Mass Assembly & Metal Enrichment in Galaxies

Brad Gibson

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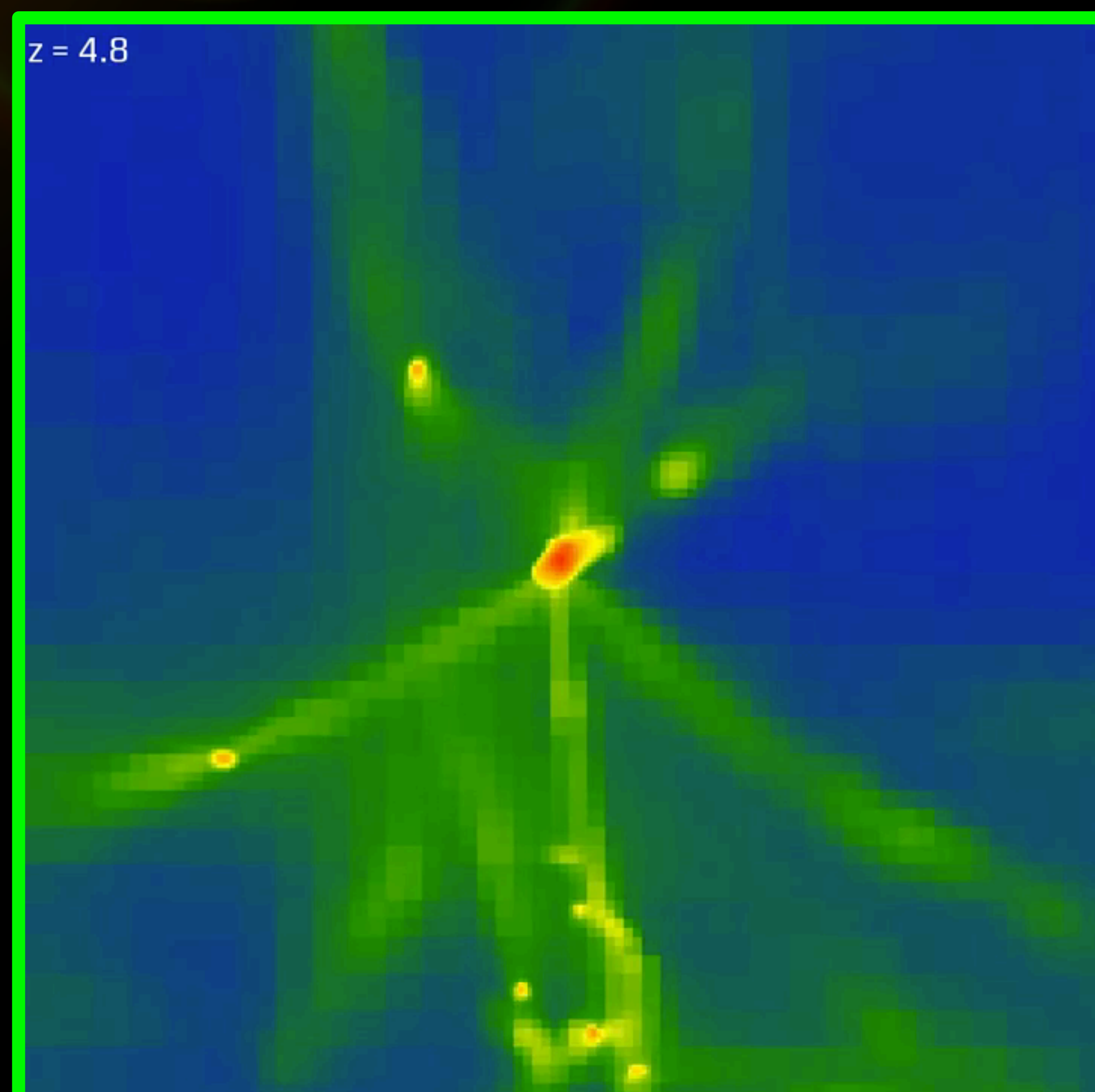
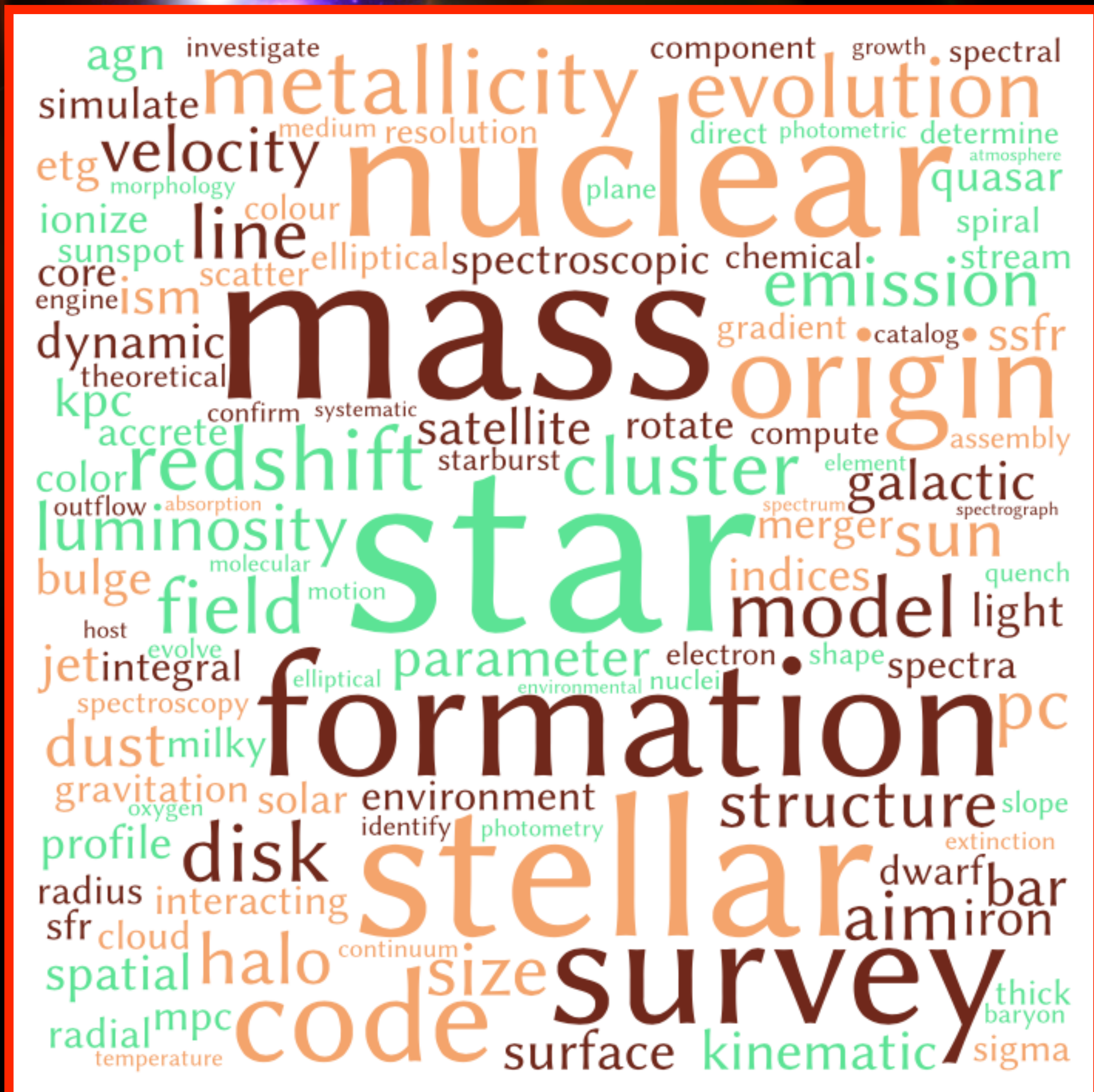


What to talk about… ?



- spectroscopy (1225) > photometry (399)
- emission (575) > absorption (113)
- kpc (360) > Mpc (115) > pc (109) > a.u. (5) > Gpc (3)
- IMF (84) + “dust” (592) + sunspots (226)

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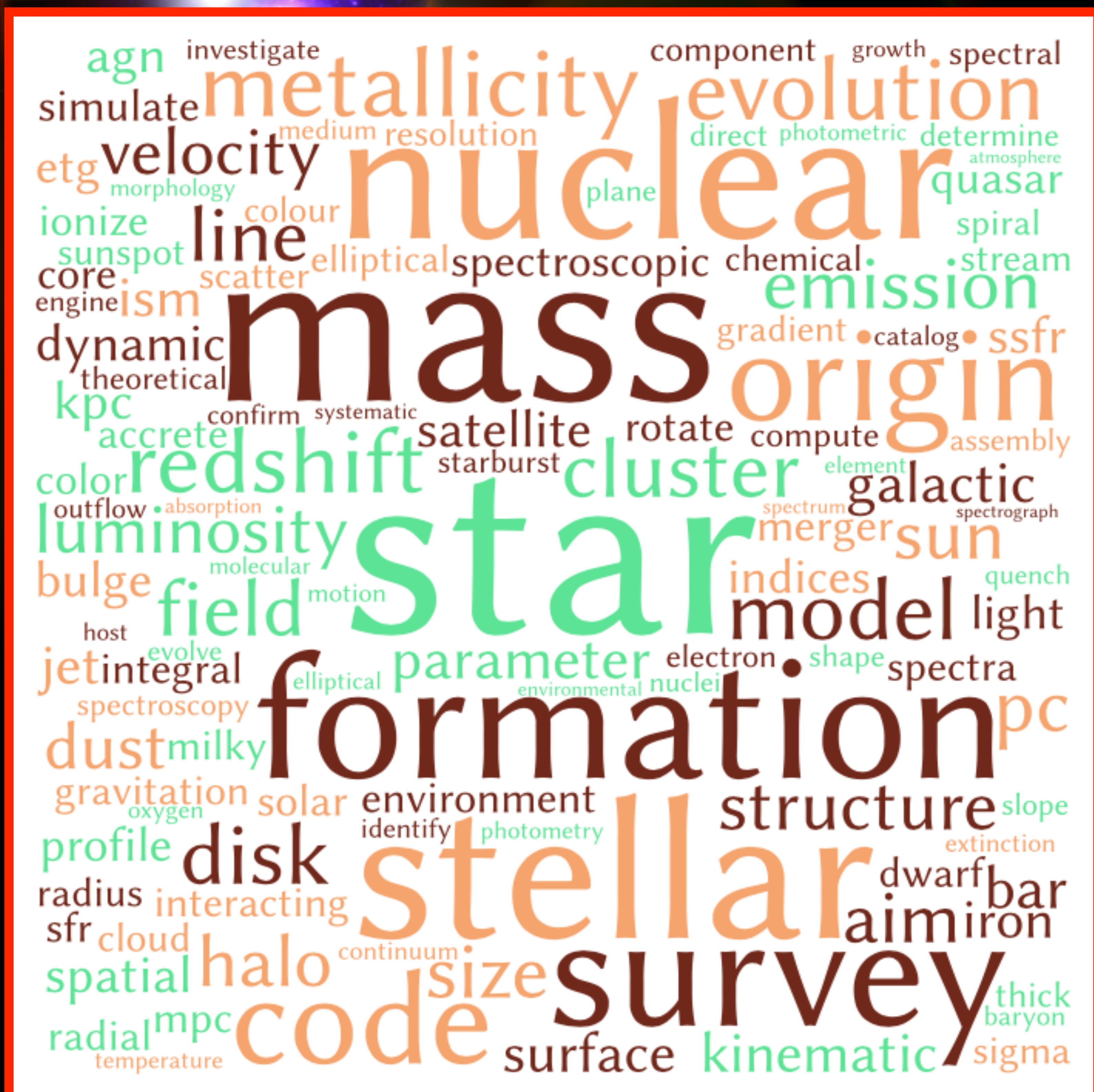

- outflows (110) > infall (25)
- "disks" (1004) > halos (561) > "ellipticals" (325) > ISM (277) > bulges (210) > bars (138)
- "mass" (2030) > "metals" (1299) > "kinematics" (879) > "luminosity" (505) > "colour" (330)
- "yields" (9)

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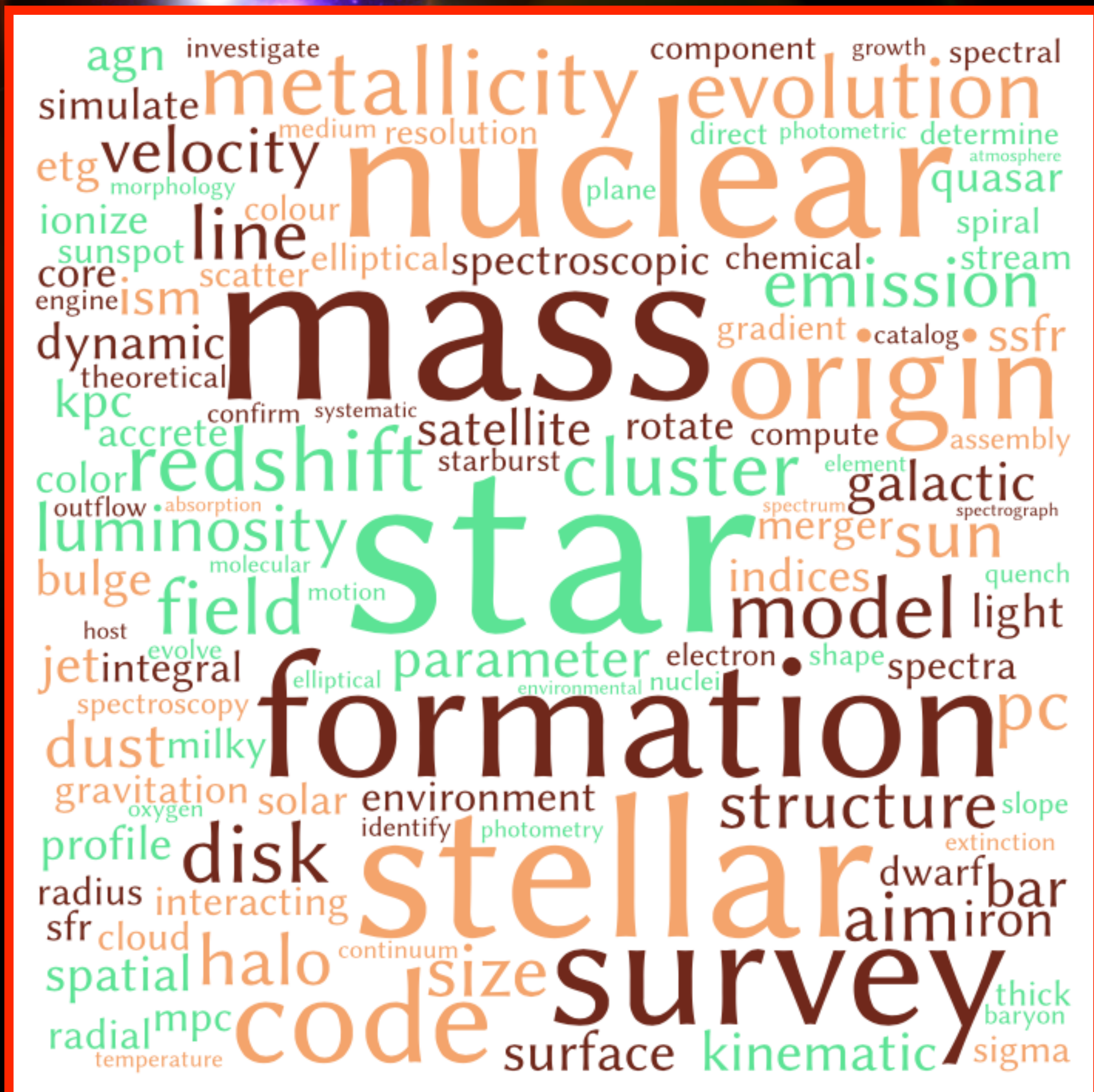

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Metal (Re-)Assembly in Disk Galaxies

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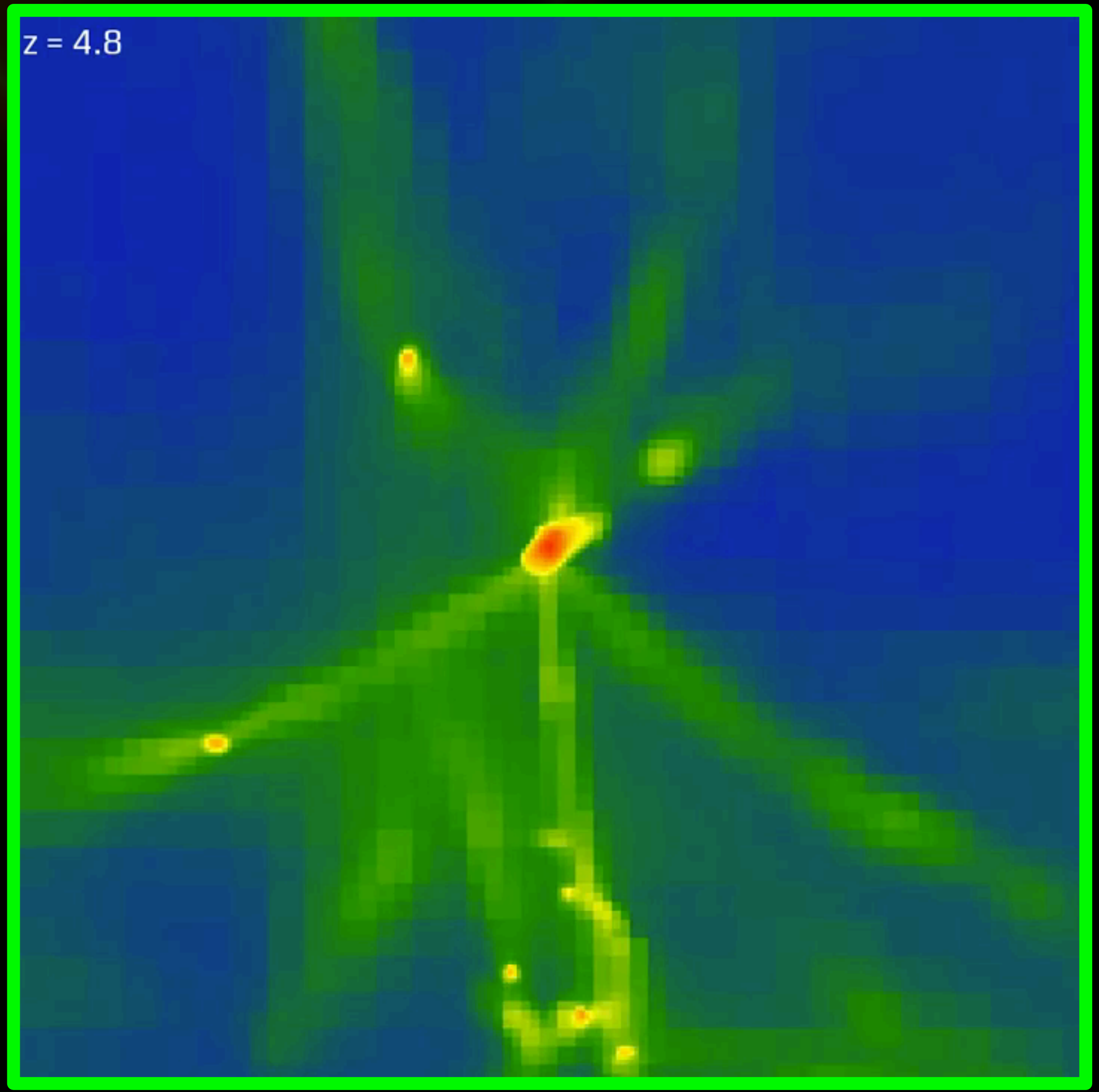
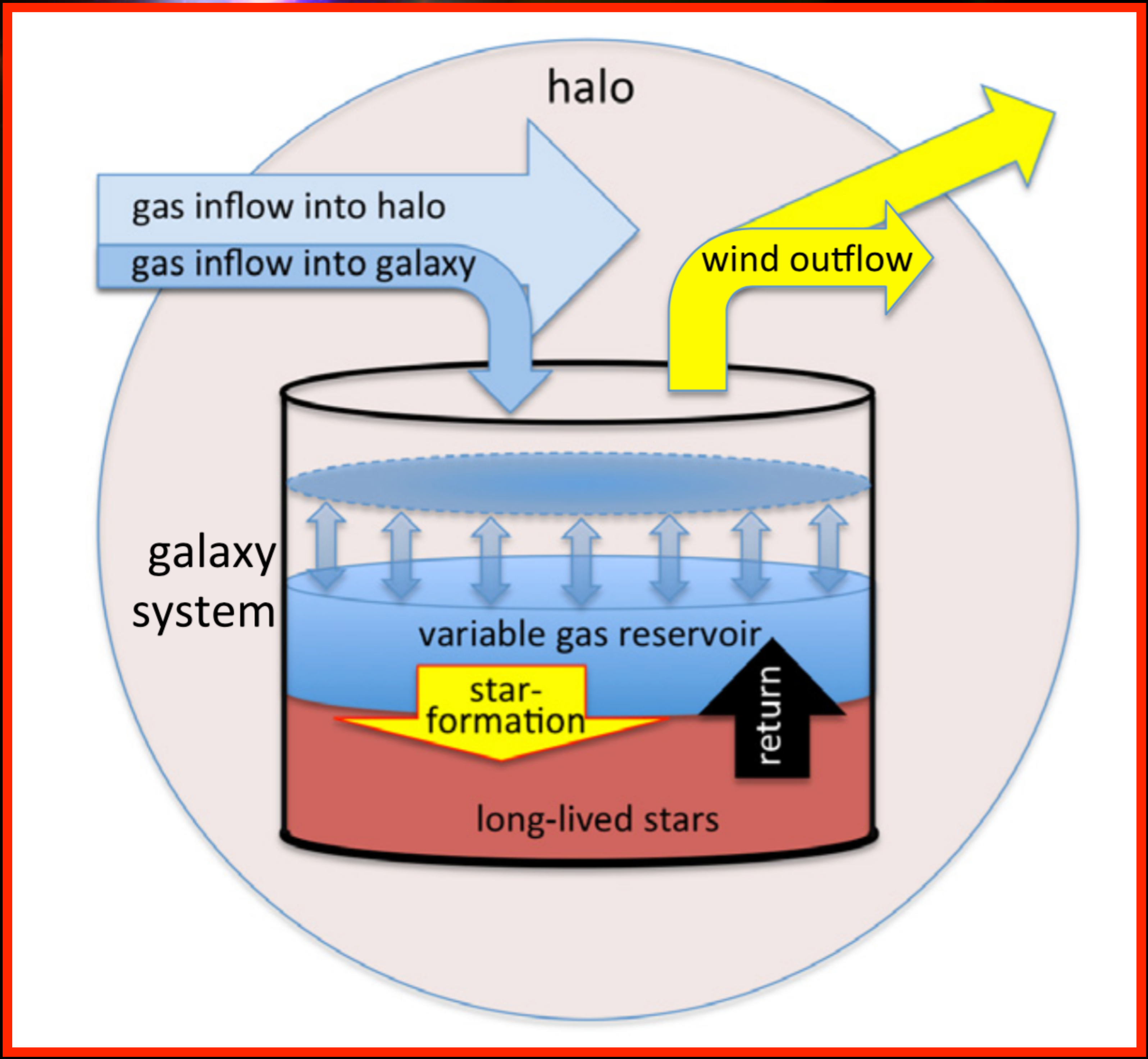


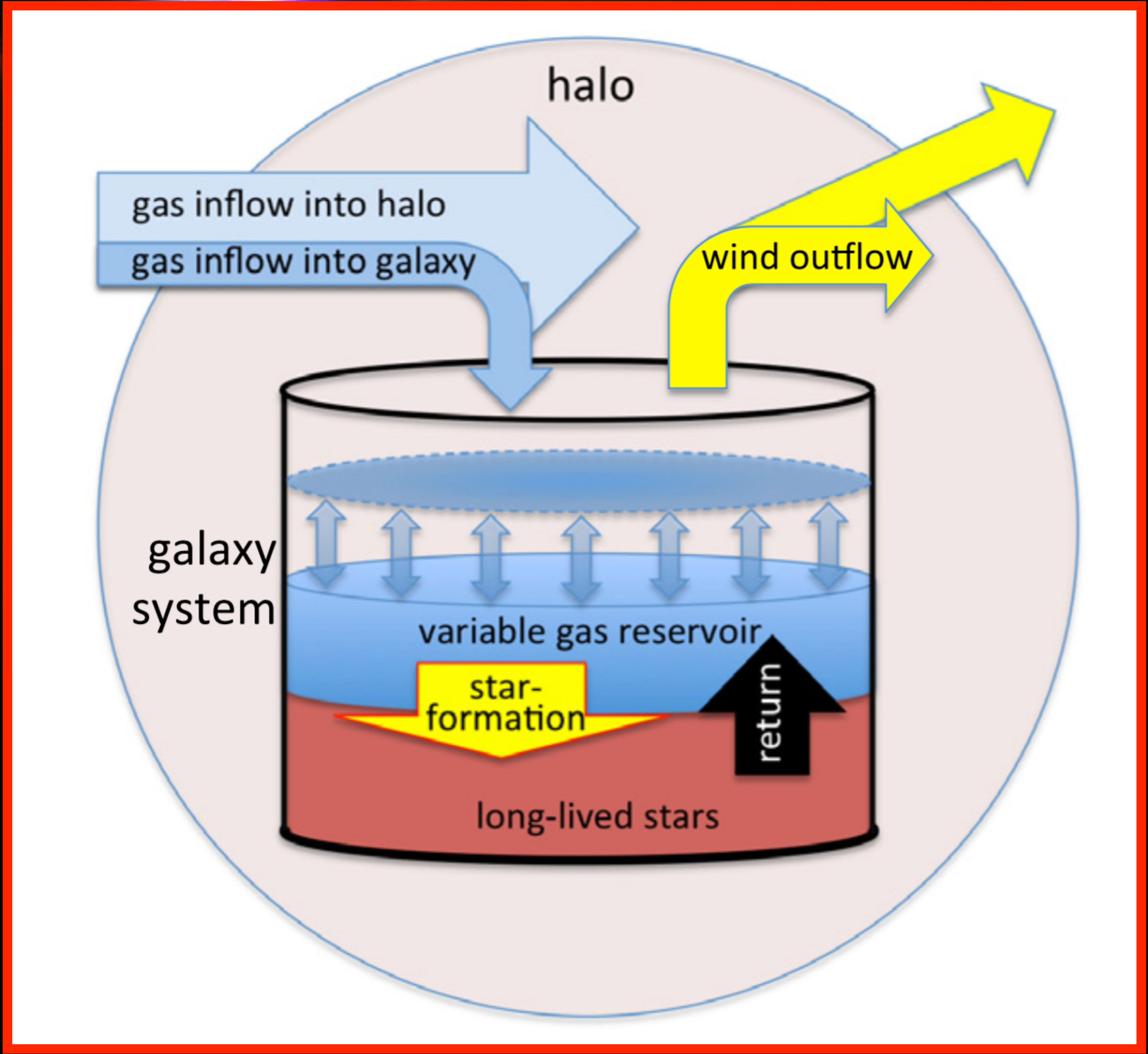
The Baryon Cycle of Galaxies



Lilly et al (2013)

- mass assembly and merger histories covered (and will be covered) by others better than I
- I want to review the "metal assembly" associated with this "mass assembly", for each component of the baryon cycle

The Baryon Cycle of Galaxies



Lilly et al (2013)

- metal assembly in galaxies is not simply the “external” assembly one might associate with the phrase, but also includes “internal” assembly (or re-assembly)
- “external” = infall, outflow, IGM, ICM, etc.
- “internal” = radial gas flows, stellar migration, abundance gradients, etc.

Outline...

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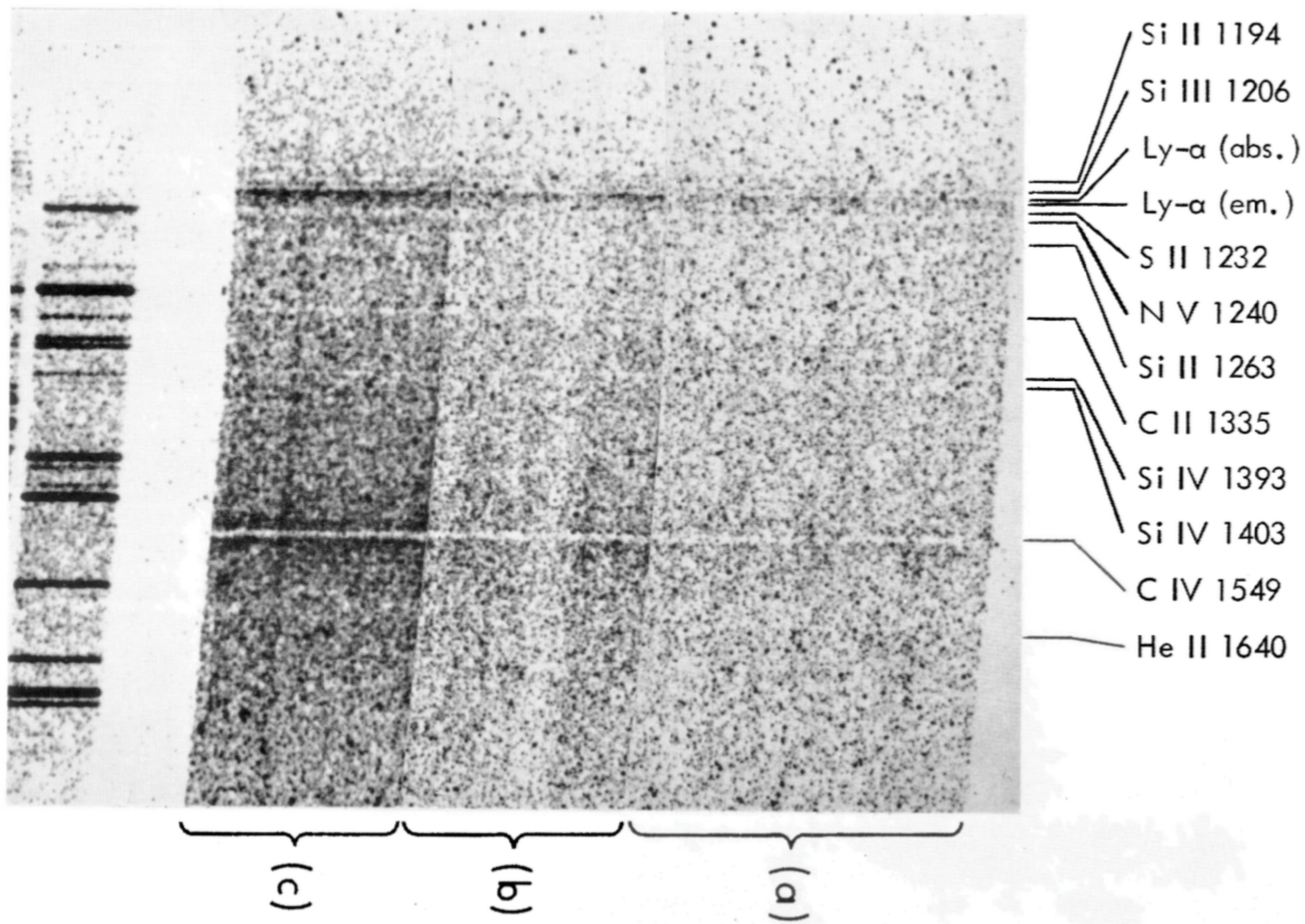
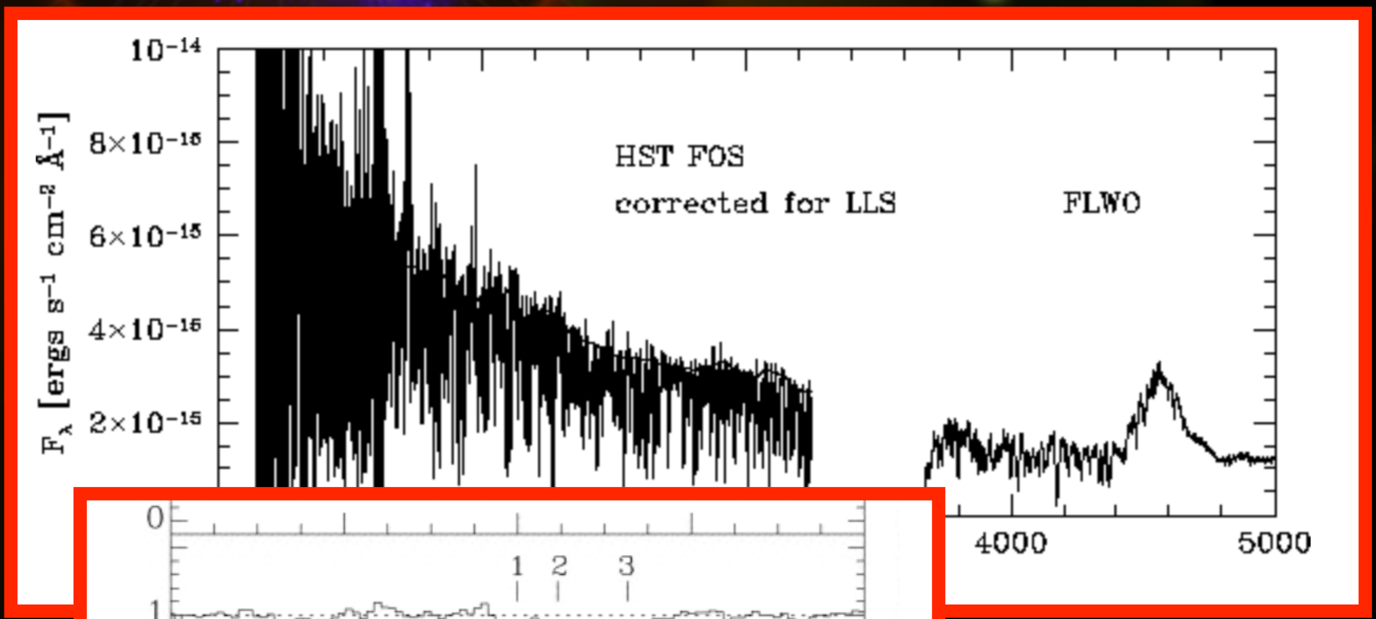
Metals in the IGM:
Known Since 1966 (e.g. 3C 191 at z=2.0)

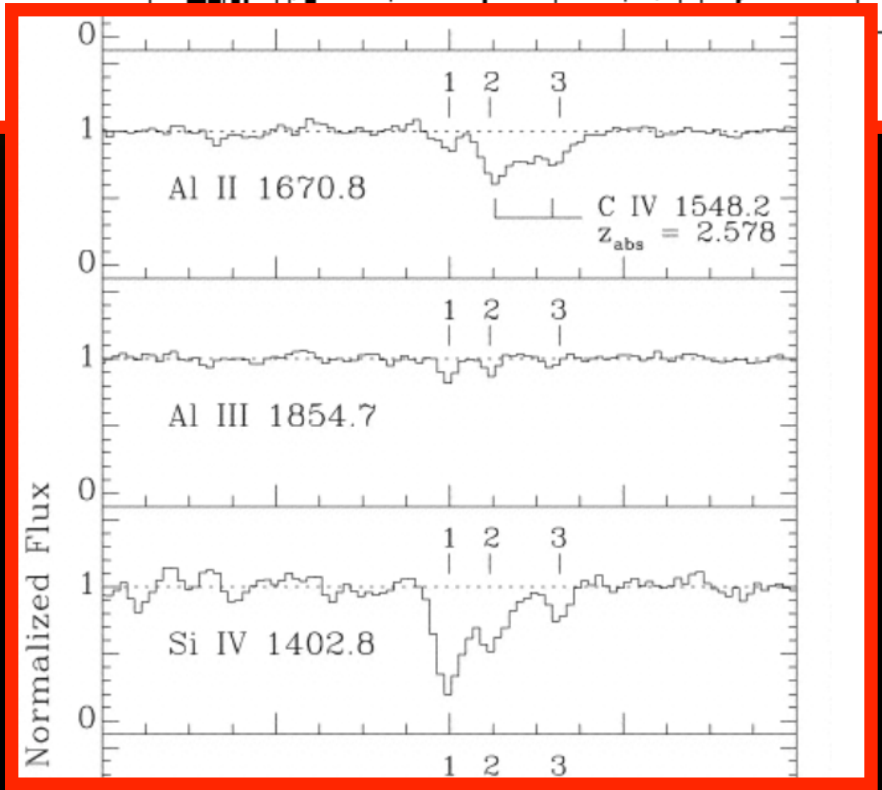


Burbidge, Lynds & Burbidge (1966)

Ultimate Fuel Reservoir: The IGM
… diffuse and dense IGM both harbour metals out to measurable 'd' and appears α-enhanced

Reimers et al (1992): [O/C] ~ +0.3 at z=2.7

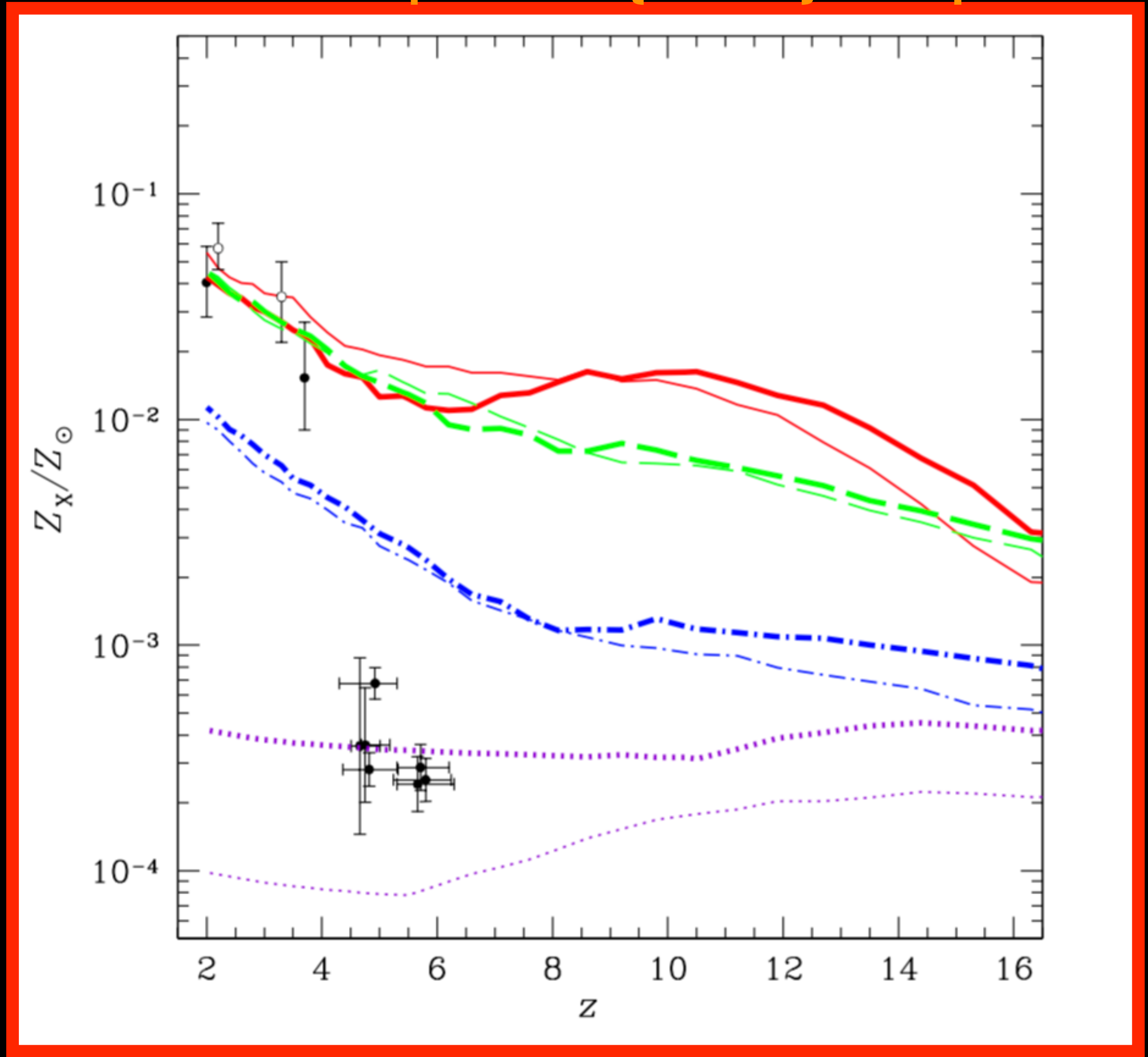




Tripp et al (1997)

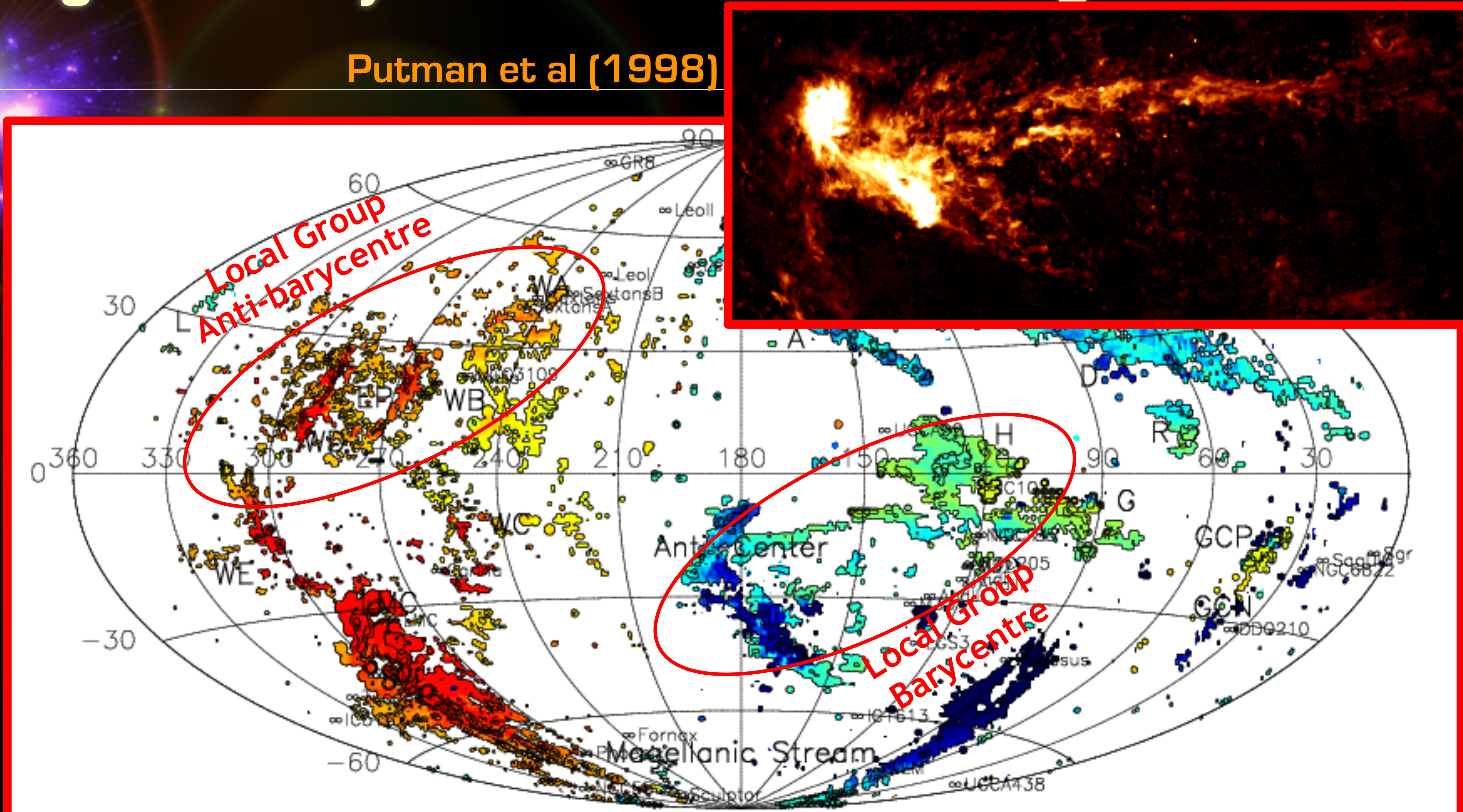
Gas Does Not Enter Halos 'Pristine'

Manrique et al (2015) Compilation



High Velocity Clouds as Local Analogs of Infall?

Putman et al (1998)



- 60% of HVC HI flux from Mag Stream (15% from Complex C)
  Mag Stream Mass: ~5×10^{8} Msun; Rest of the HVCs: ~1×10^{7} Msun
- metallicities typically ~25% solar (i.e., this is not the (unfiltered) diffuse IGM)

Talks by Putman, Fraternali

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Aside: Classical 1D Galactic Chemical Evolution

Tinsley (1980); Matteucci & Greggio (1986); etc.

$$\frac{dM_g(t)}{dt} = -\psi(t) + E(t) + A(t) - W(t)$$

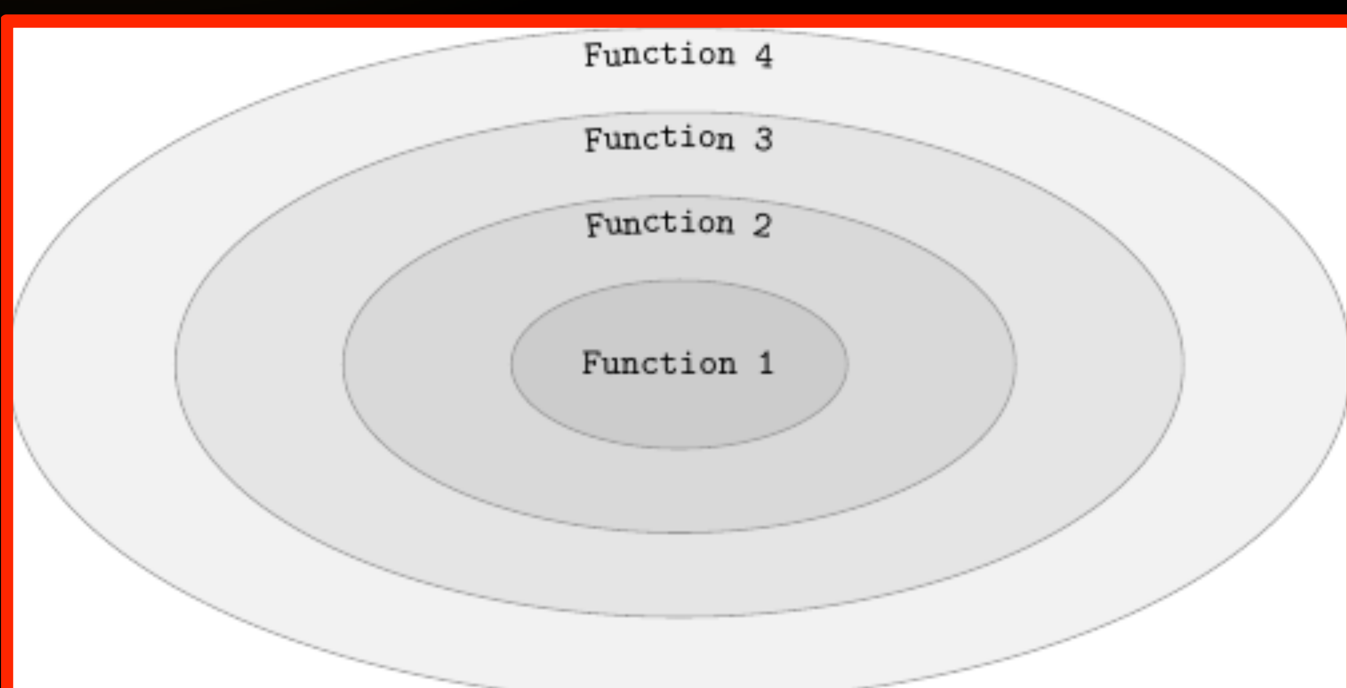
Gas accretion rate: $M_\odot$/yr

Gas outflow rate: $M_\odot$/yr

Rate of change of the gas mass: $M_\odot$/yr

Star formation rate: $M_\odot$/yr

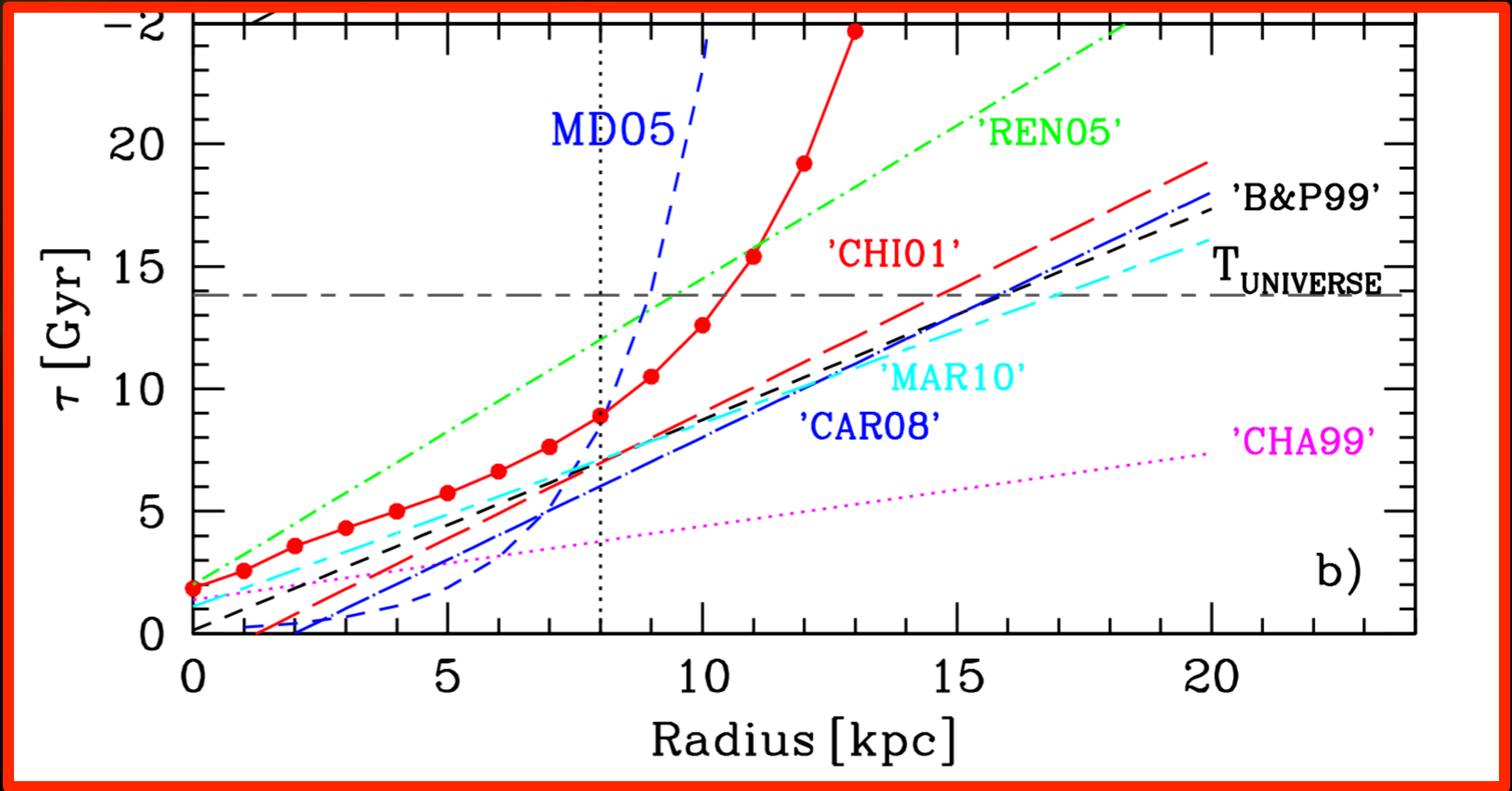
Gas returned to the ISM from dying stars: $M_\odot$/yr



- apply the above to each annulus *i* of an azimuthally-symmetric “disk”
- disk growth (“inside-out”) controlled by form of $A_i(t)$, usually represented as an exponential τ_i for each annulus *i*

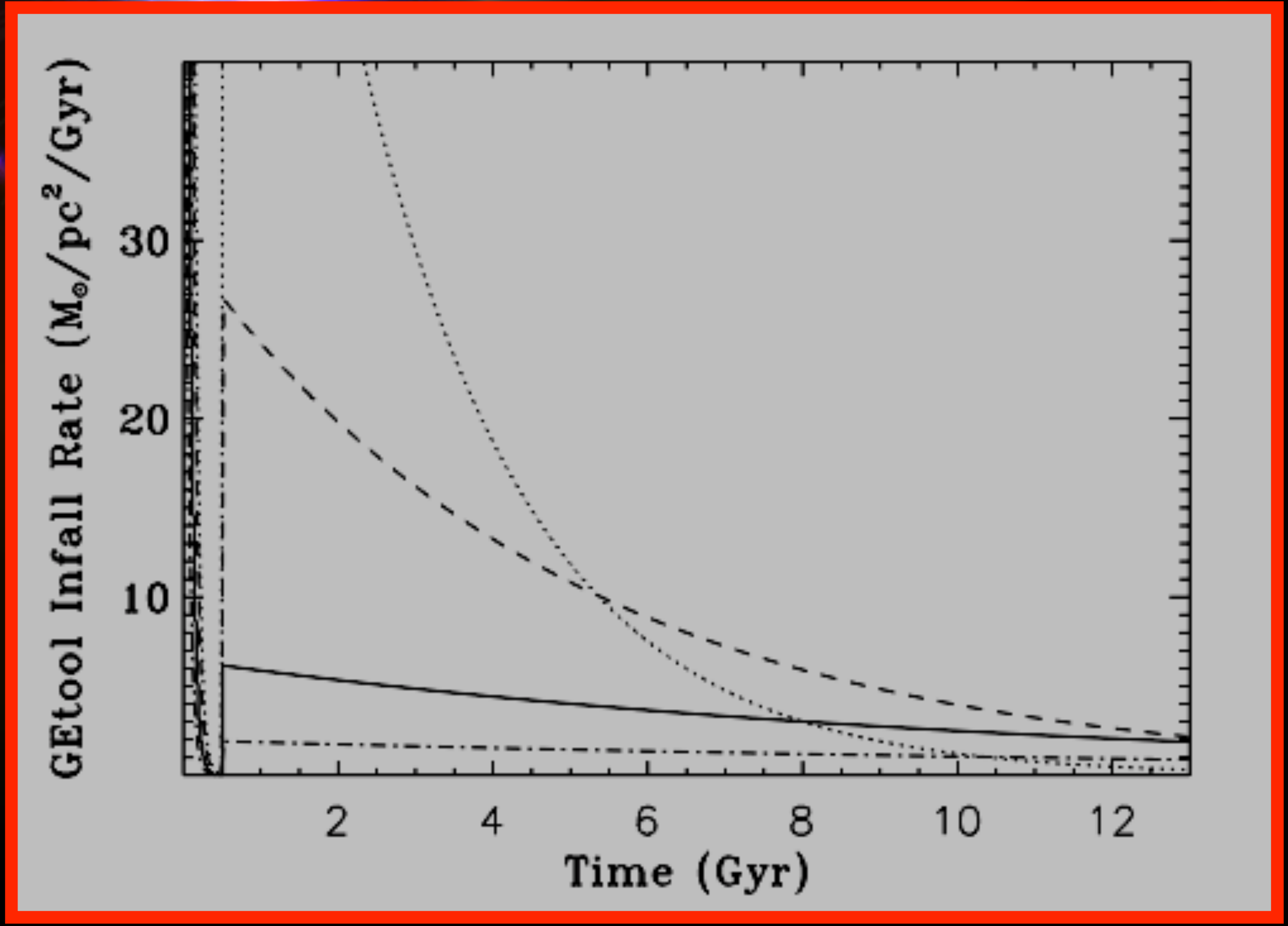
Aside: Classical 1D Galactic Chemical Evolution

Molla et al (2016,submitted)



- various functional forms adopted, but all "inside-out"
- but essentially no empirical constraints on either the rate or the direction of this infall
- from Putman's talk … for M33, infall is (more or less) 'vertical' (?)…

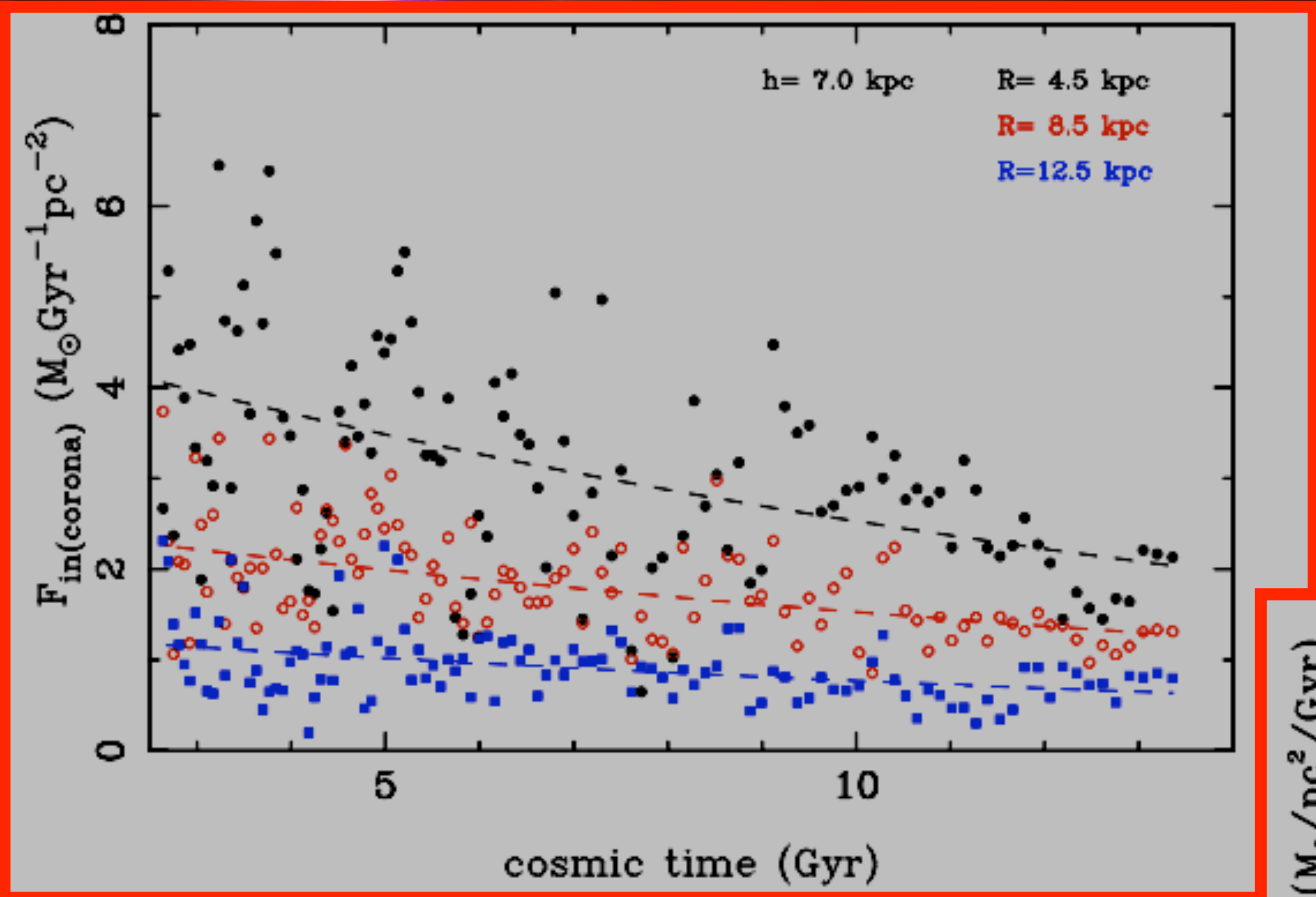
How Does Gas Get Into the Disk?



- or put into the solar mass per unit time "space"...
- again, the infall timescale is more rapid in the inner disk

How Does Gas Get Into the Disk?

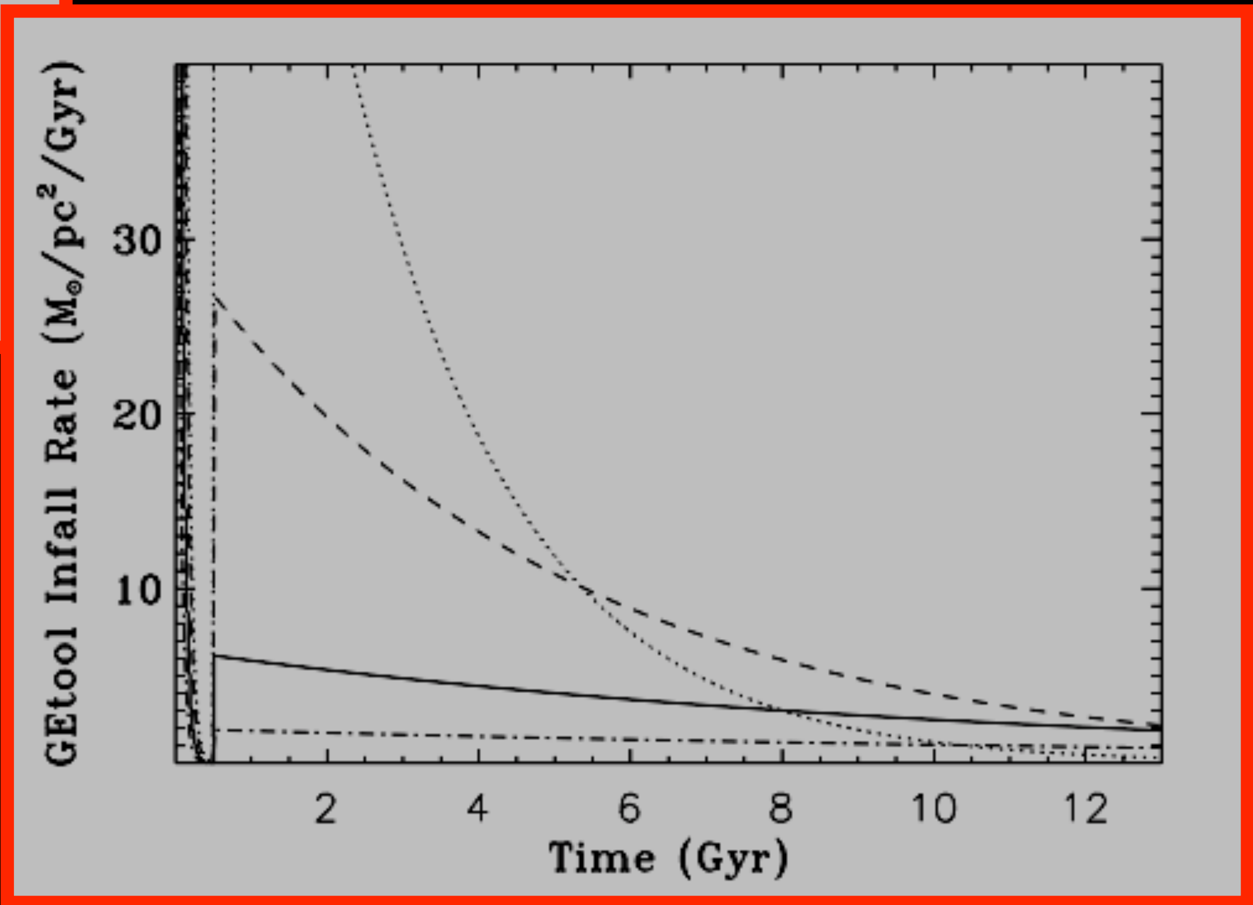
Courty et al (2010)



- inside-out formalism recovered naturally in this simulation
- gas feeding the disk today primarily orthogonal to the disk

(cf. Putman's Talk; Brook et al 2011; Kacprzak et al 2012)

- flux of gas onto the Sanchez-Blazquez et al (2009) simulated cosmological disk
- blue = stream gas
  red = coronal gas
  black= total



How Does Gas Get Into the Disk?

Brook et al (2011,MNRAS)

The Astrophysical Journal Letters, 760:L7 (5pp), 2012 November 20 doi:10.1088/2041-8205/760/1/L7

TRACING OUTFLOWS AND ACCRETION: A BIMODAL AZIMUTHAL DEPENDENCE OF Mg II ABSORPTION

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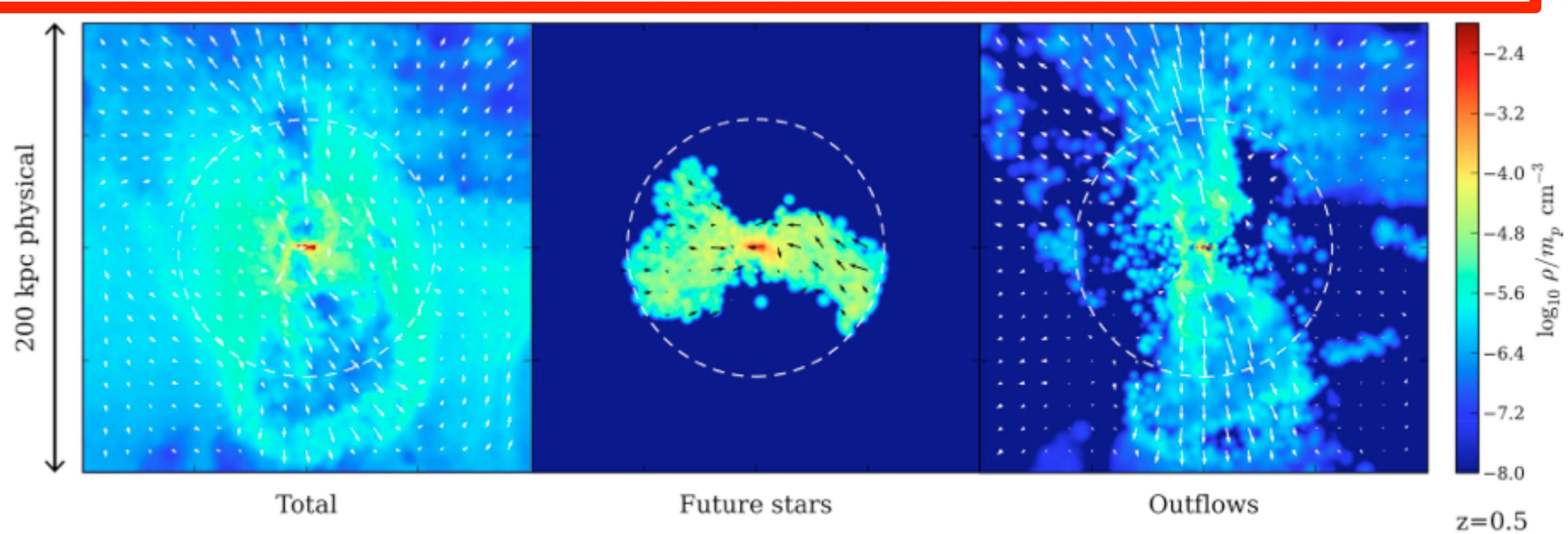
ABSTRACT

We report a bimodality in the azimuthal angle distribution of gas around galaxies as traced by Mg II absorption: halo gas prefers to exist near the projected galaxy major and minor axes. The bimodality is demonstrated by computing the mean azimuthal angle probability distribution function using 88 spectroscopically confirmed Mg II-absorption-selected galaxies [$W_r(2796) \geqslant 0.1$ Å] and 35 spectroscopically confirmed non-absorbing galaxies [$W_r(2796) < 0.1$ Å] imaged with *Hubble Space Telescope* and Sloan Digital Sky Survey. The azimuthal angle distribution for non-absorbers is flat, indicating no azimuthal preference for gas characterized by $W_r(2796) < 0.1$ Å. We find that blue star-forming galaxies clearly drive the bimodality while red passive galaxies may exhibit an excess along their major axis. These results are consistent with galaxy evolution scenarios where star-forming galaxies accrete new gas, forming new stars and producing winds, while red galaxies exist passively due to reduced gas reservoirs. We further compute an azimuthal angle dependent Mg II absorption covering fraction, which is enhanced by as much as 20%–30% along the major and minor axes. The $W_r(2796)$ distribution for gas along the major axis is likely skewed toward weaker Mg II absorption than for gas along the projected minor axis. These combined results are highly suggestive that the bimodality is driven by gas accreted along the galaxy major axis and outflowing along the galaxy minor axis. Adopting these assumptions, we find that the opening angle of outflows and inflows to be



- ‘planar’ infall coupled with ‘polar’ outflows consistent with empirical work on azimuthal MgII absorption dependence (Bordoloi et al 2011; Kacprzak et al 2012)

- new kinematics and metallicity maps for these absorbers provide new tests (Kacprzak et al 2015) ... see Glenn’s poster (#33)

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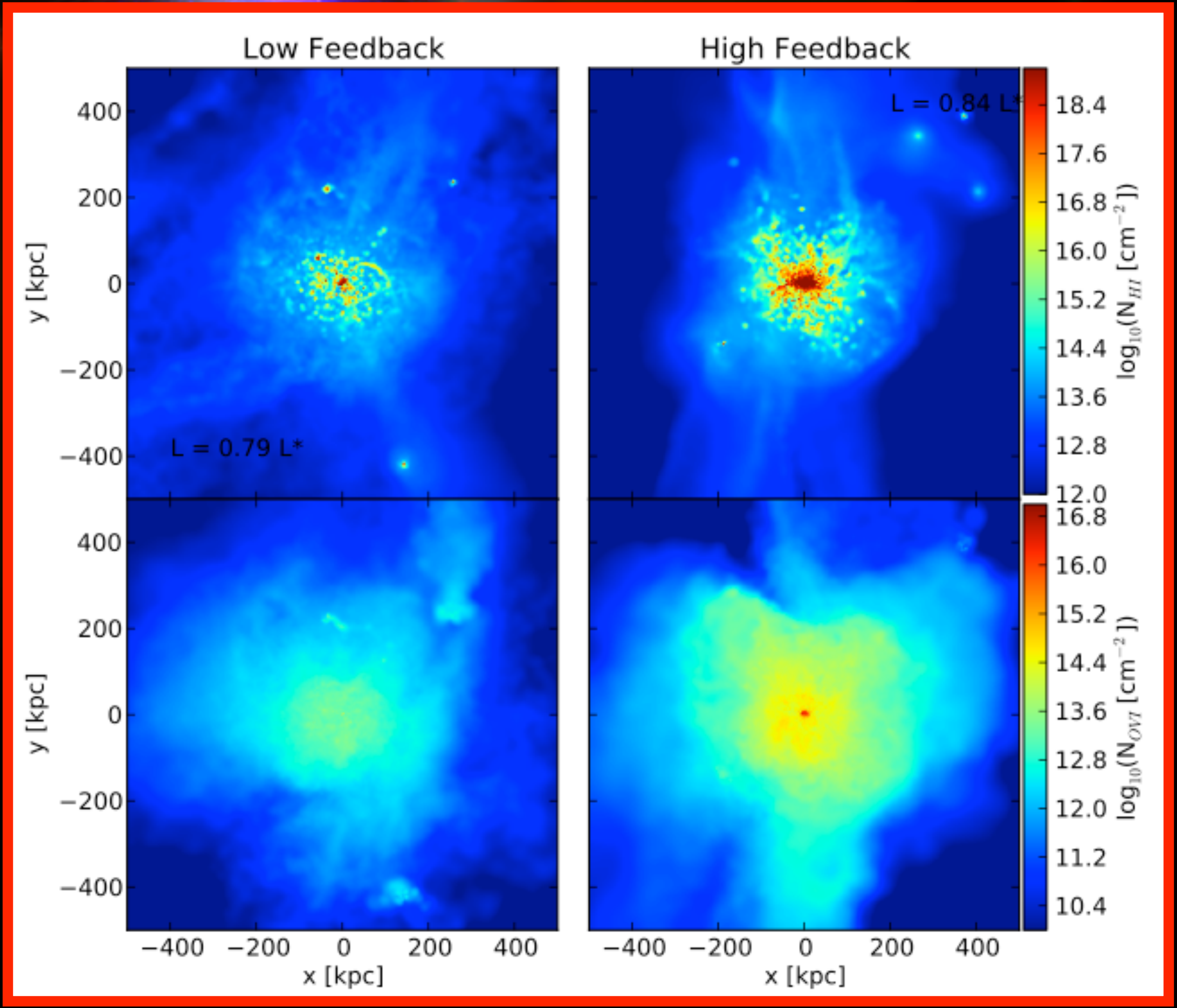
What Do Outflows Do to This Fuel?... Depends on Feedback Prescription

Stinson et al 2012)



- strong feedback results in a metal-enriched circum-galactic medium which extends to the virial radius
- a significant portion of the CGM is shock-heated to 0.3MK, giving rise to substantial OVI absorption
- models predict large reservoir of cool HI clouds that should show strong Ly-alpha absorption to several hundred kpcs

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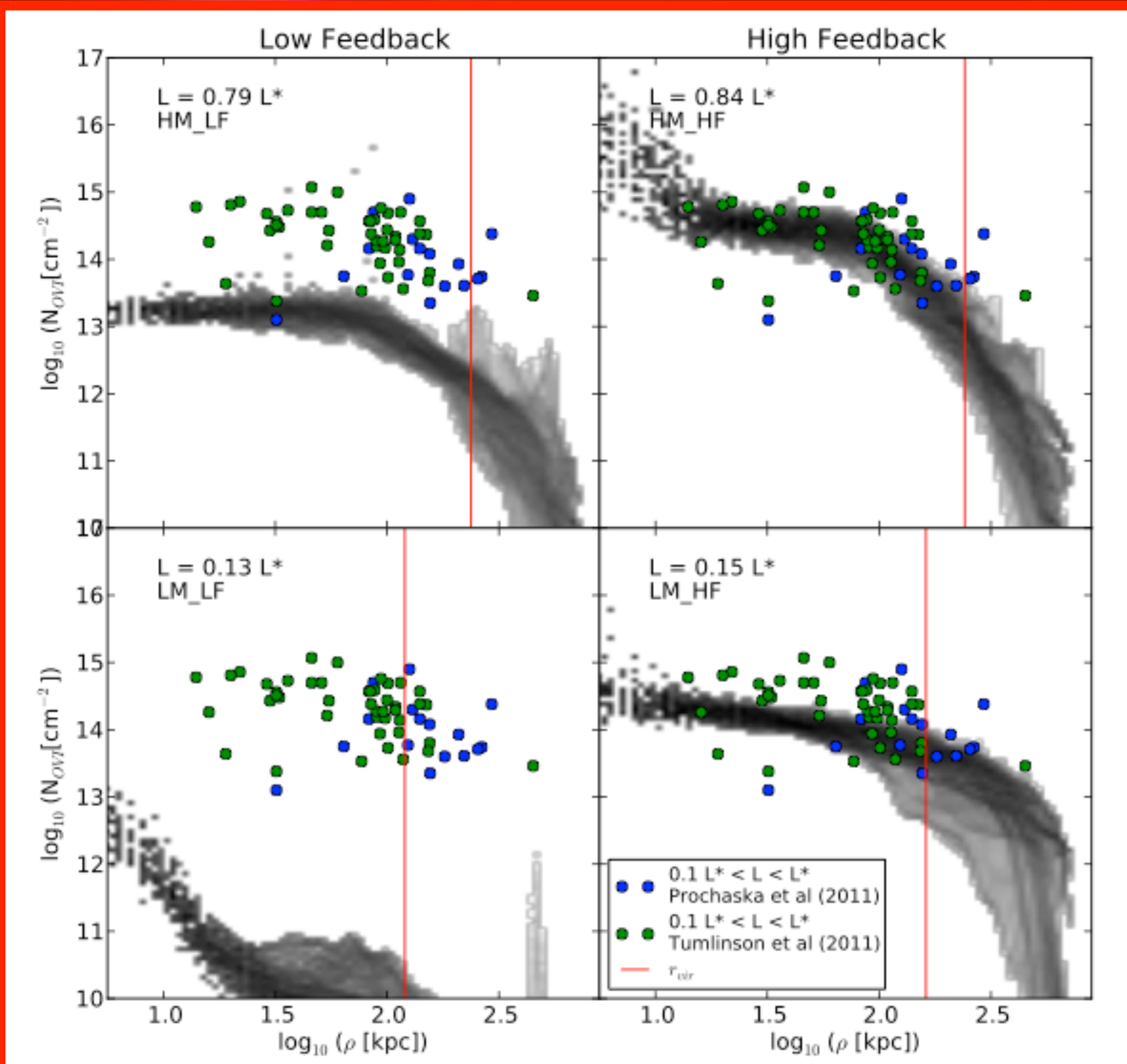

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- only high-feedback models have sufficient OVI and HI to reproduce observations (Prochaska et al 2011)

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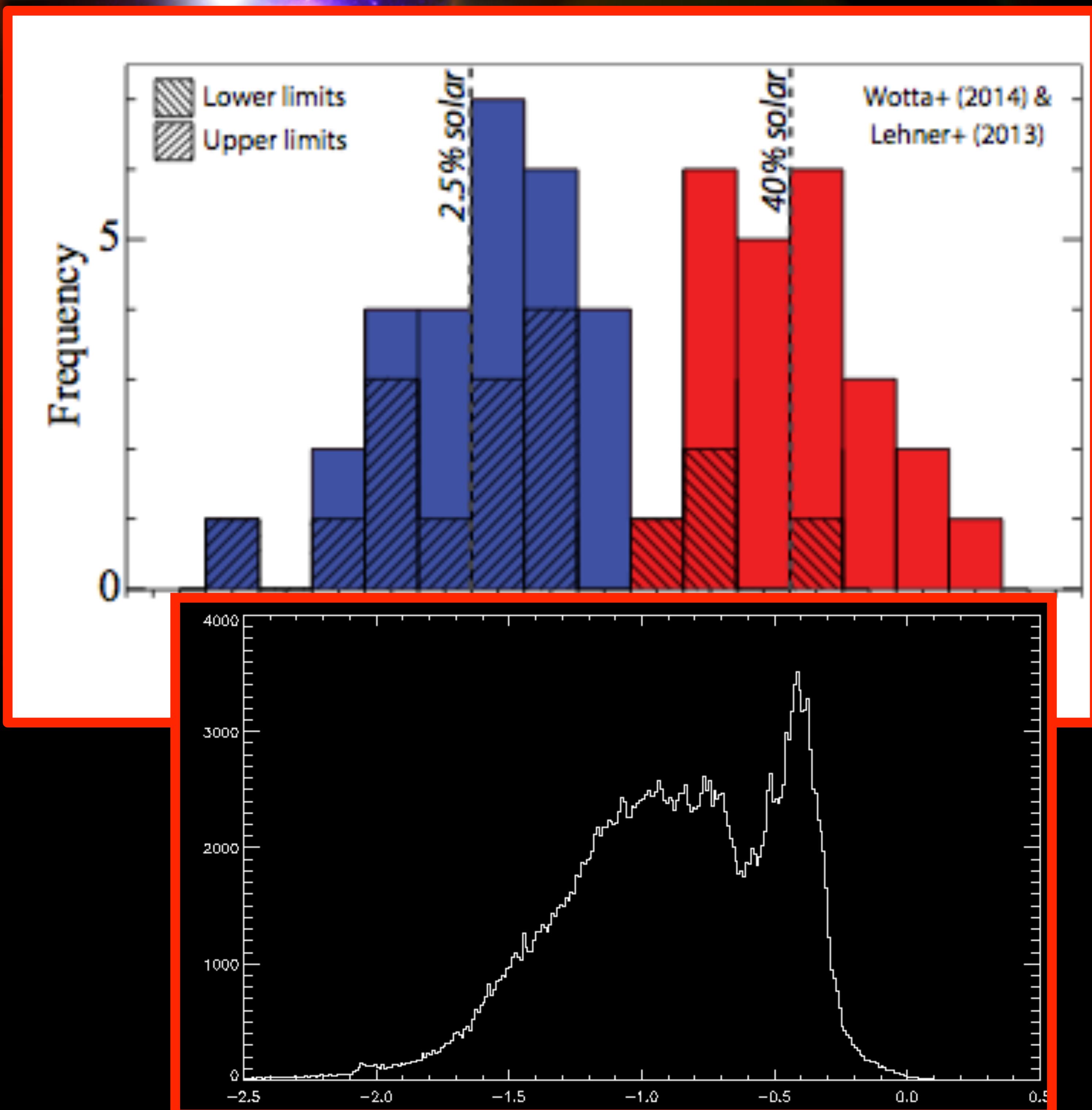
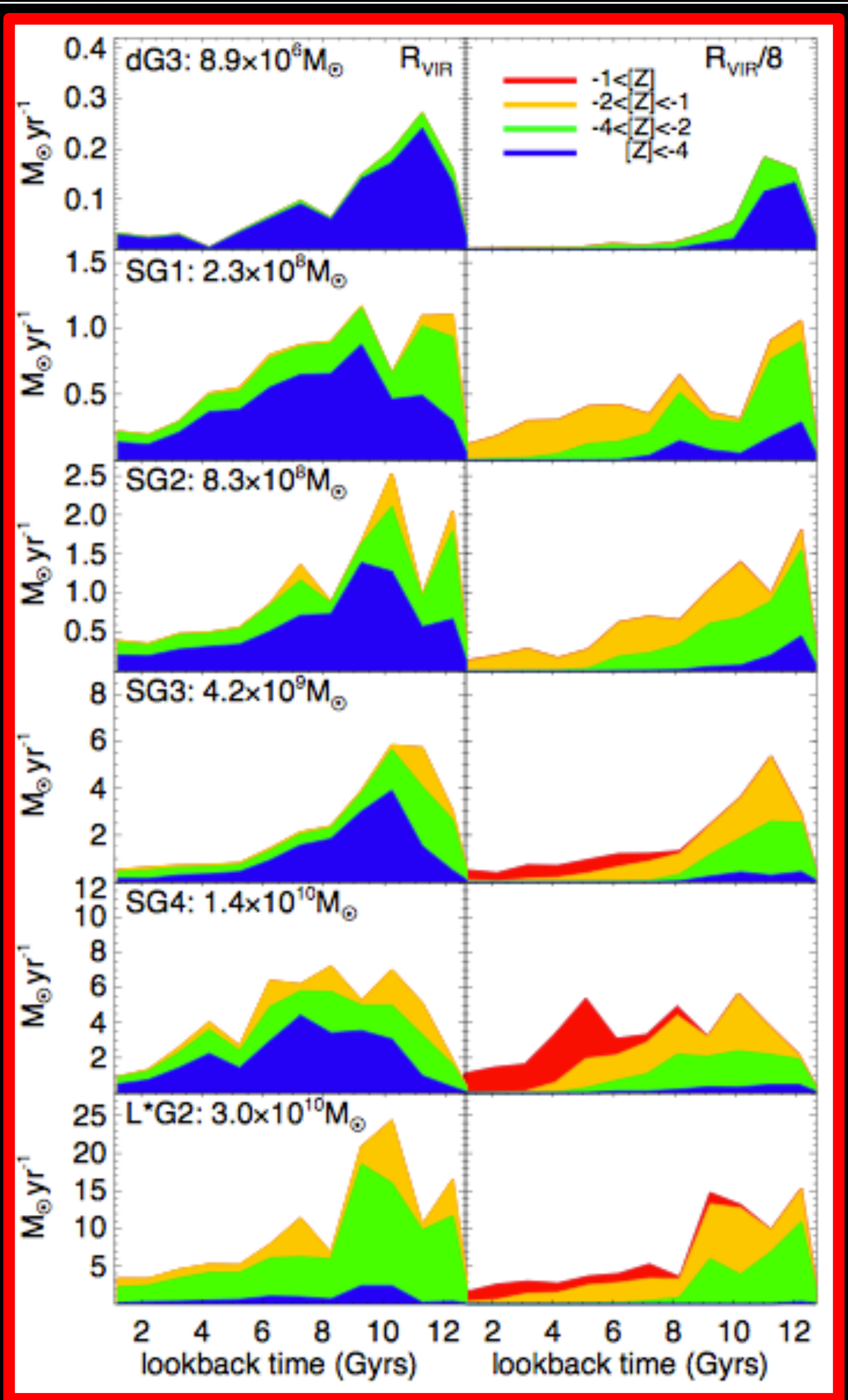


- coronal gas in external systems appears bimodal in metallicity (Lehner et al 2013; Wotta et al: LLS @ 25-150 kpc impact parm)
- checked one of our disks this morning to see what its halo MDF looked like
- metal-rich peak clearly associated with lower-halo fountains (none beyond 30kpc though)
- metal-poor peak too metal-rich… mixing too efficient?

Timescale for Metal Recycling?

Brook et al (2014); recall, Angles-Alcazar Talk (FIRE)

- infall rates through Rvir (left) and Rvir/8 colour-coded by metallicity
- **gas metallicity has been enhanced during its path through the halo**

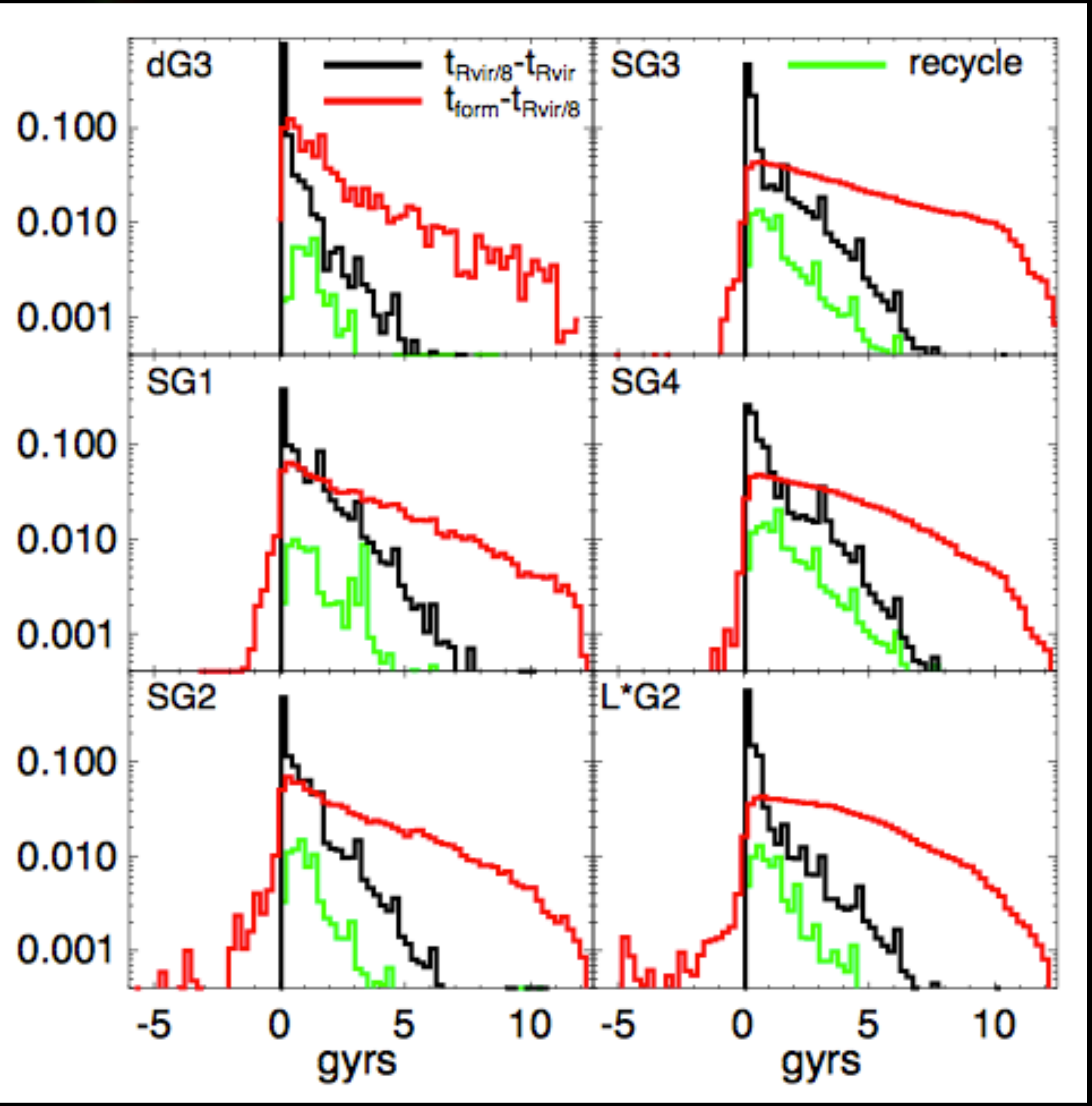


Timescale for Metal Recycling?

Brook et al (2014); recall, Angles-Alcazar Talk (FIRE)

- time taken between crossing Rvir and accretion to star forming region (black) for gas which forms stars
- time between accretion and forming stars (red)
- green shows the distribution of times of galactic fountain cycle (time between leaving SF region and being re-accreted to SF region)

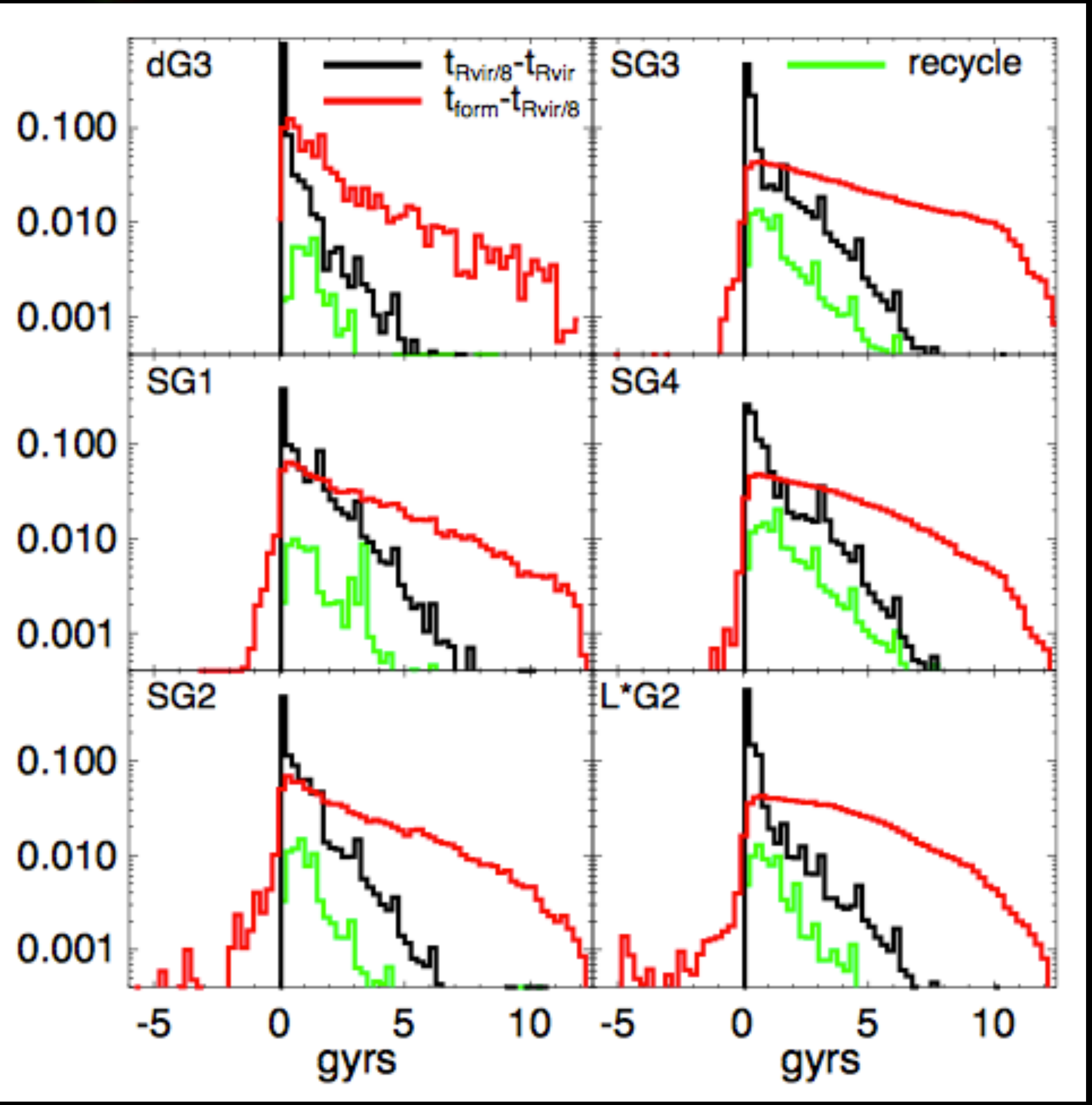
- aside: 40% of stars formed from re-cycled gas



Timescale for Metal Recycling?

Brook et al (2014); recall, Angles-Alcazar Talk (FIRE)

- fit all these timescales with exponentials
- 1 Gyr timescale for gas to go from Rvir to star forming region
- 4 Gyr timescale for gas to form stars after entering the SF region
- 1 Gyr recycle timescales



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Tentative evidence for radial inflow of gas from the Milky Way's anti-centre at -3.3km/s

- star formation is inefficient (Bonnell's Talk), so **infalling** gas has ~4+ Gyrs to wait until "conversion"
- i.e., metals have plenty of time to 'move around' (but not so much as to wipe out abundance gradients)
- recall, 1 km/s is ~1 kpc/Gyr

27. RADIAL VELOCITIES OF NEUTRAL HYDROGEN IN THE ANTICENTER REGION OF THE GALAXY

L. VELDEN

Astronomische Institute der Universität Bonn, Bonn, Germany

Abstract. An observational material of 21-cm H I emission-line profiles is investigated by a statistical method to derive the kinematical properties of the interstellar gas in the region of the galactic anticenter. A description of the method used as well as the results obtained, concerning deviations from a circular rotation, are given.

Evidence for Radial Flows?

TABLE 4

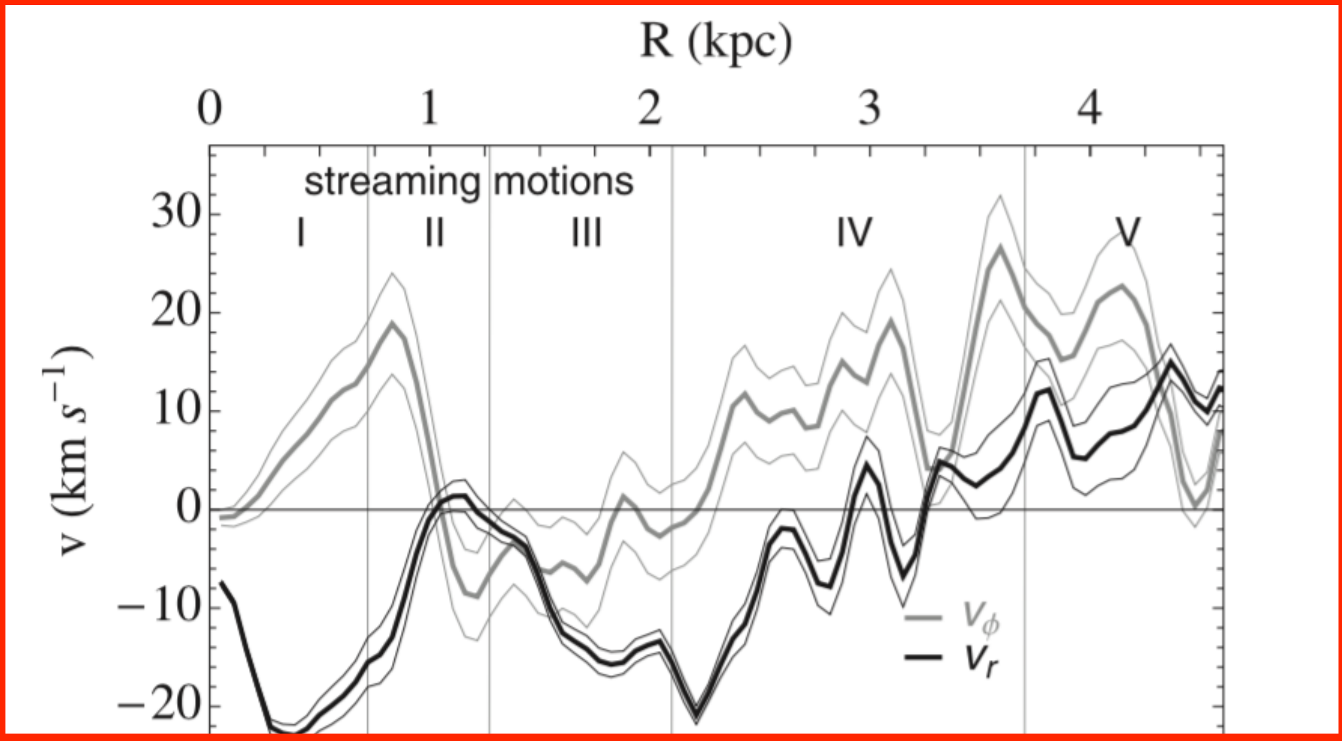
CANDIDATE REGIONS FOR RADIAL FLOWS, BASED ON s_1/s_3

Galaxy	Tracer	Radial Range	Maximum v_R	Interpretation
NGC 4321	CO	20″–40″	56 ± 5	Bar streaming
NGC 4414	CO	15″–45″	−8 ± 2[a]	Spiral streaming
NGC 4501	CO	15″–40″	48 ± 5	Bar streaming
NGC 4501	H I	40″–150″	10 ± 4	Bar streaming
NGC 5055	H I	50″–150″	−6 ± 1	Spiral streaming
NGC 5457	H I	250″–600″	−56 ± 5	Outer warp

[a] Negative values denote inflow.

Wong et al (2004)

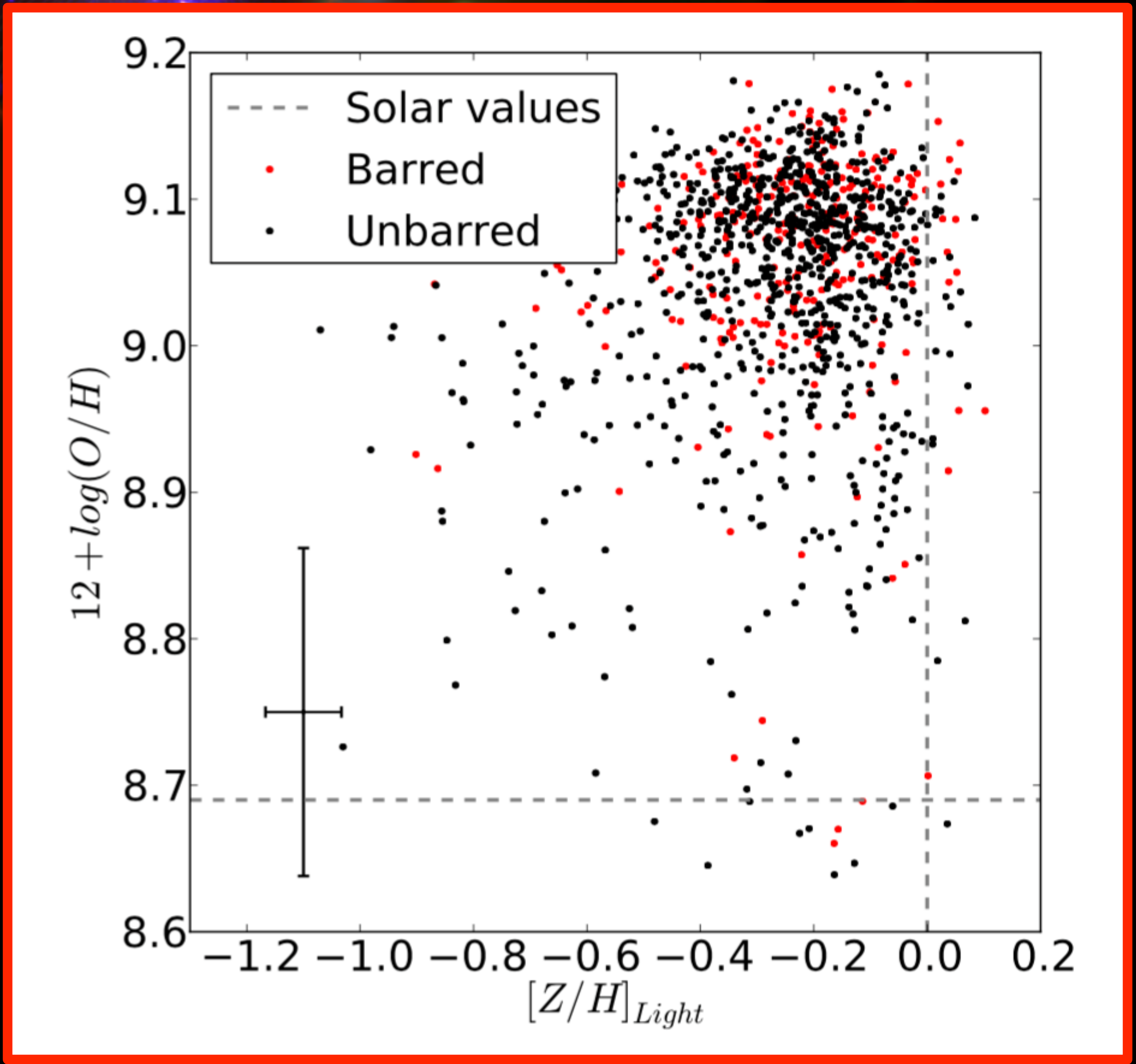
- genuine challenge for simulations/GCE models



Meidt et al (2013)

Impact on Observables for this Audience

Cacho et al (2014)



- within limitations of the data, at least in the centres of galaxies, no apparent correlation between gaseous and stellar abundances

- another challenging test for models

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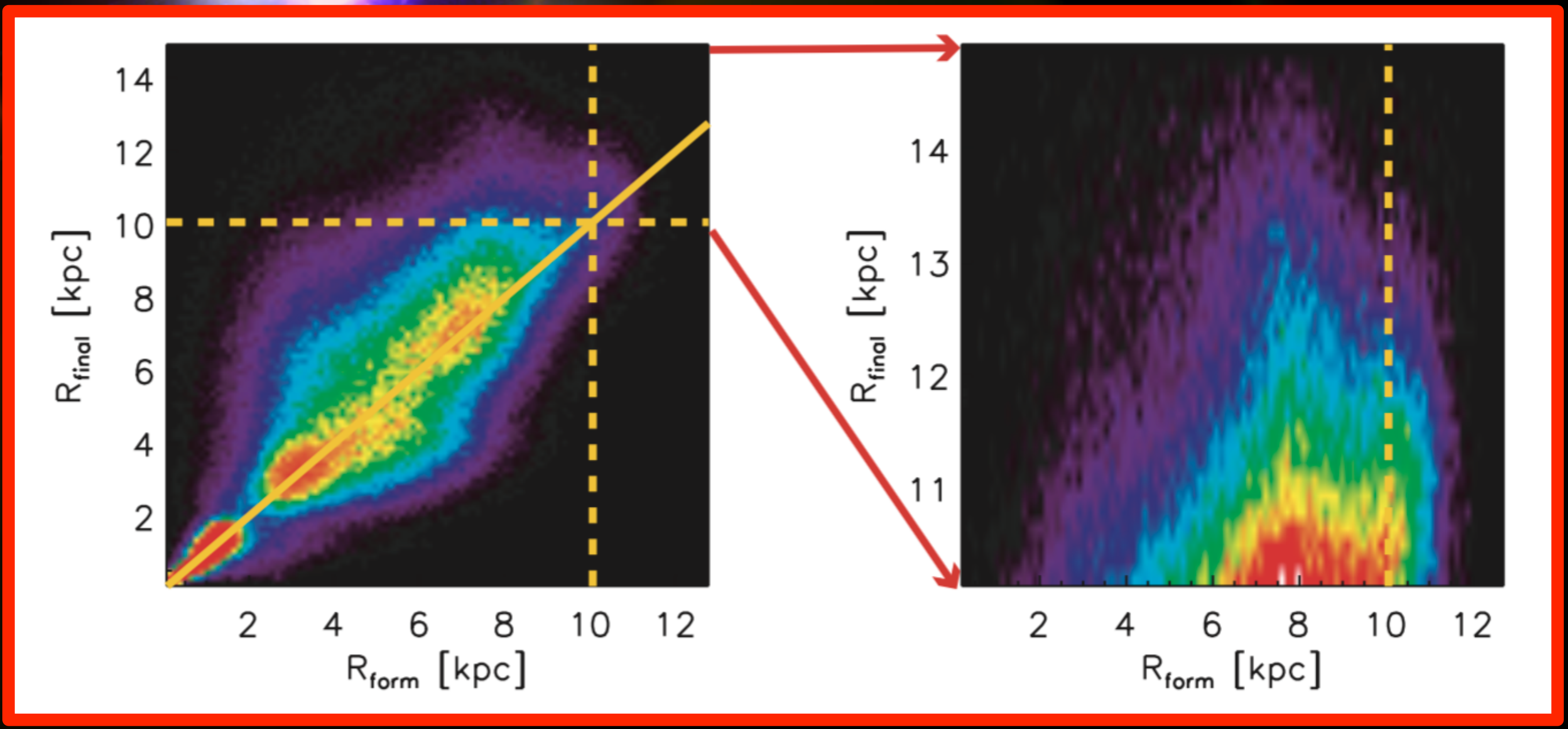
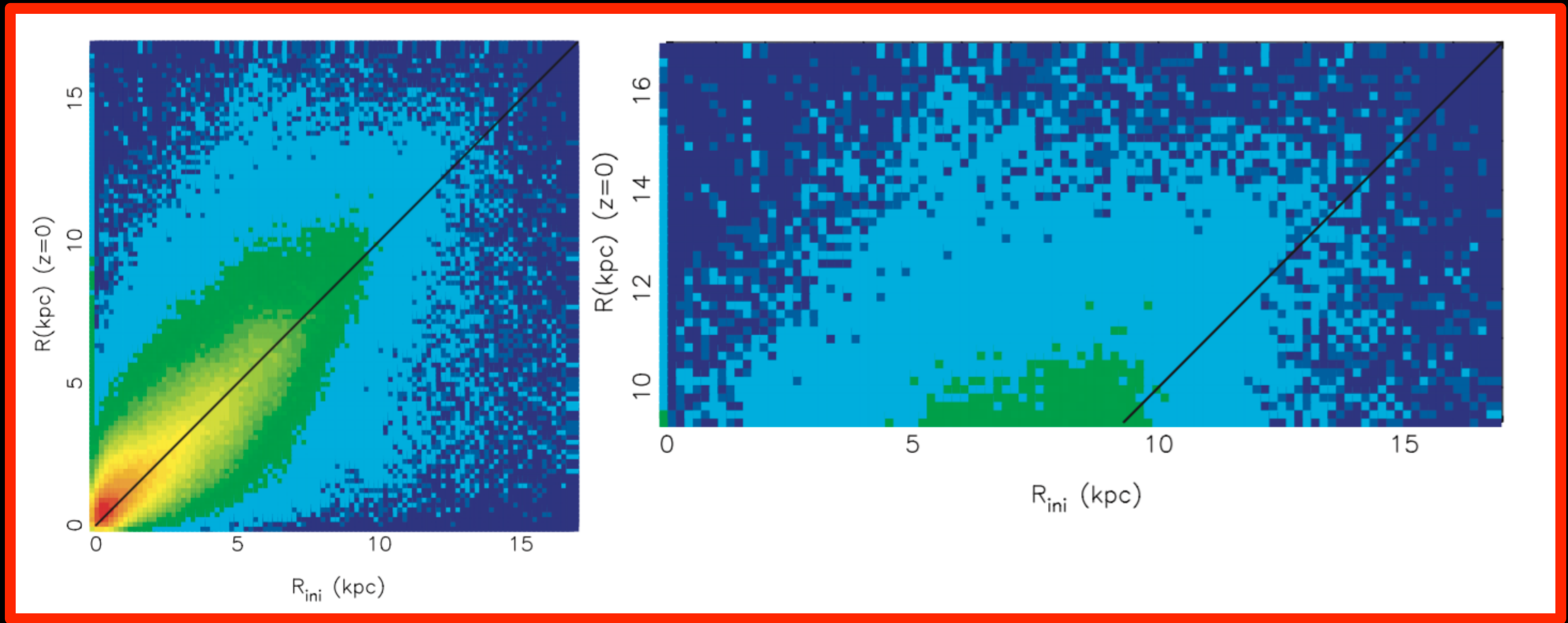
Stars Migrate Radially:
~2 - 4 kpc (on average) from their birth location
(regardless of physical/numerical mechanism)



Roskar et al (2008):
idealised simulations



Sanchez-Blazquez et al (2009):
cosmological simulations

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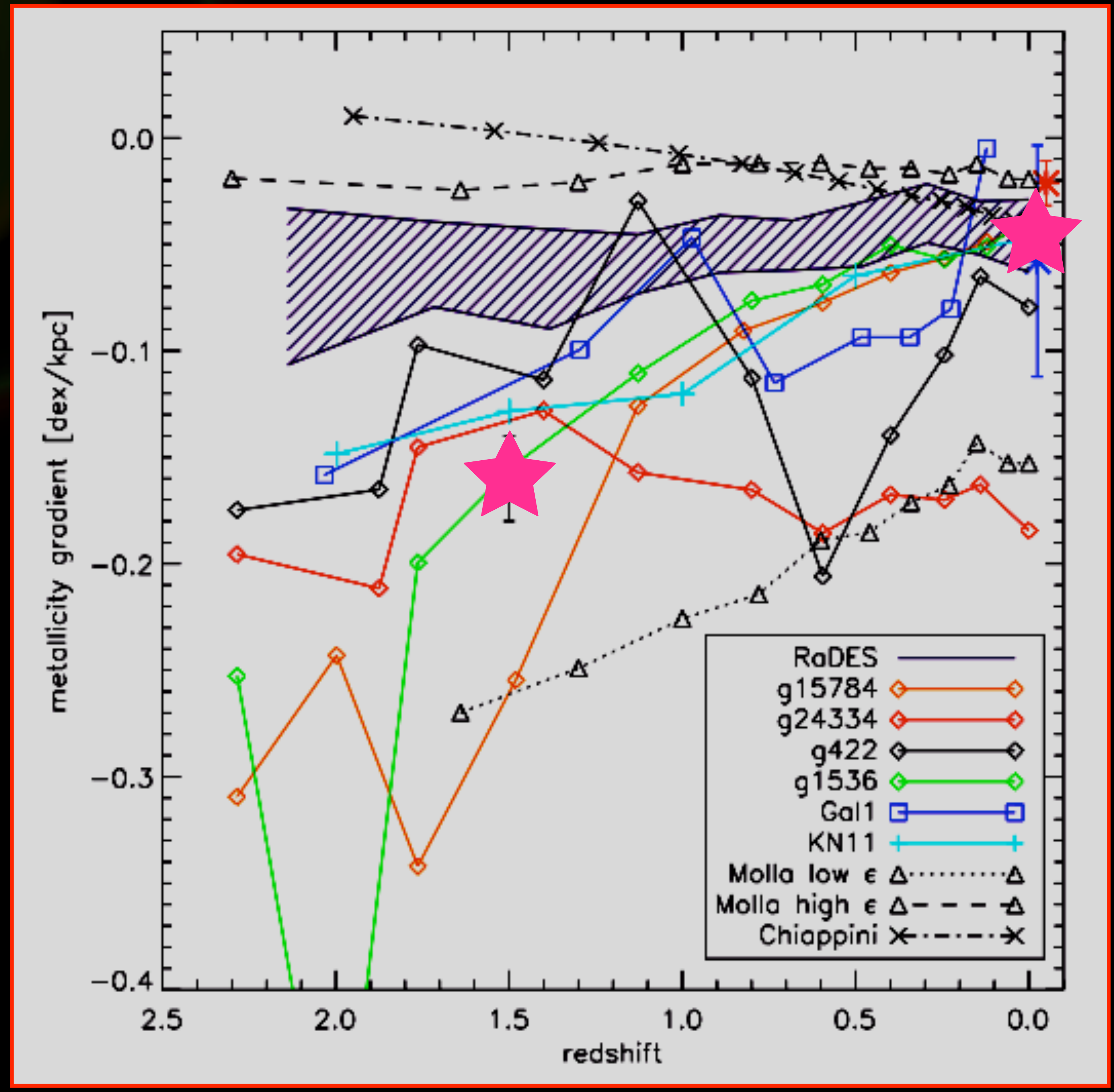
Temporal Evolution of Gradients

Pilkington et al (2012, A&A)

- Oxygen radial gradients
- -0.05dex/kpc today (factor of 3 over 10kpc)
- SPH, AMR, and analytical models agree at z=0 w/ observations
- All consistent with "inside-out" disk growth
- At high-z, SPH w/ "conservative" feedback systematically steeper
- Star formation threshold + supernova blast wave formalism differences

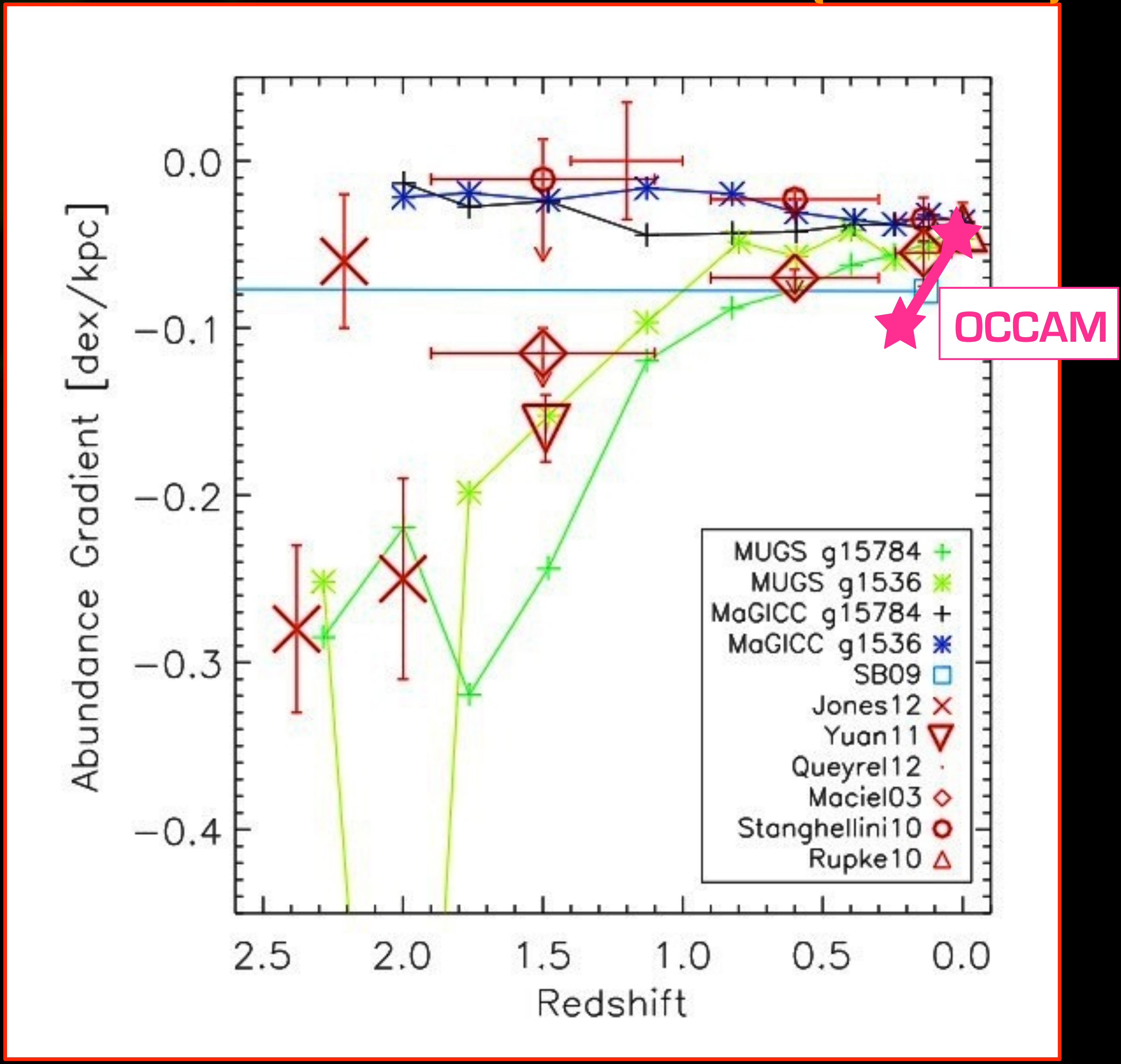


Temporal Evolution of Gradients

Tissera Talk

Gibson et al (2013, A&A)

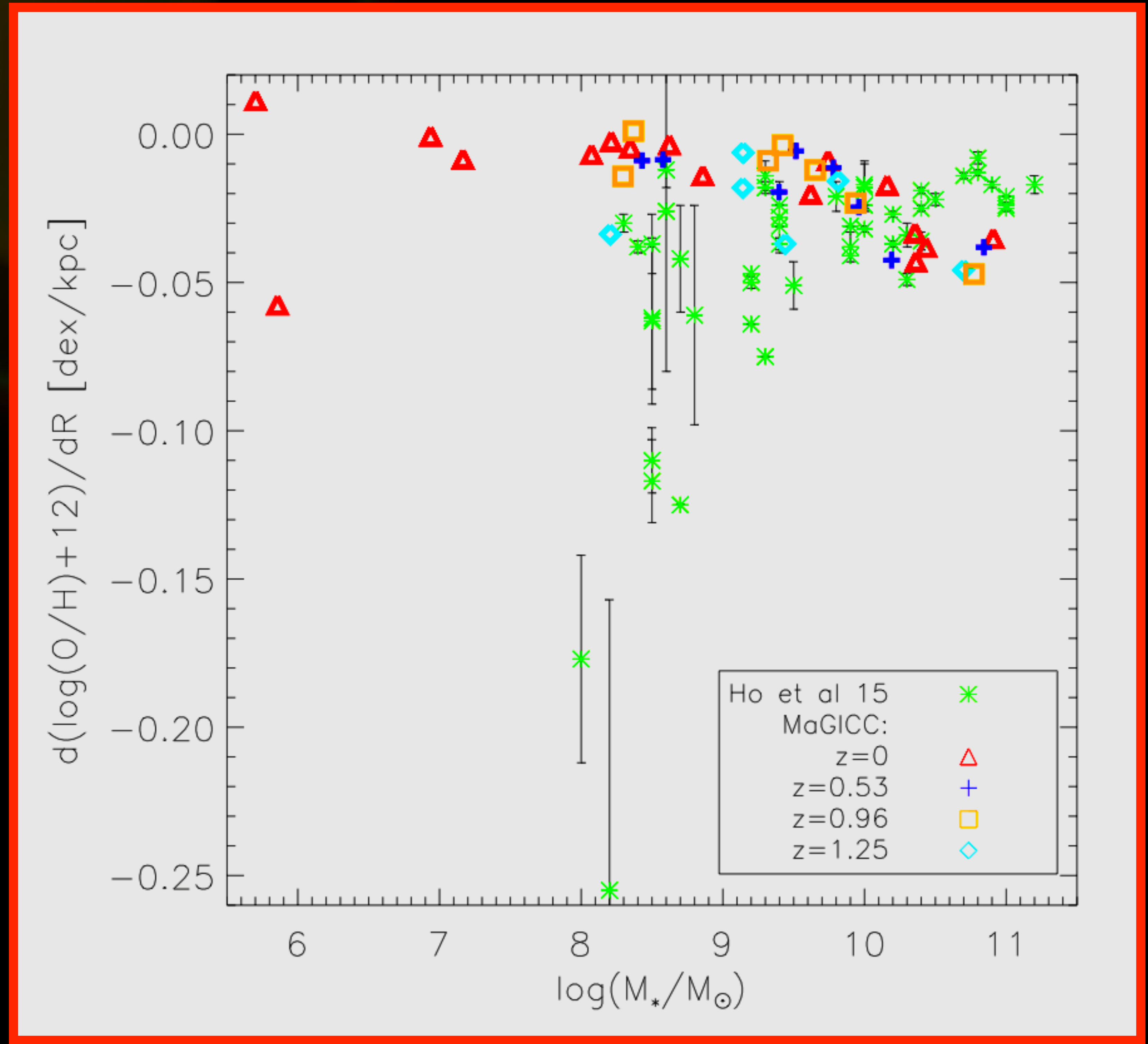
- let's zero in on that feedback issue…
- 'conventional' feedback leads to steep gradients at early times; 'strong' feedback flattens gradients significantly at all times
- preliminary statistics which suggested very steep gradients at z>1 have softened since this work (Leethochawalit et al 2016)



Mass Dependency… “strong”, mass-independent, feedback problematic for gradients?

Tissera Talk

Sancho Miranda et al (2016)



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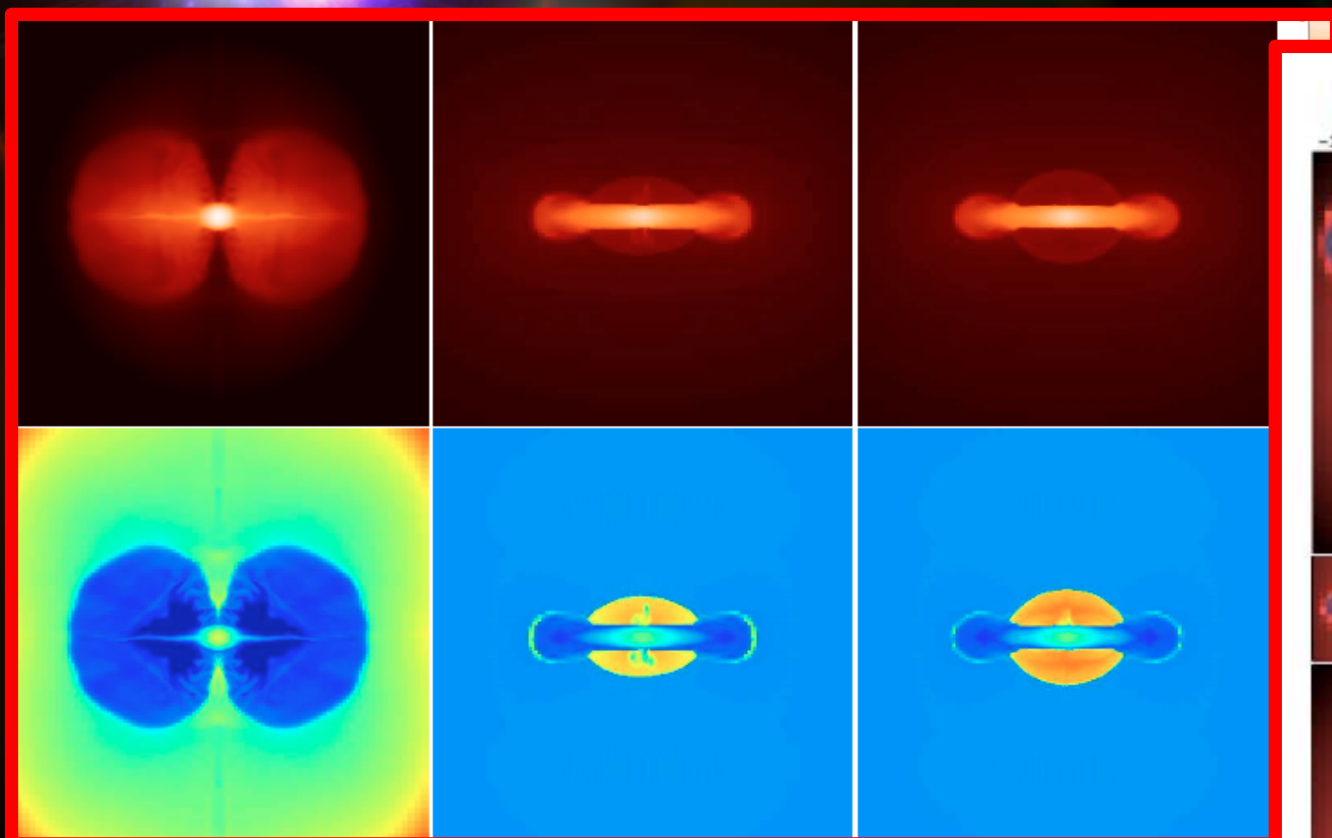
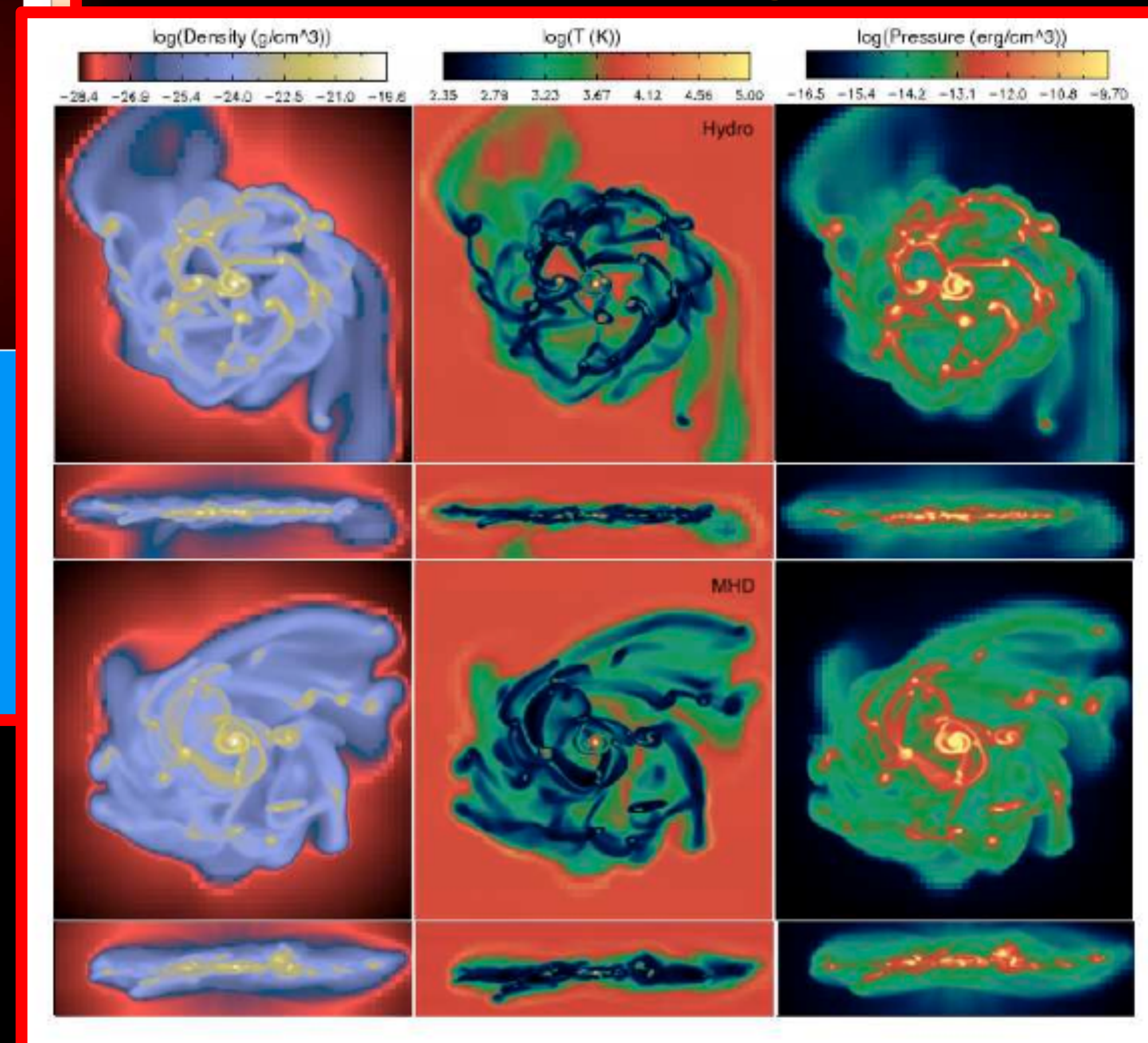
Cautionary Statement: ISM Energy Equipartition
Magnetic Fields

Wang & Abel (2009)



Dubois & Teyssier (2010)

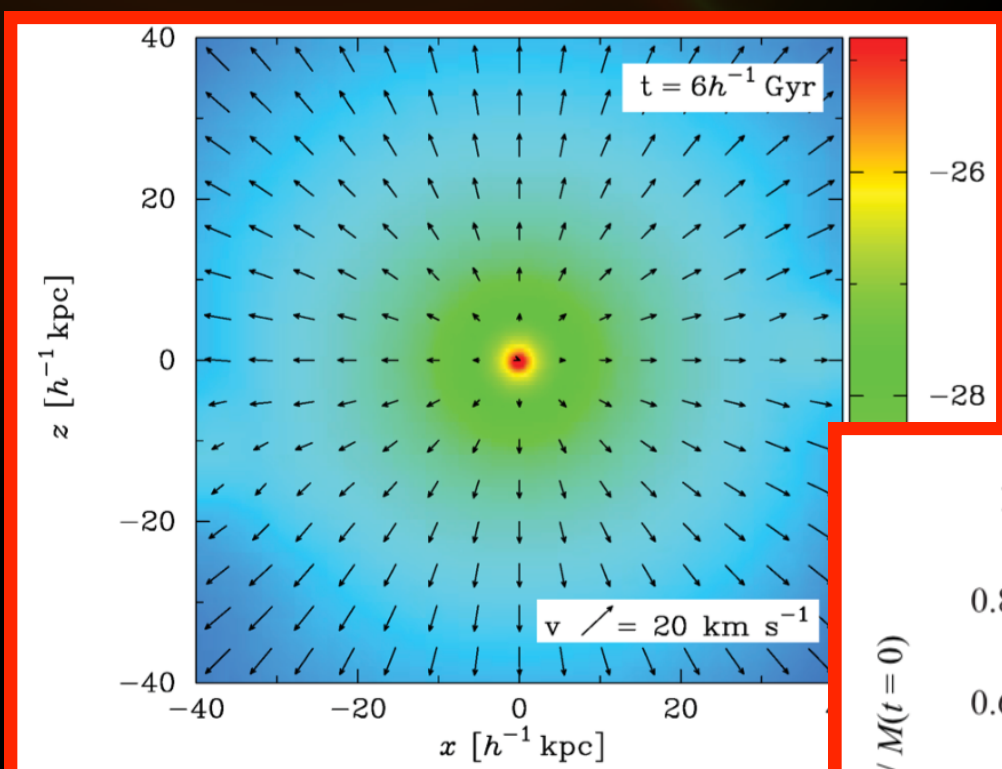


Magnetic forces provide additional disk support (~30%) and reduce star formation by 30%

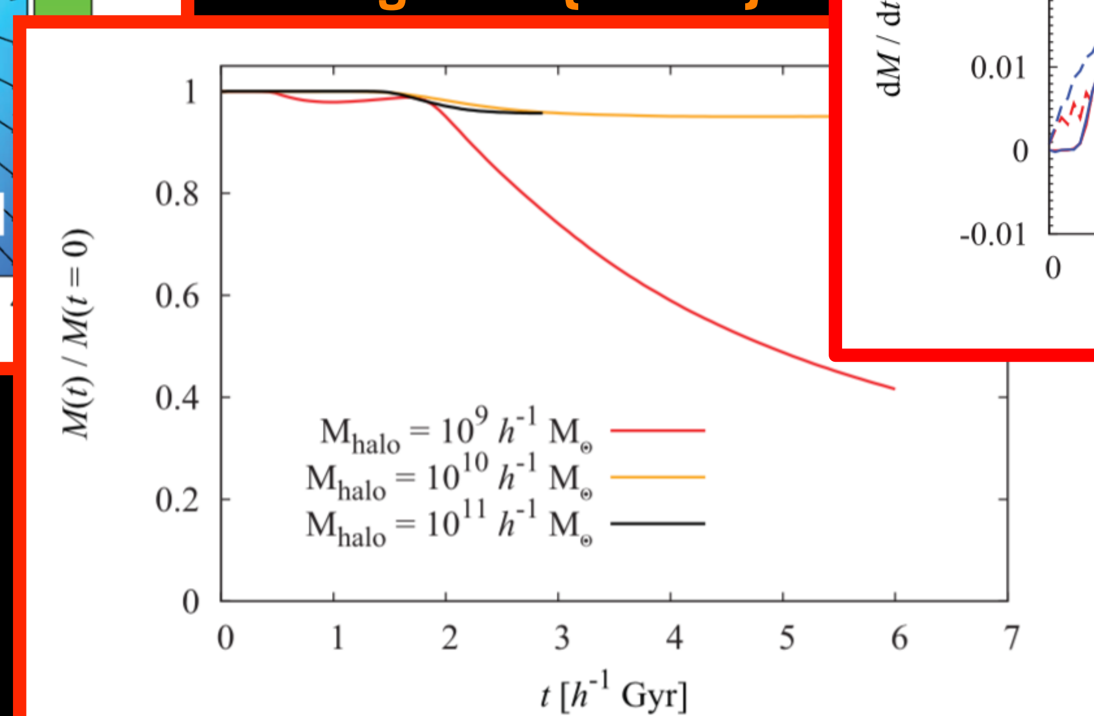
Cautionary Statement: ISM Energy Equipartition Cosmic Rays

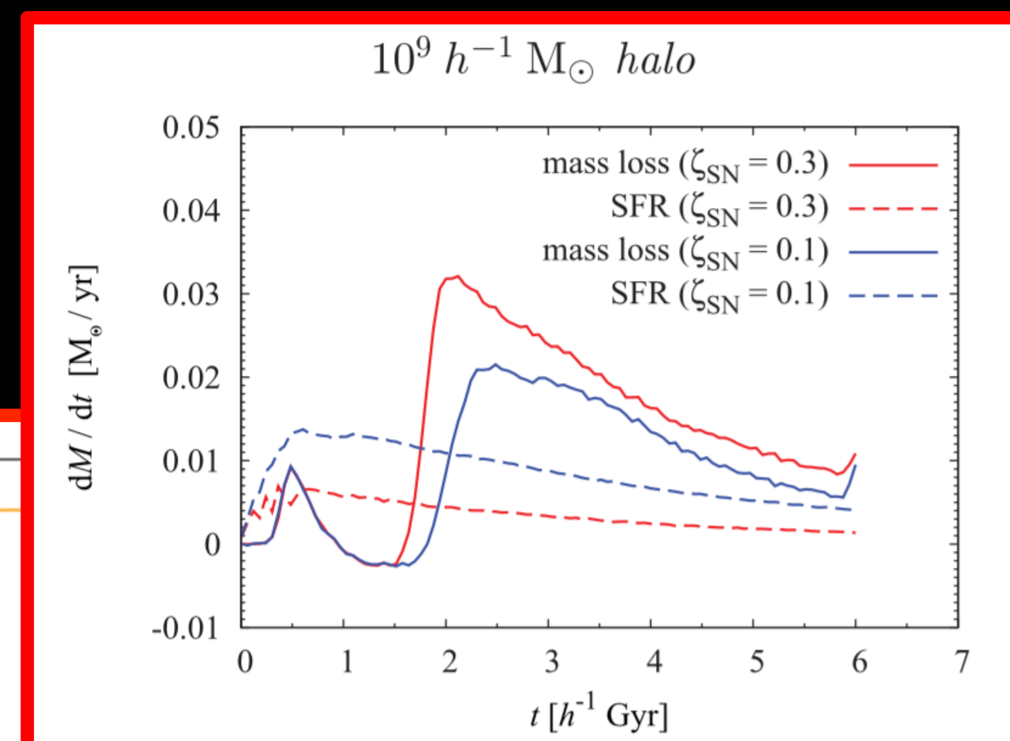
Ipavich (1975)

- CR streaming drives powerful and sustained winds for $<10^9$ M
- CR cooling works on a different timescale to normal thermal cooling, with the losses mediated by (e.g.) Coulomb losses
- gas can be CR-supported long after having lost thermal support



Uhlig et al (2012)

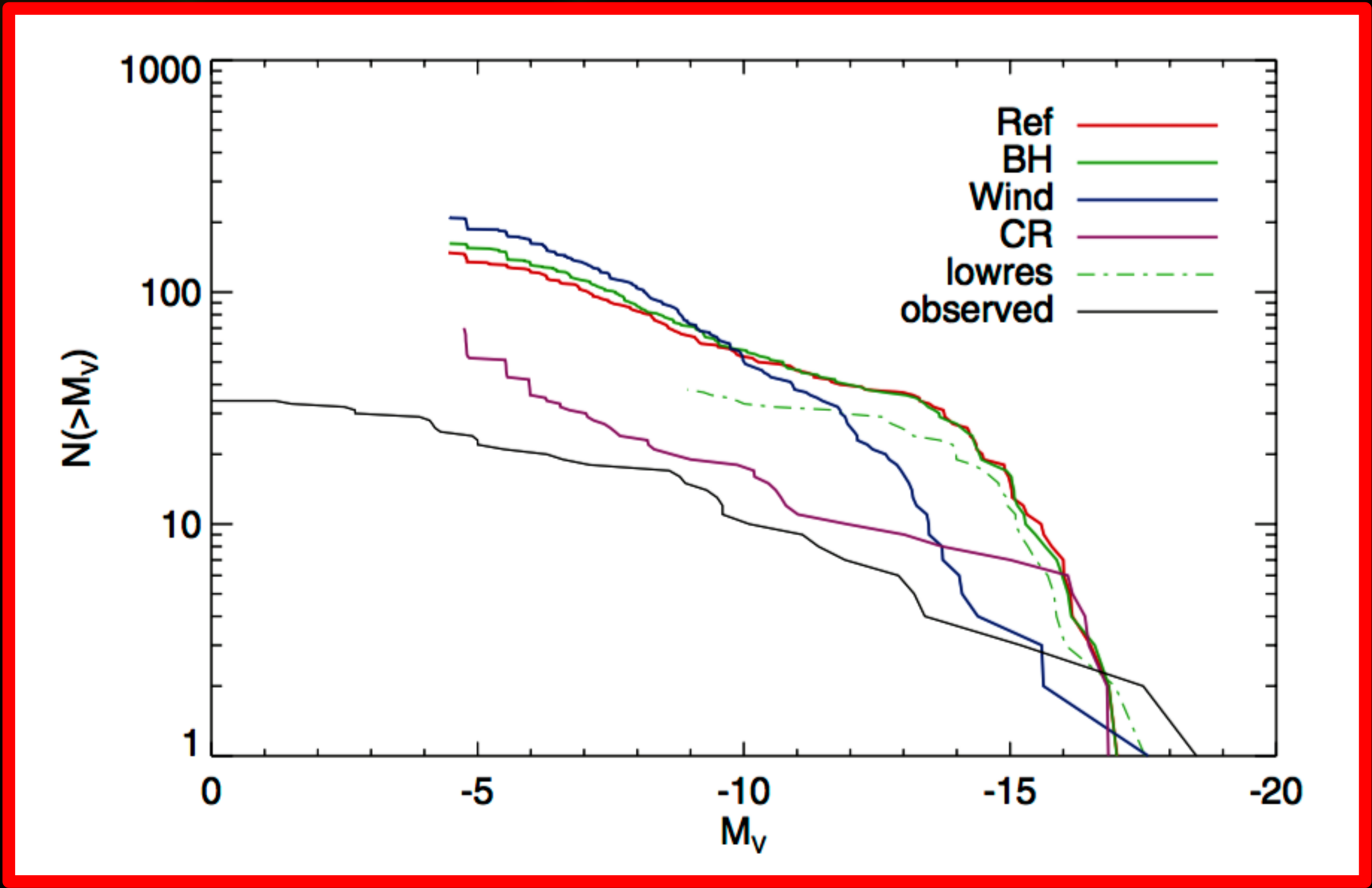




Cautionary Statement: ISM Energy Equipartition Cosmic Rays

Ipavich (1975)

- CR streaming drives powerful and sustained winds for <10^9 M
- CR cooling works on a different timescale to normal thermal cooling, with the losses mediated by (e.g.) Coulomb losses
- gas can be CR-supported long after having lost thermal support



Wadepuhl & Springel (2011)

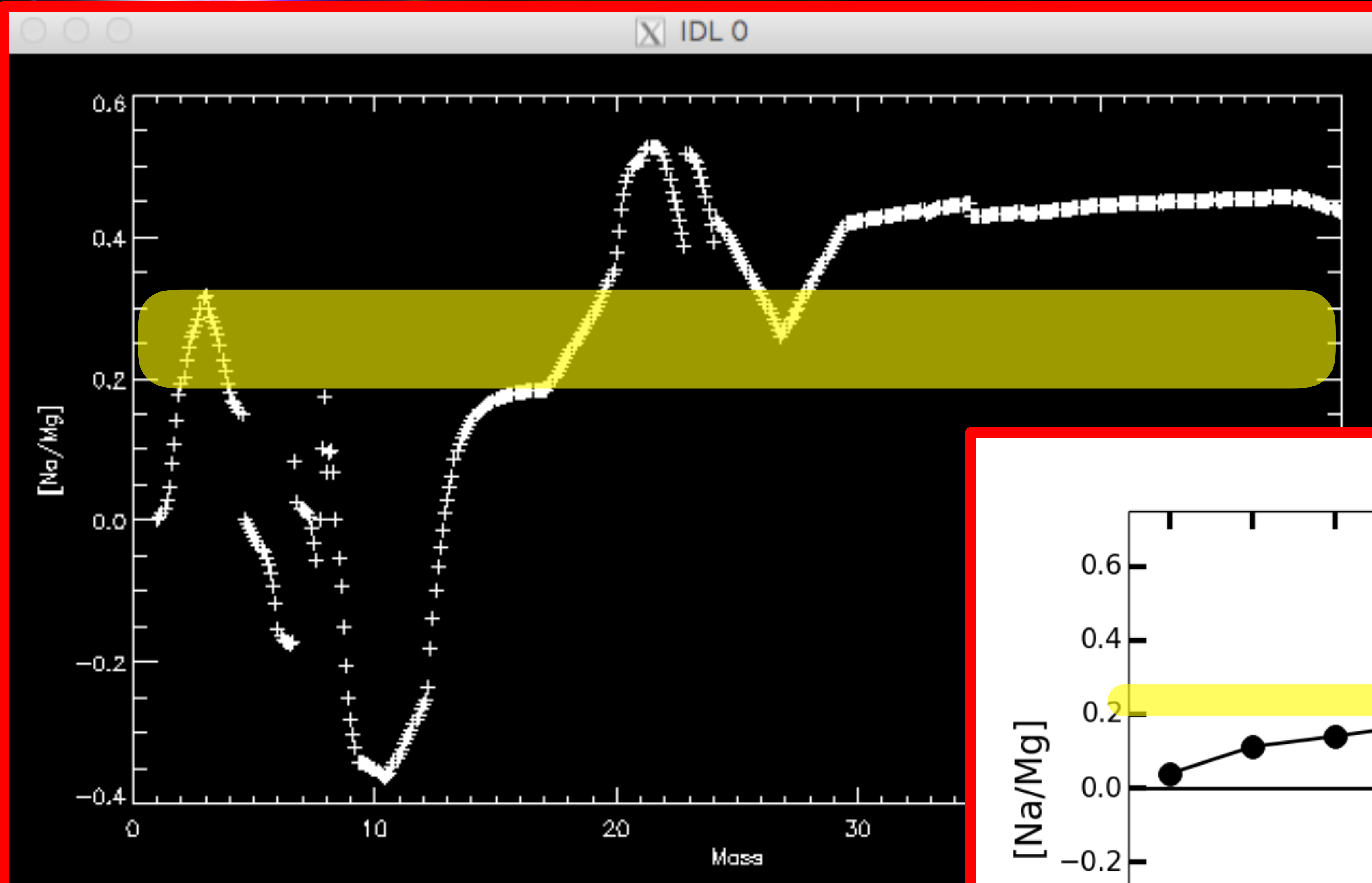
Cumulative Satellite LF

- significant suppression of low mass dwarfs
- responsible for much of the enrichment of the IGM?

Outline...

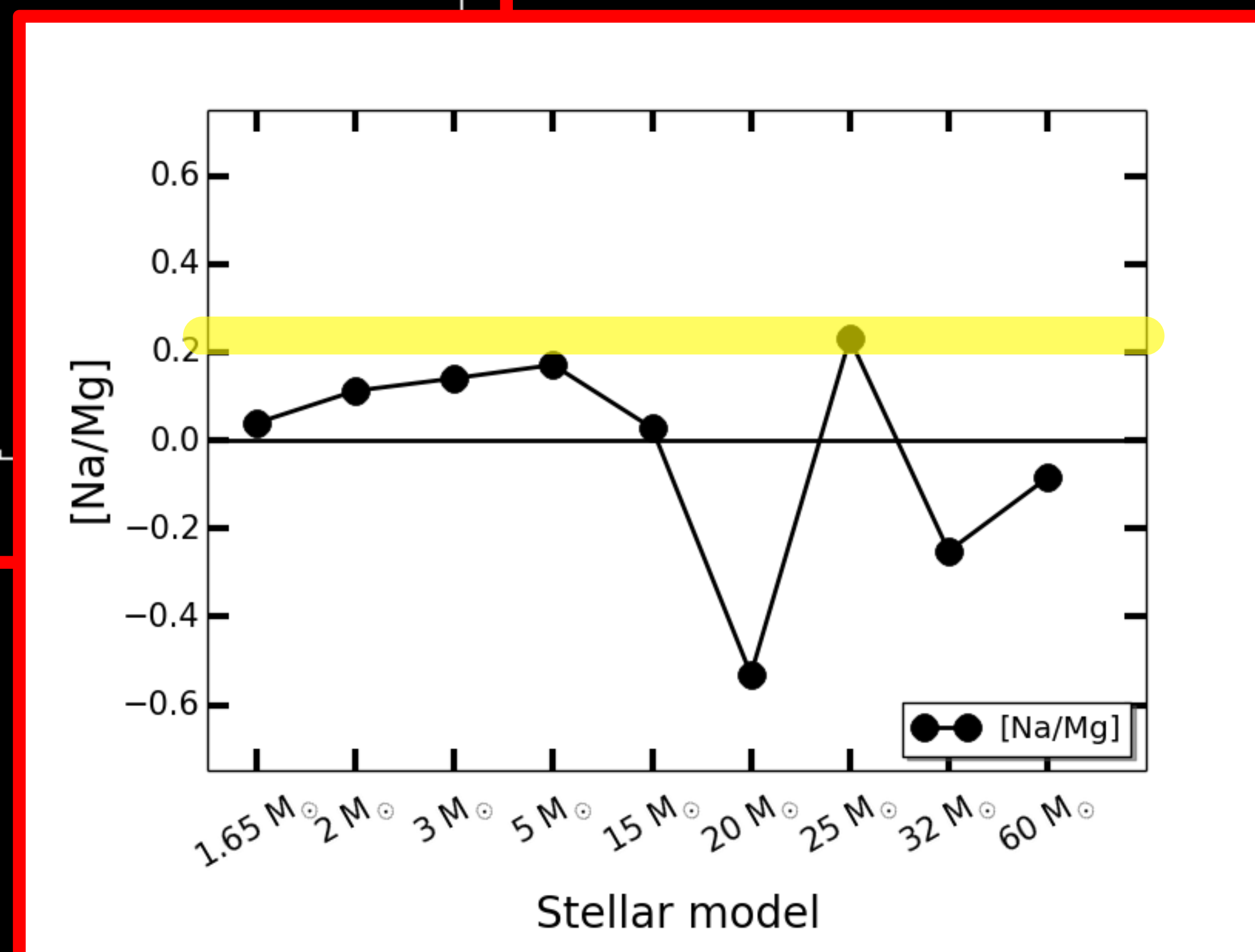
- Metal Assembly: “External”
  - IGM: Ultimate Fuel Reservoir for Star Formation
  - How Does that Fuel Reach the Disk?
  - What Do Outflows Do to this Fuel?
- Metal Assembly: “Internal”
  - What Does this Fuel Do Once it Reaches the Disk?
  - What Happens to the Stars that Form from this Fuel?
  - What is the Time Evolution of this Behaviour?
- Two Random Points In Passing
  - Feedback is Hard
  - Nucleosynthesis is Hard

Cautionary Statement: Stellar Yields
NuGrid (Pignatari et al) is changing the landscape but we are not there yet...



- recall, M87's [Na/Mg] ~ +0.2 - +0.3 (Spiniello's Talk)

Karakas (2010) +
Chieffi & Limongi (2004)



Pignatari et al (2016)

Metal (Re-)Assembly in Disk Galaxies

Thank you...

Aside: Detecting Metals Outside the Galaxy

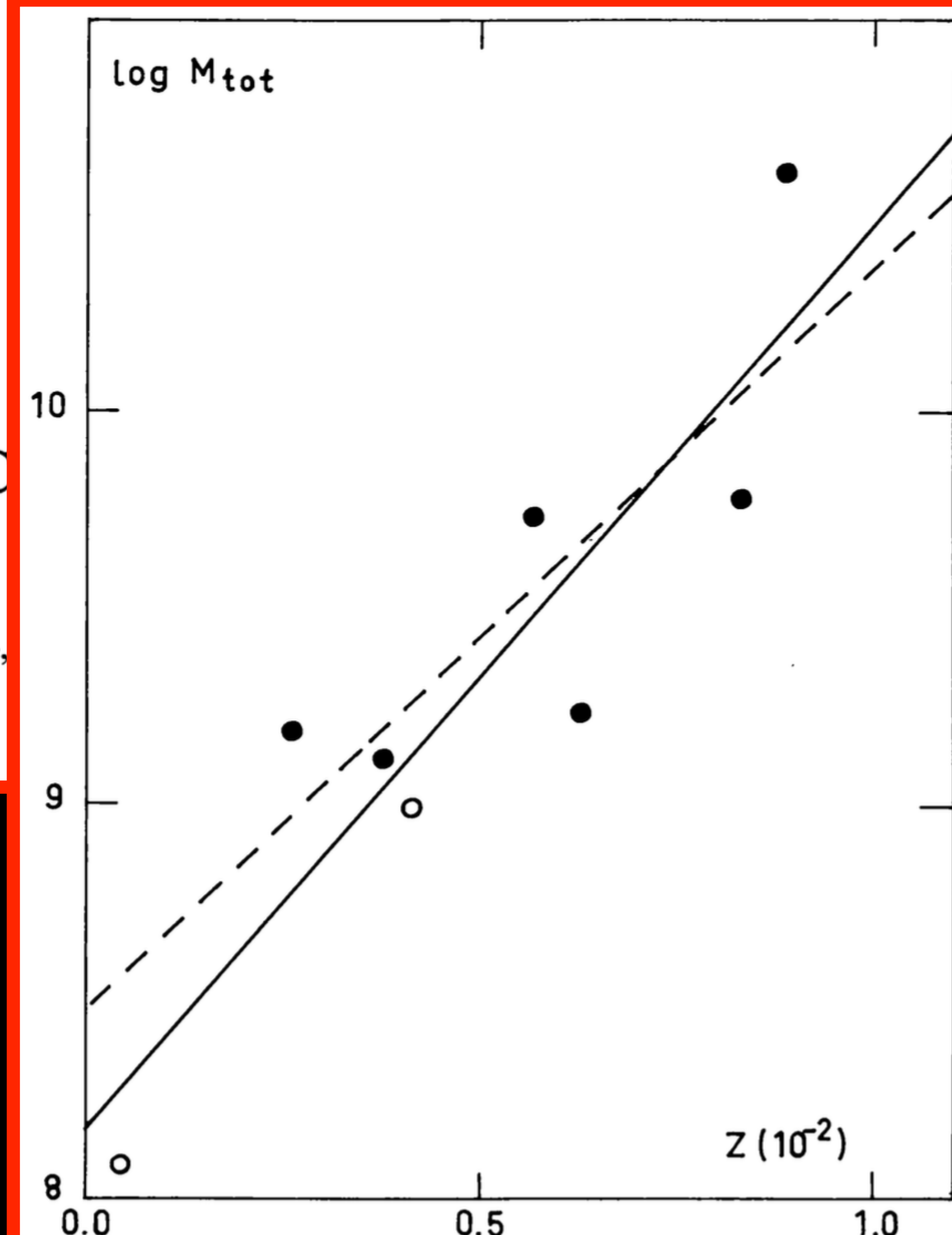
- Lequeux et al (1979) … in some sense, one of the first acknowledged and pioneering studies of extragalactic metals, in a statistical sense …

Astron. Astrophys. 80, 155–166 (1979)

Chemical Composition and Evolution of Irregular and Blue C

J. Lequeux*, M. Peimbert**, J. F. Rayo, A. Serrano, and S. Torres-Peimbert**
Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264,

Received December 27, 1978



Aside: Detecting Metals Outside the Galaxy

- Searle & Sargent (1972) … pioneering, first 100%-definitive determinations…

THE ASTROPHYSICAL JOURNAL, 173:25–33, 1972 April 1

INFERENCES FROM THE COMPOSITION OF TWO DWARF BLUE GALAXIES

LEONARD SEARLE AND WALLACE L. W. SARGENT
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology
Received 1971 September 29

ABSTRACT

The emission spectra of two dwarf compact galaxies, I Zw 18 and II Zw 40, which were earlier described as "isolated extragalactic H II regions," have been analyzed. Oxygen and neon have lower abundances (relative to hydrogen) than does the interstellar gas near the Sun, while helium has a normal abundance. These galaxies are the first metal-poor systems of Population I to be discovered; the normal helium abundance is taken as evidence that this abundance is primordial. It is shown that most of the mass in I Zw 18 and II Zw 40 is probably in the form of interstellar hydrogen gas. The observed colors are used with the composition data to infer that the present rate of star formation exceeds the past average rate. It is argued that the galaxies are either young (in the sense that most of their star formation has occurred in recent times) or that the star formation in them occurs in intense bursts which are separated by long quiescent periods. A statistical search for objects in the quiescent phase is suggested as a means of distinguishing between the two possibilities.

Aside: Detecting Metals Outside the Galaxy

- Peimbert (1968) … pioneering, first 99%-definitive determinations…

THE ASTROPHYSICAL JOURNAL, Vol **154**, October 1968

PHYSICAL CONDITIONS IN THE NUCLEI OF M51 AND M81

MANUEL PEIMBERT*
Berkeley Astronomy Department, University of California
Received February 2, 1968

ABSTRACT

Narrow-band photoelectric photometry of the nuclei of M51 and M81 was carried out with the Crossley and the 120-inch telescopes at Lick Observatory. The intensity of several emission lines, as well as of the continuum at different wavelengths, was obtained. From the [O I], [O II], and [O III] line intensities, it was found that collisions by thermal electrons are not responsible for the ionization in M81 and M51. This result, coupled with the observed Balmer decrement in M81, led to the adoption of radiation as the principal mechanism of ionization.

The radiation field needed to explain the intensity of Hα in M51 and M81 was computed for three black-body temperatures. The predicted contribution of such a radiation field to the integrated observed flux in the most favorable wavelengths of the visual region was found to be very small Large density fluctuations were found in the nuclei of M51 and M81 by comparing the $N_e(\lambda 3727)$ density with the N_e(rms) density. From the intensity of the [O I] λ6300 line, it was found that a large fraction of the material in these nuclei is in the neutral form.

Solar abundances cannot explain the relative line intensities in the nuclei of M51 and M81 Several arguments are presented which suggest an overabundance of nitrogen in the nuclei of both galaxies. From these arguments it was concluded that most of the variation of the N II/Hα intensity ratio from the spiral arms to the nuclei of both galaxies is caused by a change of the nitrogen abundance and not by a change of electron temperature.

Aside: Detecting Metals Outside the Galaxy

- Burbidge & Burbidge (1962,1965) hinted that [N,O/H] could differ from galaxy-to-galaxy, but favoured an ionisation explanation for the varying line ratios … i.e., first, tentative abundance determinations...

IONIZED GAS IN SPIRAL AND IRREGULAR GALAXIES*

E. Margaret Burbidge and G. R. Burbidge
Yerkes Observatory and Enrico Fermi Institute for Nuclear Studies, University of Chicago, and McDonald Observatory, University of Texas

Received October 24, 1961; revised December 12, 1961

small nuclei. To explain this rather general result, we can appeal either to differences in relative abundances or to quite different conditions of excitation. If we explain the effect in terms of relative abundances, then we must conclude that in the inner regions of all these galaxies there is a deficiency of hydrogen with respect to nitrogen and oxygen, as compared with the abundances of these elements in the solar neighborhood in our own Galaxy and also in the outer parts of the same galaxies. Before accepting such a fundamental result, it is necessary to determine whether such an effect could be produced by the conditions of excitation. We have found that such an explanation is possible for the extreme cases (e.g., NGC 4736, 5005, 3623). Here we may suppose that

Aside: Detecting Metals Outside the Galaxy

- earlier rich history of observing extragalactic lines, but no "chemistry"… e.g. Slipher (1917), Hubble (1924), Aller (1942), etc.

NEBULÆ.

By V. M. SLIPHER, Ph.D.

(*Read April 13, 1917.*)

In addition to the planets and comets of our solar system and the countless stars of our stellar system there appear on the sky

1942ApJ....95...52A

THE SPECTRA OF THE EMISSION NEBULOSITIES IN MESSIER 33

LAWRENCE H. ALLER[1]

ABSTRACT

The emission nebulosities in Messier 33 are similar in spectral characteristics to those of our own Galaxy and to the low-excitation planetary IC 418. The ratio of λ 5007/λ 3727 is found to be the most reliable excitation criterion for these nebulosities. The available evidence suggests that in most of these nebulosities the oxygen is predominantly in the singly ionized condition.

Aside: Detecting Metals Outside the Galaxy

- Scheiner (1899,ApJ) … claims credit for first detected "extragalactic" lines (no spectra presented)

ON THE SPECTRUM OF THE GREAT NEBULA IN ANDROMEDA.

By J. Scheiner.

spectrum of the Andromeda nebula with an exposure of seven and one half hours in January of this year. The continuous spectrum can be clearly recognized on it from F to H, and faint traces extend far into the ultra-violet. A comparison of this spectrum with a solar spectrum taken with the same apparatus disclosed a surprising agreement of the two, even in respect to the relative intensities of the separate spectral regions. The H line could be seen very distinctly, so that the band noticed on

Aside: Detecting Metals Outside the Galaxy

- Fath (1909) … dismisses Scheiner's spectra as scattered light; takes self-proclaimed credit for first "extragalactic" spectra

UNIVERSITY OF CALIFORNIA PUBLICATIONS

ASTRONOMY

LICK OBSERVATORY BULLETIN

NUMBER 149

THE SPECTRA OF SOME SPIRAL NEBULAE AND GLOBULAR STAR CLUSTERS.*

named. The spectrogram by Scheiner was probably faint and there may be some doubt as to its interpretation,

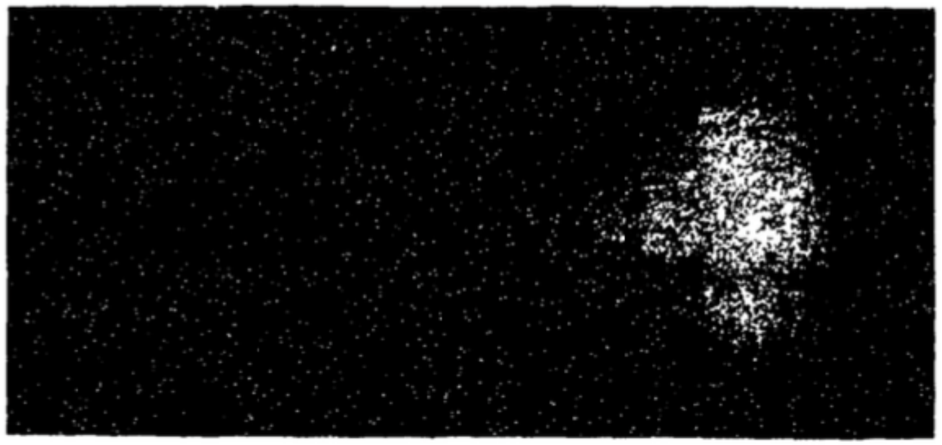


Fig. 2. ANDROMEDA NEBULA.

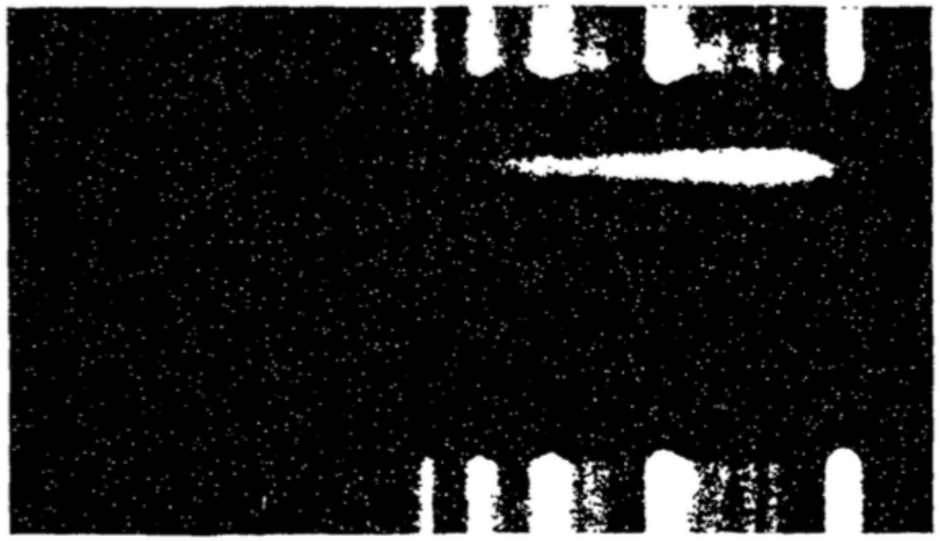


Fig. 3. SPIRAL NEBULA, N. G. C. 1068

Aside: Detecting Metals Outside the Galaxy

- Scheiner (1909,ApJ) … rebuttals were a lot more "blunt" back then!

NOTE ON THE SPECTRUM OF THE *ANDROMEDA* NEBULA

In *Lick Observatory Bulletin* No. 149, Mr. Fath makes a hardly admissible remark regarding the fact I pointed out ten years ago (*Astronomische Nachrichten*, **148,** 325, 1899) that the *Andromeda* nebula exhibits an absorption spectrum of the second stellar type. He thinks that my spectrogram was so faint as to leave some doubt in regard to my interpretation of it. He is led to this idea in a rather remarkable manner: because of the omission of any reference to my result in the third edition of Newcomb-Engelmanns *Populäre Astronomie*, although the late Director Vogel presumably had seen the plate before publishing this revised edition. Hence if a fact is not mentioned in a popular work, it is doubtful!

If Mr. Fath was in doubt in regard to my interpretation, the normal procedure would have been to consult me, when I could have assured him that the evidence of the spectrogram was entirely definite and that I was myself astonished at the result, having anticipated a spectrum of the first type. I should further have been able to call his attention to the fact that many other results of mine are omitted in the third edition of the above-mentioned work.

Doubt as to the correctness of my interpretation would have been more intelligible if Mr. Fath had reached a conclusion different from mine; but, on the contrary, he arrives at exactly the same result, and his paper accordingly is a satisfactory confirmation of mine.

J. Scheiner

Potsdam
June 1909

Aside: Detecting Metals Outside the Galaxy

- Stebbins & Fath (1906,Science) ... speaking of Fath, it has nothing to do with metals, but still one of the more interesting uses of a telescope

THE USE OF ASTRONOMICAL TELESCOPES IN DETERMINING THE SPEEDS OF MIGRATING BIRDS.

DURING the spring and fall of 1905 there was developed at the University of Illinois Observatory a method of determining the heights of migrating birds. Two ob
watched the moon's disk at night t
small telescopes placed some distance
and from the different paths seen pr
against the moon from the two stati
was possible to compute the height and
tion of flight for each bird. These m
and results are given in papers by

the others. In short, given a clear night, the moon about full, plenty of birds in flight, and a battery of telescopes, the conditions are perfect for an easy solution of the problem of the heights and speeds of migrating birds; but it will be seldom that all of these requirements are fulfilled at the same time.

JOEL STEBBINS,
EDWARD A. FATH.
UNIVERSITY OF ILLINOIS OBSERVATORY,
May, 1906.

Aside: Detecting Metals Outside the Galaxy

- Huggins (1964) … true, first extragalactic spectra (?) … M31 and M32
- M31 featureless; M32 "crossed by lines of absorption and emission"

XIII. *On the Spectra of some of the Nebulæ.* *By* WILLIAM HUGGINS, *F.R.A.S.* *A Supplement to the Paper "On the Spectra of some of the Fixed Stars.* *By* WILLIAM HUGGINS, *F.R.A.S., and* W. A. MILLER, *M.D., LL.D., Treas. and V.P.R.S."* *Communicated by Professor* W. A. MILLER, *M.D., LL.D.*

Received September 8, 1864, and printed in continuation of the paper preceding.

[No. 116. 50 h. 31 M. R.A. 0h 35m 3s·9. N.P.D. 49° 29′ 45″·7.] The brightest part of the great nebula in Andromeda was brought upon the slit.

The spectrum could be traced from about D to F. The light appeared to cease very abruptly in the orange; this may be due to the smaller luminosity of this part of the spectrum. No indication of the bright lines.

[No. 117. 51 h. 32 M. R.A. 0h 35m 5s·3. N.P.D. 49° 54′ 12″·7. Very very bright; large; round; pretty suddenly much brighter in the middle.]

This small but very bright companion of the great nebula in Andromeda presents a spectrum apparently exactly similar to that of 31 M.

The spectrum appears to end abruptly in the orange; and throughout its length

Postdoc Position Available: Chemical Evolution / Galaxy Simulations

- ad not out yet (last minute grant), but can start any time in 2016
- more or less exclusive use of our new 6,000 core cluster ('viper')

Metal (Re-)Assembly in Disk Galaxies

Thank you...