# *Lynx Mission Concept Study*

*Alexey Vikhlinin (Harvard-Smithsonian Center for Astrophysics)*
*on behalf of the Science & Technology Definition Team*

# *Lynx Science & Technology Definition Team*


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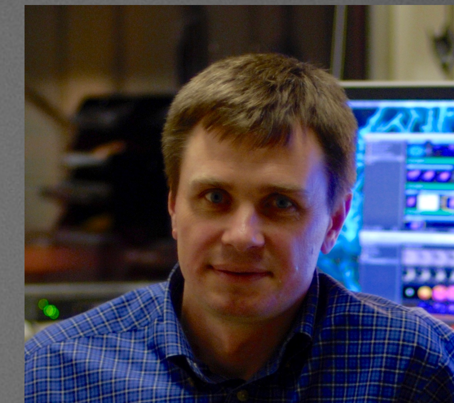
Megan Donahue
MSU


Jessica Gaskin
*MSFC, study scientist*


Laura Lopez
Ohio State


Alexey Vikhlinin (Chair)
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Piero Madau
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Mike Pivovaroff
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Joel Bregman
Michigan


Juna Kollmeier
Carnegie


Fritz Paerels
Columbia

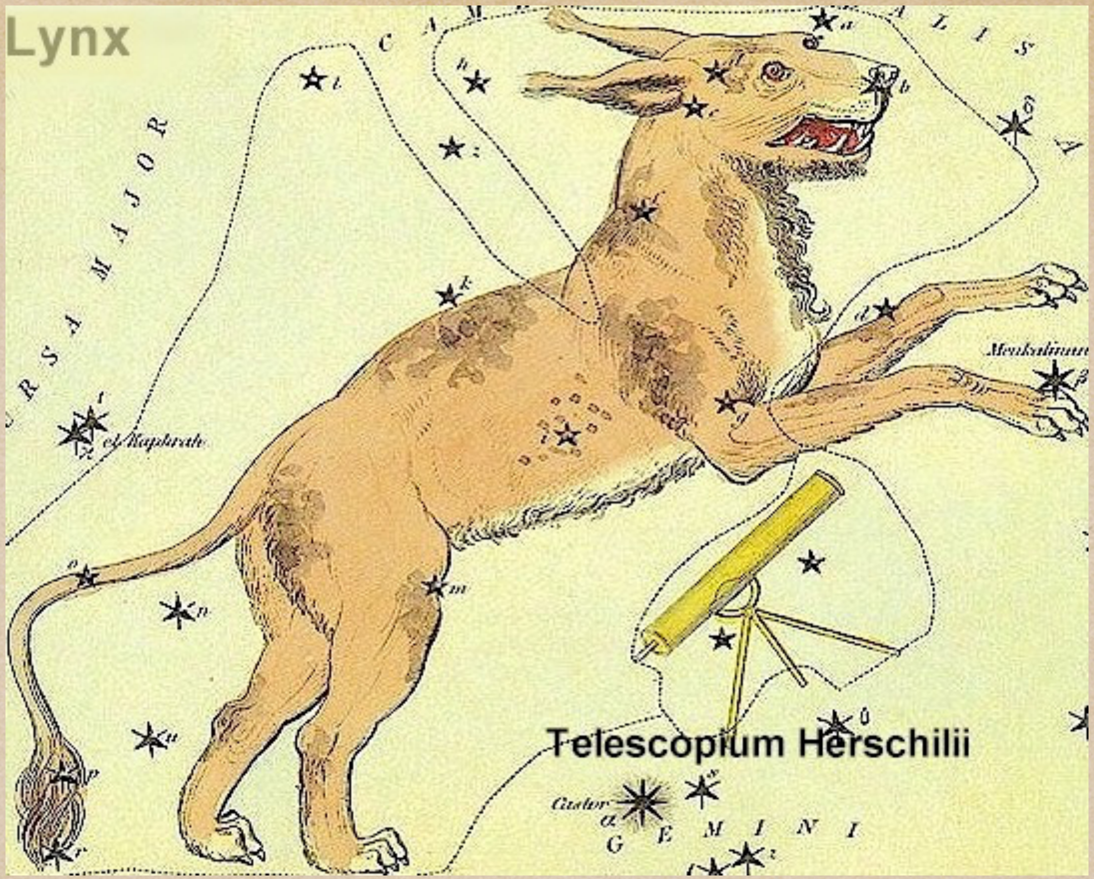

Andy Ptak
GSFC


Daniel Stern
JPL

+7 ex-officio members from NASA and foreign agencies

**+7 Science Working Groups**

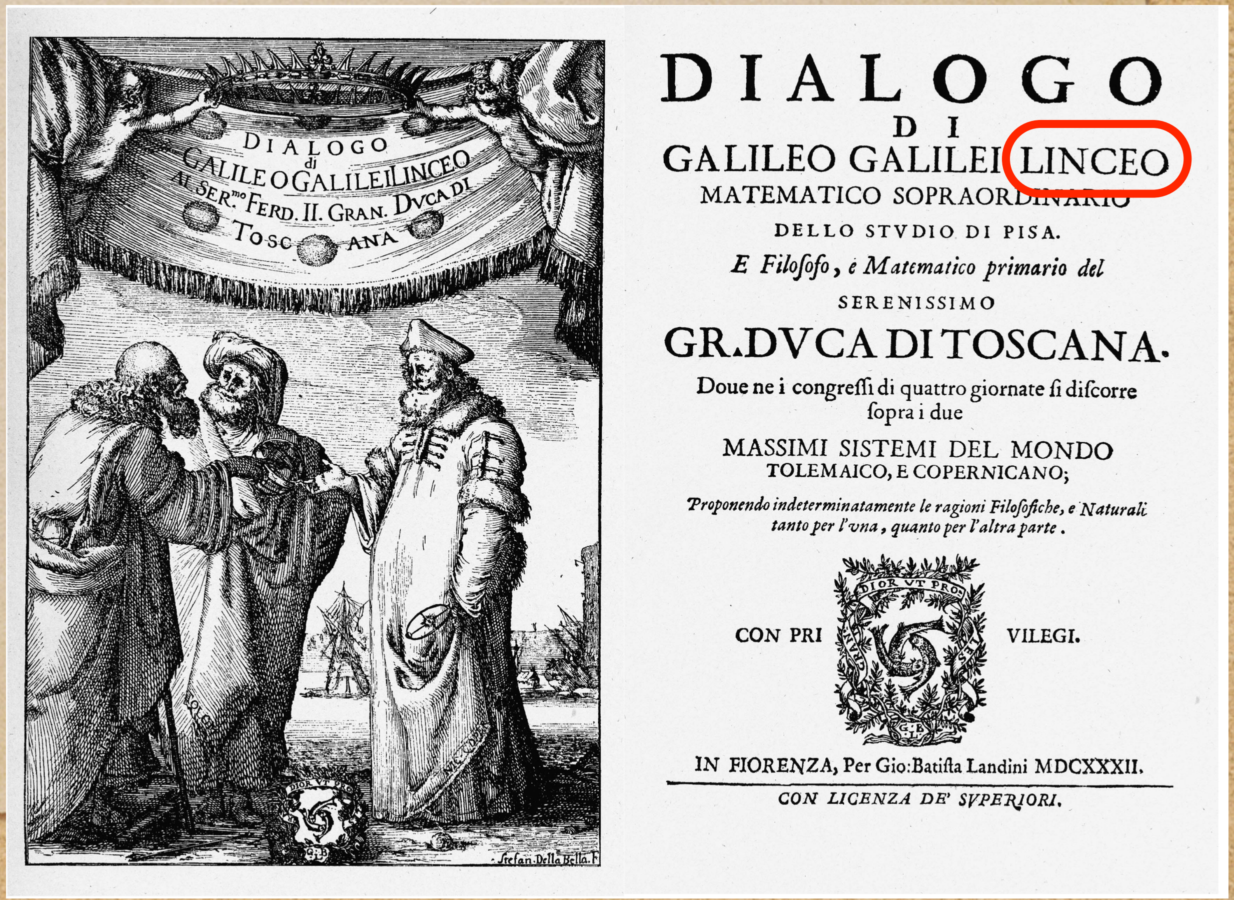
**+ Optics Working Group & Instruments Working Group**




In many cultures and traditions, Lynx is a symbol of supernatural vision, a feline that can see through the trees and rocks.

It is a common historical symbol of science and the search for knowledge, keen insight, and the ability to see the true nature of things.

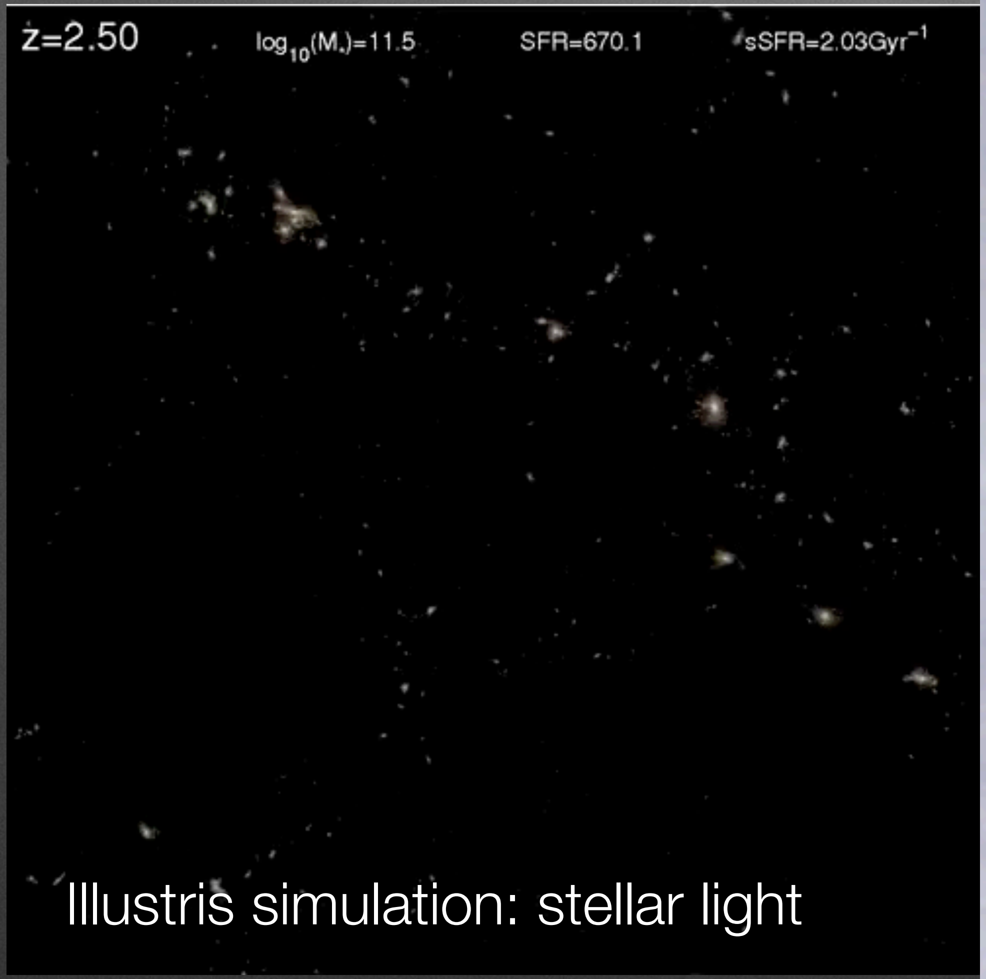
Much of the baryonic matter and the settings of the most active energy release in the Universe are visible primarily or exclusively in the X-rays, so…


DIALOGO di GALILEO GALILEI LINCEO AL SER.mo FERD. II. GRAN. DVCA DI TOSCANA

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'vna, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio:Batiſta Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

***Lynx :***

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

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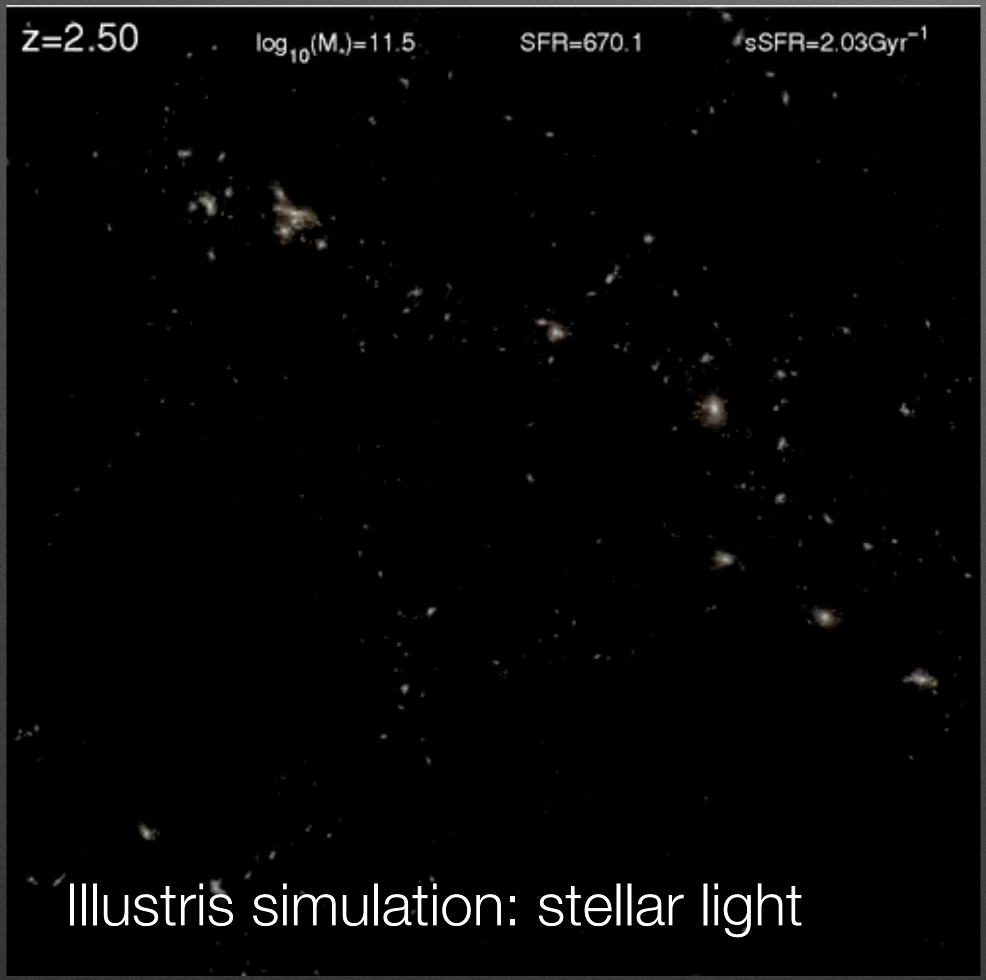
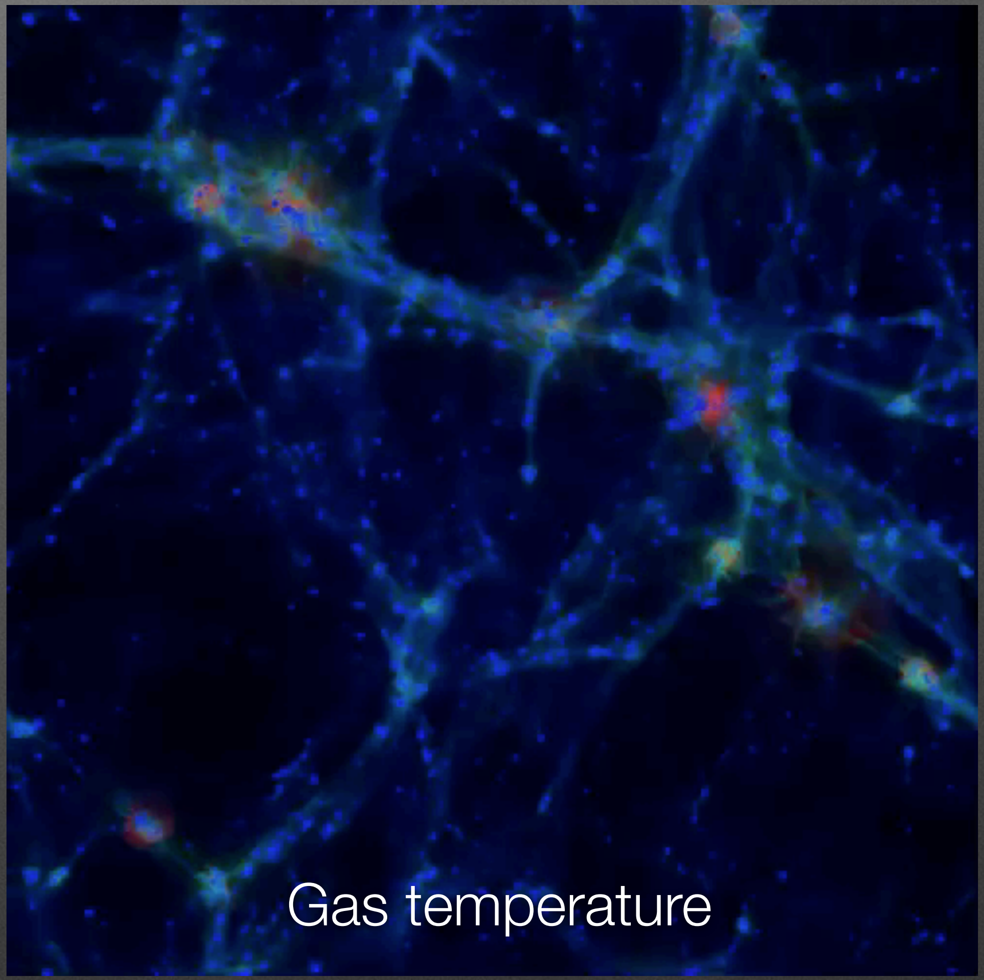
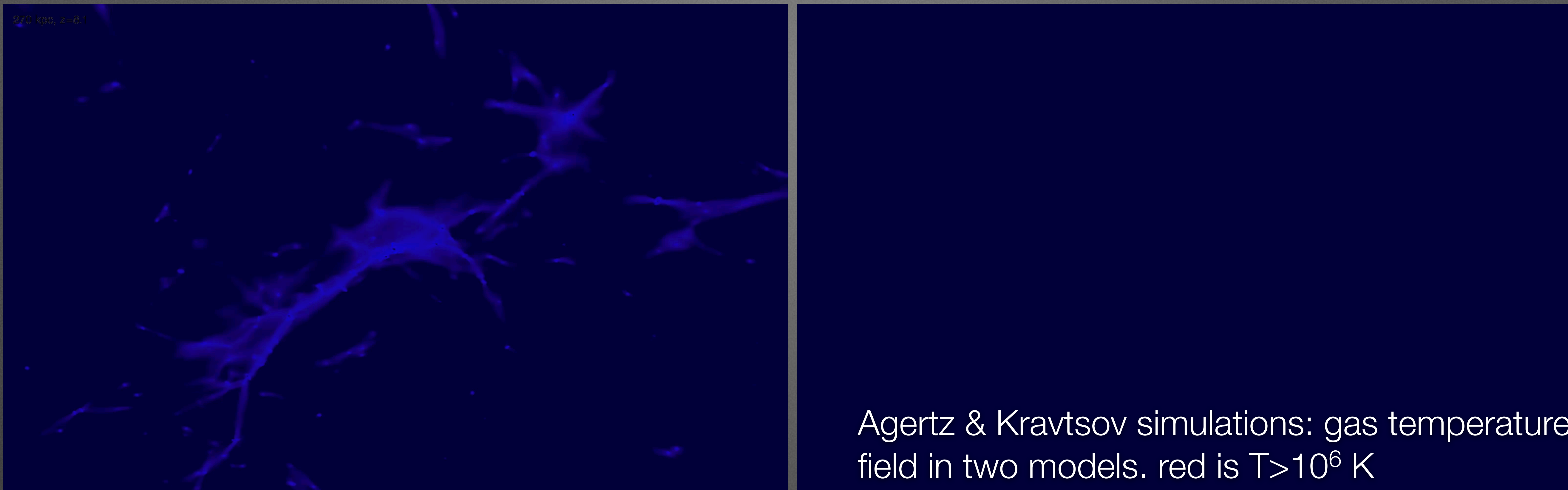


# *Development of the "Universe of Galaxies" from initial conditions*



Agertz & Kravtsov simulations: gas temperature field in two models. red is T>$10^6$ K

Galaxy formation is driven by insufficiently understood / observed resolved, and very complex processes:

> reionization; radiative cooling of the gas; **star formation**; stellar mass loss & type I SNae; **feedback from star formation**; cosmic ray physics in the ISM; black holes — BH seeds, gas accretion on BH's, BH mergers; **AGN feedback**.

OIR data don't provide enough constraining power.

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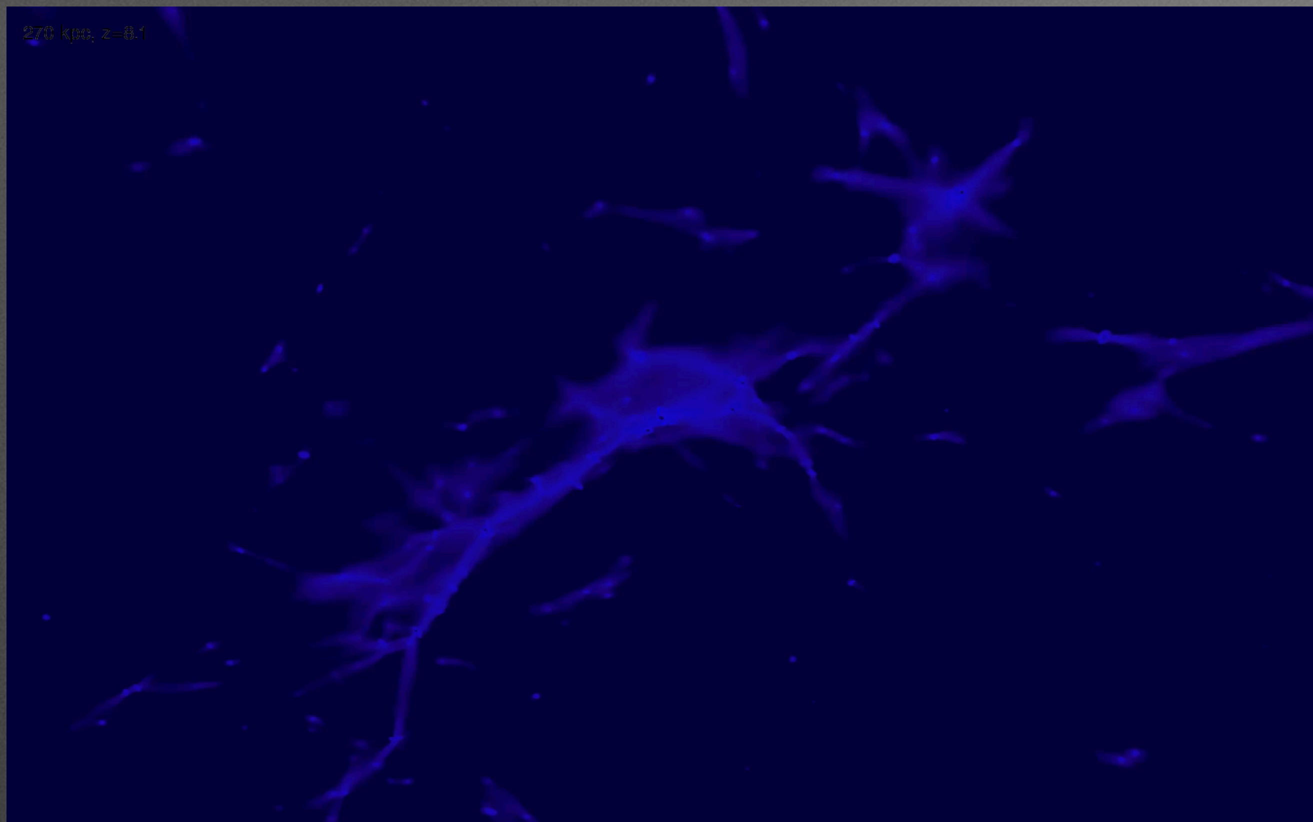

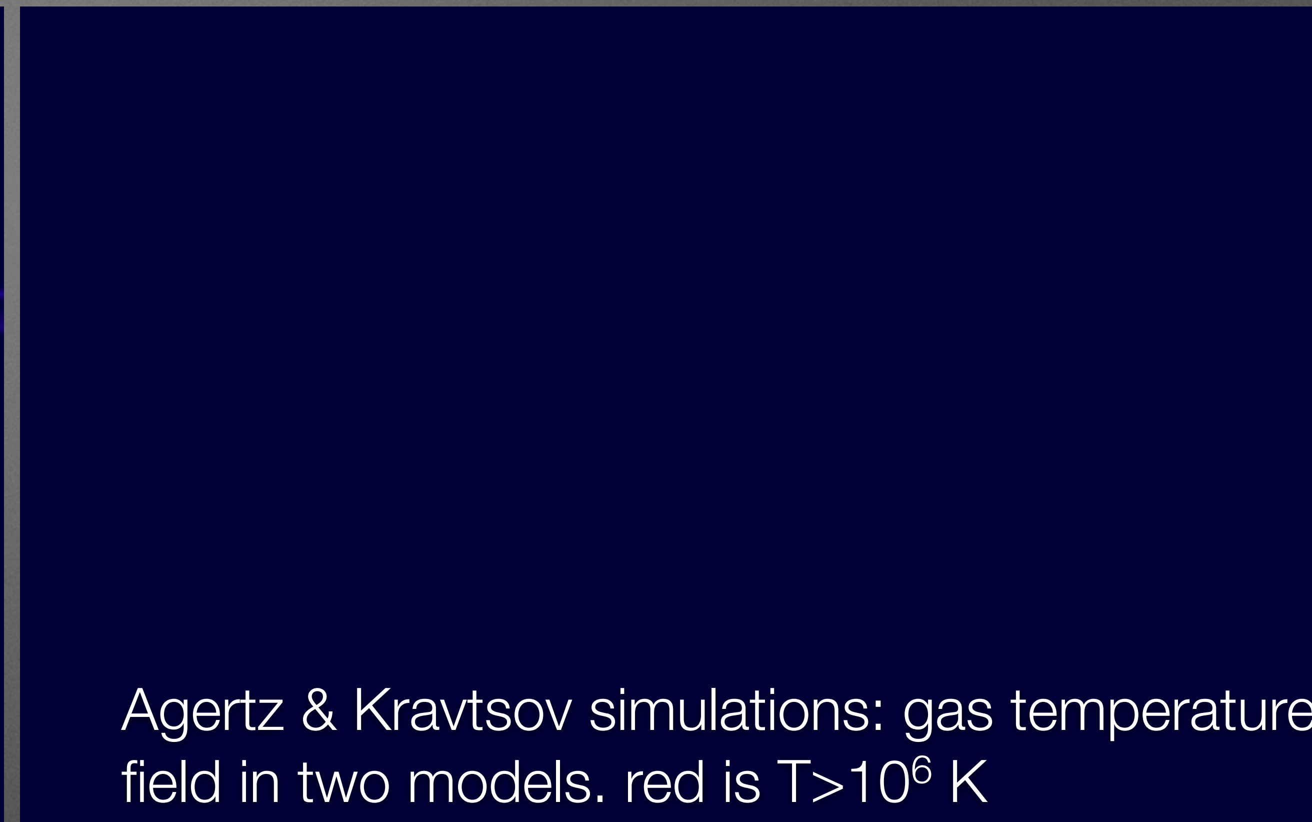

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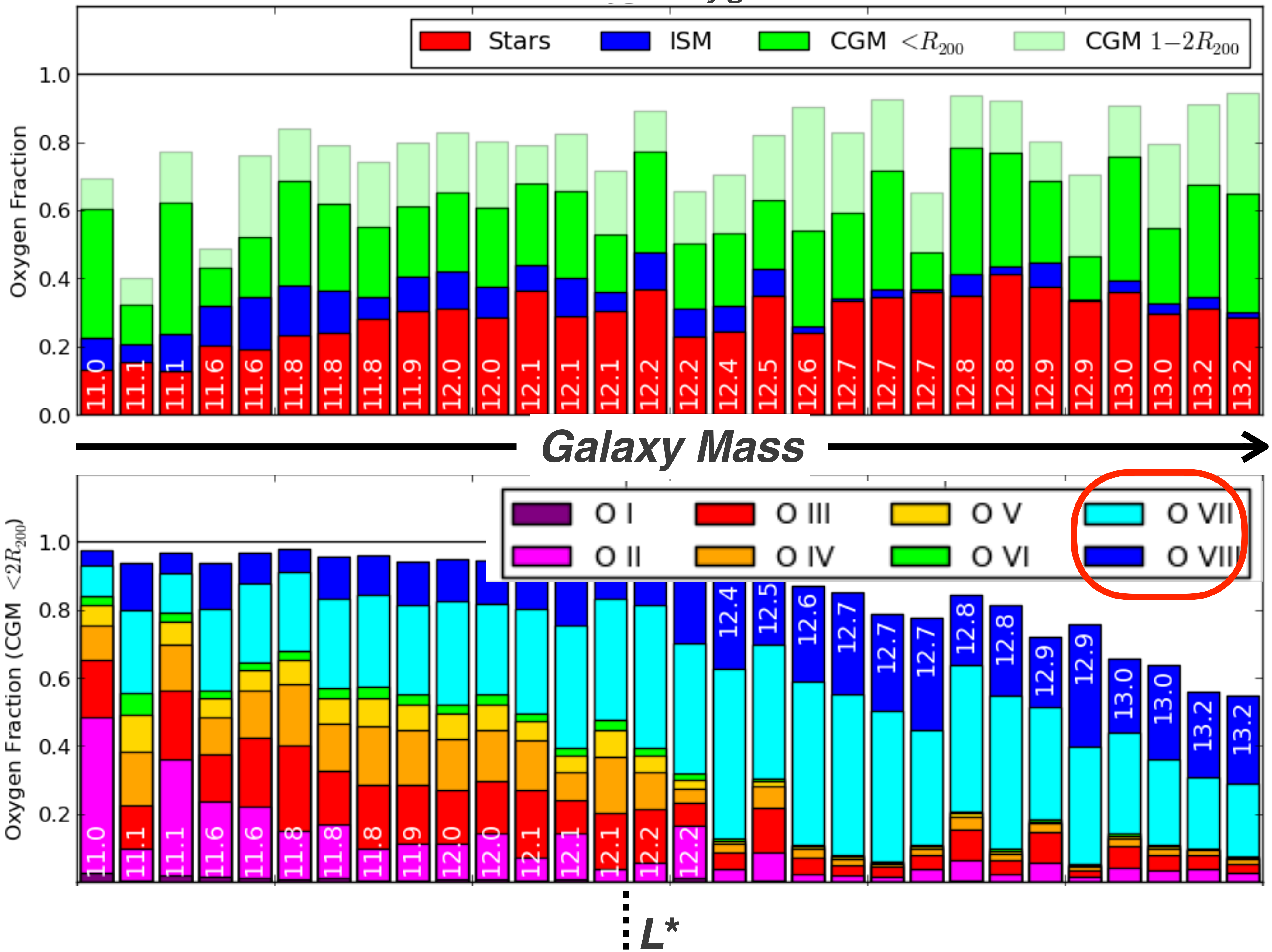
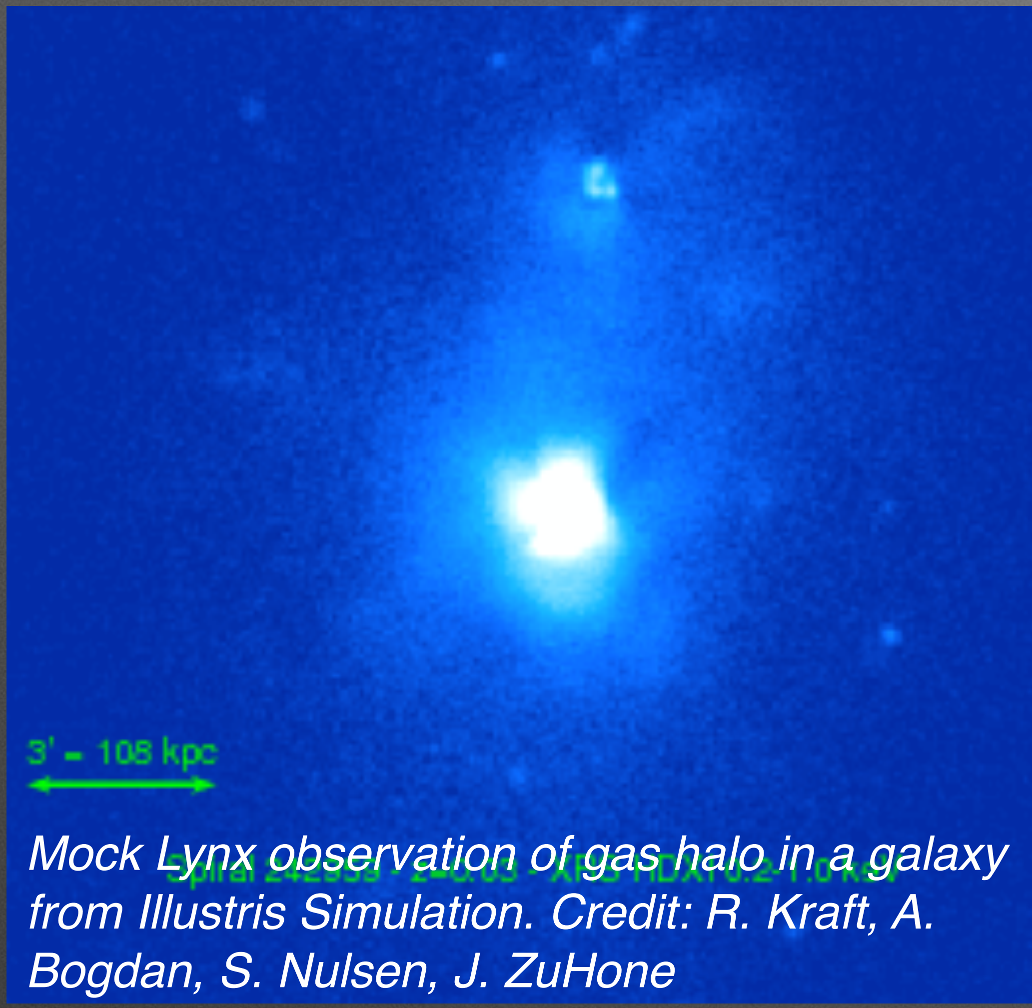
# *Much of CGM / IGM is fundamentally an "X-ray medium", and observable with Lynx*

*Oppenheimer etal '16: EAGLE simulation: Oxygen census and Ionization Fractions*

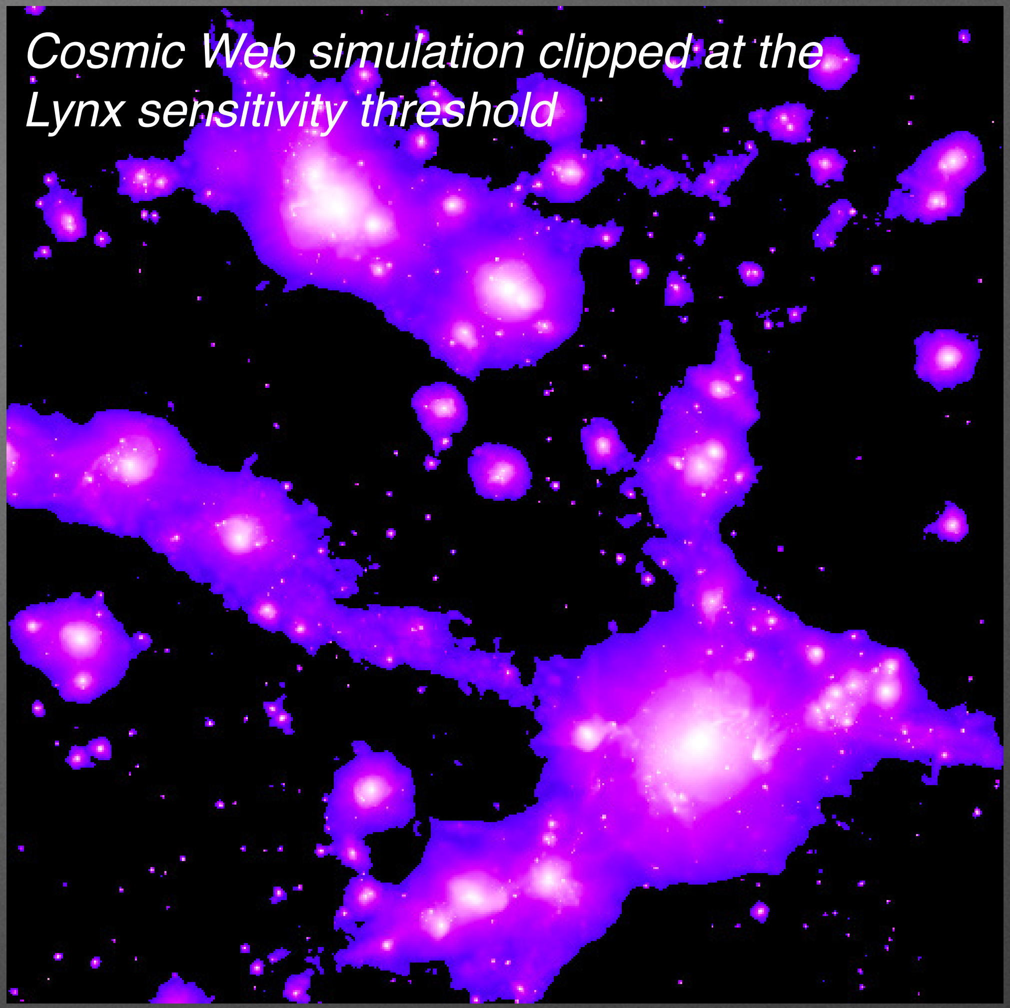



*L** galaxies: only 30% of O is locked in stars, >50% is in CGM; ~80% of that is observed in X-ray transitions (OVII at 0.57 keV, OVIII at 0.65 keV)

# *Much of CGM / IGM is fundamentally an “X-ray medium”, and observable with Lynx*

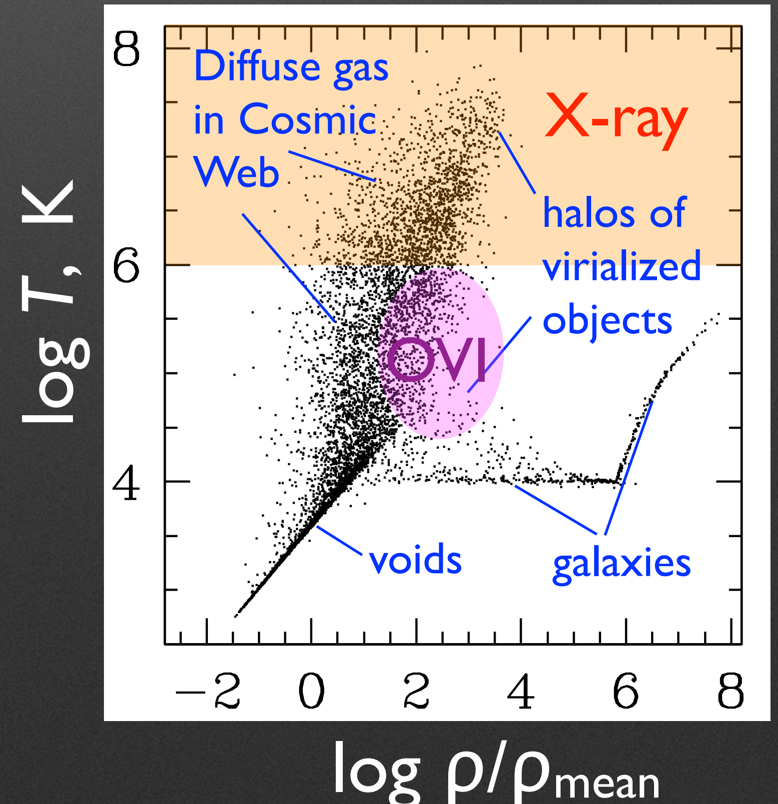



*Mock Lynx observation of gas halo in a galaxy from Illustris Simulation. Credit: R. Kraft, A. Bogdan, S. Nulsen, J. ZuHone*



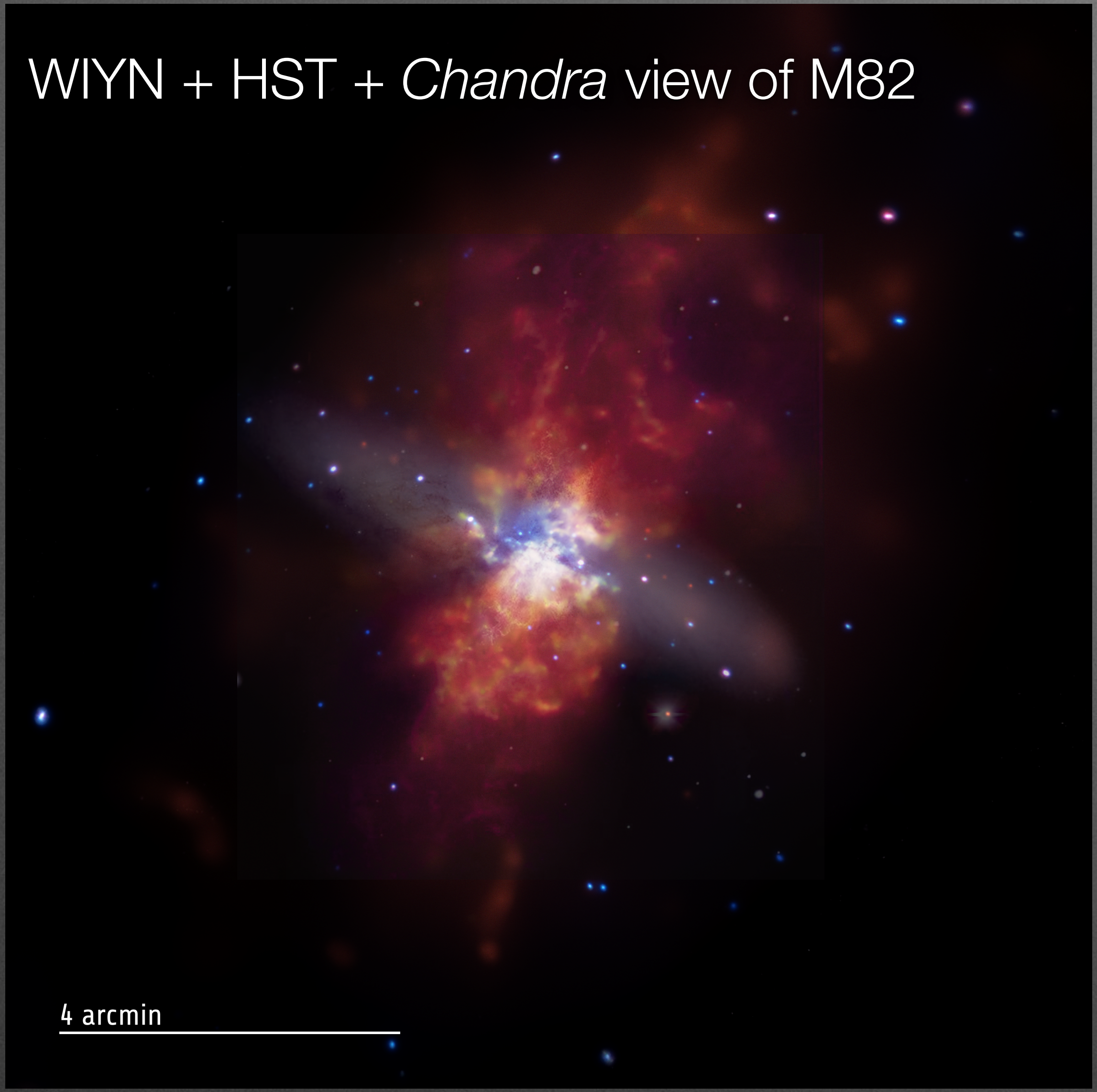
*Cosmic Web simulation clipped at the Lynx sensitivity threshold*

Hot gas in galactic halos and Cosmic Web filaments will be observable in emission with direct imaging and in absorption in X-ray gratings spectra of background AGNs.




*Phase diagram for the baryons in the Local Universe (theoretical prediction from Davé et al. 2010). Heated gas ($T>10^5$ K) in virialized halos and Cosmic Web accounts for >40% of all baryons by mass.*

# *Feedback from star formation*



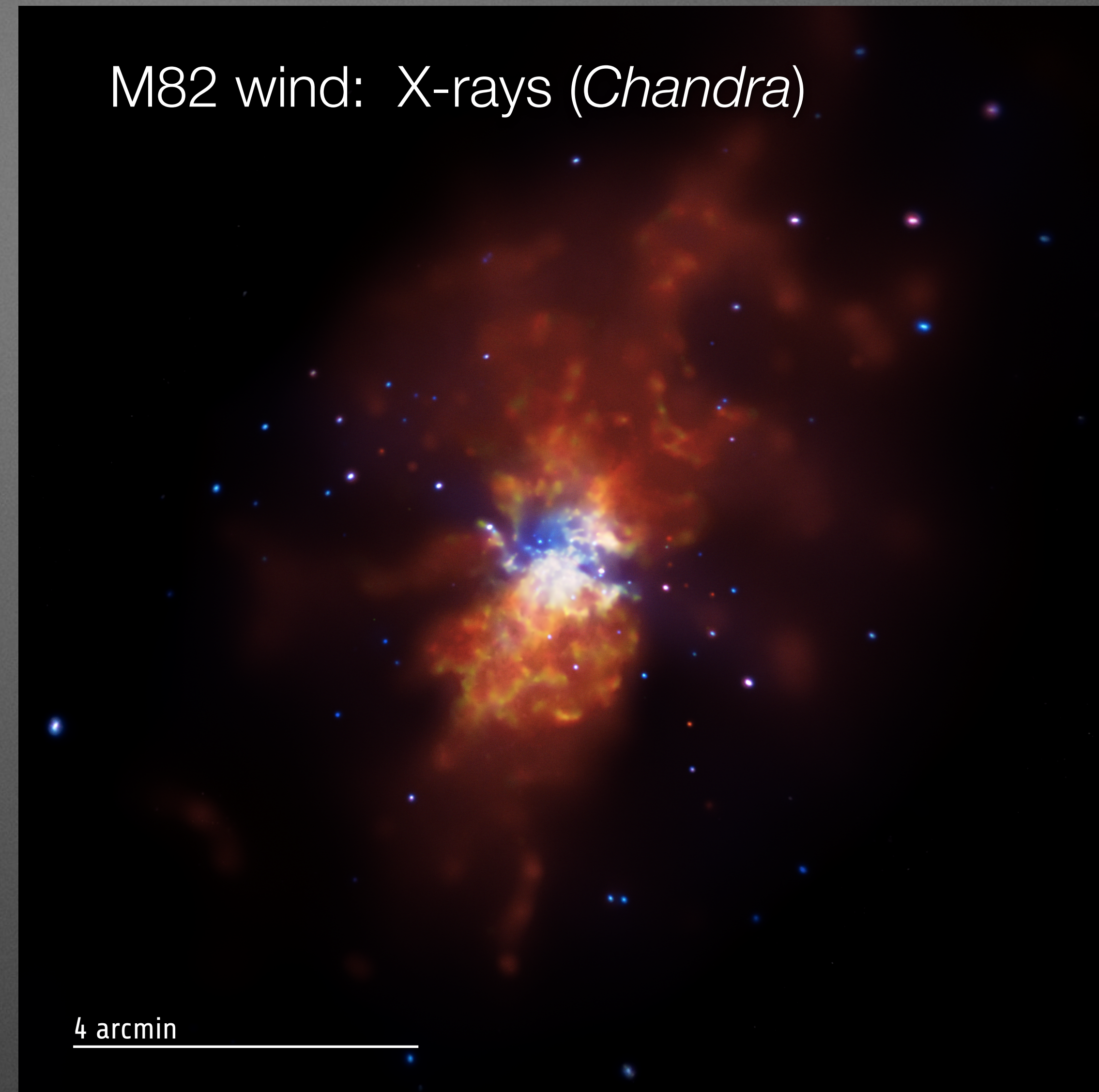

Spitzer + UKIRT + *Chandra* view of NGC 6357

Feedback from star formation is apparent on scales from individual young star forming regions to the entire galaxy. *Lynx* will observe it all.

# *Star Formation Feedback: Galaxy Winds*

M82 wind:  Optical + Hα (WIYN & HST)

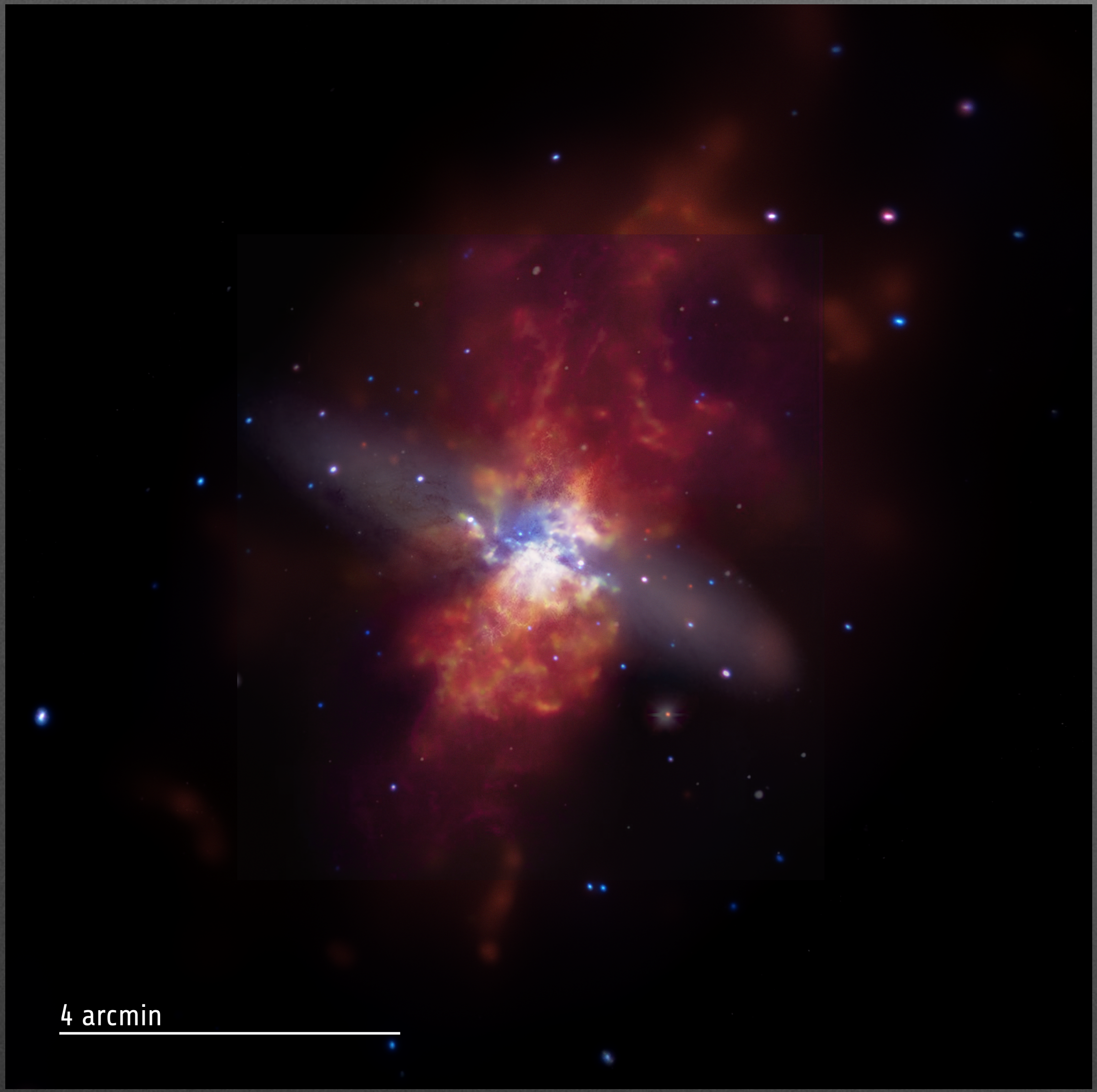
M82 wind:  X-rays (*Chandra*)




Galaxy-scale winds:

- energy & momentum budget
- launching mechanisms & sites
- transport of metals
- interaction with dust and neutral gas components
- statistics

# *Feedback: Self-quenching in Young Star Forming Regions*




Spitzer + UKIRT + *Chandra* view of NGC 6357

Generation of hot ISM in young star forming regions, destruction of star formation "fuel" (cold gas seen in the optical & IR)

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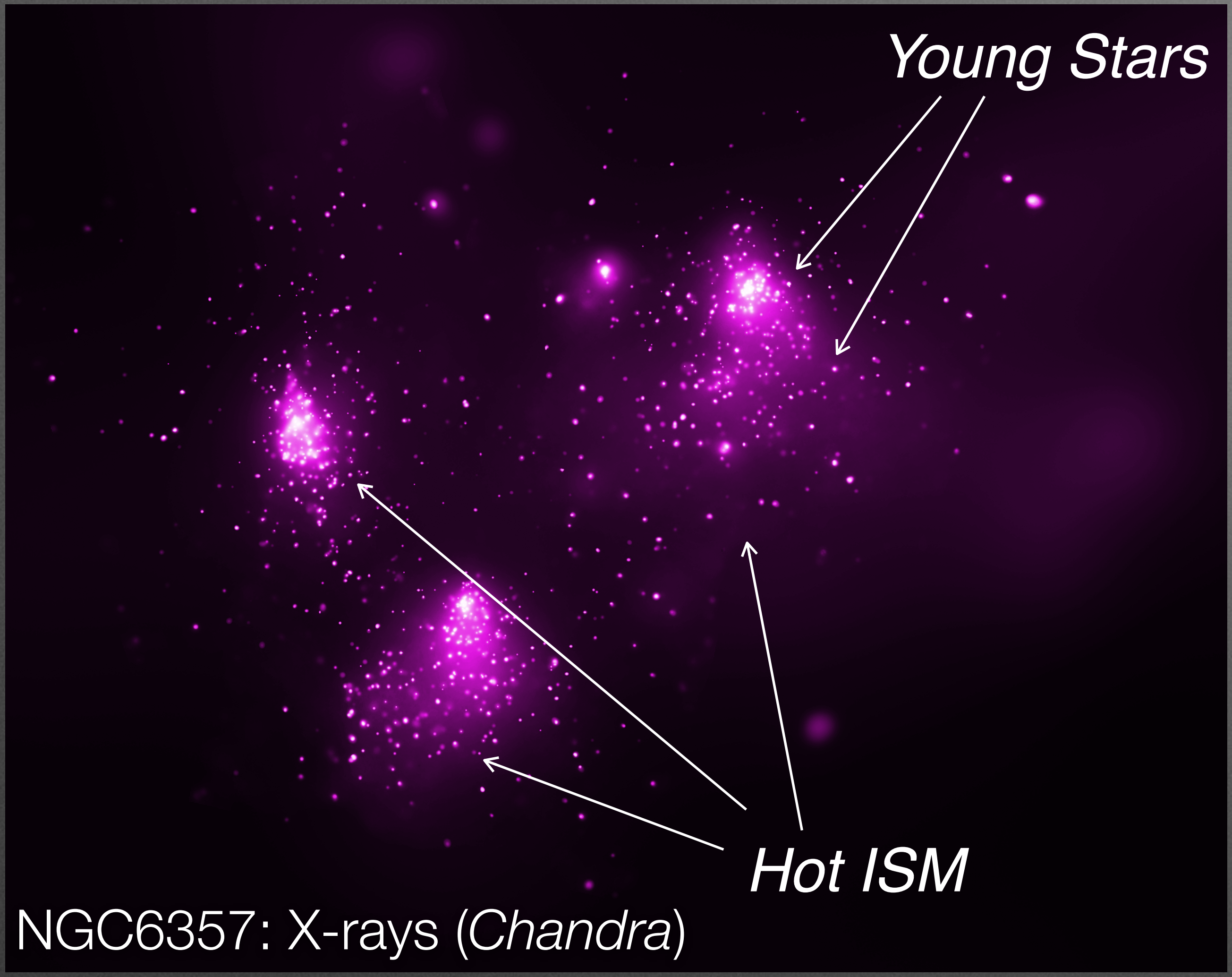


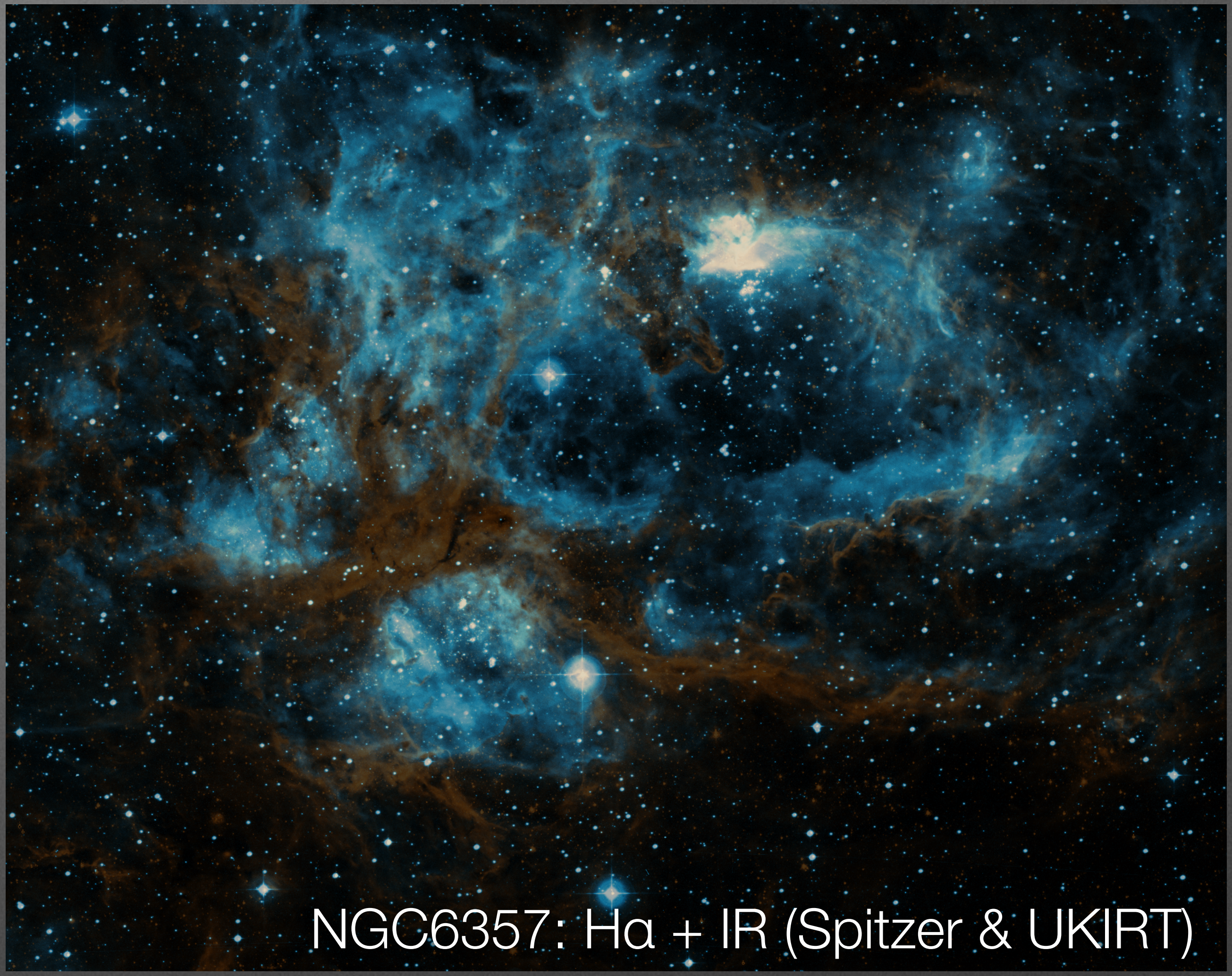


- *Chandra* X-ray data is a great tool for finding young stars. *Lynx* will be orders of magnitude better
- Hot ISM is seen as “blobs” in *Chanra* images. Statistics and data quality with *Lynx* will be comparable to the OIR data.

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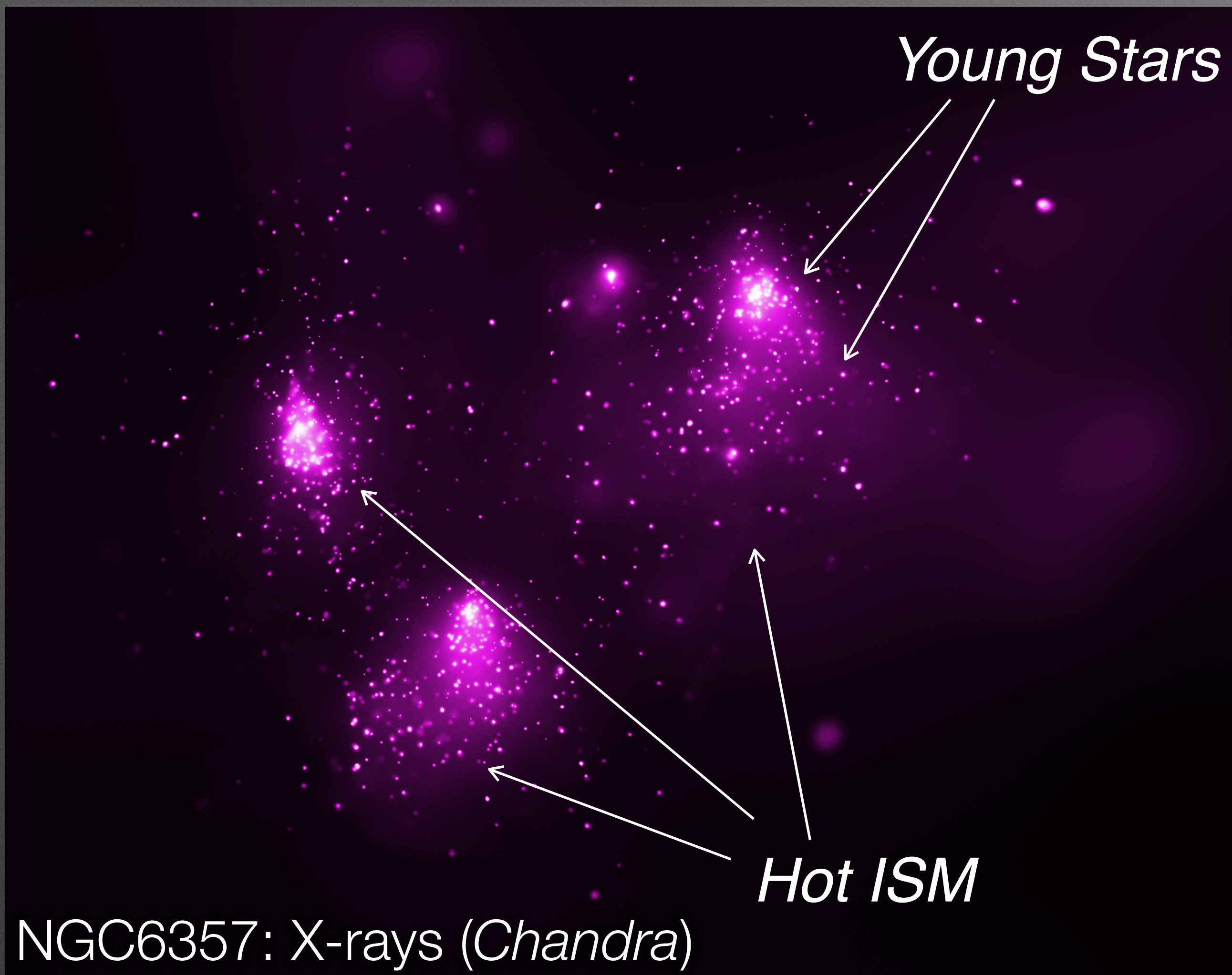


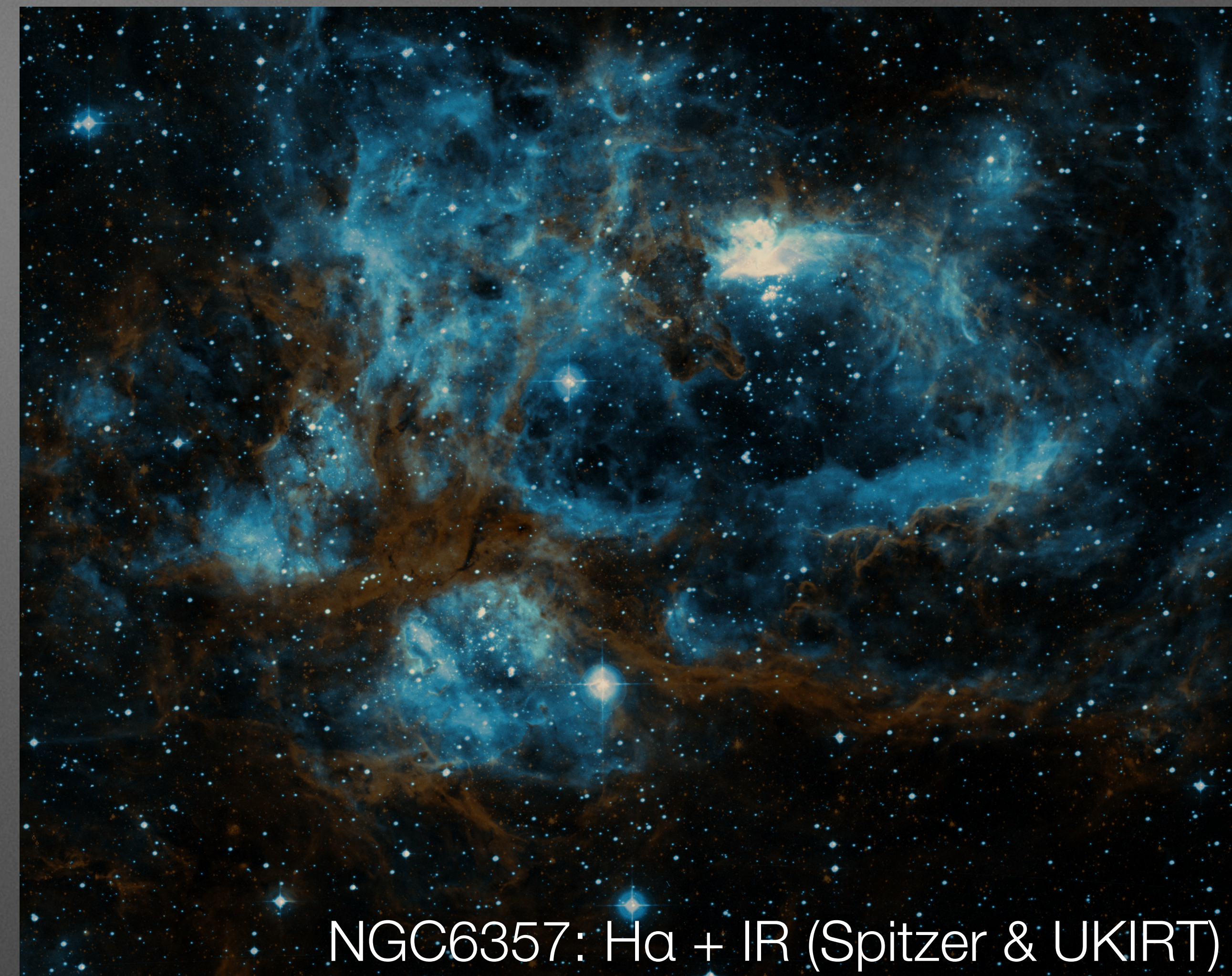


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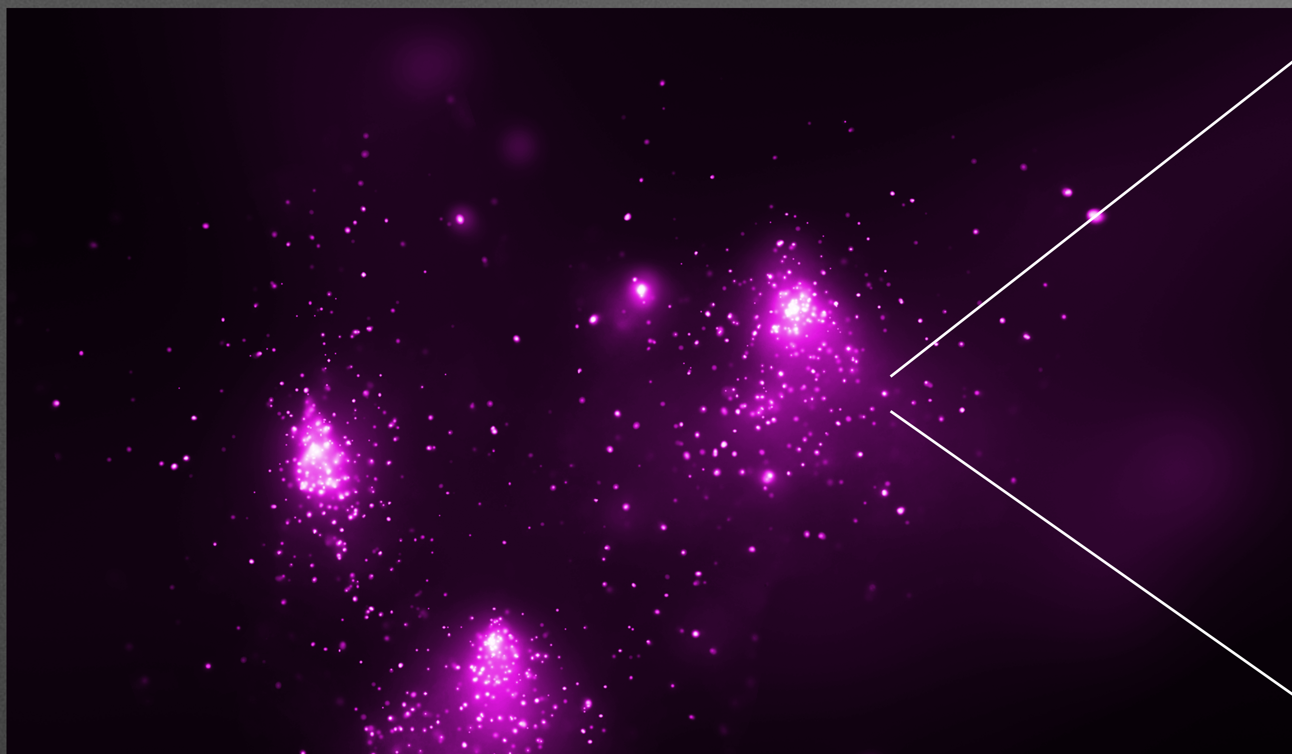
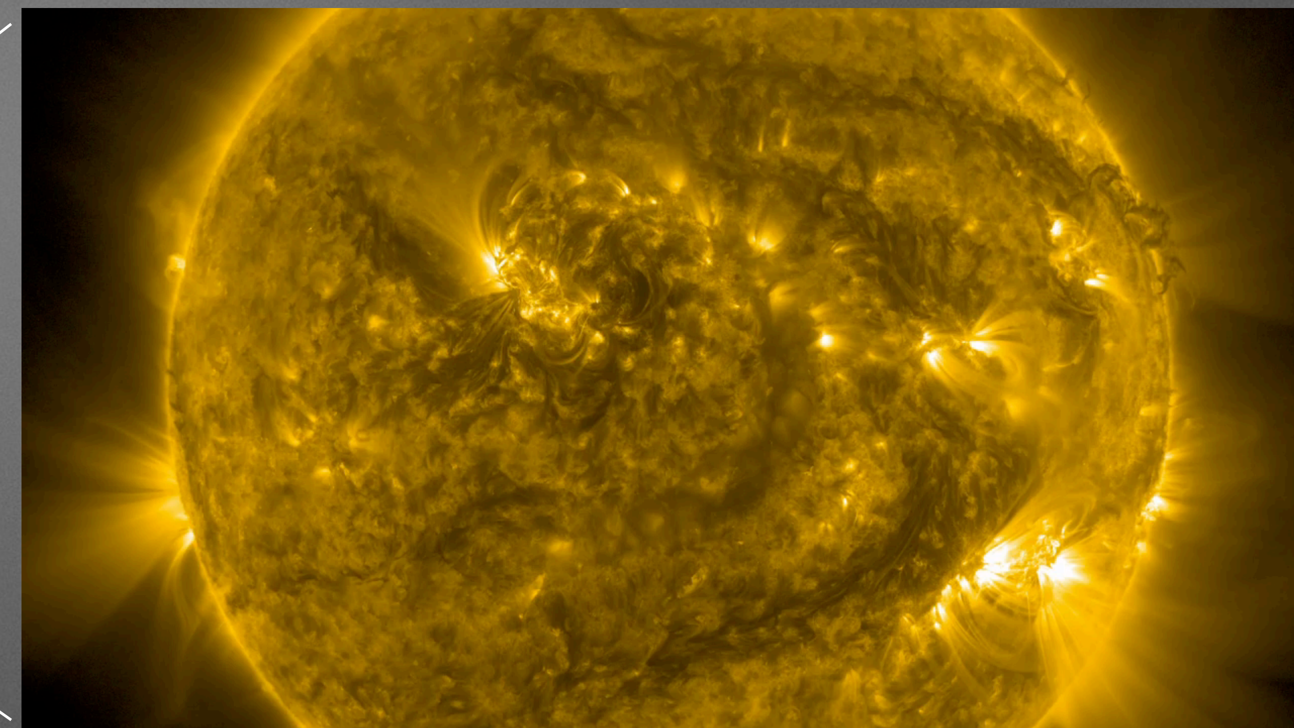
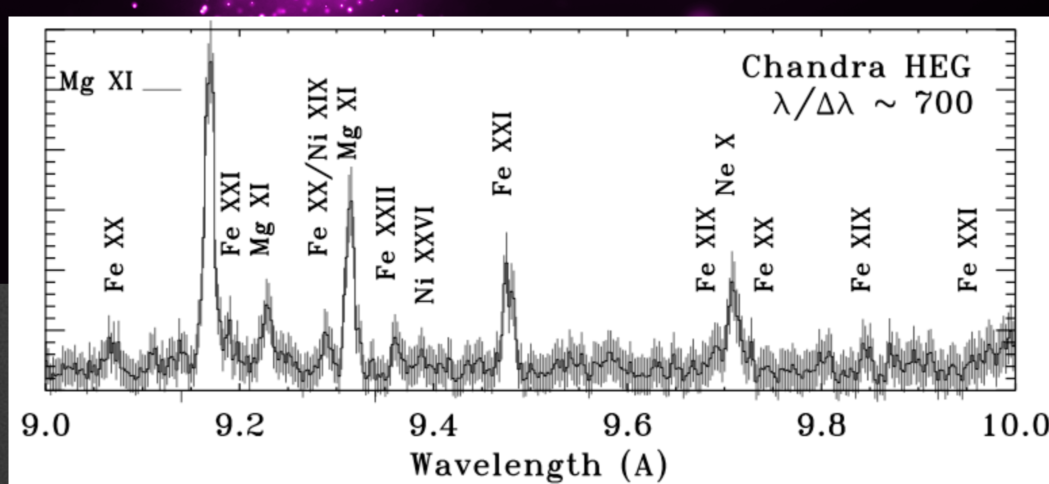
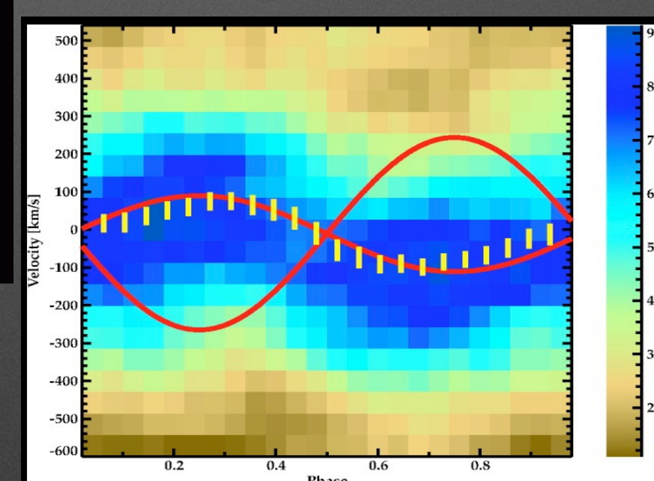
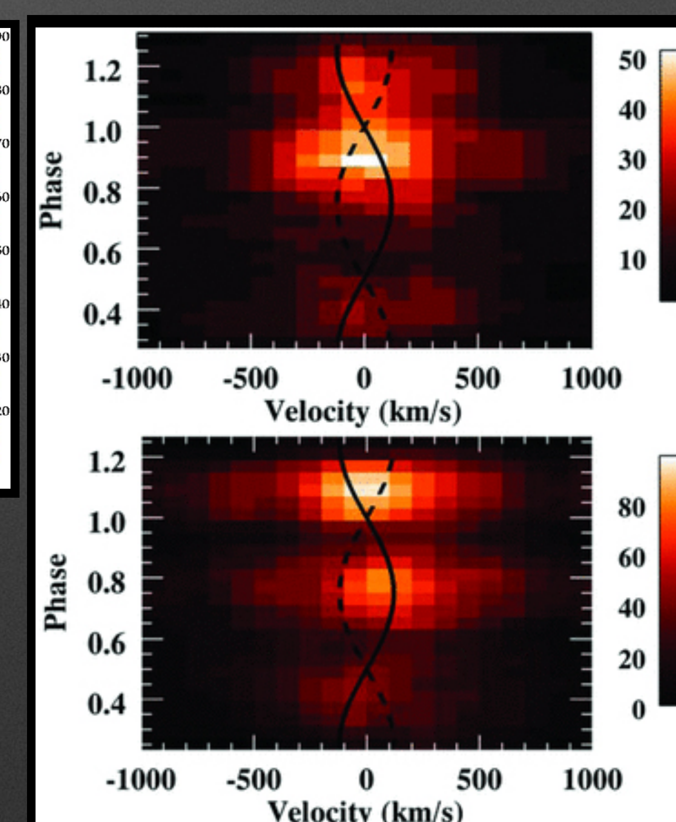
# *Stellar Astronomy with Lynx*








Coronal activity, magnetic field structure, dynamo, T Tauri stars, winds from OB stars, etc.

*Lynx* will provide >5x spectral resolution, and >100x throughput relative to *Chandra* gratings

See R. Osten's talk on Wed at the Lynx splinter session

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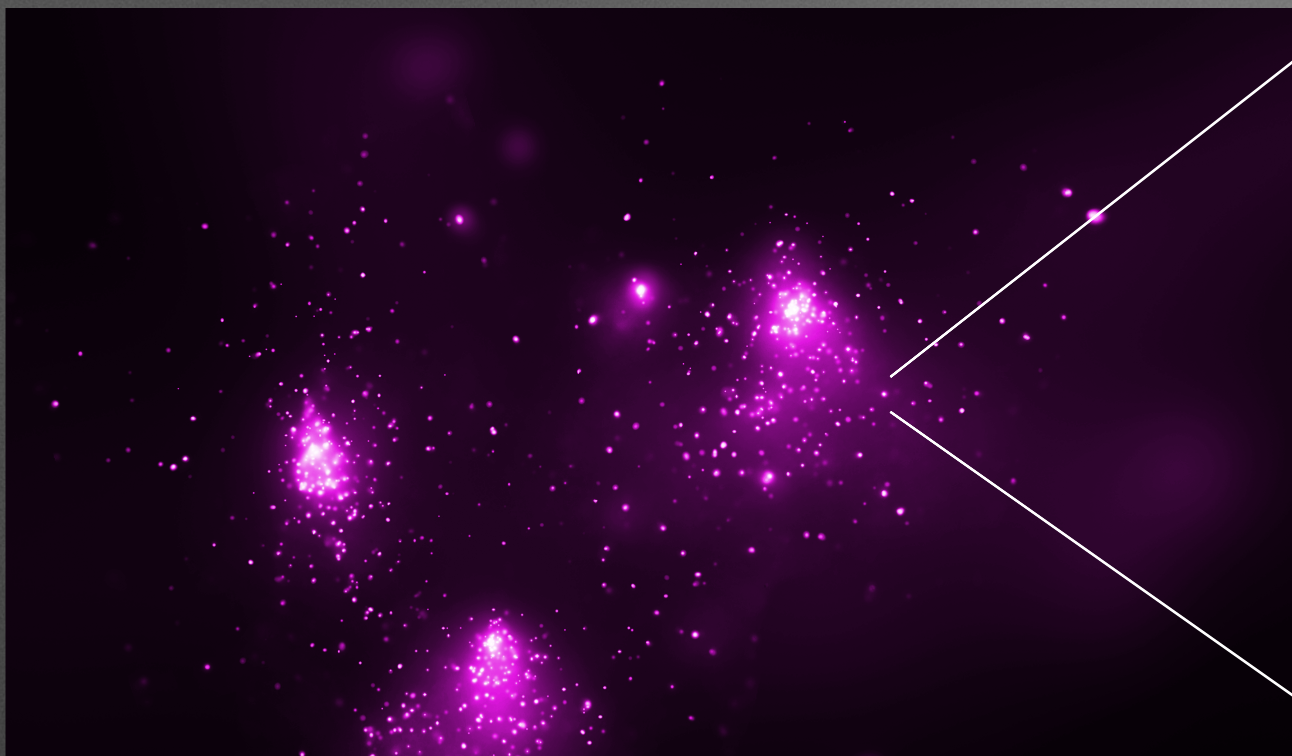

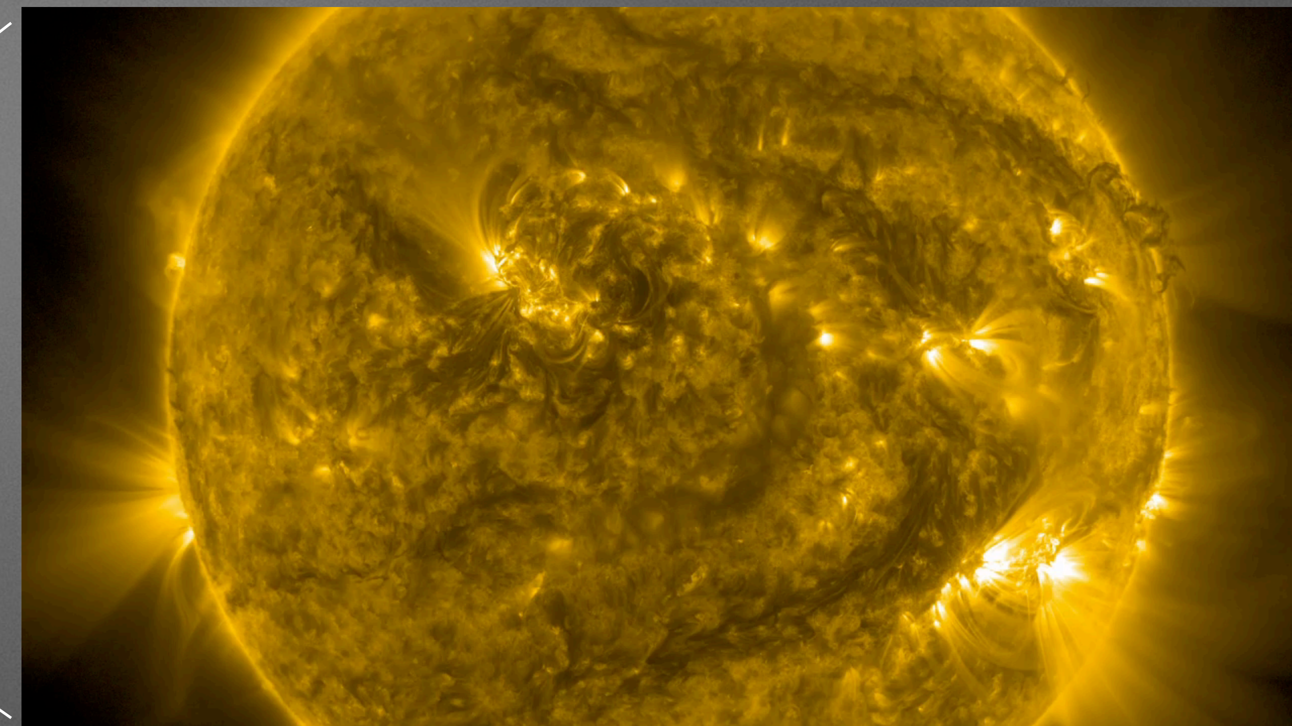

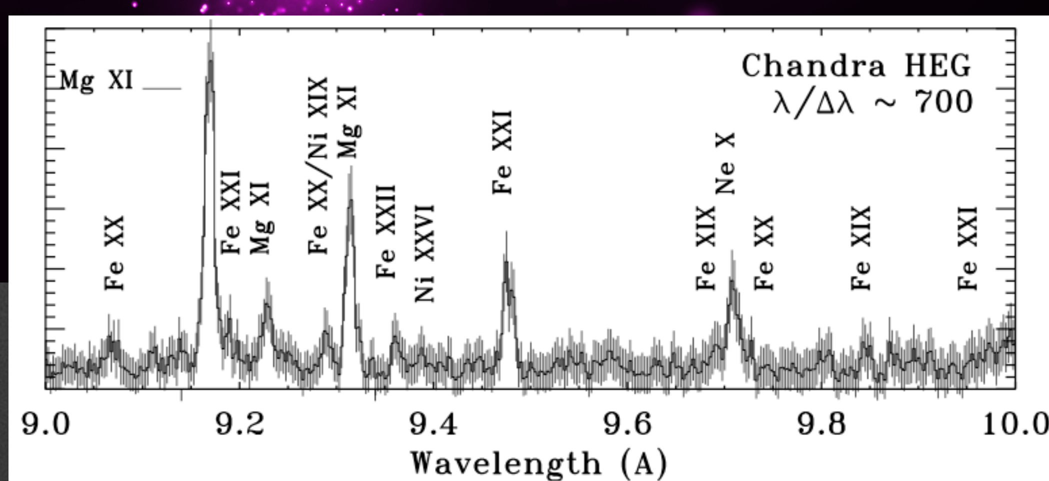


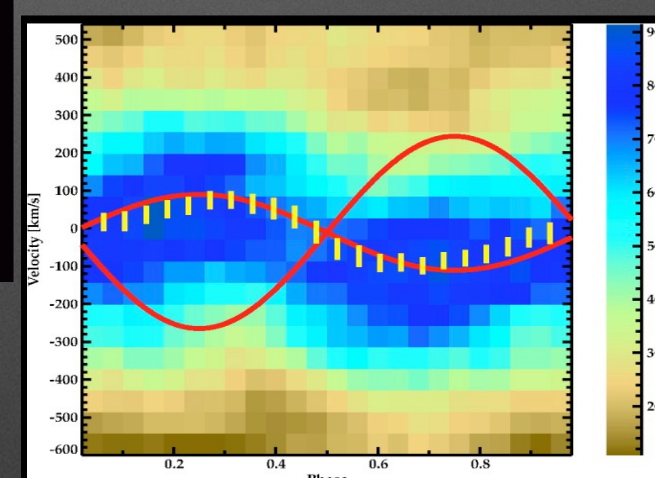


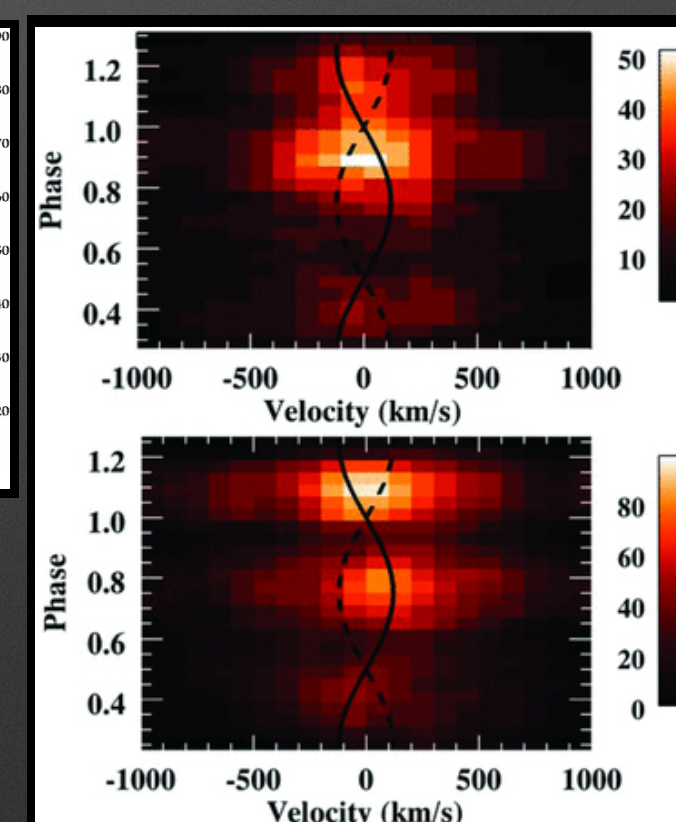


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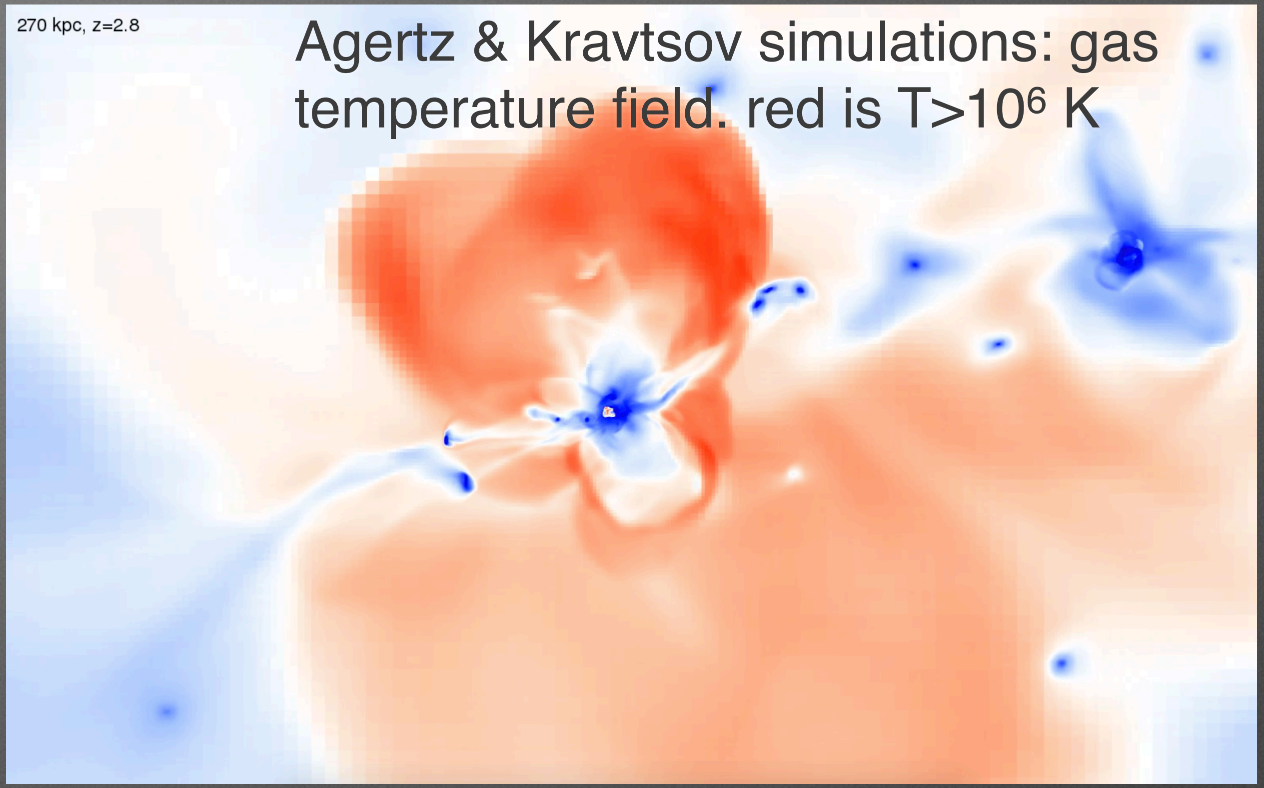
# *Feedback from Black Holes*

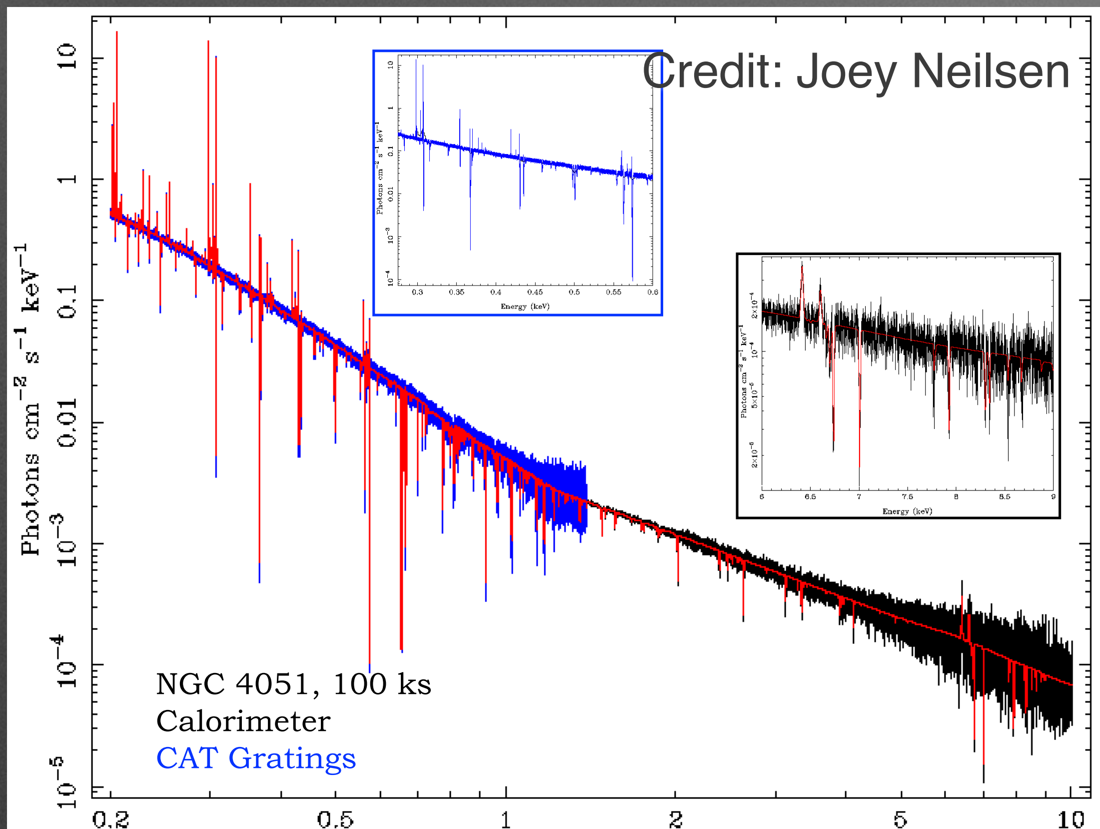
Expected to be a critical component of feedback in $L > L^*$ galaxies

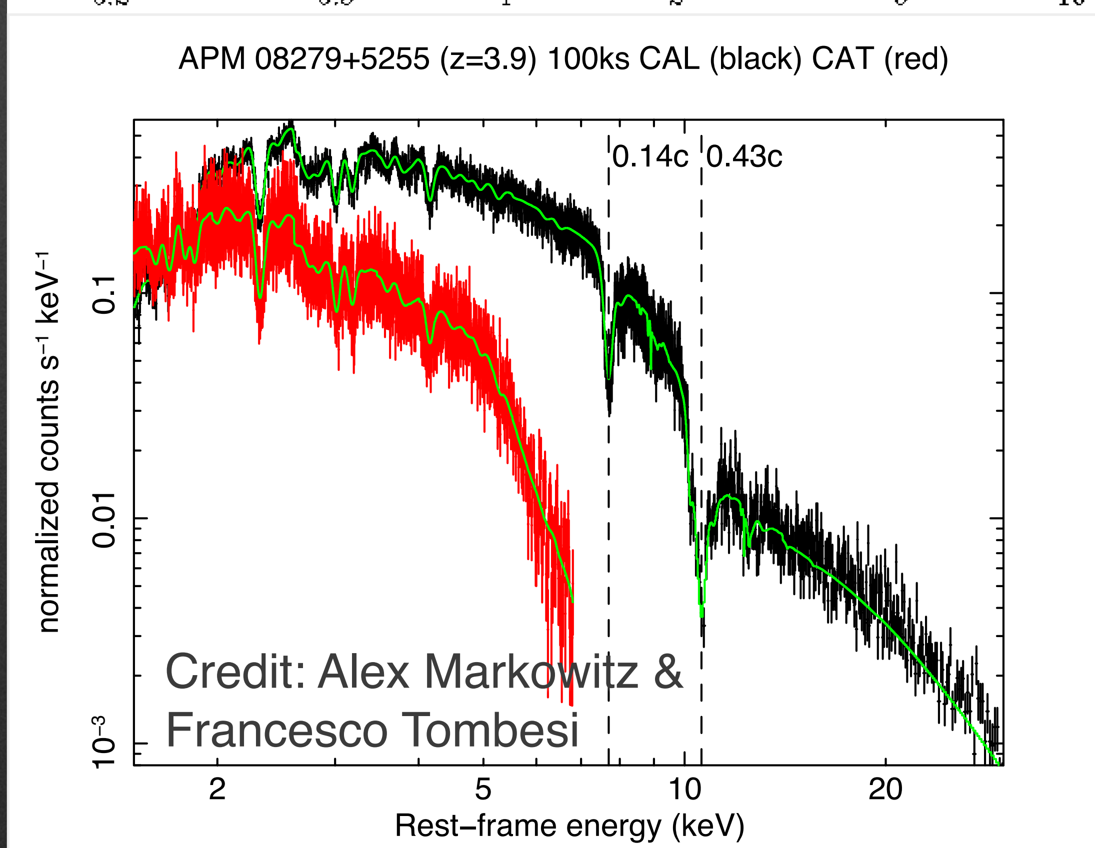
*Lynx* will provide a detailed view of every aspect of the BH feedback process

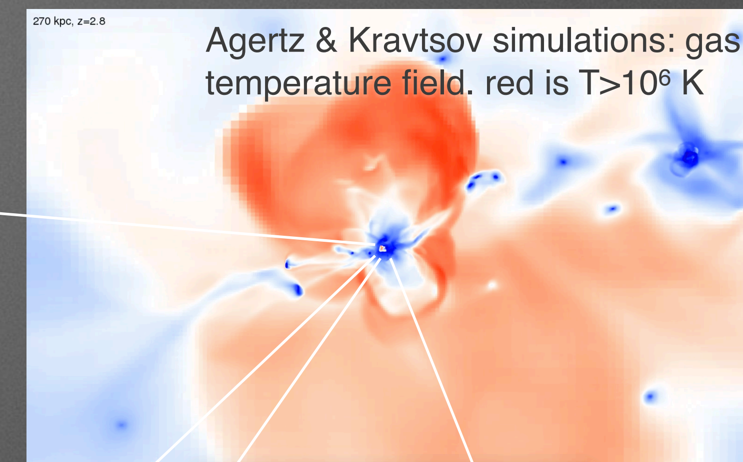


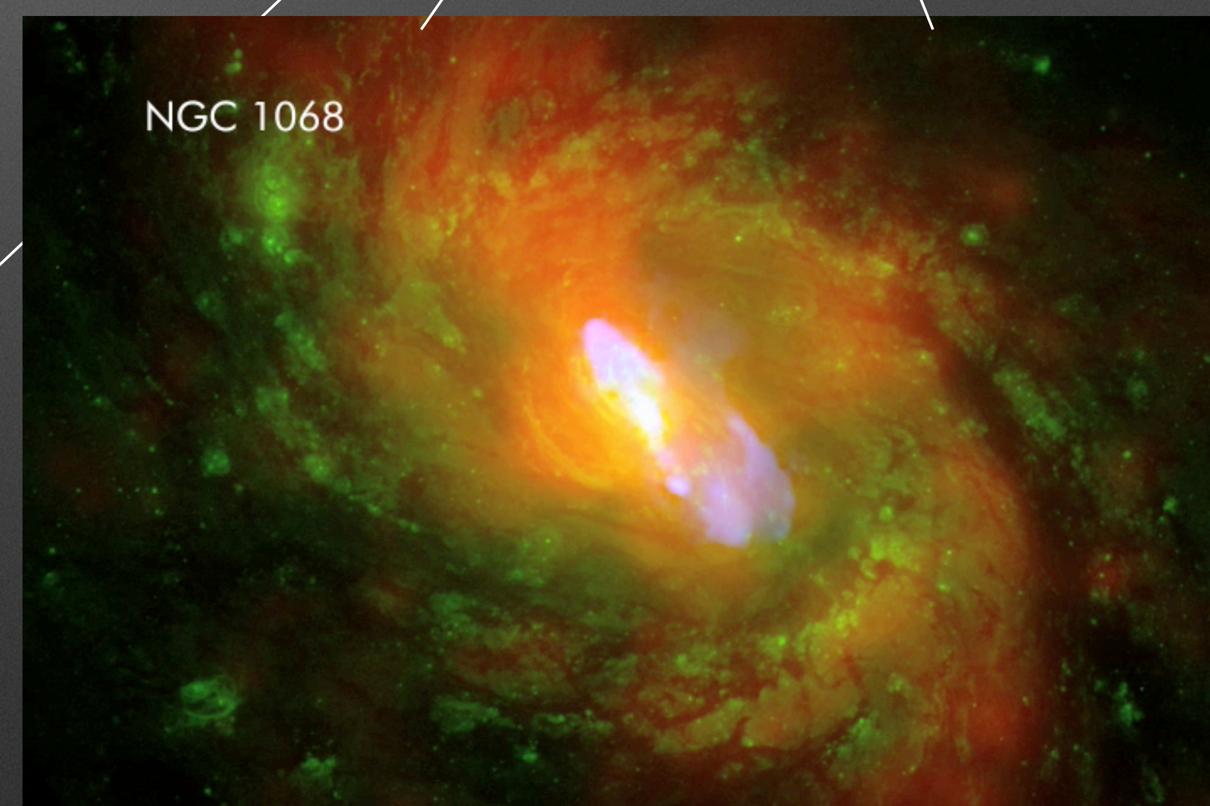
# *Feedback from Black Holes*

## *Energy and momentum flux in BH-generated outflows from spectroscopy:*




*Chandra* HETG observation of NGC1068 (Evans et al.)

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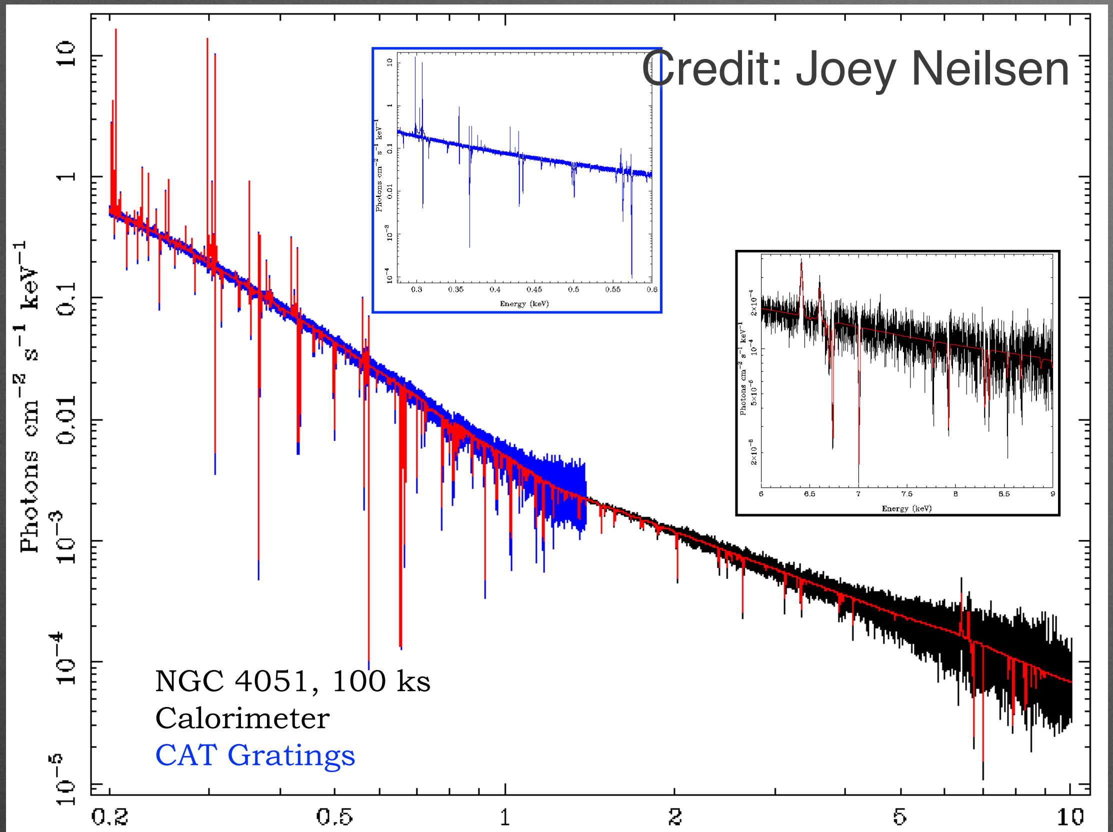


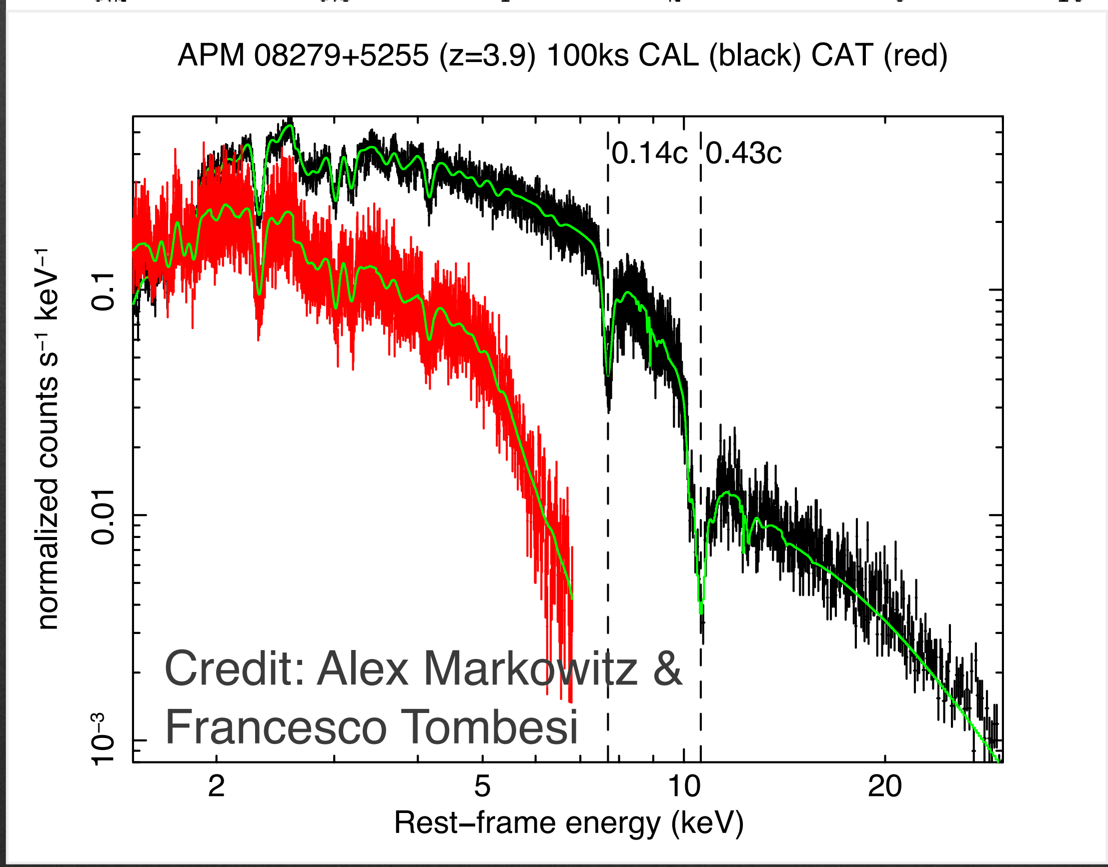


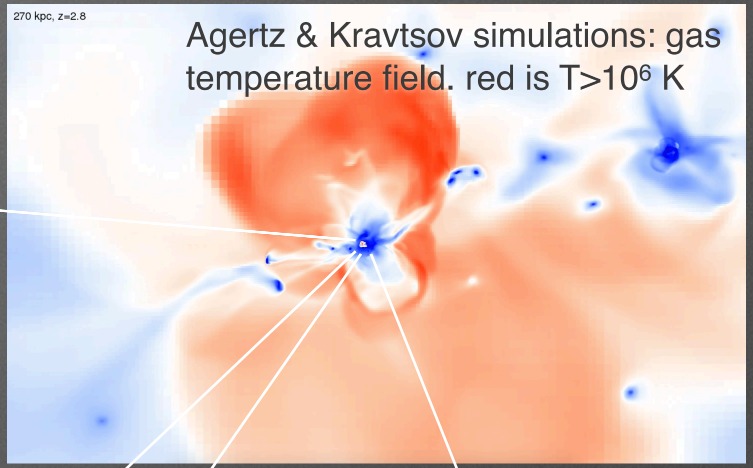


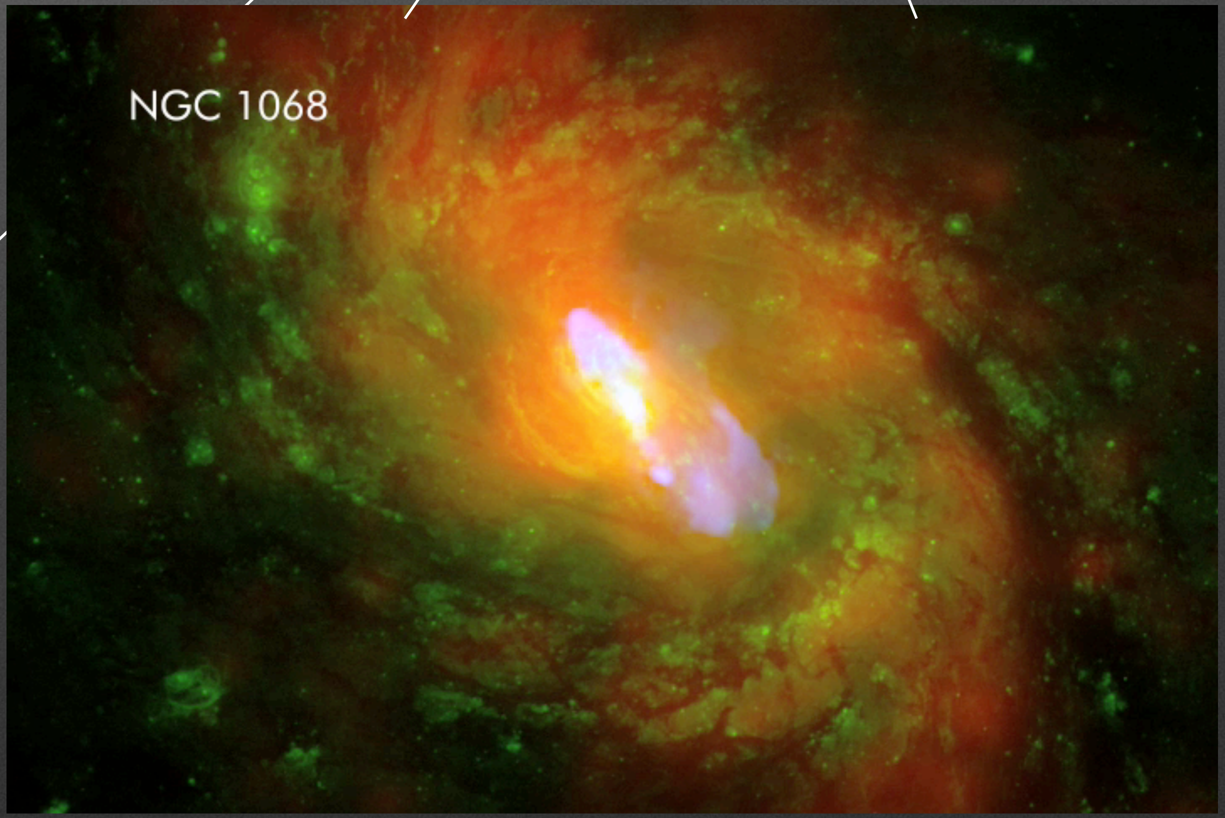


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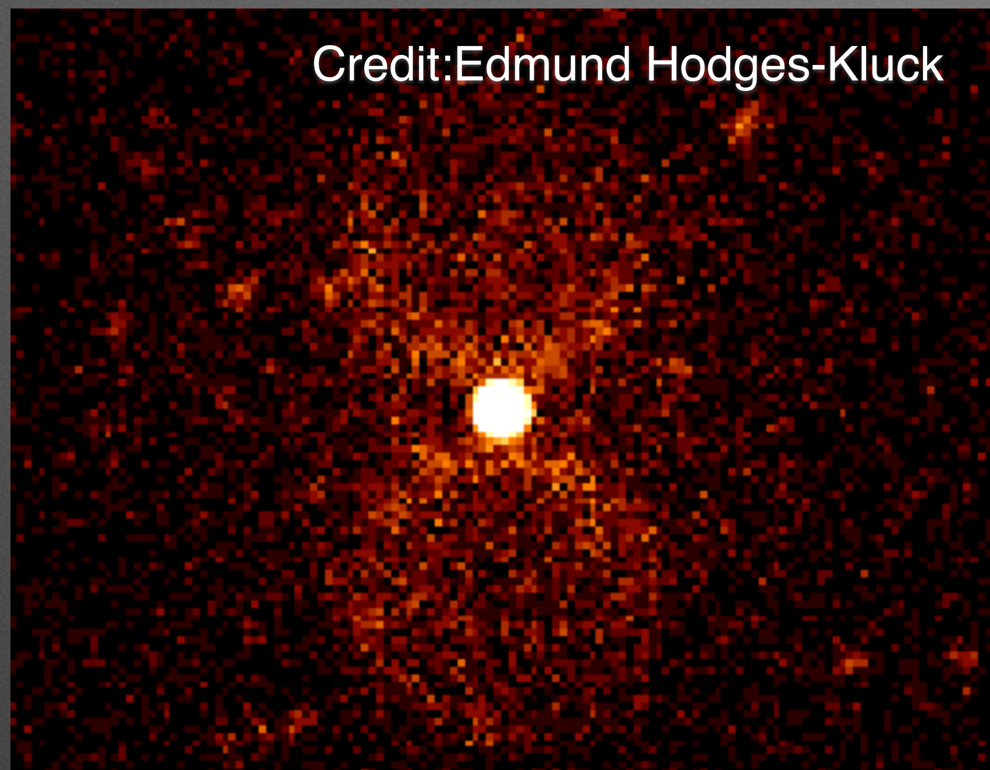
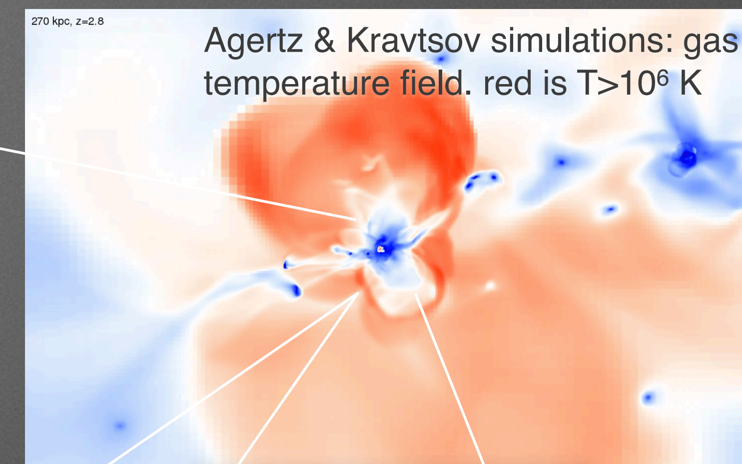
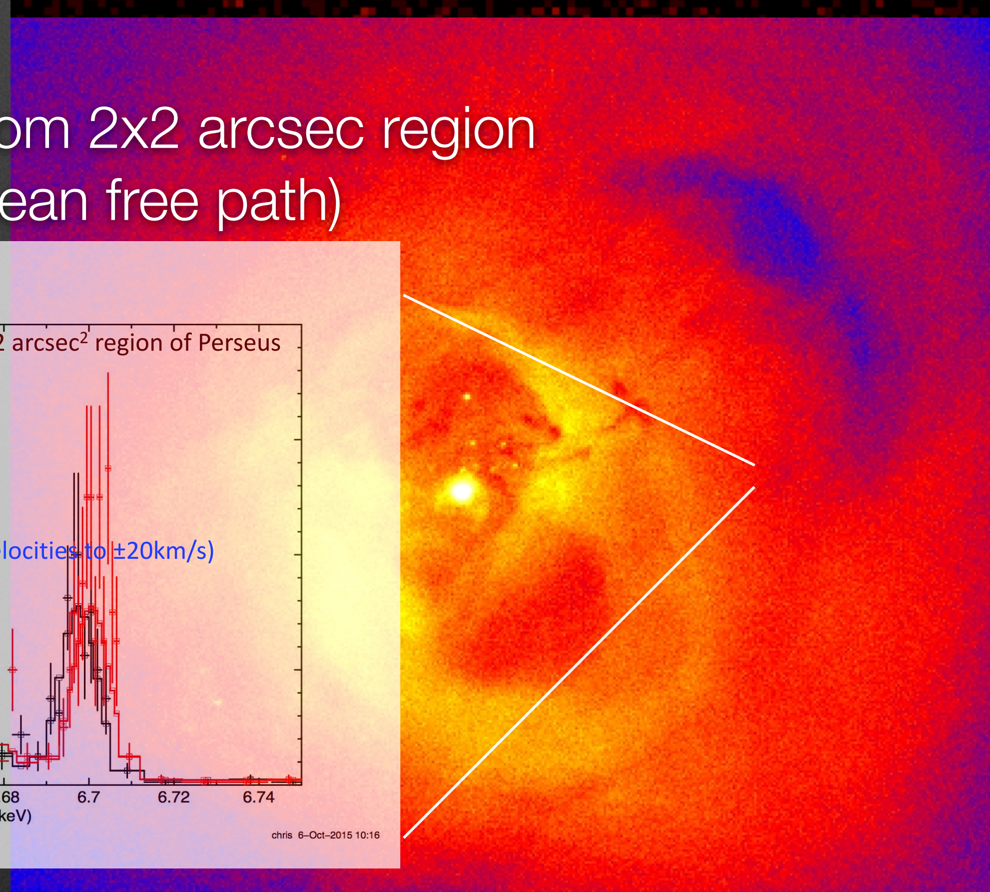
# *Feedback from Black Holes*

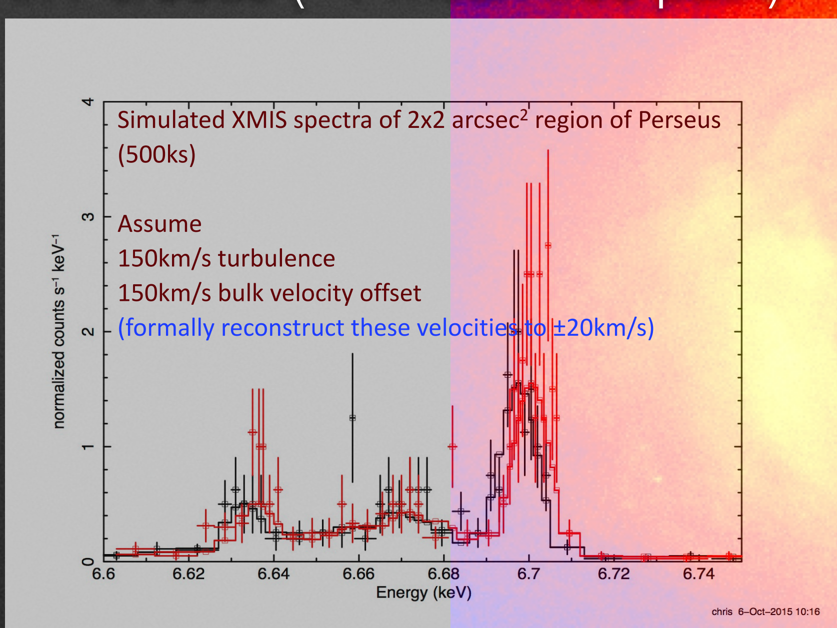
***Where, exactly how, and how much of the AGN outburst energy is dissipated in galaxies, groups, and clusters?***

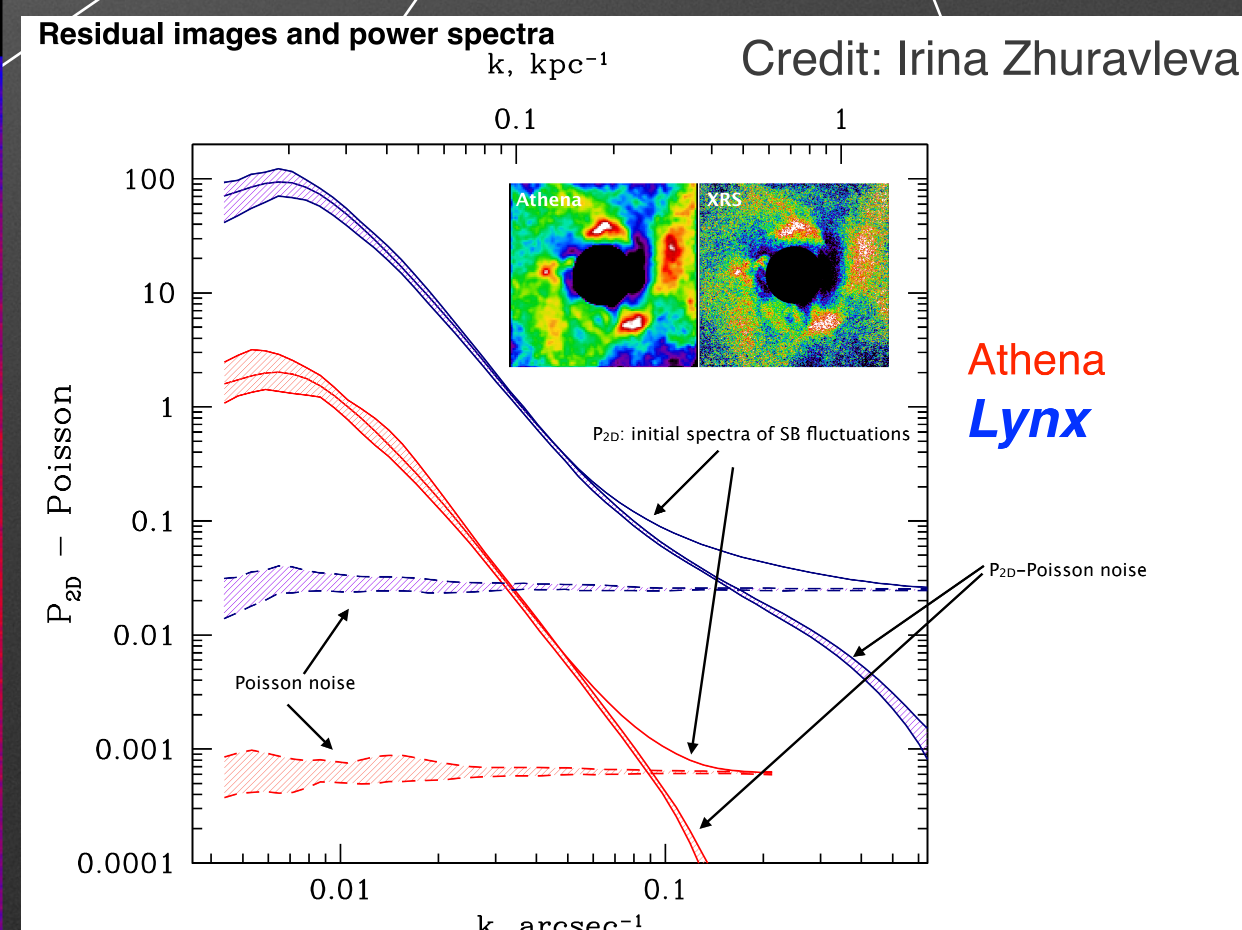



*Lynx* spectrum from 2x2 arcsec region in Perseus (~1 mean free path)



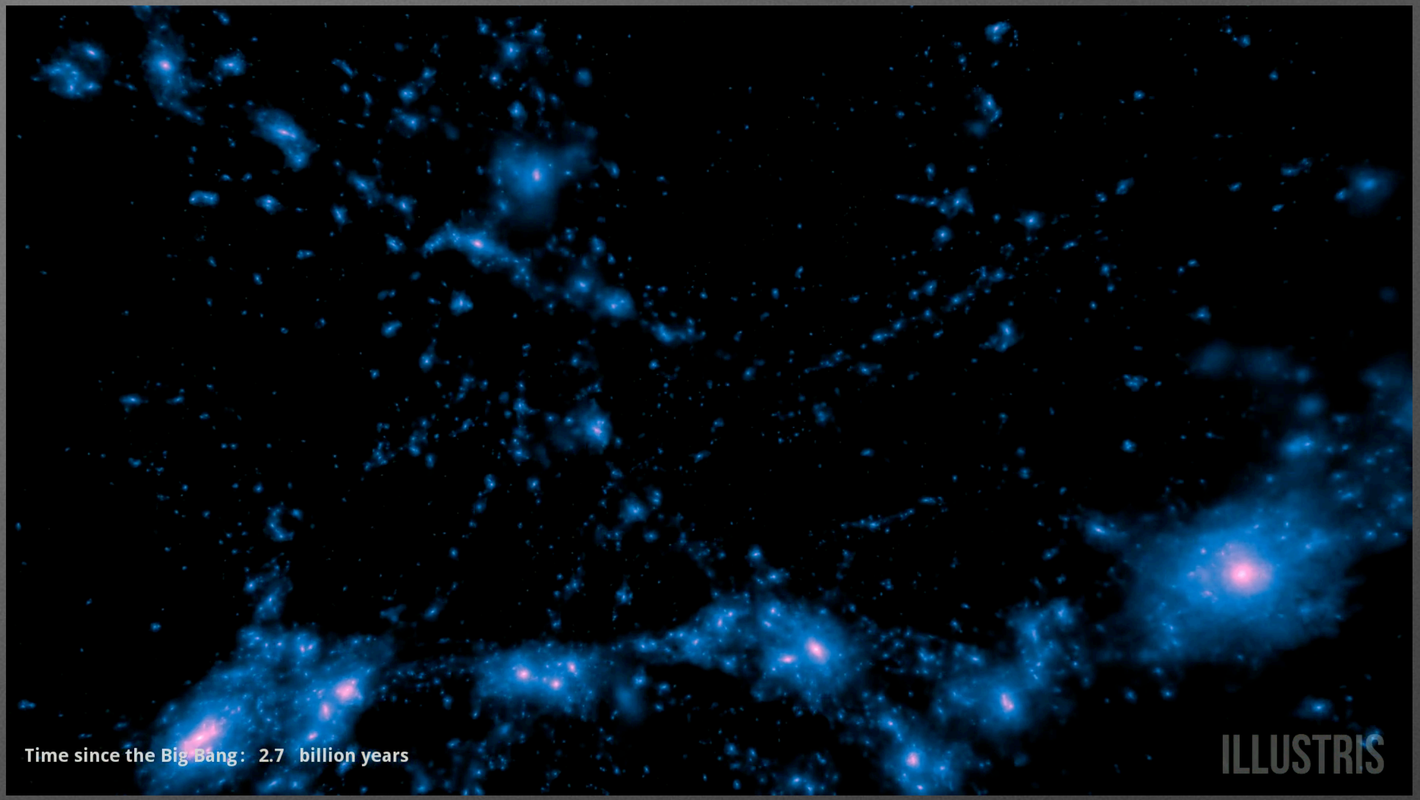


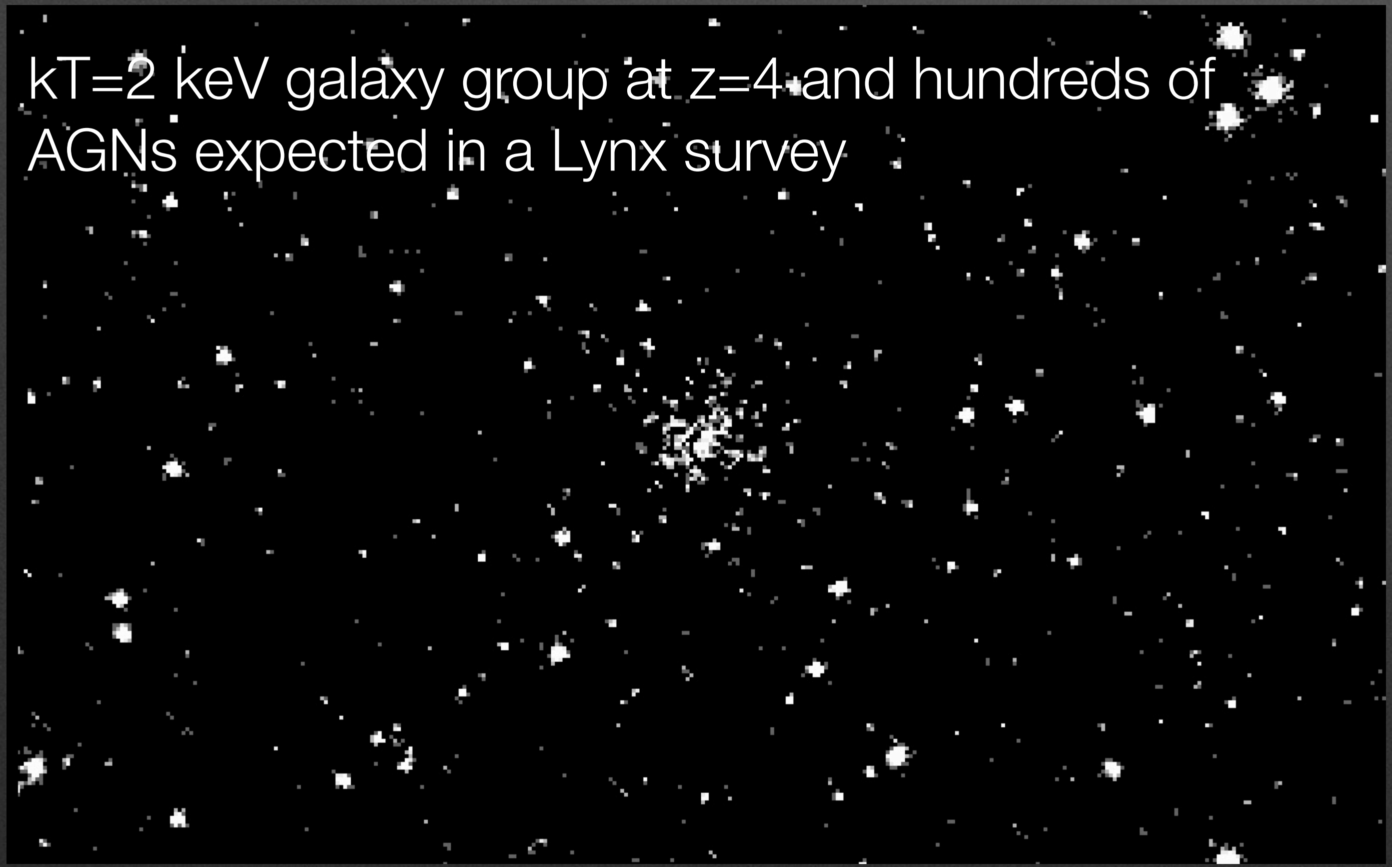



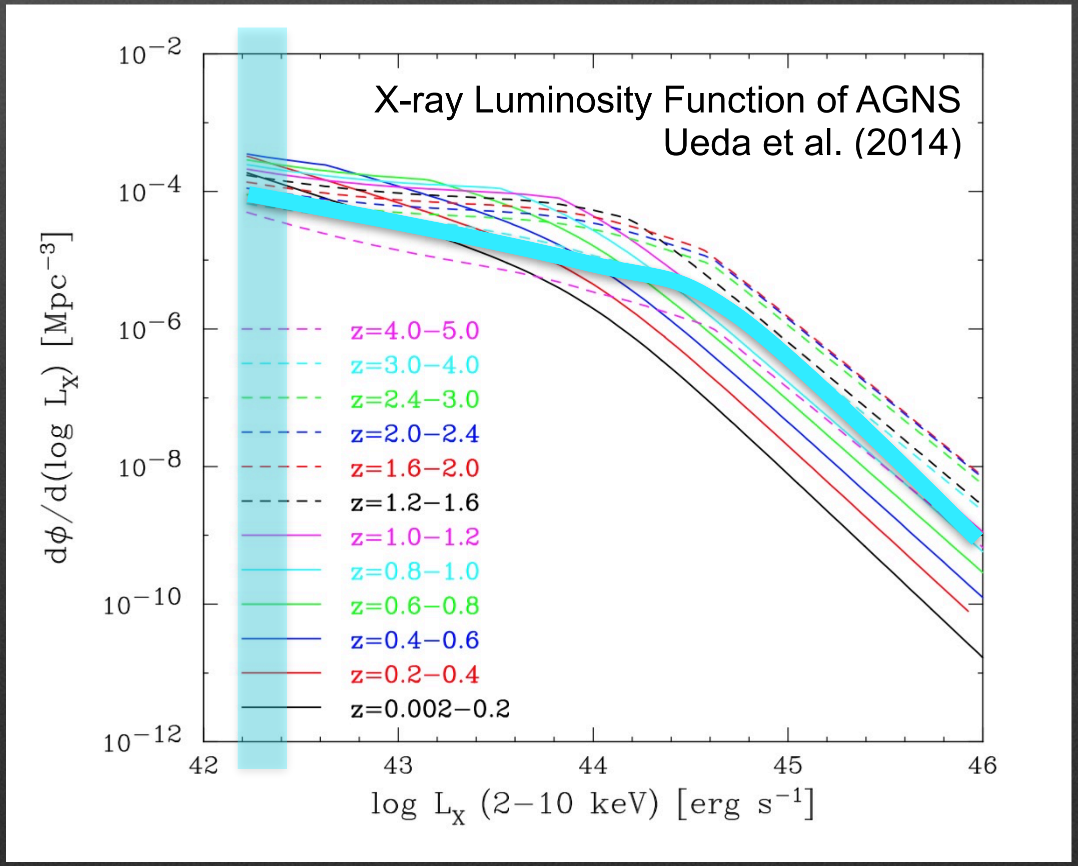
# Feedback from Black Holes

***Medium-deep Lynx Surveys will expose the emergence of prevalent BH population in galaxies after z=~6, in a range of galaxy types and density environments.***

***Lynx will find and characterize the first generation of groups of MW-sized galaxies around z~4.***



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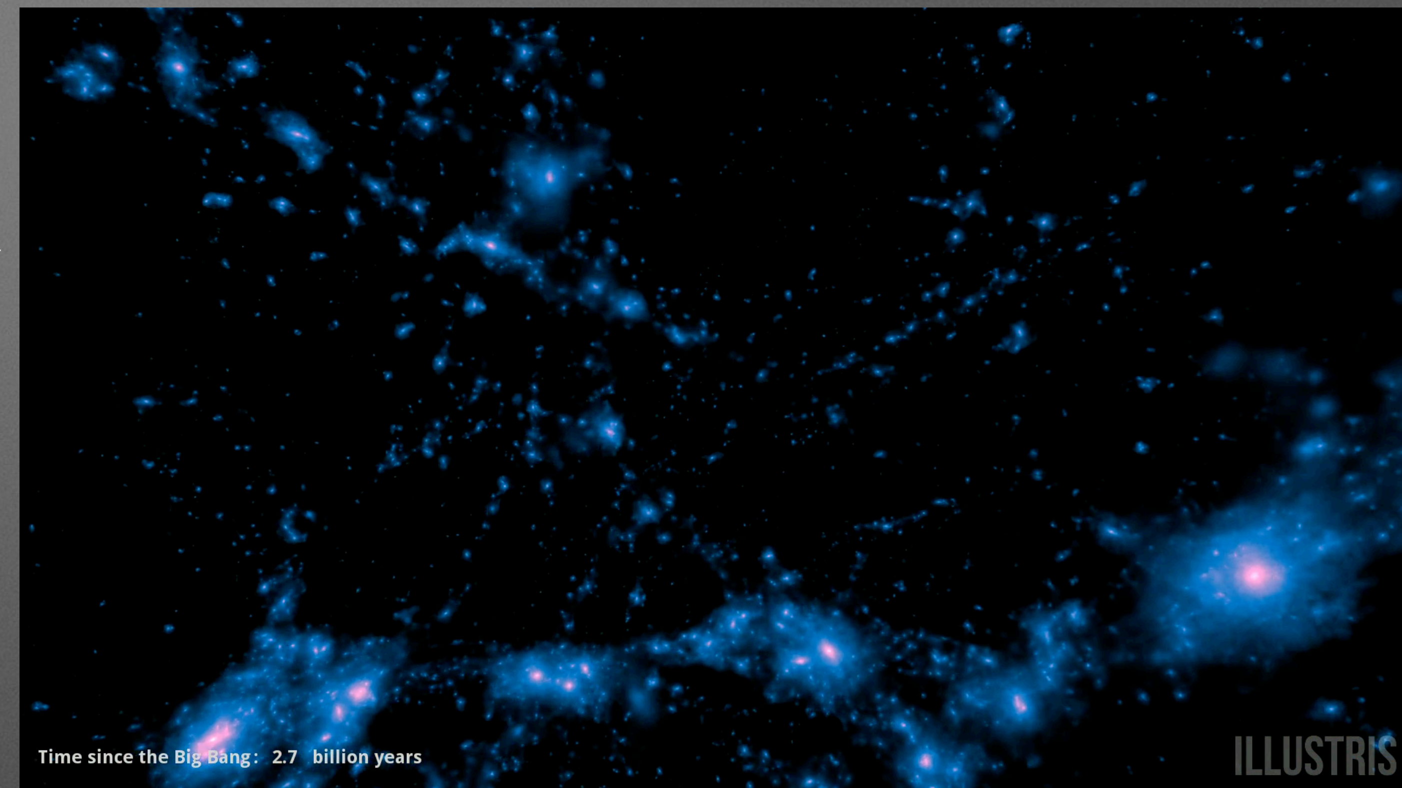
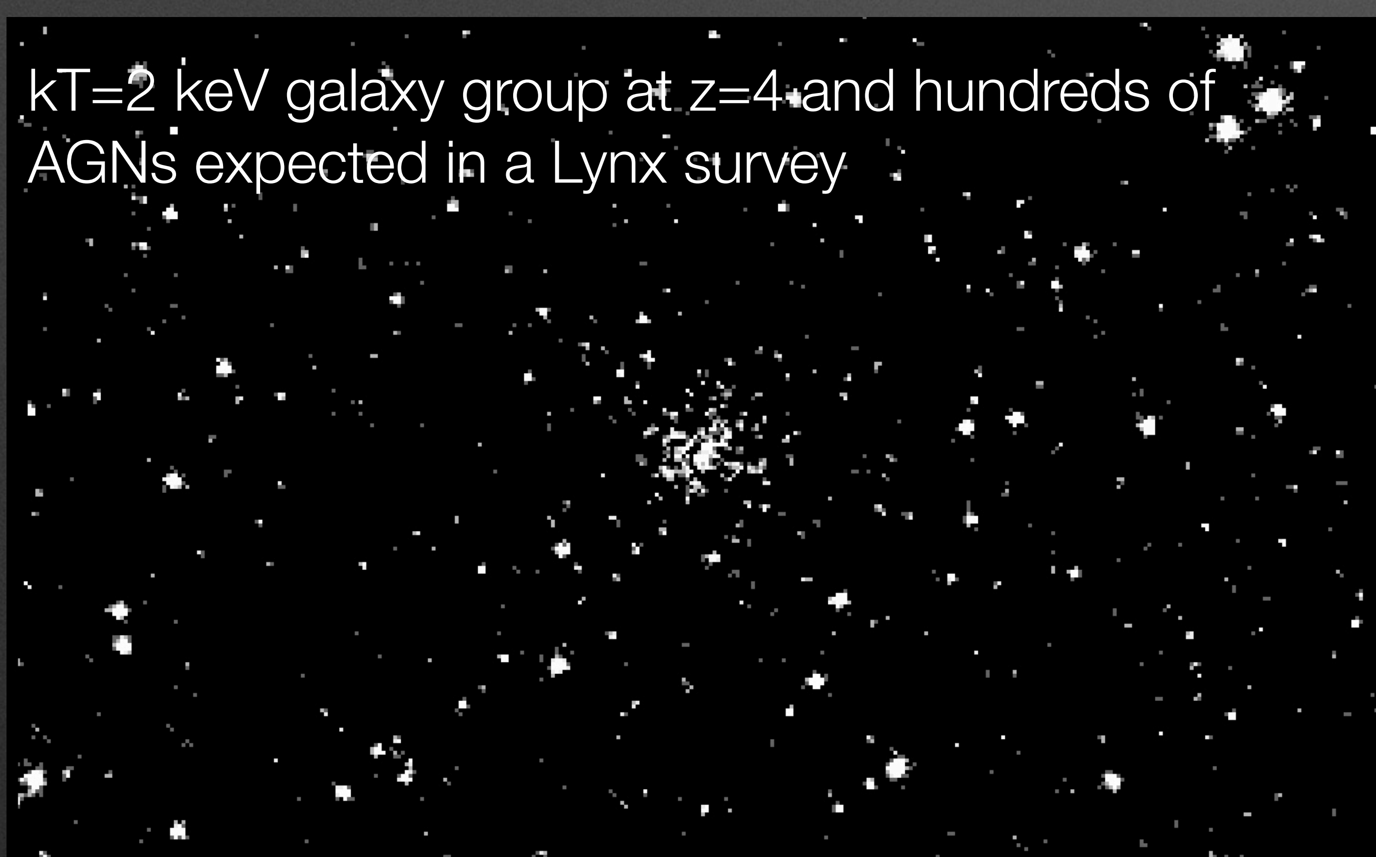
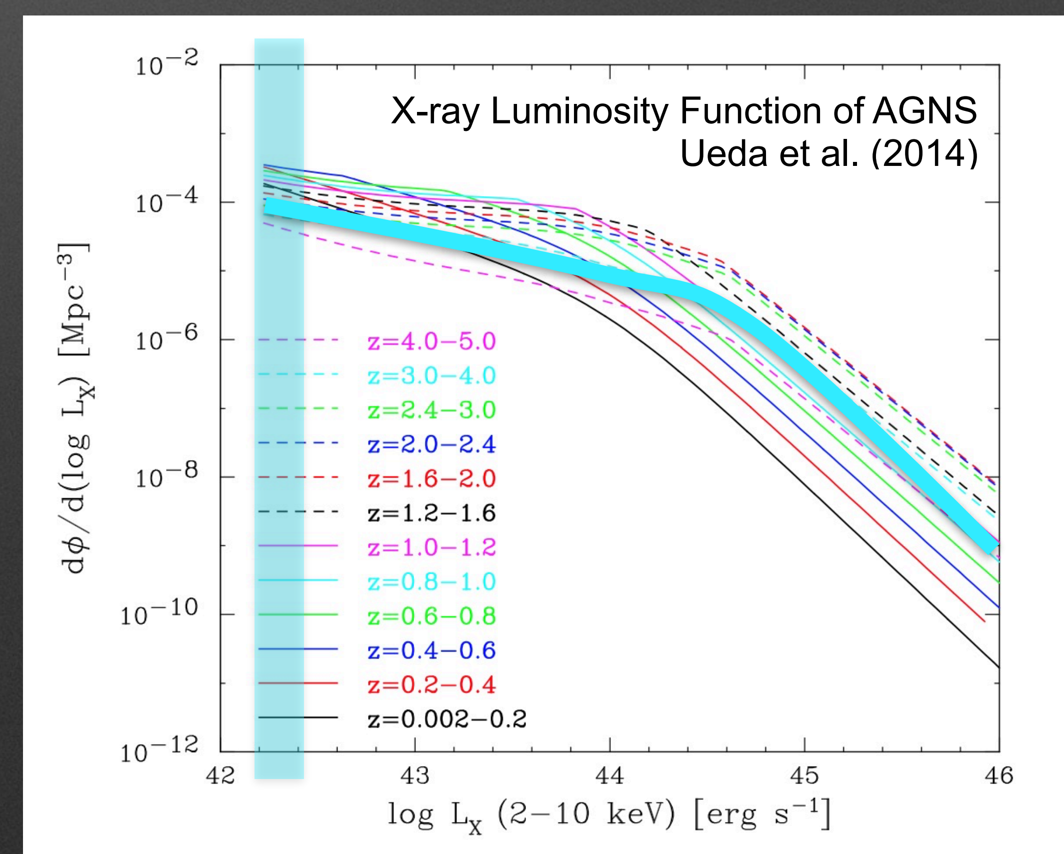


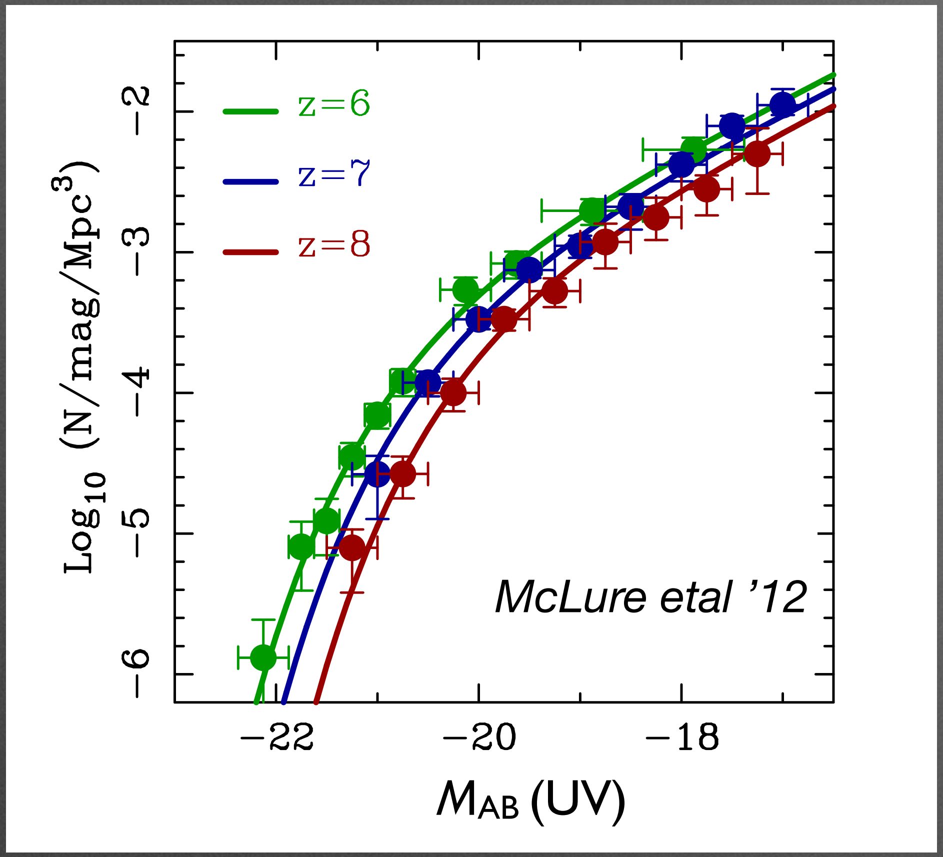



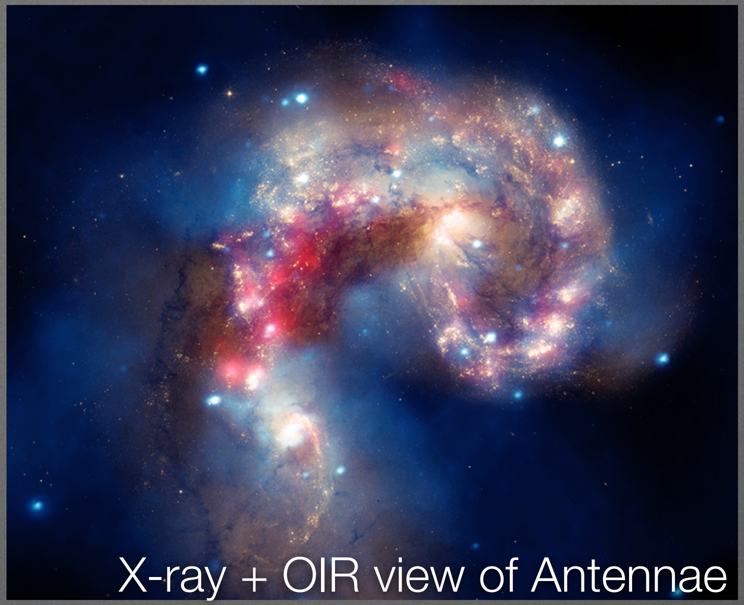



# *First Accretion Light in the Universe*

- **Origin of supermassive black hole seeds: remnants of Pop-III stars with $M_{\rm ini} \sim 10^2$ Msun vs. "heavy seeds" with $M_{\rm ini} \sim 10^4$–$10^5$ Msun**
- X-rays as tracers of star formation & metallicity in the early galaxies
- Cross-correlation of X-ray and 21cm backgrounds from the onset of the reionization epoch

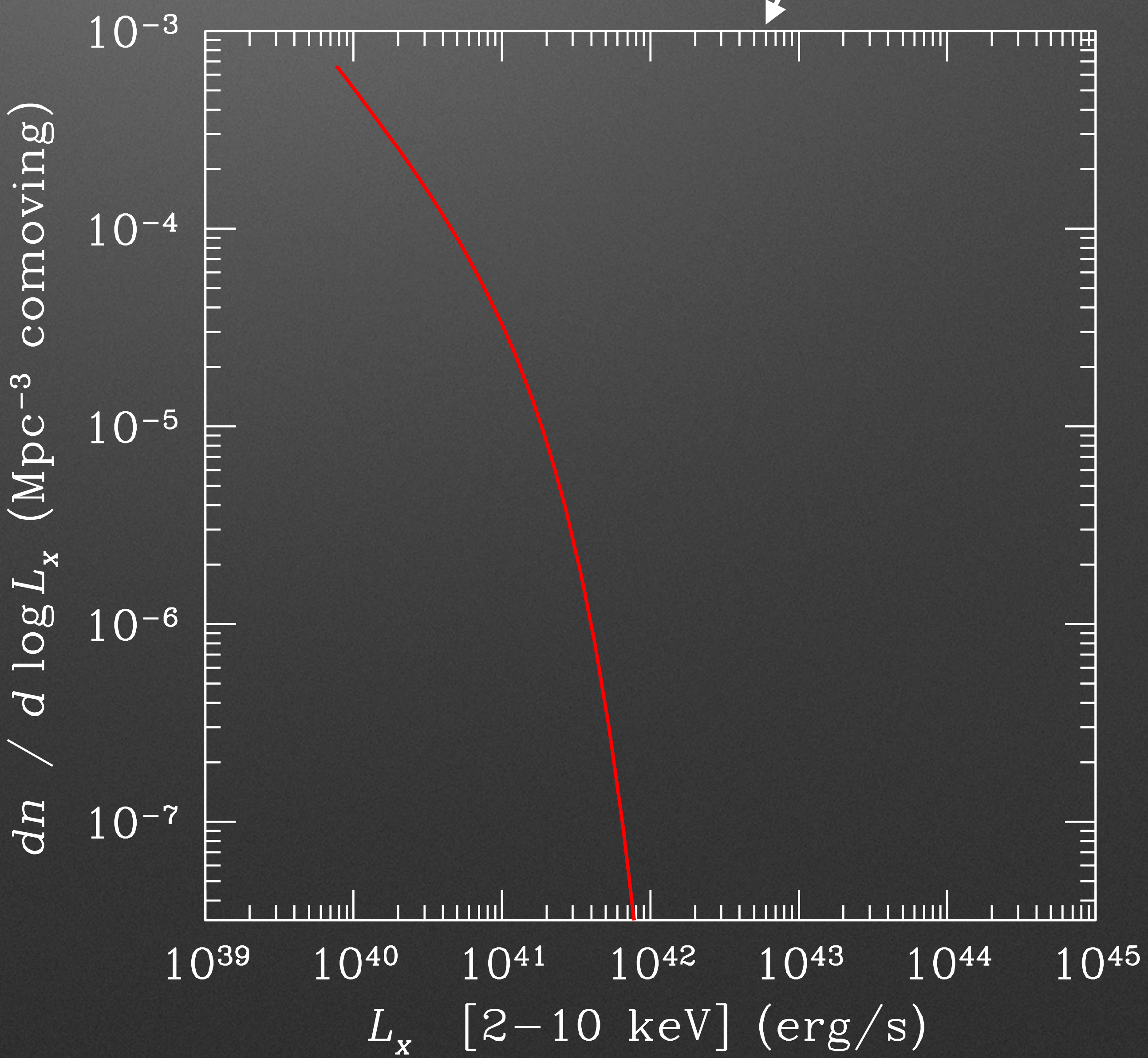
# Flux limit for SMBH seeds science




$L_X$ is due to bright high-mass X-ray binaries born within ~$10^7$ years of the starburst. $L_X = 5 \times 10^{39}$ $\mathrm{ergs}^{-1}$ per 1 $M_\odot$/yr of star formation in the 2–10 keV band unaffected by absorption. Up to ×10 higher output possible at high-*z* due to low metallicity of stellar population

X-ray predictions for z=10:



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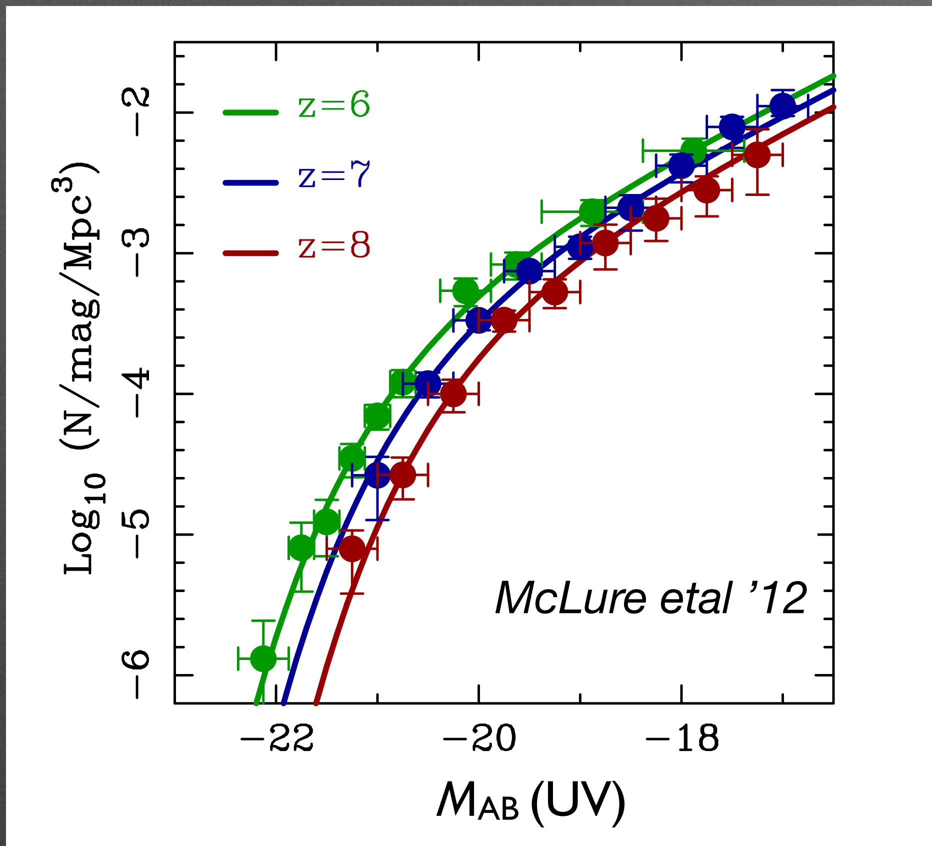
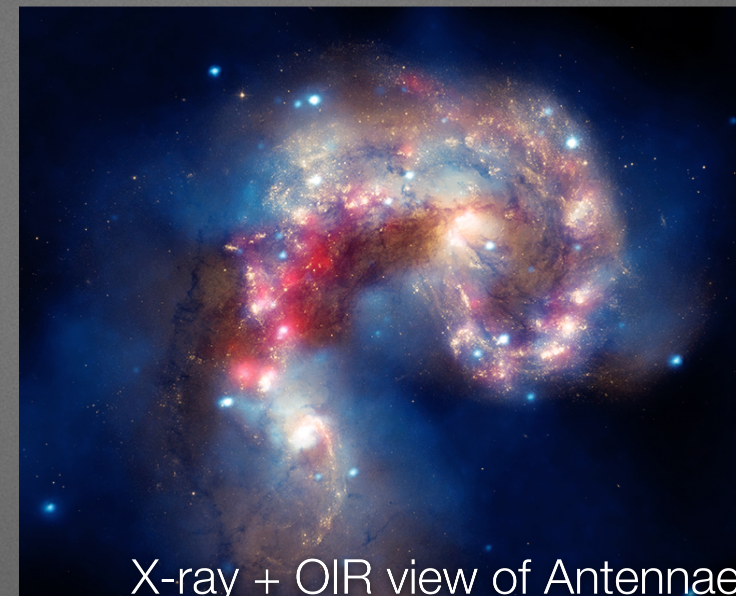
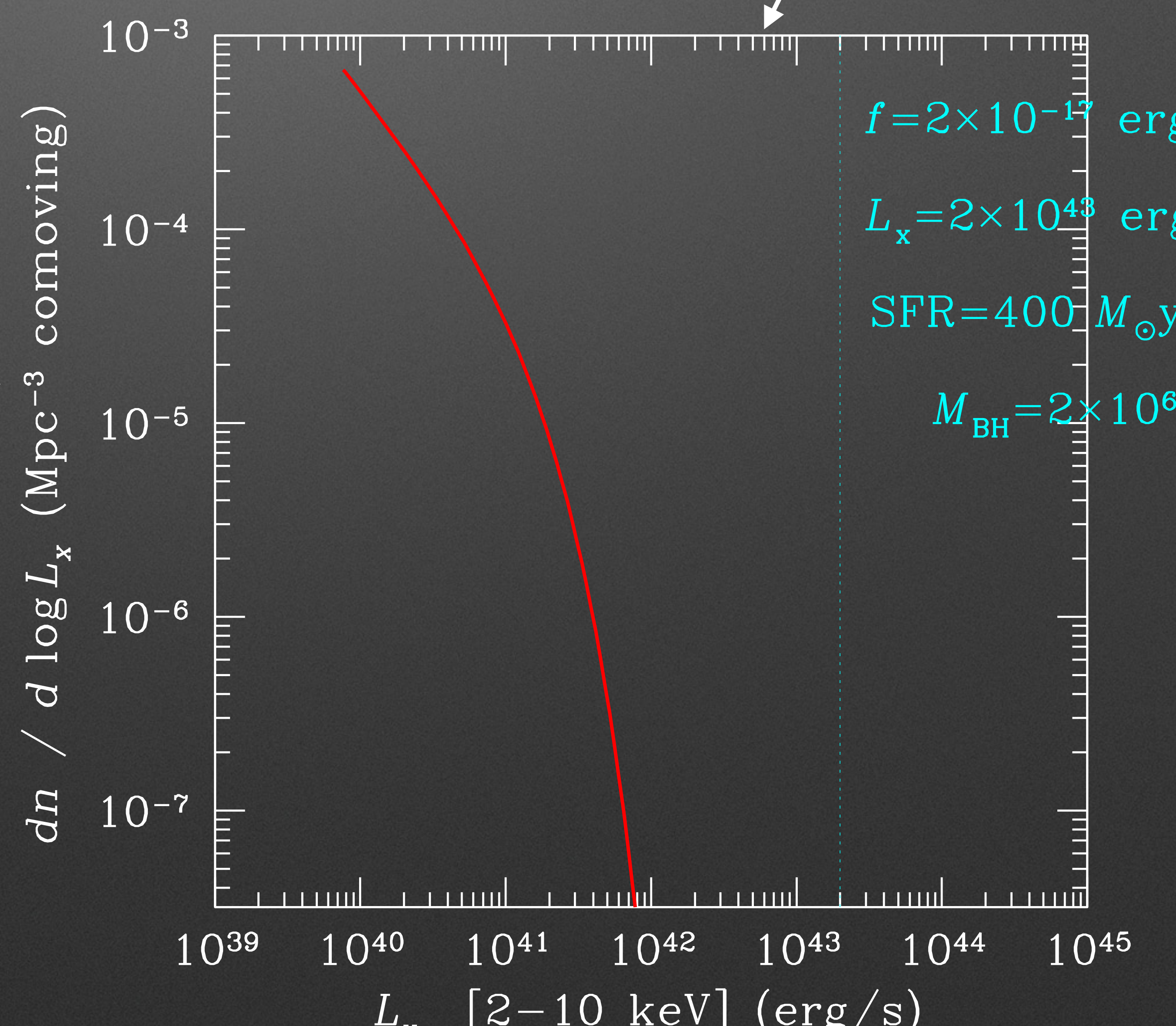


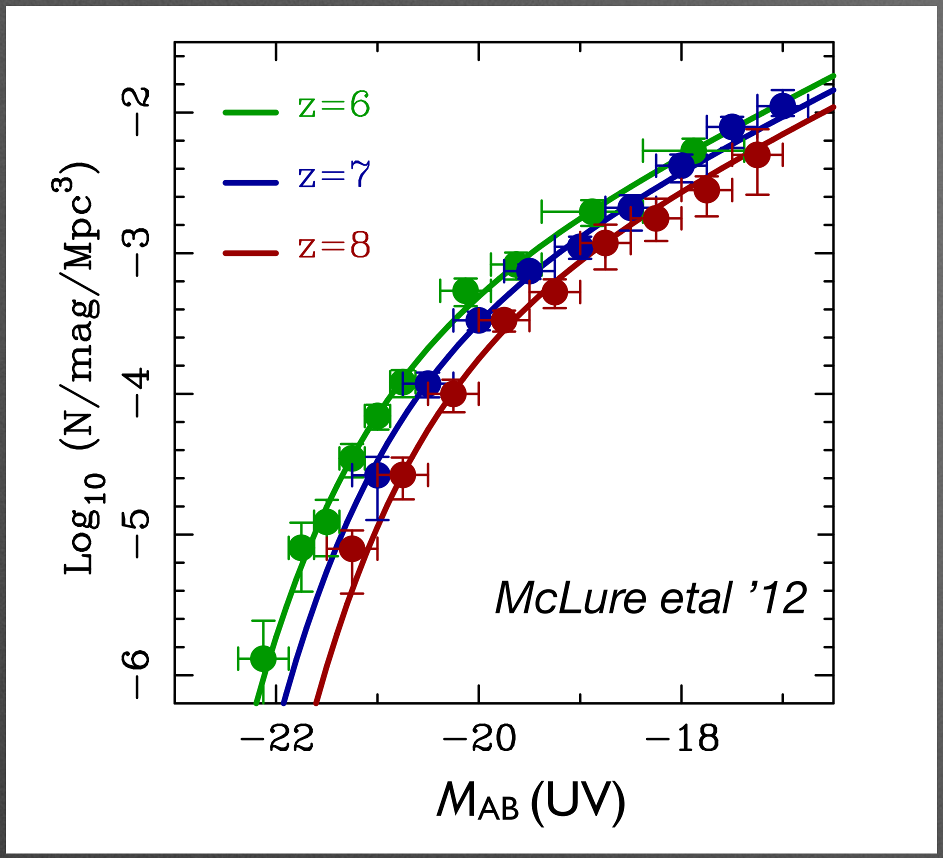



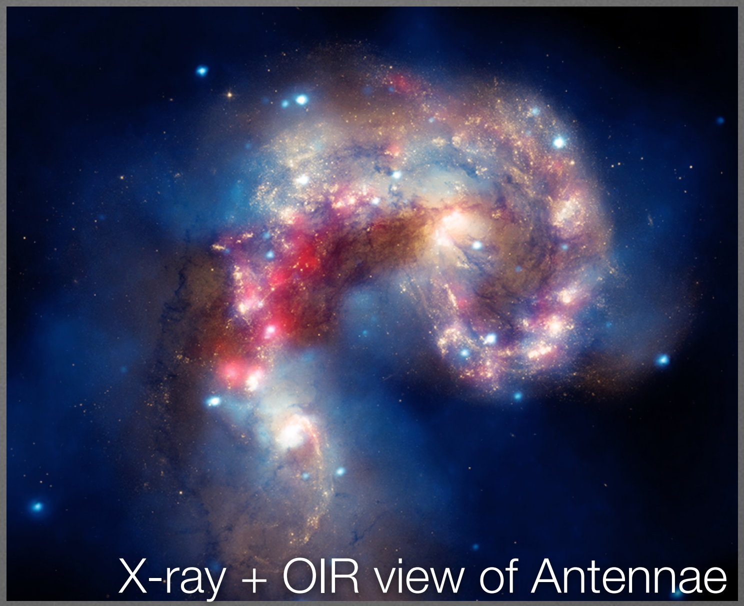

$L_X$ is due to bright high-mass X-ray binaries born within ~$10^7$ years of the starburst. $L_X$ = $5\times10^{39}$ergs$^{-1}$ per 1 $M_\odot$/yr of star formation in the 2–10 keV band unaffected by absorption. Up to ×10 higher output possible at high-*z* due to low metallicity of stellar population

X-ray predictions for z=10:



# Flux limit for SMBH seeds science

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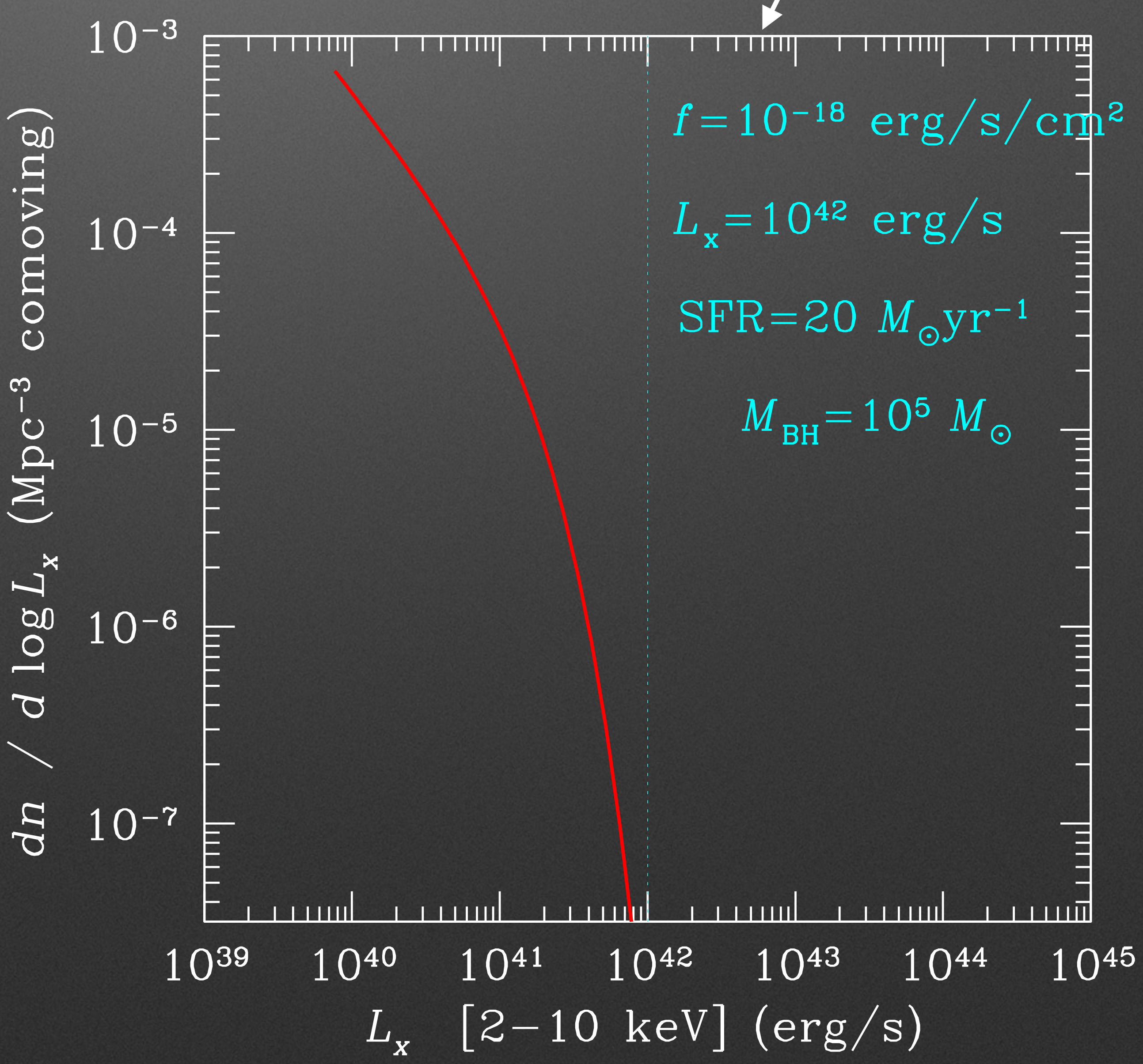
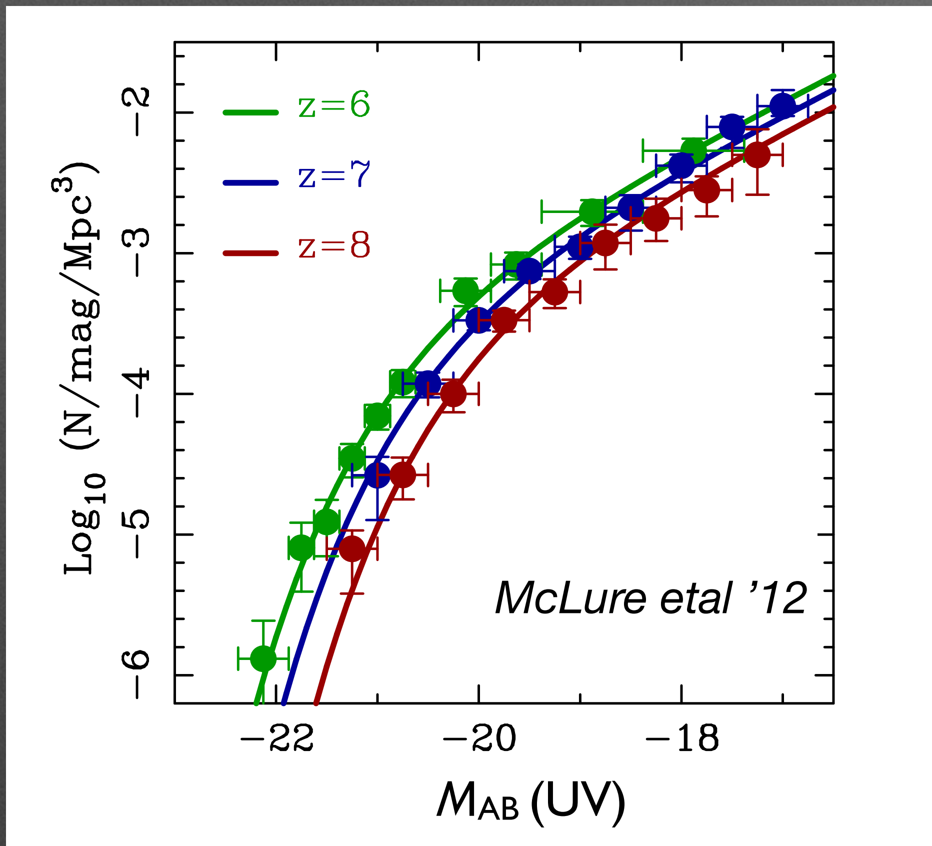
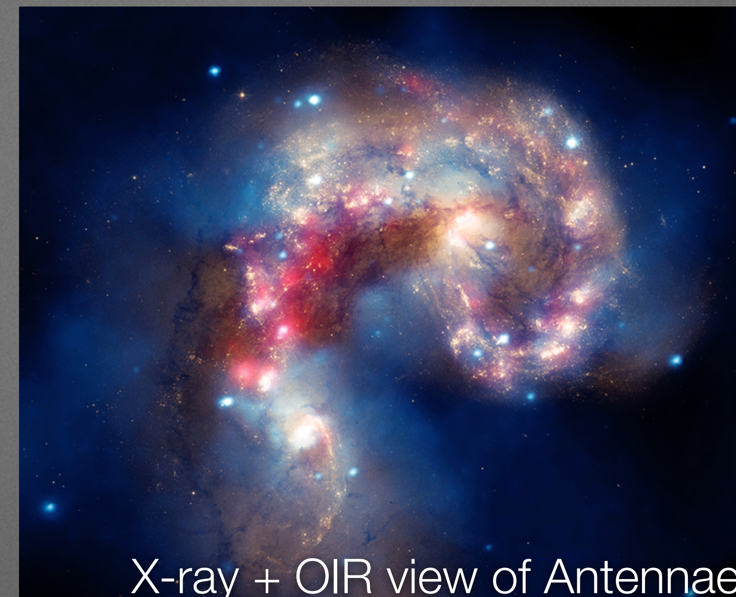


# *Flux limit for SMBH seeds science*

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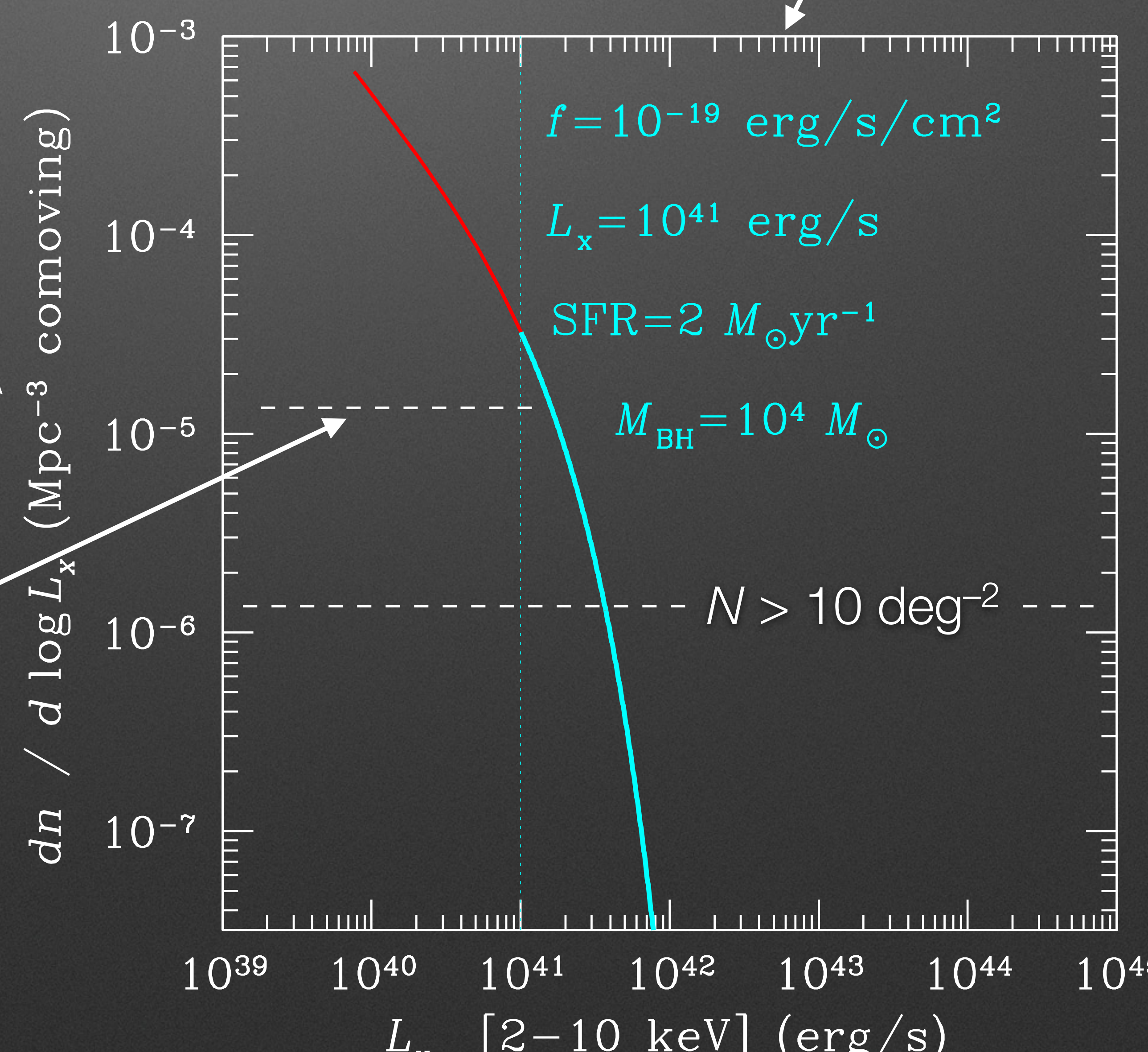
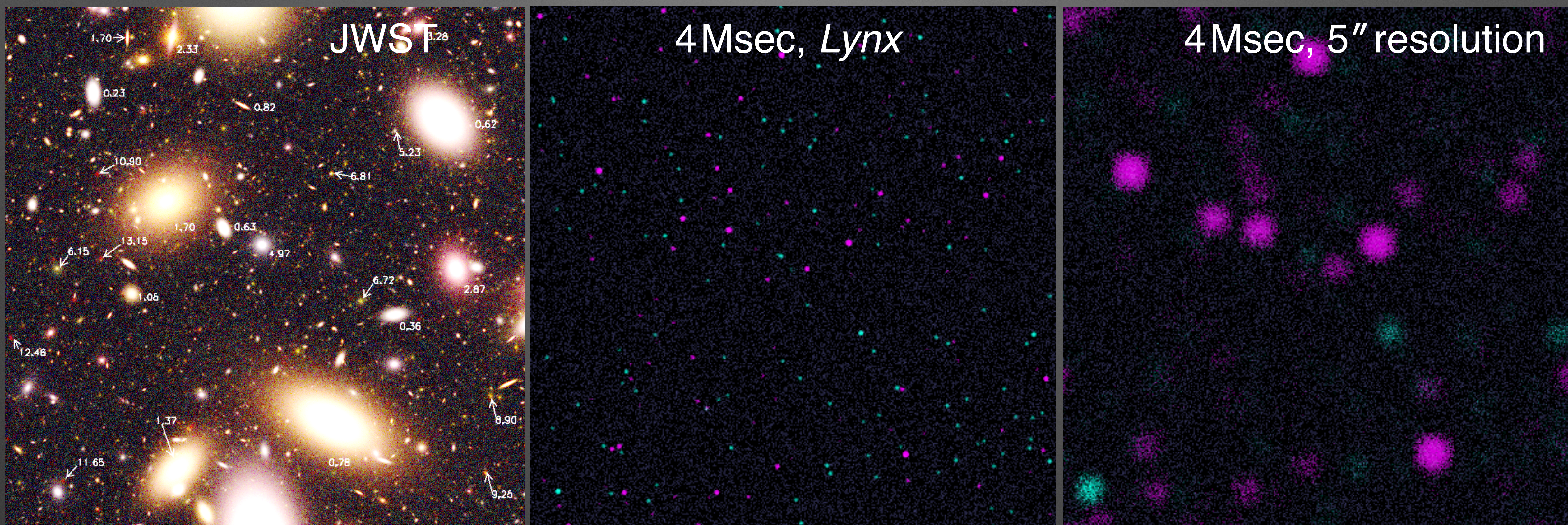



$P_{BH}$=0.001 for galaxies with
$v_{rot}$ = 75 km/s or σ ~ 25 km/s

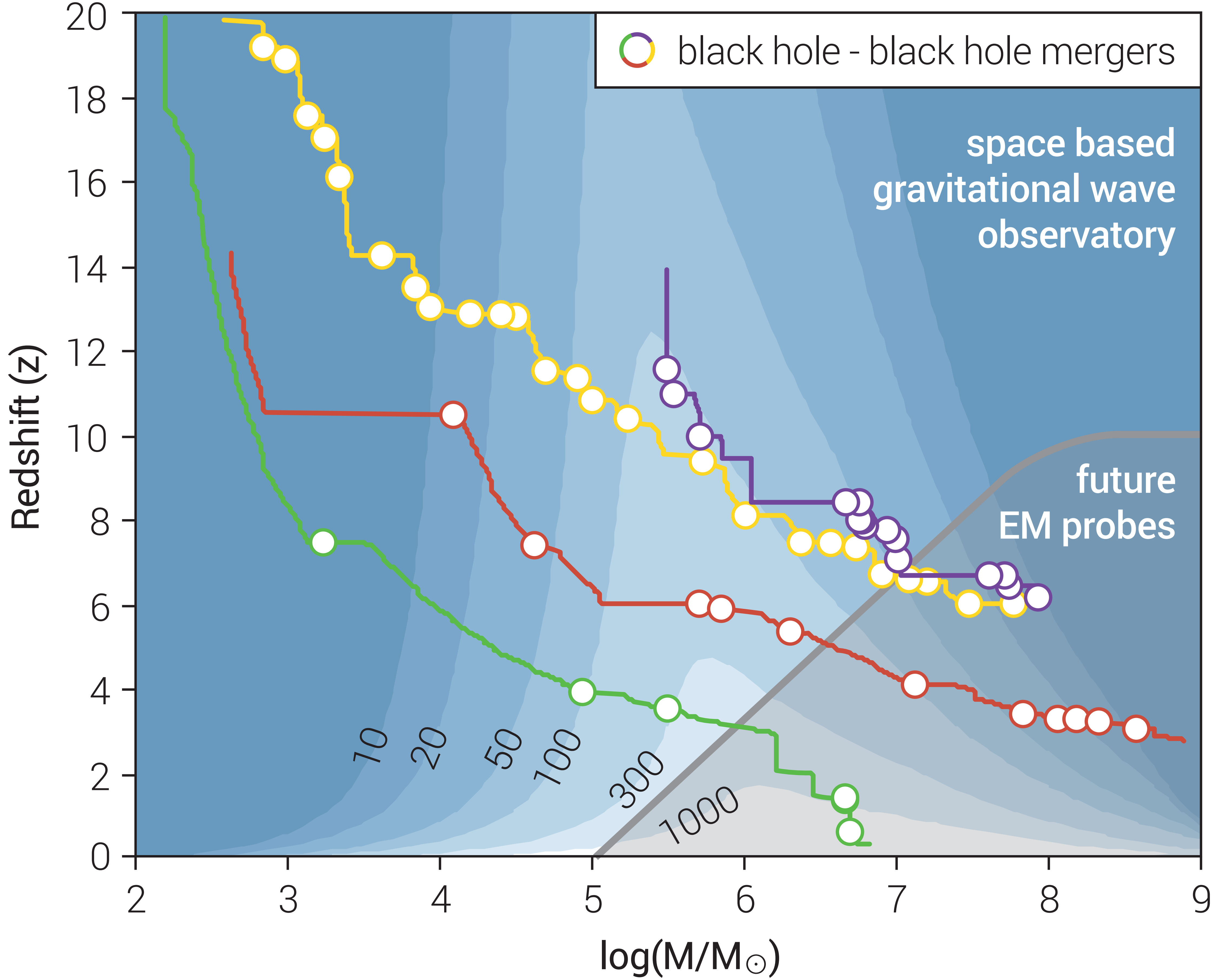
# *Nature of supermassive black hole seeds*

*Simulated 2x2 arcmin deep fields observed with JWST, Lynx, and ATHENA*

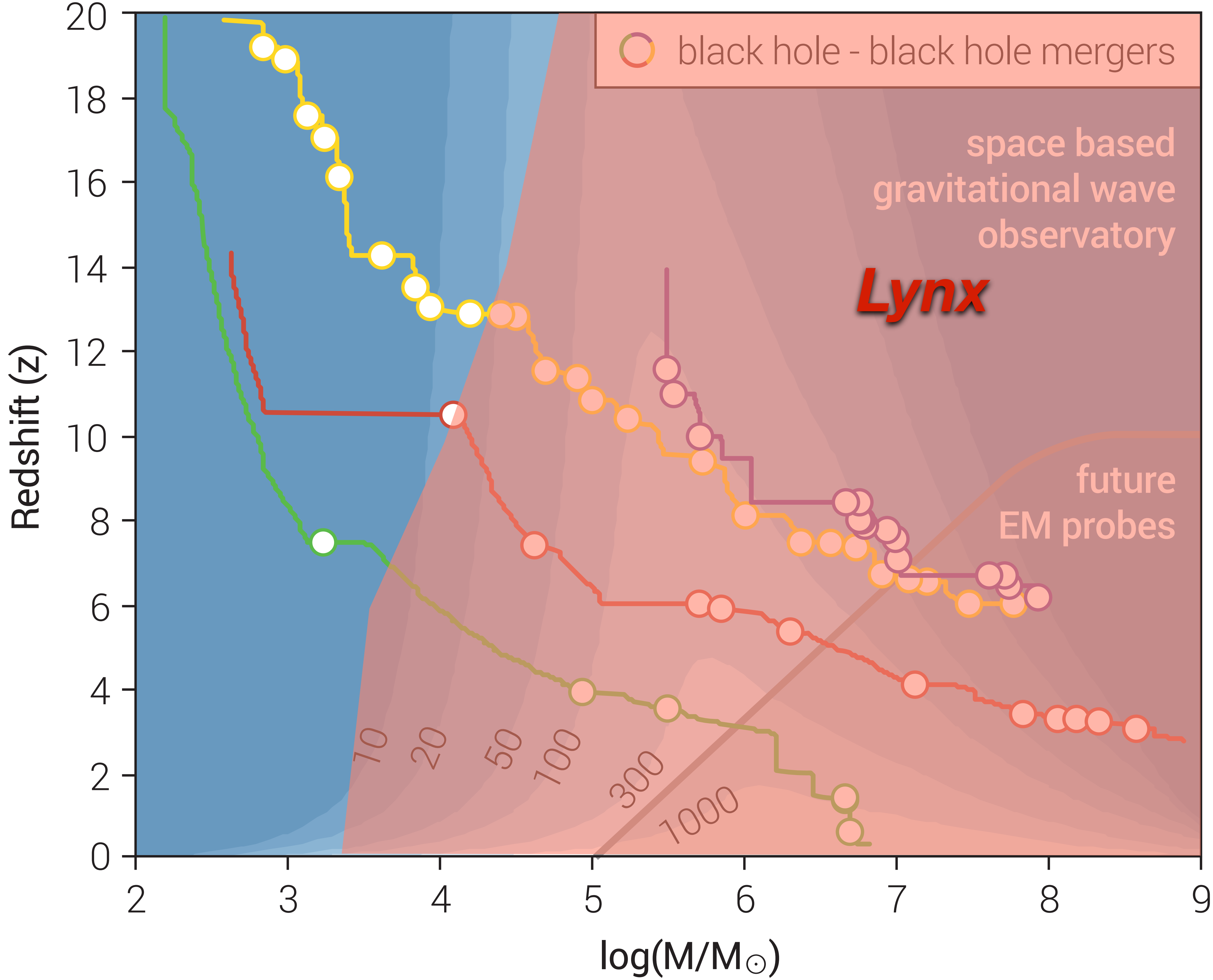



- JWST will detect ~$2\times10^6$ gal/deg$^2$ at its sensitivity limit (Windhorst et al.). This corresponds to 0.03 galaxies per 0.5″ X-ray Surveyor beam (not confused), and 3 galaxies per ATHENA 5″ beam (confused).
- Each X-ray Surveyor source will be associated with a unique JWST-detected galaxy. Limiting sensitivity, ~$1\times10^{-19}$ erg/s/cm$^2$, corresponds to $L_X \sim 1\times10^{41}$ erg/s or $M_{\rm BH} \sim 10{,}000\ M_{Sun}$ at *z=10* —well within the plausible seed mass range.
- X-ray confusion limit for ATHENA is $2.5\times10^{-17}$ erg/s/cm$^2$ (5× worse than the current depth of *Chandra* Deep Field). This corresponds to $M_{\rm BH} \sim 3\times10^6\ M_{Sun}$ at *z*=10 — above seed mass range. Confusion in O&IR id's further increases the limit ($M_{\rm BH}\sim10^7\ M_{Sun}$ at *z*=8 is quoted by ATHENA team).

# *Nature of supermassive black hole seeds*



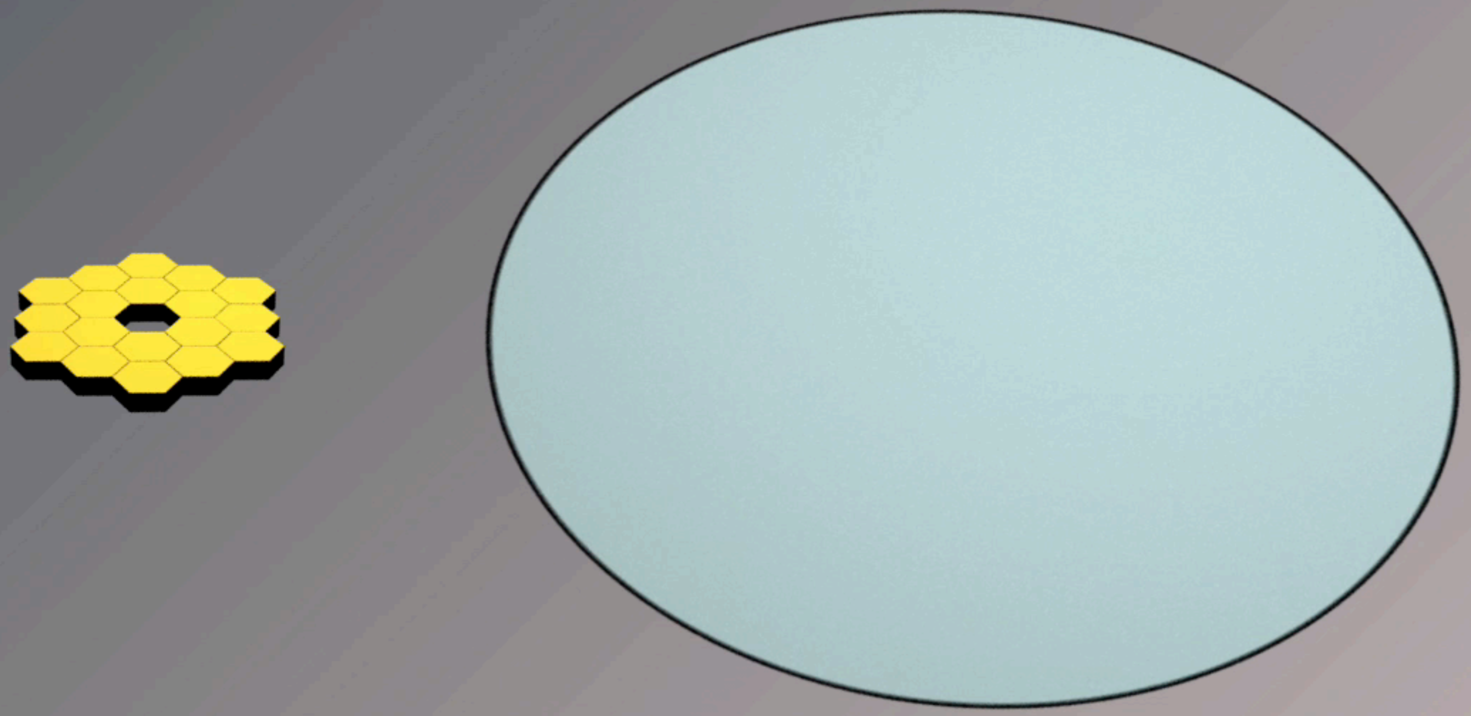
# Nature of supermassive black hole seeds



# *Key Science Requirements for Lynx mission*

- 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 — at least ~ *Chandra*-like — is key for nearly all *Lynx* science.
- Detectors should provide fine imaging, low internal background, and high resolution, spatially resolved spectroscopy.
- Very high spectral resolution ($R$ >~ 5000) in the soft band.

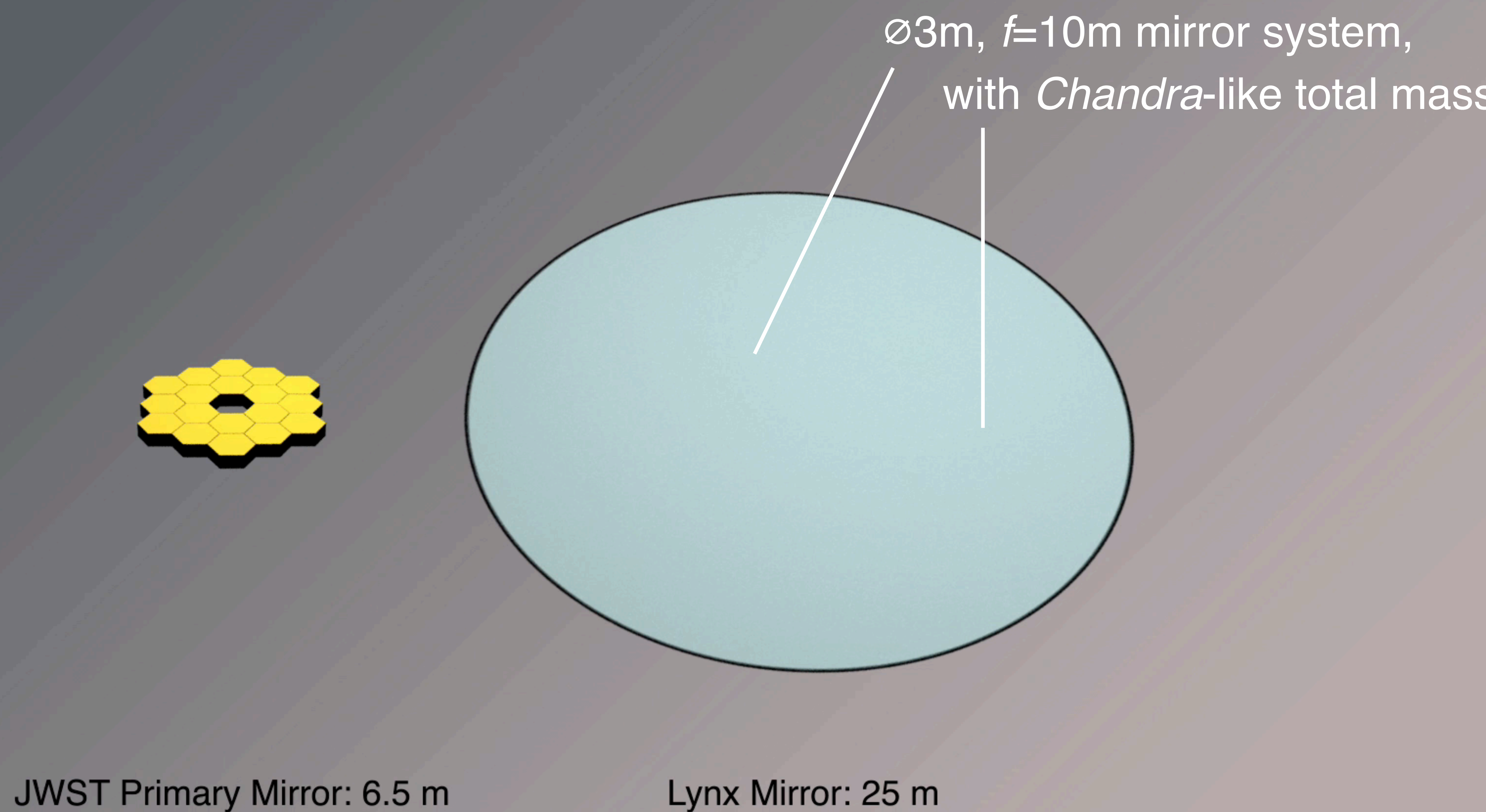
# *Overall envelope of the Lynx mission concept*



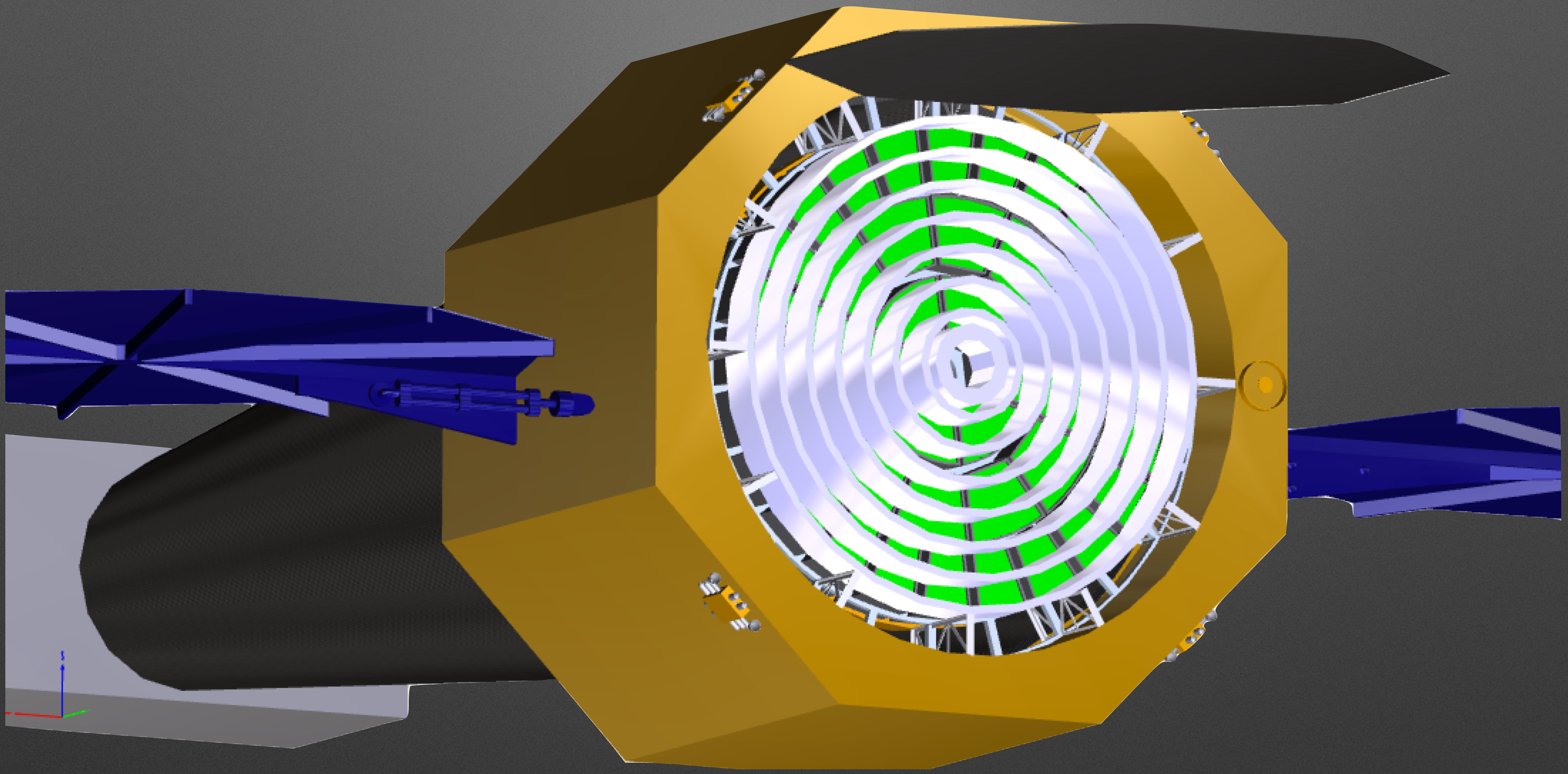
JWST Primary Mirror: 6.5 m

Lynx Mirror: 25 m

# *Overall envelope of the Lynx mission concept*

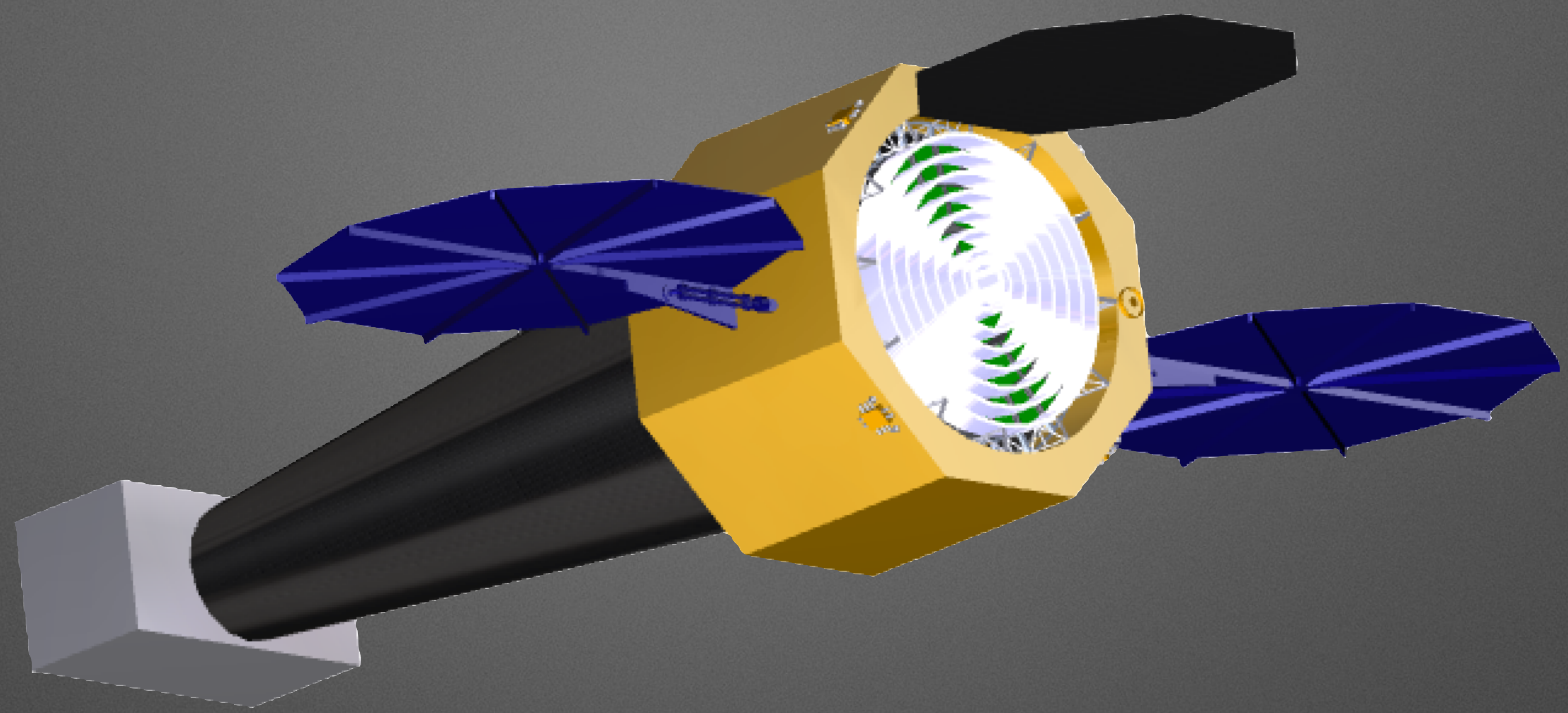


# *Leap in sensitivity: High throughput with sub-arcsec resolution*



- ×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

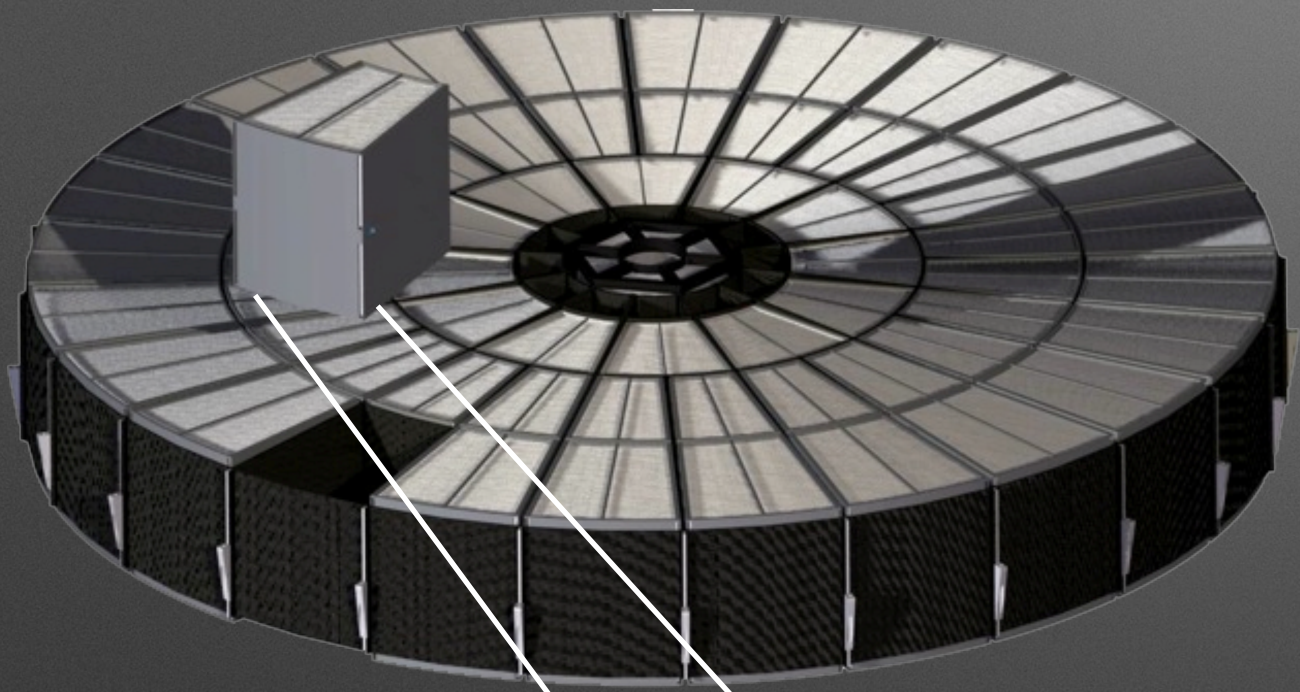
# *Lynx mission concept in a nutshell*

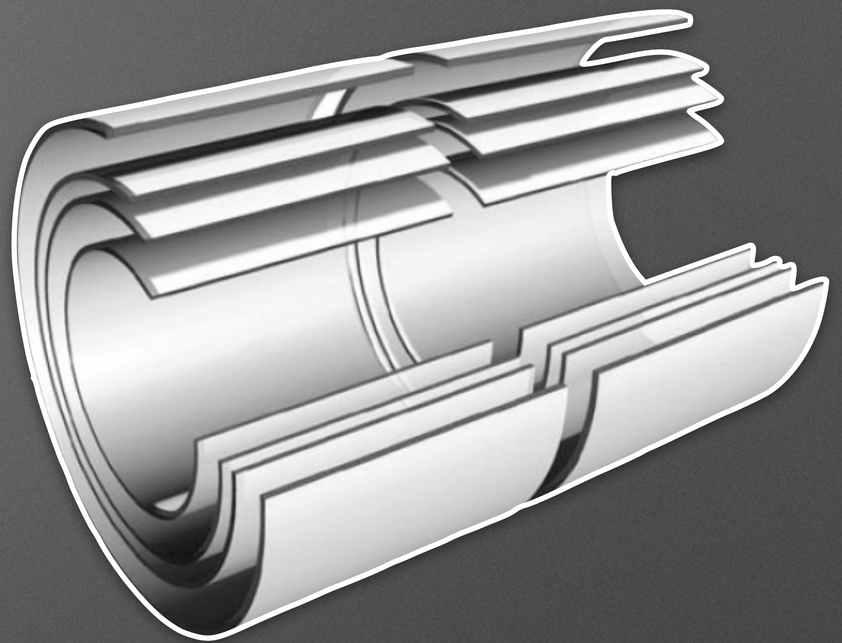


- Ambitious concept for X-ray optics. Mirrors work at grazing incidence, and are tightly packed into a **~3m diameter** envelope. New technologies are needed for manufacturing such a mirror.
- We currently aim at **~ 0.5″ angular resolution** (half-power diameter), detailed trades are pending
- **Focal length ~10m**, providing 0.2-10 keV energy band
- **A suite of 3 advanced science instruments, with requirements TBD. Instrument Working Group is in place**
    - X-ray microcalorimeter array with ~1″ pixels
    - High-definition X-ray images (Si-based active pixels array)
    - X-ray gratings with high efficiency and spectral resolving power >~ 5000

# 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



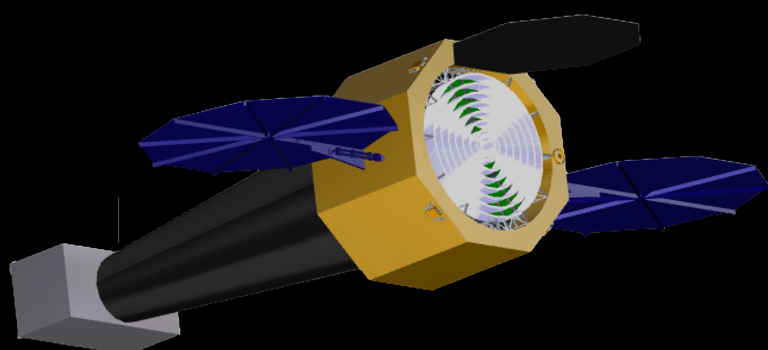


Chandra mirror shells are 2.5cm thick. 1,500 kg for 0.08m$^2$ of collecting area

*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.*

# ***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 1–2–3 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, ALMA, SKA, ATHENA

***Please come to the Lynx splinter session & Hyperwall presentations!***

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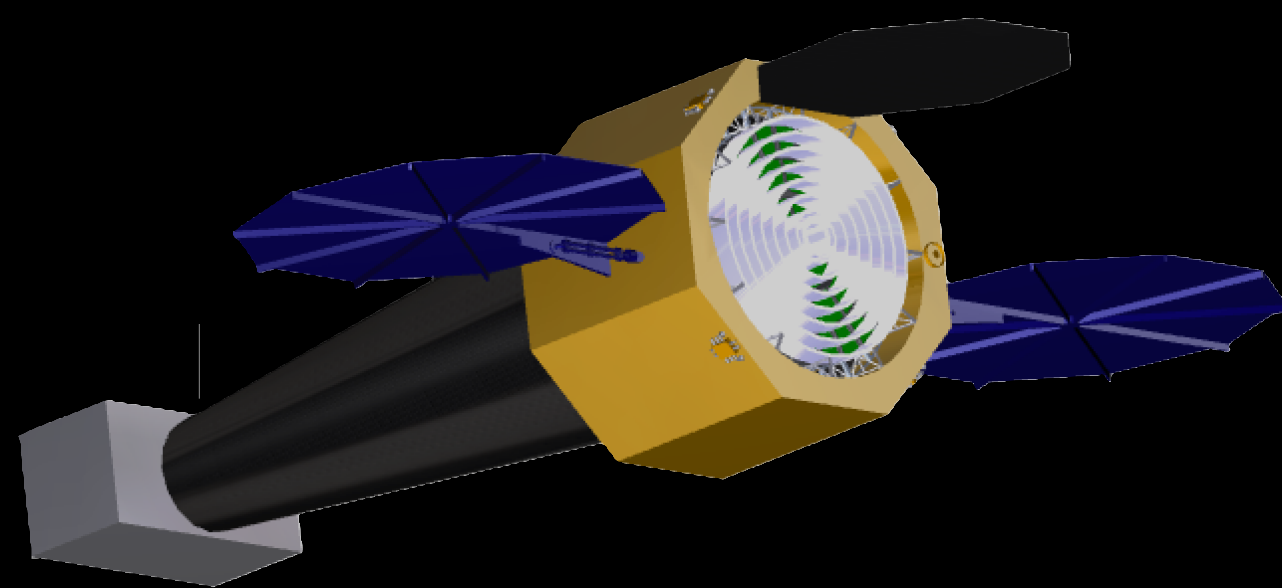

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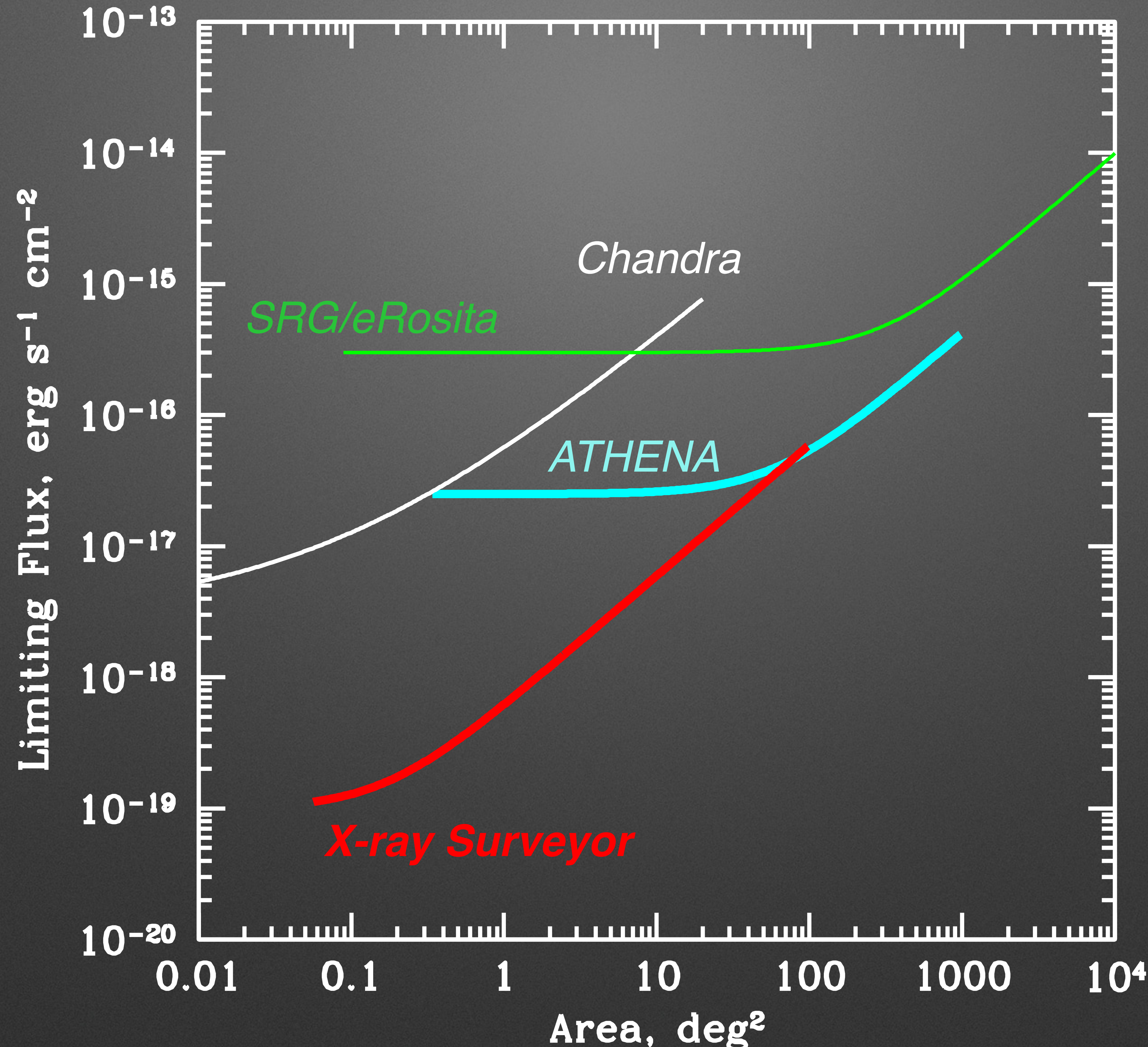
# *BACKUP SLIDES*

# Comparison of survey capabilities: Flux limit vs. area for a 15 Msec program




**×800 higher survey speed at the *Chandra* Deep Field limit**

# *X-ray Surveyor Science Goals*

The Big Questions:

***How Does The Universe Work?*** and ***How Did We Get There?***

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