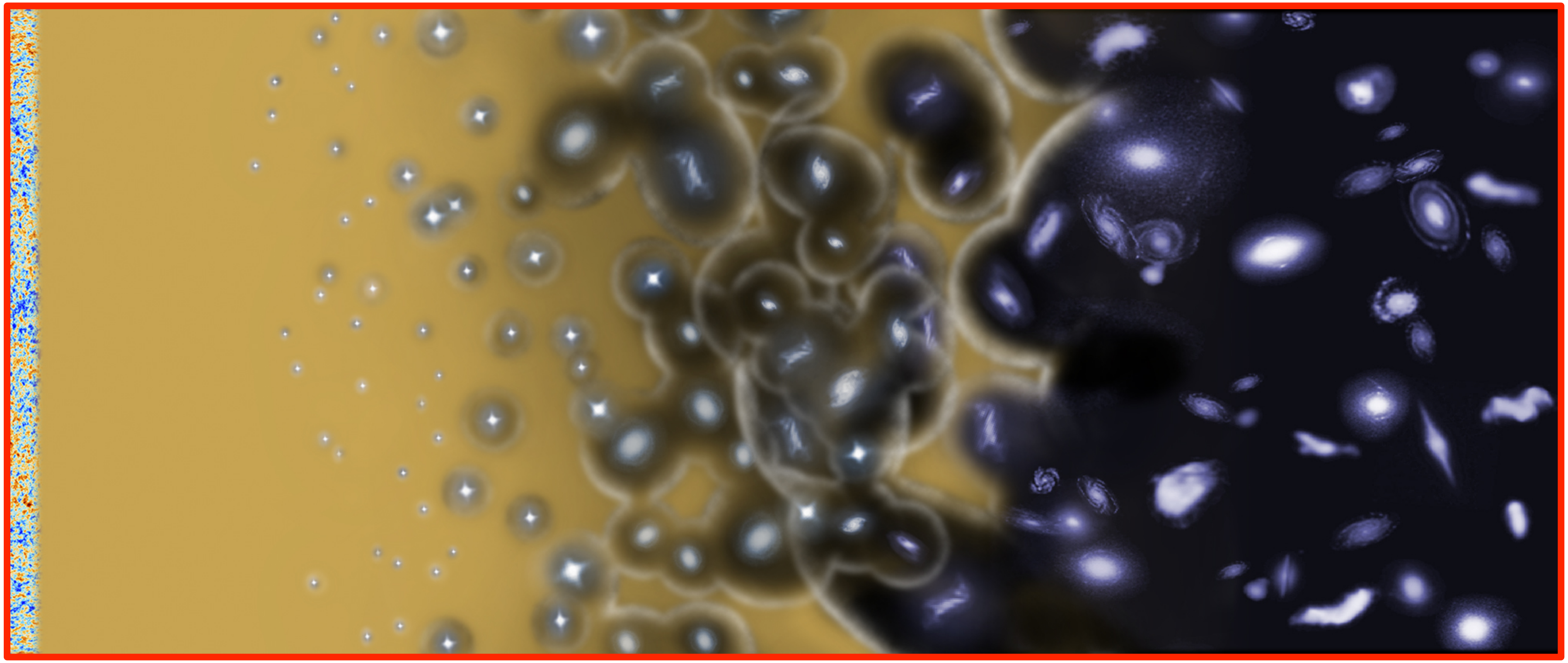
From local chemical evolution
to
cosmic chemical evolution



Credit ESA/Planck

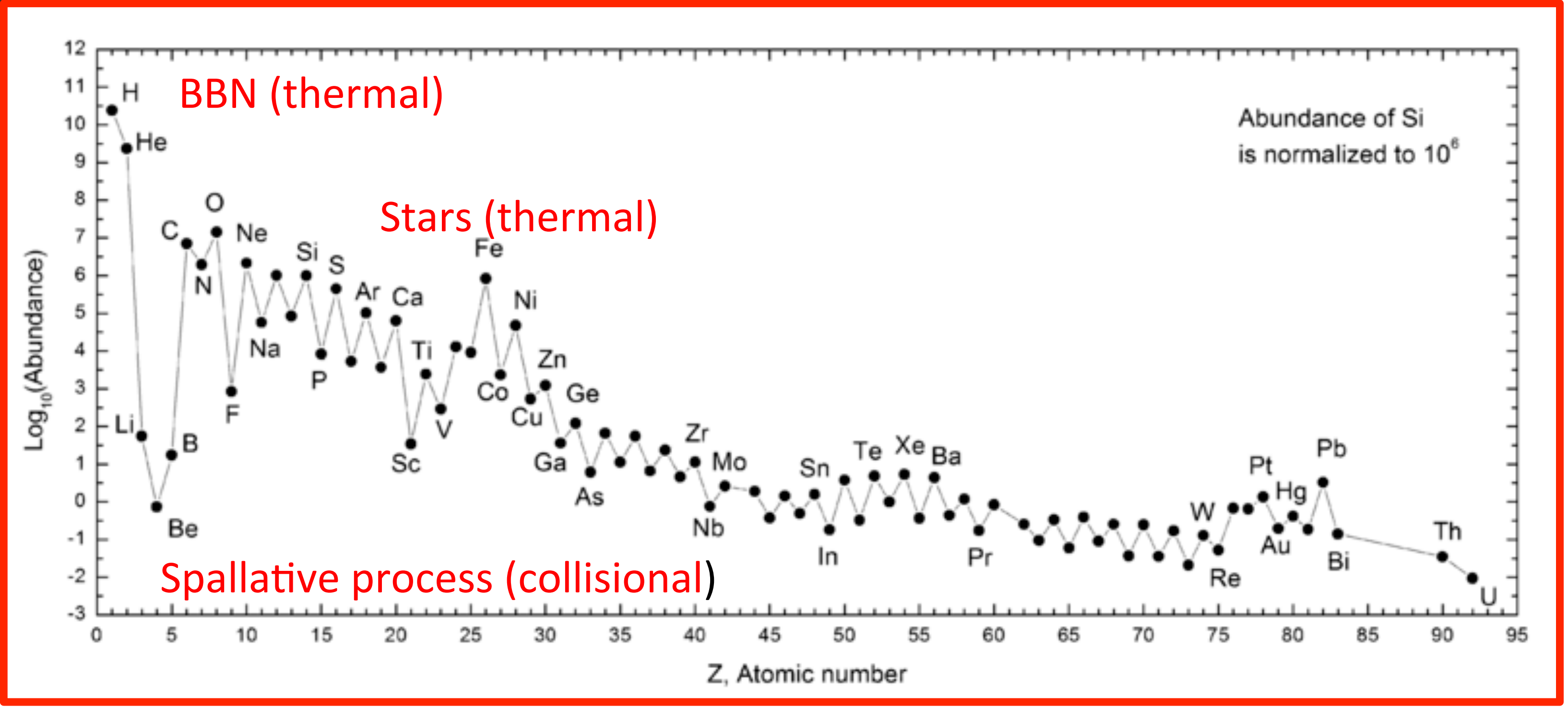
Elisabeth Vangioni
IAP/CNRS France

Minneapolis May, 2017

Main material:
“The chemical composition of the Universe”

Our Rosetta stone

Solar Abundances



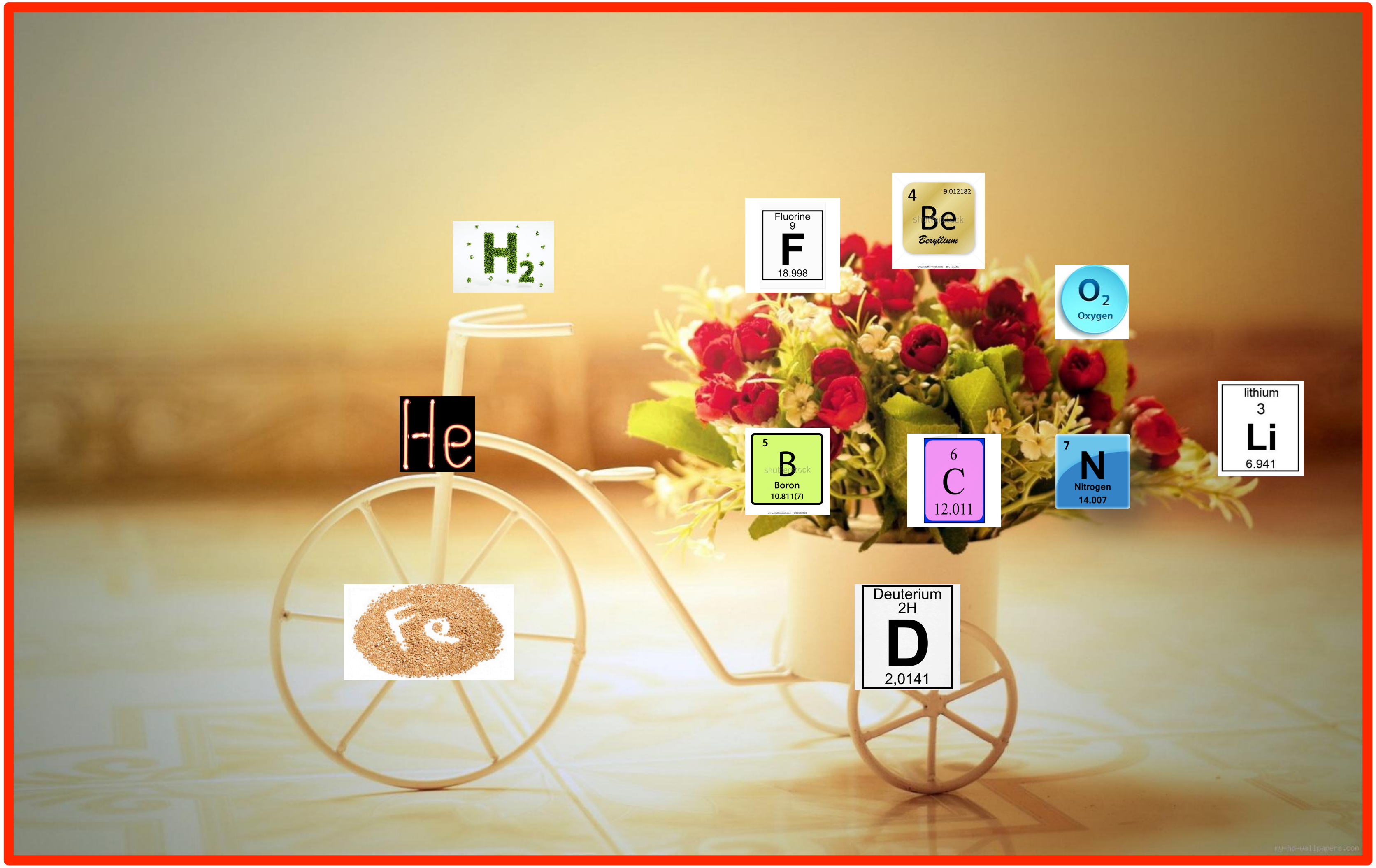
BBN (thermal)

Stars (thermal)

Spallative process (collisional)

Lodders (2003)

Happy Birthday !!



A long long time ago …..

KEITH and I began our common scientific life with light elements

1. Cosmological isotopes: D, ^{3,4} He, ^{7} Li → BBN

BeB: not cosmological elements!! BBN abundances: $10^{-20} - 10^{-15}$

2. Spallative isotopes: ^{6,7} Li, ^{9}Be, ^{10,11}B → Galactic Cosmic Rays GCR

Many results on these subjects !!!! About 15 articles/10 years

One example:
Identification of a new spallative low energy component → *next slide*

Primordial Li is a nightmare for us!!!
(see Maxim and Brian talks)
We have been trying to understand the gap (~ factor 3) between CMB constraints and observation of metal poor stars:
Unsuccessfully

Li complex → many sources:- BBN -Spallation - Stellar origins

Spallative nuclei

GCR(rapid α, p accelerated via shock wave SN) hit InterStellar Medium (CNO)

(CNO *corresponding* ***to metallicity Z*** *all elements heavier than He)* → *LiBeB*

$$dN/dt = \underbrace{Ncno/H}_{\substack{\text{ISM}\\ \text{component}\\ \text{prop to } Z(t)}} * \underbrace{\langle\sigma\rangle}_{\substack{\text{mean}\\ \text{cross section}}} * \underbrace{Fp,\alpha}_{\substack{\text{GCR flux}\\ \text{(GeV/n)}\\ \text{prop to } dZ/dt\ (\sim dN_{SN}/dt)}}$$

So, dN/dt *prop to* Z(t).dZ/dt, **B, Be(t)** ***prop to*** $\mathbf{Z^2}$ ***Secondary process in the ISM***

BUT

observations give a linear evolution between B,Be and metal enrichment

→ **New Low Energy Component:** LEC as a mirror process

α, C, O (MeV/n) accelerated via SNII hit ISM (H, He) → *LiBeB*

$$dN/dt = \underbrace{N_{H,He}}_{\substack{\text{ISM}\\ \text{constant (BBN)}}} * \langle\sigma\rangle * \underbrace{F_{\alpha,C,O}}_{\substack{\text{LEC flux (MeV/n)}\\ \text{prop to } dZ/dt\ (\sim dN_{SN}/dt)}}$$

So dN/dt *prop to* dZ/dt and **Be(t), B(t)** ***prop to*** **Z** ***Primary process in the ISM***

Modelisation: local galactic evolution

3 physical parameters

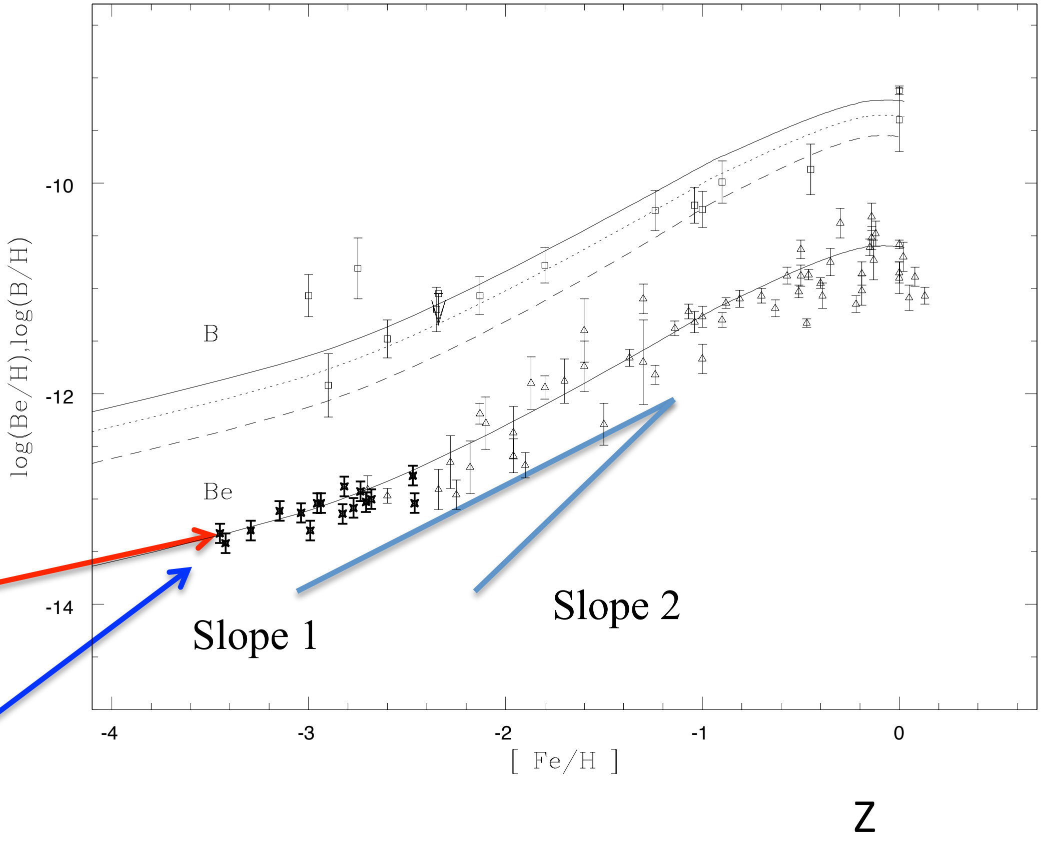
1. Star Formation Rate (SFR)
2. Initial Mass Function (IMF)
3. Stellar yields

3 production mechanisms

a. GCR (secondary)
b. LEC (primary)
c. ν spallation (Boron) (primary)

Testing the primary origin of Be and B in the early galaxy

E.Vangioni-Flam, R. Ramaty, K.Olive, M. Cassé 1998, AA 337, 714



New points

Rich et al 2009 ApJ 701, 1519

Not so bad !!

Chemical Evolution in a cosmological context

The formation of the first stars *(and galaxies)* at the end of the cosmic ‘dark ages’ is a central problem in cosmology.

From simple to complex

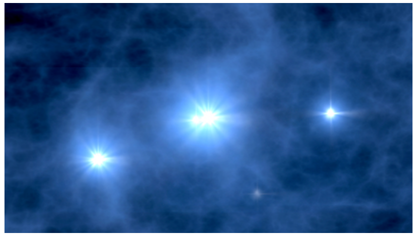
During this epoch the Universe was transformed from a simple initial state into a hierarchical system through the growth of structures: small objects formed first and then merged to form increasingly larger systems, a few 10^8 years after BB.

Since the CMB results from WMAP and Planck → early reionization has been revealed (*WMAP1: z ~ 10 – 30, but now only at z ~ 7.8 – 8.8, Planck 2016*)

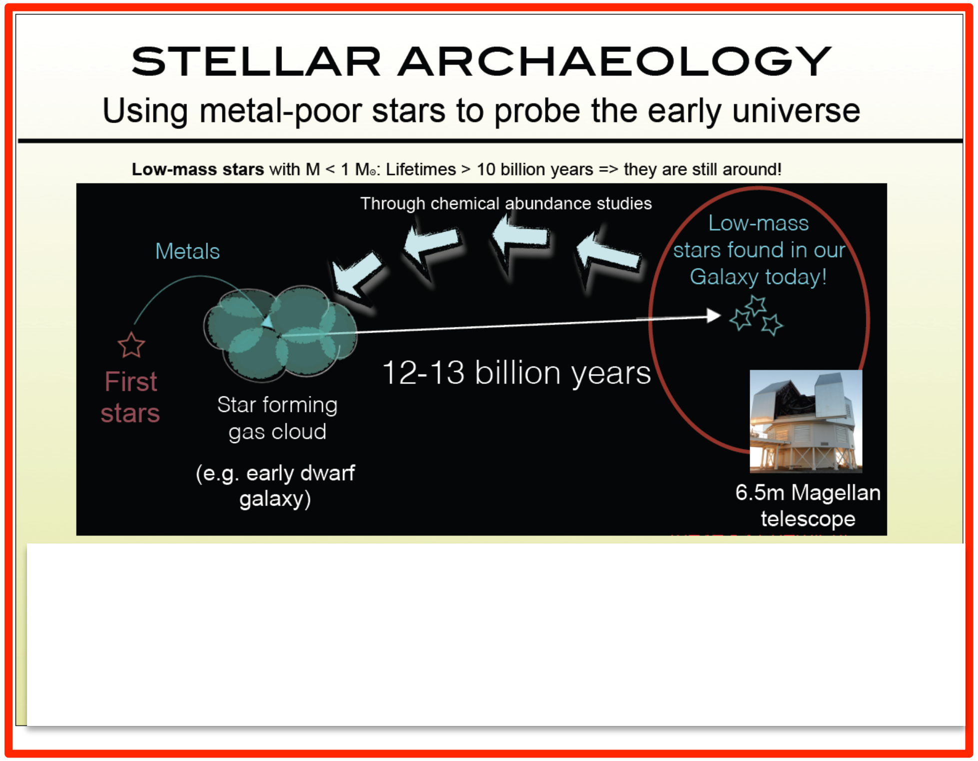
In this context, a bump of first massive stars/Pop III stars:
Stars (probably massive) containing no elements heavier than He

- their role as a reionization agent,
- how they can pollute ultra metal poor low mass stars observed today in the halo of our Galaxy,
- enrichment of the IGM,
- Potential correlation with cosmic SNII rates, long Gamma Ray Bursts or, compact objects rates ..
- and also constraints on the variation of fundamental constants (see Jean Philippe Uzan)

Z < 15 – 20, t = 200 to 300 Myr



Population III stars are born and die → SNII → pollute ISM
→ trigger new low mass stars to form
→ Population II stars are born with a very small quantity of heavy elements

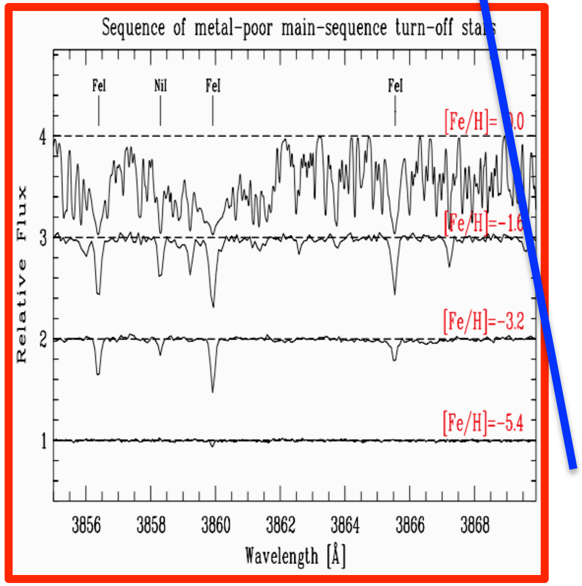


STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

Low-mass stars with M < 1 M$_\odot$: Lifetimes > 10 billion years => they are still around!

Look back time



Cosmic chemical evolution

time

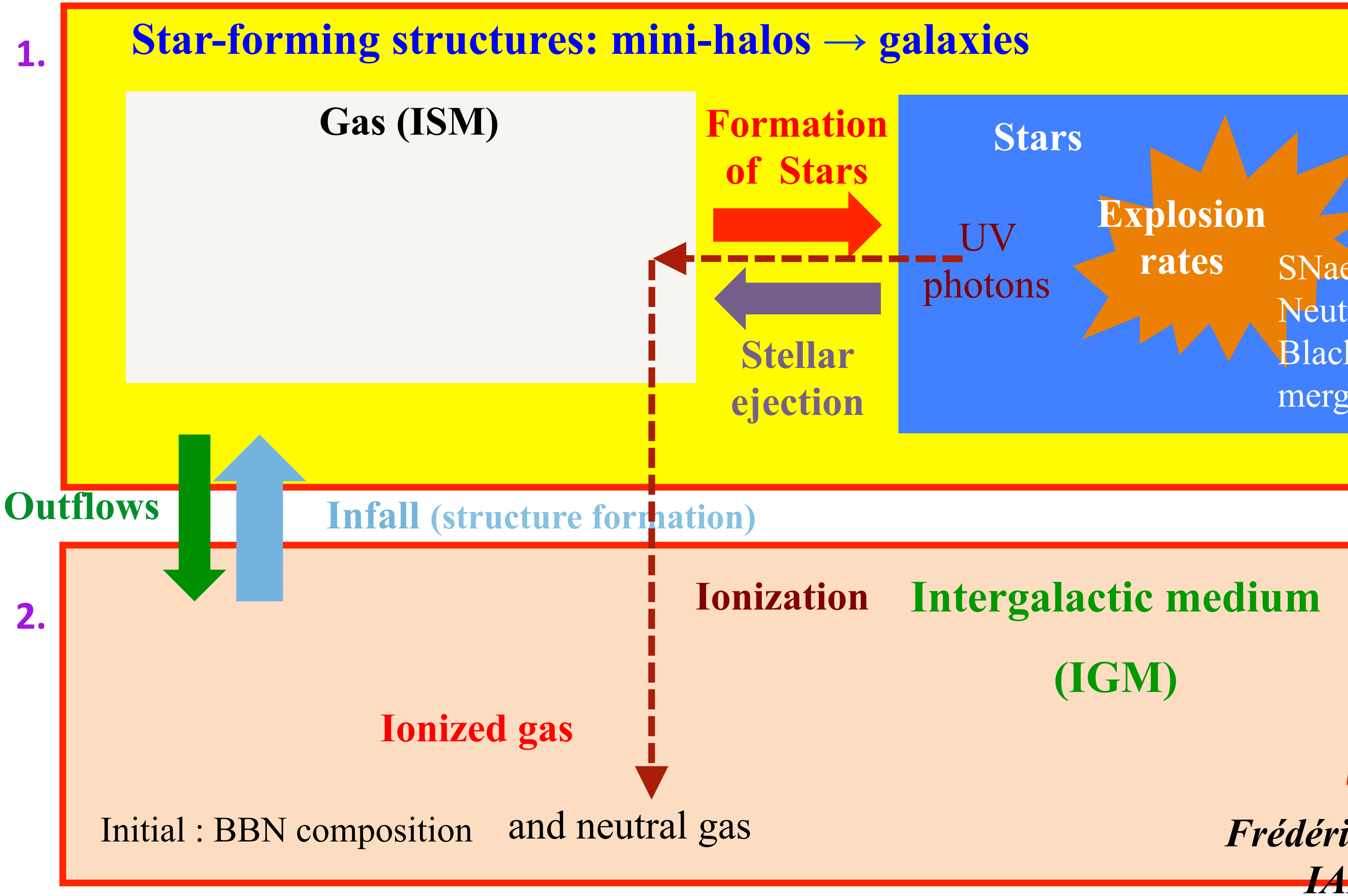
Spectrum of an ultra metal poor halo star

From A. Frebel

Cosmic chemical evolutionary model

The cycle of baryons

We describe the baryons in the Universe by two large reservoirs and four physical processes



1. **Star-forming structures: mini-halos → galaxies**

Gas (ISM)

Formation of Stars

Stars

Explosion rates

SNae
Neutrons stars
Black holes
mergers

UV photons

Stellar ejection

Outflows

Infall **(structure formation)**

2. **Ionization**

Intergalactic medium (IGM)

Ionized gas

Initial : BBN composition and neutral gas

Frédéric DAIGNE IAP

Daigne, Olive, Silk, Stoehr, Vangioni 2006 and Vangioni, Olive, Prestegard, Silk, Petitjean, Mandic, 2015

Cosmic evolution

Model parameters:

- Structure formation (taken from hierarchical scenario)
- Star Formation Rate Density, SFRD vs redshift
- Initial Mass Function (normal/Salpeter, but what about potential first stars/Pop III stars?)
- Stellar properties (lifetime, yields vs initial metallicity, ionizing flux)
- Efficiency of outflows to the IGM

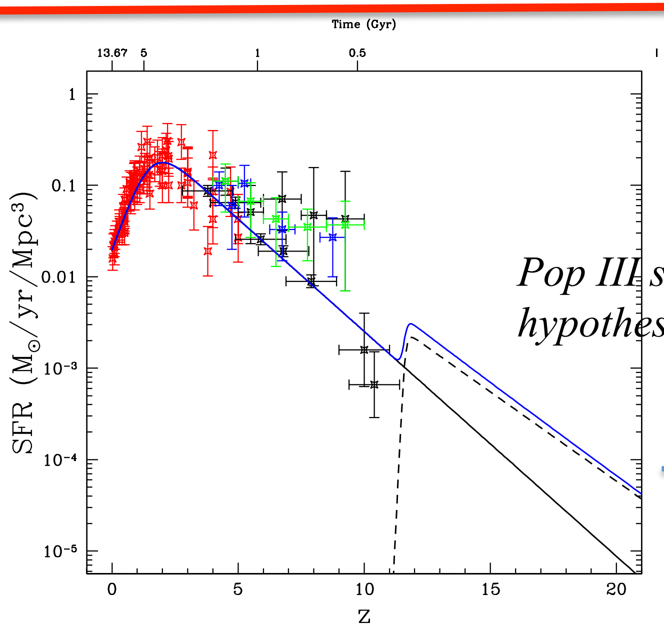
Output:

We follow:
- chemical elements from the first stars up to now in Structures and IGM
- Energy injection from these stars in ISM/IGM
- SN, black holes, neutrons stars rates vs z
- Merger rates vs z . . .

Calibrated with many observations:

- Observed cosmic evolution of SFR, of star/gaz ratio in structures vs redshift
- Observed Thomson optical depth from CMB: ionized fraction in IGM
- Observed cosmic SN (Ia, II) rates vs redshift
- Observed abundances in Damped Lyman-α (primitive structures)
- Observed abundances in IGM
- Observed abundances in ultra metal poor stars (stellar archeology)

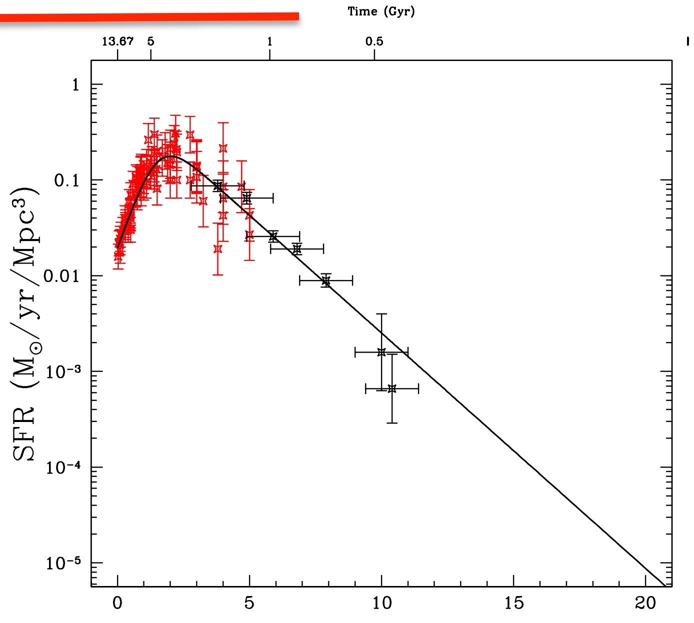
Cosmic SFR and related Reionization *What is the SFR at high z ?*

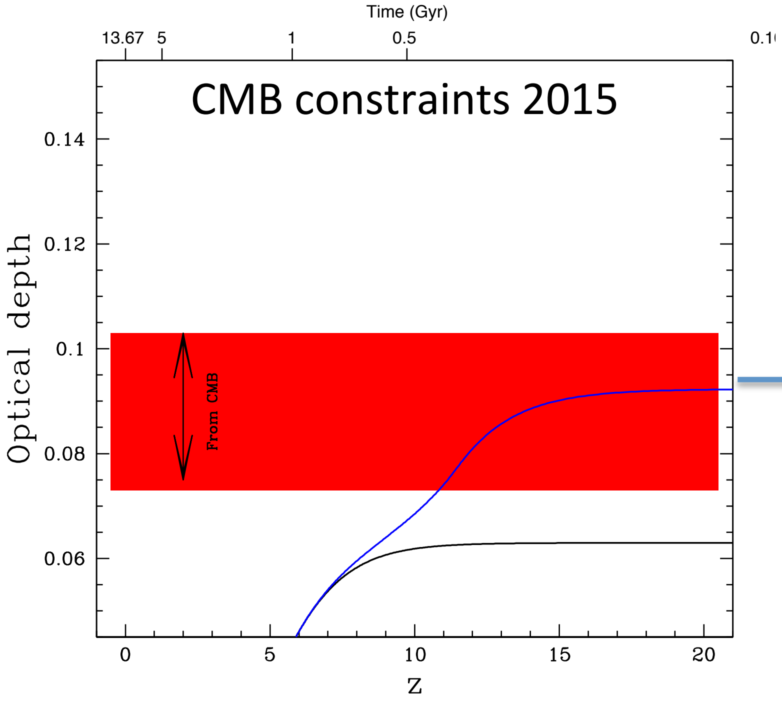


Pop III stars hypothesis

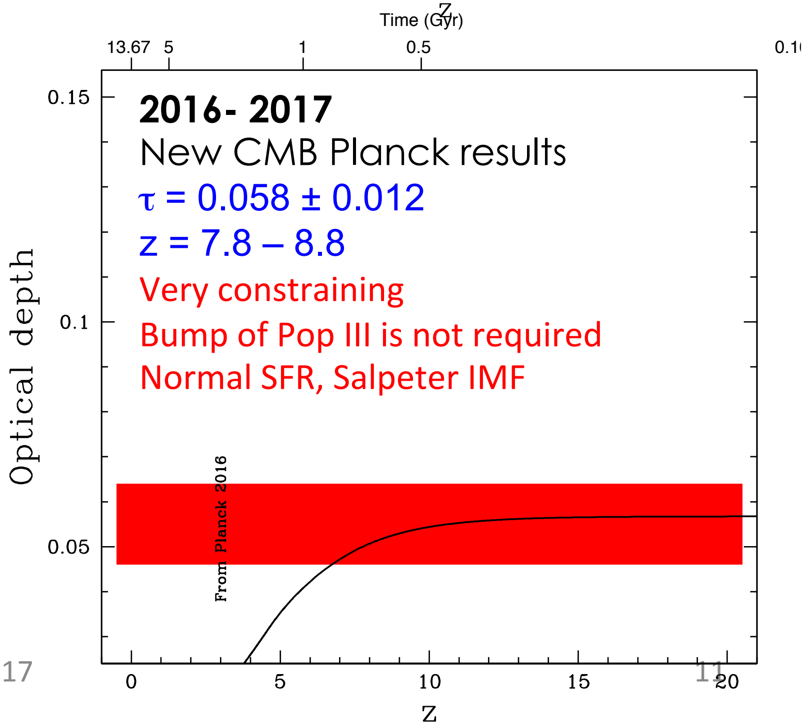
Observations from

Behroozi et al. (2014)
Bouwens et al. (2014)
Oesch et al. (2014)





CMB constraints 2015



2016- 2017

New CMB Planck results

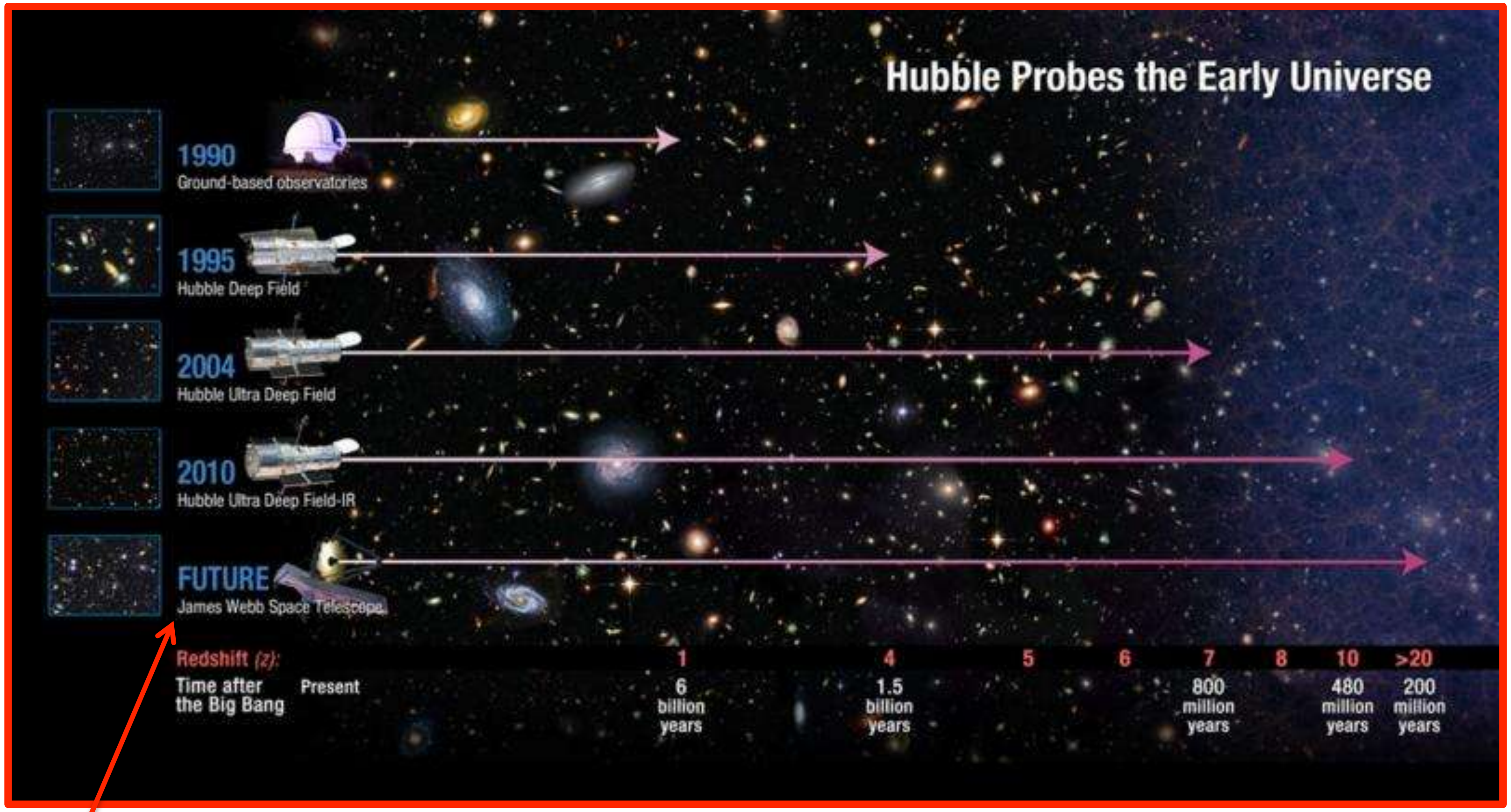
$\tau = 0.058 \pm 0.012$

$z = 7.8 – 8.8$

Very constraining

Bump of Pop III is not required

Normal SFR, Salpeter IMF



Credit NASA

JAMES WEBB SPACE TELESCOPE

Very interesting to obtain in the future more data at high redshift
Next space missions such as JWST→ to be launched in 2018
Will be able:
-- to observe the Universe when it was two hundred millions years old,
-- to probe properties of first galaxies near the epoch of reionization.

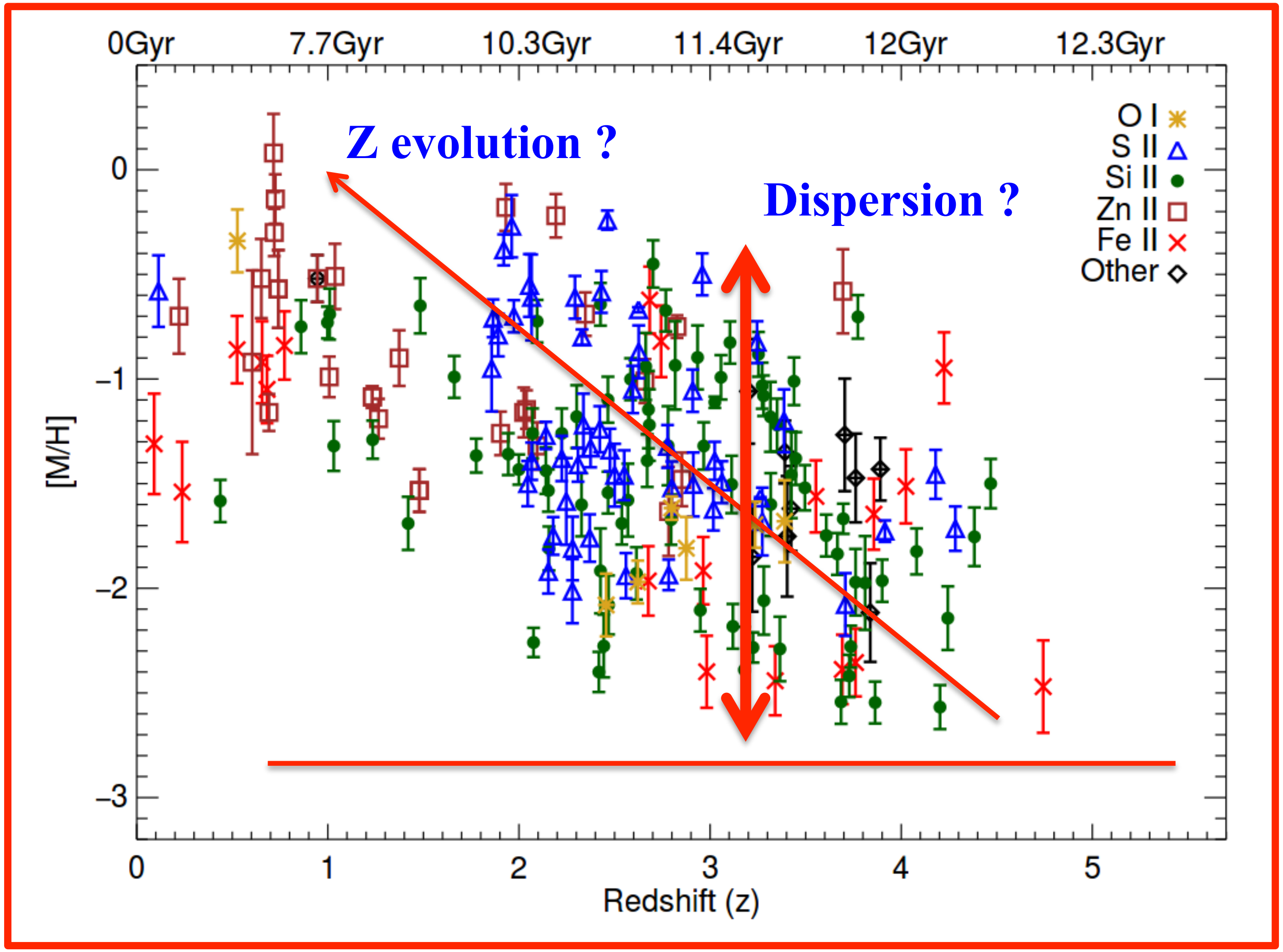
Let us a focus on two recent studies and their perspectives:

1. Cosmic evolution and dispersion of Metallicity and Deuterium
2. Cosmic evolution of binary BH and associated GW

1.

The origin of dispersion in DLA metallicities

DLAs: Damped Lyman-α systems (protogalaxies or primitive structures)



Z evolution ?

Dispersion ?

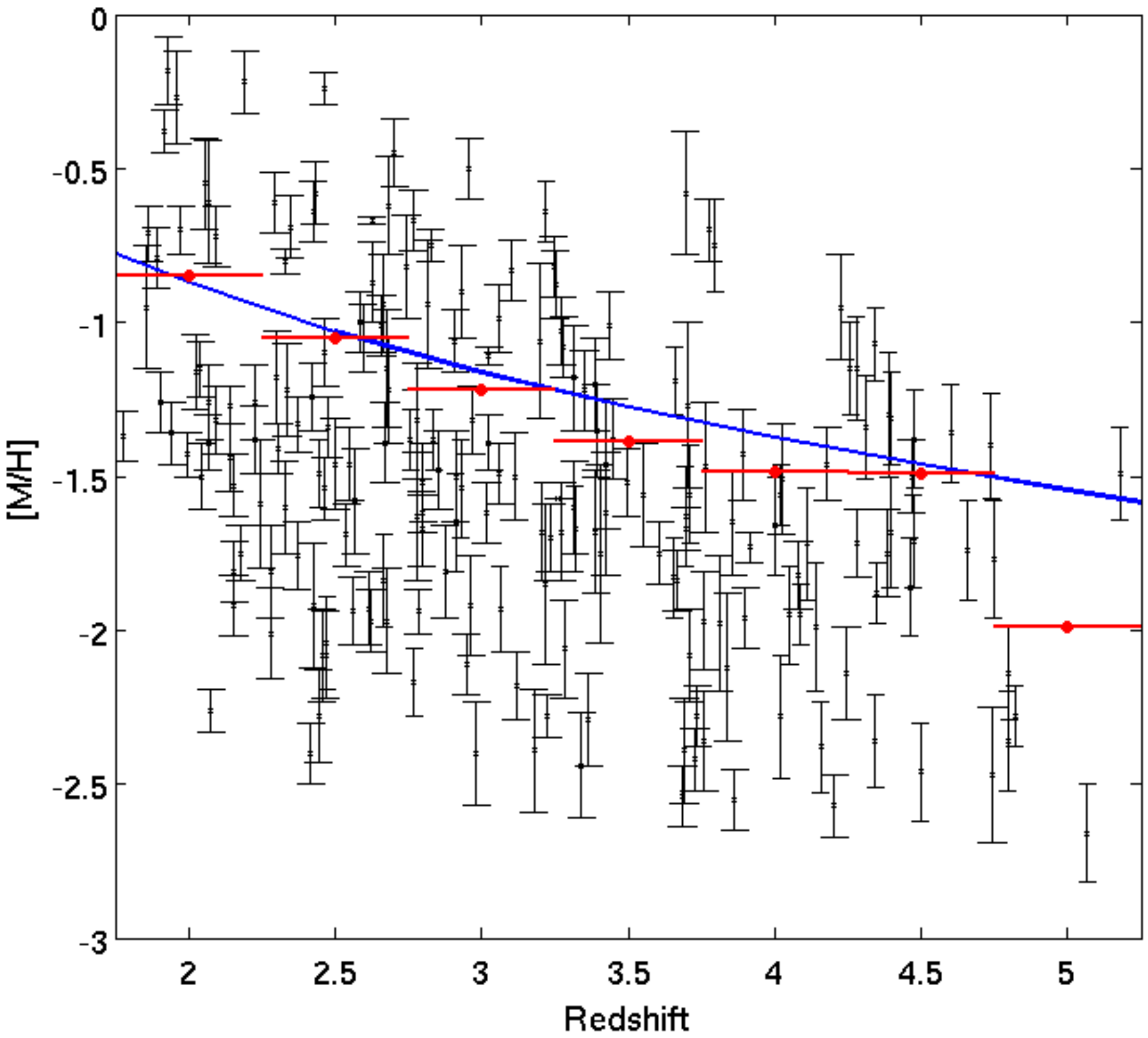
3 questions

Observed DLA metallicities [M/H]
Rafelski et al. (2012)

Lower metallicity limit ?

$[M/H] = \log(M/H) - \log(M/H)_{\odot}$

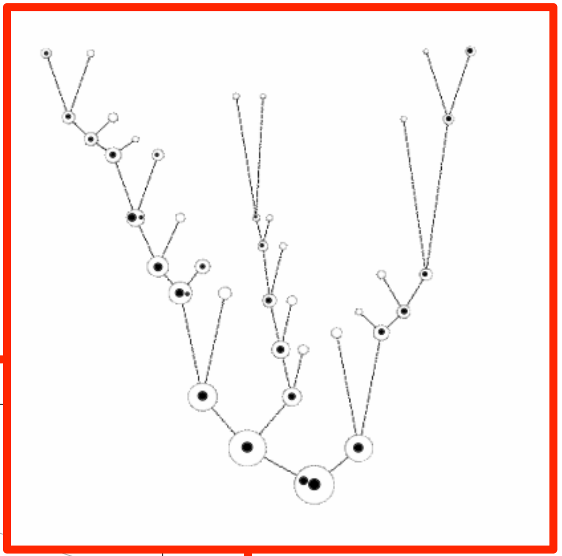
With the cosmic evolutionary model : Mean metallicity evolution in the ISM

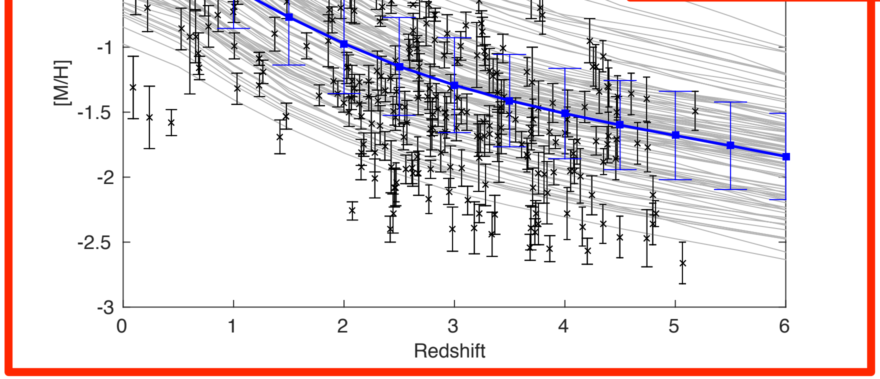


Metallicity dispersion and merger tree model

develop a new merger tree model associated to the cosmic chemical model

Irina Dvorkin, IAP





This sketch shows the merger tree history of a galaxy like the Milky Way.

Time increases from small branches and a galaxy is formed by the sequential merger of smaller systems increasing in mass in a hierarchical fashion.

Credit: Marta Volonteri (IAP)

Time

In each region, calculate the structure formation history, SFR and metal enrichment

Here: Minimal halo mass Mmin = $10^8 M_\odot$,

→ These models describe the diversity of structure formation histories.

Metallicity abundance relative to the solar value for 100 regions, each with a volume of 10^3 Mpc^3/h^3

BUT Low metal DLAs not fitted !!

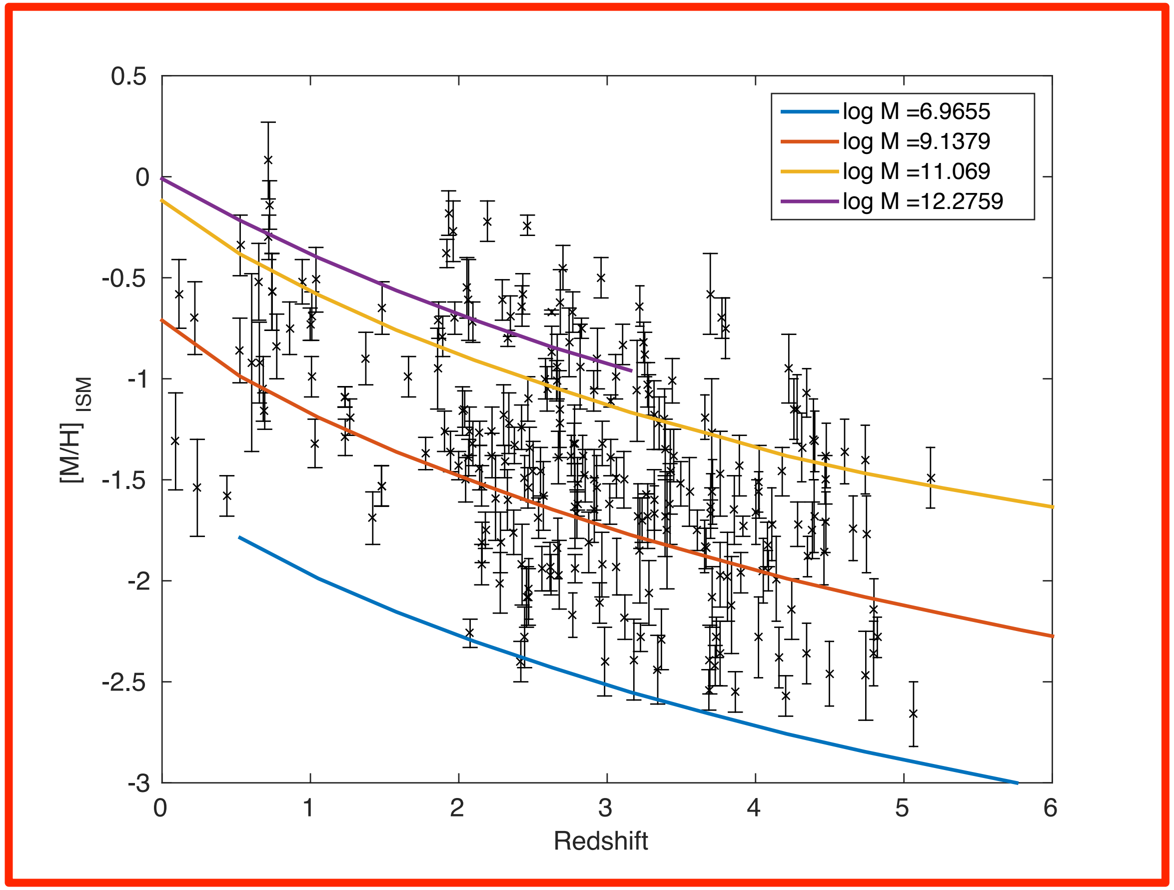
Dvorkin, Silk, Vangioni, Petitjean, Olive, 2015 MNRAS Letters, 452, 36

Next step: Lower limit of DLA metallicities

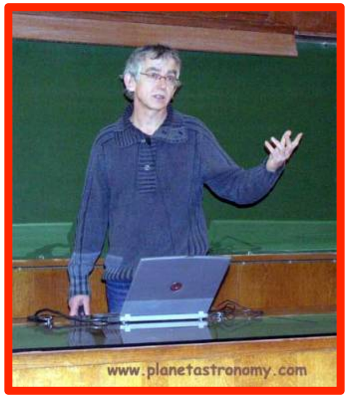
We are improving the model, typically starting from very low halo masses (10^7 Msol)

First results → fit lowest Z DLAs

Work in progress!



With Patrick Petitjean
IAP

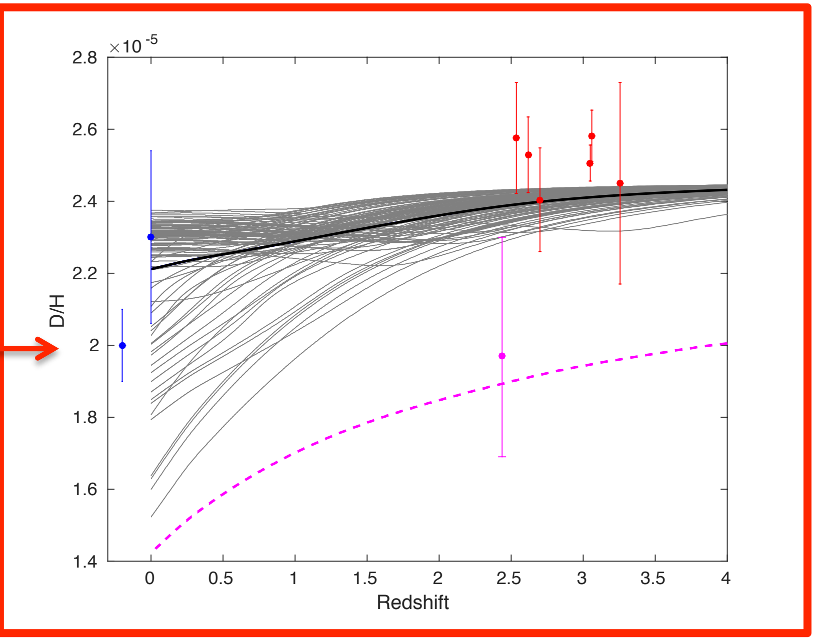


Deuterium abundances in DLAs at high z

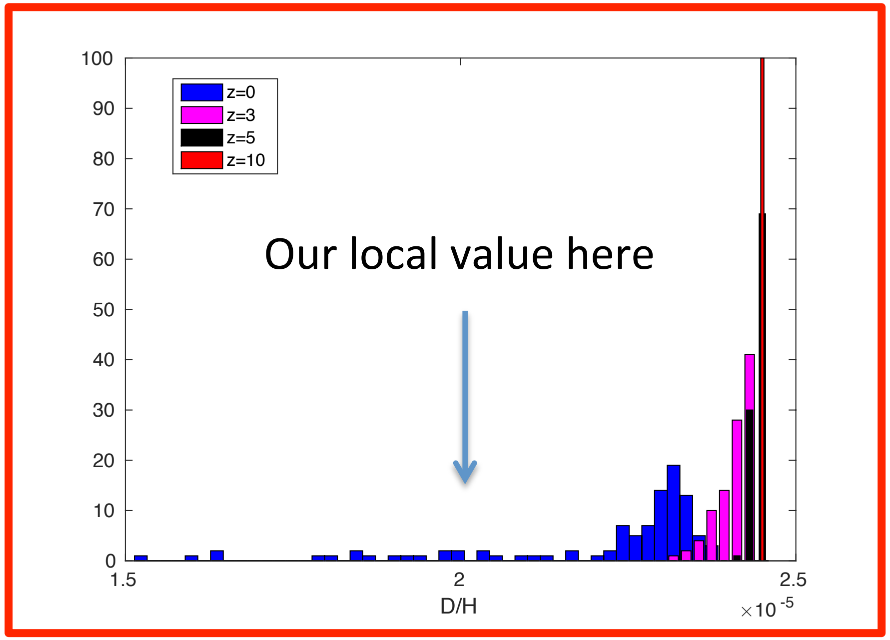
With the same merger tree model:
study of the dispersion of deuterium in a cosmic evolutionary way.

Cosmic evolution and dispersion of (D/H)

Local value



Distribution of (D/H) at different z



Our local value here

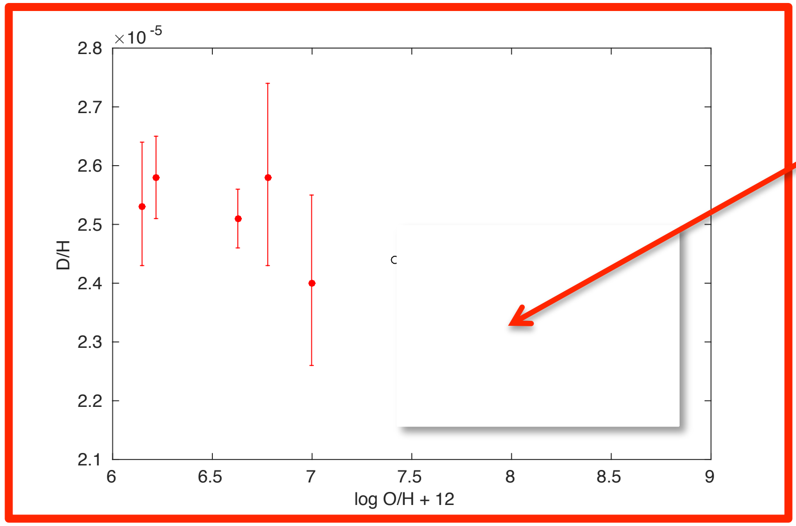
Dvorkin, Vangioni, Silk, Petitjean, Olive 2016, MNRAS, Letters, 458, 104

Using the primordial value from (Coc et al.,2015)

Next step:
Can we use D in DLAs to constrain hierarchical formation of structures ?

D/H destroyed in stars (~10^5K), Infall of primordial gas raises D/H.
So, in a given region of the Universe, D/H depends on its star formation and accretion histories

(D/H)-metallicity correlation at z = 3



Lack of data at intermediate metallicity

Pasquier Noterdaeme
IAP

WE HOPE:

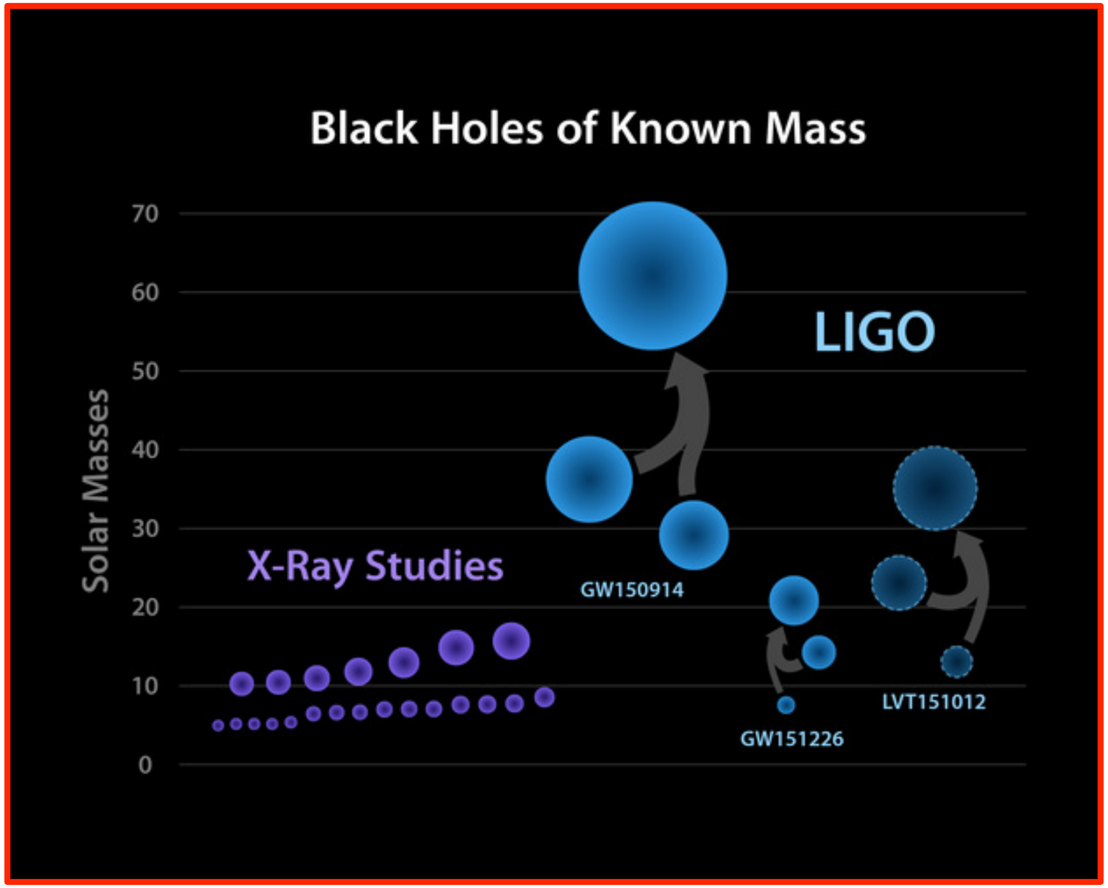
1. To get these new D observations

Yohan Dubois
IAP

2. To use our merger tree model together with hydrodynamical simulations

to follow D/H and Z and constrain key parameters of structure formation as, efficiency of SFR, accretion rate..

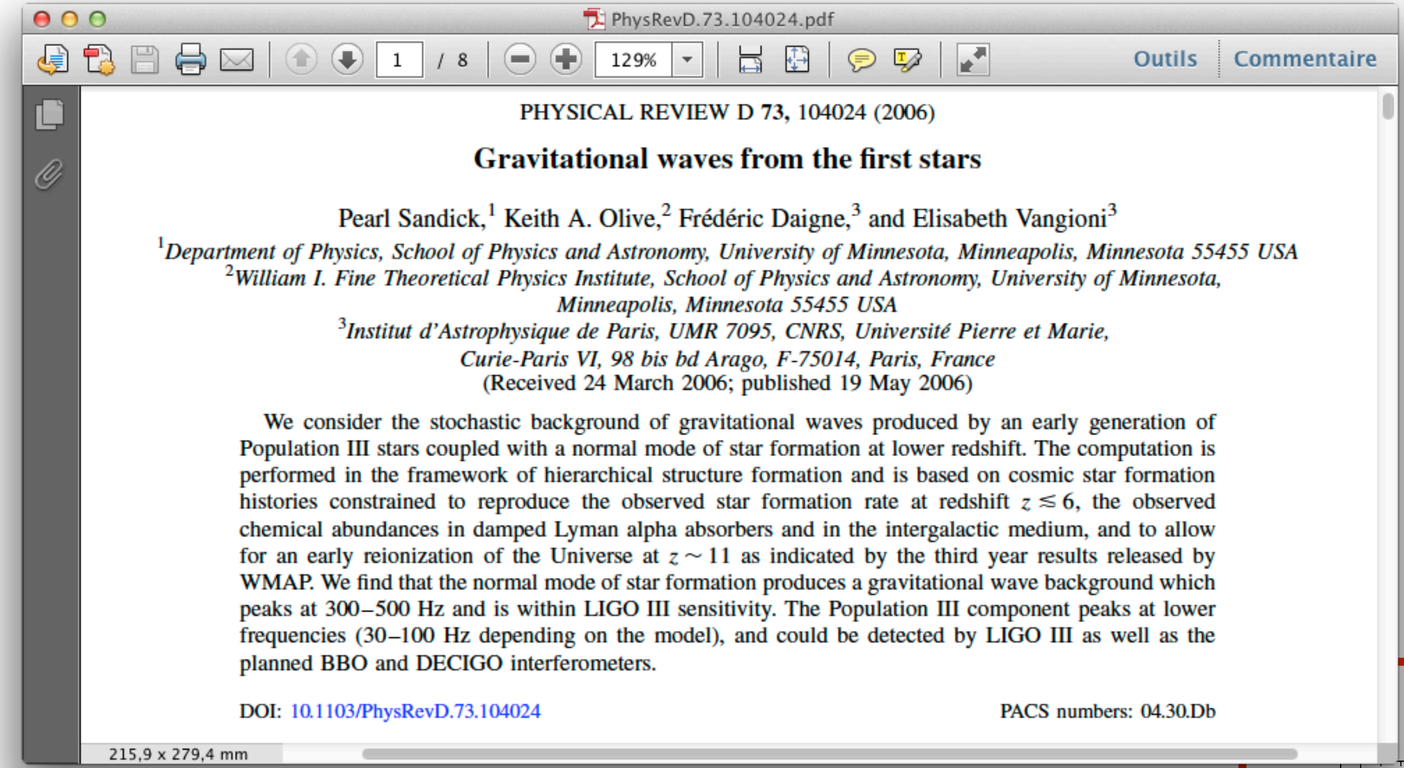
2. First stars, their remnants, their merging and GW emission



Credit LIGO

Since the great discovery by LIGO
Birth of gravitational wave astrophysics

Ten years ago, study of GW from first stars *Pearl Sandick*



PHYSICAL REVIEW D 73, 104024 (2006)

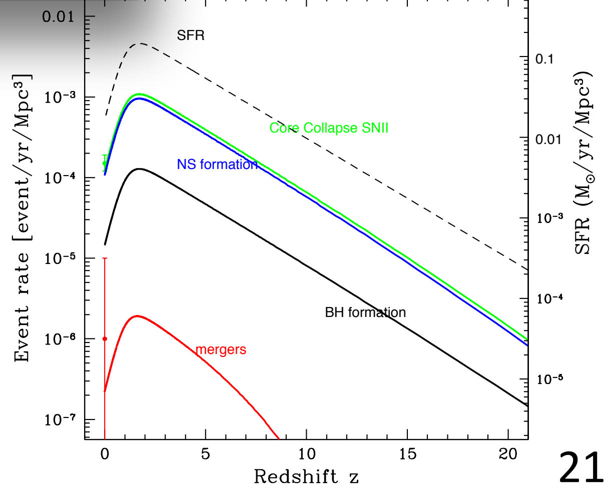
Gravitational waves from the first stars

Pearl Sandick,[1] Keith A. Olive,[2] Frédéric Daigne,[3] and Elisabeth Vangioni[3]

[1]*Department of Physics, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455 USA*
[2]*William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455 USA*
[3]*Institut d'Astrophysique de Paris, UMR 7095, CNRS, Université Pierre et Marie, Curie-Paris VI, 98 bis bd Arago, F-75014, Paris, France*
(Received 24 March 2006; published 19 May 2006)

We consider the stochastic background of gravitational waves produced by an early generation of Population III stars coupled with a normal mode of star formation at lower redshift. The computation is performed in the framework of hierarchical structure formation and is based on cosmic star formation histories constrained to reproduce the observed star formation rate at redshift $z \lesssim 6$, the observed chemical abundances in damped Lyman alpha absorbers and in the intergalactic medium, and to allow for an early reionization of the Universe at $z \sim 11$ as indicated by the third year results released by WMAP. We find that the normal mode of star formation produces a gravitational wave background which peaks at 300–500 Hz and is within LIGO III sensitivity. The Population III component peaks at lower frequencies (30–100 Hz depending on the model), and could be detected by LIGO III as well as the planned BBO and DECIGO interferometers.

DOI: 10.1103/PhysRevD.73.104024 PACS numbers: 04.30.Db



Compact objects & merger rates vs z

2017: Astrophysics with gravitational waves

a LIGO GW150914

In september 2015, LIGO found the most massive stellar black hole ever observed!

Masses: 36 $\mathbf{M}_\odot$ and 29 $\mathbf{M}_\odot \rightarrow$ **60** $\mathbf{M}_\odot$

Questions:

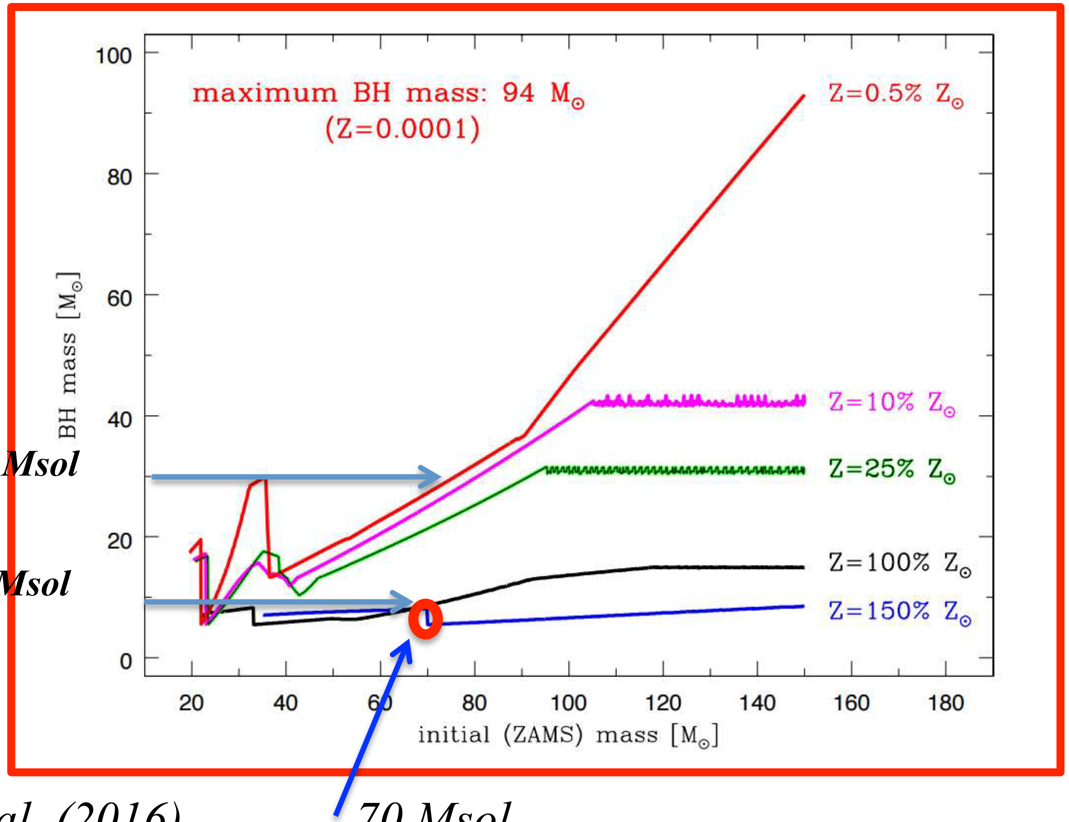
How to make so massive black holes ?
What can we learn about early stellar evolution
and black hole formation?

For memory: Two other detections: 23, 13 (35) -- 14, 7 (21) $M_\odot$

The impact of the initial metallicity of stars on the mass of black hole

Coming back to nucleosynthesis!!

Thanks to our results including cosmic metal and remnant evolutions, we are able to study the role of metallicity on the mass of black holes



30 Msol

10 Msol

70 Msol

The role of metallicity is essential

From Belczynski et al. (2016)

Different SN models and metallicities→ different masses of BH

Combining stellar and cosmic evolutions

→ we can follow self consistently metallicity and BH rate vs z

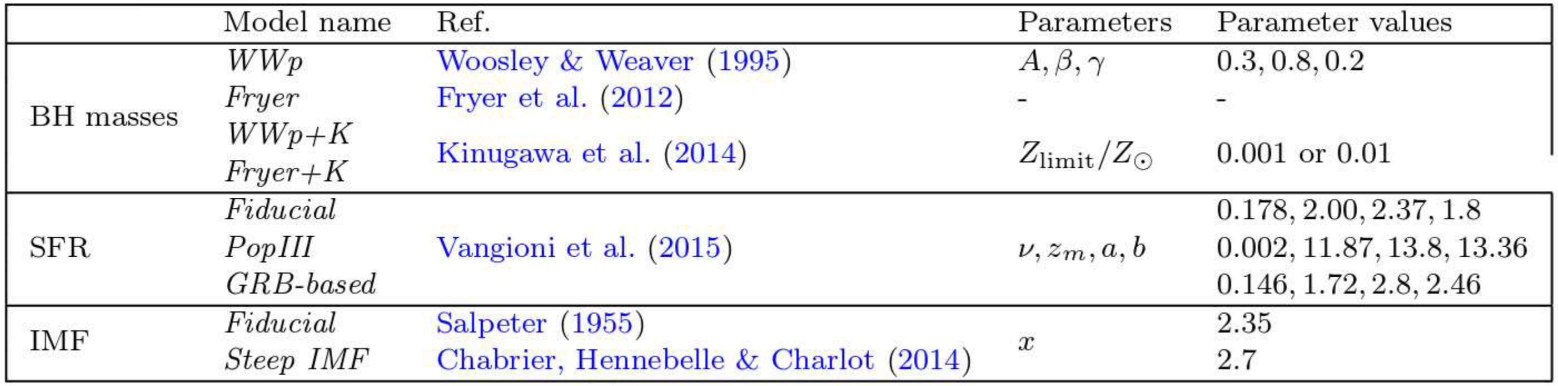
The goal: **M(**BH) = **f** (**M**initial , **Z**,.. Rotation ?)

Different explosion mechanisms

Woosley & Weaver (1995): piston-driven explosion, assuming an explosion energy

Fryer et al. (2012) : analytic model, assume time delay, calculate the explosion energy and fallback mass

*Kinugawa et al. (2014) : **MBH** = **f** (**M**core) from Herant et al. (1994);*



	Model name	Ref.	Parameters	Parameter values
BH masses	*WWp*	Woosley & Weaver (1995)	A, β, γ	0.3, 0.8, 0.2
	Fryer	Fryer et al. (2012)	-	-
	WWp+K *Fryer+K*	Kinugawa et al. (2014)	$Z_{\text{limit}}/Z_{\odot}$	0.001 or 0.01
SFR	*Fiducial*	Vangioni et al. (2015)	ν, z_m, a, b	0.178, 2.00, 2.37, 1.8
	PopIII			0.002, 11.87, 13.8, 13.36
	GRB-based			0.146, 1.72, 2.8, 2.46
IMF	*Fiducial*	Salpeter (1955)	x	2.35
	Steep IMF	Chabrier, Hennebelle & Charlot (2014)		2.7

As usual

Input

Galaxy growth (inflow and outflow) prescriptions
SFR, IMF, Stellar yields
Black hole mass as a function of
initial stellar mass and metallicity

Output

Cosmic rates of compact objects
Merger rates

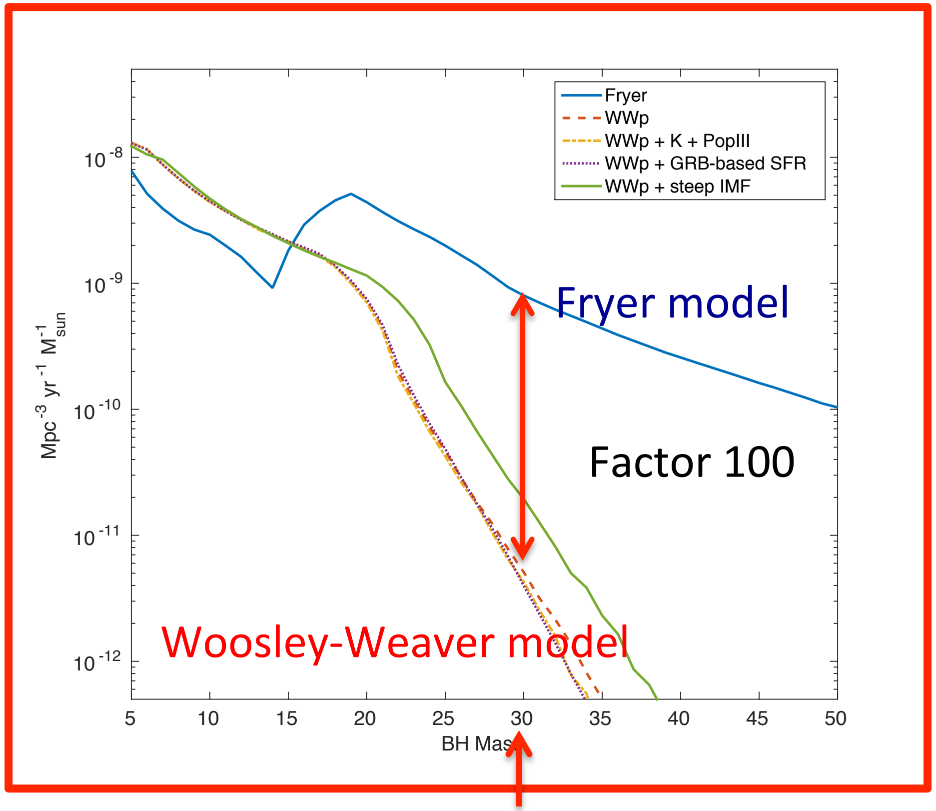
Note: to get merger rate we need to assume time delay distribution

Some results:

Dvorkin, Vangioni, Silk, Uzan, Olive MNRAS 461, 3877–3885 (2016)

Merger rate vs BH mass at z = 0

per unit BH mass Normalized to the observed merger rate:
$R = 10^{-7}\ Mpc^{-3}\ yr^{-1}$



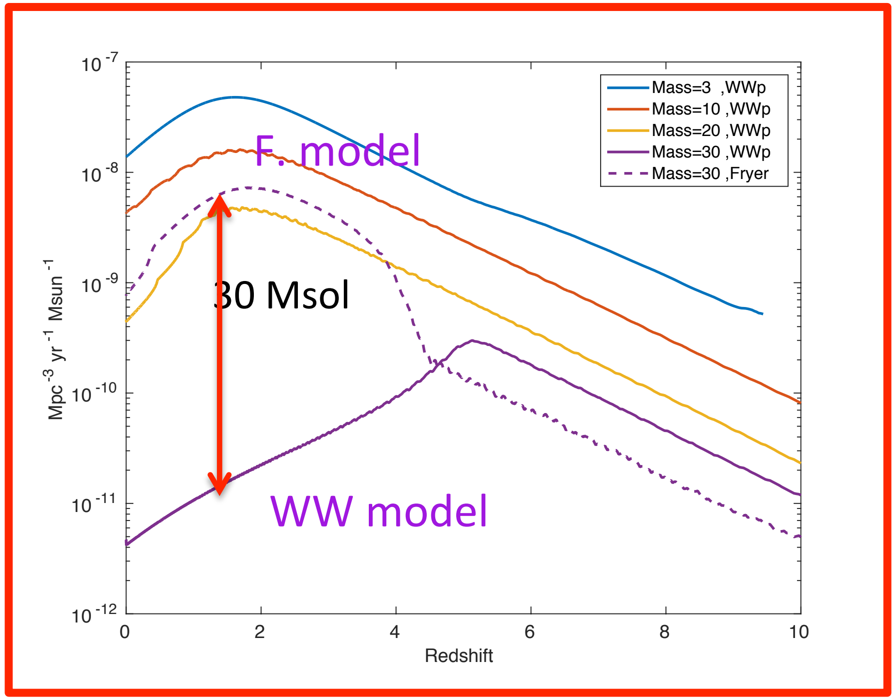
Fryer model

Factor 100

Woosley-Weaver model

30 Msol

Merger rate as a function of z
for different masses of BH



F. model

30 Msol

WW model

high dependence of SN models

An important result:

if you have a high early metal enrichment due to first massive stars,
you limit at once massive BH formation at high redshift.
That gives constraints on the pop III star rate

Finally

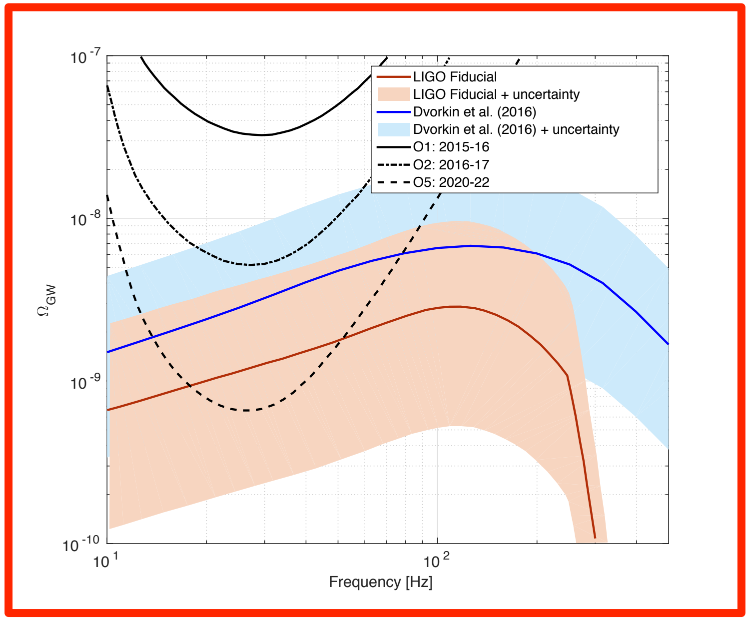
The discovery of GW coming from binary BH mergers opens a new astrophysical window

Thanks to our nucleosynthetic approach we can also

→ predict the cosmic evolution of NS-NS or NS-BH

→ calculate the Stochastic gravitational wave background

(The background due to unresolved mergers of binary BHs)



See Jean-Philippe Uzan

We have got a lot to do related to this new astrophysical field

More detections to come soon will give interesting astrophysical constraints

on stellar physics, SN explosion mechanism, Pop III stars properties, compact binary systems

expected BBH rate: 9 to 240 Gpc^{-3} y^{-1} , NS-BH rate : a few hundred Gpc^{-3} y^{-1}

Conclusion and Perspectives

Our Rosetta stone always essential in the cosmological context

and also in fundamental physics and gravitational wave astrophysics.

-- Metallicity dispersion observed in primitive structures can be explained by differences in structure and star formation histories

-- Observations of D/H in intermediate-metallicity systems at high z will be used, together with hydrodynamical simulations, to improve our understanding of the formation of structures in the Universe

-- Metallicity evolution influences drastically the formation and merger rates of BBH

→ future observations (LIGO/VIRGO) will give constraints on first massive stars and binary compact objects (BH-BH, BH-NS, NS-NS)

Remaining questions:

- Li problem ?
- What is SFR at high z?
- Adequation between the observation of elements and cosmic chemical evolution in a model of hierarchical formation of structures ?
- Role of stellar rotation on the mass of BH at any Z ?

Dear Keith, many projects in sight for the next 25 years!!!

Thank you

Keith, see you soon in Paris for new scientific adventures