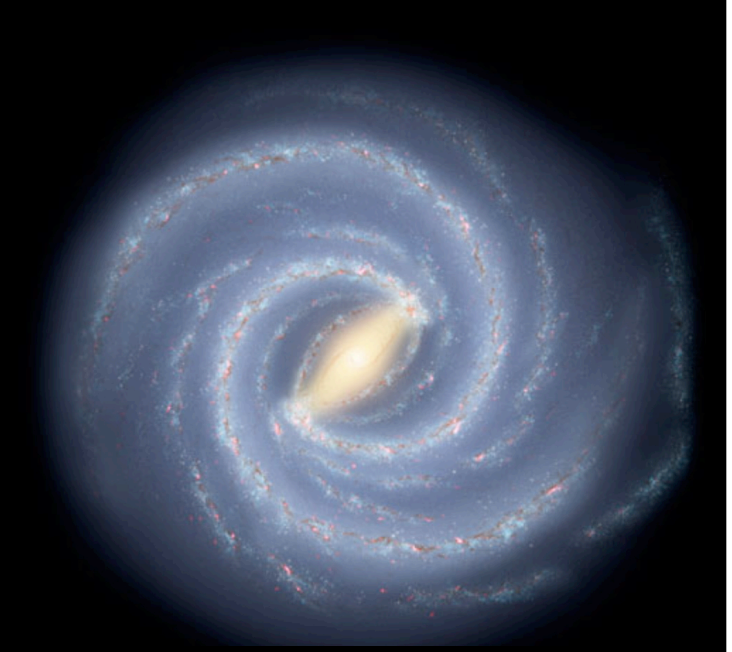


Depth perception

Trigonometric VLBI pulsar parallaxes for fun and profit

Adam Deller

April 20, 2015

ASTRON

Outline

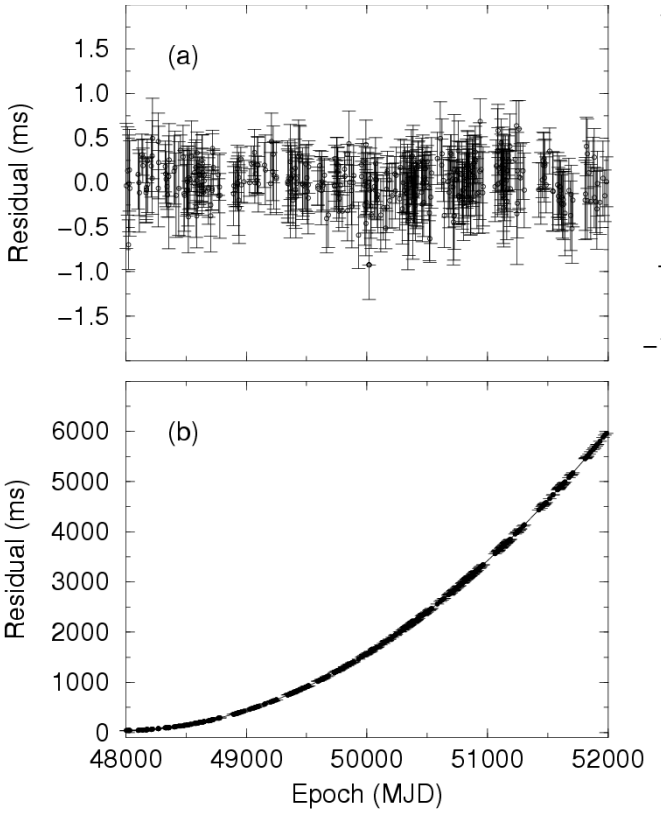
- Radio pulsars and why distance matters
- VLBI astrometry as applied to pulsars
- A short science sampler
  - PSR J0437-4715
  - PSR J1023+0038
  - PSR J2222-0137
  - PSR J0218+4232
  - Parallax ensembles
- The future of VLBI astrometry
  - How to keep obeying the “law” of ever-improving parallax accuracy

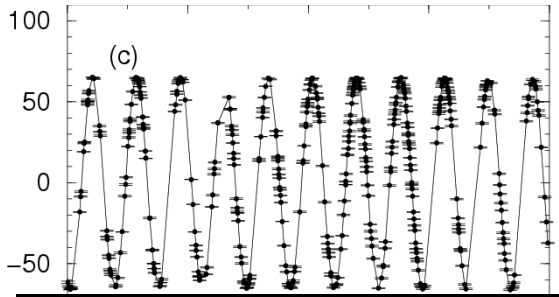
Radio pulsars and astrometry

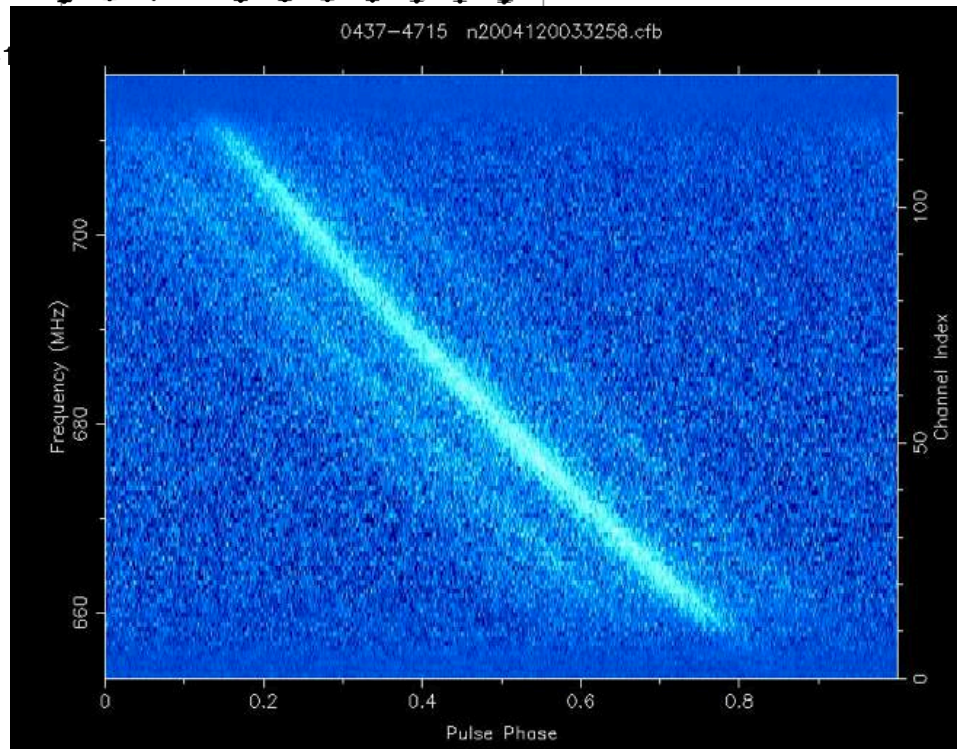
- Pulsars are highly magnetised, rapidly rotating neutron stars that emit from radio to X-ray/gamma-ray
- Flywheel-stabilised clock ticks can be used trace (changes in) propagation
- Offer observational probes of:
  - Gravitational physics
  - Nuclear physics
  - Stellar evolution

ASTRON

Pulsar timing





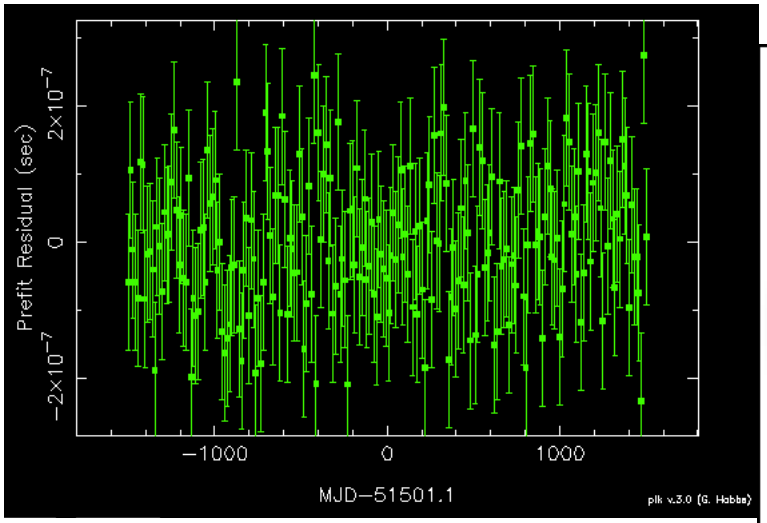


Lorimer & Kramer, 2005

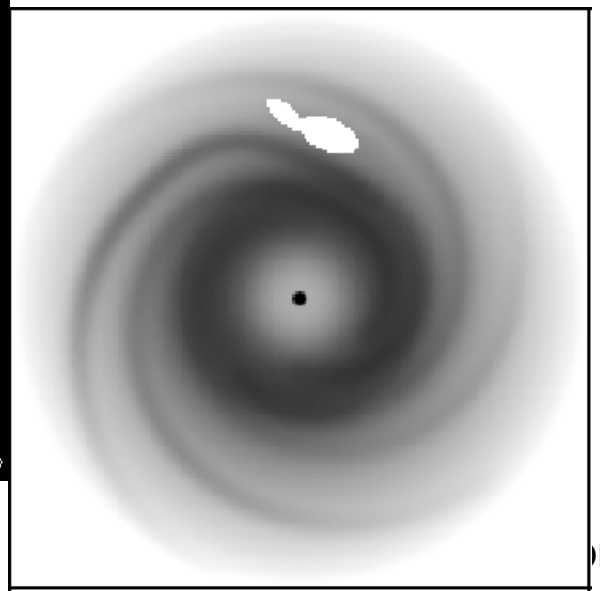
The importance of distance

- Luminosity (calibration)
- Timing (2nd order effects & degeneracies)
- Electron density (Galactic models)

NASA



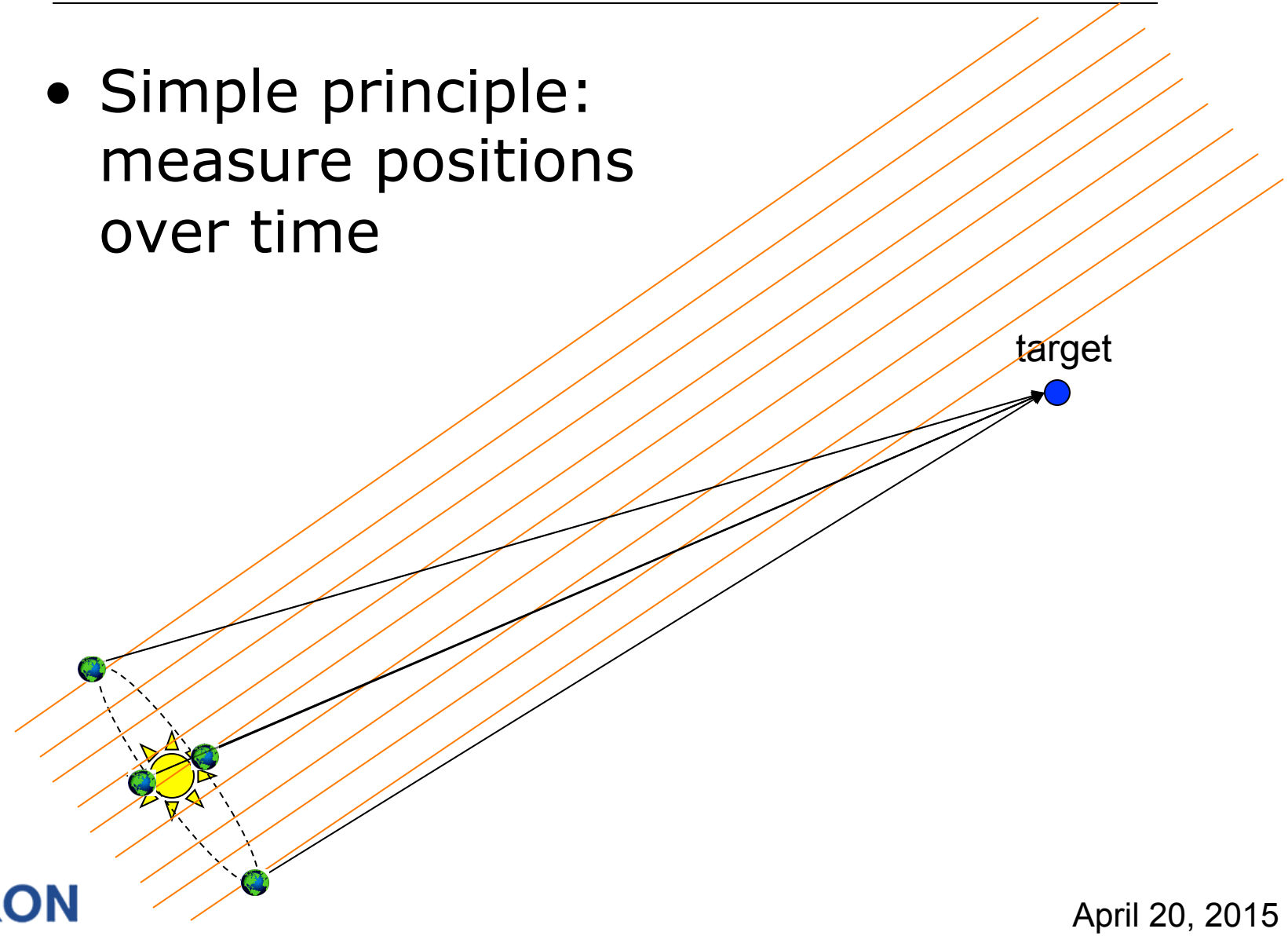
ATNF



NE2001 (Cordes & Lazio)

Distance/velocity via astrometry

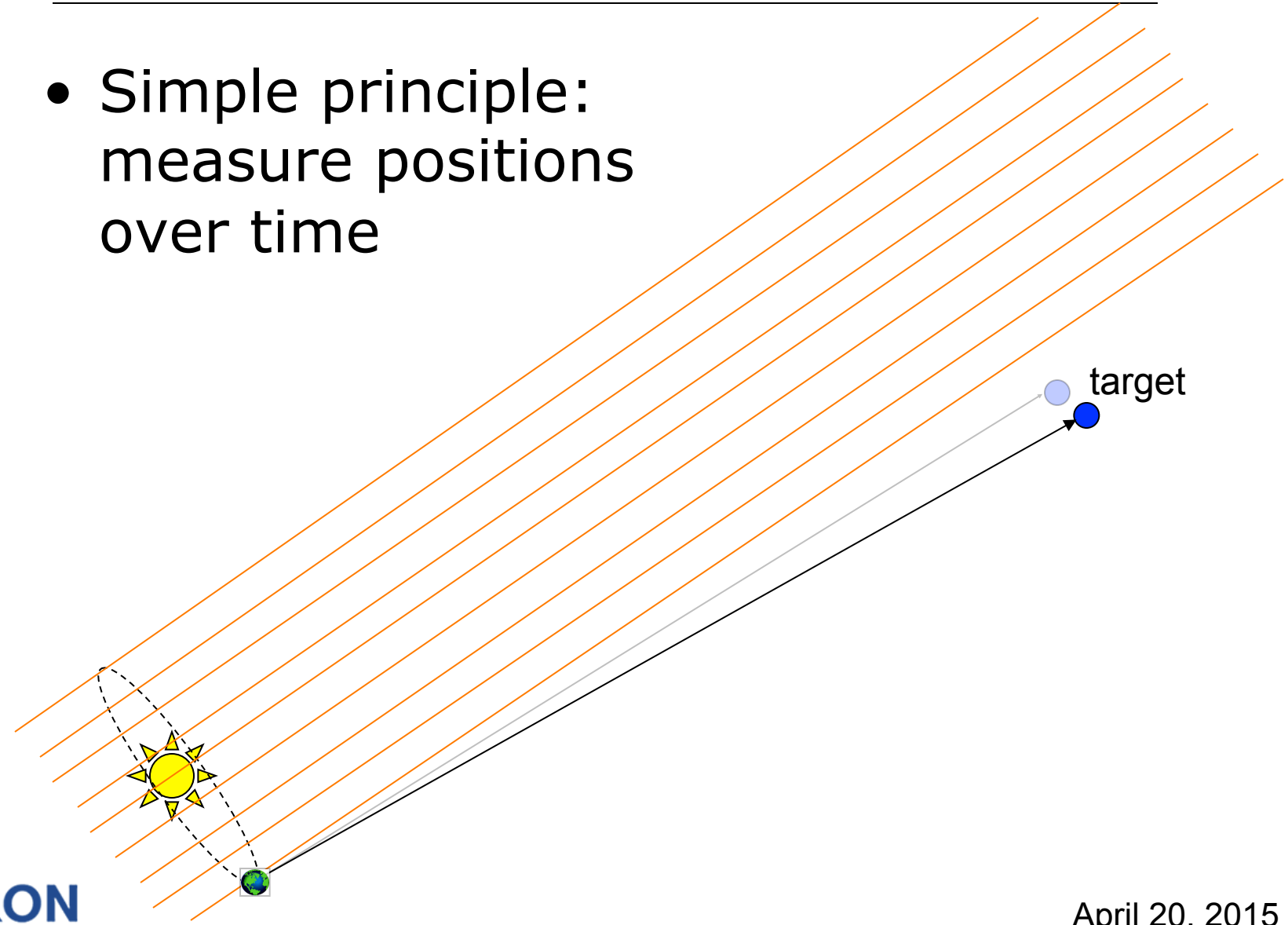
- Simple principle: measure positions over time



ASTRON

Distance/velocity via astrometry

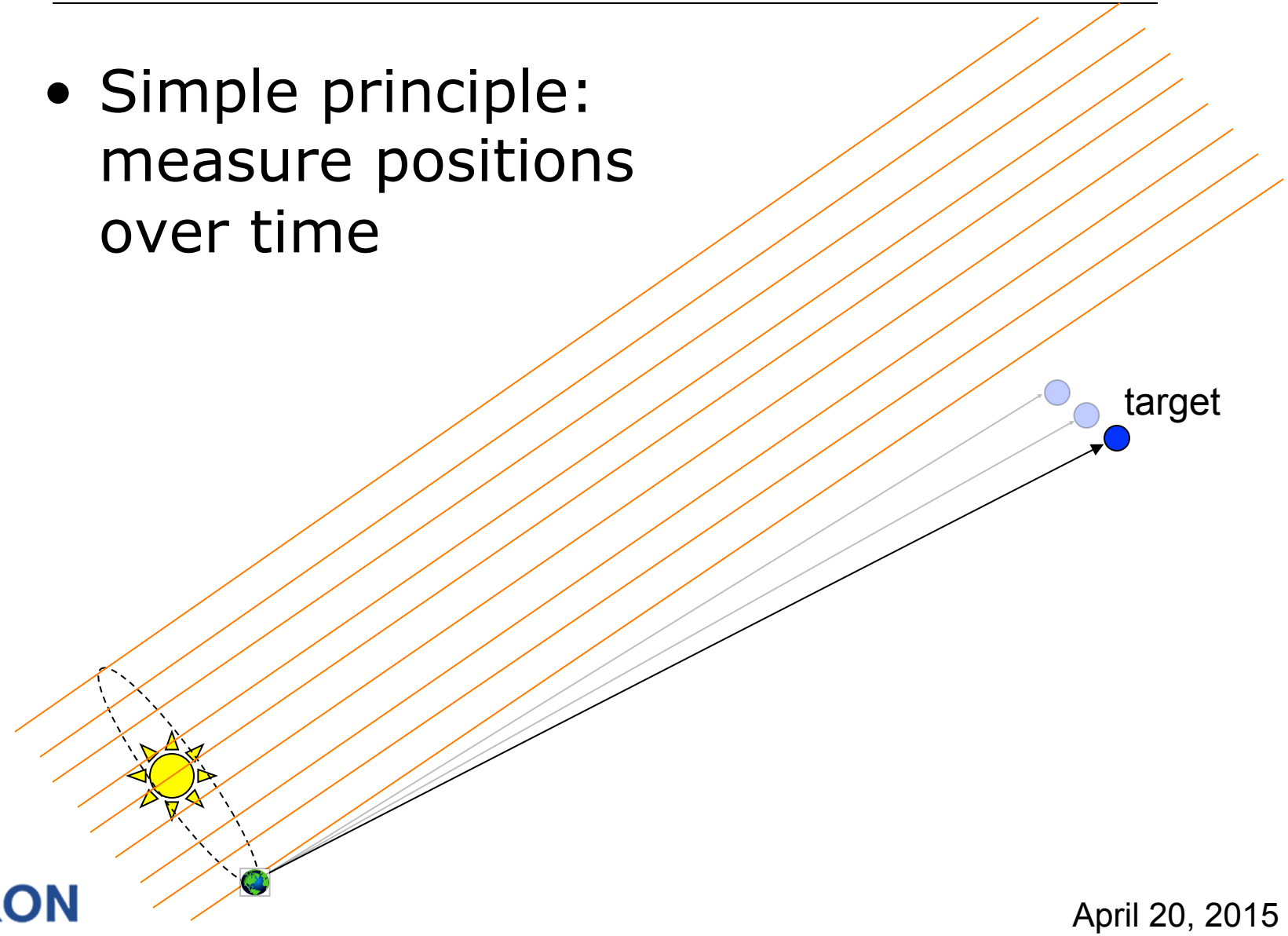
- Simple principle: measure positions over time



ASTRON

Distance/velocity via astrometry

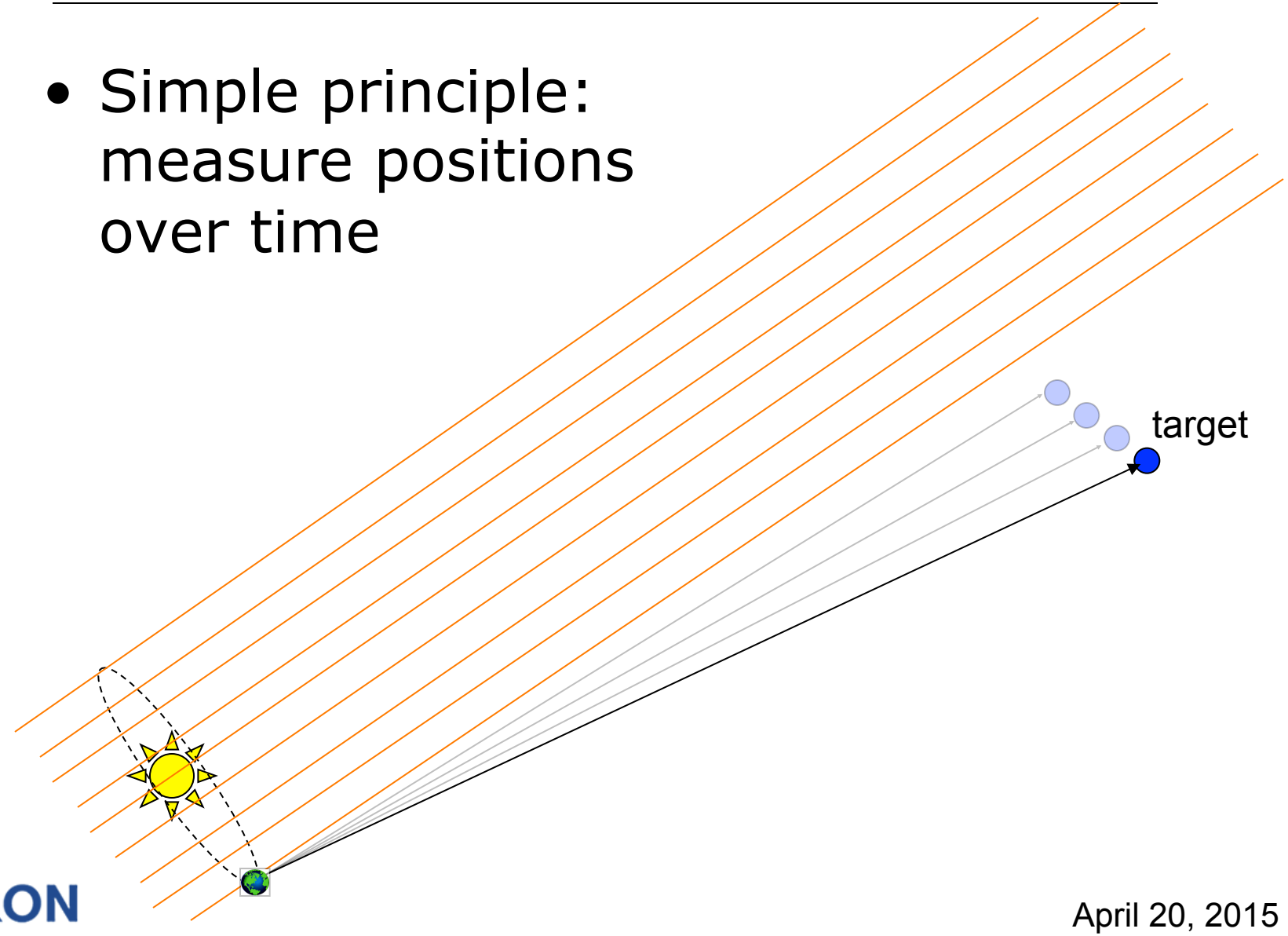
- Simple principle: measure positions over time



ASTRON

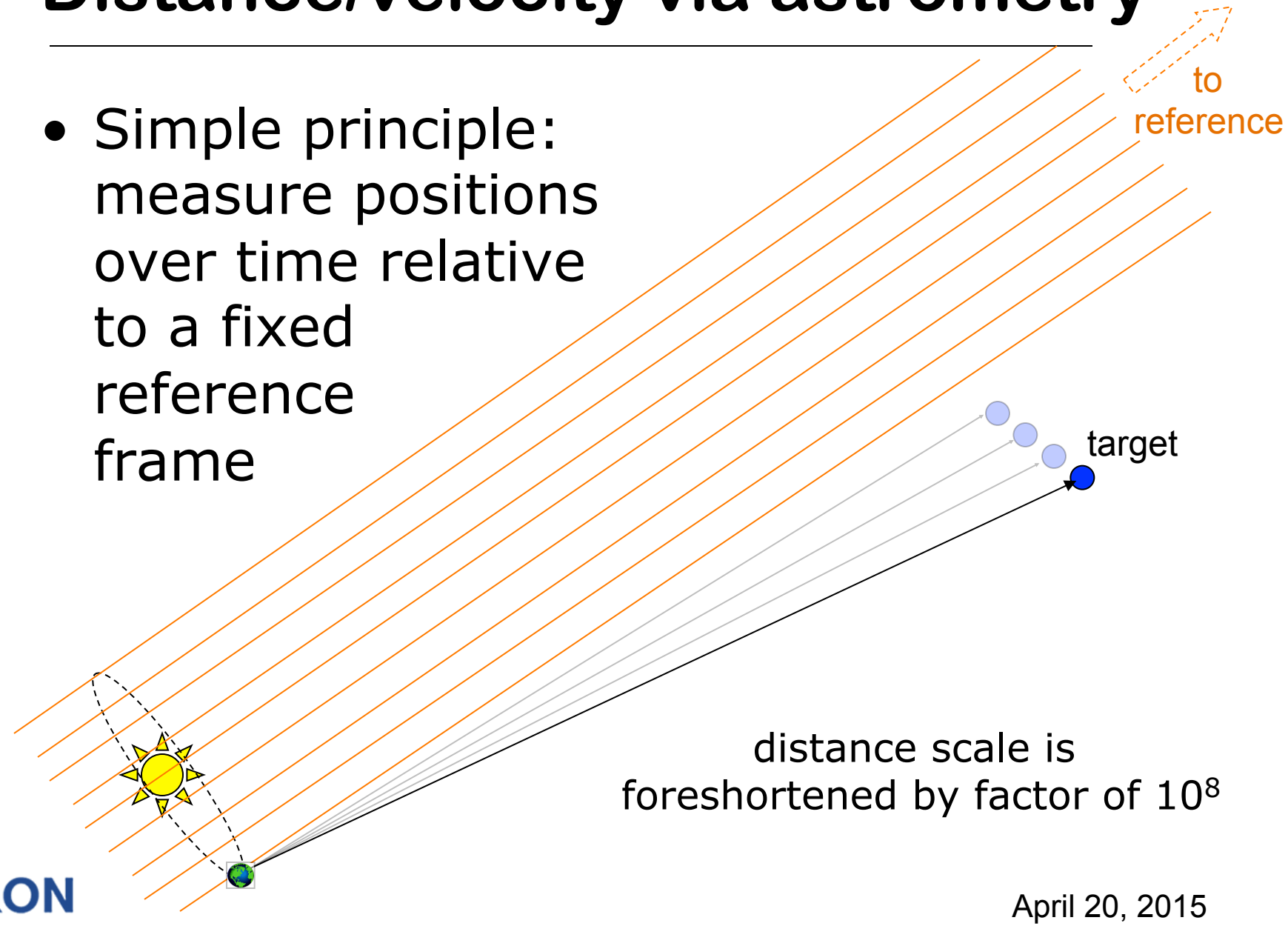
Distance/velocity via astrometry

- Simple principle: measure positions over time



Distance/velocity via astrometry

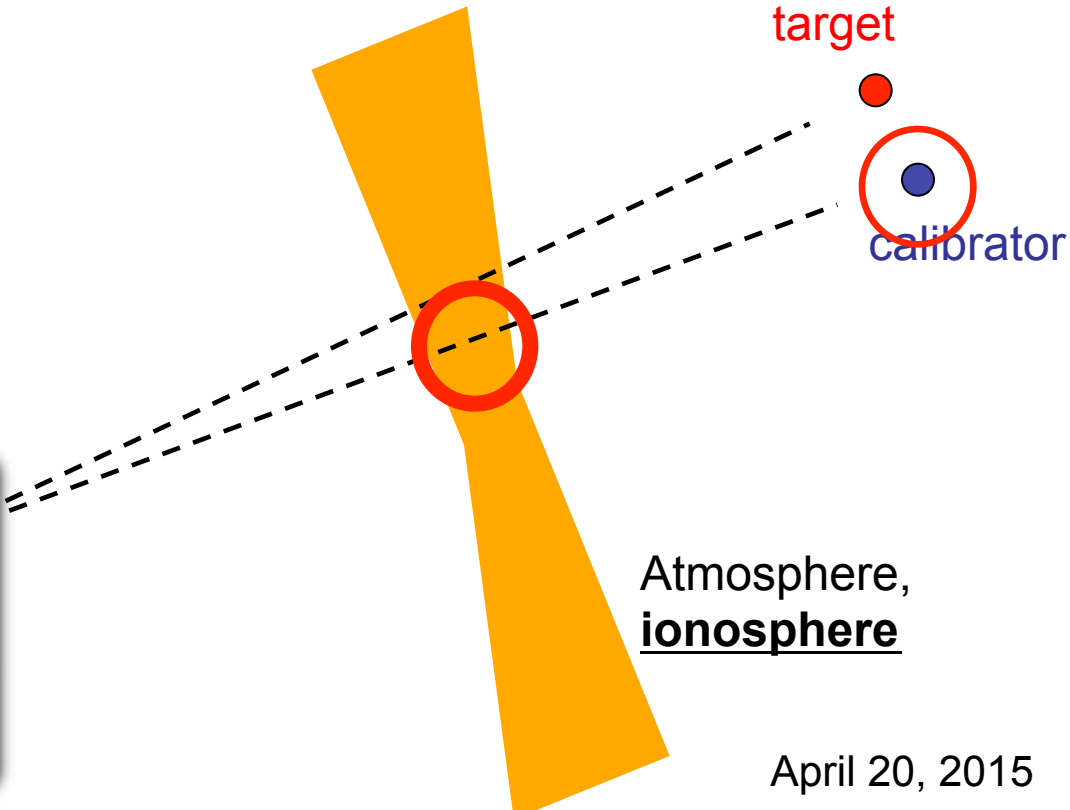
- Simple principle: measure positions over time relative to a fixed reference frame



distance scale is
foreshortened by factor of 10^8

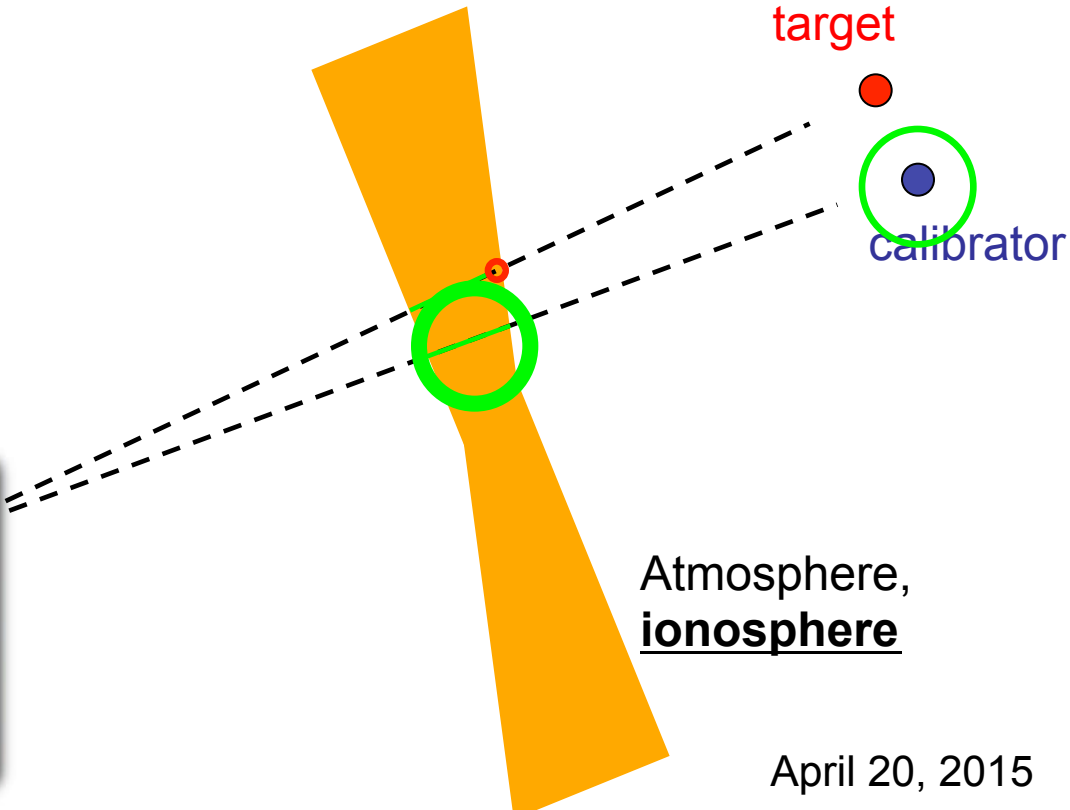
Differential astrometry

- **Calibrate**: nearby astronomical source



Differential astrometry

- **Calibrate**: nearby astronomical source
- Solve for and remove sum of all delays; residual will be of order sin(separation)

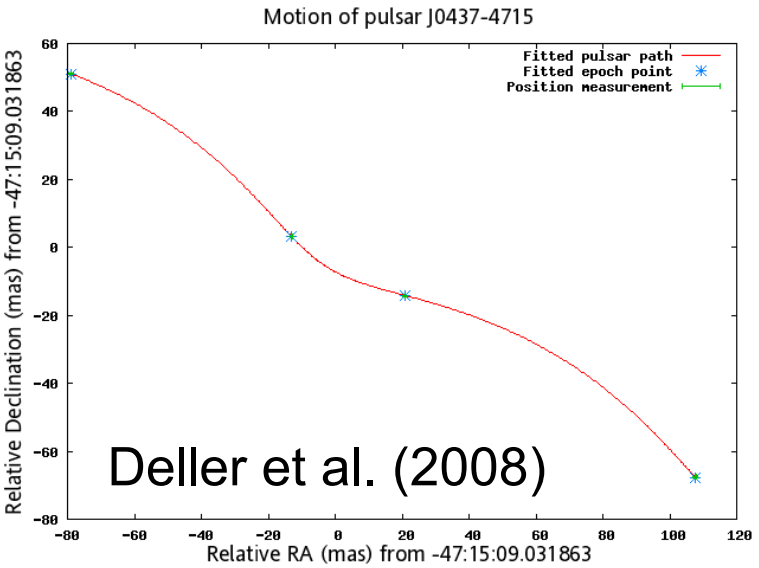


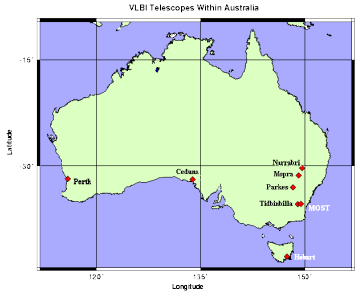
What is needed

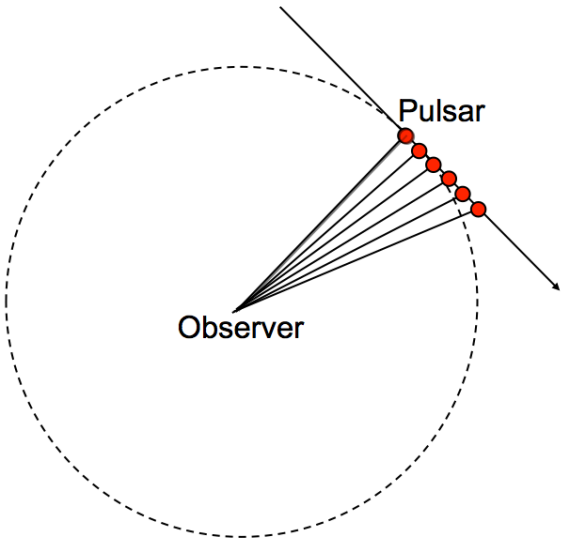
- Goal is 10σ parallax at 10 kpc: 10 μas
  - Per observation: 30 μas = 15 x 10^{-11} radian
  - Differential delay ~ **3 picosecond** on a 5000 km baseline (path length 1 mm)
- Observing at 1.6 GHz due to steep pulsar spectrum
  - Typical line-of-sight unmodeled ionospheric path delay might be 3 metres
  - Need a calibrator source within 3 arcmin!
  - Nearest known calibrator is typically ~2°
  - Need to identify "in-beam" calibrators

Science sampler 1: J0437-4715

- Nearest, brightest millisecond pulsar
- Pulsar timing: $\dot{P}_{orb}$
  - Dominated by "Shklovskii" effect
- Agreement between VLBI and timing distances gives strict limit on line-of-sight acceleration



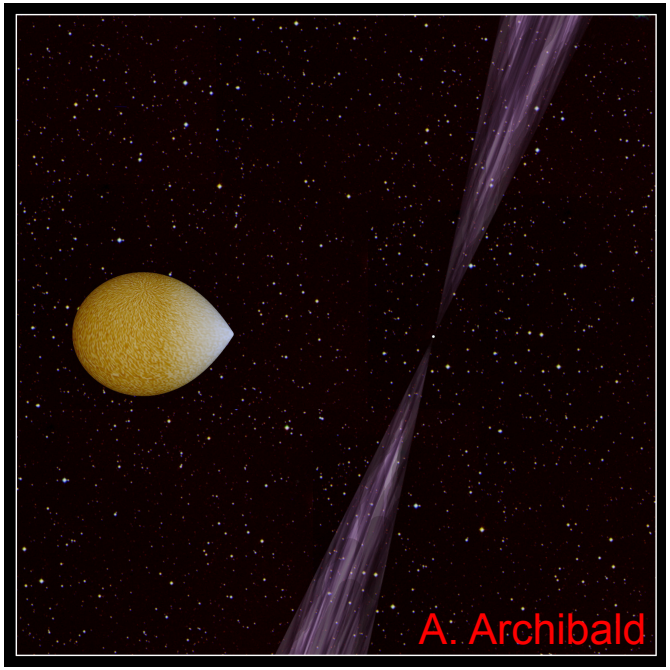


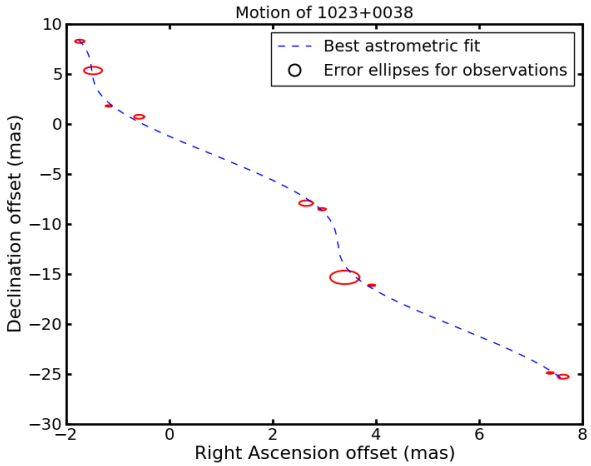


ASTRON

Science sampler 2: J1023+0038

- The first "transitional millisecond pulsar"
  - Previous LMXB state inferred after discovery as radio pulsar
- VLBA distance of 1370 ± 40 pc plus optical modeling gives inclination, pulsar mass
  - 1.71 ± 0.16 $M_{\odot}$ (Deller et al. 2012)

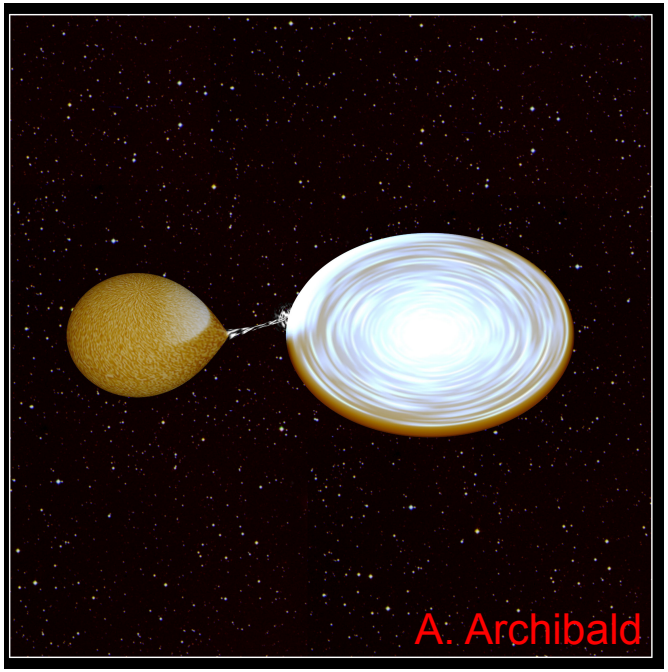




ASTRON

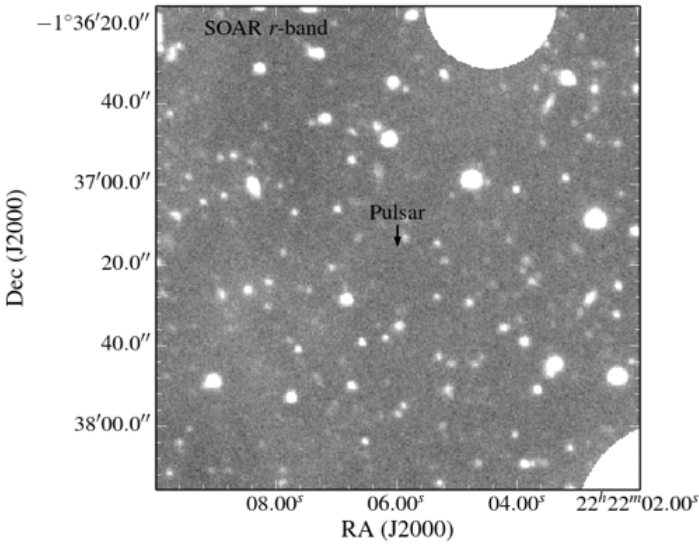
Science sampler 2: J1023+0038

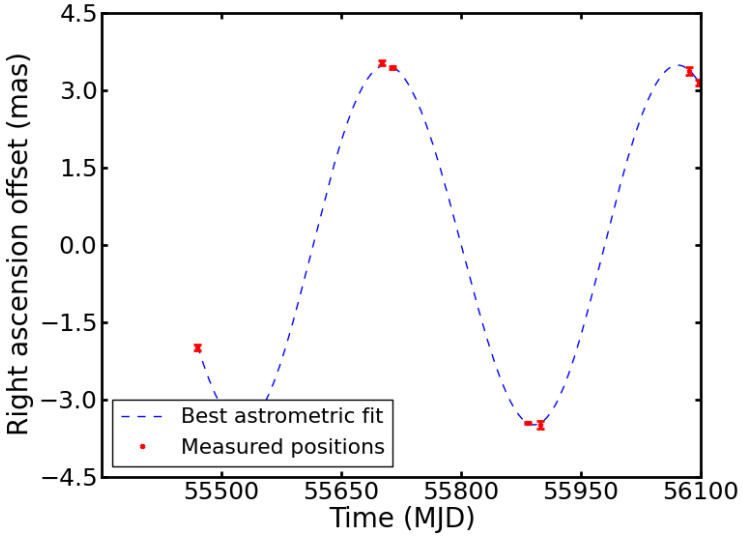
- The first "transitional millisecond pulsar"
  - Previous LMXB state inferred after discovery as radio pulsar
- Transitioned back to LMXB state in June 2013!
- Distance now used to calibrate X-ray and radio luminosity from accretion disk, jet (Deller et al. 2015)



Science sample 3: J2222-0137

- Binary pulsar; low eccentricity implies white dwarf companion
- No optical counterpart; d_{DM} underestimated?
- VLBA says no!
  - D = 267.2 ± 0.7 pc
  - Companion must be coldest white dwarf known… or very weird double neutron star!



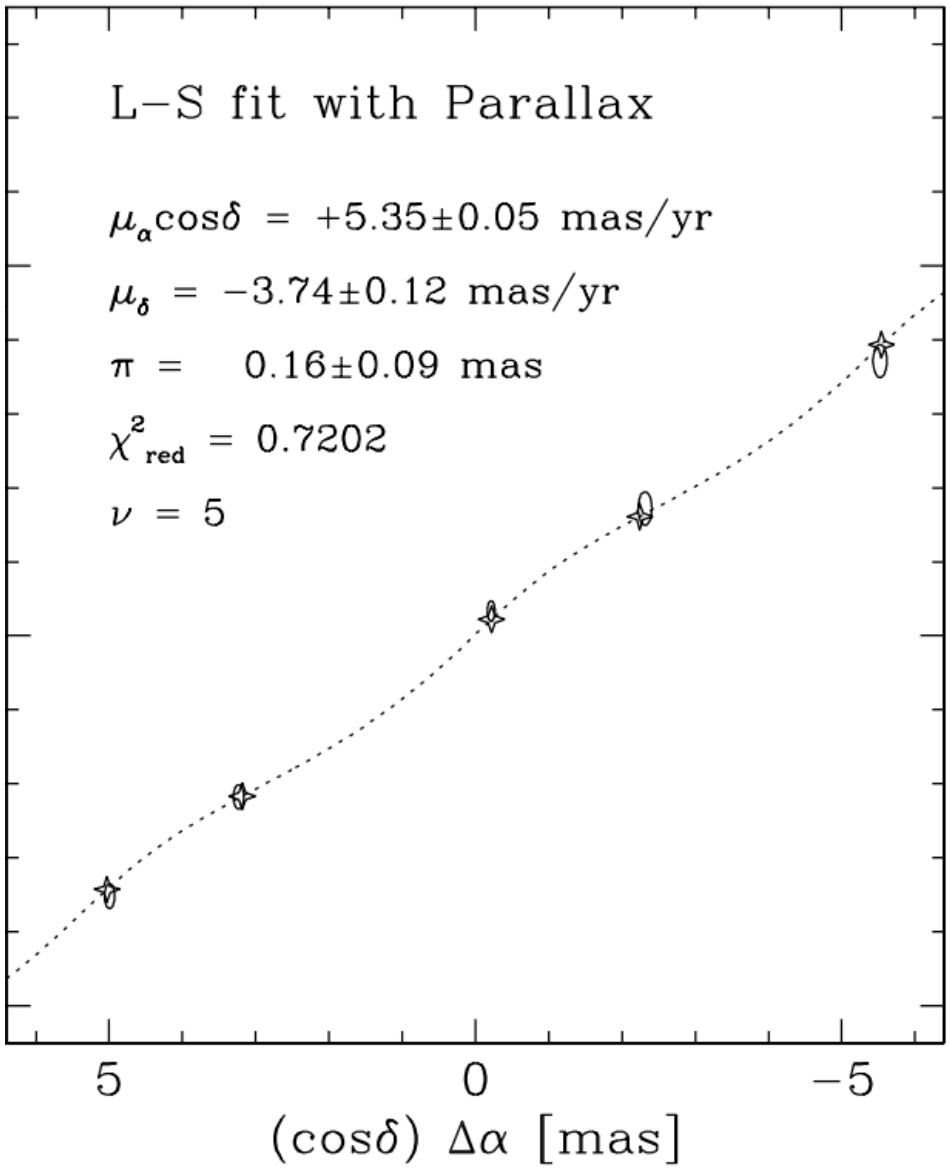


ASTRON

Deller et al. (2013), Kaplan et al. (2014)

Science sampler 4: J0218+4232

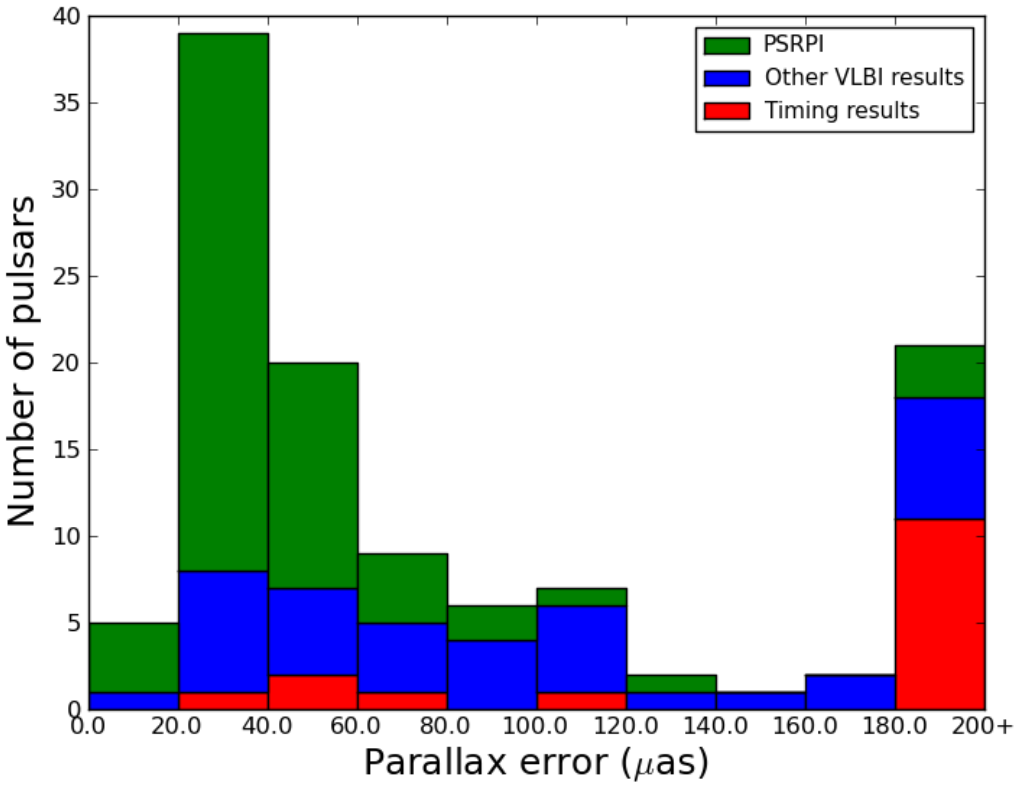
- First pulsar parallax from the EVN
- Very high γ-ray efficiency, poses difficulty for slot-gap and outer gap emission models
- Du et al., 2014



ASTRON

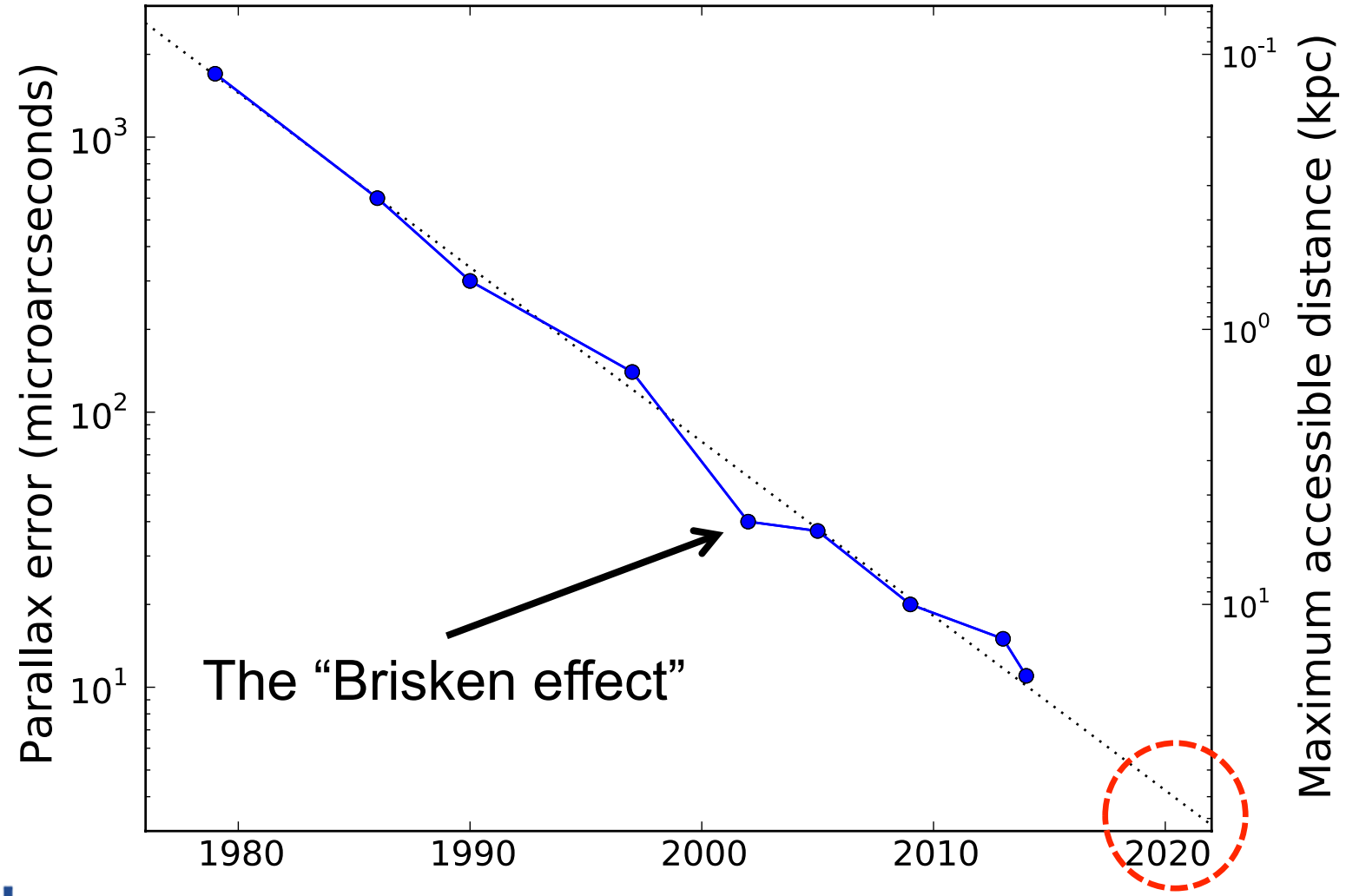
Science sampler 5: PSRπ

- 60 pulsars targeted with a parallax accuracy goal of 50 μas
- Ens
  - El
  - V
  - A

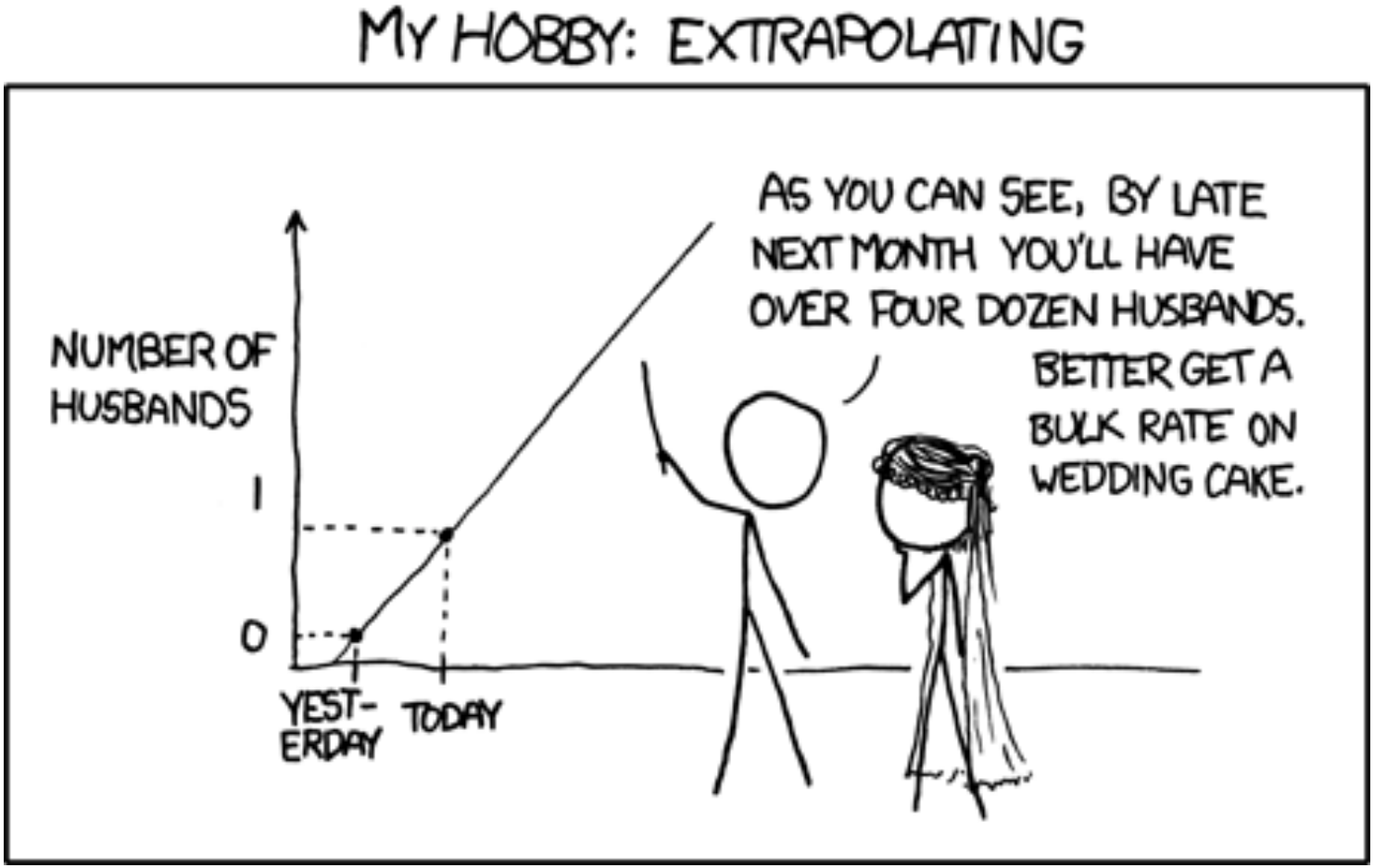


ASTRON

Historical pulsar parallax “law”



Historical pulsar parallax “law”



credit: xckd.com

Keeping the law

- Past gains have been driven by stability, sensitivity & technique improvements
  - But instrumental stability no longer limits
  - We're now utilising effectively all of L band
  - The easy gains have been made!
- Clever ionospheric modeling may squeeze more blood from the stone
  - Will require investment in hardware and software

Keeping the law

- Another solution is to just use a bigger hammer: the SKA
  - Current VLBA point source sensitivity (2 hr @ 256 MHz): **27 μJy**
  - Potential array of phased SKA1-mid, LBA + Hartebeestok (2 hr @ 512 MHz): **~2 μJy**
- Fainter targets + can use (multiple) nearby, fainter in-beam calibrators
  - Differential ionosphere reduced
  - Potential robustness to source evolution in an individual calibrator

SKA-VLBI hurdles

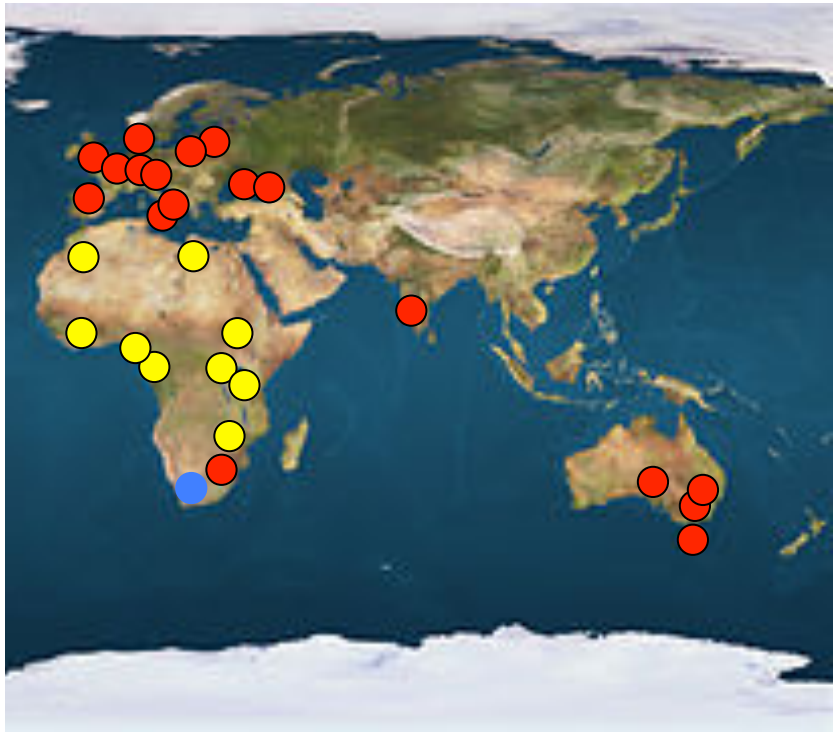
- Scheduling flexibility?
- Baseline distribution

SKA-VLBI hurdles

SKA1-mid

Existing

Potential



SKA1-mid is isolated! Intermediate-length baselines (crucial for reference source modeling) can only be provided by new dishes; e.g., the African VLBI Network

Conclusions

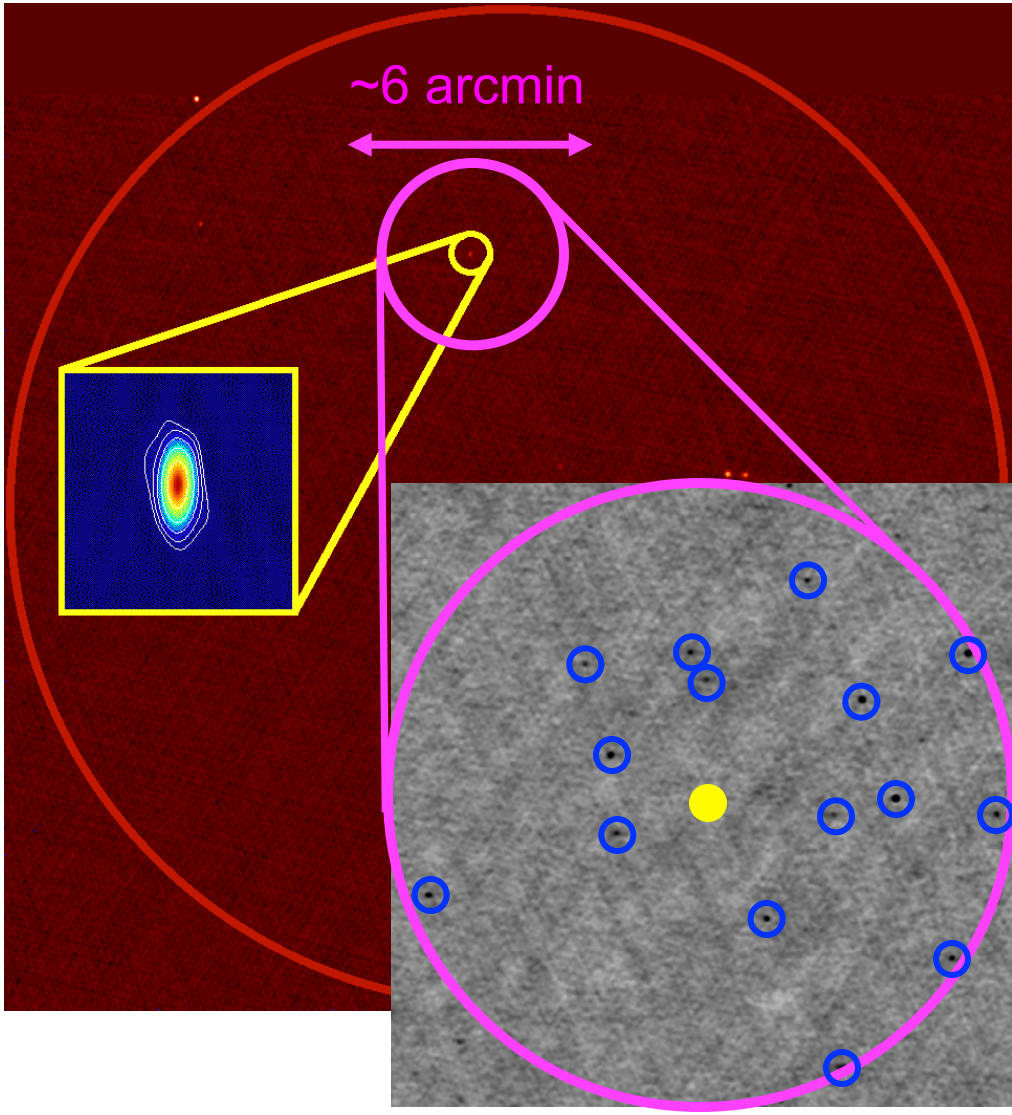
- VLBI provides invaluable information for the study of pulsars
- With current arrays/techniques, can already get accurate distances to just about any pulsar, with enough effort
- Maintaining the record-breaking tempo into the future requires SKA-VLBI, and very likely investment in the African VLBI network

Questions?

ASTRON

The future of VLBI astrometry

- Soon: some targets will have “in-beams” at 5 GHz:
  - 2-3 μas?
  - Accurate distances anywhere in the Galaxy, even nearest neighbours



The future of VLBI astrometry

- At 1 μas level, we can no longer focus solely on atmosphere/ionosphere
  - Few radio AGN are stable point sources