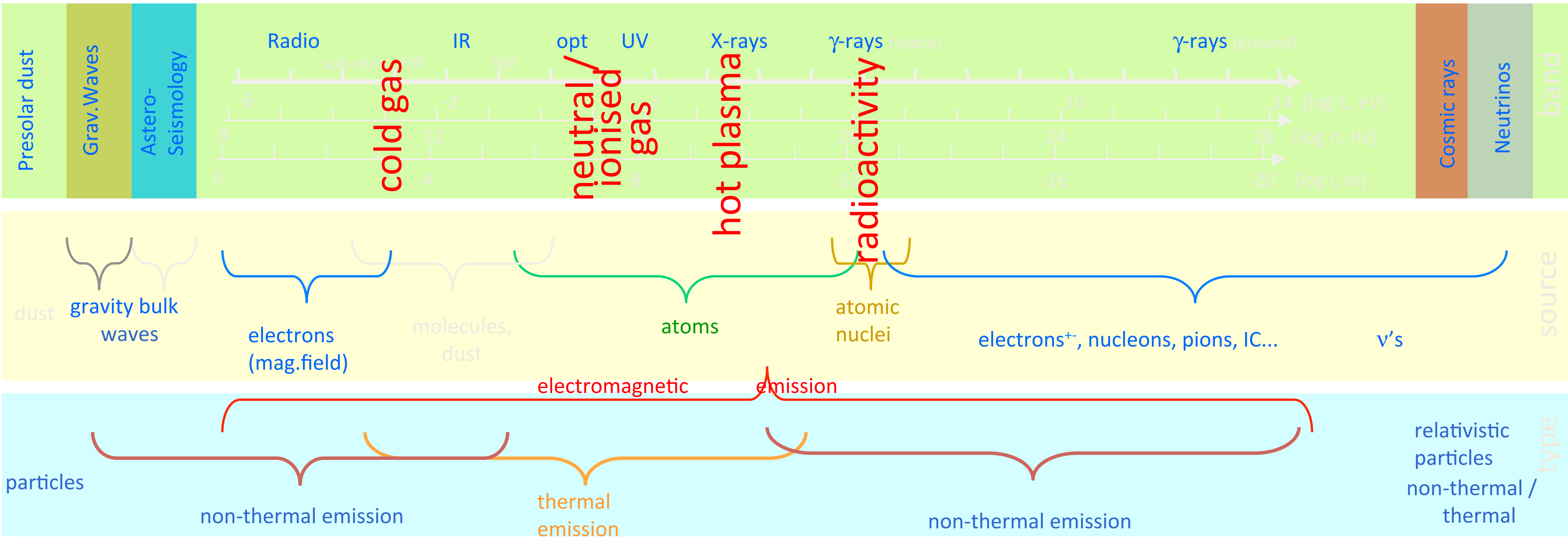
Interstellar Gas in the Universe: Observations for Nuclear Astrophysics

Roland Diehl

Contents

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

Astronomy : The Variety of Astrophysical Messengers



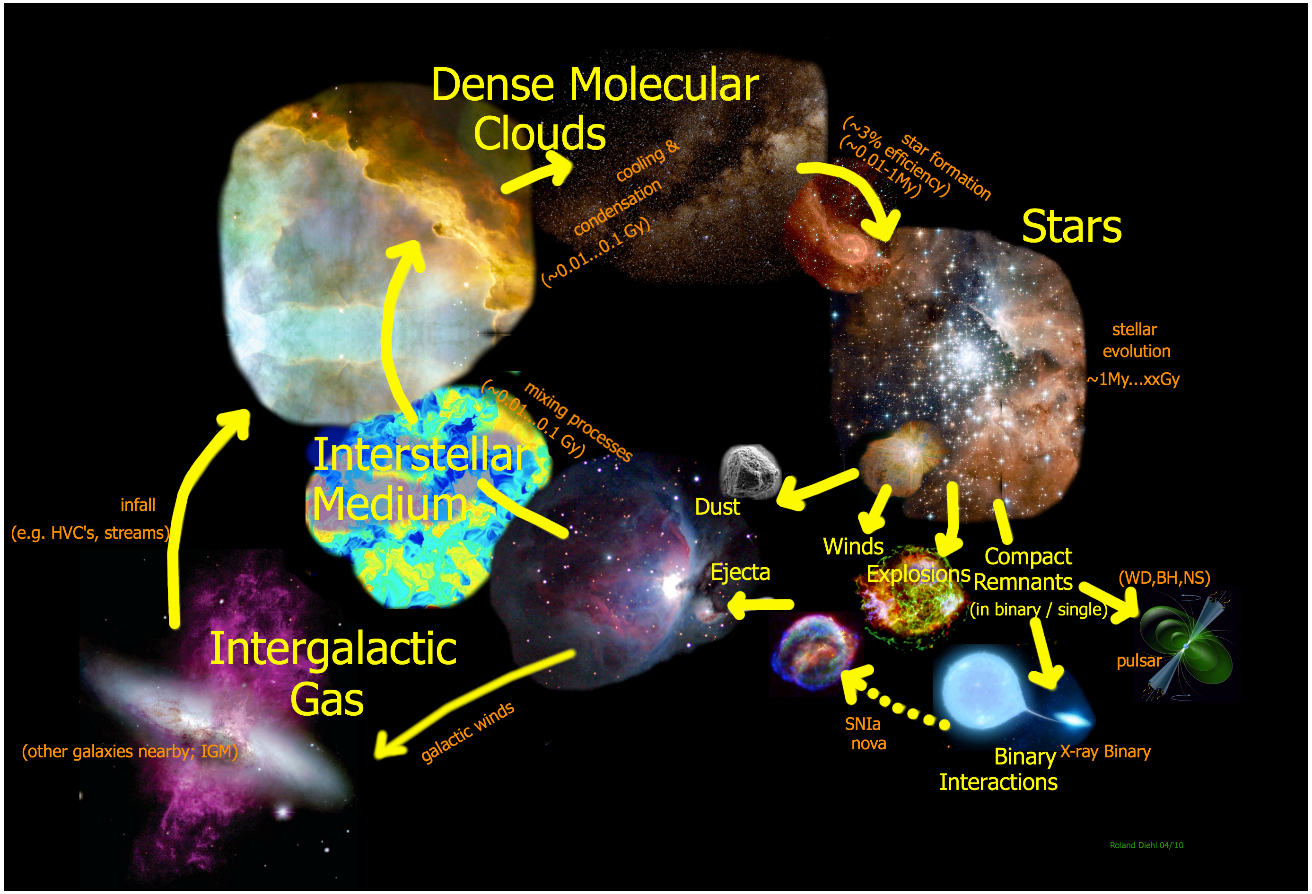
– Science targets:

– radioactivities, hot plasma (cooling, ionising sources), ionised & cold gas

– Astronomy with photons/e.m. radiation is complemented by new "messengers

Nuclear Astrophysics: Cycling Cosmic Gas

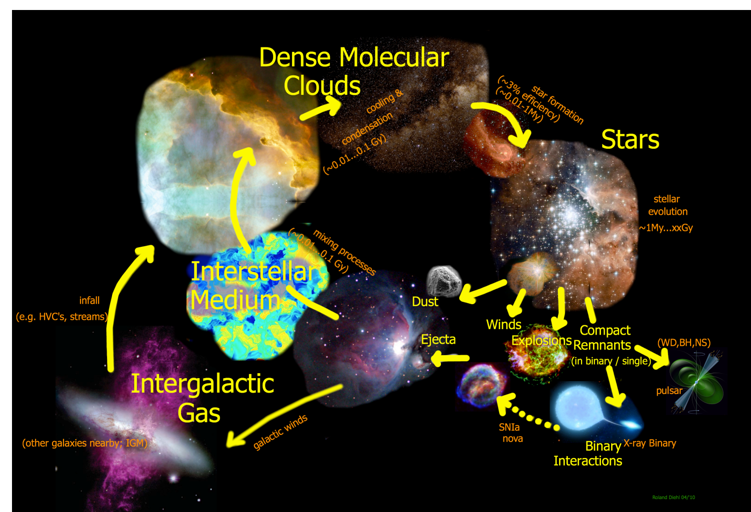
- From star formation through stellar evolution and hot→ cold gas



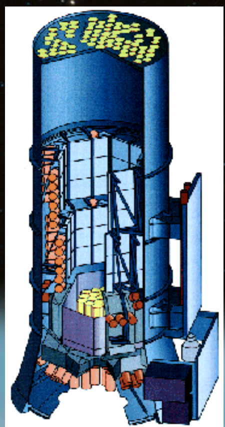
- Important Ingredients:
  - Star formation and its history; gas cooling and transport; in- and outflows

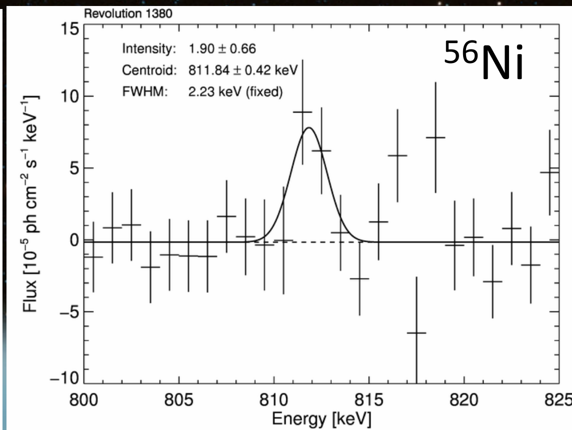
Science Questions

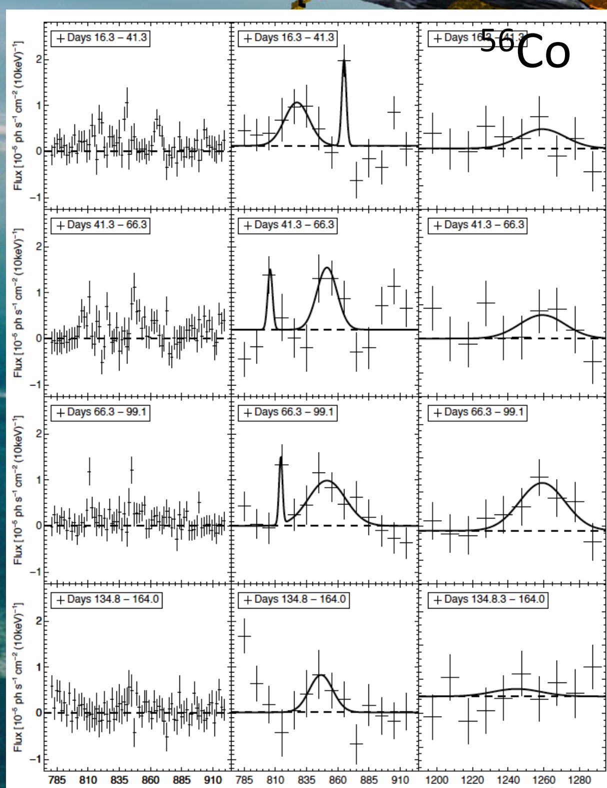
- What are the nucleosynthesis yields from sources?
  - » radioactivities (shortlived), hot plasma
- How is nucleosynthesis material propagated?
  - » radioactivities (longlived); hot and teneous gas (e.g. IGM)
- Which material leaves the galaxies?
  - » ionised gas
- How much metals did the earlier universe have?
  - » absorption spectroscopy
- How does gas get into stars?
  - » molecular lines

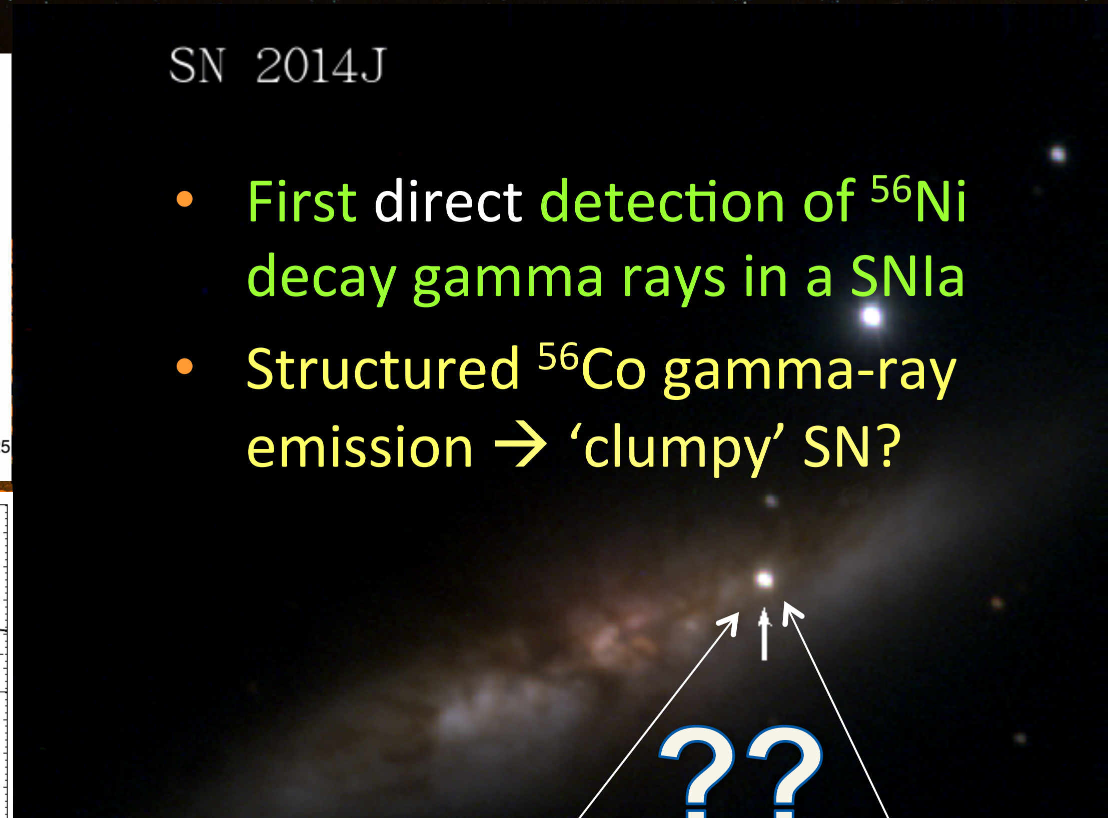


A Supernova Type Ia and its ^{56}Ni

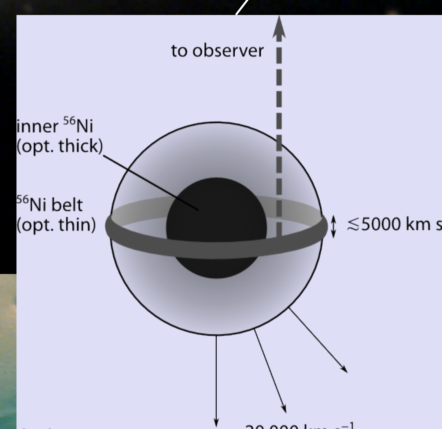


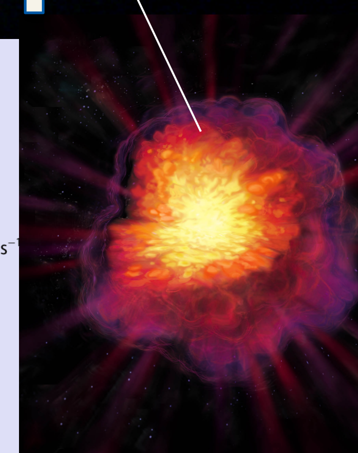






- First direct detection of ^{56}Ni decay gamma rays in a SNIa
- Structured ^{56}Co gamma-ray emission → 'clumpy' SN?



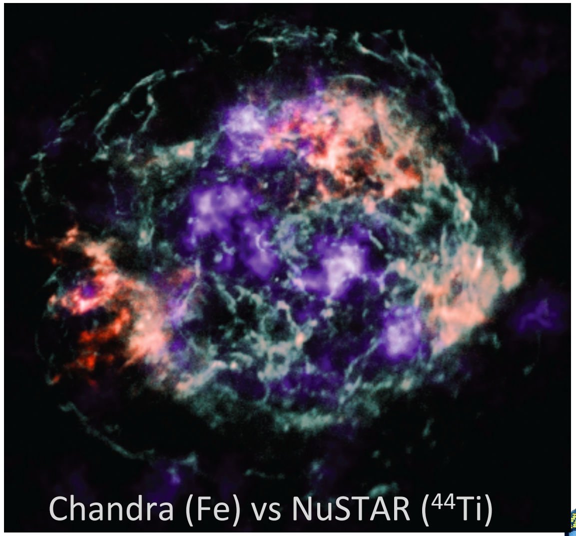


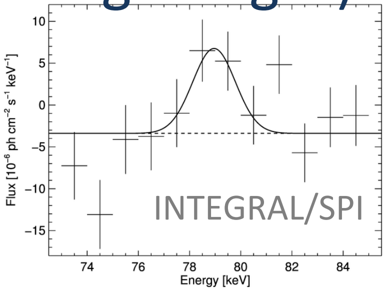
Core collapse supernova ejecta

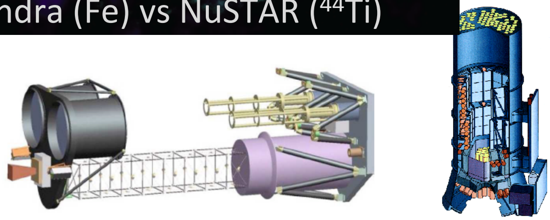
– Inner Ejecta: ^{44}Ti lines from Cas A

- First mapping of radioactivity at 68,78 keV in a SNR ever
  - ^{44}Ti Image (nucleosynthesis ashes) differs from Fe (recombining hot gas)!!
  - velocity constraints

Grefenstette et al. (Nat. 2015)
Siegert et al. (A&A 2015)

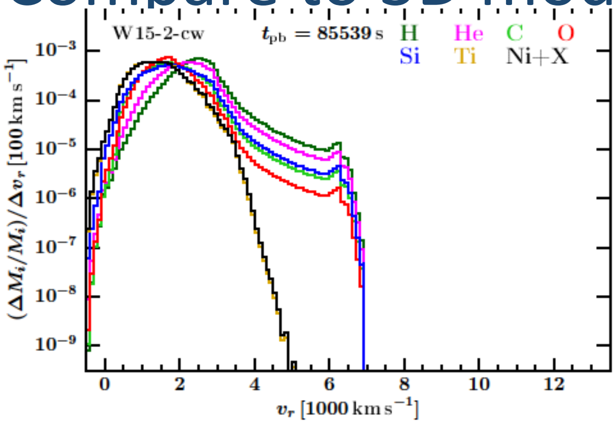


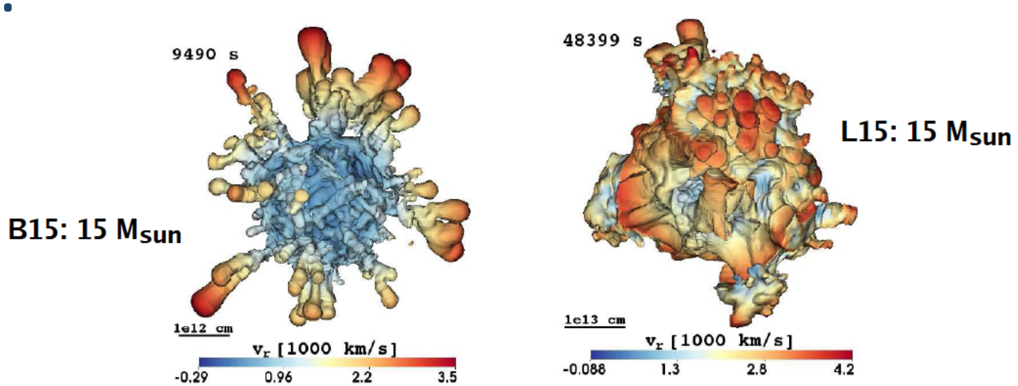




- Compare to 3D models:

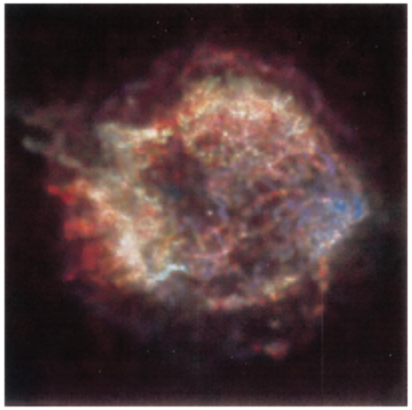
Wongwatharanat et al. (2015; 2016)





X-Ray Images/Spectra of a Supernova Remnant

- Cas A: Recombination Lines of Highly-Ionized Species



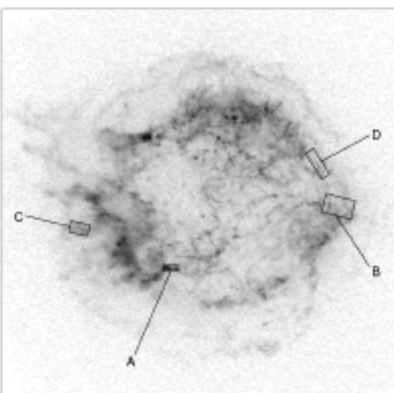
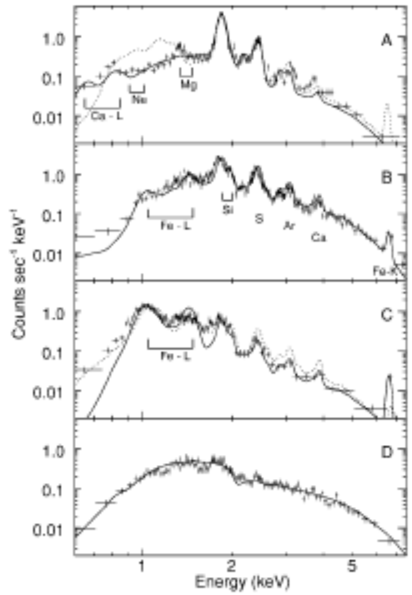
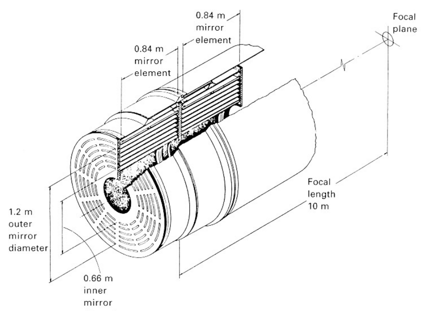
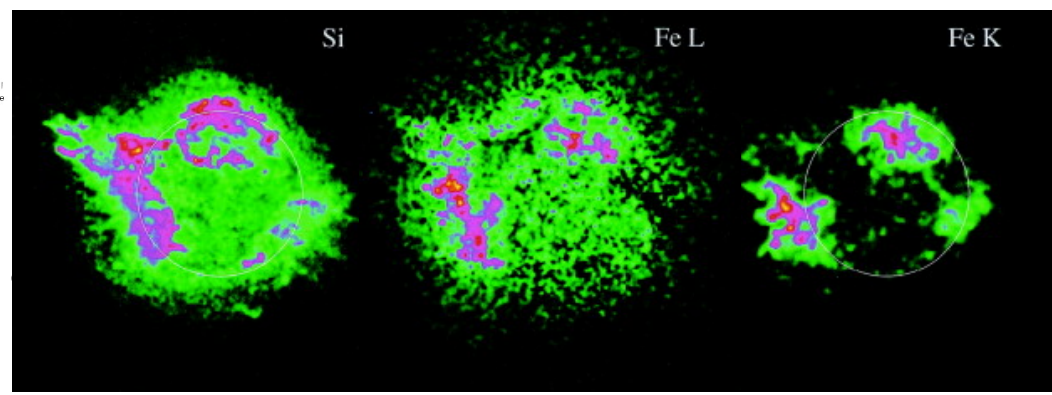


FIG. 2.—Broadband unsmoothed Chandra X-ray image of Cas A using a square-root intensity scaling. The spectral extraction regions in our study are indicated.

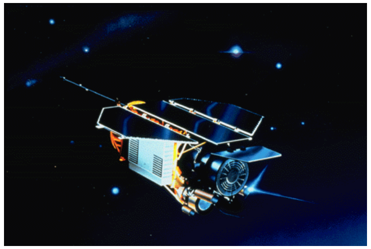




- Chandra X-ray imaging and spectroscopy
- X-Ray Lines in Fe, Si, S, Ar, Ca show Clumps with Large Enrichments
  => Ejecta(?)
- Fe Line Emission Features found Outside Si,S,Ar,Ca Line Features
  => Mixing / Turbulence During Explosion(?)
  (Hughes et al., ApJ 528, 2000; Hwang et al., ApJ 537, 2000)
- Issues: …NEI? (i.e., $T_e = T_{ion}$?)



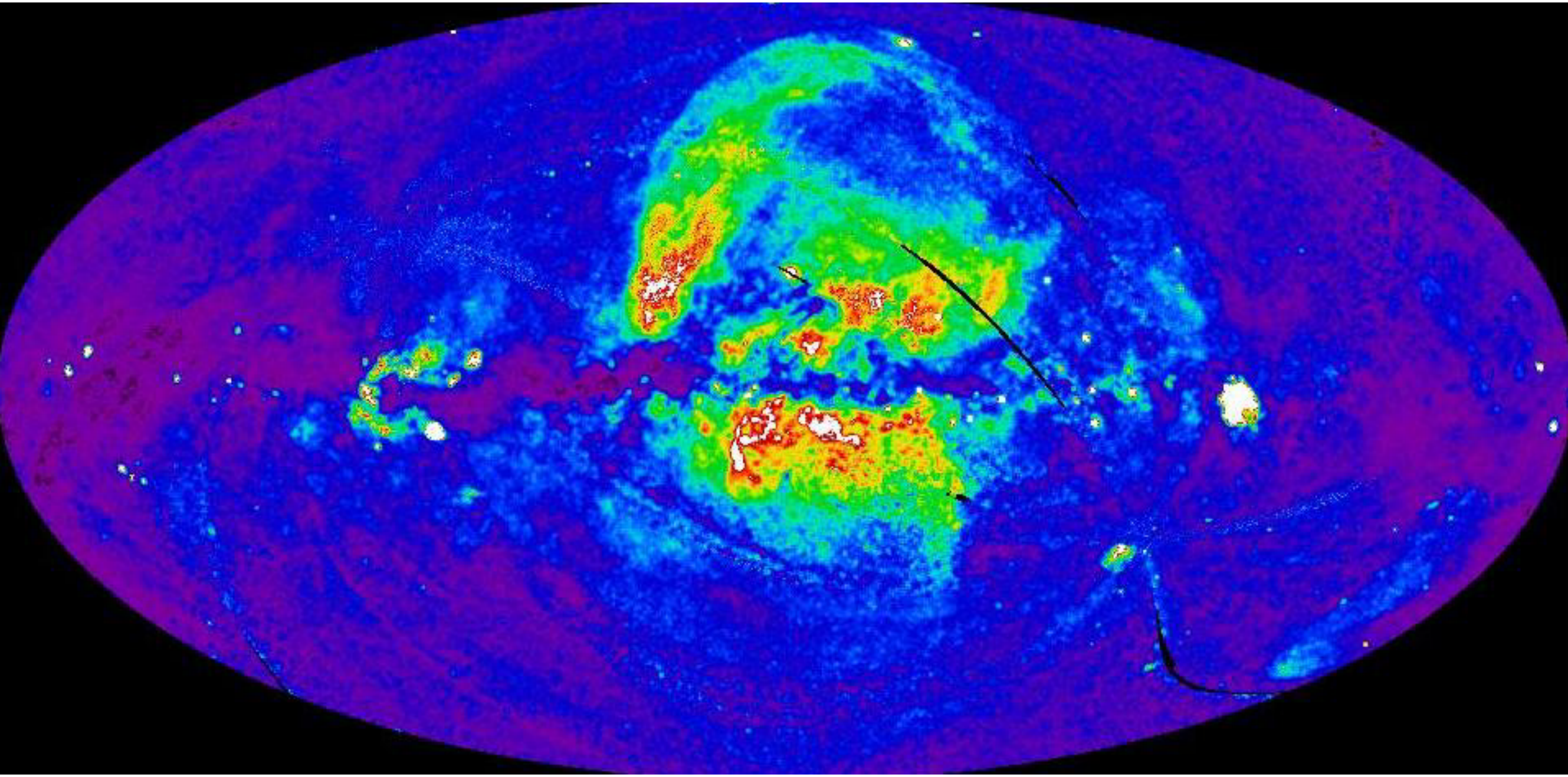
Hot gas



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

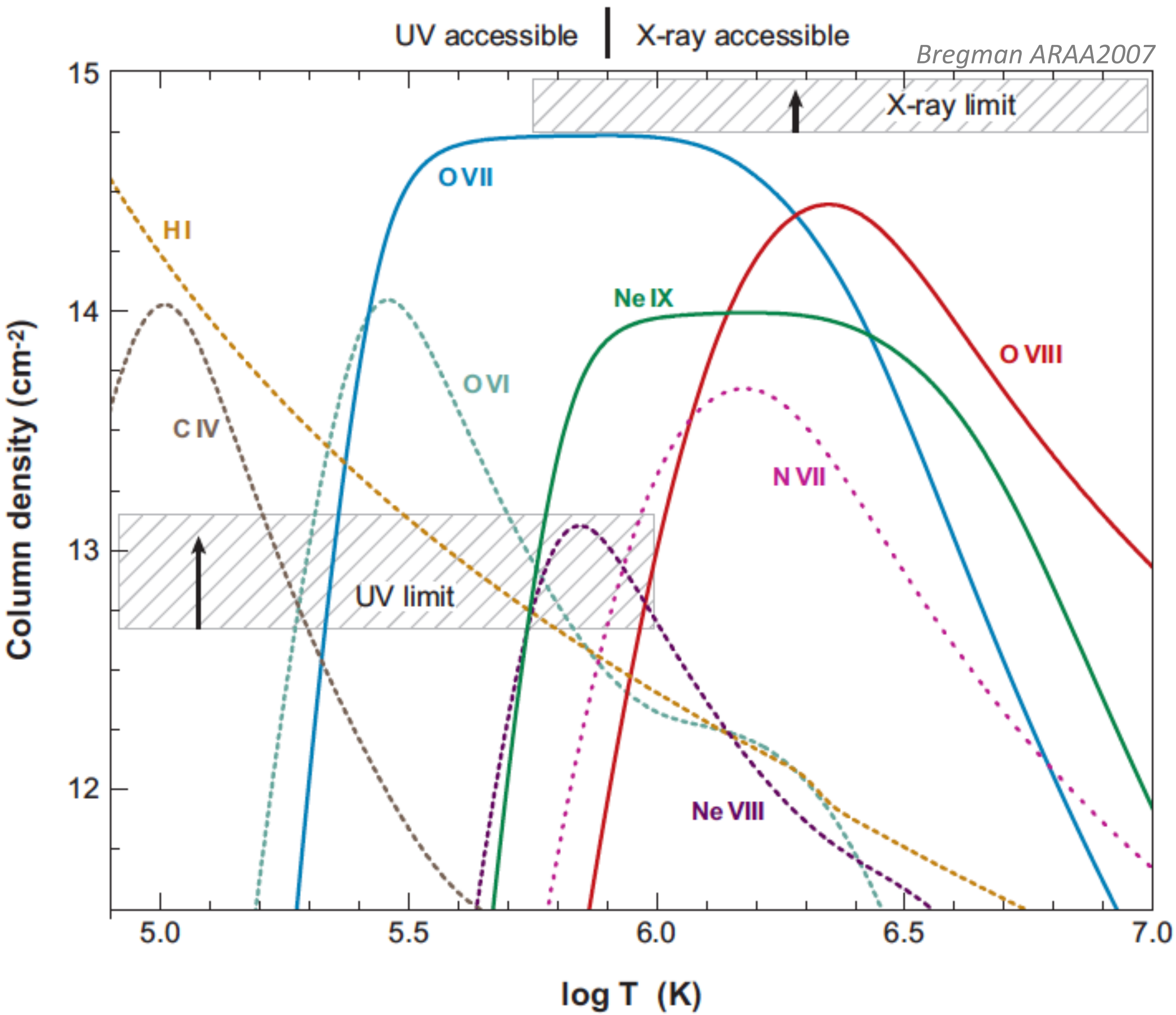
ROSAT 0.75 keV

Snowden et al. 1995, 2015



Ionised gas

- Hot gas → highly-ionised ions → recombination lines



The ion fraction distributions, represented as column densities for a total gas column of 10^{19} cm^{-2} and metallicities of 0.1 $Z_{\odot}$.

Ionised gas: X-ray absorption lines

- From Chandra observations of AGN
  - More halo gas than expected, out to 100 kpc

Gupta et al. 2012

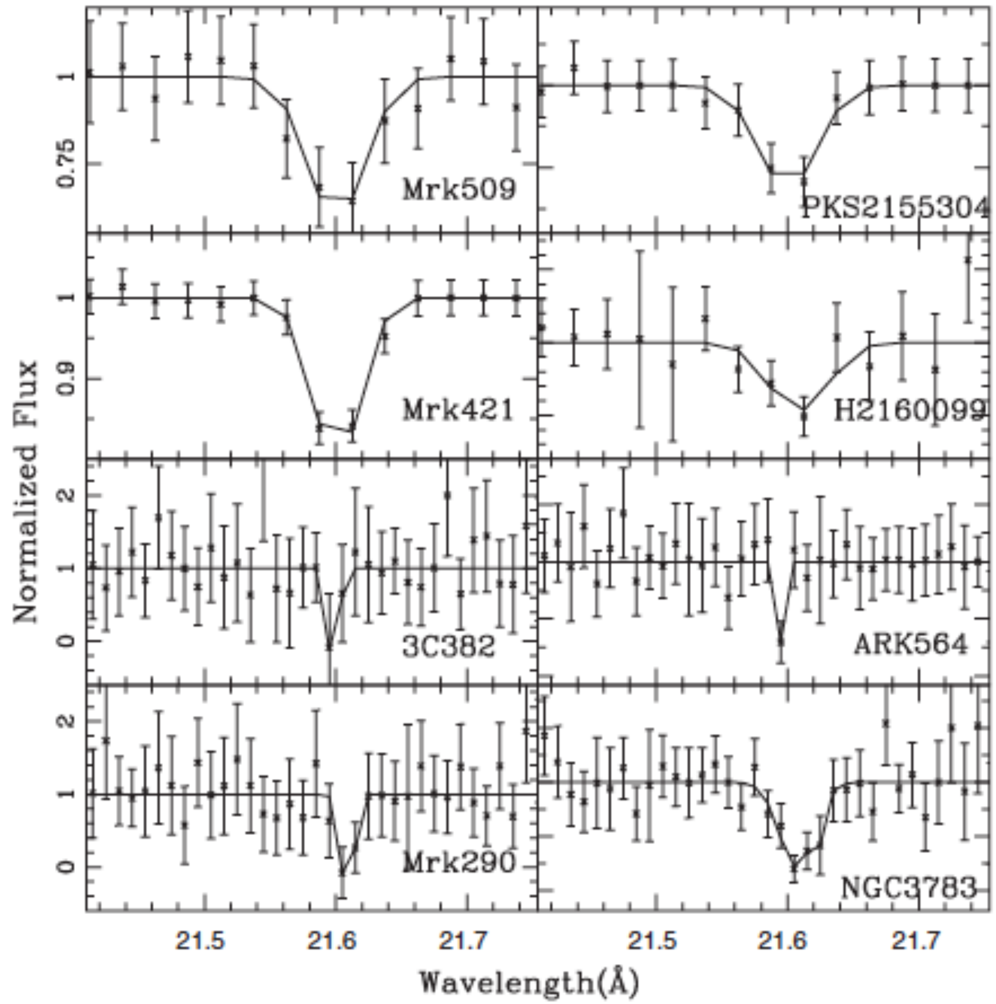
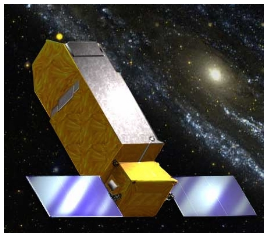


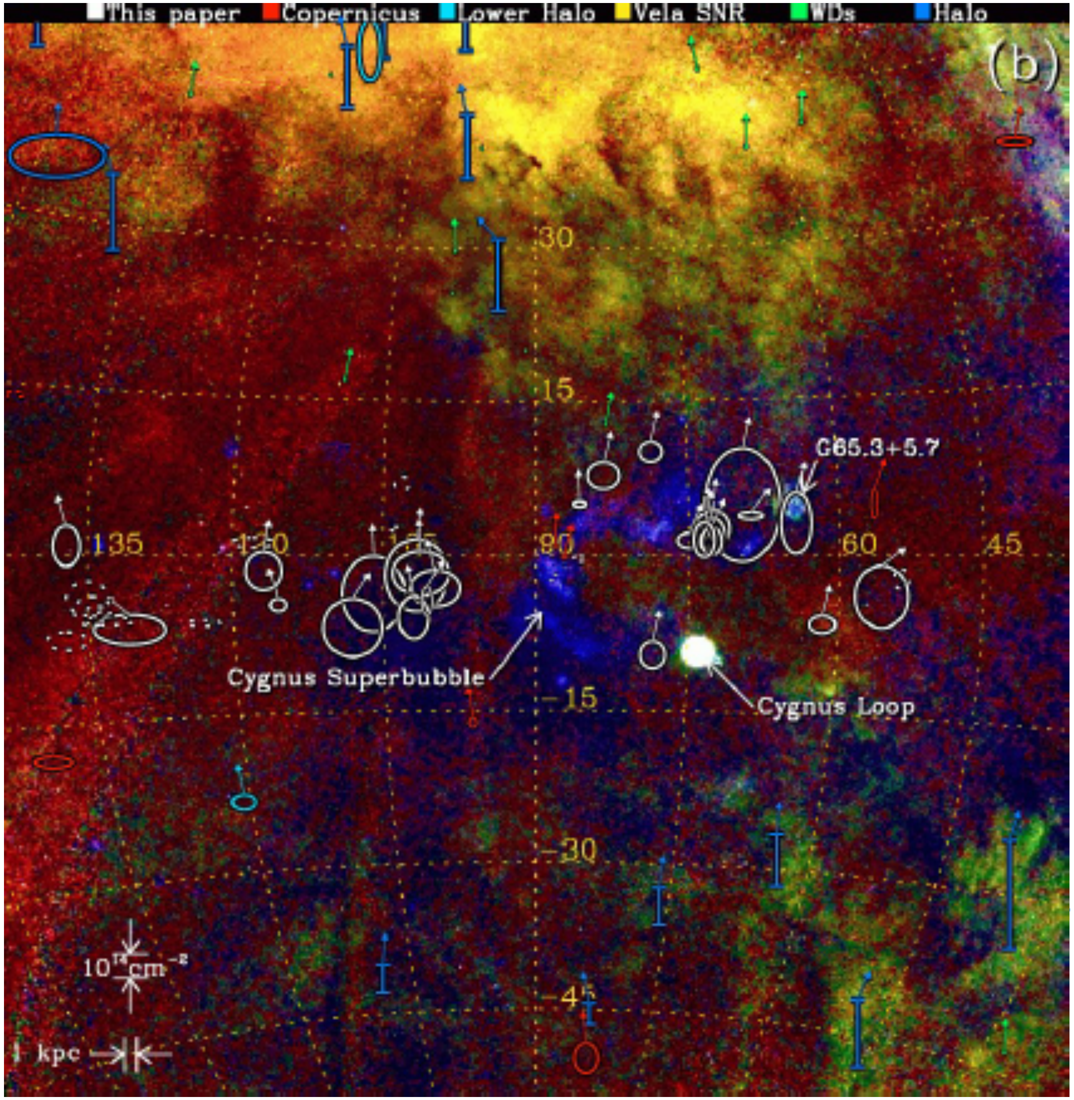
Figure 1. Normalized flux at the location of the O VII line at 21.602 Å.

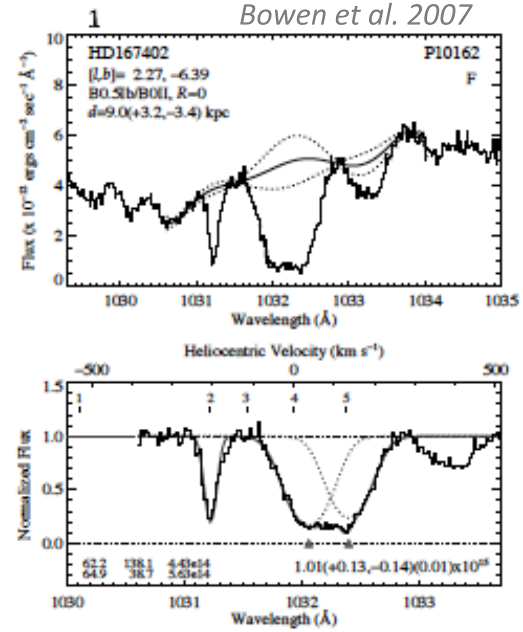
O VI observations

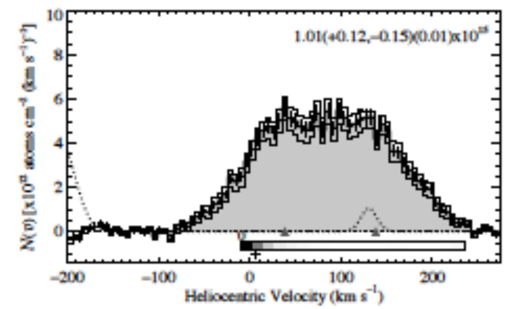
- Line absorption profiles towards star sight lines
- Comparison with diffuse X-ray emission (ROSAT)

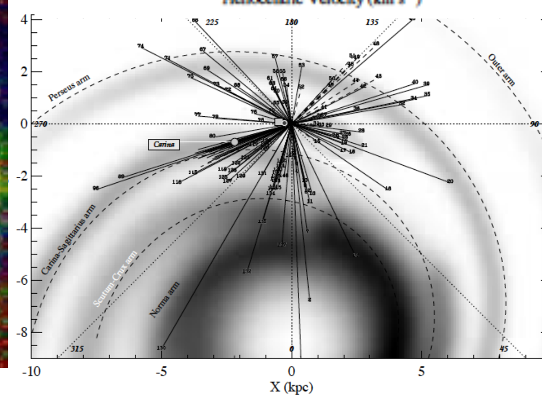
Bowen et al. 2007





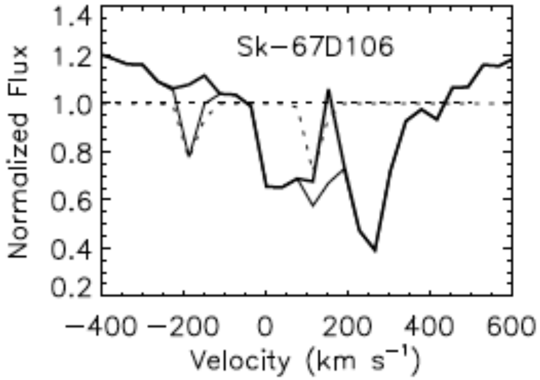


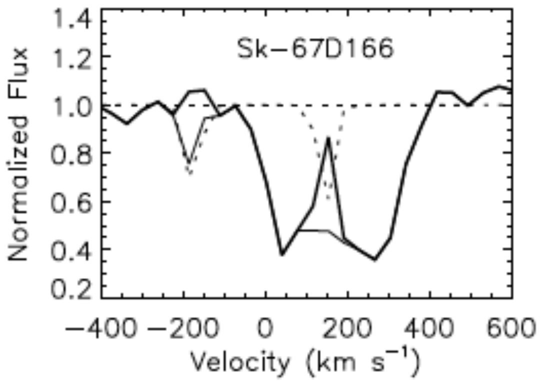


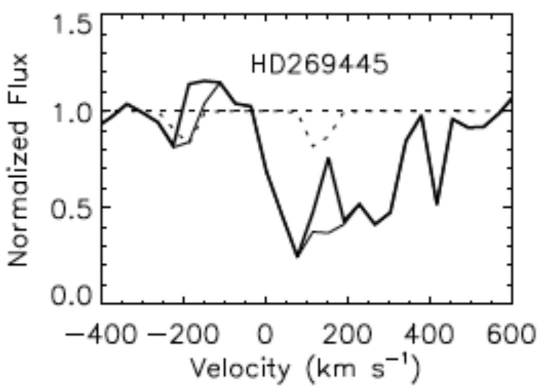


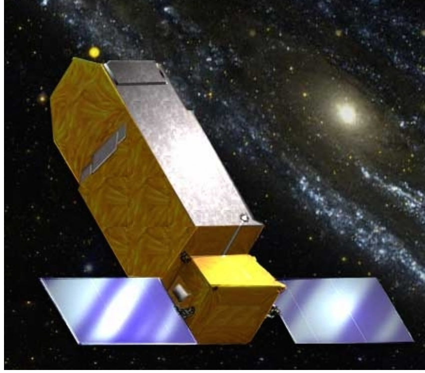
O VI observations: FUSE

Sarma et al. 2016







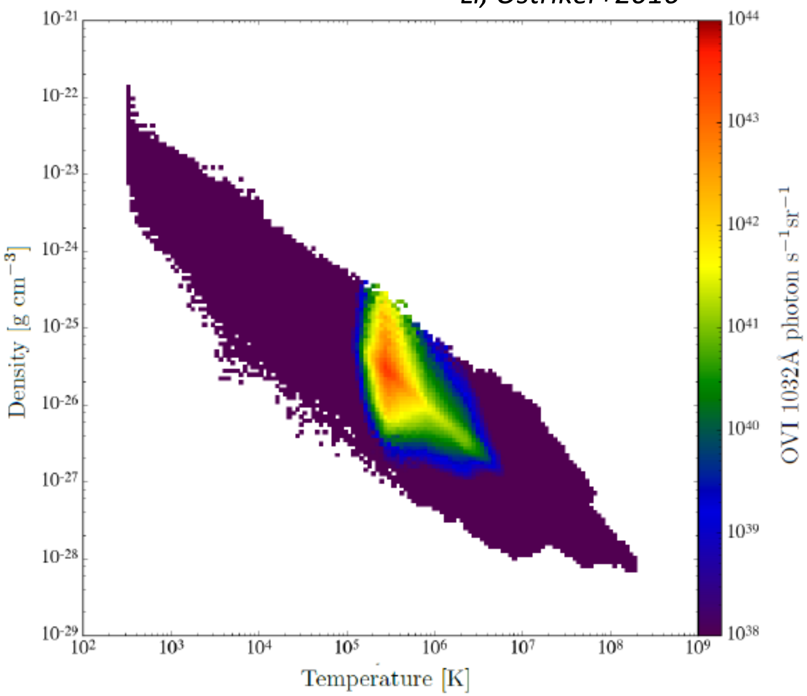


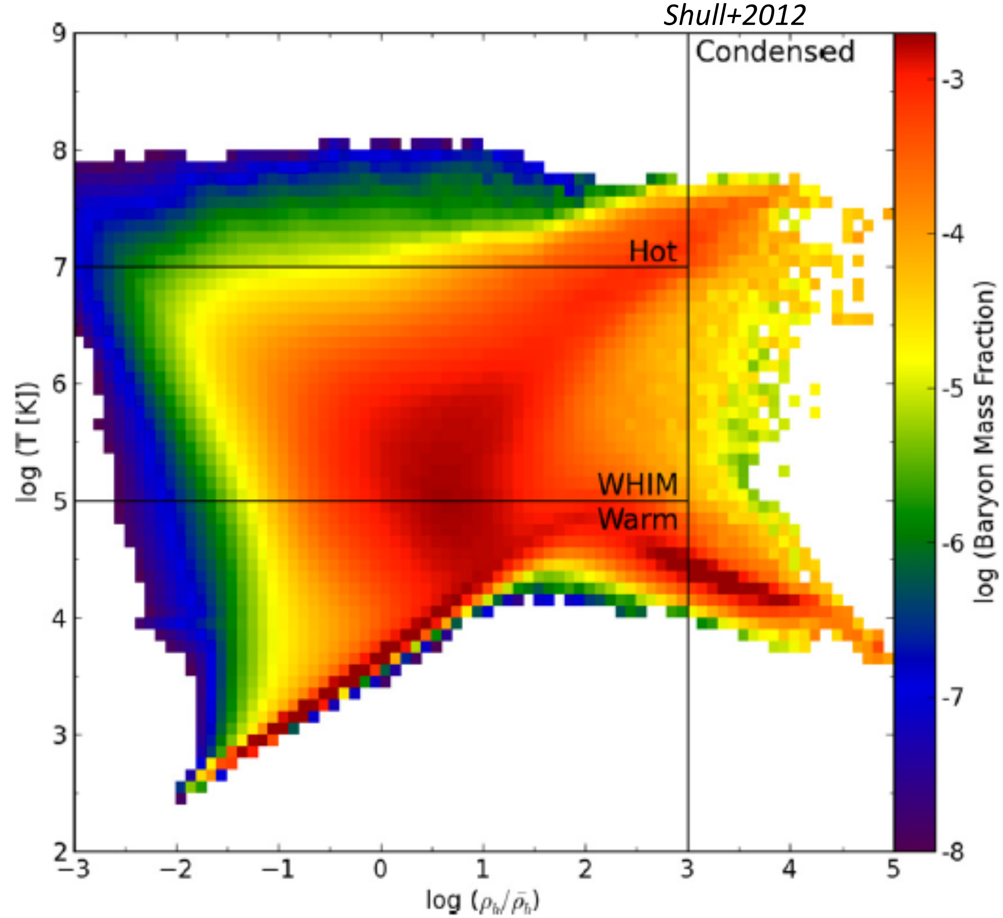
- line absorption profiles towards 69 star sight lines

  → O VI scale height (2.3±1) kpc

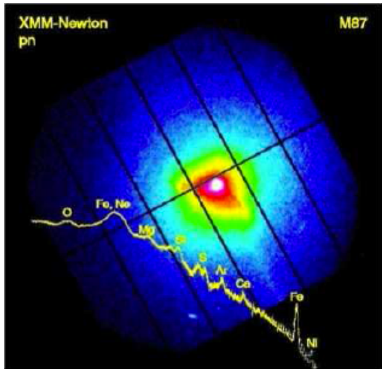
The WHIM: a challenge

- Teneous & hot gas is difficult to observe





Galaxy Cluster Gas



- Galaxy Clusters: Intergalactic gas reservoir is ~X-ray thermalised

Hitomi collaboration, Nat. 2016

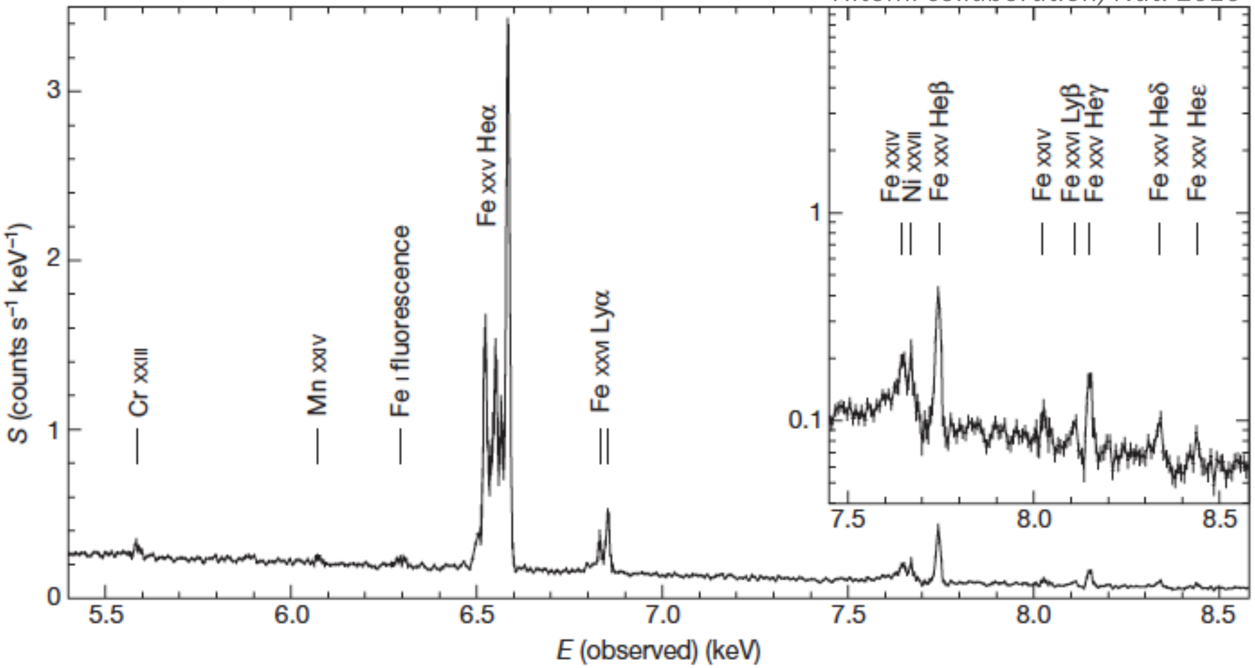
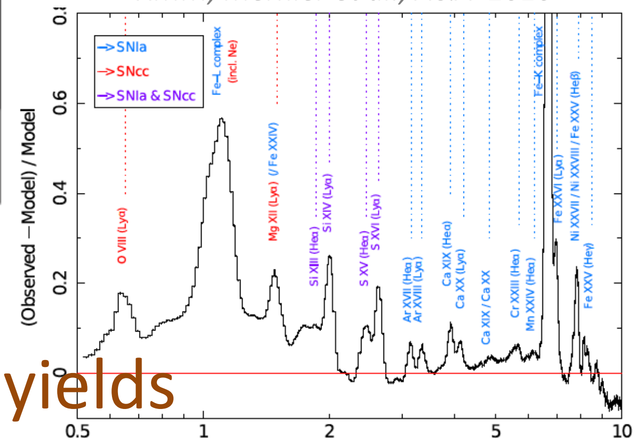


Figure 1 | Full array spectrum of the core of the Perseus cluster obtained by the Hitomi observatory. The redshift of the Perseus cluster is $z = 0.01756$. The inset has a logarithmic scale, which allows the weaker lines to be better seen. The flux S is plotted against photon energy E.

XMM, Mernier et al., A&A 2016

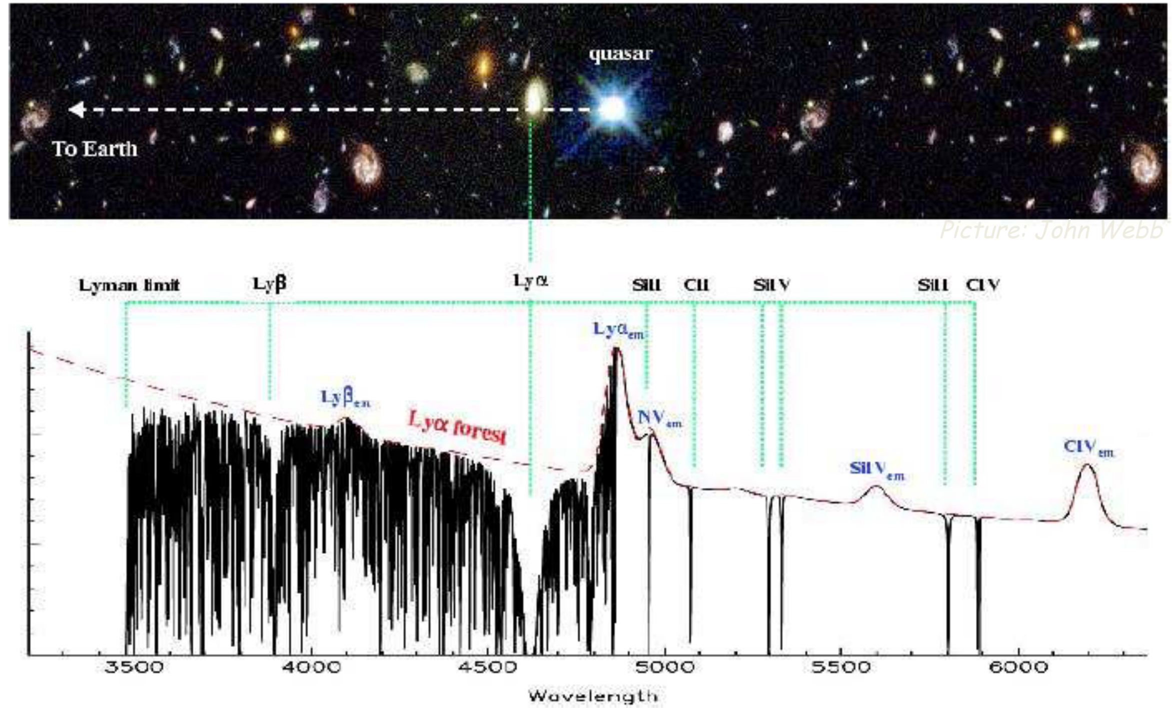


  - Enrichment of intra-cluster gas from different galaxies; → radial profiles, yields
    - » e.g.: found largely 'solar', except for enrichments in Mn/Fe, Ni/Fe

Quasar Absorption Line Spectroscopy

– Quasar:
  - Bright, Distant Source

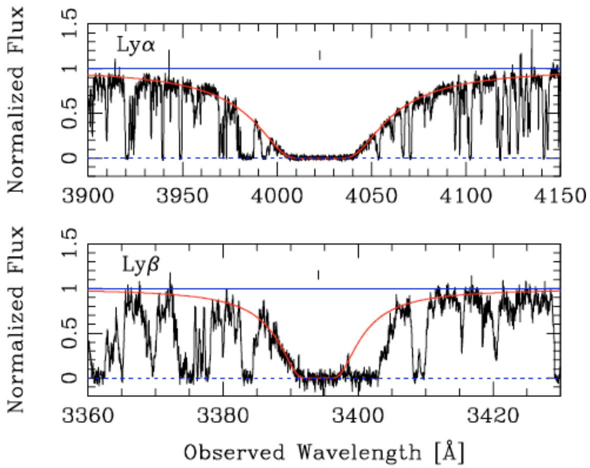
– Less-Distant Gas Clouds & Galaxies:
  - Absorption Lines
  - Closer = Lower Redshift
  - → Absorption Line Pattern
    » "Ly a forest"
    – DLA: "damped", $N_H>10^{20}cm^{-3}$: Progenitors of today's galaxies?
  - Analysis Task:
    » Extract Absorption-Line Pattern Attributed to Specific/One Galaxy/Cloud
    » Evaluate Relative Abundances



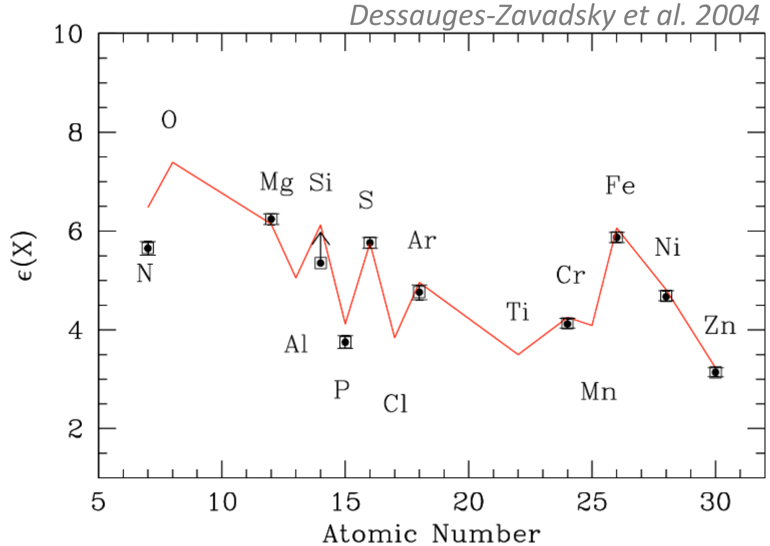
Redshift	Lookback Time (Gyr)	Lookback time (t/t_∞)
0	0	0
0.5	5.4	0.37
1	8.3	0.57
2	11.0	0.76
3	12.2	0.84
4	12.9	0.89
5	13.3	0.92
6	13.5	0.93
10	14.0	0.97
∞	14.5	1.00

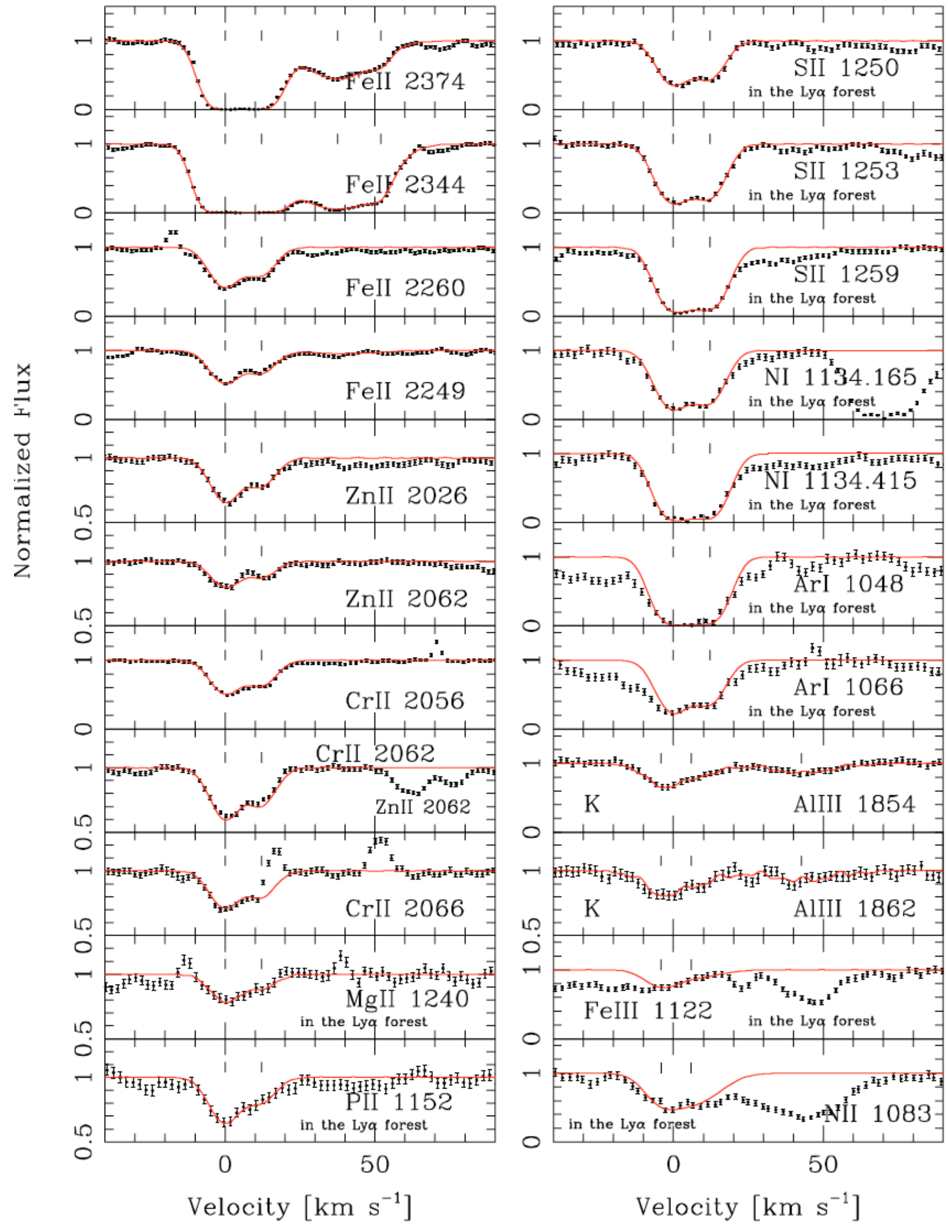
Quasar absorption lines: the distant universe

- Q0100+13, UVES spectra



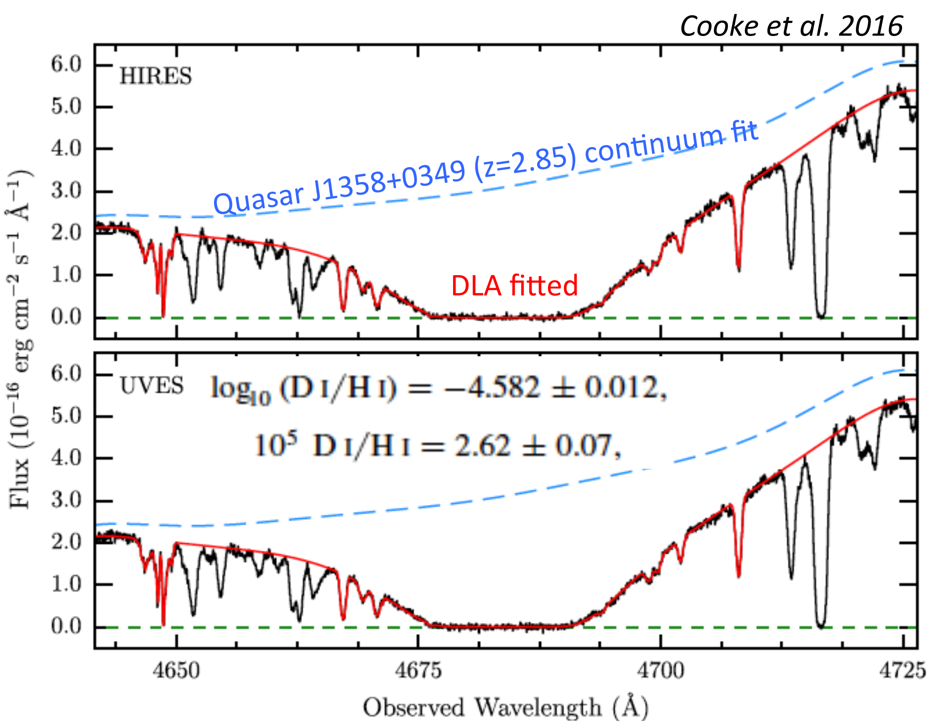
Dessauges-Zavadsky et al. 2004

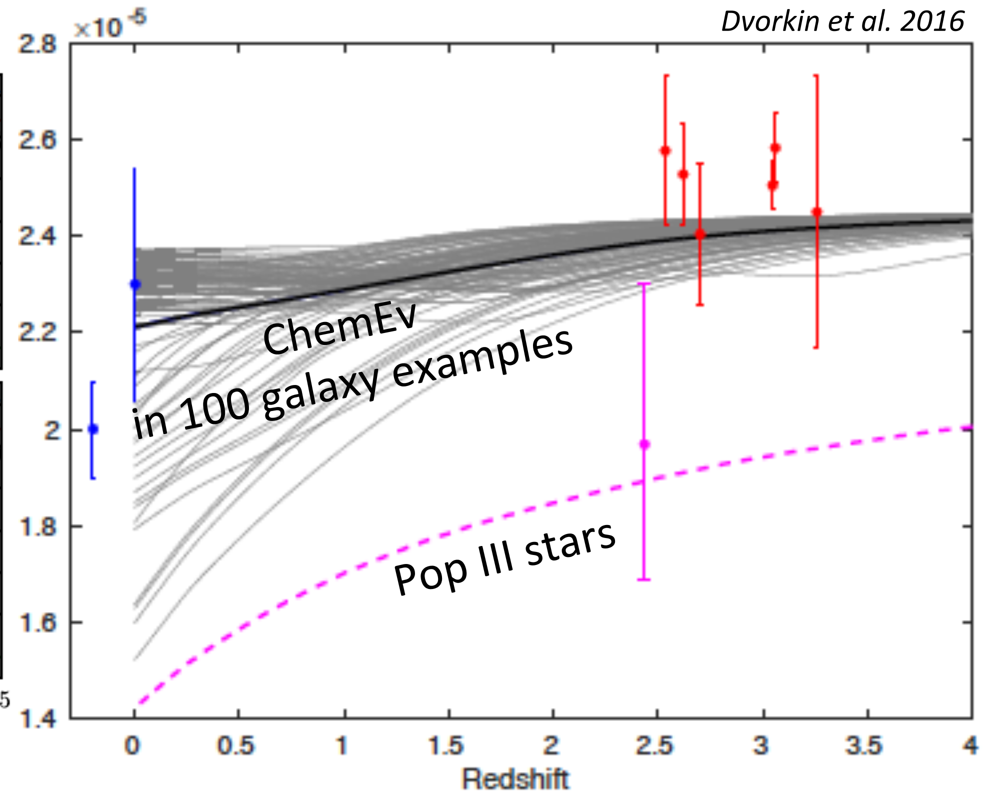


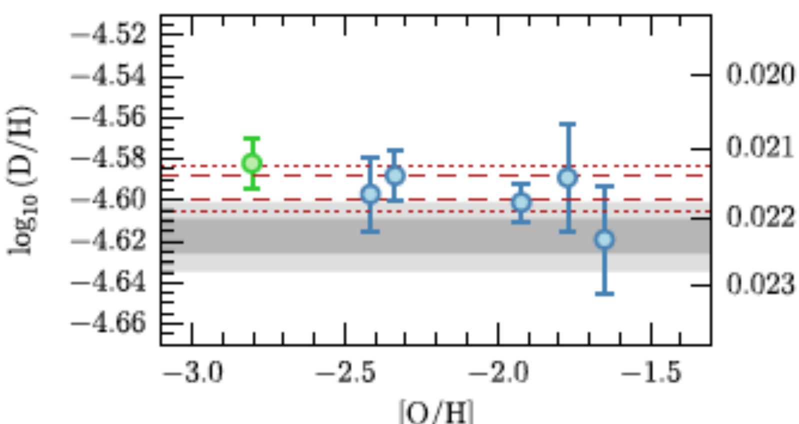


BBN constraints

- Planck CMB constraints complemented by DLAs

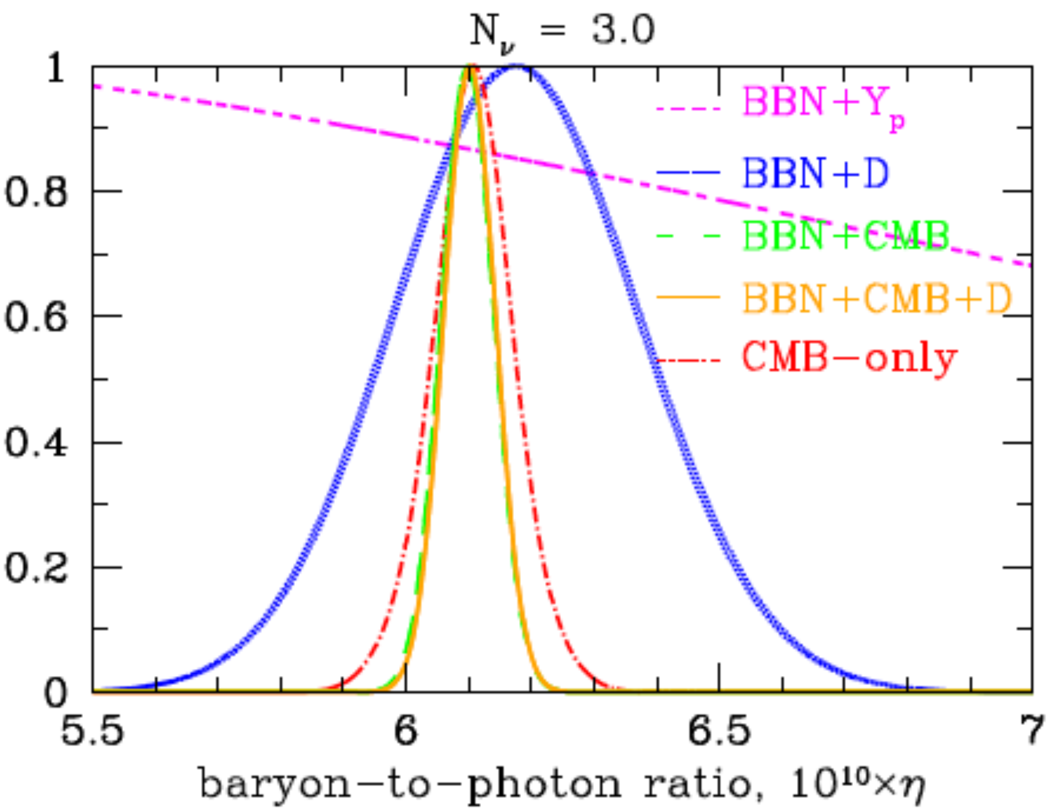


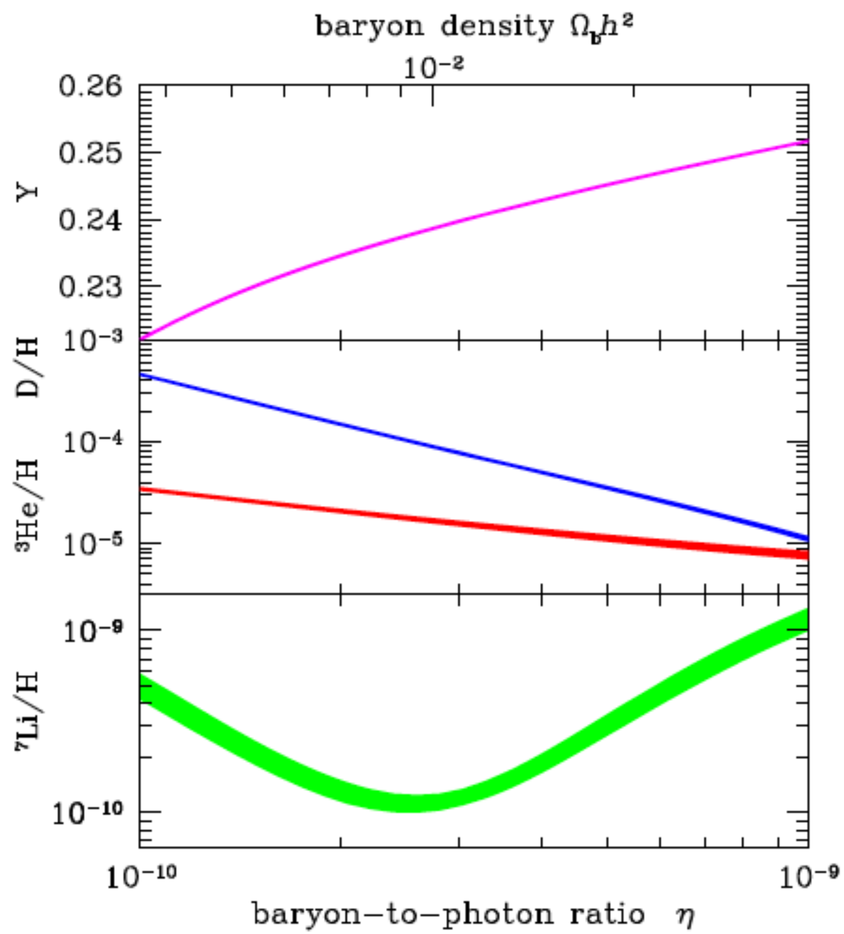




BBN constraints

- Theory and abundance observations, combined
  - Likelihood distribution for photon/baryon ratio

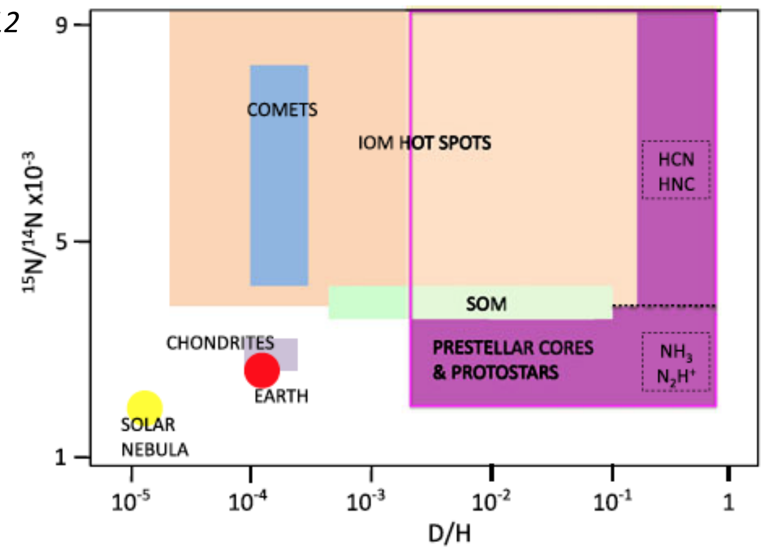




Molecular Isotopic Spectra: How Stars Form

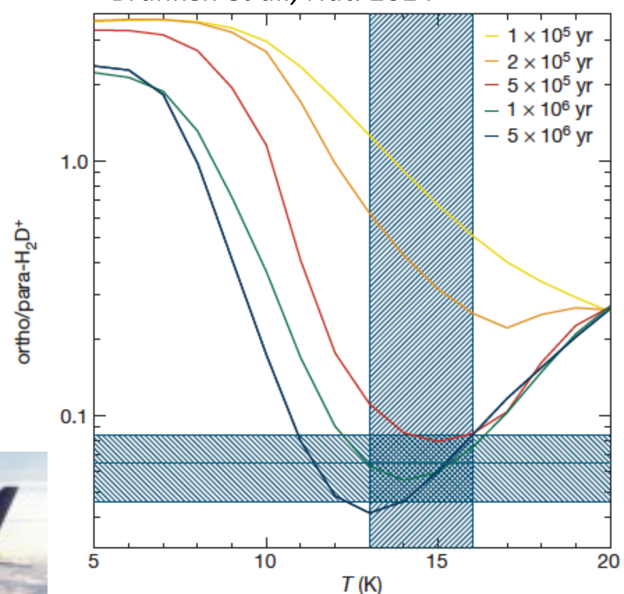
- Astro-Chemistry: Formation of molecules with isotopic preferences in light elements → D, N

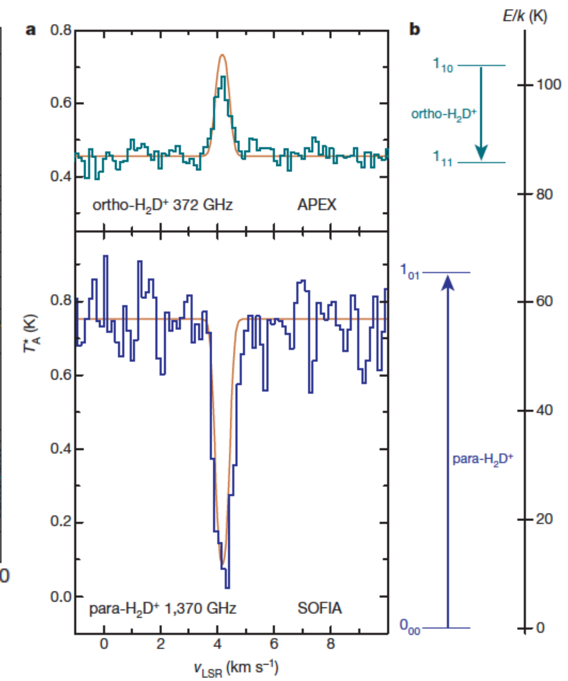
Caselli & Ceccarelli 2012

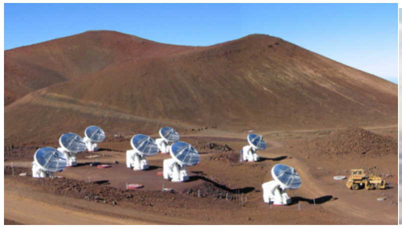


- Age constraints >2 10^5y from time needed for D/H fractionation

Brünken et al., Nat. 2014

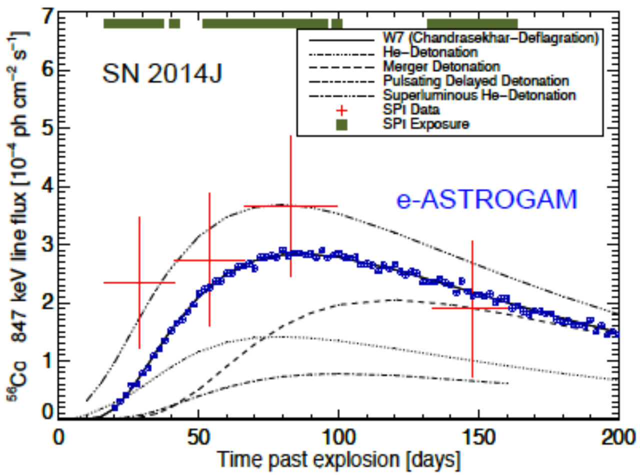


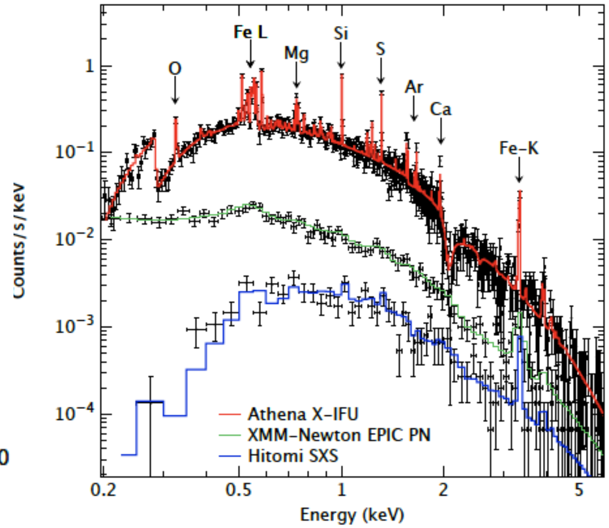


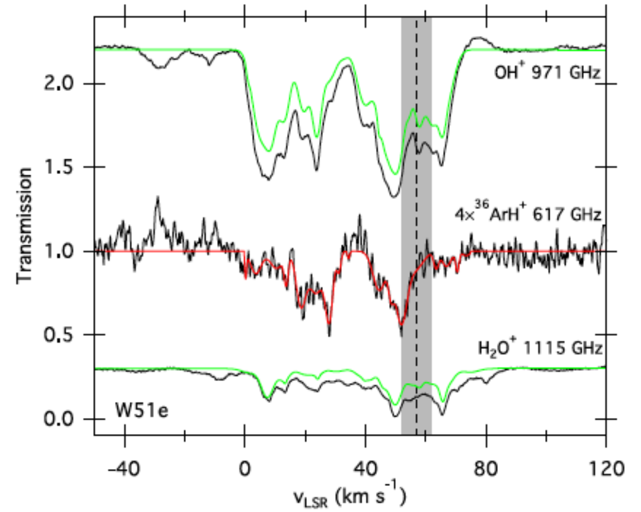


Cosmic gas: observational diversity

- from gamma rays through X-rays, UV, optical, sub-mm







- Groups in Germany
  - » gamma-rays: MPE Garching
  - » X-rays: MPE Garching, Erlangen/Bamberg
  - » UV:
  - » optical (ISM): IAAT Tübingen
  - » sub-mm: MPIfR Bonn, MPE Garching
- Prospects:
  - » γ-rays: eAstrogam (??); X-rays: Athena; UV:?; optical: ?; sub-mm: IRAM/NOEMA, ALMA