Cal X-1: an in-orbit X-ray standard candle

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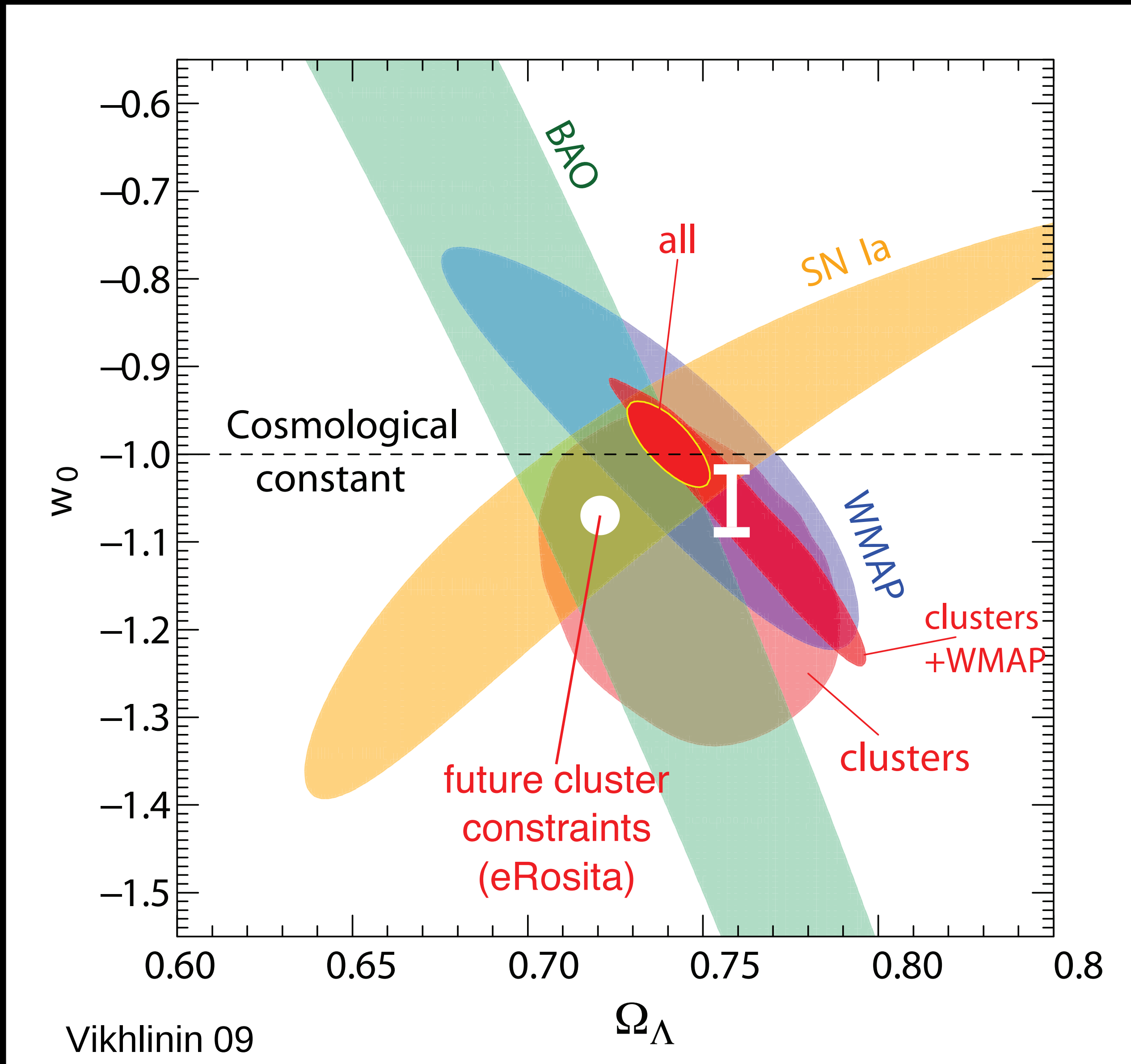
IACHEC meeting, March 29, 2017

- **Poor absolute calibration of X-ray observatories is a limitation for several fundamental astrophysical measurements**

Precision cosmology with galaxy clusters ...



±10% mass error

... only as precise as our knowledge of cluster masses

X-ray calibration and cluster masses

- If derive cluster total mass M_{tot} from hydrostatic equilibrium assumption:

$M_{\mathrm{tot}} \sim T_{\mathrm{X}}$

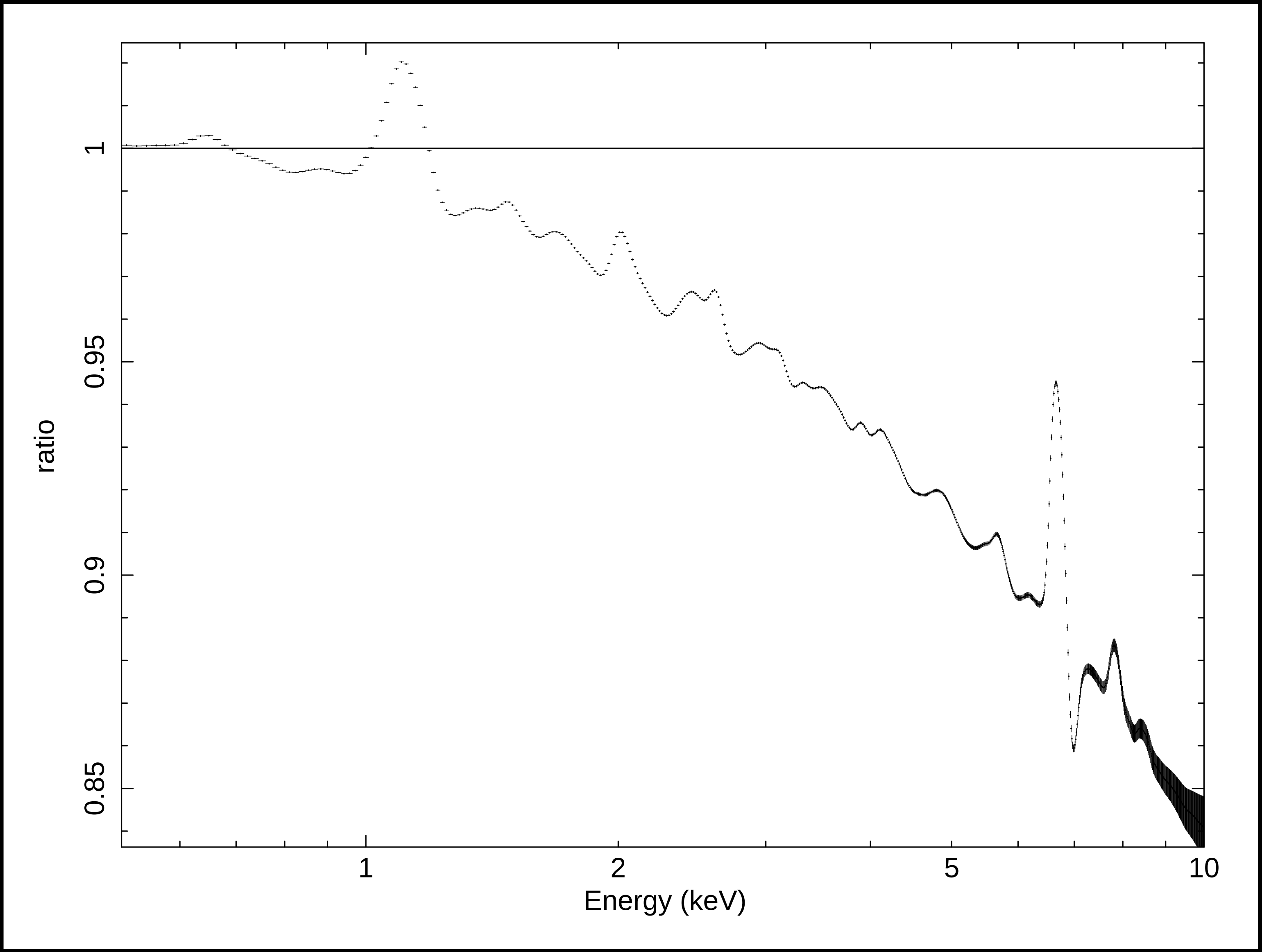
10% relative flux error at low / high energies → ~ 10% mass error

- If use cluster gas mass M_{gas} as a proxy for M_{tot}
  (easier to measure, but has systematic uncertainties):

$M_{\mathrm{gas}} \sim L_{\mathrm{X}}^{1/2}$

10% absolute soft flux error → 5% mass error

Ratio of thermal spectra (APEC) with $T = 5$ keV and 5.5 keV:



(using *Chandra* ACIS-I spectral response)

- 10% relative flux error between $E \sim$ 1 keV and 5 keV $\rightarrow$ 10% error in T

Classic X-ray / SZ Hubble constant test

- from a ratio of SZ and X-ray cluster brightness, can derive distance to the galaxy cluster:

$$d_a \sim y^2 / f_X T^2$$

where y is SZ signal, f_X is X-ray flux and T is temperature (Silk & White 78)

- currently dominated by cluster non-sphericity and small cluster samples, but this error will be nailed by averaging over big *eROSITA* and SZ samples

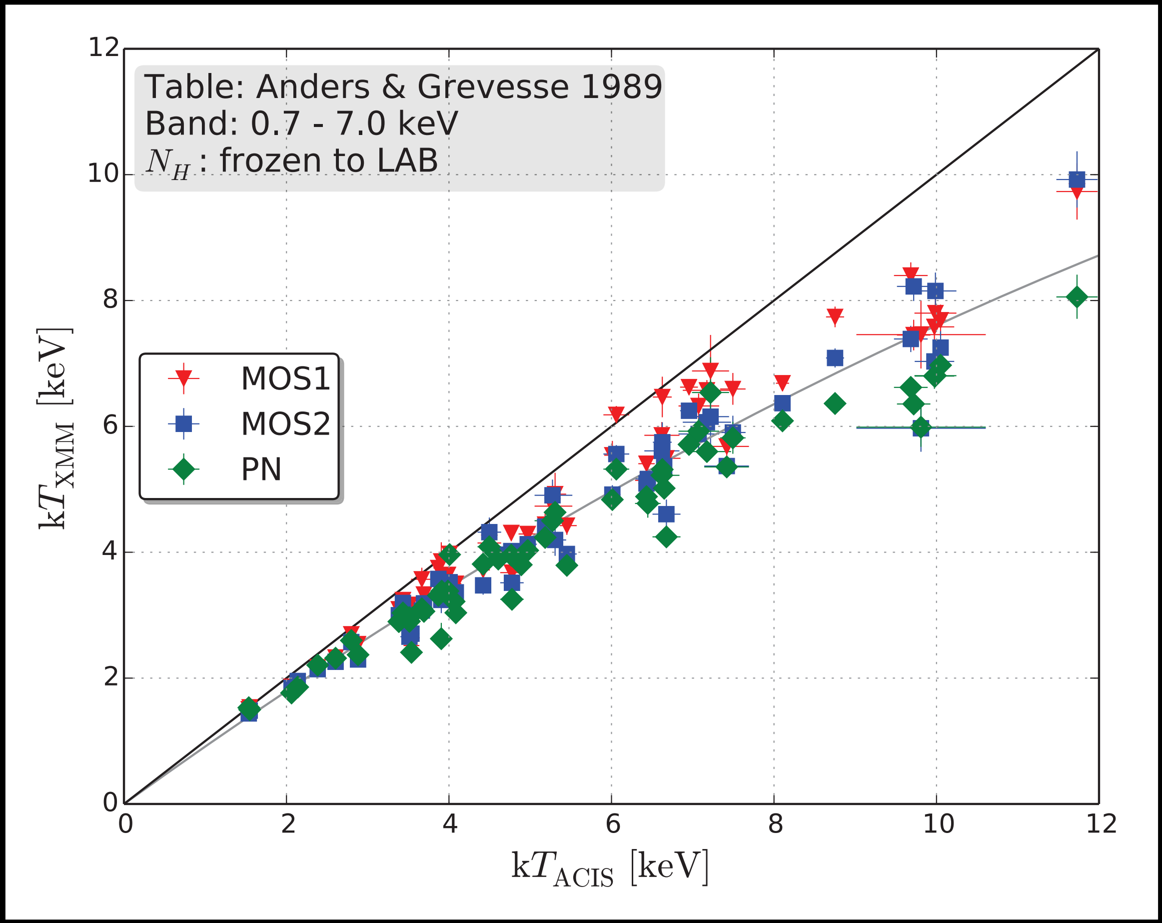
- strongly dependent on X-ray (and SZ) calibration

Neutron star equation of state

- from radii and masses of neutron stars, can derive equation of state of ultra-dense matter, inaccessible in the lab
- radius comes from X-ray flux and distance (Ozel 15)
- need $\sim$ 2% flux accuracy to distinguish between interesting eqs. of state

Current state of *Chandra* and *XMM* calibration

Temperatures for the same clusters from different instruments:



Schellenberger 15

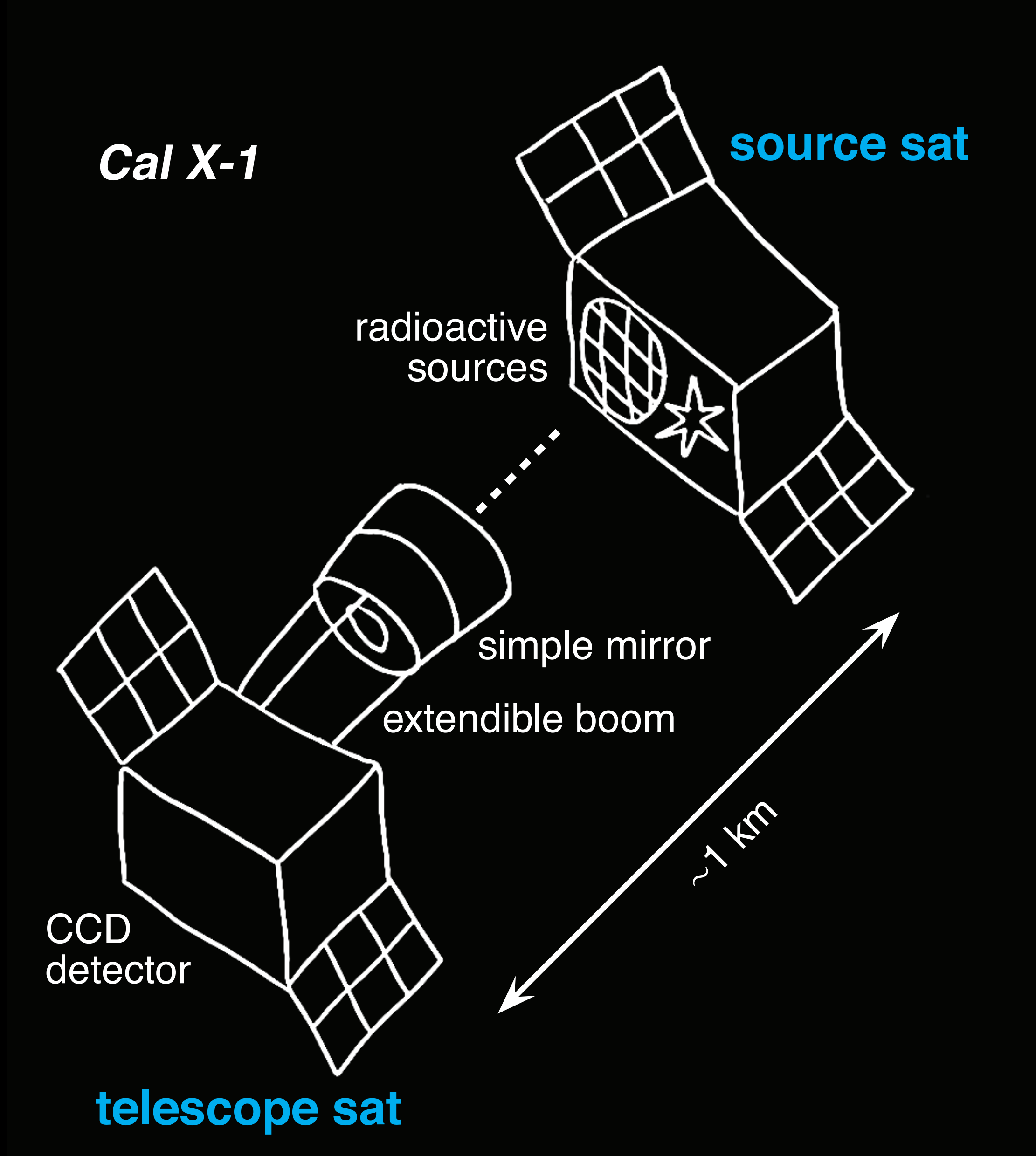
- >10% discrepancy in cluster T between *Chandra* and *XMM*
- impossible to know which instrument (if any) is correct

need $\sim$1% X-ray flux calibration accuracy;

can’t achieve this level by ground calibration

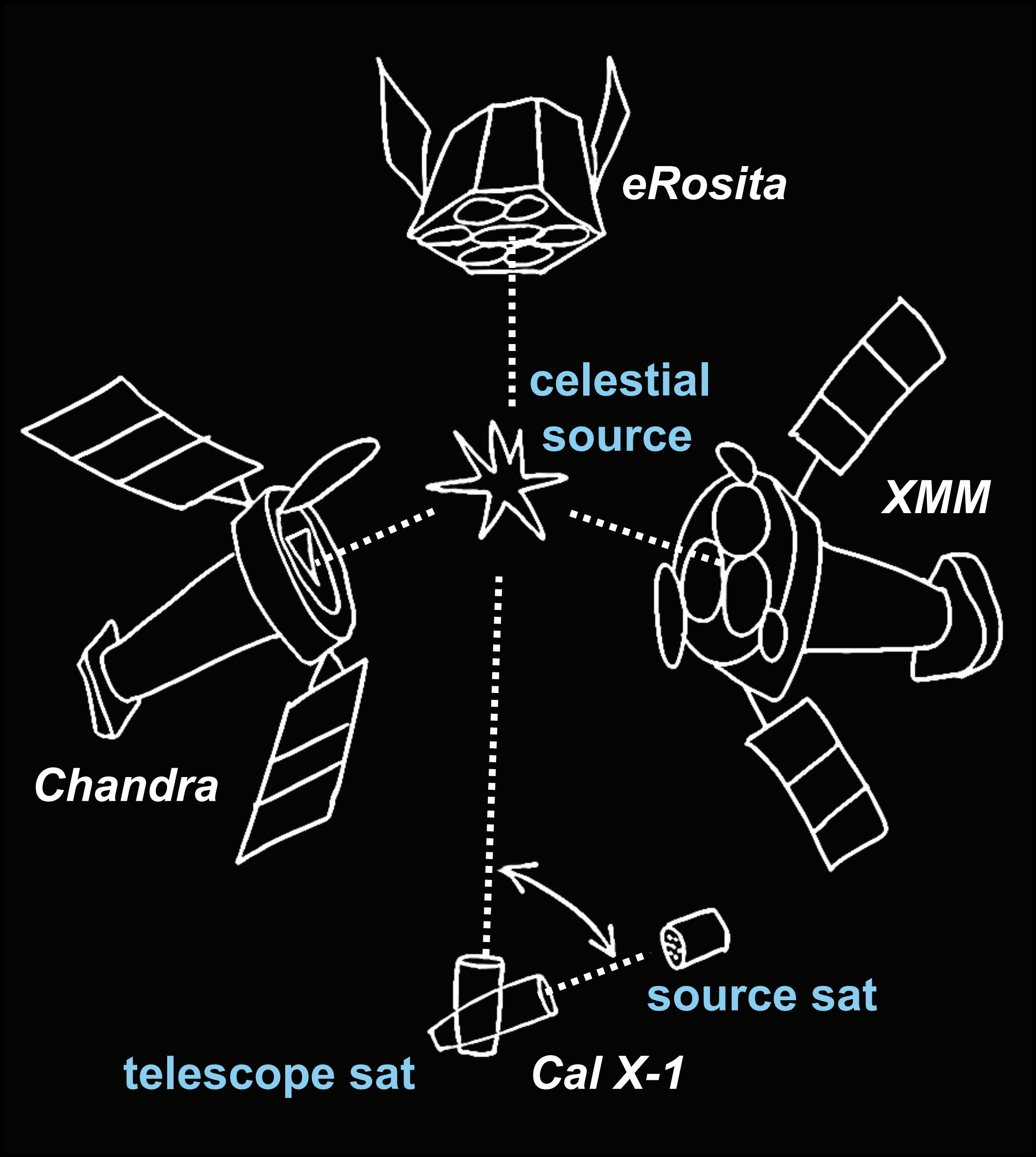
solution: an X-ray standard candle in orbit

APRA proposal submitted in March 2017 (PI K. Jahoda)



- telescope sat: d=10 cm, f=1.5 m mirror (requires extendible / coilable boom)
- source sat: ^{55}Fe source embedded in Al to produce lines at 6 keV and 1.5 keV

Cal X-1: how to calibrate X-ray Observatories



- By staggering celestial source and radioactive source observations, we cancel out calibration of *Cal X-1*

Requirements (given the CubeSat form factor)

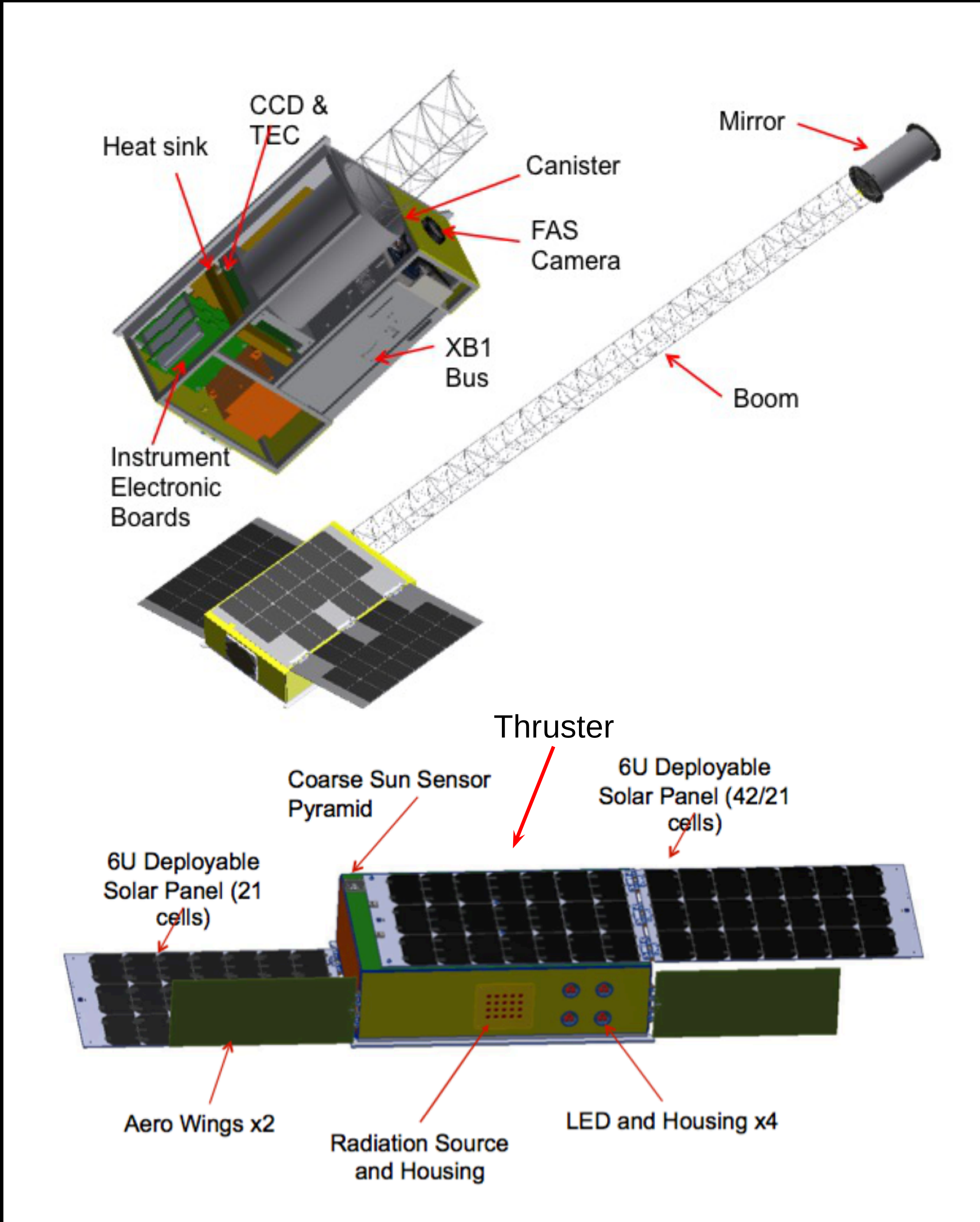
- mirror design that minimizes vignetting ($r \sim 1'$ vignetting-free spot)
- distance L between telescope and source sats: 0.7–1.5 km
  for the source to be a "point source" ($\sim 20''$) but still bright enough
- *knowledge* of distance to $< 1\%$ in L^2: < 5m for L=1 km
- radioactive source: ~ 2 Curie of ^{55}Fe to give sufficient flux
- telescope sat orientation: $< 0.5'$ to keep mirror vignetting under 1%
- source sat orientation: $< 3°$ to keep projected source size within 1%
- Formation flying: maintain $R \sim 1$ km for ~ 6 months of operation
  (at ISS orbit, requires orbit corrections with thrusters)

TelSat

6U CubeSat

SrcSat

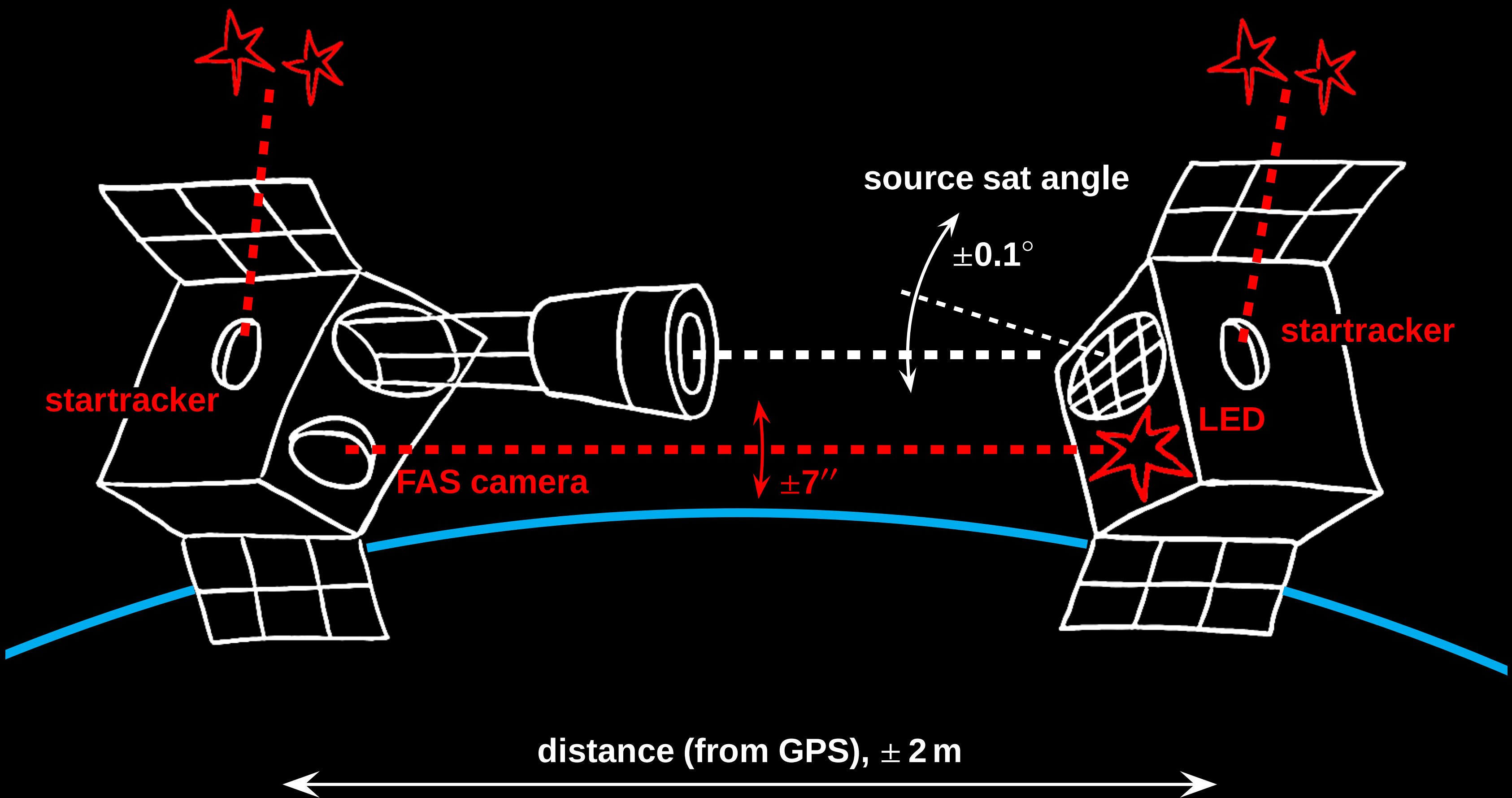
6U CubeSat



Implementation

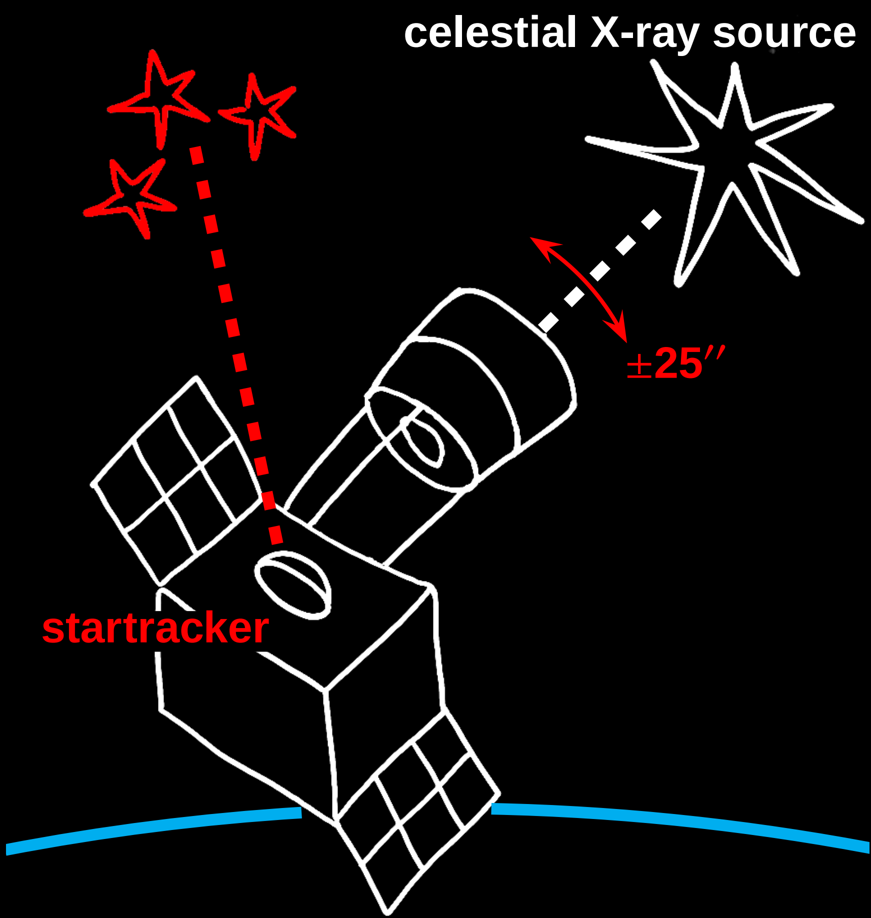
- Two CubeSats: Blue Canyon bus, come with attitude control system (2 star trackers, reaction wheels)
- Source Sat has cold-gas thruster — come OTS in CubeSat form factor
- Tel Sat has additional camera (OTS) to track LED on Source Sat
- Extendible boom: Orbital ATK makes them (scaling down by $\times 2$ needed); pack into 1% of unfolded size; stability requirements not a problem
- Mirror: Goddard, similar to *Astro-H*, *NICER*; PSF with 1’ HPD, 4’ 90% radius
- Detector: CCD made by XCAM, 22 μm pixels, $19' \times 13'$ FOV
- Radioactive source: in collab. with Eckert & Ziegler, calibrated at NIST

Navigation: observing source satellite



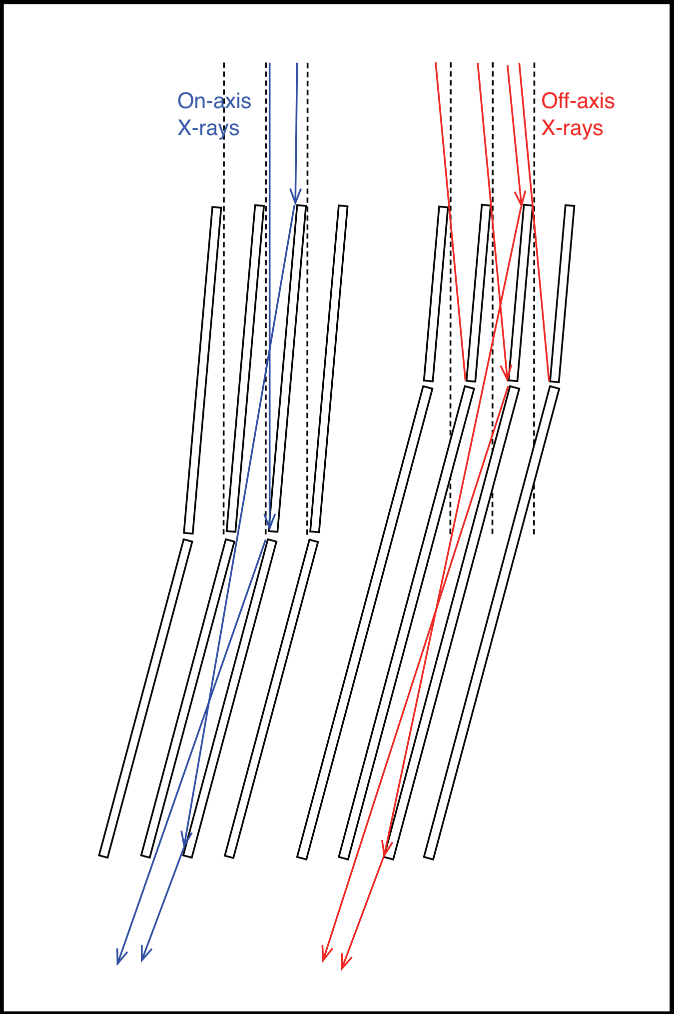
(Expected accuracy shown)

Navigation: observing celestial source

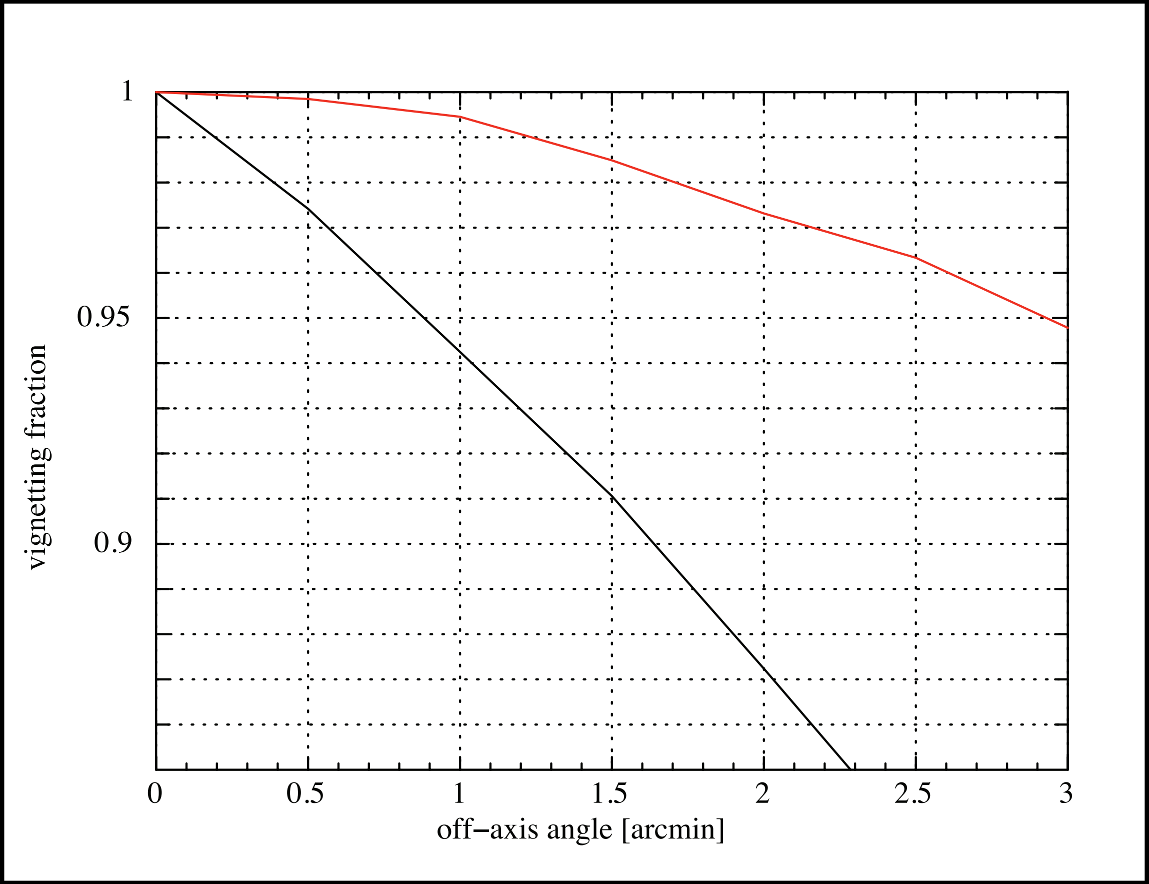


(while source sat is charging and firing thruster to correct the orbit)

X-ray mirror: vignetting-free spot



Shorter first stage



Vignetting <1% within $r = 1'$

Effective area: 18 cm^2 at 1.5 keV, 14 cm^2 at 6 keV (includes CCD QE)

Radioactive source

- ^{55}Fe particles (2–3 μm) embedded in Al film
- In best-case source geometry, number of 1.5 keV photons only 0.9% of 5.9 keV photons (Al fluorescent yield only 3.6%)
- NIST: absolute 1% calibration of source at 5.9 keV possible; at 1.5 keV needs development (but have several ideas)
- Given the small mirror, *Cal X-1* statistics will be limited by
  low brightness of radioactive source at 1.5 keV,
  low flux of celestial sources at 6 keV

Celestial sources

- Nominal source to get an idea of exposures: 3C273 (mid-range state):

  125 ks to get 10^4 cts in 0.5 keV interval around E=1.5 keV
  700 ks to get 10^4 cts in 1 keV interval around E=5.9 keV

- Variable sources need to be observed simultaneously with big Observatories

- Even 3C273 piles up *Chandra* and *XMM* in imaging modes

- At 6 keV:
  observe a brighter source with *NuSTAR*, *XARM* (or with *Chandra*, *XMM* gratings),
  then rely on cross-cal. with *Chandra* and *XMM* imaging detectors?

- At 1.5 keV:
  observe a compact extended, constant source — e.g., N132D?
  (Faint, but no need to observe simultaneously; *Cal X-1* can afford to spend 1 Ms)

	Flux uncertainty (1σ)	
	1.5 keV	6 keV
Science Requirement		
Delivered accuracy of celestial source flux	**2.0%**	**2.0%**
Expected Error Budget (L = 1 km)		
Systematic uncertainties:		
Calibration source:		
Distance *L* (from GPS) . . . . 2 m	0.4%	0.4%
Absolute source calibration	1.0%	1.0%
Source sat orientation . . . . 0.1°	0.1%	0.1%
Vignetting (off-axis angle) contributions:		
Finite source size . . . . 10″		
Finite mirror size . . . . 9″		
FAS pointing accuracy . . . . 7″		
Boom tilt stability . . . . 13″		
Total angle uncertainty . . . . 20″	0.4%	0.4%
Total cal. source systematic	1.2%	1.2%

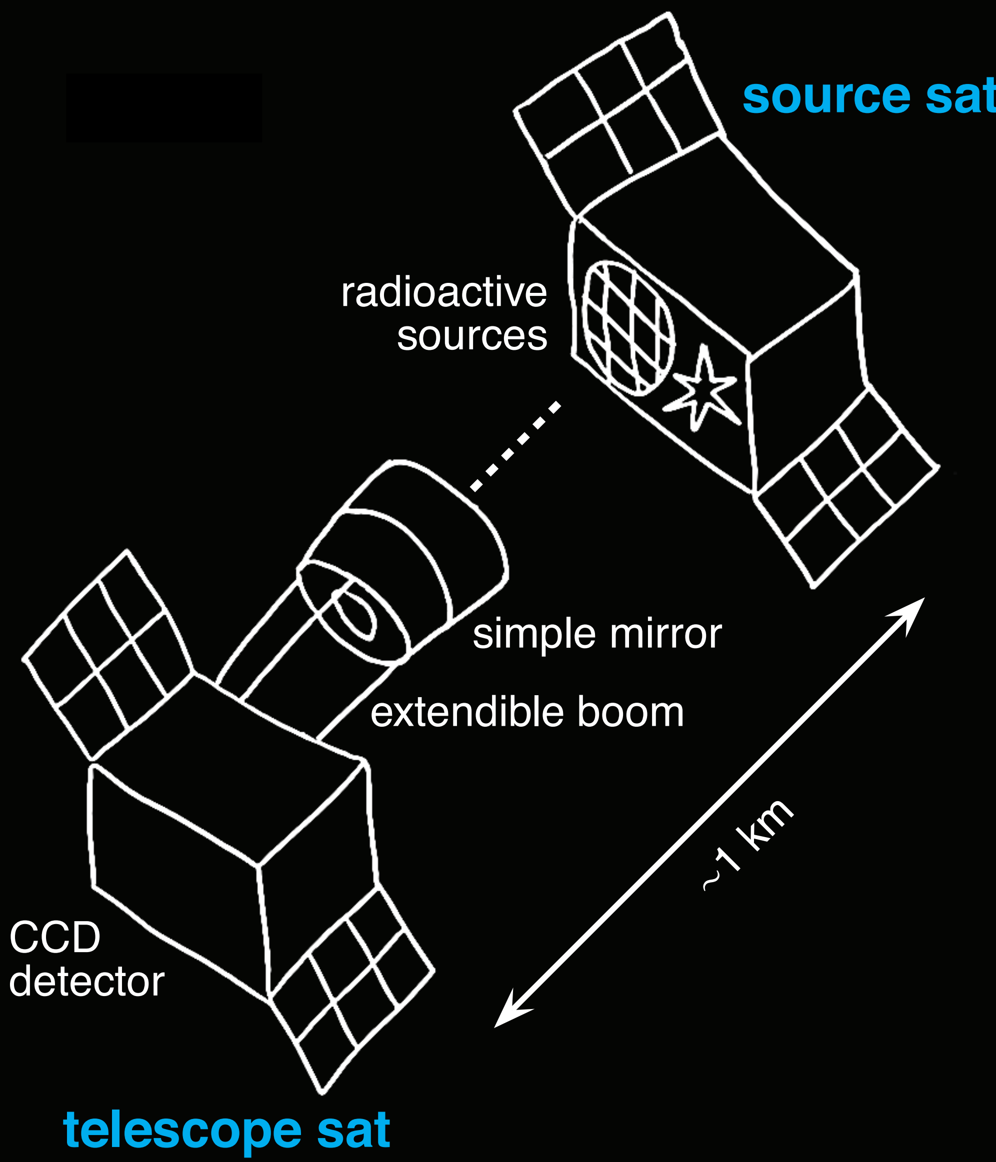
	Flux uncertainty (1σ)	
	1.5 keV	6 keV
Science Requirement		
Delivered accuracy of celestial source flux	**2.0%**	**2.0%**
Systematic uncertainties (continued):		
Celestial source:		
Vignetting contributions:		
ACS pointing accuracy . . . . 25″		
Boom tilt stability . . . . 13″		
Total angle uncertainty . . . . 30″	0.5%	0.5%
Statistical uncertainties:		
Calibration source, 500 ks	1.0%	0.1%
Celestial source: 3C273, 700 ks	0.4%	1.0%
Systematic + statistical:		
Calibration source	1.5%	1.2%
Celestial source	0.65%	1.1%
Delivered accuracy (celestial + cal. source) . . .	**1.7%**	**1.6%**

- APRA proposal submitted in March 2017:
  under $10M, build and launch late 2020 – early 2021

(hopefully while *Chandra* and *XMM* still operating)

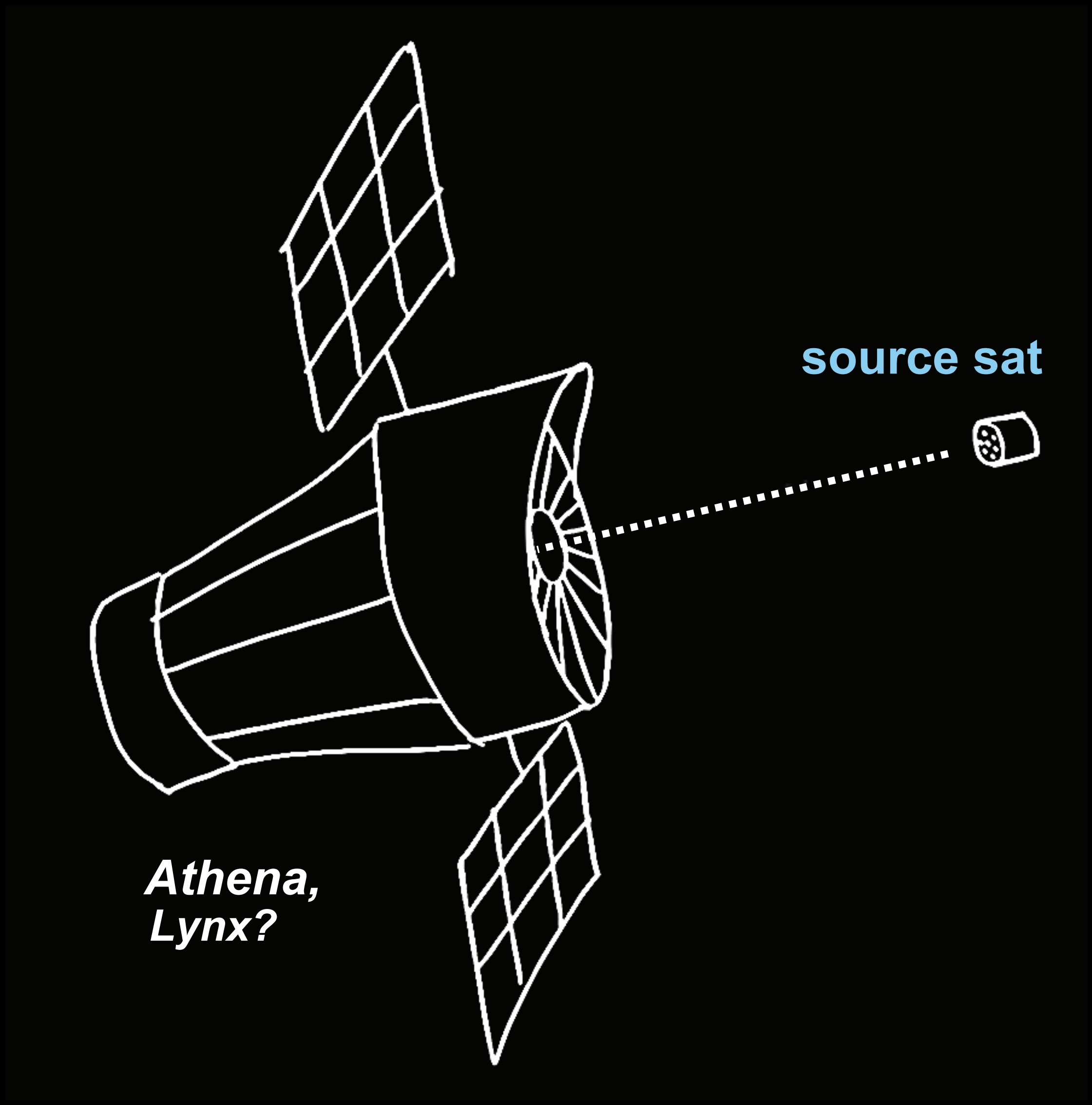
Crazy idea: what if ...

use *XARM* as TelSat? →



- *XARM* has 25× greater effective area — can observe a set of fainter, constant sources like N132D, establish standard candles in the sky

If *Cal X-1* concept proves successful ...



future observatories may fly their own source satellites