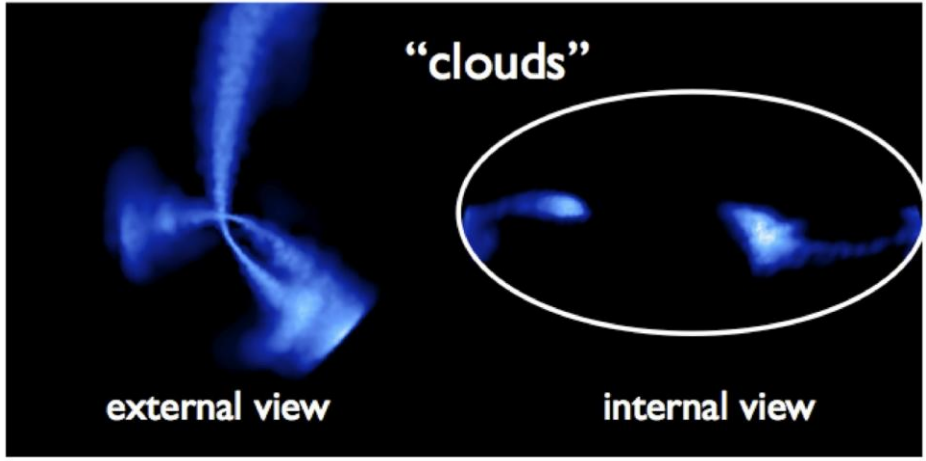
Observations:

- High speed, local, star "stream"
- Spatially diffuse

- Recent, high mass, accretion; eccentric orbit
- Connected to apocentric debris "clouds"

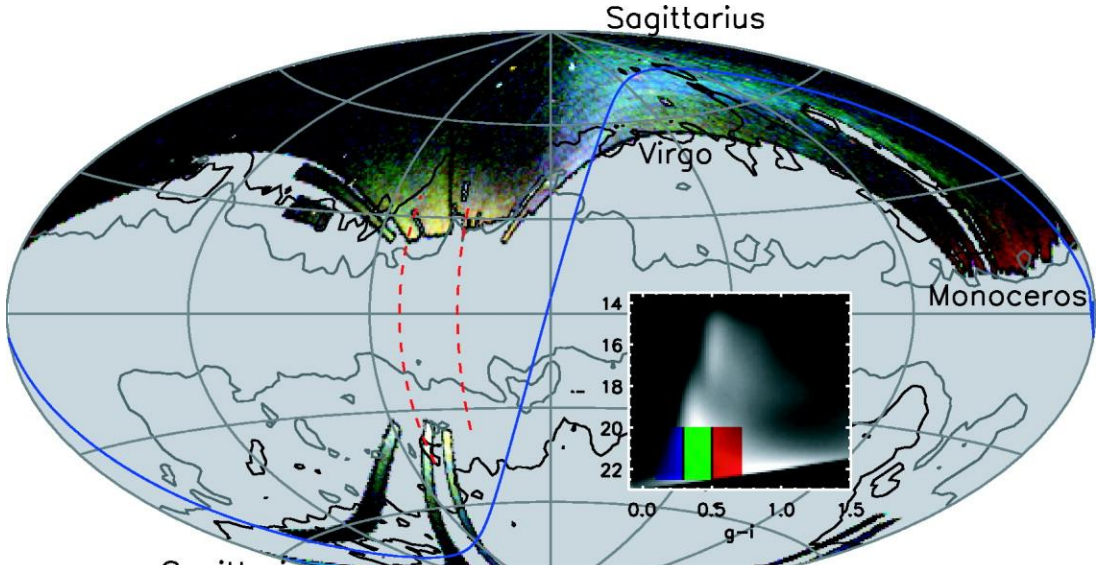
Stellar counterparts of Kuhlen et al's "Debris Flow"?



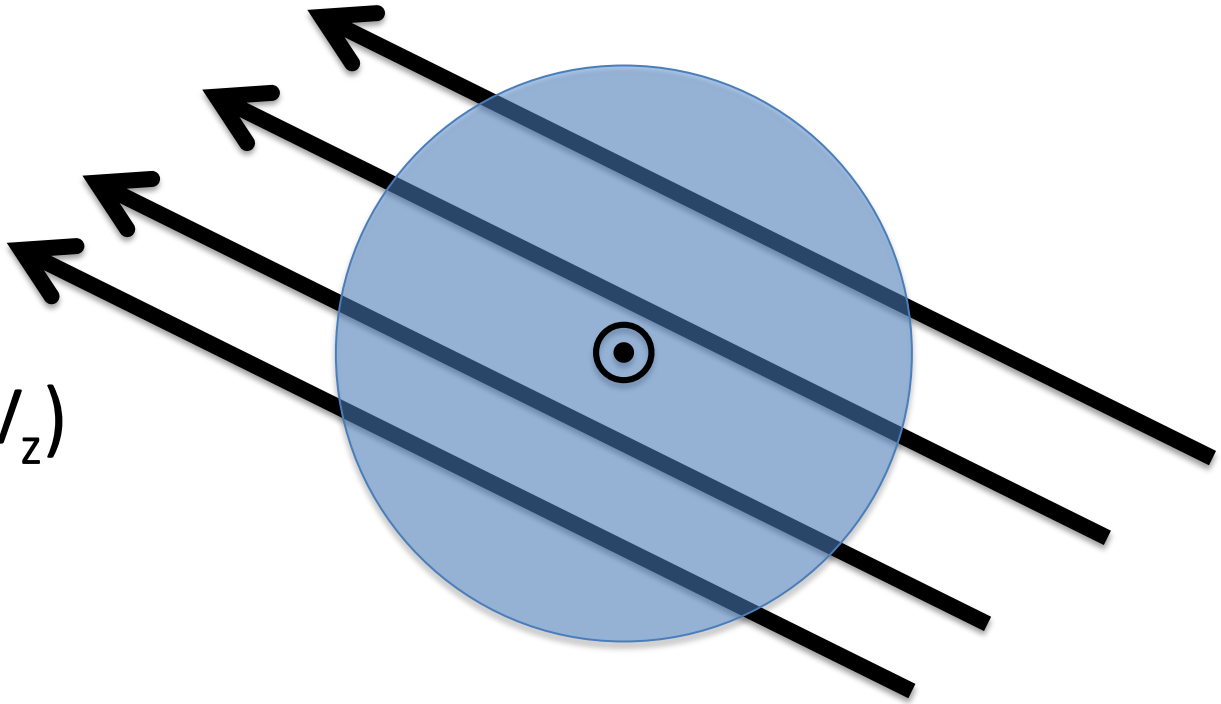


Observed stellar clouds:

- Triangulum-Andromeda (e.g. Rocha-Pinto et al '04); Virgo Overdensity (e.g. Juric et al, '08); Pisces Overdensity (e.g. Sesar et al, '07)
- Hercules-Aquila (Belokurov et al, '07)



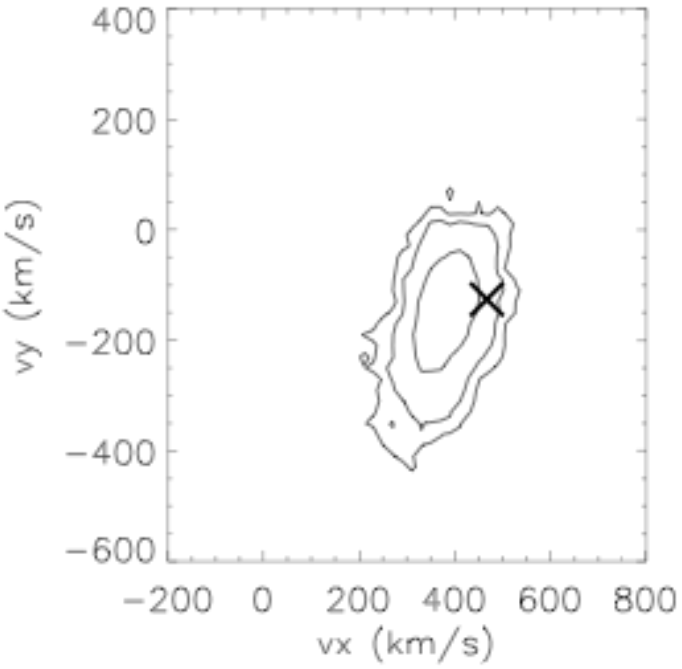
Full-space motion of pericentric streams?

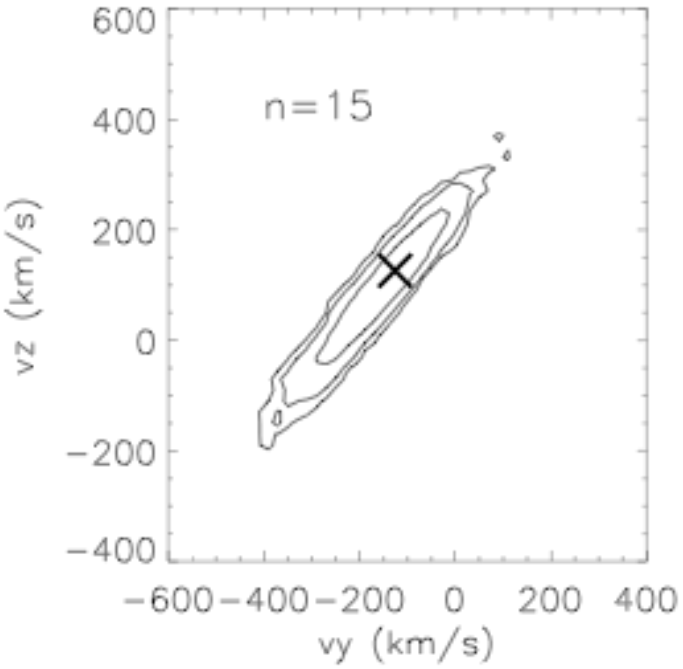


$\mathbf{V}=(V_x,V_y,V_z)$

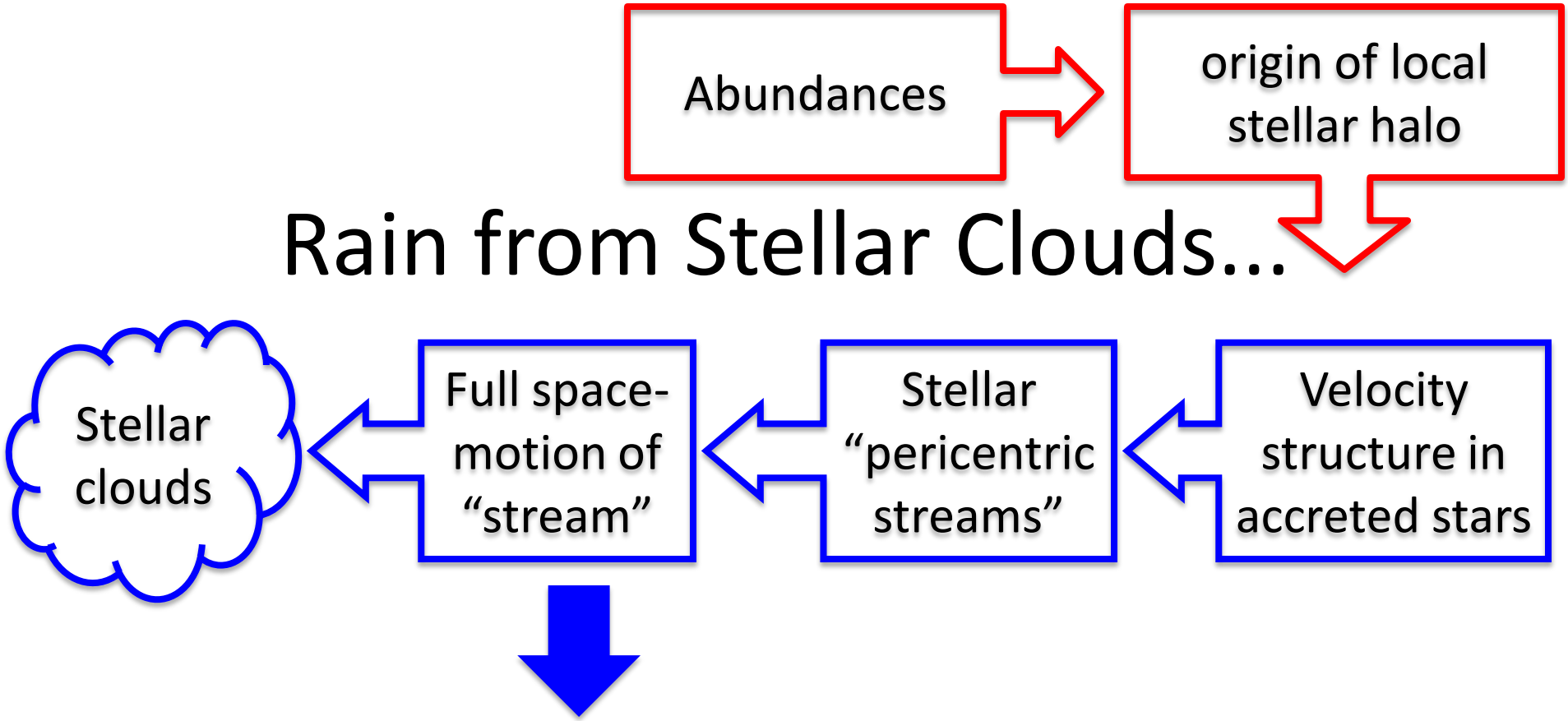
$$V_{los} = V_x\cos(l)\cos(b) + V_y\sin(l)\cos(b) + V_z\sin(b)$$

MCMC recovery of space motion from synthetic observations of 15 simulated “pericentric stream” stars.....



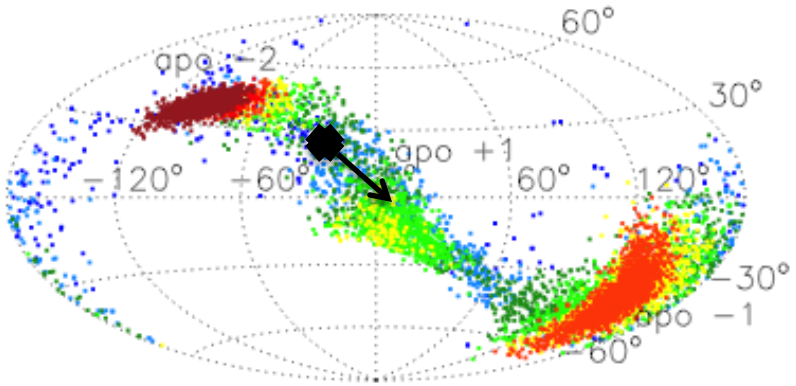


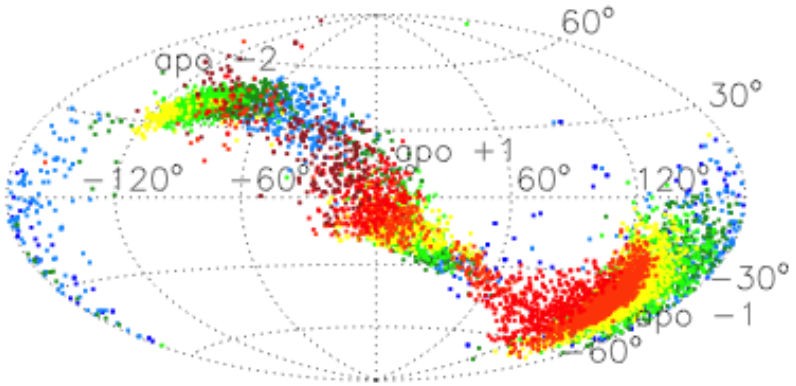
Reading the Elements....



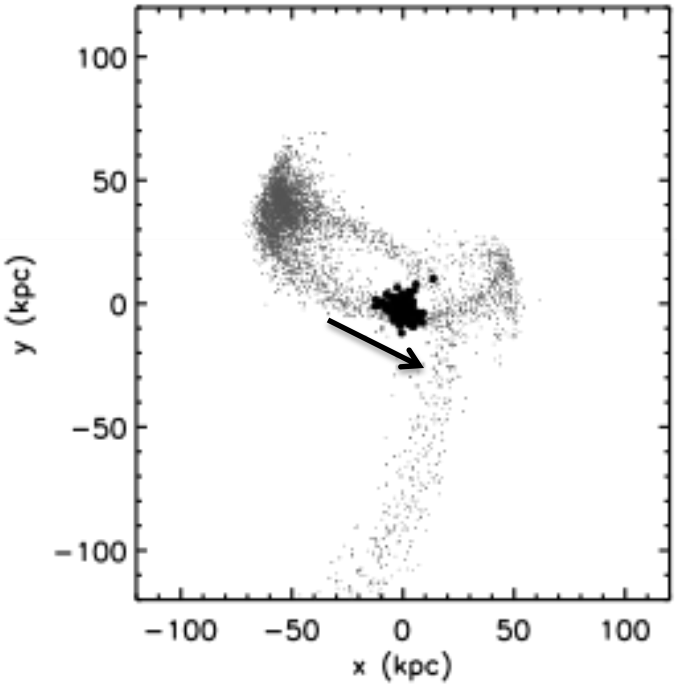
Forecasts for Direct Dark Matter Detection Experiments...

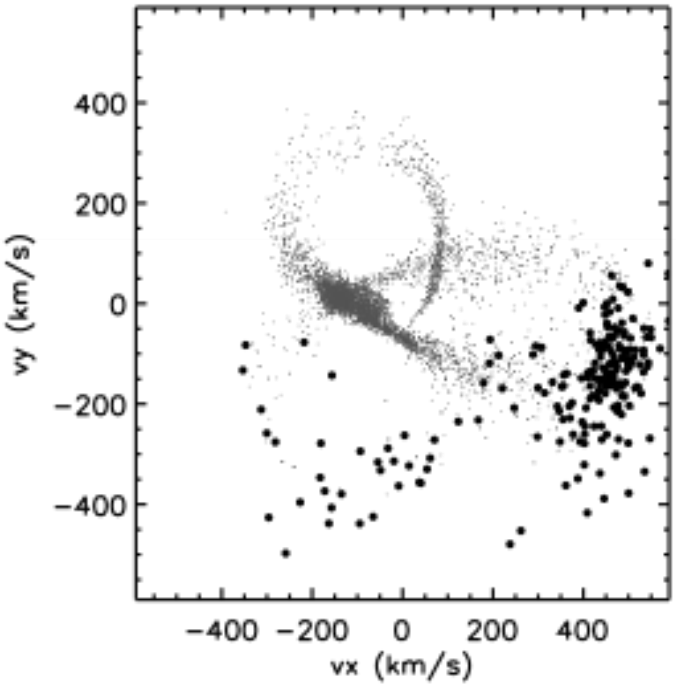
simulated debris

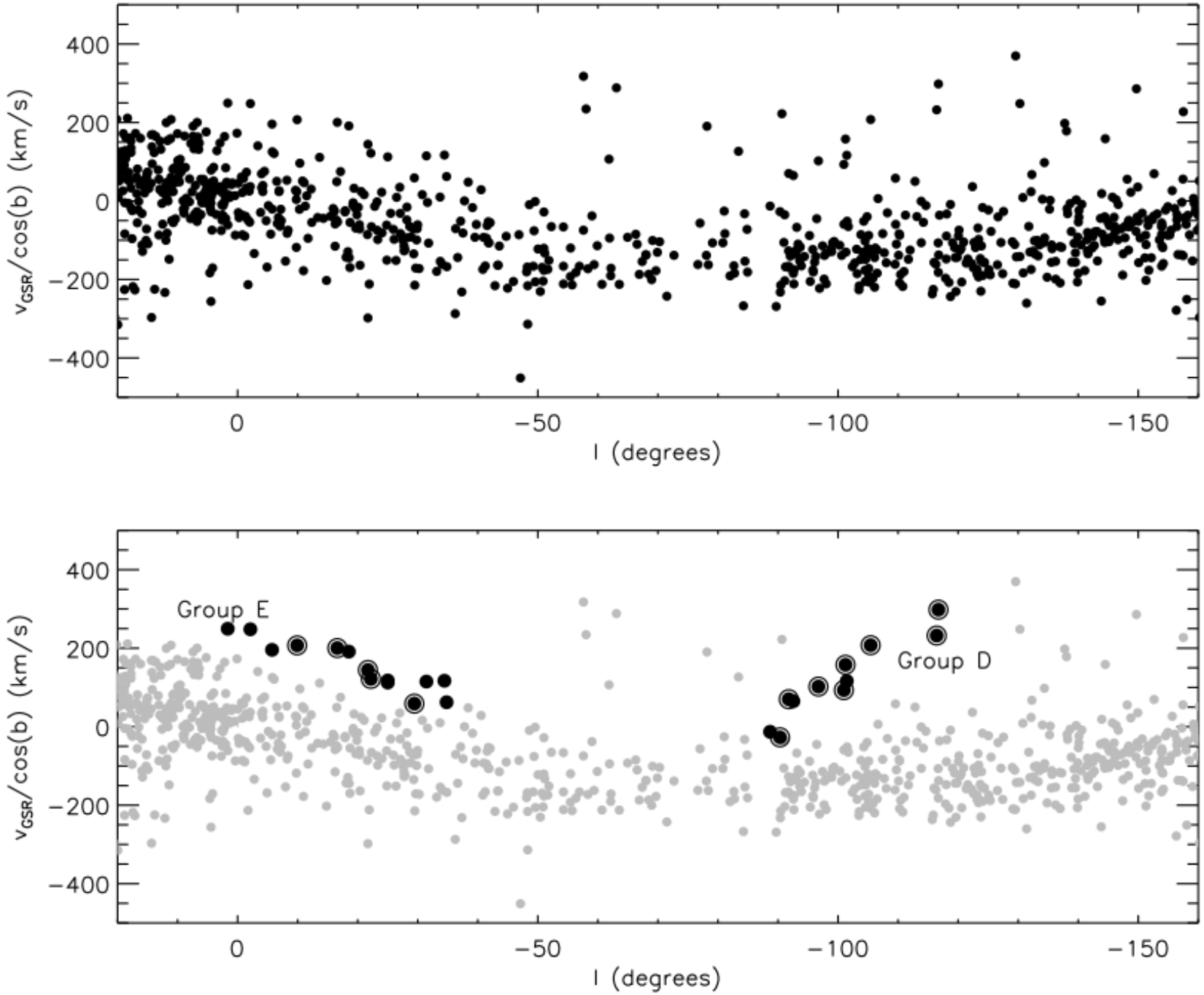


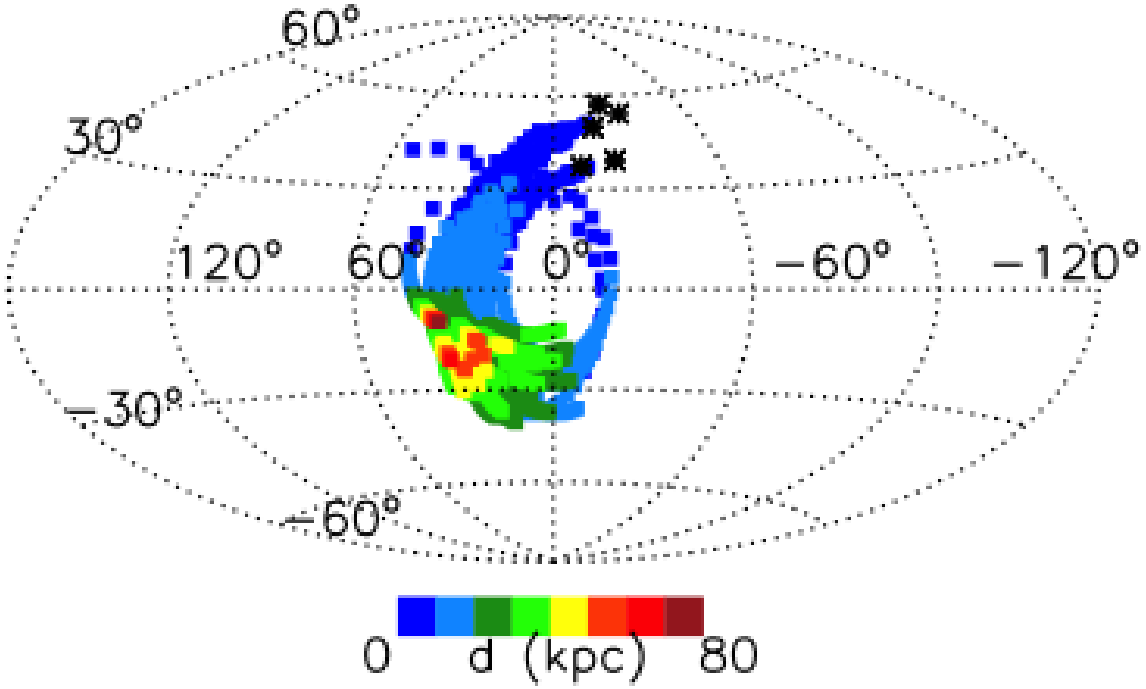


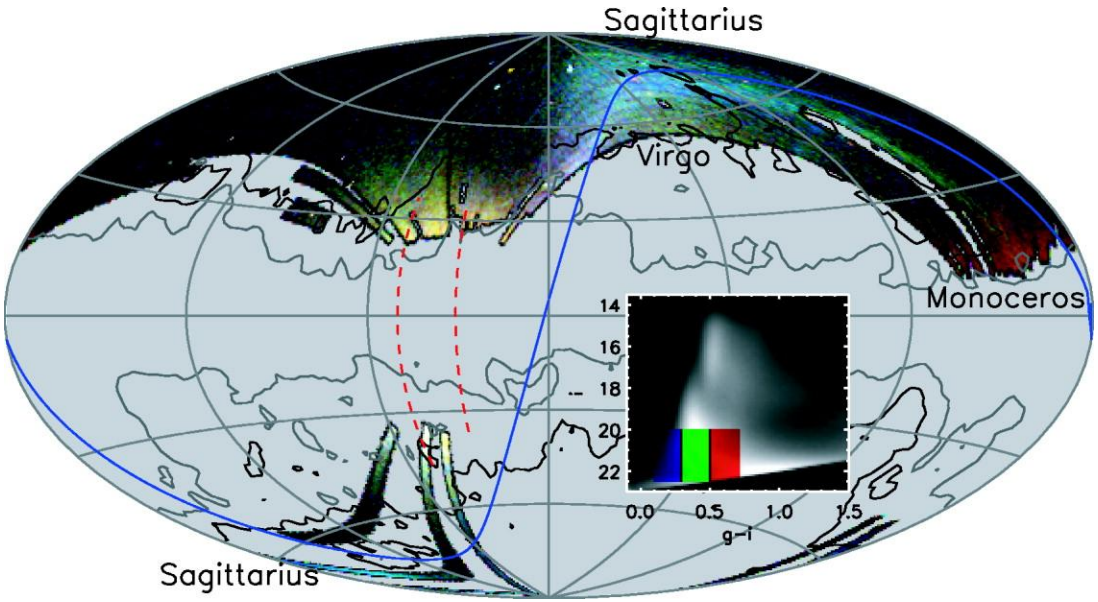
leading orbits

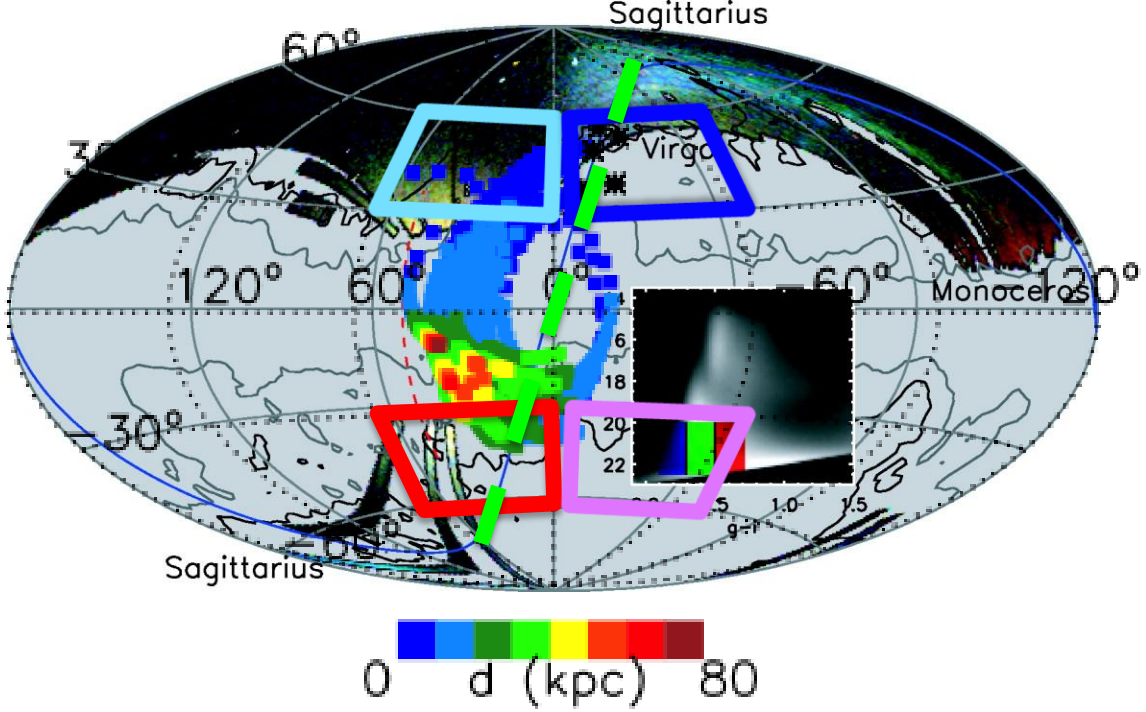


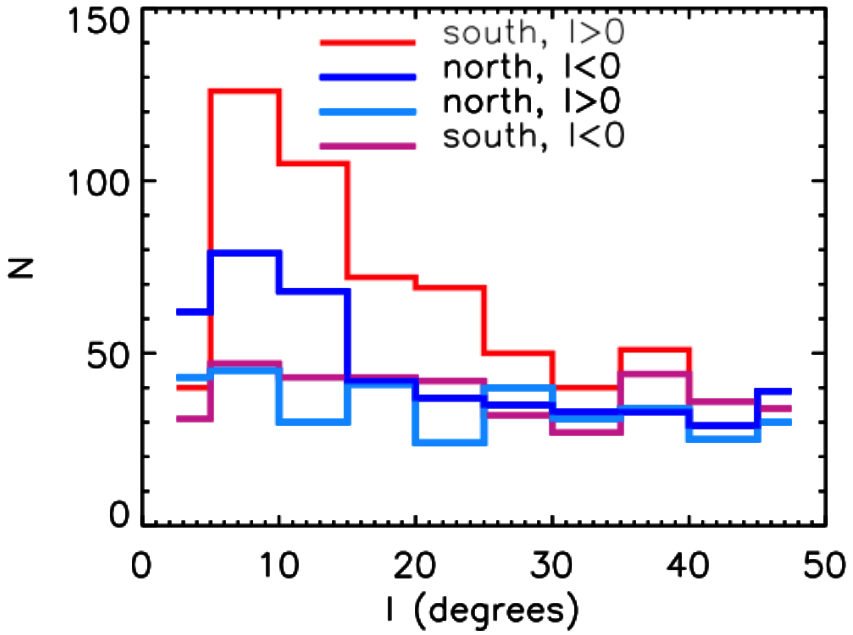



400
200
0
−200
−400
$v_{GSR}/\cos(b)$ (km/s)
0
−50
−100
−150
l (degrees)
Group E
Group D

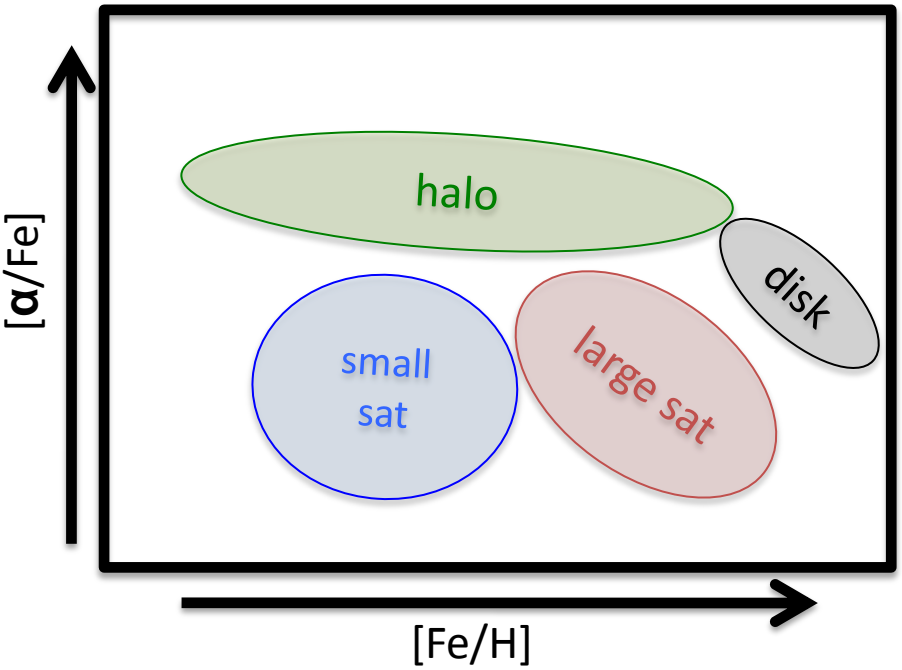

60°
30°
120°
60°
0°
−60°
−120°
−30°
−60°
0
d (kpc)
80

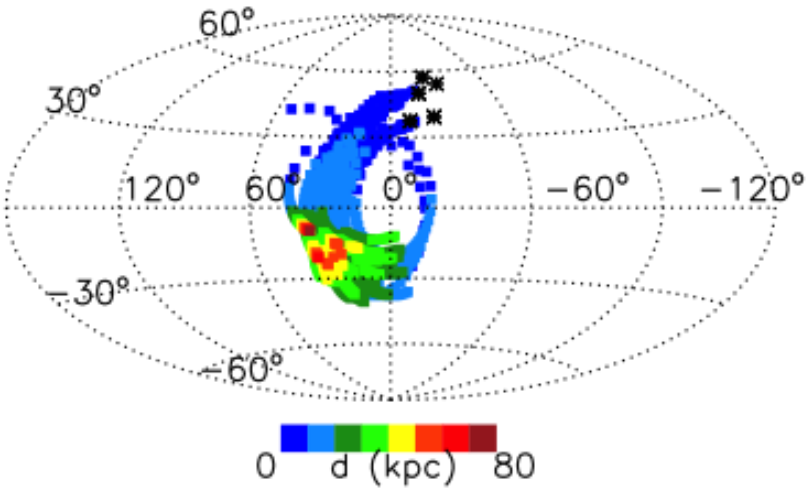

Sagittarius
Virgo
Monoceros
Sagittarius
14
16
18
20
22
0.0
0.5
1.0
1.5
g−i


Sagittarius
60°
Virgo
120°
60°
0°
60°
120°
Monoceros
30°
6
18
20
22
.5
1.0
1.5
Sagittarius
0
d (kpc)
80


150
100
50
0
N
south, l>0
north, l<0
north, l>0
south, l<0
0
10
20
30
40
50
l (degrees)

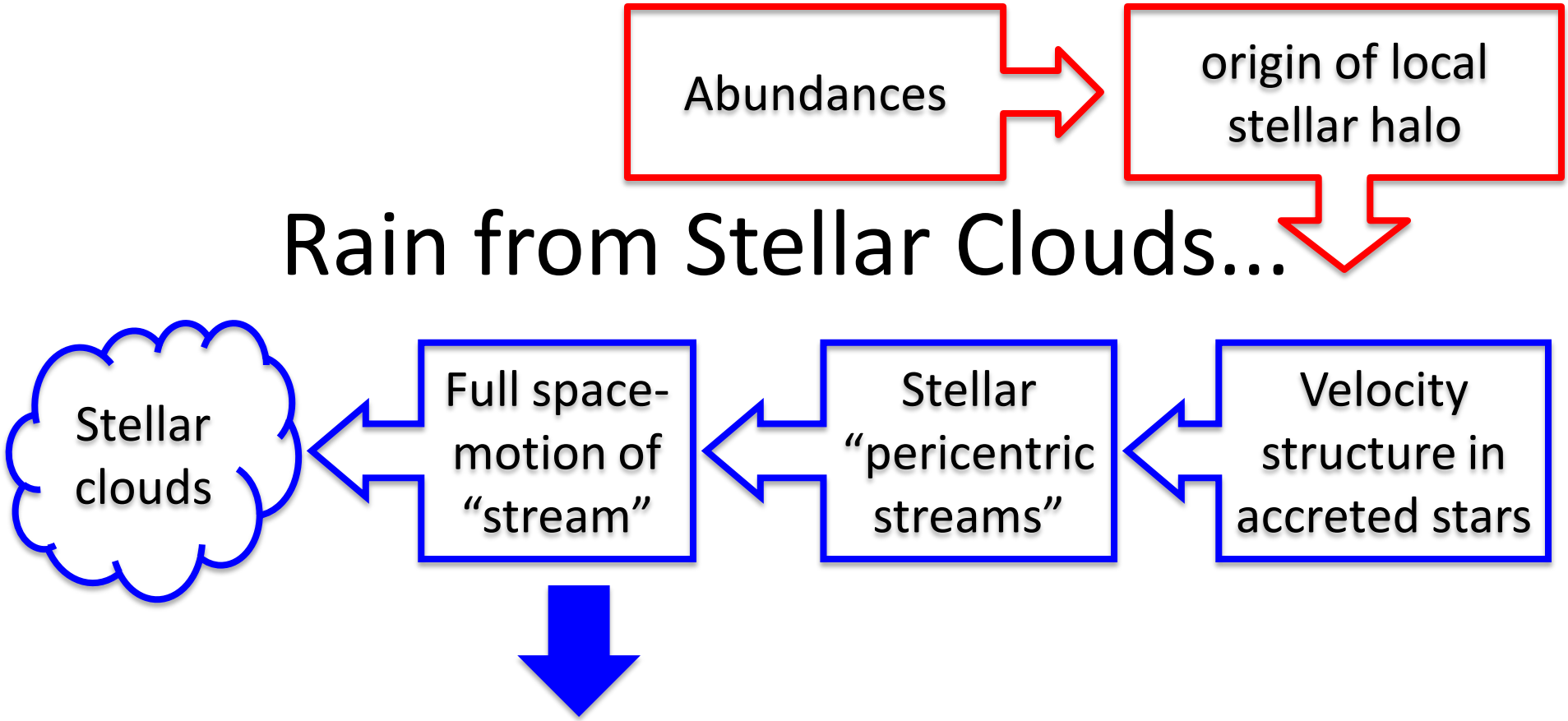
Summary





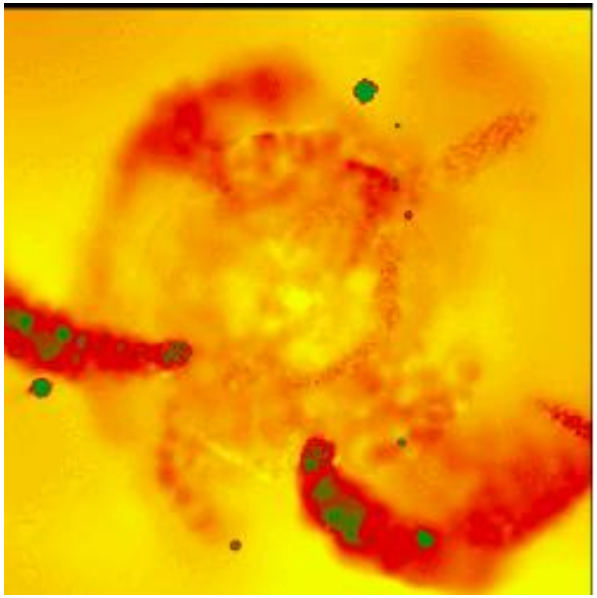
- Statistical chemical tagging:
  - Powerful for recovering accretion history
  - Suggests multiple origins for local stellar halo
- Local velocity structure in M-giants?
  - Reconstruct full space motion (with large errors)
  - Indicative of dark matter "debris flows"
  - Connect to clouds
  - Extended view of HerAq

Reading the Elements....

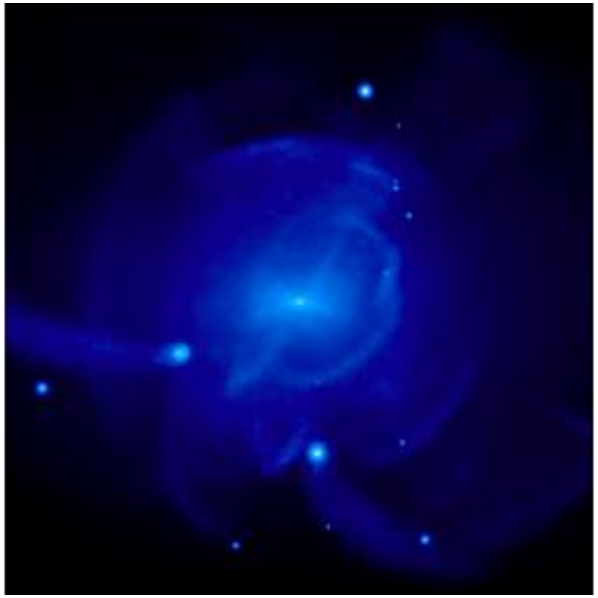


Forecasts for Direct Dark Matter Detection Experiments...

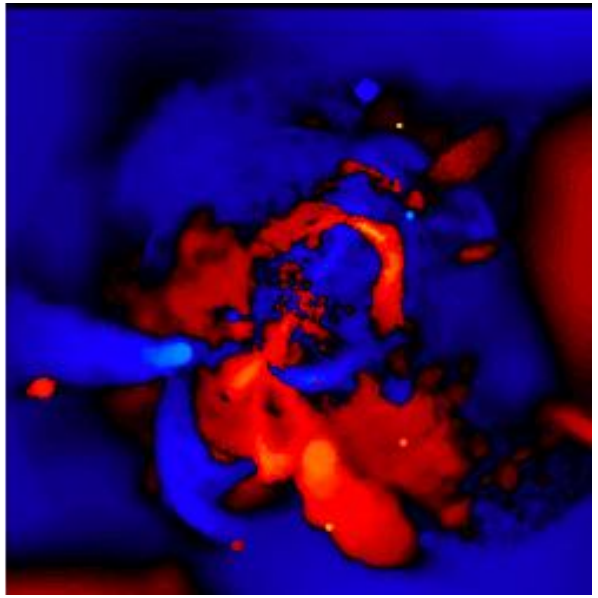
Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.



[alpha/Fe]



surface brightness



line-of-sight speed

STARS remember what GAS forgets!

phase-space structure ⇔ halo in which born

chemical abundances ⇔ birth-cloud and prior processing

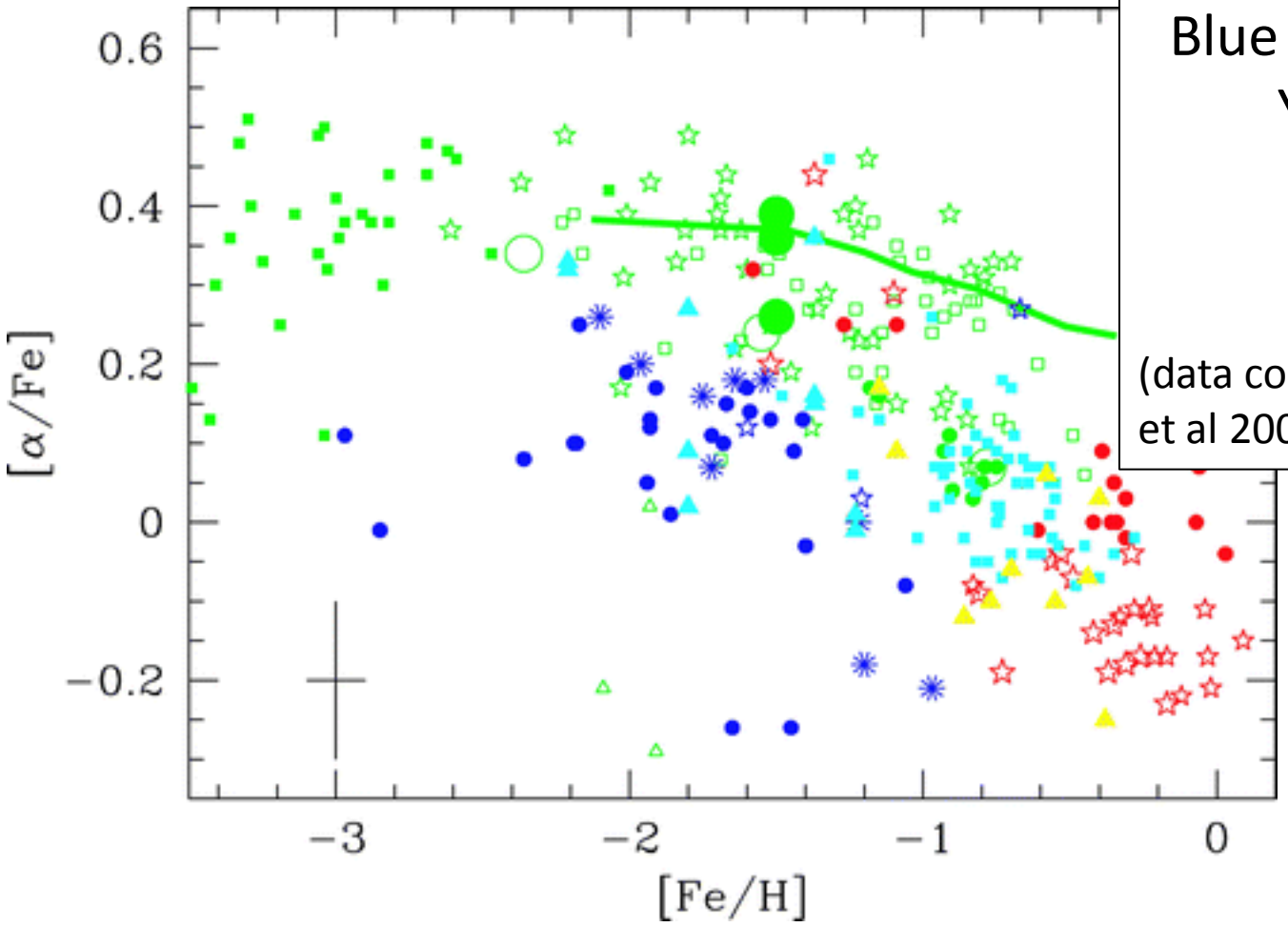
tags of origin

Freeman & Bland-Hawthorn (2002)

tracers of baryonic physics

e.g. α-elements ⇔ chemical tags

i.e. [α/Fe] *vs* [Fe/H] ⇔ birthcloud



Green - halo
Blue - low mass dSph
Yellow - dIrr
Red - Sgr
Cyan - LMC

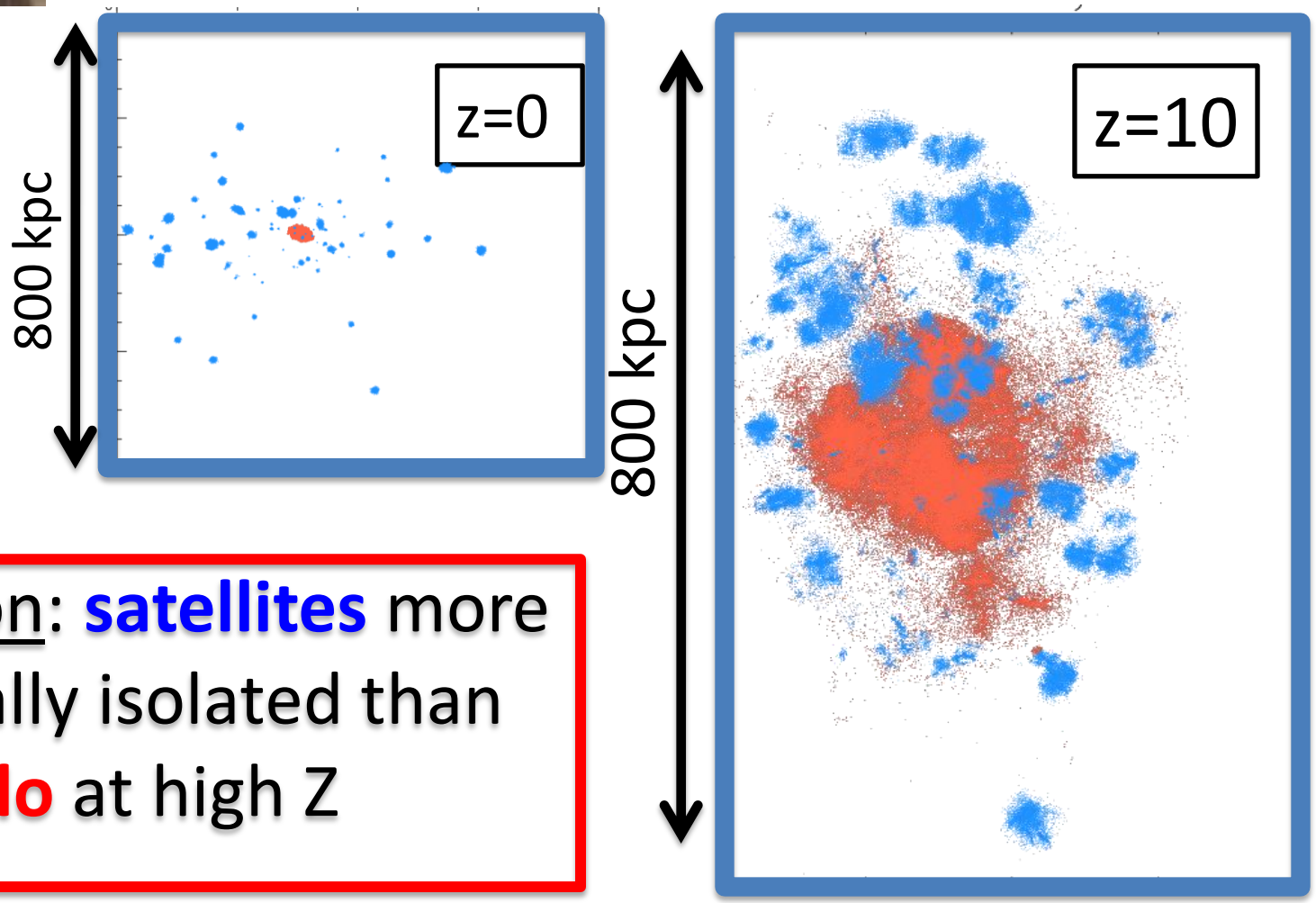
(data compilation from Geisler et al 2007)

Why?

e.g. progenitors of **satellites** *vs* **halo**?

(Lauren Corlies, Johnston, Tumlinson & Bryan, 2012*)*

Cosmological N-body simulations Tumlinson (2010)



Conclusion: **satellites** more chemically isolated than **halo** at high Z

WHY?

- Because it’s neat!
- Clouds poorly mapped/studied
- Disruptions on eccentric orbits ⇔ missing piece of accretion history
- New probes of potential over wide range of radii
- Connections validate existence of pericentric stellar flow ⇔ map dark matter debris flows?