Cosmic Origins Program Analysis Group: Status Report

Christopher Martin, Chair
COPAG Executive Committee

Outline

1. COPAG composition and activities
2. Science Goals
3. Mission/Technology Requirements
4. Burning Issues

PhysPAG Community Meeting August 13-14, 2012

1. COPAG Composition and Activities

COPAG Executive Committee

Chris Martin
Caltech (Chair)

Ken Sembach
StScI

Julianne Dalcanton
UWash

Paul Goldsmith
JPL

Chuck Lillie

Jon Gardner
GSFC

Lynne Hillenbrand
Caltech

James Lowenthal
Smith College

Paul Scowen
ASU

David Leisawitz
GSFC

2012 Tasks/SAGs

- SAG1: Science Goals, Objectives, Requirements for Cosmic Origins missions. Where are science thresholds and how do they link with Probe vs. Flagship class and aperture size?
- SAG2: Determine technology focus areas for a monolithic 4m Aperture UV/Optical/NIR mission with Internal Coronograph for Exoplanet Imaging
- SAG3: Determine technology focus areas for a segmented 8 m Aperture UV/Optical/NIR mission with External Occulter for Exoplanet Imaging
- SAG4: Determine technology focus areas for future Far IR Instruments
- SAG5: What is the scientific case for a set of linked probes and corresponding technology requirements?

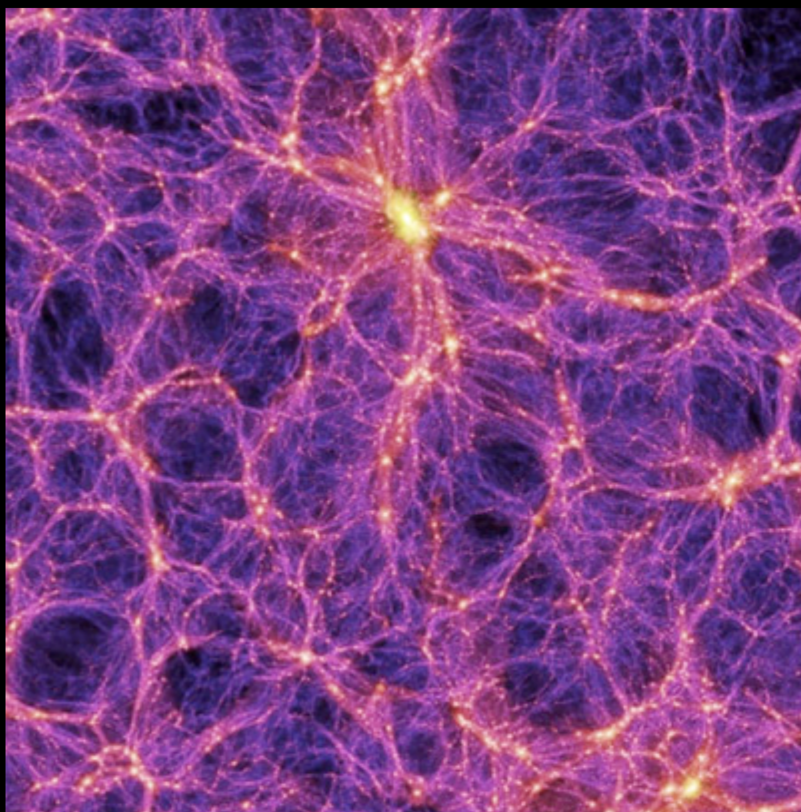
COPAG Activities 2011- 2012

- Draft Technology Assessment → ApS (Oct 19, 2011)
- Winter community workshop – Jan 8, 2012 – AAS Austin
- Attending PhysPAG meeting DC Aug 14, 2012
- Supporting NASA Cosmic Origins Program Office Science RFI Process
- Workshop at StScI 21 Sept 2012: UVO RFI, Cosmic Origins Science Objectives, Probes

2. Developing a Single, Coherent Science Story

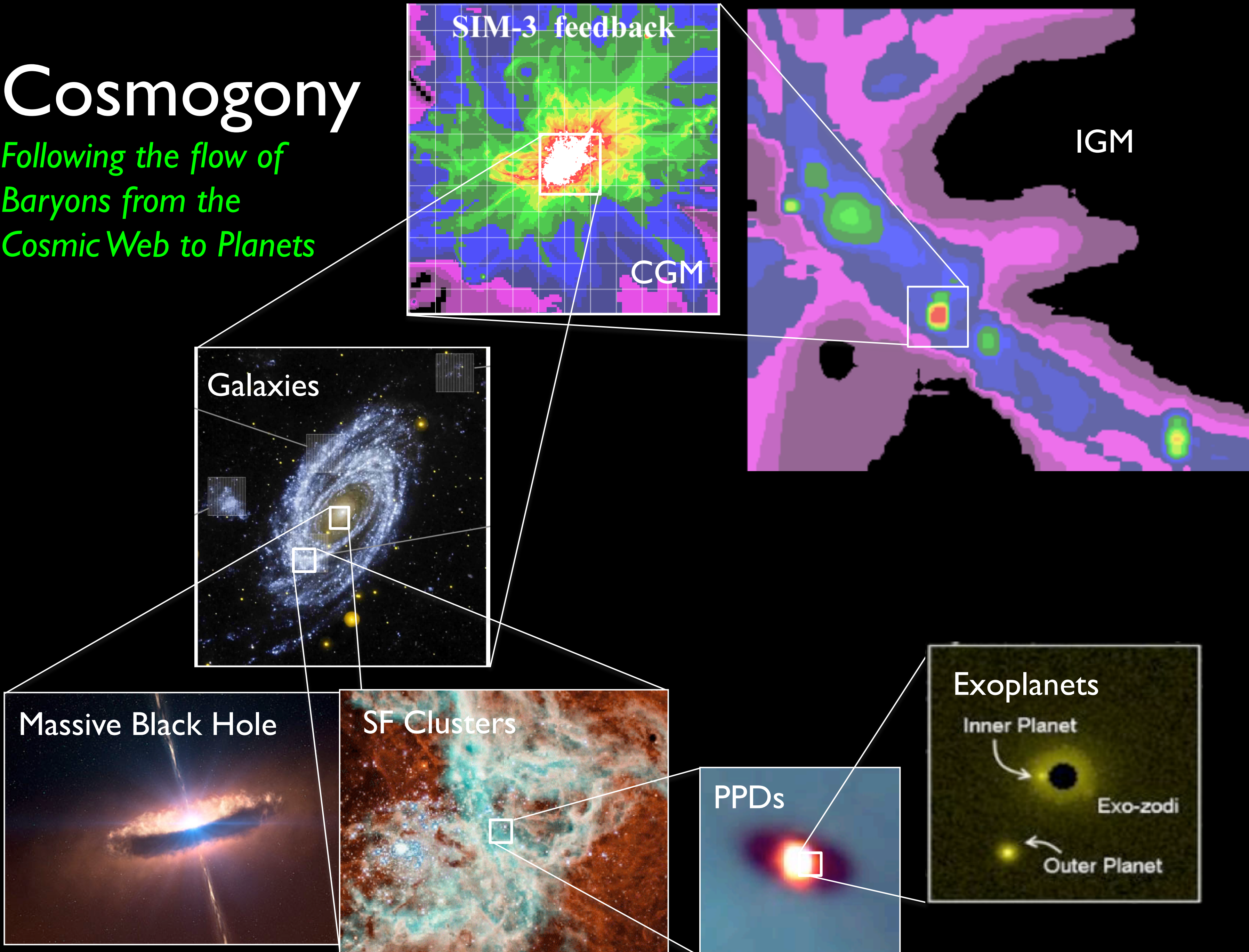
Cosmogony

Following the flow of matter from the Cosmic Web to Planets



Cosmogony

Following the flow of Baryons from the Cosmic Web to Planets



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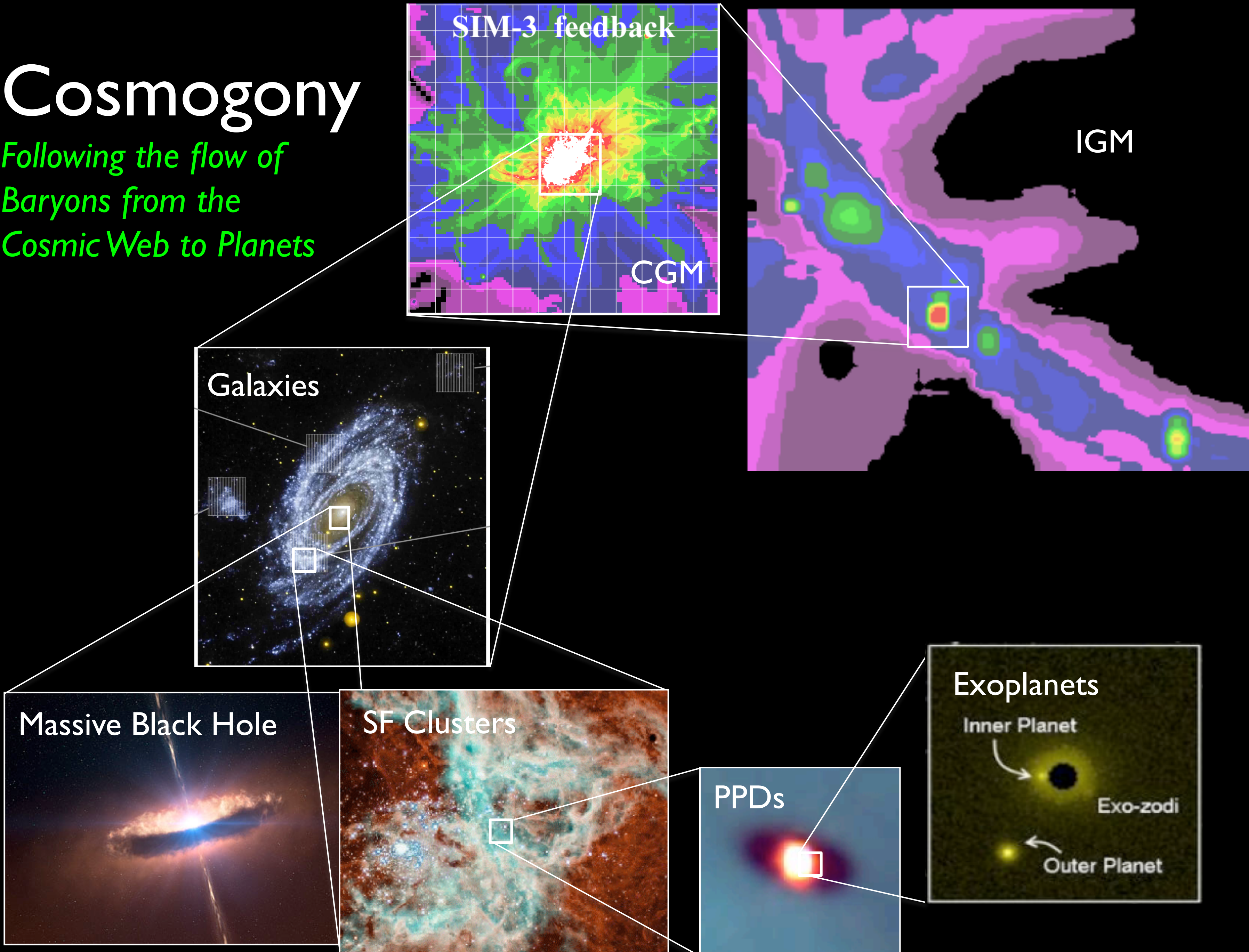

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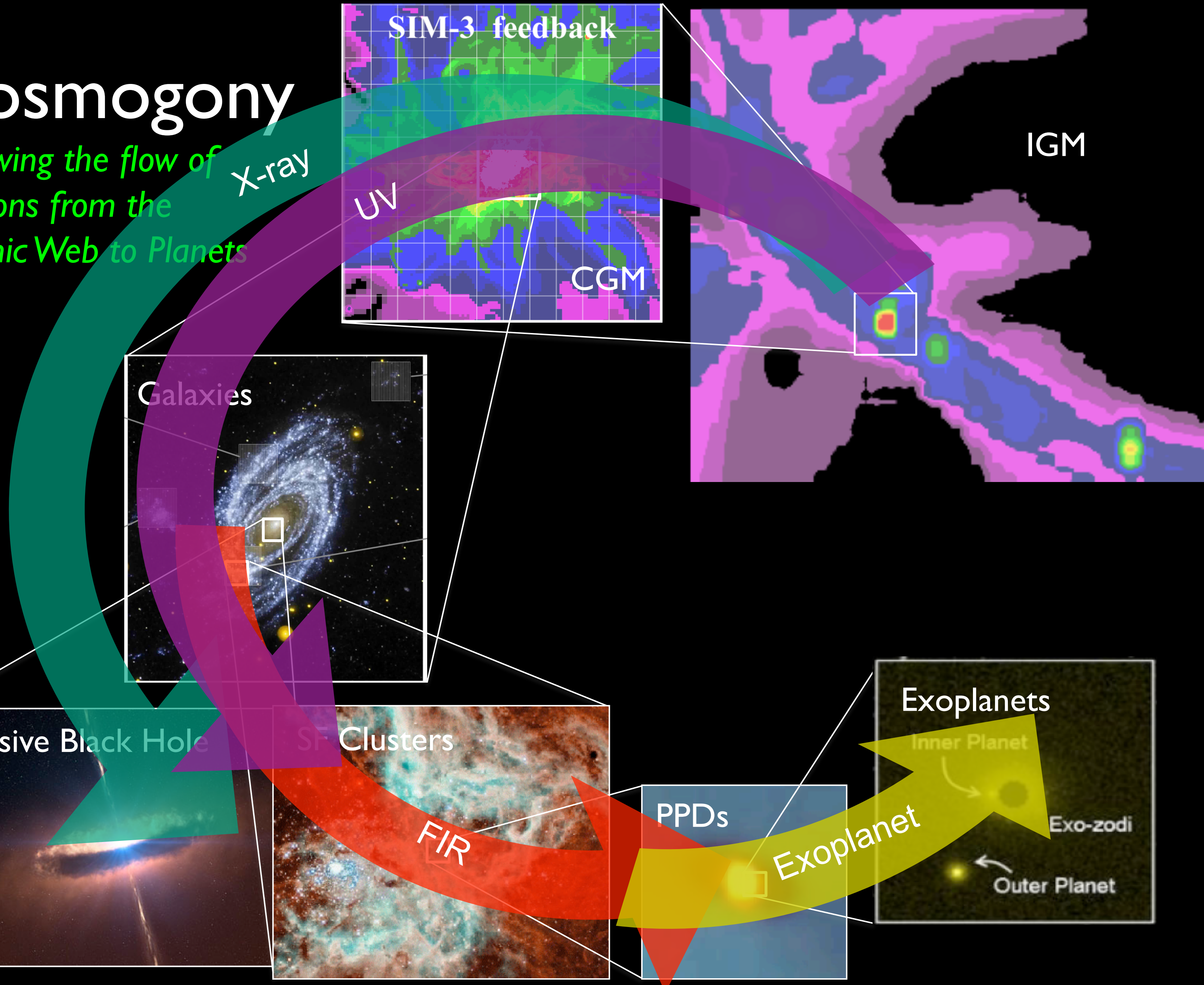

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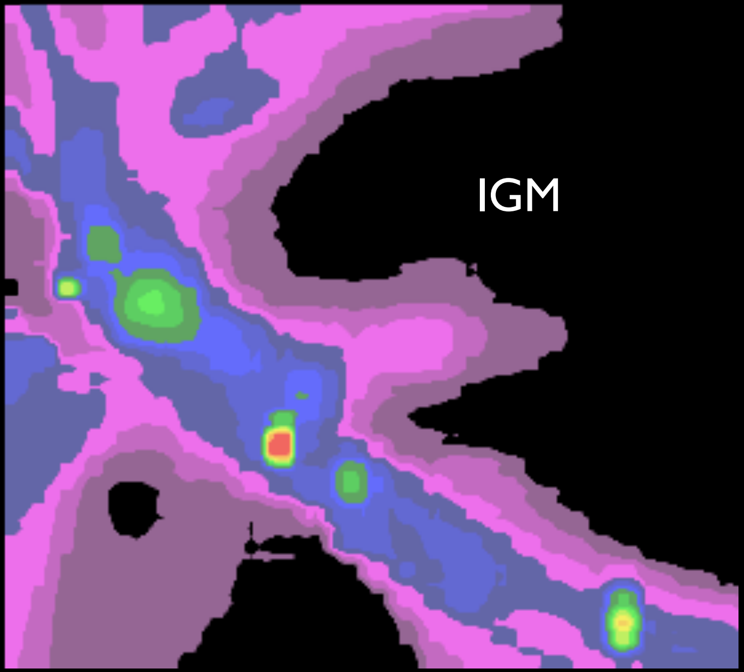
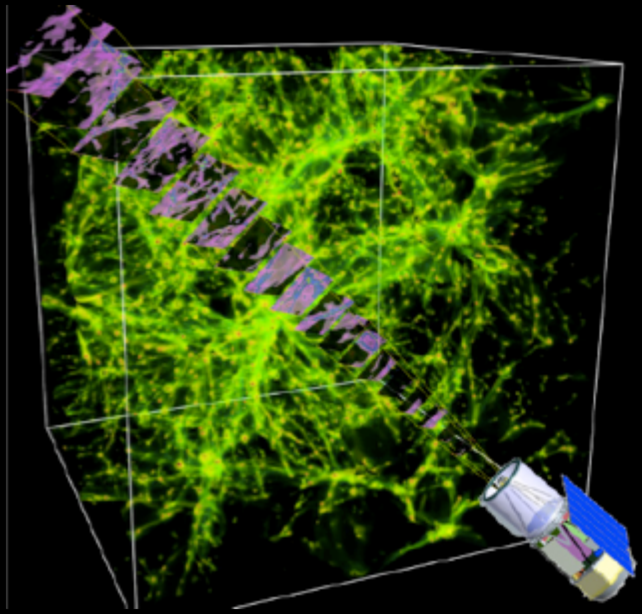


IGM (δ~1-100)

- *Where are the baryons?*
- *How does gas flow from the IGM to the CGM to galaxies?*
- *How is the IGM affected by the evolution of galaxies and massive black holes over time?*
- *Does the IGM trace dark matter?*



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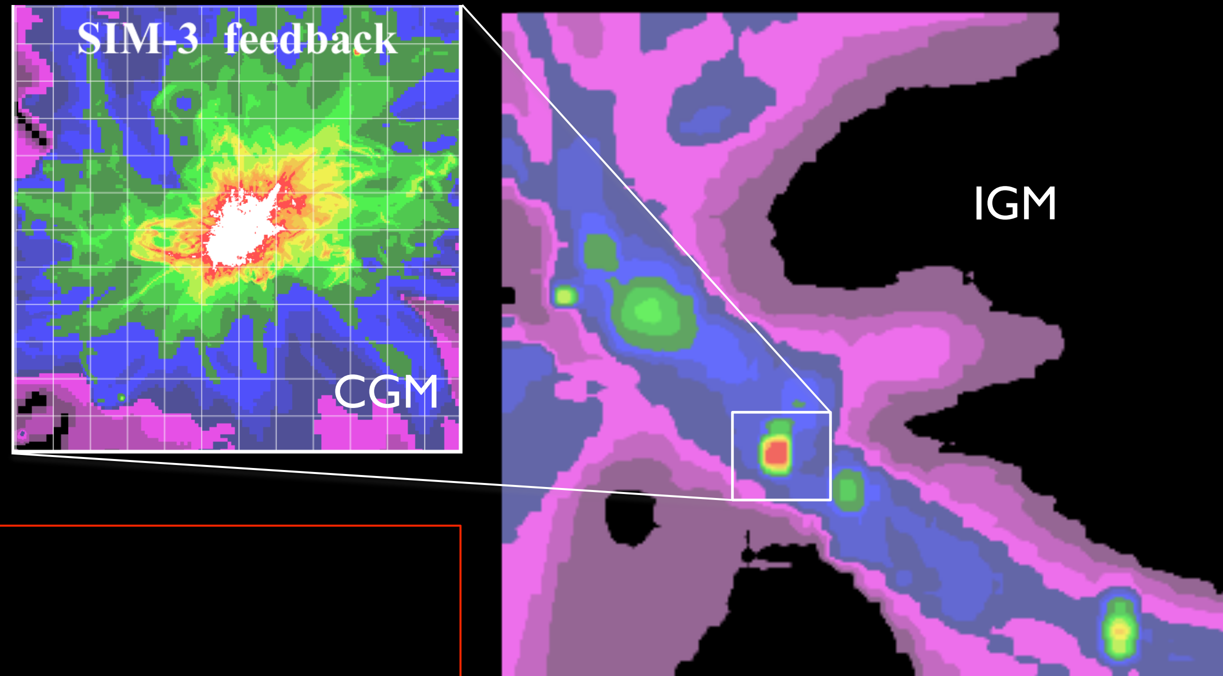
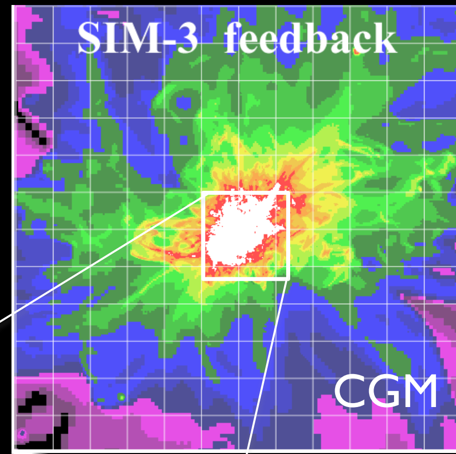


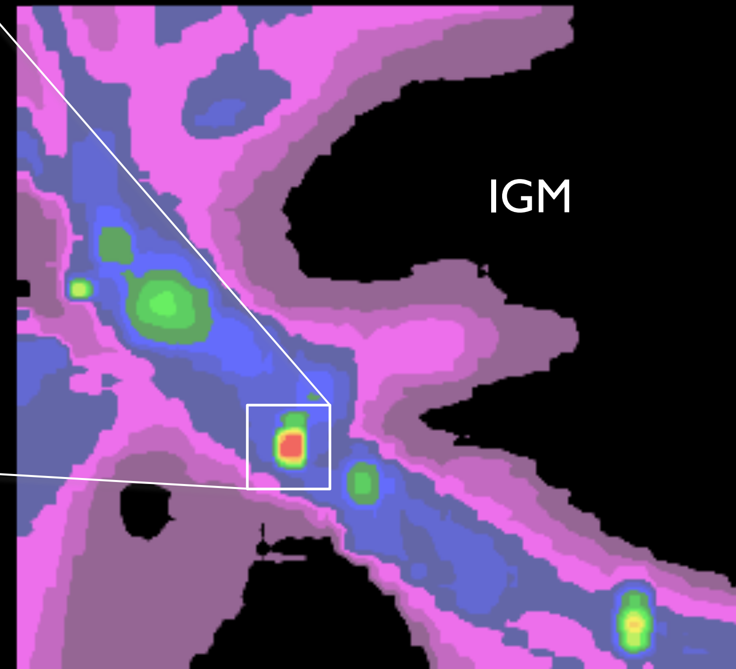
CGM ($\delta \sim 10^2 - 10^4$)

- *What are the flows of matter and energy in the circumgalactic medium?*
- *How do baryons cycle in and out of galaxies?*
- *What is in the circum-galactic medium?*
- *How are galaxies fed? How do galaxies acquire their gas across cosmic time?*
- *How does galaxy feedback work?*
- *How are the chemical elements dispersed & distributed in the circumgalactic & intergalactic media?*
- *Where are the baryons?*

Cosmogony

Following the flow of Baryons from the Cosmic Web to Planets



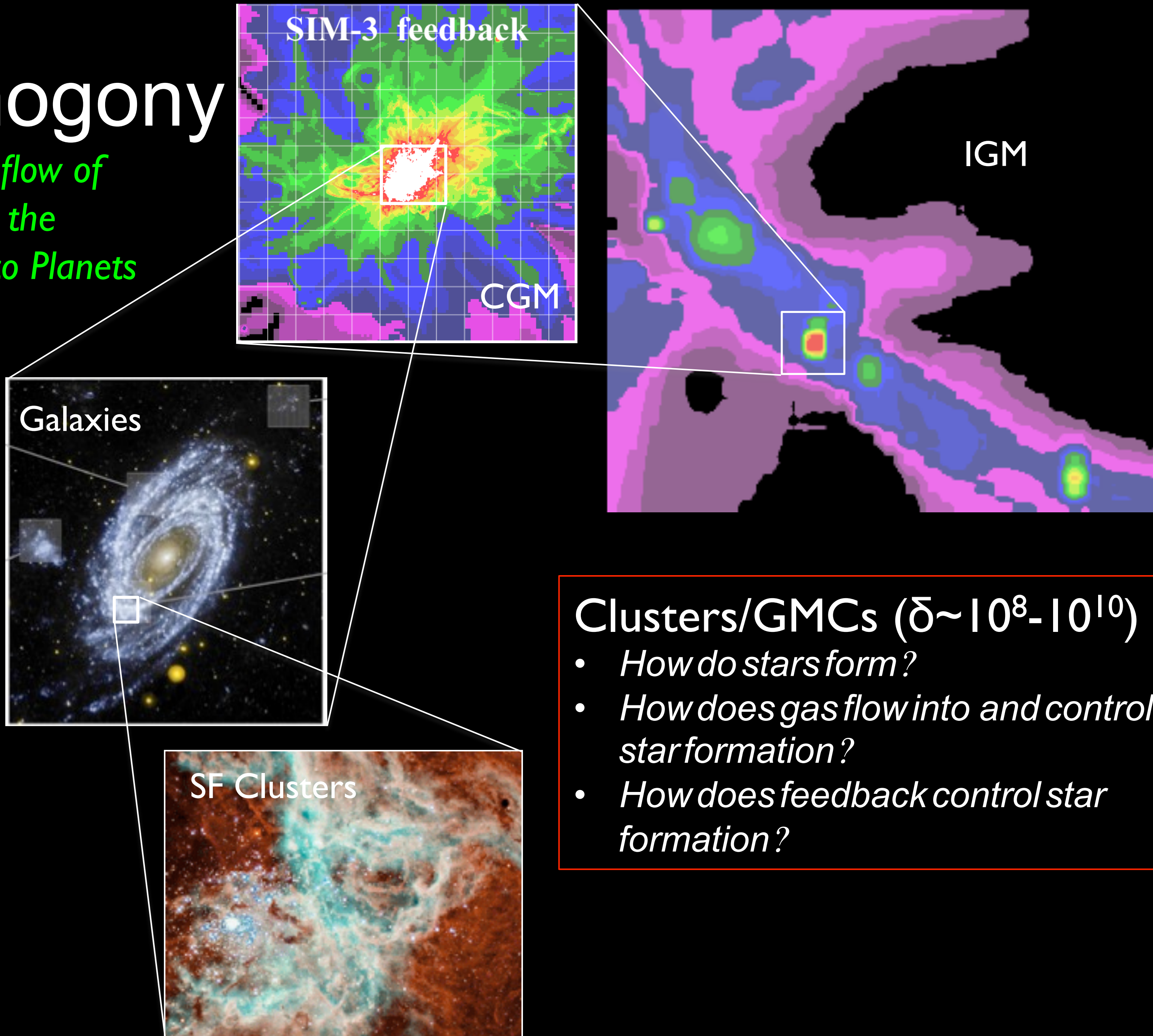


Galaxies ($\delta \sim 10^4 - 10^8$)

- *How do galaxies build up their stellar component over cosmic time?*
- *What processes regulate the conversion of gas into stars inside galaxies?*
- *How are the chemical elements dispersed and distributed in galaxies?*
- *What is the fossil record of galaxy assembly over cosmic time?*

Cosmogony

Following the flow of Baryons from the Cosmic Web to Planets



Clusters/GMCs ($\delta \sim 10^{8}$-10^{10})

- *How do stars form?*
- *How does gas flow into and control star formation?*
- *How does feedback control star formation?*

Cosmogony

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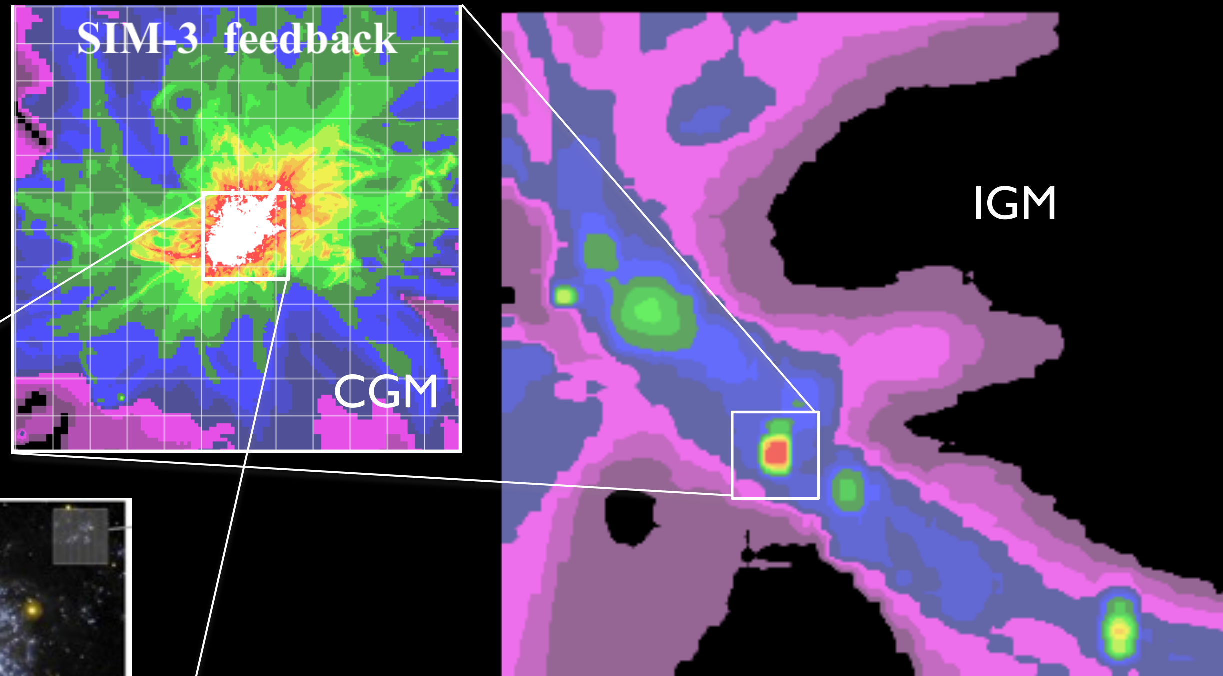

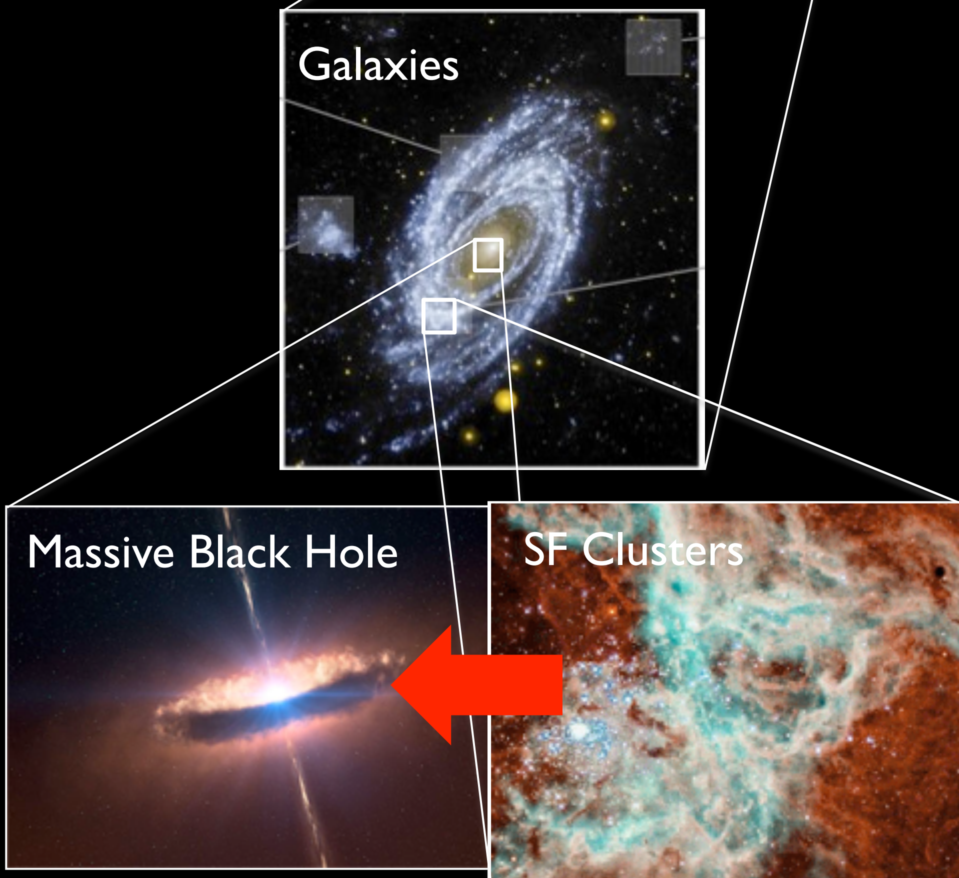

Central Black Holes ($\delta \sim 10^{29}$)

- *How do black holes grow, radiate, and influence their surroundings?*
- *How does a black hole shape the evolution of cosmic structure?*

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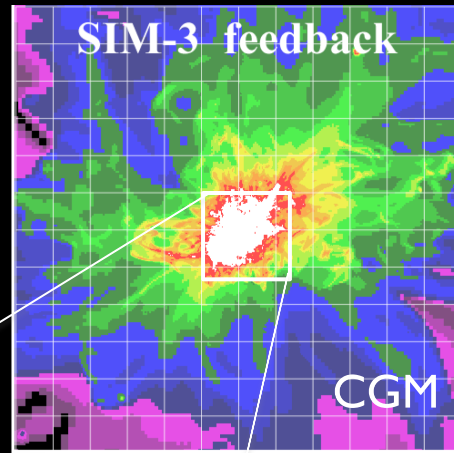

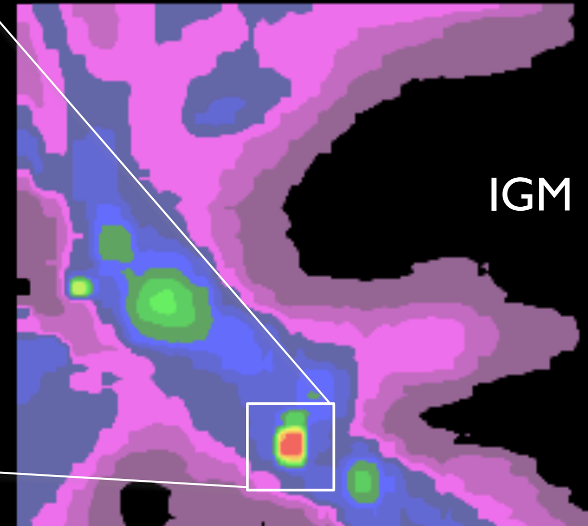

Protostars/PPDs/Young Stars ($\delta \sim 10^{16}$-10^{19})

- *How do circumstellar disks form and evolve?*
- *How do disks form planets?*

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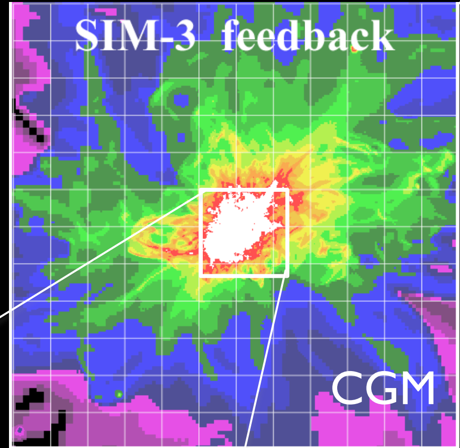
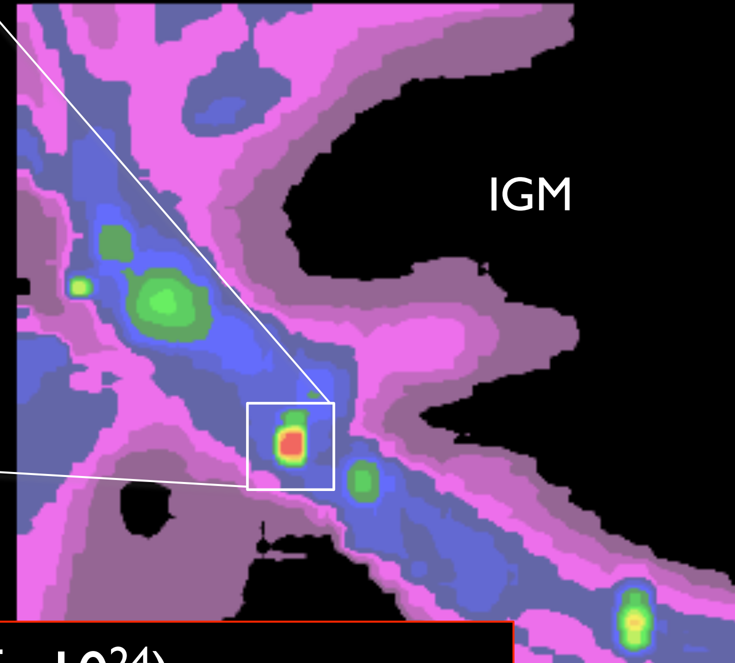
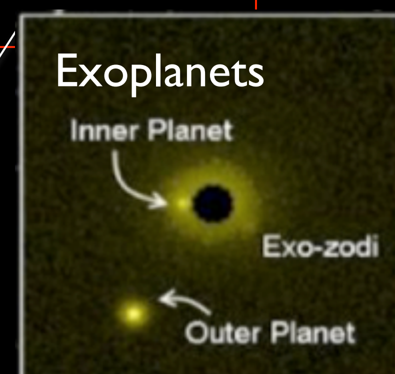




Planets (δ~10^{24})

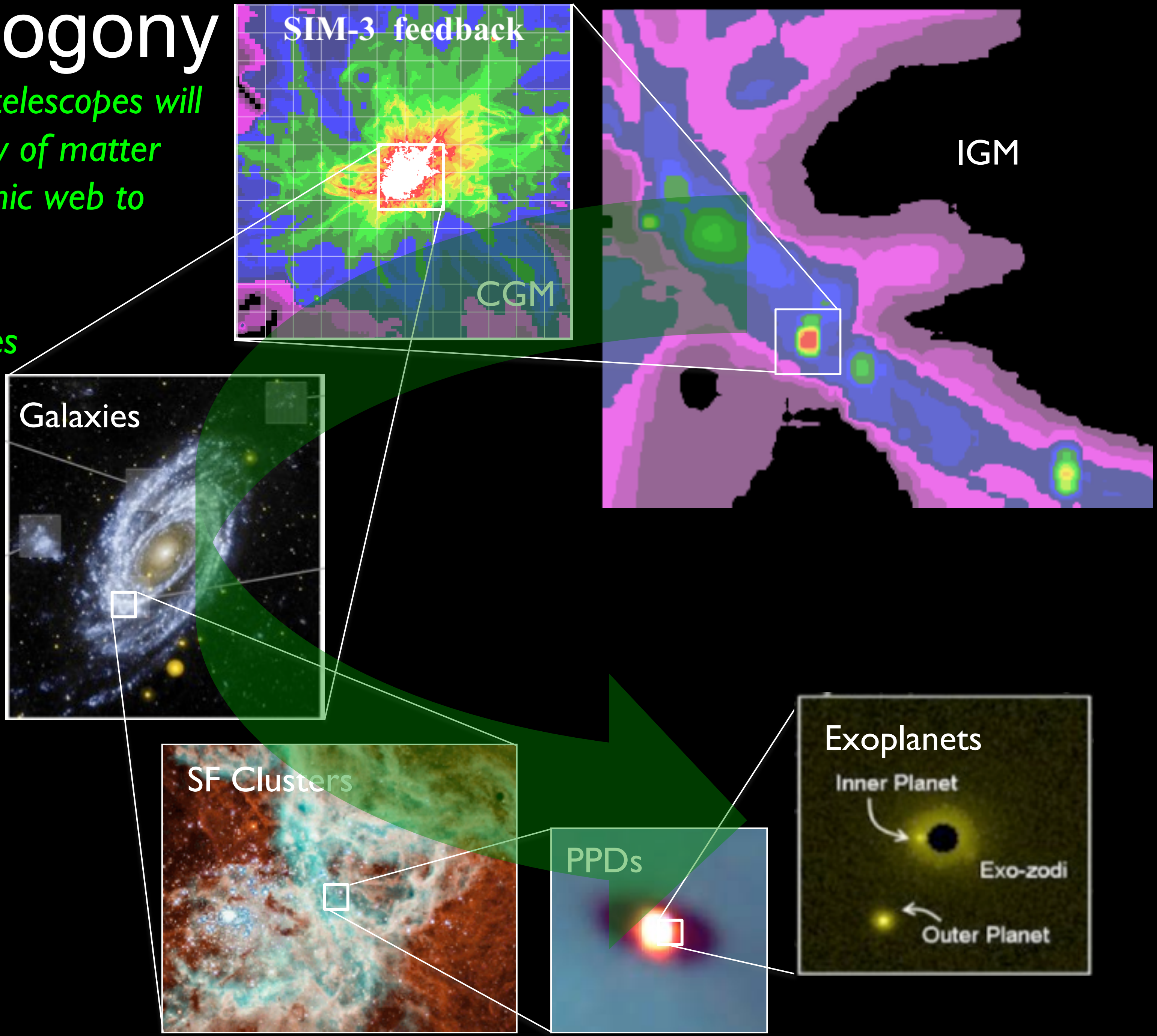
- Do habitable worlds exist around other stars?
- Can we identigy the telltale signs of life on an exoplanet?



Cosmogony

A large UVO telescopes will follow the flow of matter from the cosmic web to planets.

A set of probes may also be able to make significant progress



Cosmogony

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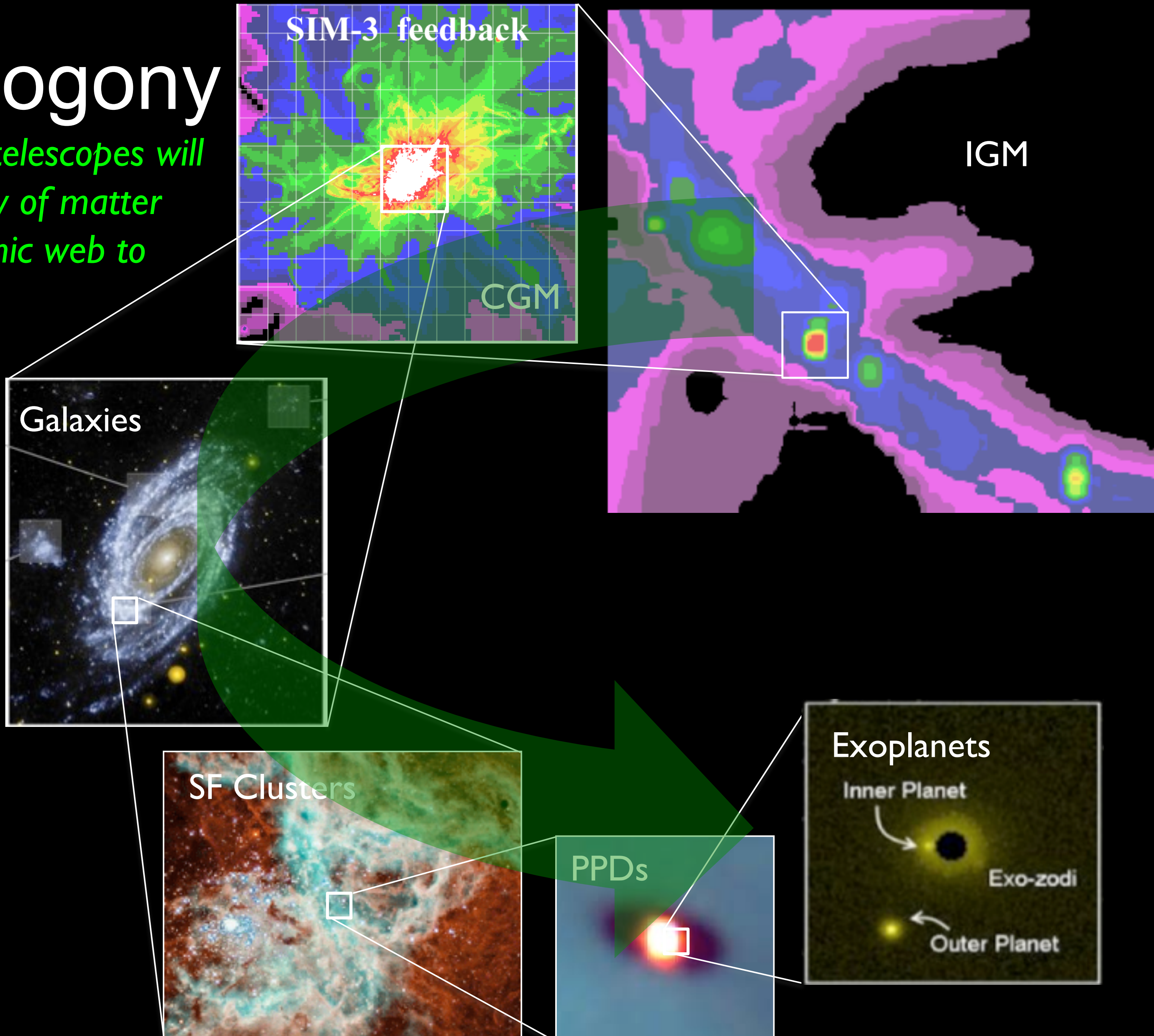

Cosmogony

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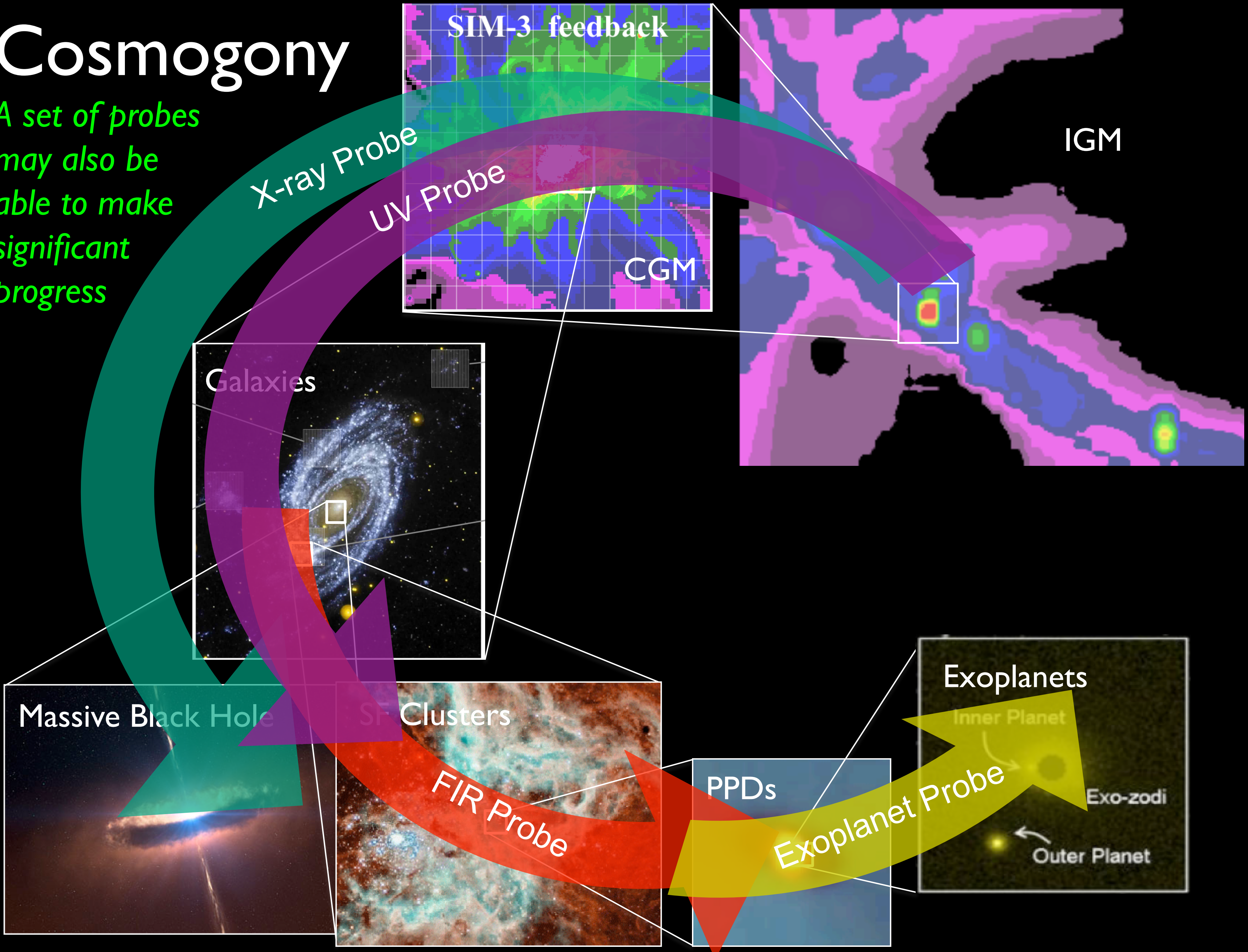

Science Goals

- **Goal 1:** Characterize the growth of large-scale baryonic structures in the intergalactic medium
- **Goal 2:** Observe and explain the assembly of galaxies over cosmic time
- **Goal 3:** Trace and understand the flows of baryons between galaxies and the intergalactic medium
- **Goal 4:** Trace and understand the cycles of matter and energy within galaxies
- **Goal 5:** Measure and explain the history of star formation in galaxies over time
- **Goal 6:** Determine how the conditions for habitability arise during planetary system formation

3. Translating This into Science Measurement Objectives & Technology Requirements

Science Measurement Objectives

- **Objective 1:** Characterize the spatial distribution of IGM absorption lines using background QSOs and galaxies through high resolution UV spectroscopy
- **Objective 2:** High angular resolution UVO imaging and imaging spectroscopy of forming galaxies and galaxy systems
- **Objective 3:** High angular resolution photometry of individual stars in a representative sample of galaxies
- **Objective 4:** UV Imaging spectroscopy of star formation regions, galaxies, CGM and IGM
- **Objective 5:** Multiobject UV spectroscopy of galaxies, CGM, CQM
- **Objective 6:** Wide field UV/optical photometry of star formation regions in nearby galaxies
- **Objective 7:** UV/optical imaging spectroscopy of protostars and Protoplanetary disks
- **Objective 8:** Far IR/sub-mm imaging and spectroscopy of forming galaxies
- **Objective 9:** Far IR/sub-mm imaging and spectroscopy of star formation regions
- **Objective 10:** Far IR/sub-mm imaging interferometric spectroscopy of SFRs, protostars, PPDs

Astro 2010 Science Questions → Cosmic Origins Measurements

	O	OUV		UV			FIR		
COSMOLOGY & FUNDAMENTAL PHYSICS	HCI/S	HRI	WFI	HRS	MOS	IFS	SPICA	10m	IF
HOW DID THE UNIVERSE BEGIN?									
WHY IS THE UNIVERSE ACCELERATING?			*X*		*X*				
WHAT IS DARK MATTER?		*X*	*X*						
WHAT ARE THE PROPERTIES OF NEUTRINOS?									
GALAXIES ACROSS COSMIC TIME									
HOW DO COSMIC STRUCTURES FORM & EVOLVE?		X	X	X	X	X	X	X	X
HOW DO BARYONS CYCLE IN & OUT OF GALAXIES, AND WHAT DO THEY DO WHILE THEY ARE THERE?		X	X	X	X	X	X	X	X
HOW DO BLACK HOLES GROW, RADIATE, AND INFLUENCE THEIR SURROUNDINGS?		X	X	X	X	X	X	X	X
WHAT WERE THE FIRST OBJECTS TO LIGHT UP THE UNIVERSE AND WHEN DID THEY DO IT?					X	X	X	X	
GALACTIC NEIGHBORHOOD									
WHAT ARE THE FLOWS OF MATTER & ENERGY IN THE CIRCUMGALACTIC MEDIUM?		X	X	X	X	X	X	X	X
WHAT CONTROLS THE MASS-ENERGY-CHEMICAL CYCLES WITHIN GALAXIES?		X	X		X	X	X	X	X
WHAT IS THE FOSSIL RECORD OF GALAXY ASSEMBLY FROM THE FIRST STARS TO THE PRESENT?		X	X	X	X		X	X	X
WHAT ARE THE CONNECTIONS BETWEEN DARK AND LUMINOUS MATTER?					X	X			
PLANETARY SYSTEMS & STAR FORMATION									
HOW DO STARS FORM?		X	X	X	X	X	X	X	X
HOW DO CIRCUMSTELLAR DISKS EVOLVE & FORM PLANETARY SYSTEMS?	X	X	X	X	X?	X	X	X	X
HOW DIVERSE ARE PLANETARY SYSTEMS?	X								X
DO HABITABLE WORLDS EXIST AROUND OTHER STARS,& CAN WE IDENTIFY THE TELLTALE SIGNS OF LIFE ON AN EXOPLANET?	X						X	X	X
STARS AND STELLAR EVOLUTION									
HOW DO ROTATION & MAGNETIC FIELDS AFFECT STARS?			X	X	X				
WHAT ARE THE PROGENITORS OF TYPE Ia SUPERNOVAE			X	X	X				
HOW DO THE LIVES OF MASSIVE STARS END?			X			X	X	X	X
WHAT CONTROLS THE MASS, RADIUS, AND SPIN OF COMPACT STELLAR REMNANTS?		X							

Example:
Measurement → UV Detector Requirements

UV Detector Property	UV High Resolution/High Contrast Imaging	UV Wide Field Imaging	UV High Resolution Spectroscopy	UV Multi-Object Spectroscopy	UV Integral Field Spectroscopy	Current Performance
QE	**Moderate**	**Moderate**	**High-Very High**	**High**	**High-Very High**	**Low-Very Low**
Format: Number of Pixels	**Very High**	**Very High**	**High-Very High**	**High-Very High**	**High-Very High**	**High**
Photon-counting	**XX**	**X**	**XXX**	**XX**	**XXX**	**YES**
Equivalent background	**Low**	**Moderate**	**Very Low**	**Low-Very Low**	**Very Low**	**Moderate**
Dynamic Range	High	High	Moderate	Moderate	Moderate	Moderate
Radiation Tolerance	Moderate	Moderate	Moderate	Moderate	Moderate	High
Time Resolution	Low	Low	Low	Low	Low	High
Out of Band Rejection	High	High	Moderate	Moderate	Moderate	High

Technology Figures of Merit

- 1. Current and projected (2020, assuming funding as specified below) performance.
  - e.g., for detectors: QE vs. wavelength, internal/dark noise, photon-counting capability, number of pixels/formats/scaleability, energy resolution, dynamic range.
- 2. Implementation and operational issues/risks:
  - e.g., for detectors requirements for cooling, high voltage, required materials/process improvements, red leak/out of band response.
- 3. Cost/time to TRL-6 and leverage:
  - What is the current TRL level, what NASA funding and time is required to reach TRL6,
  - What is the degree of difficulty of these developments
    - for example using the DOD Degree of Difficulty scale
  - What non-NASA astrophysics division resources can be brought to bear to leverage the development>
    - significant industrial involvement and prior investments, cross-division, cross-agency, private-sector investments and applications, existing infrastructure and institutional investment
- 4. Relevance to and impact on possible future missions:
  - Large 4-8 m UVOIR general astrophysics missions, Far IR/Sub mm missions
  - Joint Exoplanet imaging missions & required compatibility technologies

Cosmic Origins Technology Priorities

- ***Priority 1.*** *These technologies are* ***"mission enabling"****, and are the highest priority for immediate investment. We provide preliminary roadmaps for these technologies.*
- ***Priority 2.*** *These technologies are* ***"mission enhancing"****. Some early investment should be considered contingent upon science and mission prioritization.*
- ***Priority 3.*** *Many interesting and important technologies may be relevant to future CO missions. Some can be developed once mission choices are made. Others may be developed as part of other activities and programs. Still others may be at early stages of readiness and require more basic research support to mature. Level 3 technologies were not included in Table 3.*

Technology Matrix (example)

Name of technology	**High QE, large format photon-counting UV large-format detectors**
Priority	1 – Detectors are at the heart of every instrument. Detector performance shortfalls can only be made up with high cost increases in aperture.
Roadmap	1) 2011-2014: Investigate 2-4 technological approaches. Goal is demonstration of high QE, low/moderate noise, and moderate/high (scaleable) pixel counts 2) 2015: Downselect to 2 promising technologies that have reached TRL3-4. 3) 2015-2019: Invest in 2 technologies that provide best capabilities for UV imaging and UV spectroscopy. Scale to high/very high pixel counts. Develop low power versions of required electronics.

UVOIR Technologies

Table 3 – Cosmic Origins Technology Matrix

Name of technology	**High QE, large format photon-counting UV large-format detectors**	**UV coatings**	**Large, low-cost, light-weight precision mirrors for Ultra-Stable Large Aperture UV/Optical Telescopes**	**Deployable light-weight precision mirrors for future Very Large Aperture UV/Optical Telescopes**	**Very large format, low noise Optical/IR detector arrays**	**Photon counting Optical/IR detector arrays**
Brief description (1024)	Future NASA UV missions, particularly those devoted to spectroscopy, require high quantum efficiency (>50%), low noise (<1e-7 ct/pixel/s), large-format (>4k x \4k) photon-counting detectors for operation at 100-400nm or broader	High reflectivity, highly uniform UV coatings are required to support the next generation of UV missions, including explorers, medium missions, and a UV/optical large mission. High reflectivity coatings allow multiple reflections, extended bandpasses, and accommodate combined UV and high-contrast exoplanet imaging objectives.	Future UV/Optical telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Herschel, and to complement the ≥ 30-m ground-based telescopes that will be coming on line in the next decade. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control	Future UV/Optical telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Herschel, and to complement the ≥ 30-m ground-based telescopes that will be coming on line in the next decade. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control	Future NASA Optical/near-IR missions require large format detector arrays mosaicable in formats of ~Gpix, covering wavelengths from the optical to about 2μm.	Future NASA Optical/near-IR missions require large-format, high quantum efficiency, low dark current, and high readout speed photon counting detector arrays.

UVOIR Technologies

Name of technology	High QE, large format photon-counting UV large-format detectors	UV coatings	Large, low-cost, light-weight precision mirrors for Ultra-Stable Large Aperture UV/Optical Telescopes	Deployable light-weight precision mirrors for future Very Large Aperture UV/Optical Telescopes	Very large format, low noise Optical/IR detector arrays	Photon counting Optical/IR detector arrays
Roadmap	1) 2011-2014: Investigate 2-4 technological approaches. Goal is demonstration of high QE, low/moderate noise, and moderate/high (scaleable) pixel counts 2) 2015: Downselect to 2 promising technologies that have reached TRL3-4. 3) 2015-2019: Invest in 2 technologies that provide best capabilities for UV imaging and UV spectroscopy. Scale to high/very high pixel counts. Develop low power versions of required electronics.	1) 2011-2013: Demonstrate ALD coatings for Al+MgF_2. Demonstrate reflectivity and compatibility with internal coronograph. 2) 2013-15: Demonstrate stability of ALD coatings for exposed optics. Demonstrate compatibility of conventional coatings with internal coronograph. 3) 2015-2019: Develop large optics capability for ALD coatings.	1) 2011-2015: Demonstrate the technologies required to fabricate 4-m mirror blanks from ULE/Zerodur, Borosilicate and Silicon Carbide 2) Demonstrate the ability to grind and polish mirror blanks to achieve the required mirror figure and surface roughness for an ExoPlanet imaging mission 3) Develop a 4-m monolithic mirror that meets the requirements for a combined UVOIR/ExoPlanet mission	1) 2011-2015: Demonstrate the technologies required to fabricate 1.5-m to 3.6-m mirror blanks from ULE/Zerodur, Borosilicate and Silicon Carbide 2) Demonstrate the ability to grind and polish mirror blanks to achieve the required mirror figure and surface roughness for a UVOIR mission 3) Develop mirror segments for an 8.0 to 9.2-m deployable telescope that meets the requirements for a UVOIR mission	Defer pending mission requirement	1) 2012: Much of the relevant expertise exists outside NASA. Coordinate a small workshop to survey and assess different approaches. 2) 2012-2015: Technology development at a few vendors/labs aimed at demonstrating high QE, high speed, and low dark current photon counting focused on detector materials development and characterization. 3) 2015-2019: Focused development at two vendors/labs aiming to develop mega-pixel class photon-counting detector arrays that have been optimized for low background space astrophysics.
Priority	1 – Detectors are at the heart of every instrument. Detector performance shortfalls can only be made up with high cost increases in aperture	1 – Coating developments could extend the range of UV missions to 100 nm. Coating improvements could increase net throughput by 50-100%. Coating improvements could make a joint Exoplanet/ UVOIR mission possible.	1 – Large monolithic high precision mirror is a prerequisite for 4-m mission and may be applicable to 8-m mission. Optics technology drives mission cost and mass.	2 – Deployable large precision mirror may be required for 8-m mission (depending on launch) vehicle. A deployed mirror may require an external occulter and is less compatible with internal coronagraph	2 – Technology is available at TRL6+. Scaling to very high pixel counts is mission enhancing, but requirements and development should be mission driven.	1 – Photon-counting requirement driven by moderate to high resolution spectroscopy, missions travelling beyond the Zodiacal disk, and high time-resolution science or wavefront sensing..

Enhancement of Science Impact of Next Generation UV Technologies

Technology	Implementation Approaches	Potential impacts	Mission Enabling Factor
1) Single Photon counting UV Detector	BSMCPs + GaN Photocathodes AR+DD+EMCCDs	Major increase in QE for large format, low background, versatile detectors	5-10*
2) Next Generation UV Coatings	Atomic Layer Deposition	• High reflectivity coatings —> high performance instruments+telescopes • Broad-band coatings —> 100-120 nm coverage: key UV range • Ultra-uniform coatings —> Joint Exoplanet/UV astrophysics mission	3[‡]
3) Next Generation Diffractive optics	Electron beam lithographic patterning	• Arbitrary groove profile and shape • High performance spectrographs • High efficiency • Low scatter • Wide-field, multi-object, high efficiency spectrographs	2-4[§]
Total Improvement Factor	Data grasp ($A_{eff} \times N_{objects}$) factor	20-250	
	Aperture reduction factor (linear): F_A	2-4	
	Cost reduction factor: F_A^2	4-16 (e.g., 10B$ → 600M-2.5B$)	

Far IR/Sub mm Technologies

Name of technology	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	Cryocoolers
Brief description (1024)	Future NASA Far-IR missions require large format detectors optimized for the very low photon backgrounds present in space. Arrays containing up to tens of thousands of pixels are needed to take full advantage of the focal plane available on a large, cryogenic telescope. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Future NASA Far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy. Arrays containing up to thousands of pixels are needed to take full advantage of the spectral information content available. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Large telescopes provide both light gathering power, to see the faintest targets, and spatial resolution, to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires that these telescopes be operated at temperatures that, depending on the application, have to be as low as 4K. Collecting areas on the order of 10m are needed.	Interferometry in the far-IR provides sensitive integral field spectroscopy with sub-arcsecond angular resolution and R ~ 3000 spectral resolution to resolve protoplanetary and debris disks and measure the spectra of individual high-z galaxies, probing way beyond the confusion limits of current and next-generation single-aperture far-IR telescopes. A structurally-connected interferometer would have the aforementioned capabilities. Eventually the formation-flying interferometric telescope envisaged in the 2000 Decadal survey would provide Hubble-class angular resolution, but that is beyond the scope of this technology plan. Telescopes are operated at temperatures that have to be as low as 4K.	Detectors for far-IR and certain X-ray missions require temperatures in the tens of mK. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling. Powerful, efficient cryocoolers are needed to cool the optical components of far-IR telescopes and provide the heat sink for sub-Kelvin coolers.

Far IR/Sub mm Technologies

Name of technology	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	Cryocoolers
Roadmap	Presently have working 10-19 W Hz-1/2 detectors in small arrays. Advance TES bolometers and MKIDs in parallel to TRL ~ 5, then downselect to one detector type. Demonstrate multiplexing in arrays of 256 elements for interferometry. Further develop larger arrays for single-aperture telescope mission.	1) Grating spectrometer proposed as US instrument on SPICA will require these detectors – the timescale for SPICA has moved to the right since 2010 Decadal report so that there is time for technology development if it is started in a timely manner (2012). 2) Missions beyond SPICA such as SAFIR/CALISTO will have even greater need as background limit will be even lower and they will be capable of handling larger arrays.	The telescope for SPICA is expected to be provided by ESA based on Herschel experience. For 10m class mission, materials, surface, and metrology must be developed. Note that since telescope will be cooled to approximately 4K, the test and measurement challenge is extreme.	Telescope requirement is modest (1 m diameter) in comparison to single aperture telescope. The technical challenges for far-IR interferometry are detectors and cryocooling. Metrology is easy (1 micron tolerance). JWST will demonstrate wavefront control at 10x shorter wavelengths, where it's harder. The interferometric technique described above is nearly mature and requires only modest funding to complete the maturation to TRL 6 for application on a Probe-class mission.	Pick up from JWST and IXO development efforts. Advance sub-K continuous ADR coolers in parallel with 4 K cryocoolers to satisfy predicted performance requirements for each (heat lift at specified temperature stages). Finally, integrate coolers into a cryo-thermal system and verify system thermal performance in sub-scale models representative of flight-sized elements. For missions further in the future, the impact of larger focal planes should be included in a comprehensive analysis of overall cryogenic system requirements.
Priority	1 – Enabling for far-IR spatio-spectral interferometry. 2 – Required for background-limited photometry and very low-resolution spectroscopy	1 – Required for dispersive R~1000 spectrometer with cold telescope, required to achieve background-limited spectroscopy	1 – Significant technology development is required to advance understanding of capability for both of these types of missions to the point that a decision made on the basis of science case (which is very different) can be made.		1 – 4 K and sub-K cryocooling technology is enabling for far-IR spatio-spectral interferometry, and enabling or enhancing for a large far-IR single-aperture telescope.

4. Burning Issues

3 (Provocative?) Observations

- We (the space astrophysics community as a whole) need to deal with the coming crisis
- We need to change the cost paradigm
- We need to invest (more) in technology

The Coming Crisis

- The next logical stage is flagships
- Flagships = 10B$
- NASA Astrophysics Budget = 1B$/yr
- 50% to Flagships ➔ 1 Flagship/20 years

The Coming Crisis

Burning Issue #1: Community Destiny

- The Problem
  - We have become too balkanized as a community (as scientists and implementers) and (perhaps?) too focused on narrow science and interests.
  - NWNH had to invent a new mission (WFIRST) because the community (represented by three separate but equally important groups) could not come together with a unified vision
  - While the x-ray and gravitational wave communities actually put forward a coherent vision, the UV/optical/NIR community could not settle on a single path forward.
  - We have not taken sufficient notice of the coming crisis or have taken a parochial view.
- The Solution?
  - More cross-community dialogue (this meeting!)
  - More self-organized leadership
  - A common vision?

Burning Issue #2: Probes vs. Flagships

- The Problem
  - Flagships take so long (20-30 years) they can become obsolete before launch, and cannot sustain a vibrant community nor respond to current science
  - Flagships are too big to fail, and subject to forces far beyond our control
  - The failure of a flagship could end the field in U.S.
  - The richness and synergy of the Great Observatory program will never be repeated.
- The Solution?
  - Can a compelling case be made for a program of linked probes in the intermediate term?
  - Example: Cosmogony Probes
    - Probe 1: Wide field UV/Optical Imaging & Spectroscopy
    - Probe 2: X-ray spectroscopy
    - Probe 3: Far IR Probe
    - Probe 4: Exoplanet Imaging Probe

Burning Issue #3: How Do Take Ownership of Costs and if Possible Change the Cost Paradigm?

- The Problem
  - Costing is mysterious and a black box, and "competition sensitive"
  - Costing builds in prior history and therefore becomes a self-fulfilling prophecy
  - Not understanding real costs is while discussing missions and science is like not understanding gravity while discussing cosmology and astrophysics.
  - More modest missions using existing technology are now considered flagships (e.g., WFIRST).
  - Many excellent Probe-class mission proposals were forwarded to Astro2010, only to be sunk by ICE.

Burning Issue #3: How Do Take Ownership of Costs and if Possible Change the Cost Paradigm?

- The Solution?
  - **Early investment:** *Serious* investments in technology must be made up front. They must be carefully prioritized.
  - **Ownership:** : Cost must be treated like other technical requirements and understood to be optimized and controlled by scientist-builders.
  - **Transparency:** How can we lower mission cost without understanding why costs grow? In order to discuss, compare, and refine future missions we must have common, consistent, and transparent cost estimating tools. (Ideally multiple methodologies to provide cross-checks).
  - **Break Cost Paradigm:** We must incentivize cost efficiency and change the cost growth paradigm
    - But: NASA centers and aerospace companies are *not incentivized* to make cost estimation a transparent and level process.
    - The community must push hard for NASA HQ to take the lead to change this.
  - **Discipline and Consistency:** Example--Probes cost <1B$, but are assessed 100% cost contingency. If 2B$ is ever in danger of being exceeded, cancel mission and proceed to next in list, no matter how much has been spent.