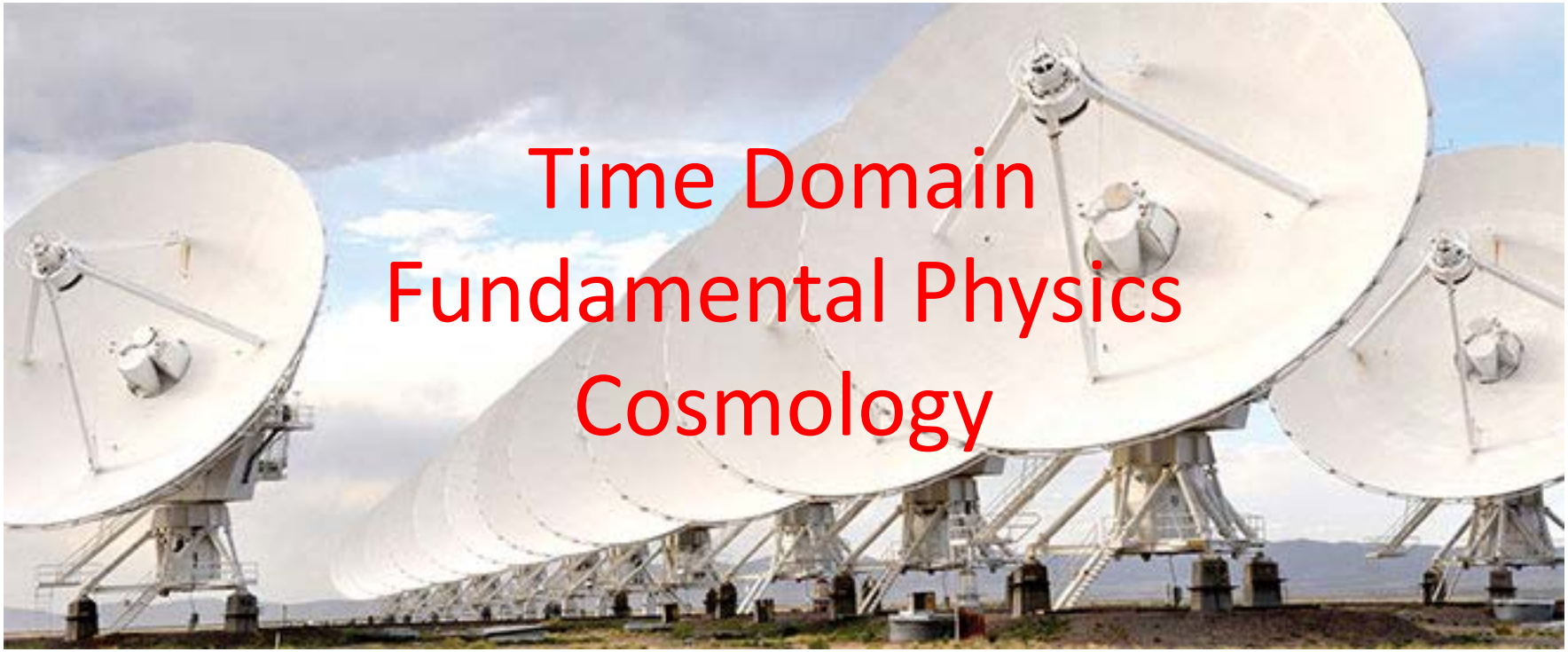
NGVLA
Science Working Group:

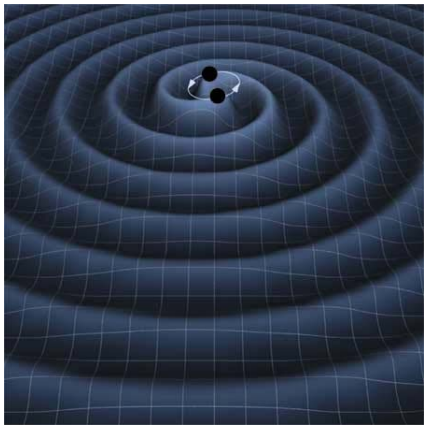


Participants

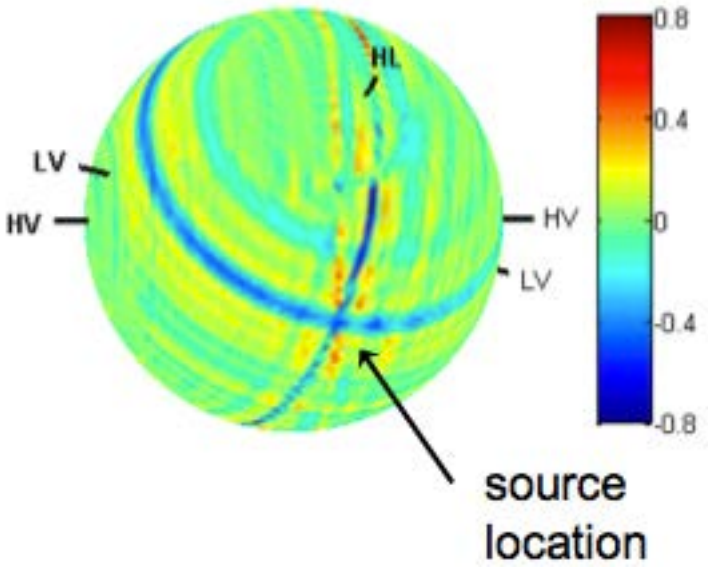
Geoffrey C. Bower[1], Paul Demorest[2], James Braatz[3], Avery Broderick[4], Sarah Burke-Spolaor[2], Bryan Butler[2], Tzu-Ching Chang[5], Laura Chomiuk[6], Jim Cordes[7], Jeremy Darling[8], Jean Eilek[9], Gregg Hallinan[10], Nissim Kanekar[11], Michael Kramer[12], Dan Marrone[13], Walter Max-Moerbeck[2], Brian Metzger[14], Miguel Morales[15], Steve Myers[2], Rachel Osten[16], Frazer Owen[2], Michael Rupen[17], Andrew Siemion[18]

Time Domain

Advanced LIGO and GW Detection

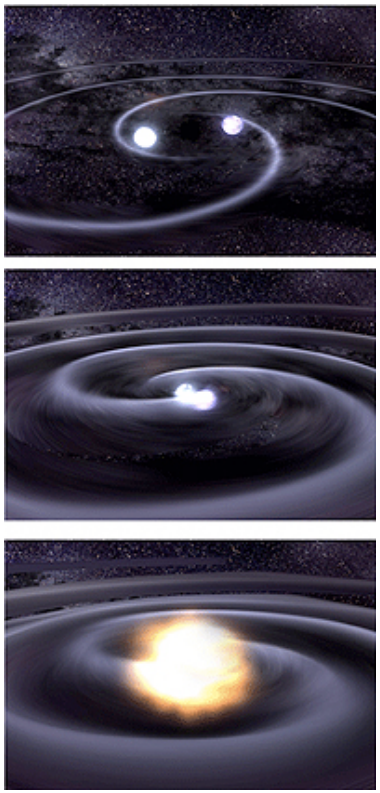


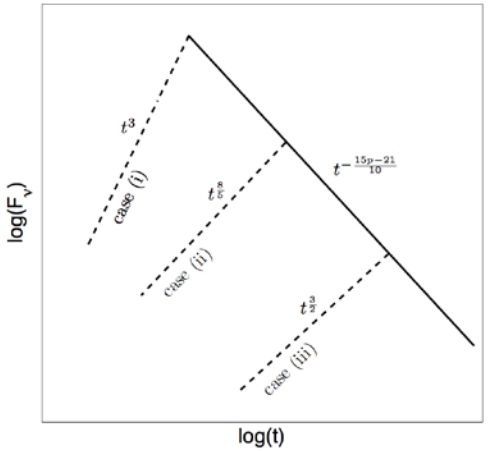
Major Increase in Sensitivity in 2016+



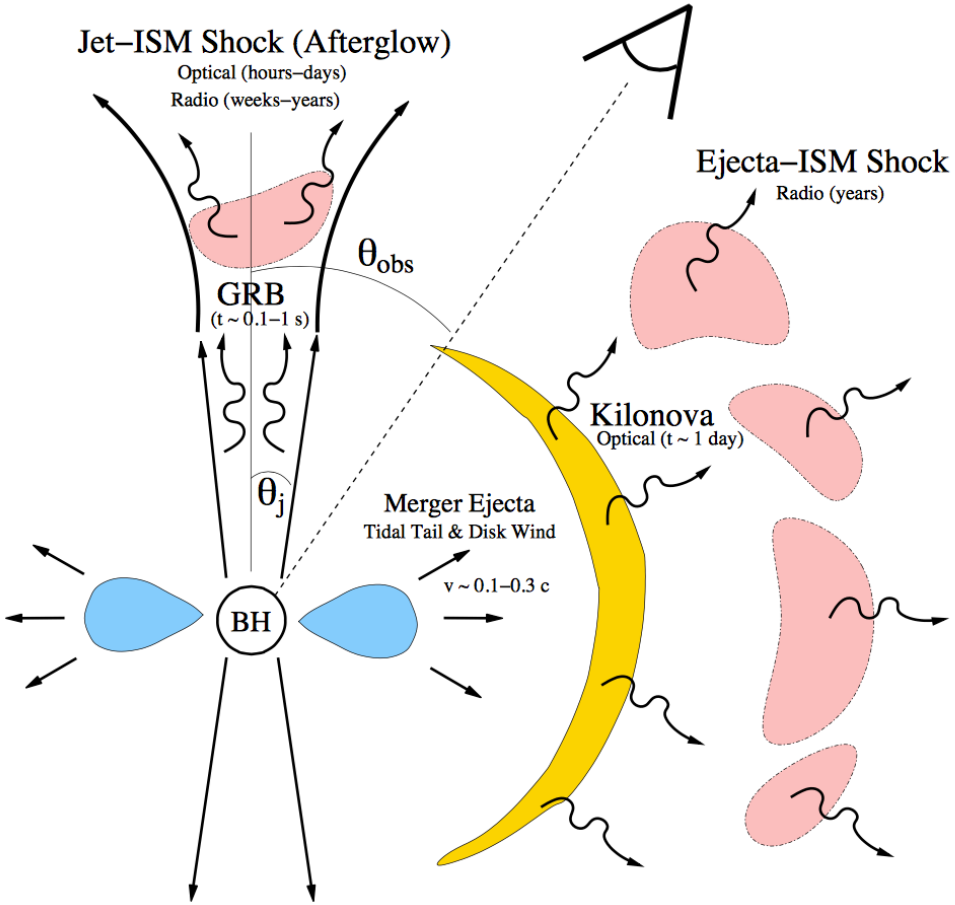
But source localization is poor

Radio Counterparts of LIGO Gravitational Wave Sources



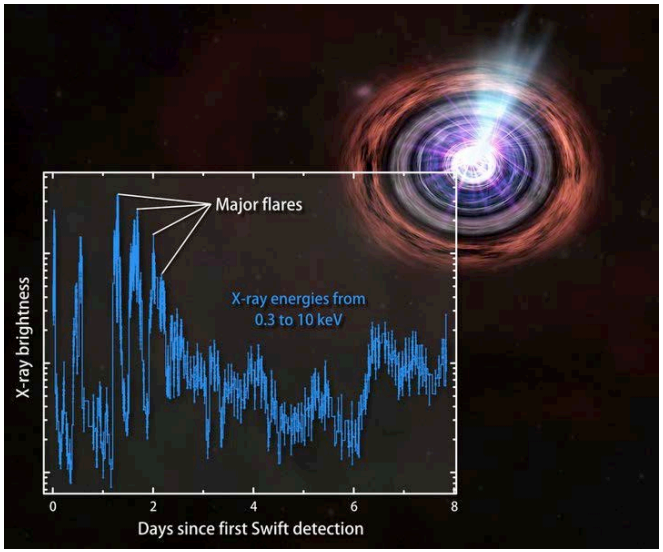


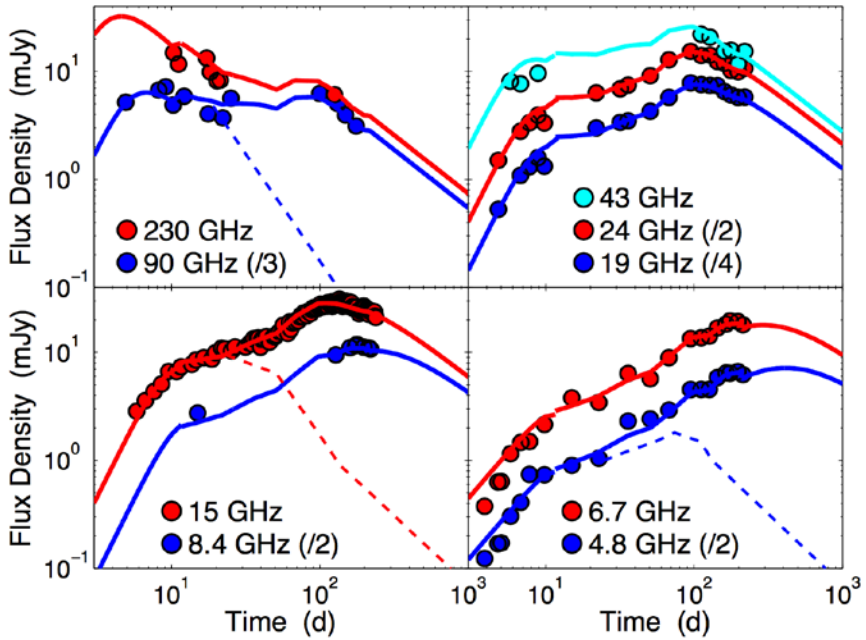
Nakar & Piran (2011)



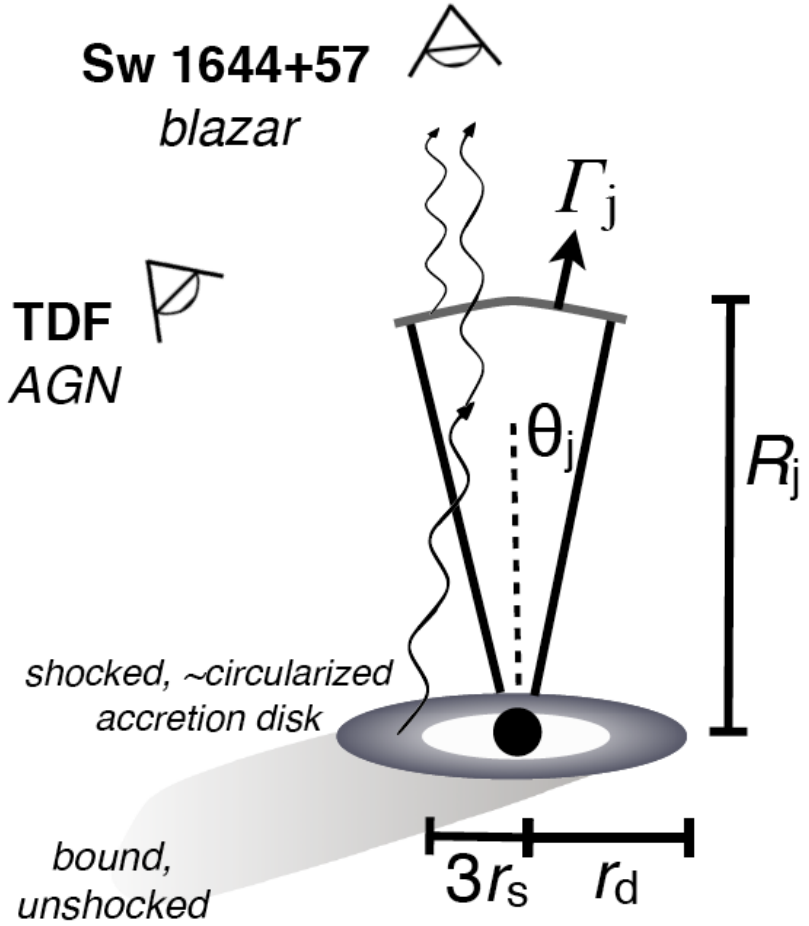
Metzger & Berger 2012

Jetted Stellar Tidal Disruption Events





Berger et al. 2012

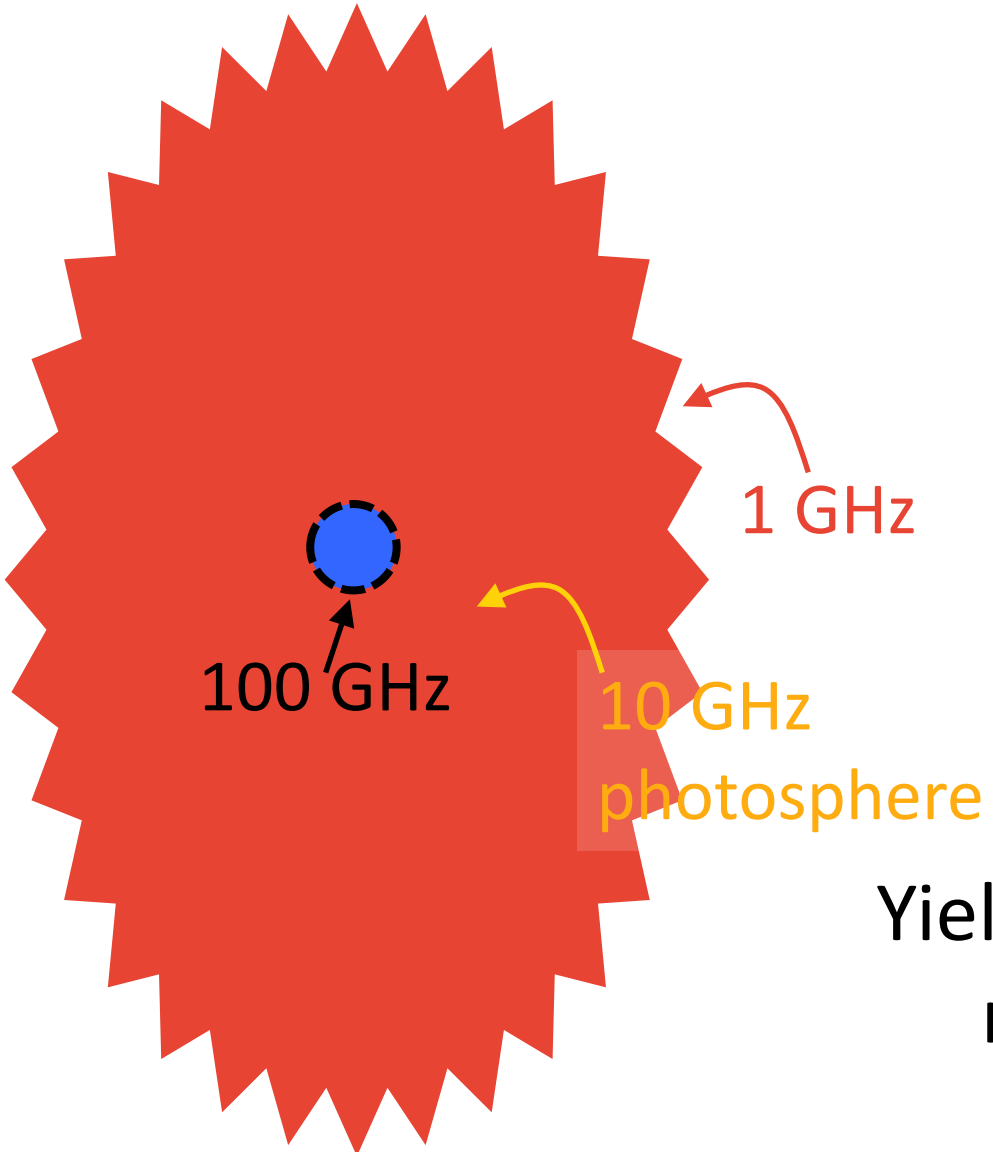


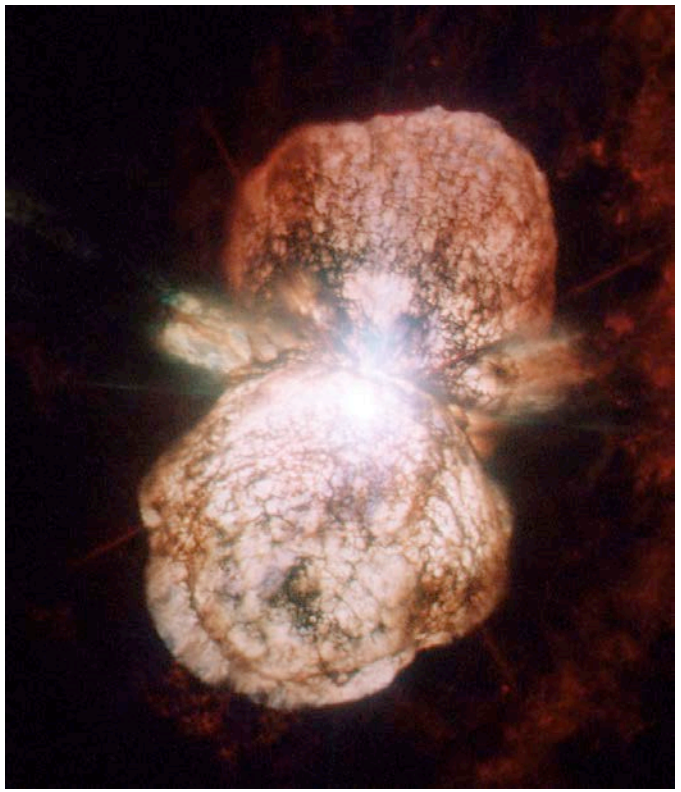
Bloom et al. 2011

Synchrotron Radio Emission from Shocked ISM Around Black Hole (Giannios & Metzger 2011)

Peeling the Onion:

Frequency agility ➔ Radio tomography

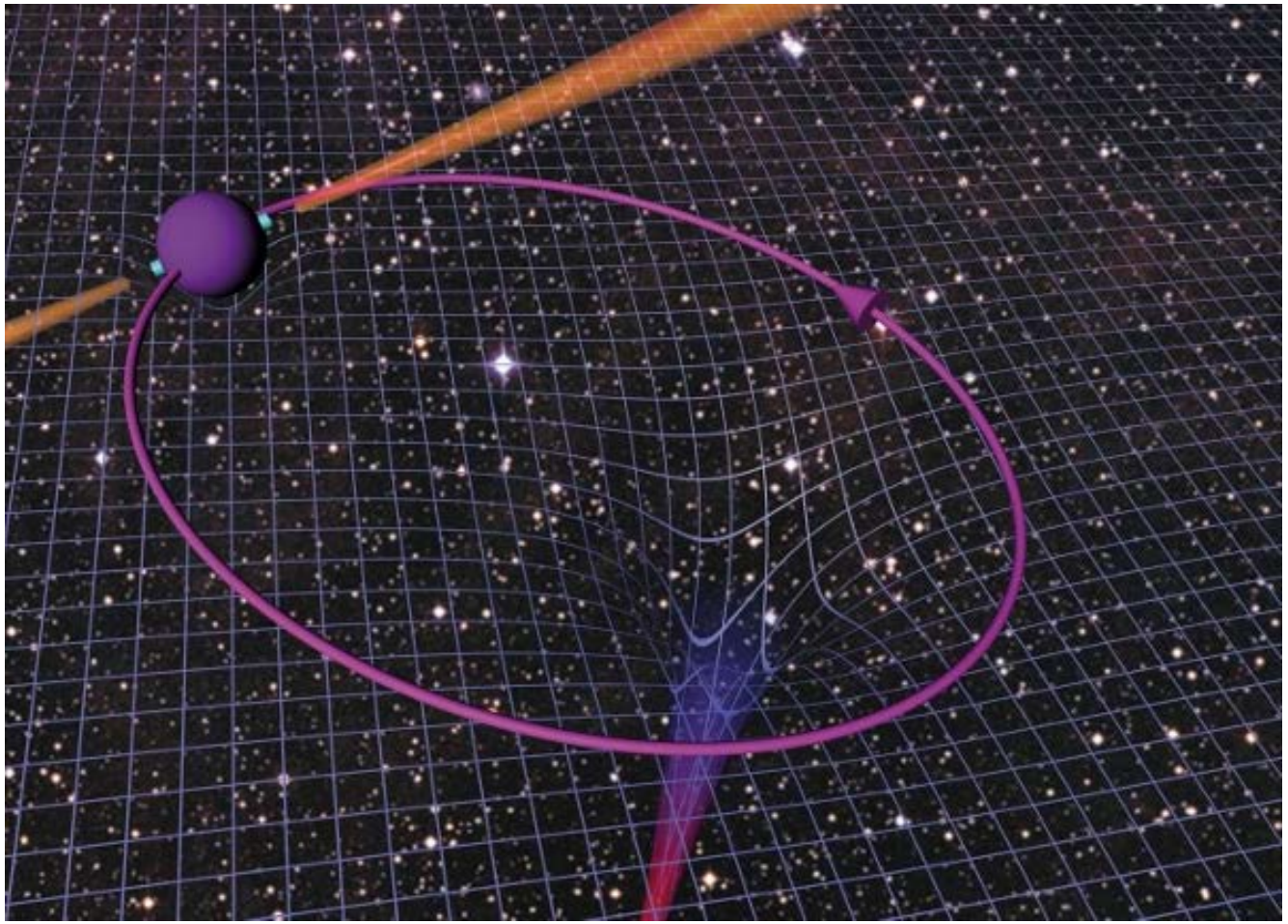




Yields density profiles, total masses, 3D geometry

Fundamental Physics

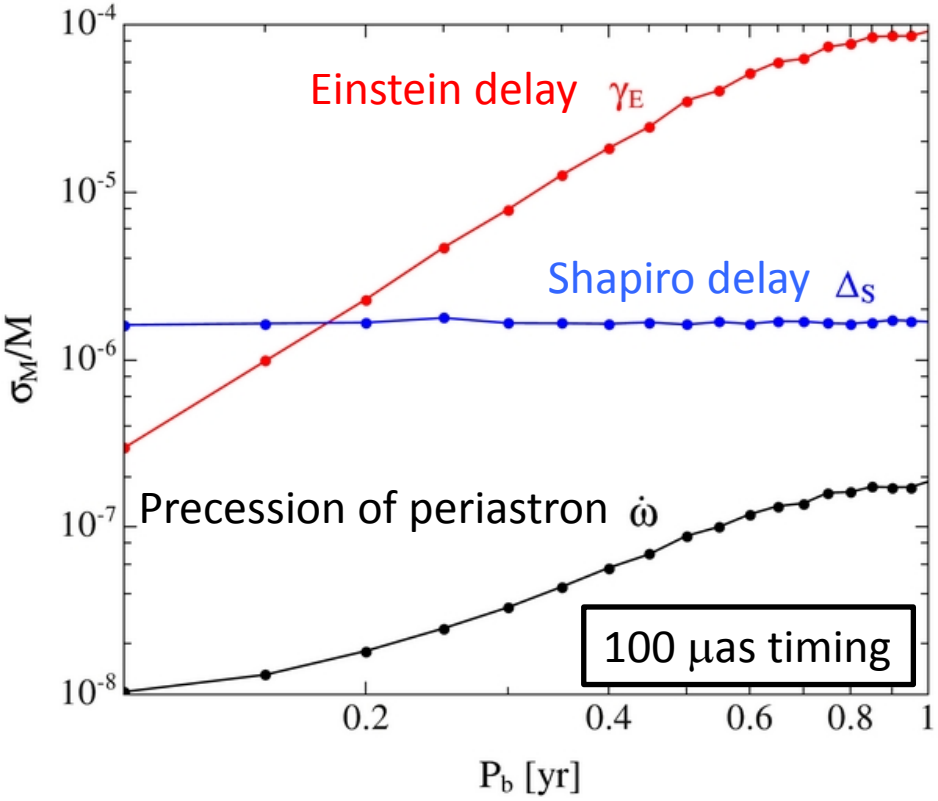
A Pulsar in Orbit Around a BH



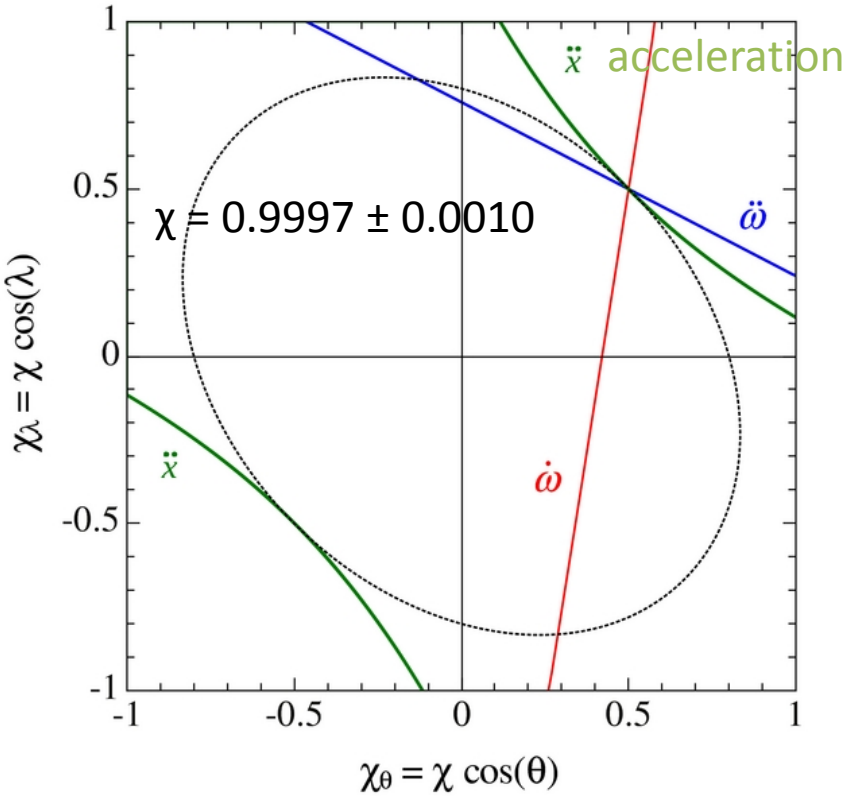
Kramer et al

Using Pulsars to Measure Spacetime Around Sgr A*

Black Hole Mass

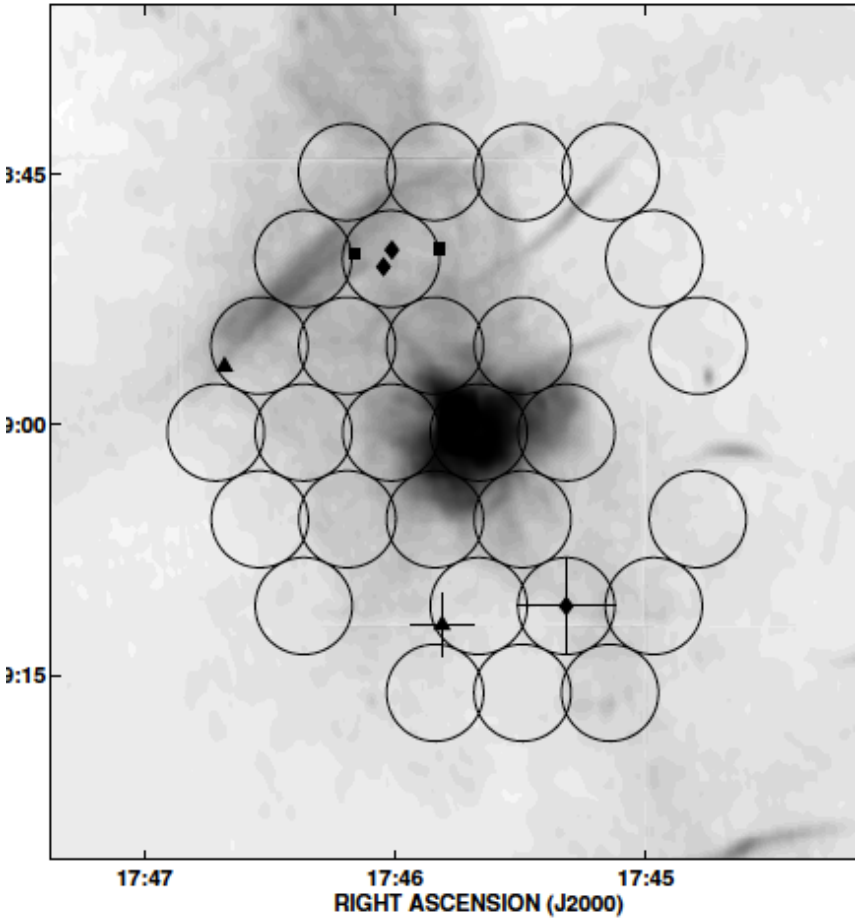


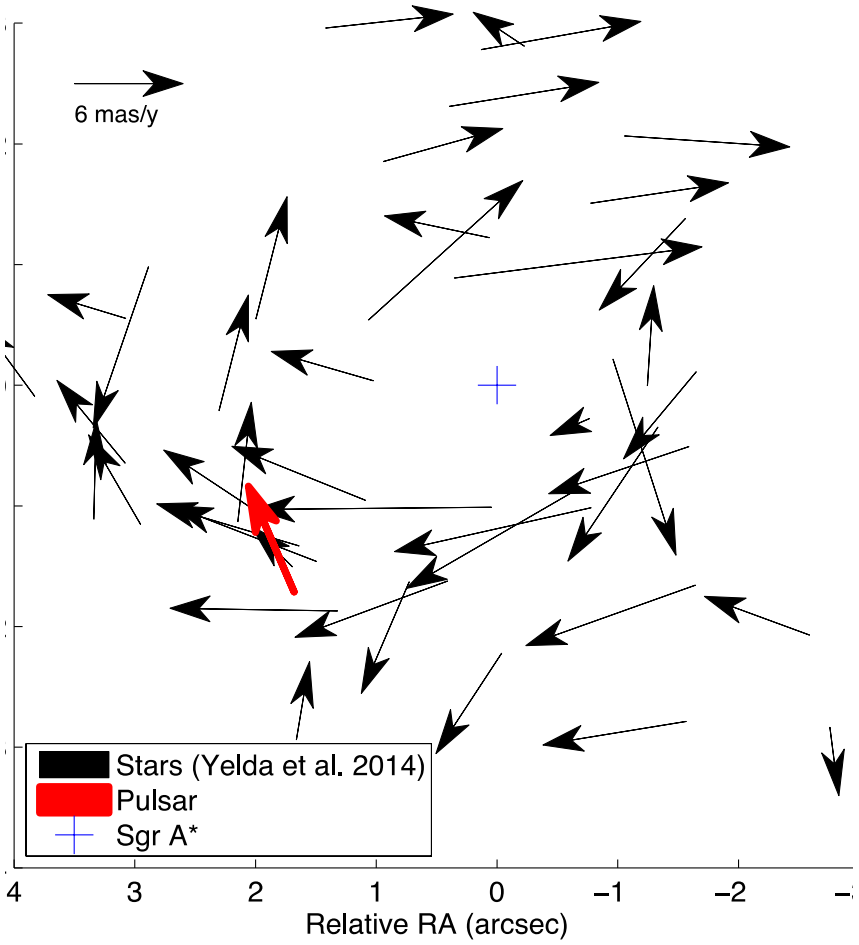
Black Hole Spin



Liu et al 2012

Galactic Center Radio Pulsars

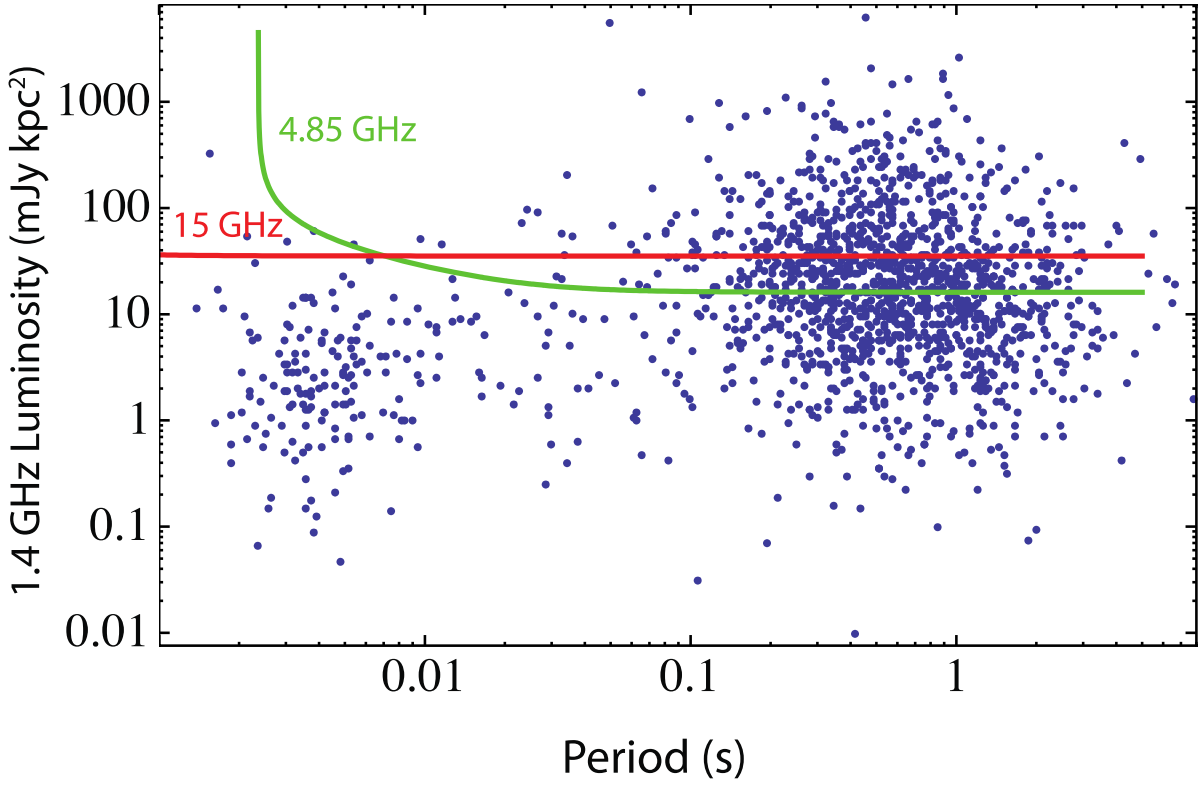




Deneva et al 2009

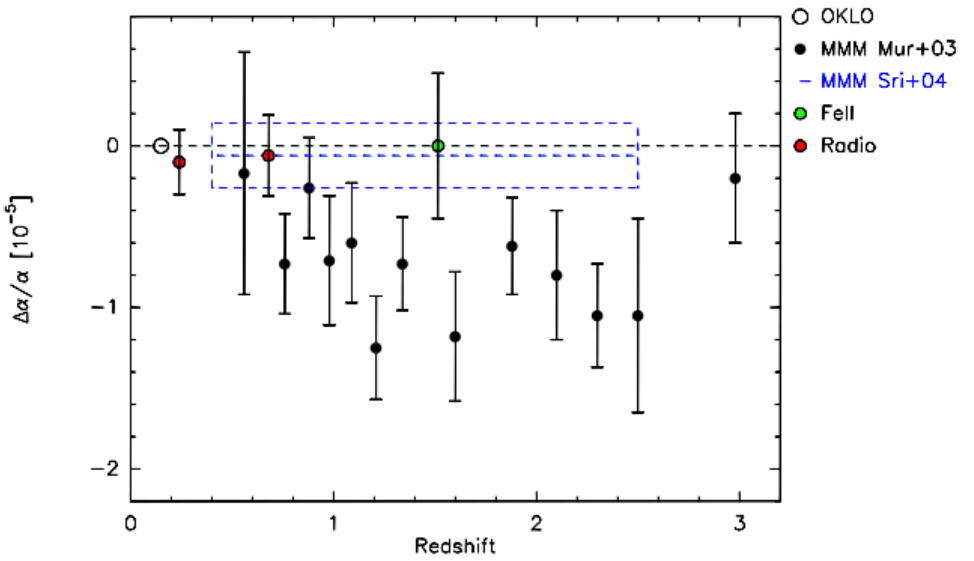
Bower et al 2014

Revised GC PSR Sensitivity

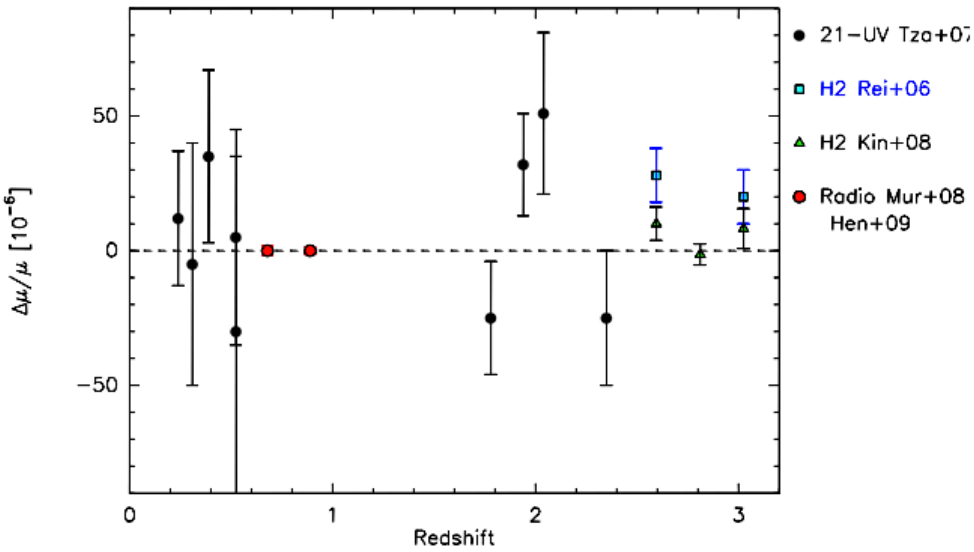


Macquart & Kanekar 2014

Fundamental Constant Evolution



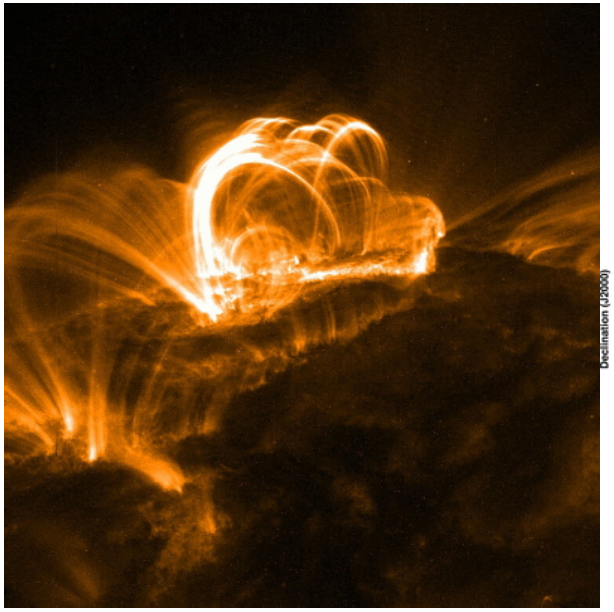
Combes et al 2009



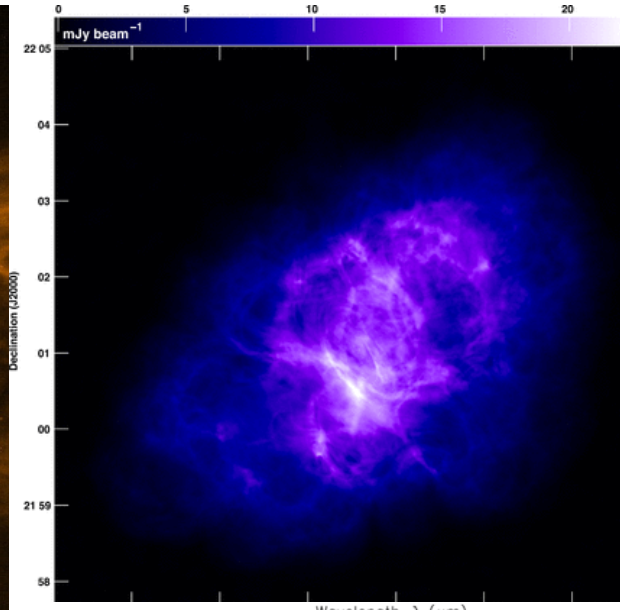
- Many molecular transitions sensitive to changes in □/□ Few systematics if all lines from single molecule.
- Best constraints on changes in μ !
  - $[\Delta\mu/\mu] < few \times 10^{-7}$ (NH_3, CH_3OH: Effelsberg, GBT, VLA)
- Sensitivity to changes in □/□ increases non-linearly with telescope sensitivity, due to multiple absorbers and multiple techniques.
  - 10 × VLA: $[\Delta\mu/\mu] \sim$ few × 10^{-10} from $z \sim 2$.

Plasma Physics

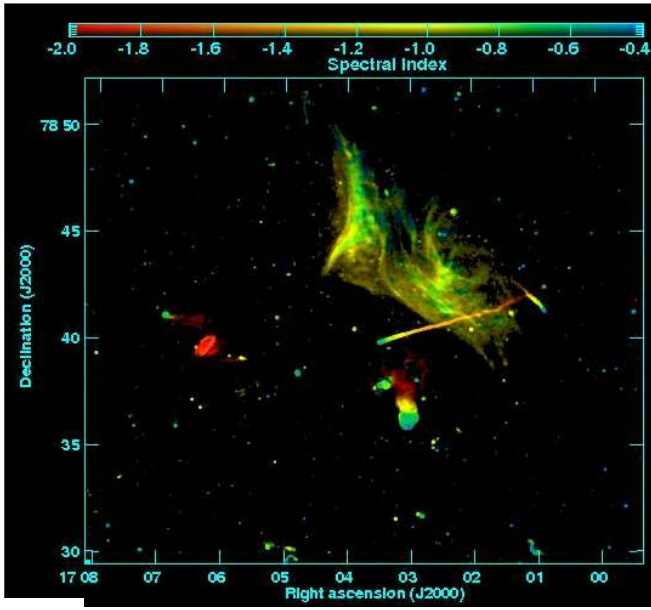
Solar Flares



Crab Nebula



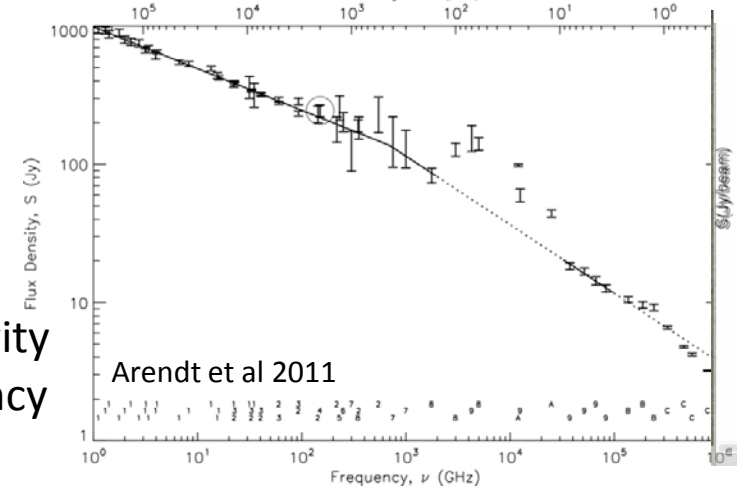
Abell 2256



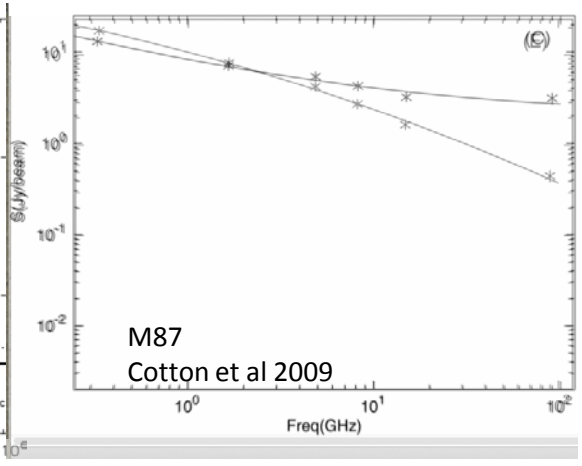
- Particle acceleration
- Magnetic reconnection

Requirements

- Surface brightness sensitivity
- Broad, continuous frequency coverage

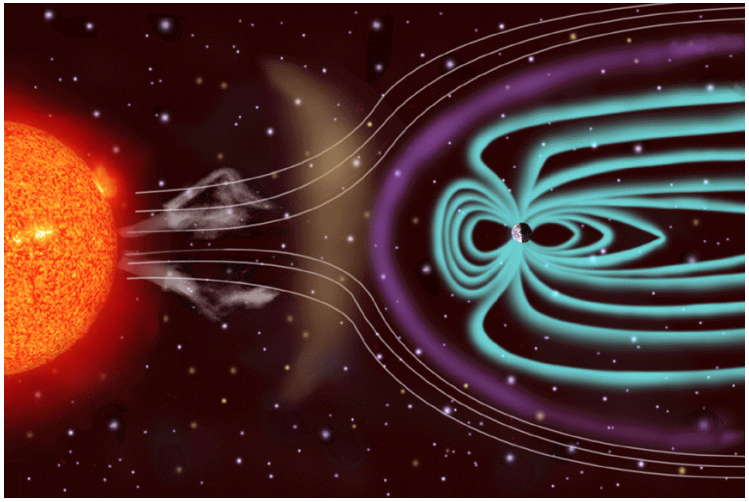


Arendt et al 2011



M87
Cotton et al 2009

Revealing the Plasma Physics of Star-Planet Interactions



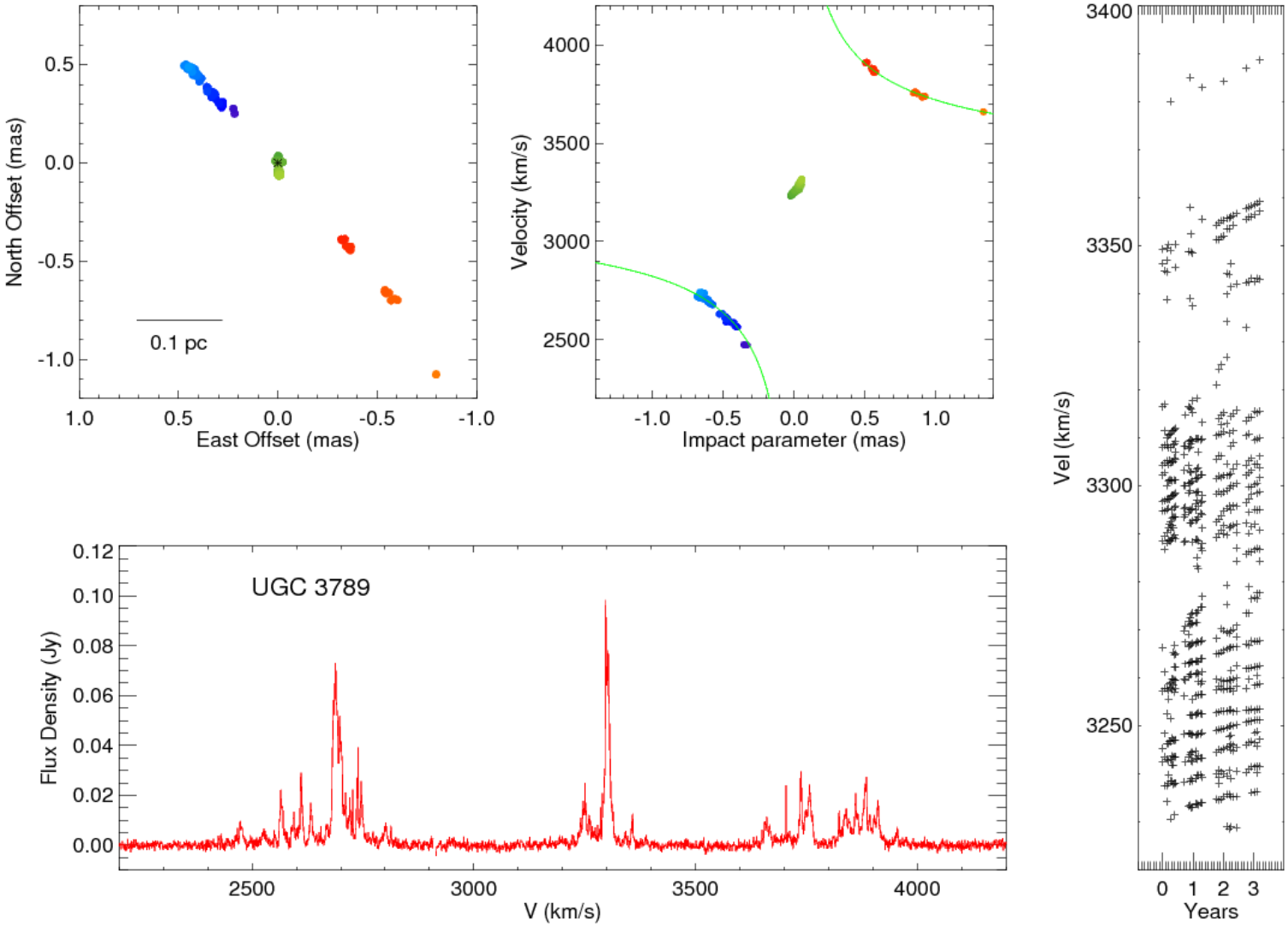
Earth-Sun interaction is complex, composed of radiation, particles and magnetic field interactions

artist's conception of evaporating exoplanet atmosphere

- Cool stellar mass loss characterized by an ionized stellar wind ➜ favors higher radio frequencies for detection
- Star-exoplanet interactions: evaporation of atmosphere from close-in planetary companion
- Particle flux interaction with exoplanet magnetic field can affect planetary dynamo
- NGVLA can provide the most sensitive direct detection of the stellar wind

Cosmology

The H_2O Megamaser in UGC 3789



Summary of Results for Megamaser Science

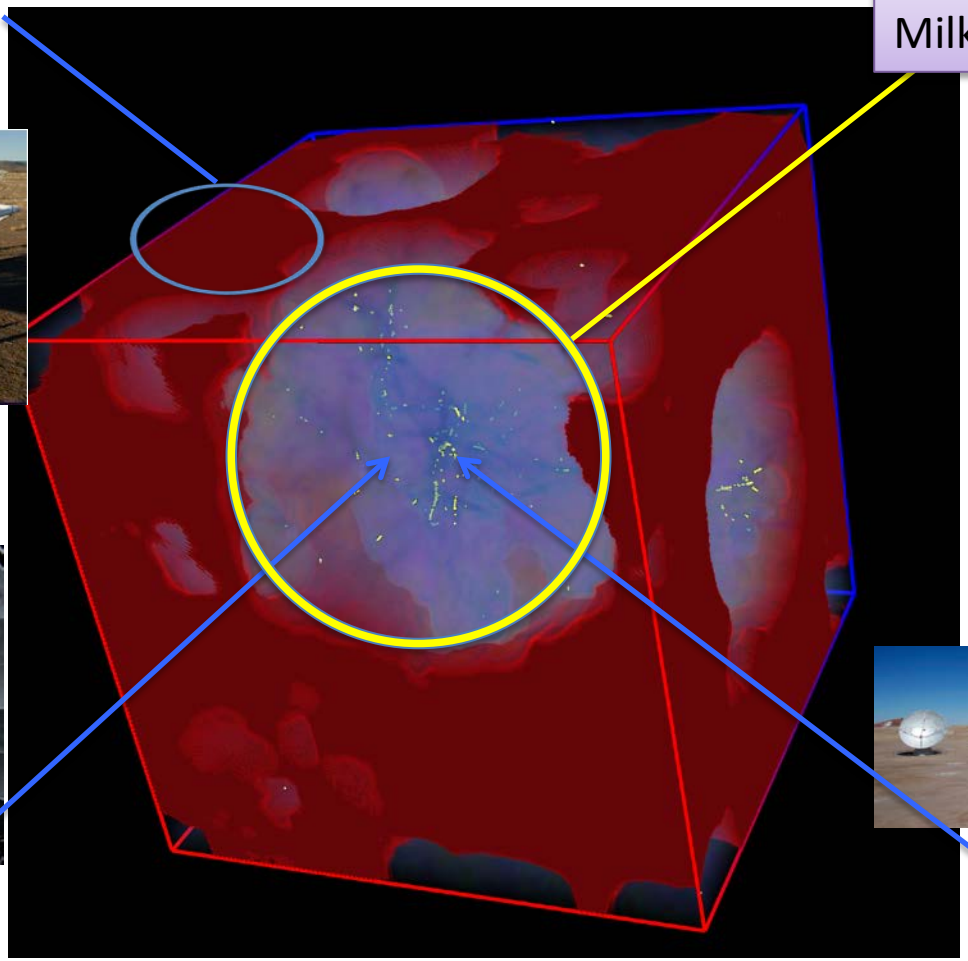
- One-step, geometric measurement that provides a critical complement to standard candles.
- Megamasers determine $H_0 = 70.4 \pm 3.6$ km s^{-1} Mpc^{-1}.
- Megamasers have determined *gold standard* masses of SMBH in ~20 galaxies.
- Megamasers provide the only means of direct imaging gas in AGN on sub-pc scales.

Goals and Requirements for a Next Gen Radio Telescope for Megamaser Science and Astrometry

- H_0 to ~1%
- BH masses in >> 100 galaxies.
- ~20% of its collecting area in long baselines (~ 5000 km).
- UV coverage requirements are modest. The long baselines could be achieved with ~ 5 100-m class apertures.
- Frequency coverage for the long baselines must include up to 22 GHz to get the H_2O line.

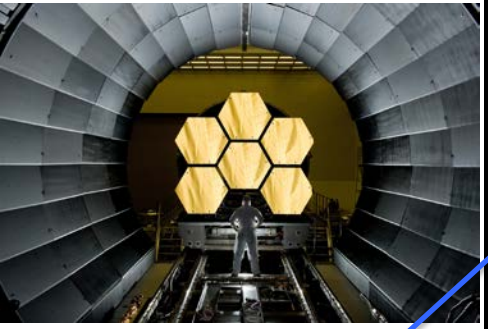
Intensity Mapping the Cosmic Web

Neutral Hydrogen



The Multitude of Galaxies: Milky Way Building Blocks

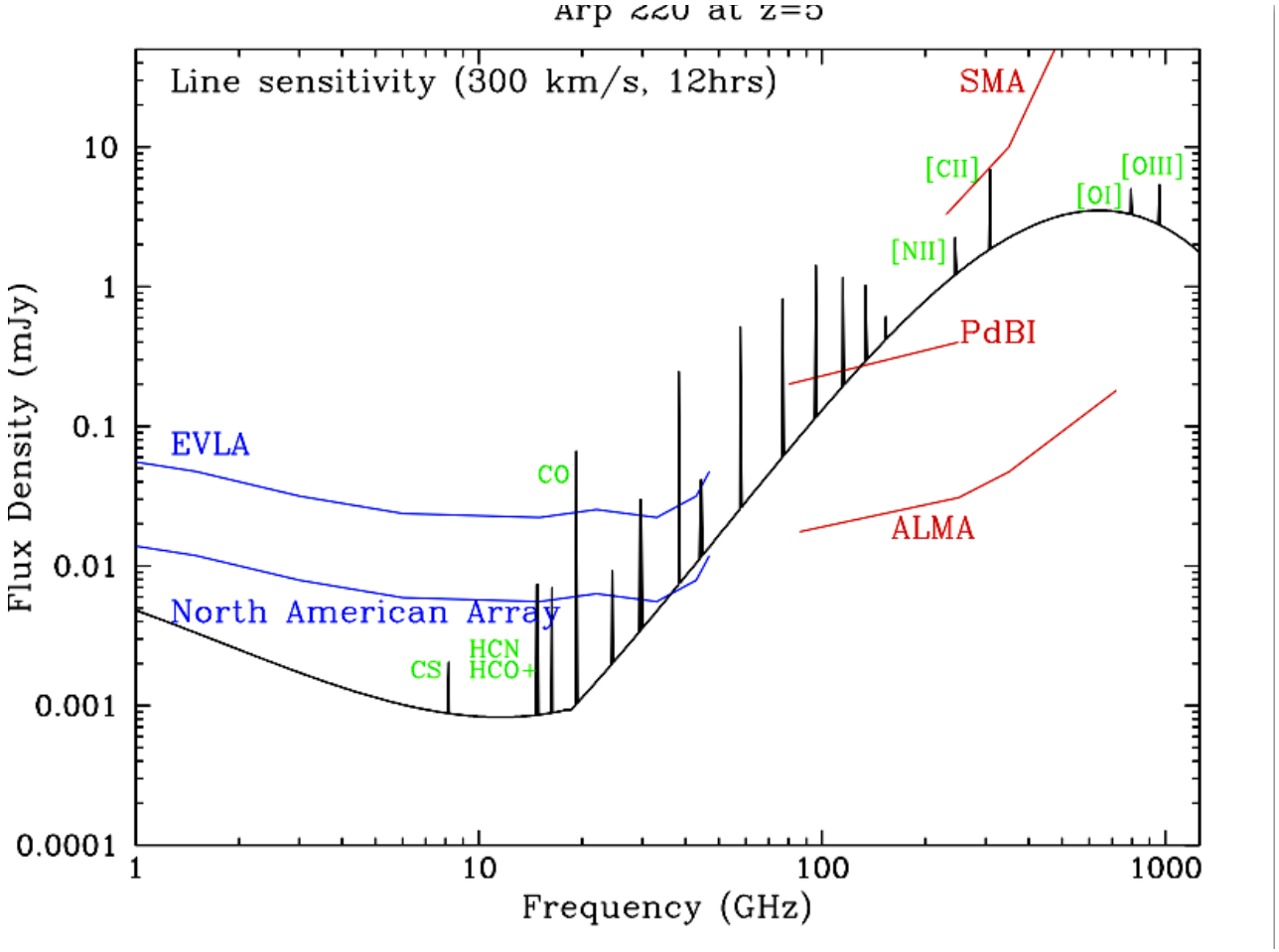
NGVLA



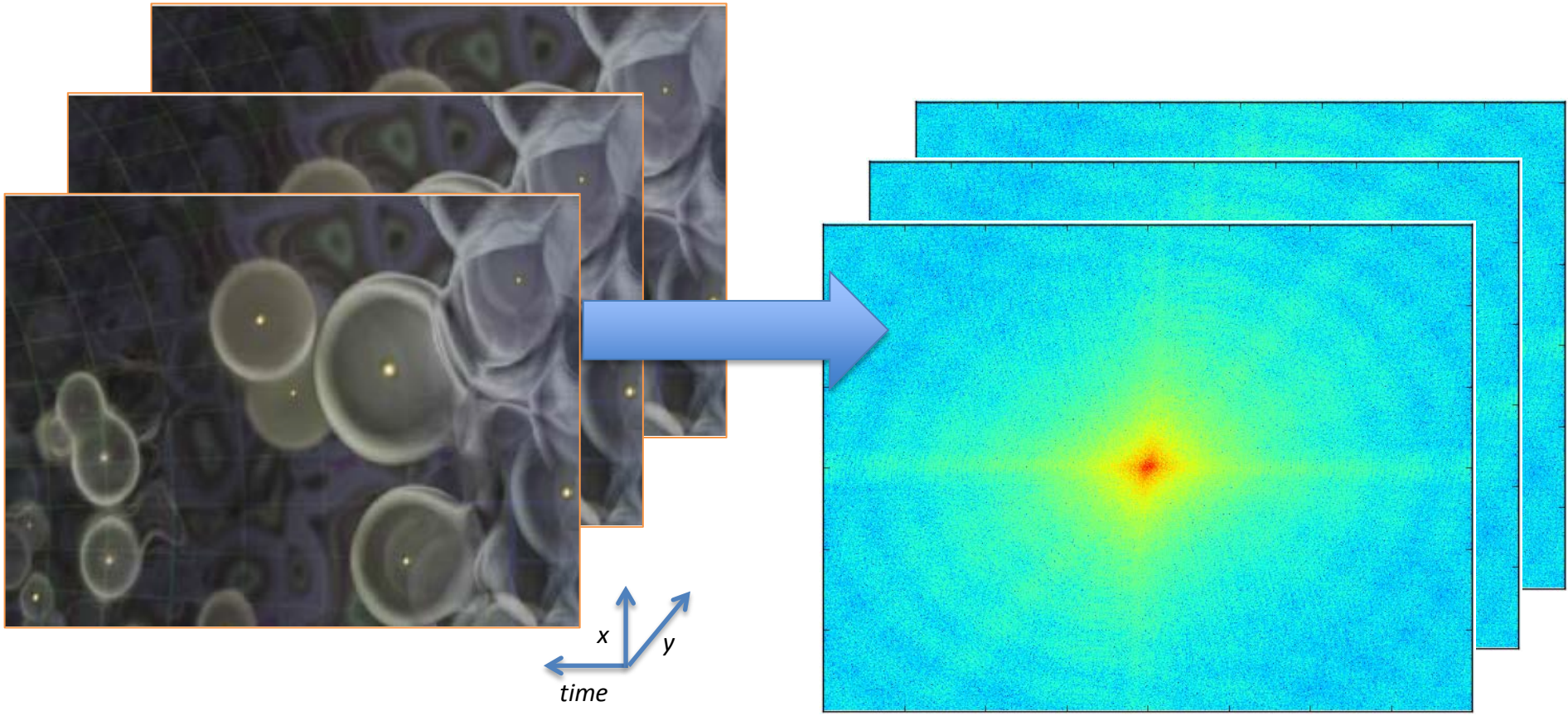
Dust & Ionized Gas

Massive Galaxies

Even NG VLA Is Limited in the Galaxy Population it Can See



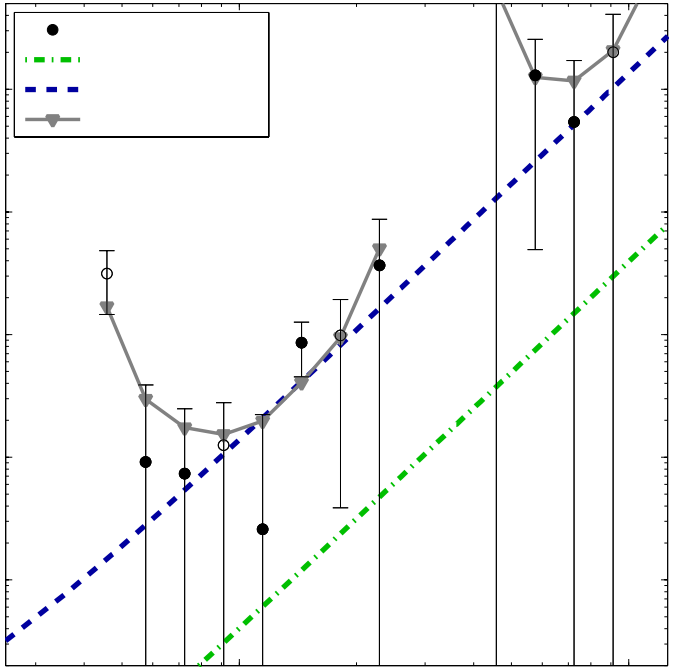
Detect the Integrated Luminosity Function with the 3D Power Spectrum



Same approach as taken for microwave background and HI EoR

CO 1-0 Power Spectrum at 2.3 < z < 3.3

- Wide field of view
- Dense (u,v) coverage
- Broad frequency coverage
- Coarse frequency resolution



Keating et al (2015)

Real-Time Cosmology

All observables are functions of time:

$$\dot{z} = H_o(1+z) - H(z)$$

$$\dot{D}_L/D_L = H_o + \dot{z}\,(1+z)^{-1}$$

$$\dot{D}_A/D_A = H_o - \dot{z}\,(1+z)^{-1}$$

$$\dot{F}/F = -2\,\dot{D}_L/D_L$$

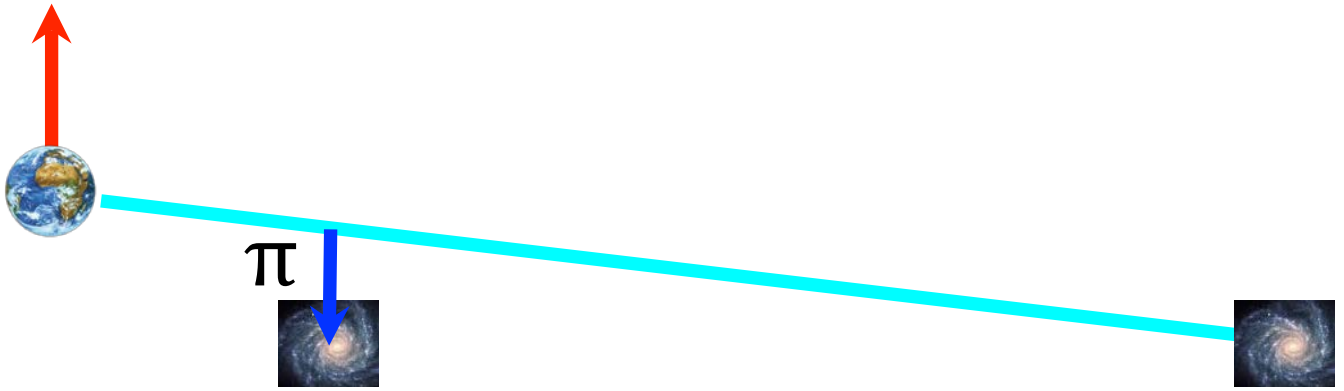
CMB (time reveals 3D structure)

...

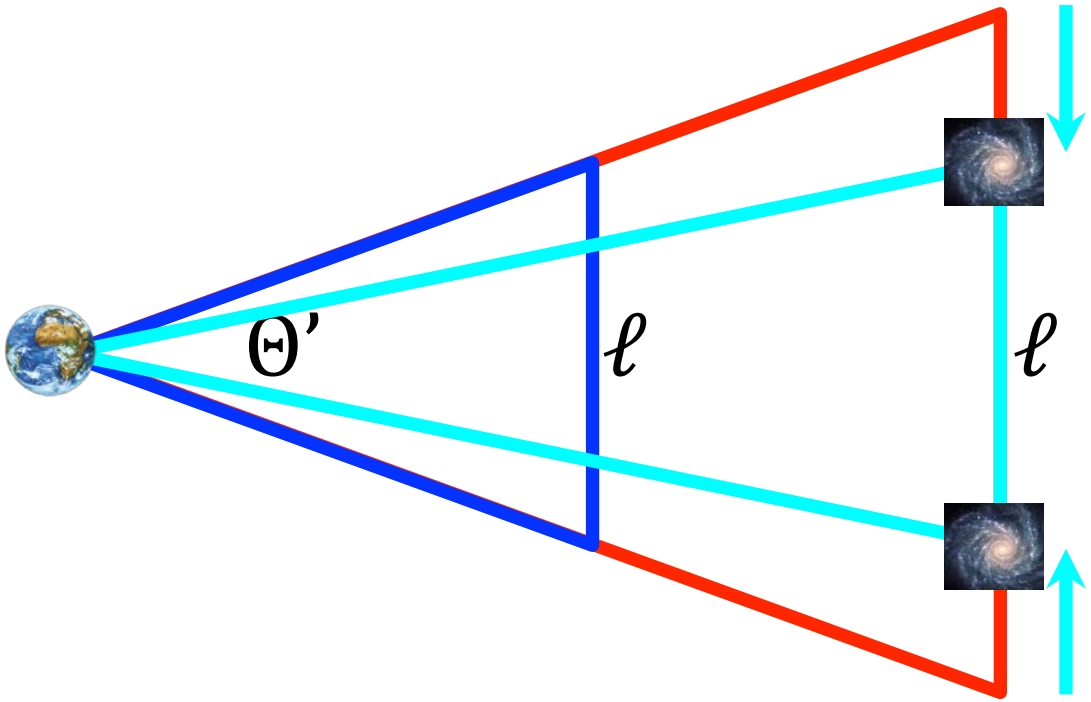
Order of magnitude: $H_o = 7.4 \times 10^{-11}\ \mathrm{yr}^{-1}$

$H_o = 15\ \mu\mathrm{arcsec\ yr}^{-1}$

Extragalactic Parallax



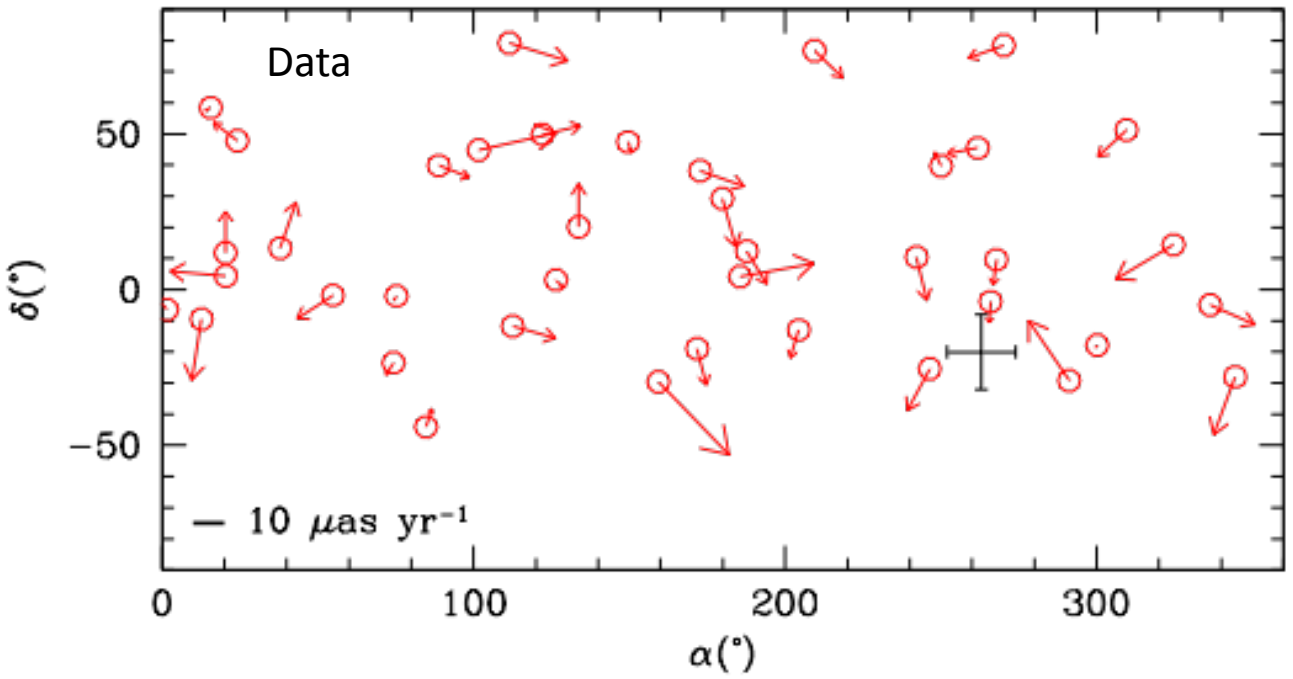
Growth of Structure → BAO

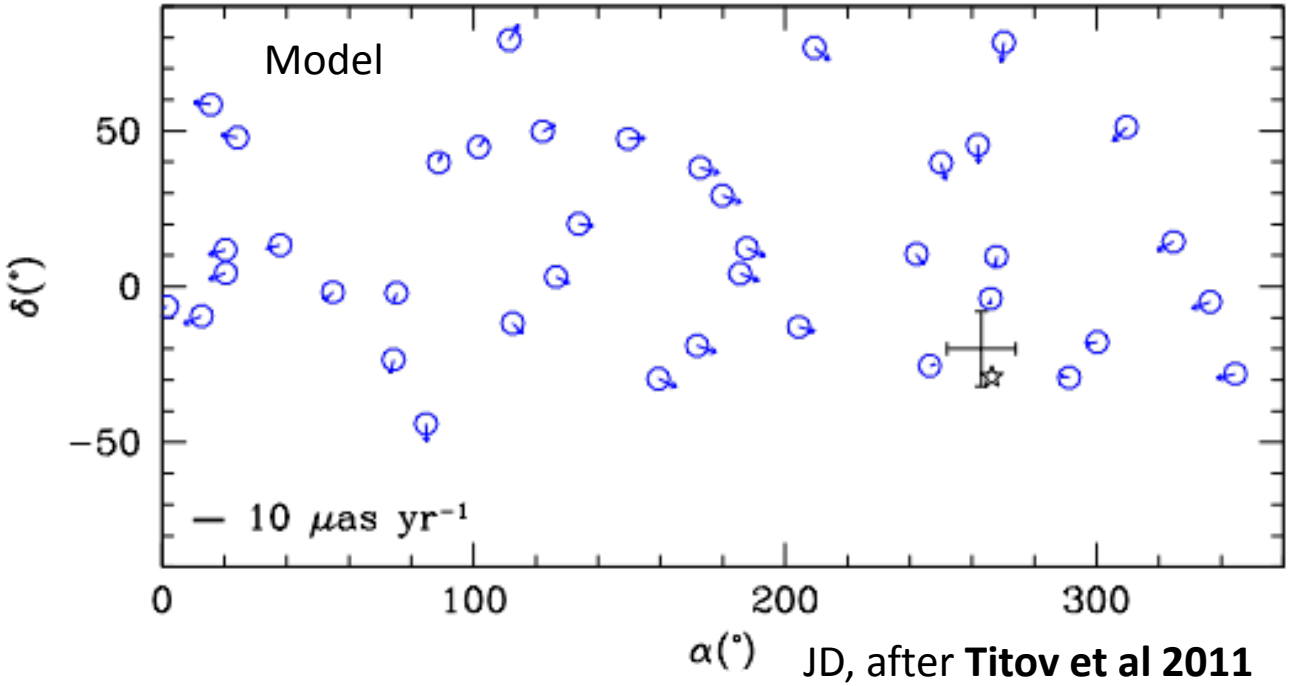


- ICRF sources show large intrinsic PM.
- Best-fit dipole shows significant convergence at Galactic Center due to Solar acceleration (inducing a secular aberration drift).

μ = 5 μarcsec yr $^{-1}$

a = 0.7 cm s^{-1} yr $^{-1}$





JD, after **Titov et al 2011**

Proper Motion: Now and Future

	Objects	PM_object	PM_global
VLBI now	500	10s of μarcsec yr $^{-1}$	5 μarcsec yr $^{-1}$
NGVLA	10^4	10s of μarcsec yr $^{-1}$	0.1 μarcsec yr $^{-1}$
GAIA	10^6	150 μarcsec yr $^{-1}$	1 μarcsec yr $^{-1}$

H_o = 7.4 x 10^{-11} yr $^{-1}$=15 μarcsec yr $^{-1}$

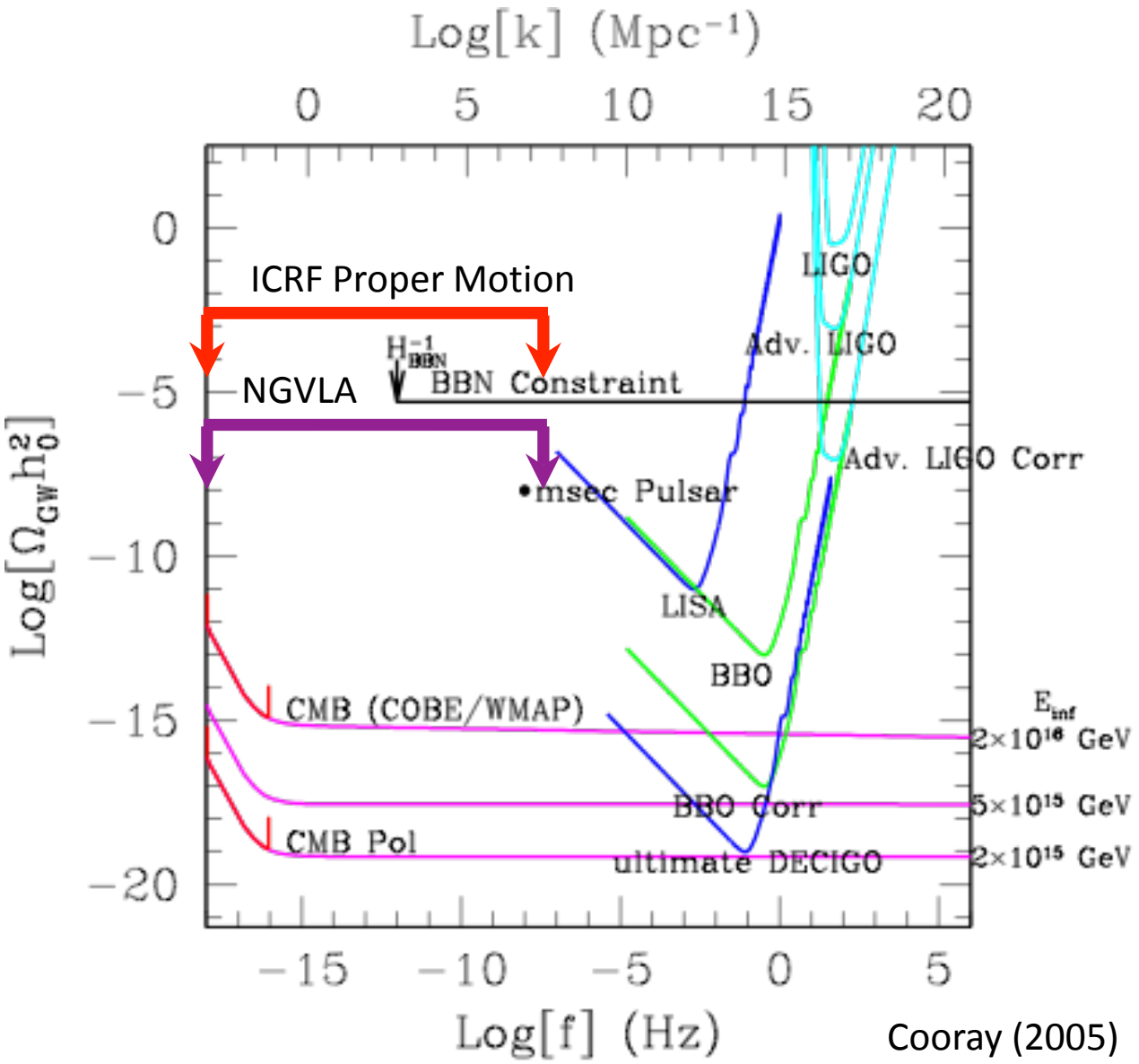
Individual parallax distances: to ~8 Mpc for NGVLA

Isotropy of expansion: 7% of H_0 currently, 0.1% for NGVLA

BAO: At z = 0.5, θ_{BAO} = 4.5° (ℓ ~ 40)

$\rightarrow d\theta_{BAO}/dt_o = -$ **H_o** $\theta_{BAO} = -1.2$ **μarcsec yr $^{-1}$**

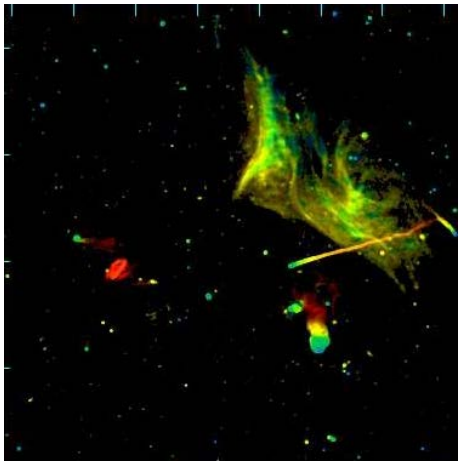
Gravitational Waves

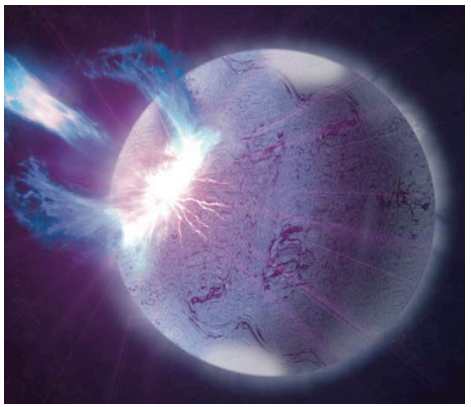


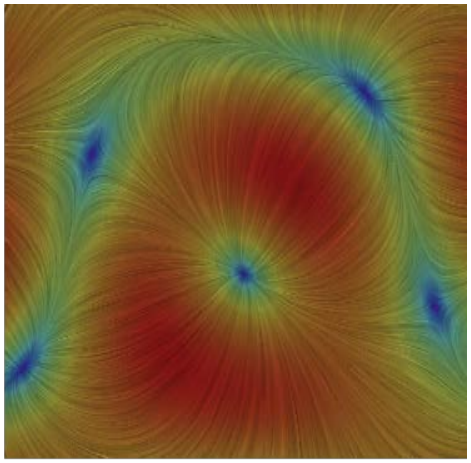
Cooray (2005)

Key Science

- Transients
  - Explosive transients including EM GW sources
- Fundamental Physics
  - Pulsar orbiting Sgr A*
  - Plasma Physics
- Cosmology
  - Megamaser astrometry
  - Real-time cosmology







Technical Requirements

Technical Requirement	Science Case
Long Baselines	Megamasers, astrometry, resolved galactic transients
Compact Configuration	Plasma physics, intensity mapping, GC pulsars, megamasers, fundamental constants
Wide Field of View/Survey Speed	Intensity mapping, EM GW sources
High Frequencies (> 50 GHz)	Fundamental constants, intensity mapping, plasma physics, transients
High Time Resolution (imaging, beamforming)	GC Pulsars
Real time processing	Transients