Synergy SWG

Randall Smith & Rob Petre (science leads)

Outline

- Synergy SWG process and status
- Examples of future capabilities and possible areas of synergy
- Emerging themes
  - Multimessenger followups (TMT, GW observatories, neutrino obsrvatories)
  - Probing the interiors of active galaxies (ALMA, CTA, E-ELTs)
- Derived key XRS requirements

Synergy SWG Activities

- **SWG telecons**
  - Four telecons thus far
  - Over 20 participants in each
  - Discussions are focused on learning about capabilities of future facilities
  - Trying to identify "strong" synergies – where XRS + observatory yields results not obtainable using the observatories individually

- **For each facility, 20 minute presentation covering:**
  - Capabilities, science goals, & timelines for <insert facility name here>
  - Areas of synergy with XRS; XRS capabilities needed

- **Action assigned to presenter plus volunteers to develop slides describing key synergies with XRS**
  - Progress report due after one telecon (~2 weeks)
  - Slides due after the second (~4 weeks)

- **Final products are brief set of slides highlighting key science and a report with details**

- **Haven't yet entered synergy panel inputs into spreadsheet or started simulations**
  - Activities for the next 2-3 months

- **Synergy team workshop March 21-22 at SLAC**
  - Agree on highest priority science objectives and design drivers
  - Produce first draft of white paper chapter

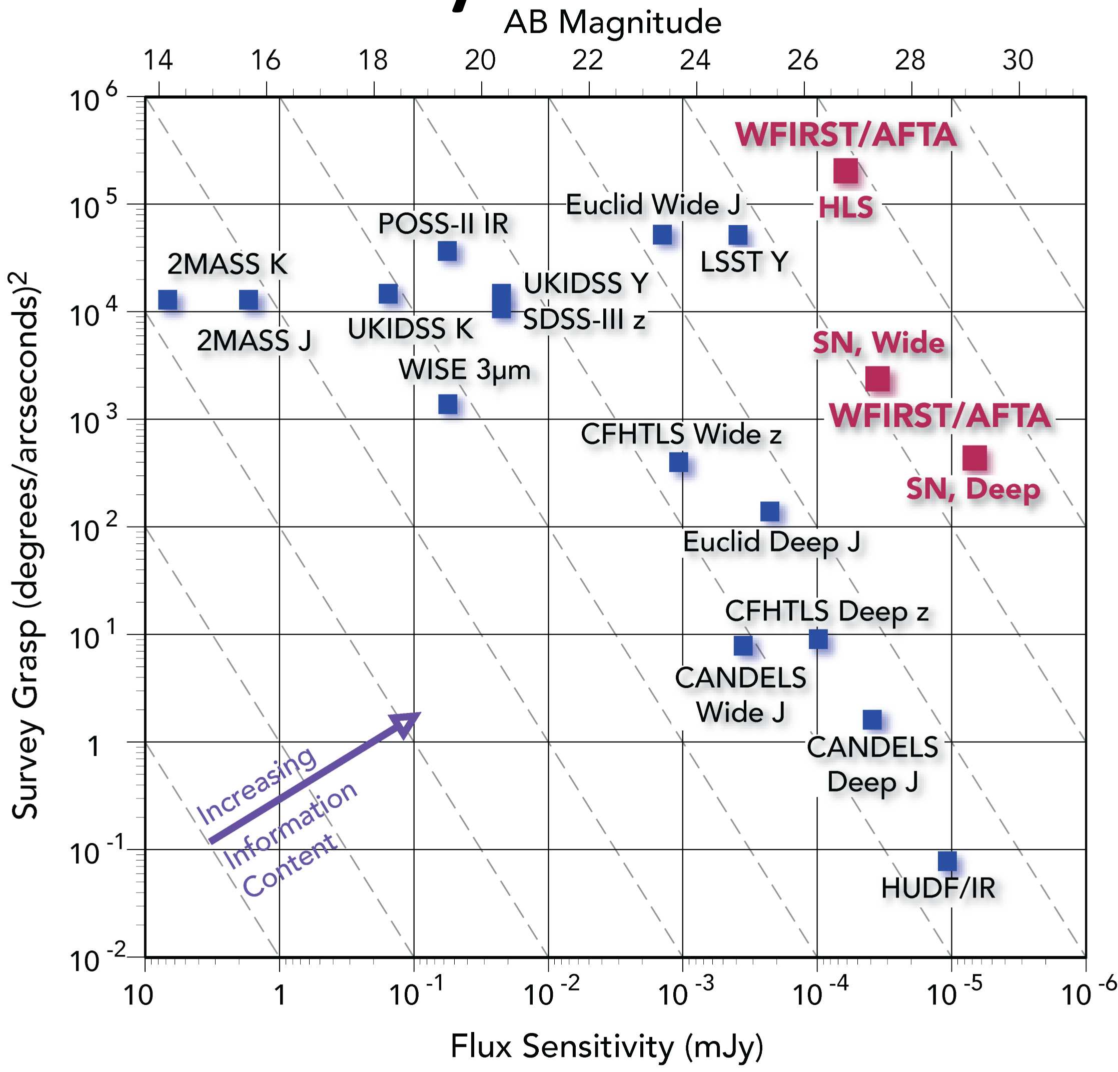
Major New Facilities for 2030-35

- **Thus far:**
  - WFIRST (Griffiths)
  - ALMA (Tremblay)
  - ELT's – TMT, GMT, E-ELT (Skidmore)
  - GW observatories (Gezari)
  - SKA (Turriziani)
  - LSST (Antoniou)
  - CTA (Kieda)
  - Neutrino observatories (Santander)

- **Still to come (among others):**
  - JWST, Hubble, eROSITA, TESS (archival)
  - NgVLA
  - Athena
  - Event Horizon Telescope
  - SPICA

WFIRST Surveys

- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Will be completed by the time of XRS launch
  - Provides deep catalog of sources with known redshifts, ideal place to select targets where XRS could distinguish accreting SMBH from nuclear starburst region Flexibility to choose optimal approach



Near Infrared Surveys

R. Griffiths - WFIRST

Areas of Potential Synergy between XRS and WFIRST

2.4M, NIR, launch 2027?

- **Clusters of Galaxies**

  WFIRST is expected to discover ~40,000 $M>10^{14}$ M_O clusters out to z~3 in the 2000 sq.deg. area of the high latitude survey (HLS)

  Evolution of clusters: WFIRST lensing studies will enable identification of mergers of clusters of galaxies (Bullet Cluster etc.)

  X-ray-selected groups vs. weak-lensing groups

- **Galaxies and AGN**

  Photometric redshifts for a sample of hundreds of millions of galaxies out to z=3 will be a huge asset to studies of the evolution and clustering of galaxies and AGN.

  Evolution of all types of galaxies in X-rays vs visible/IR, including massive galaxies and star-forming galaxies

  Obscured AGN (thousands per sq. deg. ?)

  Faint end of the AGN LF (and re-ionisation of the universe)

  WFIRST HLS will be used to discover hundreds of galaxy-scale lensed AGN

CMB/SZ Synergies with XRS

"CMB" generally covers frequencies of ~30-400 GHz.

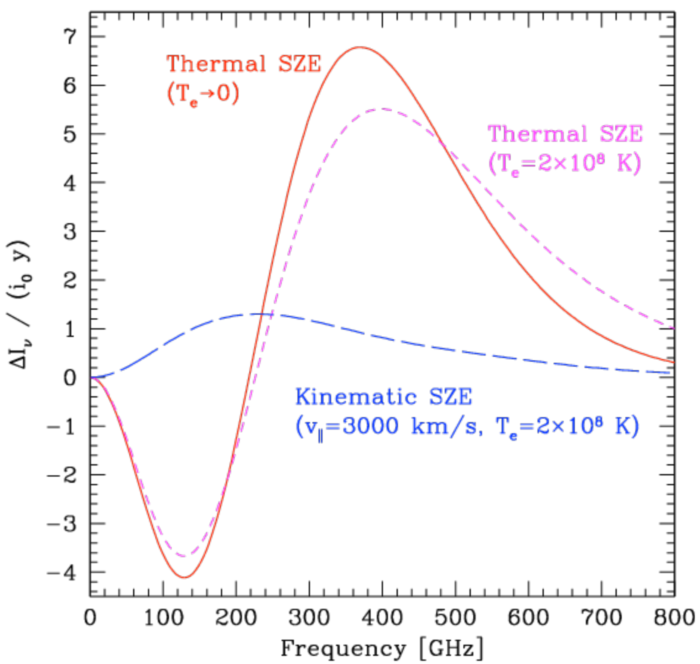
Typical resolution @100GHz

- Survey telescopes: >1'
- Single large dishes: >9"
- Interferometers: arbitrarily small

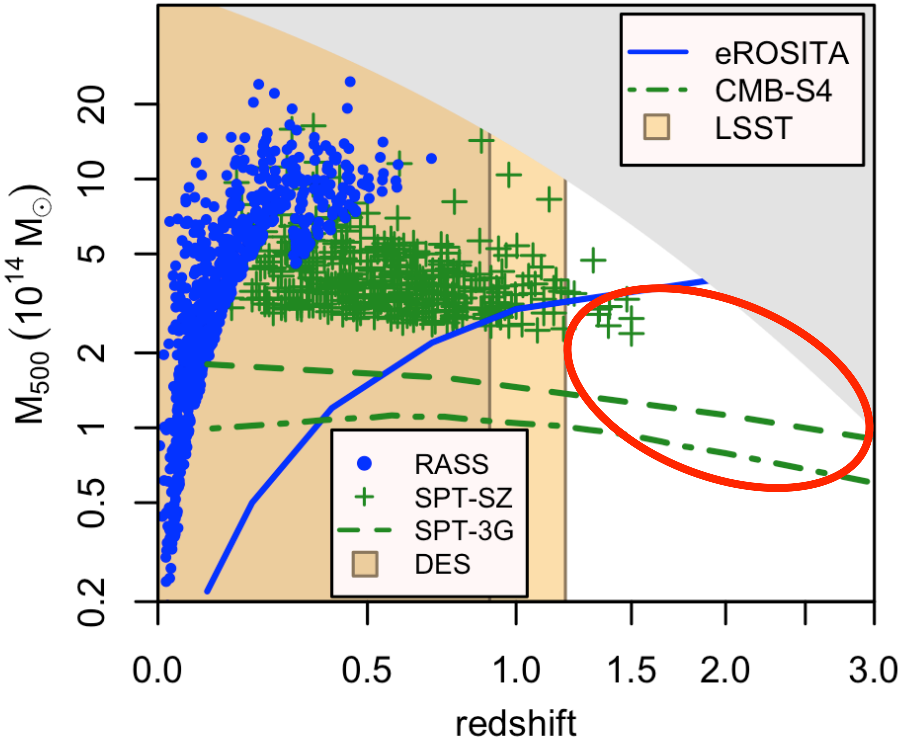
Survey data produce catalogs of clusters (through the SZ effect) and radio/dusty/ star-forming galaxies out to high redshifts.

Traditional observatories can resolve these signals on smaller scales.

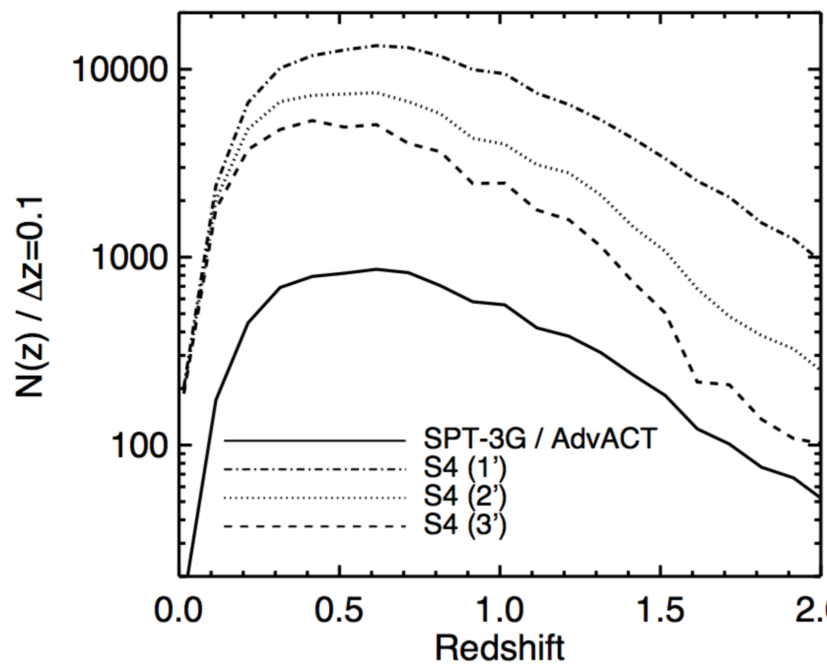
Sunyaev-Zel'dovich effect: the spectral distortion of the CMB caused by inverse-Compton scattering in the intracluster medium.

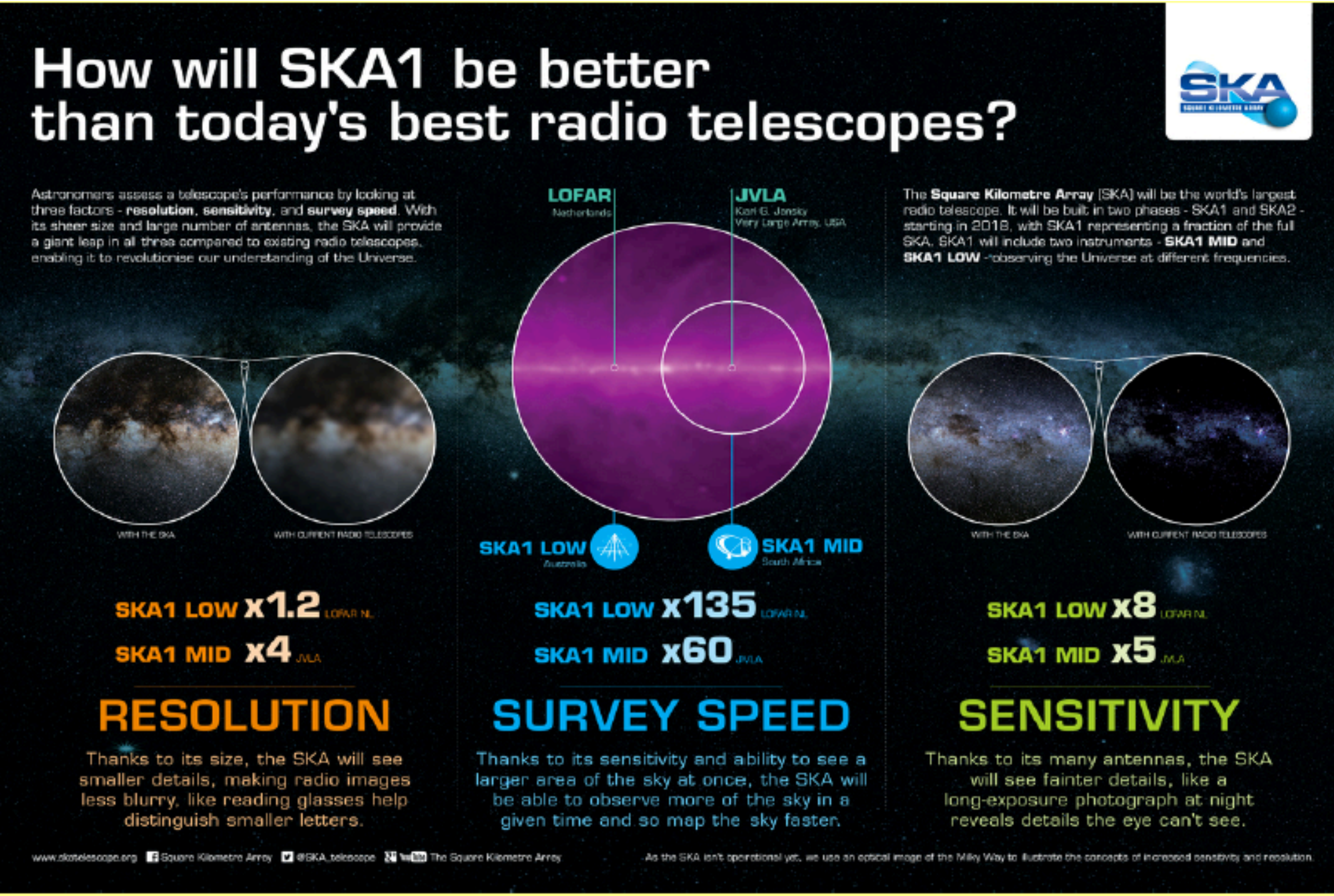


Synergies with CMB surveys



Next-generation CMB surveys will identify and calibrate the masses of the largest clusters at redshifts 2-3. These are the targets for key XRS studies of the thermodynamics and enrichment of newly virialized clusters.




How will SKA1 be better than today's best radio telescopes?
SKA
Astronomers assess a telescope's performance by looking at three factors - resolution, sensitivity, and survey speed. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.
LOFAR
Netherlands
JVLA
Karl G. Jansky Very Large Array, USA
The Square Kilometre Array (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.
WITH THE SKA
WITH CURRENT RADIO TELESCOPES
SKA1 LOW
Australia
SKA1 MID
South Africa
WITH THE SKA
WITH CURRENT RADIO TELESCOPES
SKA1 LOW x1.2 LOFAR NL
SKA1 MID x4 JVLA
RESOLUTION
Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.
SKA1 LOW x135 LOFAR NL
SKA1 MID x60 JVLA
SURVEY SPEED
Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.
SKA1 LOW x8 LOFAR NL
SKA1 MID x5 JVLA
SENSITIVITY
Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.
www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array
As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.

Possible areas of synergy with XRS

- Galaxy Evolution (surveys)

(starburst, AGN, galaxy clusters, ULXs)

and cluster cosmology

$\begin{cases} \textit{HI} \\ \textit{Continuum} \end{cases}$

- Cosmic Magnetism (AGN jets, galaxy clusters, possibly the cosmic web)
- Gravitational Waves (see also Suvi Gezari talk)
- Pulsars (Multiwavelength view)
- Transients (GRBs, TDEs, SNae, AGNs, FRBs, etc.)

→ ToOs with XRS?

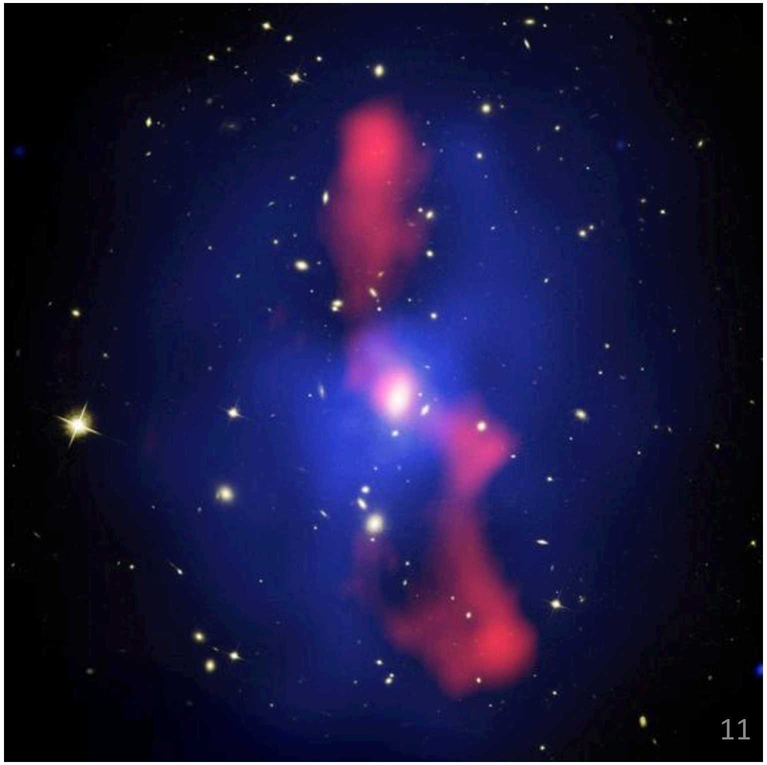
- Discovery of the Unknow Unknowns!

Synergies with ALMA

ALMA will provide measurements of the SZ effect on scales comparable to XRS resolution (unlike single dishes). With wide spectral coverage, we can also constrain gas velocities and temperature through 2nd-order spectral distortions.

Key X-ray/SZ synergies exploit the complementary sensitivities to gas density, temperature and pressure to study

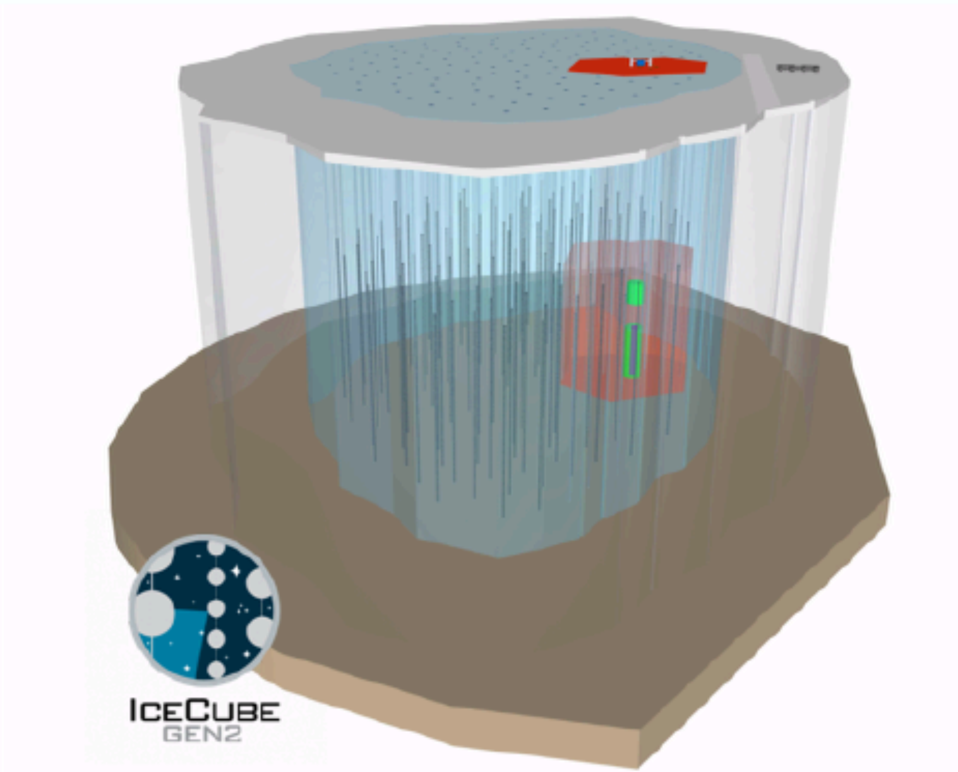
- Properties of shocks
- Energy budget of ICM cavities
- Turbulence and energy transport in the ICM



We can look at things things at low redshifts now, but only superb resolution and sensitivity can extend these studies to redshifts >1, and even to the epoch of cluster formation!

Future neutrino telescopes

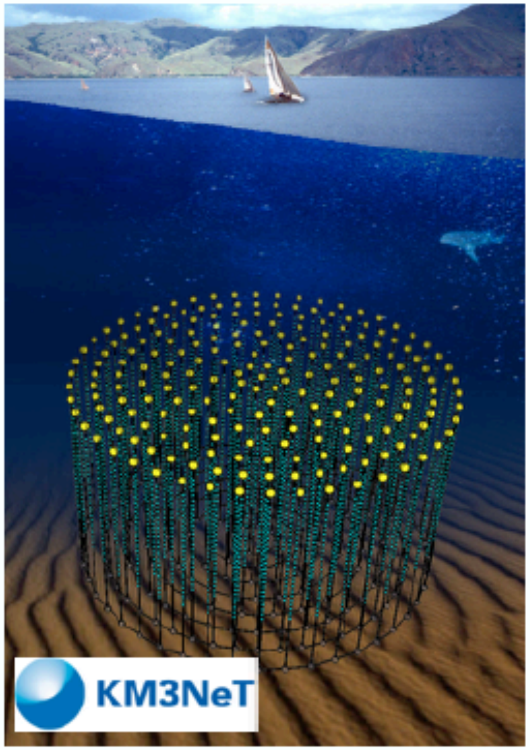
IceCube - Gen2



https://arxiv.org/abs/1412.5106

~10 km³
optimized for high energies

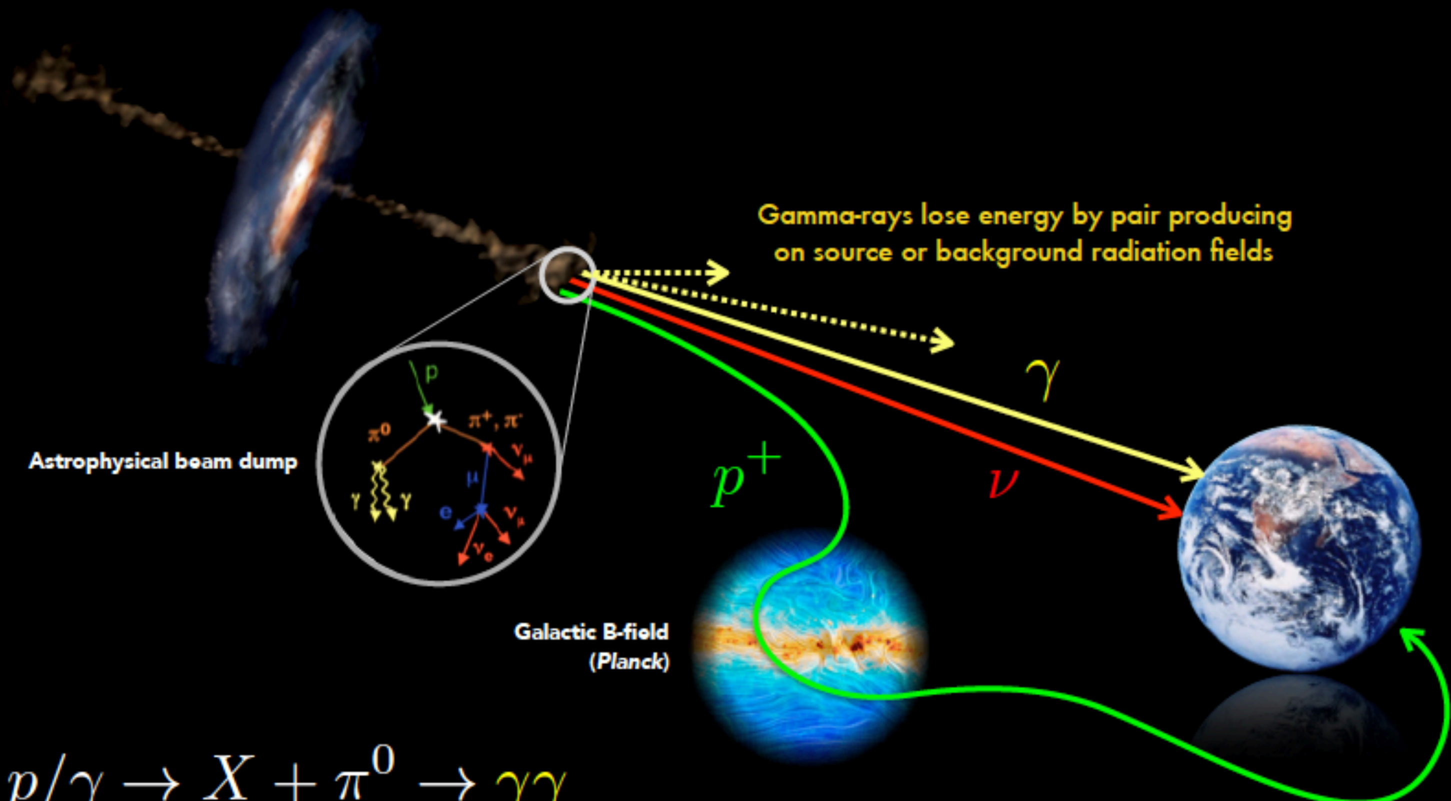
KM3NeT



https://arxiv.org/abs/1601.07459

ARCA - 0.1 km^3 at Italian site
KM3NeT 2.0 - 1 km^3

Neutrinos as tracers for cosmic-ray sources



$$p + p/\gamma \to X + \pi^0 \to \gamma\gamma$$
$$\to X + \pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

Neutrinos provide a view of the most energetic events in the universe at *all* distances

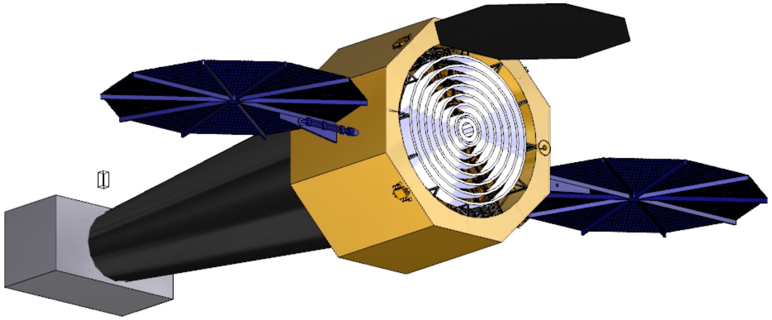
Gravitational Wave Observatories

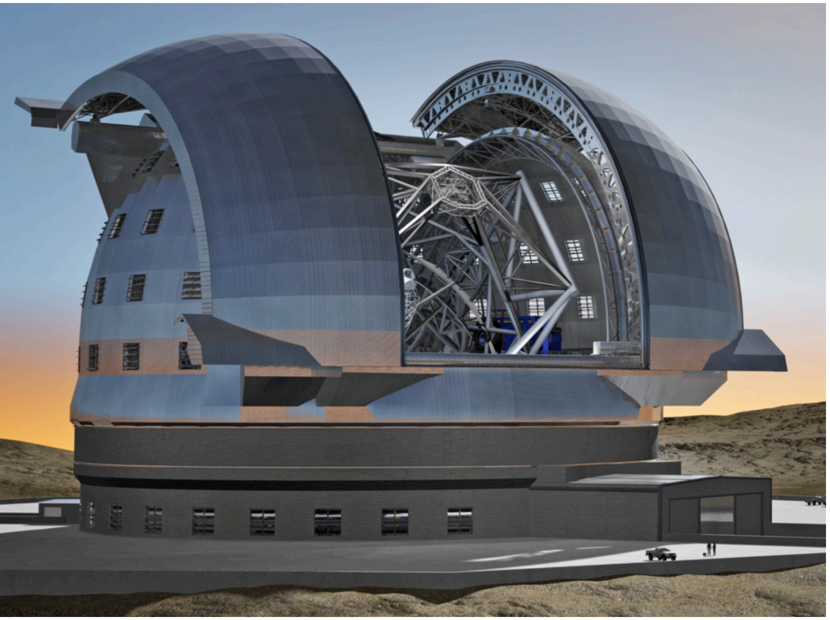
f (Hz)	Detector	Main Science Goals
$1\text{-}10^3$	Advanced LIGO+Virgo (current) LIGO-India (?), KAGRA (Japan,?)	BH-BH,BH-NS,NS-NS (z<0.1)
10^{-4}–1	eLISA (2030s)	$10^4\text{-}10^7$ M_{sun} BH (z<20), EMRIs (z<0.7)
10^{-9}–10^{-7}	IPTA (current)/SKA (2020s)	$10^{8\text{-}10}$ M_{sun} MBHB backgnd, individual MBHs out to Virgo

Obvious Synergies with X-ray Surveyor:

- Census of massive black holes (M_{BH}, spin) and their merger history (unbiased by accretion luminosity!)
- Primordial seed black holes at high redshift!
- Stellar-mass black hole population in galactic centers.
- Multiband GW Astronomy (Sesana 2016): Using eLISA detection as a precursor to detection of BHB coalescence in Adv. LIGO 10 yr later, enabling multiwavelength follow-up of electromagnetic counterpart with a localization of < 1 deg^2

S. Gezari – GW observatories





39 meters
E-ELT
Northern Chile

30 meters
TMT
Hawaii or La Palma

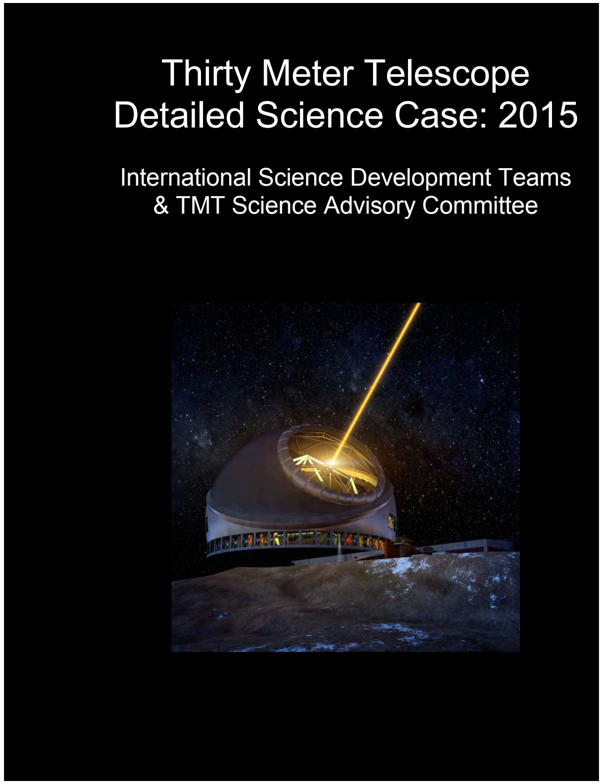
24.5 meters
(22 meters)
GMT
Northern Chile

XRS/ELTs Science Synergies

- Significant overlap in key science areas
  - Used TMT 2015 Detailed Science Case for comparison
  - A lot of complimentary science programs in each area
    - Each facility studies different aspects of a science area
    - Improves overall understanding within science areas
- Several science programs REQUIRE BOTH X-ray and ground based ELT observations
  - Some programs require contemporaneous observations
- Important to consider XRS/ELTs synergies
  - Leap in capabilities between Chandra to XRS and 10m to 30m class ELTs are comparable in terms of sensitivity
  - Timescale of XRS overlaps with the lifetimes of the ELTs
    - Drives a need for complimentary capabilities (who really knows now what science will be done!)

Significant overlap in key science areas

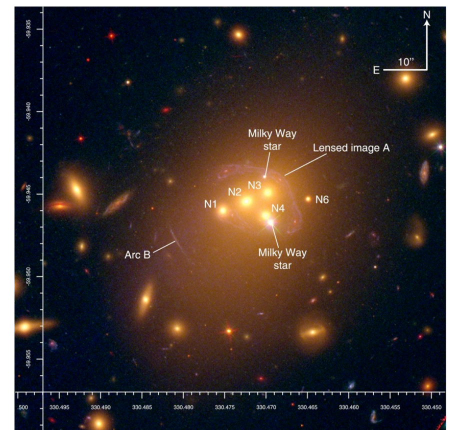
XRS Science Area	TMT Science Area
The Origin and Growth of the First Supermassive Black Holes	Coevolution of supermassive black holes and galaxies; AGN Fueling and Feedback
	Dust and the Structure of the Central Engine
	Time variability, probing the structure and processes in the central engine
Galaxy Evolution and the Growth of Cosmic Structure	Galaxy Formation and the Intergalactic Medium
	Coevolution of supermassive black holes and galaxies; AGN Fueling and Feedback
The Physics of Matter in Extreme Environments	Physics of extreme objects – Neutron Stars
	Studying Tidal Disruption Events and Supermassive Black Holes
The Physics of Feedback and Accretion in Galaxies and Clusters	How does the distribution of dark matter relate to the luminous stars and gas we see?
	The formation of passive galaxies and the birth of the Hubble Sequence
	The Census of Baryons and the Baryon Cycle
	Feedback and the Physics of Galaxy Quenching
	The Intergalactic Medium
	Coevolution of supermassive black holes and galaxies; AGN Fueling and Feedback
The Origin and Evolution of the Stars that make up our Universe	Exploration of the Milky Way and Nearby Galaxies
	The Birth and Early Lives of Stars and Planets

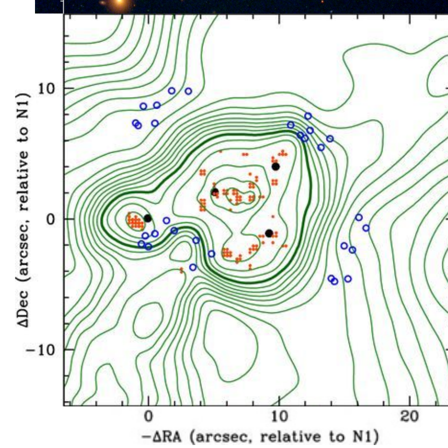


No programs are 'site dependent'

Programs requiring both X-ray and ground based ELT observations

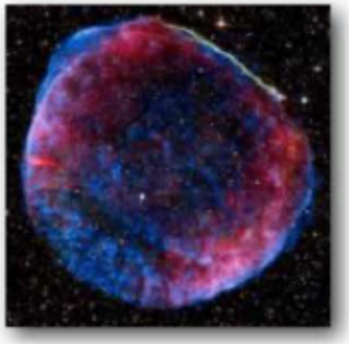
- Dark Matter Self-Interaction Cross Section and the Masses of High Redshift Clusters
  - Optical observations provide stellar mass distribution and dark + baryonic matter distribution from lensing
  - Arc second spatial scale observations of X-ray emission from hot IGM ensure full inventory of baryonic matter





CTA Main Scientific Themes

Cosmic Particle Acceleration



- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

Probing Extreme Environments

- Processes close to neutron stars and black holes
- Processes in relativistic jets, winds and explosions
- Exploring cosmic voids

Physics frontiers – beyond the Standard Model

- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high-energy photons?
- Do axion-like particles exist?

Adapted from J. Knödlseder.
More information on Astroparticle Physics, Vol. 43, 1-356 (2013) & CTA Contributions to the 2015 ICRC Conference [arXiv:1508.05894]

X-ray Imager/CTA Synergies

- ✓ VHE emission localization in M87 (jet v. SMBH)
- ✓ Morphological SNR/PWN Shell structure
- ✓ Galactic plane /LMC localization
- ✓ Galaxy Clusters
- ✓ Fast Transients
- ✓ SFR nearby galaxies

CTA Website:
http://www.cta-observatory.org

LSST

- Key Science Themes
  1. Probe the Nature of Dark Matter and Dark Energy
  2. Catalog the Solar System
  3. Explore the changing sky
  4. Study the Milky Way structure and formation

LSST will repeatedly scan the sky south of +10 deg Dec. accumulating ~1000 pairs of 15 sec exposures through ugrizy filters. This concept, the so-called "universal cadence", will yield the main 18,000 sq. deg. deep-wide-fast survey (typical single visit depth of r ~24.5) and use about 90% of the observing time.

The remaining 10% of the time will be used to obtain improved coverage of parameter space such as ultra deep frequent observations, observations with very short revisit times (~1 minute), and observations of "special" regions such as the Ecliptic, Galactic plane, and the Magellanic Clouds.

LSST catalog will be a treasure trove for follow-up observations of all claases of source. If LSST operates into the 2030's, coordinated observations especially of time variable sources would be extremely valuable.

Time domain astronomy with TMT, LSST, and GW observatories (and others)

- X-ray observations using XRS will provide unique information about time variable sources seen by other observatories *and their precursors*
  - Can provide far more precise location and possibly faster response than Athena
- XRS has the potential to probe deeper into the universe to find counterparts than any other existing or planned X-ray observatories

TMT: From Science to Subsystems

Athena slew time ~2 hours
What does XRS need?

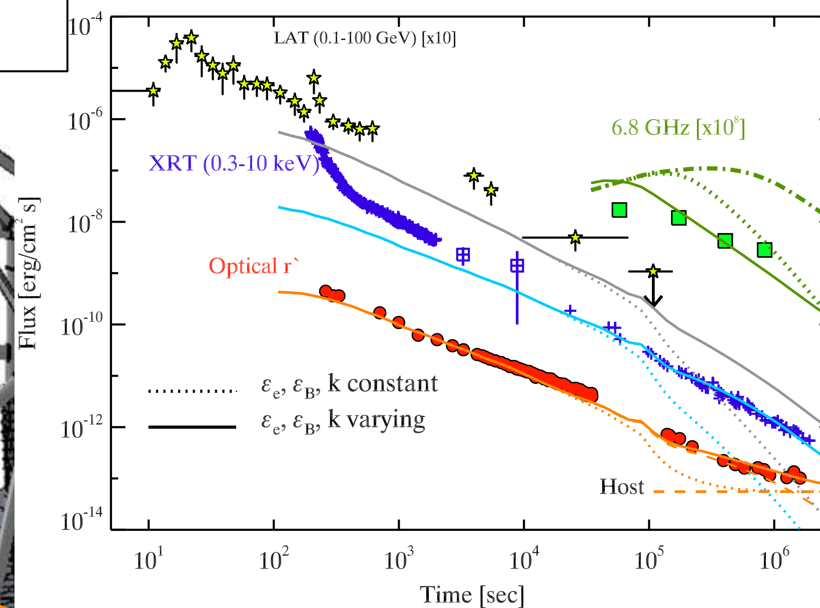
<u>Transients – GRBs/kilonovae/supernovae/tidal flares/Gravitational Wave/cosmic rays/solar system/?</u>

10 minute maximum system response time

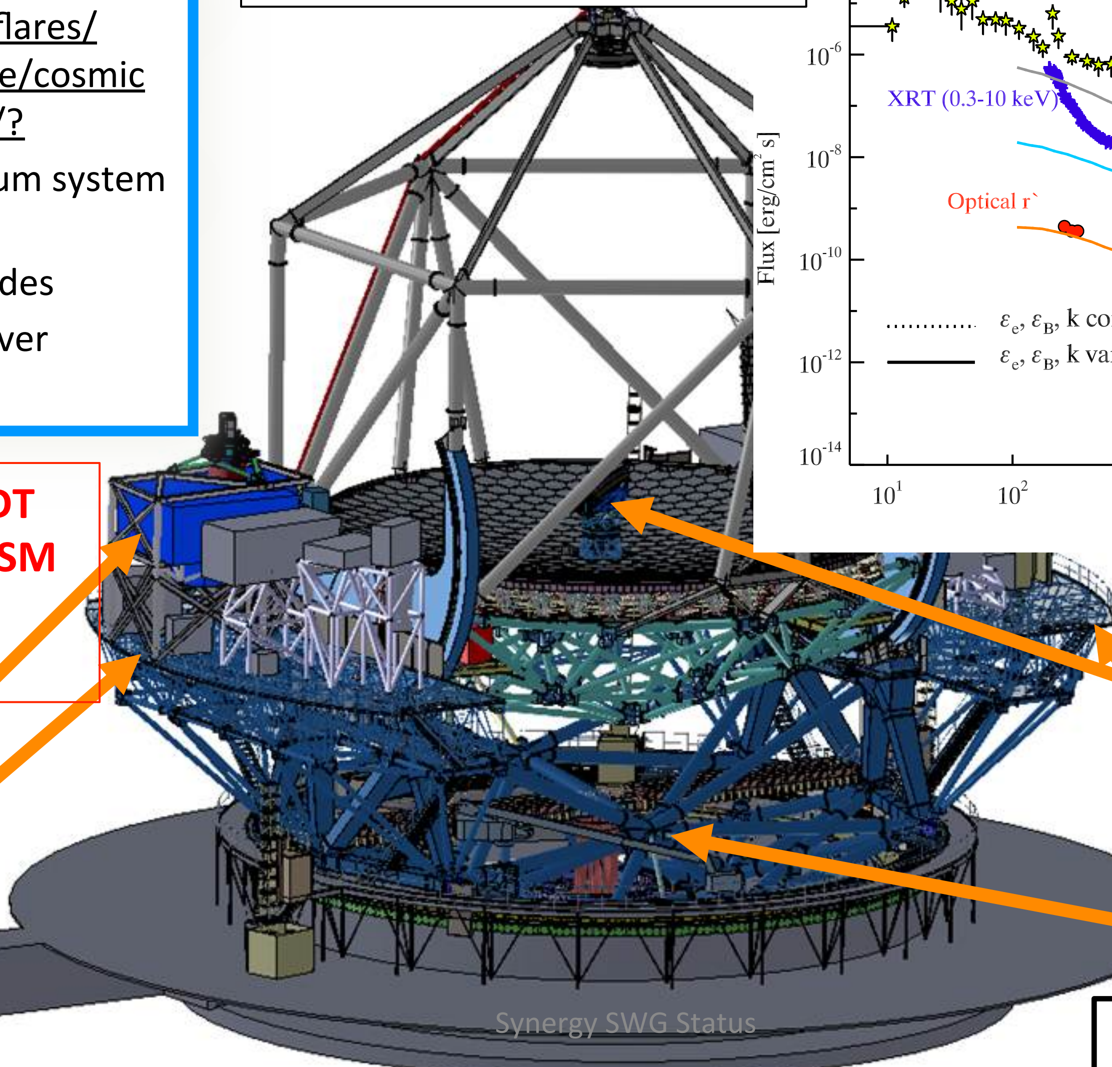
Rapid readout modes

IEEE 1588 timeserver

ToO programs



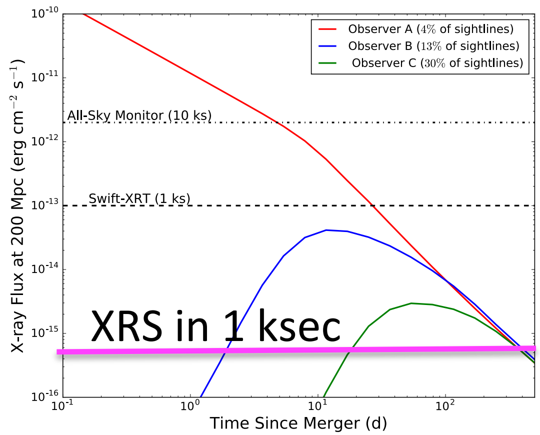
PTRWG + TD-ISDT
LGRBs + high-z ISM & IMF
SGRBs + GWs



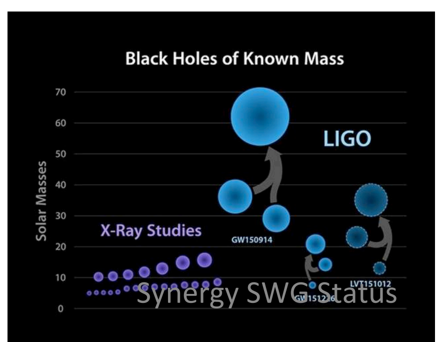
W. Skidmore - TMT

XRS-GW Killer Science Apps

- XRS can localize Advanced LIGO NS-NS mergers. Off-axis afterglow detection requires sensitivity and wide area!

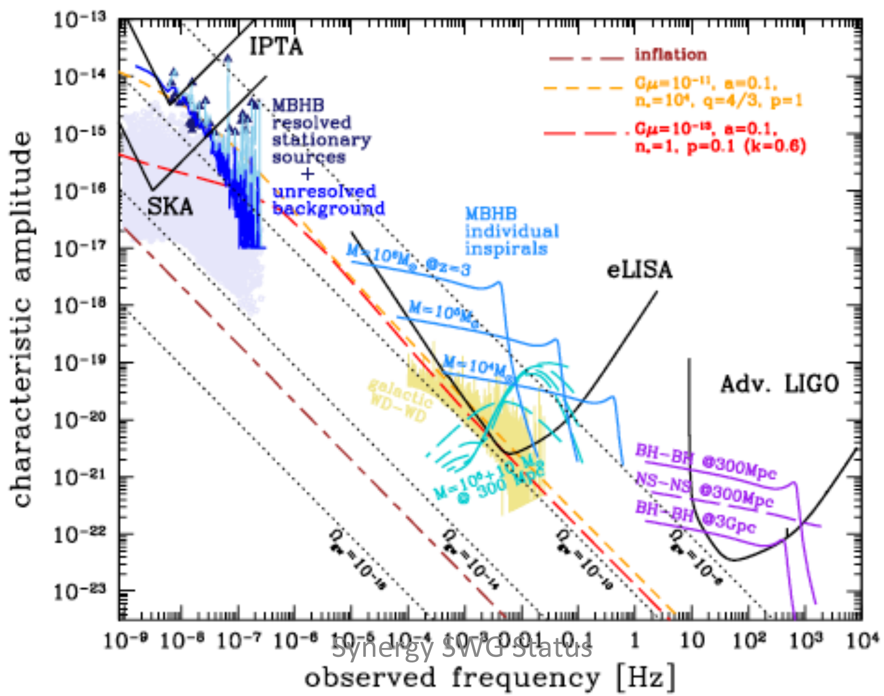


- XRS will probe the compact binary population out to that are progenitors and potential precursors to Advanced LIGO GW sources.



XRS-GW Killer Science Apps

- XRS will probe the stellar remnants in compact binary systems in galaxy nuclei that are potential reservoirs of extreme mass ratio inspiral (EMRI) events detected by eLISA.
- XRS will probe the SMBH seed population ($> 10^4$ M_{sun}) out to z~10 merging in the eLISA band.
- XRS will probe the kpc-scale dual AGN population, the SMBH mass function, and periodically varying quasars powered by accreting SMBHBs: important inputs into the PTA SMBHB background.



Janssen et al. 2014

Probing the Cores of Active Galaxies

X-ray Surveyor can potentially locate dual, recoiling, merging AGN

- These will be the source of GW signal seen in LISA!
- X-ray Surveyor can find the EM counterpart of a merger event

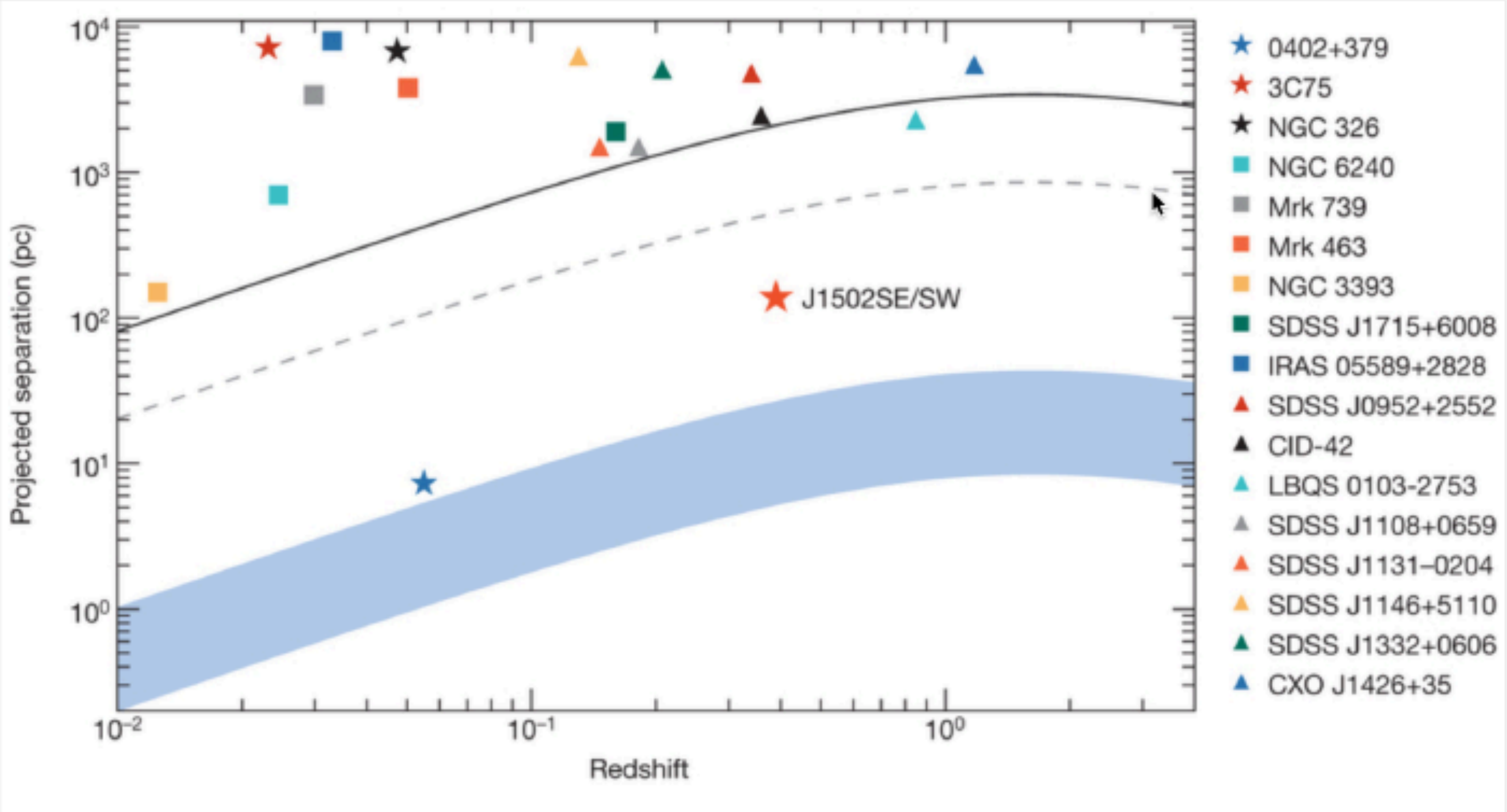
X-ray Surveyor can probe deep into the cores of galaxies at z ~ 1, and:

- connect the outflowing gas seen in ALMA and TMT (and other large optical/NIR observatories) to X-ray observable outflows in both AGN and starforming galaxies
- determine the source of the HE gamma ray and radio variability

Programs requiring both X-ray and ground based ELT observations

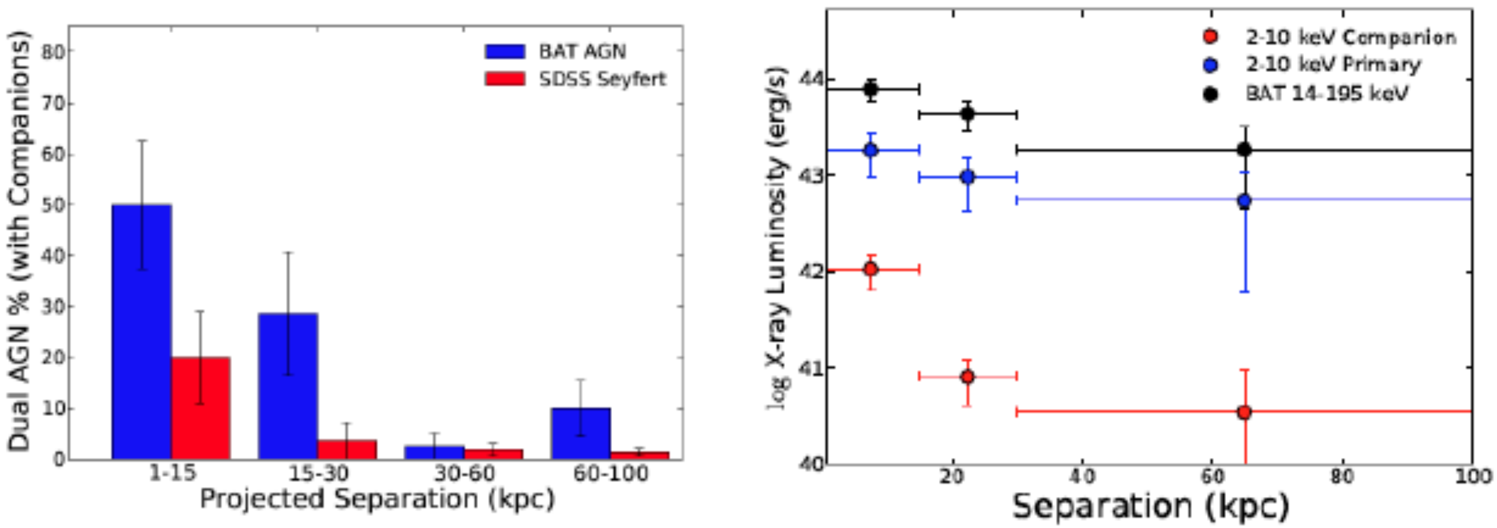
- The growth of Super-Massive Black Holes
  - XRS will give black hole spin and radius
  - XRS will detect accreting massive black holes in high redshift galaxies (found by JWST) and Quasars (found by LSST)
    - M_{BH} is provided by ELTs
  - XRS will study feedback around AGN as well as the AGN themselves and energy injection their host galaxies
    - ELTs will study star formation and other processes in the host galaxies themselves

Dual AGN confirmed with Direct Imaging



Within 10 kpc, Deane et al. 2014, nature

Dual AGN Fraction with Separation



Dual AGN Activity Increases at Closer Separations

X-ray luminosity increases dramatically at small separations (< 5 kpc)

Consistent with merger-driven model

More SMBH growth happens in the later stages of a merger process

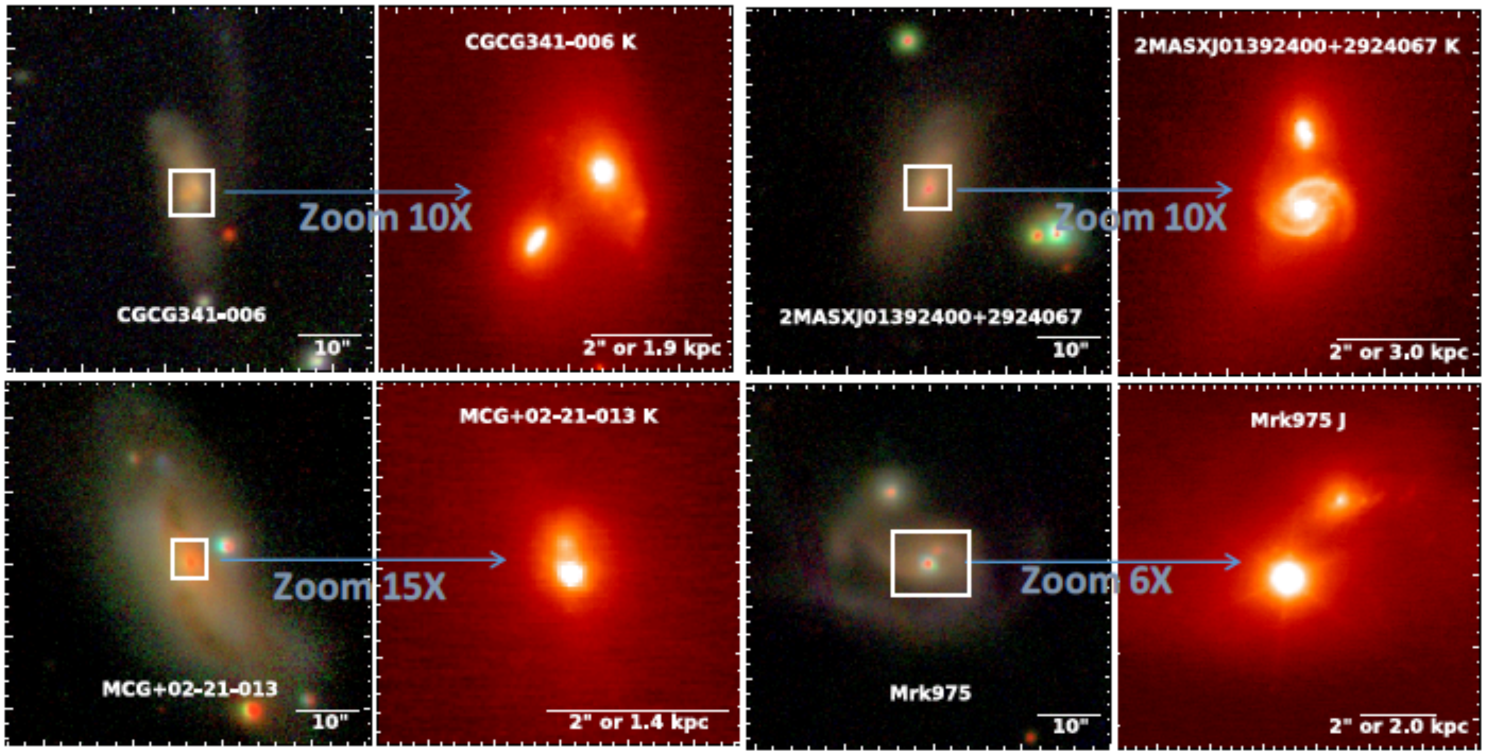
All close (<30 kpc), major merger, non elliptical systems are duals!!!

Koss et al. 2012b, ApJL 746,22

Best resolution possible is important

How can we go further to understand mergers and AGN?

AO Detected Mergers (<3 kpc)



BAT AGN in <3 kpc mergers, ~15% of obscured luminous AGN

Koss et al. Submitted
Not public

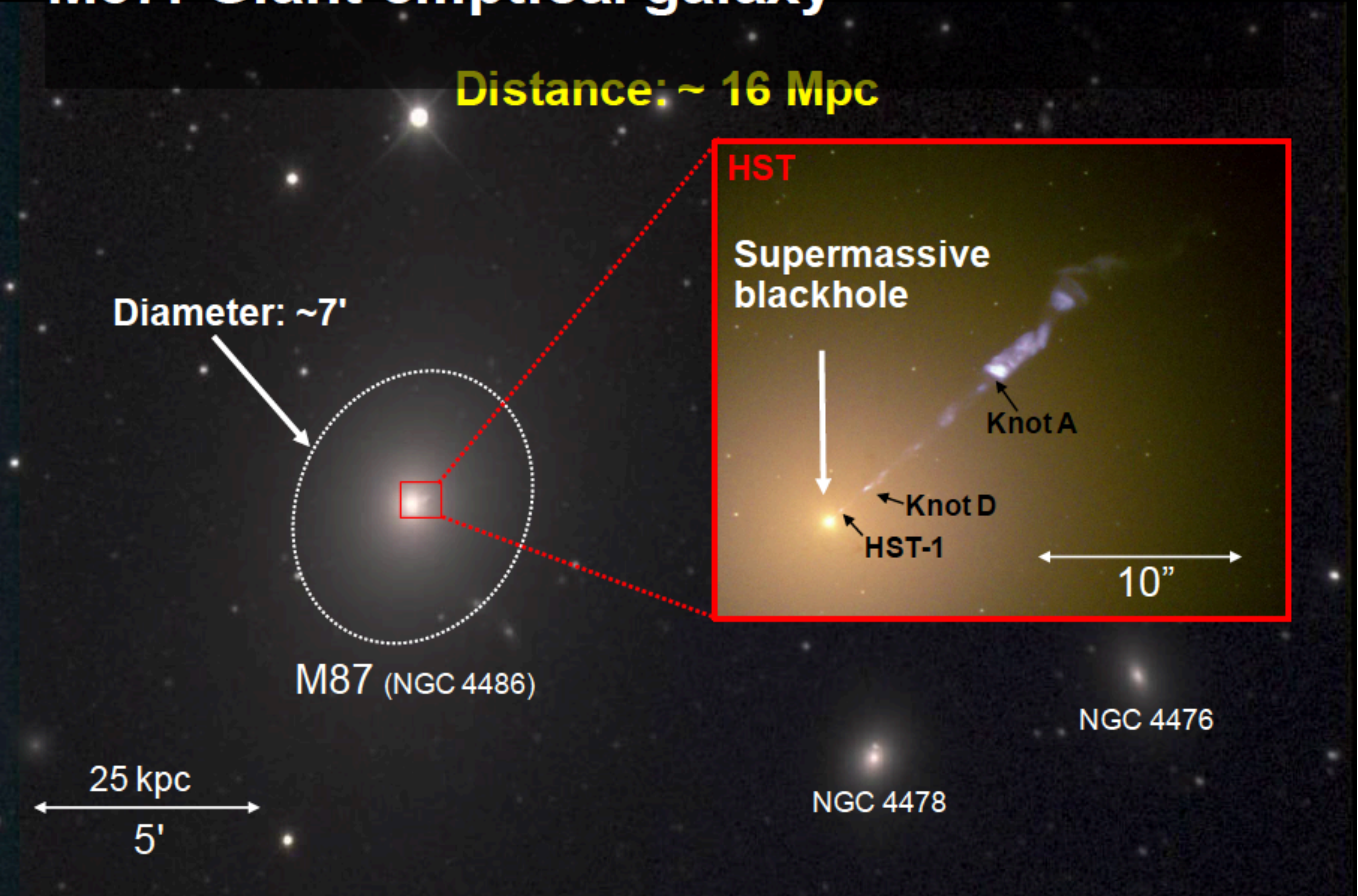
Best resolution possible is important

These are all highly absorbed AGN, identified by BAT

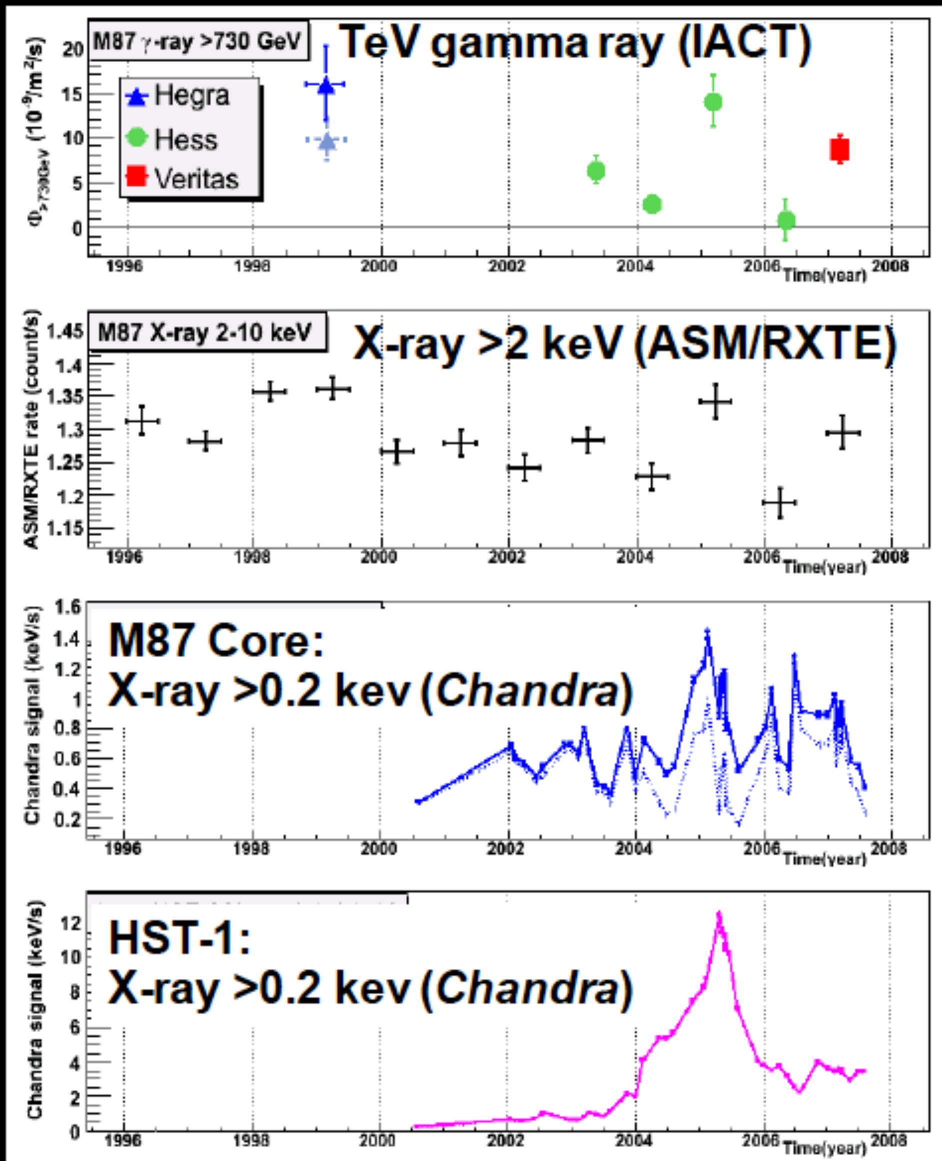
Surveyor Summary

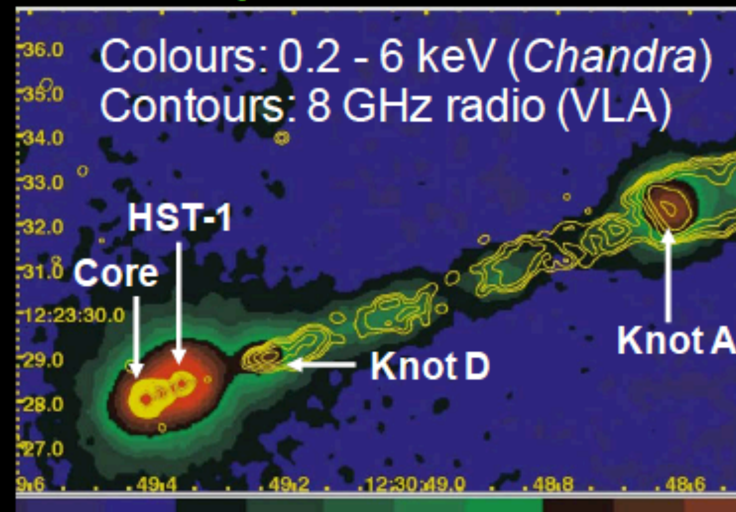
- *Dual AGN fraction is 10% at low redshift*
- *Mergers exist at all scales with dual AGN peaking small separations*
- *Current Chandra studies limited to on-axis studies because of sharp drop in PSF with off-axis, particularly at 6-7 keV*
- *Desire for best PSF in largest area possible for X-ray surveyor*

Synergy example 1:
M87: Giant elliptical galaxy



Correlation study with X-ray emission





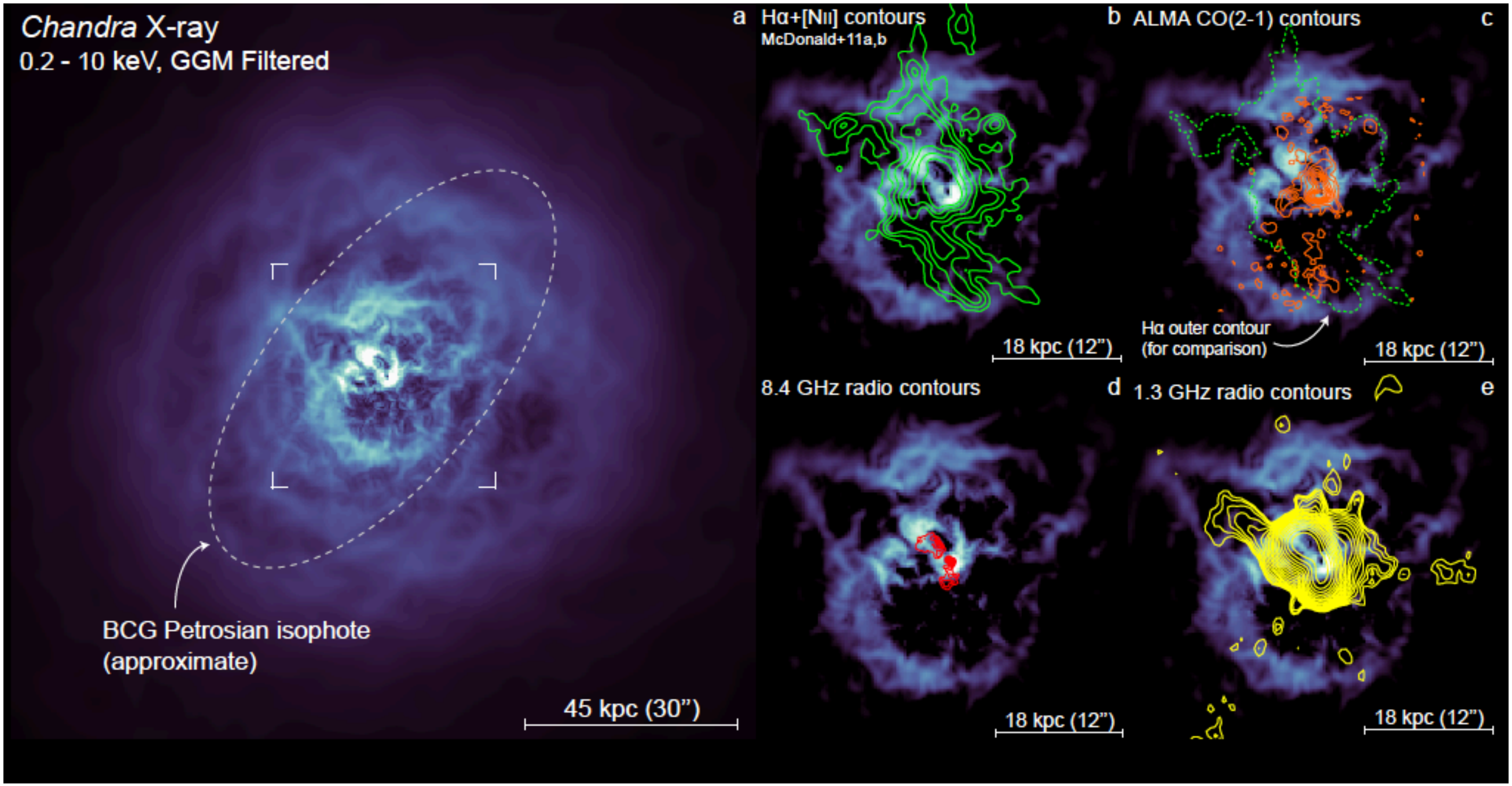
Correlates well with ASM

M87 Core: Perhaps?

HST-1: Perhaps not…..

Athena can't do this!

XRS + ALMA can look inside galaxies at z=1



Abell 2597 cool core (z = 0.08)

G. Tremblay - ALMA

X-ray Surveyor Drivers

- **These two examples suggest the following X-ray Surveyor requirements**
  - High enough sensitivity to perform synergistic studies with ALMA and others of distant galaxies and clusters and to detect faint counterparts of time variable events
  - highest possible angular resolution throughout 0.1-10 keV band
  - rapid response to transient events
  - extended energy band
- **Need to assess**
  - Whether high resolution spectroscopy is needed (or whether moderate spectral resolution suffices)
  - True need for hard X-ray band
  - Whether additional capabilities is required (e.g., polarization)
  - Degree of distinction from Athena capability

We will be quantifying these requirements over the next few weeks

Backup

Areas of Potential Synergy between XRS and WFIRST

- **Coronagraphic:** WFIRST observations will allow detailed study of individual AGN host galaxy morphologies and halos.

- **AGN winds:** IFU imaging and mid-IR molecular hydrogen observations of collisional galaxies, and galaxies with powerful AGN winds. (selection via the grism survey)

- **Deep Fields** WFIRST will be able to make almost 100 times larger than the Hubble deep fields.

- **The HLS grism survey** will discover ~2600 $z > 7$ quasars with H magnitude < 26.5, with an estimated 20% of those quasars being at $z > 8$.

- **Strongly-lensed quasars** Independent cosmological probe, time delays

- **Star-Forming Galaxies** The H-alpha line will be used to probe SFR that are at least 10 – 20 solar masses per year over the range $1 < z < 2$. The estimated surface density of such galaxies is about 10^4 per square degree, implying the total survey will produce H-alpha measurements for over nearly 20 million galaxies.

- **Supernovae**

  The WFIRST Supernova Survey will potentially detect supernovae out to z~4.

  WFIRST will conduct a three tiered deep supernova survey, a shallow survey over 27.44 deg2 for SNe at z <0.4, a medium survey over 8.96 deg2 for SNe at z <0.8, and a deep survey over 5.04 deg2 for SNe out to z =1.7 and then will use an

  (IFU) to take spectra of ~2700 distant supernovae discovered in its synoptic imaging survey

- **Galactic Bulge Survey**

  The WFIRST survey of the Galactic Bulge will consist of 10 contiguous fields covering a total of about 2.8 sq. degs., observed six

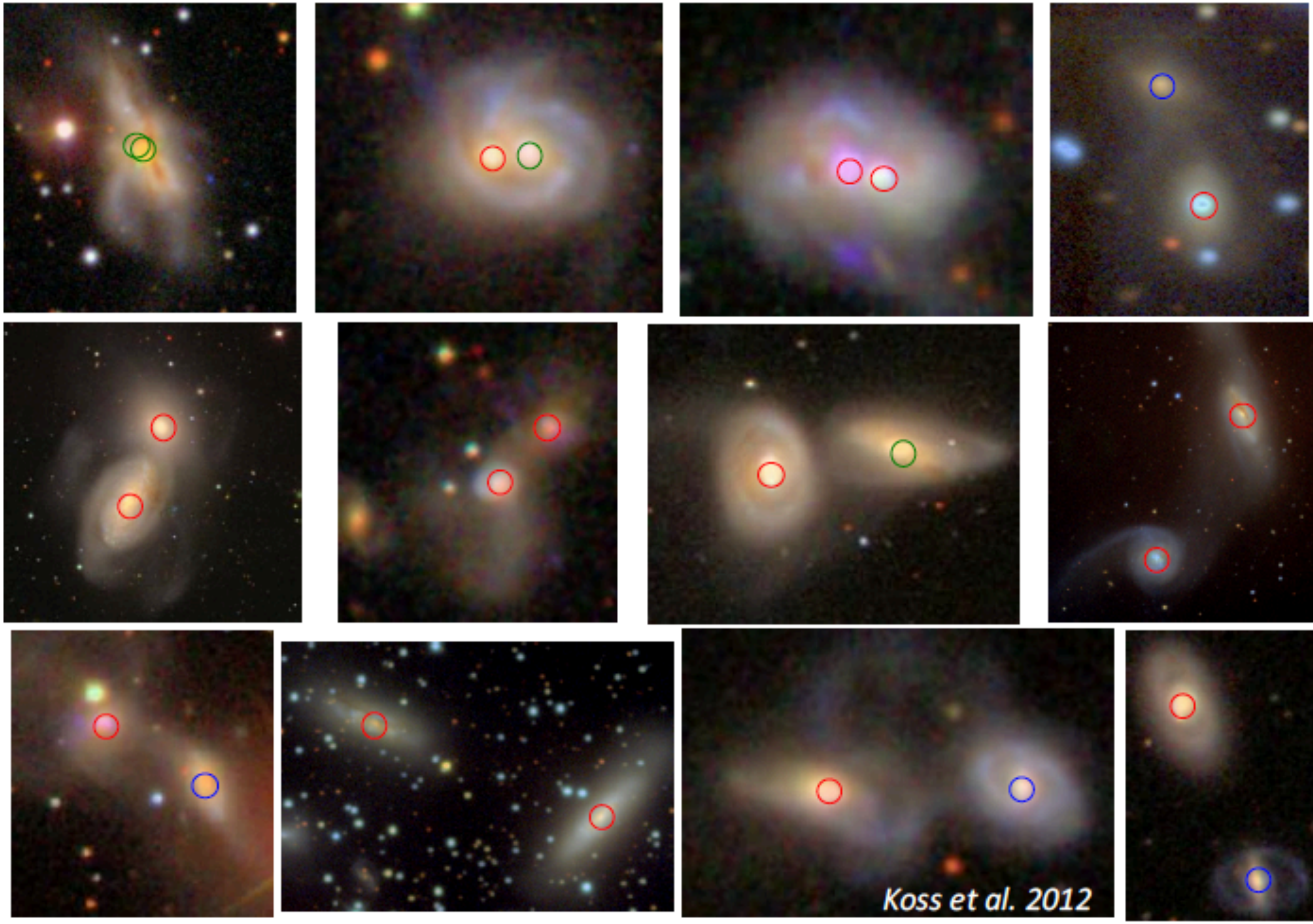
Current and Future SZ Observatories

Experiment		bands (GHz)	# det	θ'(GHz)	2016	2017	2018	2019	2020	2021	2022	2023	2024
Ground based (ongoing/funded):													
ACT:	*ACTpol*	90/150	3108	1.3'(150)									
	Adv-ACTpol	28/41/90/150/230	5792	1.3'(150)									
Polarbear:	*PB2*	90/150	7588	3.5'(150)									
	Simons Array	90/150/220	22,764	3.5'(150)									
SPT:	*SPTpol*	90/150	1536	1.0'(150)									
	SPT-3G	90/150/220	16,260	1.0'(150)									
BICEP:	*KECK*	90/150/220	2560	30' (150)									
	BICEP3	90	2560	25' (90)									
CLASS:		40/90	590	40' (90)									
		40/90/150/220	5108	24' (150)									
CMB-S4		30/ / / / / /300	~500,000	≈1.0'(150)									
Balloon based (ongoing/funded):													
SPIDER2		150/280	2000	30' (150)									
PIPER		200/270/350/600	1200	21' (150)									
Satellite (pending):													
Litebird		15-bands from 40-400	2276	30' (150)									
Pixie		400-bands from 30-6000	multi-moded	100' (all)									

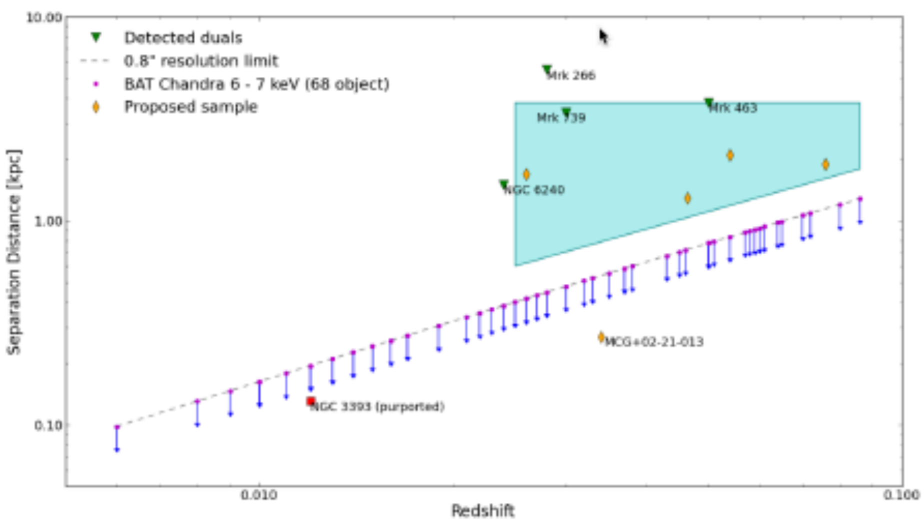
Programs requiring contemporaneous X-ray and ground based ELT observations

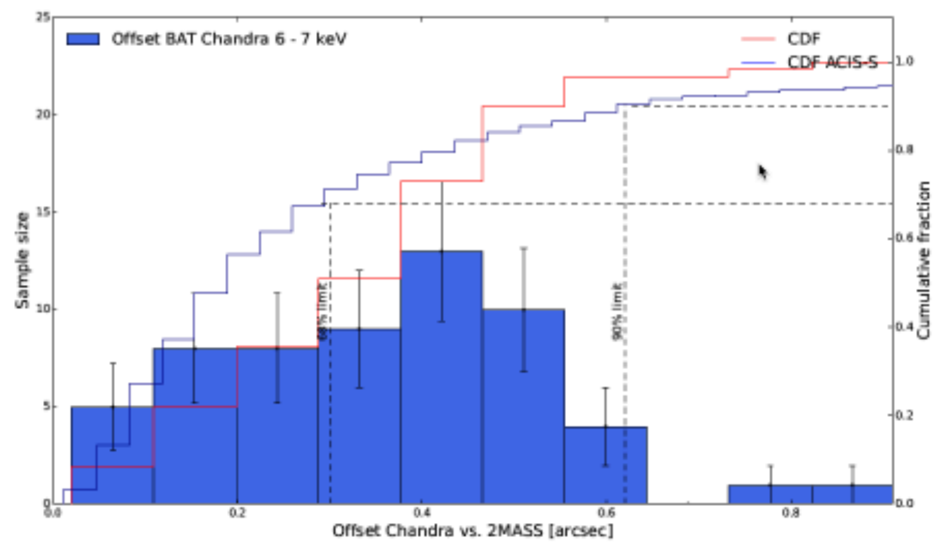
- The Neutron Star Equation of State
  - Rapid X-ray spectroscopic observations give the NS mass and radius from Doppler broadening of narrow atmospheric absorption lines
  - Rapid optical spectroscopy allows astroseismology of the target
  - Time resolution of 0.1ms and absolute timing of 10μs for both X-ray and ground based observations

Dual AGN Study X-rays+Optical (16/167)



Constraints on Recoiling Black Holes from Chandra





Limited to several 100 pc with Chandra limits from BAT sample (on axis)
Don't see any clear signs of recoiling BHs among BAT AGN (massive galaxies)
Desire for best PSF in largest area possible for X-ray surveyor

Not public