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 observatories)
  – 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

R. Griffiths - WFIRST
Areas of Potential Synergy between XRS and WFIRST

2.4M, NIR, launch 2027?

• **Clusters of Galaxies**

  WFIRST is expected to discover \( \sim 40,000 \, M > 10^{14} \, M_\odot \) clusters out to \( z \sim 3 \) 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?

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 revolutionize our understanding of the Universe.

**Resolution**

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

**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.

**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.
Possible areas of synergy with XRS

- Galaxy Evolution (surveys) (starbursts, AGN, galaxy clusters, ULXs) and cluster cosmology

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

- ~10 km³
- optimized for high energies

KM3NeT

- ARCA - 0.1 km³ at Italian site
- KM3NeT 2.0 - 1 km³

https://arxiv.org/abs/1412.5106

https://arxiv.org/abs/1601.07459
Neutrinos provide a view of the most energetic events in the universe at all distances.
## Gravitational Wave Observatories

<table>
<thead>
<tr>
<th>$f$ (Hz)</th>
<th>Detector</th>
<th>Main Science Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10^3</td>
<td>Advanced LIGO+Virgo (current) LIGO-India (?), KAGRA (Japan,?)</td>
<td>BH-BH, BH-NS, NS-NS ($z &lt; 0.1$)</td>
</tr>
<tr>
<td>$10^{-4}$–$1$</td>
<td>eLISA (2030s)</td>
<td>$10^4$–$10^7 M_{\odot}$ BH ($z &lt; 20$), EMRIs ($z &lt; 0.7$)</td>
</tr>
<tr>
<td>$10^{-9}$–$10^{-7}$</td>
<td>IPTA (current)/SKA (2020s)</td>
<td>$10^8$–$10^9 M_{\odot}$ MBHB background, individual MBHs out to Virgo</td>
</tr>
</tbody>
</table>

**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$^2$
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

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

• 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 classes 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?

Transients – GRBs/kilonovae/supernovae/tidal flares/
Gravitational Wave/cosmic rays/solar system/?
10 minute maximum system response time
Rapid readout modes
IEEE 1588 timeserver
ToO programs

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

NFIRAOS fast switching science fold mirror
-X Nasmyth structure

Articulated M3 for fast instrument switching
+X Nasmyth structure
Fast slewing and acquisition

Table S10.
List of parameters used for the model plotted in the Figure S7. We assumed $k = (t/t_k)$ (and same functions for $e$ and $B$).

Figure S7.
The optical, X–ray, –ray and radio light curves are interpreted as forward shock afterglow synchrotron emission, as derived applying the van Eerten et al. model. Dotted lines corresponds to the first line in Table S10, namely $e$, $B$ and the fraction $k$ of accelerated electrons are constant. The solid line corresponds to the model when varying these microphysical parameters. The dot–dashed line shown only for the radio band, corresponds to the model with only $e$ and $B$ varying in time and with constant $k$.
XRS-GW Killer Science Apps

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

![Graph showing XRS response](image)

- 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 ($> 10^4 M_{\text{sun}}$) out to $z \sim 10$ 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.
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 $z \sim 1$, 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!!

Best resolution possible is important

How can we go further to understand mergers and AGN?

AO Detected Mergers (<3 kpc)

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

Distance: ~ 16 Mpc

M87 (NGC 4486)

Diameter: ~7'

Supermassive blackhole

HST

Knot A

Knot D

HST-1

NGC 4476

NGC 4478

25 kpc

5'

10''
Correlation study with X-ray emission

M87 γ-ray > 730 GeV
TeV gamma ray (IACT)

M87 X-ray 2-10 keV
X-ray > 2 keV (ASM/RXTE)

M87 Core:
X-ray > 0.2 keV (Chandra)

HST-1:
X-ray > 0.2 keV (Chandra)

Colours: 0.2 - 6 keV (Chandra)
Contours: 8 GHz radio (VLA)

HST-1: Perhaps not.....
Athena can’t do this!

Correlates well with ASM

M87 Core: Perhaps?
XRS + ALMA can look inside galaxies at $z=1$

**Chandra X-ray**
0.2 - 10 keV, GGM Filtered

**Abell 2597 cool core ($z = 0.08$)**
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 $\sim 2600$ $z > 7$ 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 $z \sim 4$.
  - WFIRST will conduct a three-tiered deep supernova survey, a shallow survey over 27.44 deg$^2$ for SNe at $z < 0.4$, a medium survey over 8.96 deg$^2$ for SNe at $z < 0.8$, and a deep survey over 5.04 deg$^2$ for SNe out to $z = 1.7$ and then will use an (IFU) to take spectra of $\sim 2700$ 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 times per year, assuming continuous coverage. This will be the first large-scale, deep imaging of the Galactic Bulge.
# Current and Future SZ Observatories

| Experiment | bands (GHz) | # det | \(\theta'\) (GHz) | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|------------|-------------|-------|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Ground based (ongoing/funded):** | | | | | | | | | | | | |
| ACT: ACTpol | 90/150 | 3108 | 1.3' (150) | | | | | | | | | |
| ACTpol 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 | \(\approx 1.0'\) (150) | | | | | | | | | | | | |
| **Balloon based (ongoing/funded):** | | | | | | | | | | | | |
| SPIDER2 | 150/280 | 2000 | 30' (150) | | | | | | | | | |
| PIPER | 200/270/350/600 | 1200 | 21' (150) | | | | | | | | | | | | |
| **Satellite (pending):** | | | | | | | | | | | | |
| Litetbird | 15-bands from 40-400 | 2276 | 30' (150) | \(\blacklozenge\) | | | | | | | | | |
| Pixie | 400-bands from 30-600 | multi-moded | 100' (all) | \(\blacklozenge\) | | | | | | | | | | | |
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