Interstellar astrometric navigation

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First European Interstellar Symposium, Luxembourg, December 2024

Image source: Samuel Walters (1857)
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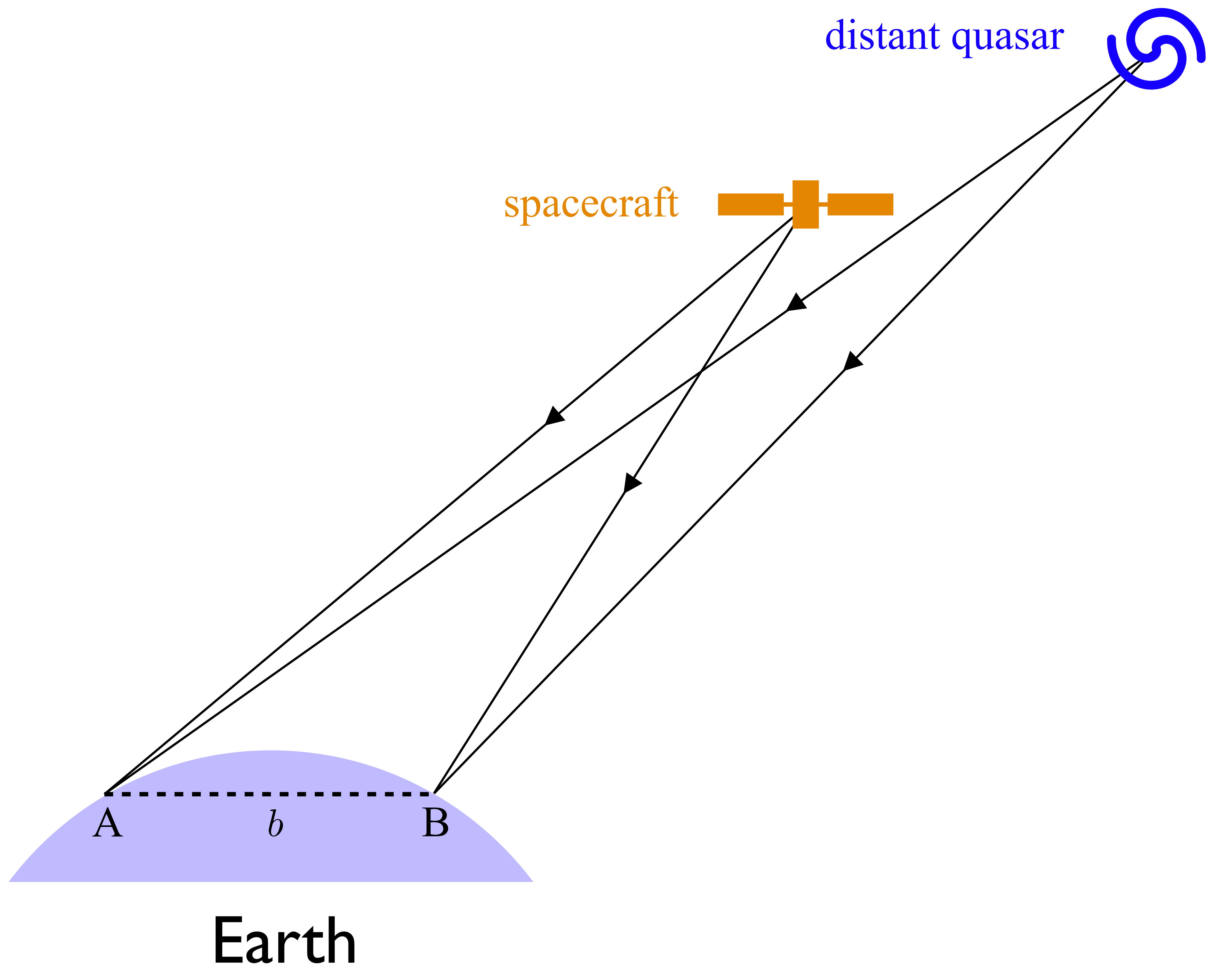
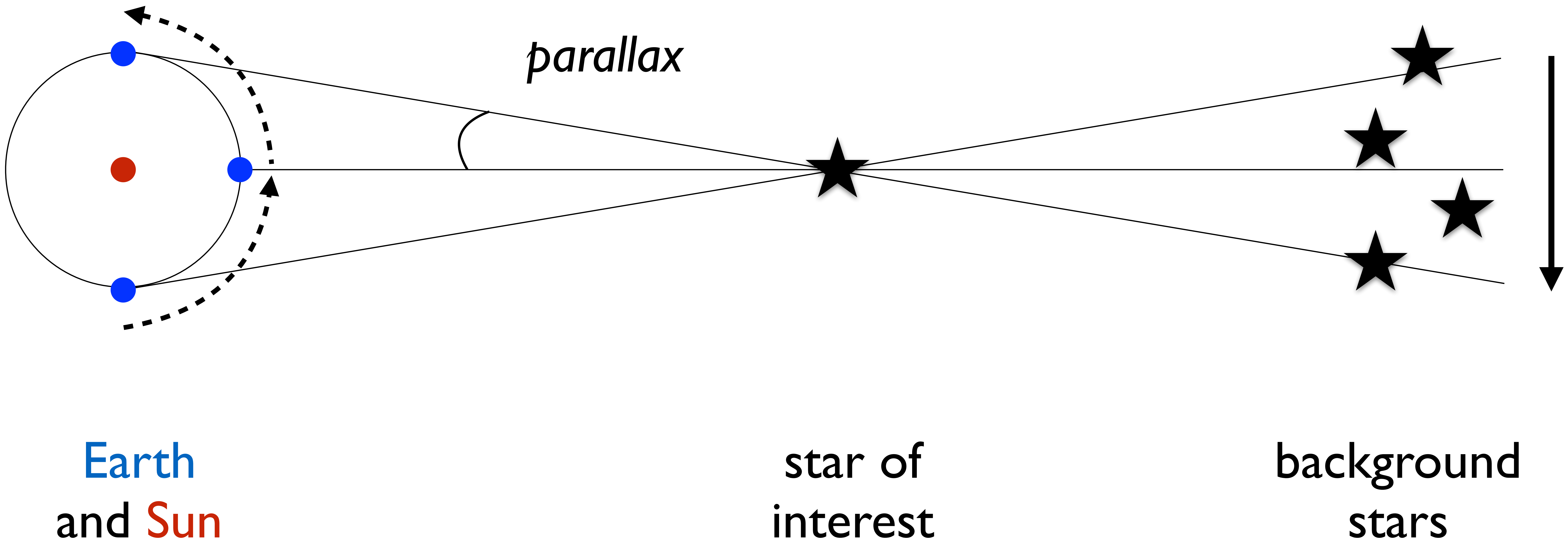
Navigation requirements

- On-board position and velocity required for
  - determining and correcting trajectory
  - pointing instruments and the antenna
- Navigation in the solar system
  - inertial: accelerometers, gyroscopes, clocks
  - Earth-based ranging, e.g. delta-DOR
- Interstellar navigation
  - must be entirely autonomous



Interplanetary navigation using delta-DOR

Parallax



- By definition, a star 1 pc (3.26 ly) away has a parallax of 1 arcsecond (5 µrad)
- Turn the use of parallax around: knowing distance, determine change in position

Aberration

- Also for photons: consequence of relative motion and the finite speed of light
- Position of stars change our velocity relative to them changes

Aberration

- Apparent position of any star from Earth varies over the year by ± 21” (30 km/s)

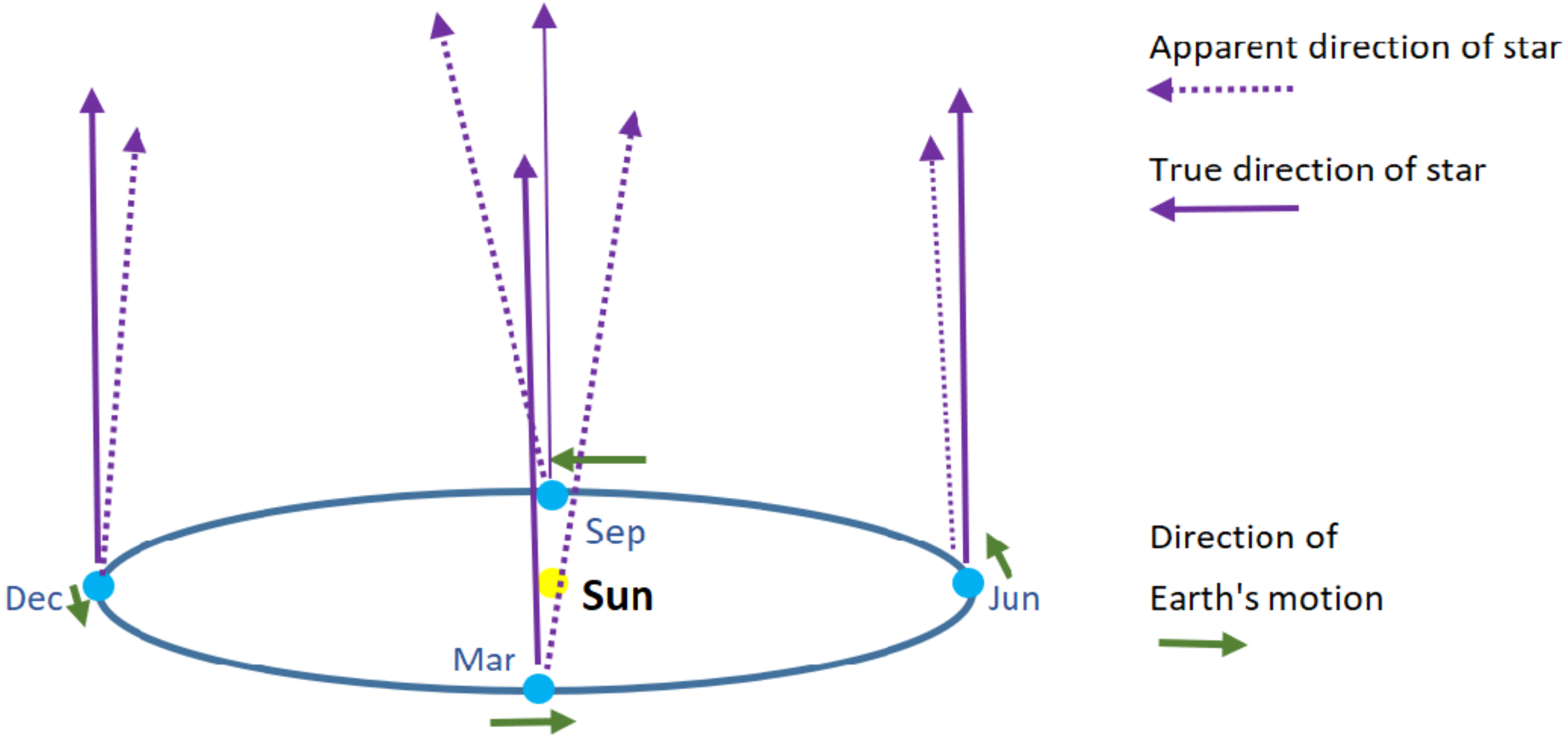
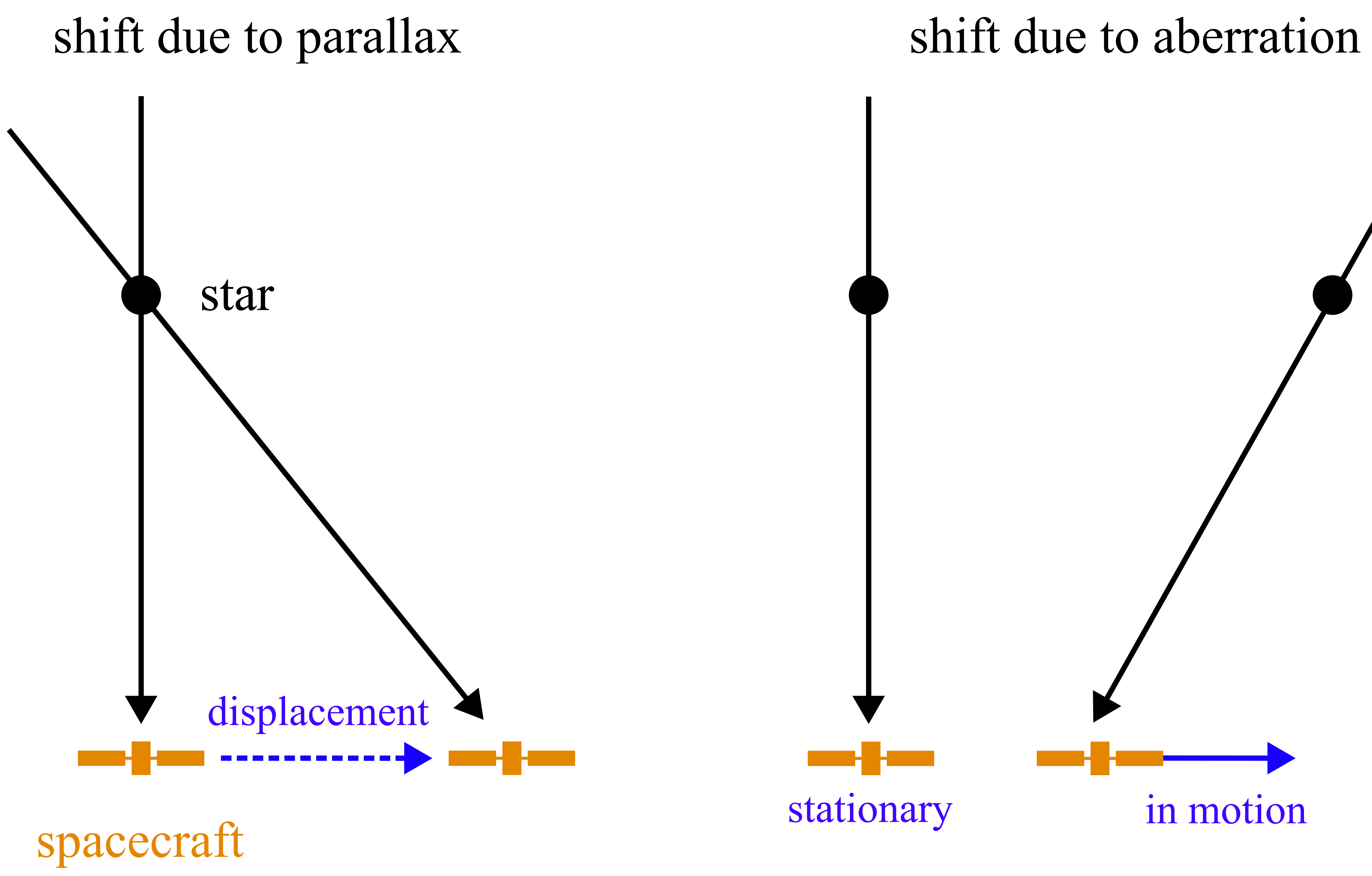


Image source: https://thesciencegeek01.files.wordpress.com

Combined parallax and aberration



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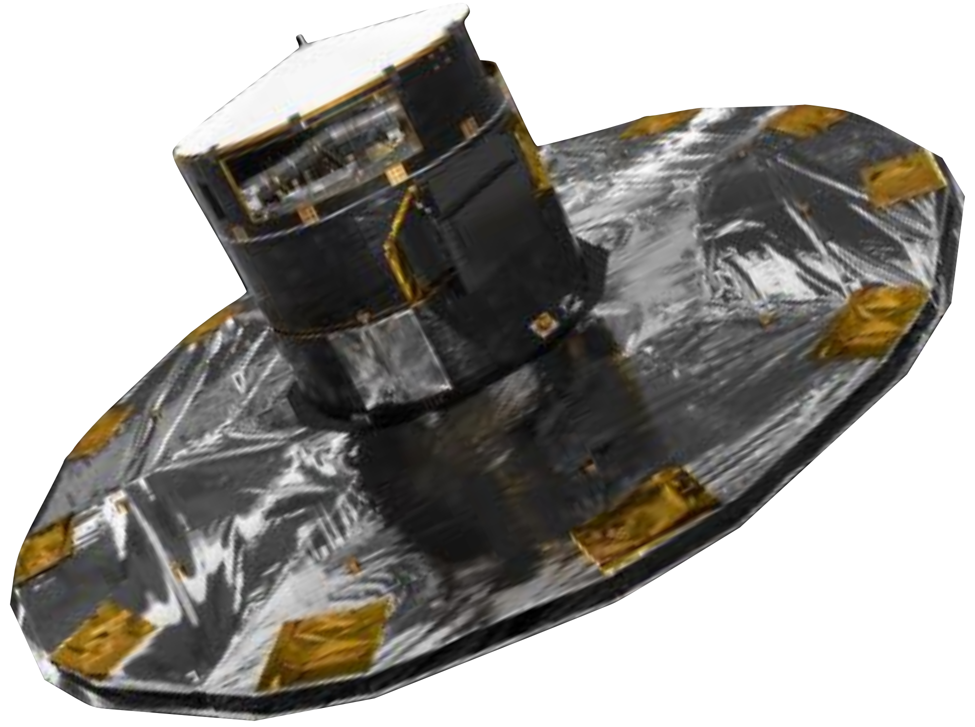
Stellar astrometric navigation

- Stars also move relative to the Sun
- To navigate, need to know 3D positions and 3D velocities of stars
- Need multiple stars to untangle effects of parallax and aberration
- ESA's Gaia Galactic survey mission



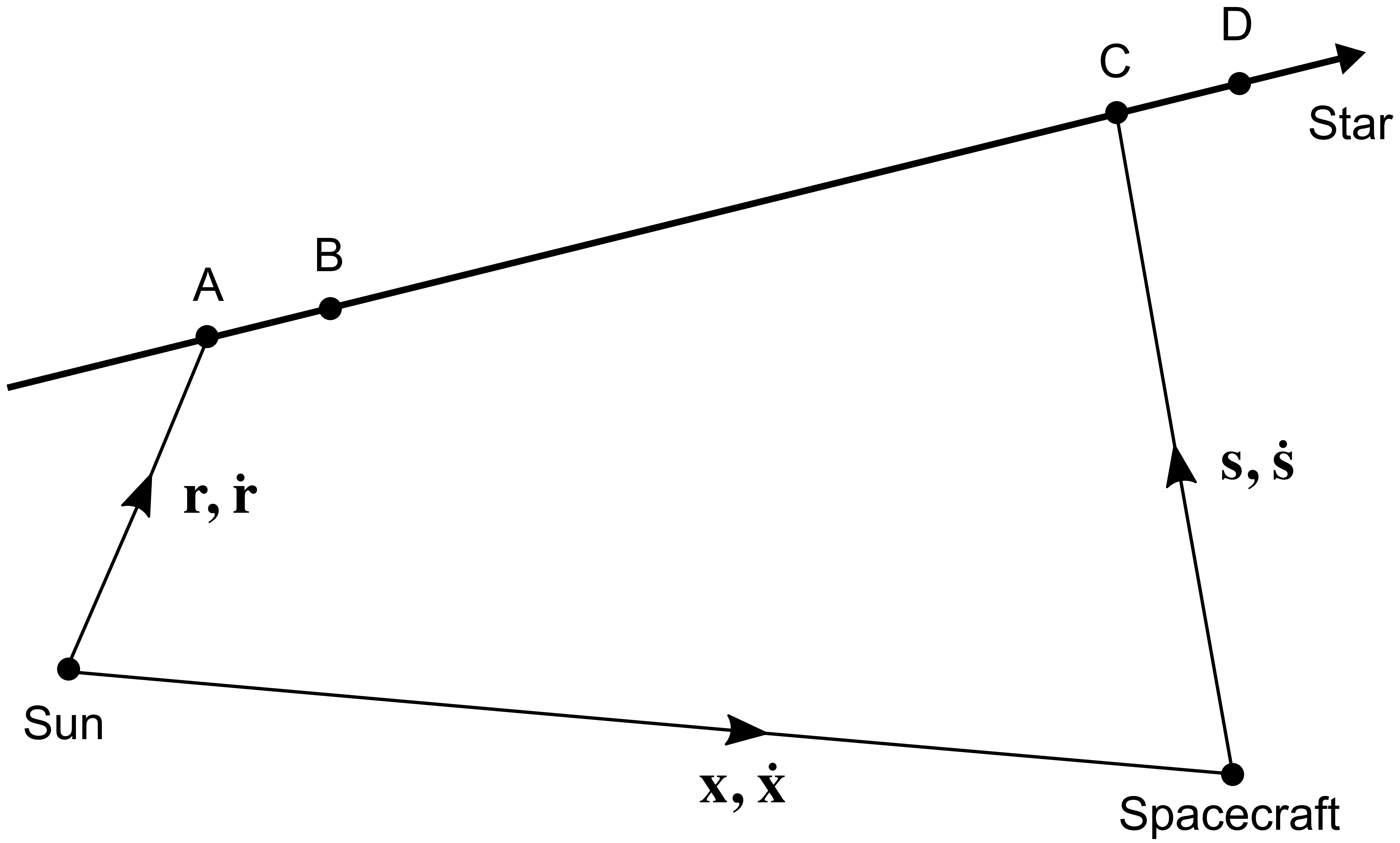
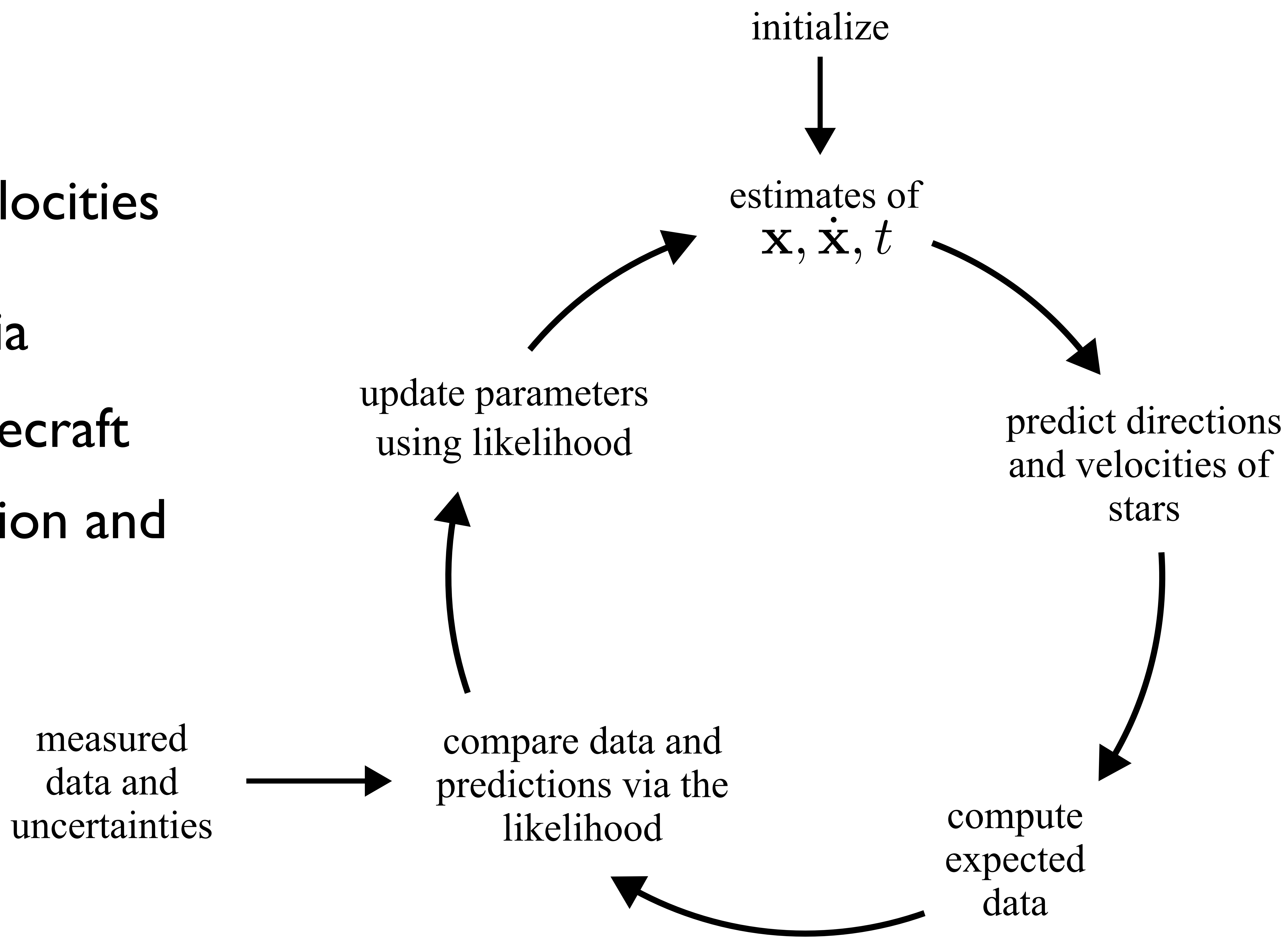


Image source (left): ESA/ATG medialab

Iterative solution

- We have
  - catalogue of 3D positions & 3D velocities of stars relative to Solar System Barycentre (SSB, ≃ Sun) - from Gaia
  - measured star positions from spacecraft
  - initial estimates of spacecraft position and velocity (x, xdot)
- Bayesian Monte Carlo



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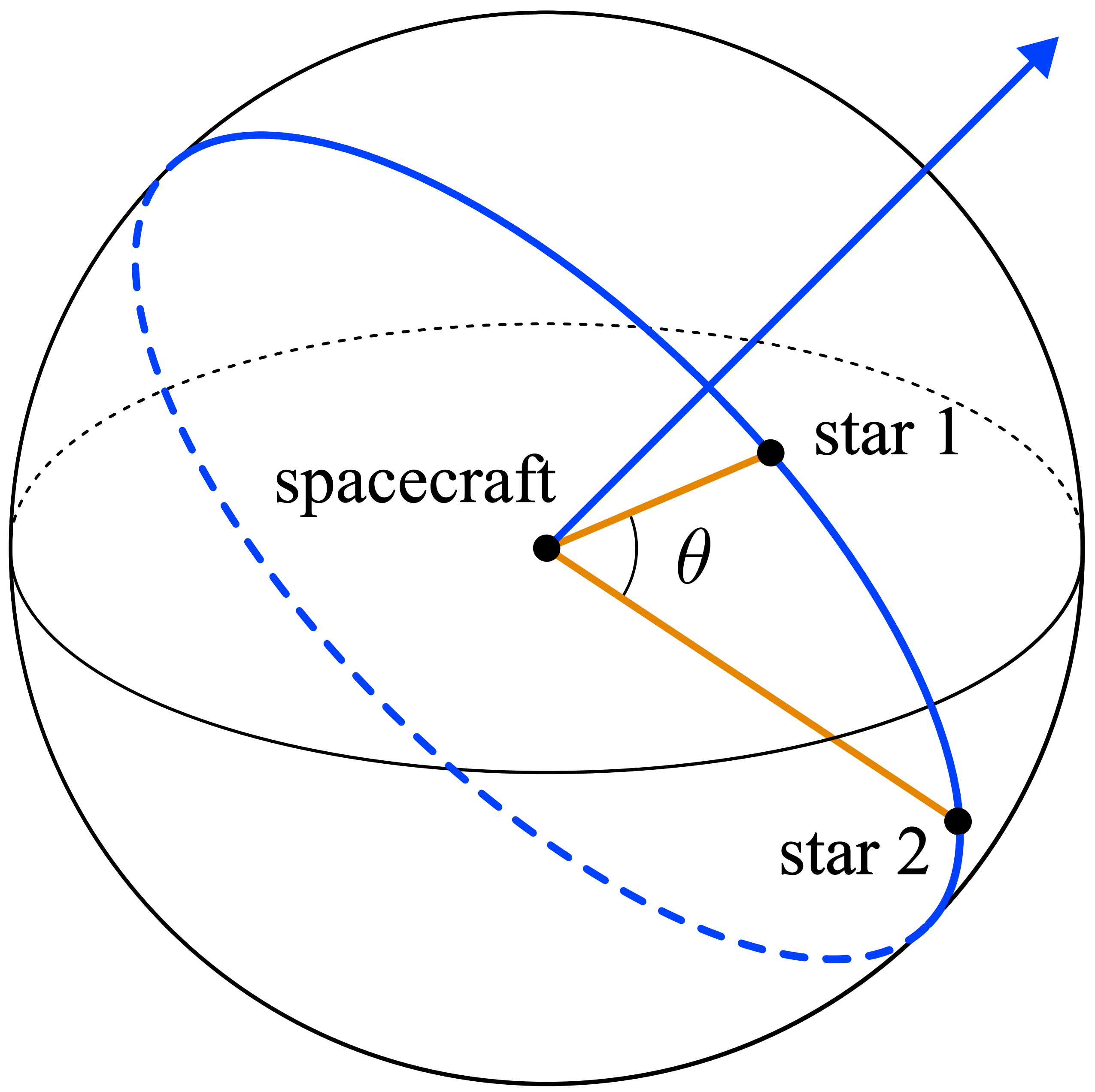
Spacecraft measurements

- Cannot measure angular coordinates (e.g. Right Ascension and Declination) accurately in a local coordinate system
- So measure angular separations (θ) between pairs of stars



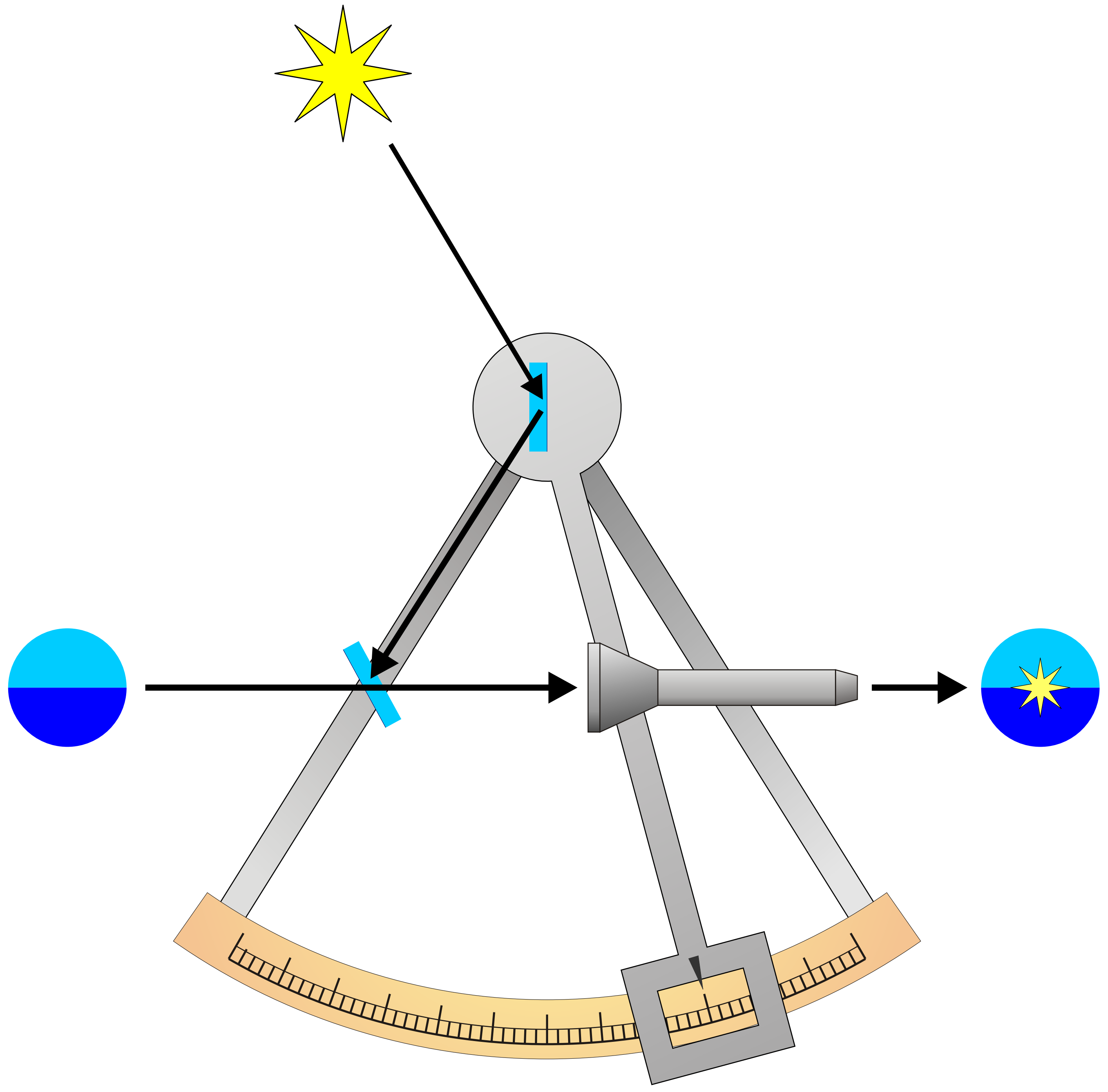
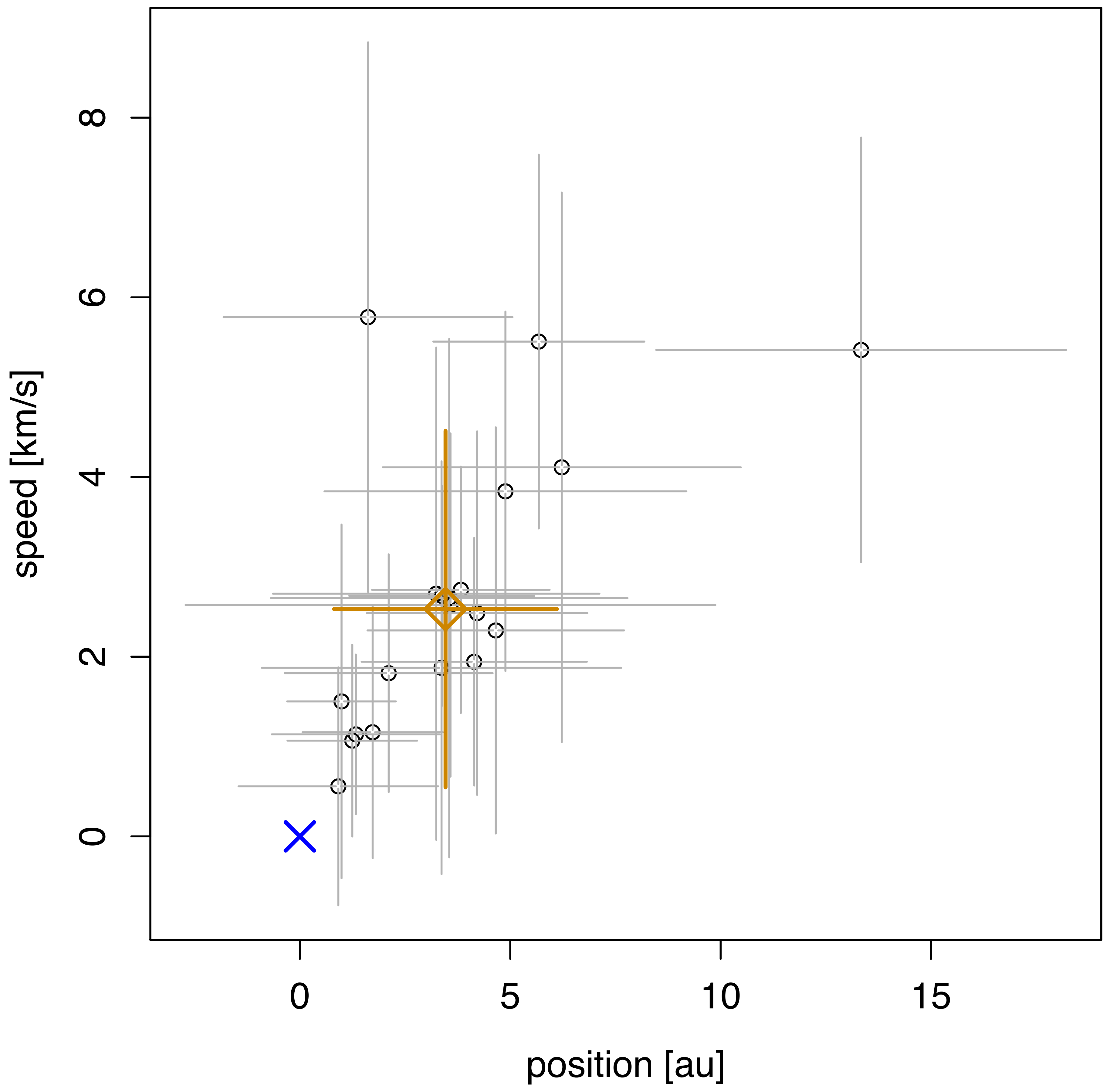


Image source (right): modified from wikimedia commons (CC0)

Tests on simulated data

- 20 (nearest) stars
- 1” angular measurement accuracy
- Spacecraft placed/directed at random w.r.t. Sun
  - position: 0.1 to 10 ly away
  - velocity: 0.0 to 0.5 c
- Run iterative solution
- Evaluate for multiple setups

Inferred velocity and position accuracy



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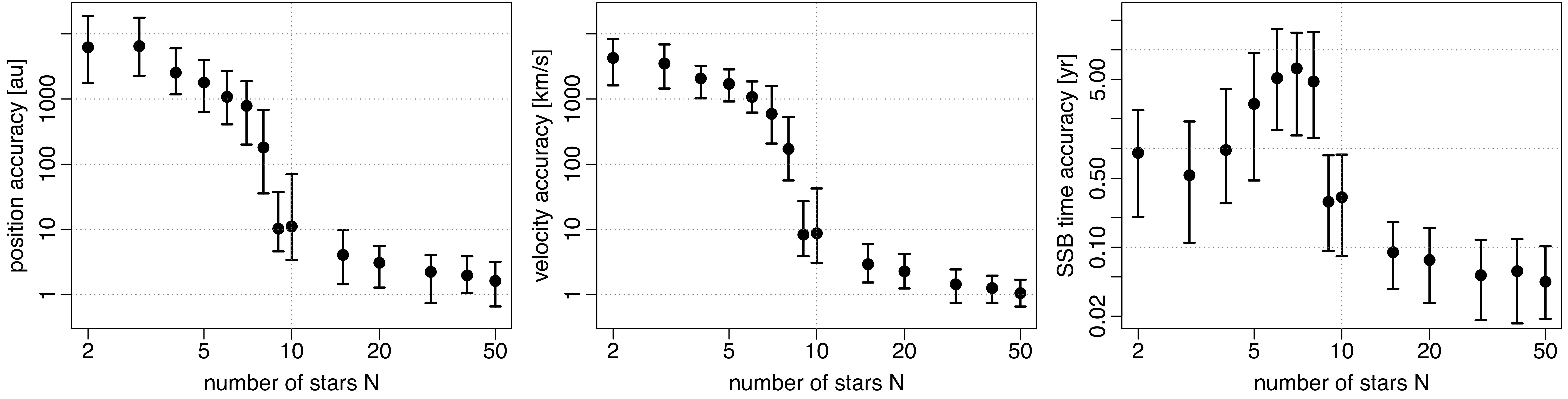
Performance: varying number of stars (1” measurements)



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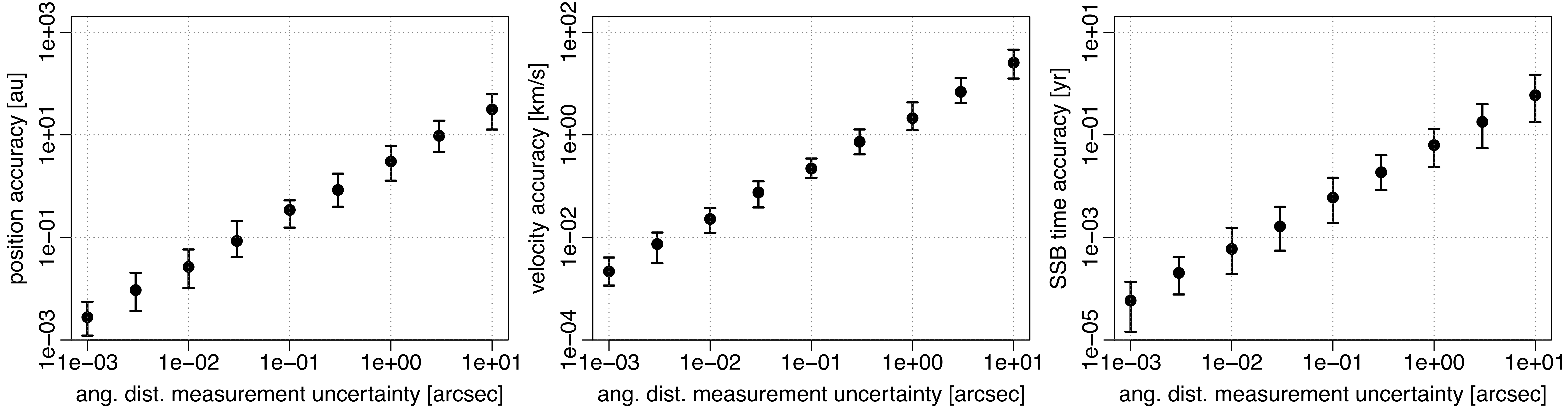
Performance: varying measurement uncertainties (20 stars)

With 20 stars measured at 1mas accuracy
can determine spacecraft position to 0.003 au, velocity to 2 m/s



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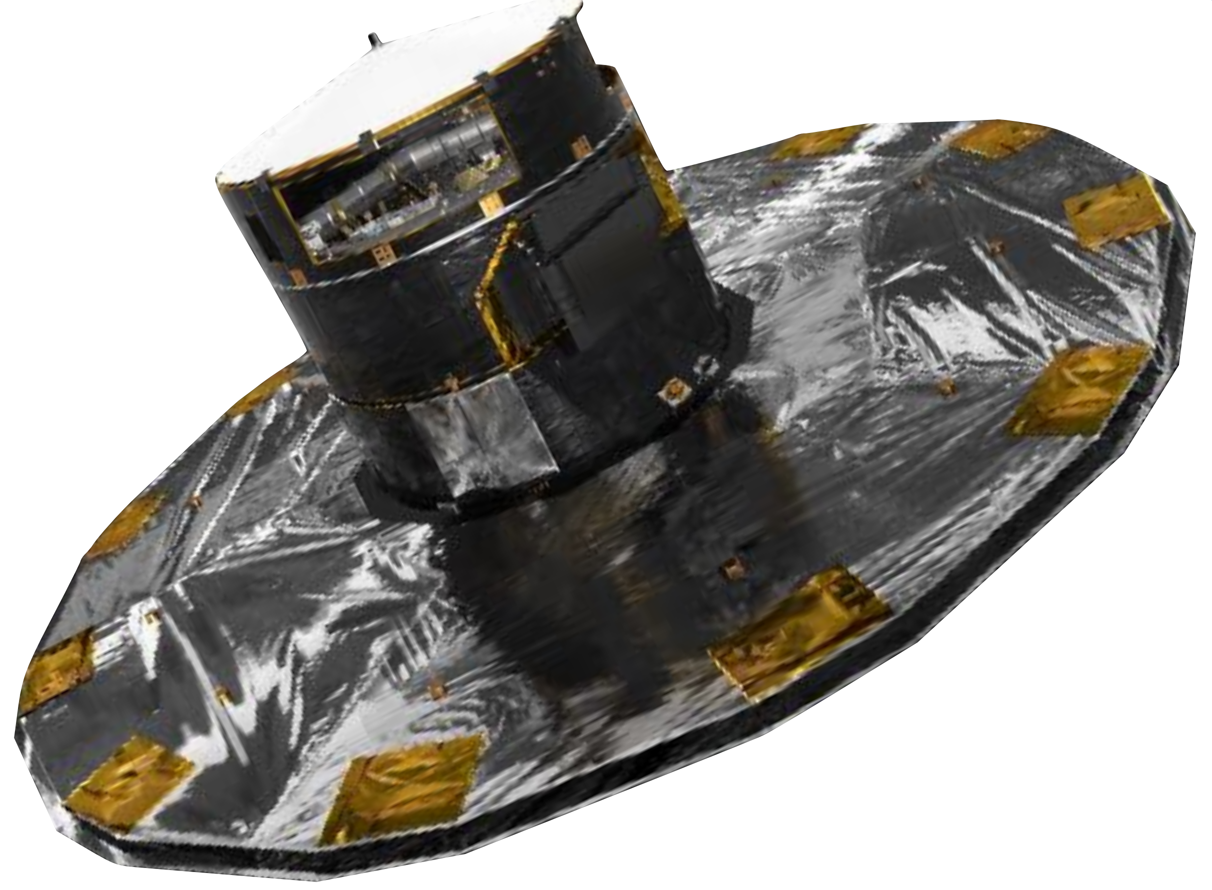
Context

- Principle similar to Gaia, but in reverse
- Do not need to know SSB time
- Can use radial velocities instead (or as well)
  - need ~0.1 km/s Doppler measurement accuracy to determine position to 1-2 au
- Pulsar navigation gives more accurate positions, if you have a very good initialization
  - but for interstellar also need pulsar parallaxes



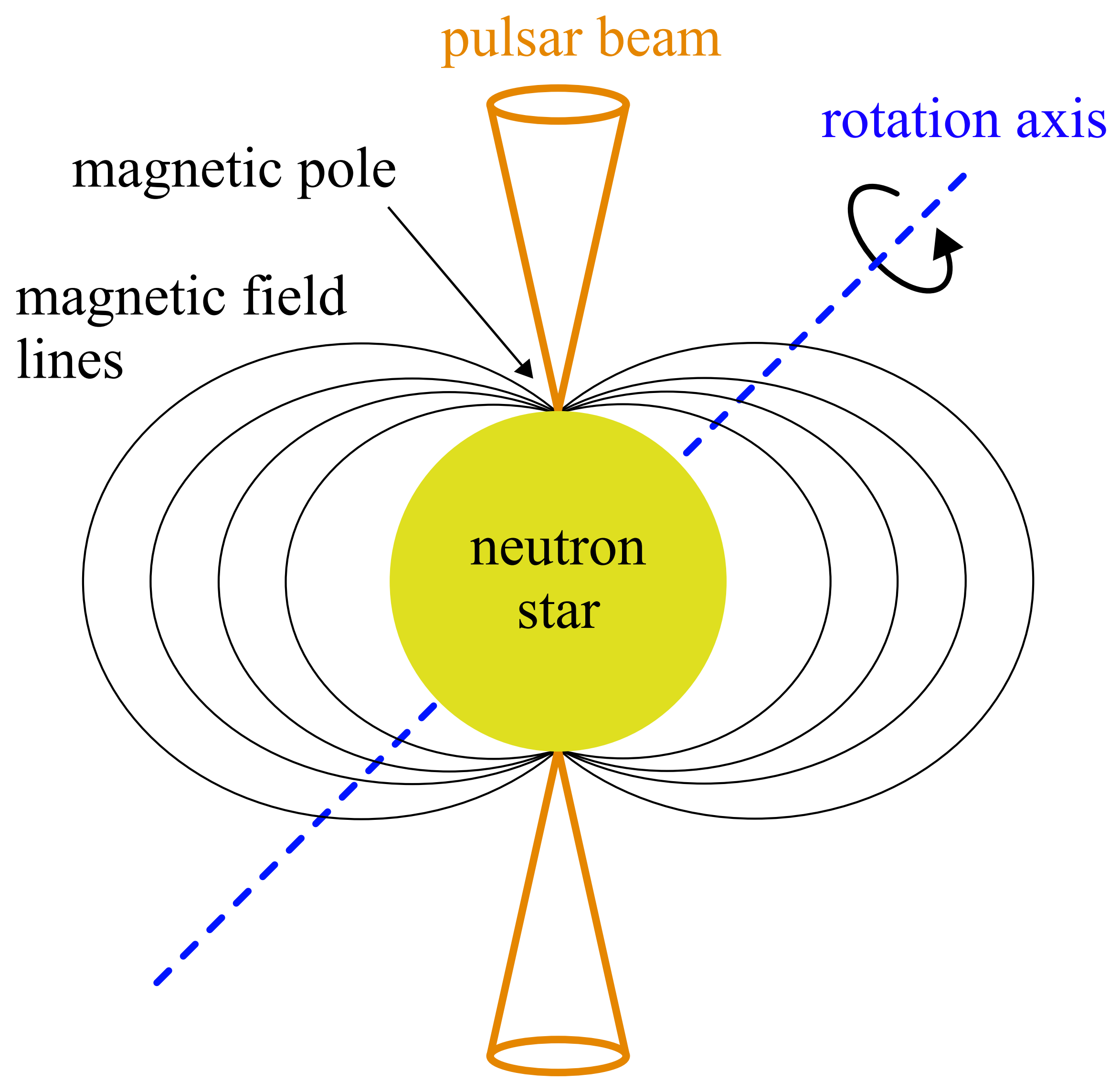


Image source (top): ESA/ATG medialab

Conclusions

- Principle
  - Exploit parallax effect and aberration to determine spacecraft position and velocity
- Measurements required
  - Only angular separations between pairs of stars (local, instantaneous)
- Navigation accuracy
  - Using 20 stars with 1mas accuracy, can locate spacecraft to 0.003 au, 2 m/s
- Works at large distances (100s of ly) from Sun and at relativistic velocities
- For more details see Bailer-Jones 2021 (PASP 133, 074502)