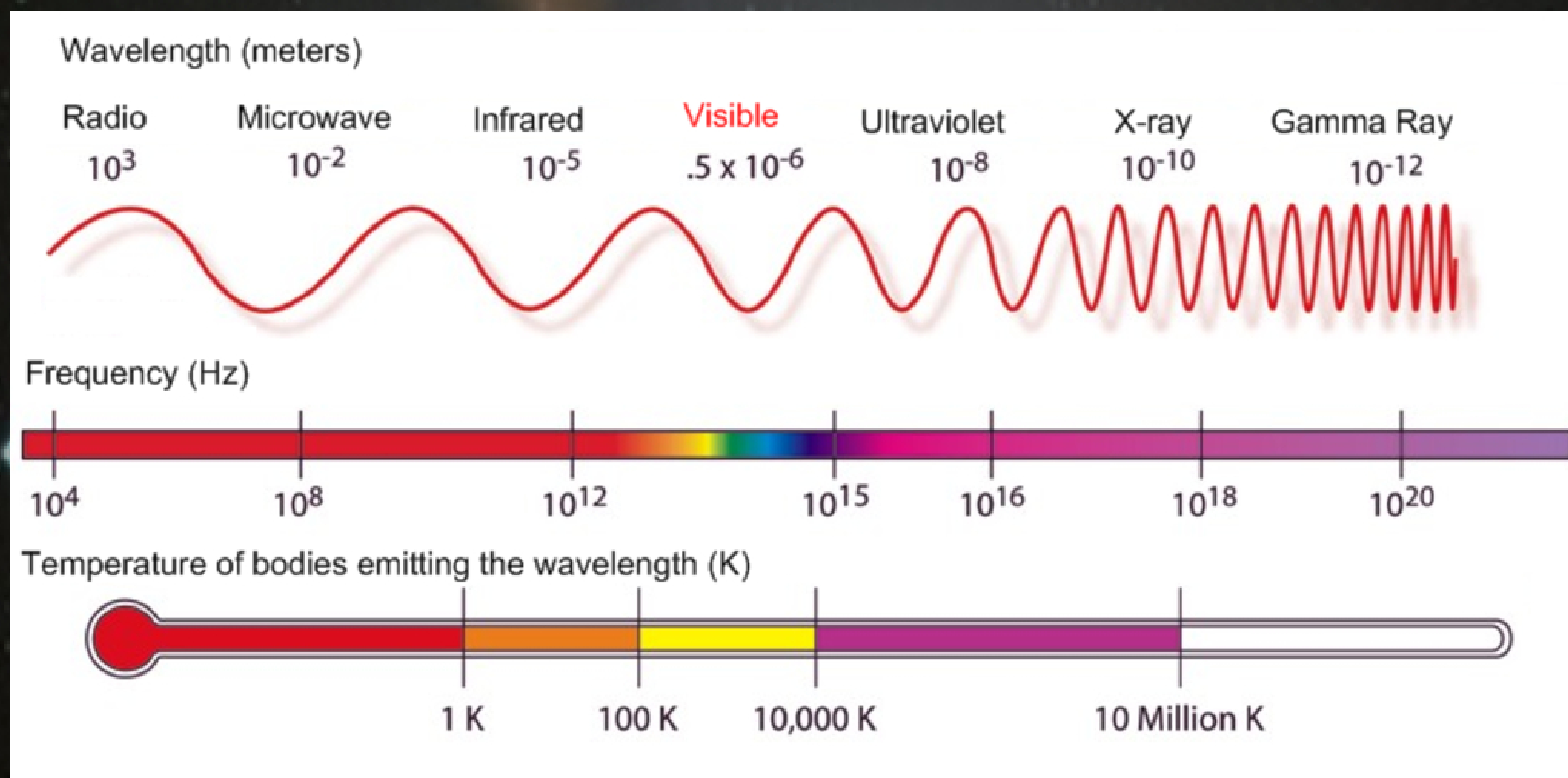
Can Small Satellites be used to do Astronomy?



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and
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Disclaimer

- X-ray Astronomer - Bias
- Long wavelength not covered - previous workshop Steve Unwin

Decadal Survey

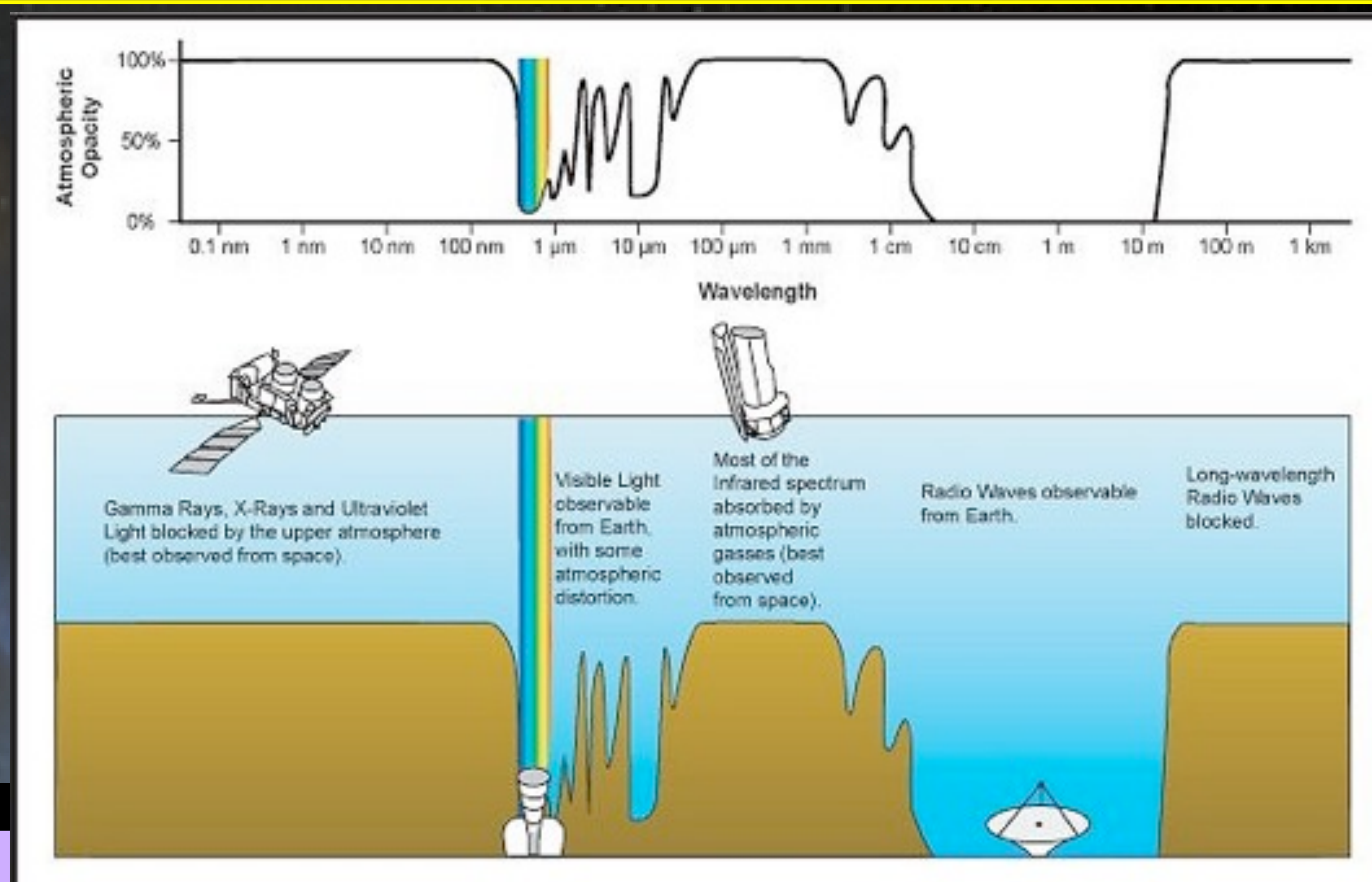
- **New Worlds New Horizons Priorities**
  - WFIRST - IR Survey
  - Explorer Program - Increased Budget
  - ~~IXO - International X-ray Observatory (with ESA)~~
  - ~~LISA - Laser Interferometer Space Array (with ESA)~~

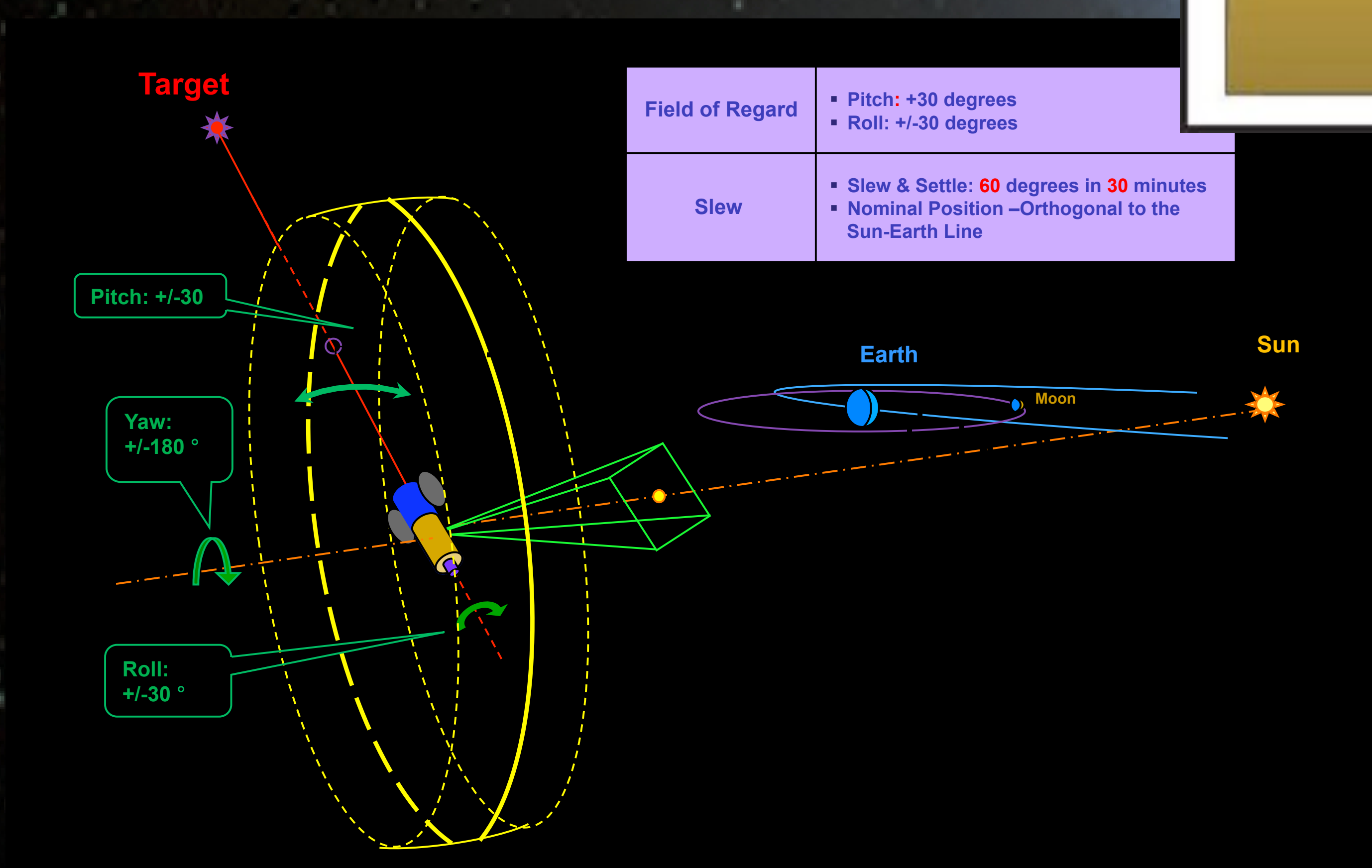
- **All large missions, observatories, facility class**
  - Science goals stretch capabilities to their limits
  - Can not be achieved with smaller missions

- **Leaves open focused, niche science to complement the flagship missions**
- **If we are smart and clever the answer is YES!**

Why Do Astronomy from Space ?

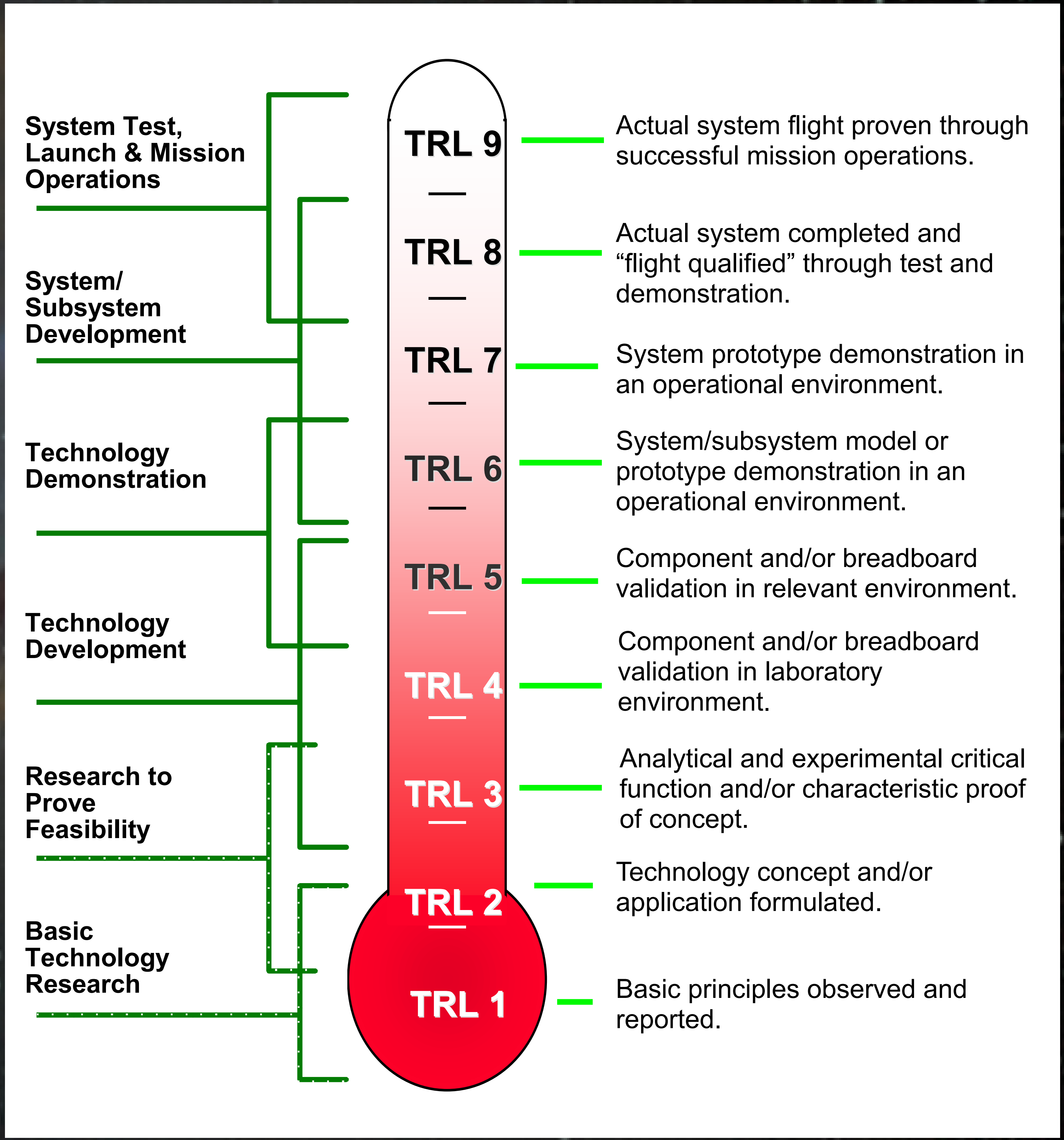
★ **Space is better!**
- Atmospheric transmission
- “Seeing”
- Weather
- Continuous viewing
- Field of regard, over time all sky





Other Considerations

- **Why not do astronomy from space?**
  - Cost, Cost, Cost ...
  - Risk and Complexity
  - Long time, low rate
- **Are there advantages to small missions?**
  - Faster
  - Education/Training
  - Lower 'overhead' on a small (low cost) mission
  - Less management
  - Technical Readiness Level (TRL)



Photon Hungry (Starved) Science

- Over most of the EM band, detector efficiency is approaching 100%, only small gains are possible
- Optic performance varies widely with band, e.g. in visible reflectivity and transmission are very good, in UV there is a lot of room for improvement (factors of a few at least)
- The real way to get more photons is to have larger apertures, i.e., BIG telescopes
- SMALL telescopes need to fill a niche that will not be done by the big missions

VIsible and Near IR Fluxes

- **There are few really bright astronomical objects**
  - ~6,000 stars as bright as $m_V = 6$ (explain this?)
    - Flux from $m_V = 6$ star is ~3,500 photons s^{-1} cm^{-2}
  - Sun, moon really bright, solar system planets less
  - Some transient events are bright - Novae and Supernovae but rare
  - Stars in nearest galaxy are already very faint, but total light is not
- **Typical Photon Rates**

Band	Central λ (μm)	Δλ/λ	Jy (m=0)	ph s^{-1} cm^{-2} (m=6)	ph s^{-1} cm^{-2} (m=18)	ph s^{-1} cm^{-2} (sky)
U	0.36	0.15	1810	1,630	2.6×10^{-2}	1.6×10^{-2}
B	0.44	0.22	4260	5,630	8.9×10^{-2}	2.9×10^{-2}
V	0.55	0.16	3640	3,500	5.8×10^{-2}	4.4×10^{-2}
R	0.64	0.23	3080	4.260	6.7×10^{-2}	2.7×10^{-2}
I	0.79	0.19	2550	2,910	4.6×10^{-2}	1.8×10^{-2}
J	1.26	0.16	1600	1,540	2.4×10^{-2}	1.0×10^{-2}
H	1.60	0.23	1080	1,490	2.4×10^{-2}	1.0×10^{-2}
K	2.22	0.23	670	930	2.0×10^{-2}	0.8×10^{-2}

- **Sky Background**
  - ~22-23 mag/arcsec^2
- **Hard for small missions to study faint objects, and few bright ones**

Example

- **How faint a star can be monitored with a small telescope to look for Earth-like planet?**
- **Assume a very broad band with from 400-800 nm and a total optical efficiency of 70%**
- **‘CubeSat’ primary ~8.5cm diameter => 40 cm^2 (includes efficiency)**
- **Detected photon rates:**

m_v	ph cm^{-2} s^{-1}	cts s^{-1}	t(3-σ) s
6	18,000	720,000	420
7	7,150	286,000	1,050
8	2,850	114,000	2,625
9	1,150	46,000	6,525
10	450	18,000	16,650

- **For Earth-like planets, typical dip is >0.01% (radius 1/10 Jupiter)**
  - Need >1/10,000 precision => 3×10^8 counts/measurement
  - Transits are ~10 hours long
- **Hard if fainter than m_v~7, super-Earths easier (3x)**

Signal to noise problem

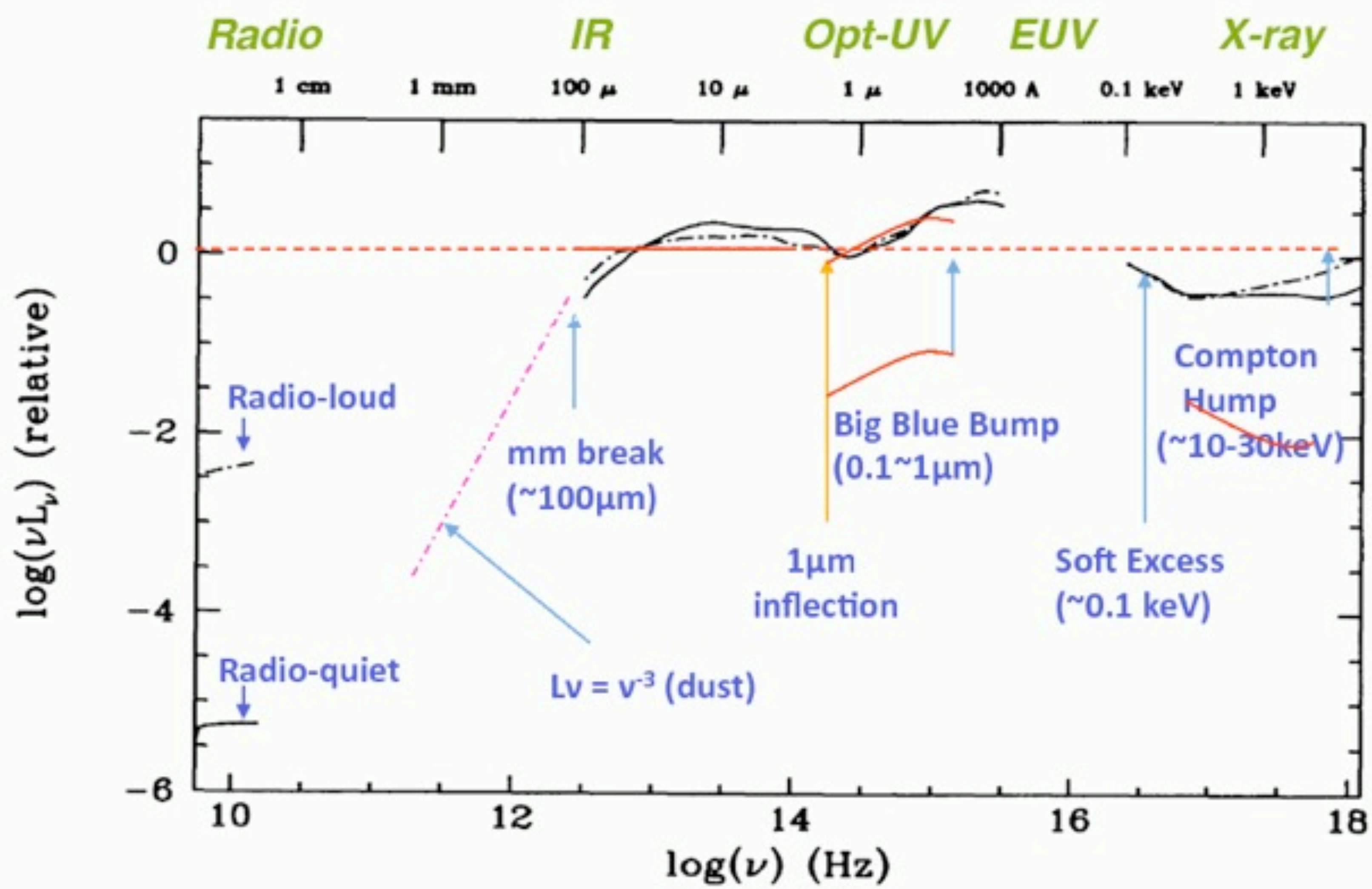
$$\mathrm{SNR} = \mathrm{S}/\sqrt{\sigma_\mathrm{S}^2 + \sigma_\mathrm{B}^2} = \mathrm{S}/\sqrt{\mathrm{S}+\mathrm{B}}$$

- ★ **Alternative to large area is long observation time**
  - Can go fainter, but becomes background limited
    - Mainly sky background
    - SNR only increases as $t^{1/2}$
- ★ **Main background is the sky (dark current and read noise are assumed to be small)**
- ★ **Typical integration time for 5σ detection is ~30 minutes to reach 18-th magnitude in most of the optical NIR bands**
- ★ **There are thousands of AGN this bright**
  - Time resolution depends on the flux, many objects vary on short time scales and need high flux to get past shot noise

Spectral Energy Distribution (SED)

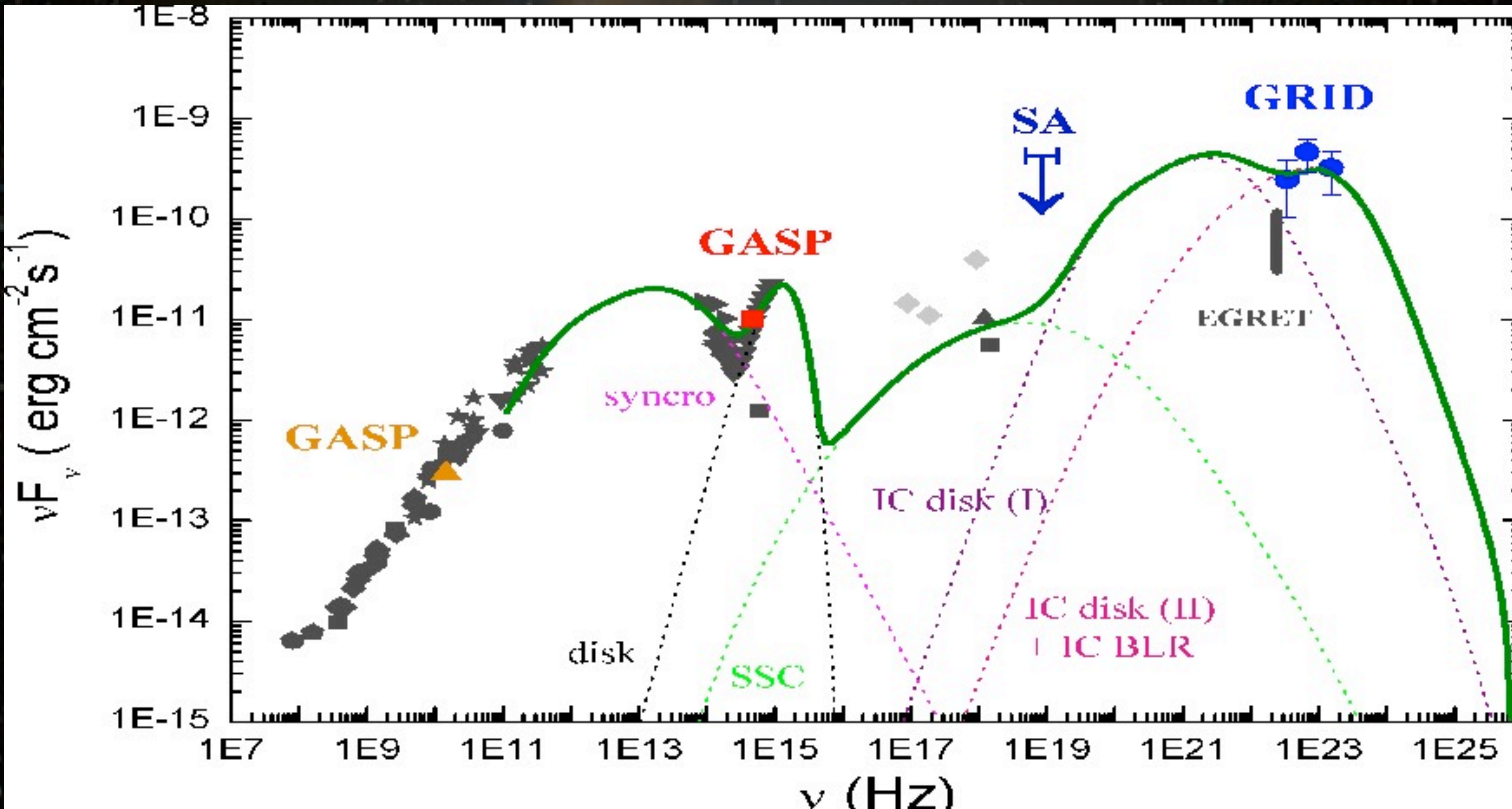
Radio-loud, Radio-quiet: quasars that look virtually identical at all other wavelengths can differ by a 1000 in their radio emission. Radio-loud quasars have a powerful jet moving at relativistic speeds (i.e. close to the speed of light) made up of energetic particles, themselves moving near the speed of light in a magnetic field. This causes them to radiate light by the synchrotron process.

Big Blue Bump: This feature dominates the quasar emission by a modest factor. It is likely due to emission from an accretion disk around the central supermassive black hole that has a range of temperatures from ~100,000K to ~1000K.



Elvis et al., 1994, ApJS, 95, 1

Horizontal line: shows equal power per decade [or octave, or any equal sized division in log(nu)]. A quasar keeps its power output almost constant from the far-infrared (100mu) to X-rays (10keV), with excursions of only a factor of a few.



GRID
SA
GASP
EGRET
syncro
GASP
IC disk (I)
IC disk (II)
+ IC BLR
disk
SSC
νF_ν (erg cm^-2 s^-1)
ν (Hz)
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
1E7
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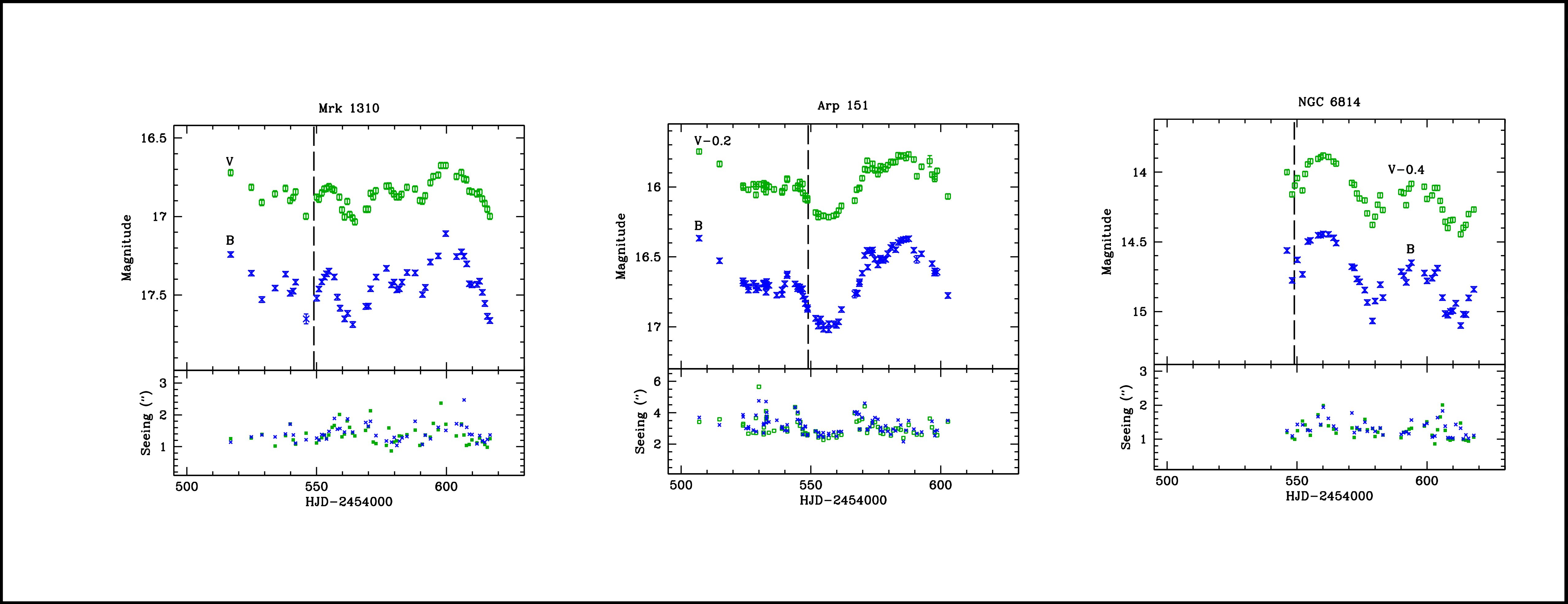
1E23
1E25

AGN Variability



Examples of AGN Variability

Walsh, J.L., et al. 2009

Potential Areas

- ★ **Lunar water mapper**
- ★ **Bright AGN (blazar) monitoring**
- ★ **QSO survey in NIR (limited to bright QSO, modest redshift, may be done well enough already)**
- ★ **Solar science**
  - Flux monitor (bolometric? Broad band?, Long term)
- ★ **Technology test bed**
  - New optics (e.g., adjustable X-ray mirrors)
  - New detectors (e.g., CMOS APS)
- ★ **Solar system objects**
  - Jupiter Aurora (UV) monitor (planet rotation)
- ★ **Diffuse Emission**
  - X-ray spectroscopy of ISM, solar wind charge exchange
- ★ **Timing**
- ★ **Polarization and other new discovery space**

What would it take?

Requirements

- ★ **Most astronomical observations need three axis stable pointing**
  - generally arcmin pointing and sub-arcmin down to arcsec stability
- ★ **Look away from very bright objects**
  - E.g., avoid sun and moon, and perhaps planets
- ★ **Stable thermal environment**
  - Photometric accuracy
  - Stable optics (PSF)
  - Often cold (optics and detectors)

Hubble Space Telescope

Additional Considerations

★ **Power**
- Usually low power available on small satellites (mass, volume)
- Okay in general - sensors, spacecraft systems
- More power needed for active cooling of sensors, thermal systems for optics

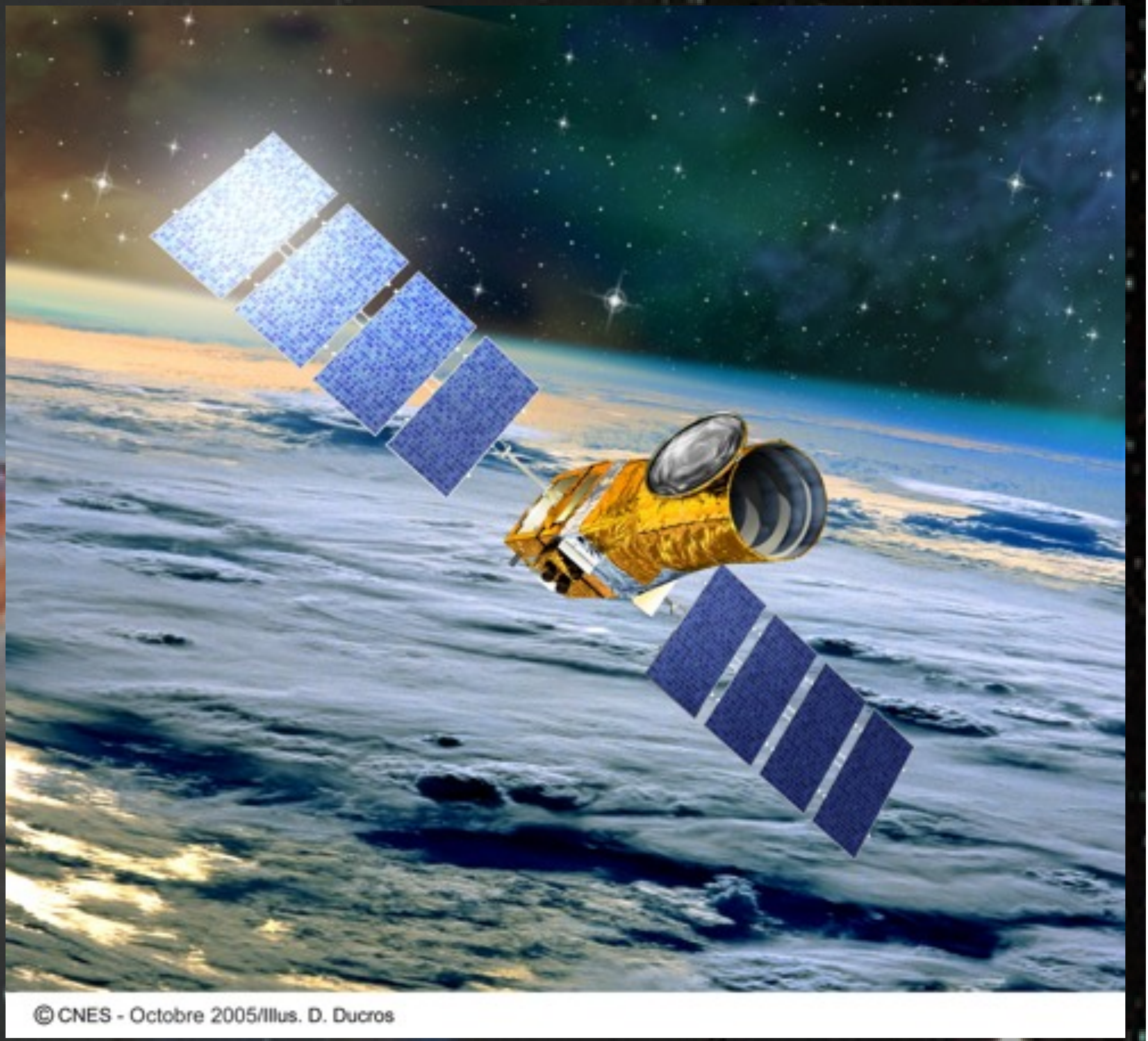
★ **Data Storage**
- Images are large (megapixel), depends on cadence
- Spectra mostly 1-D (not data intensive), but IFU and Echelles are 2-D
- Temporal time series depends on cadence and duration

★ **Bandwidth**
- Low earth obits (LEO) typical for secondary payloads, hitchhikers, etc., allows high data rates, but short stations passes
- High earth orbits may require more power and//or high gain antenna

★ **Orbit**
- Drift away orbit would permit cold telescope for IR

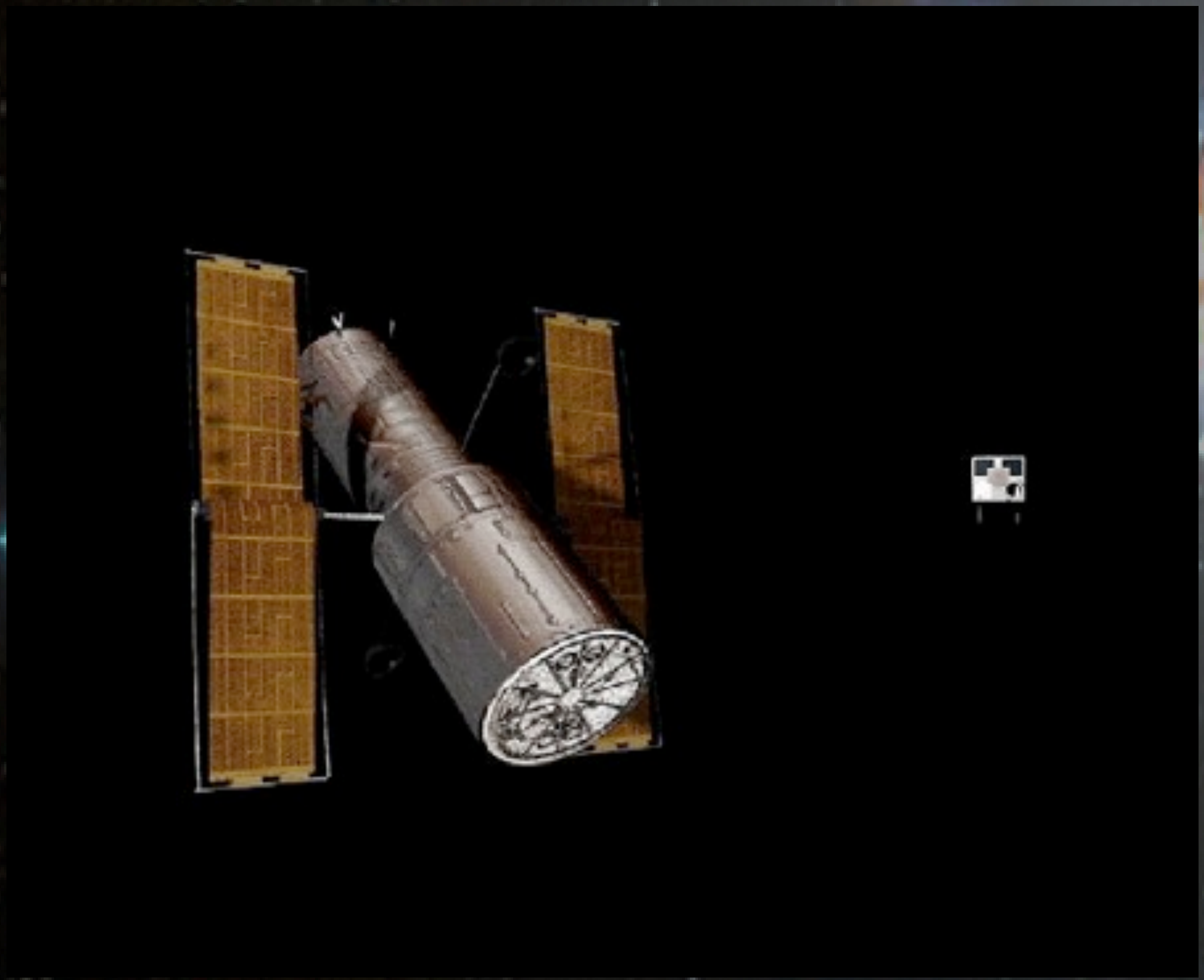
CoRot

- **Mass between 570 and 630 kg**
  - Payload mass around 270 kg
  - Length 4100 mm
  - Diameter 1984 mm
  - Electric power 380 W
  - Pointing accuracy 0.5 arcsec
  - Telemetry 900 Mbit/day
  - Mass memory capacity 2 Gbit
  - Mission duration 2.5 years minimum



MOST (My Own Space Telescope)

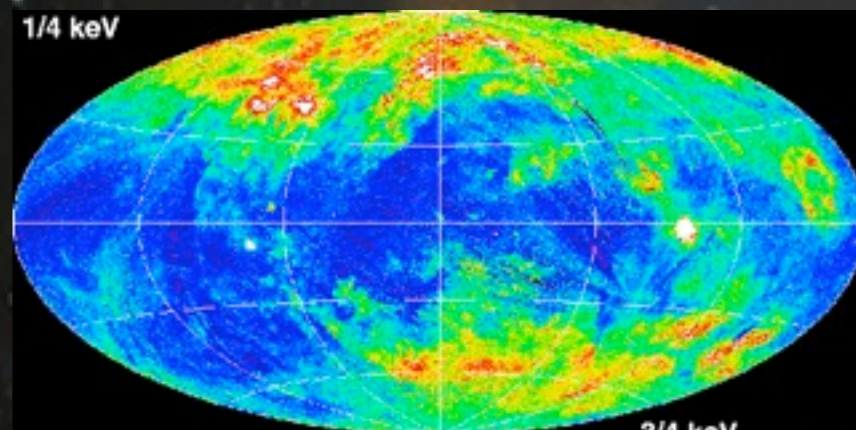
- **MOST** is a suitcase-sized (65 cm x 65 cm x 30 cm, 60 kg) microsatellite designed to probe stars and extrasolar planets by measuring tiny light variations undetectable from Earth. This can be done with such a small telescope (15 cm aperture) thanks to new Canadian attitude control technology.



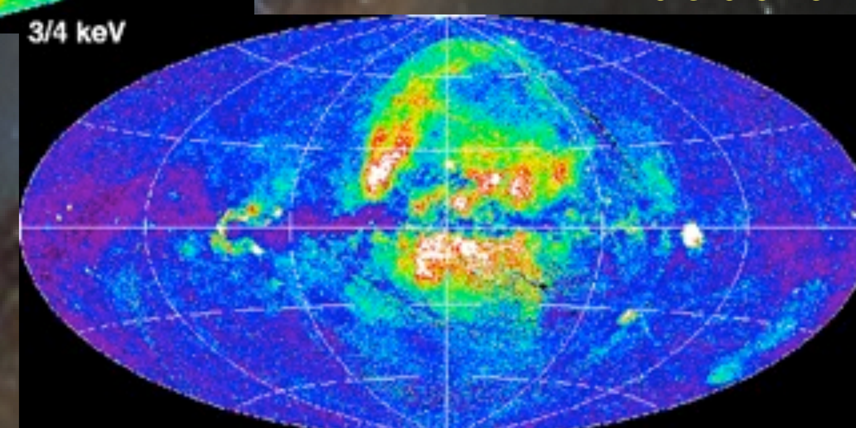
Another Example

ROSAT Soft X-ray Sky (0.1-2.0 keV)

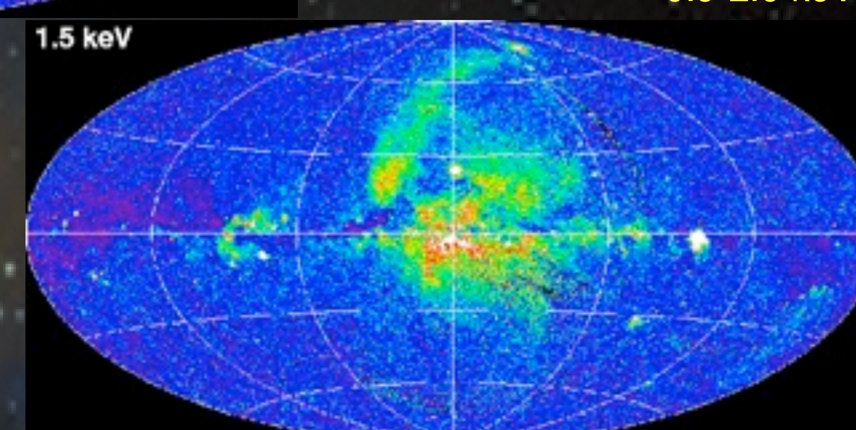
0.1-0.4 keV



0.5-0.9 keV



0.9-2.0 keV



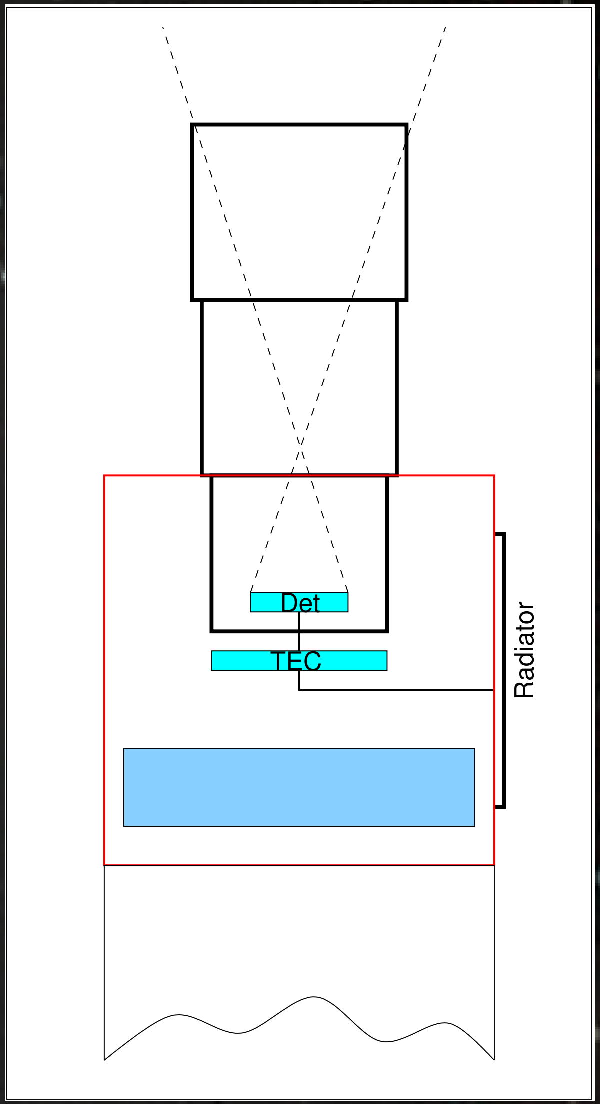
- **Major source of background for X-ray observatories**
  - Dominates the sky at energies below ~1 keV
  - Source is warm and hot ISM, perhaps a local bubble from a past SN
  - Previous observations with thin window proportional counters

SoftX CubeSat

- **Spectrum of Diffuse Soft Galactic X-rays with modest spatial resolution and modest (Si) spectral resolution**
- **Assume a CMOS thinned backside illuminated sensor**
  - 1024 x 1024 x 16μm, 5° x 5° FoV
  - Expected count rates:

Band (keV)	Rate (ph s^{-1})
0.15 - 0.4	0.75
0.4 - 0.6	0.16
0.6 - 0.9	0.16
0.9 - 1.1	0.06

  - Can accumulate ~10,000 sec/FoV over entire sky in one year, gives enough counts for low resolution (R~10's) spectroscopy in each band



Summary of Ideas (in no order)

Science Topics (Astrophysics)	Science Objective	Methodology / Technology	Target	Technology Challenges
Measment of low-energy diffuse background from the interstellar medium (local hot bubble)	Low spatial resolution (moderate spectral resolution) of the low-energy background - integrated emission of stellar events, measurement of a supernova remnant and thermal propagation into the interstellar medium (a key to star formation)	X-Ray Mission, Colimated CCD or CMOS detector (small), readout electronics	Sun-sync orbit looking away from Earth	Technically ready now
Broadband Spectral Energy Distribution (SED) via a constellation of telescopes operating in different bands	Characterization of AGN with contemperaneous measurments across EM spectrum, espically filling in the UV region and IR	Constellations	All-sky survey	Coordination of observations and large dat volumes
Wide field x-ray observatory	All sky survey 100 times more sensitive than current	Gossamer grazing incidence optics need to be developed	All-sky survey	Light weight optics
IR observation search for very distant/bright quasars	Synoptic surveys and time history of black hole growth (evolution of supermassive black holes)		A drift-away orbit (passive cooling) or LEO (may still require telescope cooling)	Challenge could involve cooling the detectors and getting performance out to 3-5 microns (to get Quasars of higher redshift)
Understanding the origin and causes of reionization of the early universe	What properties do galaxies need to have to contribute to reionization (done in the UV below 912 angstroms) Need to understand what factors control the escape of ionizing photons in order to understand whether escape from galaxies caused reionization	Perform a survey and correlate with high escape fractions from observations	Performed from LEO with 10s of SmallSats (can get a good start with one)	Development of good coatings on the optics and high efficiency UV detectors. Pointing stability from 1-3 arcsec needed (frame time) so this could be an issue for CubeSats, but not SmallSats
Independent but cooperative observations in UV, X-Ray, and IR				