Near InfraRed Spectroscopy from Space
Several European and French proposals:
the Space Project for Astrophysical and Cosmological Exploration (SPACE)

Denis Burgarella
Laboratoire d'Astrophysique de Marseille, Aix-Marseille Université
38 rue Frédéric Joliot-Curie, 13013 Marseille, France
Email: denis.burgarella@lam.fr

Carlo Schmid, LAM, Marseille, France
Stéphanie Escoffier, CPPM, Marseille , France
Laurence Tresse, LAM, Marseille , France
Frédéric Zamkotsian, LAM, Marseille , France

Space Project for Astrophysical and Cosmological Exploration (SPACE)

- Part of this talk was meant to present the SPACE project to ESA.
- SPACE being very similar to ATLAS, the following points developed for SPACE are also very relevant for ATLAS.

Main Contributors:

Extragalactic Astrophysics and Cosmology:

- *Andrew Bunker*
- *Denis Burgarella*
- *Hakim Atek*
- *Chris Pearson*
- *José Miguel Rodriguez Espinosa*
- *Rychard Bouwens*
- *Daniel Schaerer*
- *Karina Caputi*
- *David Alexander*
- *David Rosario*
- *David Sobral*

Milky Way Studies: from the Global Structure to Dust Characterization:

- *Laurent Pagani*
- *Julien Montillaud*
- *Céline Reylé*
- *Nadège Lagarde*
- *Sylvie Cabrit*
- *Isabelle Ristorcelli*

Technology Challenges:

- Wide-field NIR+MIR detectors
- Lightweight Large Mirror: *Marc Ferrari*
- Deformable Mirror for Active Optics: *Marc Ferrari*
- Wide-field Integral-Field Spectrograph: *Ray Sharples*
- Micro-Mirror Arrays: *Frédéric Zamkotsian*

Core Proposing Team

Last, First Name	Email	Country
AFONSO, Jose	jafonso@oal.ul.pt	Portugal
ALVAREZ MARQUEZ, Javier	javier.alvarez@cab.inta-csic.es	Spain
ATEK, Hakim	atek@iap.fr	France
AUDARD, Marc	Marc.Audard@unige.ch	Switzerland
BAES, Maarten	maarten.baes@ugent.be	Belgium
BUAT, Veronique	veronique.buat@lam.fr	France
BUNKER, Andy	Andy.Bunker@physics.ox.ac.uk	United Kingdom
CAPUTI, Karina	karina@astro.rug.nl	Netherlands
CONSELICE, Christopher	conselice@gmail.com	United Kingdom
COORAY, Asantha **(OST Study Chair)**	acooray@uci.edu	USA
FERRARI, Marc	marc.ferrari@lam.fr	France
FLORES, Hector	hector.flores@obspm.fr	France
GALLEGO, Jesus	j.gallego@fis.ucm.es	Spain
GALLIANO, Frederic	frederic.galliano@cea.fr	France
LAGARDE, Nadege	nadege.lagarde@utinam.cnrs.fr	France
LE FEVRE, Olivier	olivier.lefevre@lam.fr	France
MALEK, Katarzyna	Katarzyna.Malek@ncbj.gov.pl	Poland
MONTILLAUD, Julien	julien.montillaud@univ-fcomte.fr	France
OESCH, Pascal	pascal.oesch@unige.ch	Switzerland
PAGANI, Laurent	laurent.pagani@obspm.fr	France
PEARSON, Chris	chris.pearson@stfc.ac.uk	United Kingdom
POLLO, Agnieszka	gnieszka.pollo@ncbj.gov.pl	Poland
PRANTZOS, Nikos	prantzos@iap.fr	France
REYLE, Celine	celine@obs-besancon.fr	France
RODRIGUEZ ESPINOSA, Jose MIguel	jre@iac.es	Spain
SAKON, Itsuki **(OST, MISC)**	isakon@astron.s.u-tokyo.ac.jp	Japan
SCHAERER, Daniel	daniel.schaerer@unige.ch	Switzerland
SHARPLES, Ray	r.m.sharples@durham.ac.uk	United Kingdom
SOBRAL, David	d.sobral@lancaster.ac.uk	United Kingdom
ZAMKOTSIAN, Frederic	frederic.zamkotsian@lam.fr	France

OST: NASA Origins Space Telescope

Outline of the Presentation

- Main Science Questions
  - Global Philosophy
  - Extragalactic Astrophysics and Cosmology
- Some Requirements
- International Space Context
- Technology Challenges

Outline of the Presentation

- **Main Science Questions**
  - Global Philosophy
  - Extragalactic Astrophysics and Cosmology
- Some Requirements
- International Space Context
- Technology Challenges

Outline of the Presentation

- **Main Science Questions**
  - **Global Philosophy**
  - Extragalactic Astrophysics and Cosmology
- Some Requirements
- International Space Context
- Technology Challenges

Einstein A., Infeld L. 1938
The evolution of Physics, Cambridge, UK: Cambridge University Press

« *In nearly every detective novel since the admirable stories of Conan Doyle* ***there comes a time when the investigator has collected all the facts he needs*** *for at least some phase of his problem.*

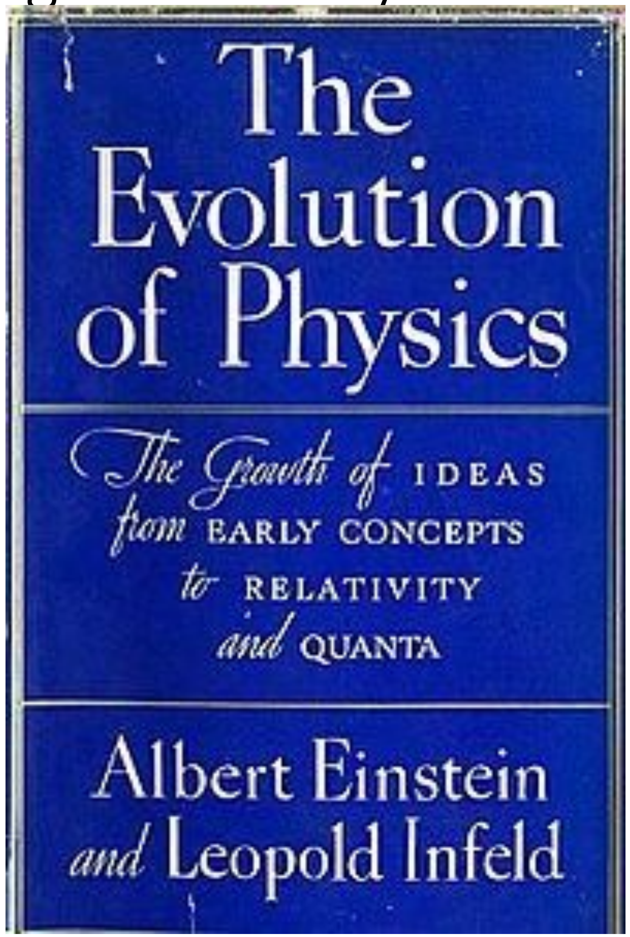
These facts often seem quite strange, incoherent, and wholly unrelated. The great detective, however, realizes that ***no further investigation is needed at the moment****, and that only pure thinking will lead to a correlation of the facts collected.*

So ***he plays his violin, or lounges in his armchair****, when suddenly, by Jove,* ***he has it****!*

Not only does he have an explanation for the clues at hand but he knows that certain other events must have happened.

Since he now knows exactly where to look for it, he may go out, if he likes, to collect further confirmation for his theory. »

And this is a great analogy to defining the requirements for a mission. We know what we are looking for and we know how to carry this out.



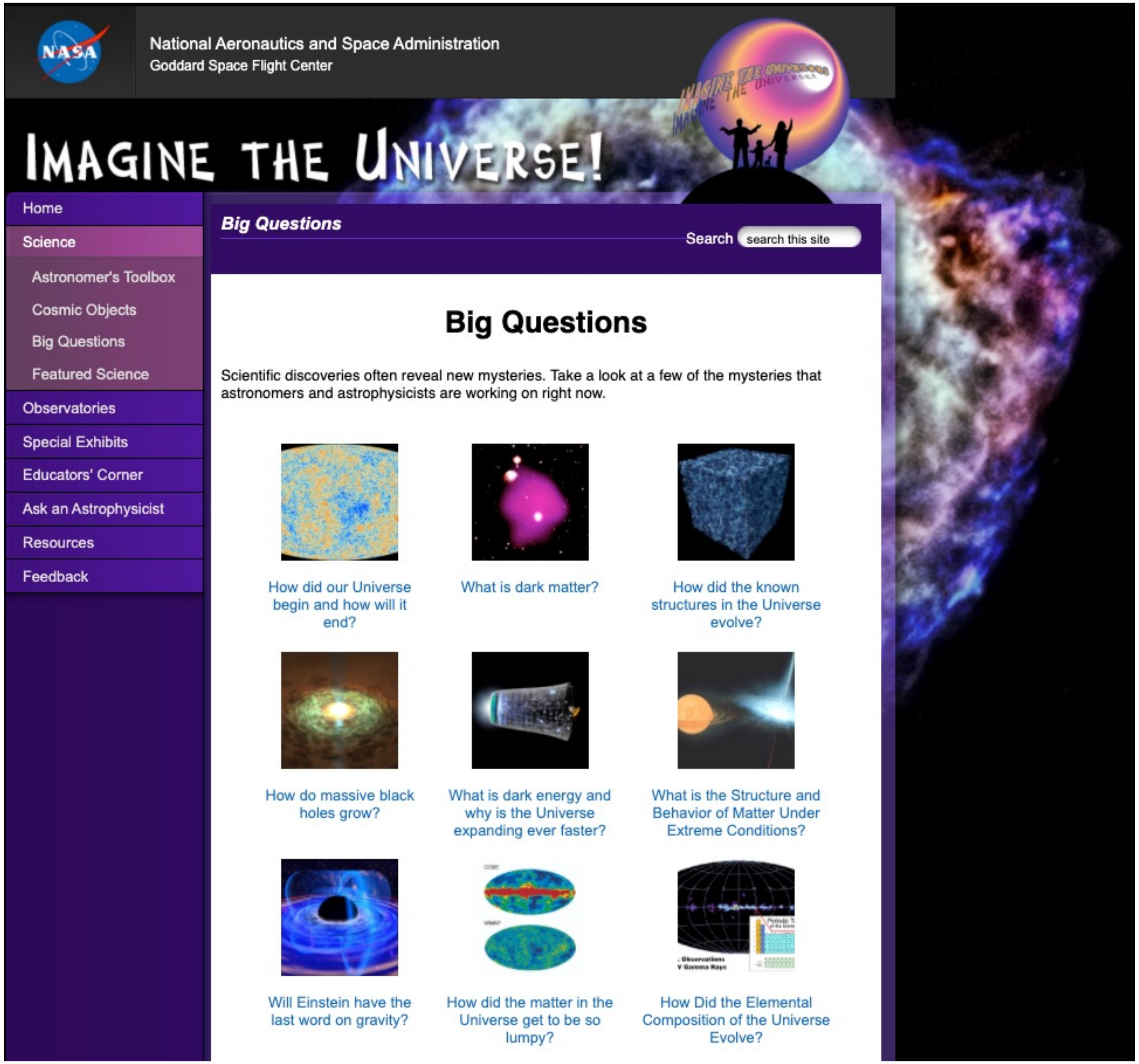
What is the next phase?

- We need to adopt this **efficient** strategy (including instrument requirements) to identify the first galaxies and black holes. We **cannot rely on pure chance,** as we do today.
- This phase of collecting a sample of these first objects is the only way forward.
- Its legacy value is immeasurable as there are not other possibilities to build such a sample, and identify the first objects and explore the universe just after the Dark Ages.

Outline of the Presentation

- The Proposing Team
- **Main Science Questions**
  - Global Scientific Philosophy
  - **Extragalactic Astrophysics and Cosmology**
- Some Requirements
- International Space Context
- Technology Challenges

NASA’s Big Questions



ESA’s Cosmic Vision 2015 – 2025?

4.2 The Universe taking shape

Tracing cosmic history back to the time when the first luminous sources ignited, thus ending the dark ages of the Universe, has just begun. At that epoch the intergalactic medium was reionised, while large-scale structures increased in complexity, leading to galaxies and their supermassive black holes.

Goals

1. Find the very first gravitationally-bound structures that were assembled in the Universe – precursors to today's galaxies, groups and clusters of galaxies – and trace the subsequent co-evolution of galaxies and super-massive black holes

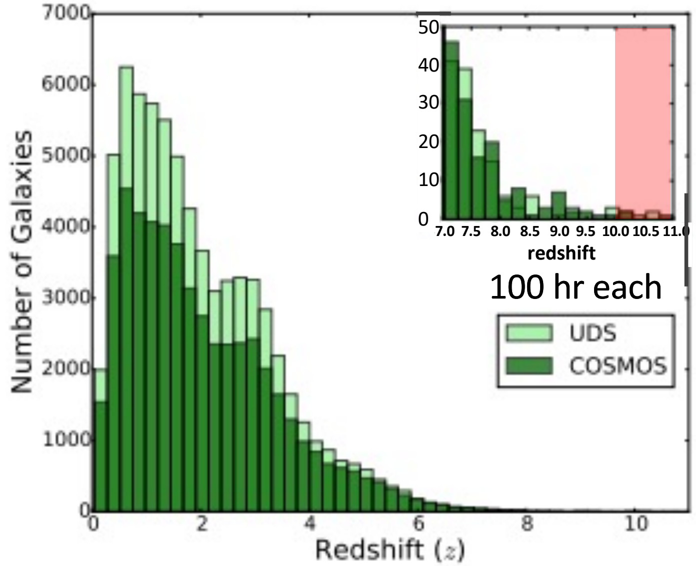
Table 3. A summary of the key features of the galaxy samples predicted (by EGG) to be detected with *JWST* in the the COSMOS-CANDELS and UDS-CANDELS fields, assuming a *JWST* observing time committment of $\simeq$ 100 hr to each field (see Section 4.3)

Field	Area /arcmin^2	Mass Range $\log_{10}(M_\star/M_\odot)$	Median Mass $\log_{10}(M_\star/M_\odot)$	Redshift range	Median z	SFG-QG Ratio	No. of Galaxies
COSMOS	$\simeq$150	5.02 – 11.90	8.45	$0.050 < z < 11.69$	2.019	11.10	51,879
UDS	$\simeq$250	5.11 – 11.86	8.48	$0.050 < z < 10.92$	1.969	10.97	69,766

Kemp et al. 2019: « *Maximising the power of deep extragalactic imaging surveys with the James Webb Space Telescope”*

Most distant astronomical objects with spectroscopic redshift determinations

	Name	Redshift (z)	Light travel distance§ (Gly)[1]	Type	Notes
	GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
	MACS1149-JD1	z = 9.11	13.26	Galaxy	Confirmed galaxy[3]
	EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[4]
	A2744 YD4	z = 8.38	13.20	Galaxy	Confirmed galaxy[5]
	GRB 090423	z = 8.2	13.18	Gamma-ray burst	[6][7]
	EGS-zs8-1	z = 7.73	13.13	Galaxy	Confirmed galaxy[8]
	z7 GSD 3811	z = 7.66	13.11	Galaxy	galaxy[9]
	ULAS J1342+0928	z = 7.54	13.1	Quasar	[10]



ESA’s Cosmic Vision 2015 – 2025?

4.2 The Universe taking shape

Tracing cosmic history back to the time when the first luminous sources ignited, thus ending the dark ages of the Universe, has just begun. At that epoch the intergalactic medium was reionised, while large-scale structures increased in complexity, leading to galaxies and their supermassive black holes.

Goals

1. Find the very first gravitationally-bound structures that were assembled in the Universe – precursors to today's galaxies, groups and clusters of galaxies – and trace the subsequent co-evolution of galaxies and super-massive black holes

Will JWST do it? Probably not.

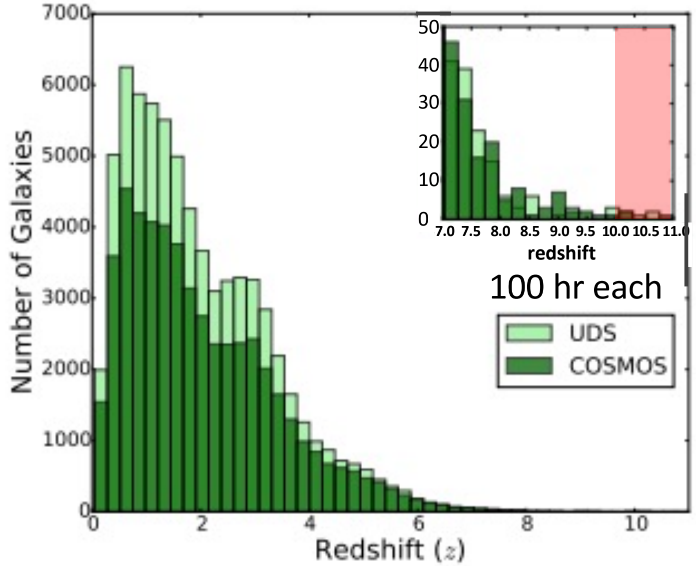
Table 3. A summary of the key features of the galaxy samples predicted (by EGG) to be detected with *JWST* in the the COSMOS-CANDELS and UDS-CANDELS fields, assuming a *JWST* observing time committment of $\simeq$ 100 hr to each field (see Section 4.3)

Field	Area /arcmin^2	Mass Range $\log_{10}(M_\star/M_\odot)$	Median Mass $\log_{10}(M_\star/M_\odot)$	Redshift range	Median z	SFG-QG Ratio	No. of Galaxies
COSMOS	$\simeq$150	5.02 – 11.90	8.45	$0.050 < z < 11.69$	2.019	11.10	51,879
UDS	$\simeq$250	5.11 – 11.86	8.48	$0.050 < z < 10.92$	1.969	10.97	69,766

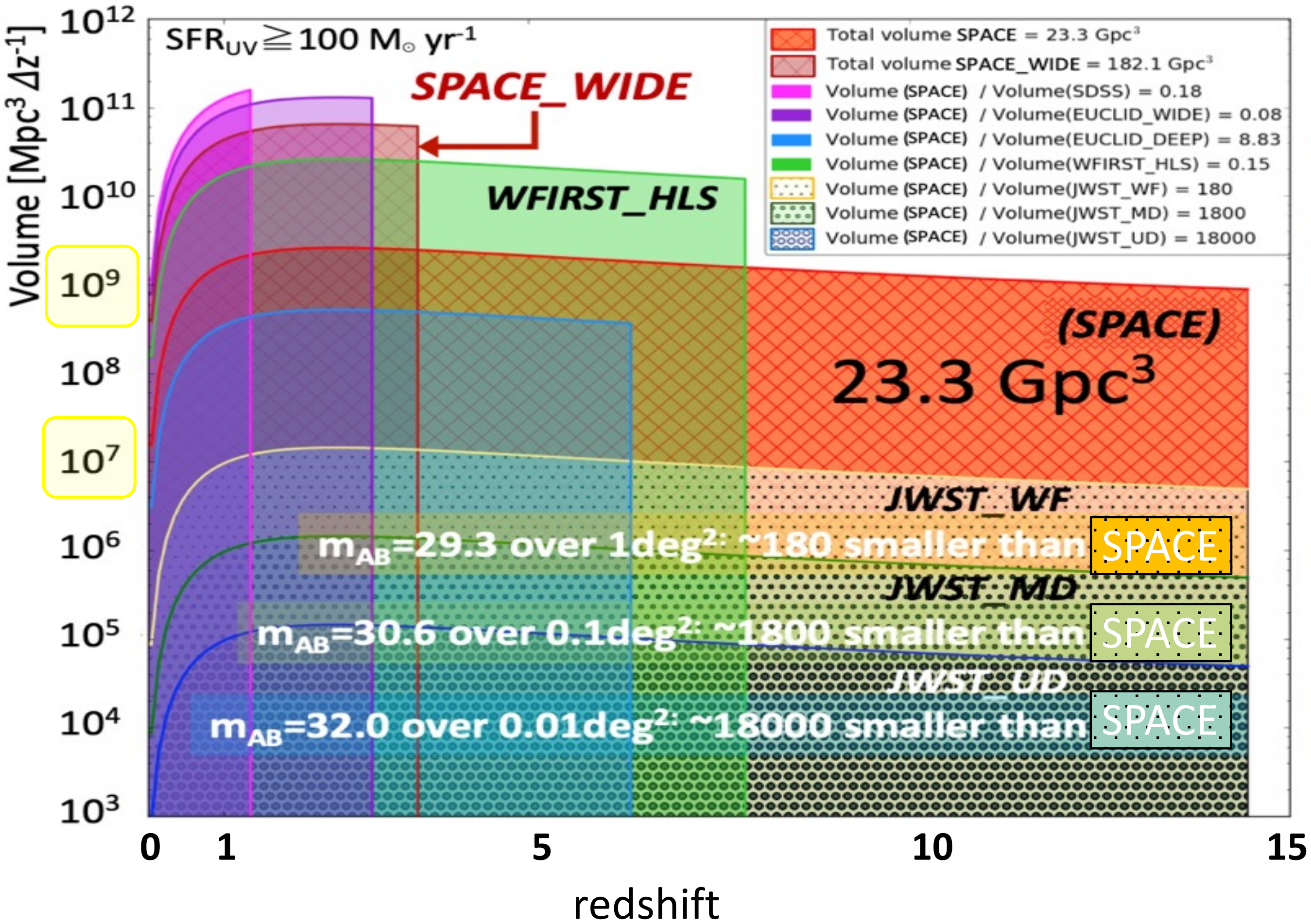
Kemp et al. 2019: « *Maximising the power of deep extragalactic imaging surveys with the James Webb Space Telescope”*

Most distant astronomical objects with spectroscopic redshift determinations

	Name	Redshift (z)	Light travel distance§ (Gly)[1]	Type	Notes
	GN-z11	z = 11.09	13.39	Galaxy	Confirmed galaxy[2]
	MACS1149-JD1	z = 9.11	13.26	Galaxy	Confirmed galaxy[3]
	EGSY8p7	z = 8.68	13.23	Galaxy	Confirmed galaxy[4]
	A2744 YD4	z = 8.38	13.20	Galaxy	Confirmed galaxy[5]
	GRB 090423	z = 8.2	13.18	Gamma-ray burst	[6][7]
	EGS-zs8-1	z = 7.73	13.13	Galaxy	Confirmed galaxy[8]
	z7 GSD 3811	z = 7.66	13.11	Galaxy	galaxy[9]
	ULAS J1342+0928	z = 7.54	13.1	Quasar	[10]



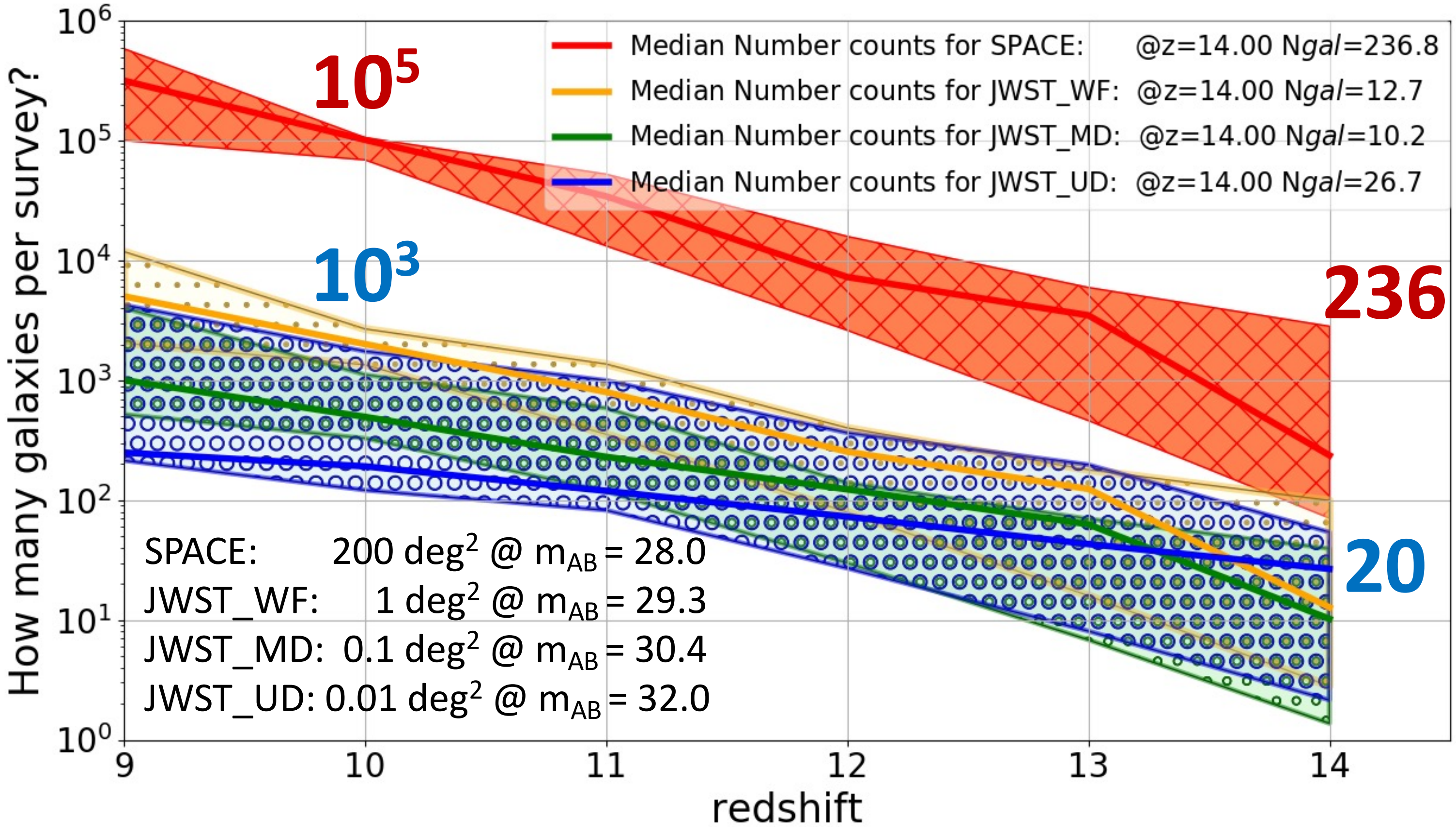
The First Galaxies: we need to explore large volumes



- SPACE's volume and ratio to other projects with respect to SPACE.
- SPACE's 200 deg^2 survey to m_{AB} = 28 will reach:
  - **10%** the volumes of the EUCLID WIDE and Roman ST HLS surveys but at much higher redshift
  - **180 to 18000 times** the volumes of JWST surveys

The First Galaxies

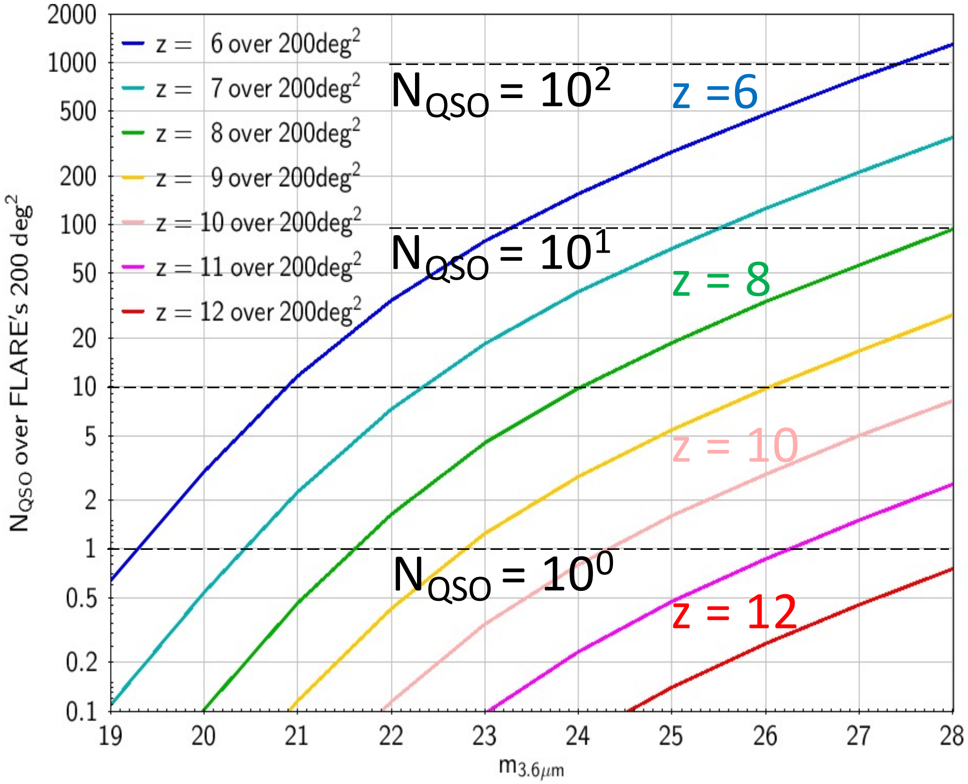
Number of galaxies to z = 14, photometrically detected in SPACE's 200 deg² and the three JWST surveys over 1 deg², 0.1 deg² and 0.01 deg² (Mason et al. 2015)



Since Big Bang: 478 Myrs | 372 Myrs | 300 Myrs

- JWST surveys would have ~ 20 objects each
- SPACE will provide ~ 240 objects @ z = 14
- Only after this, we will be able to address the questions related to the first stars, galaxies and black holes.

Formation and Growth of the First Super-Massive Black Holes



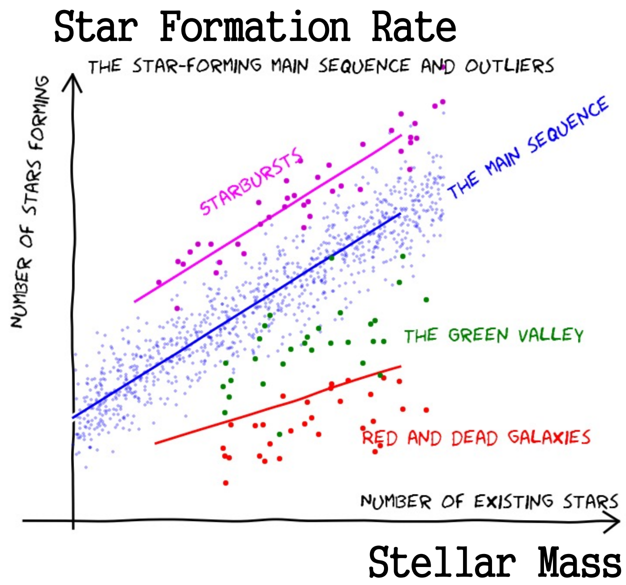
- Predictions calculated by David Rosario using the Venemans et al. (2013) quasar luminosity function and the SDSS composite quasar spectrum for a 200 deg² survey.
- SPACE limiting magnitude will be $m_{AB} = 28$.
- **Synergy with Athena**

Blackboard for Requirements:

- ✓ Wide instantaneous field of view (~ 0.5–1 deg^2) to build a wide-field survey (100 – 1000 deg^2)

Understanding the building of galaxies: the main sequence of galaxies at z > 6

(e.g. Noeske et al. 2007, Rodighiero et al. 2011)



- We need the **near-IR** and **mid-IR** light to collect the rest-frame stellar light in the early universe:
  - $\lambda_{\text{STELLAR MASS}} = 2\ \mu m \Rightarrow \lambda_{\text{stellar mass}} = 22\ \mu m$ **@ z = 10**
  - $\lambda_{\text{STAR FORMATION RATE, UV}} = 0.2\ \mu m \Rightarrow \lambda_{\text{SFR\_UV}} = 2.2\ \mu m$ **@ z = 10**

z \ mAB	25	26	27	28	29
5	6741	257674	2.8E+06	20084	73187
6	54	12773	307300	3873	20241
7	0	325	23164	532	4282
8	0	4	1165	55	730
9	0	0	44	5	96
10	0	0	1	0	13

Number of galaxies detected by the two WFIRST Wide (yellow) and Deep (blue) surveys at 5 < z < 10 that OST-MISC could detect. To build SFR vs. $M_\star$ for WFIRST-detected objects

➔ Need NIR-MIR for $M_\star$.

Blackboard for Requirements:

- ✓ Wide instantaneous field of view (~ 0.5 – 1 deg^2) to build a wide-field survey (100 - 1000 deg^2)
- ✓ Near-IR, mid-IR because we want to estimate the stellar mass of objects in the EoR, at $6 < z < 14$

Did we address all of the questions in Cosmic Vision 2015 – 2025?

4.3 The evolving violent Universe

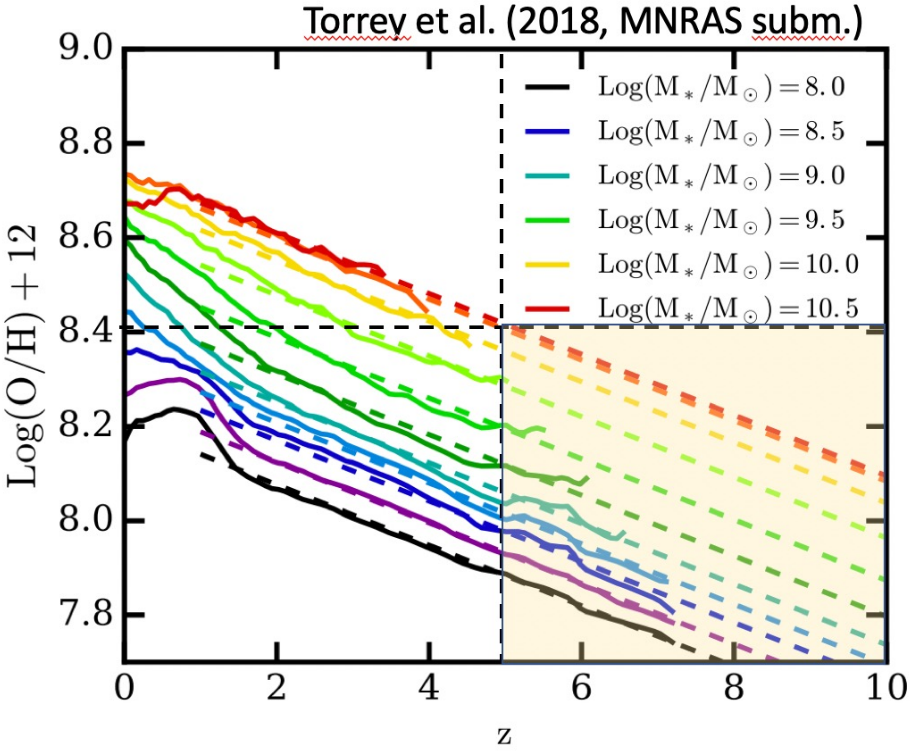
Nature offers astrophysicists the possibility of observing objects under much more extreme conditions, in terms of gravity, density and temperature, than anything feasible on Earth. On the one hand, black holes and neutron stars are unique laboratories where the laws of physics can be probed under these extreme conditions. On the other hand, the same objects were the driving engines of the birth and evolution of galaxies, of the creation of heavy elements such as iron, and more generally, of the transformation of the primordial hydrogen and helium from which stars and galaxies were first being formed.

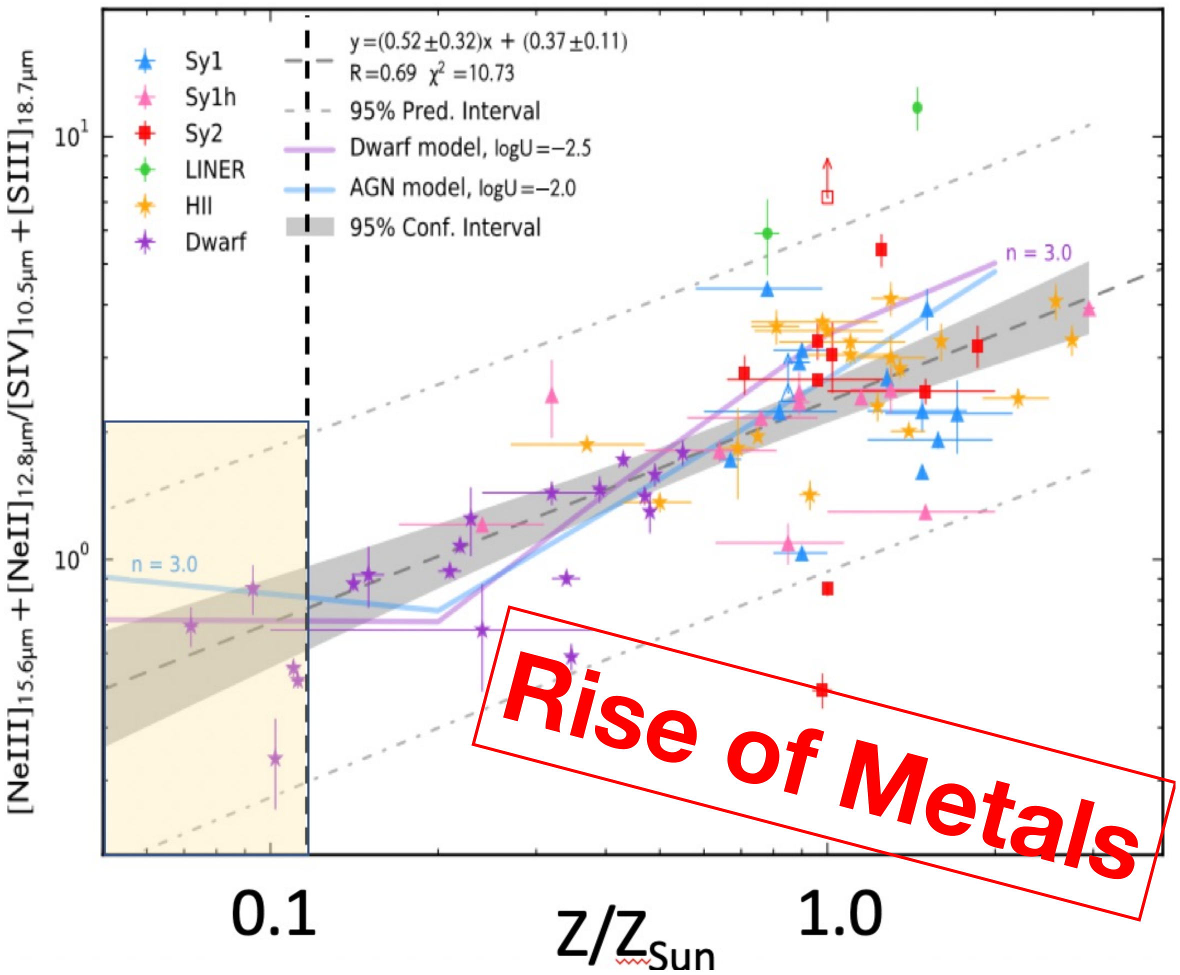
Goals

1. Trace the formation and evolution of the super-massive black holes at galactic centres – in relation to galaxy and star formation – and trace the life cycles of chemical elements through cosmic history

How can we address this fundamental question?

- Mass-metallicity relation (e.g. Tinsley 1980) indicates how star formation and chemical enrichment proceed in galaxies as a function of mass.
- At what rate was the Universe enriched with metals?
- In what types of galaxies did the bulk of this enrichment happen?
- When were galaxies suitably enriched to support the development of life?





i. Galaxies build stellar mass with time
ii. Higher redshift galaxies have lower mass
iii. We know there is a mass – metallicity relation
iv. Lower mass galaxies have lower metallicities
v. Higher redshift galaxies have lower metallicities

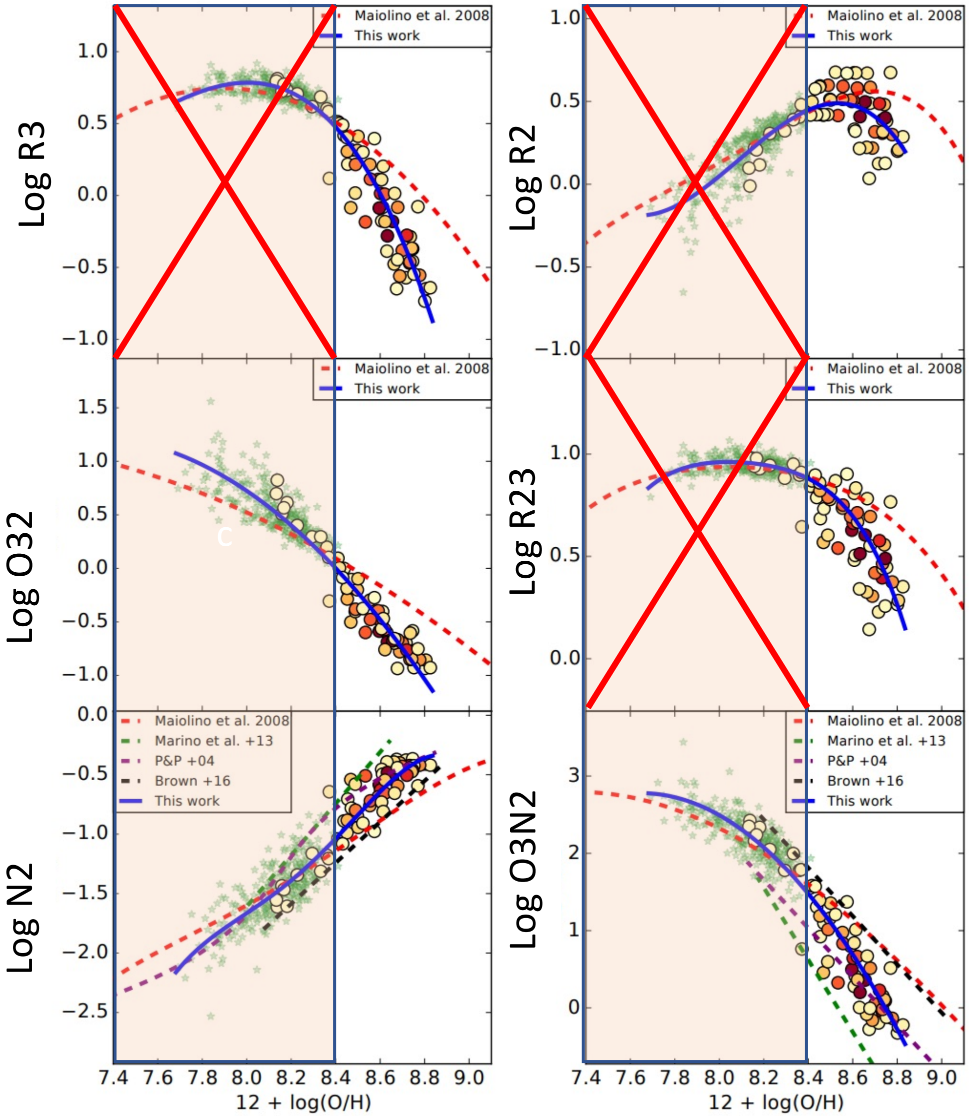
Rest-frame bright optical lines?

- Fine structure IR lines not useful at high redshift and low metallicity because of degeneracy.
- PAH bands, e.g. 3.3 μm are promising but needs JWST to confirm and calibrate.

Best option to measure metallicities at z > 6

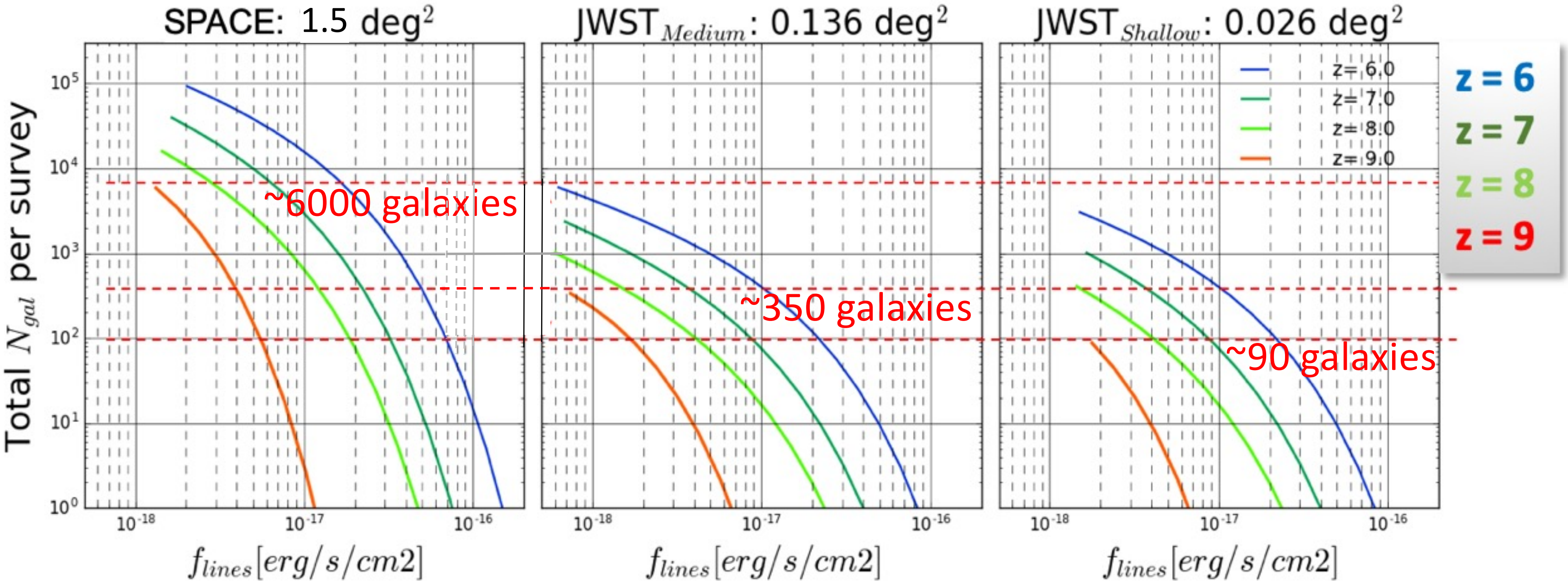
- **same tracers from z = 0 to z = 10 – 12+**
- **Safe and well-calibrated method for *low stellar mass / low - metallicity / high redshift objects.***

- ~~R3 ([OIII] λ5007/Hβ)~~
- ~~R2 ([OII] λ3727/Hβ)~~
- O32 ([OIII] λ5007/[OII] λ3727)
- ~~R23 (([OII] λ3727+[OIII] λ4959, 5007)/Hβ)~~
- N2 ([NII] λ6584/Hα)
- O3N2 (([OIII] λ5007/Hβ)/([NII] λ6584/Hα))



Curti et al. (2017)

How many galaxies in SPACE vs JWST Spectroscopy?

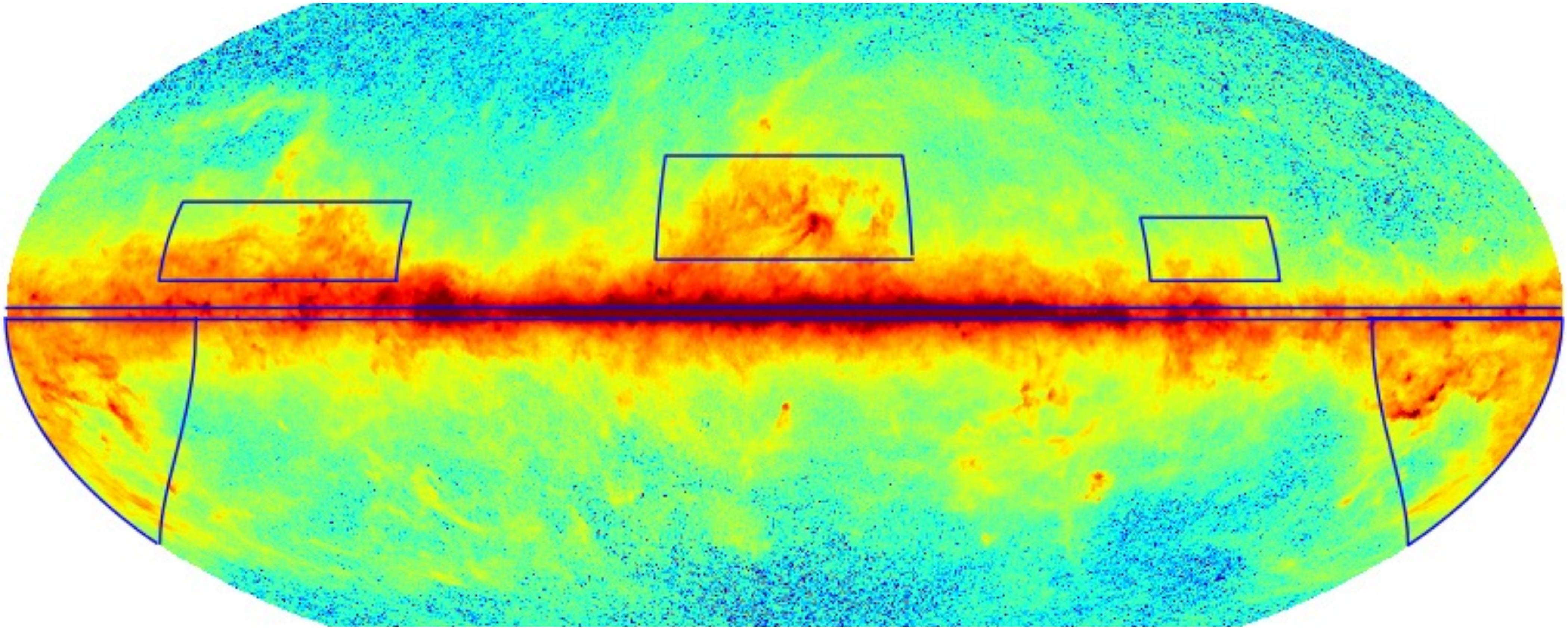


Number of galaxies detected via [OIII]5007 line and Hα (slightly different redshift range).

At any redshift, SPACE will detect > 15 times the number of objects that JWST could collect.

Blackboard for Requirements:

- ✓ Wide instantaneous field of view (~ 0.5 – 1 deg^2) to build a wide-field survey (100 - 1000 deg^2)
- ✓ Near-IR, mid-IR because we want to estimate the stellar mass of objects in the EoR, at $6 < z < 14$
- ✓ Near-IR and mid-IR spectroscopy to measure the metallicity of all objects at $z > 5$ (IFU, MOS?)



This strategy also necessary for a Milky Way Survey

The Gould Belt regions are Cepheus, Centaurus, Lacerta, Lupus, Orion, Perseus, Scorpius, Vela, Canis Major, Carina, Crux, Ophiuchus, Puppis, Serpens, and Taurus. ***The total surface including the galactic plane on about ±1° height (720 deg^2) would cover several 1000 deg^2***.

Outline of the Presentation

- The Proposing Team
- **Main Science Questions**
  - Global Scientific Philosophy
  - Extragalactic Astrophysics and Cosmology
- **Some Requirements**
- International Space Context
- Technology Challenges

Which Science Mission to Address the Science Questions?

Summary of the Requirements for the NIR+MIR

Size of the primary mirror	**> 3m**
Wavelength range	3 – 28 μm (cold: a few K)
Pixel scale imaging	0.2 – 0.4 arcsec
Spectral resolution imaging	3 - 5
Instantaneous imaging field of view	0.5 – 1 sq. deg. (2 x 2 x 4K)
Limiting flux mAB (1h, @ 5μm, SNR = 5)	~ 28
Pixel scale spectroscopy	~ 1 arcsec
Instantaneous Spectroscopic field of view (MOS)	0.5 – 1 sq. deg.
Instantaneous Spectroscopic field of view (IFS)	1 sq. arcmin.
Spectral resolution (Low resolution)	20 – 50
Spectral resolution (Medium resolution)	500 – 1000
Limiting line flux (1h, @ 5μm SNR = 5)	$10^{-18} – 10^{-19}$ erg/cm^2/s

International Space Context: this concept is unique

To our knowledge, no past, present or future project can address the scientific objectives detailed in this WP for several reasons:

- **AKARI and WISE:** not deep enough, low angular resolutions
- **JWST, SPICA/SMI and present OST/MISC:** field of view too small
- **ELT: optical+NIR:** wavelength range not adequate
- **ALMA, NOEMA, NIKA2, LMT:** no Near-IR and mid-IR and field of view too small
- **NIKA2, LMT:** no Near-IR and mid-IR and no spectroscopy

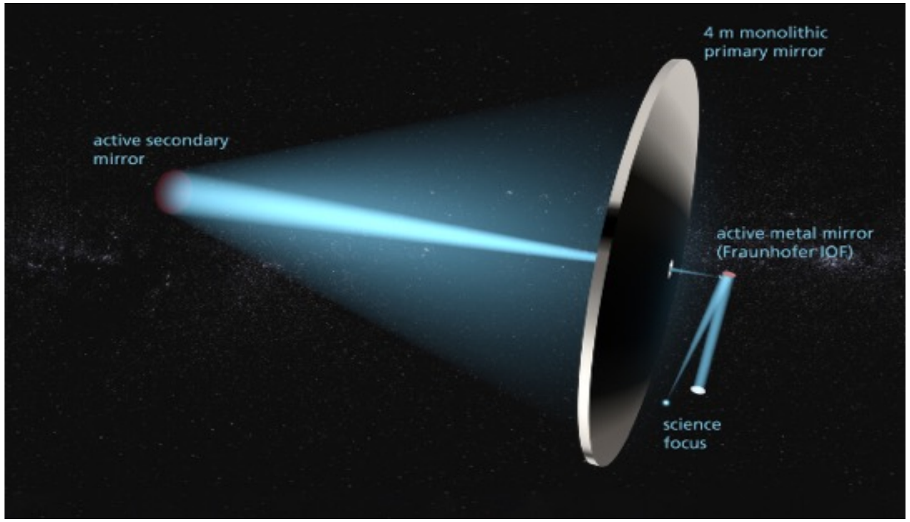
Technology Expertise in Marseille, France

- Deformable Mirror for Active Optics
- Wide-field Integral-Field Spectrograph
- Micro-Mirror Arrays
- Simulations and Massive Analysis of Spectra with the CIGALE code

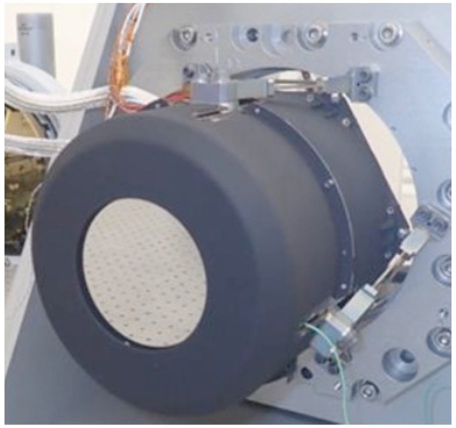
- It will be unlikely that I will have enough time to give details on this and I will just fly over the next slides.
- Please look at the Slack for more information.

Deformable Mirror (DM)

- In-flight correction of thermo-elastic and gravity varying induced deformations of large lightweight mirrors using active loop with wave front sensors and deformable mirrors.
- In Europe, ESA recently funded a number of programmes to further develop DM technologies for space applications.
- Other European and national agencies have funded DM developments; either to push forward new concepts or increase the TRL of already developed and used technologies.

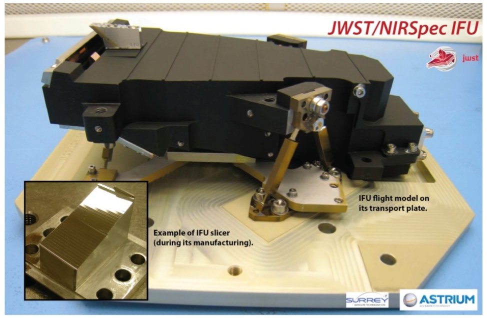


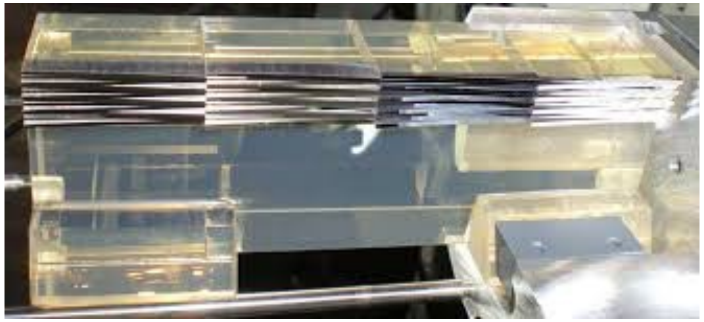
STOIC concept with 4m monolithic mirror and active deformable mirrors © Fraunhofer IOF



MADRAS DM
© Thales-Alenia-Space & LAM

Image slicers



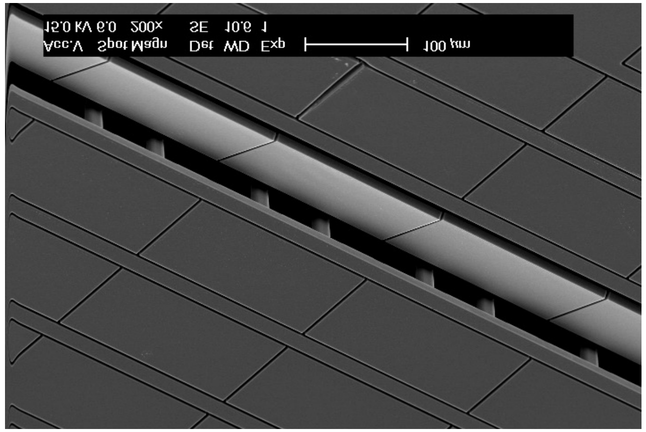


- The technology for producing image slicers for integral field spectroscopy using diamond-machining techniques is now mature, and scalable from smaller field prototypes developed for NIRSpec and MIRI on JWST.
- For instance, a method for cost efficient and highly performant manufacturing of spherical image slicers was developed and patented in collaboration with the Winlight company.
- The technology was applied to VLT-MUSE instrument and is proposed for E-ELT and space instruments.

Left: The Image Dissector Array (IDA) manufacturing constitutes a WINLIGHT Optics/CNRS patent. Innovative methods, developed conjointly by LAM (Laboratoire d'Astrophysique de Marseille, France) and WinLight Optics (Marseille, France), allow reaching high performances (accurate roughness, sharp edges, surface form, etc.) with standard glass manufactured components while saving costs and time by an order of magnitude compared with classical techniques. This IDA is constituted by 48 slices. Right: Main picture: The NIRSpec IFU flight model. The IFU is roughly the size of a shoe box and weighs less than 1 kg. Insert: The image slicer, a key element of the IFU, pictured during manufacture. Each slice visible in the picture is less than 1 mm wide. Credit: R. Sharples / University of Durham, United Kingdom.

Micro-mirror arrays (also F. Zamkotsian’s talk)

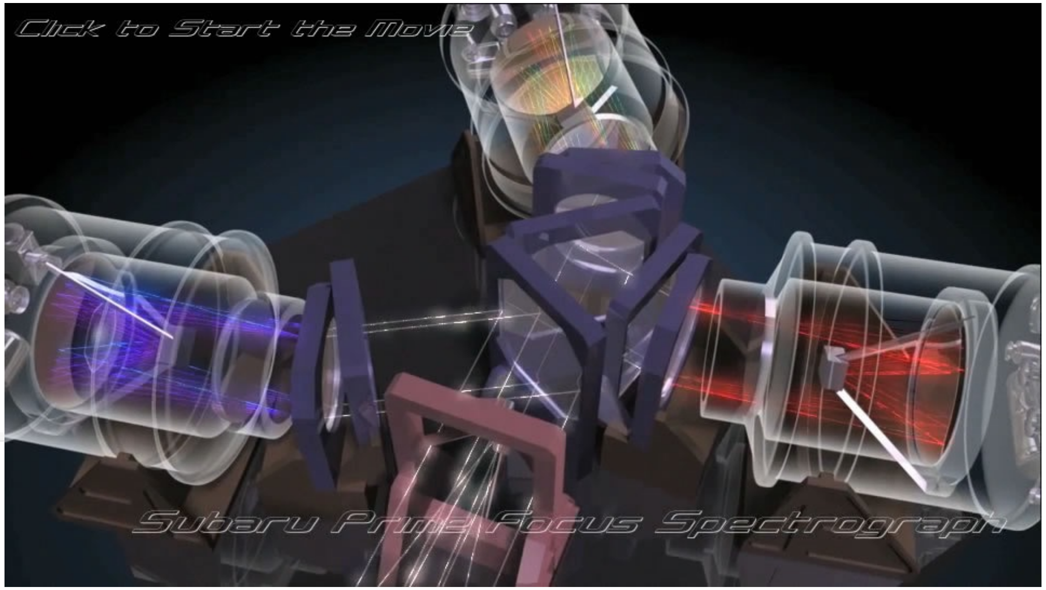
- The scientific return from future Astrophysical space missions could be optimized using MOEMS (MicroOpto-Electro-Mechanical systems) devices like large micromirror arrays (MMA).
- Multi-object spectrographs (MOS) are powerful tools for space and ground-based telescopes for the study of the formation and evolution of galaxies.
- This technique requires a programmable slit mask for astronomical object selection; 2D MMAs are suited for this task. MOEMS has been used to build JWST NIRSpec.
- In Europe, several options exist as the one from Laboratoire d’Astrophysique de Marseille (LAM, France) and the Centre Suisse d’Electronique et de Microtechnologies (CSEM, Switzerland) engaged in a European development of MMAs, called MIRA, exhibiting remarkable performances in terms of surface quality as well as ability to work at cryogenic temperatures.
- MMA with 100 x 200 µm2 single-crystal silicon micromirrors were successfully designed, fabricated and tested down to 162 K. They are designed to work at 30K and there are no blocking points that would prevent them to work at 5K.
- In order to fill large focal planes (mosaicking of several chips), we are currently developing large micromirror arrays to be integrated with their electronics.



Micro-mirror array with high fill factor in the long direction providing long slits. Each mirror measures 200 x 100 µm^2. Our project will take advantage of the already available building blocks to design, realize and package customized micro-mirror arrays perfectly suited for our instruments. 2D arrays are built on wafer with Through Wafer Vias in order to allow routing of the device on wafer backside, foreseeing integration with dedicated ASICs. Like for CCDs, mosaicking will permit wide fields of view. Credit: F. Zamkotsian / LAM & CSEM.

CIGALE: simulations and photo-spectroscopy fitting

- Spectral simulations for VLT-MOONS performed with *CIGALE.*
- In a recent team meeting, it was decided to also perform spectral simulations for SUBARU-PFS.

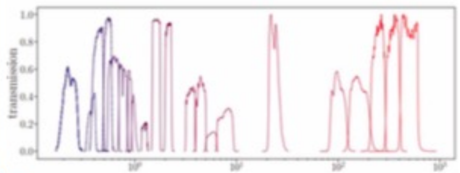


CIGALE: simulations and photo-spectroscopy fitting

Simulated catalogues of spectra with CIGALE: from data or models

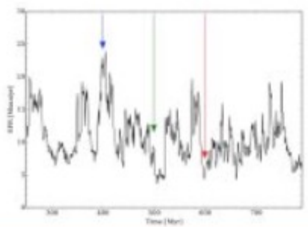
INPUT

Photometric catalogue + photo-z



OR

SFH from models



CIGALE machine

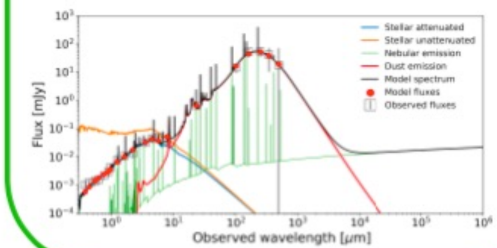
- SFH (various)x SSP (BC03)
- Nebular emission (Cloudy)
- Attenuation (stars /lines)
- AGN (Skirtor)
- IR (dust) templates
- IGM

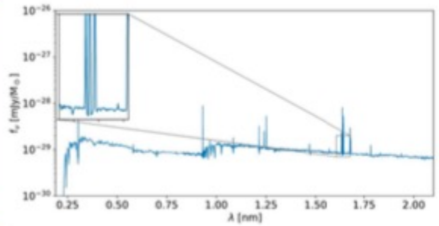
Energy balance between stellar and dust emission

- SSP (BC03)
- Nebular emission (Cloudy)
- Attenuation (stars /lines)
- AGN (Skirtor)
- IR (dust) templates
- IGM

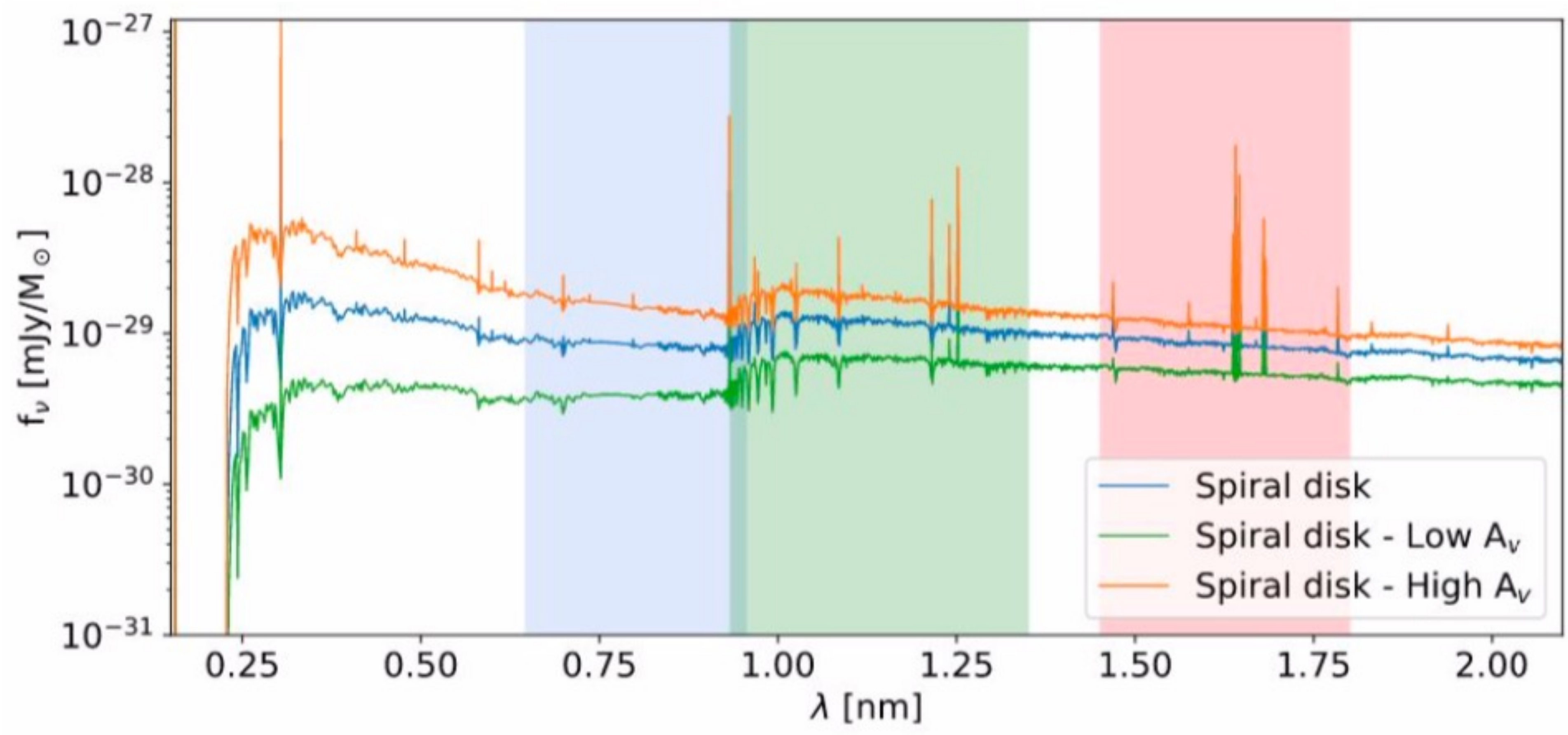
OUTPUT

- Spectra at the resolution of the SSP
- Any additional filter/spectral feature
- Physical parameters



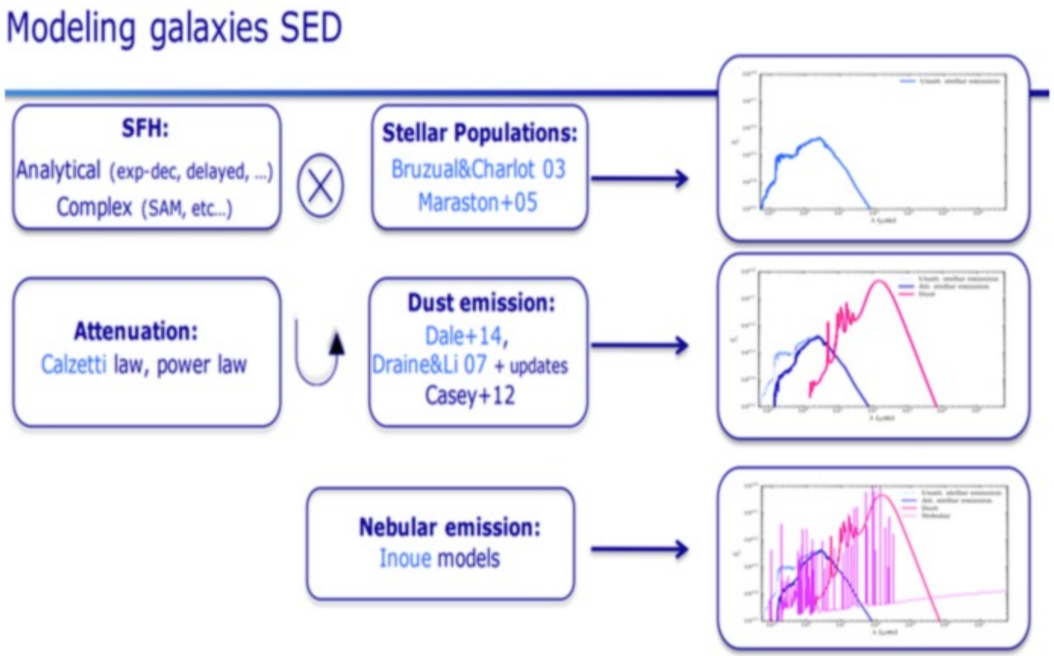


CIGALE: simulations and photo-spectroscopy fitting



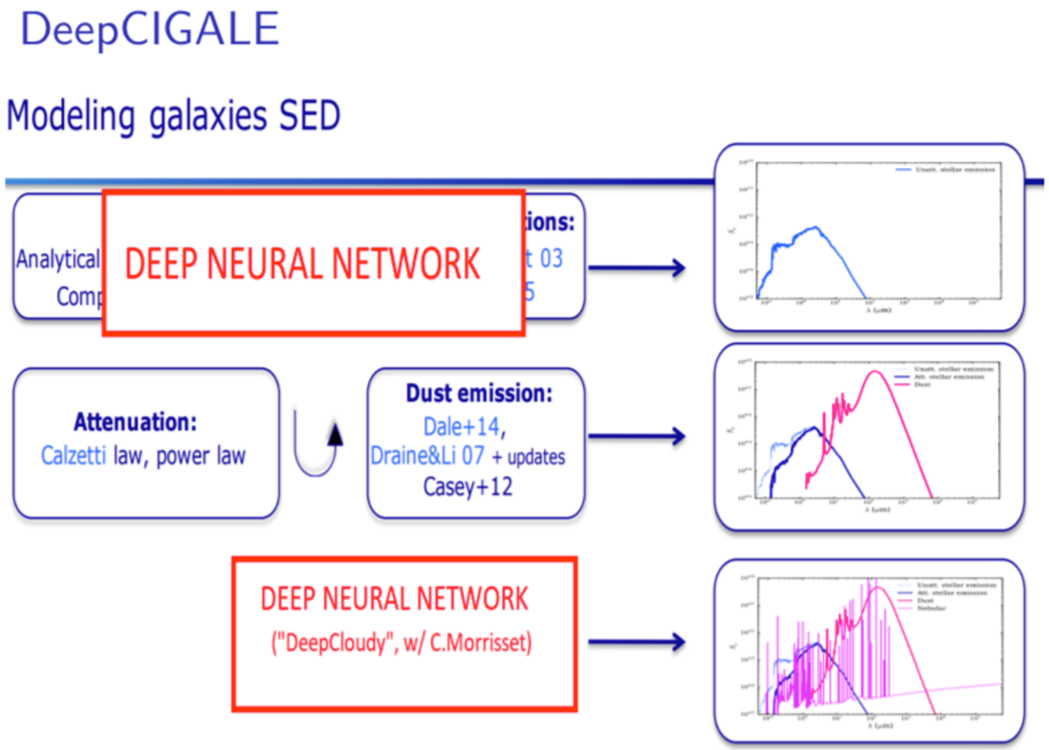
CIGALE: simulations and photo-spectroscopy fitting

CIGALE



For each point on the parameter grid :
Compute the corresponding SED, compute the χ^2, weight the parameters.

CIGALE: simulations and photo-spectroscopy fitting

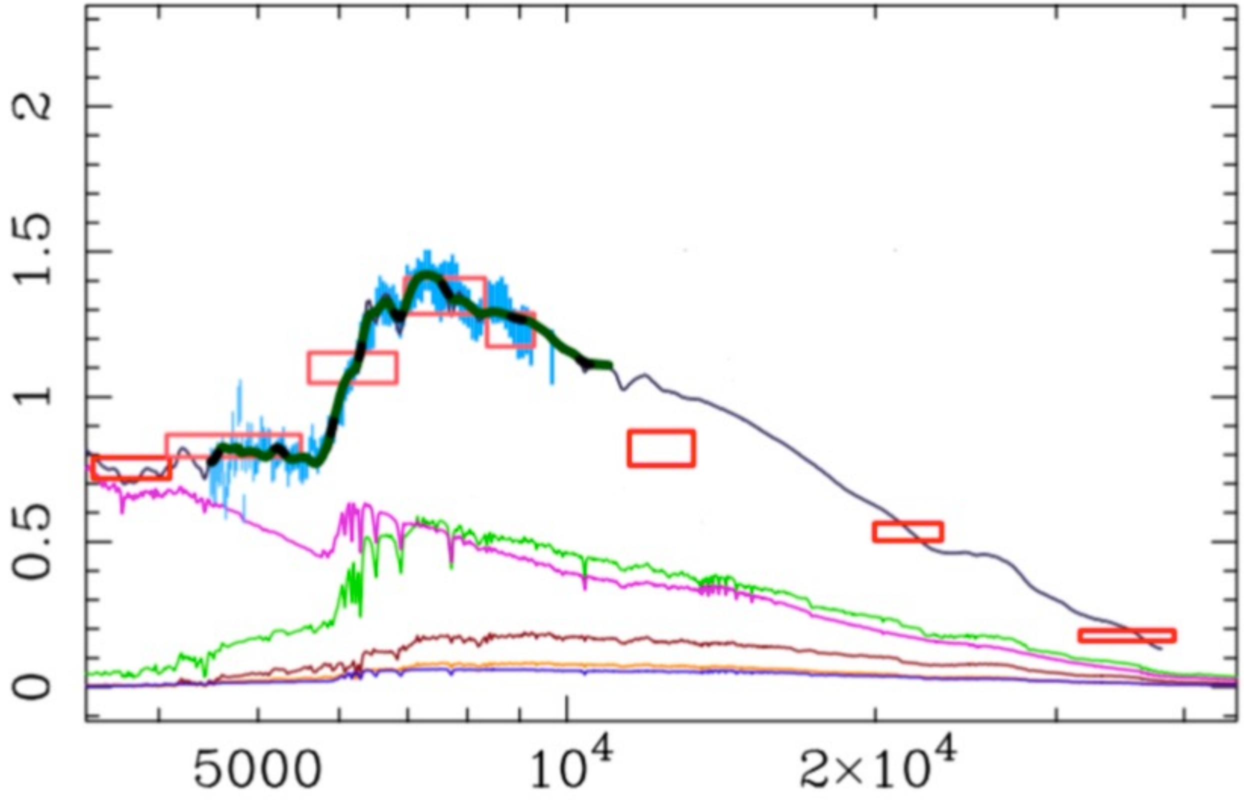


For each point on the parameter grid :
Compute the corresponding SED, compute the χ^2, weight the parameters.

CIGALE: simulations and photo-spectroscopy fitting

- The new CIGALE can already handle both photometric and spectroscopic data.
- The new Deep-CIGALE will improve the speed but also use a new statistical algorithm.
- Recent features: X-ray module with polar dust, AGN emission lines, new emission lines from Deep-Cloudy.

Multiple data sources



The End

ATLAS is a very interesting and promising project.

Its unique characteristics (including of course the wavelength range and the wide FoV) are the key to decipher and understand the early universe.

Thank You

Have a nice Summer 😎
(21 June 2021 at 03:32 UTC)