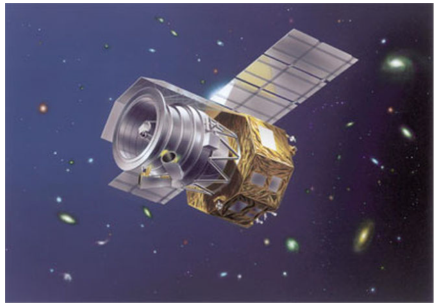
Massive Stars: what next? Future Ground and Space Facilities

(A somewhat biased review)

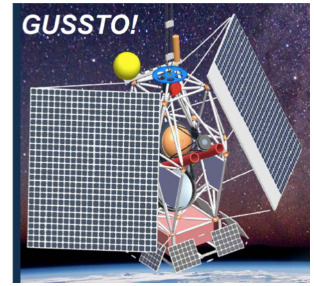
Dimitra Rigopoulou
Univ. of Oxford, UK

The context : in Space

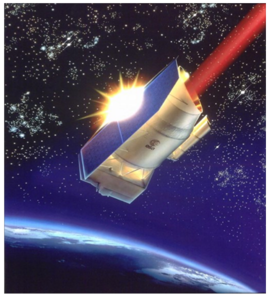


AKARI (2006-11)

Herschel (2009-2013)

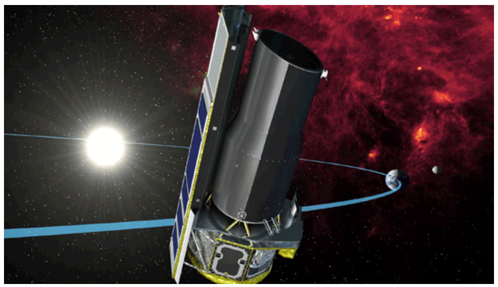


GUSSTO (early ‘20s)

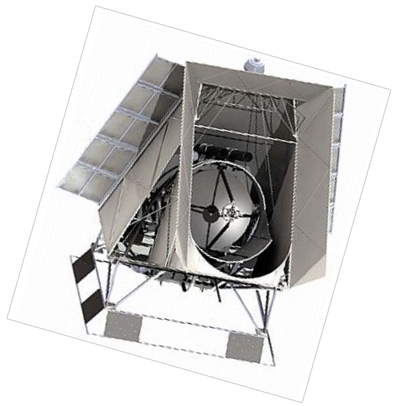


ISO(1995-98)

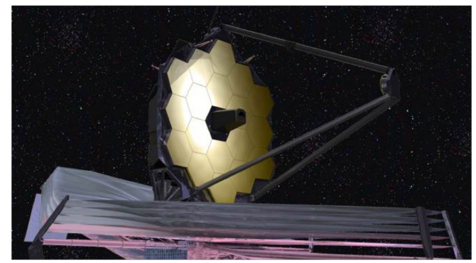
IRAS (1983)



Spitzer (2003-)



BLAST-Pol

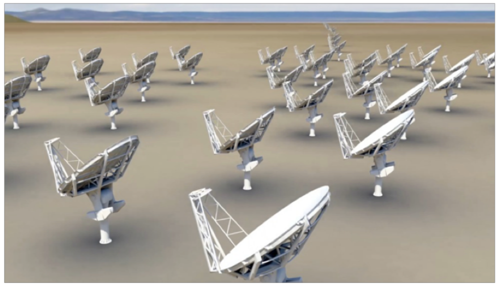


JWST (sch. 2021)

The context : on the ground

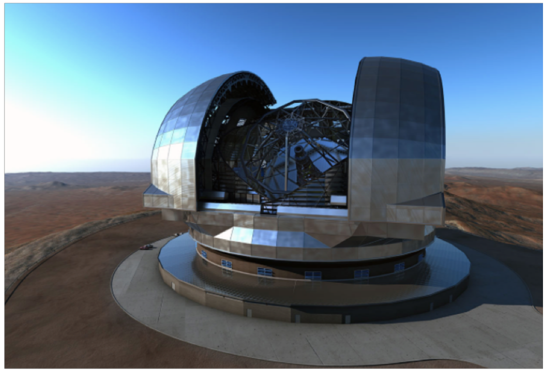
ALMA

VLA

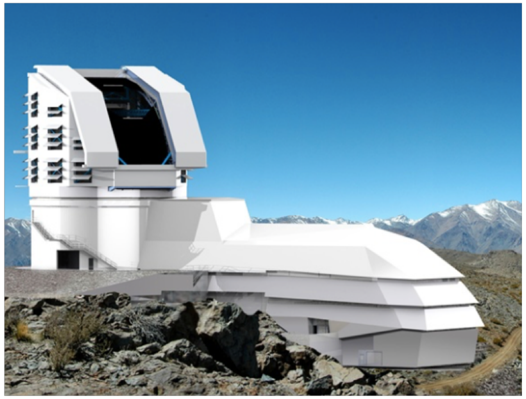


ng-VLA

VLT & 8-10m class



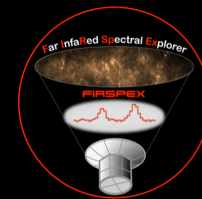
ELT (first light ~2024)



LSST (first light ~2022)

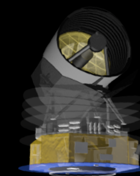
Outline of this talk

Large scale view of Star Formation
Feedback from Massive Stars
CO-dark clouds



FIRSPEX

MIR Spectroscopy
Polarised dust & Filaments

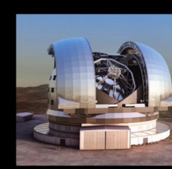


SPICA

Feedback/shocks and cosmic rays
Evolved stars
ISM properties of the MW & Nearby Galaxies

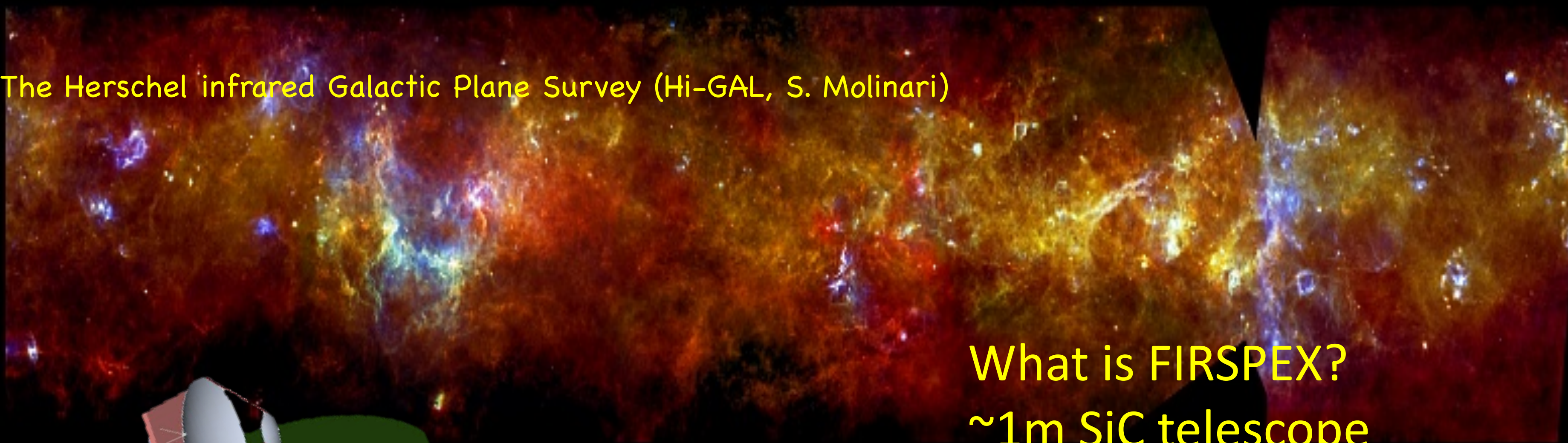
OST

Pop III Stars w ELT- HARMONI
Resolved Stellar Pops

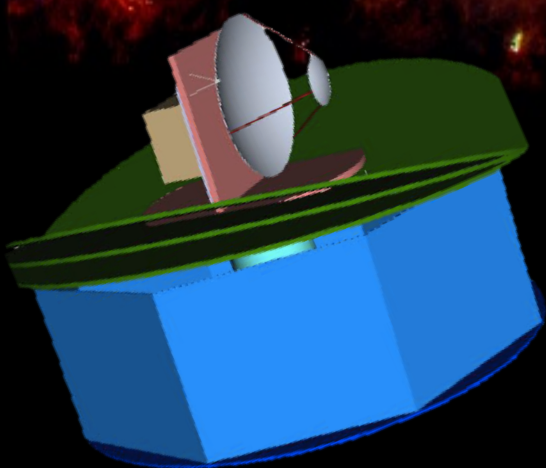


ELT

Probing the Life-Cycle of the ISM in the Universe: the FIRSPEX concept



The Herschel infrared Galactic Plane Survey (Hi-GAL, S. Molinari)



What is FIRSPEX?

~1m SiC telescope

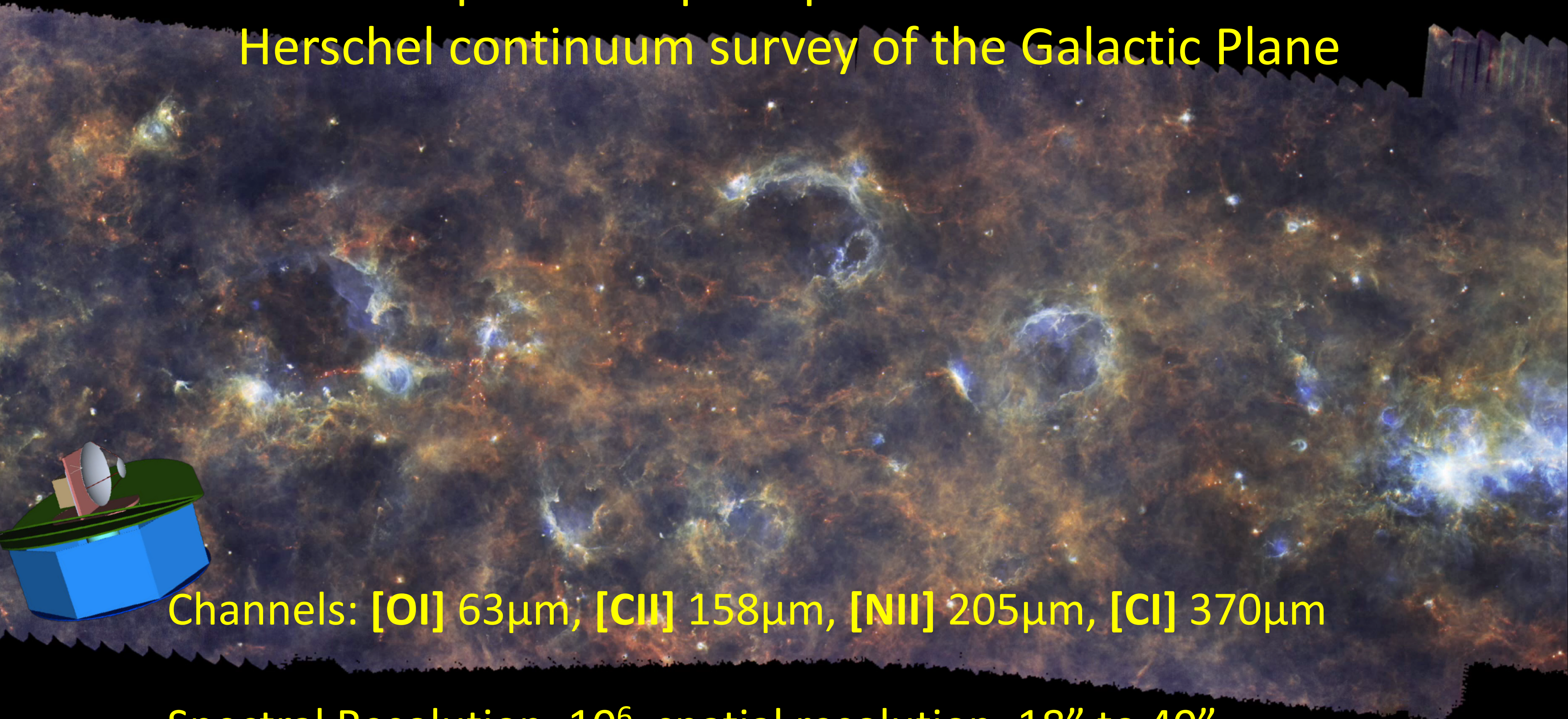
Heterodyne Payload SIS/HEB

Mechanically cooled to 4K

UK-led multi-lateral mission (UK/India/China/Europe)

The Herschel infrared Galactic Plane Survey (credit: S. Molinari, 2012, 2016

Spectroscopic equivalent to the Herschel continuum survey of the Galactic Plane



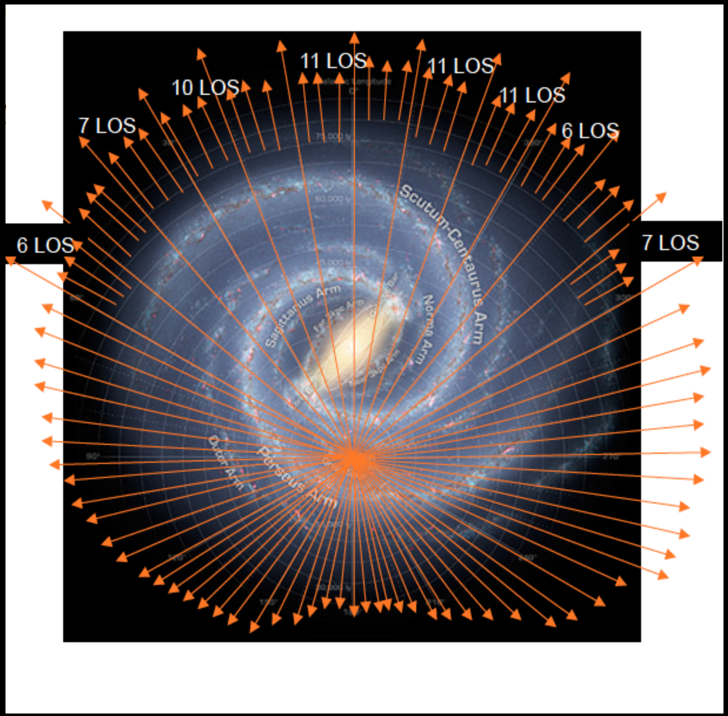
Channels: **[OI]** 63μm, **[CII]** 158μm, **[NII]** 205μm, **[CI]** 370μm

Spectral Resolution: 10^6, spatial resolution: 18” to 40”

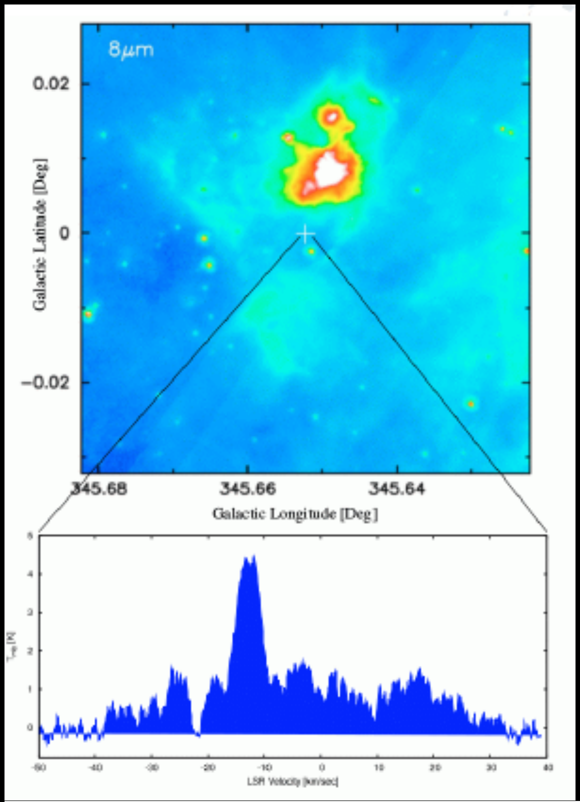
Provide resolved 3D distribution of different ISM phases

Heritage & Motivation

Herschel-HIFI

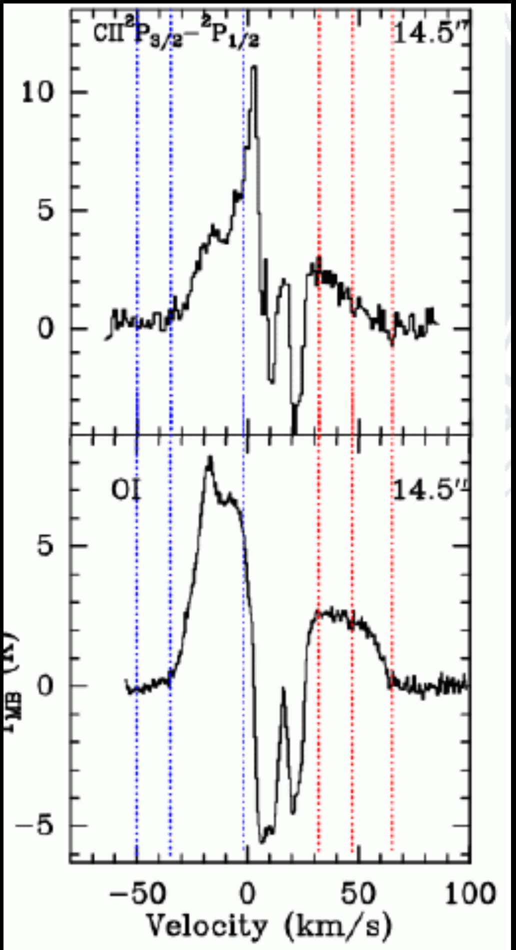


GOTC+ (Pineda et al. 2010, 2013)



Example of [CII] emission associated With massive star-forming region. The line of sight G345.65+0.0 passes near several bright HII regions as shown in Spitzer 8um image

GREAT-SOFIA

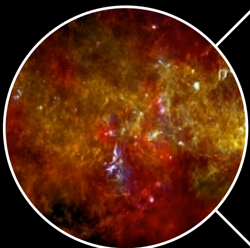


SOFIA: Typical line profiles (Leurini et al. 2015)

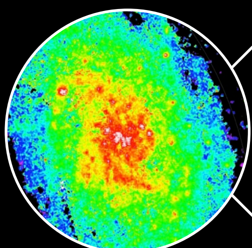
Spectral Resolution is Key!

FIRSPEX Core Science & Sensitivity

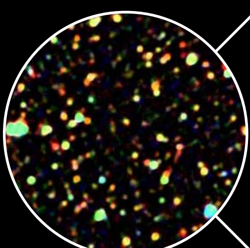
To find out more on FIRSPEX: http://futuremission.wix.com/firspex



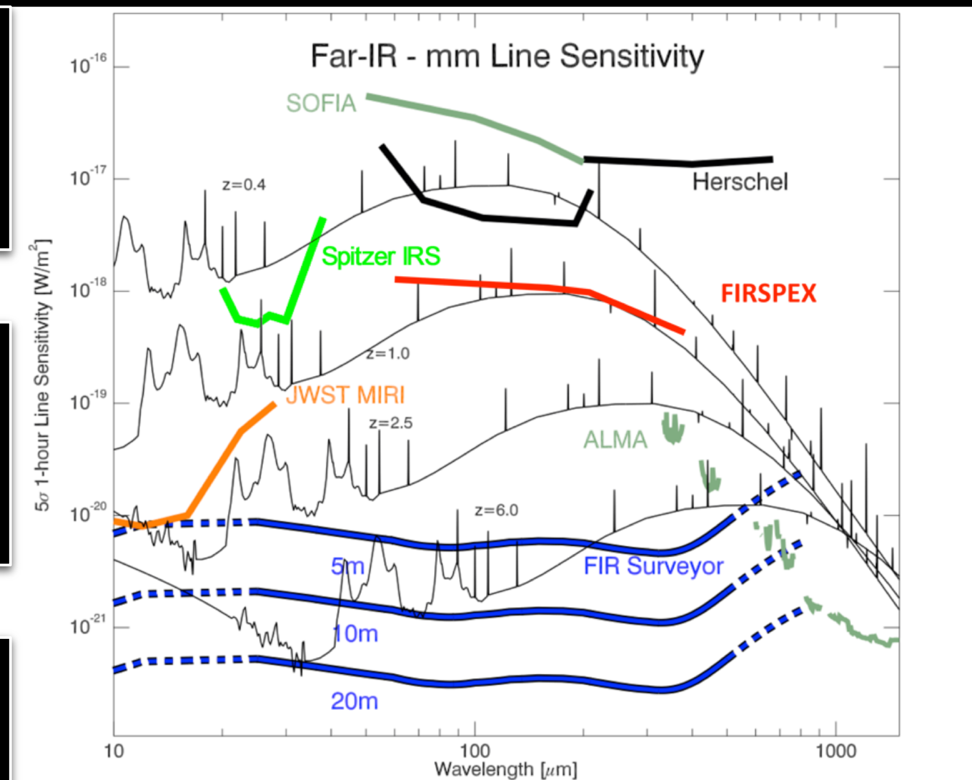
The ISM in our Galaxy: large area survey of the Galactic Plane



Nearby Galaxies: survey of nearby Starburst/Normal Galaxies and AGN, mapping the ISM

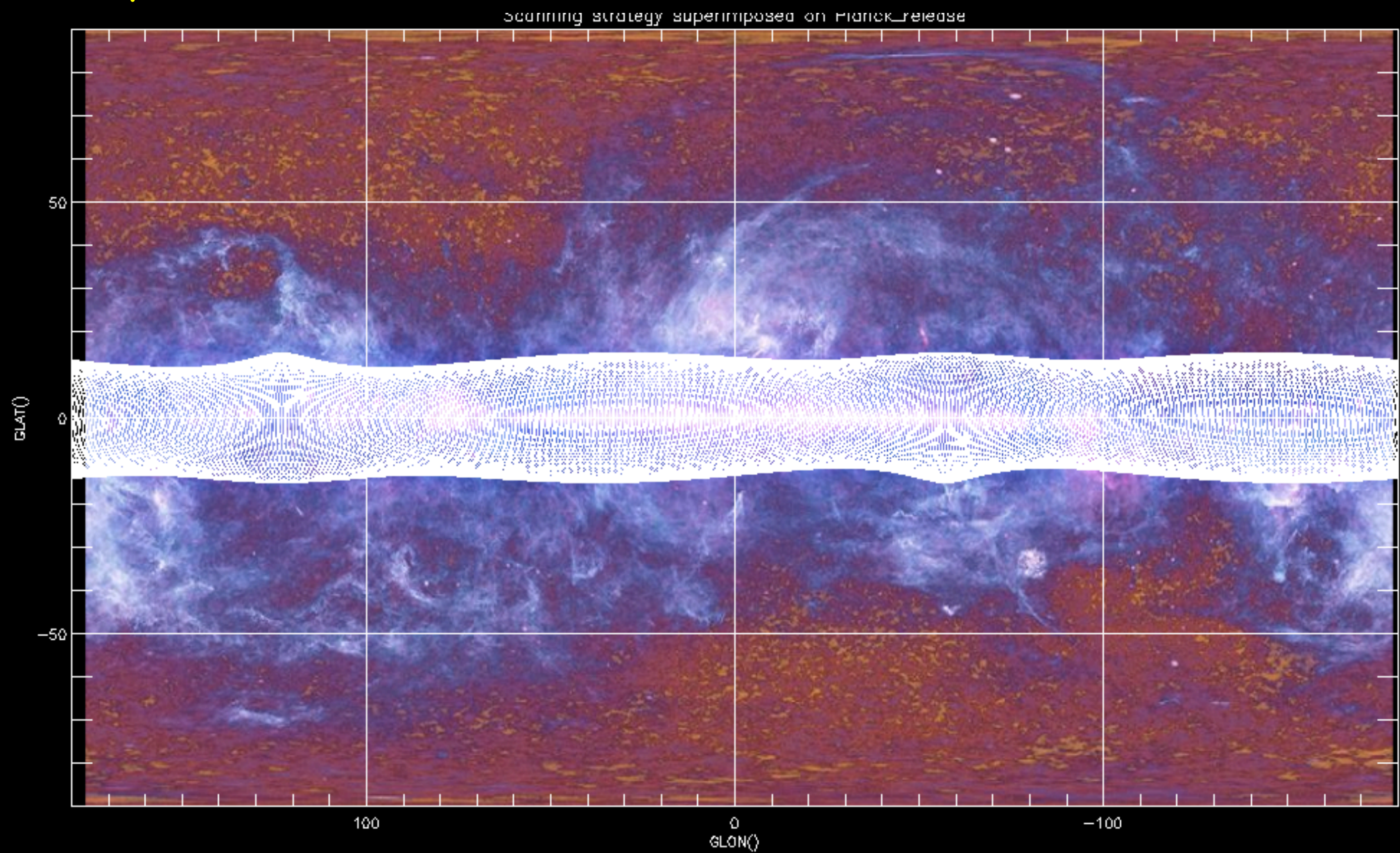


Blind deep survey of extragalactic fields, FIR FS Lines number counts and ISM in intermediate redshift Galaxies



FIRSPEX Deep GP Survey

Cover 3600sq degrees simultaneously in all four bands
Effective spatial resolution 2.4′ (telescope beams 0.3 -1.9′)
2 passes of the GP :full survey ~2 yrs



[CI]: 3.77×10^{-17} Wm^{-2} (0.02K), [CII]: 2.7×10^{-17} Wm^{-2} (0.18K)
[NII]: 2.7×10^{-17} Wm^{-2} (0.18K), [OI]: 4.3×10^{-17} Wm^{-2} (0.28K)

Probing different gas phases

Complex configuration
- Mixture of phases including HII regions
- Separated in velocity space

Velusamy et al. (2013)

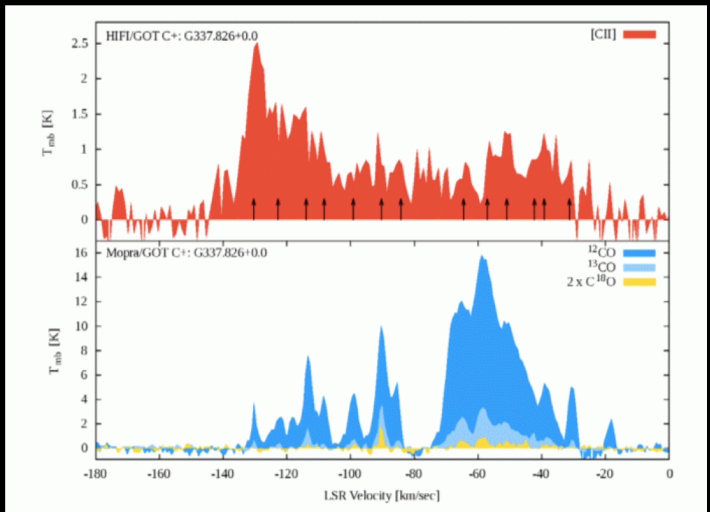
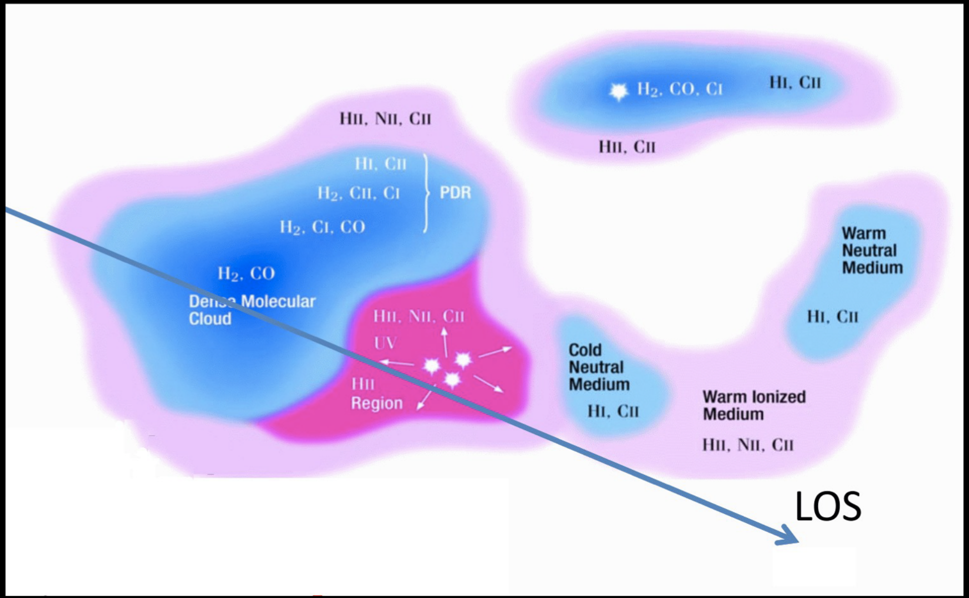


Fig. 1. [C II], ^{12}CO, ^{13}CO, and C^{18}O spectra towards the line-of-sight G337.826+0.0. The arrows indicate the [C II] components that have ^{13}CO counterparts.



[CII] from HII regions, CNM, PDRs
- [NII] from HII regions, little from WIM
- [OI] for hot dense gas
- [CI] for part of CO-dark gas

need all data at same velocity resolution

Pineda et al. (2014)

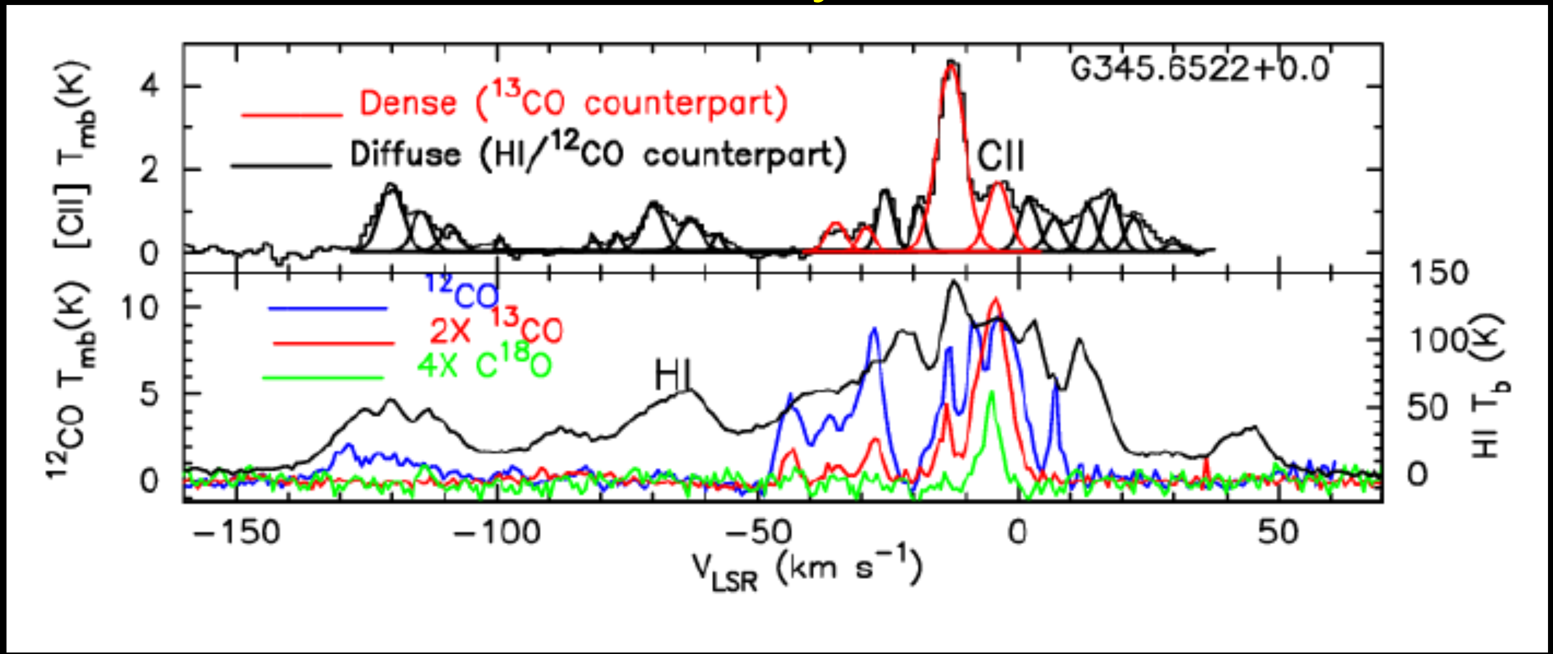
The FIRSPEX Galactic Plane Survey

CO-dark clouds: how much gas are we missing?

- CO-dark molecular clouds: large envelopes of atomic gas and a transition region where H2 molecules survive. Hydrogen in molecular form and Carbon is in C+ (not in CO)

→ **detectable in C+**

As much as 1/3 of the C in the Galaxy is located in CO-dark clouds

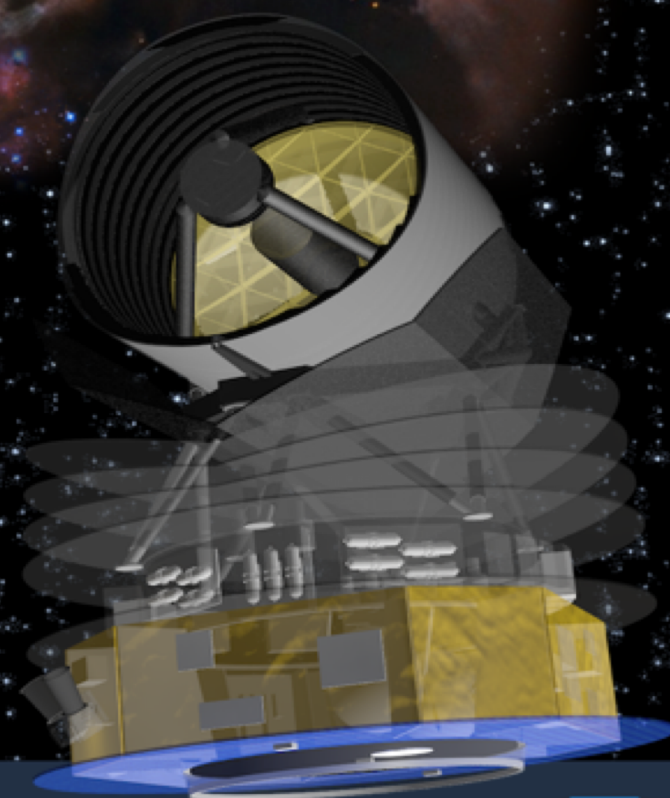


FIRSPEX DEEP GP Survey: the questions

- How do molecular clouds form?
- What fraction of the baryonic matter is in CO-dark clouds?
- What is the impact of radiative feedback on the ISM?

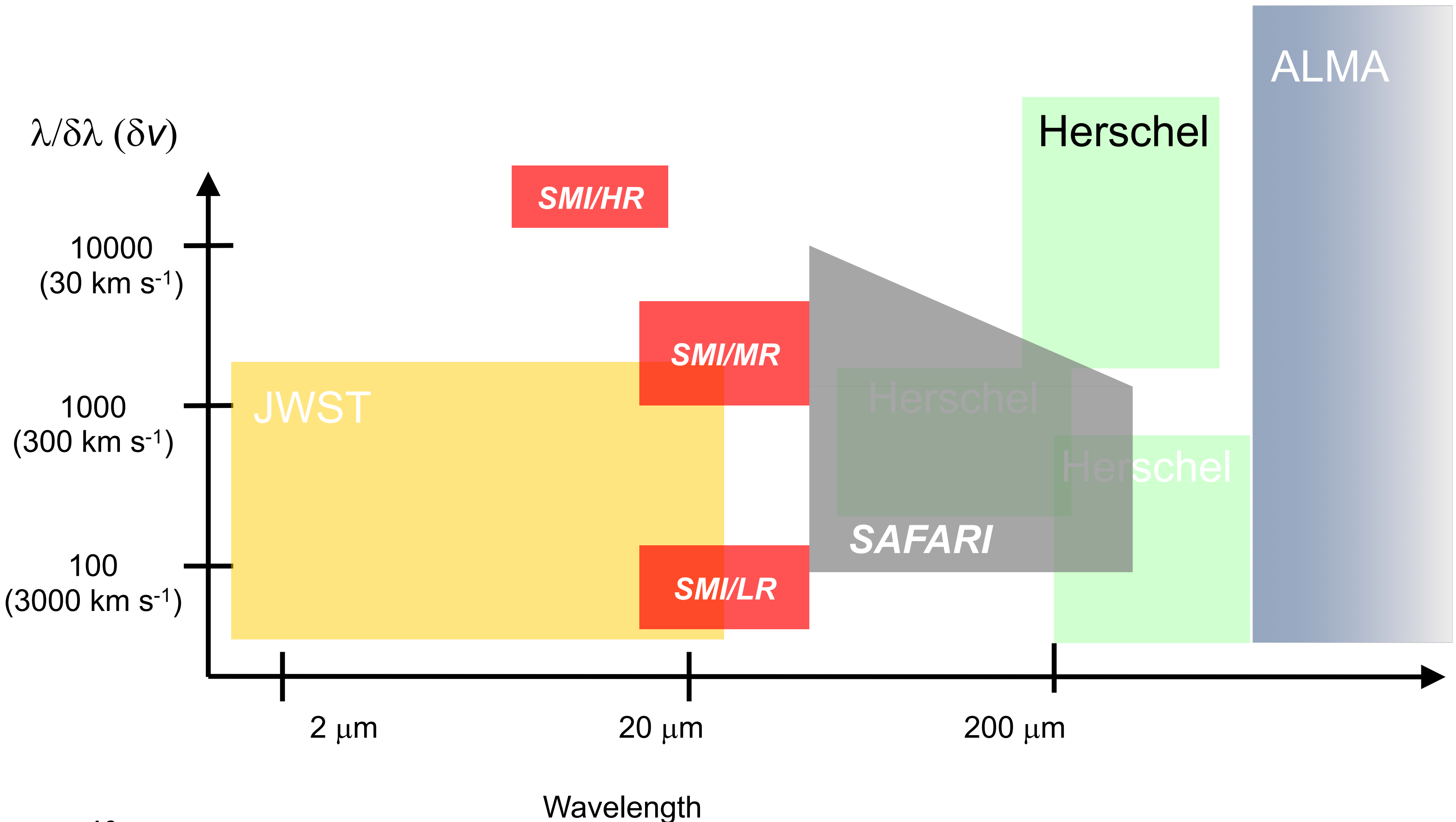
A joint ESA/JAXA Infrared Space Observatory SPICA

A 2.5m telescope (cooled to 8K)
MIR-Spectrometer/camera (SMI)17-36microns
SAFARI: 34-230 microns (TES), R~300
Martin Pupplet R~3,000-11,000
POL: imaging polarimeter 110,220,350 microns
Currently in Phase A study (ESA M5)



SRON

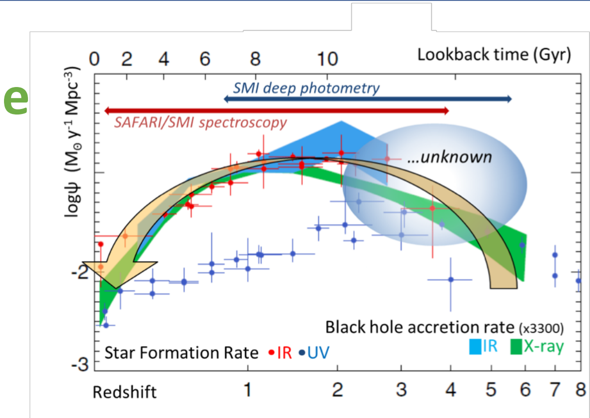
SPICA capabilities - spectral resolution



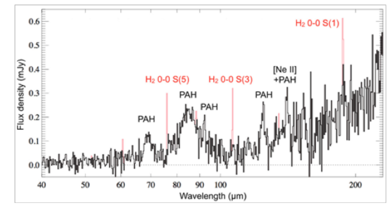
Credit: P. Roelfsema

Science Objectives – mission design drivers

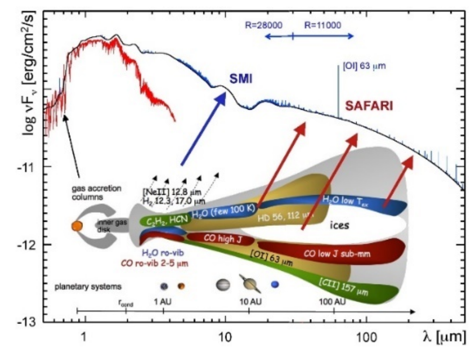
- What processes govern **star formation across cosmic time**
  - what starts it, controls it, and stops it?
  - What are the major physical processes in the most obscured regions of the universe?
  - How is this related to the enrichment of the universe with metals



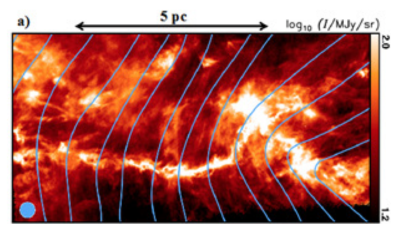
- What is the **origin** and composition of **the first dust**, how does this relate to present day dust processing?



- What is the thermal and chemical **history** of the **building blocks of planets**?



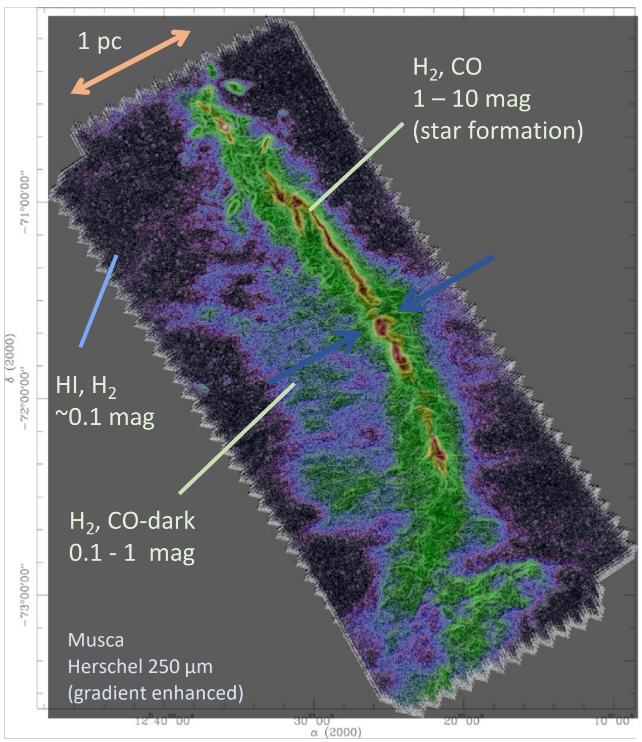
- What is the role of magnetic fields in dust filaments?



Credit: P. Roelfsema

Turbulence dissipation - Origin of filaments

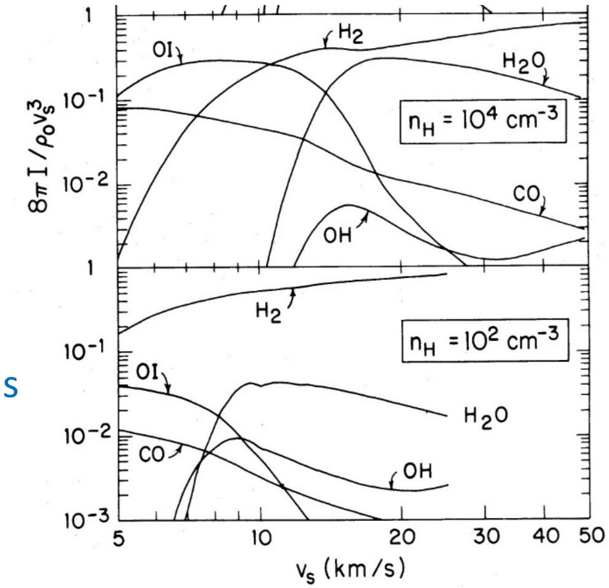
- Star Formation is a (very) dynamical process
- Turbulence partly dissipates through low-velocity shocks
  - Weak cooling lines (shocks): [OI] 63mm, high-J CO, H_2 lines.
  - Mixture of weak PDRs and shocks, initial conditions for astro-chemistry (gas, dust, ices): HD lines, dust/water ice features.



Credit: P. Roelfsema

From HI to dense SF filaments (~1 pc long flows)

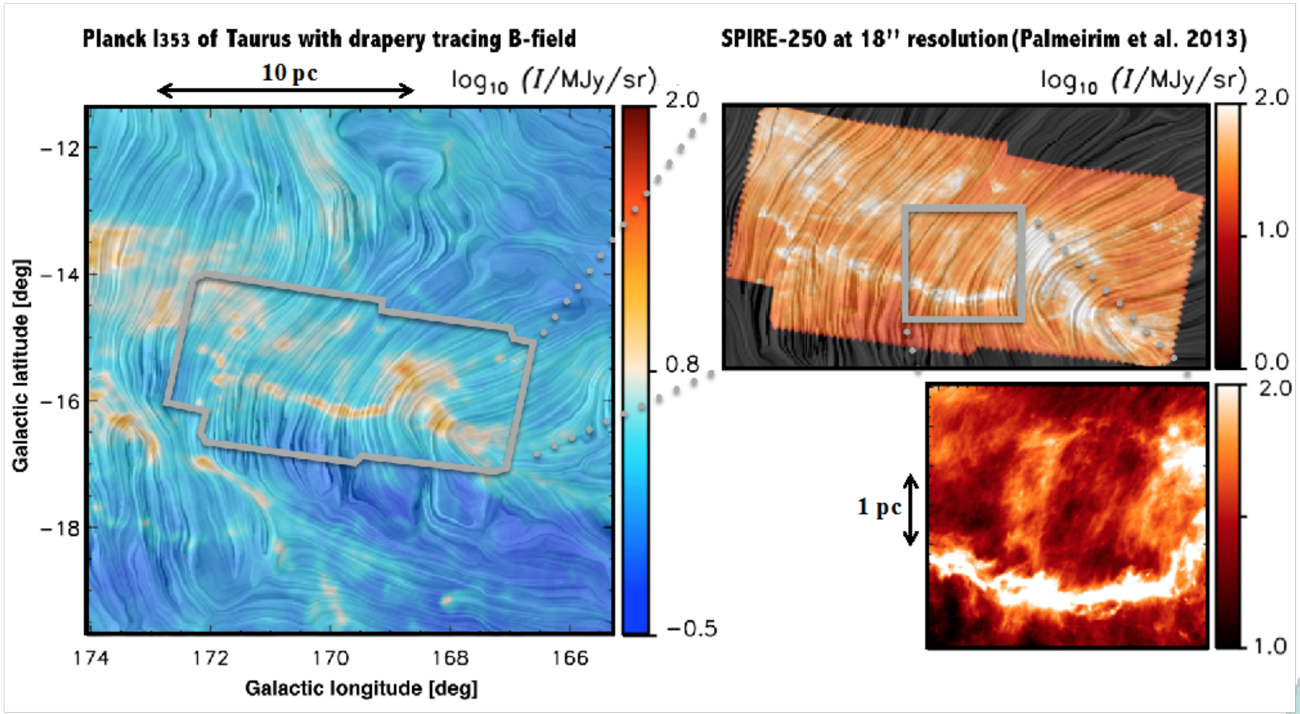
Draine et al. (1983) main gas coolants for magnetized shocks



Cooling lines from weak PDRs and cold turbulent ISM are too weak to be studied so far …

SPICA will directly measure gas cooling in the formation of clouds and SF filaments

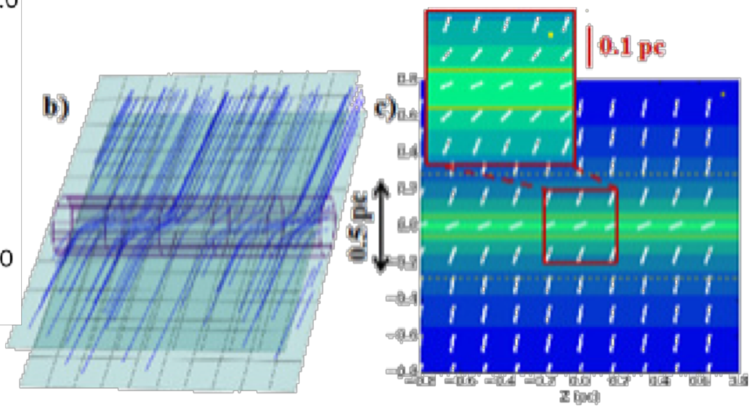
Magnetic fields – driver of star formation in ISM filaments?



2.7 deg ~ 3 pc

Example:
Taurus B211 filaments

Herschel 250 μm and PLANCK magnetic field



POL will probe the link between magnetic field, low-density filaments (striations) and dense star-forming filaments

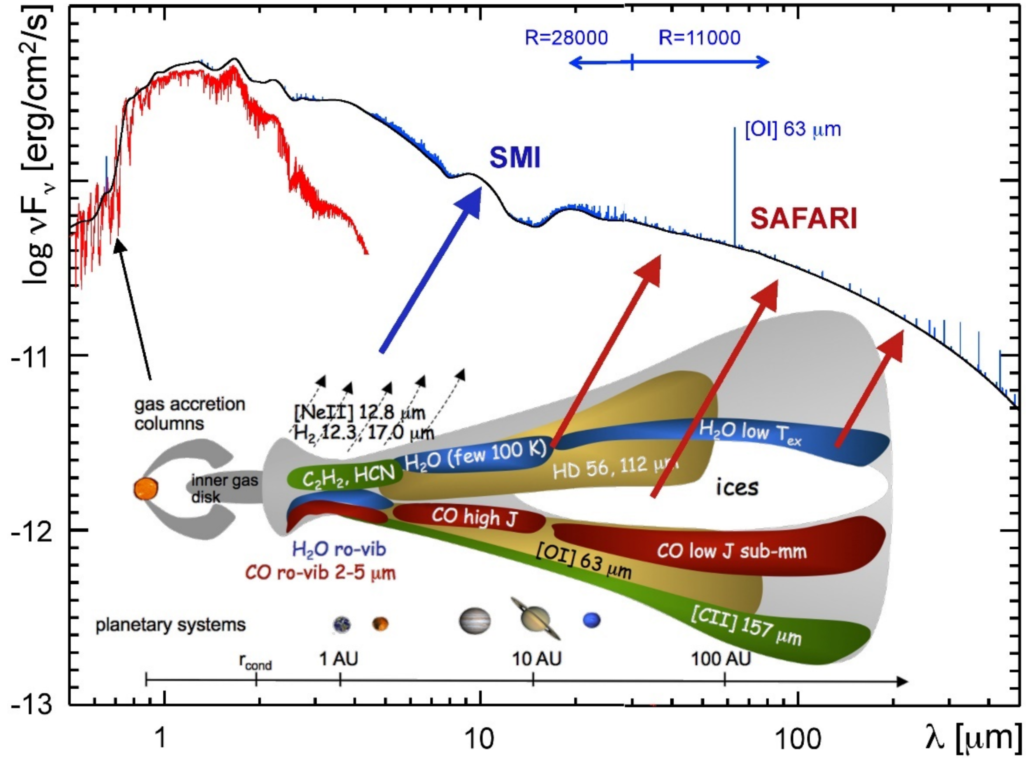
characteristic filament width of 0.1 pc observable out to d ~ 350 pc

not accessible to ALMA, neither to ground-based SCUBA2-Pol, NIKA2-Pol, neither to SOFIA, nor to balloon-borne Super BLAST-Pol

Talks by J.D. Soler and L. Fissel

Unique areas of planet formation to be studied with SPICA:

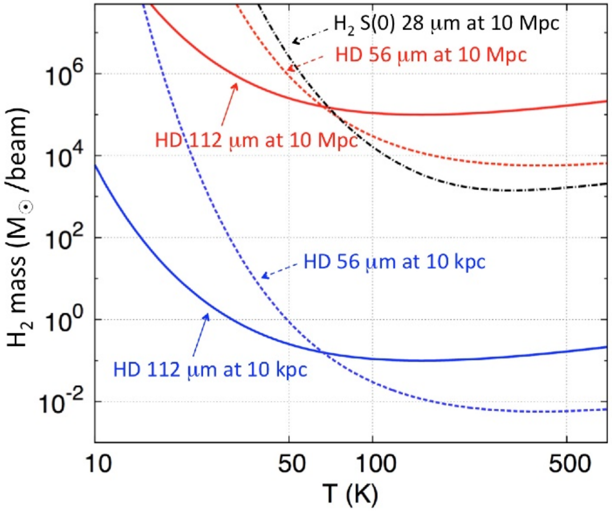
- The water trail → tracing the snow line
- From pristine dust to differentiated bodies
  → *making the link to the Solar System*
- The gas revolution:
  → measuring the reservoir in planet forming regions
- Gas dissipation and photo-evaporation
  → setting the clock for planet formation

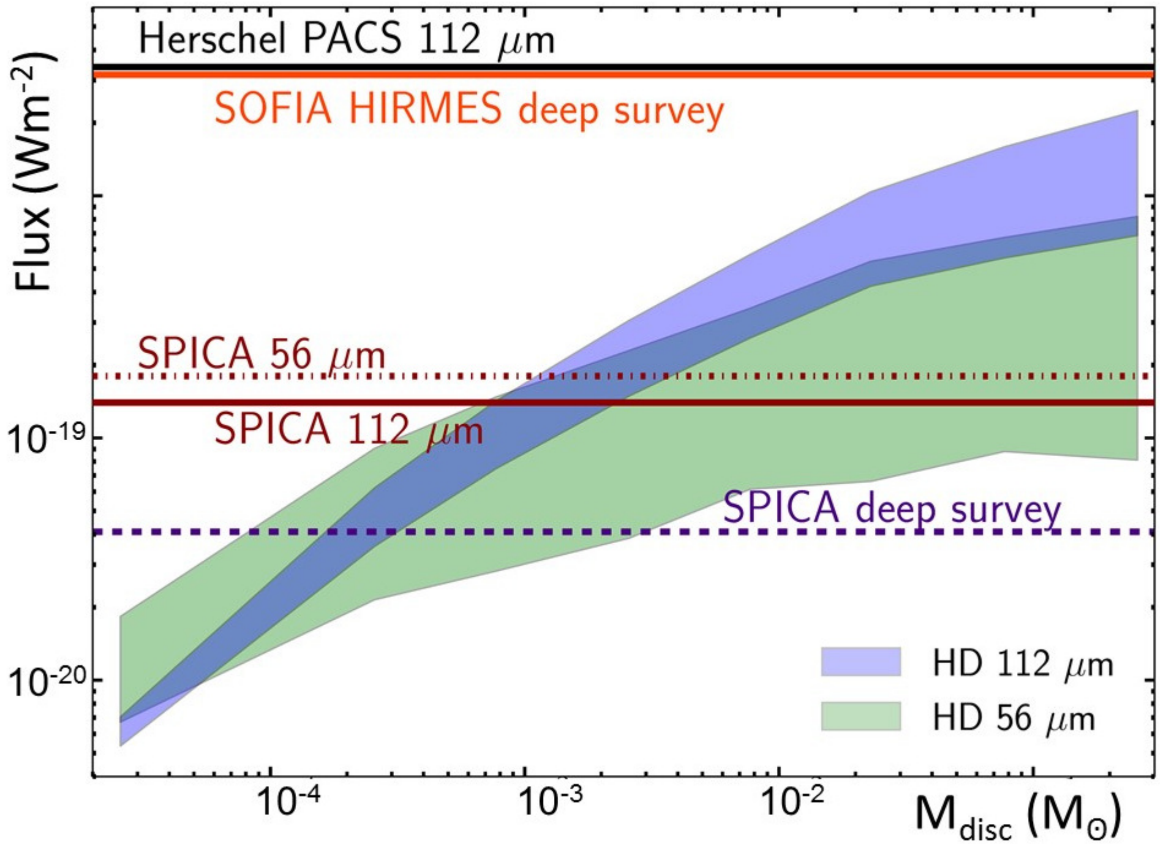


Credit: P. Roelfsema

HD – probing the mass of planetary disks

- HD 56/112 μm lines in the SAFARI bands
  - Direct tracer of gas mass in PPD's
  - Opens new domain of disk masses

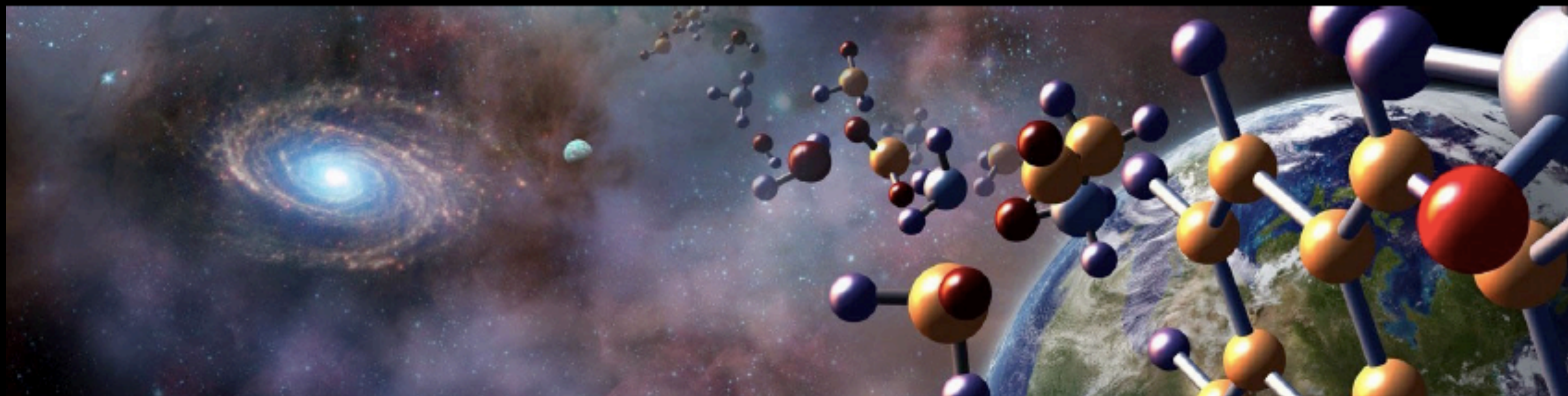




Trapman et.al. 2017

ORIGINS Space Telescope

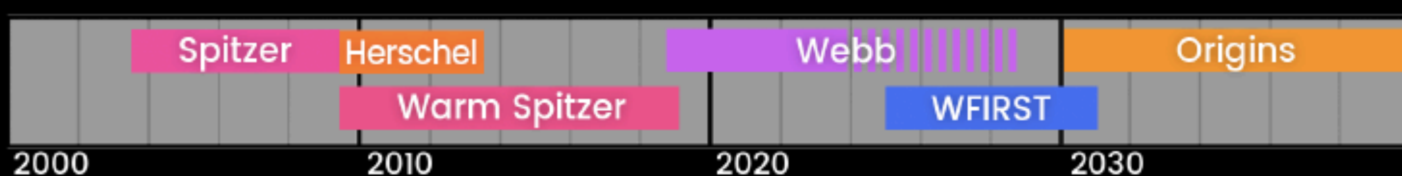
From the Rise of Metals to Water for Habitable Worlds



NASA Mission concept for 2020 Decadal review; launch 2030ish

6 µm – 1000 µm (ish), Large aperture 8-15 m

Study Chairs: Margaret Meixner & Asantha Cooray



UNIVERSITY OF OXFORD

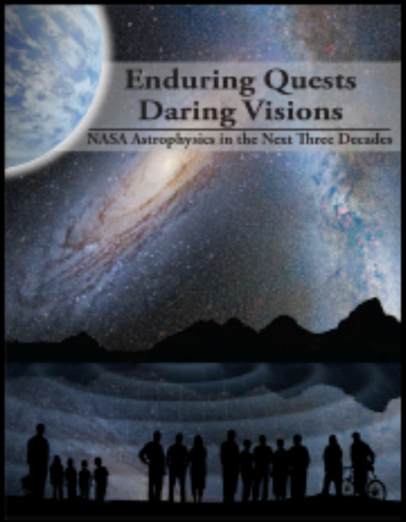
The Origins Space Telescope

ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

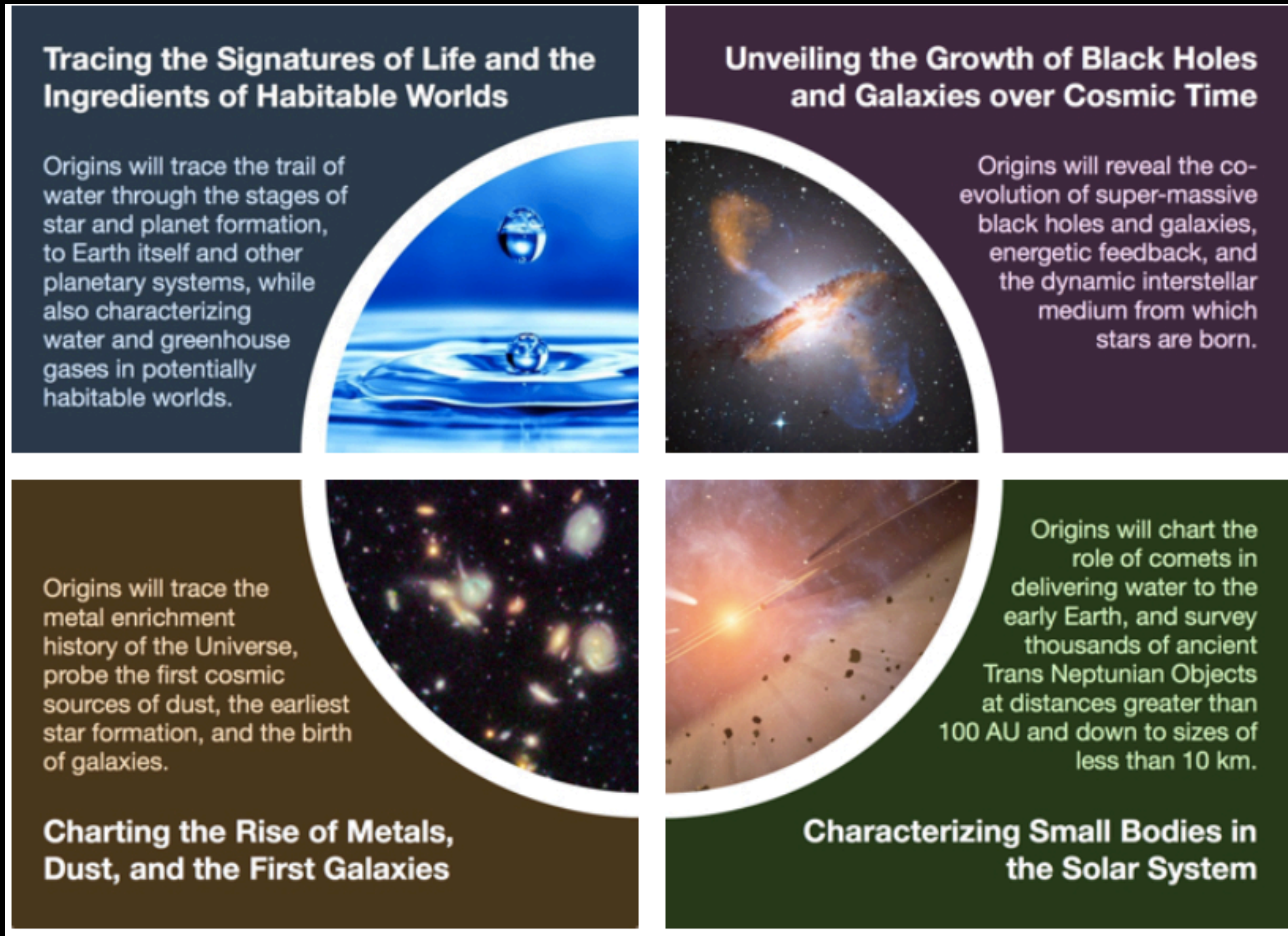
NASA flagship class mission concept for the 2020 Decadal review.

Comes from the NASA Astrophysics Roadmap.



- <6 µm – 600 µm (diffraction limit around 20-40 µm)
- 4.5-5K actively-cooled 8-13m aperture operating at L2
- large gain in sensitivity => new spectroscopic capabilities
- exoplanet study capabilities via a mid-IR coronagraph
- modular instrument suite with robotic serviceability at L1
- Mission aimed at mid 2030s: post JWST, concurrent with WFIRST, Athena, LISA, and 25m-35m ground-based optical/IR facilities.
- Science goals and measurement requirements in 2030+

Credit A. Cooray & M. Meixner


Tracing the Signatures of Life and the Ingredients of Habitable Worlds
Origins will trace the trail of water through the stages of star and planet formation, to Earth itself and other planetary systems, while also characterizing water and greenhouse gases in potentially habitable worlds.
Unveiling the Growth of Black Holes and Galaxies over Cosmic Time
Origins will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.
Origins will trace the metal enrichment history of the Universe, probe the first cosmic sources of dust, the earliest star formation, and the birth of galaxies.
Charting the Rise of Metals, Dust, and the First Galaxies
Origins will chart the role of comets in delivering water to the early Earth, and survey thousands of ancient Trans Neptunian Objects at distances greater than 100 AU and down to sizes of less than 10 km.
Characterizing Small Bodies in the Solar System

Science coverage will be broad: highlight some of the goals

- First Billion Years:
    - Protogalaxies
    - Galaxy evolution
- Galaxy and Blackhole Evolution
    - ISM probes for galaxies
    - Rise of metals
- Nearby Galaxies & Milky Way:
    - Polarization
    - Feedback in galaxies
    - Water transport
- Planetary systems: Formation & Exoplanets
    - Dust disks
    - Gas disks
    - Exoplanet atmospheres
- Solar system
    - Small body census
    - Planet IX
    - Isotopes and origin of Earth water

ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

NASA

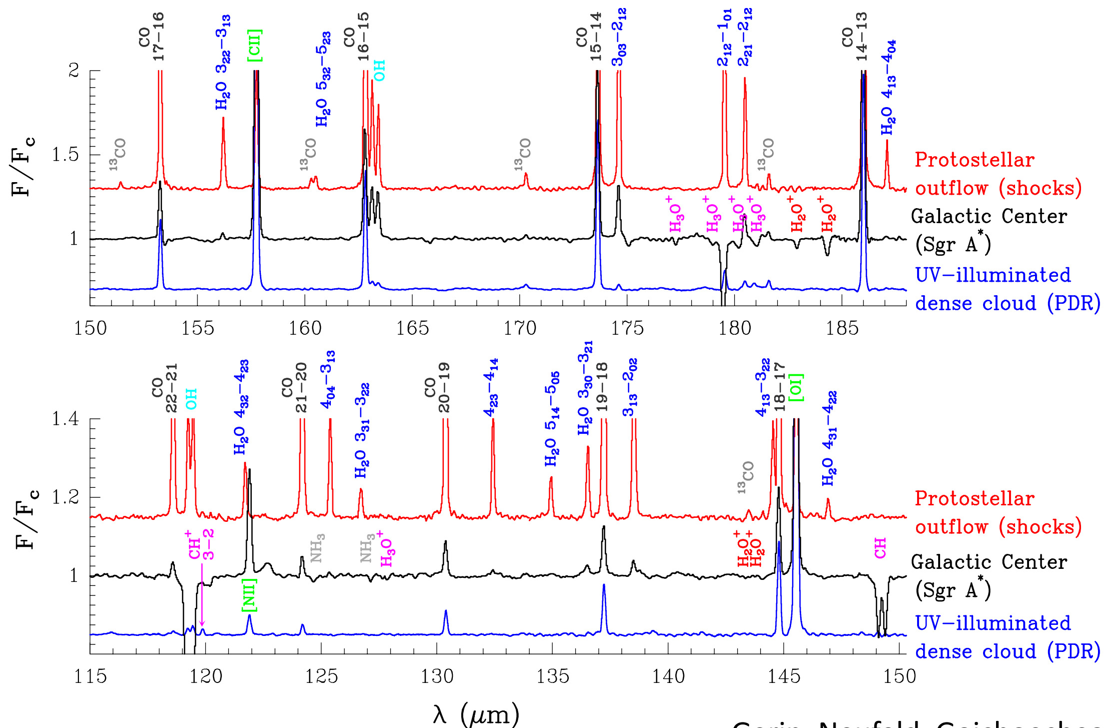
Instrument Specifications

Instrument	Wavelength Coverage	Spectral Resolving Power (λ/Δλ)	Number of spatial pixels or sky beams	Typical Required Sensitivity:	Other
Mid-Infrared coronagraph/ imager/IFU	<6 (~2?) to 40 μm	imager: R~10; IFU: R>3000	~10^7	photometric: 1 μJy @10 μm	coronagraph 10^{-7}-10^{-8} IWA=2λ/D
Imager + Polarimeter	35 to 600 μm (5-10 channels)	R~10	~500,000	1 μJy - 10 mJy (confusion limit)	polarimetry, spectral line filters
Low-Res Spectrometer	35 to 600 μm	low-res~500 high-res~10^4	100 per channel	10^{-21} W/m^2 (spectral line)	4-5 channels
High-Res Heterodyne Spectrometer	150 to 600 μm	~10^7	10 - 100	2 mK in 0.2 km/s @ 1 THz	polarized, background limited
Mid-Res Spectrometer	50 to 600 μm	low-res ~ 8x10^4 high-res~5x10^5	100	10^{-21} W/m^2 5 σ (spectral line)	photo-counting

Science Driver for OST-HERO

Massive Stars and Feedback

How do massive stars form?
Scaled up version of low mass SF (Zinnecker & Yorke)
OR
Competitive accretion (Tan & McKee)



Gerin, Neufeld, Goichoechea 2016

FIR coolants (CO, H_2O, OH crucial
In tracing proto-stellar activity

Sample size is crucial as is high spectral resolution
Spatial resolution is necessary to study individual protostars: ~1" angular-resolution
1"≈500AU at the distance to Orion,
1"≈5,000 AU at ~5 kpc typical distance of high-mass star-forming regions in the Milky Way

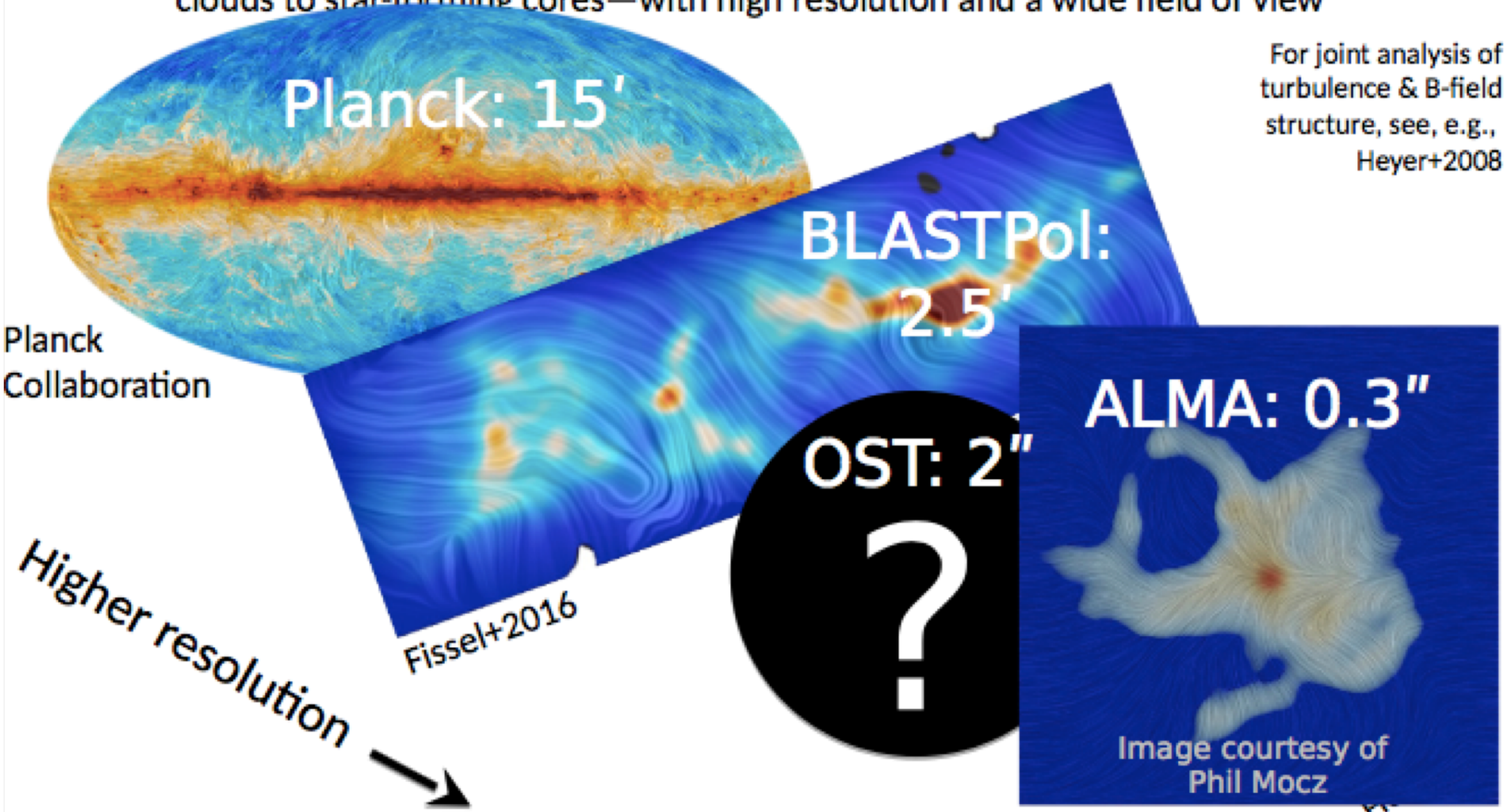
Science driver for OST-FIP

ORIGINS Space Telescope

Compelling science

Magnetic fields and turbulence

The Origins Space Telescope will characterize magnetic fields and turbulence from molecular clouds to star-forming cores—with high resolution and a wide field of view



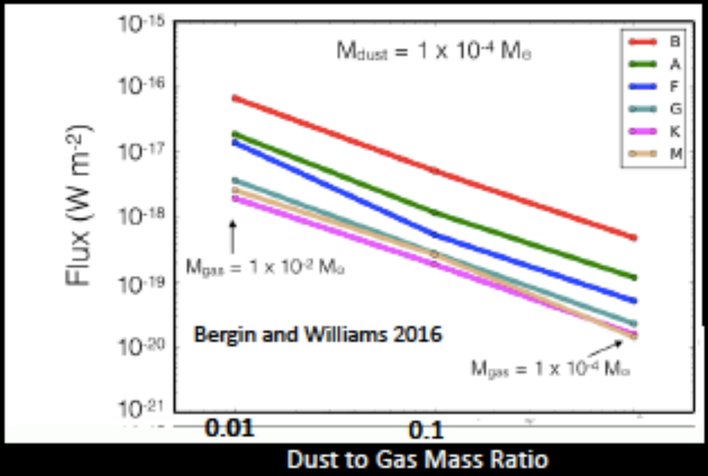
ORIGINS Space Telescope

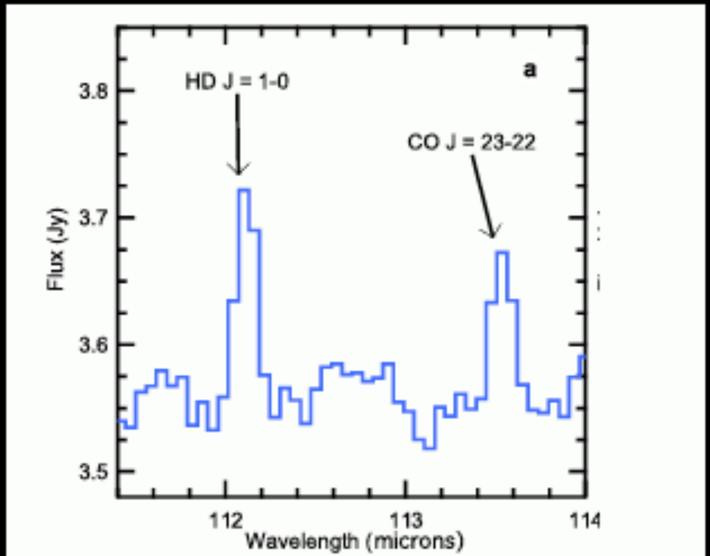
Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

NASA

Probing the total gas content during the time of planet formation

What are the timescales of gas/ice giant and super-Earth formation? What is the total gas content to unlock the ability to follow the implantation of C, H, O, N into pre-planetary materials?. **Use HD to measure the gas mass in disks down to cool stars with a gas/dust mass ratio of unity.**





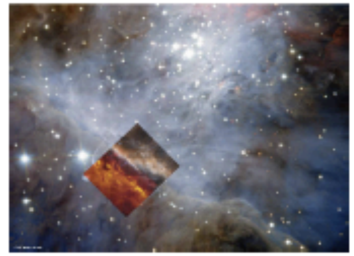
Herschel Detection of HD J = 1-0 towards TW Hya providing the first (semi)direct contraints on the gas mass (Bergin et al. 2013)

Science Motivation 1

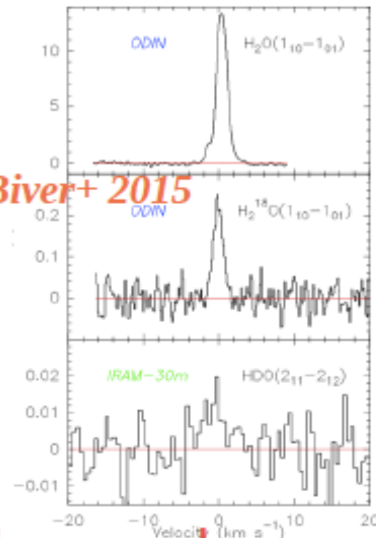
4, Tracing the signatures of life and the ingredients of habitable worlds : water content from ISM
to protoplanetary disks

7, Revealing the interplay between stars, black holes, and interstellar matter over cosmic :Trace feedback through radiation, shocks & cosmic rays

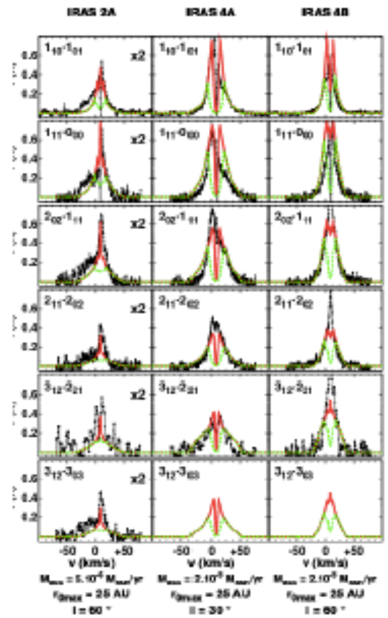
29, Tracing the signatures of life and the ingredients of habitable worlds:
distribution of D/H values in outer Solar system comet



Goicoechea+ 2016



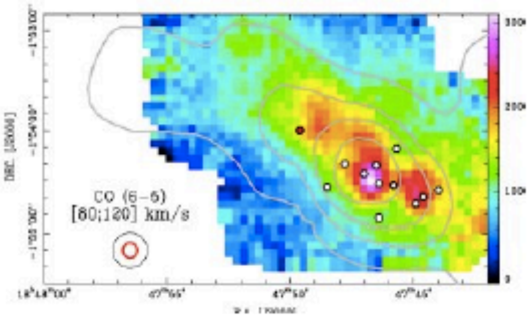
Biver+ 2015

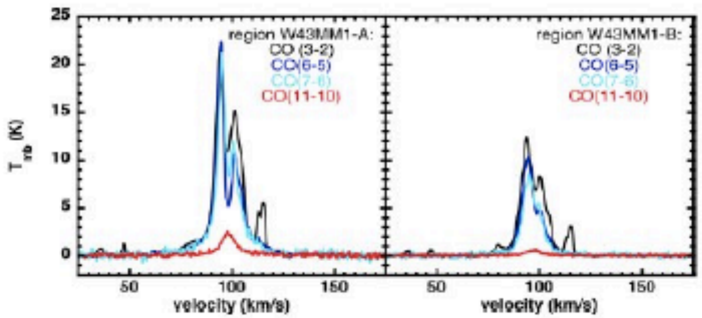


Yvart+ 2015

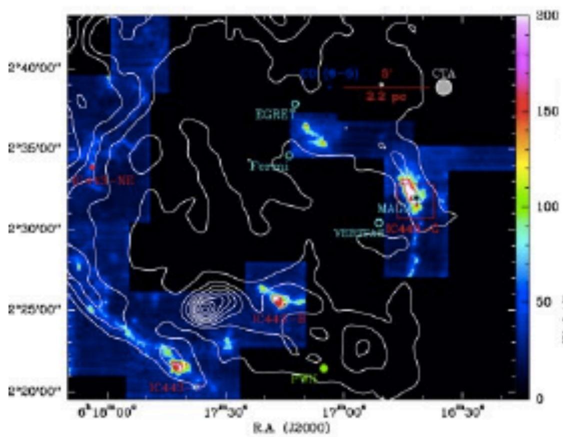
Analysis of spectral lines with complex profiles require **high spectral resolution** (R ~ 10^5 to 10^7, dv ~ 0.05 to 3 km/s) → *Heterodyne Instrument*

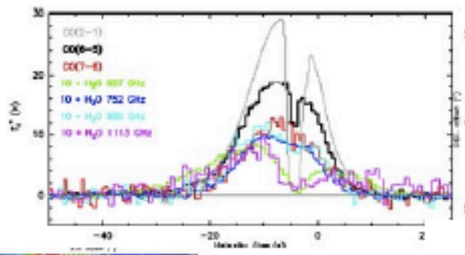
From slow shocks to fast shocks:

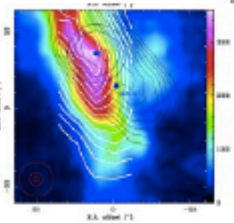




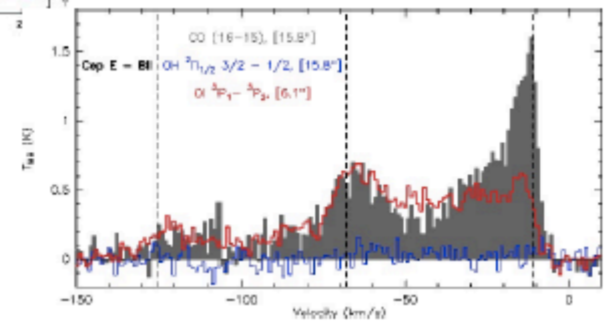
W43 : formation of GMC in colliding flows, slow shocks and enhanced star formation. Extended CO(11-0) emission ! (Louvet, Gusdorf, Motte +)



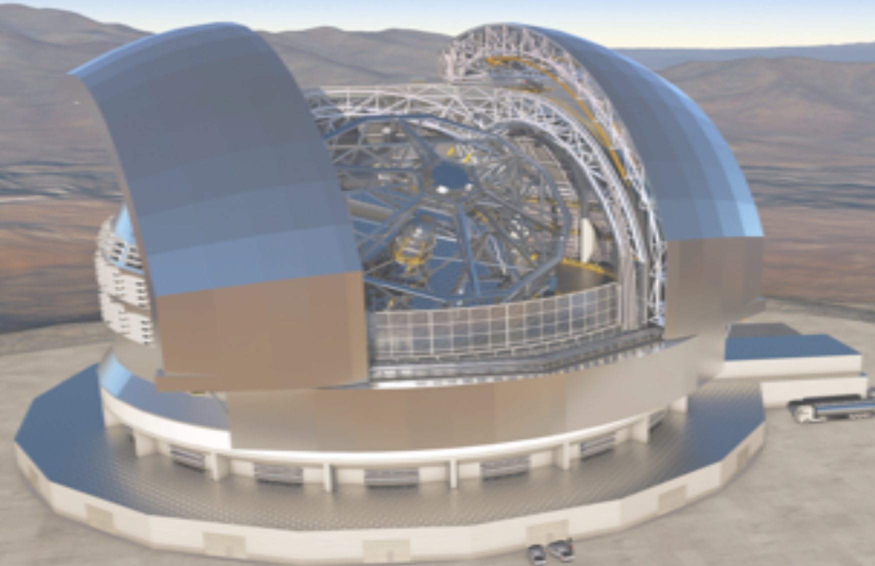


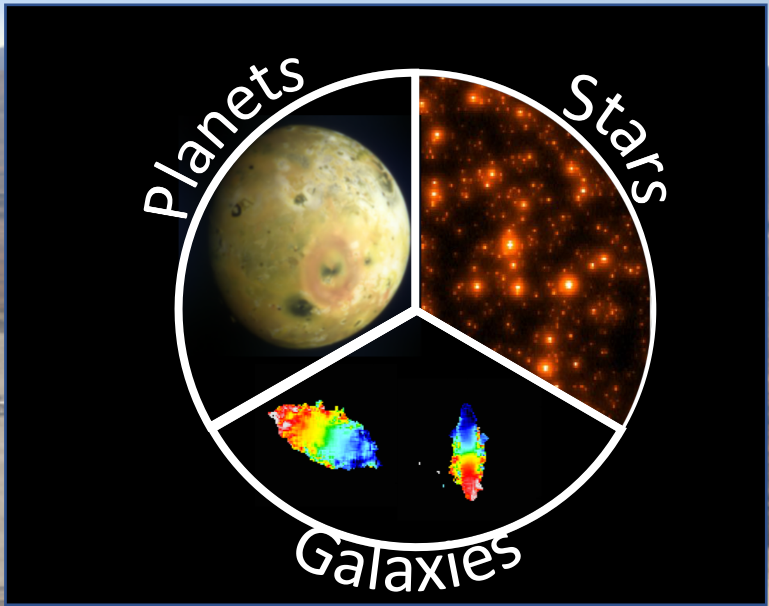


High velocity shocks in IC443 and CepE jet. Gusdorf+



HARMONI – the first light ELT spectrograph





First light work-horse spectrograph
Due in 2024

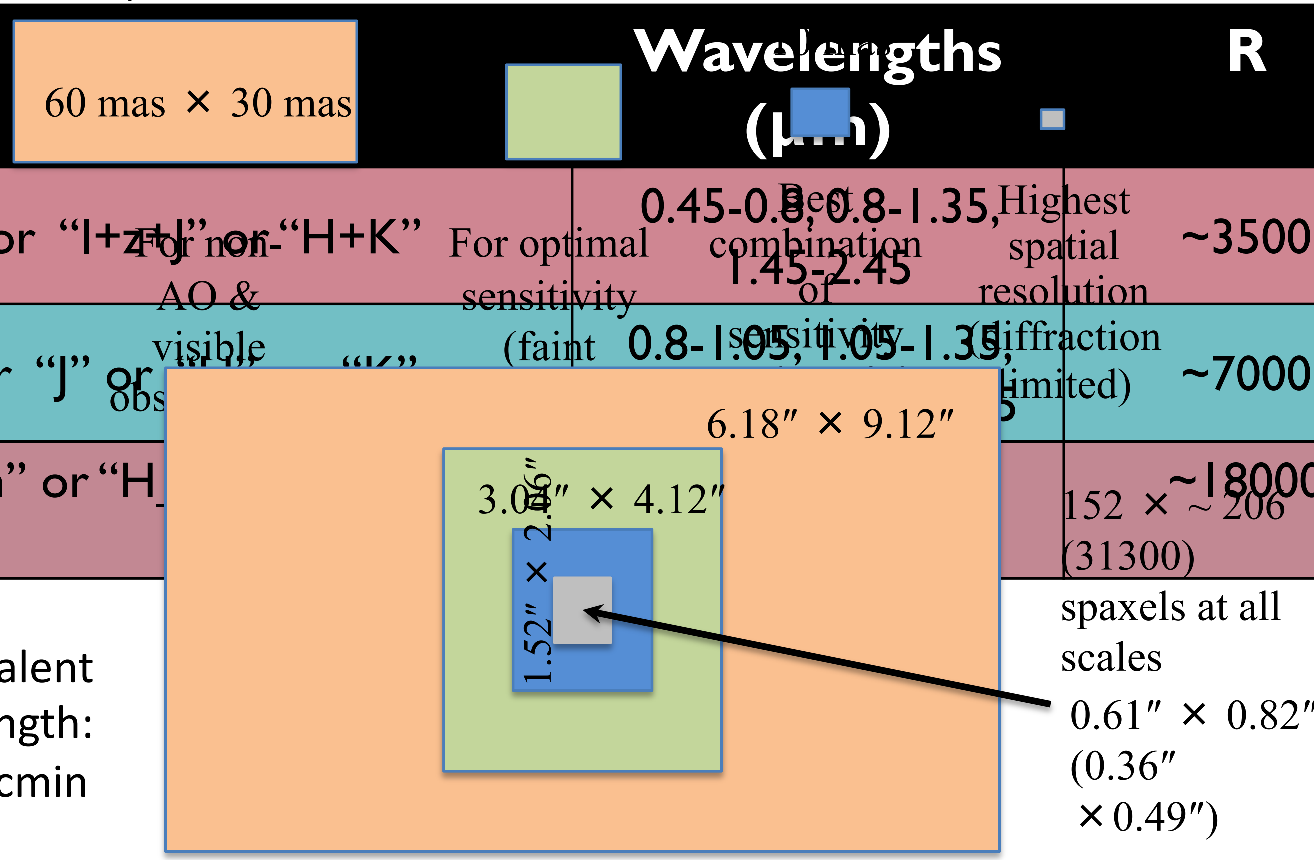
Credit: N. Thatte

ESO
Durham University
UNIVERSITY OF OXFORD
RAL Space
ONERA
CSIC
UK Astronomy Technology Centre
CRAL
LAM
IPAG
irap

HARMONI: workhorse spectrograph for the ELT

HARMONI spectral setup

	Wavelengths (μm)	R
"V+R" or "I+z+J" or "H+K"	0.45-0.8; 0.8-1.35, 1.45-2.45	~3500
"I+z" or "J" or "H" or "K"	0.8-1.05, 1.05-1.35, …5	~7000
"Z" or "J_high" or "H_…		~18000



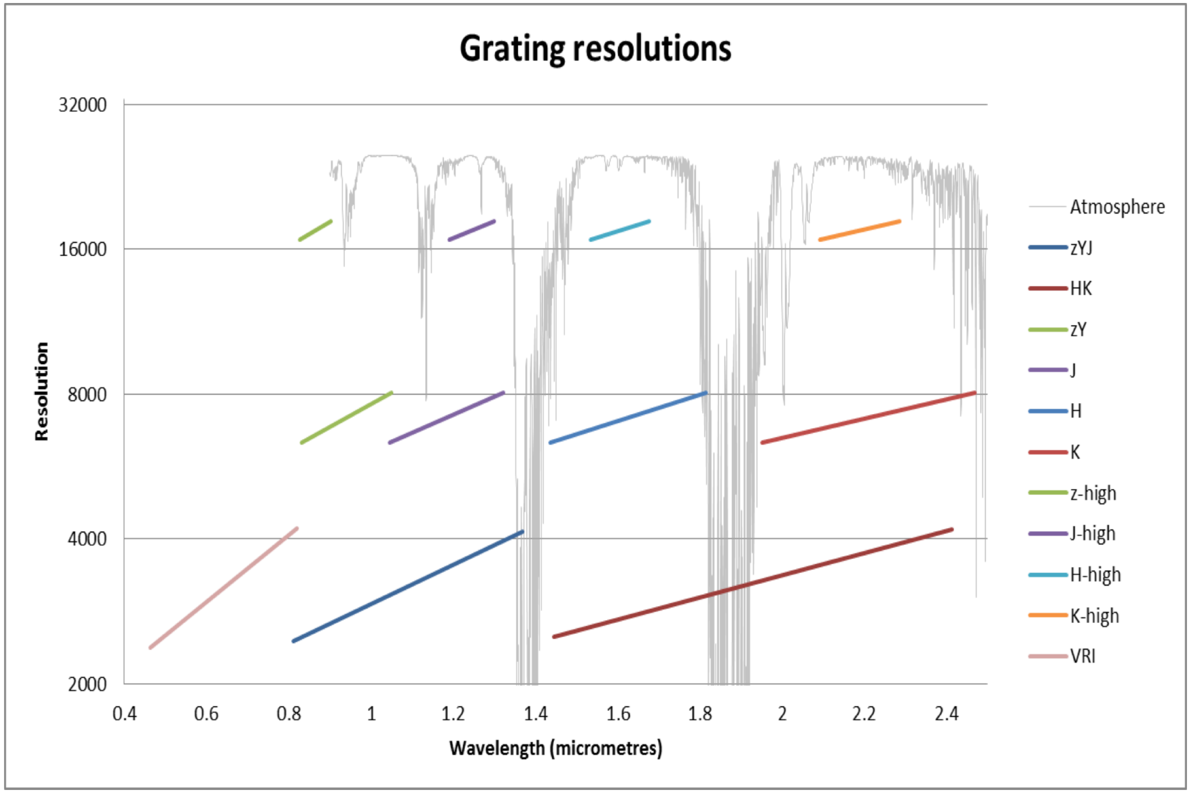
Equivalent slit length: 16 arcmin

or

3.2 metres in ELT focal plane

HARMONI: Spectral resolution

Name	R	λ_{min}	λ_{max}
VIS	3300	0.463	0.820
zYJ	3300	0.810	1.370
HK	3300	1.450	2.450
zY	7200	0.830	1.050
J	7200	1.046	1.323
H	7200	1.435	1.815
K	7200	1.951	2.469
z-high	17500	0.827	0.903
J-high	17500	1.190	1.300
H-high	17500	1.534	1.676
K-high	17500	2.093	2.287

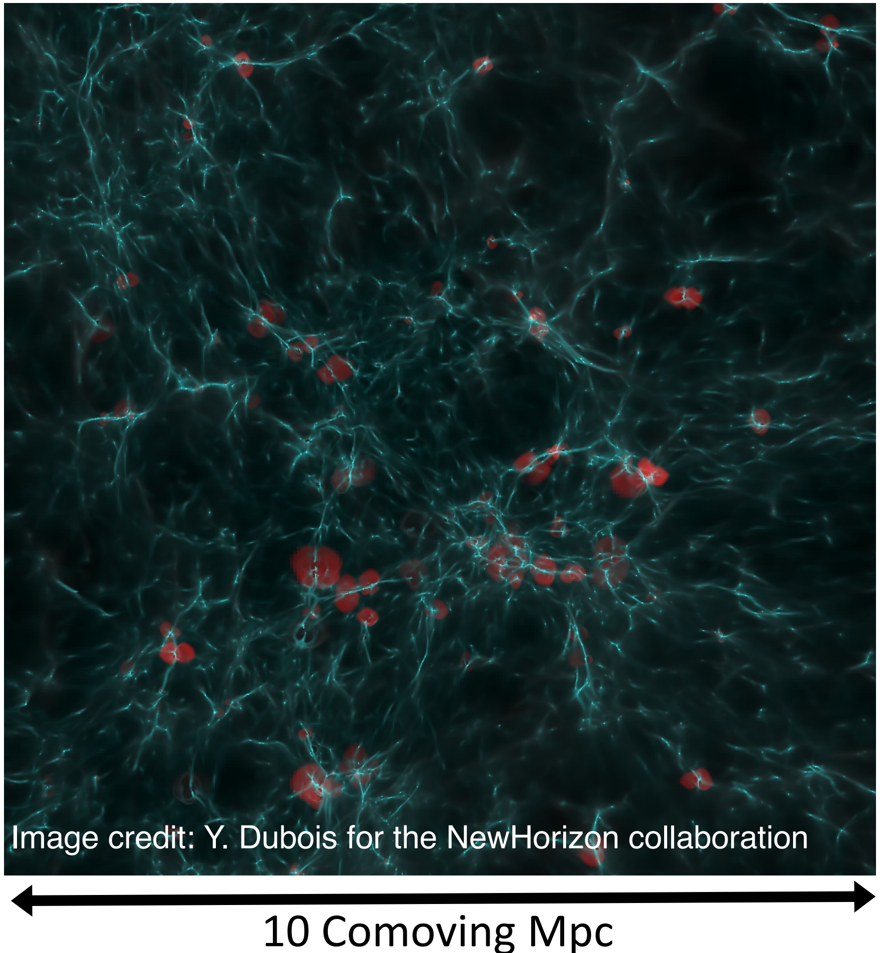


- 10 near-IR gratings + 1 VIS grating
- Not simultaneous, not 'tunable'

Observing Pop III stars with ELT-HARMONI

Simulation Suite: NewHorizon

- Adaptive Mesh Refinement (AMR) hydrodynamical code RAMSES.
- Mass resolution =10^6 M⊙ (DM) and 10^4 M⊙ (stellar). Highest spatial resolution of 40pc
- Includes: UV background heating (z<10), metal-dependant
- gas cooling to 0.1K and AGN
- SN feedback uses the Kimm et al., (2015) model
- Star formation based on Federrath & Klessen, (2012)
- Simulations covers 10<z<0.7 after >40million CPU hours



Galaxy from NewHorizon selected for low metallicity and >50% stellar mass have ages <2Myrs (i.e. should be visible Pop.III stars)

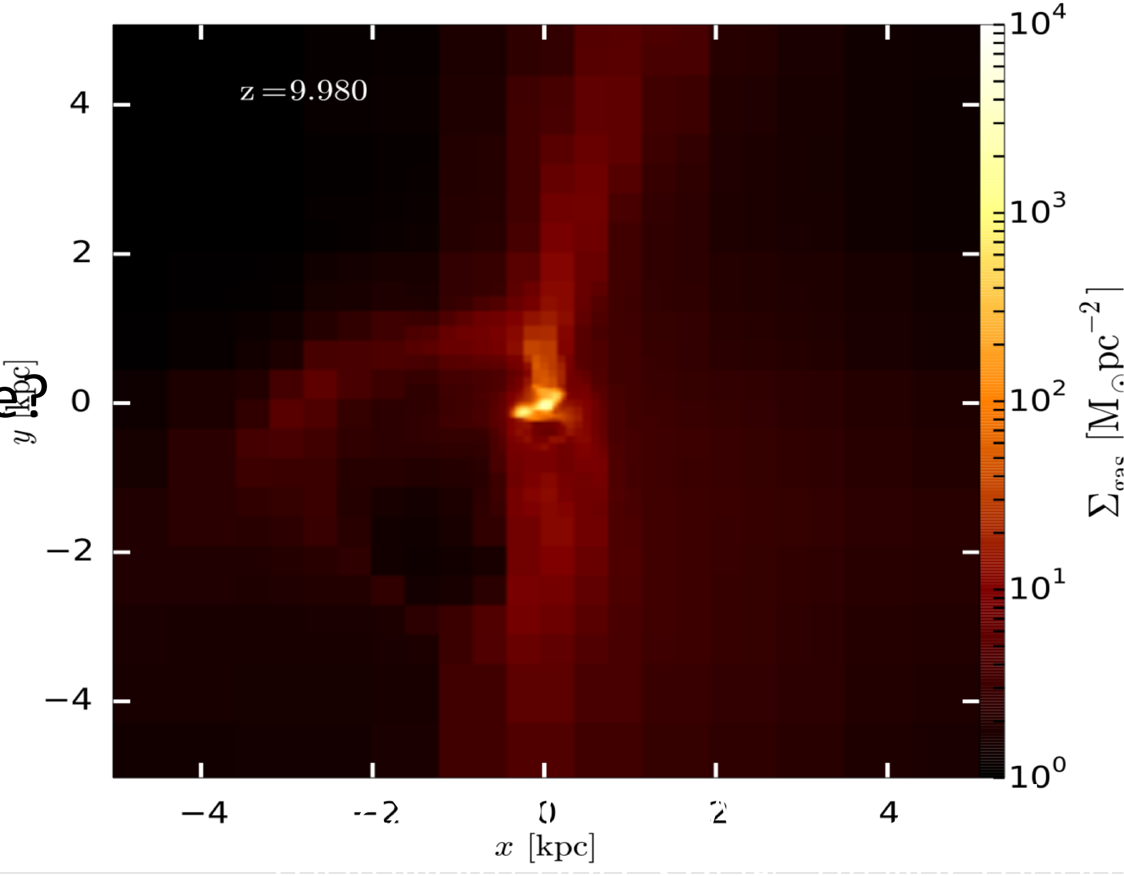
credit: Kearn Grisdale

Observing PopIII stars with ELT-HARMONI

Results of the Simulations

- HARMONI likely to be able to observe and resolve spectra from Pop. III stars.
- What would these spectra look like?

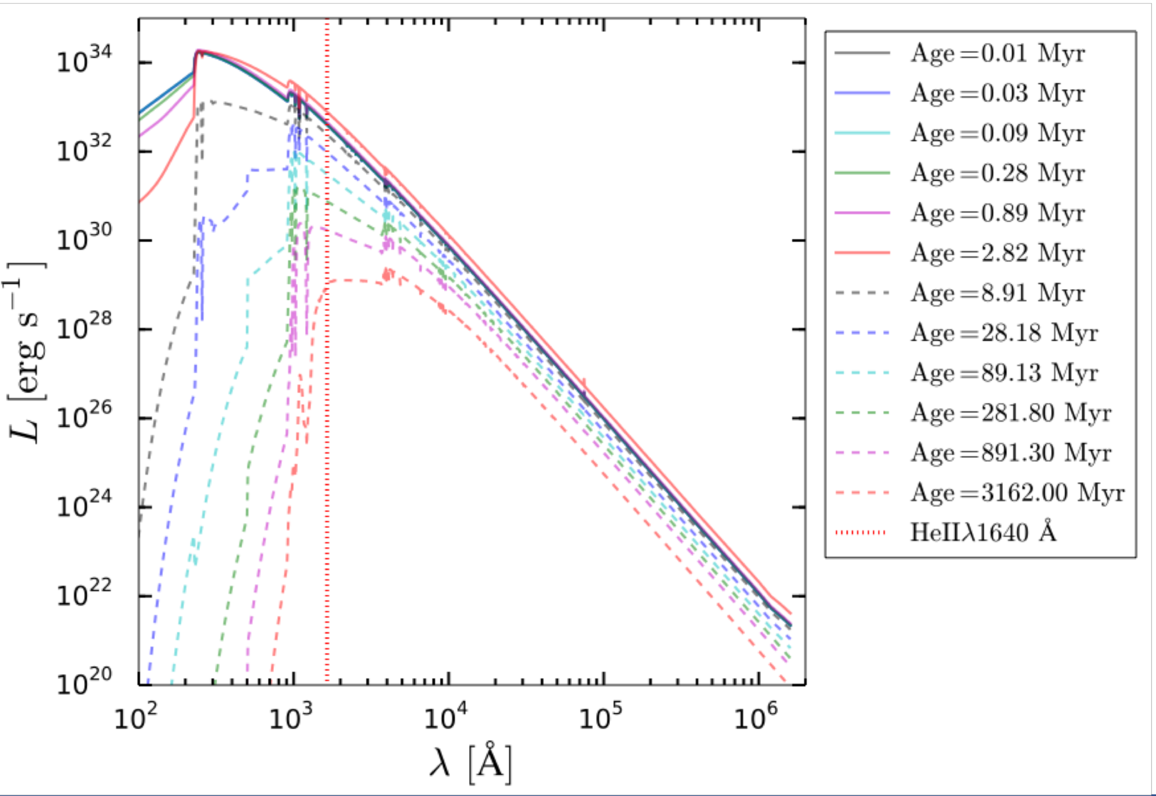
- Modelling spectra by combining NewHorizon simulations, CLOUDY, Stellar SED models and HSIM
- Primary focus on the He II 1640 Å line

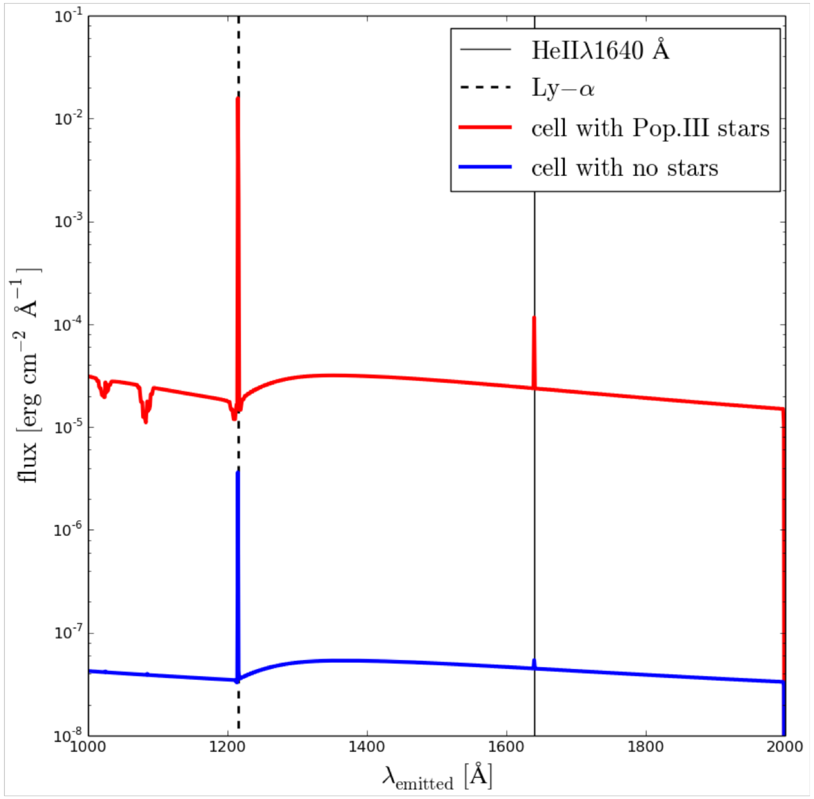


credit: Kearn Grisdale

Observing Pop III stars with ELT-HARMONI

- Use of the Yggdrasil Stellar SED models (Zackrisson et al., (2011) for Pop.III stars
- Assumes a Kroupa IMF for each star particle
- Other IMFs available for testing.
- SED at multiple stages in stellar life cycle





K. Grisdale et al. in prep

Summary

A number of missions are under development or study
To be launched in the next 5- 10 years

- Focus on ISM phases / MS feedback : high spectral resolution studies
- Zoom in on magnetic fields matching the resolution of existing dust map
- Early phases of PPDs – link to planet formation
- Emphasis on MIR/FIR lines → shocks/ chemistry / energetics

From the ground: ELT spatial resolution comparable to ALMA
Resolved stellar pops, Pop III Stars

Massive Stars:
The future is bright

Thank you!