Probing high-z GRBs with X-ray spectroscopy

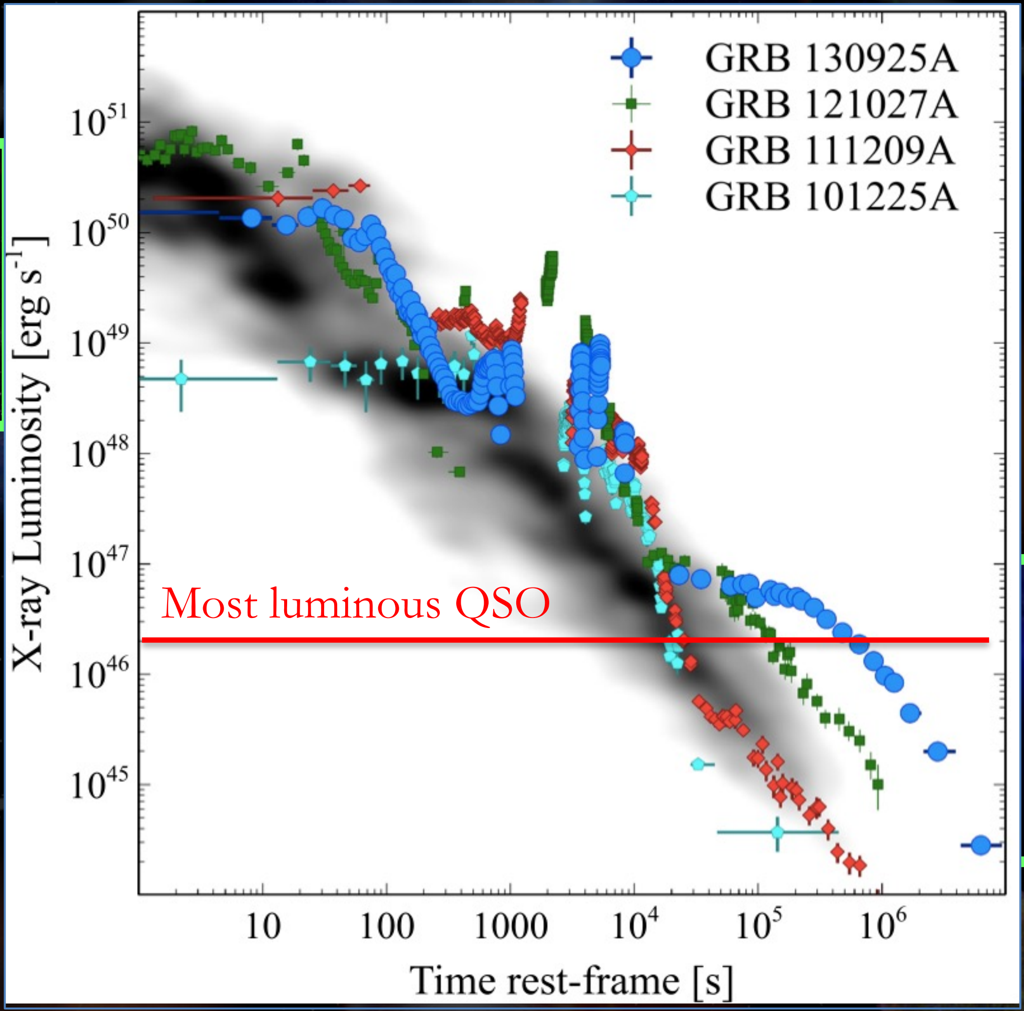
Luigi Piro
IAPS/INAF
collaborators: A.Thakur, A. Luminari, F. Nicastro

Outline

- GRB as beacons into the Dark high-z universe
- Early Universe: primordial (popIII) vs popII star populations and metal enrichment
- X-ray absorption spectroscopy as a probe
- Time variable photoionization codes
- What a popIII-GRB might look like
- Future perspectives with (new)Athena

The Brightest Beacons

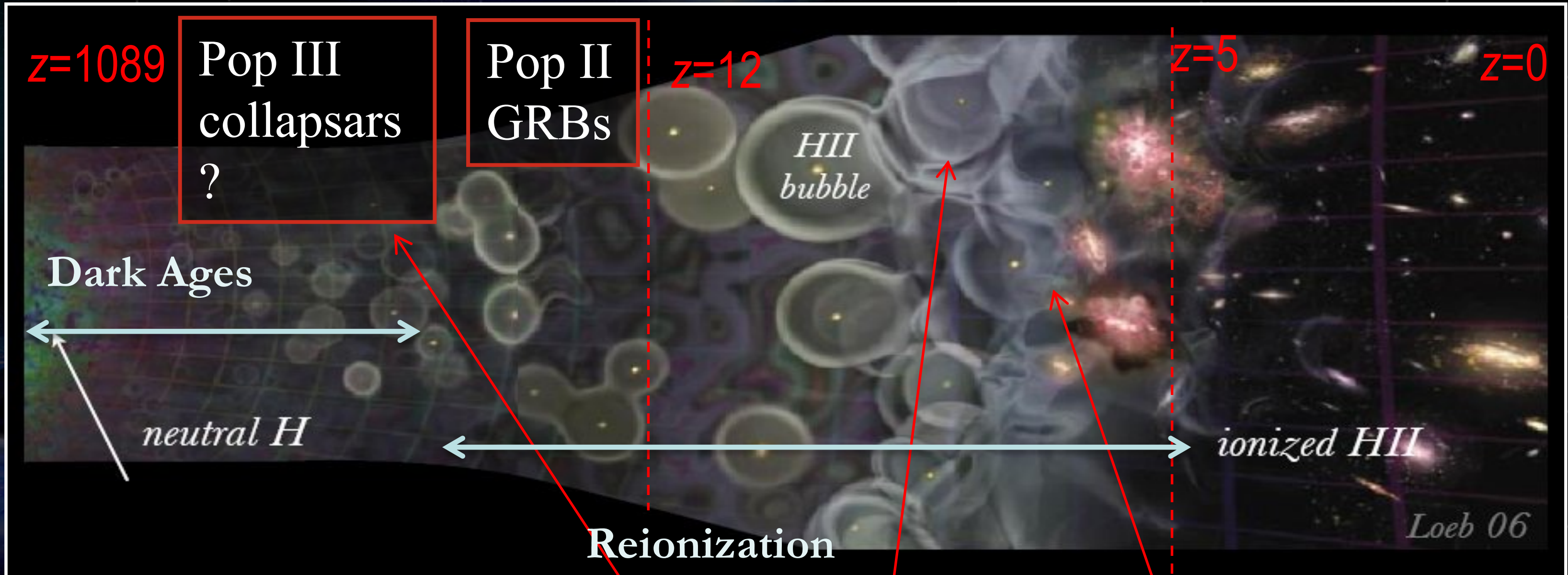
Star metallicity low during this era – number of stars that produce GRBs is higher

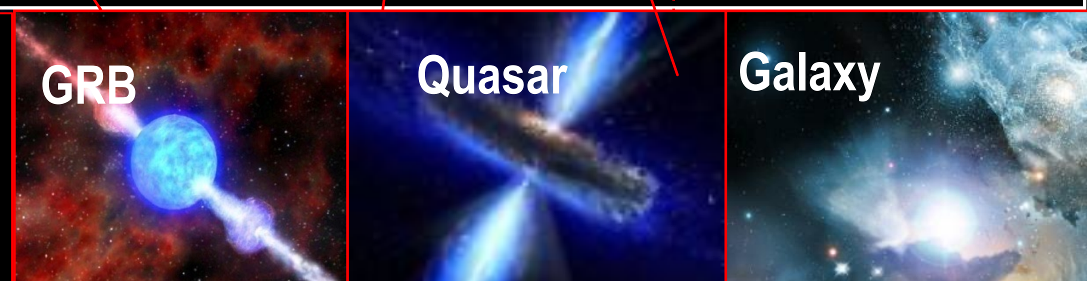


LP et al 14

Number of bright quasars is dropping off very rapidly

The first stars, the first BH, the first metals

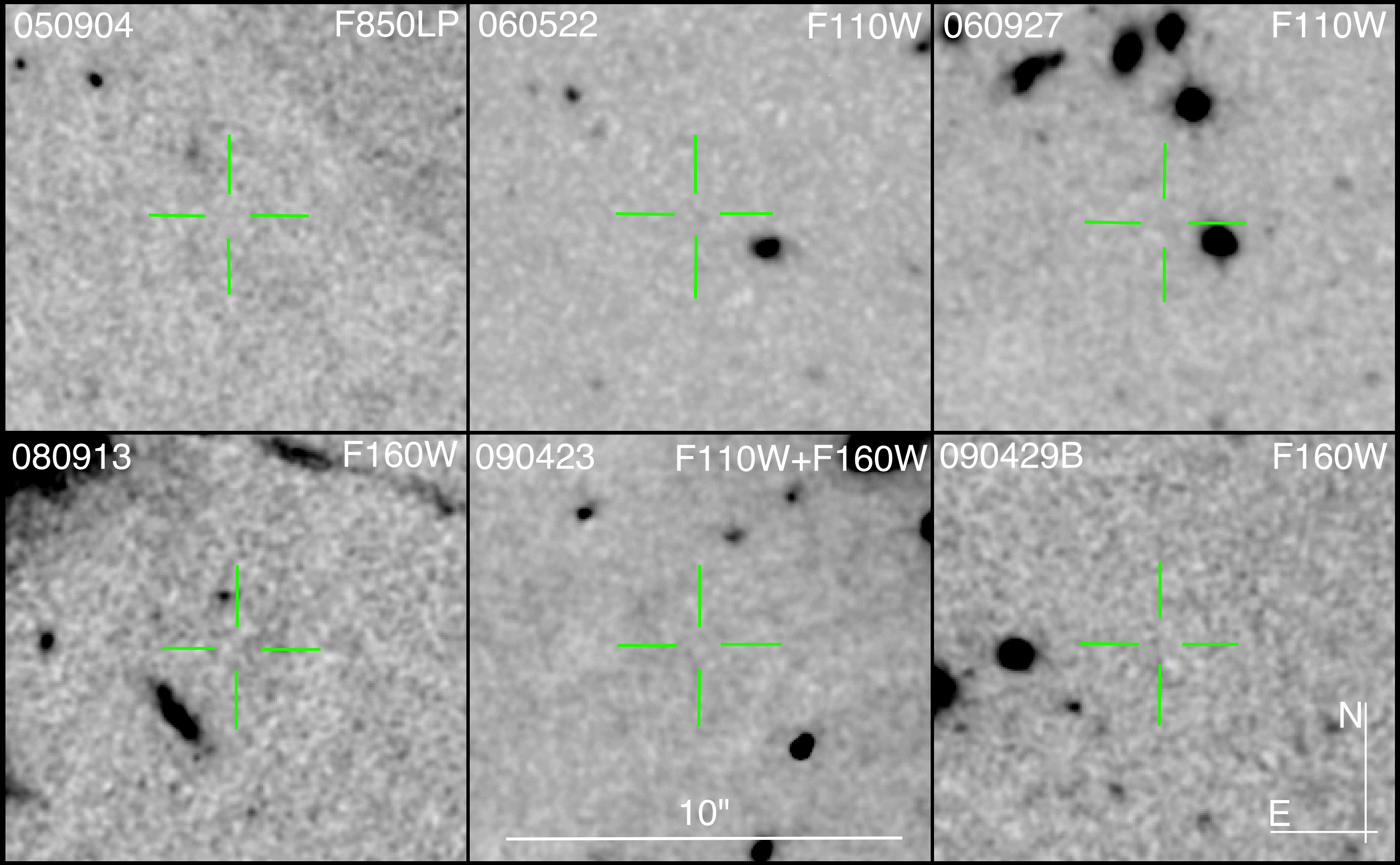




- A dominant proportion of high-z star formation takes place in galaxies beyond the reach of JWST (either too faint or too distant) ; their nature will hardly be known, but **they will be GRB hosts**.

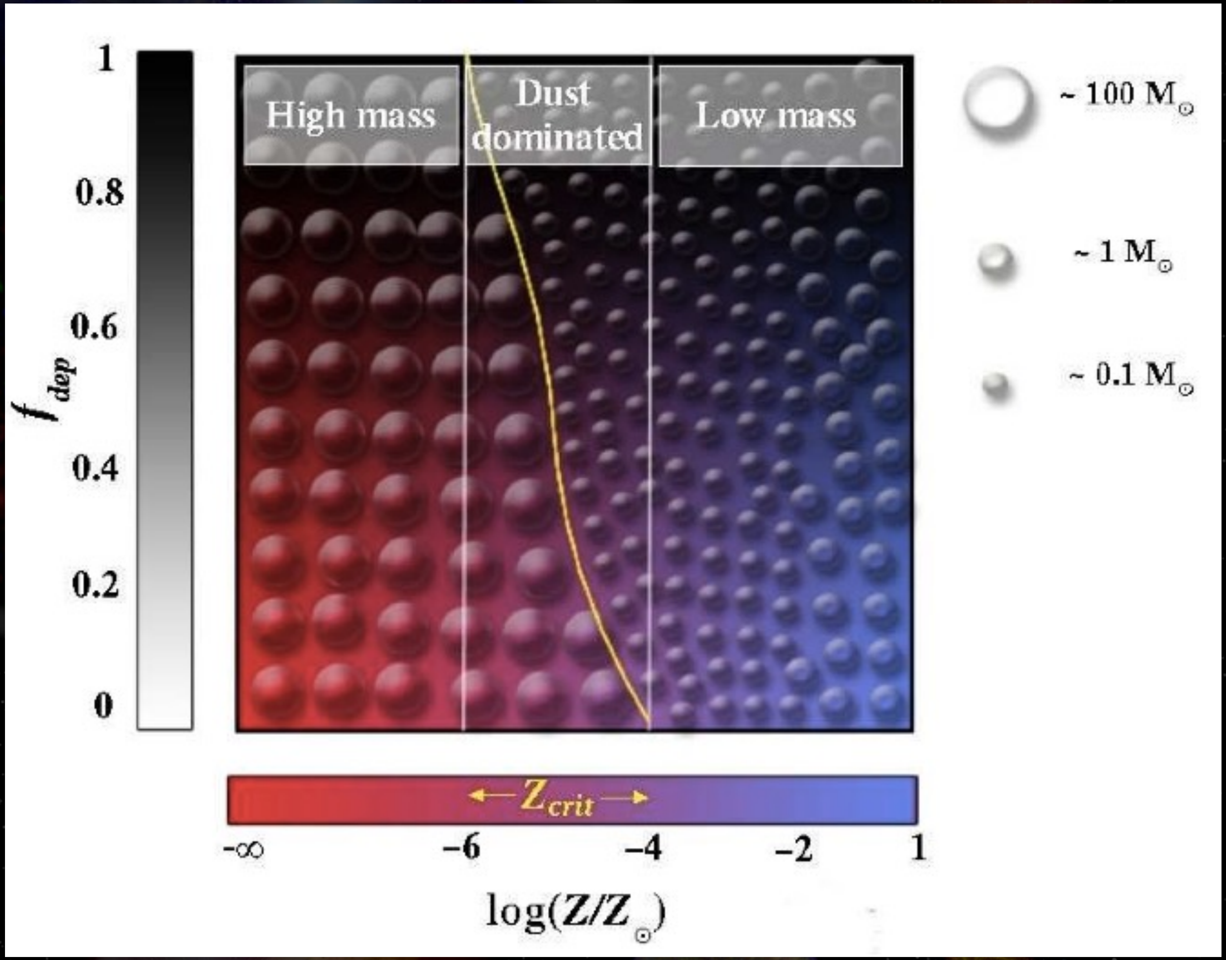
- There will likely be no direct detections of population III sources; **pop III collapsars predicted to produce GRB-like events**.

GRBs: pathways to "unvisible" protogalaxies



Pop III

- $Z<Z_{cr} \approx 10^{-4}$ formation of clouds M>100 Msun
- the final mass popIII: gas accretion vs radiation feedback, typical ~40-50 Msun but [10-1000 Msun] possible

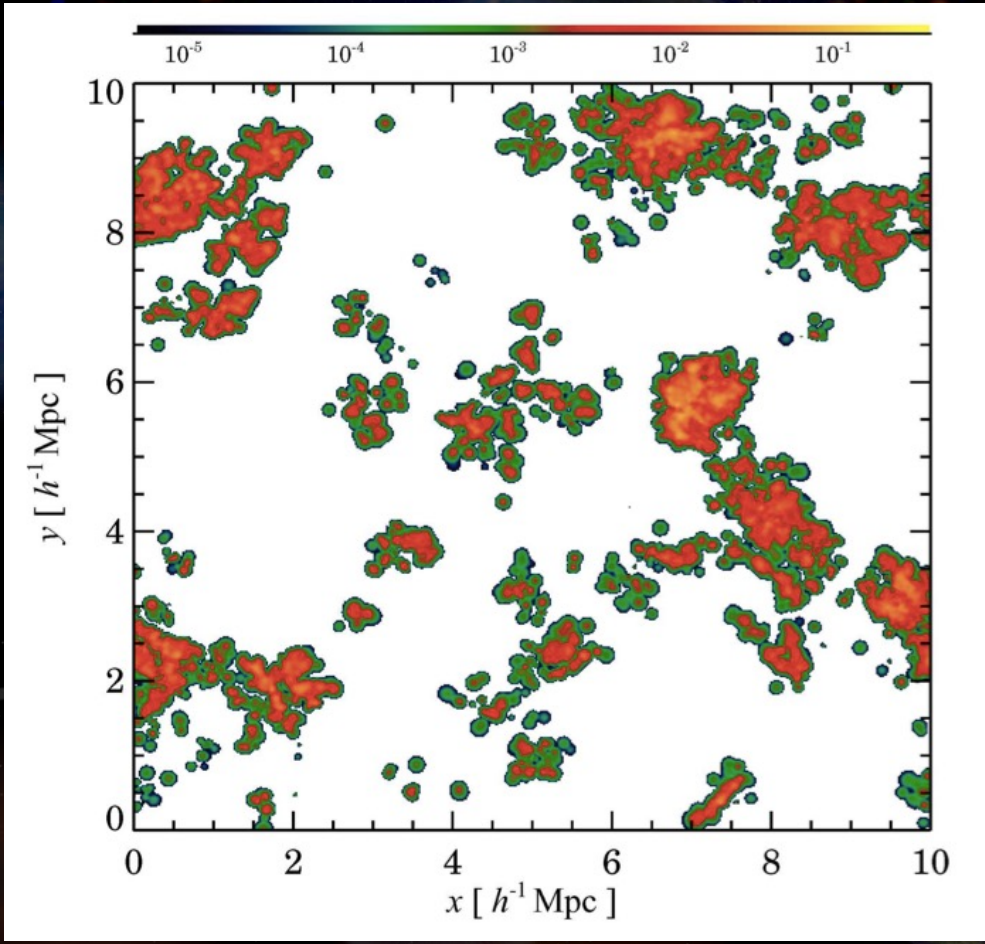


Schneider 2005

popIII-popII transition

- Chemical enrichment is highly inhomengenous: popIII and popII coexhists for a long period

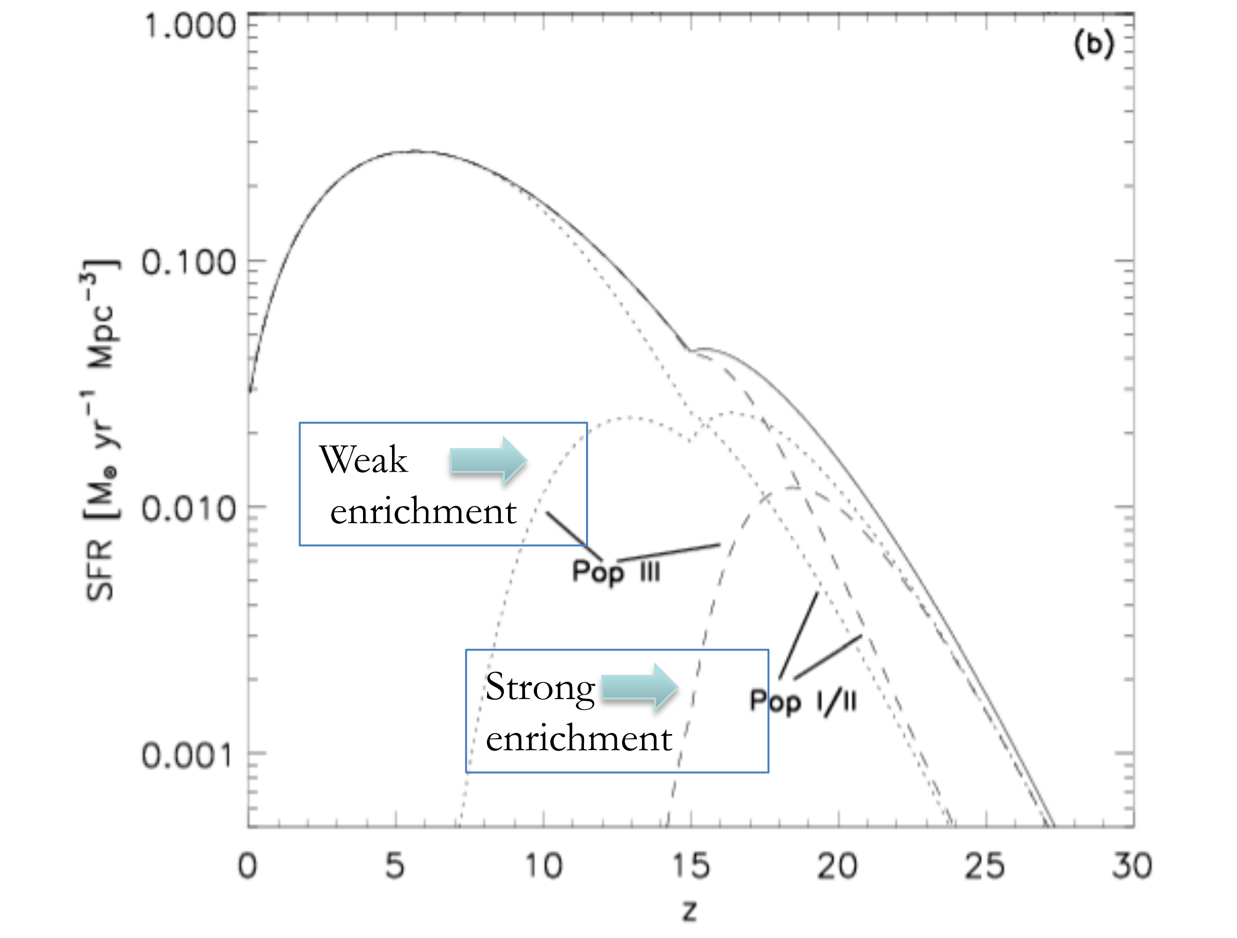
z=5



Tornatore et al 2007

popIII vs popII

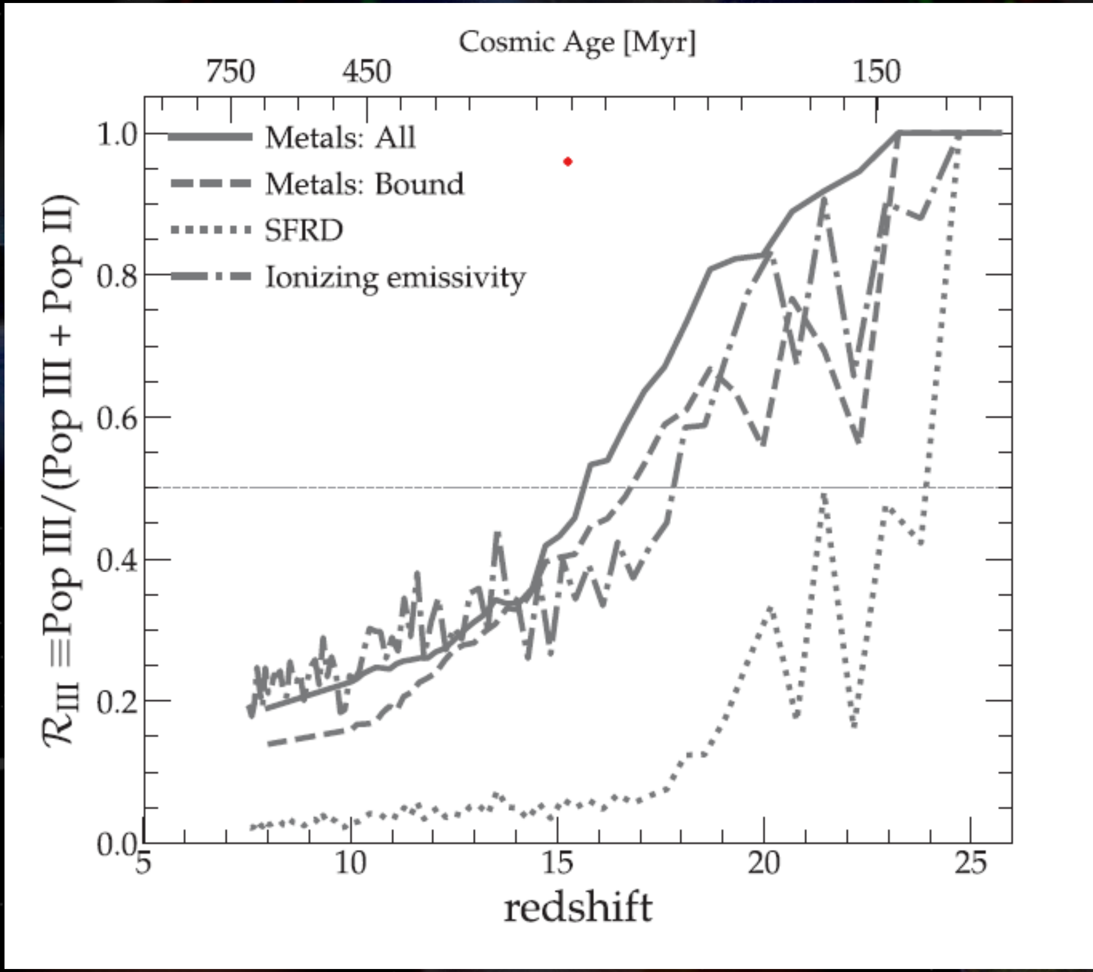
popII GRBs are expected to exist at redshifts z~15-20 and popIII are expected to form down to z<2.5



Bromm&Loeb 2006

History of metal enrichment

Fractional metal enrichment by popIII stars



Jaacks et al 2019

Probing the history of metal enrichment with GRBs

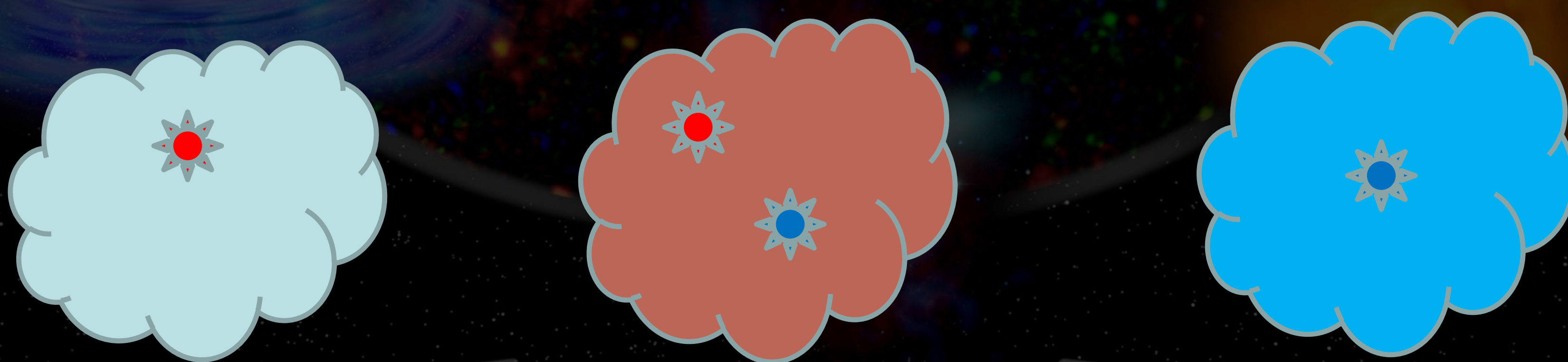
popIII explosion in pristine environment

popIII enrichment →

popIII and popII explosion in popIII-enriched environment

popII enrichment →

popII explosion in popII-enriched environment

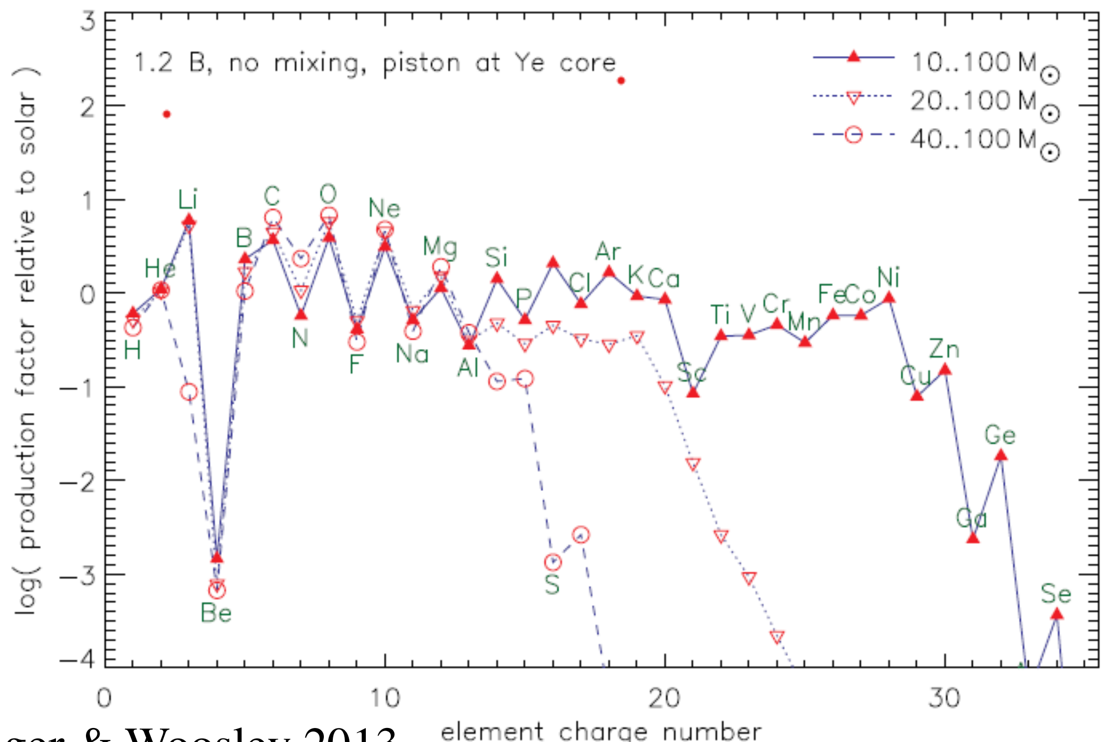


z> 15-20
popIII GRBs in pristine environment

15-20<z<5
popIII and popII GRBs in popIII environment

15<z
popII GRBs in popII environment

popIII vs popII metal enrichment



Heger & Woosley 2013

popIII vs popII metal enrichment

- the abundance pattern of ejecta following the evolution and explosion of metal-free stars with masses 10 – 100 $M_\odot$. When the supernova yields are integrated over a Salpeter initial mass function (IMF), **the resulting elemental abundance pattern is qualitatively solar, but with marked deficiencies of odd- Z elements**.

- The helium core dominates in determining the synthesis of abundant elements. Reducing the metallicity reduces the synthesis of odd-Z elements and neutron-rich isotopes because the neutron excess after helium burning depends on the initial abundance of C N O.

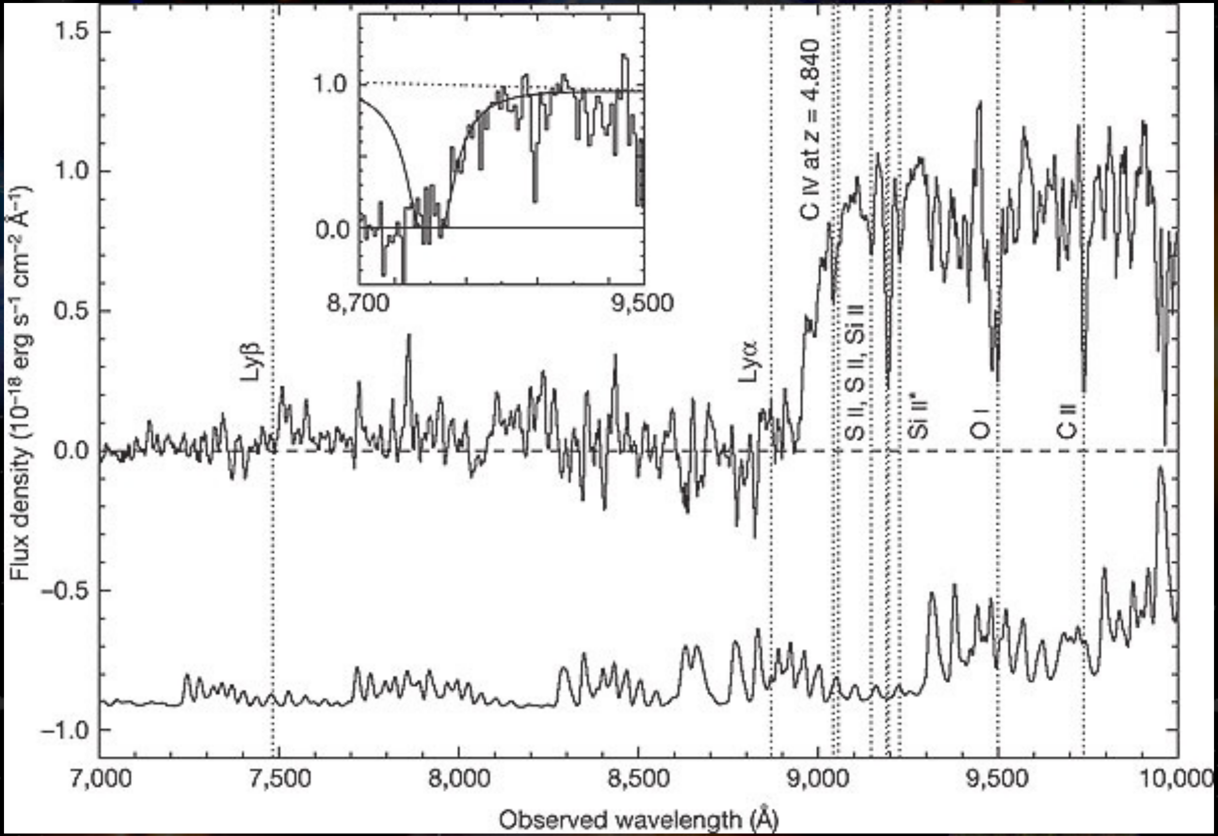
- Note that the odd/even effect is large (upto a factor of 10 in relative abundance odd/even elements).

- Heavier elements yields depends on the low mass cut off, **paucity of heavier elements at M> 40 $M_\odot$ that can be used to determine the IMF of popIII star**

- Caveat: Model dependant (mixing/nomixing, explosion assumptions)

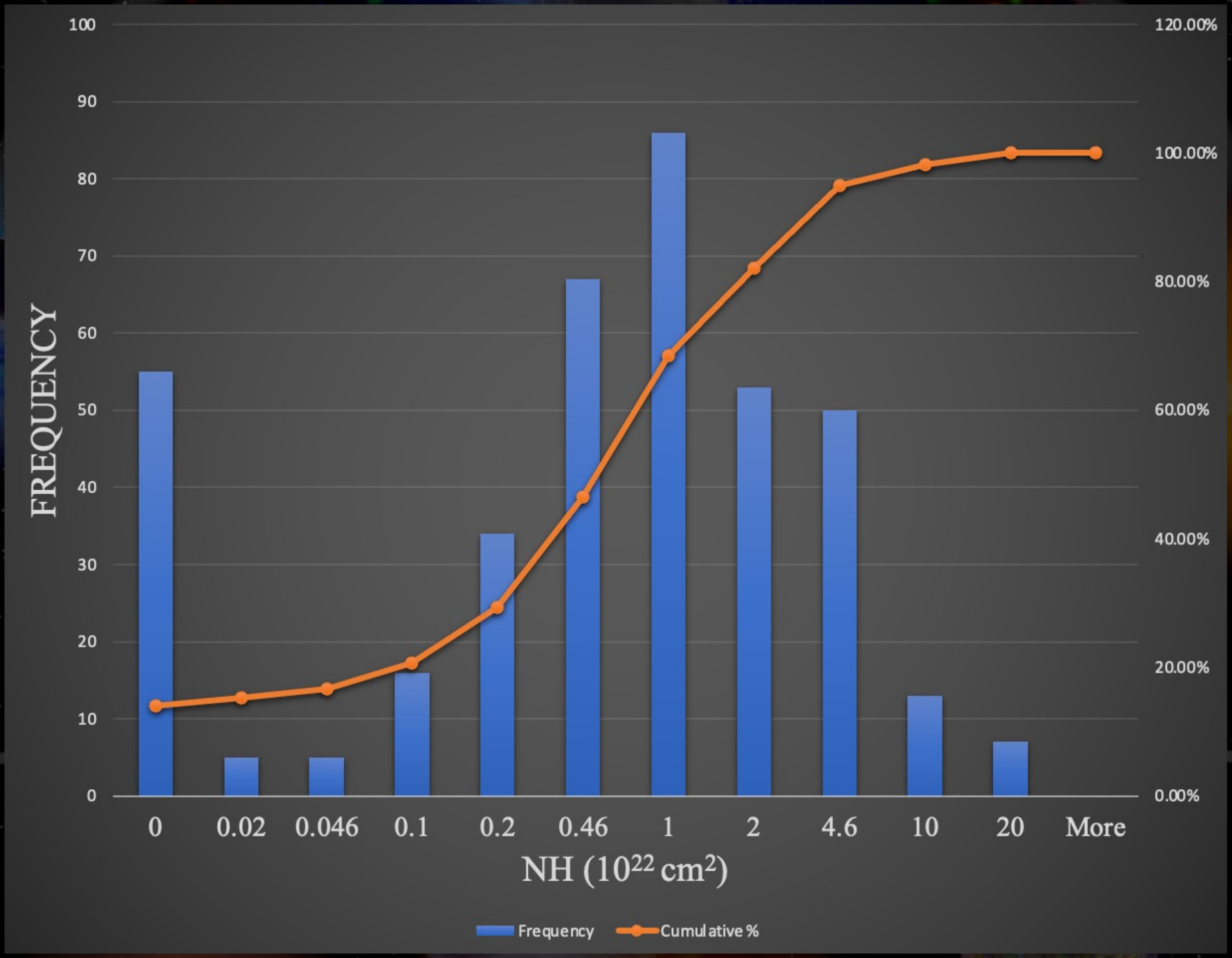
Determining Environments with GRBs

Afterglow spectroscopy can provide redshift, chemical abundances, dust, & molecular content



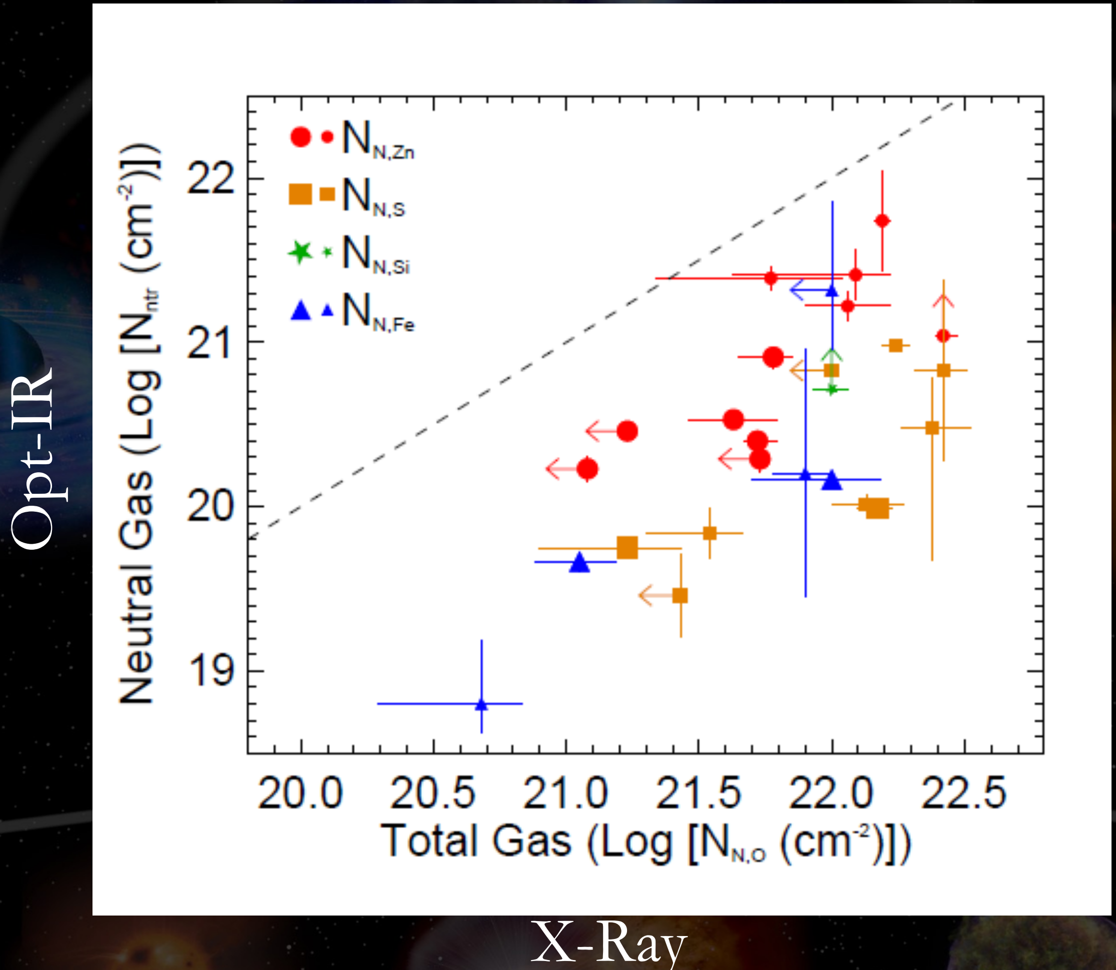
GRB050904 z=6.3
Kawai et al 2006

X-ray absorption in GRBs



Present sample (393) of SWIFT GRB with measured z

X-rays probe the close ionized environment

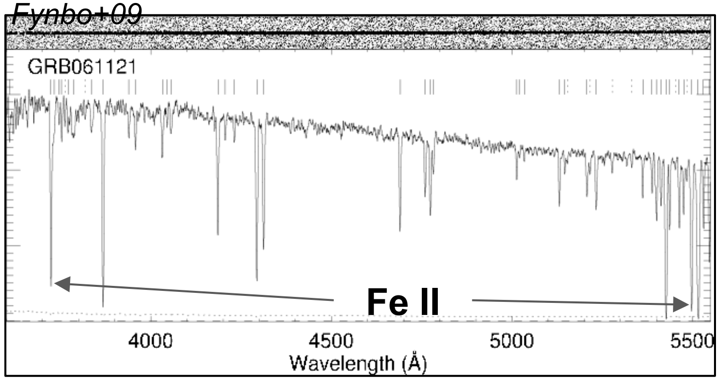


Schady et al 2010

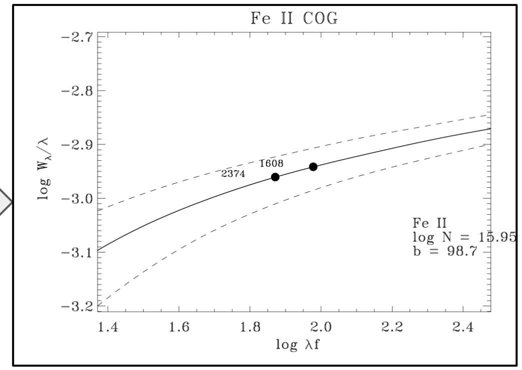
Neutral absorption using the optical

Equivalent widths from optical spectrum

Fynbo+09

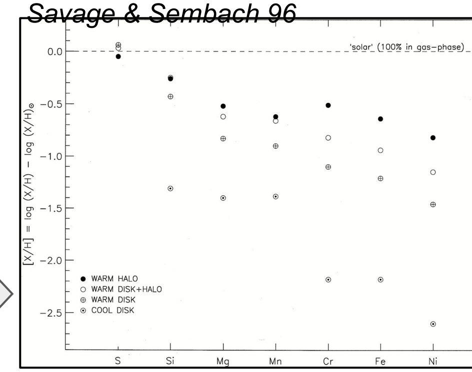


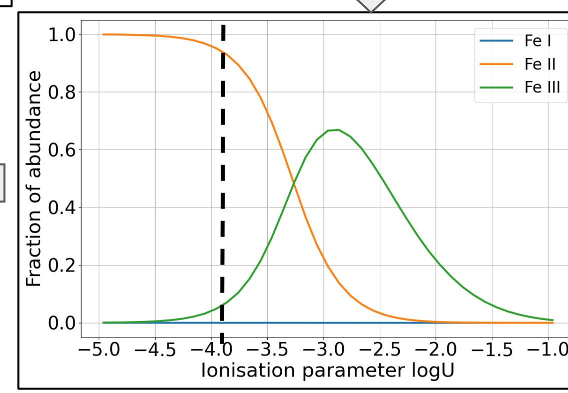
Derive ionic column from curve of growth, Here, $N_{Fe} \sim 10^{16}$



Correct for dust depletion using gas phase abundances

Savage & Sembach 96





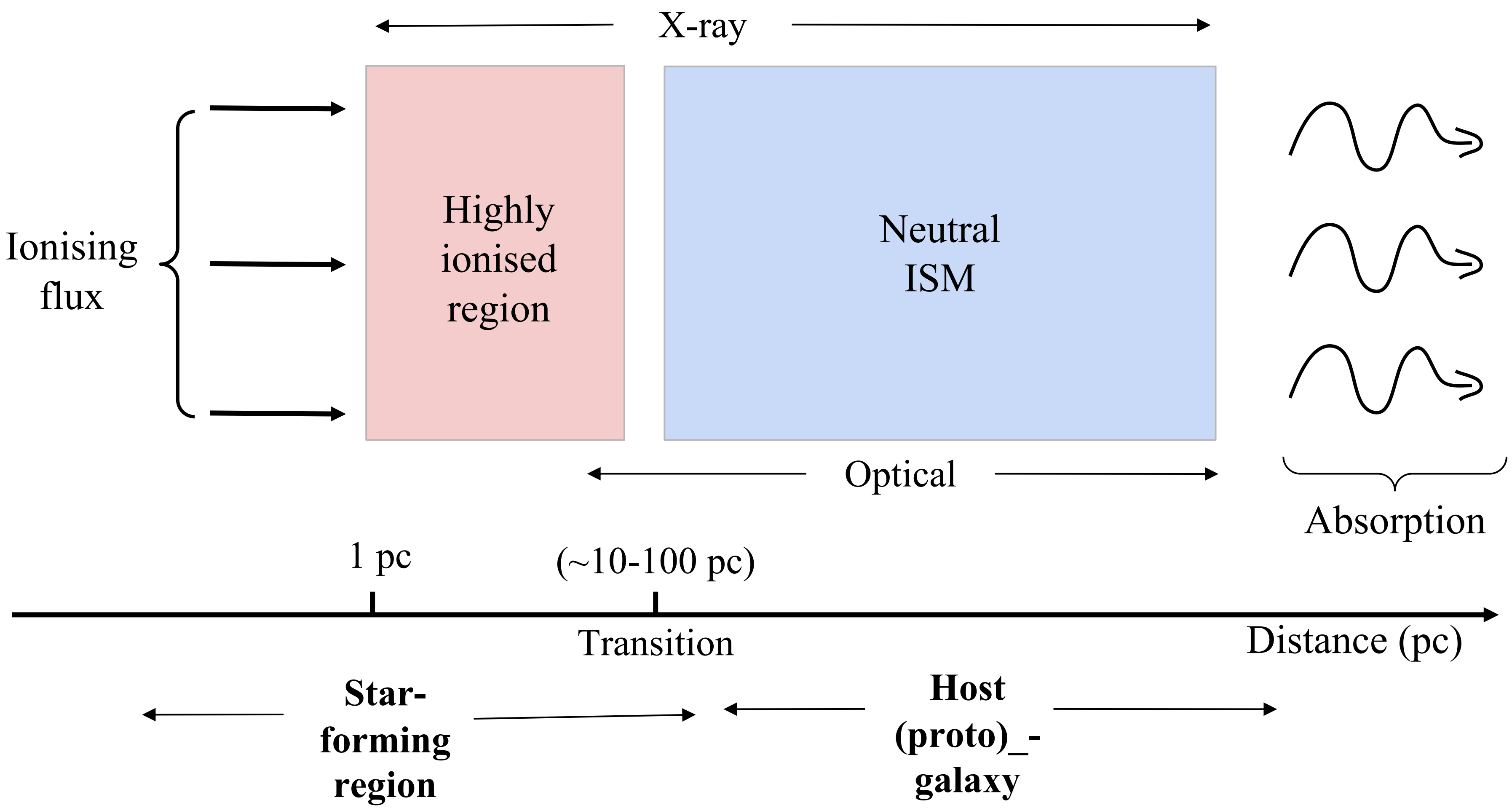
Correct for ionisation fraction

Convert to equivalent hydrogen column density assuming solar abundances

Use as proxy of neutral absorption at host ***Z*** for X-ray fitting

Thakur et al 23, in prep

Location of absorbers

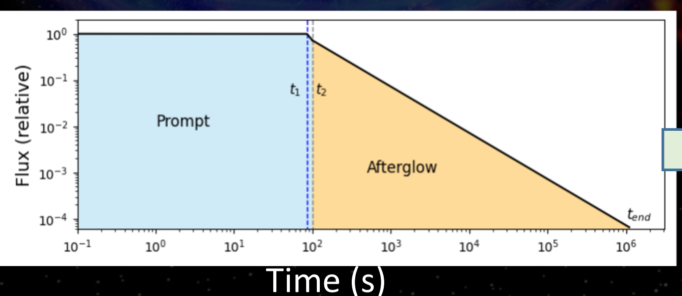


TEPID: Code outline

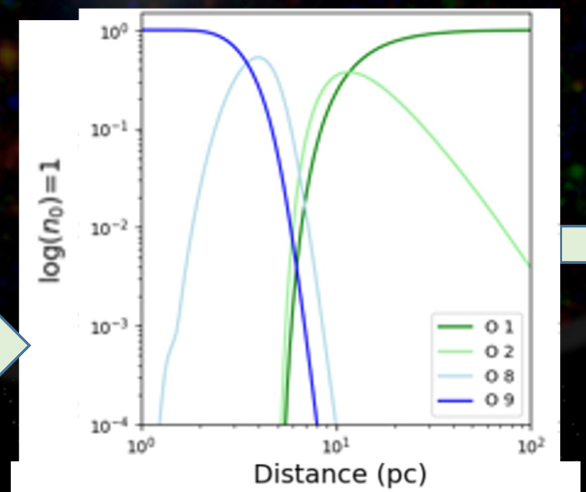
Time-**E**volving **P**hoto**I**onisation **D**evice

Work flow of TEPID:

1. Input quantities:
   i. Lightcurve/Luminosity
   ii. Gas density
   iii. Initial ionic abundances

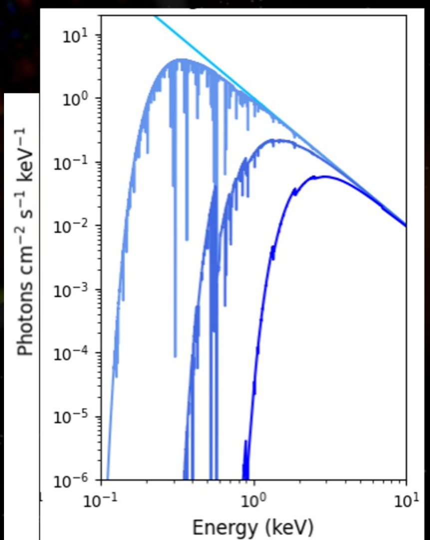


2. Time evolving computation:



Temporal evolution of the ionisation and temperature of the surrounding ISM

3. Absorption spectrum:

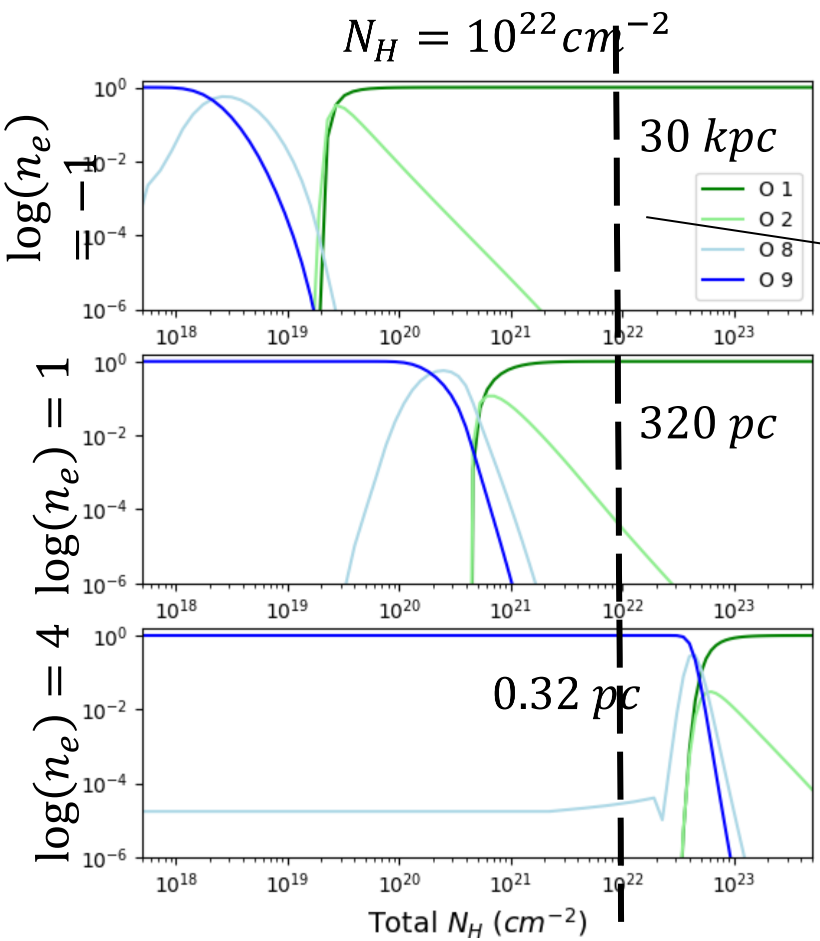


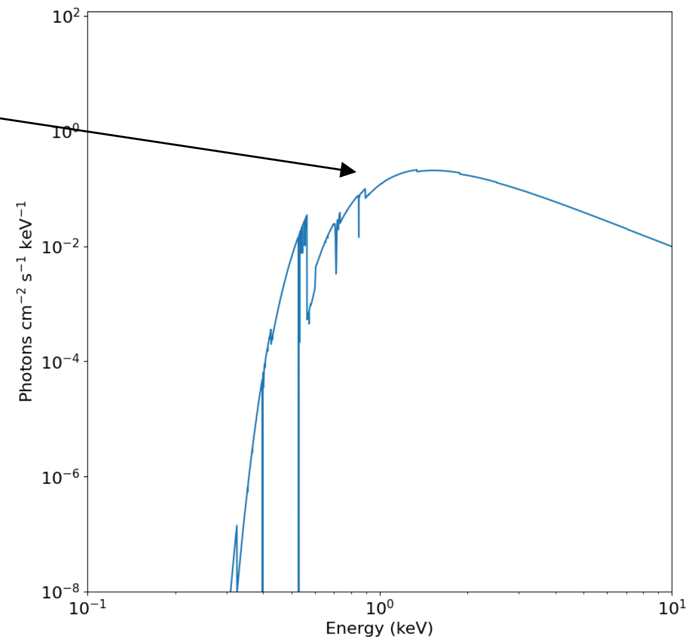
Time-resolved optical to X-ray spectra as a function of the ISM density and distance

Luminari et al, 2022

X-ray absorption spectra

Breaking the degeneracy in density





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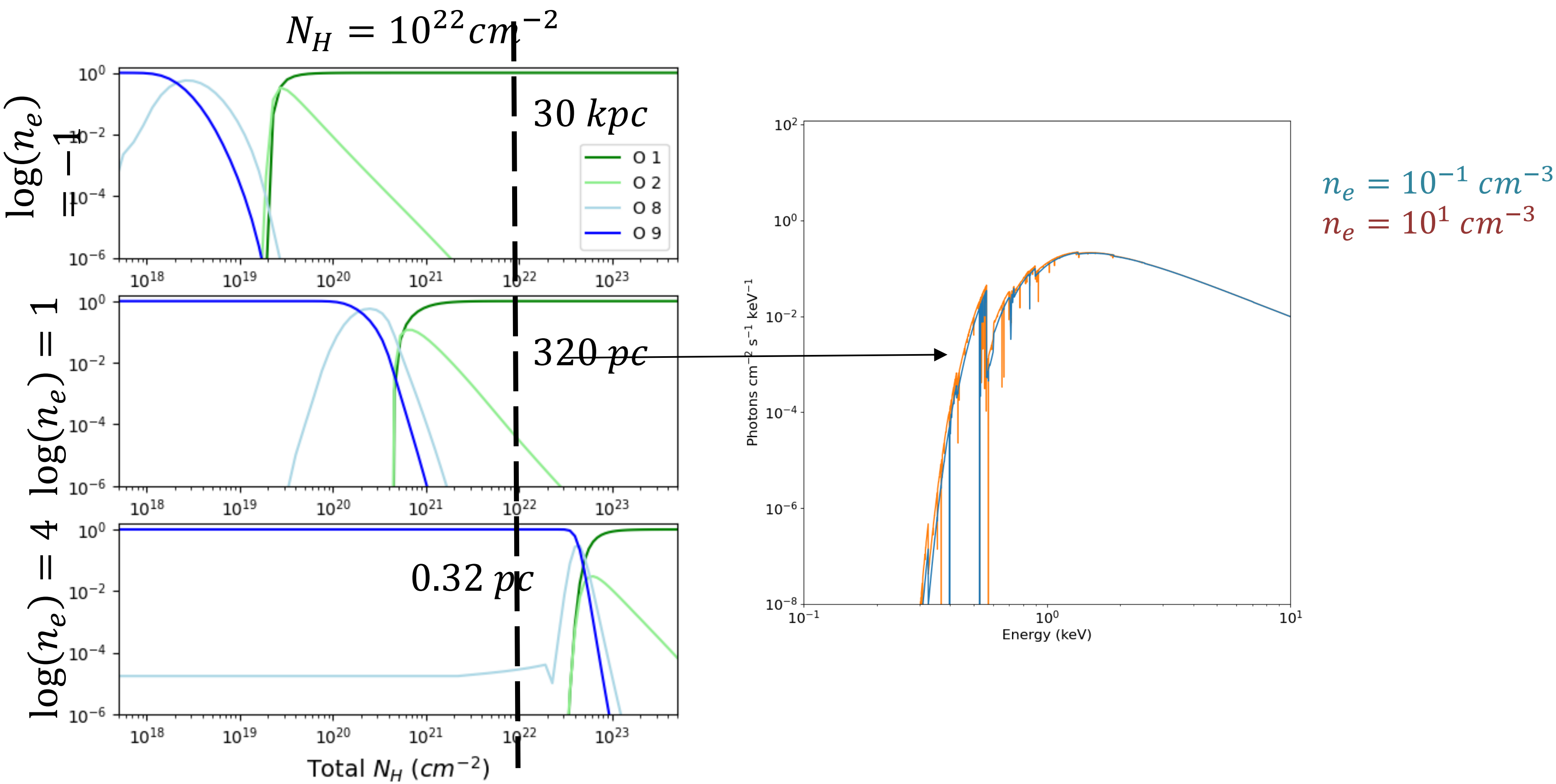
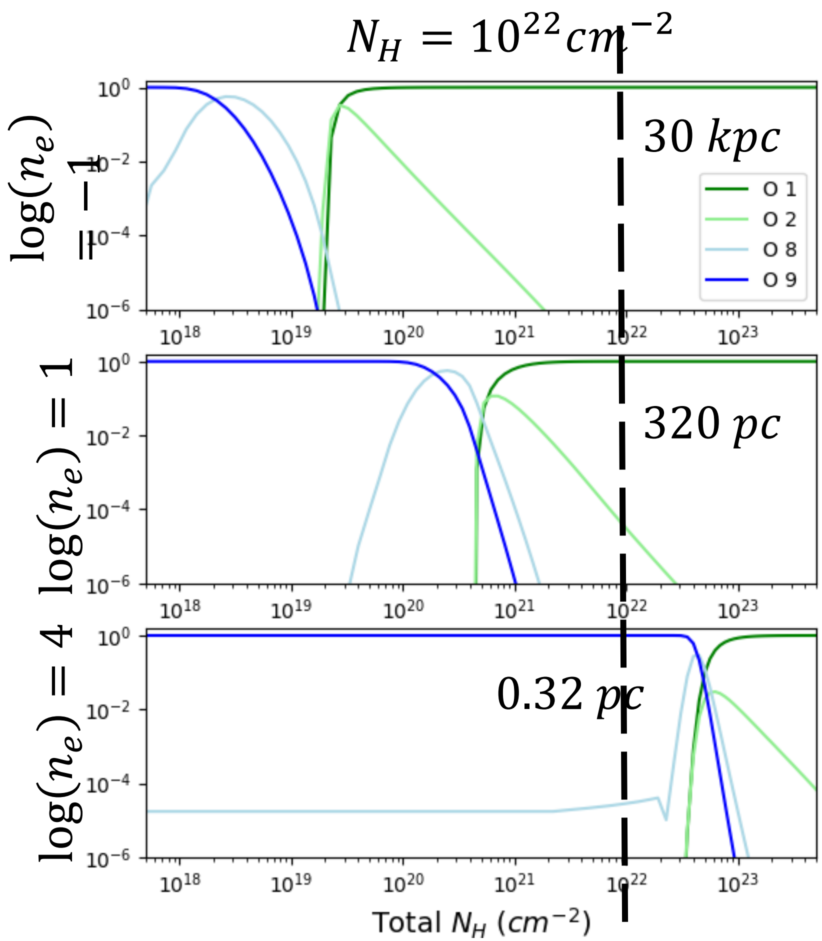
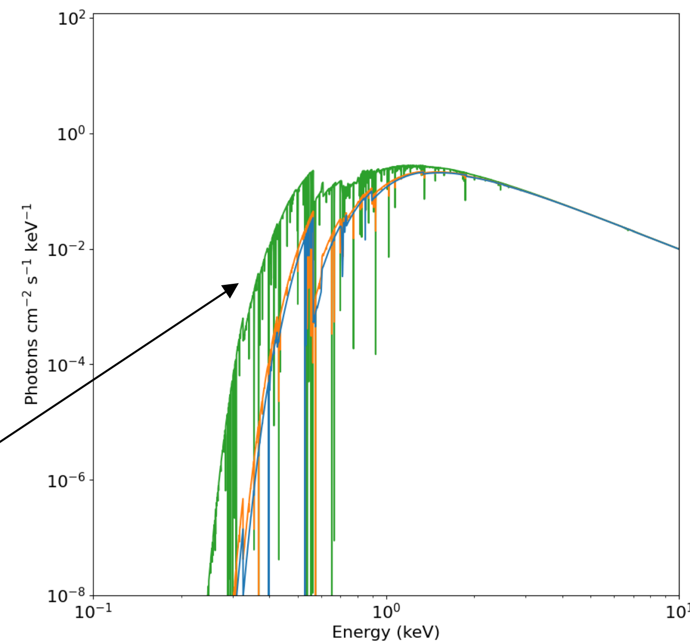


X-ray absorption spectra

Breaking the degeneracy in density





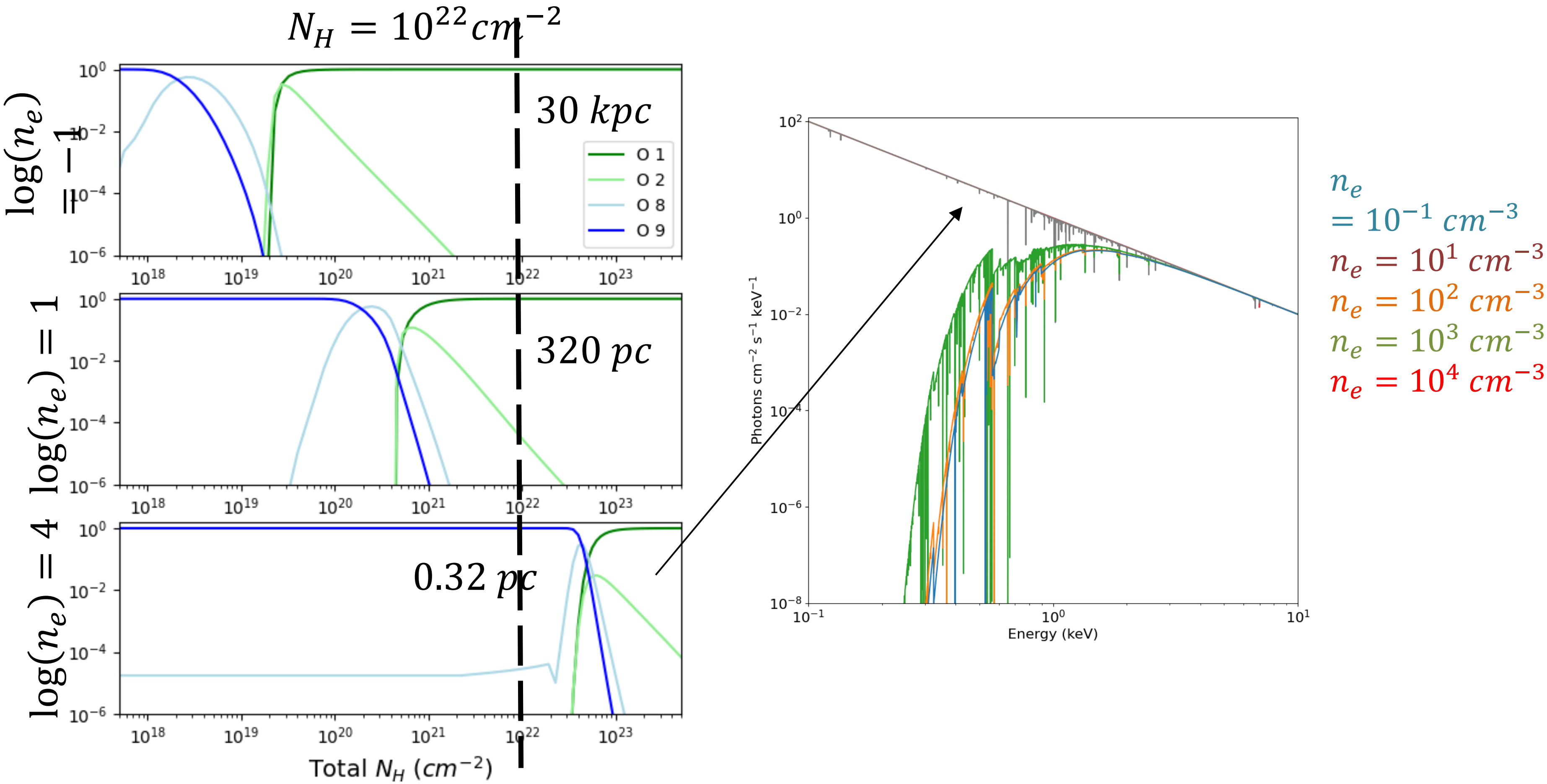
$n_e = 10^{-1}\ cm^{-3}$

$n_e = 10^{1}\ cm^{-3}$

$n_e = 10^{2}\ cm^{-3}$

X-ray absorption spectra

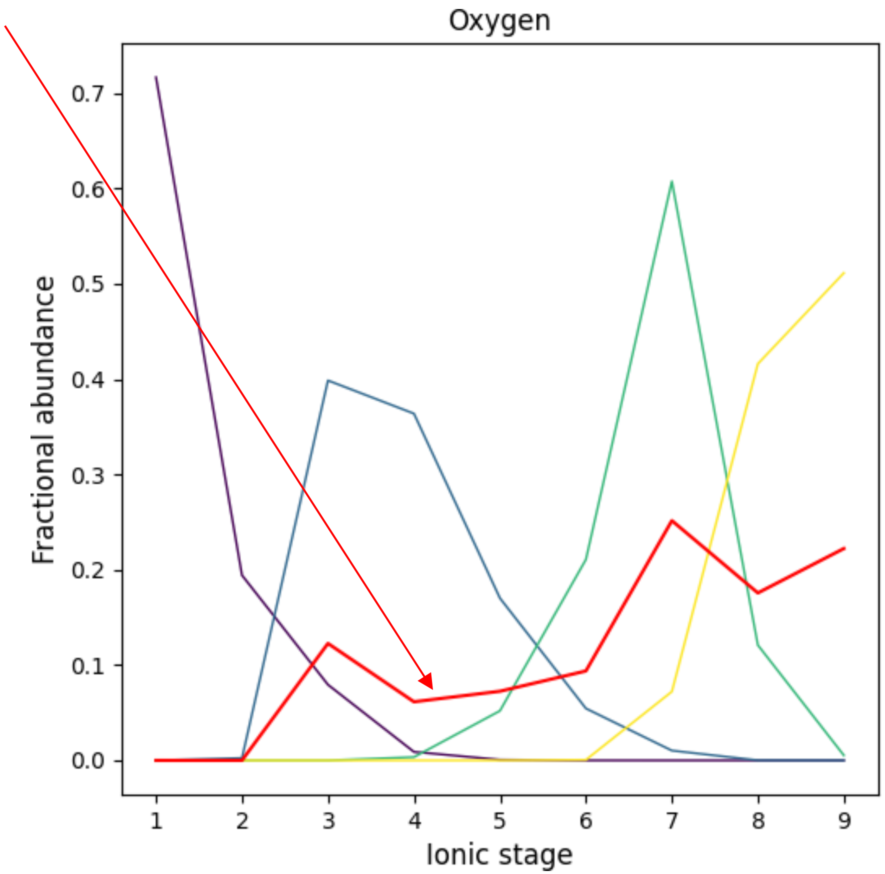
Breaking the degeneracy in density



Time evolving photoionization

Ion abundances cannot be mimicked by single zone equilibrium distribution:

Average oxygen ion abundances
with TEPID for $N_H = 10^{22} cm^{-2}$
and $n_e = 10^{1} cm^{-3}$:



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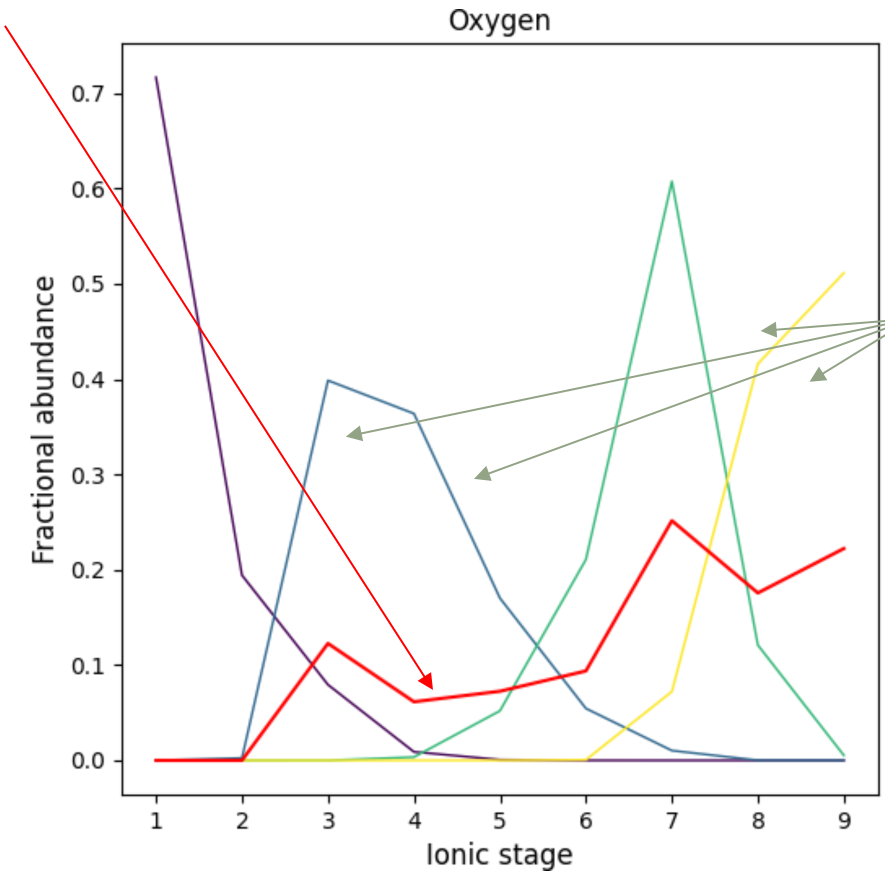
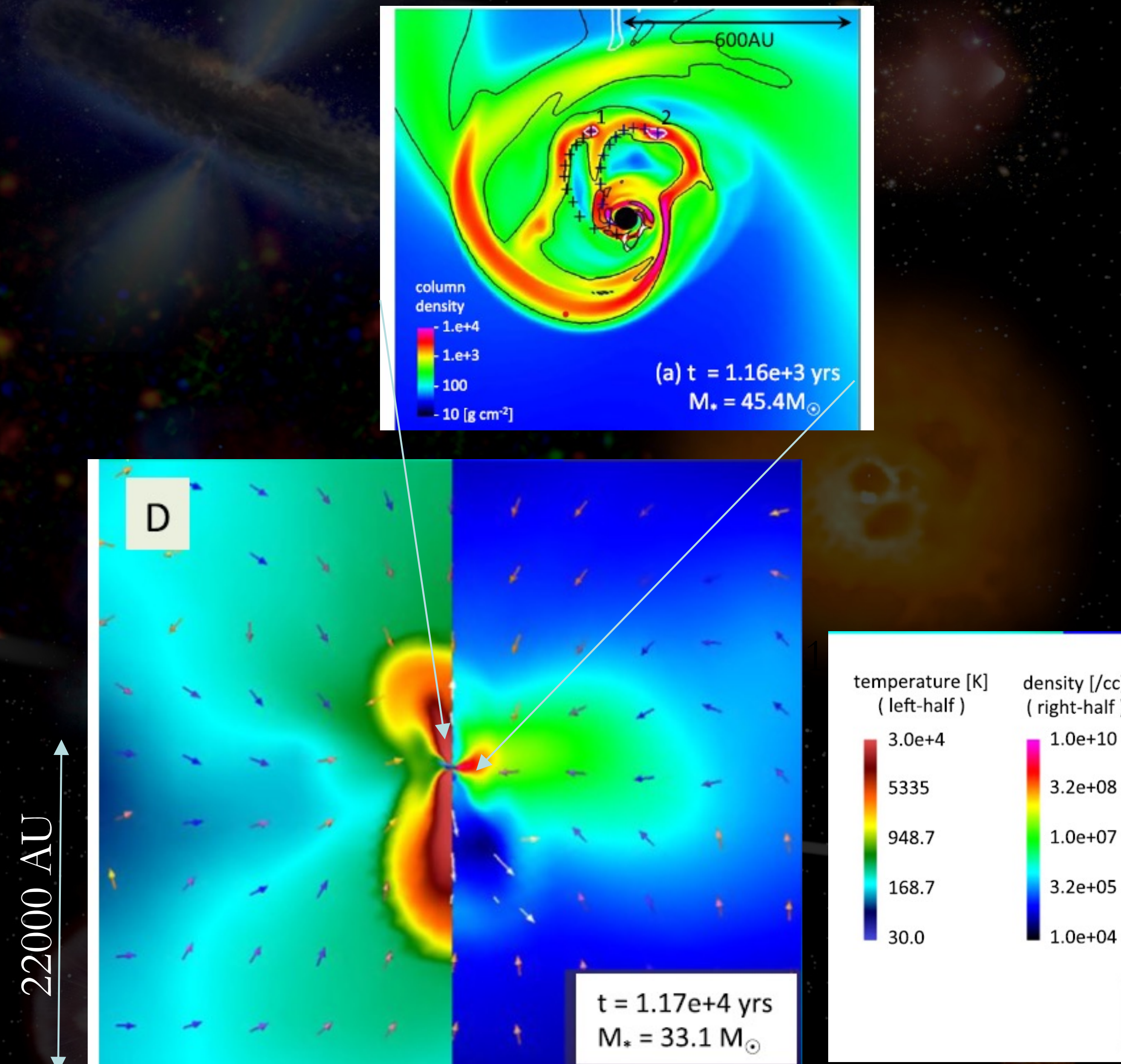


Average oxygen ion abundances in photoionisation equilibrium for $N_H = 10^{22} cm^{-2}$ and $\log(\xi) = -1.5, -0.5, 0.5, 1.5$

PopIII environment at the formation

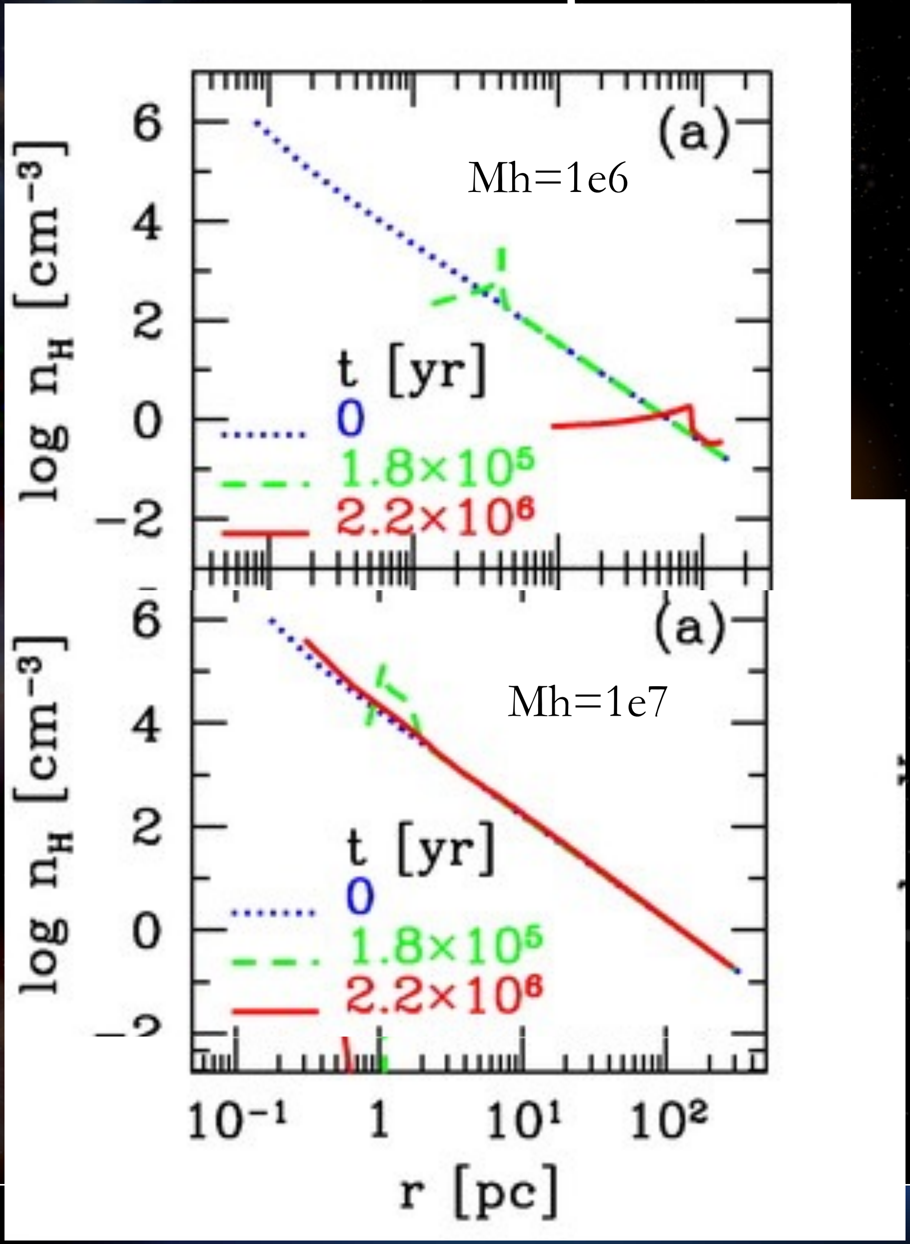
- Density >1e4 cm-3
- Formation of AD
- Column densities $>10^{24}$ cm^{-2}

Hosokawa et al 2016



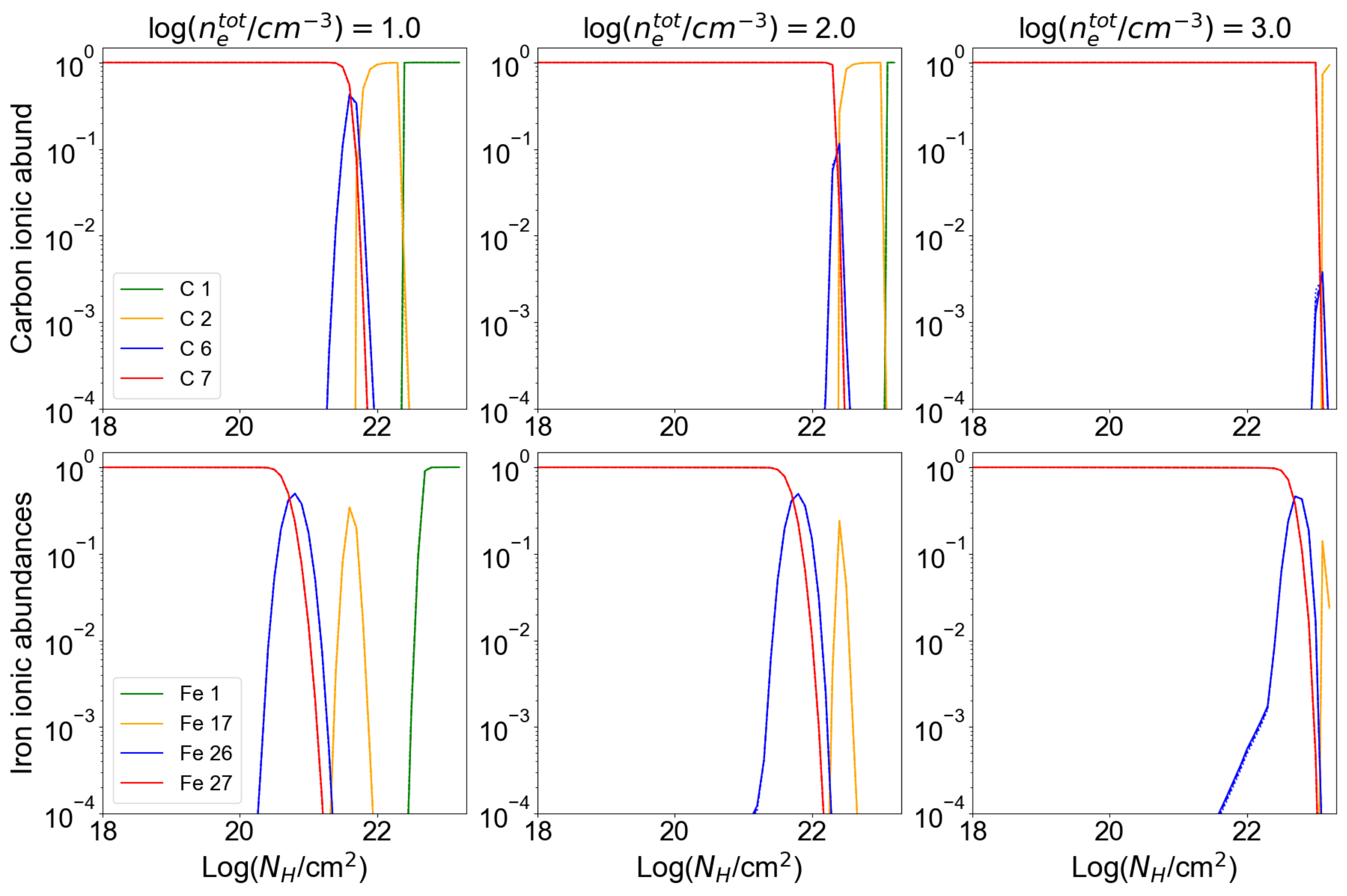
PopIII environment at the explosion

- Radiation pressure may evacuate the circumstar region, depending on the halo mass (initial density)
- Density 1-10^4 cm^{-3}
- Kitayama et al 2004

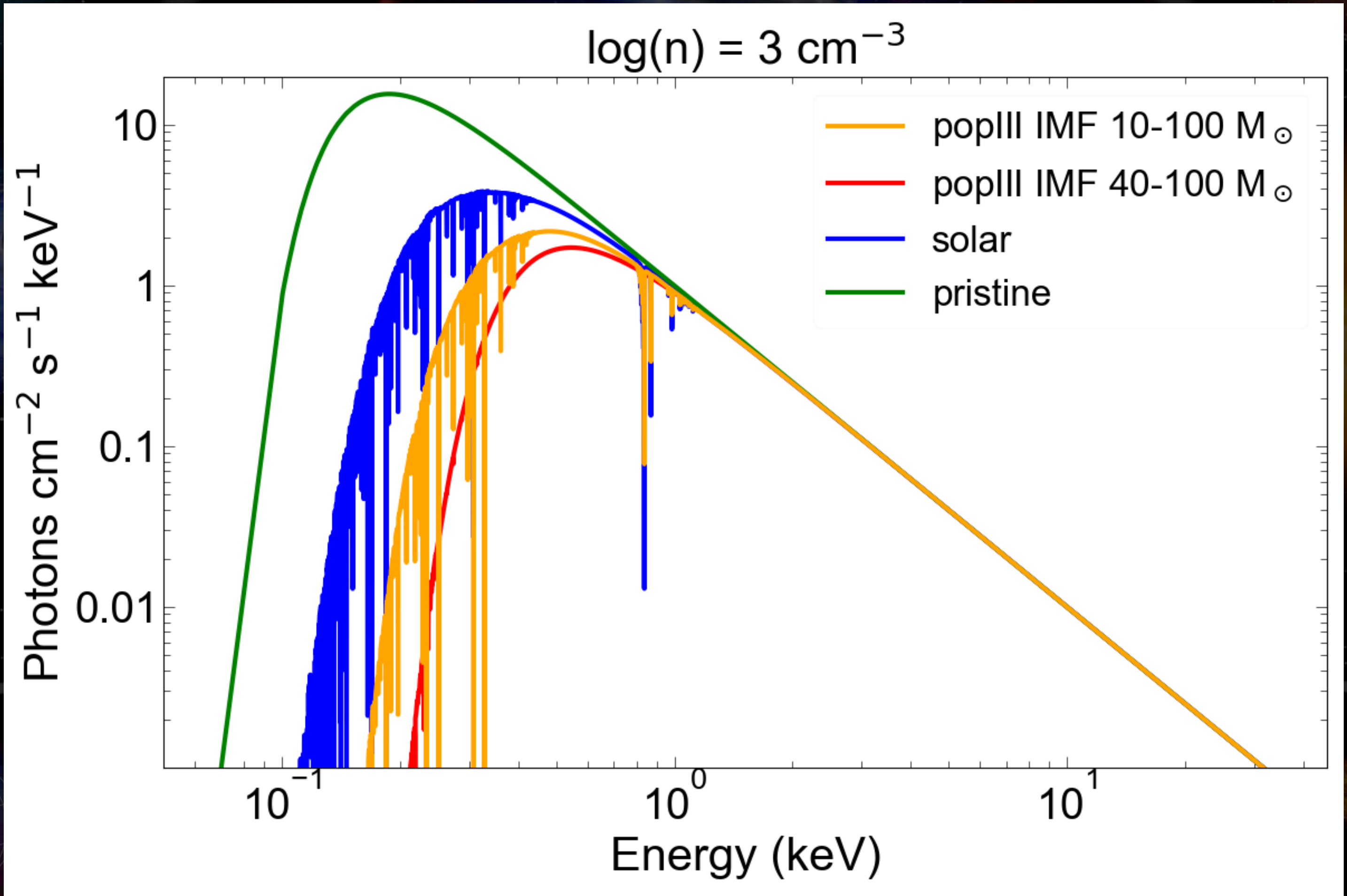


The case of a high-z GRB

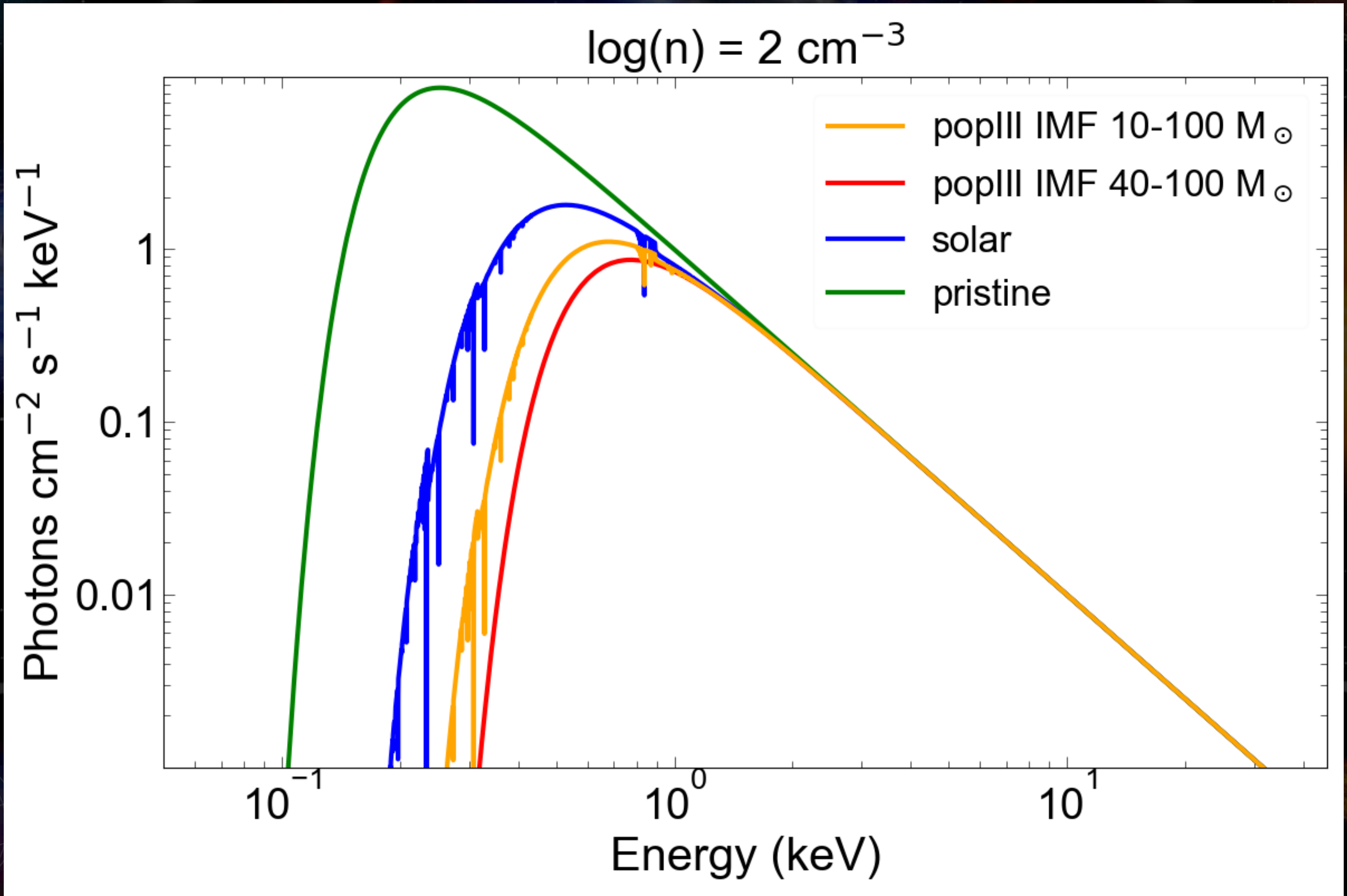
NH=8 10^{22} cm-2, n=10-1000, constant density,
Lion=observed (typeII) GRB

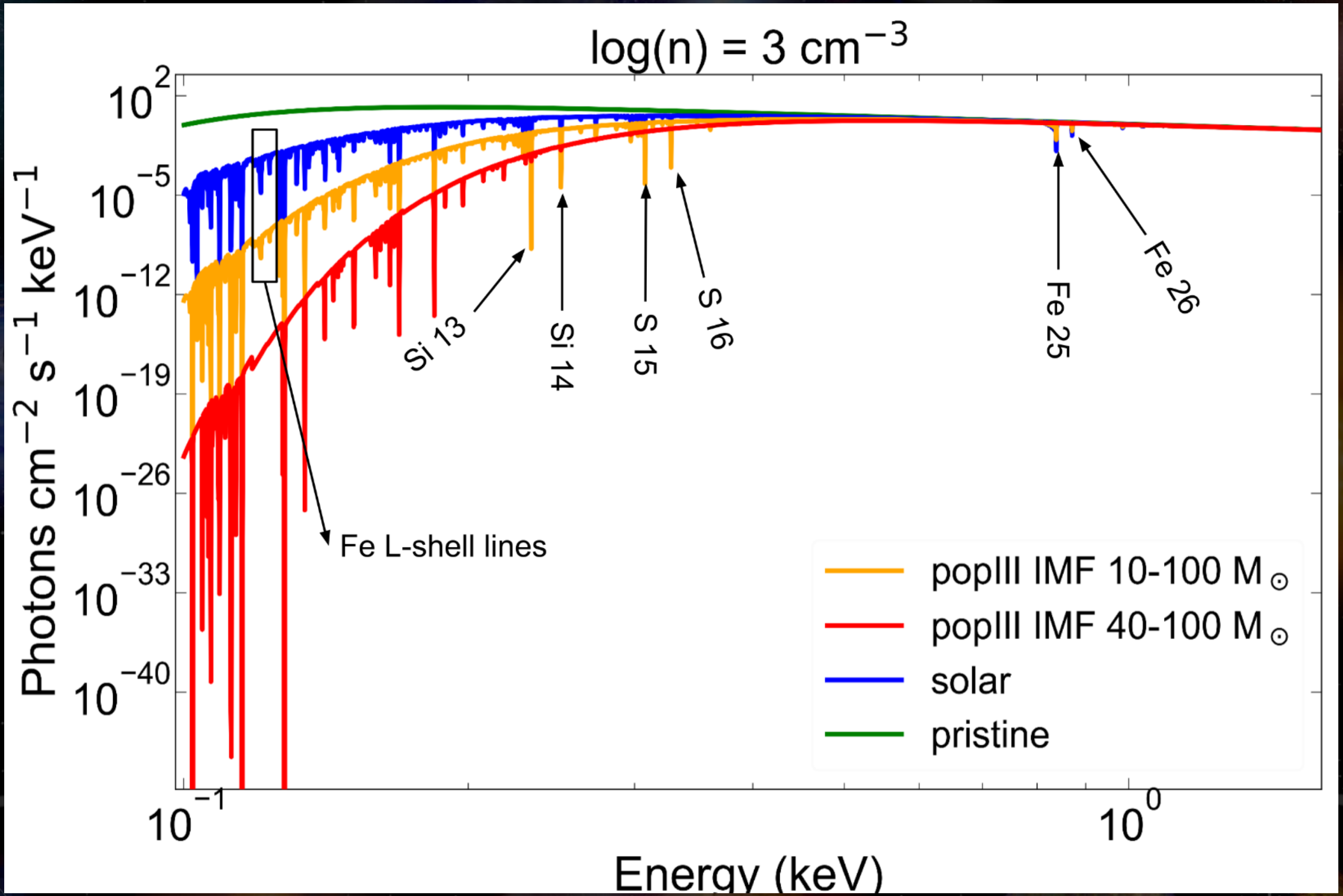


Ionization of the close environment for pristine, popIII and popII



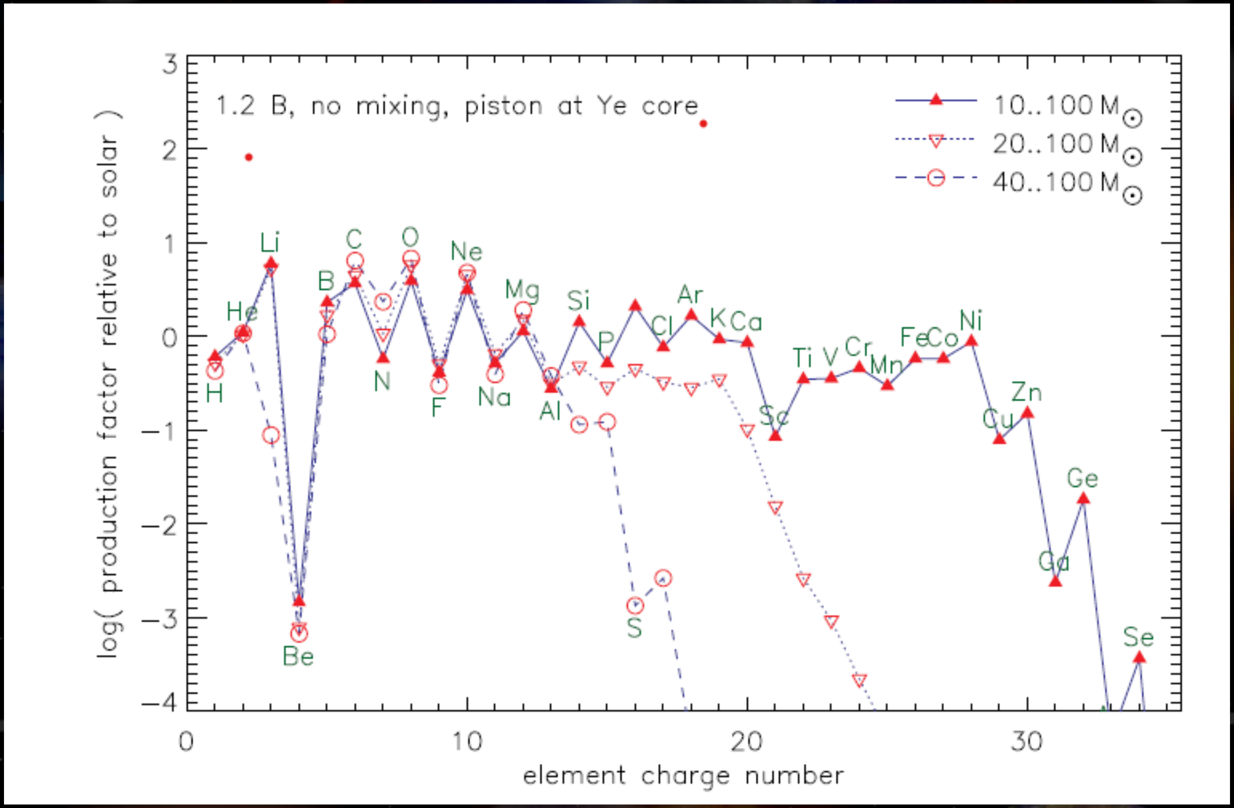
Ionization of the close environment for pristine, popIII and popII





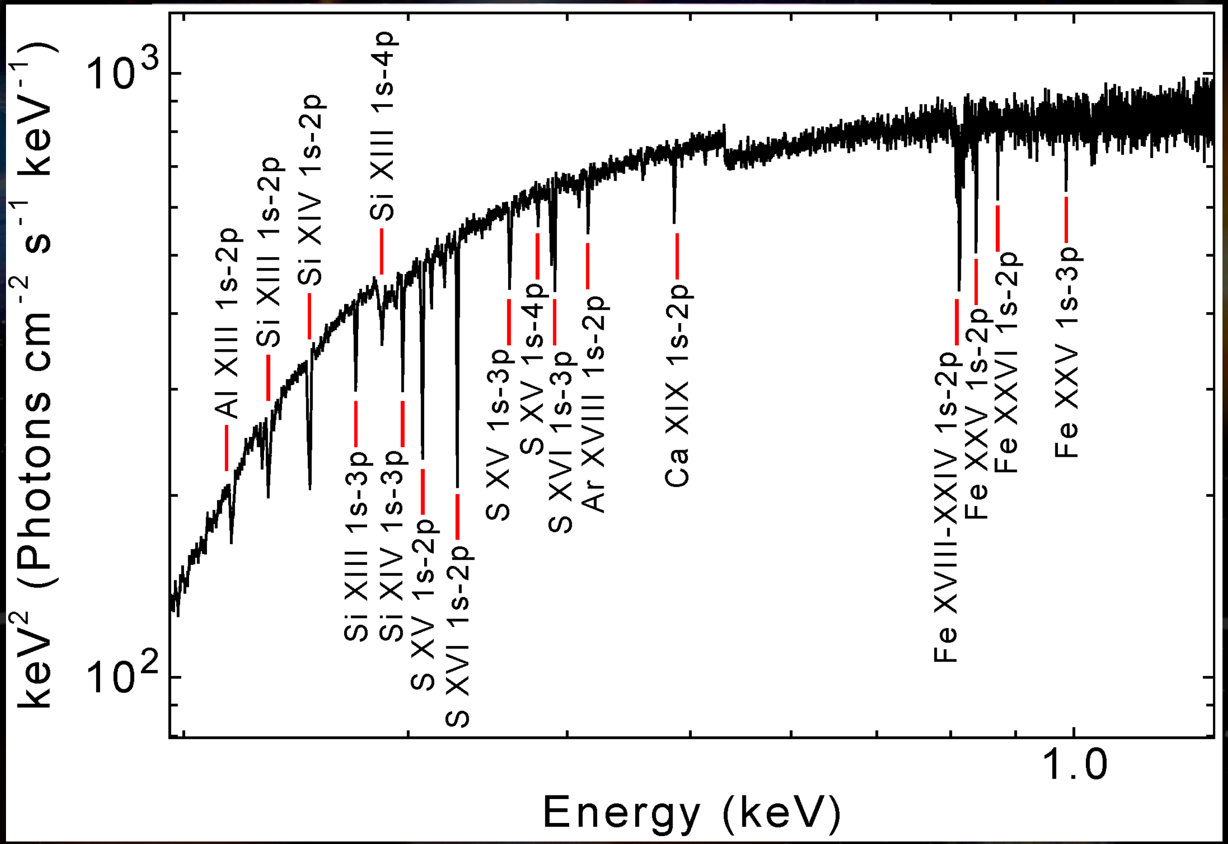
Caveat: overall absorption assume same dilution factor in various environs, not affecting line ratios diagnostics.

popIII vs popII metal enrichment



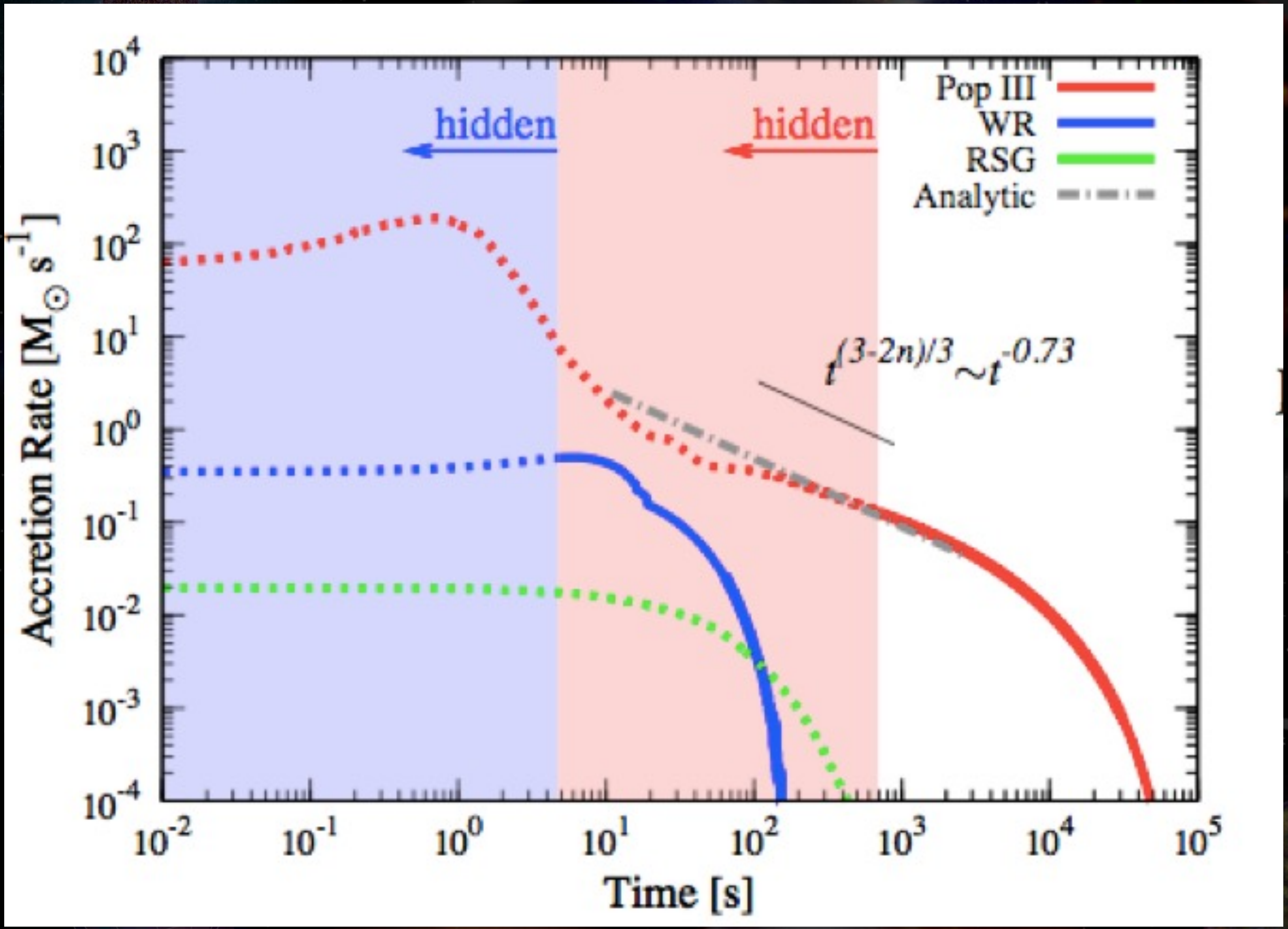
Follow-up of high-z GRB with (new)Athena

Narrow & weak X-ray lines require new capabilities



Piro et al 2022

popIII GRBs



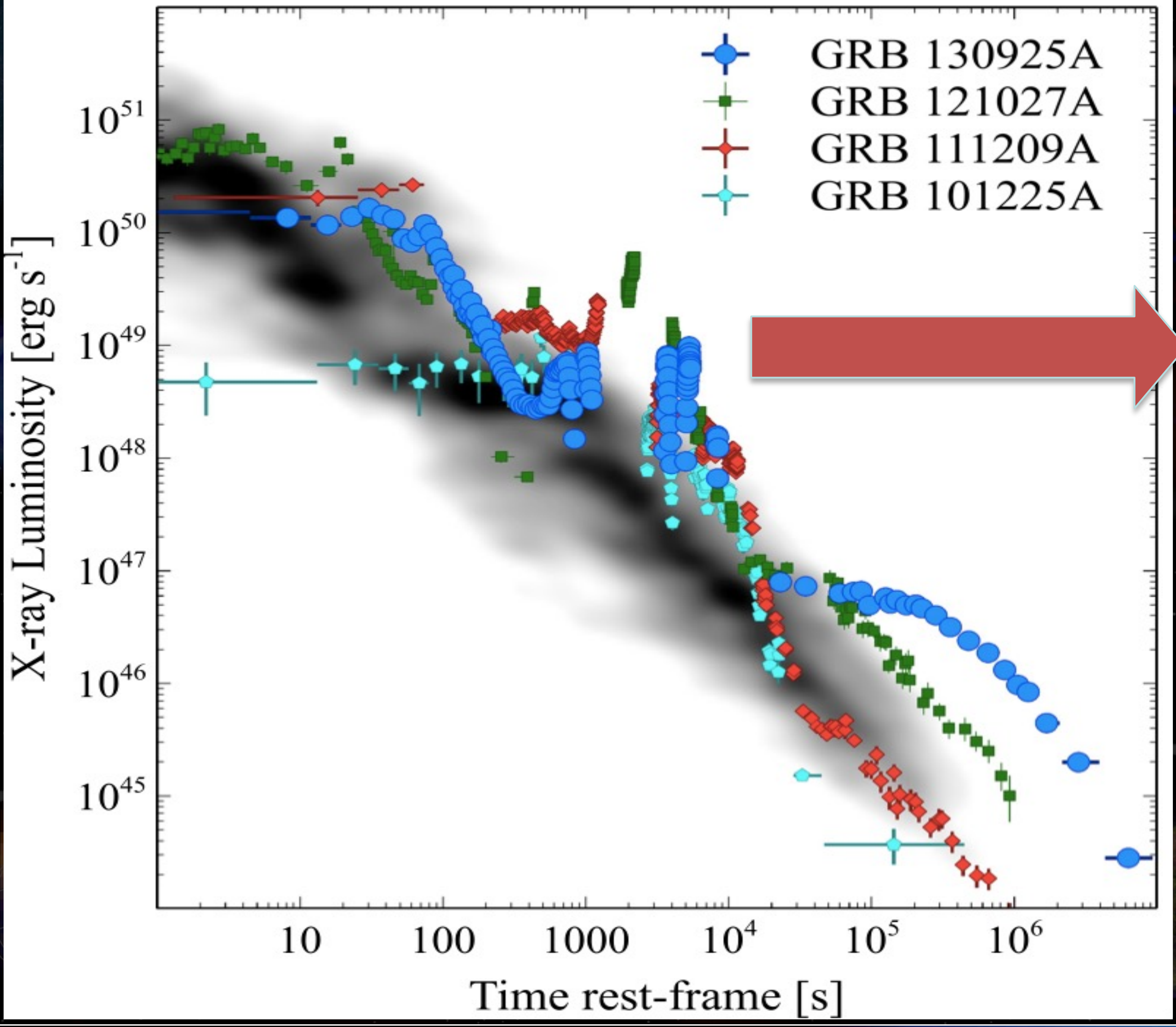
$T_{90}=10^4$ s

$Eiso=10^{55}$ erg

$L=10^{52}$ erg/s

Suwa&Ioka 2011

Ultralong GRB: a popIII analogue?



Flux@z=10

10^{-11} erg/cm^2/s

LP et al 2014

Ultralong as proxy popIII GRBs

- Low metallicity Blue SuperGiant (Gendre et al. 13) => low mass rate, external stellar layers able to fuel central engine for

$$t_{ff} \approx 10^4 R_{12}^{3/2} M_{50}^{-1/2} \ \mathrm{s}$$

- Evidence of afterglow with very low density wind and hot thermal cocoon associated to low metallicity BSG (LP et al 2014)
- Close (z<0.7) and few

Conclusions

- Identifying the size of formation of the first stars and metals in the Universe => Transformational science
- A few high-z events worth many thousands
- High-z GRBs and popIII GRBs and history of metal enrichment require high-resolution spectroscopy in X-rays =>new-Athena