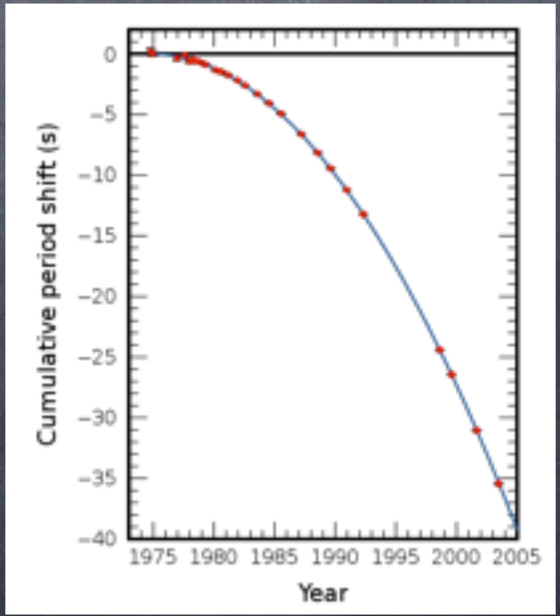
Gravity Wave Astronomy

Gravitational waves are often described as ripples in space-time. In general relativity, mass leads to a curvature of space-time. Gravity waves are produced by accelerating masses (if the motion is not perfectly symmetric).

Gravity waves have not yet been detected, though we do have indirect evidence for their existence. For example the Hulse-Taylor binary, which is a neutron star-neutron star binary. Its orbit has decayed in agreement with energy loss due to gravitational waves.

Hulse and Taylor won the 1993 Nobel Prize in Physics



Gravity Wave Astronomy

Potential gravitational wave sources include:

- supernovae (unless perfectly symmetric), gamma-ray bursts
- orbiting compact object binaries (two neutron stars, two black holes, etc.)
- coalescence of a binary system
- spinning object that is non-axisymmetric (neutron star with a mountain)
- relic gravity wave background from the Big Bang
- phase transitions in the early universe (decoupling of fundamental forces)

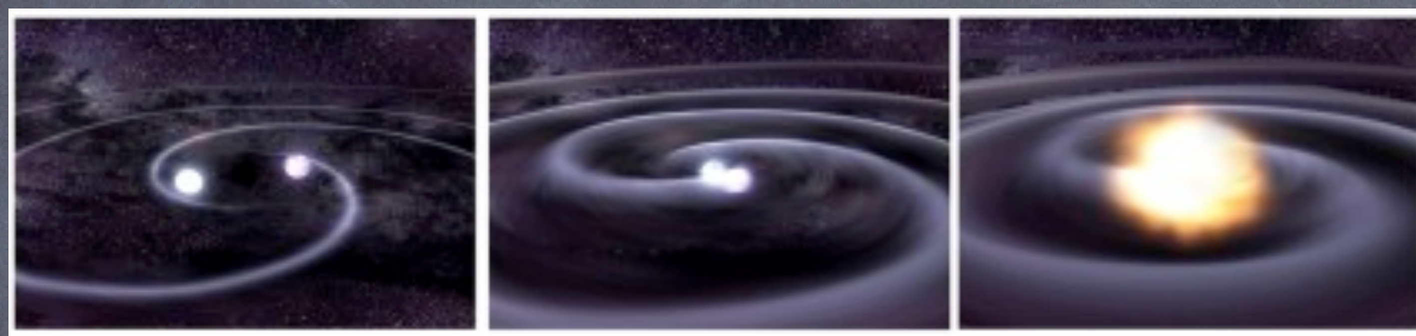
Gravity Wave Production

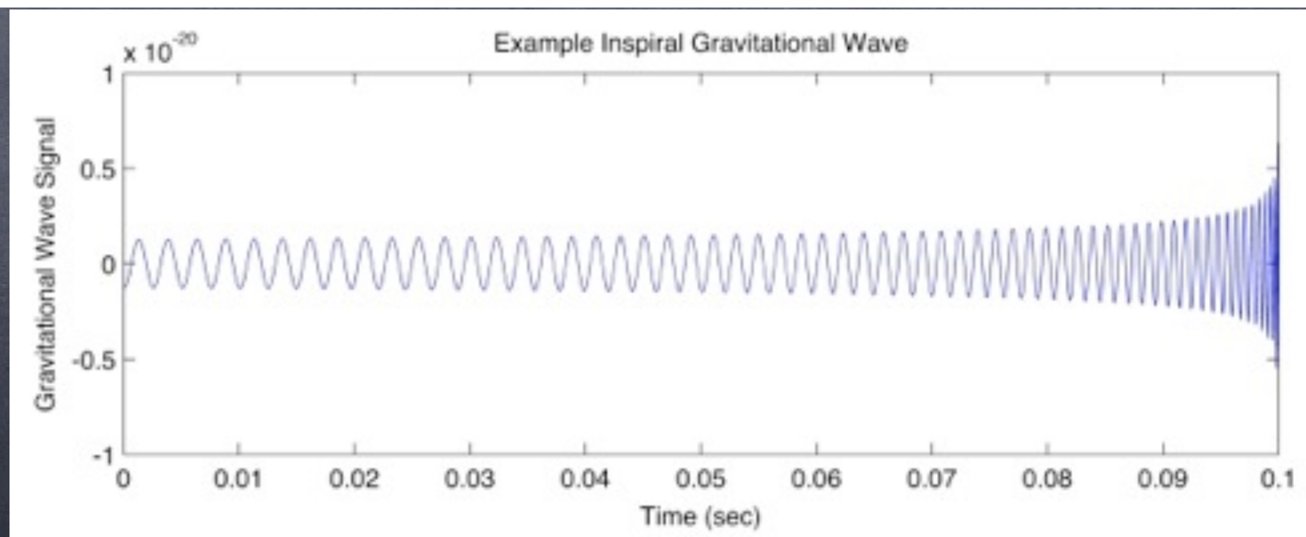
illustration of a binary black hole system

NASA's Imagine the Universe site

Gravity Wave Production

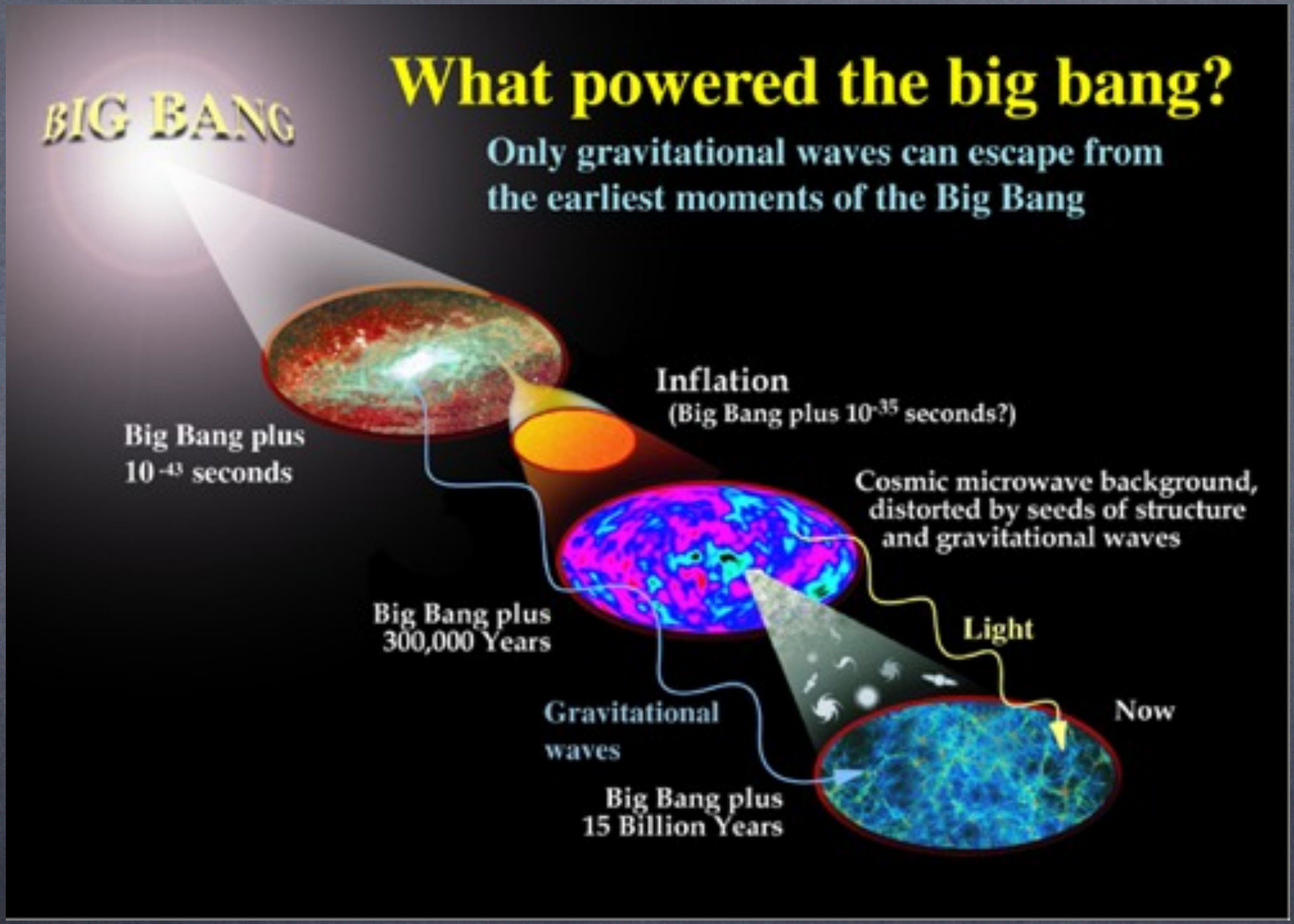
inspiral of a binary system





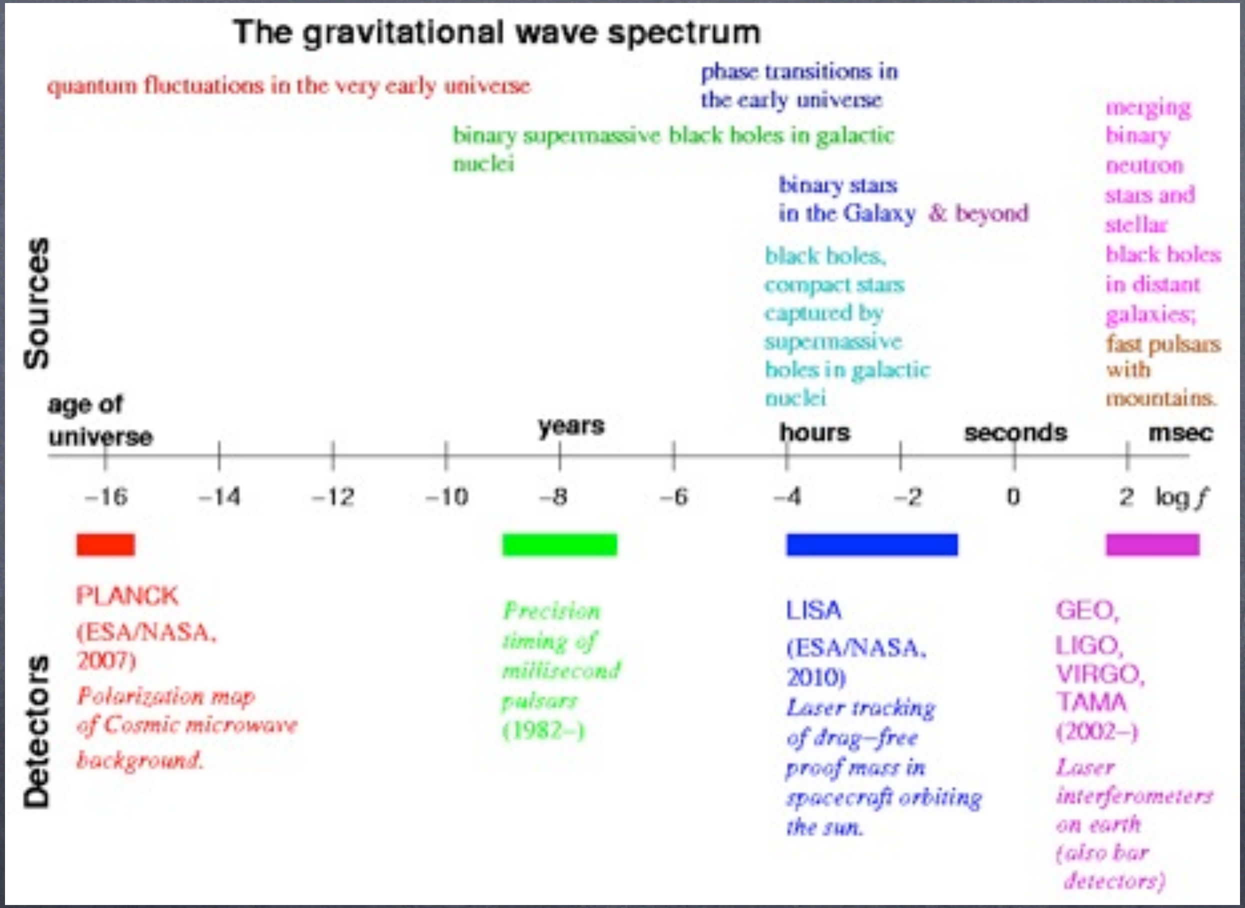
LIGO Website

Gravity Wave Production



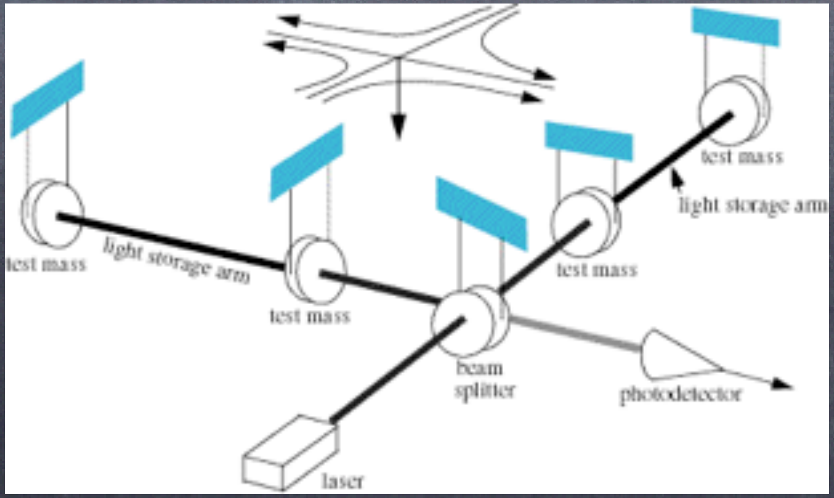
NASA, LIGO Website

Gravity Wave Astronomy

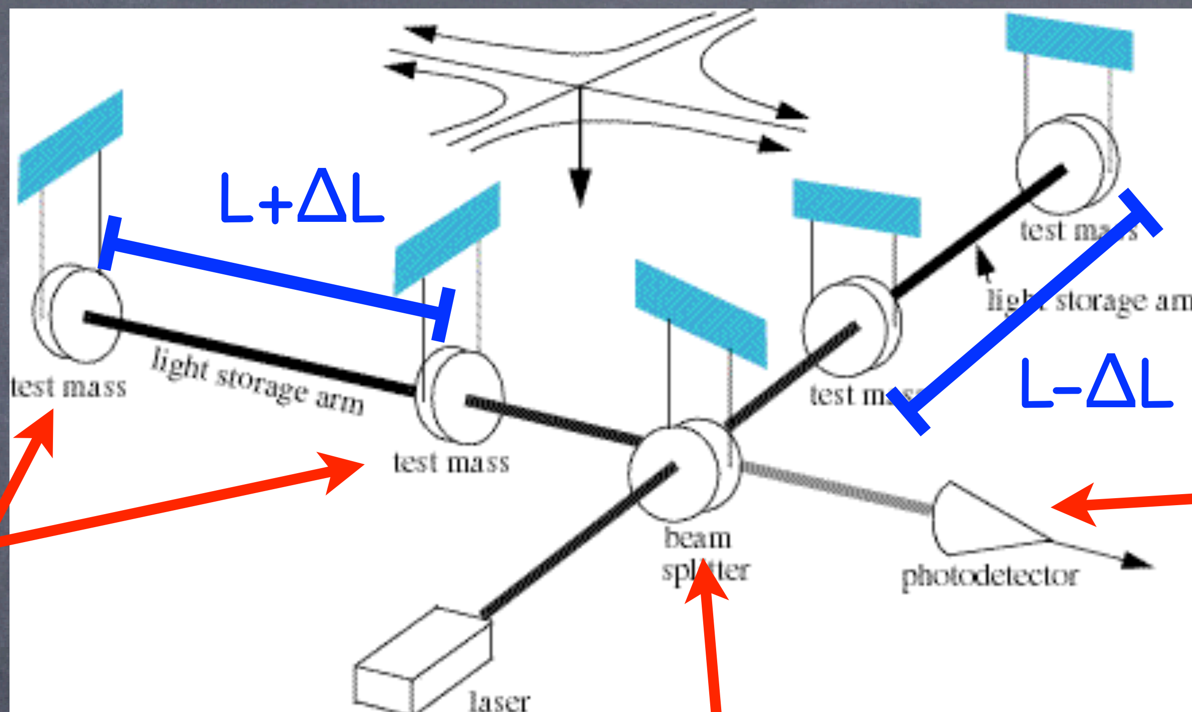


Gravity Wave Detection

Gravity waves can be detected using laser interferometers. Gravitational waves compress in one direction and stretch in the perpendicular direction. Lasers are used to accurately measure the distance to freely moving test masses at large distances in two perpendicular directions. If a gravitational wave passes the relative distance along the arms changes. The lasers will then be slightly out of phase (originally tuned to destructively interfere).



Gravity Wave Detection



Suspended mirrors at either end of the arms

After about 75 trips the light is recombined

Laser split in to two beams

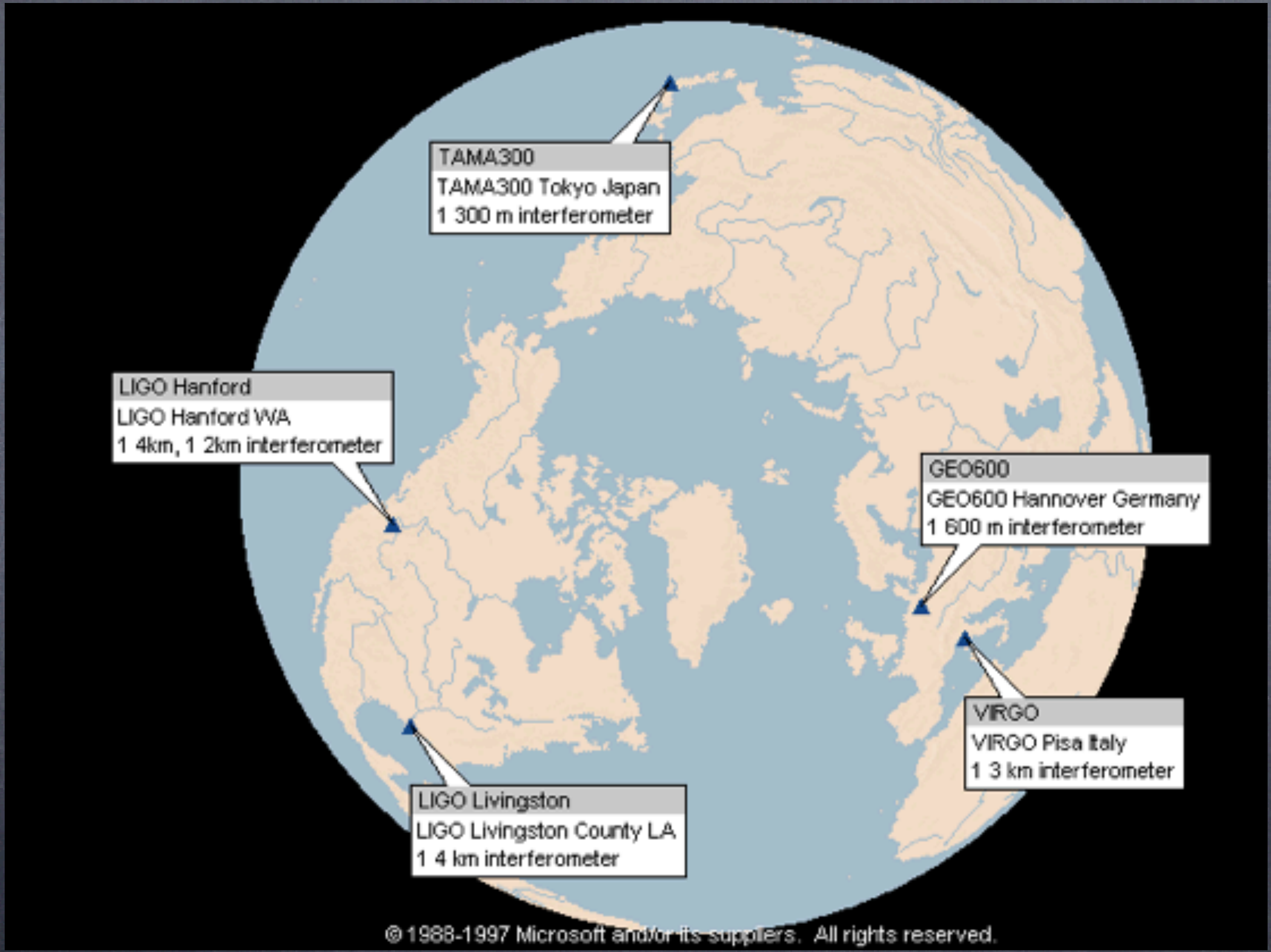
$\Delta L = hL \approx 10^{-18}$ m for a strong gravitational wave, so $h \approx 10^{-21}$ for a few km baseline.

LIGO

LIGO has two observatories one in Washington State and one in Louisiana, separated by about 3000 km. Each has L-shaped, high vacuum arms 4 km in length. Having two sites allows for confirmation of a signal and triangulation (difference in arrival time of less than 10 msec).

Advanced LIGO is scheduled to start in 2014 and will give a factor of 10 improvement in sensitivity. Upgrades include a higher power laser, new test masses, upgraded seismic isolation system...

Network of

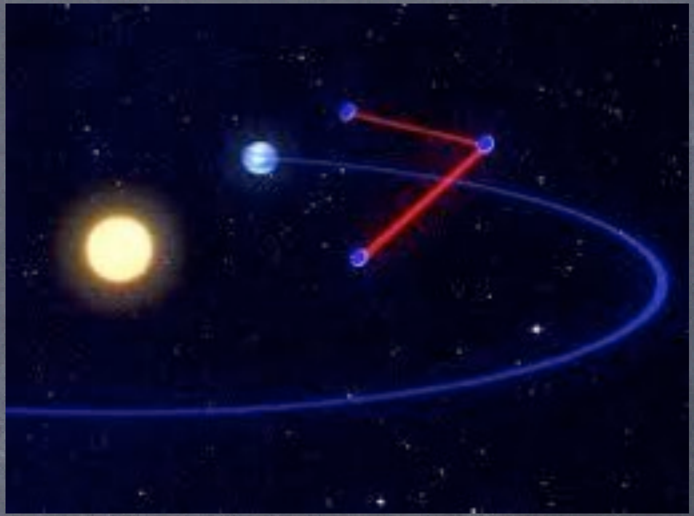


lecture by Kip Thorne

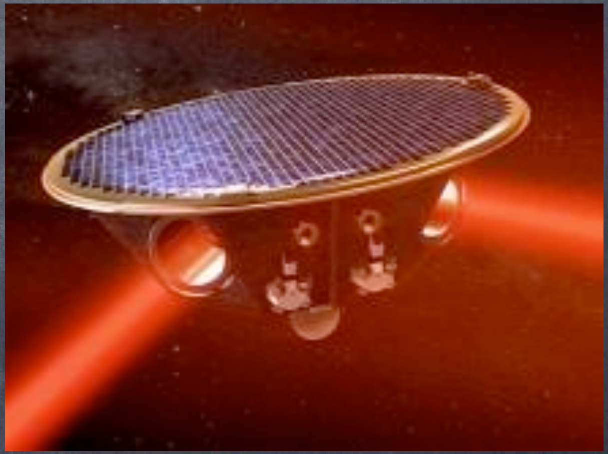
eLISA/NGO

(ESA L-class mission)

Due to budget problems, ESA and NASA are no longer working together on LISA. ESA is pursuing a mission on their own.



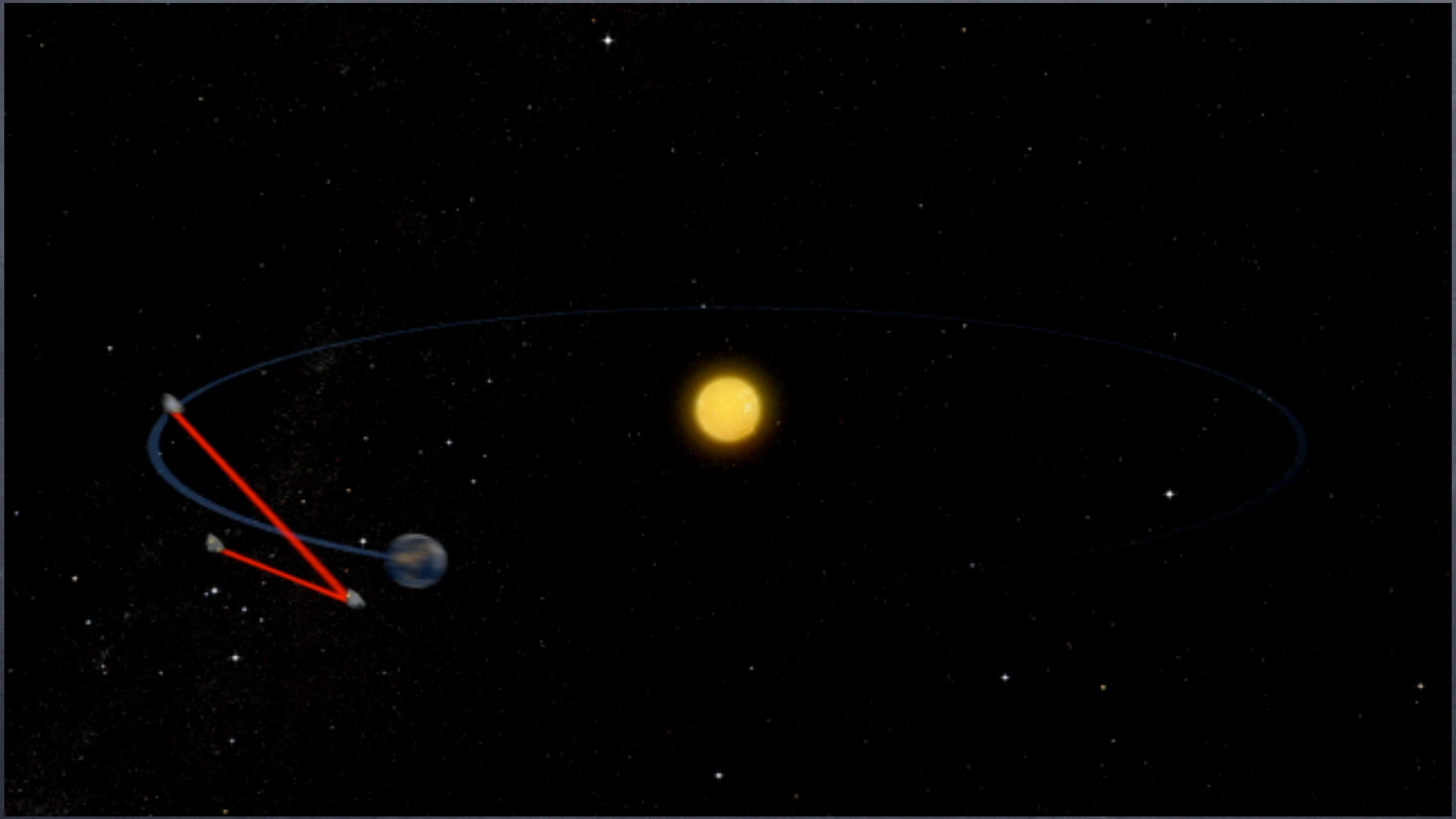
eLISA/NGO will be composed of three spacecraft separated by 10^6 km. Distance is measured to free falling test masses inside the spacecrafts. (Note: 1 AU = 149×10^6 km)



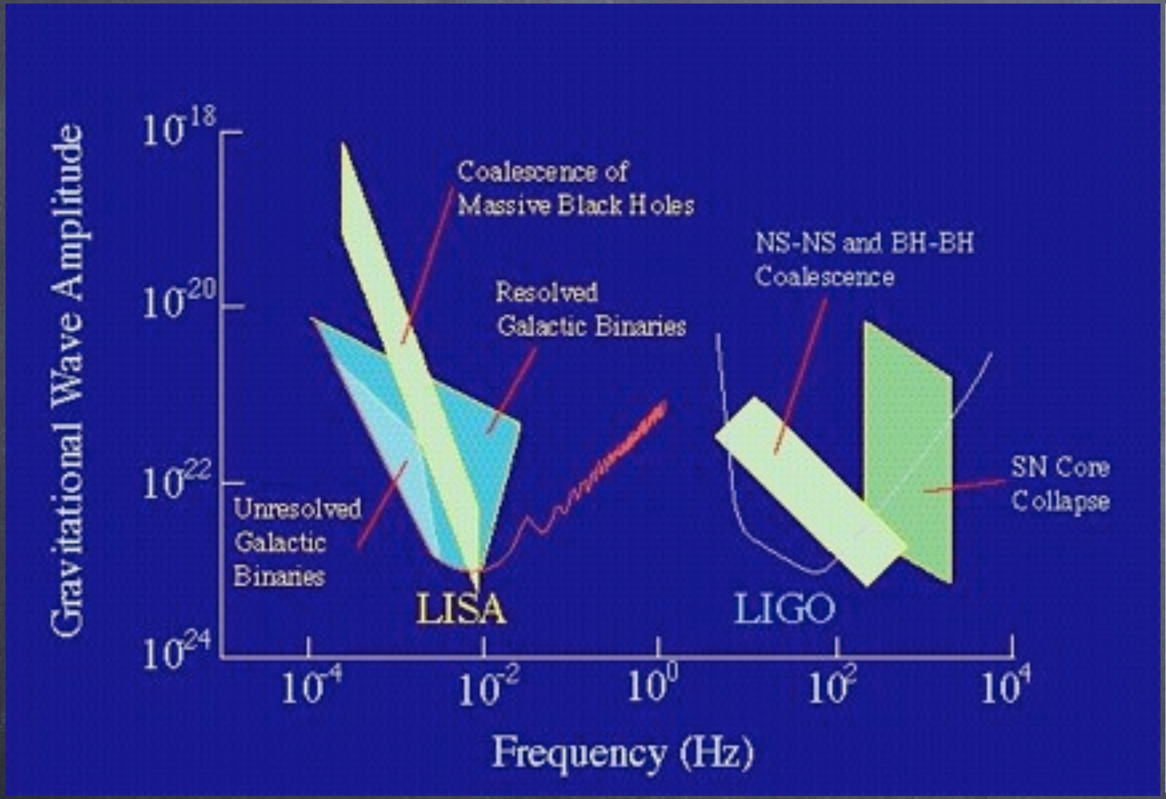
LISA Pathfinder 2015: test of technology for LISA including spacecraft control and accuracy of laser interferometry. It will place two test masses in free fall and test controlling and measuring their motion.

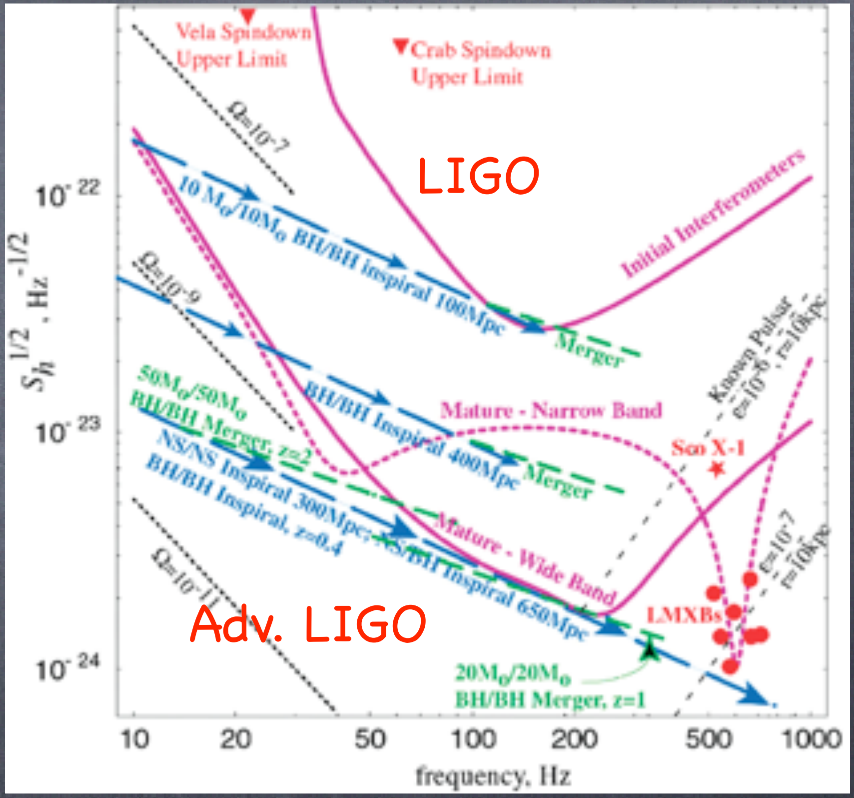
* Not selected by ESA in the last round *

eLISA Orbit



Sensitivity





Pulsar Timing Array

Detect gravitational waves using an array of millisecond pulsars.

A passing gravitational wave would advance or delay the radio pulses as they travel to Earth. Changes in an individual pulsar would be difficult to interpret, but an array of pulsars should show correlated delays.

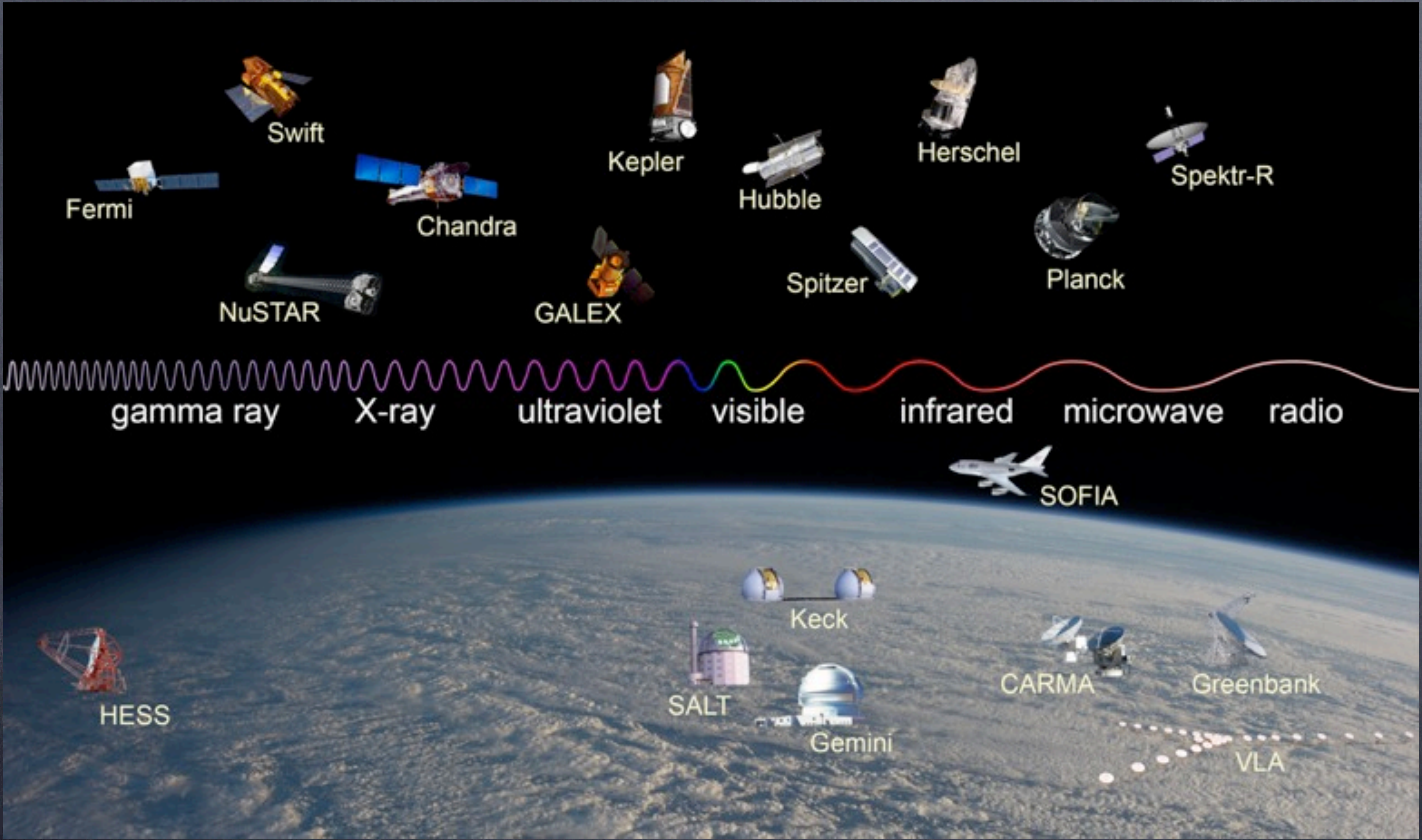
Currently three projects:

- Nanohertz Observatory for Gravitational Waves (NANOGrav), uses Arecibo and the GBT
- the European Pulsar Timing Array (EPTA)
- the Parkes Pulsar Timing Array (PPTA)

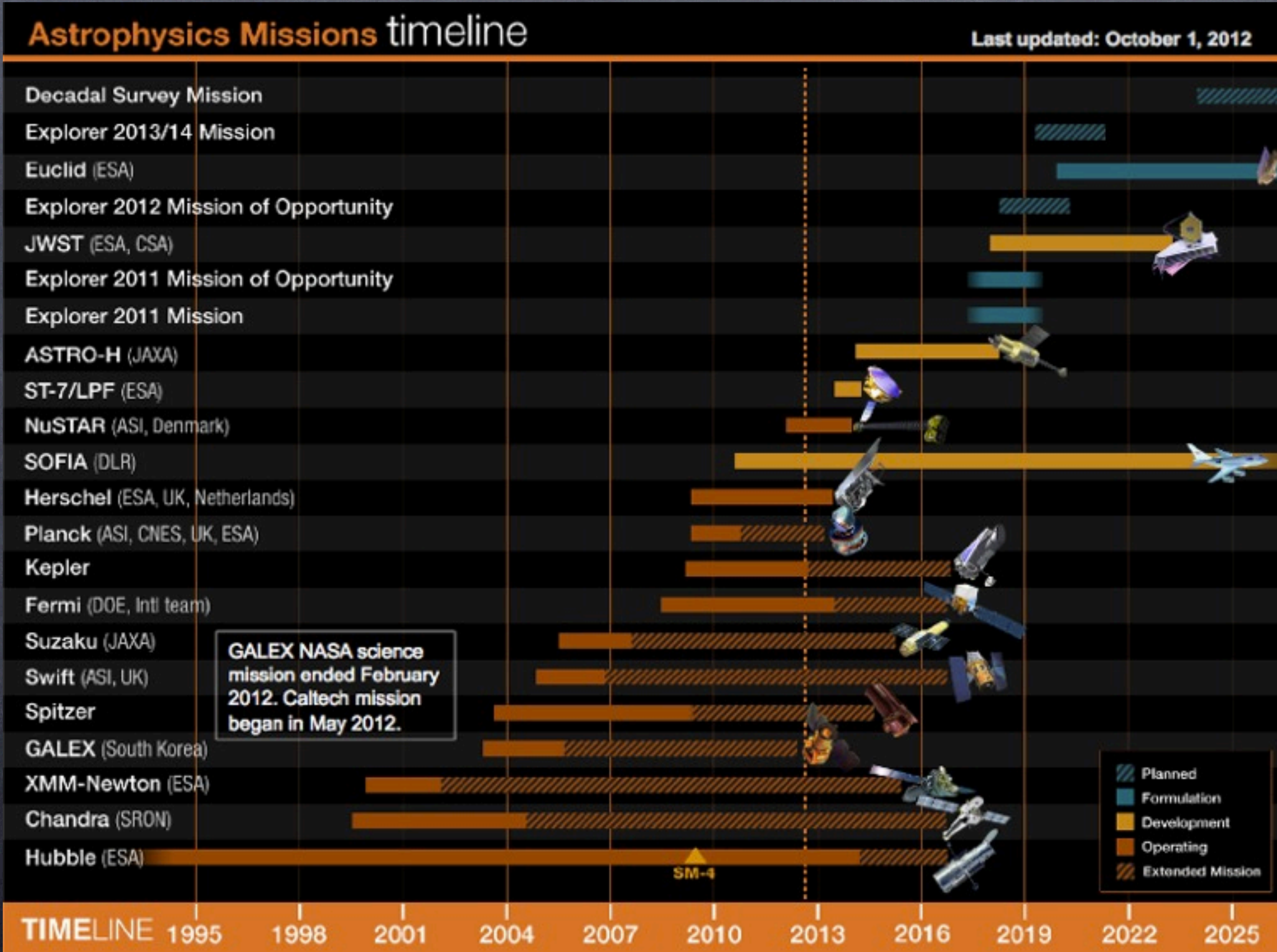
Scott Ransom, "Pulsars are Cool. Seriously.", arXiv:1211.3138

Future Astronomical Facilities

Current



NASA's Imagine the Universe site


Astrophysics Missions timeline
Last updated: October 1, 2012
Decadal Survey Mission
Explorer 2013/14 Mission
Euclid (ESA)
Explorer 2012 Mission of Opportunity
JWST (ESA, CSA)
Explorer 2011 Mission of Opportunity
Explorer 2011 Mission
ASTRO-H (JAXA)
ST-7/LPF (ESA)
NuSTAR (ASI, Denmark)
SOFIA (DLR)
Herschel (ESA, UK, Netherlands)
Planck (ASI, CNES, UK, ESA)
Kepler
Fermi (DOE, Intl team)
Suzaku (JAXA)
Swift (ASI, UK)
Spitzer
GALEX (South Korea)
XMM-Newton (ESA)
Chandra (SRON)
Hubble (ESA)
GALEX NASA science mission ended February 2012. Caltech mission began in May 2012.
SM-4
Planned
Formulation
Development
Operating
Extended Mission
TIMELINE 1995 1998 2001 2004 2007 2010 2013 2016 2019 2022 2025

Future Radio

Improvements, New Capabilities:

- open up new frequency ranges with new low frequency capabilities
- major jumps in sensitivity
- improved spatial resolution

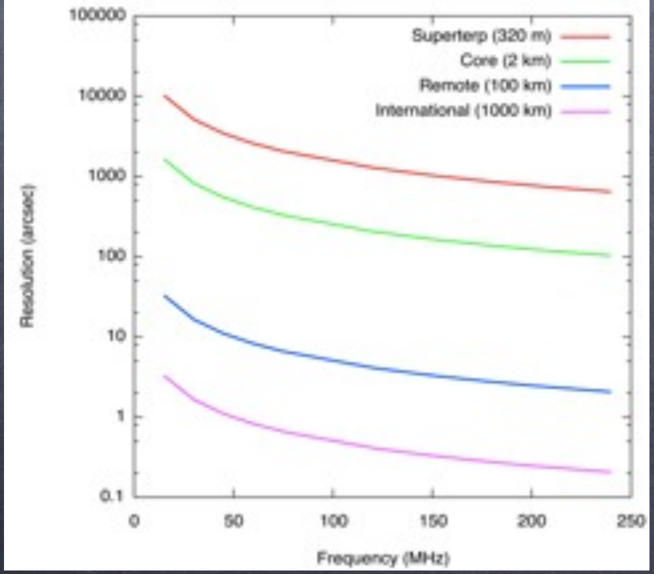
Near Term Telescopes

New Low Frequency Facilities:

LOFAR: 10 - 240 MHz, ~25,000 small antennas, 40 stations in the Netherlands, 5 in Germany, 1 each in Britain, France, and Sweden, max baseline 1000 km, partially operational now

LWA: 10-88 MHz, 13,000 antennas over 400 km, 1/53 stations working

Largely unexplored frequency range, big gains in sensitivity. Science drivers include redshifted 21 cm line at z>6 (epoch of reionization), studying high-z radio galaxies.



LOFAR website

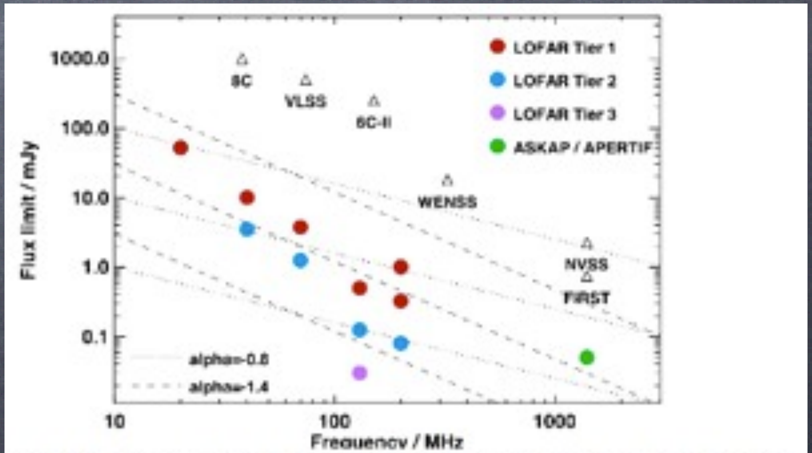


Fig 2 - Flux limits (5 sigma) of the proposed LOFAR surveys compared to other existing radio surveys. The triangles represent existing surveys. The lines represent different power-law ($S \sim \nu^{\alpha}$, with $\alpha = -1.4$ and -0.8) to illustrate how, depending on the spectral indices of the sources, the LOFAR will compare to other surveys.

arXiv: 1001.2384

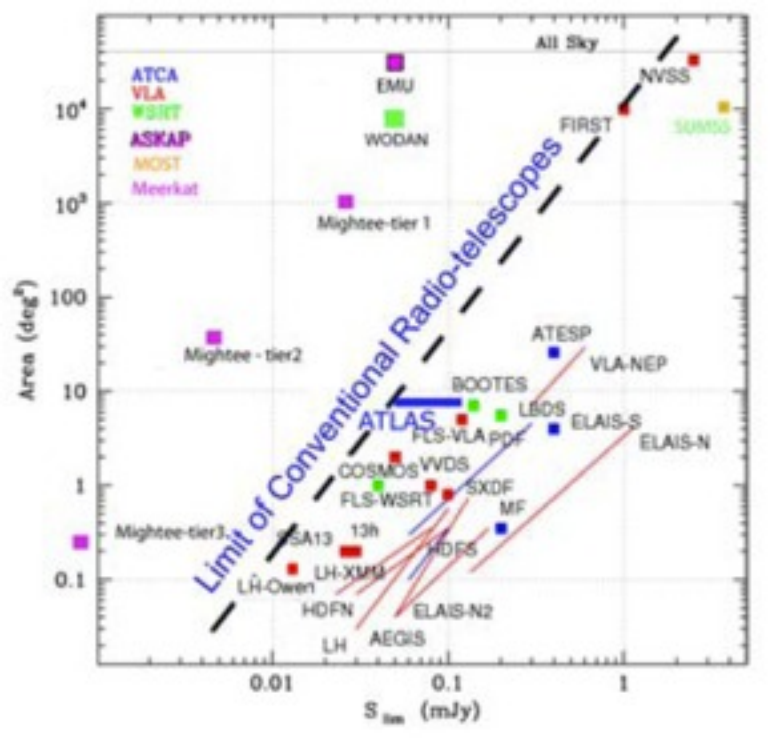
Near Term Telescopes

Precursors to SKA:

Australian SKA Pathfinder: 0.7-1.8 GHz, 36 12-m dishes, max baseline 4 km, min baseline 20ish m, in commissioning

ASKAP has a large field of view (30 deg^2) and is optimized for surveys. Will go ~10x deeper than current surveys

MeerKAT: 0.5-14 GHz, 64 13.5-m dishes, complete 2016-18, in South Africa, max baseline 20 km, min baseline 29 m



arXiv: 1210.7521

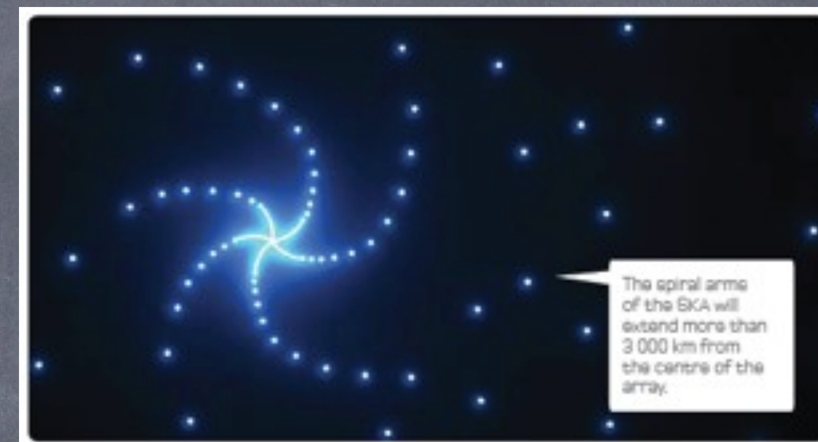
Future Telescopes

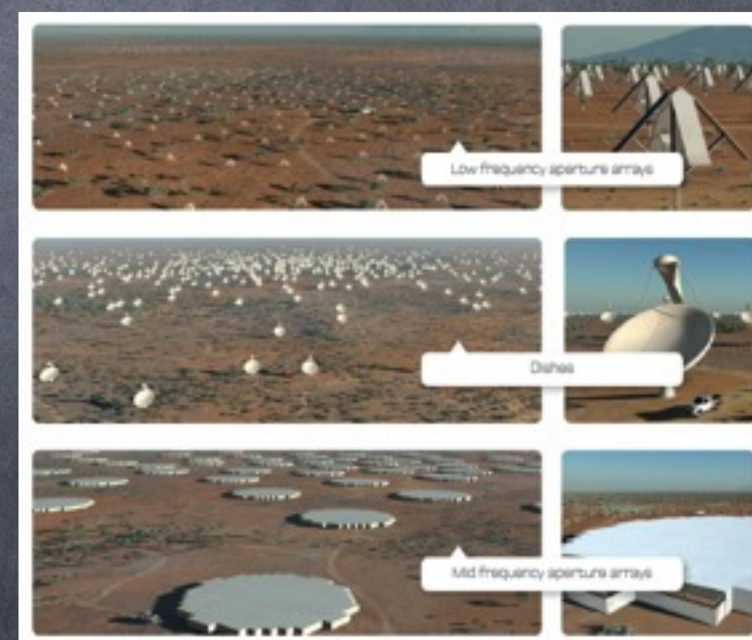
Square Kilometer Array (SKA): circa 2024

- 70 MHz to 10 GHz
- collecting area equal to 1 km^2
- located in the southern hemisphere and incorporating both ASKAP and MeerKAT
- longest baseline >=3000 km

Science:

- 21 cm from a billion galaxies, map large-scale structure in radio
- reionization
- pulsar tests of general relativity (gravity wave detection, pulsars orbiting BHs
- cosmic magnetism (Faraday rotation)





SKA Fact Sheet

Future Microwave

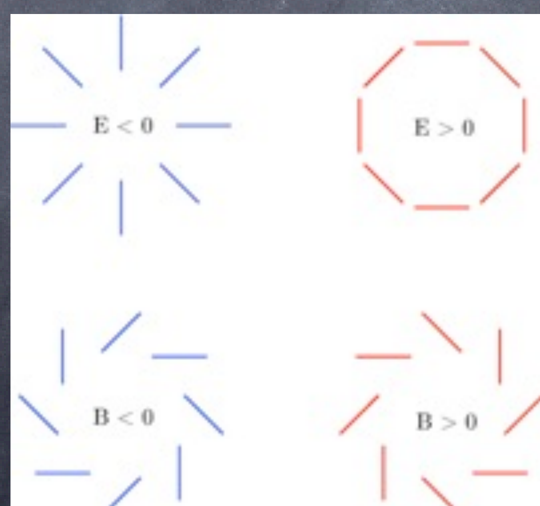
Improvements, New Capabilities:

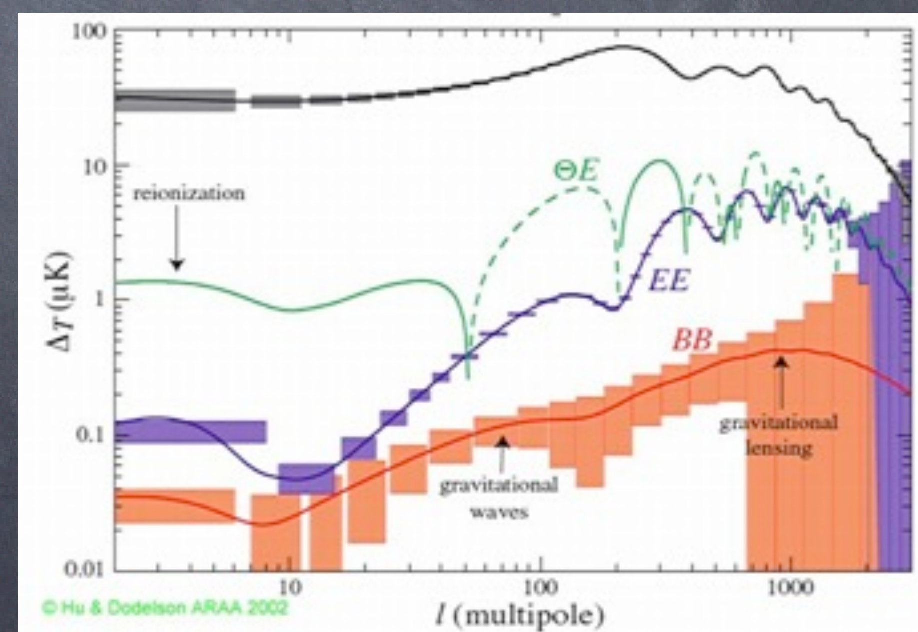
- polarization

Experiments: SPTpol, ACTPol, Planck, POLARBEAR

Thompson scattering

gravity waves, lensing mixes E with B





Future Infrared

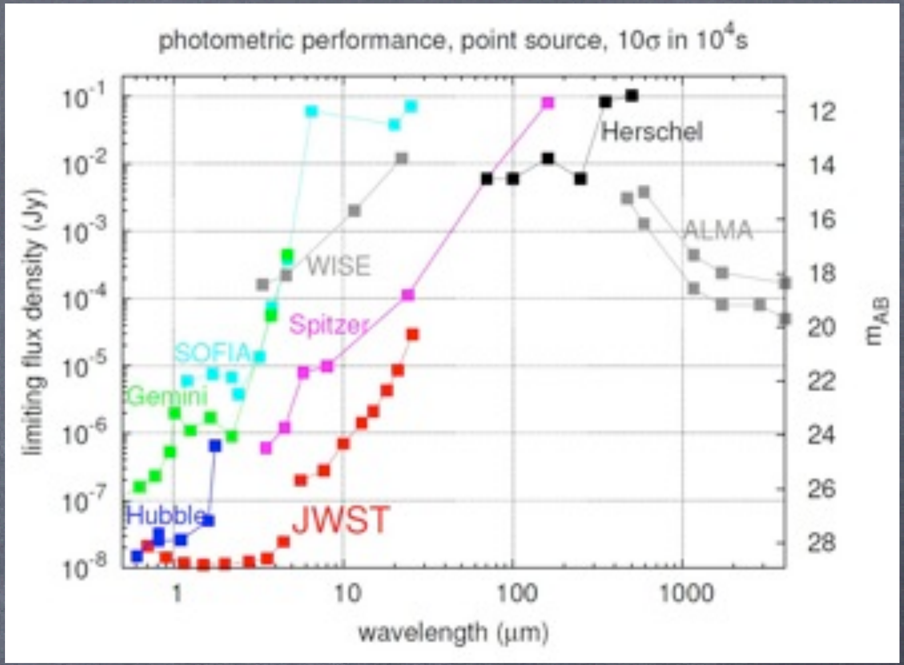
Improvements, New Capabilities:

- sensitivity
- spatial resolution

Future Telescopes

James Webb Space Telescope:

- 6.5 m telescope, near-IR to mid-IR
- launch planned for 2018
- instruments: NIR camera,
  NIR spectrograph,
  MIR imager/spectrograph



Space Infrared Telescope for Cosmology and Astrophysics (SPICA):

A proposed mid and far-IR satellite joint between Japan, ESA, NASA(?), current plan is 2022

- 3.5-m mirror (similar to Herschel), 3.5 to 210 μm
- colder than Herschel for better far-IR

Future Optical

Improvements, New Capabilities:

- sensitivity
- large-area surveys: statistics, depth, variability
- spatial resolution: ground (AO), space (JWST)

Future Telescopes

Thirty meter class telescopes (TMT, GMT, ELT):

- Thirty Meter Telescope: 30-m, 0.3–28 μm, Mauna Kea
- Giant Magellan Telescope: 25-m, 0.3-25 μm, Las Campanas, Chile
- Extremely Large Telescope: 39-m at Cerro Armazones, Chile

TMT early instruments will include:

- WFOS: optical wide-field, multi-object spectrograph
- IRIS: near-infrared IFU spectrometer with imaging capability
- IRMS: near-infrared spectrometer with imaging capability

The near-IR instruments will use the AO system, and the plan is to get diffraction limited resolution (~10 milliarcsecs).

Science (some): first galaxies, epoch of reionization, supermassive black holes form and relationship of black hole growth to galaxy evolution, Earth-mass extrasolar planets and planetary atmospheres

Scale of the ELT

Surveys

Current Surveys:

Dark Energy Survey:

- 5000 deg^2 survey in 5 bands, Blanco 4-m telescope
- 10 SN fields observed every ~5 days

Pan-STARRs: 4 1.8-m telescopes (1 operational, PS2 2013)

- survey all objects visible from Hawaii to an apparent magnitude 24
- prime mission to detect asteroids, but will be great for all types of variable objects: SN, variable stars, extrasolar planets, GRBs ...

Future Surveys:

LSST: (2022)

- 6-band (0.3-1.1 μm) 20,000 deg^2 survey
- 8.4-m telescope with a 3.5 deg diameter FOV, will image the entire survey area every 3 days

Euclid: (2020)

- ESA satellite, 1.2-m telescope, wide survey 15,000 deg^2 survey
- optical and NIR imaging, NIR spectroscopy
- weak lensing and baryon acoustic oscillations

Surveys

The primary goal these large-area surveys is to probe cosmology/dark energy, but also galaxy evolution, map the Milky Way. Pan-STARRs and LSST will also provide the first large (and deep) surveys for optical transients.

Transient sources include:

- Supernovae and GRBs
- gravitational lens variability
- AGN and blazars
- microlensing events
- variable stars
- possibly stellar disruptions by black holes, binary mergers, ...

LSST will provide the possibility for triggering on interesting sources including those from other wavelengths.

--> The major challenge will be identifying the important variable sources, since every LSST image will contain normal source variations and instrumental artifacts!

Future UV

Improvements, New Capabilities:

?

The UV community is currently going through a planning phase for future missions and science. A moderate mission concept could go forward ~2015 or large ~2019.

NASA RFI in 2012 for Science Objectives and Requirements for the Next UV/Visible Astrophysics Mission Concepts: http://cor.gsfc.nasa.gov/RFI2012/

UV Astronomy HST and Beyond Meeting: http://uvastro2012.colorado.edu/program.shtml

First Name	Last Name	Title	Ang. Res.	Tel. Diam.	λshort	λlong	FOV	Spec. Res.	Sensi-tivity	Phot?	Spec?	Mux?	Time?	Science Category
Theodore	Gull	How do molecules and dust form in massive interacting winds?	<0.010"						<<HST		Y	MOS		Stars
Judith	Provencal	The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution		2m+	912Å	3000Å	10'x10'	50,000	V~35	Y	Y	IFU		Stars
James	Lawler	The Origin of the Elements Heavier than Iron			1900Å	3050Å	10'x10'	60,000			Y	MOS		Stars
Coralie	Neiner	UVMag: Stellar physics with UV and visible spectropolarimetry			1170Å	0.87μm		25,000	V~10	Y; pol			Y	Stars
Richard	Ignace	Response to Request for Information: NNH12ZDA008L								Y; pol			Y	Stars
Kenneth	Carpenter	Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems	<0.0001"							Y	Y		Y	Stars
Paul	Scowen	Understanding Global Galactic Star Formation	0.020"	1.5m-4m	2500Å	0.95μm	15'x15'			Y				Star Formation
Paul	Scowen	The Magellanic Clouds Survey - a Bridge to Nearby Galaxies	<0.1"	2m-4m	2000Å	~1μm	10'x10'	30,000	10^{-16} erg/s/cm^2	Y	Y			Star Formation; Stars
Aida	Wofford	Massive Stars: Key to Solving the Cosmic Puzzle		≥10m	912Å	0.9μm		6,000			Y			Nearby Galaxies; Stars
Martin	Barstow	Conditions for Life in the Local Universe			1000Å	3000Å		100,000		Y	Y			Nearby Galaxies; Stars
Thomas	Brown	The History of Star Formation in Galaxies		8-16m					V~35	Y				Nearby Galaxies
Paul	Goudfrooij	Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies		2m/8m			20'x20'			Y	Y	MOS		Nearby Galaxies
Benjamin	Williams	The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies	4xHST	8m-10m			100xHST			Y				Nearby Galaxies
Karl	Gordon	A Census of Local Group Ultraviolet Dust Extinction Curves	0.1"		1150Å	4100Å		1000		Y	Y			Nearby Galaxies
Michael	Shull	The Baryon Census in a Multiphase Intergalactic Medium		>4m	<1000Å			~100,000	2mÅ EW		Y			IGM
Todd	Tripp	Quasar Absorption Lines in the Far Ultraviolet: An Untapped Gold Mine for Galaxy Evolution Studies			1000Å			like COS	<<HST		Y			IGM
Ana	Gomez de Castro	Seeking into the anthropic principle			1000Å	4000Å								IGM
Claudia	Scarlata	The escape fraction of ionizing photons from dwarf galaxies	1"		2000Å	0.63μm		5000	~32nd AB	Y	Y			IGM
David	Schiminovich	Science from IGM/CGM Emission Mapping			1250Å	4000Å	4'x4'	5000	5 Y/cm^2/s/s		Y	MOS		IGM
Stephan	McCandliss	Project Lyman: Quantifying 11 Gyrs of Metagalactic Ionizing Background Evolution			1000Å	4000Å	0.5°^{2}		10^{-4} FEFU		Y	MOS		IGM
Gerard	Kriss	Synergistic Astrophysics in the Ultraviolet using Active Galactic Nuclei		8m	900Å	3200Å		15,000	10 FEFU		Y		Y	AGN; IGM
Steven	Kraemer	Active Galactic Nuclei and their role in Galaxy Formation and Evolution	<0.0001"					~500		Y	Y			AGN
Bradley	Peterson	UV Spectroscopic Time Domain Studies of Active Galactic Nuclei			1100Å	3000Å		600			Y		Y	AGN
Matthew	Hayes	Extragalactic Lyman-alpha Experiments in the Nearby Universe			1216Å	3500Å	0.1°^{2}	100	10^{-16} erg/s/cm^2		Y	Any		Galaxy Evolution
Paul	Scowen	Galaxy Assembly and SMBH/AGN-growth from Cosmic Dawn to the End of Reionization	≤0.040"	2.4m-4m	1216Å	~1μm	15'x15'		~30th AB	Y	Y	Slitless		Galaxy Evolution
Sara	Heap	A UV/Optical/Near-IR Spectroscopic Sky Survey for Understanding Galaxy Evolution		0.5m-2.4m	2000Å	1.7μm			0.001 FEFU		Y			Galaxy Evolution
Olivier	Doré	An Optical and Ultraviolet Cosmological Mapper	30"	0.5m	1216Å	0.85μm			10^{-16} erg/s/cm^2	Y	Y			Galaxy Evolution
Charlie	Noecker	Exoplanet Science of Nearby Stars on a UV/Visible Astrophysics Mission		2m-4m	UV	NIR		100		Y; coron.	Y		Y	Planets
Timothy	Cook	Ultraviolet imaging of exoplanets		0.5m-1.5m						Y; coron.	Y			Planets
Kevin	France	From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy			912Å	4000Å	10'x10'	100,000	0.01 FEFU		Y	MOS		Planets
Michael	Wong	Solar System Science Objectives with the Next UV/Optical Space Observatory	0.05"		UV	IR		2500		Y	Y		Y	Solar System
Patrick	Côté	Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths	0.15"	1m			0.67°^{2}		NUV~26	Y			Y	Multiple
Jason	Tumlinson	Unique Astrophysics in the Lyman Ultraviolet			912Å	1216Å		50,000	~30th AB		Y	MOS or IFU		Multiple
Melville	Ulmer	White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)		2.4m	UV	Vis	6'x6'		~10X HST	Y	Y			Multiple

Future X-ray

Improvements, New Capabilities:
(near term gains)

- hard X-ray sensitivity and spatial resolution
- spectral resolution
- all-sky survey depth

Near Term

Hard X-ray Imaging:

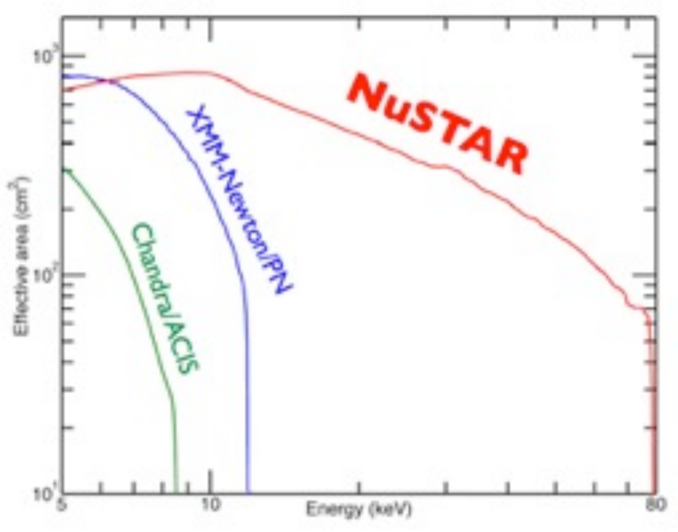
- NuSTAR (2012): 5-80 keV, 10″ resolution
- ASTRO-H (2014): similar to NuSTAR

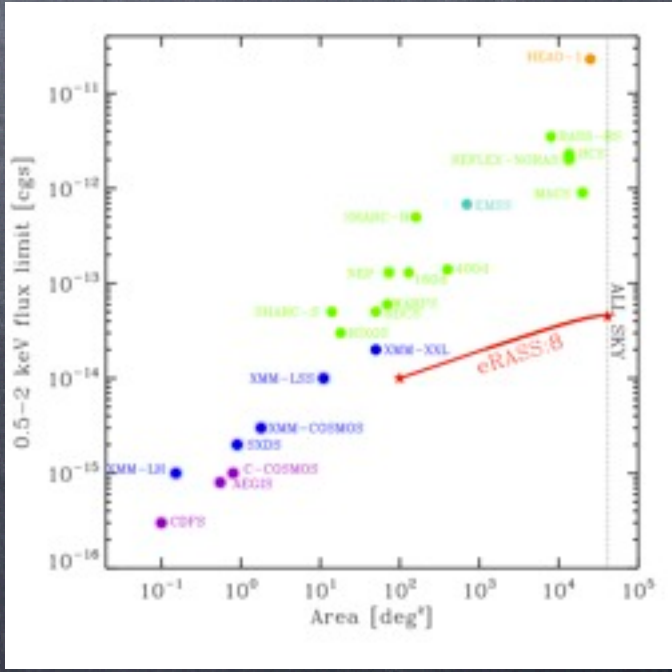
High Resolution Spectroscopy:

- ASTRO-H (2014): microcalorimeter 7 eV resolution

X-ray Surveys:

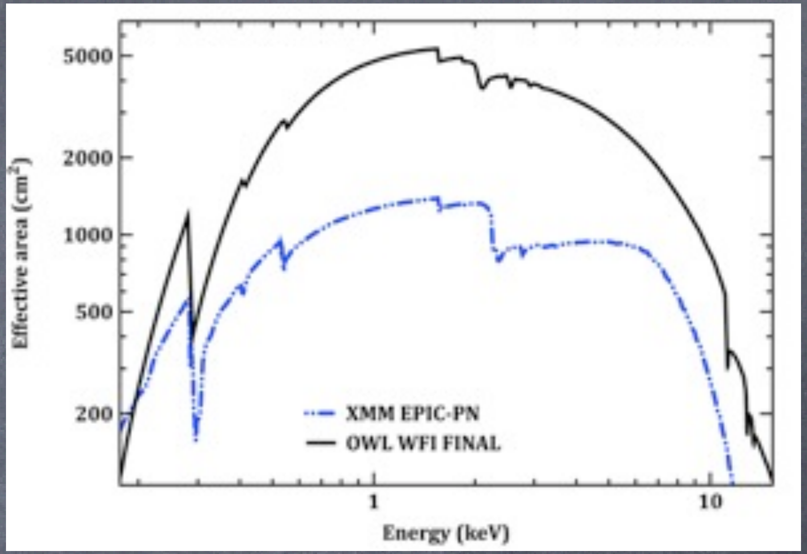
- eROSITA (2014), 0.5-10 keV, 15″-30″ resolution





Future X-ray Telescopes

ATHENA:
(formerly known as IXO and Con-X)
launch ???, orbit at L2
Wide-Field Imager: 24′ FOV, 0.1-15 keV
    5-10″ resolution, factor of 5 in
    effective area over XMM
X-ray Microcalorimeter Spectrometer:
    3 eV spectral resolution



--> Not selected in the last ESA round, now being proposed as ATHENA+

Future X-ray Telescopes

In 2011, NASA had a call for future X-ray mission concepts to address IXO science: http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

Notional Missions/Instruments include:

- A large high-spectral resolution calorimeter array
- A high-spectral resolution grating (better for point sources and below 1 keV)
- A wide-field imager for deep, high-z surveys

Technology improvements include lightweight optics and calorimeter array development.

Table 5.1-4. Notional Missions

Mission	Energy range	ΔE	Effective Area m^2 @ keV	Ang. Res.*	Field of view	Focal length	Cost Goal	MDL Cost
N-CAL	0.2–10 keV	< 3 eV (inner pixels)	0.5 @ 1 0.2 @ 6	10"	4"	9.5 m	<$1B	$1.2 B
N-XGS	0.2–1.3 keV	$\lambda/\Delta\lambda$ > 3000	0.05 @ 0.2–1.3	10"	n/a	4 m	<$600M	$0.8B
AXSIO	0.2–10 keV (XMS) 0.2–1.5 keV (XGS)	< 3 eV $\lambda/\Delta\lambda$ > 3000	0.93 @1.25 0.2 @ 6 0.1 @ 0.3–1	10"	4'	10 m	<$2B	$1.5B
N-WFI	0.2–10 keV	150 eV	0.7 @ 1 0.2 @ 6	7"	>24'	6 m	<$1B	$1.0B

*Measured in HPD

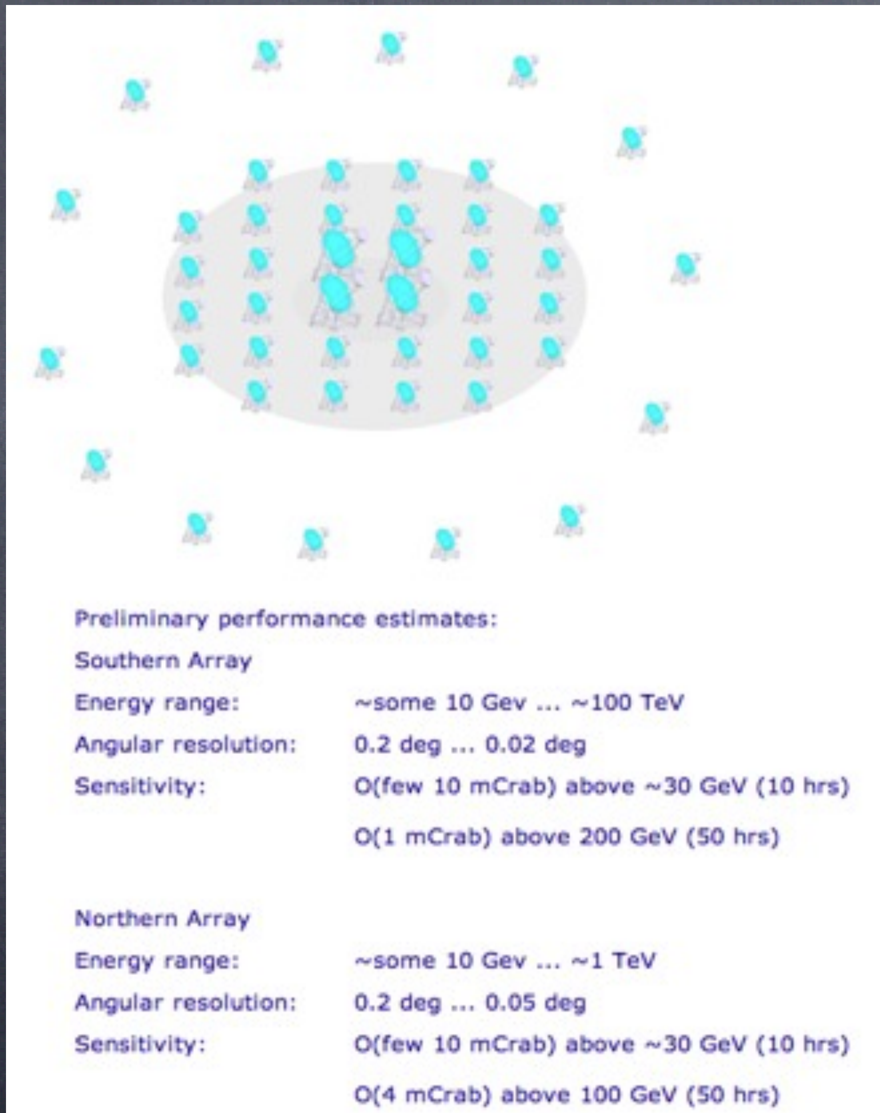
X-ray Mission Concepts Final Report

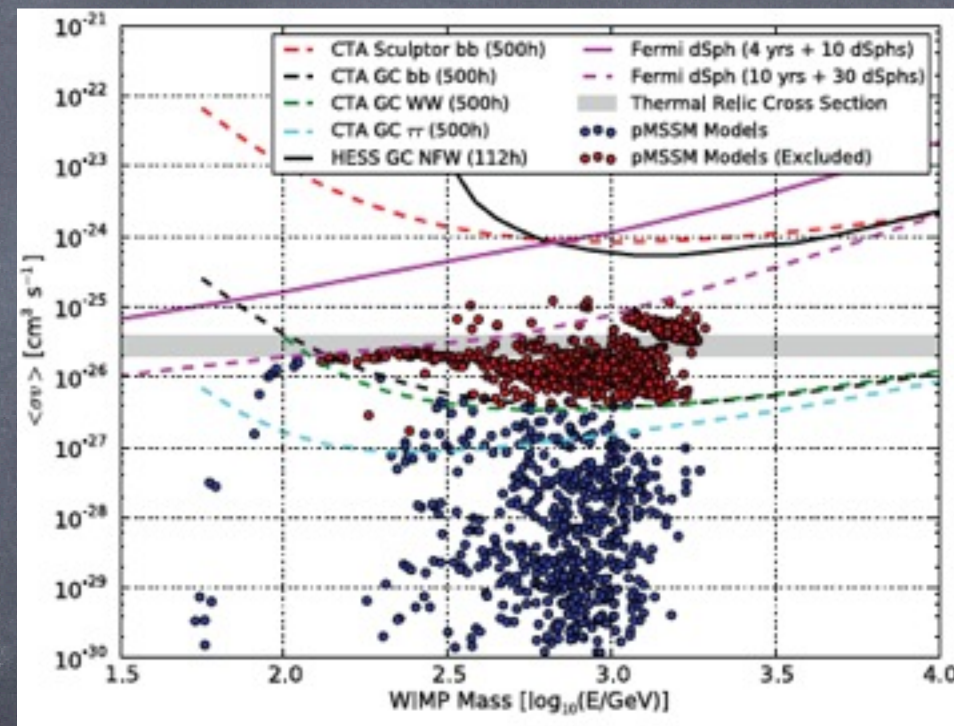
Future Gamma-ray

Improvements, New Capabilities:

- sensitivity above ~10 GeV

Cherenkov Telescope Array





CTA website

Future Missions

GAMMA-400:

new space mission for the 100 MeV - 3 TeV range, Russian mission, planned for 2018

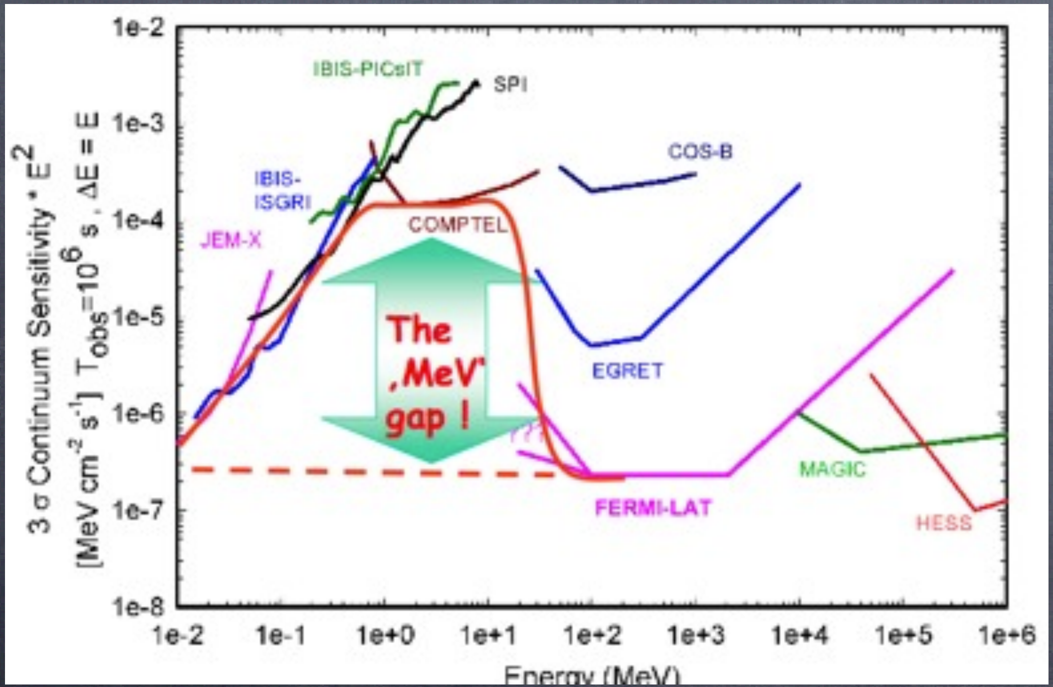
- angular resolution of 1-2 deg at 100 MeV, 0.01 deg > 100 GeV
- spectral resolution of 1% >100 GeV (Fermi 10%)
- effective area of ~4000 cm^2 at 100 GeV (Fermi ~7000 cm^2)

	Fermi-LAT	GAMMA-400
Orbit	560 km	500-300000 km
Energy range	100 MeV - 300 GeV	100 MeV - 3000 GeV
Sensitivity area	1.8 m^2	0.64 m^2
Coordinate detectors	Si strips with pitch 0.23 mm	Si strips with pitch 0.1 mm
Angular resolution (E_γ > 100 GeV)	~0.1°	~0.01°
Calorimeter - thickness, r.l.	CsI 8.5	BGO + CsI(Tl) + Si strips ~25
Energy resolution (E_γ > 10 GeV)	~10%	~1%
Proton rejection factor	10^4	~10^6
Mass, kg	2900	2600
Telemetry downlink volume, Gbytes/day	20	100

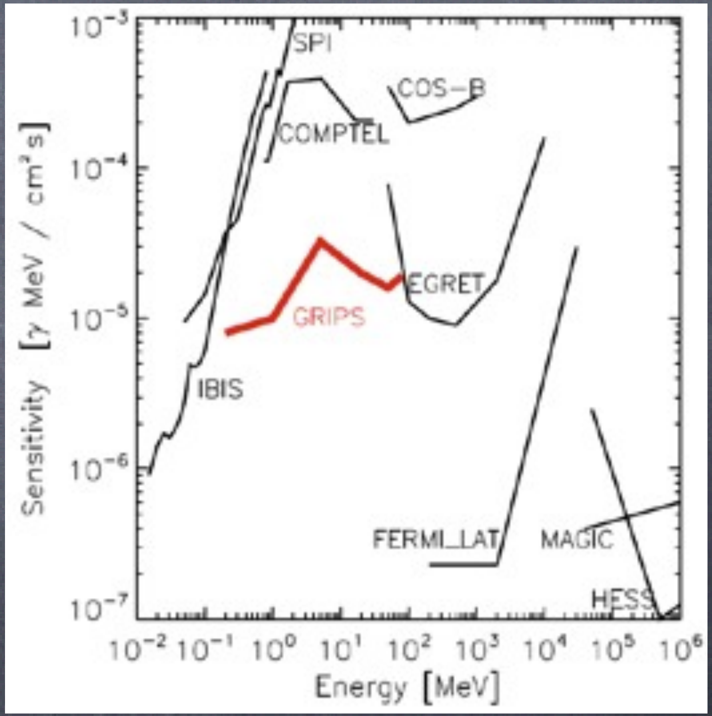
Galper et al. 2012, arXiv:1201.2490

Proposed Missions

GRIPS (Gamma-Ray Imaging, Polarimetry and Spectroscopy): proposed mission to fill the MeV gap



Kanbach, SLAC talk, 2009



Foley et al., SPIE 2012