THE *LYNX* MISSION

REVEALING THE INVISIBLE UNIVERSE

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-On behalf of the Science and Technology Definition Team (STDT)

ASTROPHYSICS

Decadal Survey Missions

1. Lynx – X-Ray Mission
2. LUVOIR – Large UV Optical IR
3. OST - Origins Space Telescope Far IR
4. HabEx – Habitable Exoplanets

Lynx STDT Community Members


Alexey Vikhlinin, SAO (Co-Chair)


Feryal Özel, Arizona (Co-Chair)


Steve Allen, Stanford


Megan Donahue, MSU

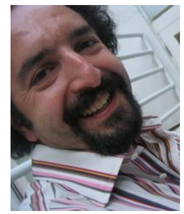

Laura Lopez, Ohio State


Jessica Gaskin, MSFC (Study Scientist)


Mark Bautz, MIT


Ryan Hickox, Dartmouth


Piero Madau, UCSC


Daniel Stern, JPL


Eliot Quataert, Berkeley


Zoltan Haiman, Columbia


Niel Brandt, Penn State

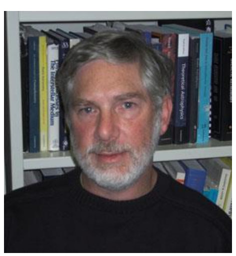

Tesla Jeltema, UCSC


Rachel Osten, STScI


Dave Pooley, Trinity


Chris Reynolds, UMD


Andrey Kravtsov, Chicago


Joel Bregman, Michigan

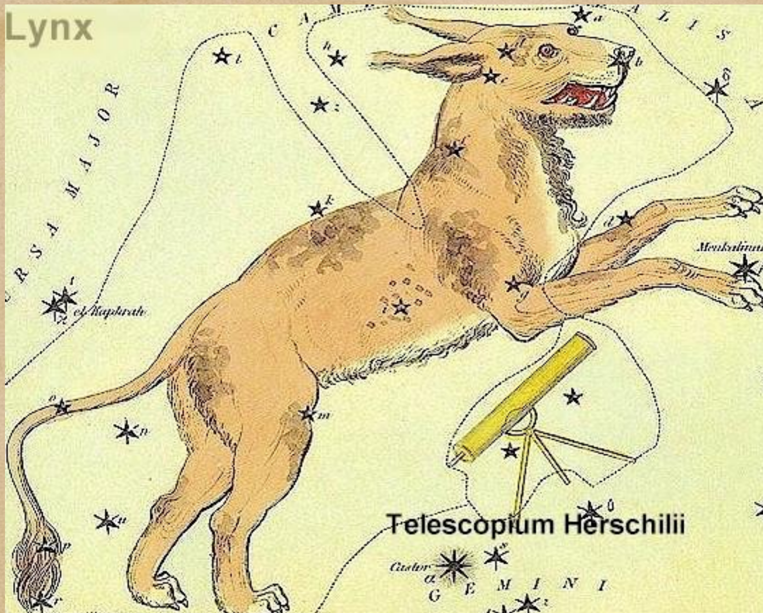

Juna Kollmeier, OCIW

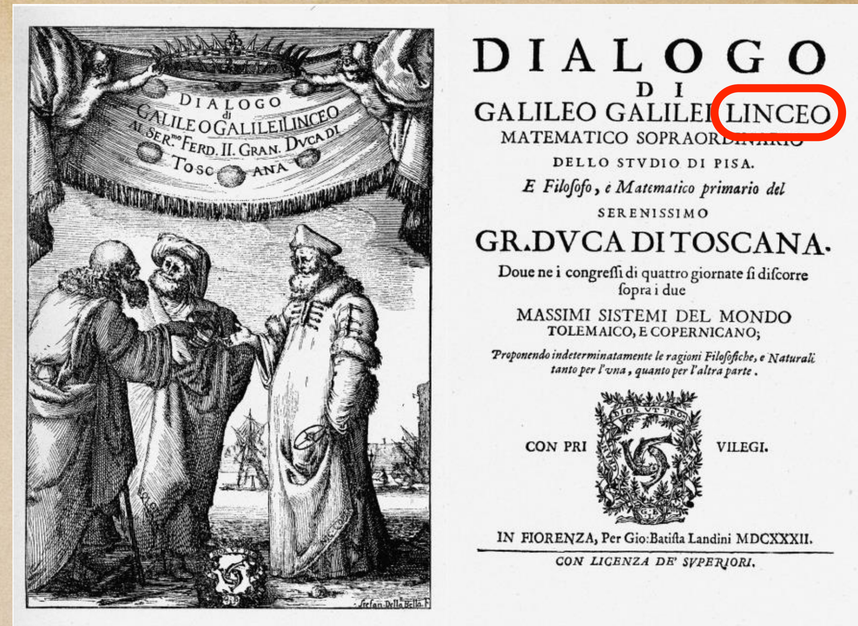

Frits Paerels, Columbia


Andy Ptak, GSFC

- **8 Science Working Groups**
- **Optics Working Group**
- **Instrument Working Group**
- **7 ex-officio International members**

About **3oo** total members!




DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.
Doue ne i congreſſi di quattro giornate ſi diſcorre
ſopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali
tanto per l'una, quanto per l'altra parte.
CON PRIVILEGI.
IN FIORENZA, Per Gio: Batiſta Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

- A symbol of great insight
- Ability to see through rocks and trees to **reveal the true nature of things**.

The historic Accademia dei Lincei (Academy of the Lynx) based their name on this ability to perform incisive and penetrating investigations of the natural world.

Galileo himself was a proud member, and **the Academy of the Lynx coined the term telescope** for his marvelous device for peering into the cosmos.

Much of the baryonic matter and the settings of the most active energy release in the Universe are visible primarily or exclusively in the X-rays, so…

Scientifically Compelling

THE BIG QUESTIONS:

How does the Universe work?

and

How did we get here?

Science goals mapped into the structure of the Science Working Groups:

- First Accretion Light in the Universe
- Cycles of Baryons in and out of Galaxies
- Physics of Energy Feedback
- Physics of Cosmic Plasmas
- Stellar Lifecycles
- Evolution of Structure and AGN populations
- Physics of High Density Matter, Compact Objects, and Accretion

Lynx Science Requirements

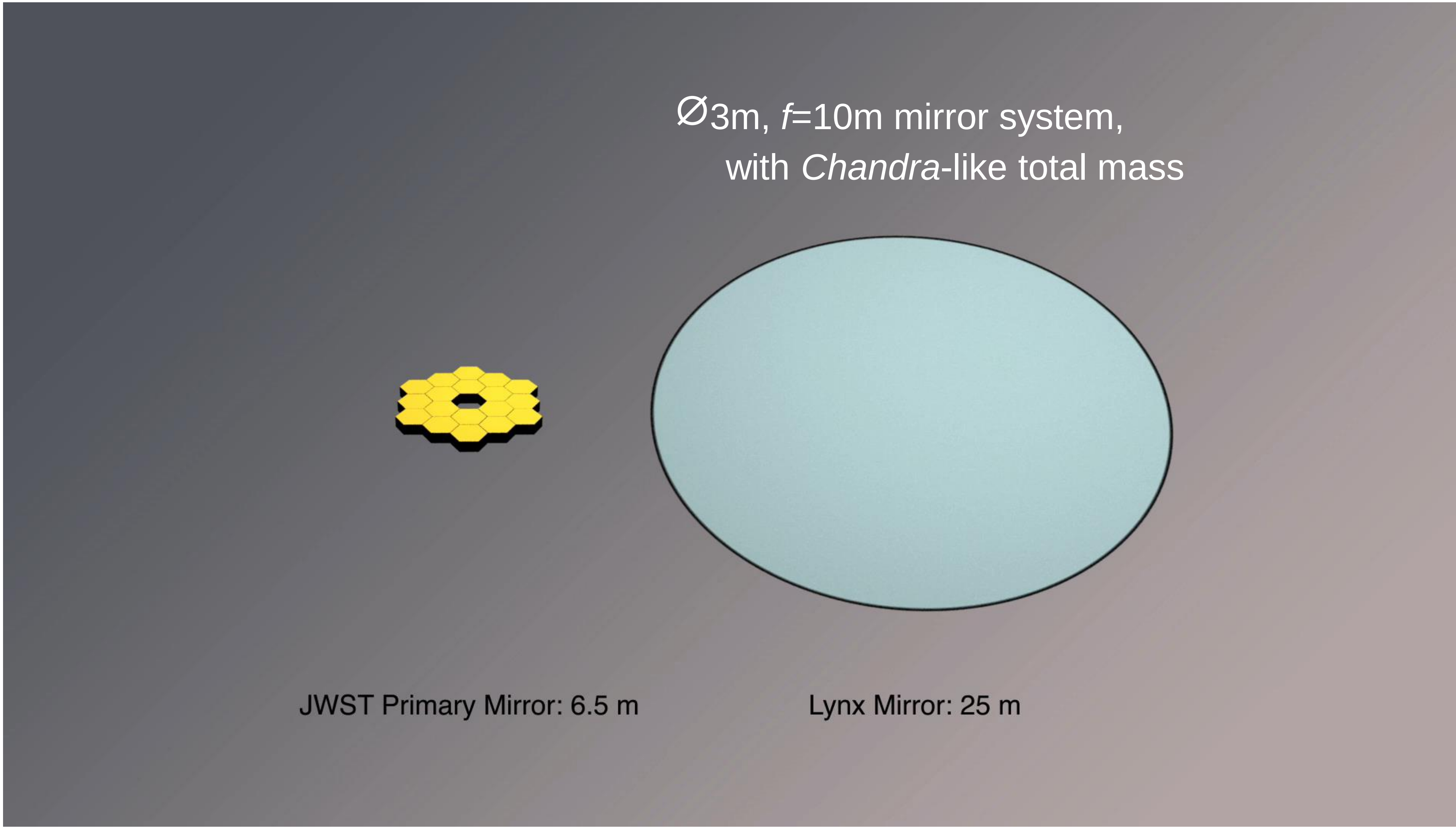
LEAPS IN CAPABILITY

- High sensitivity in the soft X-ray band. First Accretion Light science requires mirror effective area >~ 2 square meters at $E < 2$ keV.
- High angular resolution (sub-arcsec) is key for nearly all *Lynx* science. Desire 0.5 arcsec or better resolution.
- Detectors should provide fine imaging, low internal background, and high resolution, spatially resolved spectroscopy.
- Very high spectral resolution (R >~ 5000) in the soft band.

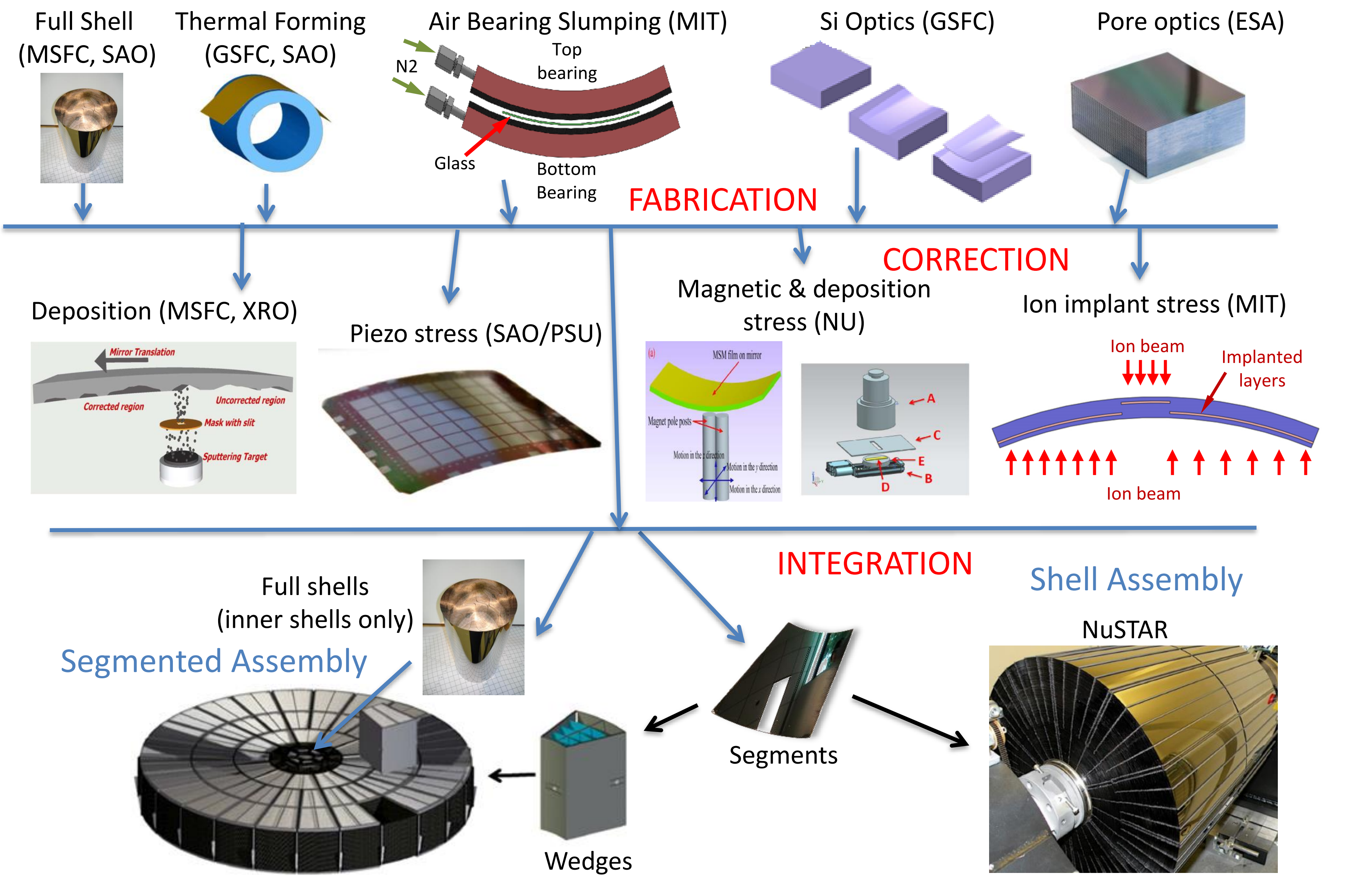
Lynx Optics & Science Instruments

- **Large-Area High-Angular-Resolution Optical Assembly**
- **High Definition X-Ray Imager**
- **X-Ray Microcalorimeter Imaging Spectrometer**
- **X-Ray Grating Spectrometer**

Lynx X-Ray Optics and Concept



Taxonomy of X-ray Telescope Fabrication



Thanks to Dan Schwartz

Schattenburg –NASA PCOS SIG, 04/2016

Mirror Fabrication

Full Shell

Metal, fused silica (MSFC, SAO)

Replication

Diamond turn mandrel
Electroform replication

Direct Fabrication

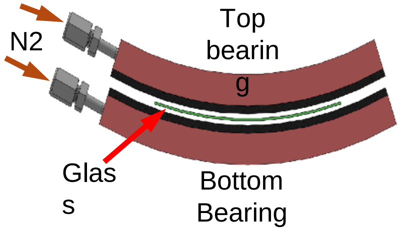
Zeeko polishing machine

Segmented

Glass thermal forming (GSFC, MIT, SAO)

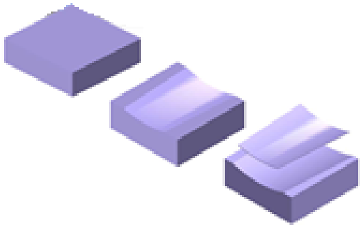
Slumping (GSFC, SAO)

Air bearing slumping (MIT)

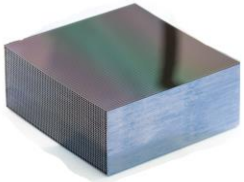


Silicon optics

Slice & polish (GSFC)

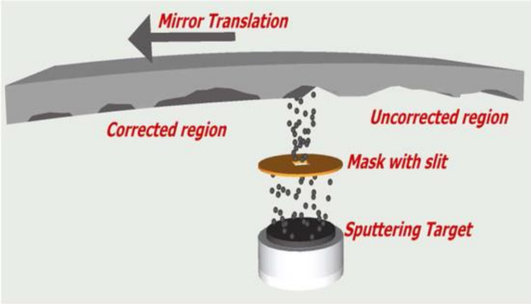


Pore optics (ESA)



Mirror Correction

Material Add or Subtract



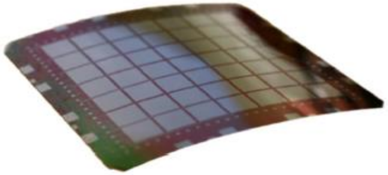
Sputter deposition (MSFC, XRO, Inc.)

Multipass metrology/polish (GSFC, MSFC)

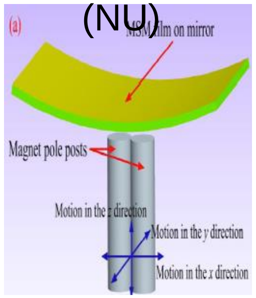
Others (ion polish, magnetorehologic polish, fluid jet polish, etc.)

Stress Layer

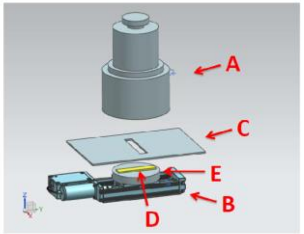
Piezo stress (SAO/PSU)



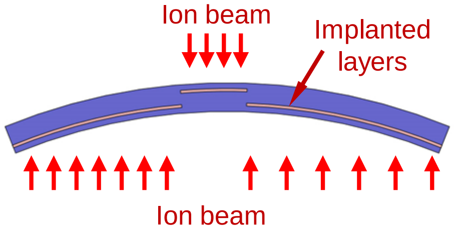
Magnetic stress (NU)



Sputter deposition stress (NU)

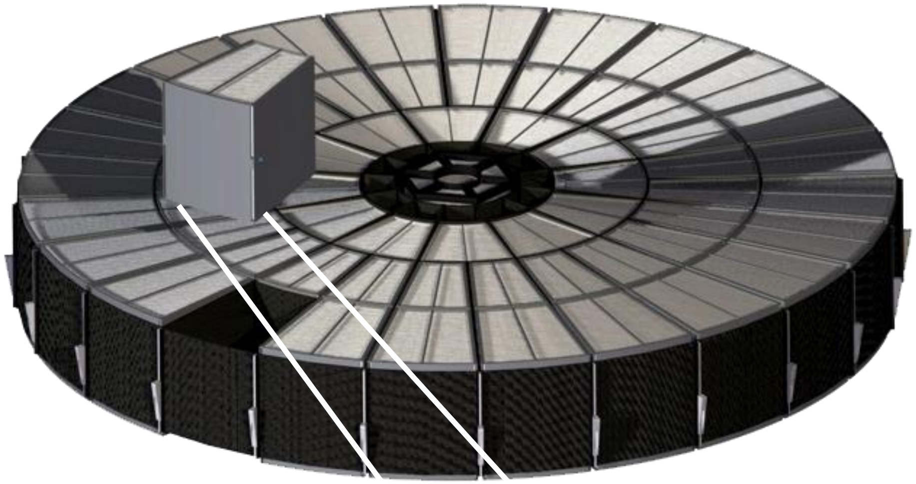


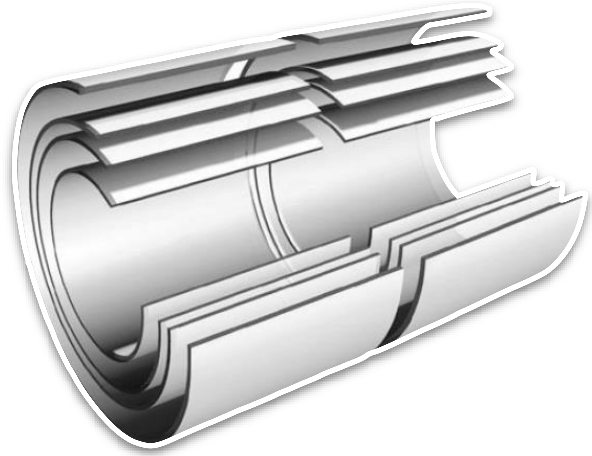
Ion implant stress (MIT)



Next-Generation X-ray Mirror

New mirror is built from densely packed thin mirror elements. 3.0m outer diameter. ~1200 kg for 2.3m^2 of collecting area

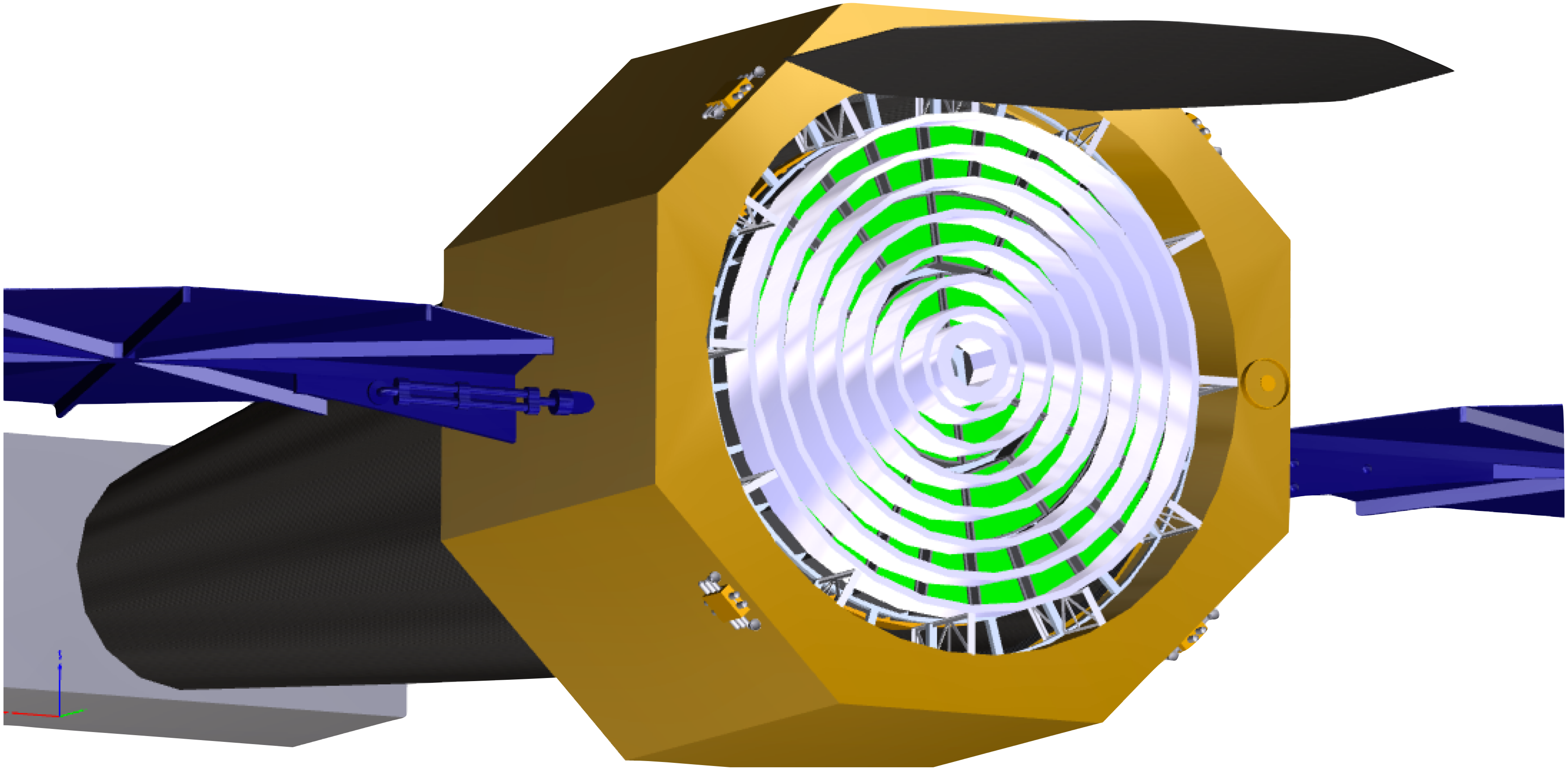




Chandra mirror shells are 2.5cm thick. 1,500 kg for 0.08m^2 of collecting area

Innovative technologies for mirror elements are pursued at MSFC, SAO, GSFC, MIT, etc. Optics Working Group is in place, with a charge to facilitate technology development, industry participation, and assist the STDT with the trades and development of the technology development roadmap.

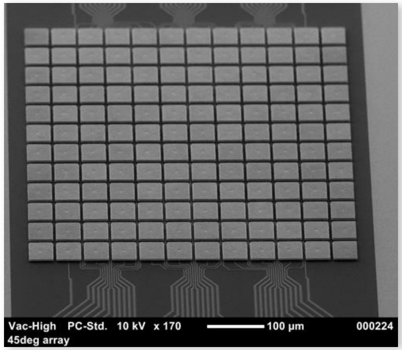
High throughput with sub-arcsec resolution

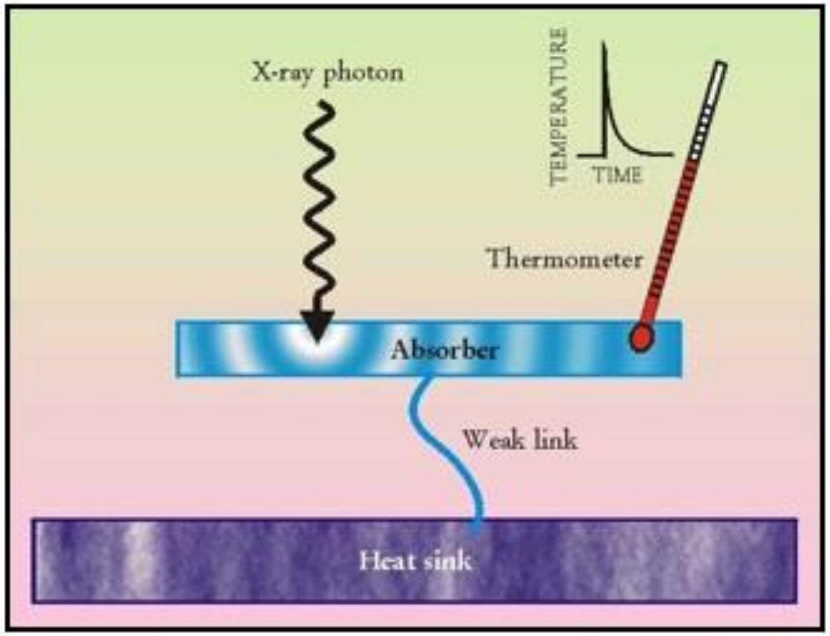


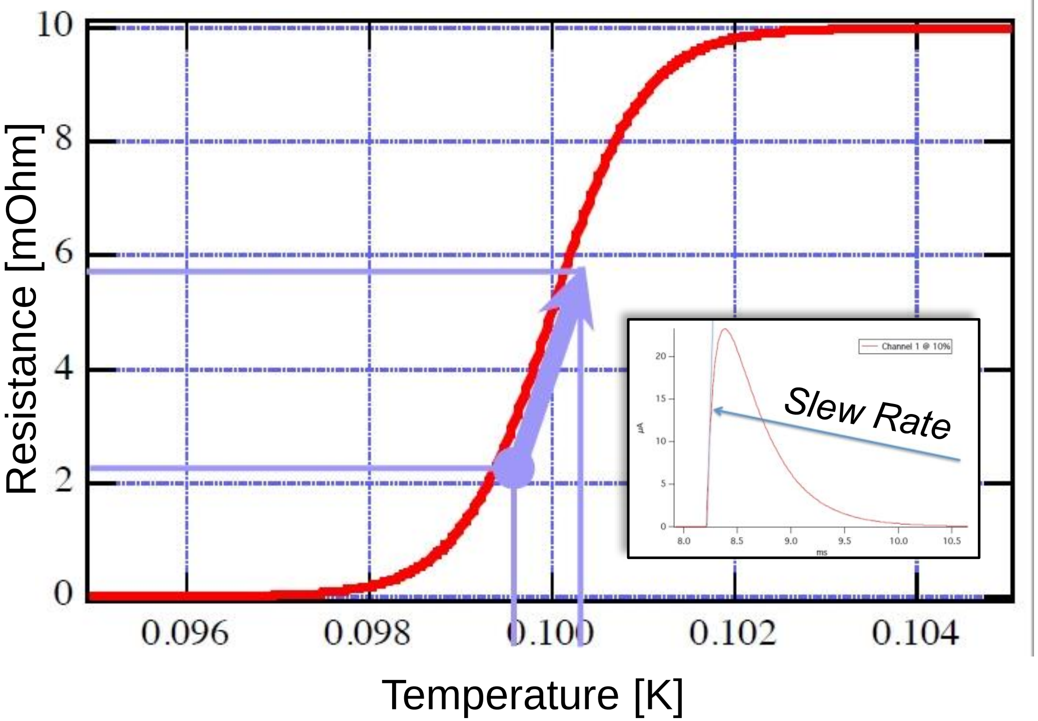
- × 50 more effective area than *Chandra.*
- × 16 larger solid angle for sub-arcsec imaging — out to 10 arcmin radius
- × 800 higher survey speed at the Chandra Deep Field limit

X-ray Microcalorimeter Imaging Spectrometer (“Whiskers”)

Parameter	**Goal**
Energy Range	0.2 – 10 keV
Spatial Resolution	1 arcsec
Field-of-View	5 arcmin x 5 arcmin (min)
Energy Resolution	< 5 eV
Count Rate Capability	< 1 c/s per pixel
Pixel Size / array size (10-m focal length)	50 µm pixels / 300 x 300 pixel array





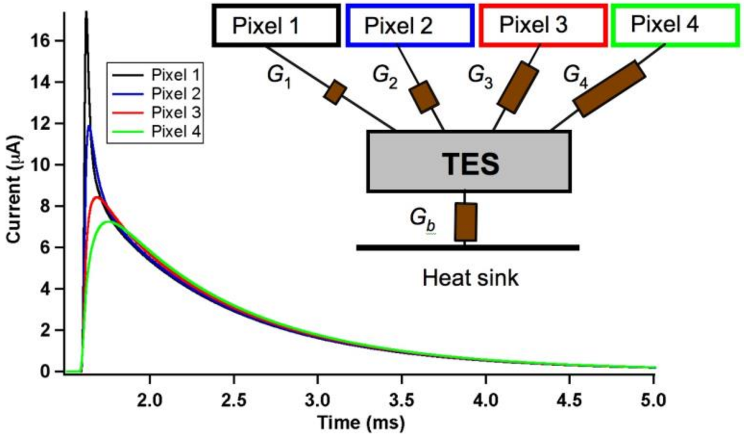


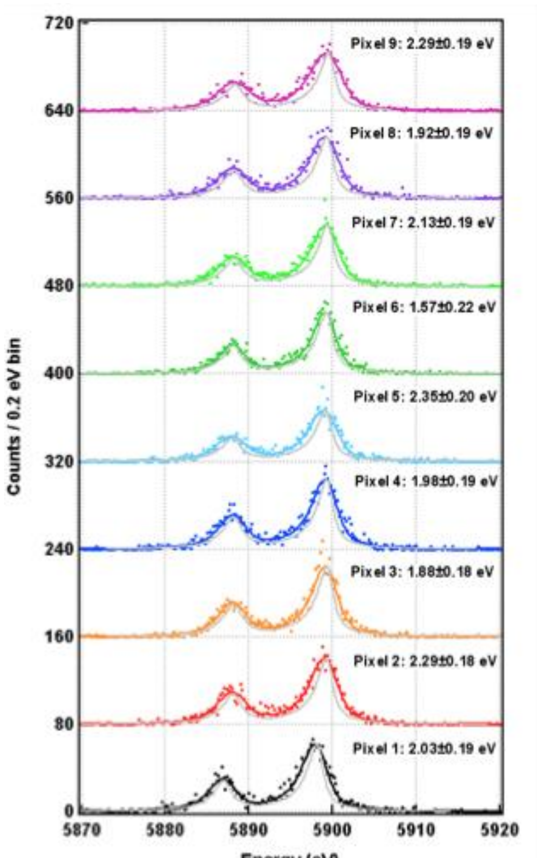
__Challenge:__ Develop multiplexing approaches for achieving ~10^5 pixel arrays

X-ray Microcalorimeter Imaging Spectrometer (“Whiskers”)

Progress with respect to multiplexing:

- Transition Edge Sensors (TES) with SQUID readout.
- Multiple absorbers per one TES (“Hydra”design)





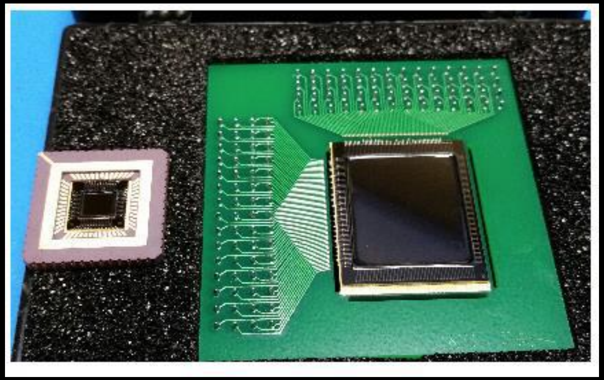
- Lab results with 3 × 3 Hydra, 65μm pixels on 75 μm pitch shows 2.4 eV (FWHM) resolution at 6 keV
- 20-absorber TES Hydras have been successfully implemented. Absorbers are 50x50x4.2μm electroplated Au
- $<\Delta E_{FWHM}> = 3.39 \pm 0.18$ eV at Cr(5.4 keV) for all 20 pixels.

Smith, S.J., et al., IEEE Trans. on Appl. Superconductivity, 2009
Kilbourne, C., et al, response to RFI : Concepts for the Next X-ray Astronomy Mission submission, 2011

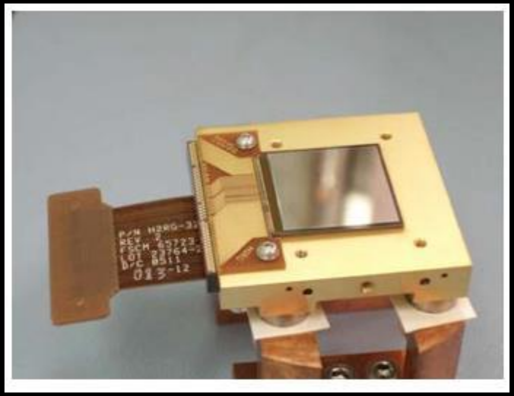
High Definition X-ray Imager ("Spots")

Parameter	Goal
Energy Range	0.2 – 10 keV
Field of View	22 arcmin x 22 arcmin
Energy Resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Quantum Efficiency	> 90% (0.3-6 keV), > 10% (0.2-9 keV)
Pixel Size / Array Size	<16 µm (< 0.33 arcsec/pixel) / 4096 x 4096 (or equivalent)
Frame Rate	> 100 frames/s (full frame) > 10000 frames/s (windowed region)
Read Noise	< 4e$^-$ rms

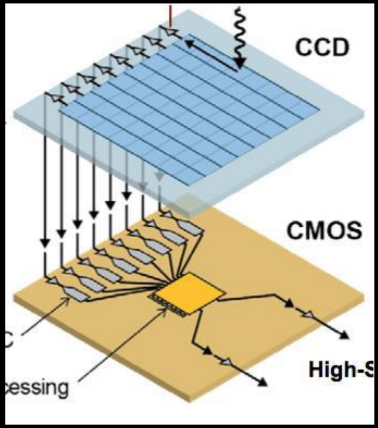
All have been demonstrated individually



Monolithic CMOS (Sarnoff/SAO, and MPE)



Hybrid CMOS (TBE/PSU)



Digital CCDs w/ CMOS readout (LL/MIT)

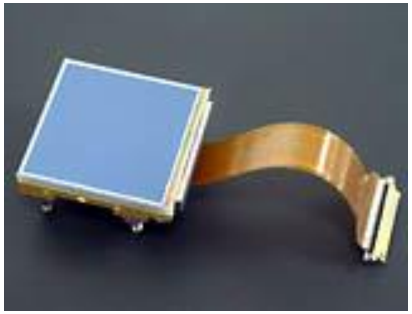
Challenges: Develop sensor package that meets all requirements, and approximates the optimal focal surface

Advantages of Active Pixel Sensors

Current State of the Art

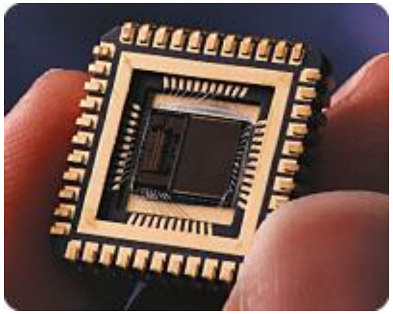
- All of the key requirements are met by one or more of the sensor technologies
- No single sensor meets them all – lots of work to do!

Teledyne



Hybrid
– Multiple bonded layers, with layers for photon detection and readout circuitry optimized independently
-Need lower read noise <4e⁻

Sarnoff

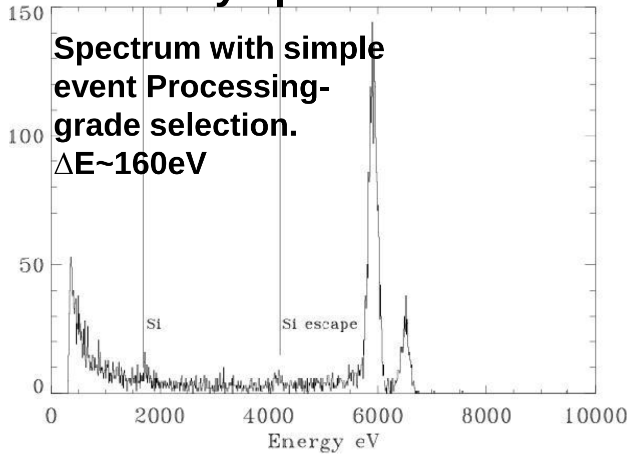


Monolithic
– Single Si wafer used for both photon detection and read out electronics
– *Need improved QE*

Key Advantages:

- Orders of magnitude higher frame rates: (>100 full-frame/sec, >10000 subframe/sec)
- Significantly improved radiation hardness
- Fully addressable (i.e. high speed windowing)
- Near Fano-limited resolution over entire bandpass
- Lower power
- Near room temperature operation
- Large format (up to 4Kx4K abuttable devices)

55Fe x-ray spectrum. T=300K



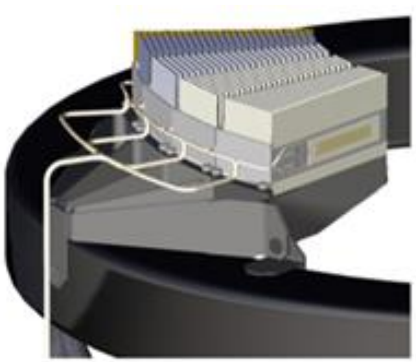
X-Ray Grating Spectrometer ("Claws")

Resolving power = 5000 & effective area = 4000 cm^2

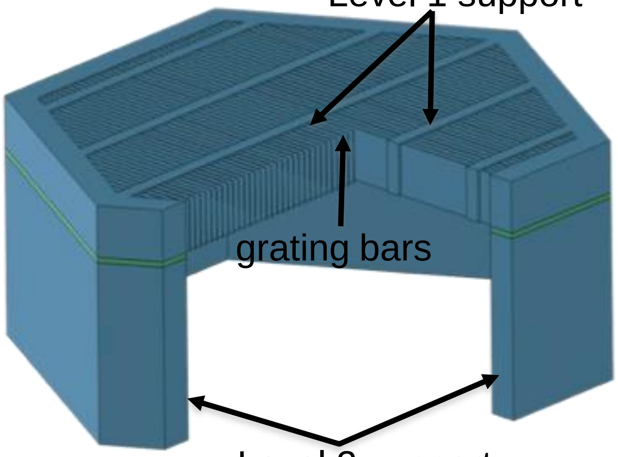
- Energy range 0.2 – 2.0 keV

Blazed Off-Plane Reflection gratings

(Univ. of Iowa)



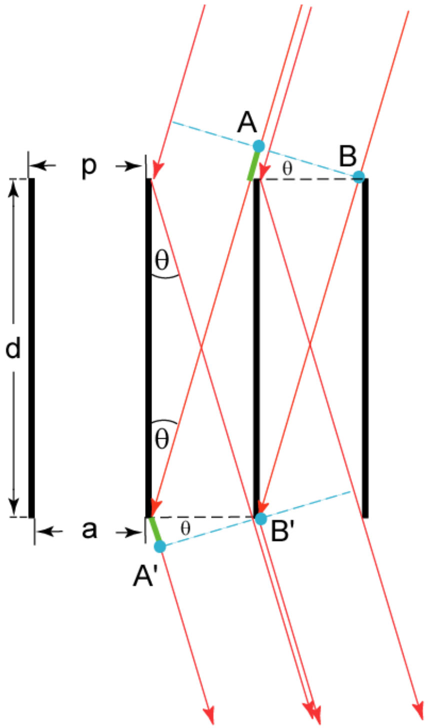
Critical Angle Transmission (CAT) gratings (MIT)



Challenges: improving yield, developing efficient assembly processes, and improving efficiency

Critical Angle Transmission Gratings (MIT)

- CAT grating combines advantages of transmission gratings (relaxed alignment, low weight) with high efficiency of blazed reflection gratings.
- Blazing achieved via reflection from grating bar sidewalls at graze angles below the critical angle for total external reflection.
- High energy x rays undergo minimal absorption and contribute to effective area at focus.



Grating equation:

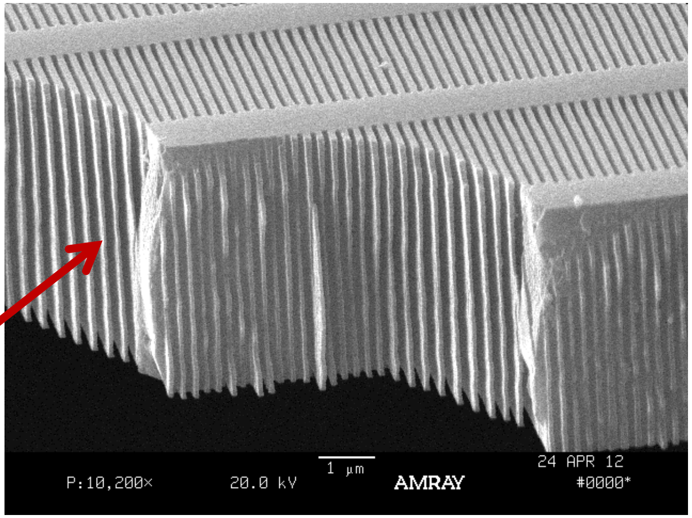
$m\,\lambda = p\,(\sin(\theta) + \sin(\beta_m))$,
m = diffraction order

Blazing: $\beta_m \sim \theta$

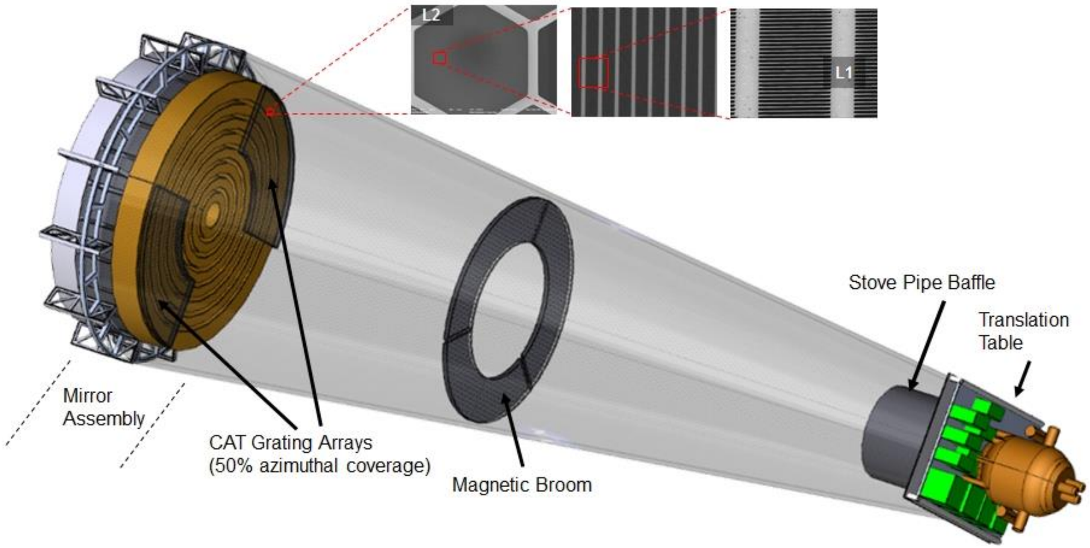
High reflectivity:
$\theta < \theta_c$ = critical angle of total external reflection

Strawman:
Silicon grating, $\theta = 1.5^{\circ}$
p = 200 nm
b = 40 nm
d = 6 μm
aspect ratio d/b = 150

200 nm pitch
CAT grating bars

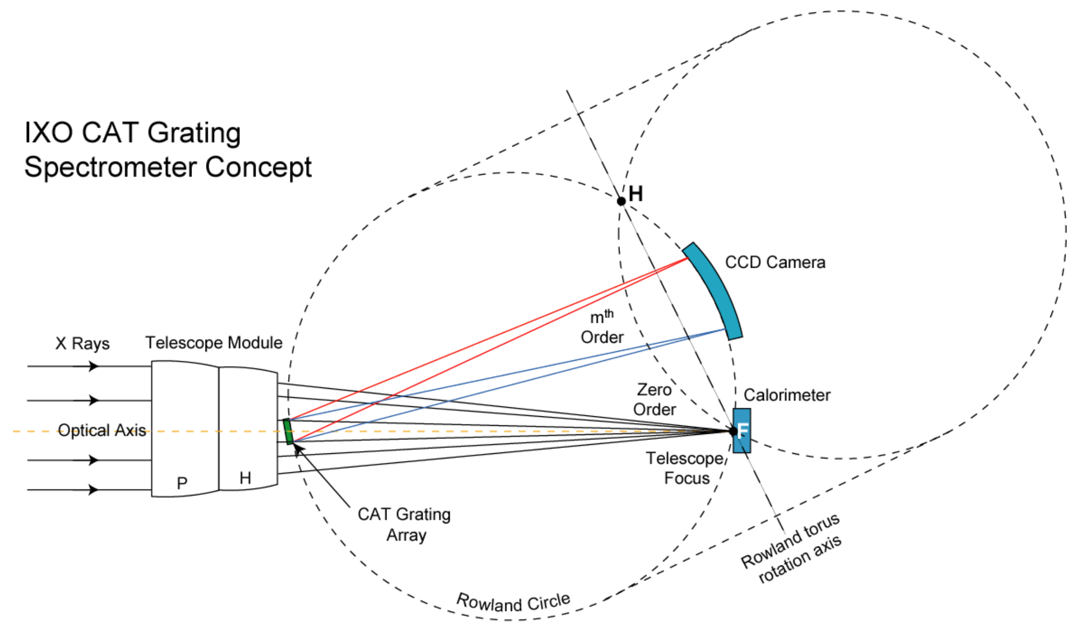


Critical Angle Transmission Gratings (MIT)

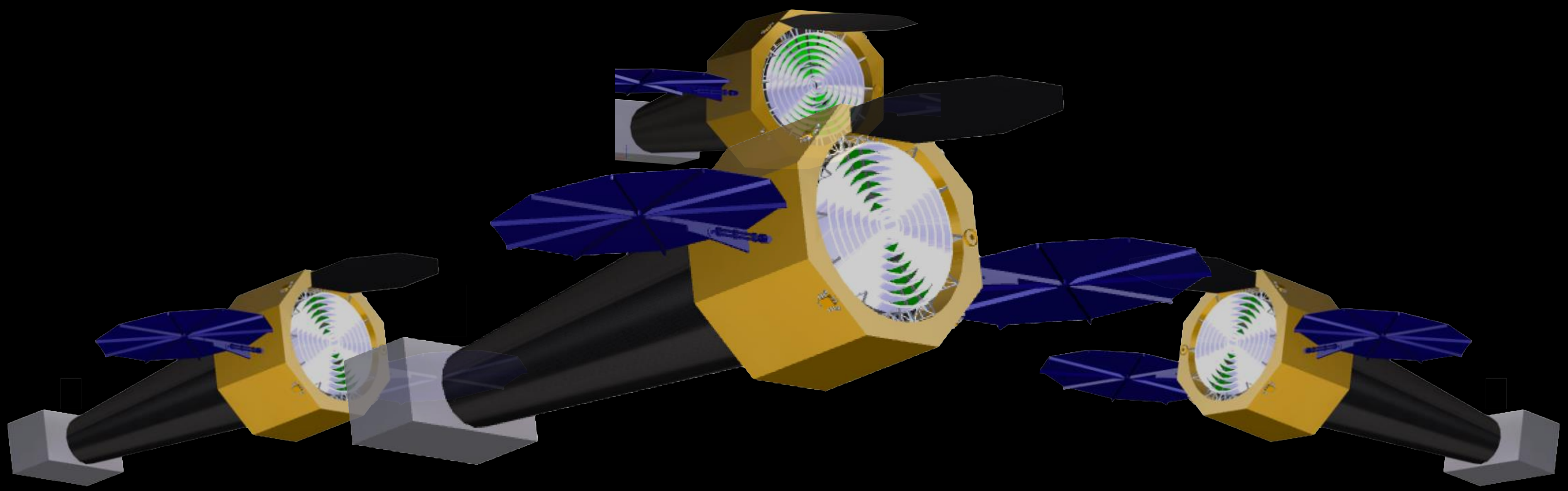


Advantages:
- low mass
- relaxed alignment & figure tolerances
- high diffraction efficiency
- up to 10X dispersion of Chandra HETGS
- no positive orders (i.e., smaller detector)

- Gratings, camera, and focus share same Rowland torus.
- Blazed gratings; only orders on one side are utilized.
- Only fraction (50%) of mirrors is covered: "sub-aperturing" boosts spectral resolution.



LYNX
X-ray vision into the "Invisible Universe"
for true understanding of the origins and underlying physics of the cosmos



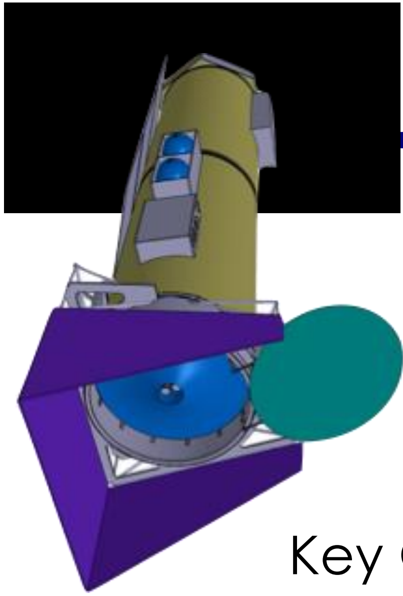
- ***Leaps in Capability:*** large area with high angular resolution for 2–3 orders of magnitude gains in sensitivity, field of view with subarcsec imaging, high resolution spectroscopy for point-like and extended sources. May be possible with a *Chandra*-like overall mission envelope.

- ***Scientifically compelling:*** frontier science from Solar system to first accretion light in Universe; revolution in understanding physics of astronomical systems.

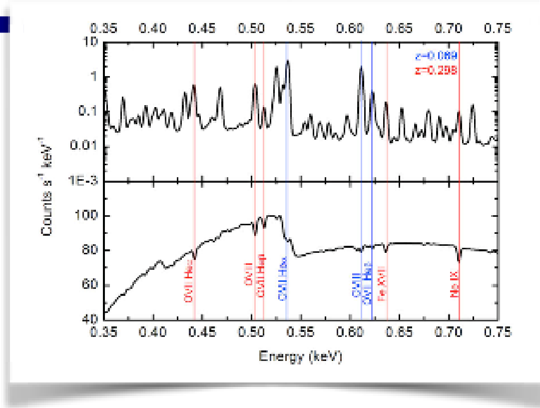
- ***Synergy:*** Great synergy and complementarity with the next-generation facilities —JWST, WFIRST, GSMT, LISA, ALMA, SKA

wwwastro.msfc.nasa.gov/lynx

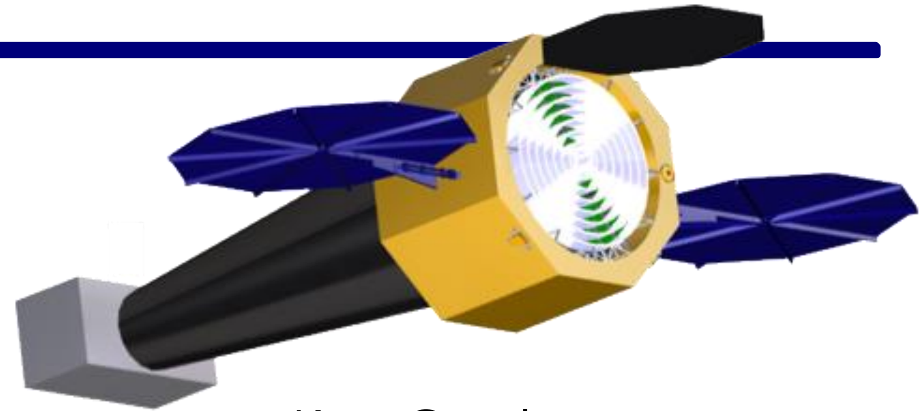
BACKUP SLIDES



Athena



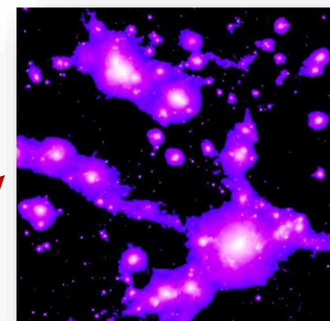
X-ray Surveyor



Key Goals:

- Microcalorimeter spectroscopy ($R \approx 1000$)
- Wide, medium-sensitivity surveys

Area is built up at the expense of angular resolution (10× worse) & sensitivity (5× worse than *Chandra*)



Chandra

Key Goals:

- Sensitivity (50× better than *Chandra*)
- $R \approx 1000$ spectroscopy on 1″ scales, adding 3rd dimension to data
- $R \approx 5000$ spectroscopy for point sources

✓ Area is built up while preserving *Chandra* angular resolution (0.5″)

✓ 16× field of view with sub-arcsec imaging

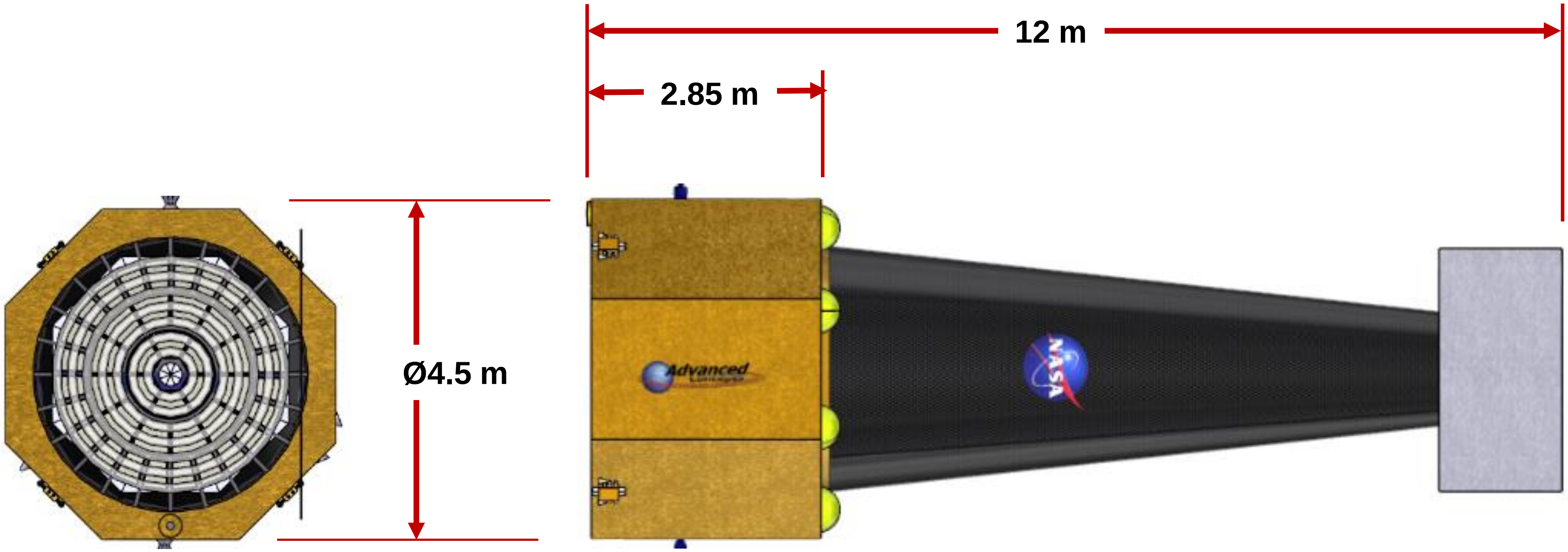
A Successor to *Chandra*

- Angular resolution at least as good as *Chandra*
- Much higher photon throughput than *Chandra* (observations are photon-limited)

✓Incorporated relevant prior (Con-X, IXO, AXSIO) development and *Chandra* heritage

✓ Limits most spacecraft requirements to *Chandra-like*

✓ Achieves *Chandra-like* cost ($2.95B for Phase B through launch)



The Lynx Science Case

Doug Swartz
Universities Space Research Association

Discovery Space Science vs Targeted Questions

Great Observatories of the 1980's and 1990's:

- *Hubble, Compton, Chandra, Spitzer*
- Open Discovery Space

Targeted Missions addressing Specific Questions:

- *Planck, Kepler*
- Meeting Gov't-funded "Metrics"

What will be the mission for the 2030's ?

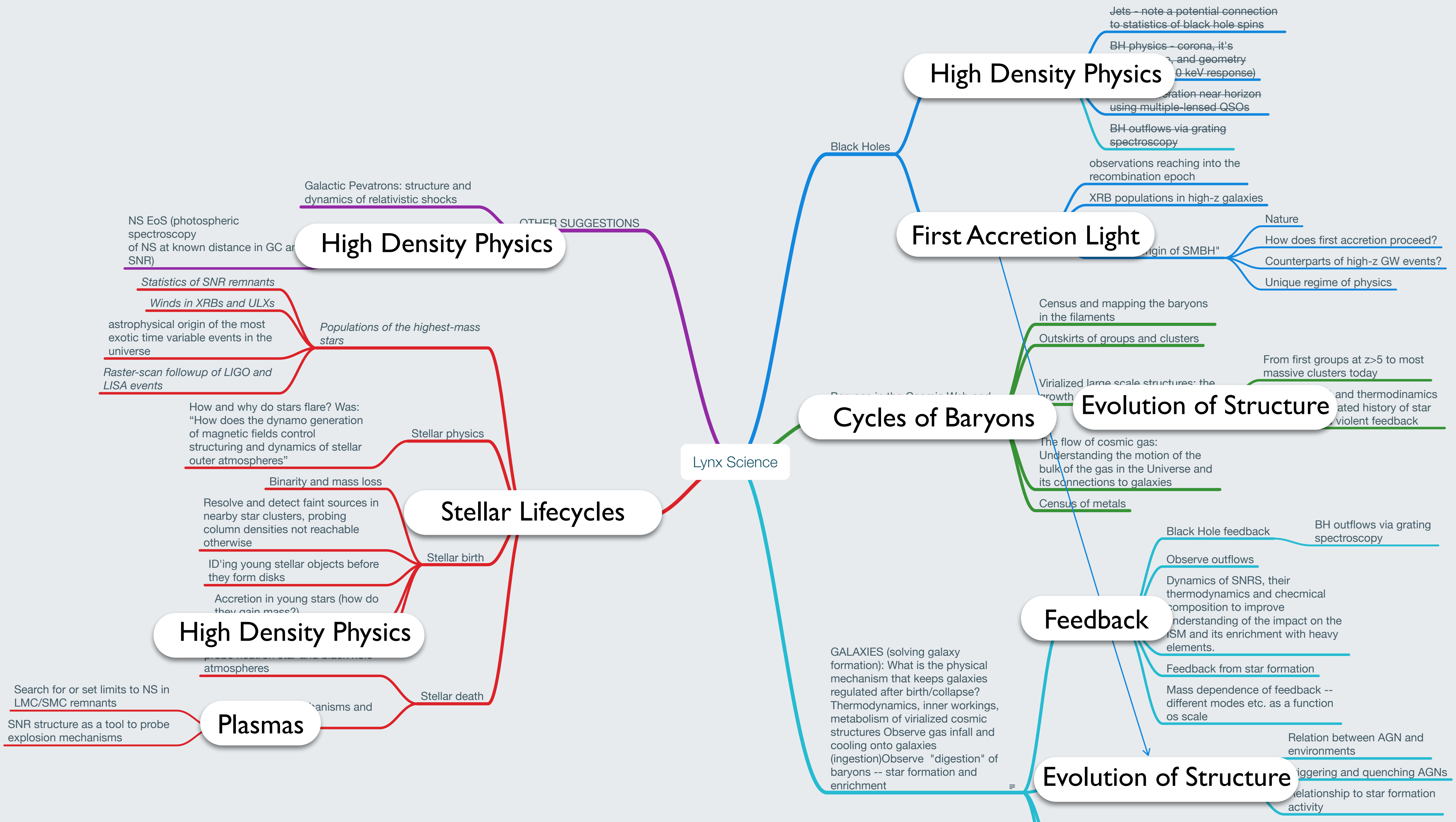
- Steve Kahn @ Lynx Synergy Workshop

Key Theme: How Did We Get Here?

- NASA Science Mission Directorate - PCOS Program

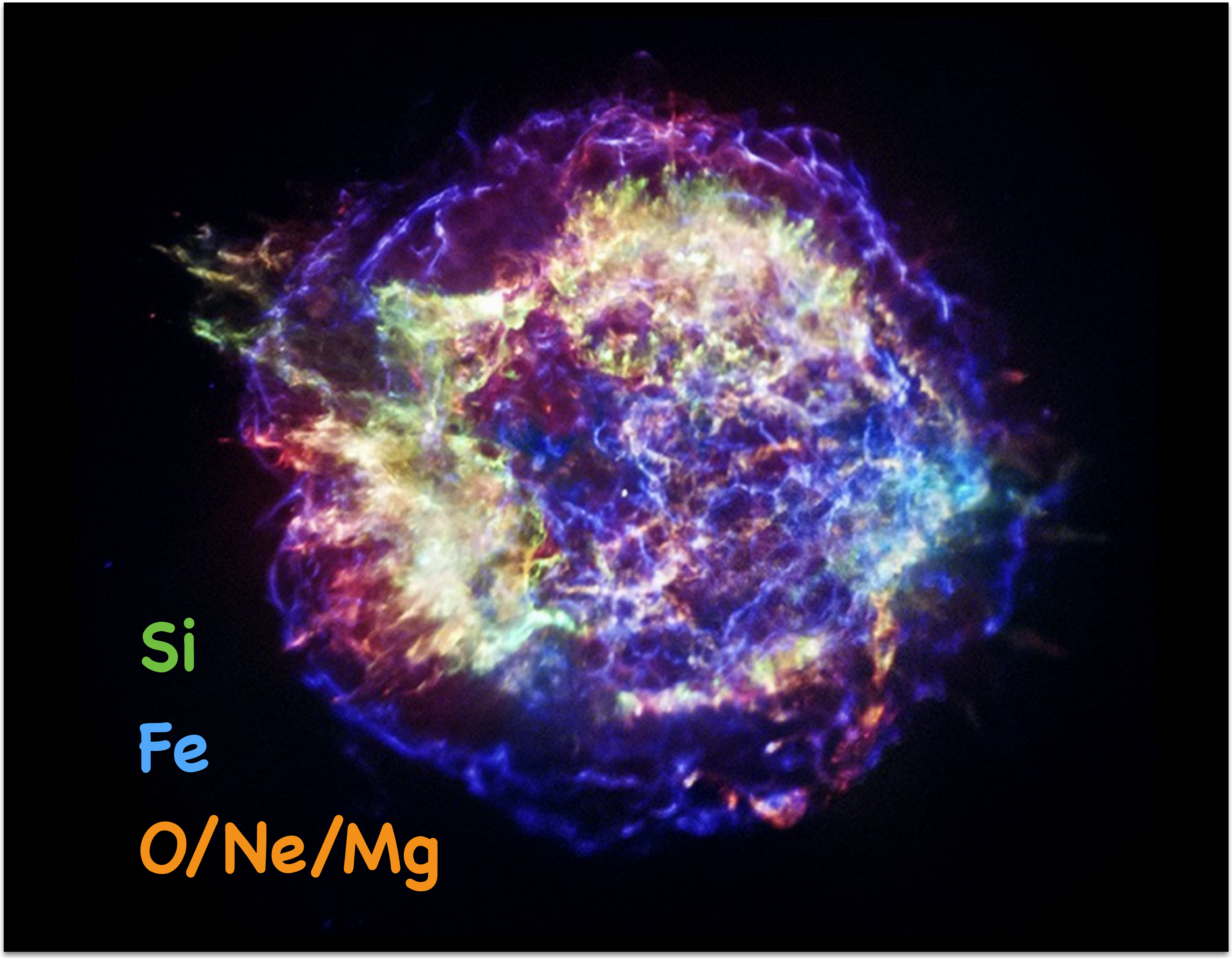
Though astronomers have been studying stars for thousands of years, it is only in the past 35 or so years that they have been able to employ instruments that detect light across the entire electromagnetic spectrum–from radio waves to gamma rays–to peer into the dusty clouds where stars are born in our own Galaxy. **If we are to comprehend how the universe makes stars–and planets that orbit them today–we must continue to study stars and galaxies with ever more powerful telescopes.**

It is still unknown whether the universe created black holes with the first generation of stars or whether these exotic objects were created by the first generation of stars. **Because black holes represent the most extreme physical conditions of spacetime and generate some of the most energetic phenomena following the Big Bang, black holes are the ultimate physical laboratories for testing theories of the universe.**

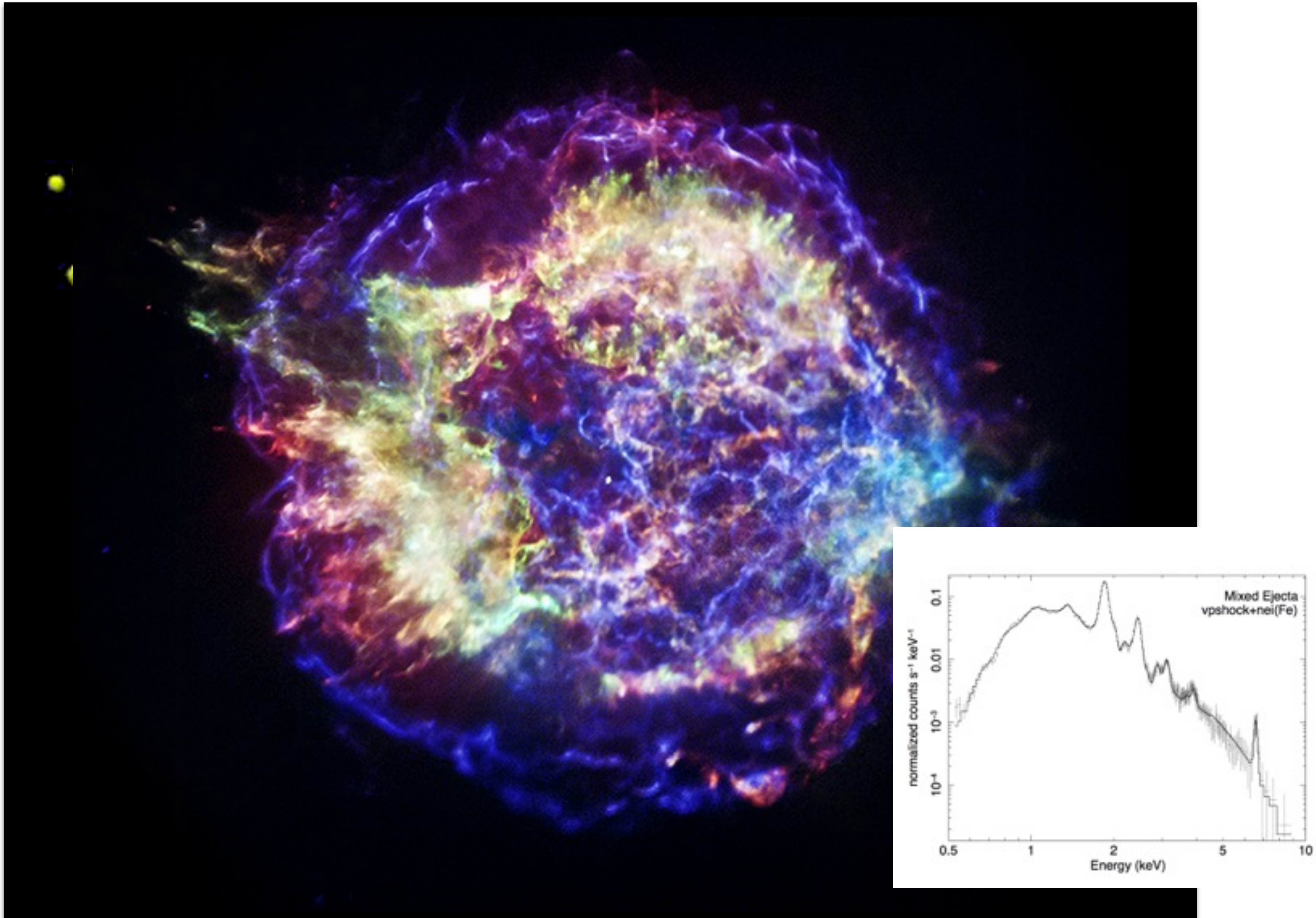


Seven Science Working Groups

Cassiopeia A SNR



Cassiopeia A SNR



Imagine what can be done with a micro-calorimeter !

NGC 6357 Star-Forming Region

Supernova-blown Cavities

- Giant HII region w/ 3 MYSCs
- 1.7 kpc distant; ~30' diameter
- 3100 X-ray sources
  - magnetic reconnection flares, protostars, massive star wind shocks
  - add IR: best stellar census
- unresolved emission is hot plasma due to massive star wind shocks
- transport of metals
  - ISM heating = star formation quenching, gas dispersion, turbulence
    =>stellar feedback

orange IR (cold gas+dust) blue Optical (HII)
purple X-ray (stars+hot gas)

- Leisa Townsley et al.

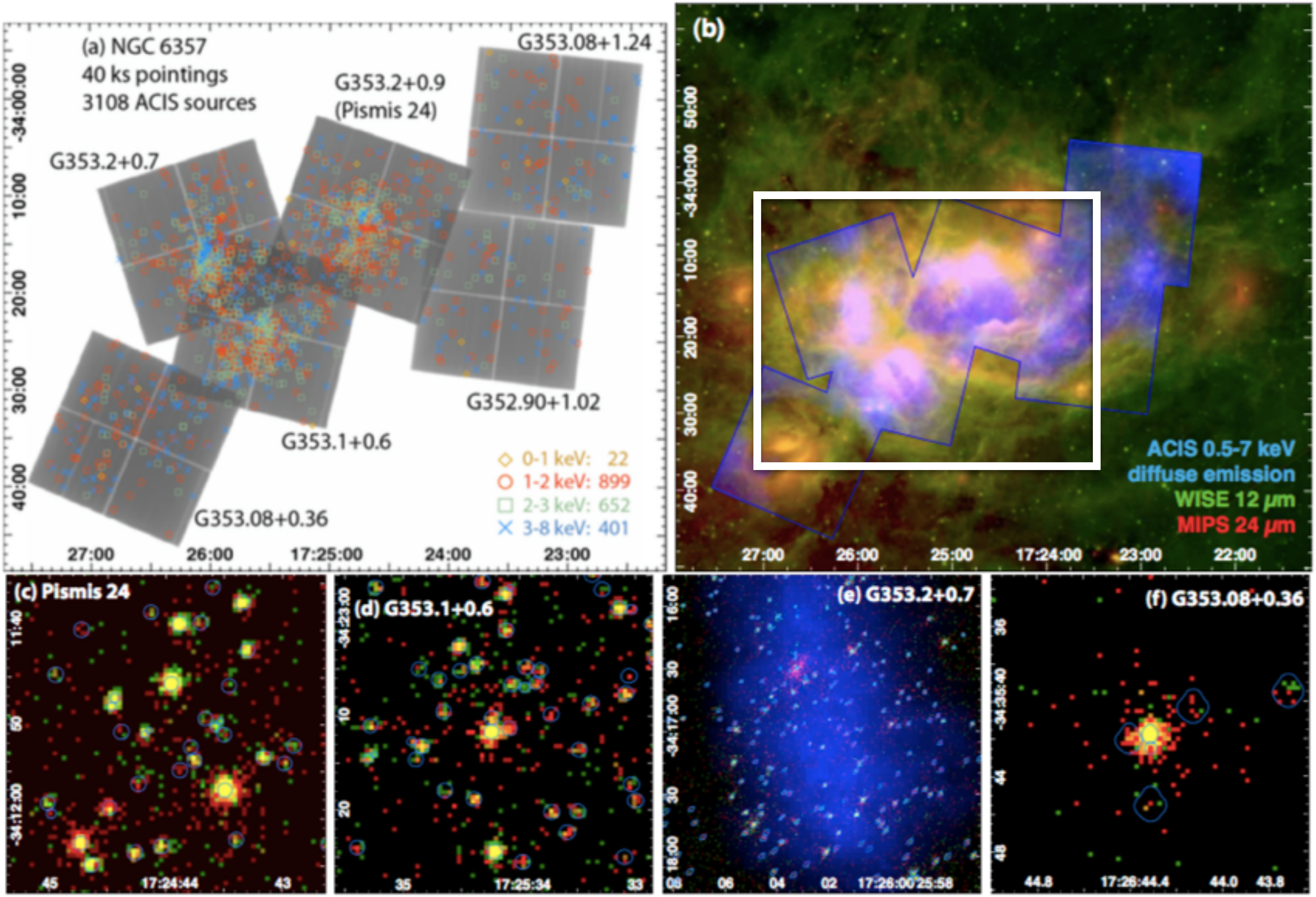
NGC 6357 Star-Forming Region

- Giant HII region w/ 3 MYSCs
- 1.7 kpc distant; ~30' diameter
- 3100 X-ray sources
  - magnetic reconnection flares, protostars, massive star wind shocks
  - add IR: best stellar census
- unresolved emission is hot plasma due to massive star wind shocks
- transport of metals
  - ISM heating = star formation quenching, gas dispersion, turbulence

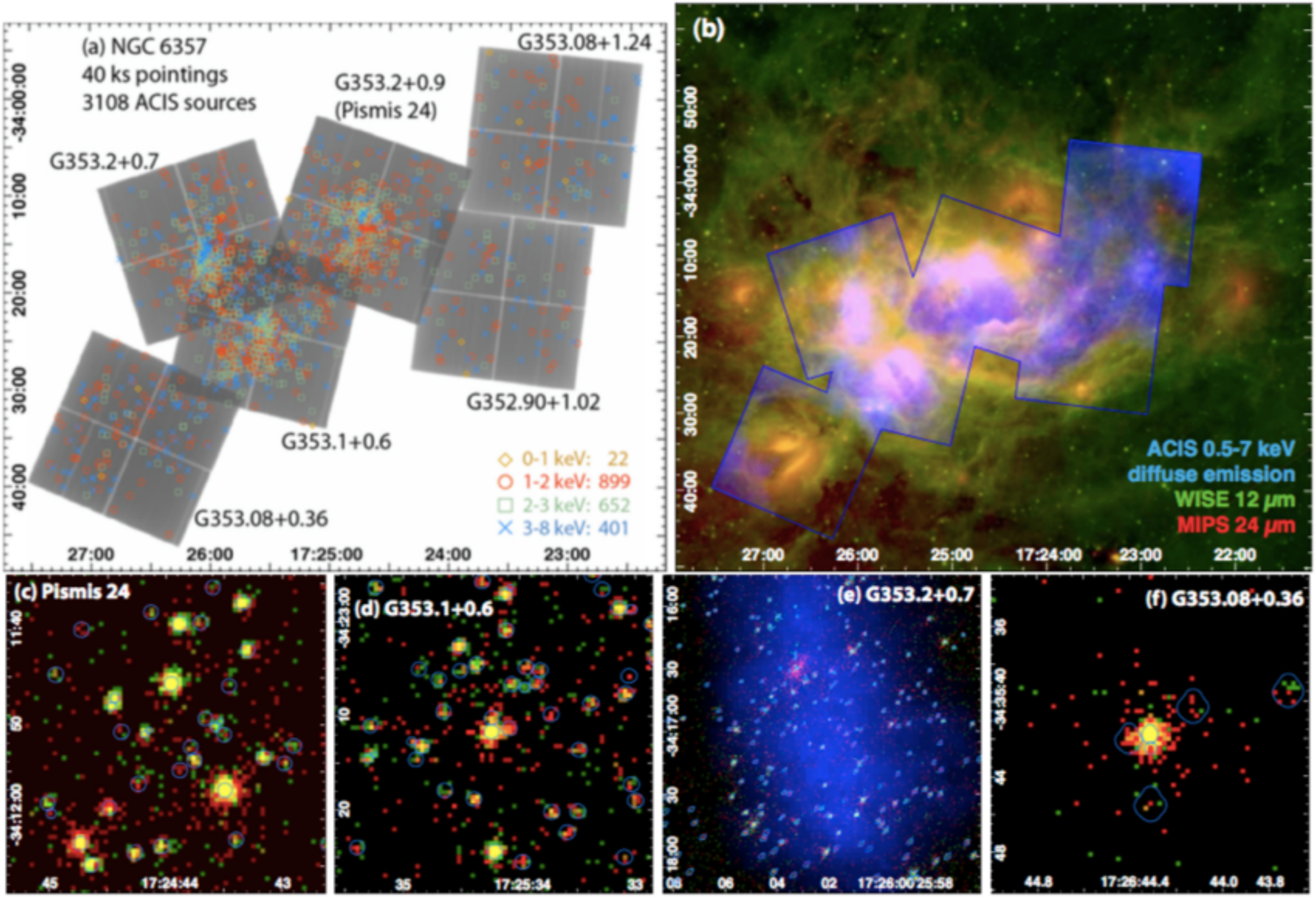
    =>stellar feedback

orange IR (cold gas+dust) blue Optical (HII)
purple X-ray (stars+hot gas)

- Leisa Townsley et al.



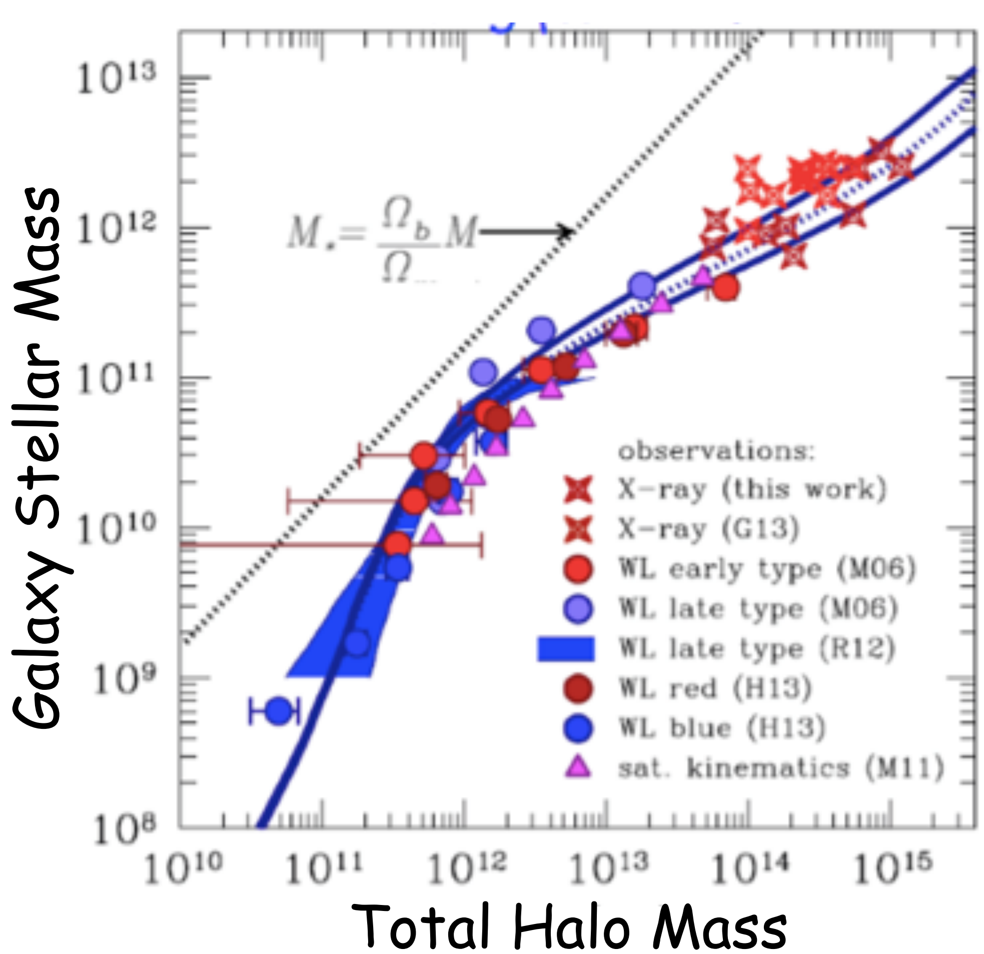
(a) NGC 6357
40 ks pointings
3108 ACIS sources
G353.08+1.24
G353.2+0.9
(Pismis 24)
G353.2+0.7
G352.90+1.02
G353.1+0.6
G353.08+0.36
0-1 keV: 22
1-2 keV: 899
2-3 keV: 652
3-8 keV: 401
(b)
ACIS 0.5-7 keV
diffuse emission
WISE 12 μm
MIPS 24 μm
(c) Pismis 24
(d) G353.1+0.6
(e) G353.2+0.7
(f) G353.08+0.36



Imagine Chandra resolution with 30x throughput !

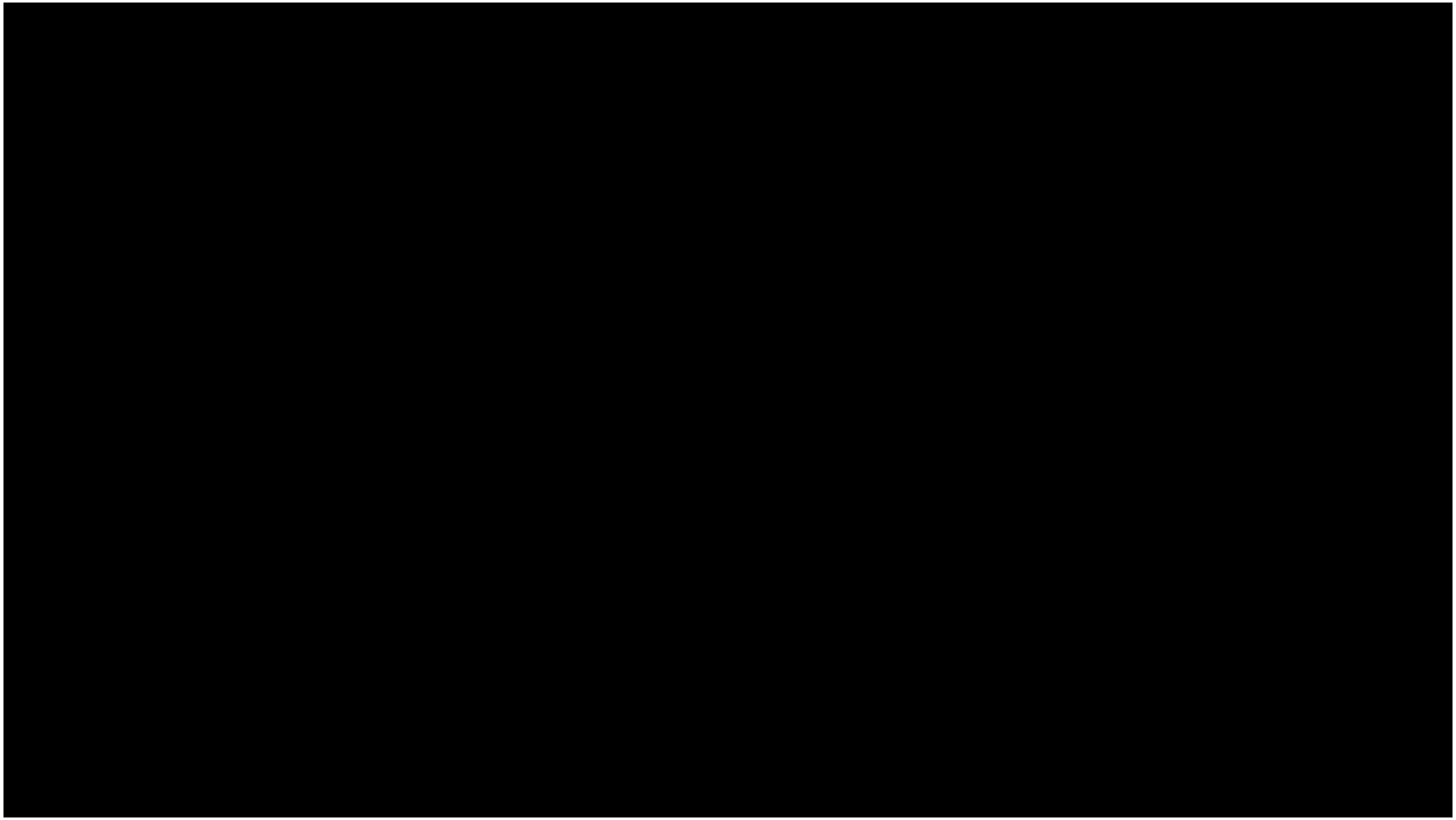
M82 Starburst Galaxy

- **stellar feedback** extends to galactic scales
- drives baryons into the CGM and regulates galaxy growth
- SNe in dwarf galaxies
- **AGN feedback** in massive galaxies



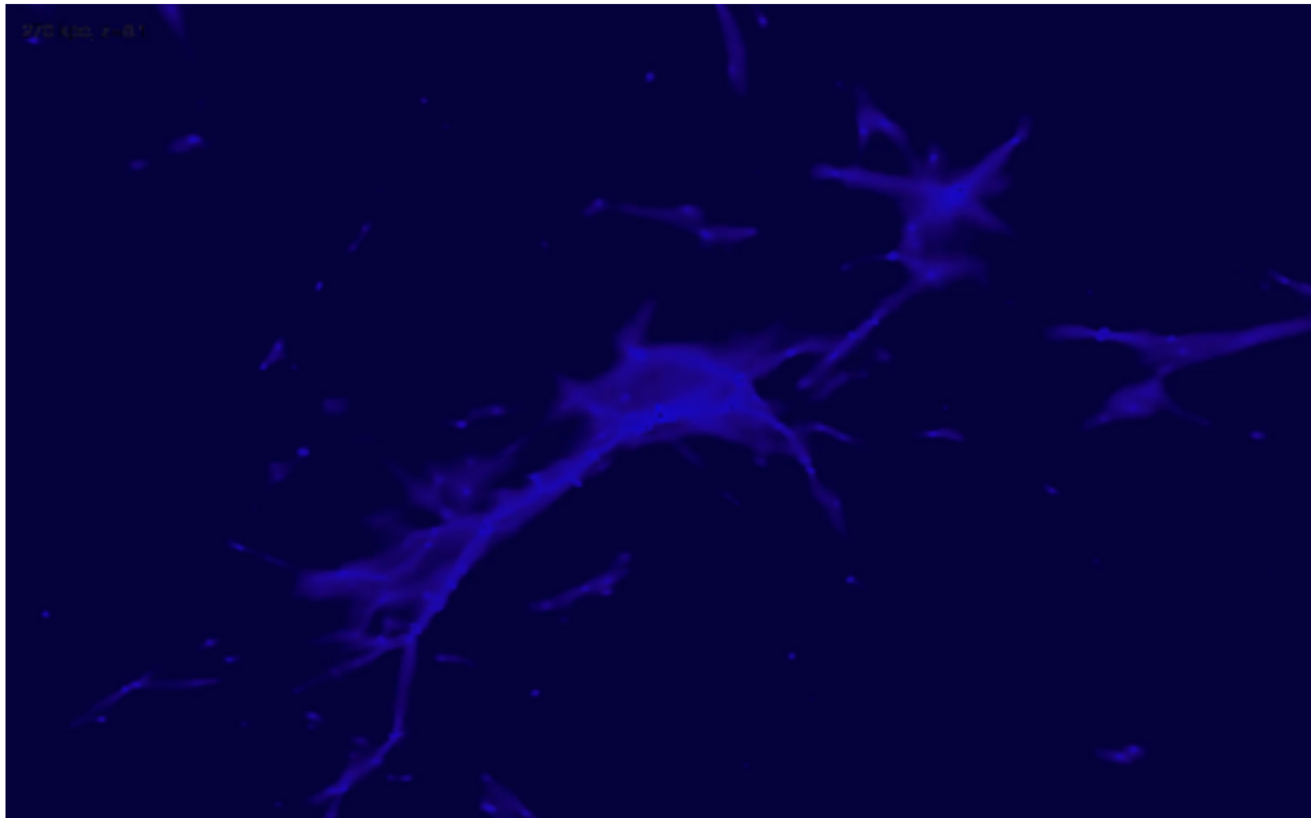
cool warm and hot X-ray-emitting galactic super wind in M82

Optical light sees 'only' the stars



- actual distribution of galaxies in the nearby Universe to z~0.1
- traces the Cosmic Web filaments, galaxy groups, and clusters of galaxies

Optical light sees 'only' the stars



- **AGN feedback** regulates growth of LSS (groups/clusters) at cosmic web 'nodes'
- Hot, diffuse IGM contains most of the baryons (UV absorption spectra sample only a small fraction)

- Color denotes gas Temperature
- Same simulations but different feedback treatments give very different observational results

- Agertz & Kravtsov ApJ (2015)

Imagine tracing the Cosmic Web with X-ray spectroscopy !

First accretion light in the Universe

OPEN QUESTIONS

Masses of initial BH seeds
Early accretion history of seed BHs
Contribution to Re-ionization
Observational signatures of Super-Eddington flows
Importance of mergers
When do the correlations between BHs and their hosts get set-up

- Priya Natarajan @ X-ray Vision Workshop

First accretion light in the Universe

Low-mass Seeds from Pop III stars at z~20

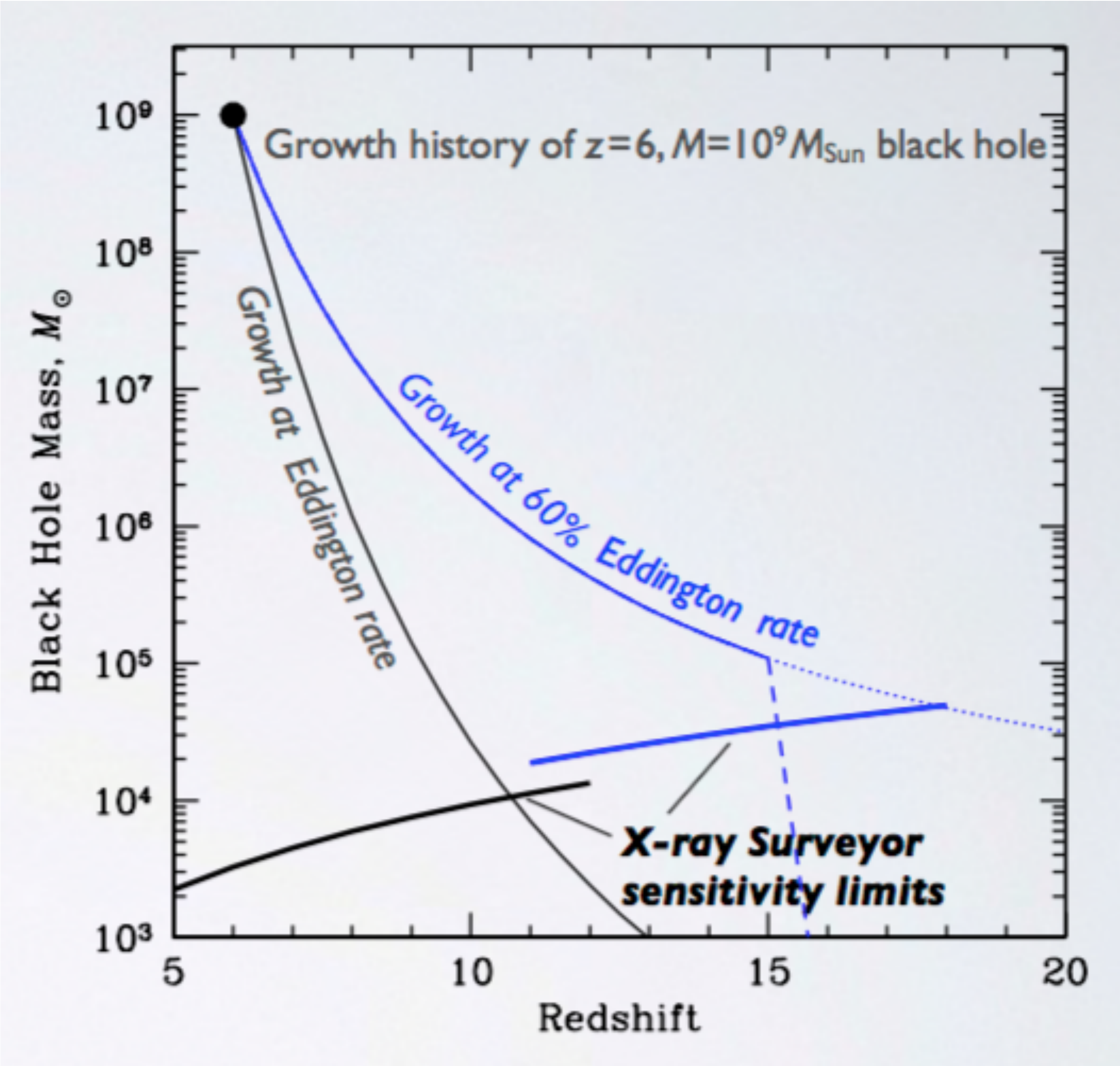
- 10-100 $M/M_\odot$ but mass and number of first stars uncertain
- A challenge to grow to 10^9 $M/M_\odot$ by z~3; requires super-Eddington growth

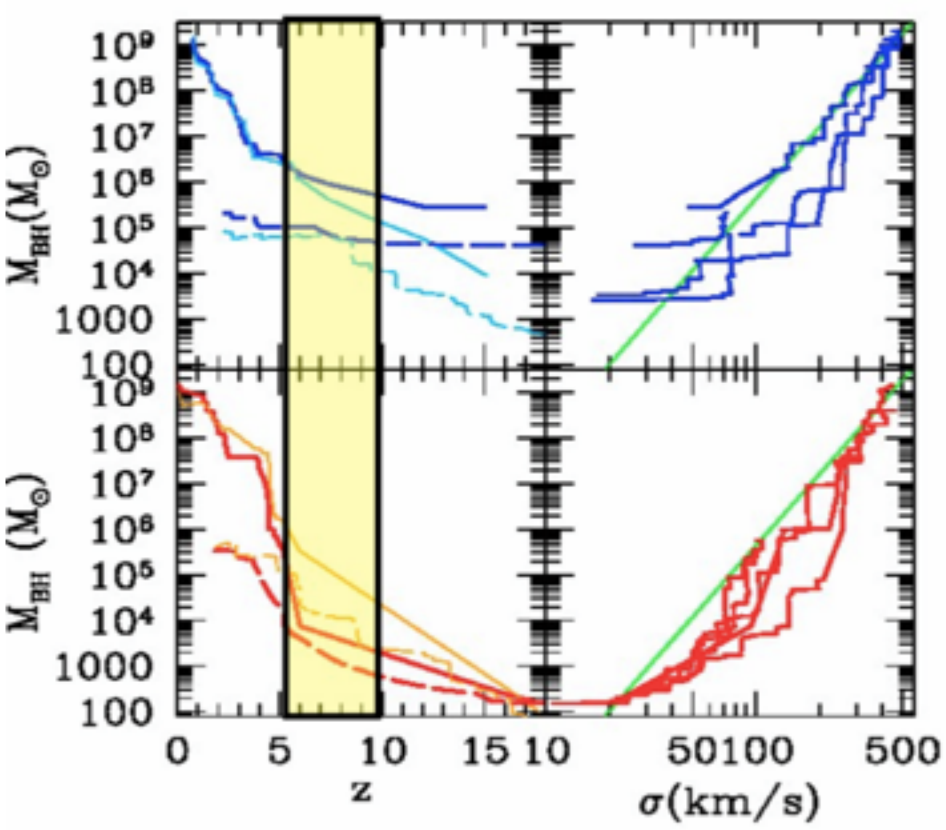
Massive Seeds by Direct Collapse

- 1000 $M/M_\odot$ collapse of a nuclear star cluster
- Higher mass seeds only postulated
- Must mitigate H_2 cooling
- Must avoid fragmentation of porto-galaxy & centrally concentrate mass

Masses of Initial Black Hole Seeds

First accretion light in the Universe





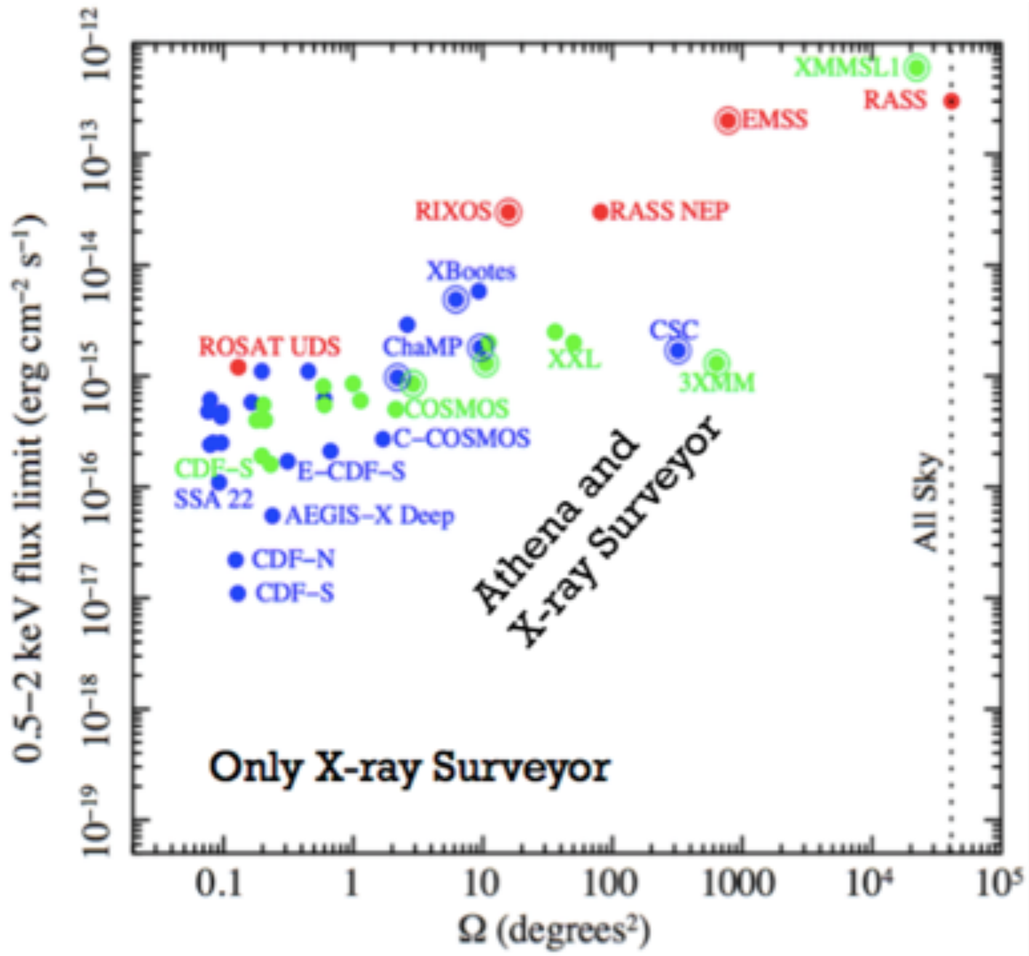
massive seeds

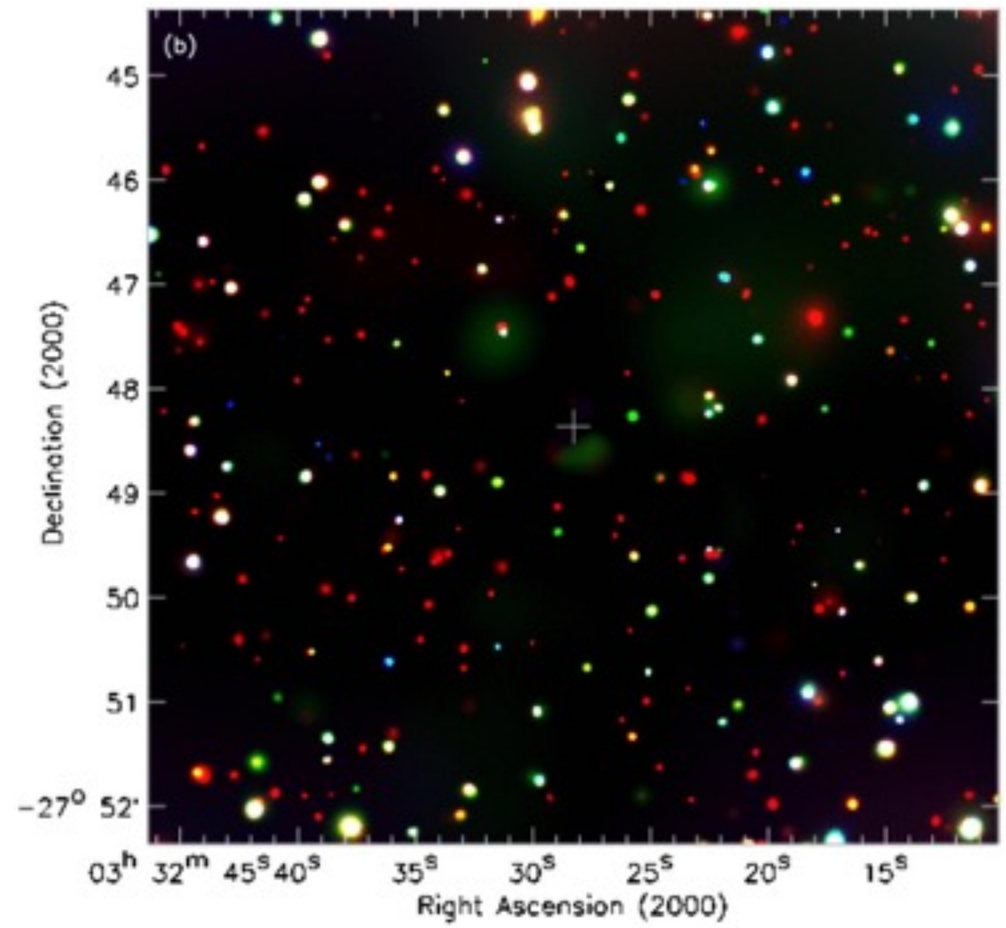
vs.

Pop III remnants

Early accretion history of seed black holes

First accretion light in the Universe

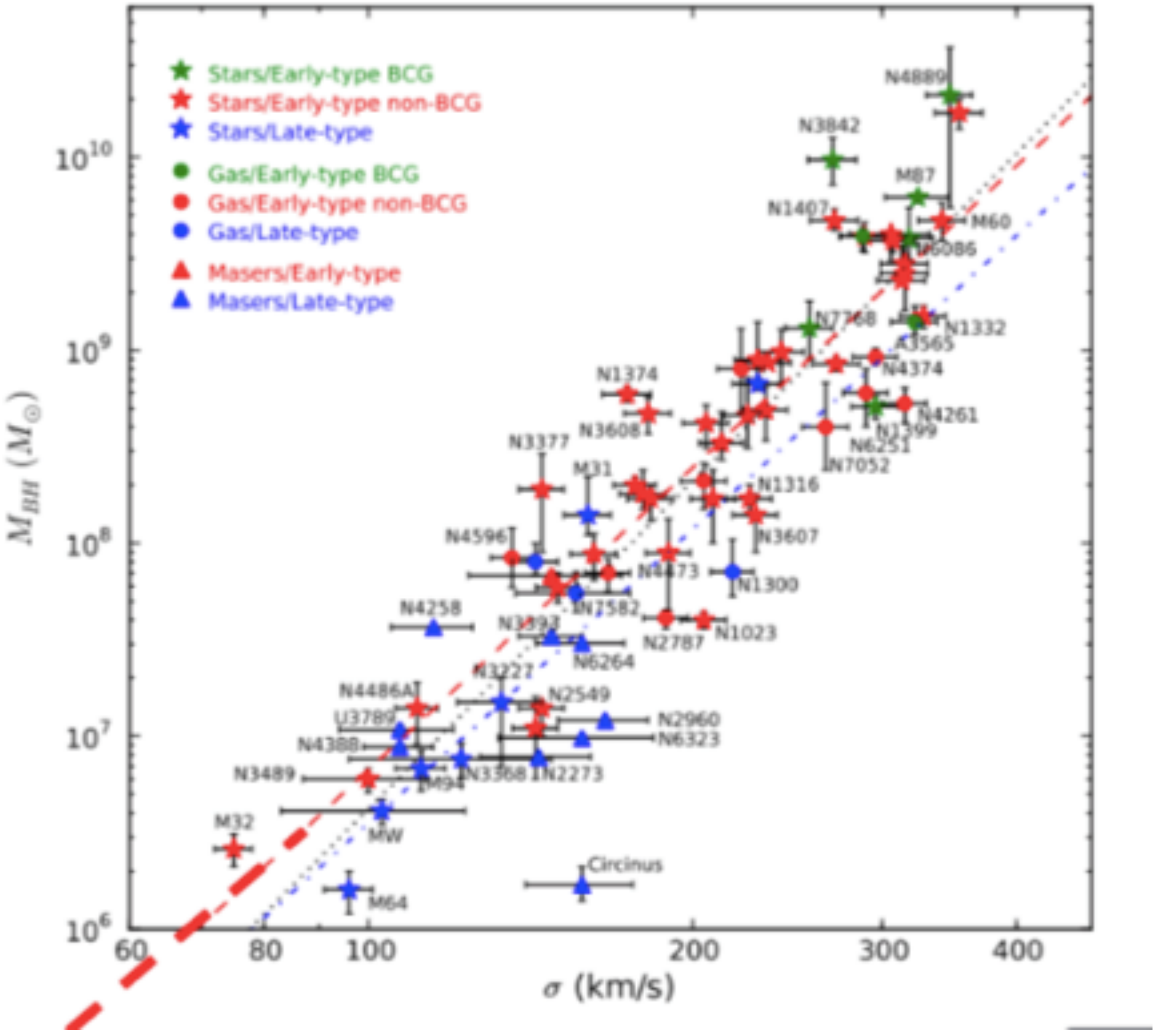


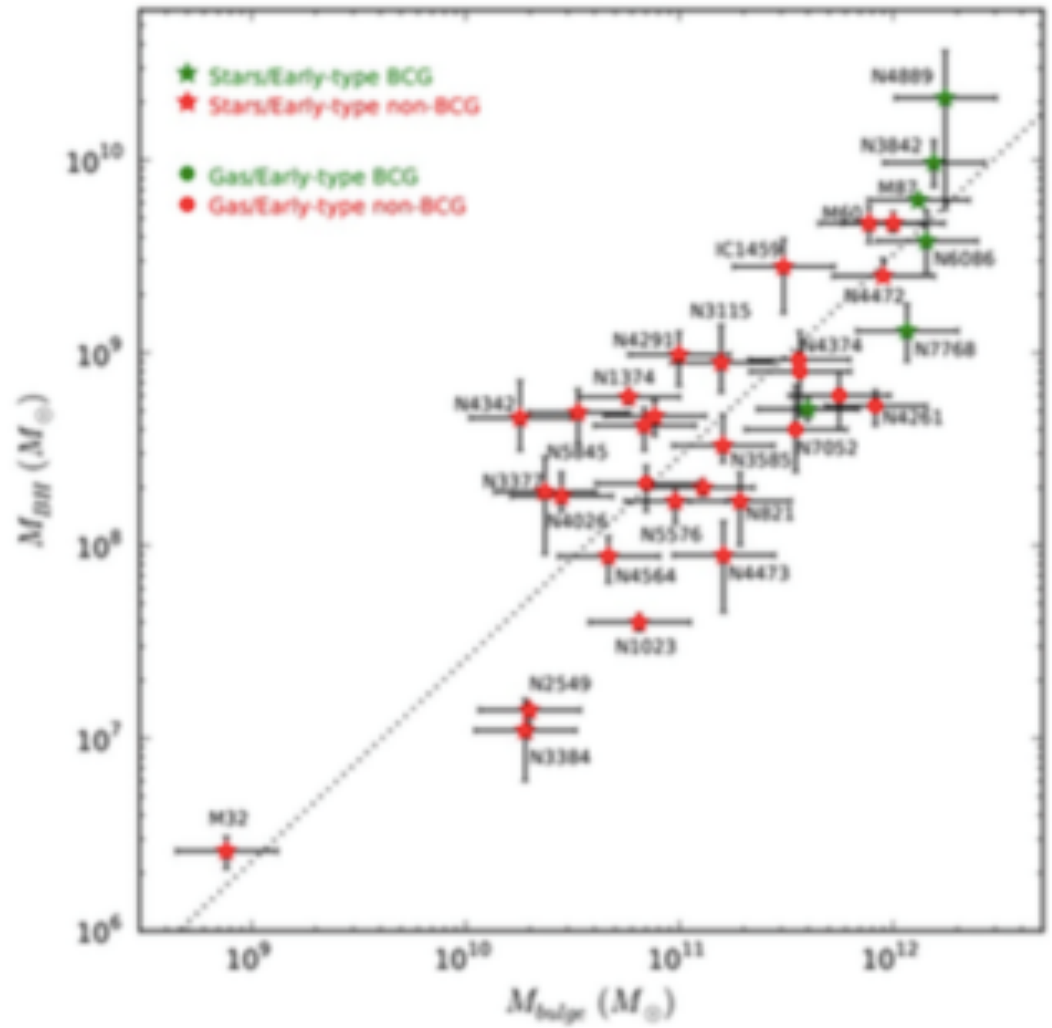


Only Lynx has the sensitivity and angular resolution needed:

- Can detect $5x10^4$ $M_\odot$ seeds at z~10
- Confusion limit: expect only 0.03 galaxies per 0.5" Lynx beam

First accretion light in the Universe





It is still unknown whether the universe created black holes with the first generation of stars or whether these exotic objects were created by the first generation of stars.

When do the correlations between BHs and their hosts get set up

It's tough to make predictions, especially about the future

- Yogi Berra