Multiwavelength astrometric detection strategies for black holes

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THE ROYAL SOCIETY

Science & Technology Facilities Council

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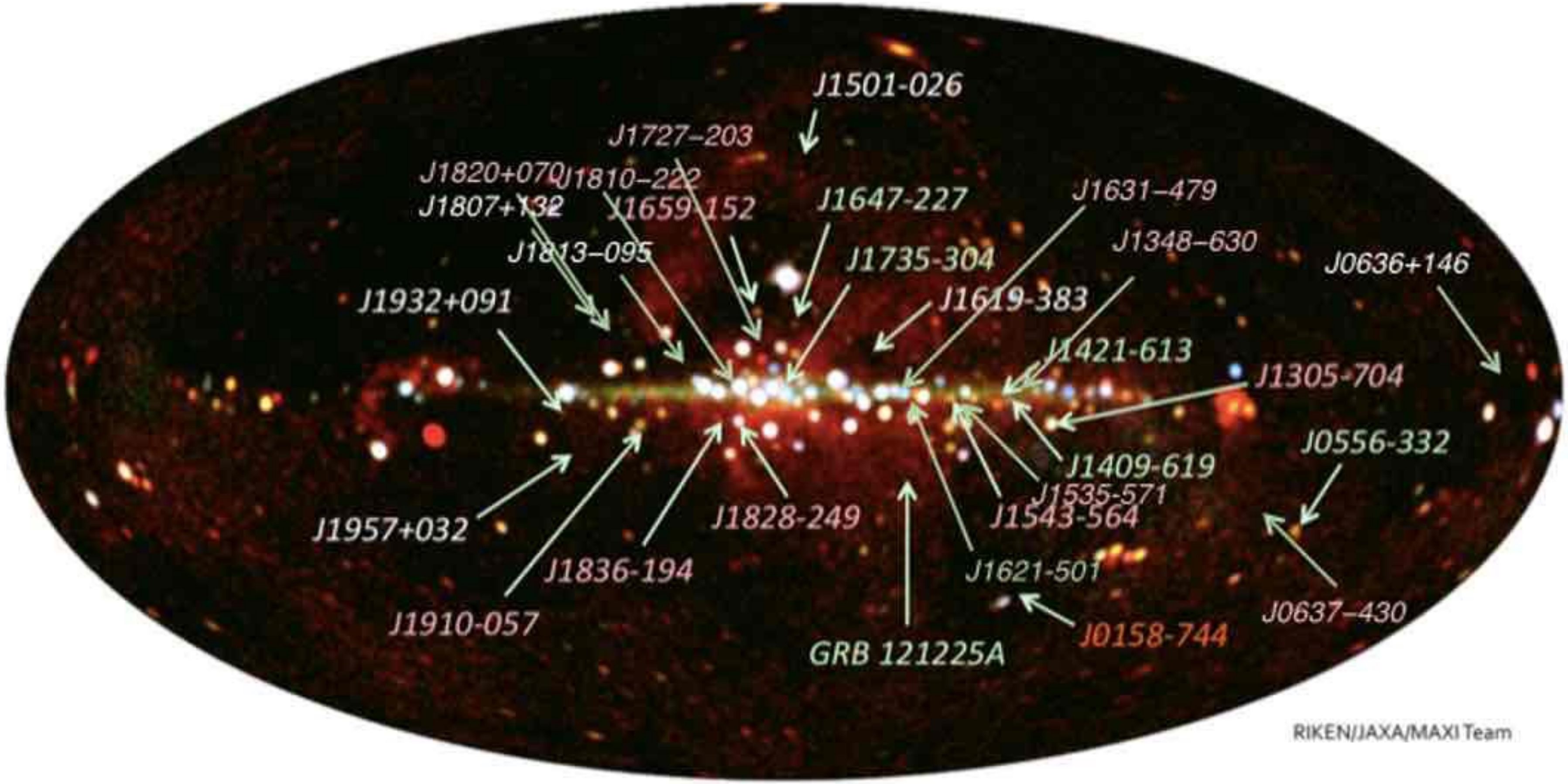
Accreting BH/NS binaries in the Milky Way in X-rays.
MAXI/ISS 10-year sky map.

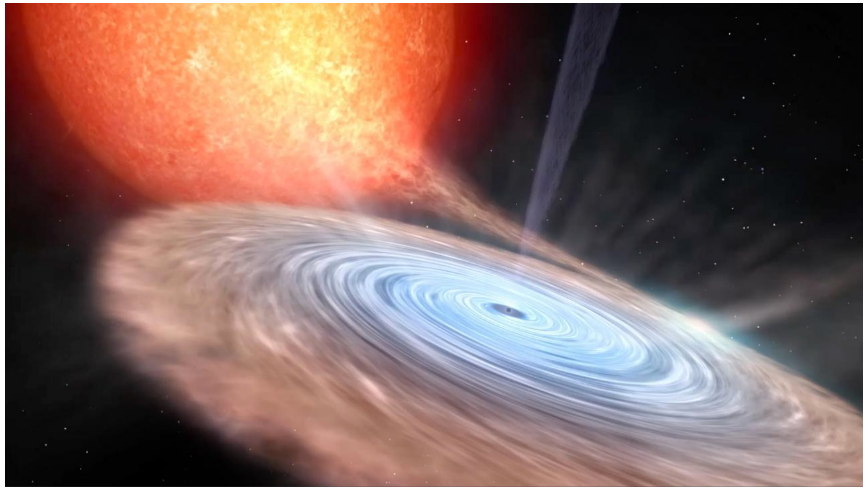


RIKEN/JAXA/MAXI Team

Red= soft X-rays; blue = hard X-rays.

Compact Object (BH or NS) Demography

- If most massive stars collapse to compact objects, then (perhaps) ~1% of stars form compact objects (<~100 $M_\odot$).
- One isolated stellar-mass black hole known (Sahu et al. 2022, Lam et al. 2022), many isolated neutron stars known (likely formed in binaries?). **⇒ other talks**
- Some (unknown) fraction will be found in binary systems. Estimates range from ~10^3 to ~10^8 systems in the Galaxy (Kalogera 1999, Pfahl 2003, Tetarenko et al. 2016).
- Currently only ~30 dynamically confirmed black holes known in the Milky Way.
- Binaries allow systems to be followed up and studied in detail.
- But binary companion can completely alter stellar evolutionary pathways.



Accreting compact object binary system (IAC)

Major Questions in Black Hole Astrophysics

- How many black holes are there in a Milky Way galaxy? (Isolated / In binaries / [non]-Accreting?)
- What is their mass spectrum? Minimum/Maximum/Gaps? Are there any intermediate-mass BHs?
- What are their natal condition dependences (metallicity, natal kicks, compact object type)?
- How does binary evolution alter their life cycle?
- Do all massive star undergo supernova? Any ‘direct collapse’ black holes?
- What is the spin distribution of black holes?

- What causes accretion outbursts?
- How are relativistic jets launched?

Milky Way Black Hole Search Strategies (in binaries)

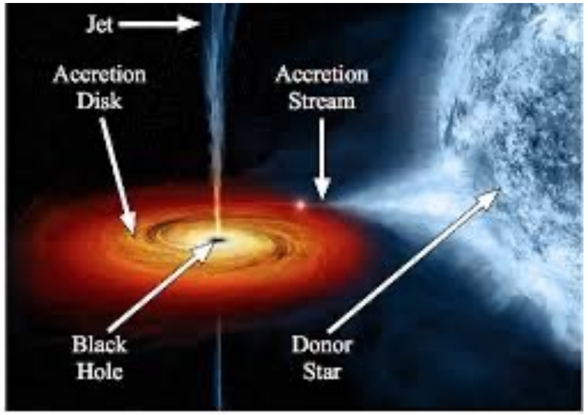
- **Imaging** surveys (*eROSITA*, future radio surveys) ⟹ search for quiescent continuum emission, especially in X-rays and radio; Gandhi et al. 2022, Maccarone et al. 2020….

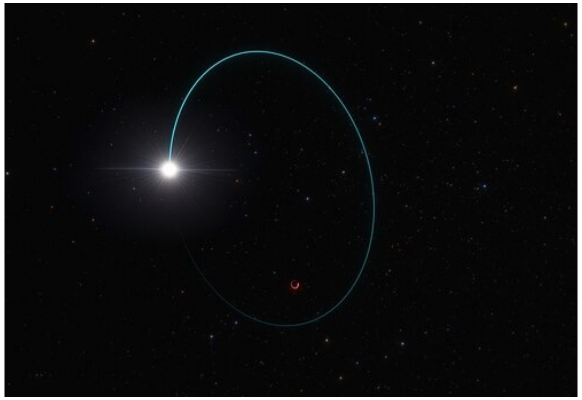
- **Synoptic** surveys (VRO, *eROSITA*) ⟹ search for quiescent variability; Johnson et al. 2019, Gomel et al. 2021….

- **Self-lensing**; Masuda & Hotokezaka 2019; Wiktorowicz et al. 2021….

- **Spectroscopic** surveys ⟹ search for quiescent accretion disc / donor emission through radial velocity variations, Hα emission; Casares et al. 2014, Yi et al. 2019, Price-Whelan et al. 2020….

- **Astrometry**; Gould & Salim 2002, Belokurov et al. 2020, Gandhi et al. 2022, El-Badry et al. 2022…24, Gaia Collaboration 2024….

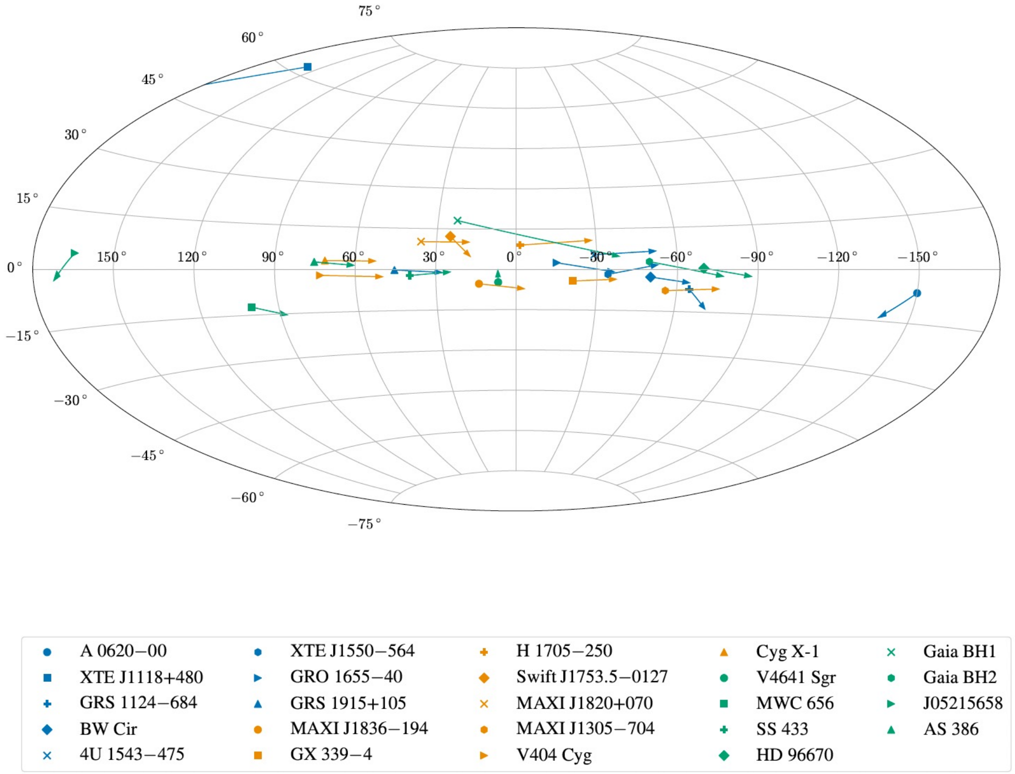


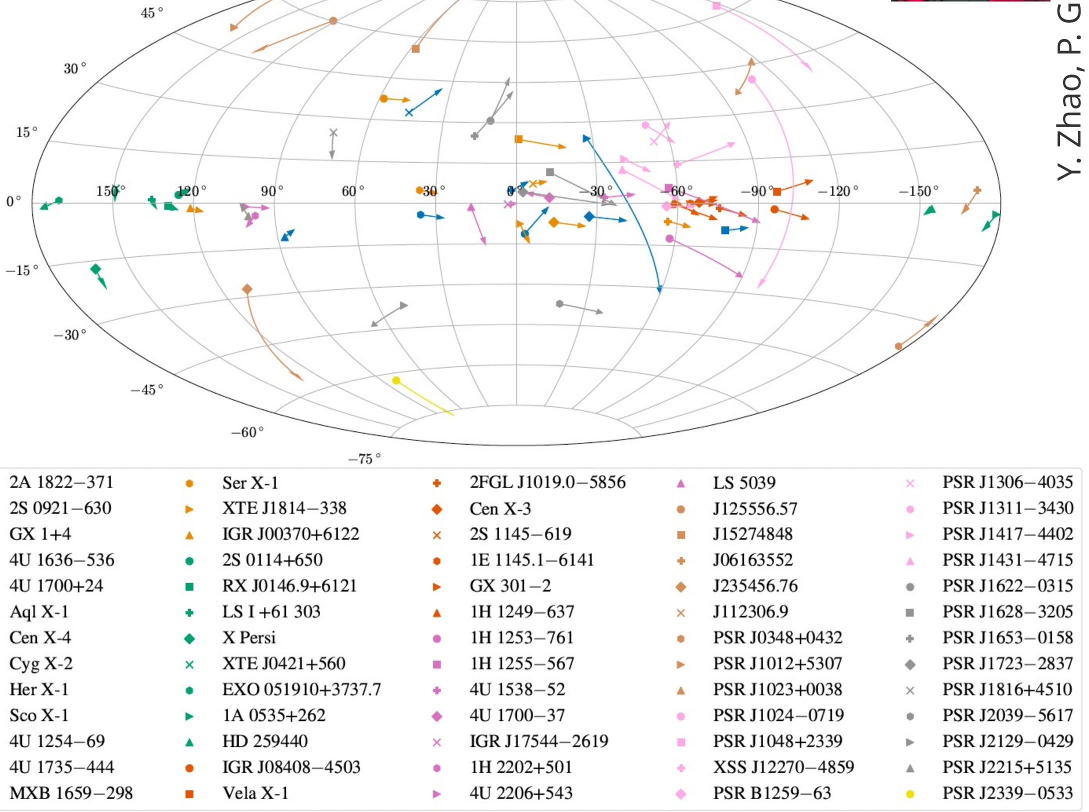


Compact Object kinematics from *Gaia* DR3

89 compact object binaries (NS, BH, accreting, non-interacting)
with precise distances, masses and 3D kinematics

Y. Zhao, P. Gandhi et al. (2023)





Black Holes

Neutron Stars

‘Natal Velocity Kicks’

- Kick imparted to remnant at the instant of supernova explosion (Fryer & Kusenko 2006; Belczynski et al. 2017).
- **Mass-loss kicks** (recoil) expected if there is mass loss (Blaauw 1961, Nelemans et al. 1999).
- **Additional Natal kicks?** Neutrino kicks, Neutron Star fallback kicks, Hydrodynamic asymmetries, Gravitational Wave recoil (e.g. Lai 2004, Janka 2013).
- Several 100 km/s for pulsars (Hobbs et al. 2005).
- Strong kicks can unbind binary systems. Observational constraints on black hole kicks are sparse (e.g. Fryer et al. 2012, Repetto et al. 2017, Gandhi et al. 2019, Atri et al. 2019, Varma et al. 2022).


UNIVERSITY OF WARWICK / MARK GARLICK

Non-interacting binaries / Non-Single Star Astrometric Solutions

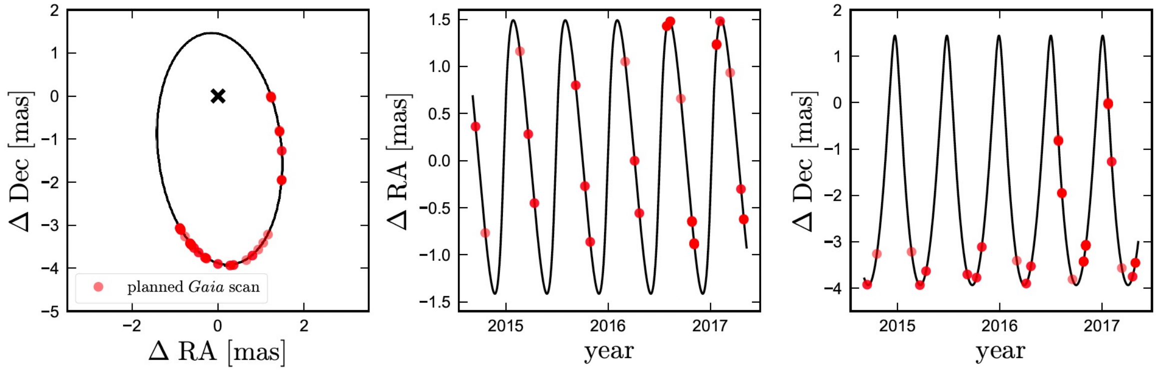
⇒ Lu talk

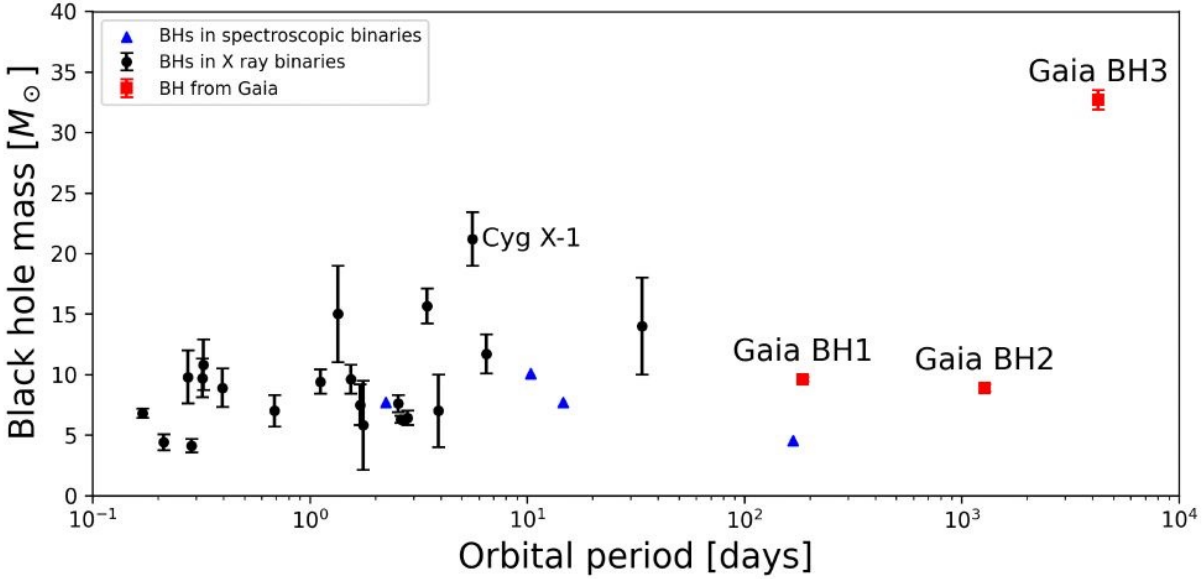
- Non-interacting compact binaries in wide orbits should outnumber accreting systems.

- A few systems now beginning to be robustly identified (Thompson et al. 2019, Shenar et al. 2022), but still questioned ().

- Among these are astrometrically identified systems in very wide orbits (El-Badry et al. 2022, 2023, Chakrabarti et al. 2022, Panuzzo et al. 2024).

- Evolution non-trivial to explain.





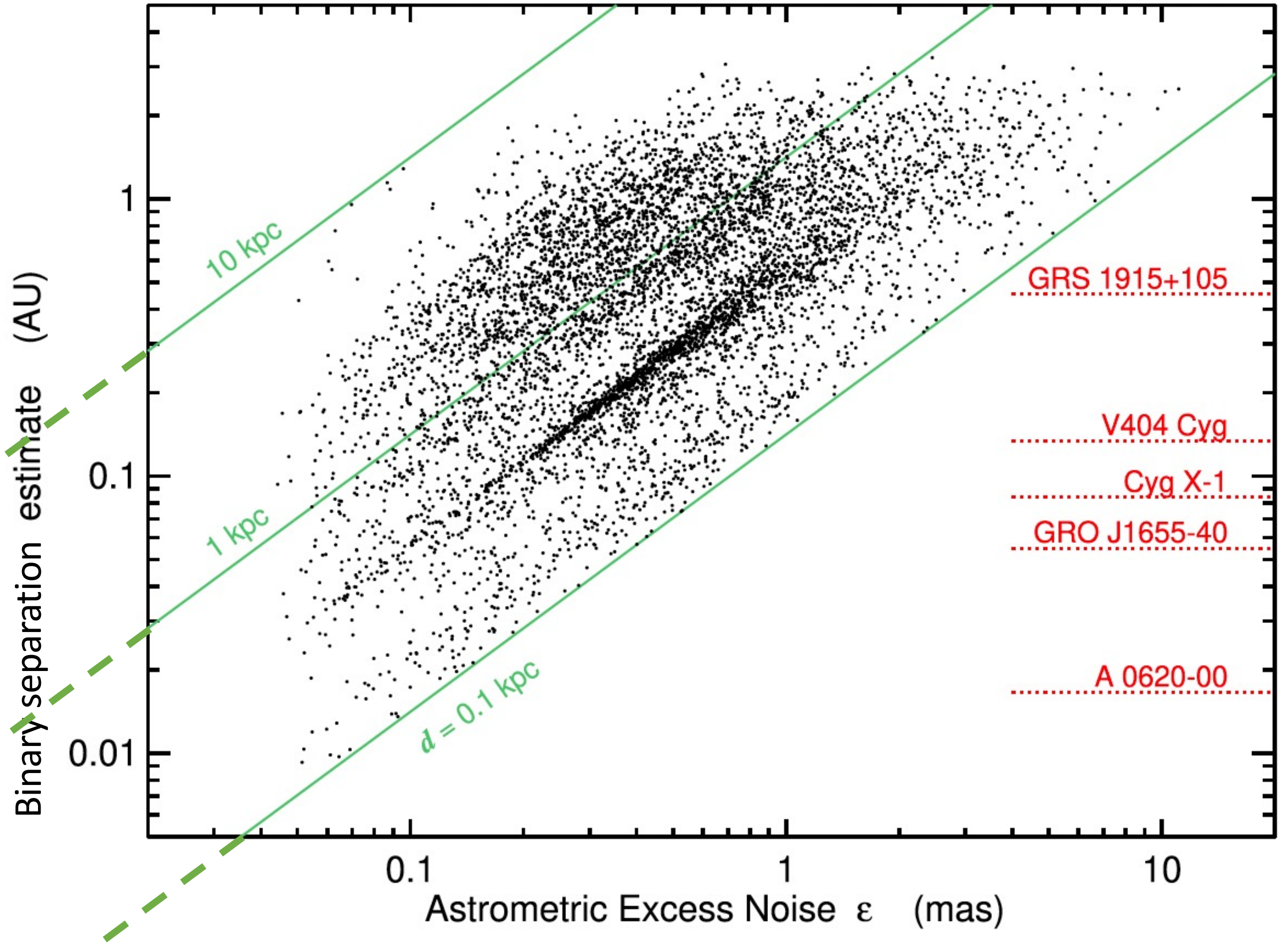
Theia: Novel astrometric parameter space

- Construct well-selected *volume-limited* samples.
- Need well-understood **selection function**.
- Good understanding of systematics (e.g. attitude noise).

- With precision σ, should be able to sample all accreting BHs in binaries out to distance

$$\sim 10\ \mathrm{kpc} \times \left(\frac{a}{0.1\ \mathrm{AU}}\right)\left(\frac{10\ \mu as}{\sigma}\right).$$

- Probably need to target ~1000 deg^2 in/near the Galactic plane (or more at higher latitudes).



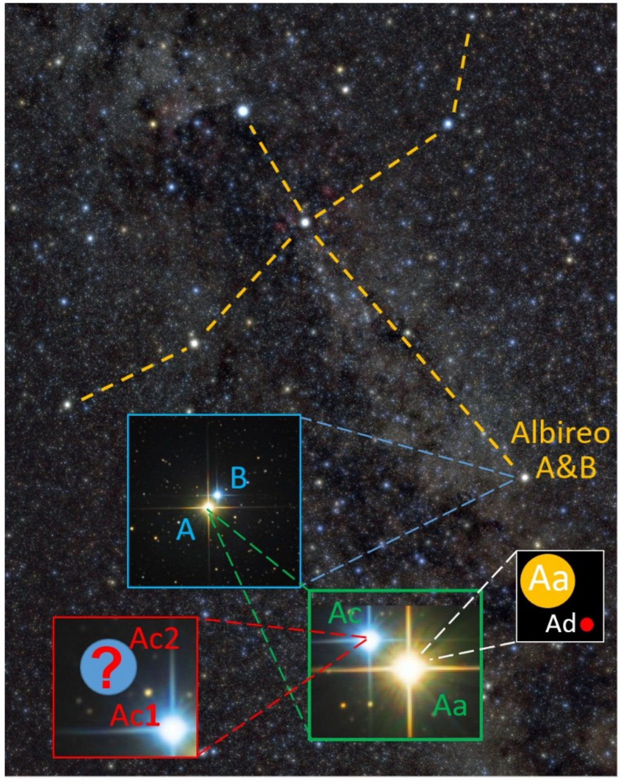
X-ray sources with astrometric excess noise (Gandhi et al. 2022)

Theia: Novel astrometric parameter space

- Can start to model the actual Milky Way to find undetected BHs.
- Search for sources with evidence of unmodeled ‘**acceleration**’.
- Statistically identify primordial BH populations.
- Need good model of the Galaxy.
- Need long time baseline. Can use *Gaia* priors.

IMAGE OF THE WEEK

MISSING MASS IN ALBIREO AC: MASSIVE STAR OR BLACK HOLE?



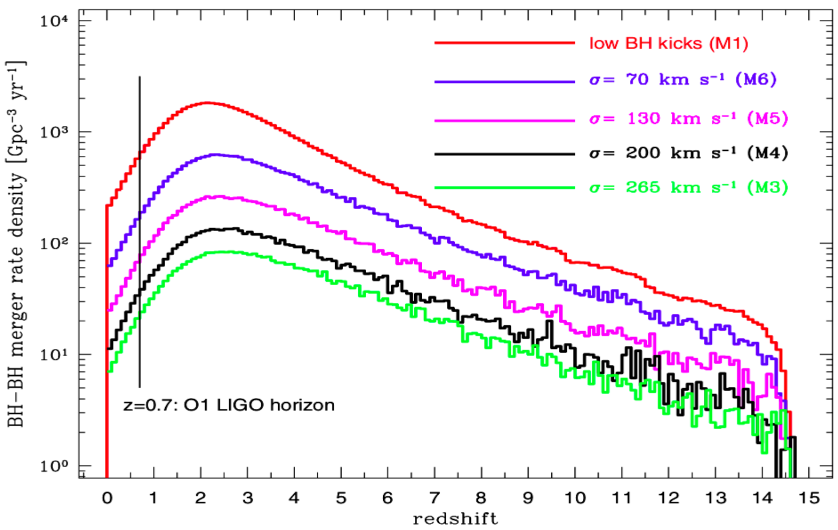
Theia: Novel astrometric parameter space

- Gravitational Wave (GW) source prediction and follow-up:

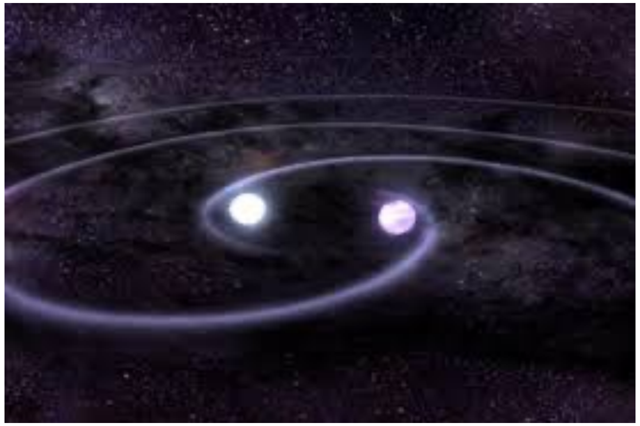
1) Natal kick distribution will better constrain the GW merger rate.

2) LISA/other GW observatories should uncover compact object binaries.

  - Measure proper motions.
  - Measure system parameters.
  - e.g. ZTF J1539 (7 min. white dwarf binary; Burdge et al. 2019). Separation ~ 20 μas.
  - Will need long integrations to allow for source brightness.



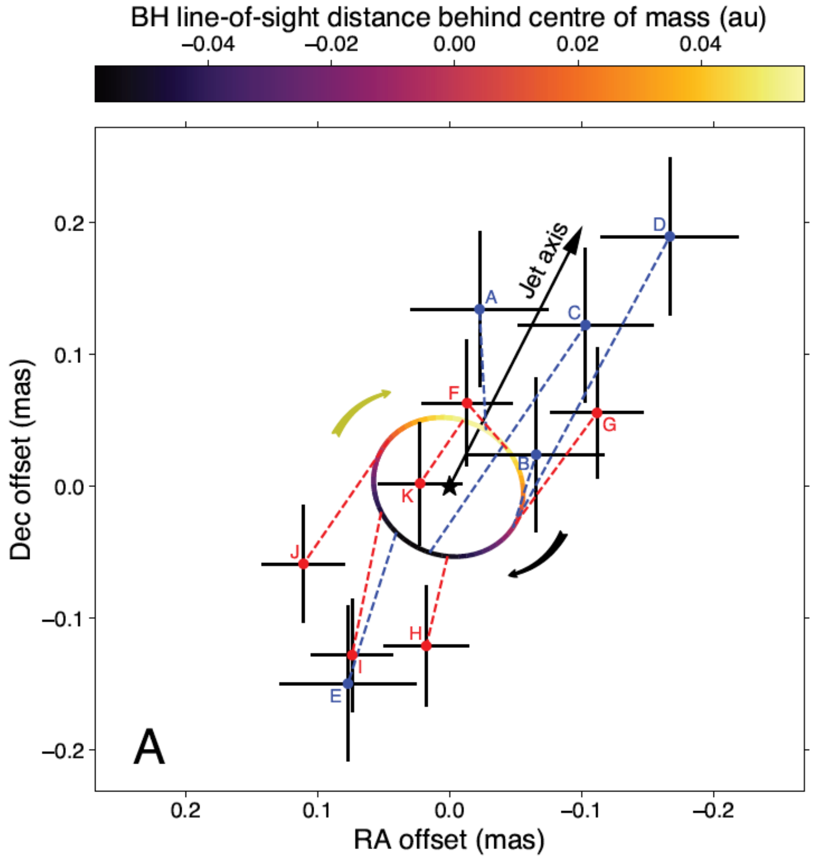
Belczynski et al. (2017)



Theia: Novel astrometric parameter space

- <u>Constraining system geometry in accreting BHs.</u>
- Measure orbital separation, inclination, direction of rotation, higher order ellipticity, …
- Search for offsets between binary orbital and jet axis, black hole spin axis…

⇒ Maccarone talk



Cyg X-1: Miller-Jones et al. 2021

Nancy Grace Roman Telescope (2027-)

- Top large mission space priority of ASTRO2010 Decadal Survey
- Wide-Field Imager: 0.28 deg^2 (100× Hubble), 0.5–2.3 microns.
- JASMINE will pave the way to Roman.

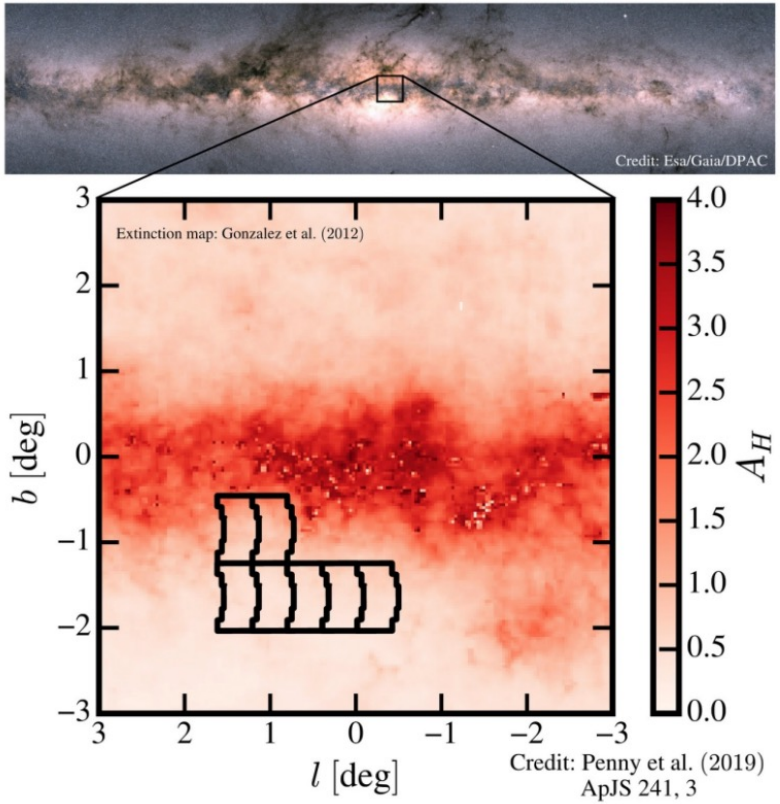
Galactic Bulge Time Domain Survey

- Search for Exoplanets in microlensing down to sub-Earth masses
- Photometric measurements of ~240 million stars brighter than 25th mag in W146.
- High-precision astrometry ~3-10 microarcsec.

Galactic Plane Survey

- ~700 hours committed.
- Exact survey parameters under discussion.

Theia needs to be competitive in the post-Roman era.



Credit: Penny et al. (2019) ApJS 241, 3

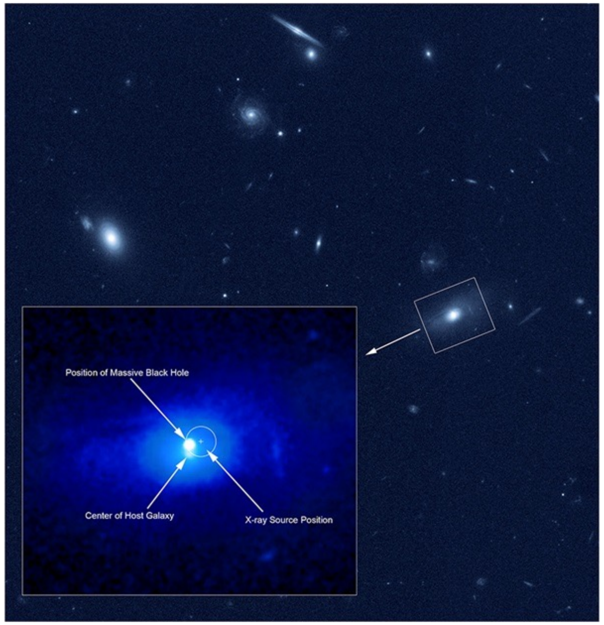
Massive Black Hole Kicks

⇒ Schwartzman talk

- Merging massive black holes (~10^{4-9} $M_{\odot}$) can undergo large gravitational wave recoil.
- Dynamical interactions can slingshot BHs out of galactic nuclei.
- Magnitude : ~1000s km/s

- Current searches ongoing:
  - spectroscopic dual AGN candidates (e.g. dual/asymmetric emission lines).
  - Radio VLBI searches for dual AGN candidates.
  - All remain controversial (need to distinguish galaxy mergers from kicked SMBHs)

- ***Theia: Identify many dual/offset AGN (~pc separation) within the brightest nearby AGN, if they exist.***



Kim et al. (2017)

A case for X-ray Astrometry?

- X-rays are arguably the best probe of ongoing accretion.

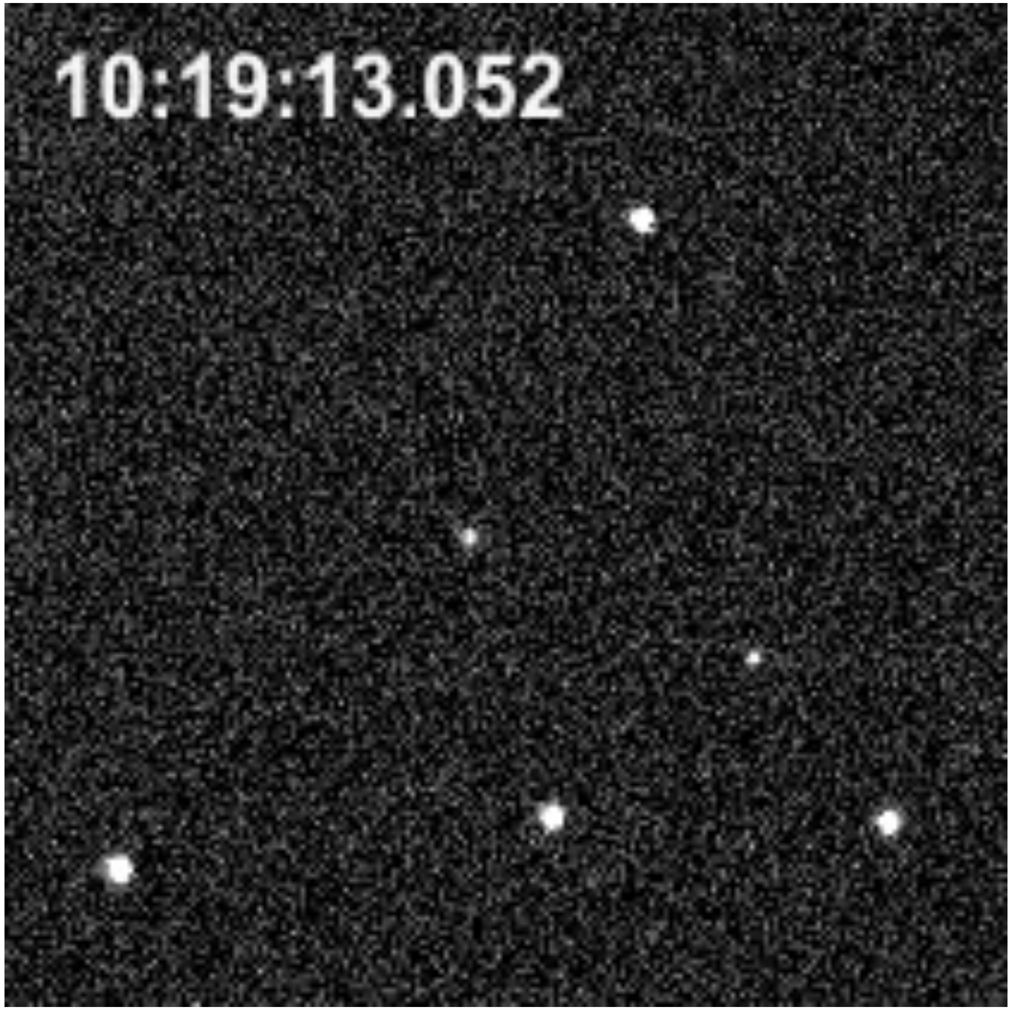
- But… X-ray telescopes have poor localisation precision.
  - Typical PSF >~ tens of arcsec.
  - Best so far ~0.5 arcsec (Chandra).
  - cf. *Gaia* (1.45 x 0.5 m) nominal best PSF ~0.086 arcsec (best localisation precision ~ microarcsec).

- Challenge: X-ray polishing technology cannot deliver diffraction-limited precision.

- Solution: Use precision *timing* (occultations) instead, as a proxy for spatial precision.

Using Occultations for precision astrometry

- Instant of (de)occultation determines source location.
- Astrometric precision then depends upon timing precision.
- Old technique. Need to boost collecting area to reach precision to ~10 mas (1-d).
- Also need a highly stable reference frame => Challenging from orbit.



(Gandhi 2024, Mereghetti et al. 1990)

“High Throughput X-ray Telescope on a Lunar Base”

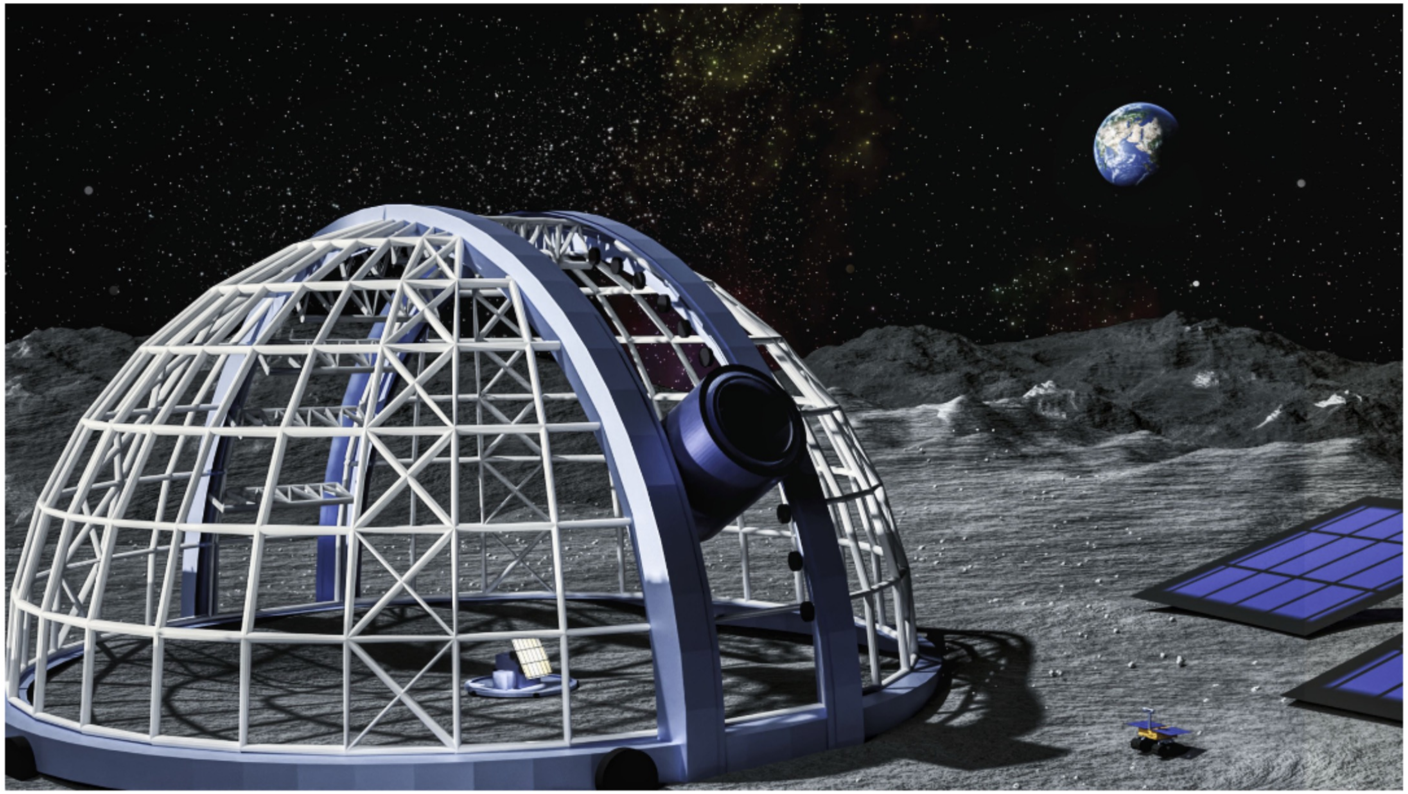
Paul Gorenstein, 1990, in “Astrophysics from the Moon”, AIP

Speculative 21st Century High Throughput (>100 m^2) Lunar X-ray Observatory

Using Occultations for precision astrometry

- Plenty of (repeated) occultations will be possible from the lunar surface.
- X-ray (and IR) occultations enable astrometry of optically obscured sources in the Galactic plane.
- Can develop novel custom occulters and easily deploy them on the lunar surface.

(Gandhi 2024)



Challenges

- Lunar Dust
  - Ionised micron-sized abrasive particles.
  - Will need care, screens, regular cleaning.

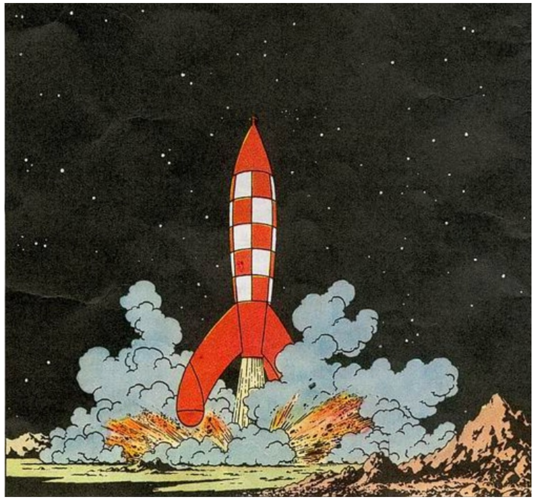
- Seismic activity
  - Weak tidal quakes fairly common.
  - Strong quakes/Meteroid impacts rarer.
  - Need anti-seismic isolation, suspension, realignm

- Thermal gradients
  - *T*~250 K between day and night.
  - 'Peaks of eternal light' much more s
  - Need thermal insulation, microc adioisotope heaters (night).

- Background
  - Sky background simil bit.
  - But stronger parti e sun-lit background.

- Human activity
  - Competition with c wavelengths.
  - Dust from launch/la ding sites.

But none of these are insurmountable.



Hergé