Chemical Evolution and Nuclear Astrophysics

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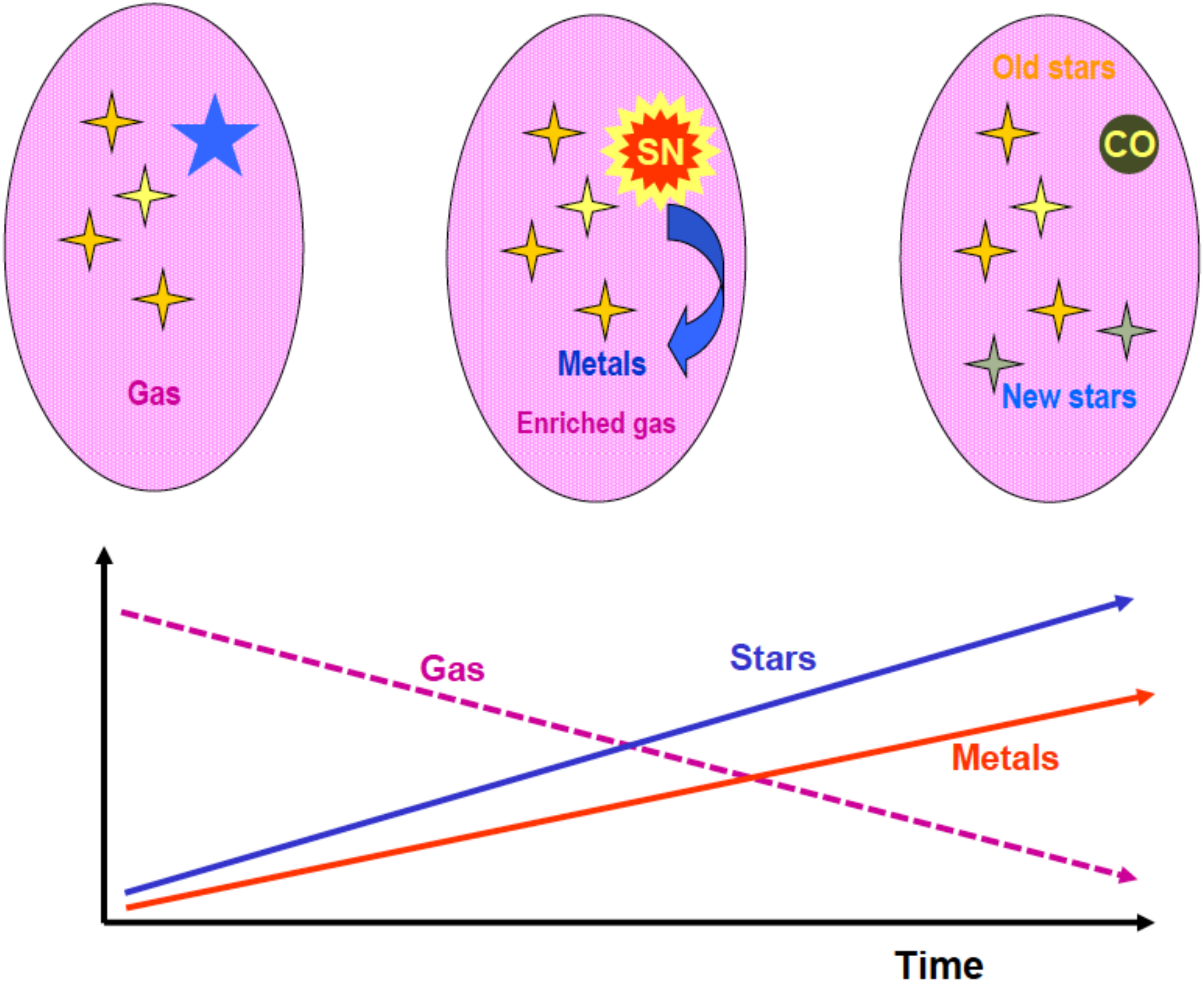
with contributions by Cristina Chiappini

Contents

- The astrophysical quests
- Astronomical messengers
- Examples across messenger categories
  - Cosmic abundances (direct, indirect)
  - Cosmic objects (where nuclear physics is key)
- Prospects and Challenges

Conceptual View: Cosmic Abundance Evolution

- 

Contributions of Stars to Abundance Enrichments

courtesy Nikos Prantzos

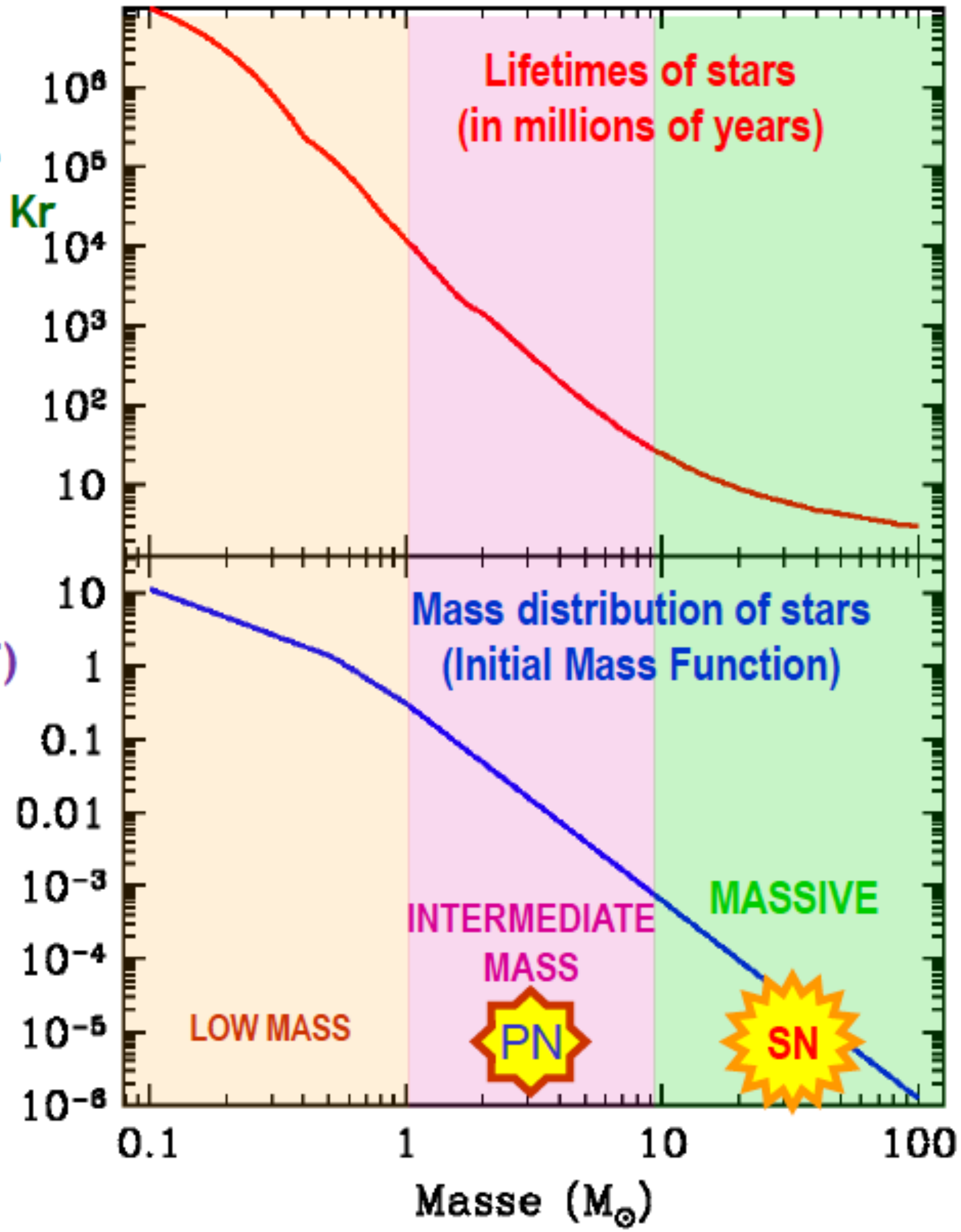
-

Massive stars (M > 10 Mʘ) contribute almost all of the nuclei between C and Kr and neutron-rich (r-) nuclei

Intermediate mass stars (1<M/Mʘ<10) produce s-nuclei and *part of* He3, He4, N14, C12, C13, O17, F19

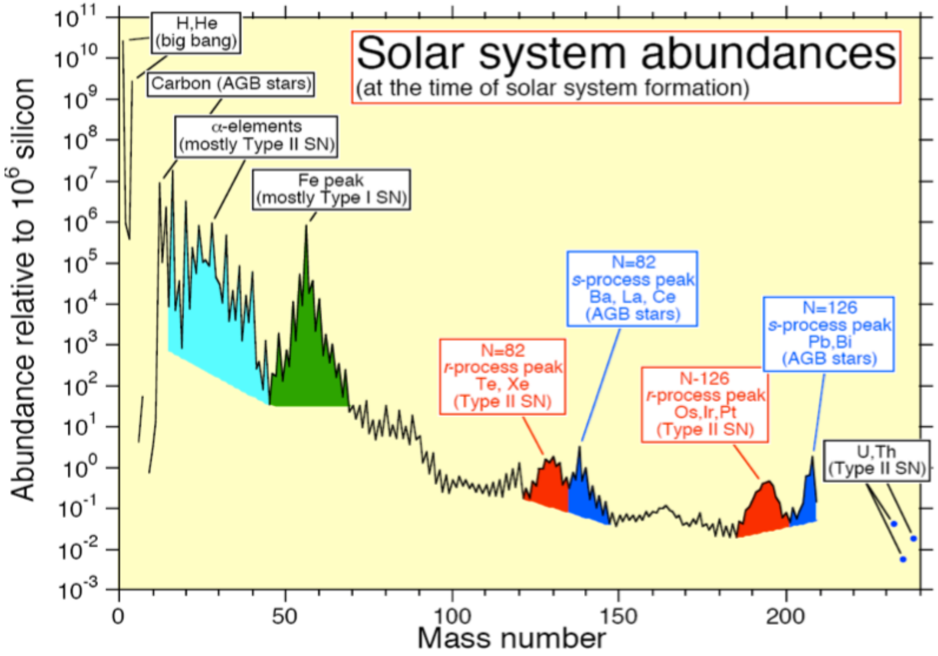
and are more efficient (because of IMF) in *astrating* fragile elements (e.g. D)

Low mass stars (M < 1 Mʘ) are "eternal" and just block gas, removing it from circulation

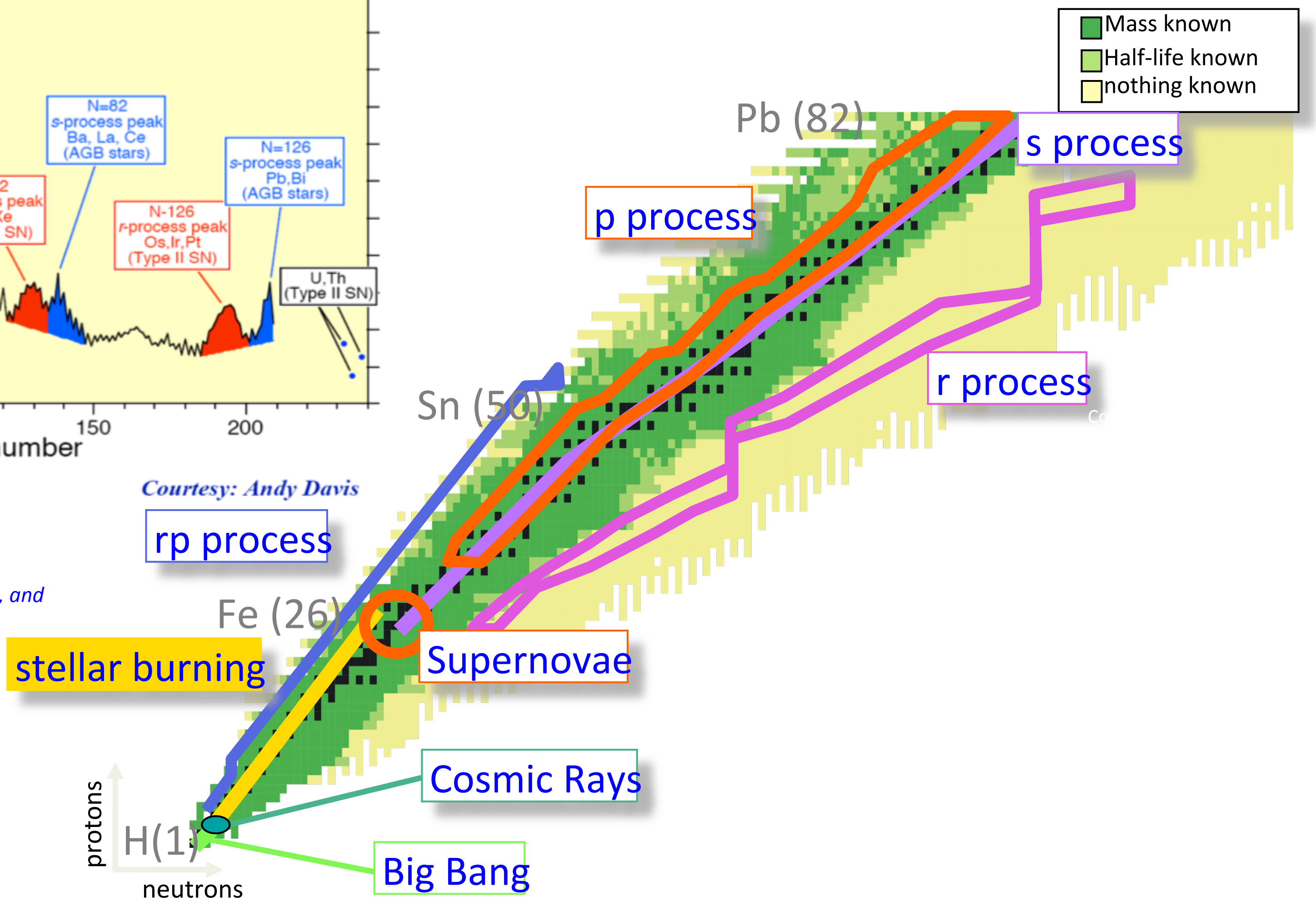


Cosmic origins of the variety of nuclides

Associating different "processes" with nuclide groups – that's what we teach…
… and know is superficial (or even wrong)

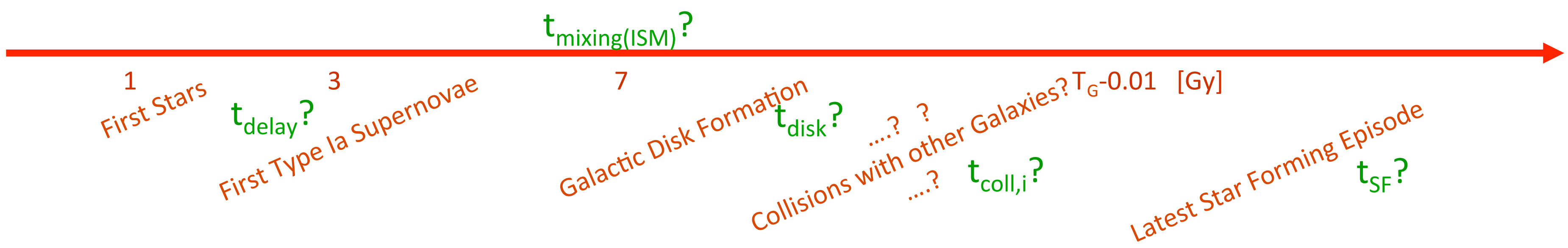


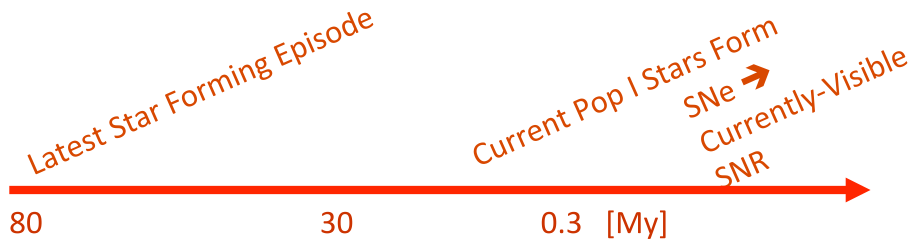
Courtesy: Andy Davis

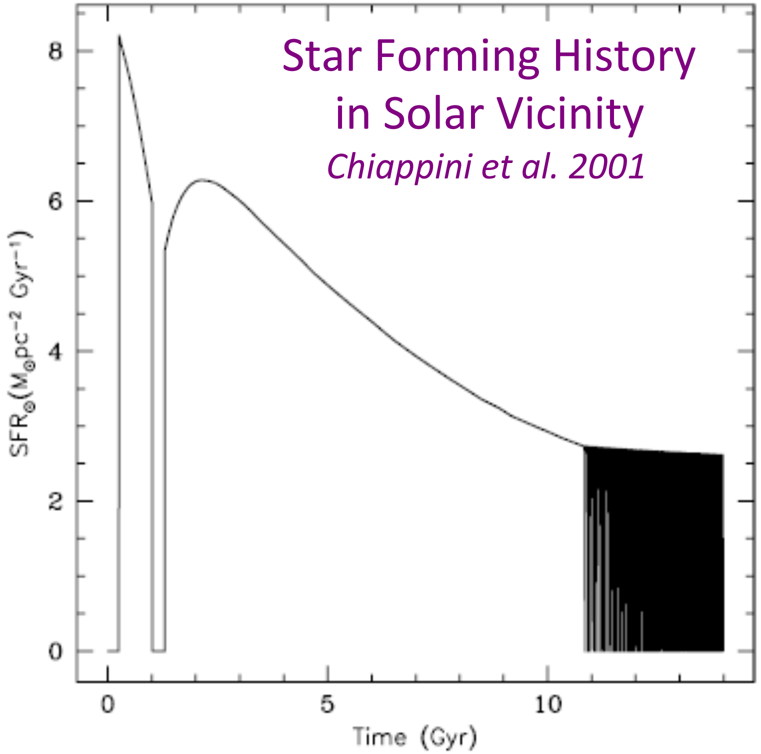


cmp. Burbidge, Burbidge, Fowler, and Hoyle, RMP 1959

Time Domains of Star-Formation in our Galaxy

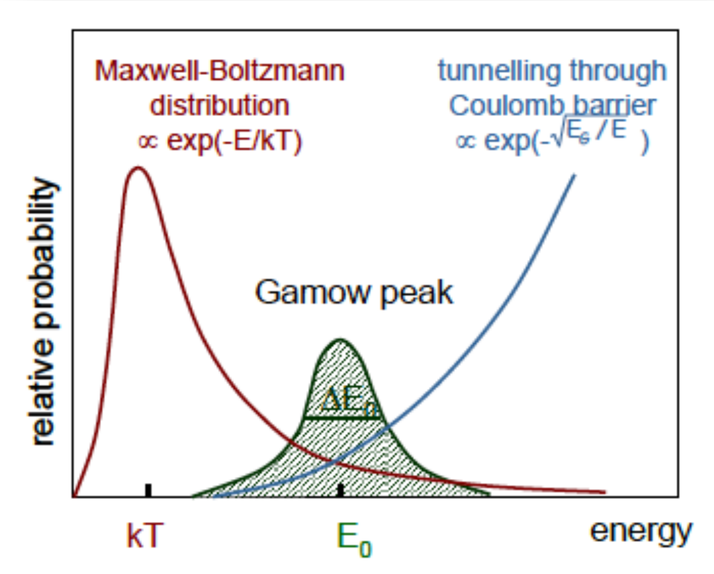


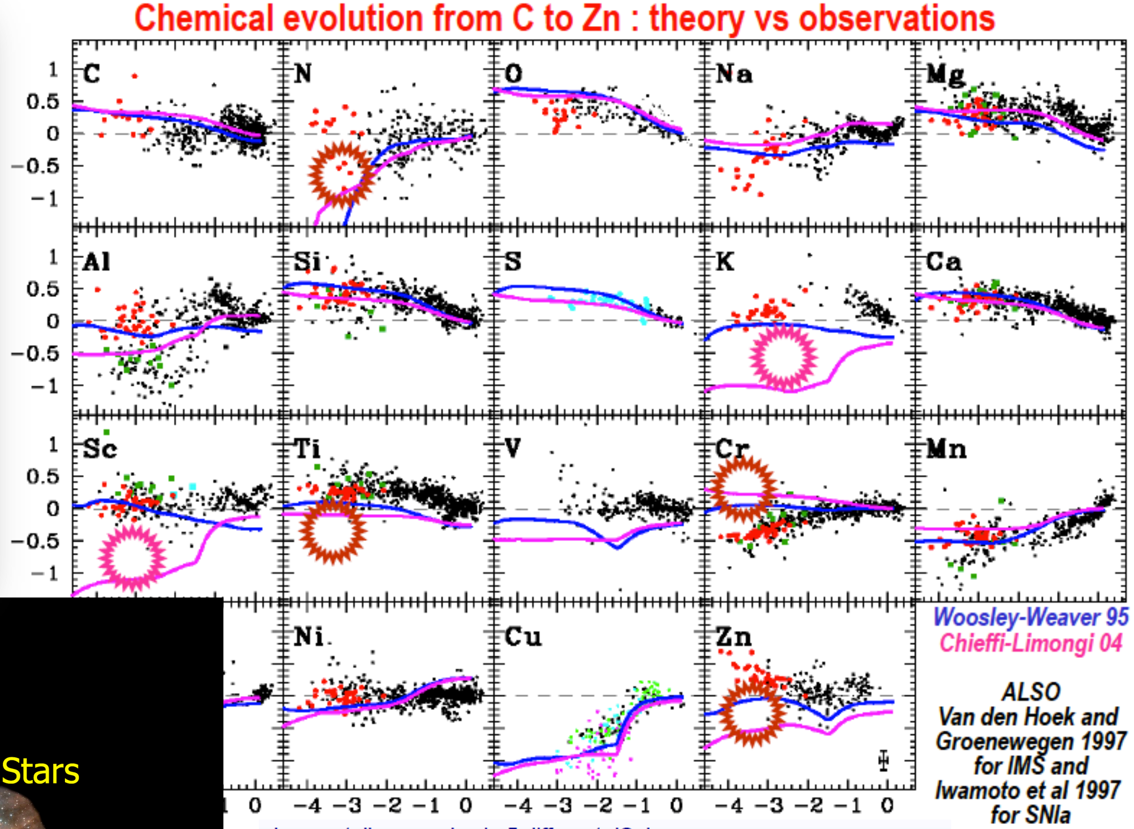


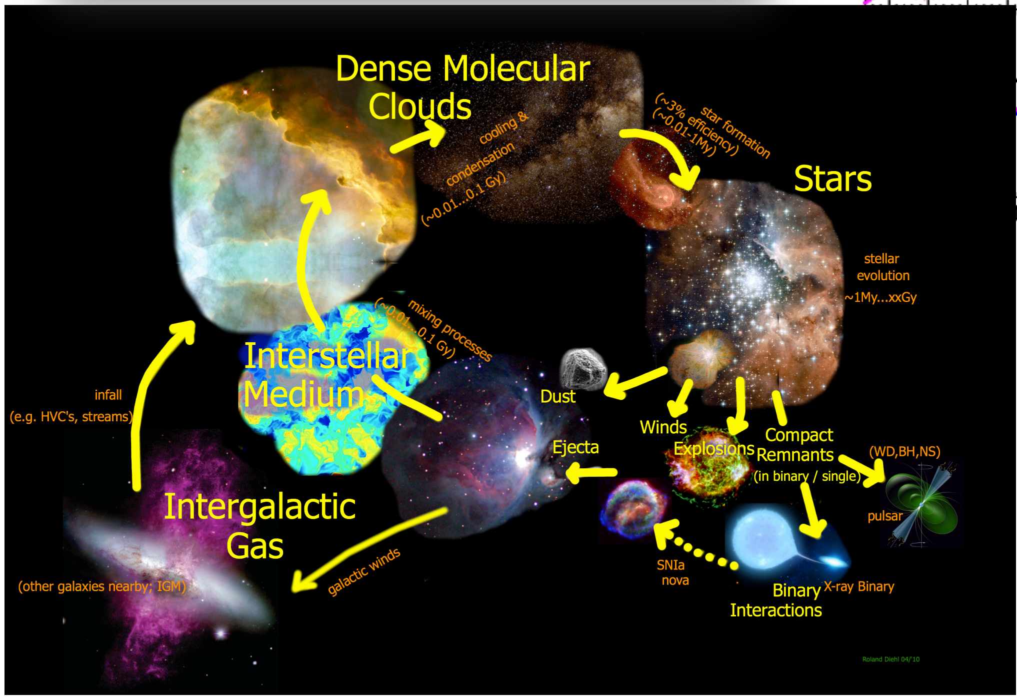


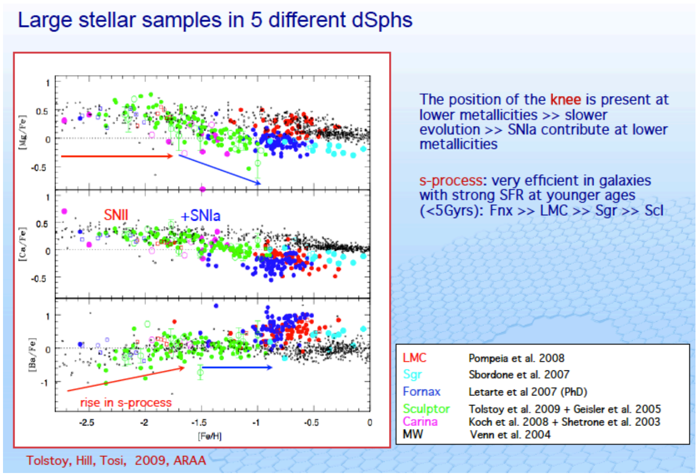
- We see…
  - Stars Ages 0…13 Gy
  - SNR,Pulsars Ages 0.03…30 ky
  - HII Regions Ages 0…5 My
  - Parental Clouds Ages 0.01…0.1 Gy
- …a highly fragmented and biased set of nucleosynthesis tracers

Chemical Evolution: Complex, Unsolved





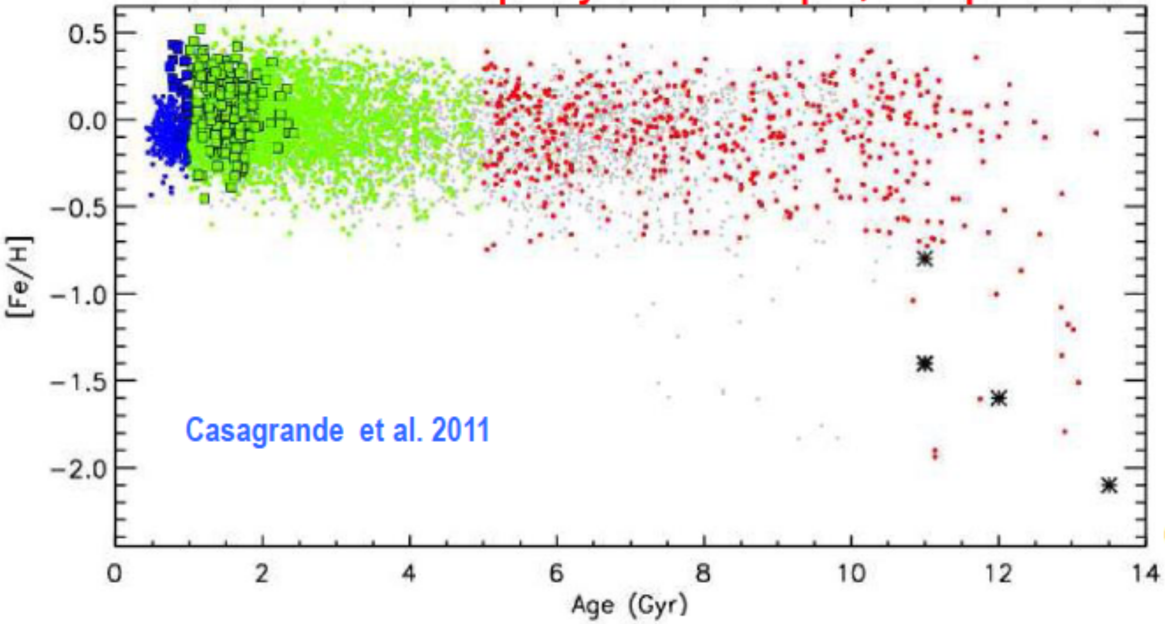


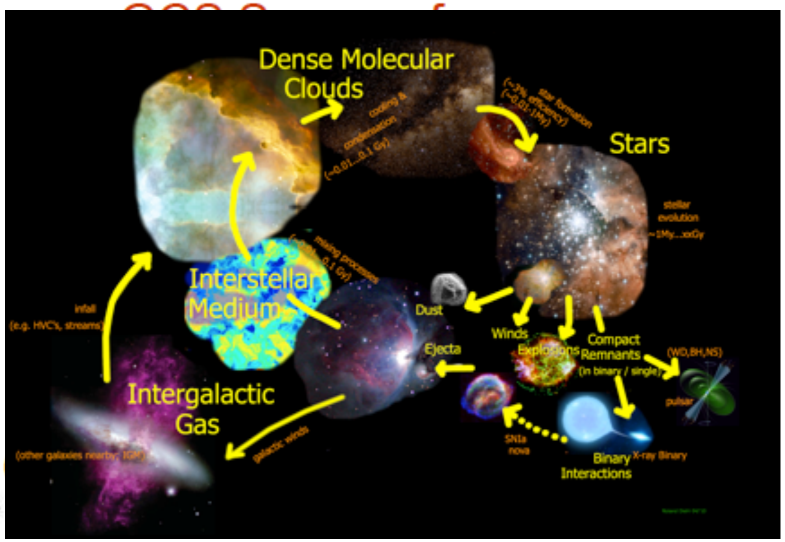


Compositional Evolution – a Challenge

- *From Lecture Series at Universe Cluster by Nikos Prantzos, Nov'14*

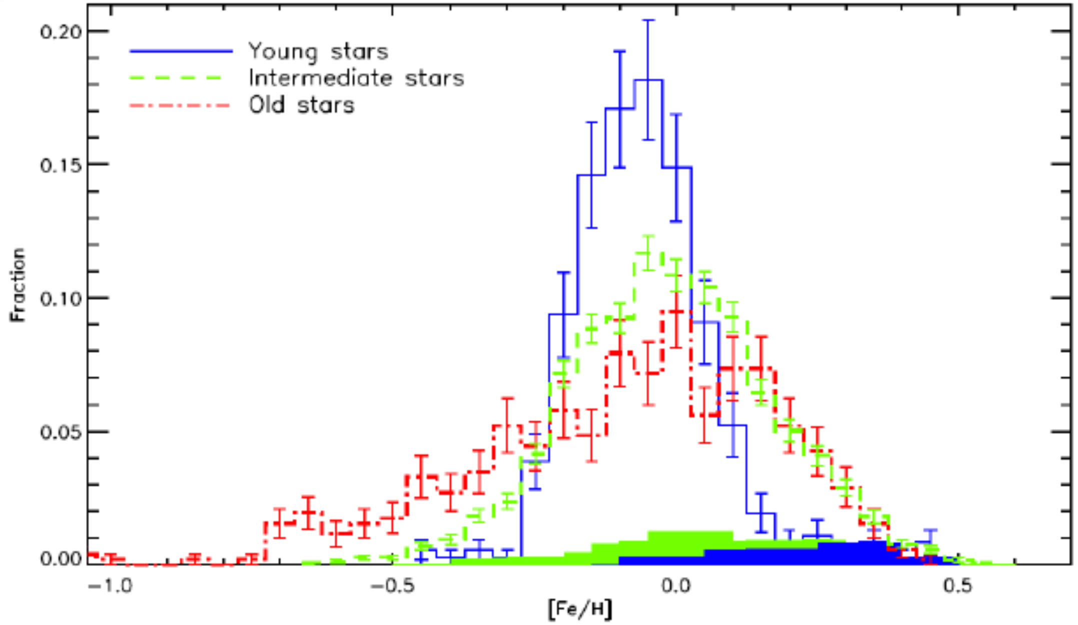
Inadequacy of the simple, independent-ring models





Old stars of **both** ***high*** and ***low*** metallicities

Inadequacy of the simple (independent ring) model (*Edvardsson et al. 1993, Haywood 2006*)

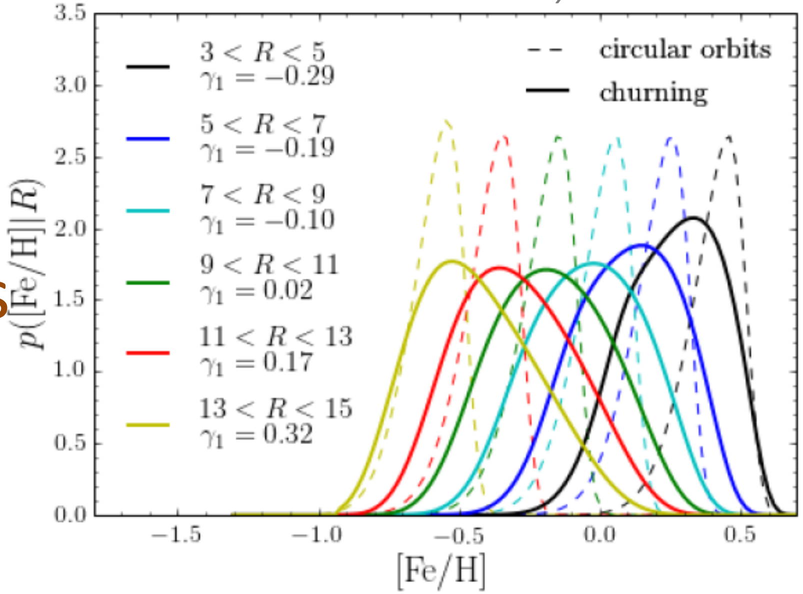


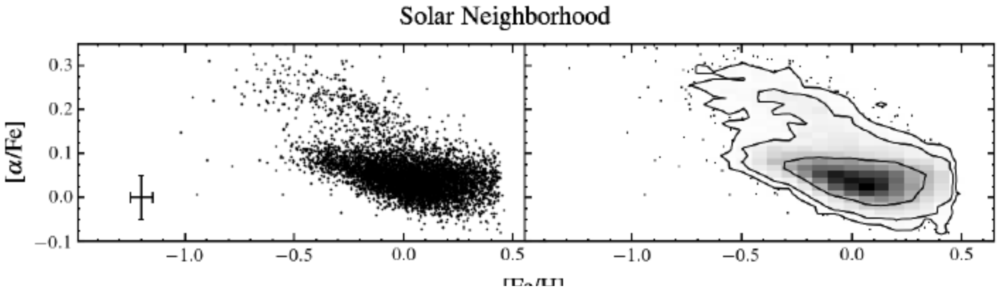
Abundance Measurements

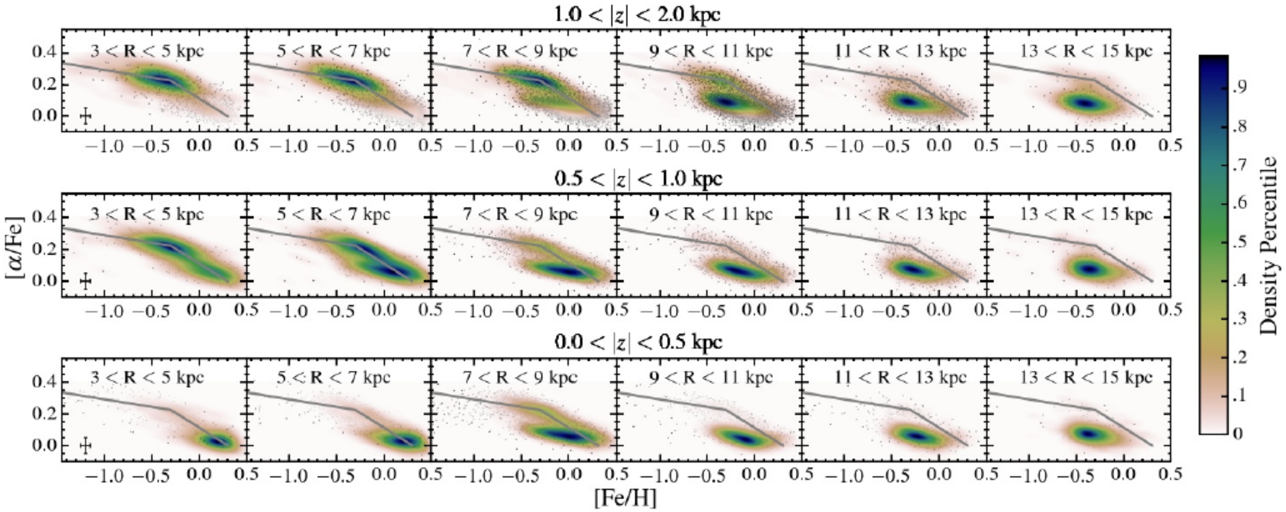
- SDSS/APOGEE
    - ~70000 stellar spectra
      → metal abundance distributions

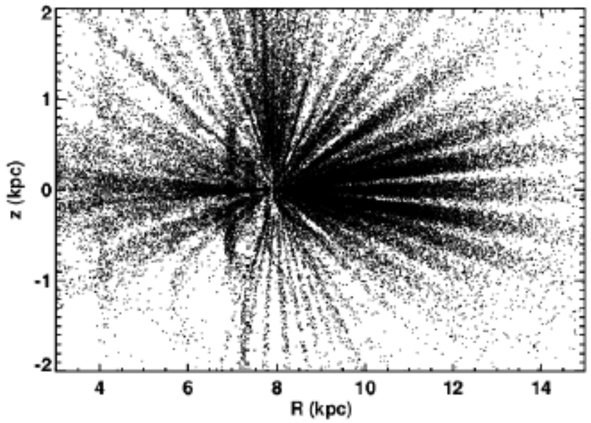
– stellar metal yields & migrations

Hayden et al. 2015









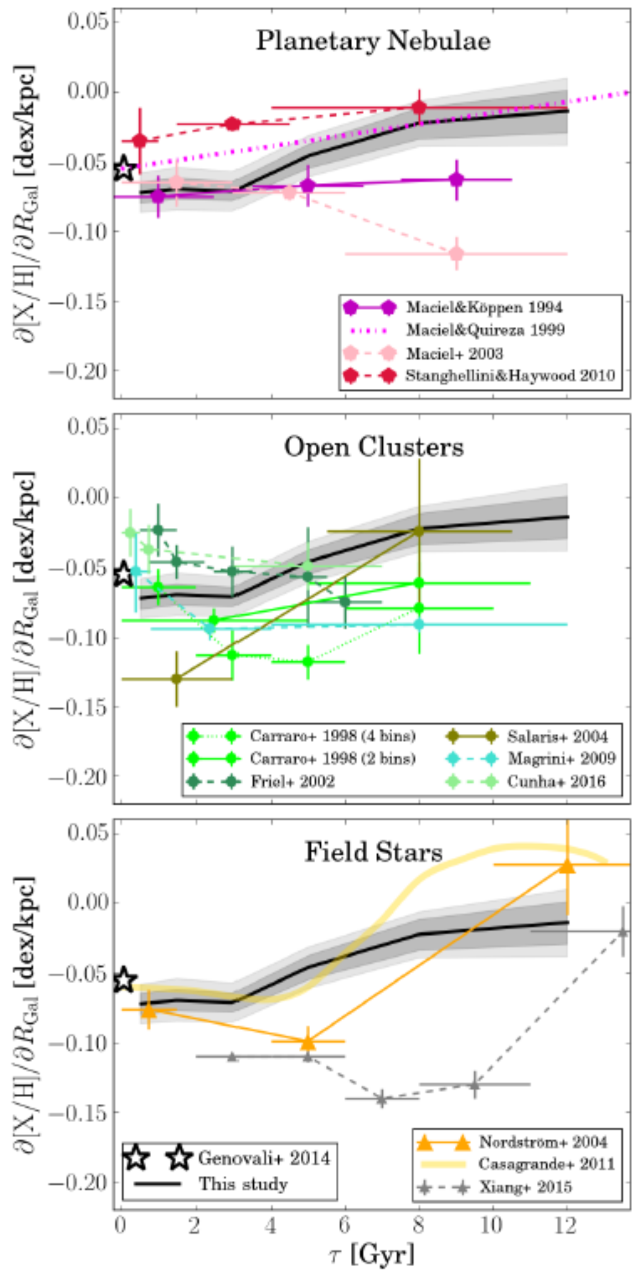
Abundance Measurements

- Issues:

Anders et al. 2016:

: There is no consensus about the evolution of the Galactic radial metallicity gradient over cosmic time, not among groups using the same tracers, and sometimes not even among the same groups, or the same datasets. This is essentially due to five reasons:

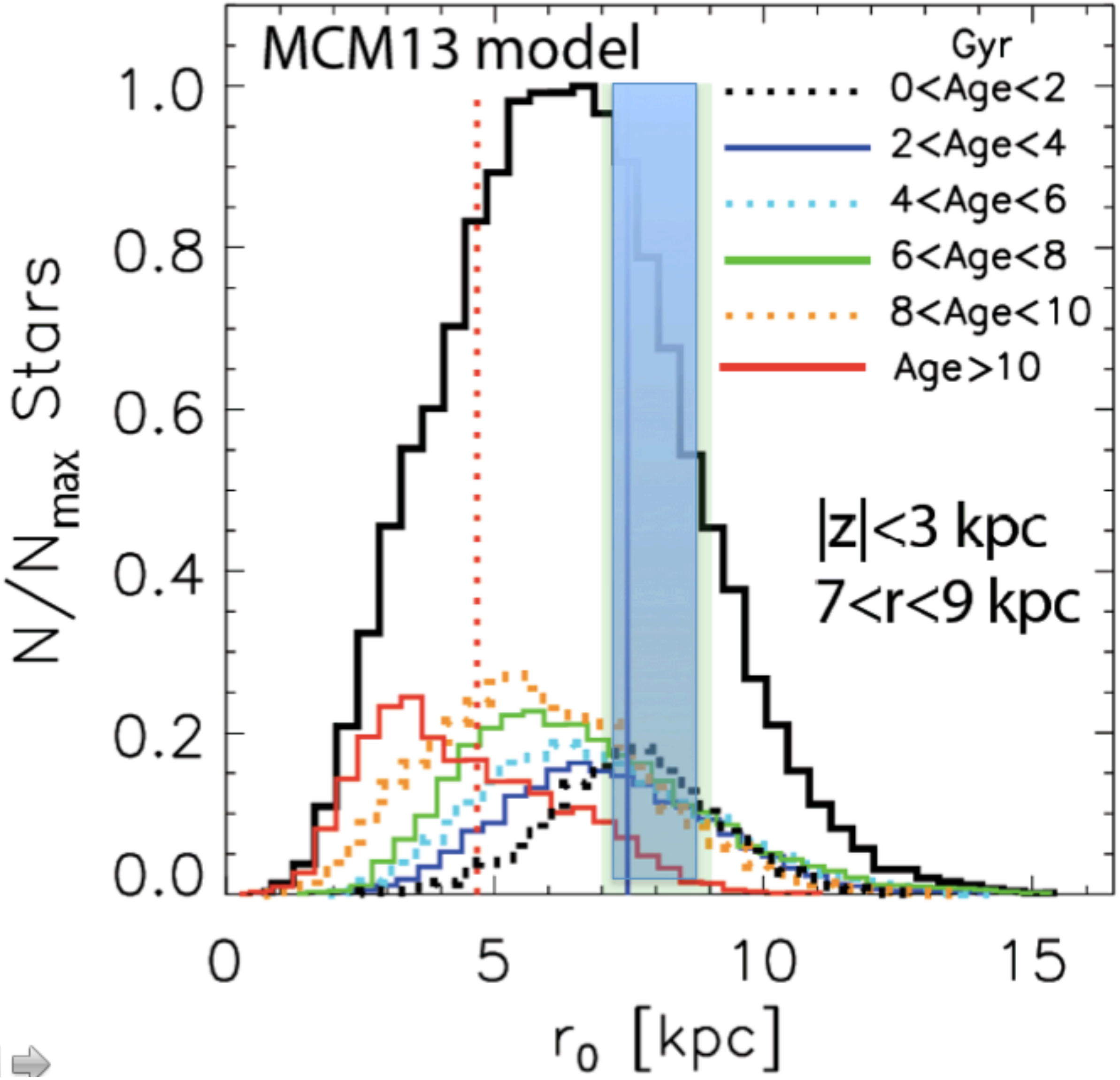
1. Different radial and vertical ranges of the disc considered;
2. Different age, distance, and abundance scales among different groups, and between different tracer populations, especially in the case of PNe;
3. Different selection biases for the various tracers;
4. Insufficient statistics;
5. Different fitting methods, handling of outliers, etc. (Sec. 4.1).



Chemodynamical Modeling: Radial Migration

Mosaic of stars born at different $R_{initial}$ at different times

- New Approach: Chemodynamical model of the MW (Minchev, Chiappini, Martig 2013, 2014)



r_0 = Birth Radii in kpc

Input chemistry:
Thin disk only

Self-consistent dynamics:

N-body simulation in cosmological framework:
early mergers,
gas infall,
bar,
spirals,
radial migration

Help from Asteroseismology: Distances!

- Uncertainties in distances ~ 15 %; <5% for high quality data

$$\log d = 1 + 2.5 \log \frac{T_{\rm eff}}{T_{\rm eff,\odot}} + \log \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} + -2 \log \frac{\Delta\nu}{\Delta\nu_\odot} + 0.2(m_{\rm bol} - M_{\rm bol,\odot}),$$

d is expressed in pc, $m_{\rm bol}$= apparent bolometric magnitude, $M_{\rm bol,\odot}$= absolute solar bolometric magnitude.

- **Seismic log g -> uncertainty of 0.03 dex**

[spectroscopic usually 0.1-0.3 dex!]

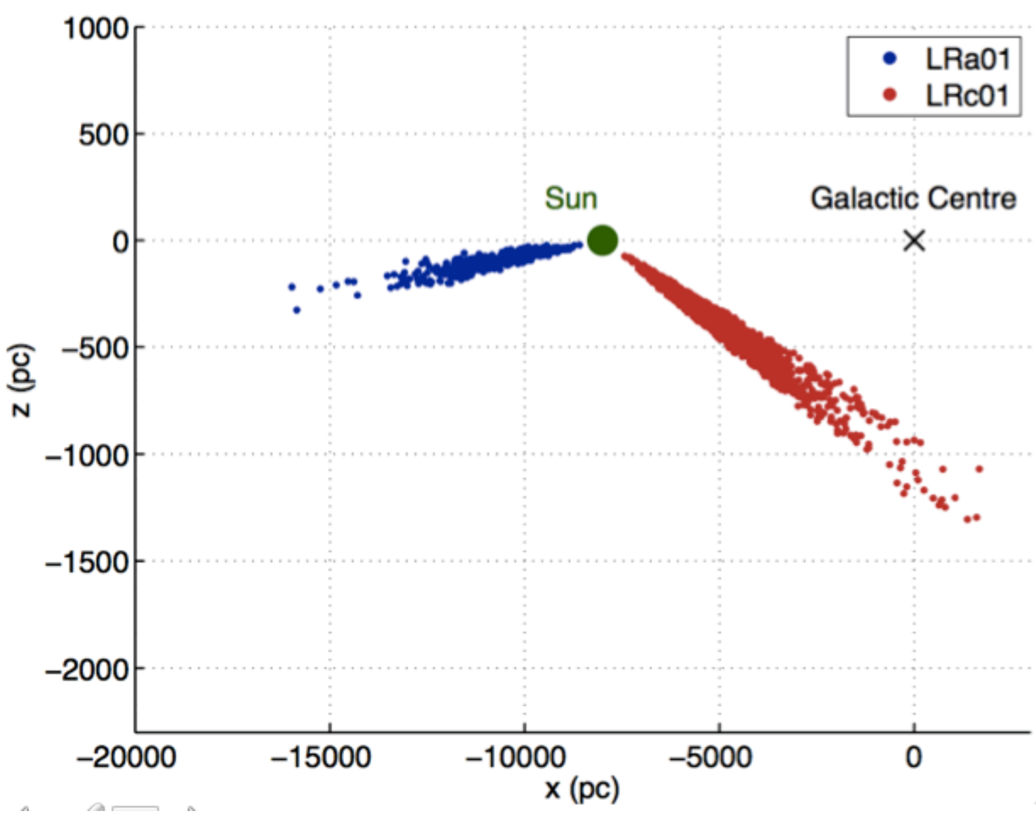
$$\log g = \log g_\odot + \log\left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) + \frac{1}{2}\log\left(\frac{T_{\rm eff}}{{\rm T}_{\rm eff,\odot}}\right)$$

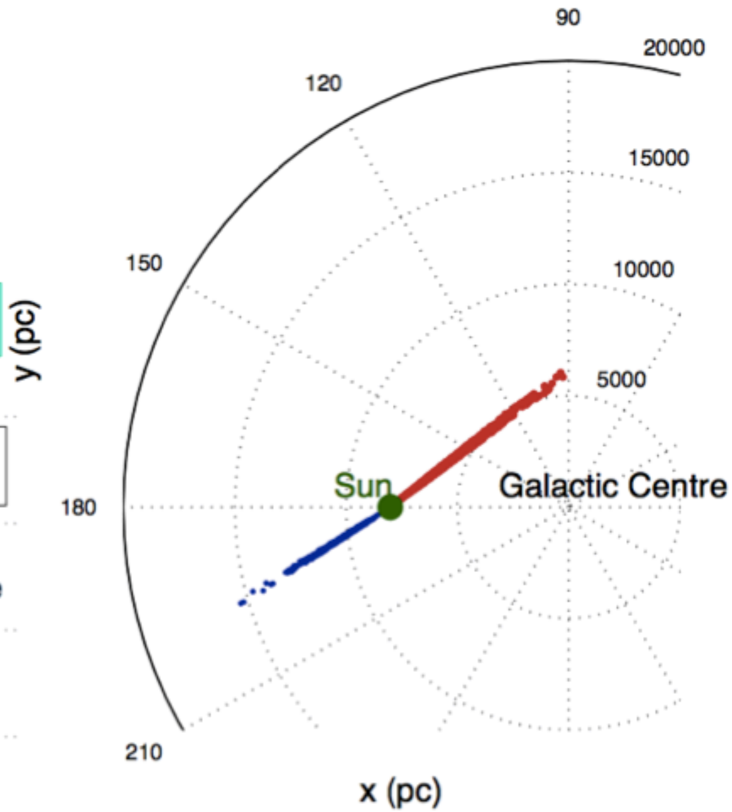
Help from Asteroseismology: Distances!

CoRoT

First use of asteroseismology to determine precise distances for a large (~2000) sample of field stars (giants) spread across nearly 15 kpc of the Galactic disc.

Different Mass Distributions -> Age vertical gradient





Miglio, Chiappini, Morel, Barbieri, Chaplin, Girardi, Montalban, Noels, Valentini, Mosser, Baudin, Casagrande, Fossati, Silva Aguirre & Baglin 2013, MNRAS 429, 423
[LRa01+Lrc01 analysis]

Other issues…

- How long does it take to get matter recycled?
    - Efficiency?? Lock up in stars, dust. Loss towards IGM
- How do stars change the conditions for star formation?
    - “feedback”
- How well do we understand the cycle of matter?
    - Budget: missing baryons. Outflows, infall? Cosmic SFH?
- Are specific sources dominating some parts?
    - r process: one source?

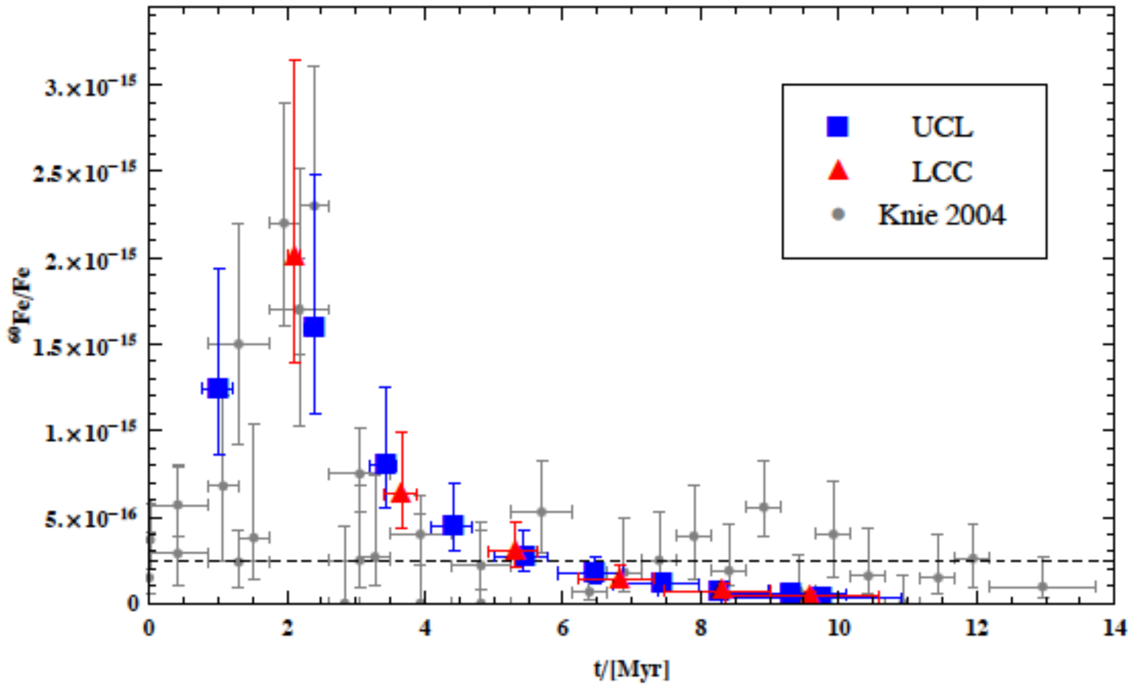
- …

Supernova Ejecta from a Nearby Event

- ^{60}Fe Clearly Seen in Oceanfloor Samples

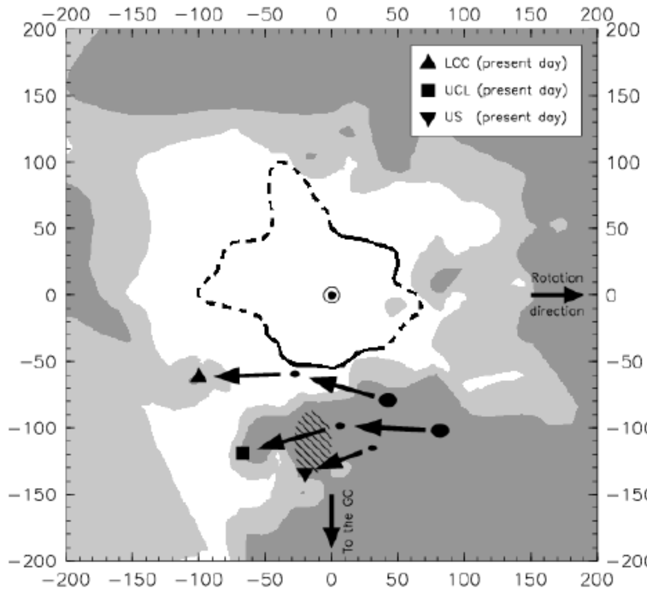
→ SN ~2-3 My ago

Knie et al. 2004; Fitousi et al. 2008; Feige 2014; Fimiani et al. 2015



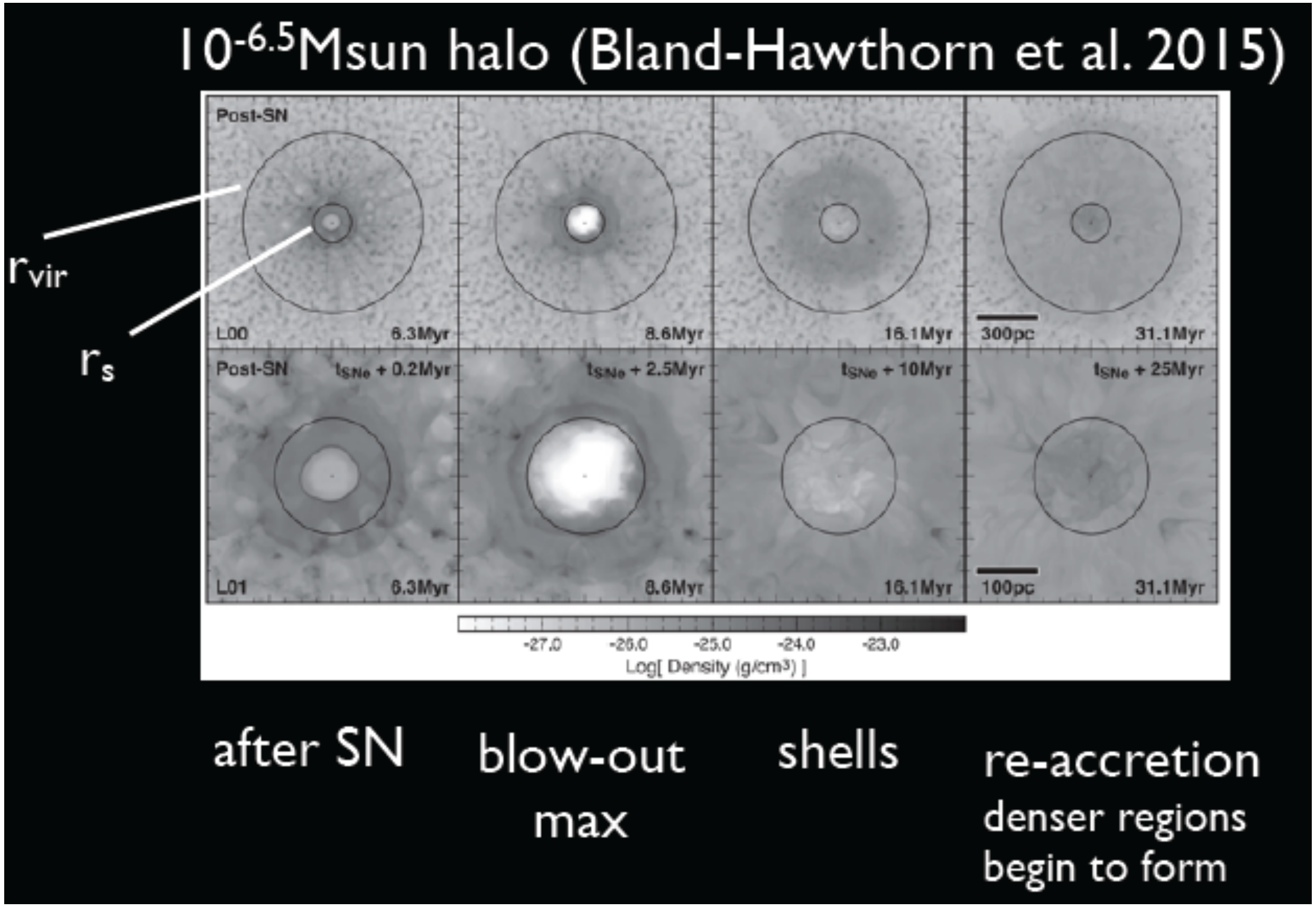
The computed data (UCL: blue, LCC: red) plotted over the ^{60}Fe measurements (black points) with an ISM density of n = 1 atom/cm^3.

Feige+ 2014



Stellar & Supernova Feedback

- Winds and supernovae drive gas away from SFRs
  - Galactic chimneys, fountains
  - Special "laboratories": Globular clusters, dwarf galaxies



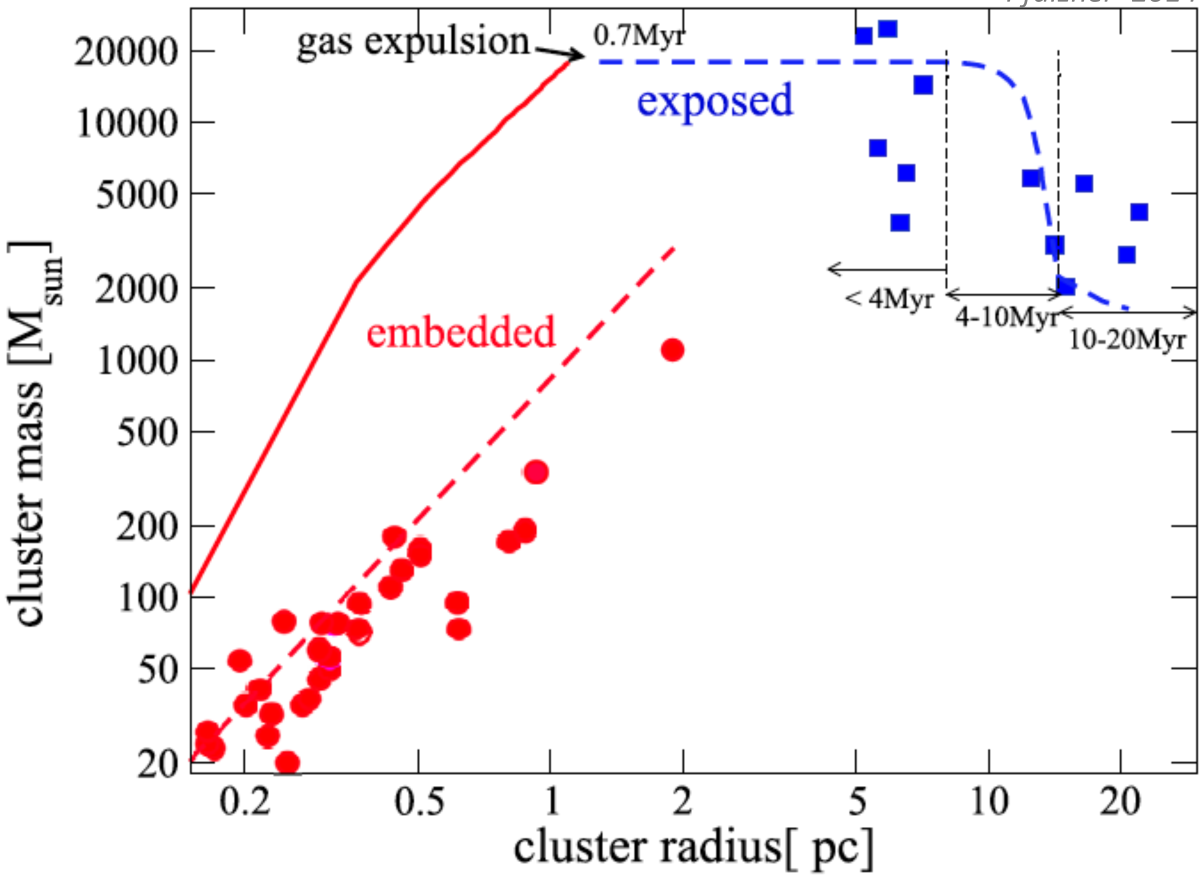
Globular Clusters

Massive-Star Cluster Birth & Evolution

Issues: (…OC's, YMC's, GC's…)

- Formation monolithic or hierarchical?
- Role of initial gas mass?
- Role of gas expulsion?

Pfalzner+2014



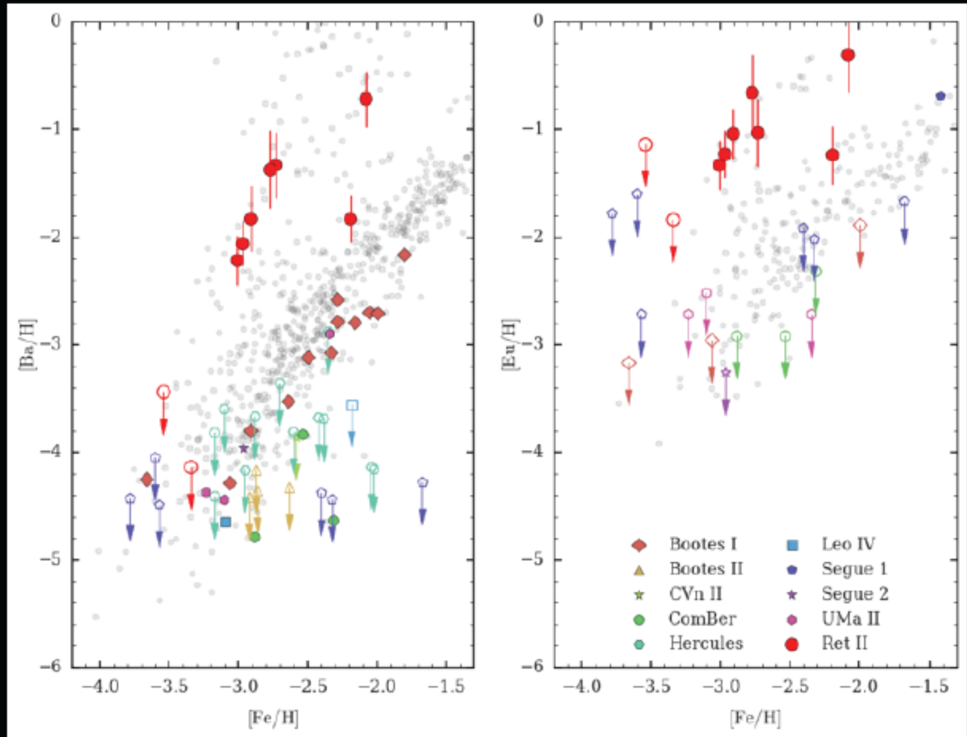
- How does gas expulsion happen???

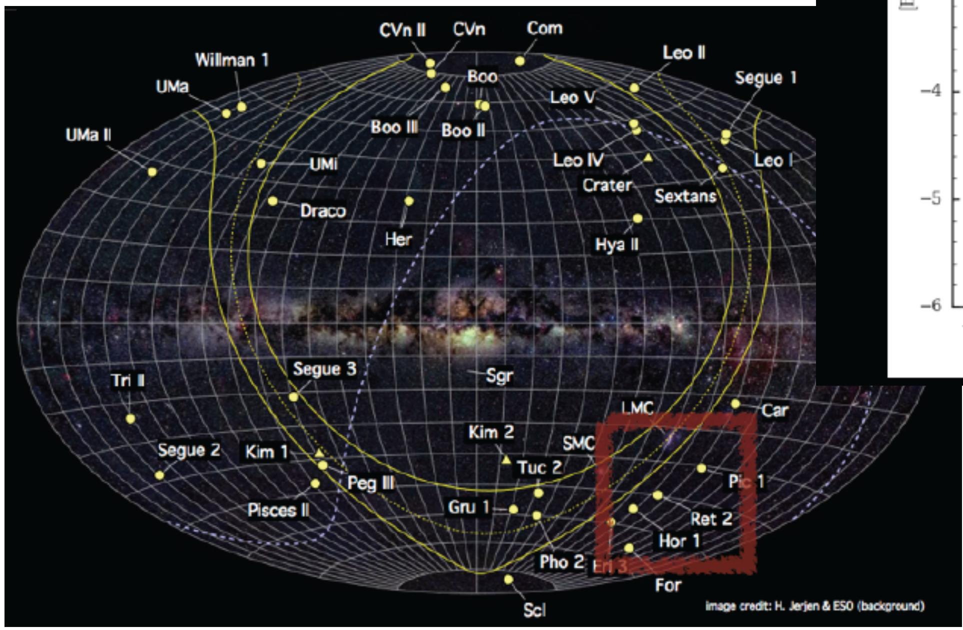
- *see also Banerjee & Kroupa 2015, Gentry+ 2016, Krause+2016, Li+2016, Pfalzner+2016, Yadev+2016, …*: an active field!

New laboratories: dwarf satellite galaxies

- Few stars → simple enrichment history
  - Ret II:
    high and homogeneous
    r enrichment:
    case for NS merger?
    - » Ji, Frebel 2016

Ret II stars >100x higher neutron-capture element abundances than other UFDs

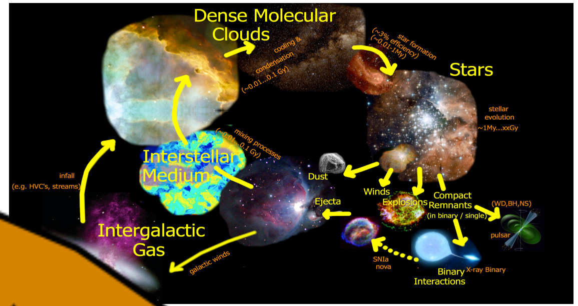


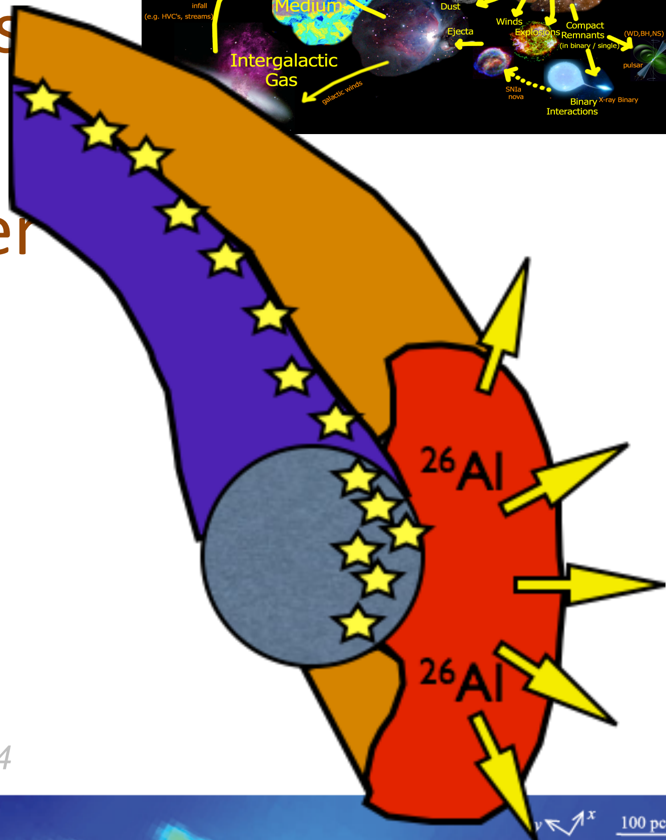


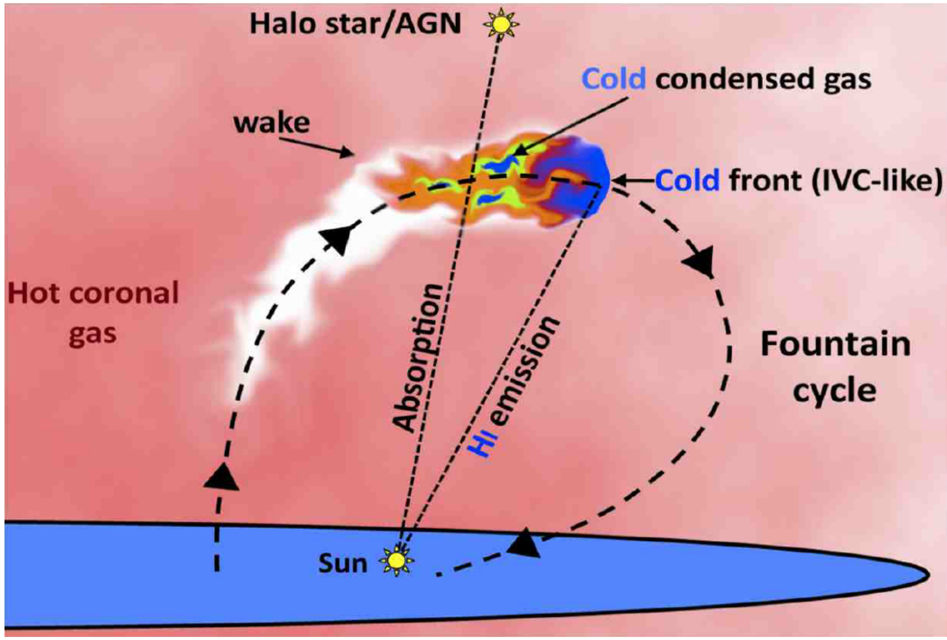
The Cycle of Gas in a Galaxy

How the Galaxy's Disk and Halo "communicate"

- Chimneys around massive-star groups eject gas into halo
- Constancy of Star Formation Rate over Galaxy-Evolution Times (Depletion would be Fast)

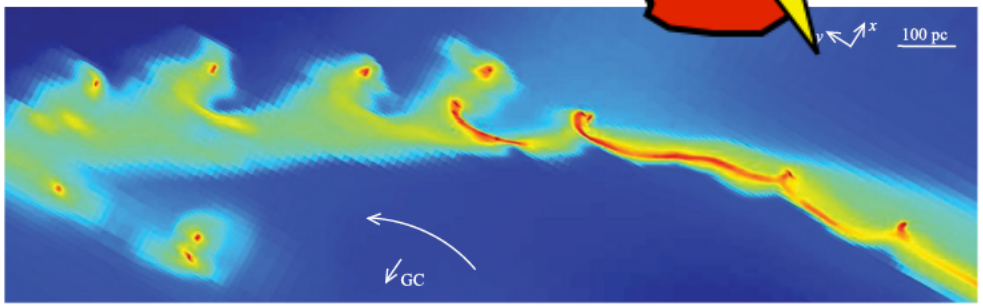






Marasco, Fraternai, & Binney 2011; Fraternali et al. 2013

Renaud et al. 2014



Atomic gas: HI 21 cm line

- GASS & EBHIS survey "HI4PI" *(Ben Bekhti et al. 2016)*

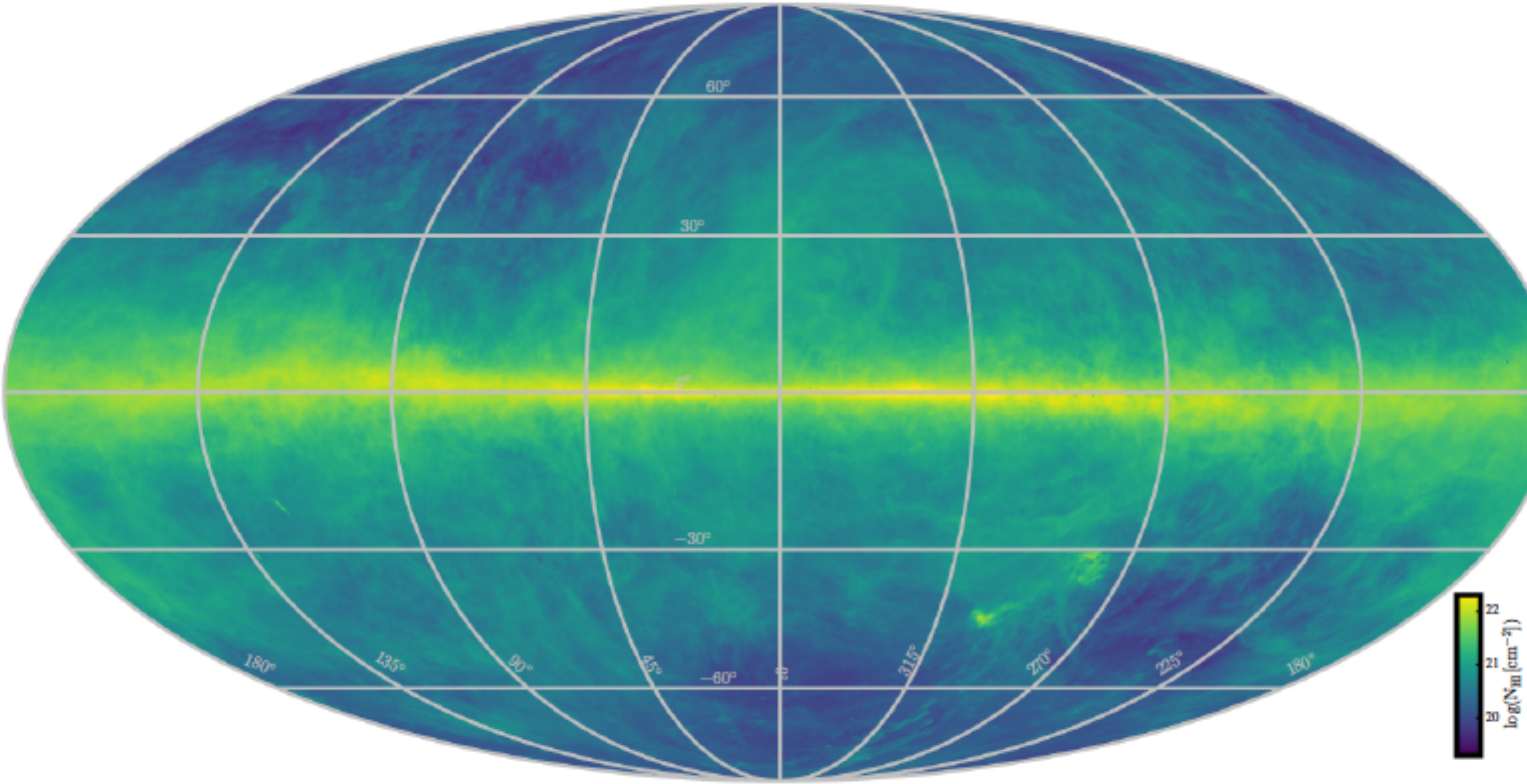
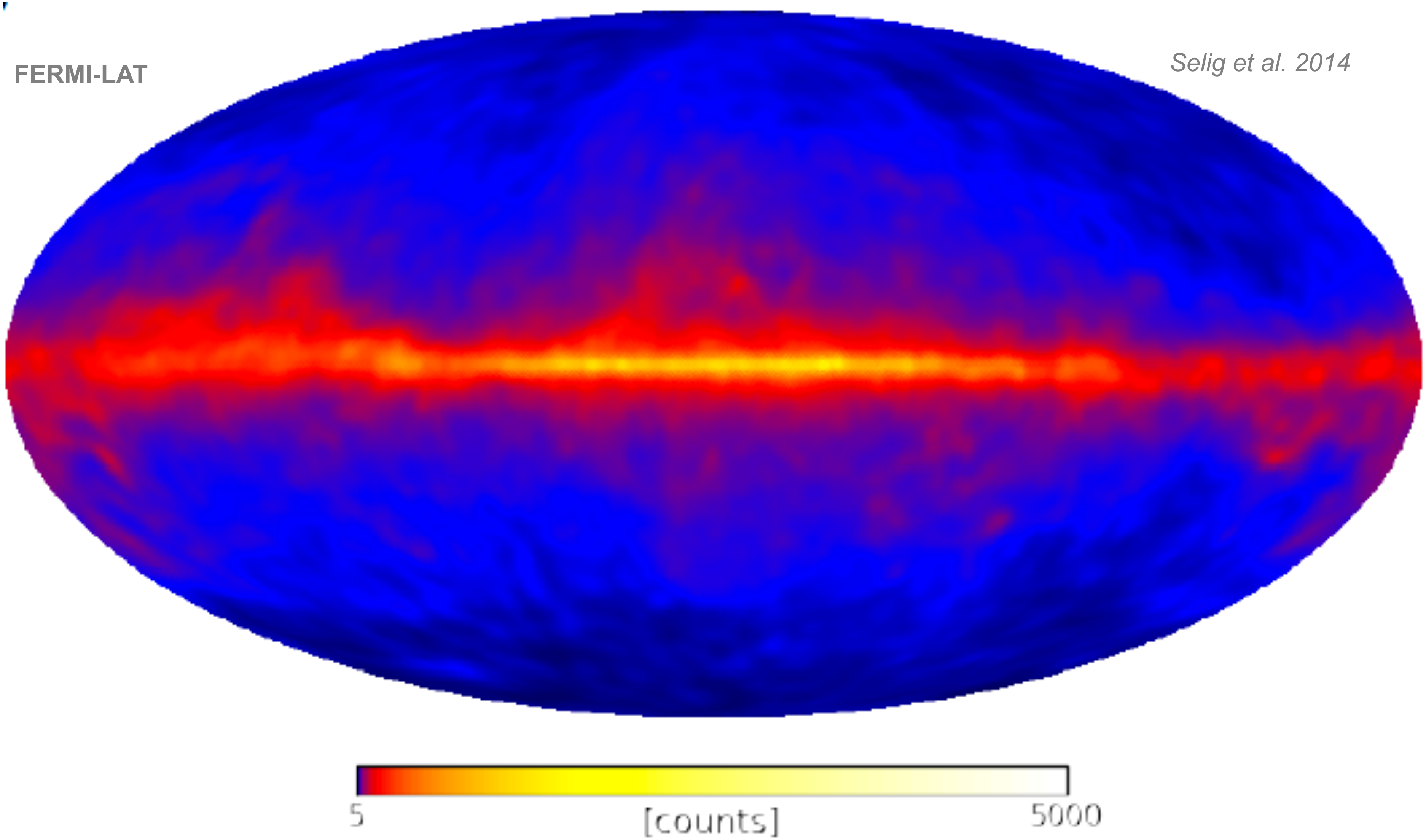


Fig. 2. HI4PI: all-sky column density map of H I gas from EBHIS and GASS data as integrated over the full velocity range $-600 \le v_{lsr} \le 600\ km\ s^{-1}$. The map is in Galactic coordinates using Mollweide projection.

Interstellar gas of our Galaxy

- Fermi gamma-rays: Cosmic rays illuminating ISM

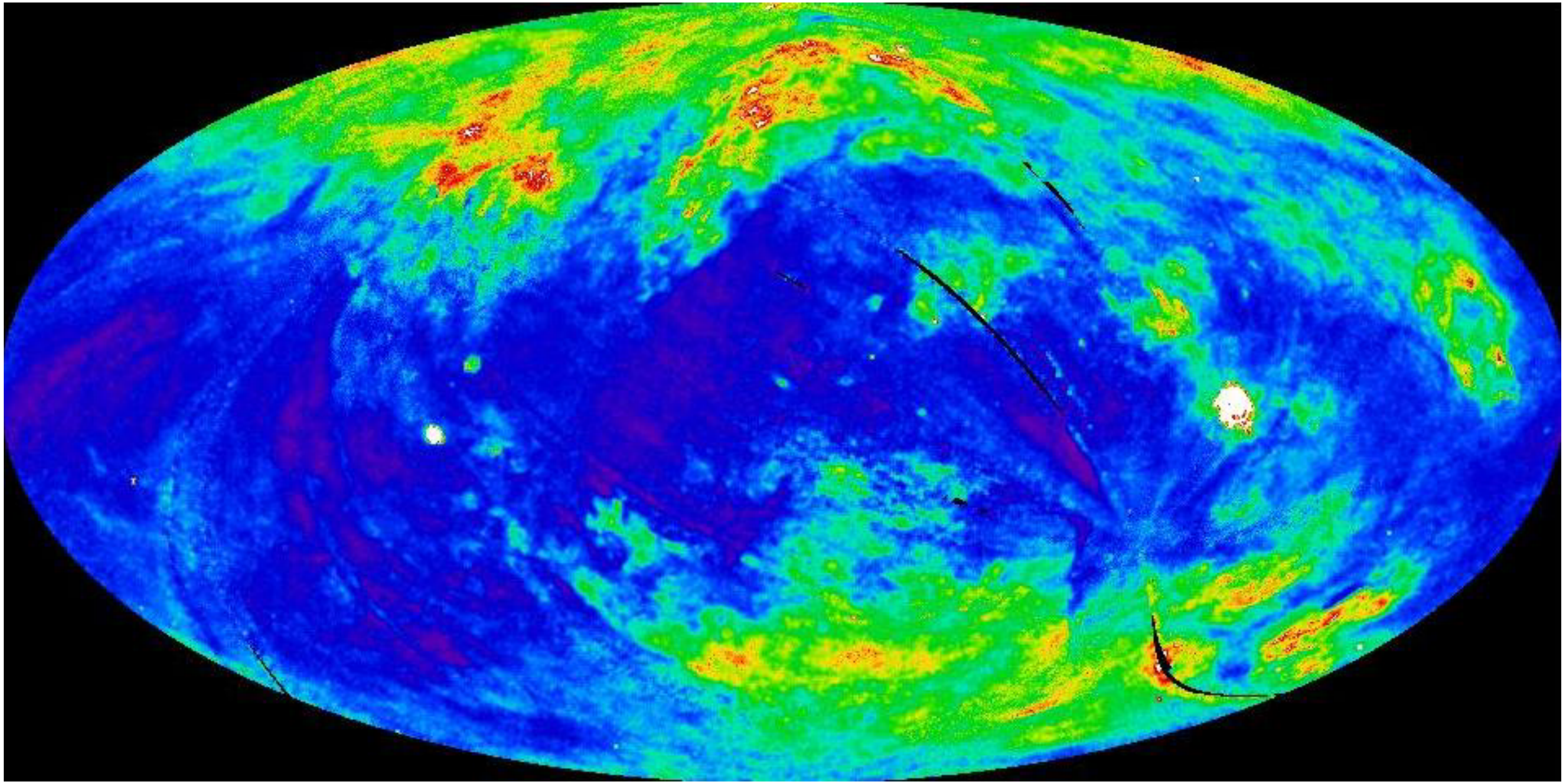


Hot gas of our Galaxy

- X-rays: thermal emission from hot gas
  - Absorbed within the Galactic Disk

ROSAT 0.25 keV

Snowden et al. 1995, 2015

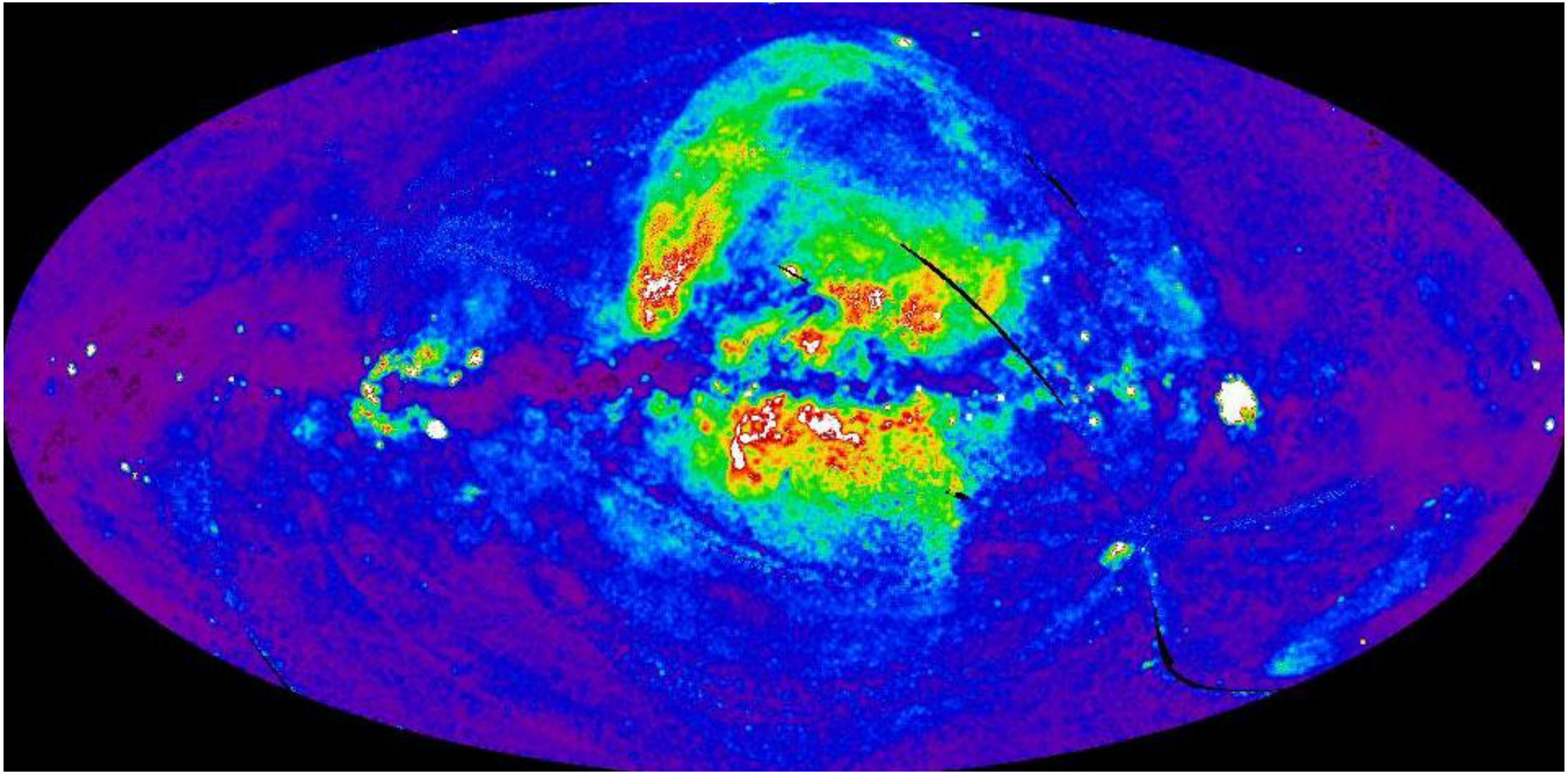


Hot gas of our Galaxy

- X-rays: thermal emission from hot gas
  - Local bubble, Loop I, Cygnus SB, Vela SNR, …

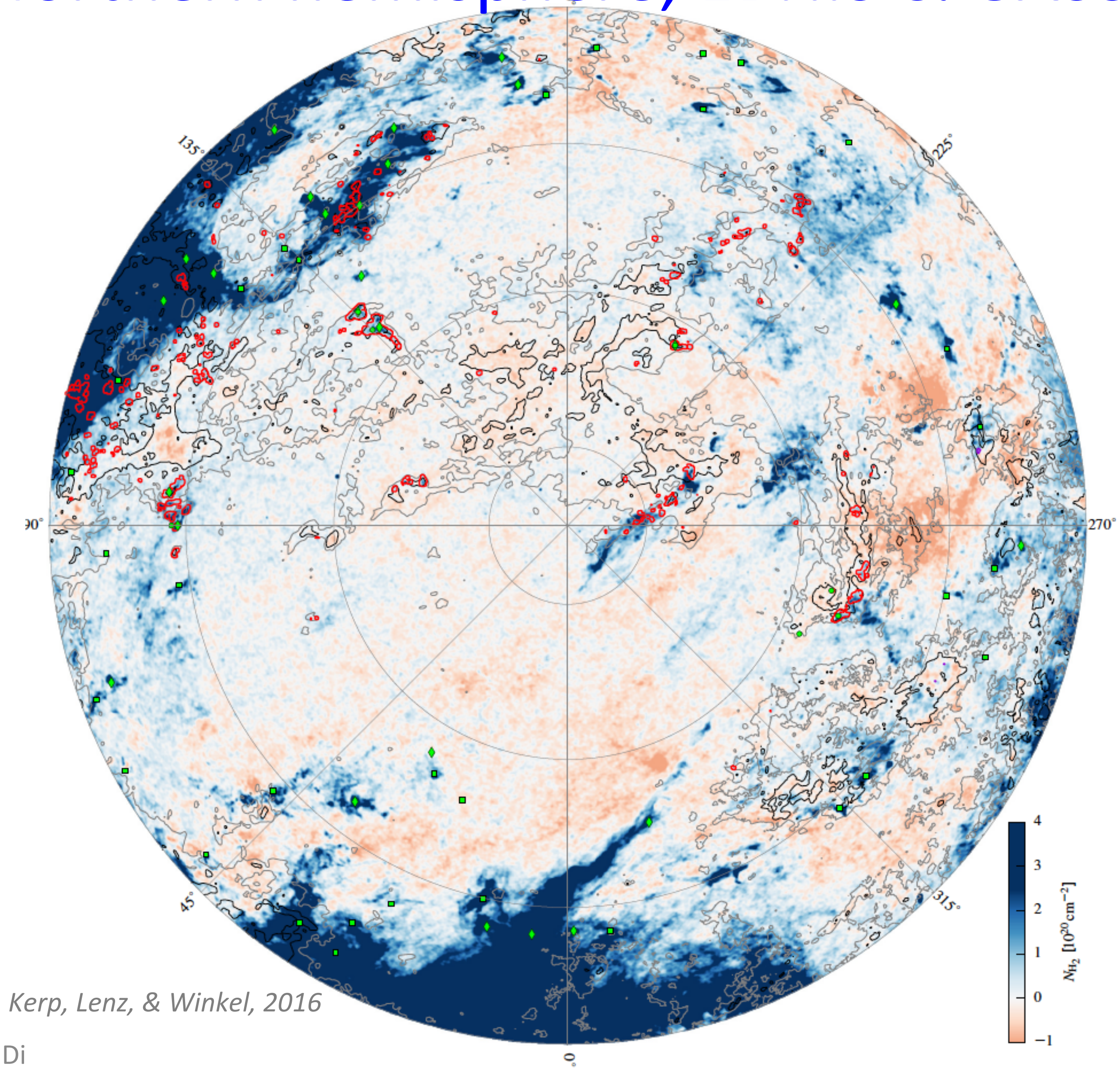
ROSAT 0.75 keV

Snowden et al. 1995, 2015



HI observations: Infalling clouds

- Northern hemisphere, EBHIS & GASS

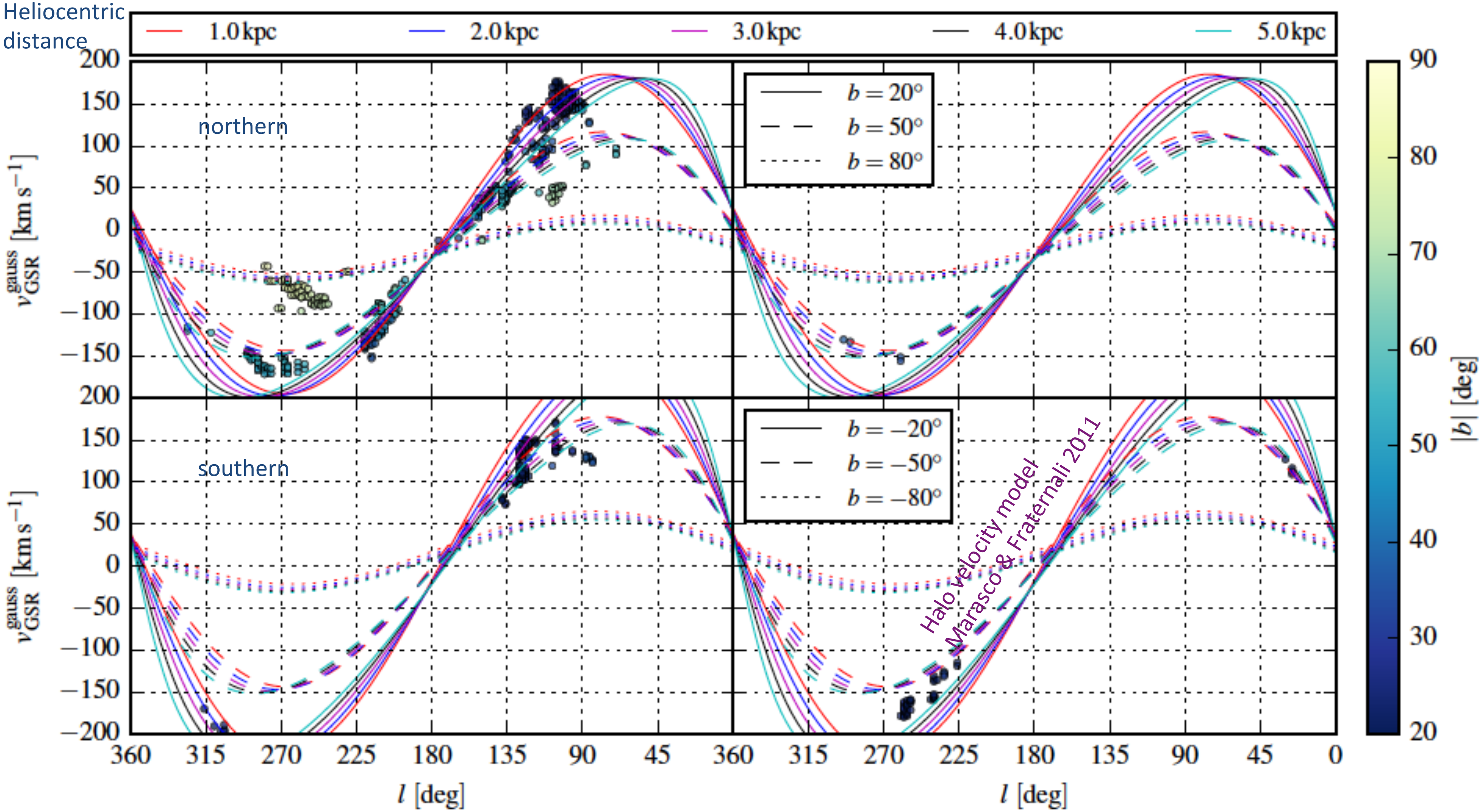


Röhser, Kerp, Lenz, & Winkel, 2016

HI observations: Infalling clouds

- Velocities → Origin in Galactic fountains

Röhser, Kerp, Lenz, & Winkel, 2016



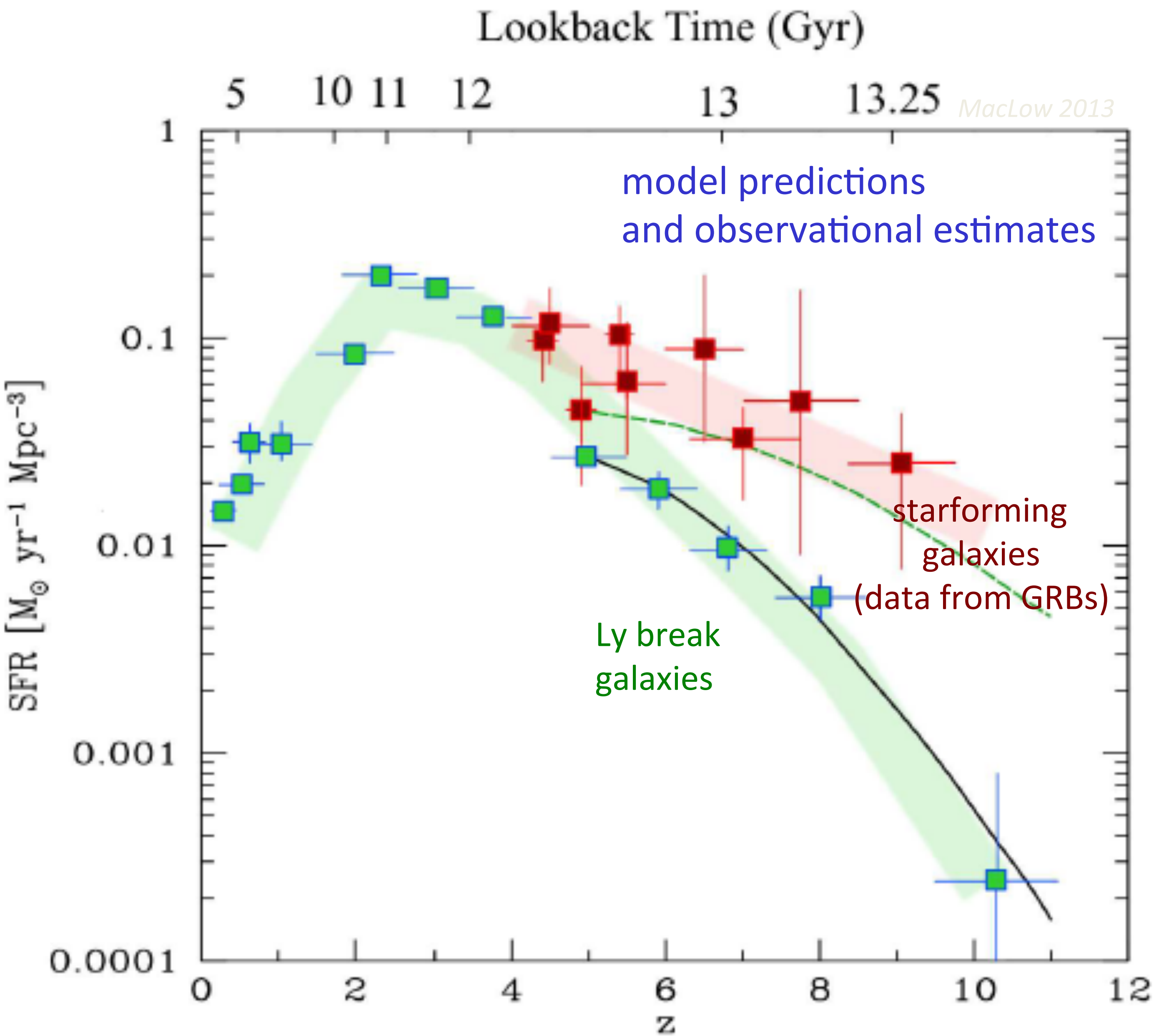
From chimneys to galactic winds

- How does gas leave a galaxy?

- Fermi bubbles

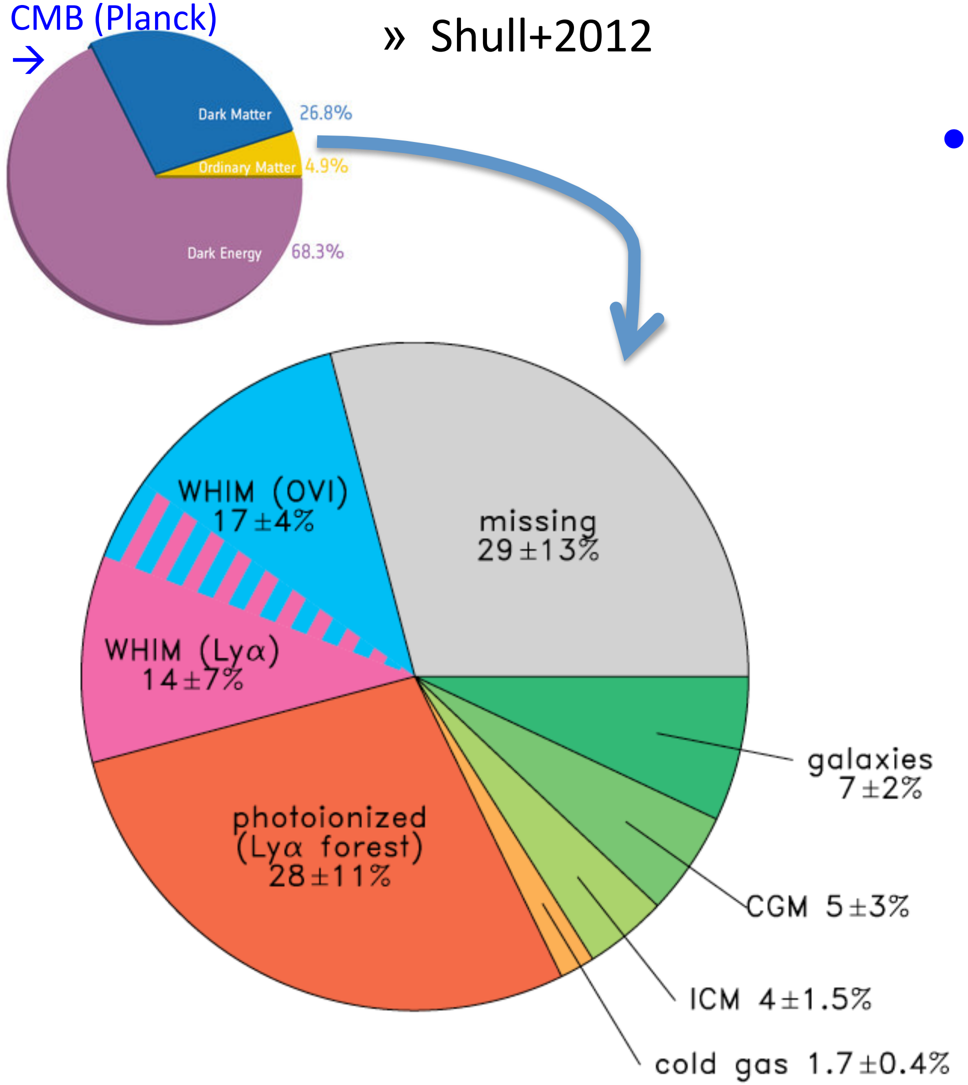
Star formation: cosmic history

- We cannot easily probe the distant/early universe



Cosmic Matter Budget: Missing Baryons

- Adding up observations of different matter components
  - » Shull+2012



- Ly α observations

Describing compositional evolution

- Numerical schemes (SPH) allow to handle
  - Complex mixture of source processes
  - Inhomogeneities of matter and evolution
  - Mixing on different spatial and temporal scales
- How do we ensure "understanding"
  - Analytical prescriptions
  - Limiting cases and situations
  - Link to observations, addressing / avoiding degeneracies

Chemical Evolution Descriptions

- Include all relevant sources and sinks
  - Stars, supernovae; rare but partially very efficient sources
  - Compact stars, dust; intergalactic medium
- Understand source properties, as evolving
  - Star formation history, environmental influences
  - Metallicity dependent frequencies and yields
- Understand gas and matter flows
  - Hot, cold gas; compact stars; galaxy-halo interface

- Establish observational tests of sub-areas
  - Observation analyses towards ChemEv ingredients
  - ChemEv modeling of observables
- Establish standards for interfaces, tools
  - See JINA-CEE, MESA, NUGRID, …

Chemical Evolution in Germany

- Simulating the interstellar medium
  - Groups in Heidelberg, Berlin, Garching, Köln
- Analysing stellar abundances in ChemEv context
  - Groups in Potsdam, Heidelberg

- Here is a specific need for enhancing links to other nuclear-astrophysics efforts
  - Observations' diversity
  - Source models
  - Gas dynamics
  - Numerical schemes and tools