Cosmology, high-energy astrophysics, & fundamental physics in the ESA space science programme

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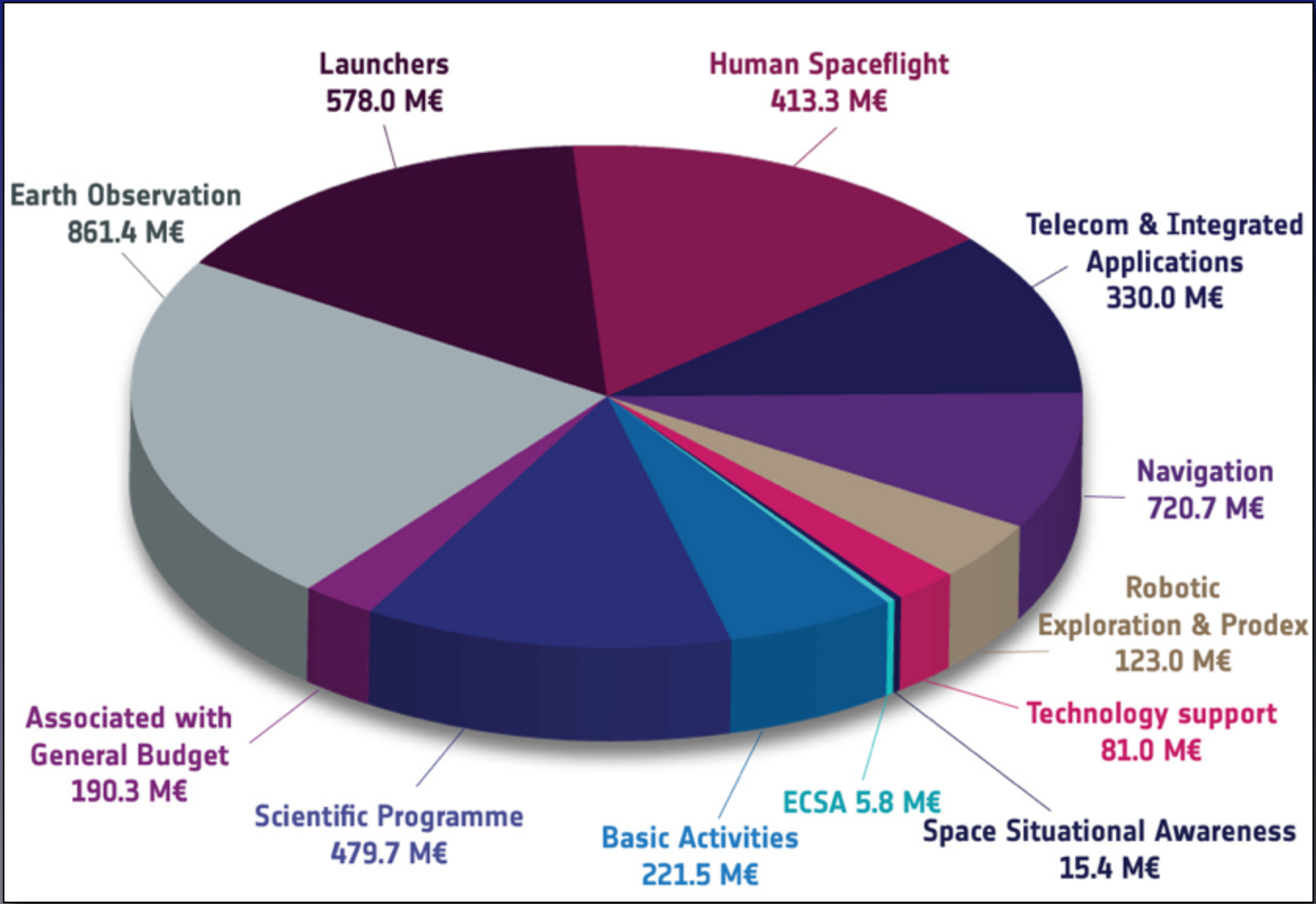
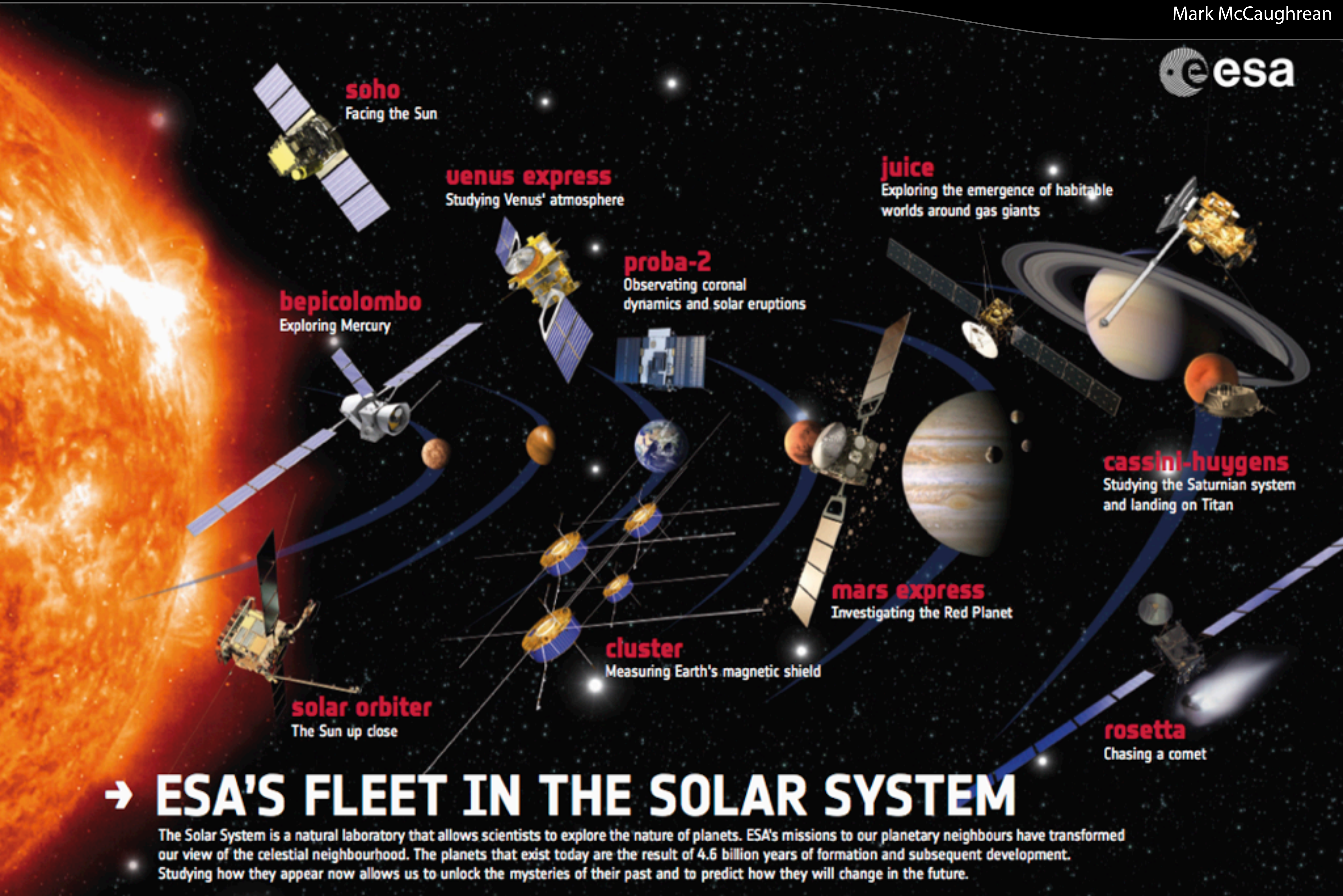
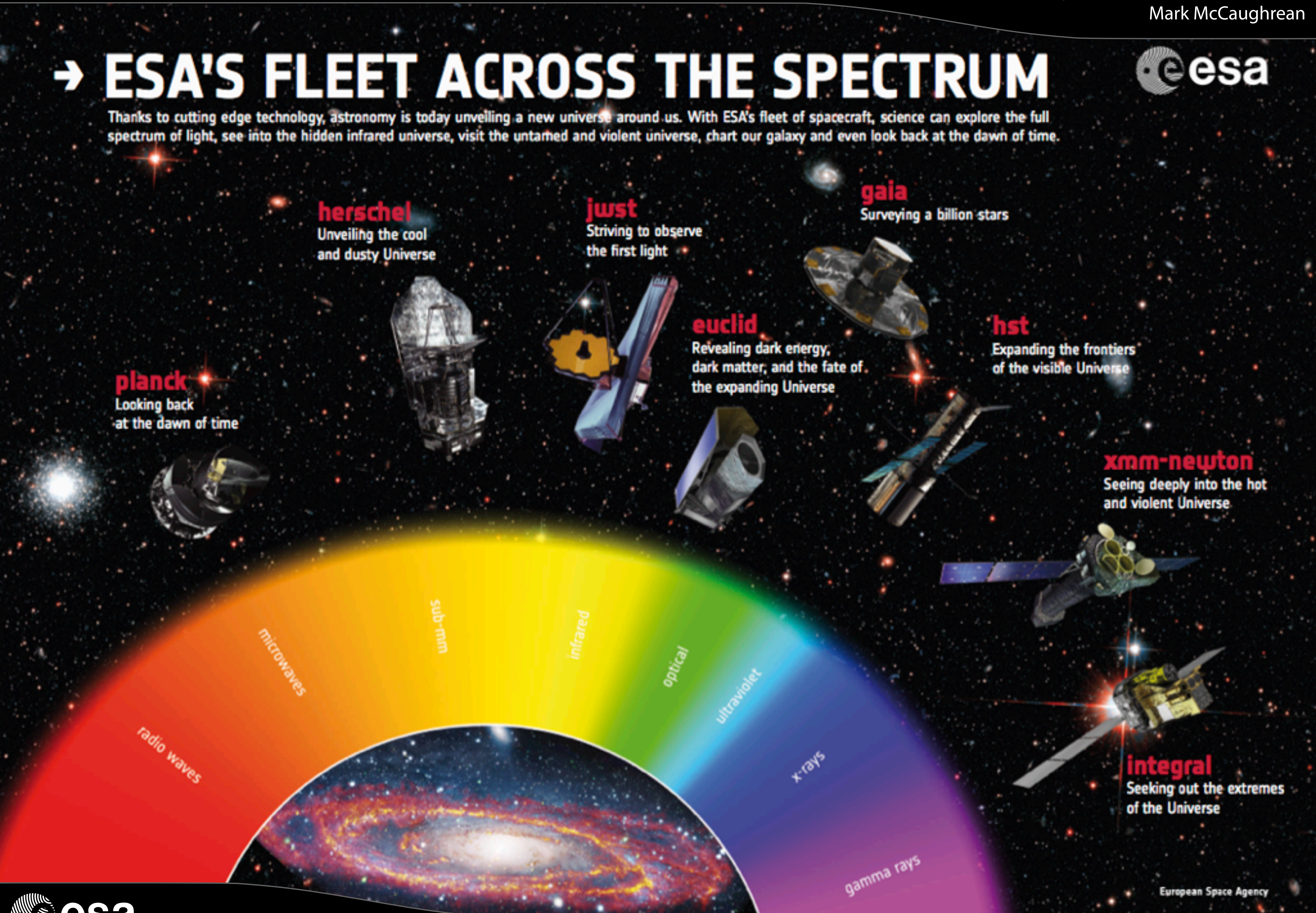
ESA by numbers



ESA budget 2012


esa
soho
Facing the Sun
venus express
Studying Venus' atmosphere
juice
Exploring the emergence of habitable worlds around gas giants
proba-2
Observating coronal dynamics and solar eruptions
bepicolombo
Exploring Mercury
cassini-huygens
Studying the Saturnian system and landing on Titan
mars express
Investigating the Red Planet
cluster
Measuring Earth's magnetic shield
solar orbiter
The Sun up close
rosetta
Chasing a comet
ESA'S FLEET IN THE SOLAR SYSTEM
The Solar System is a natural laboratory that allows scientists to explore the nature of planets. ESA's missions to our planetary neighbours have transformed our view of the celestial neighbourhood. The planets that exist today are the result of 4.6 billion years of formation and subsequent development. Studying how they appear now allows us to unlock the mysteries of their past and to predict how they will change in the future.
European Space Agency


→ ESA'S FLEET ACROSS THE SPECTRUM
esa
Thanks to cutting edge technology, astronomy is today unveiling a new universe around us. With ESA's fleet of spacecraft, science can explore the full spectrum of light, see into the hidden infrared universe, visit the untamed and violent universe, chart our galaxy and even look back at the dawn of time.
herschel
Unveiling the cool and dusty Universe
jwst
Striving to observe the first light
gaia
Surveying a billion stars
euclid
Revealing dark energy, dark matter, and the fate of the expanding Universe
hst
Expanding the frontiers of the visible Universe
planck
Looking back at the dawn of time
xmm-newton
Seeing deeply into the hot and violent Universe
integral
Seeking out the extremes of the Universe
radio waves
microwaves
sub-mm
infrared
optical
ultraviolet
x-rays
gamma rays
European Space Agency

Future ESA space science missions

Missions in implementation

- Gaia (2013)
- LISA Pathfinder (2014)
- BepiColombo (with JAXA; 2015)
- Microscope (with CNES; 2016)
- ASTRO-H (with JAXA; 2017)
- JWST (with NASA, CSA; 2018)

ExoMars robotic exploration (with Roscosmos)

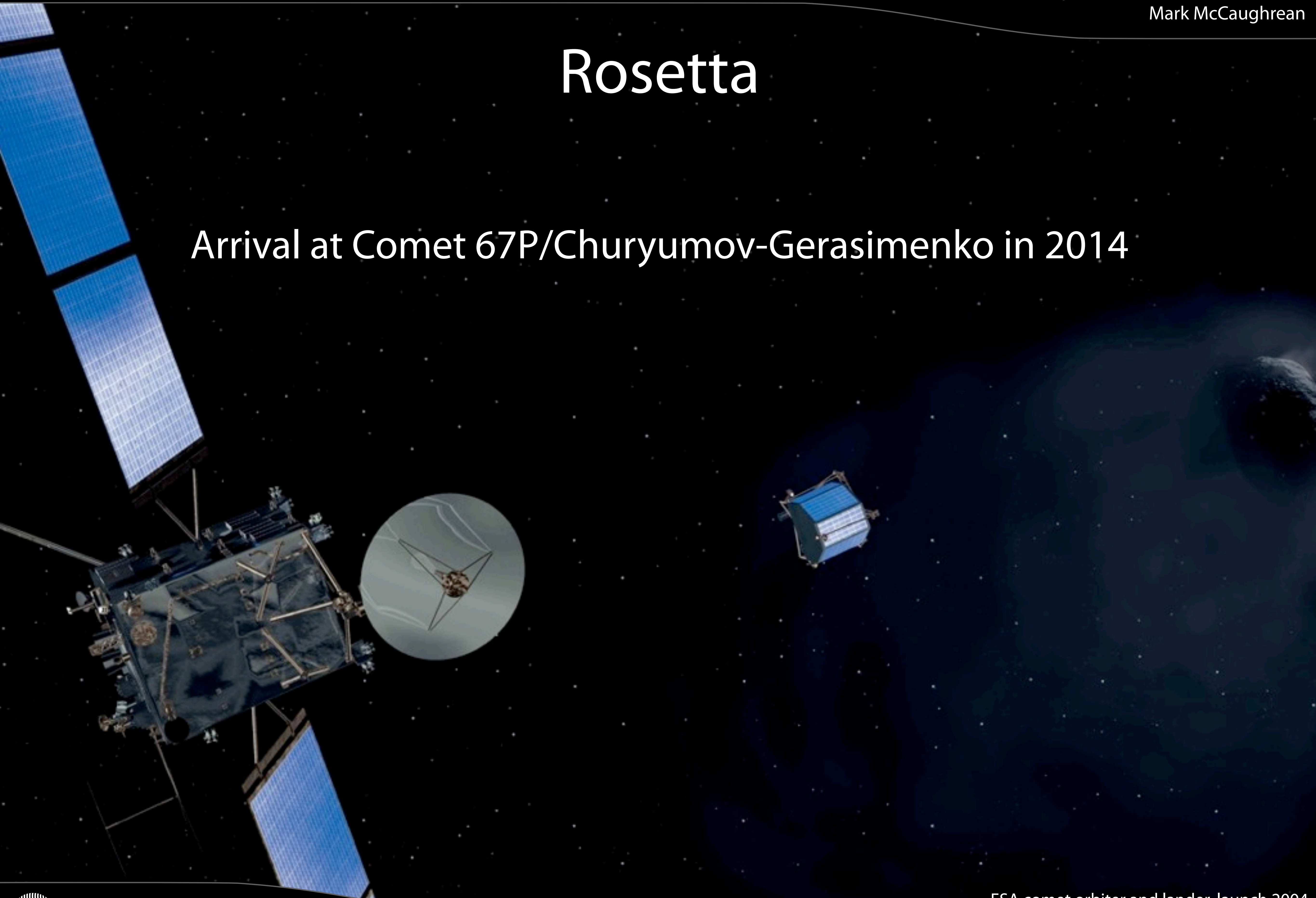
- Trace Gas Orbiter + EDL (2016)
- Joint rover mission (2018)
- Goal: Sample Return

Missions under study

- CHEOPS
- EChO
- JUICE
- LOFT
- Marco Polo-R
- PLATO
- SPICA (with JAXA)
- STE-QUEST

Rosetta

Arrival at Comet 67P/Churyumov-Gerasimenko in 2014



ESA comet orbiter and lander, launch 2004

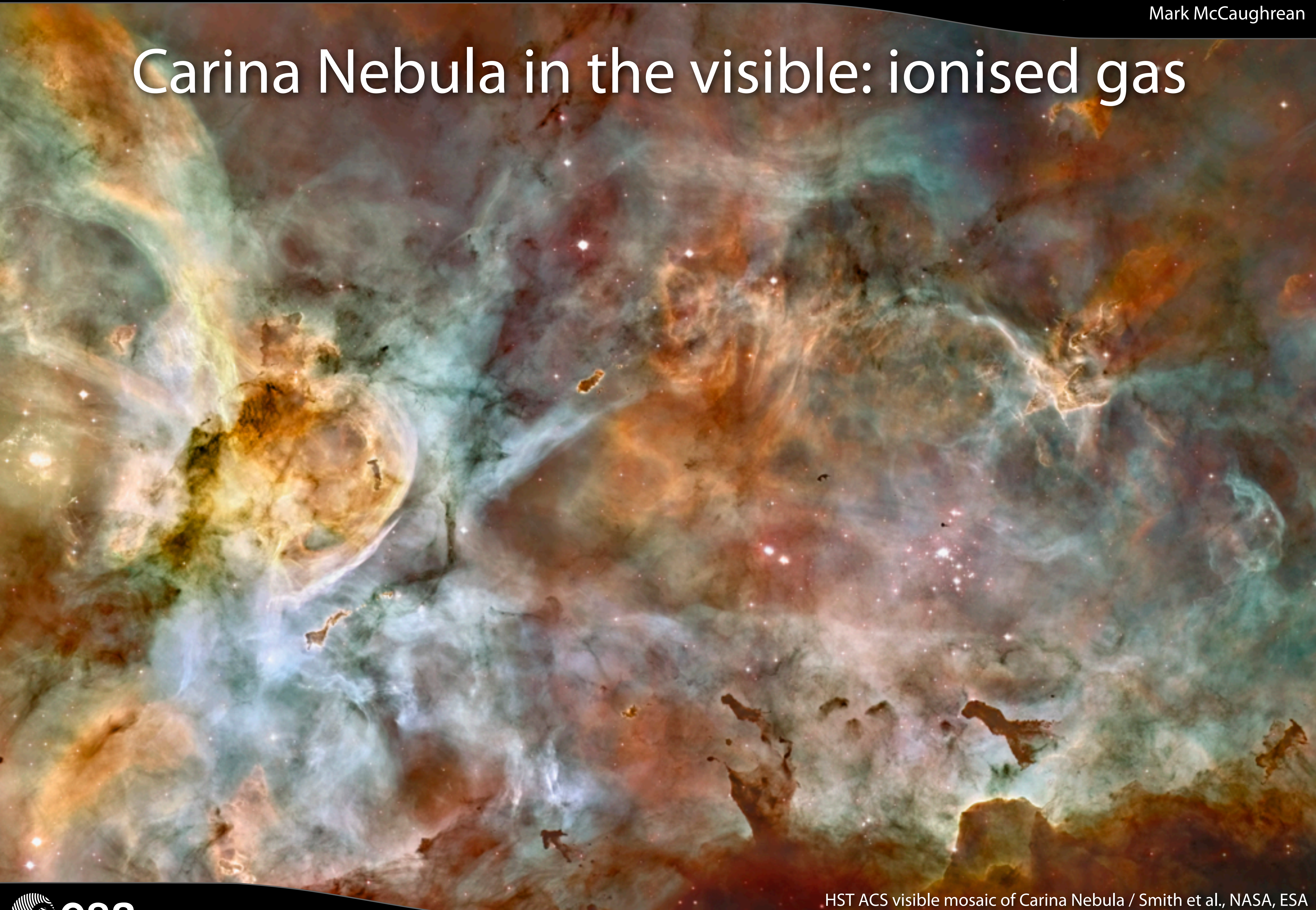
Herschel Space Observatory

ESA-NASA far-infrared astrophysics observatory, launched 2009

Carina Nebula in the far-IR: cool dust

Herschel PACS + SPIRE far-infrared mosaic of Carina Nebula / Preibisch et al., ESA

Carina Nebula in the visible: ionised gas

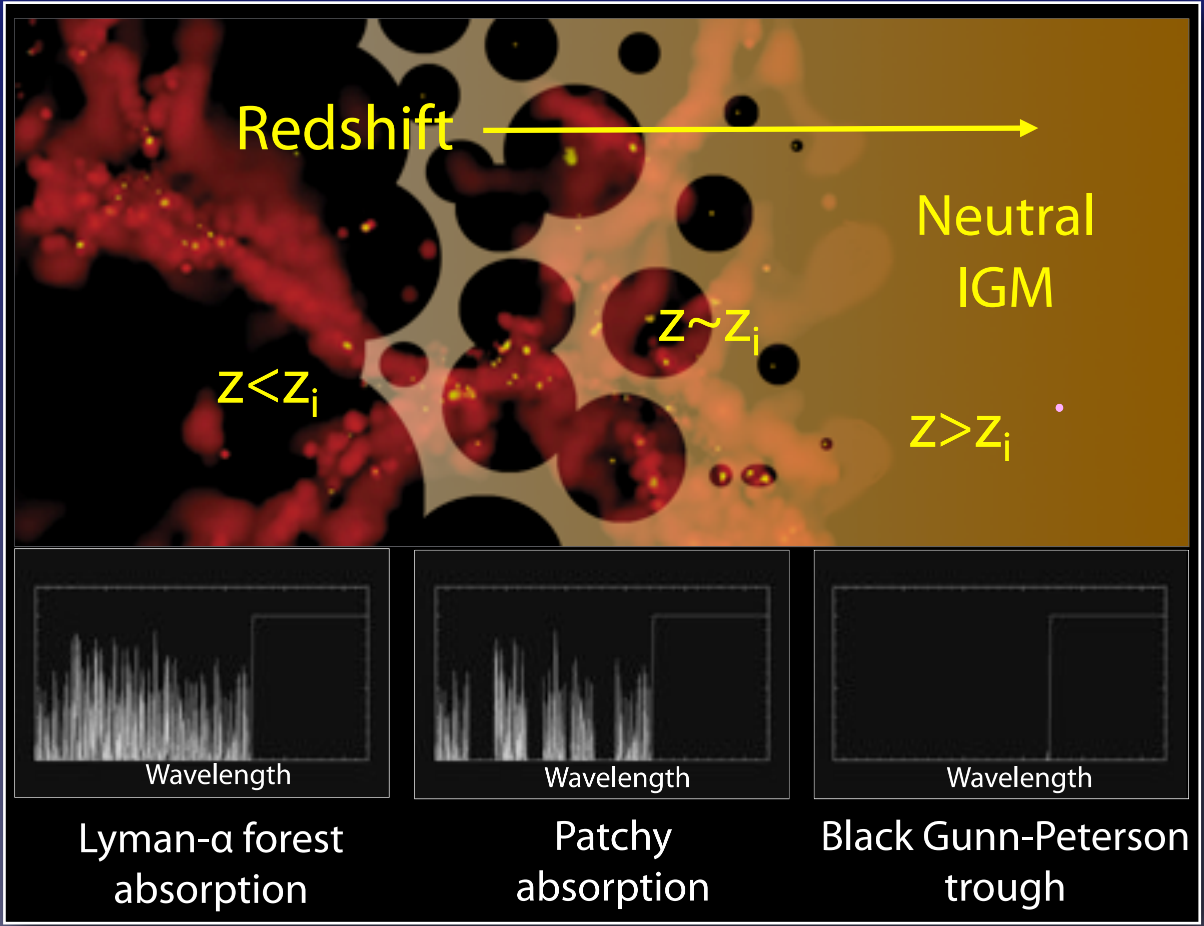


HST ACS visible mosaic of Carina Nebula / Smith et al., NASA, ESA

Hubble Space Telescope

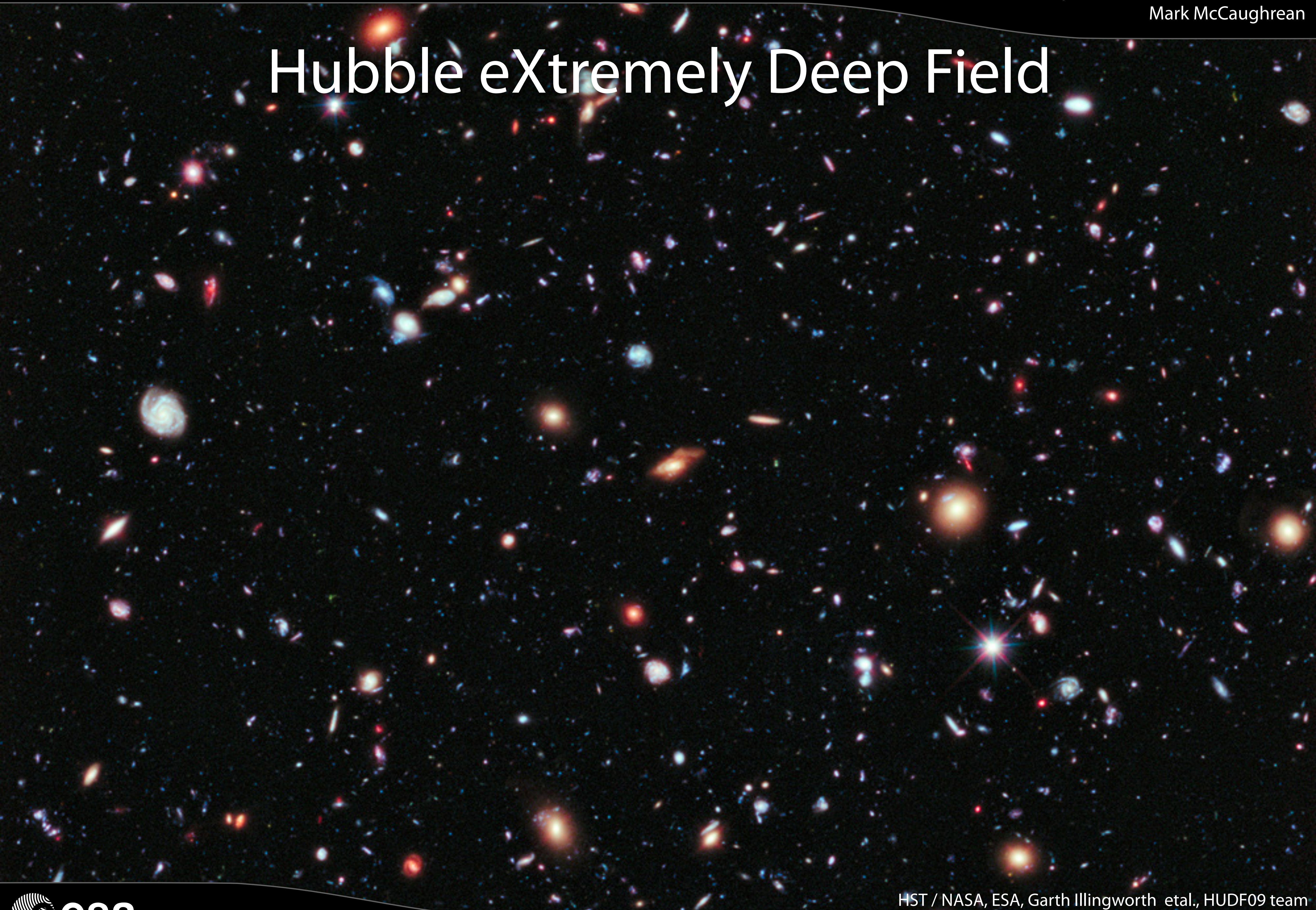
NASA-ESA UV-optical-near-IR astrophysical observatory, launched 1990, last servicing May 2009

Epoch of reionisation



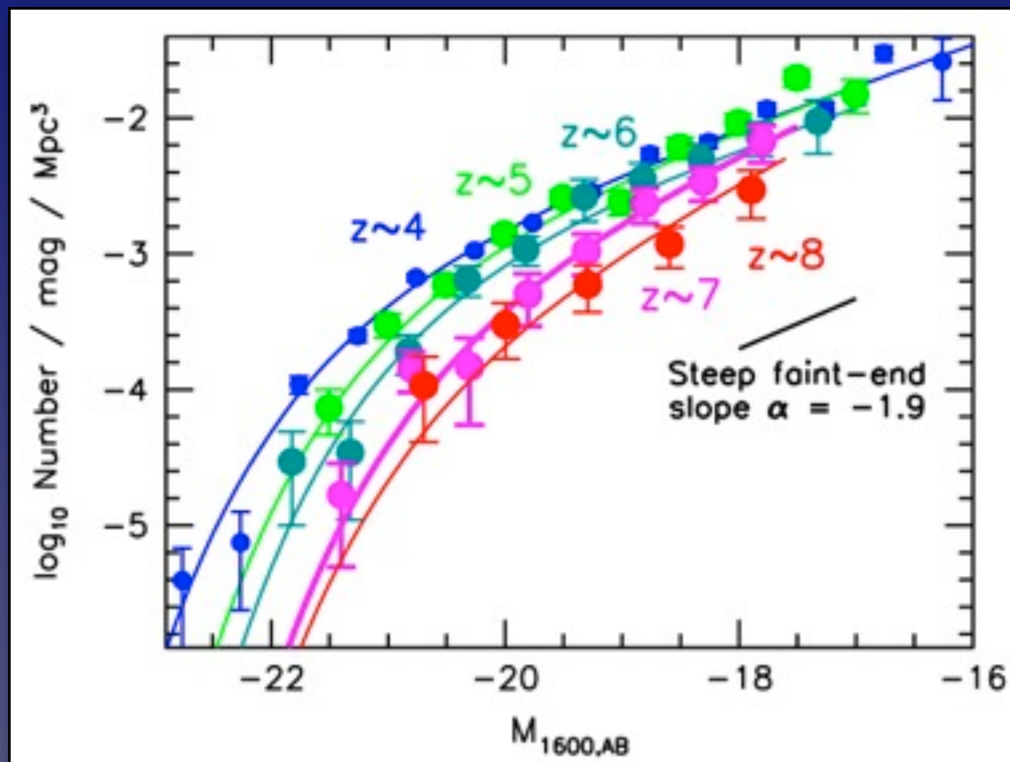
- Following the Big Bang, the Universe was fully ionised and opaque
- After cooling, recombination occurred, leading to CMB
  - Intergalactic medium became neutral and transparent: the "Dark Ages"
- Subsequently reionised to ~10%
  - When did it occur? Which sources caused it? What can we learn about "first light"?

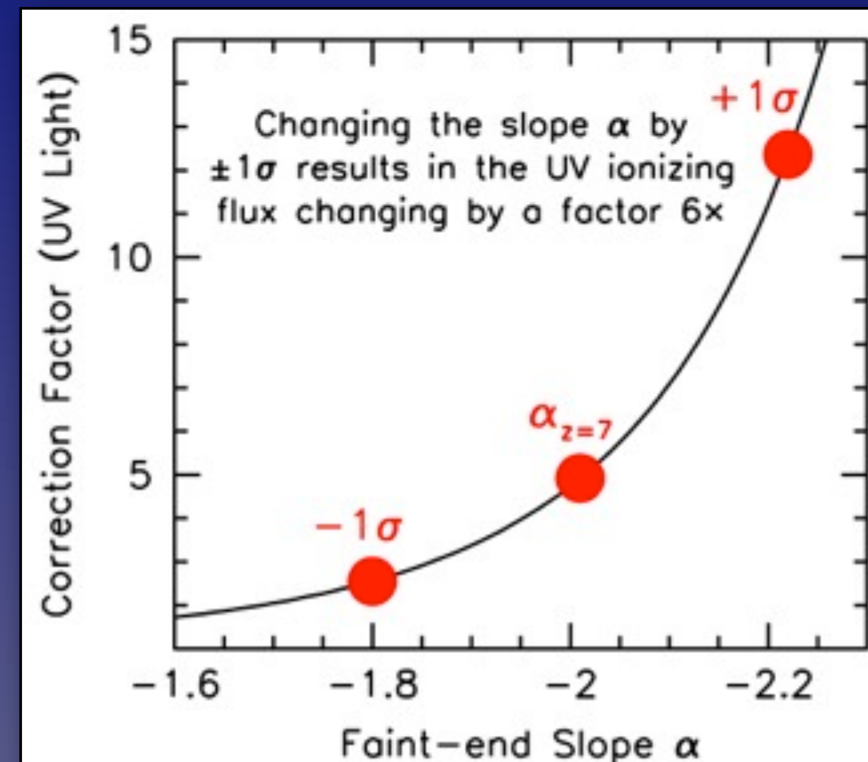
Hubble eXtremely Deep Field



HST / NASA, ESA, Garth Illingworth etal., HUDF09 team

Clues from recent ultra-deep HST survey

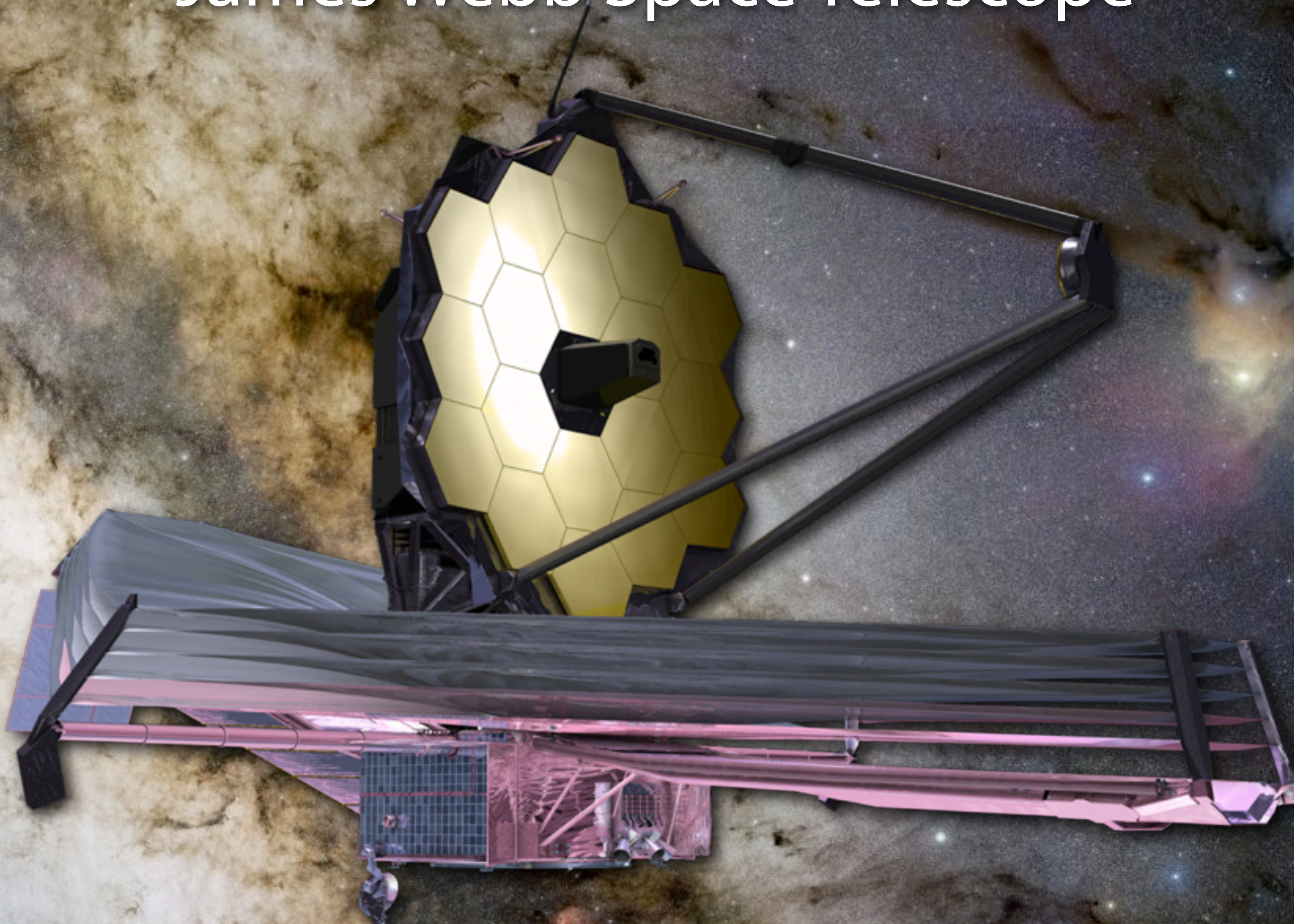




- Not enough big, bright star-forming galaxies at high redshift
- However, faint end of UV luminosity function steepens at high-z
  - Low-luminosity galaxies could generate enough UV photons to reionise Universe
  - However, uncertainties in slope too large to be sure
- JWST will provide definitive answer
  - Deep near-IR imaging surveys with NIRCam: AB~30.6 in 60 hrs
  - Low-res multi-object spectroscopic follow-up with NIRSpec: AB~27.5 in 60 hrs

Deep HST HUDF-09 image (AB~29) / NASA, ESA, Bouwens et al. (2012, ApJL 752 L5)

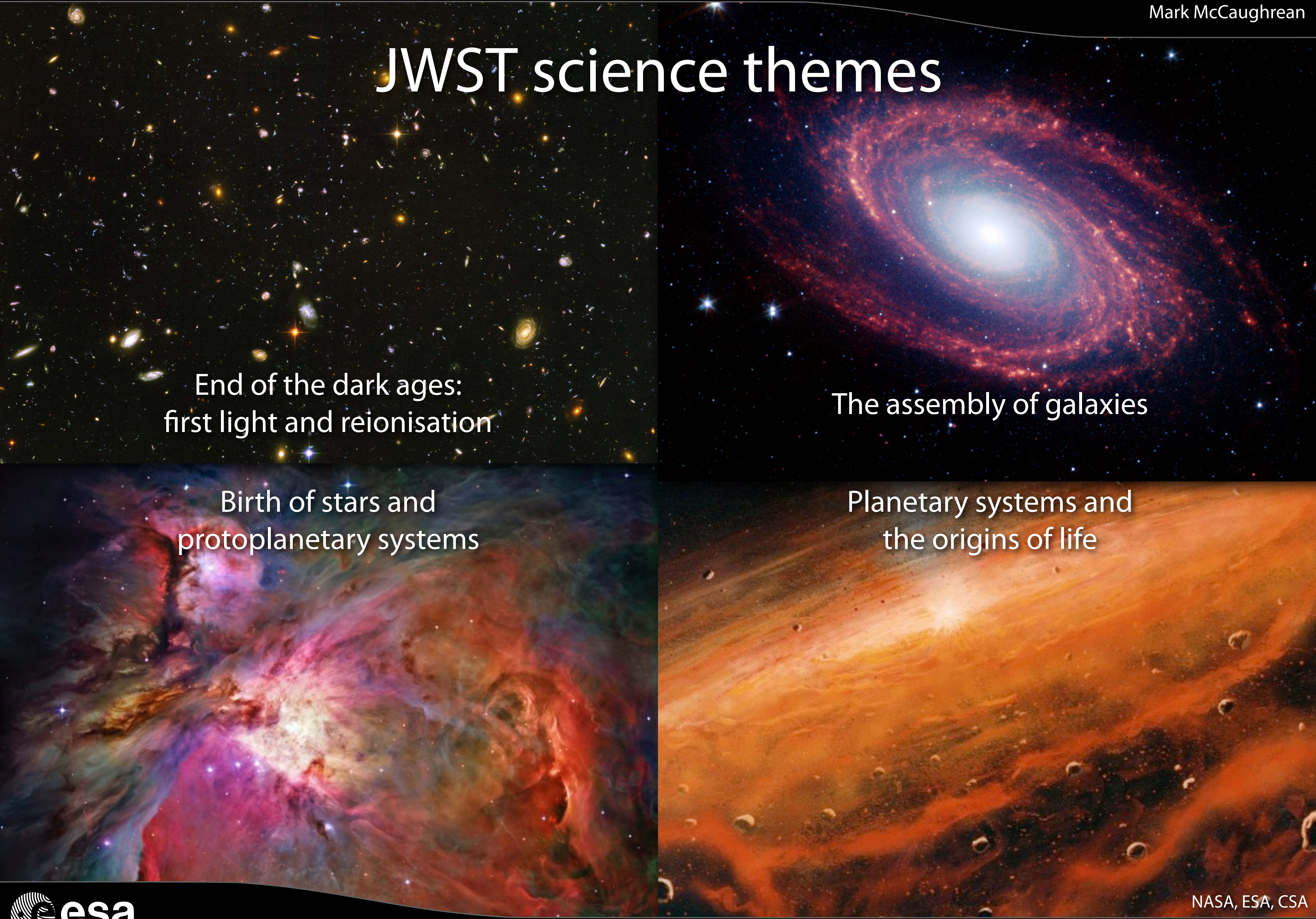
James Webb Space Telescope



Background: ESO/S. Guisard

NASA-ESA-CSA optical-infrared astrophysics observatory, scheduled launch 2018

JWST science themes



Cryo-acceptance test of gold-coated segments

XRCF at MSFC / NASA, ESA, CSA / Tinsley, Ball Aerospace, Quantum

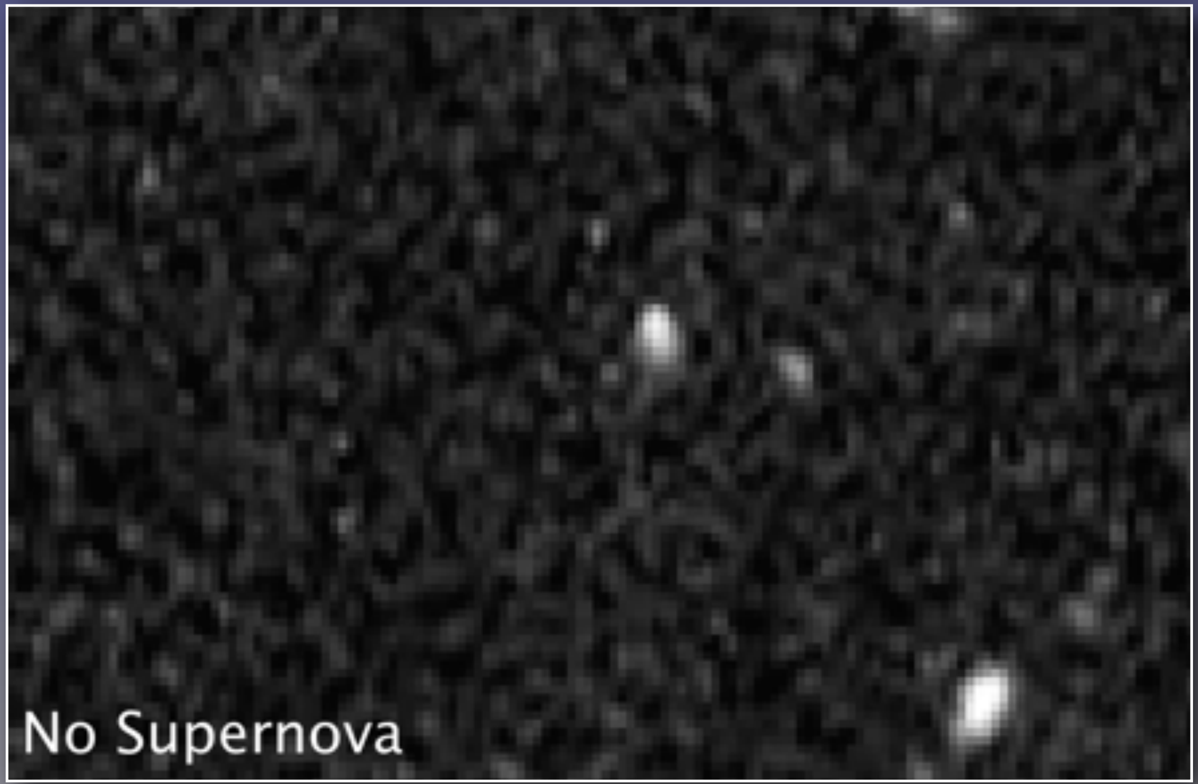
JWST mirrors ready for shipping

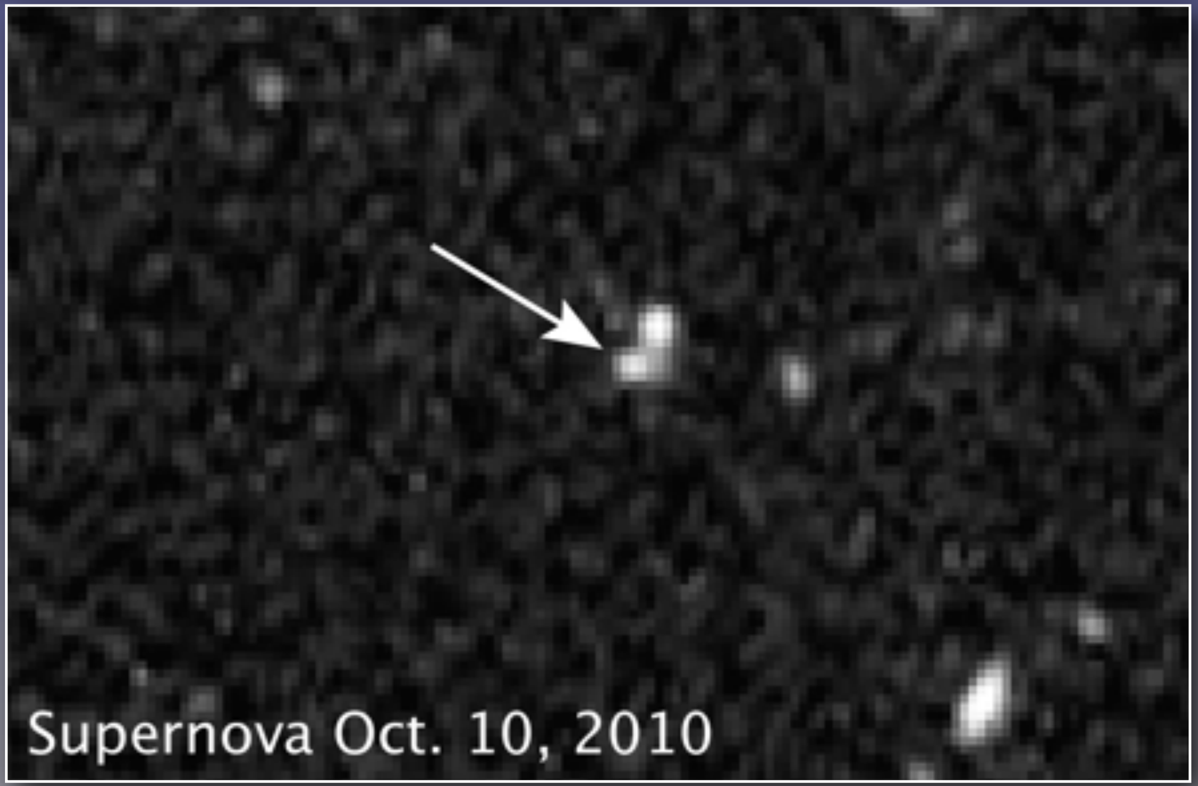
NASA, ESA, CSA / Ball Aerospace

Supernova 1994D in NGC4526

HST / NASA, ESA, Hubble Key Project Team, High-z Supernova Search Team

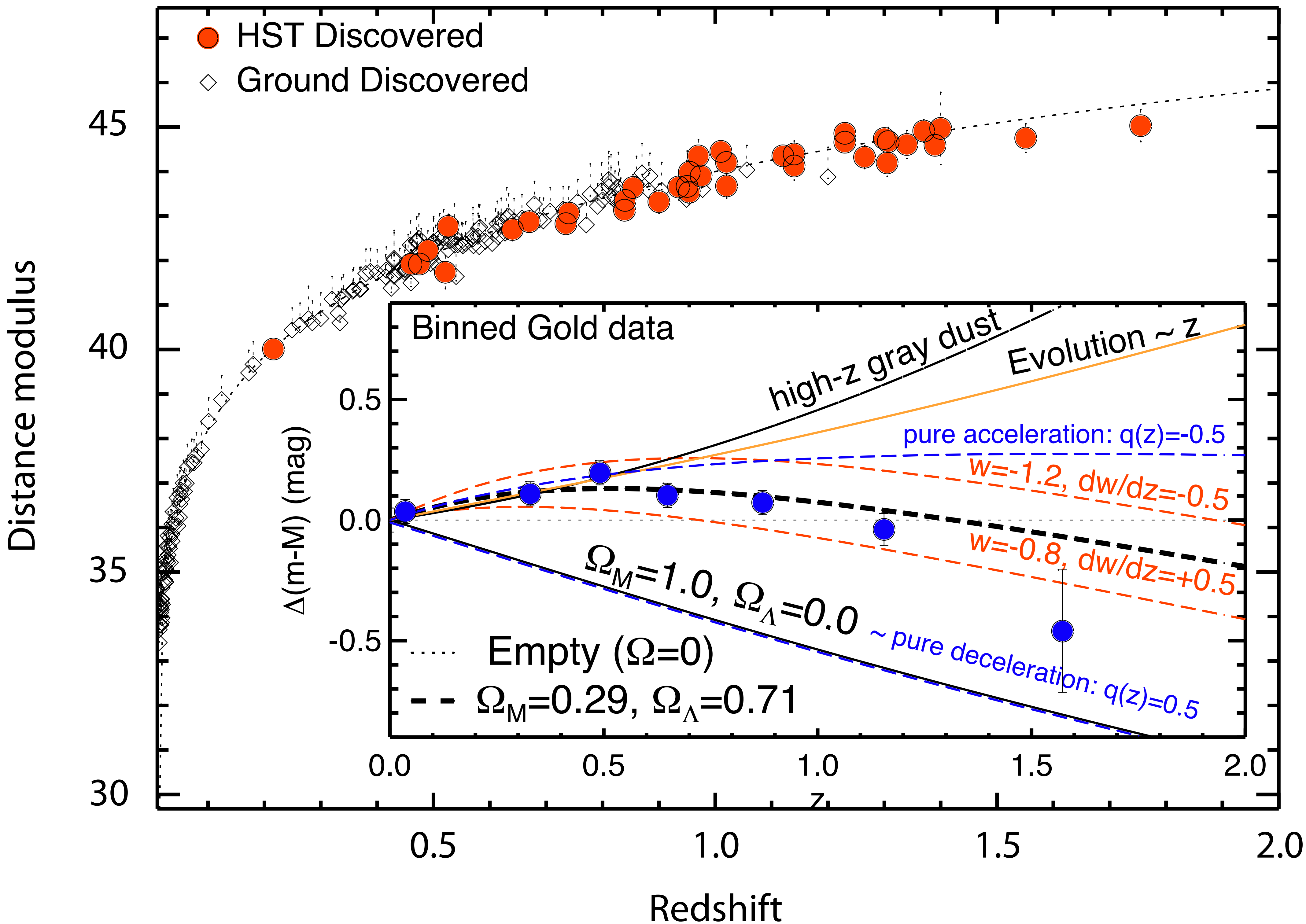
A very distant Type 1a supernova





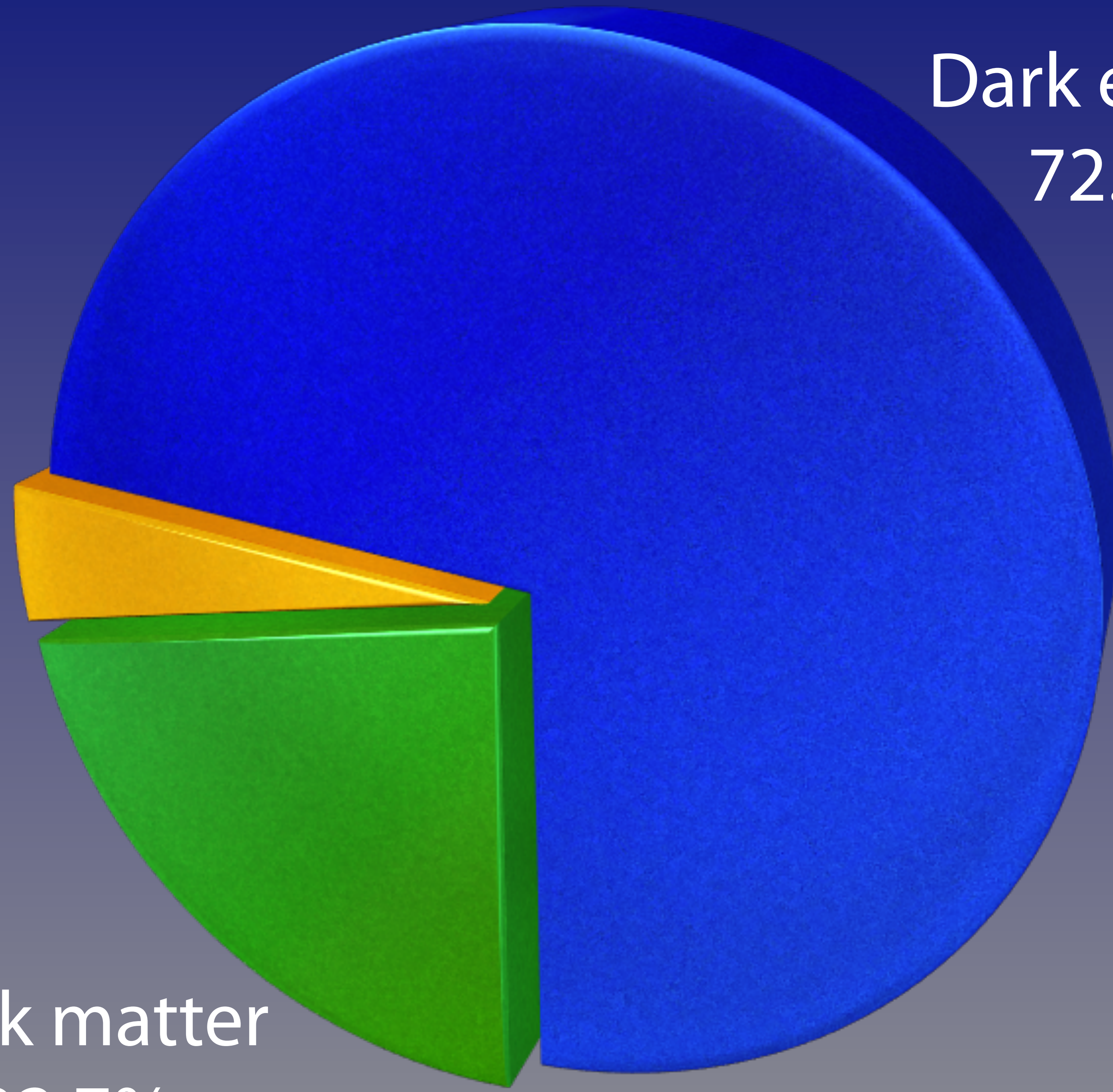
HST WFC3 / Supernova in Hubble Ultradeep Field / ESA, NASA, Adam Riess, Steven Rodney

Evidence for an accelerated expansion



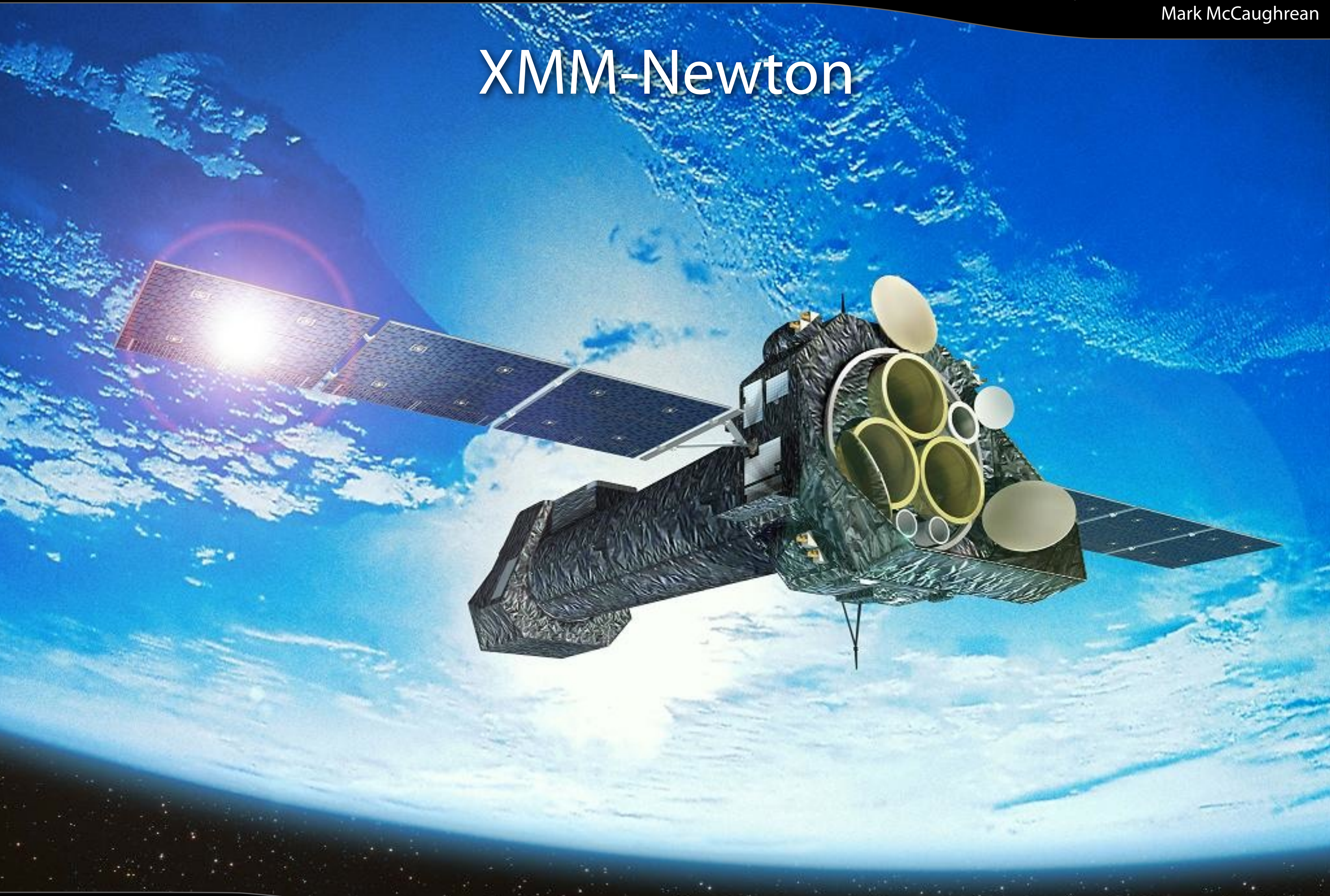
Supernova Type 1a Hubble diagram, Riess et al. 2007

Concordance cosmology today



NASA WMAP 7-year results, Jarosik et al. (2010)

XMM-Newton

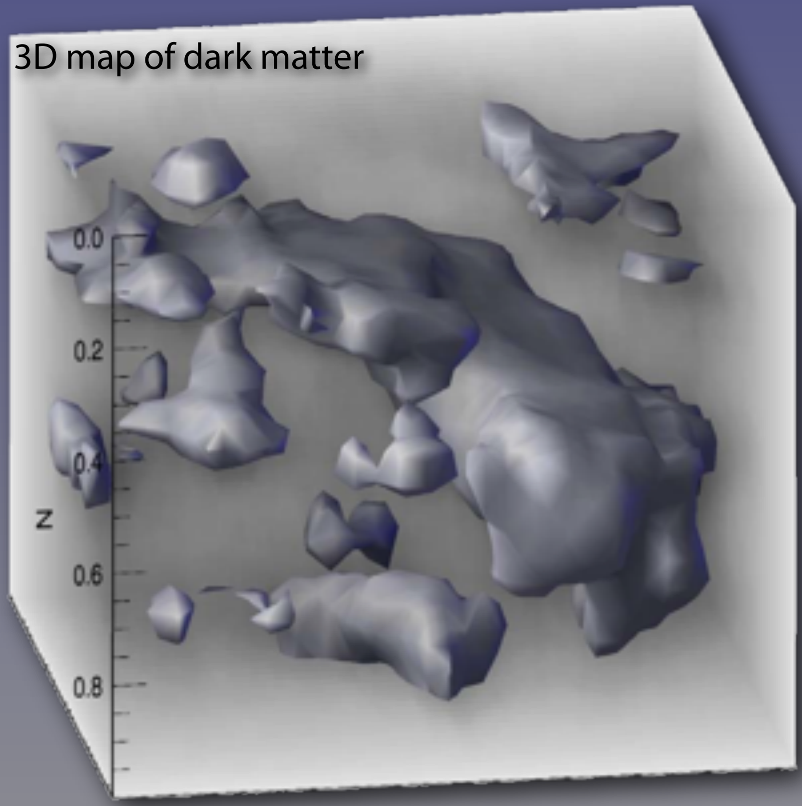


ESA X-ray astrophysics observatory, launched 1999

Dark matter maps reveal cosmic scaffolding

- Deep multi-λ survey of COSMOS field
  - 1.67 square degree field
  - 1000 hrs with HST
  - 400 hrs with XMM-Newton
- Sensitivity to different components
  - Optical-infrared: cold baryonic matter
  - X-ray: hot baryonic matter
  - Gravitational lensing: total matter (baryonic + dark)
- Tomographic reconstruction of dark matter
  - Large scale distribution resolved in 3D
  - Loose network of filaments, growing over time
  - Intersections coincident with massive galaxy clusters
  - Consistent with numerical simulations of gravitational structure formation

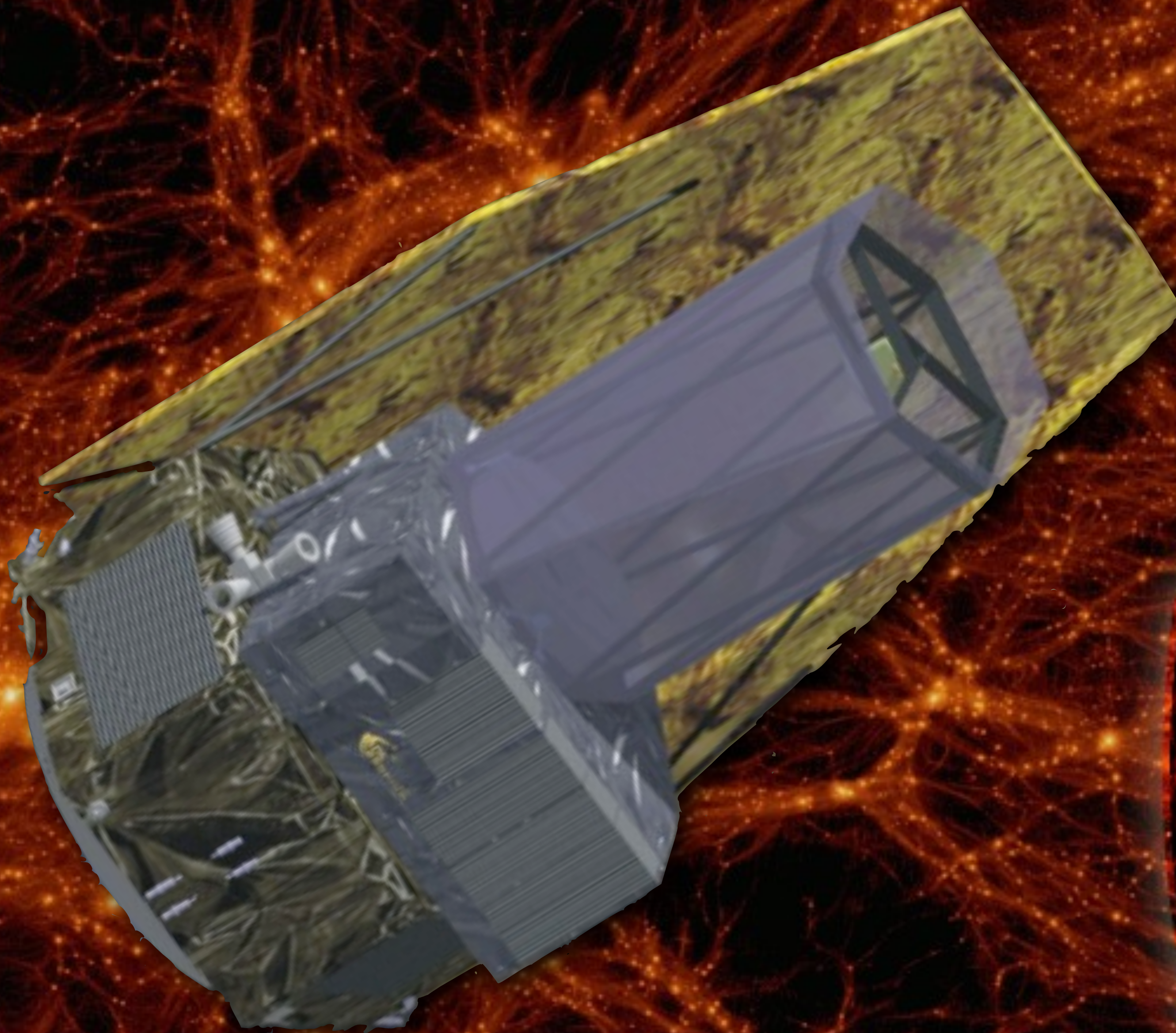

Red: X-ray emission; Blue: dark matter map

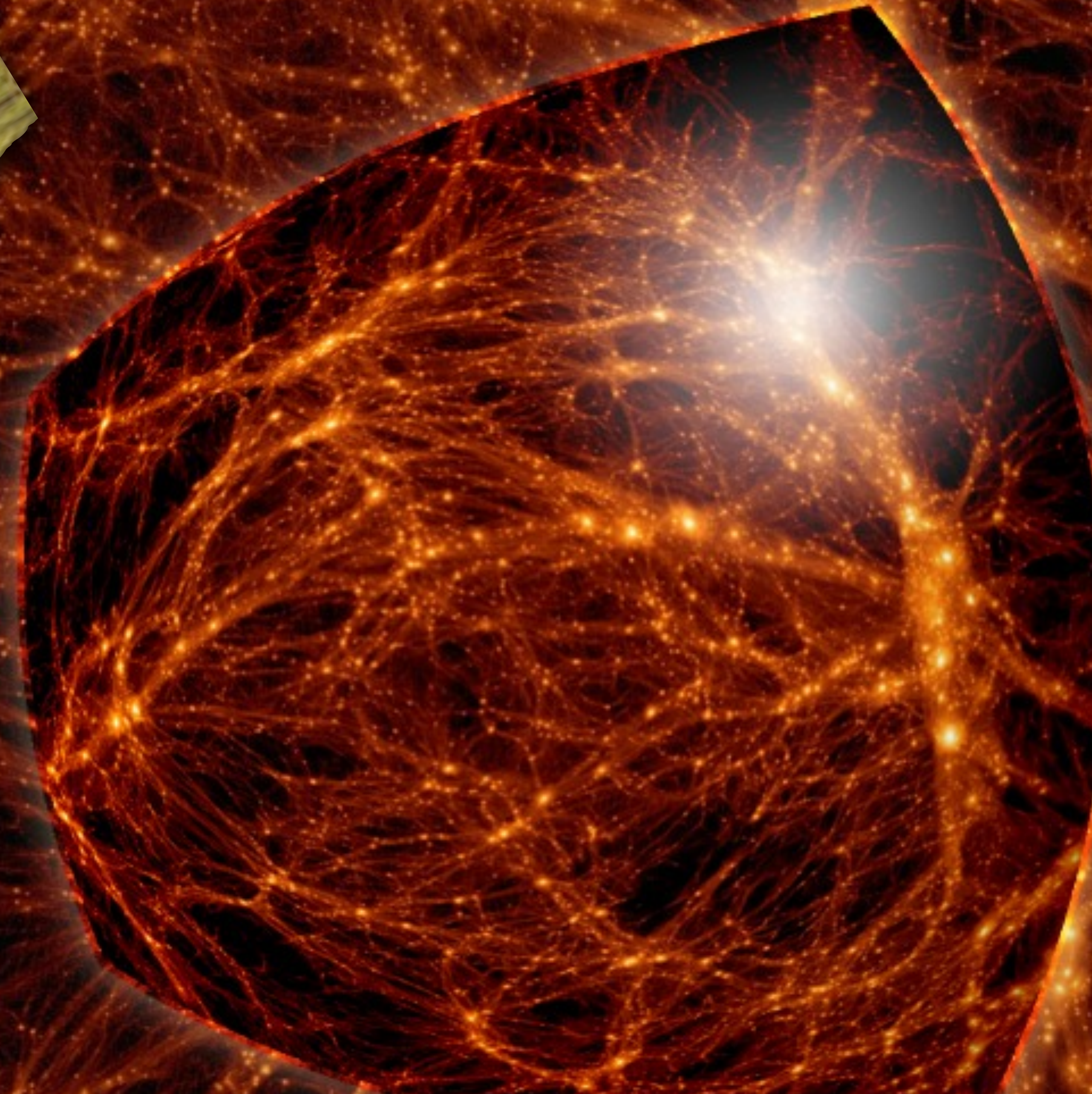


Massey et al. (2007, Nature)

Euclid

Cosmic Vision M2 mission



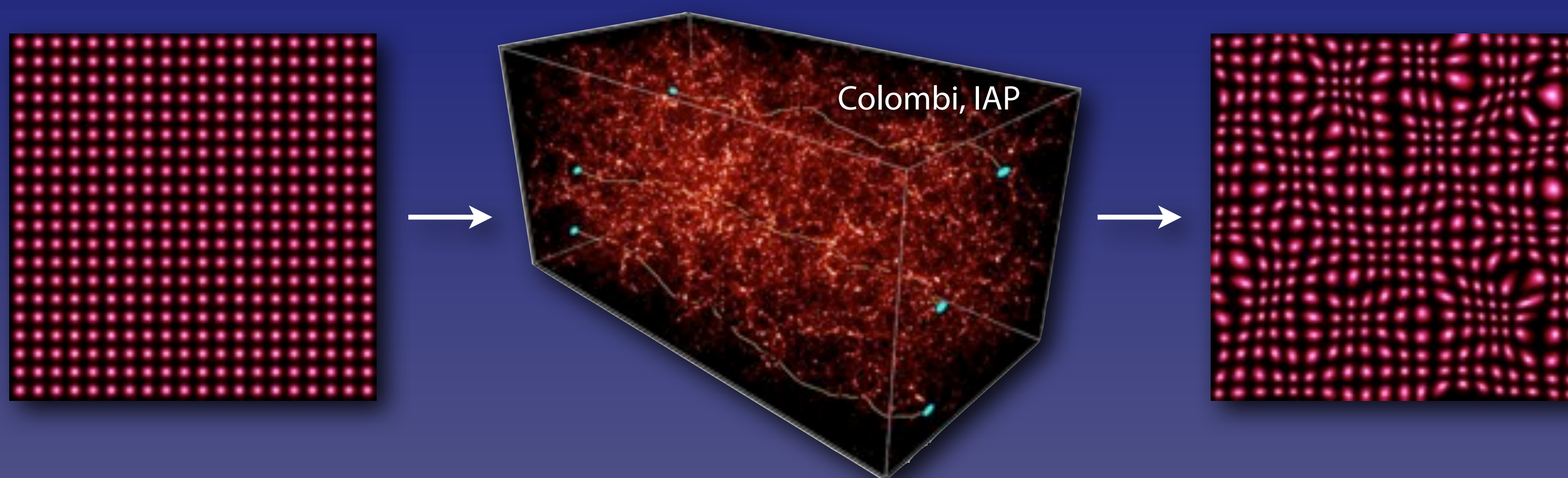


1.2m passively cooled telescope to survey 15,000 deg^2
Visible imaging: RIz(AB) = 24.5 10σ point source limit
Near-IR imaging: YJH(AB) = 24 5σ point source limit
Near-IR R=400 spectroscopy to H(AB) = 22

ESA dark Universe astrophysics survey mission, launch 2019

Multiple probes of evolving cosmic structure

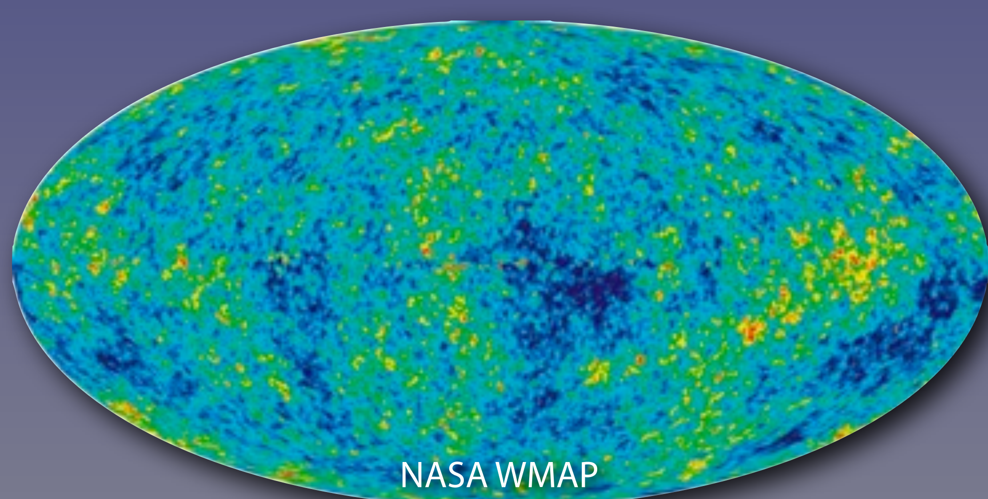
Weak lensing

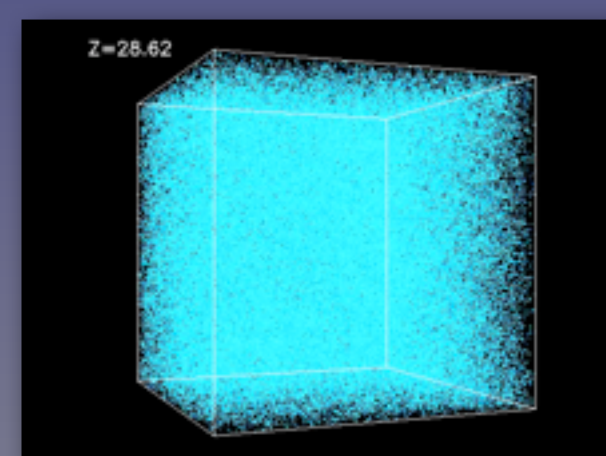


Galaxy shapes systematically distorted by intervening matter (baryonic and dark)

Wide-field, high-resolution visible imaging measures shear; near-IR imaging photometry measures photo-z's for lensed galaxies

Baryon acoustic oscillations





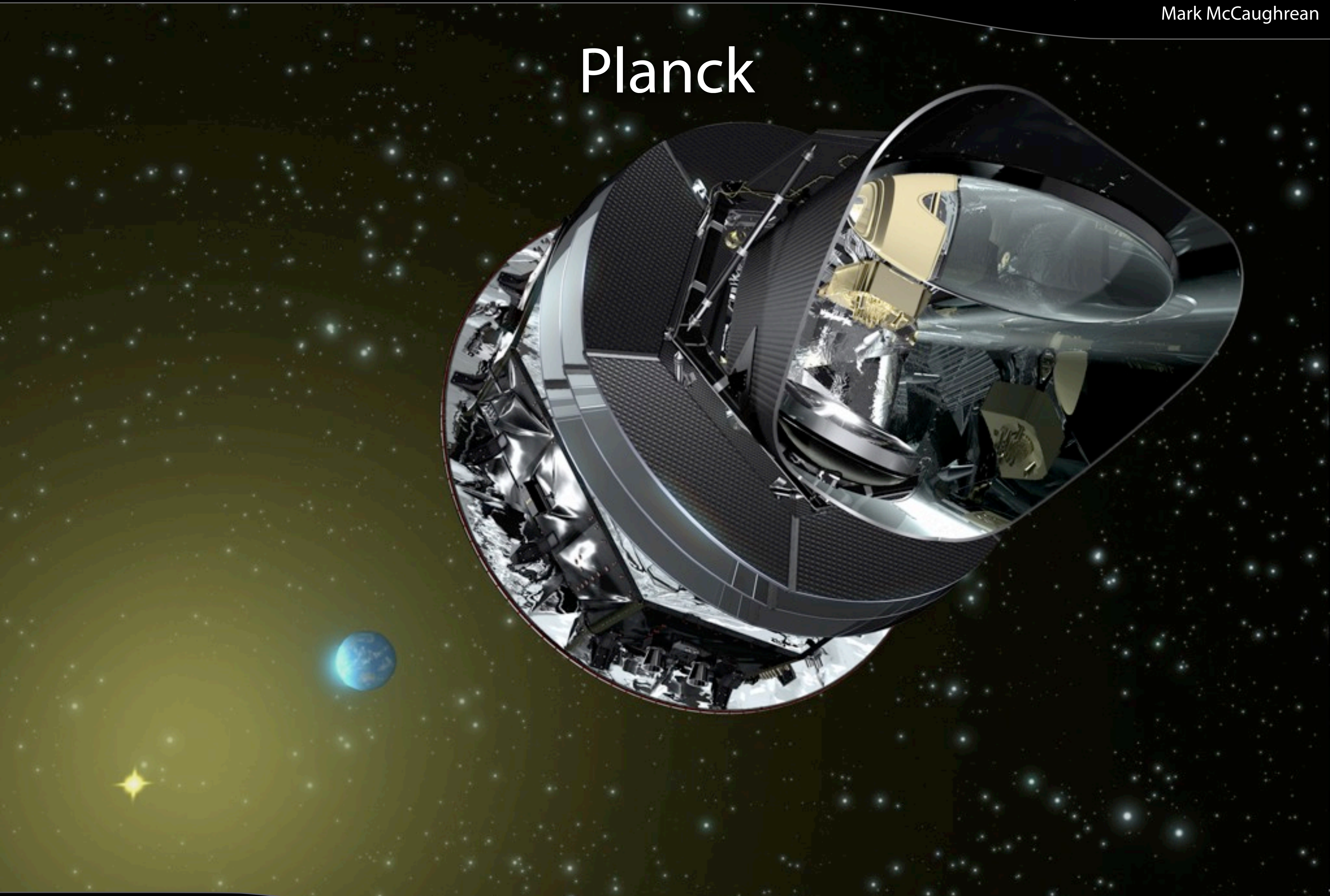
Center for Cosmological Physics, Chicago

Initial structure imprinted on Universe at recombination has characteristic scale; follow its evolution as standard ruler to present epoch (now ~ 150 Mpc)

Near-IR spectroscopy provides accurate redshifts and 3D maps

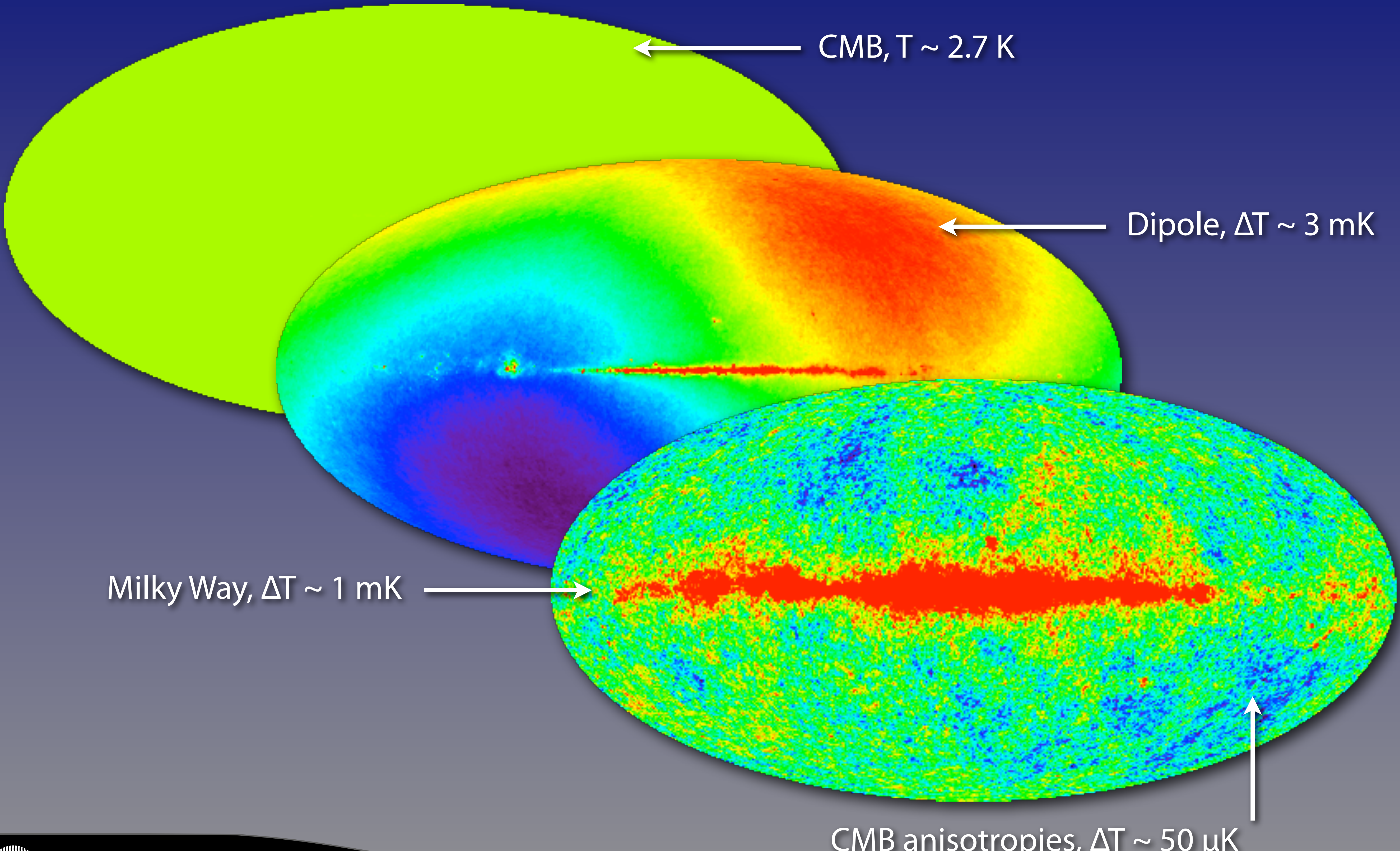
Combined with Planck data, Euclid will yield DE parameters w to <1% and w_a to < 5%
Very large legacy survey data set for many other kinds of science

Planck

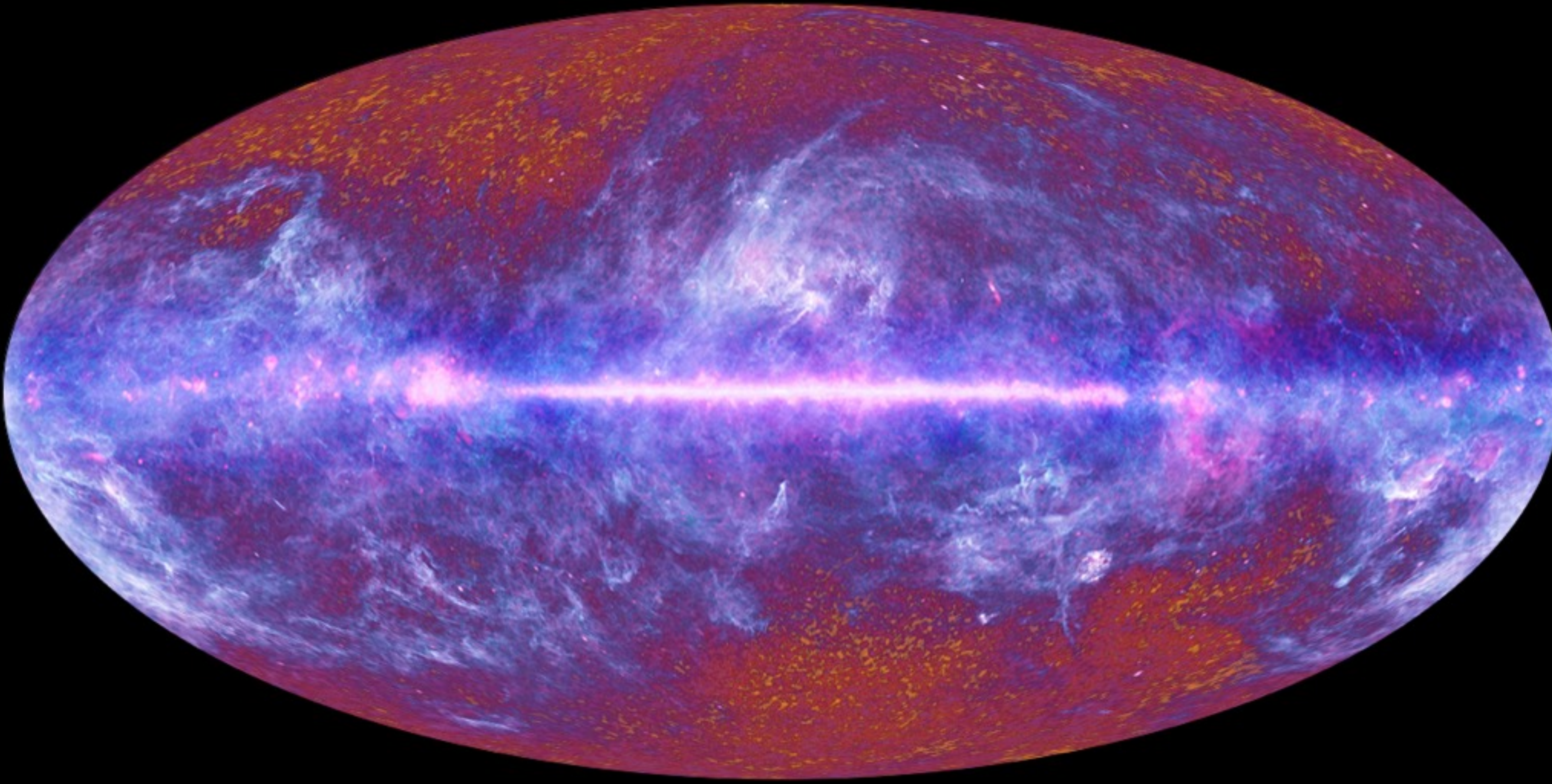


ESA cosmic microwave background experiment, launched 2009

The needle in the haystack

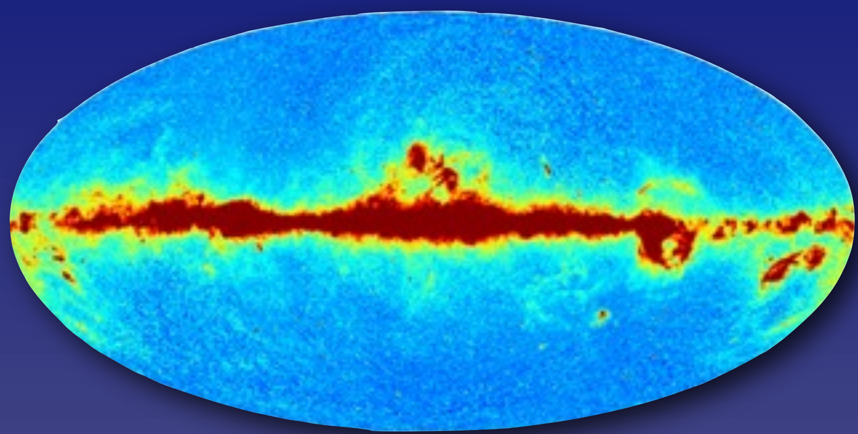


Planck all-sky image

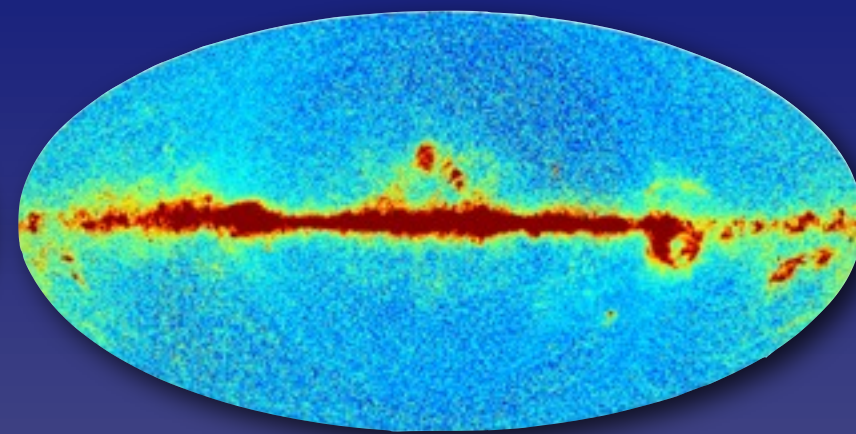


ESA, HFI & LFI consortia; released July 2010

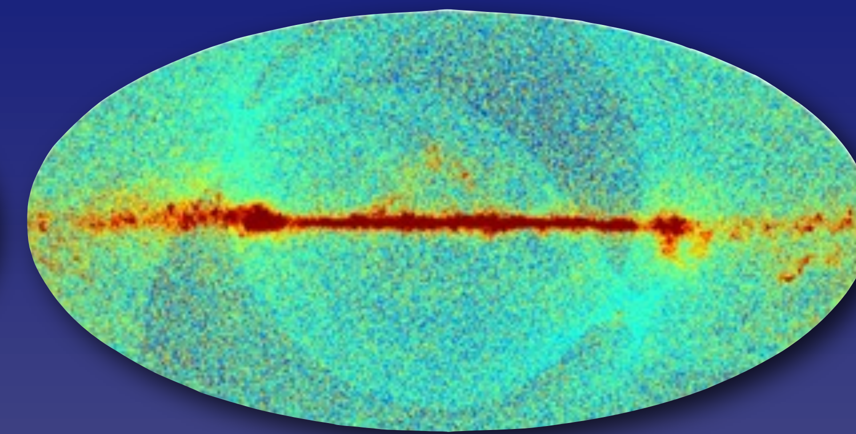
Planck foregrounds



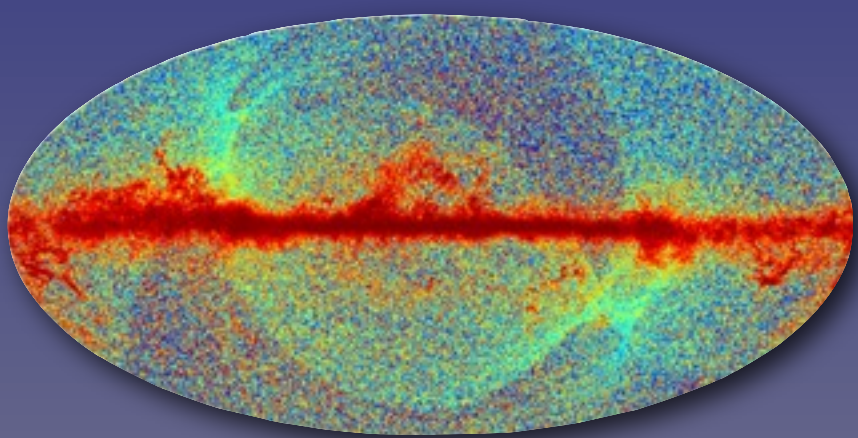
LFI 30GHz



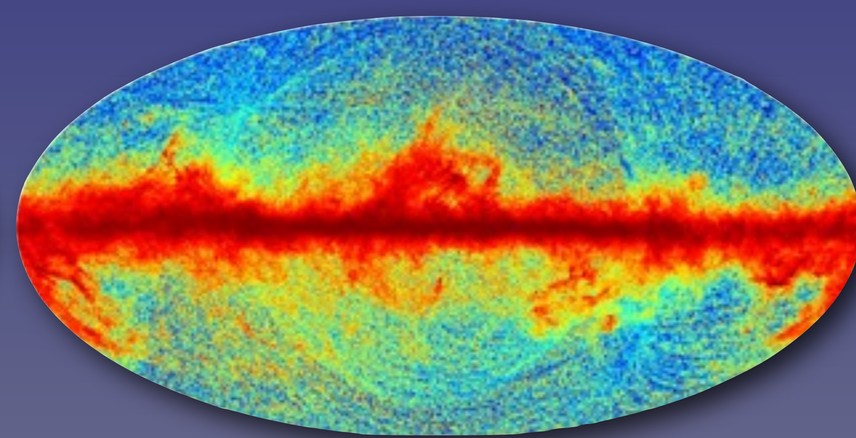
LFI 44GHz



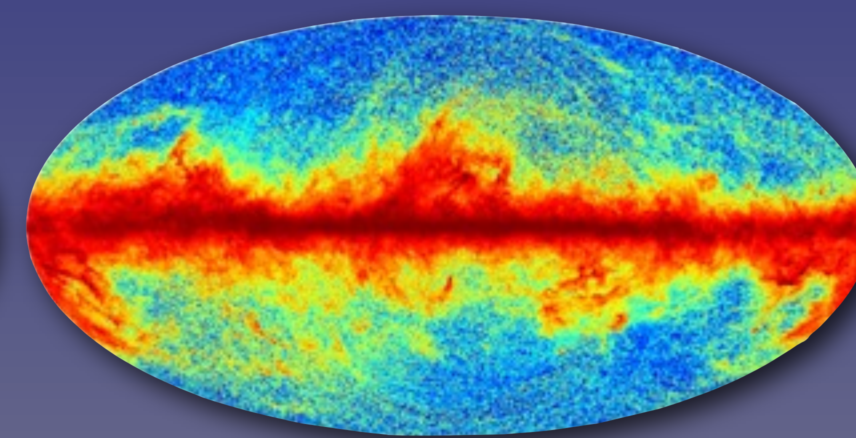
LFI 70GHz



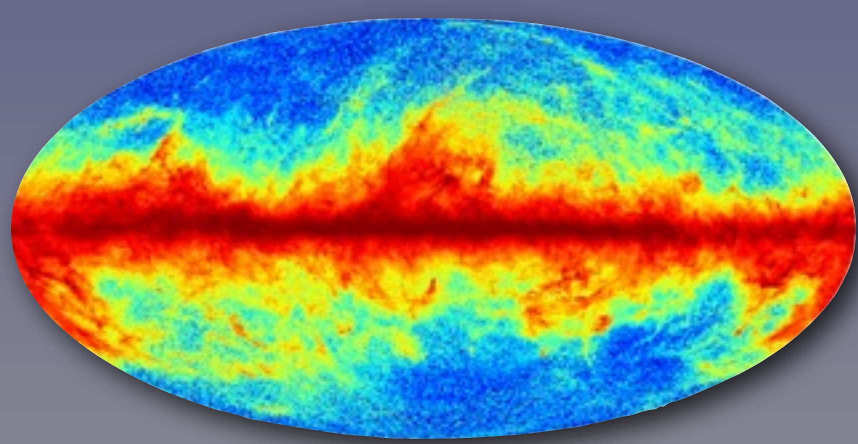
HFI 100GHz



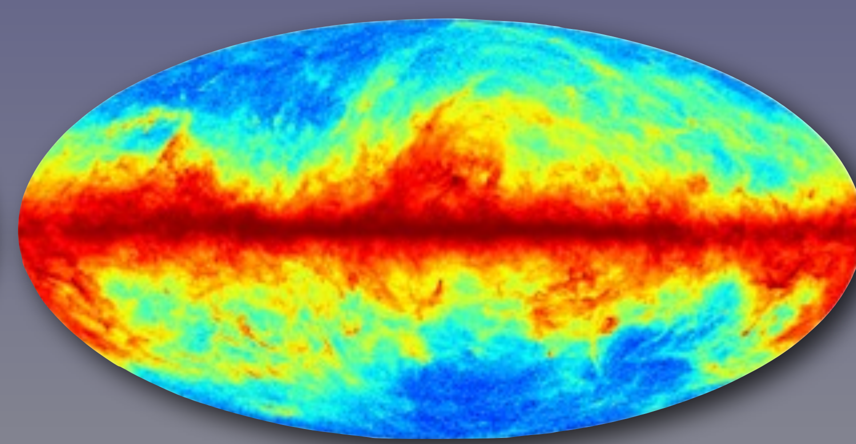
HFI 143GHz



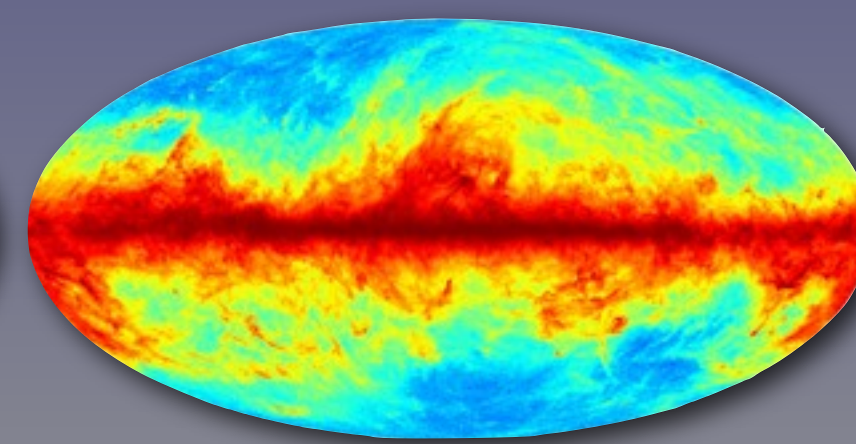
HFI 217GHz



HFI 353GHz



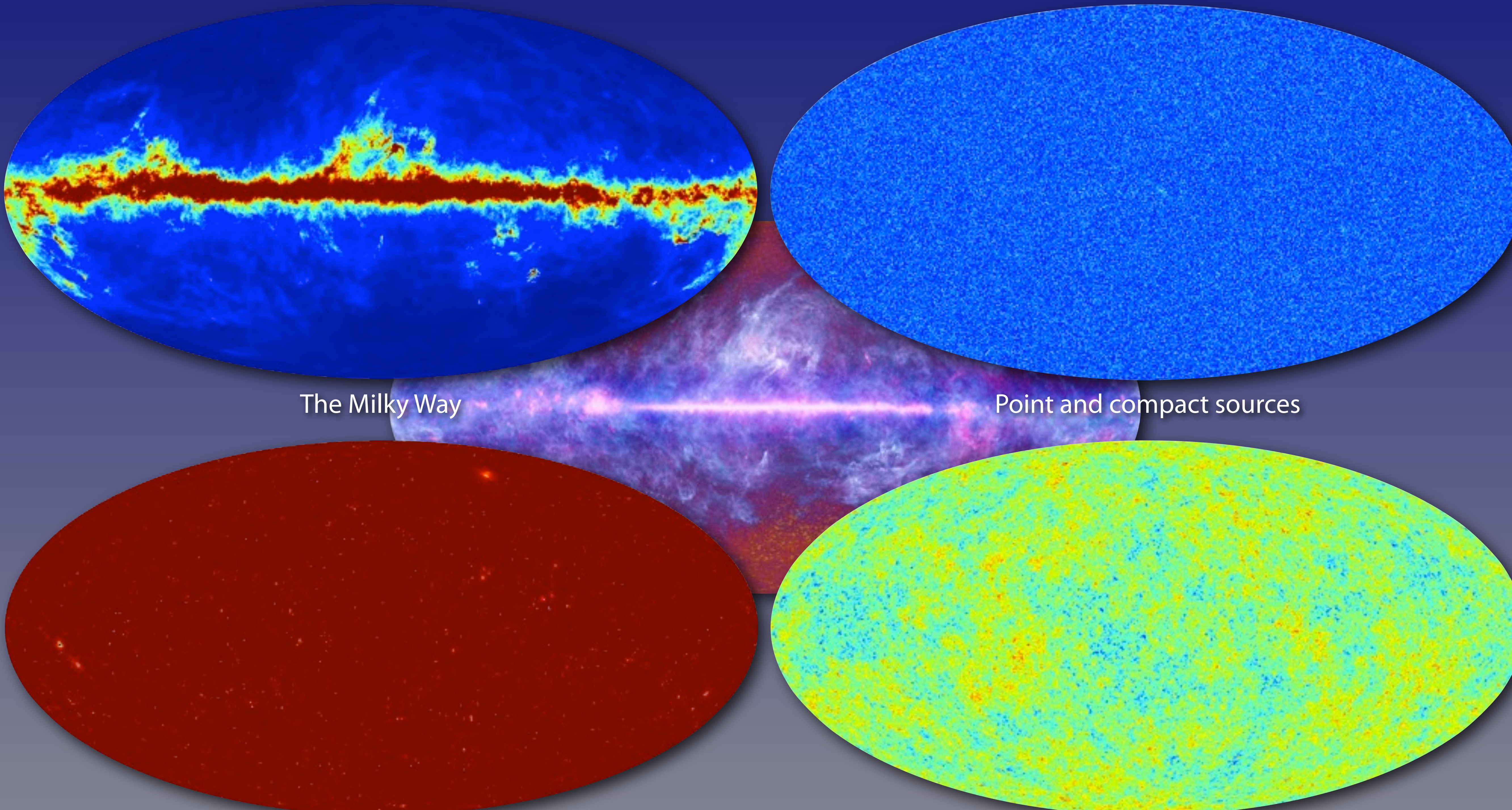
HFI 545GHz



HFI 857GHz

CMB-subtracted foregrounds / ESA, HFI & LFI consortia, Planck Collaboration

Decomposition



The Milky Way

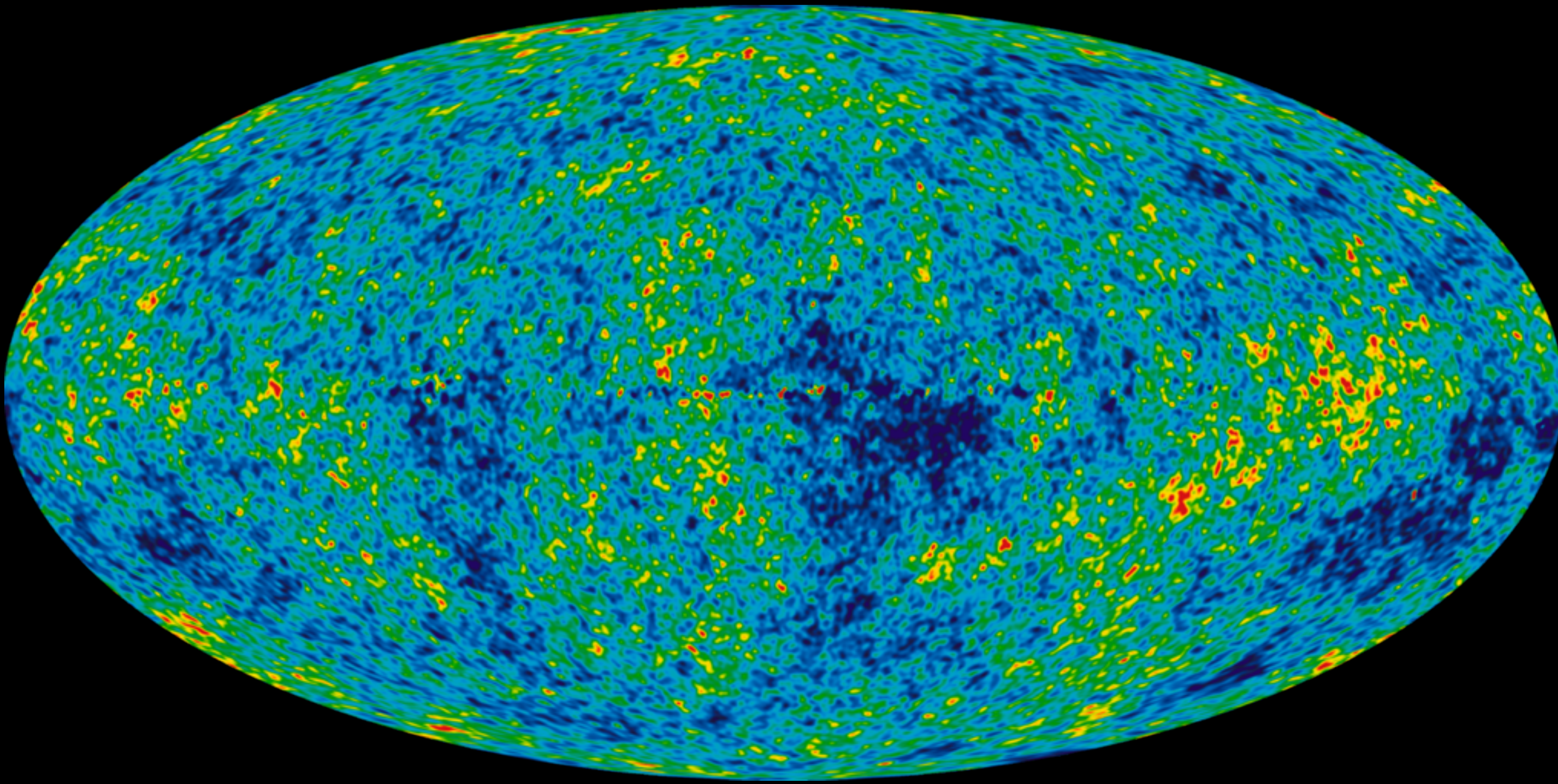
Point and compact sources

Sunyaev-Zel'dovich effect

Cosmic Microwave Background

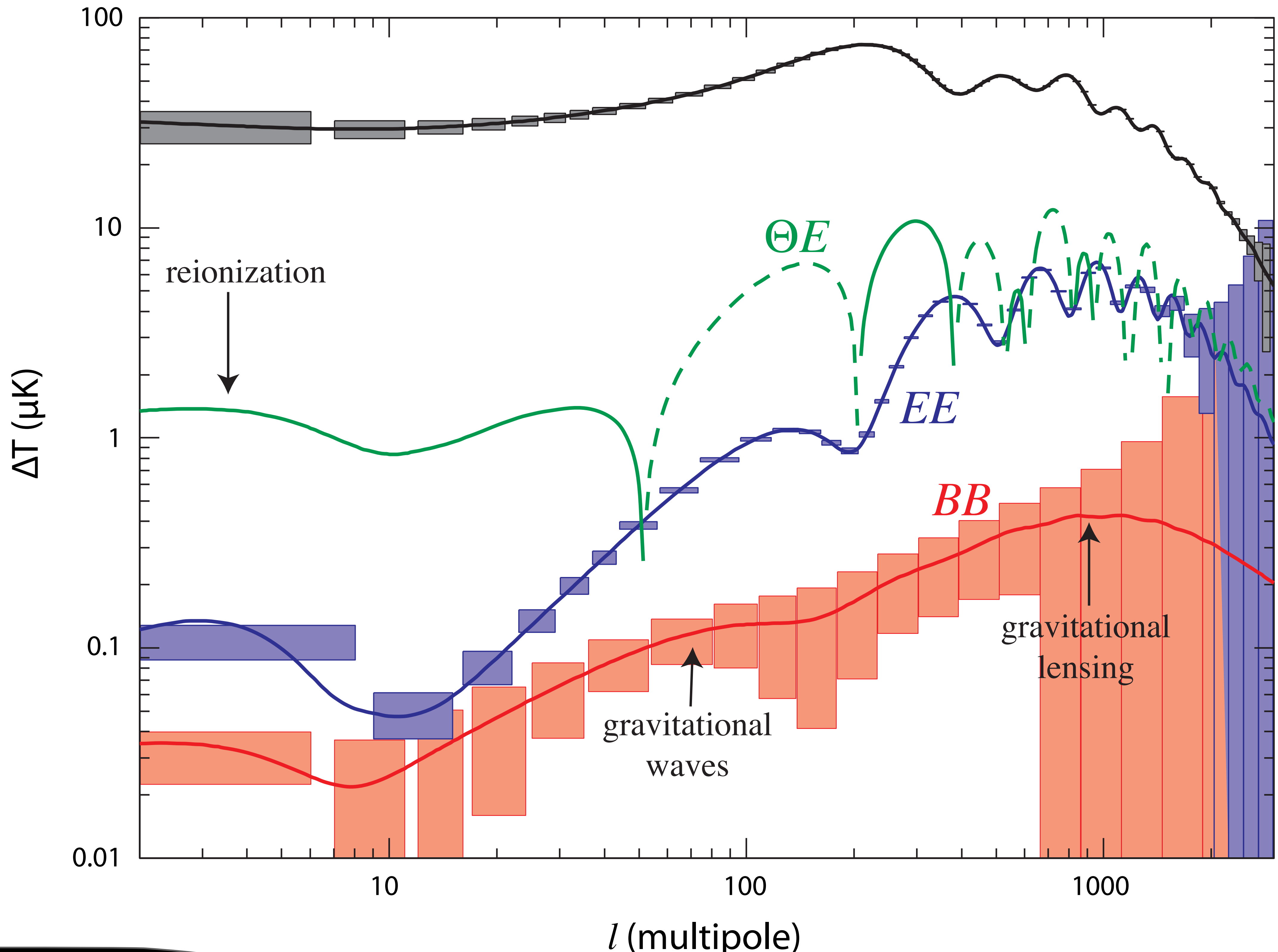
ESA, HFI & LFI consortia, Planck Collaboration

WMAP 7-yr CMB map



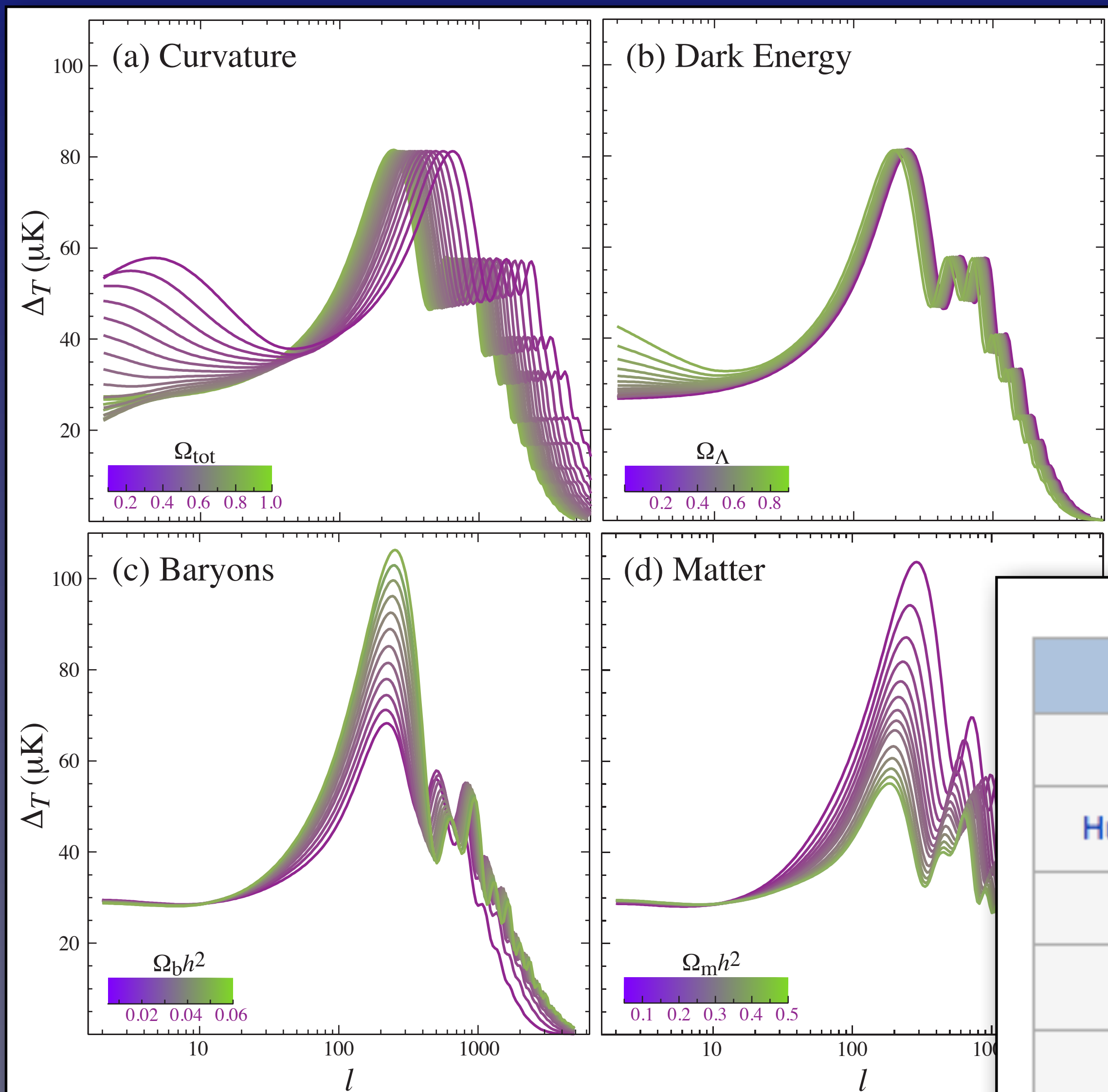
WMAP, Jarosik et al. (2010) / NASA

Predicted temperature anisotropies



Hu & Dodelson (2002, ARAA)

Fitting the CMB power spectrum



Best-fit cosmological parameters from WMAP seven-year results[20]

Parameter	Symbol	Best fit (WMAP only)	Best fit (WMAP + BAO[21] + H_0[22])
Age of the universe (Ga)	t_0	13.75 ±0.13	13.75 ±0.11
Hubble's constant (km/Mpc·s)	H_0	71.0 ±2.5	$70.4^{+1.3}_{-1.4}$
Baryon density	Ω_b	0.0449 ±0.0028	0.0456 ±0.0016
Physical baryon density	$\Omega_b h^2$	$0.022\,58^{+0.000\,57}_{-0.000\,56}$	0.022 60 ±0.000 53
Dark matter density	Ω_c	0.222 ±0.026	0.227 ±0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ±0.0056	0.1123 ±0.0035
Dark energy density	Ω_Λ	0.734 ±0.029	$0.728^{+0.015}_{-0.016}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ±0.030	0.809 ±0.024
Scalar spectral index	n_s	0.963 ±0.014	0.963 ±0.012
Reionization optical depth	τ	0.088 ±0.015	0.087 ±0.014

WMAP 7-yr CMB temperature power spectrum, Jarosik et al. (2010); parameter variations, Hu & Dodelson (2002)

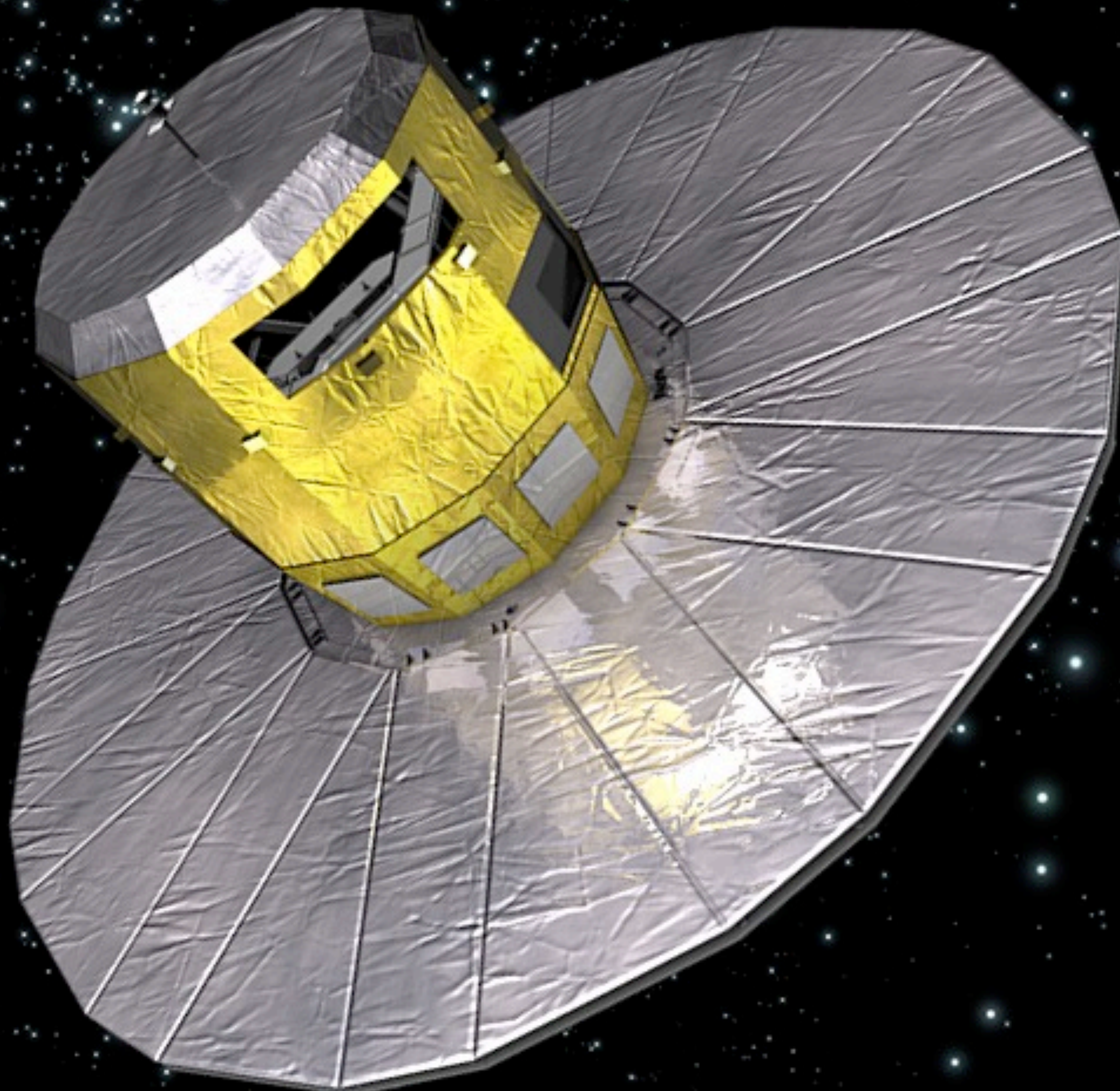
The promise of Planck

- Planck improvements over WMAP:
  - Spatial resolution (x 3)
  - Sensitivity (x 10)
  - Frequency coverage (30–857 GHz vs 23–94 GHz, 9 bands vs 5 bands)

- > 4 all-sky surveys *completed* by HFI: end-of-life January 2012
- > 7 all-sky surveys will soon be *completed* by LFI
- End-of-mission: sometime in 2013

- Early science and compact source catalogue: January 2011
- Additional science: January 2012
- *CMB temperature maps & first cosmology science: ~ March 15, 2013*
- CMB polarisation data (E-mode yes, B-mode?): early 2014

Gaia



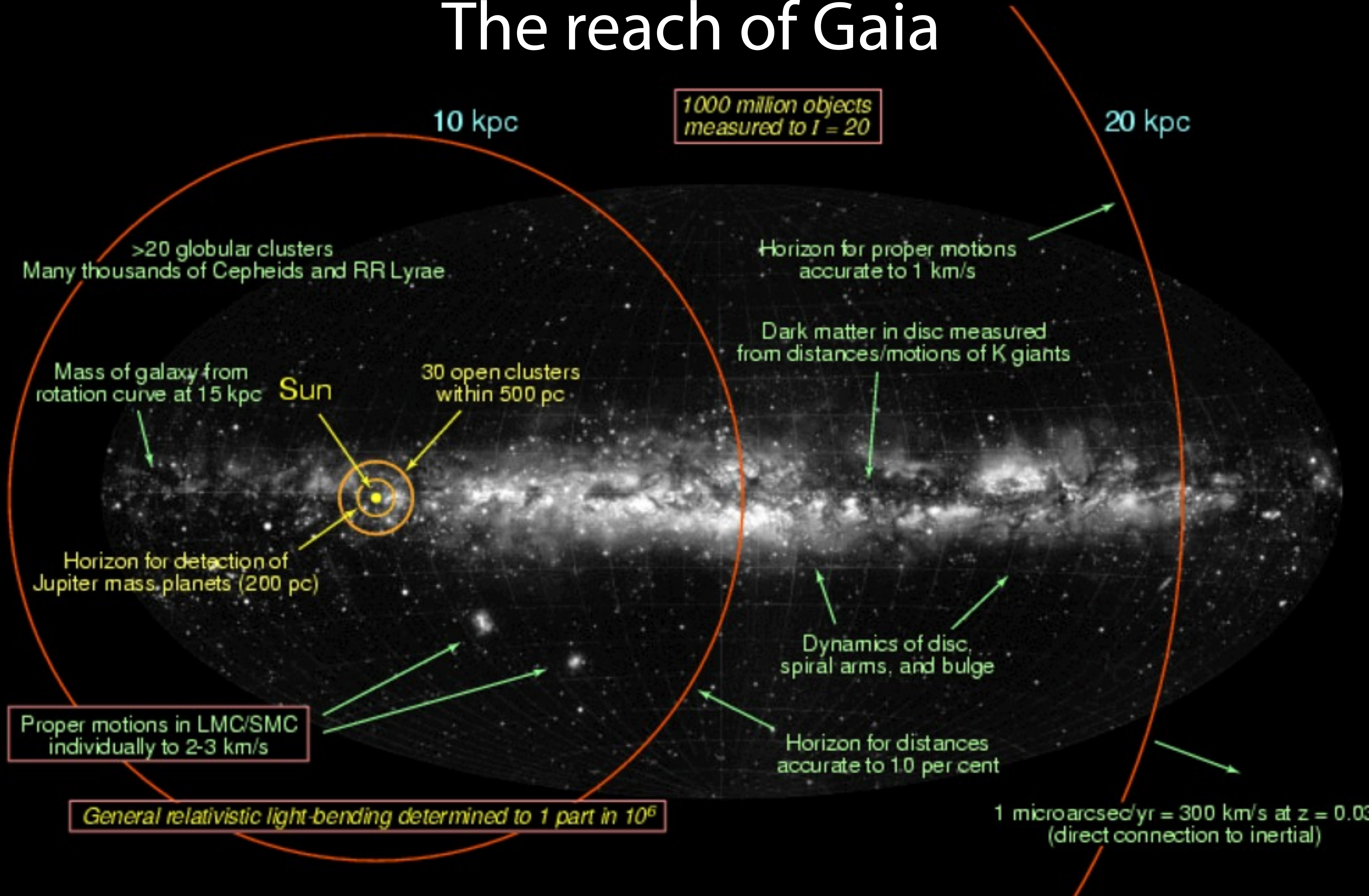
Scanning satellite measuring two fields simultaneously onto a gigapixel CCD array

Microarcsecond astrometry of a billion stars to V~20 to determine positions and velocities on plane-of-sky

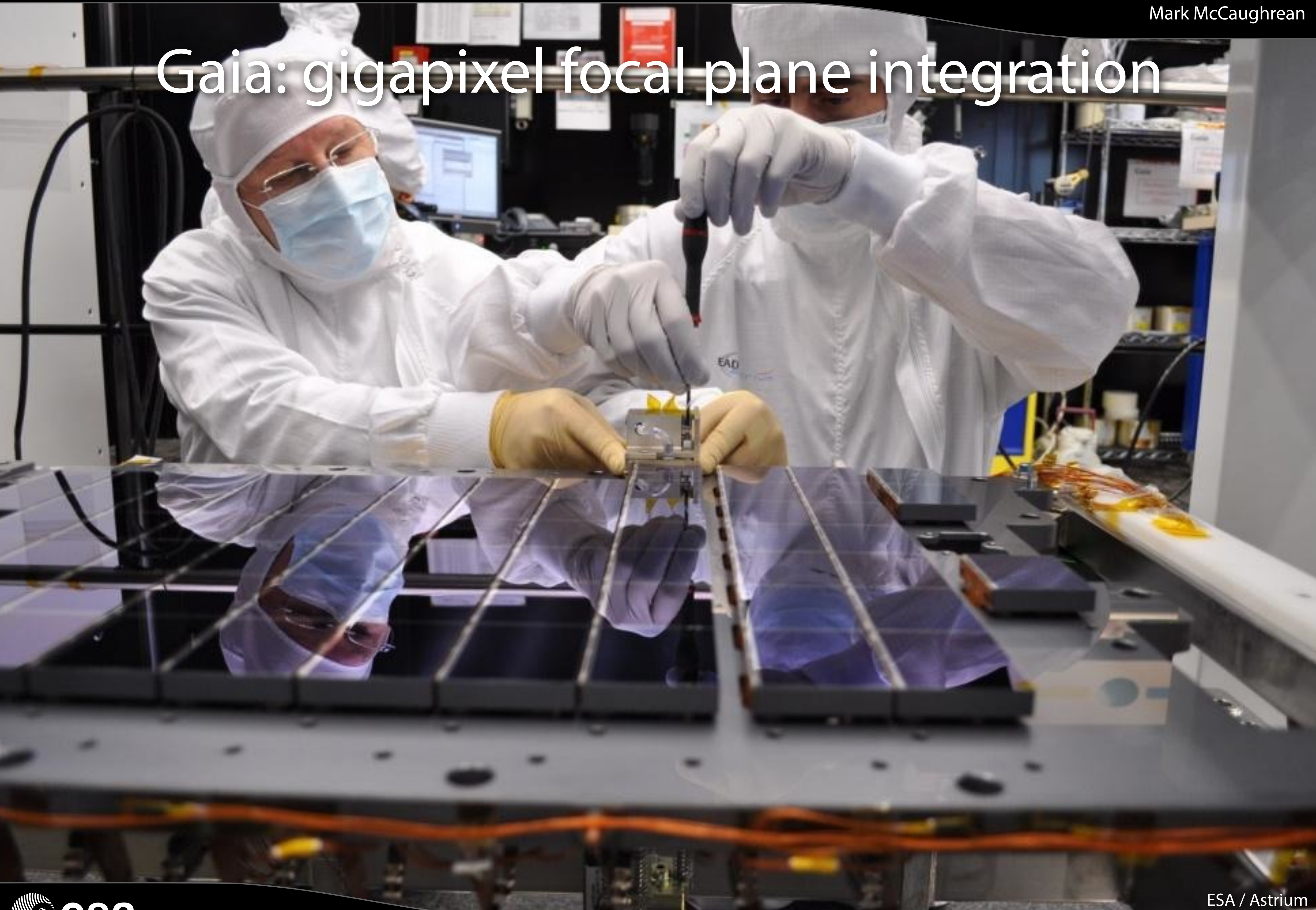
Radial velocity spectroscopy to measure line-of-sight velocities

ESA precision astrometry mission, scheduled launch 2013

The reach of Gaia



Gaia: gigapixel focal plane integration

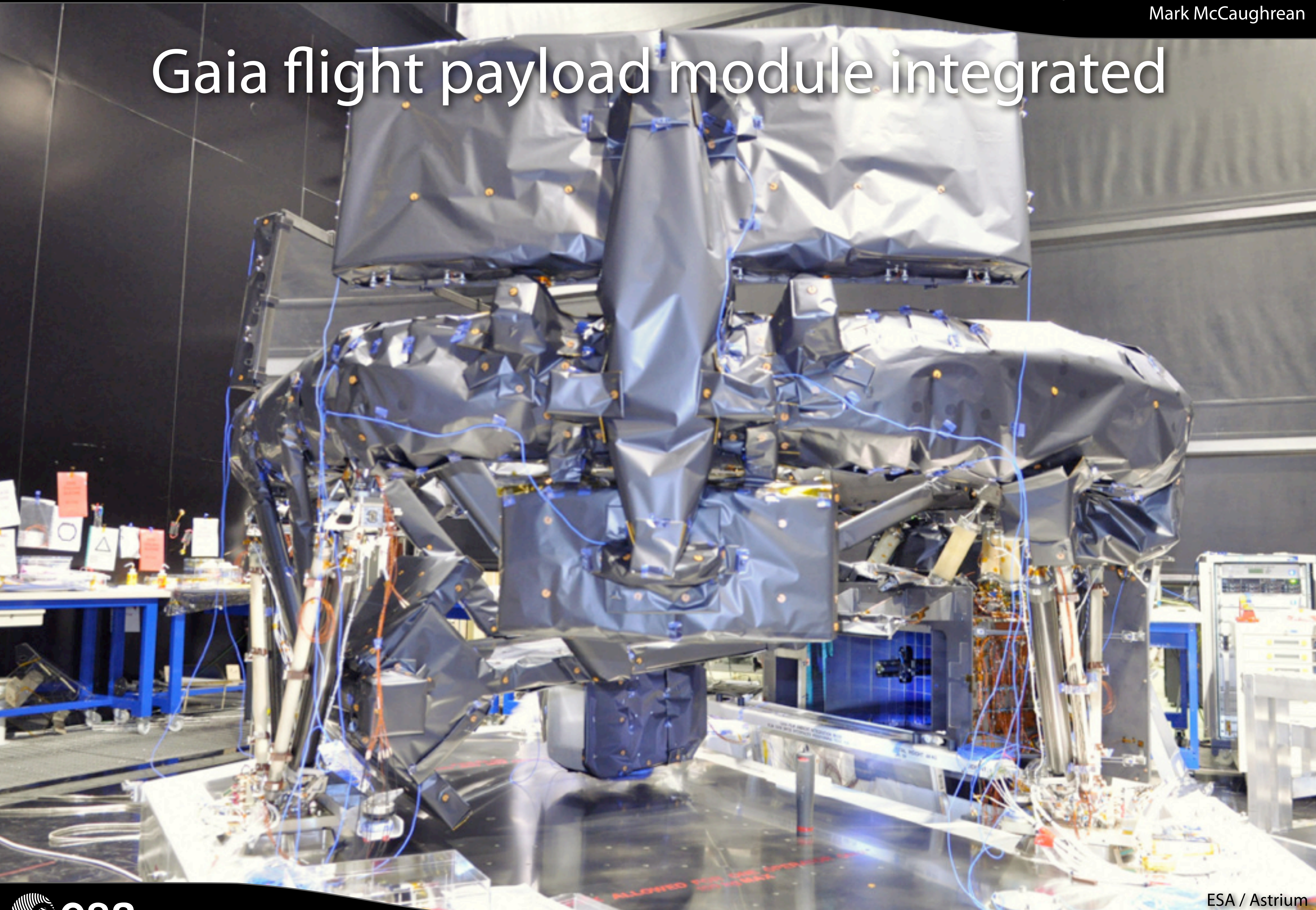


ESA / Astrium

Gaia: sunshield deployment

ESA / Astrium

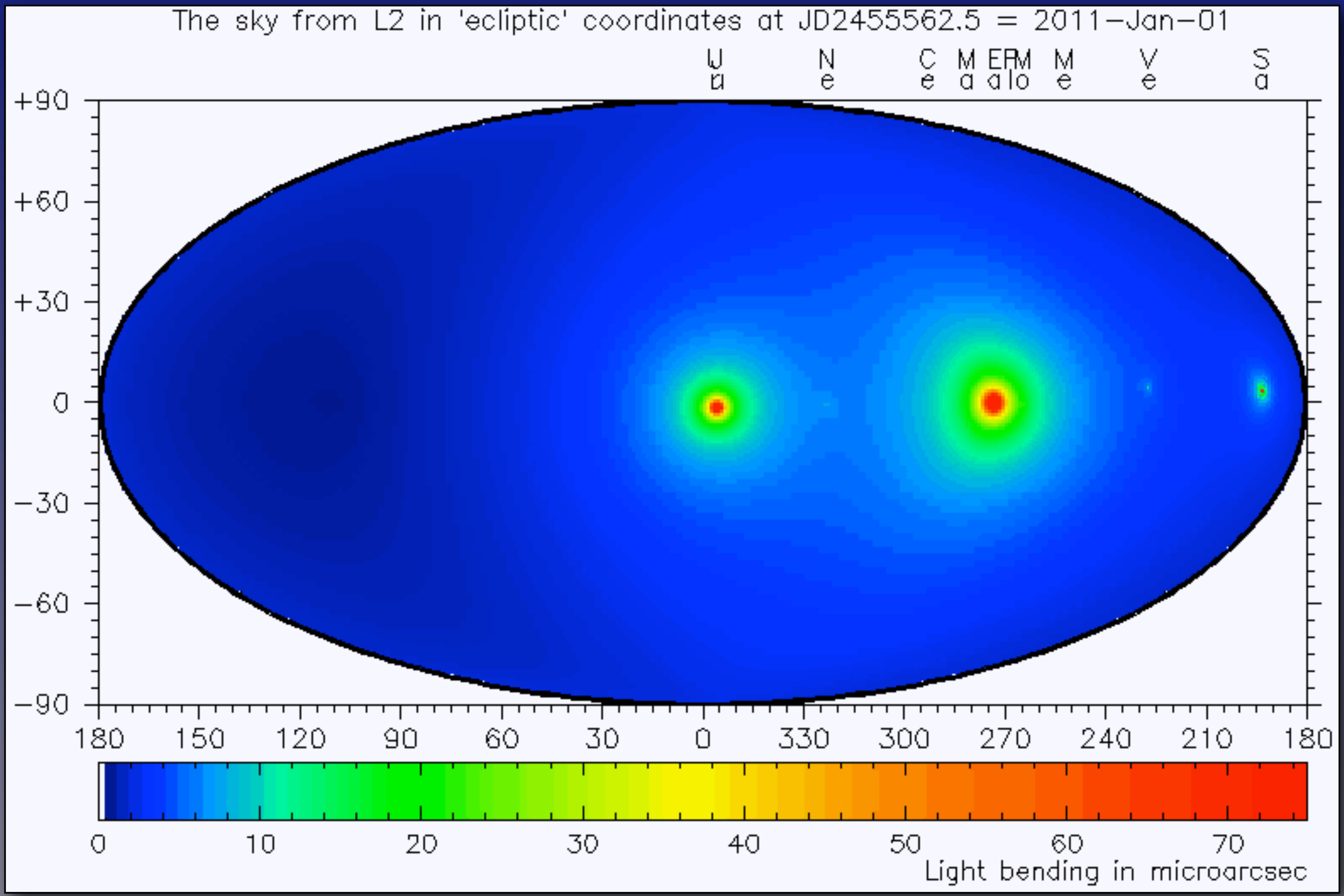
Gaia flight payload module integrated



Gaia science goals

- In the Milky Way:
  - Distance and velocity distributions of all stellar populations
  - Spatial and dynamic structure of disk and halo
  - Formation history of the galaxy
  - Detailed mapping of galactic dark matter distribution
  - Rigorous framework for stellar structure and evolution theories
  - Large-scale survey for extra-solar planets (~7,000)
  - Large-scale survey for Solar System bodies (~250,000)
- Beyond the Milky Way:
  - Precise distance calibration to LMC/SMC (cf. impact on dark energy)
  - Rapid reaction alerts for supernovae and burst sources (~20,000)
  - Quasar detection, redshifts, microlensing structure

Gravitational deflection in the Solar System



Light bending *after* subtraction of much larger deflection due to the Sun

Jos de Bruijne / ESA

Gaia and fundamental physics

- Gaia requires full GR modelling to deliver 1 microarcsec astrometry
  - Motion of Solar System
  - Motion of Gaia
  - Light propagation: aberration, light deflection
  - Description of observed objects: orbits, parallax, proper motion, radial velocity
- In turn, can make significant contributions to fundamental physics
  - In addition to dark energy and dark matter science
- Weak-field light deflection in Solar System
  - Wide range of angles from Sun; empirical tests of angular distance dependence
  - PPN γ (space curvature parameter) measured to $\sigma_\gamma \sim 2 \times 10^{-6}$
  - Careful control of systematics vital (e.g. velocity of Gaia, Basic Angle variation)
  - Subtle deflections due to planets: monopole, quadrupole, gravitomagnetic?

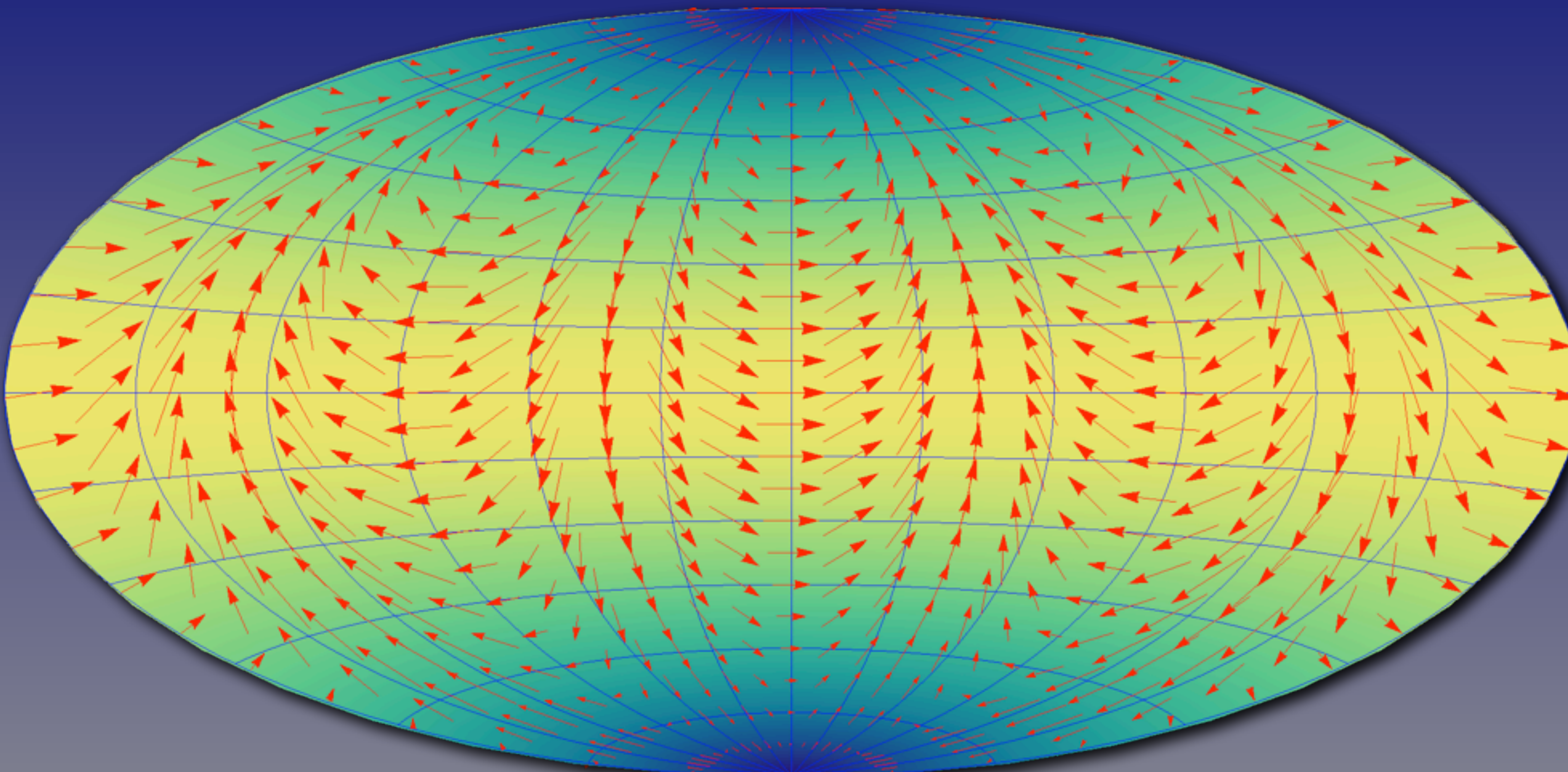
Courtesy Sergei Klioner, TU Dresden

Gaia and fundamental physics

- Relativistic effects on Solar System objects
  - Perihelion precession, 2-body and 3-body effects with asteroids, etc.
- Astrometry for optical counterparts to interesting objects
  - e.g. neutron stars, black holes in X-ray binaries: masses, orbital inclinations
- Pattern matching in reference frame
  - Accurate positions, distances, proper motions for dense field of bright sources > 1500 deg^{-2}, ~ 20 000 primary sources with $G < 18$ mag, linked to quasar frame
  - Creates accurate, long-lived reference frame, drift ~0.4 microarcsec yr^{-1},
  - Can search for global patterns in proper motions, e.g.:
    - Acceleration of Solar System towards Galactic Centre to test galactic potential
    - Constraints on very low frequency gravitational waves
    - Stochastic primordial GW flux at $\nu < 10^{-8}$ Hz (cf. Gwinn et al. 1997 for VLBI)
    - Individual GW to much higher frequencies ~ 10^{-2} Hz?

Courtesy Sergei Klioner, TU Dresden

Model patterns in Gaia global proper motions



Acceleration towards Galactic Centre

Gravitational wave propagating in direction δ = 90°

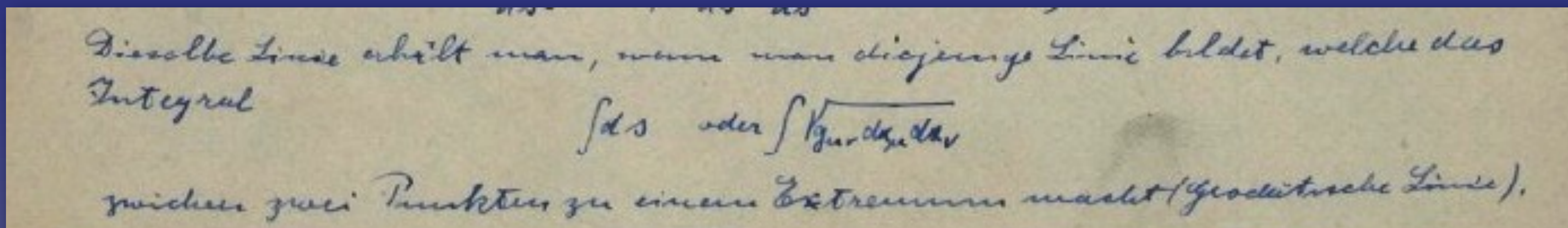
Courtesy Sergei Klioner, TU Dresden

LISA Pathfinder

ESA gravitational wave detection technology testbed, scheduled launch 2014

LISA Pathfinder and geodesics

- Most basic assumption of GR is that free particles follow geodesics unless acted upon by an unbalanced force



Dieselbe Linie erhält man, wenn man diejenige Linie bildet, welche das Integral

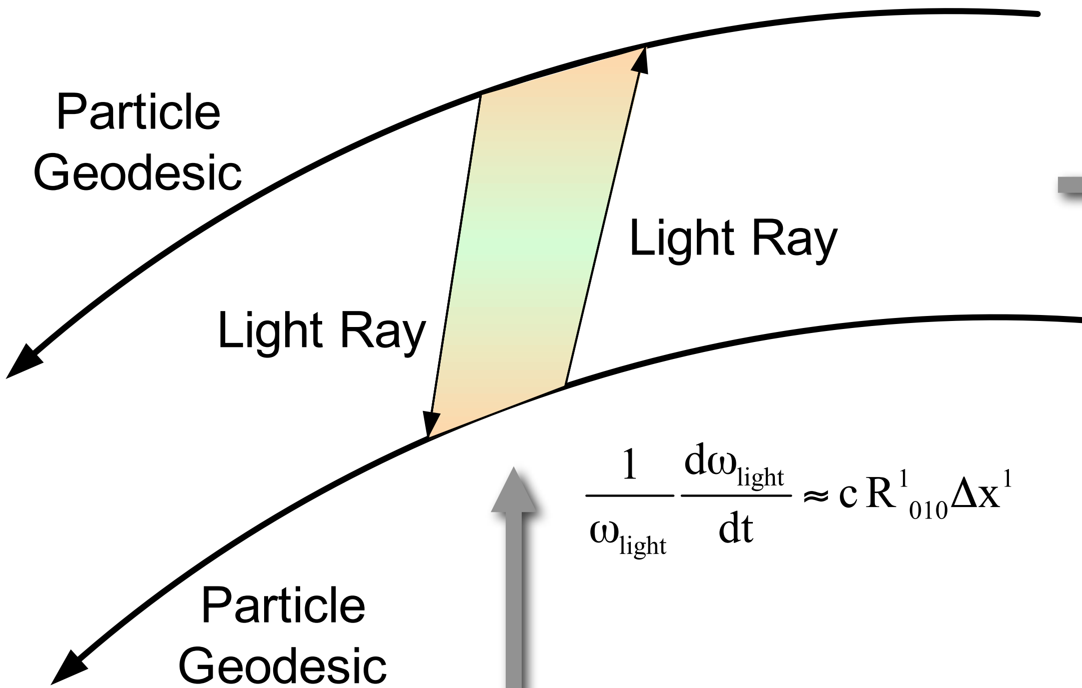
$$\int ds \quad \text{oder} \quad \int \sqrt{g_{\mu\nu} dx_\mu dx_\nu}$$

zwischen zwei Punkten zu einem Extremum macht (Geodätische Linie).

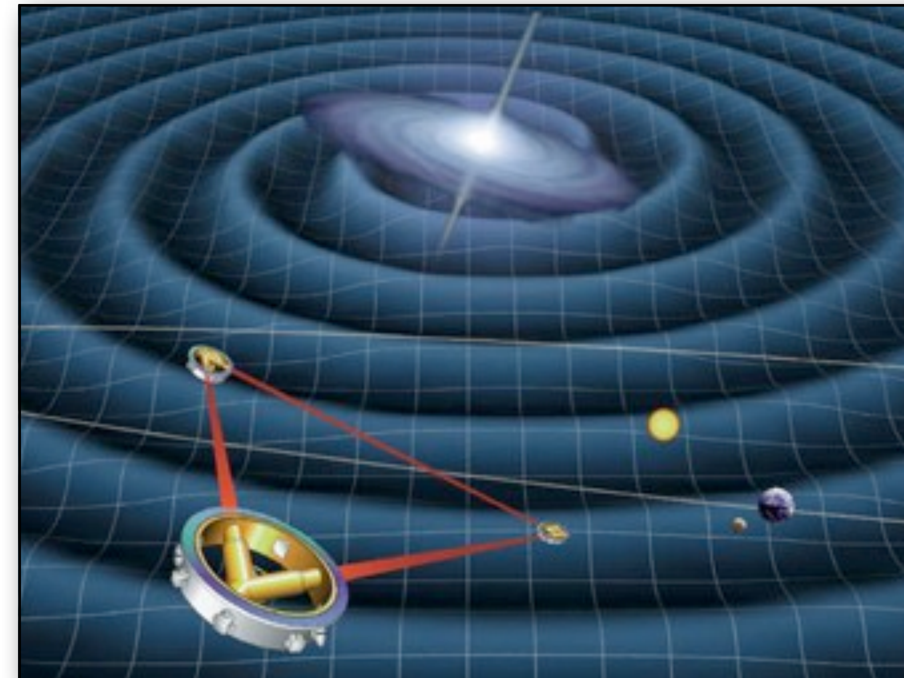
Definition of geodesics from Einstein's "The Meaning of Relativity"

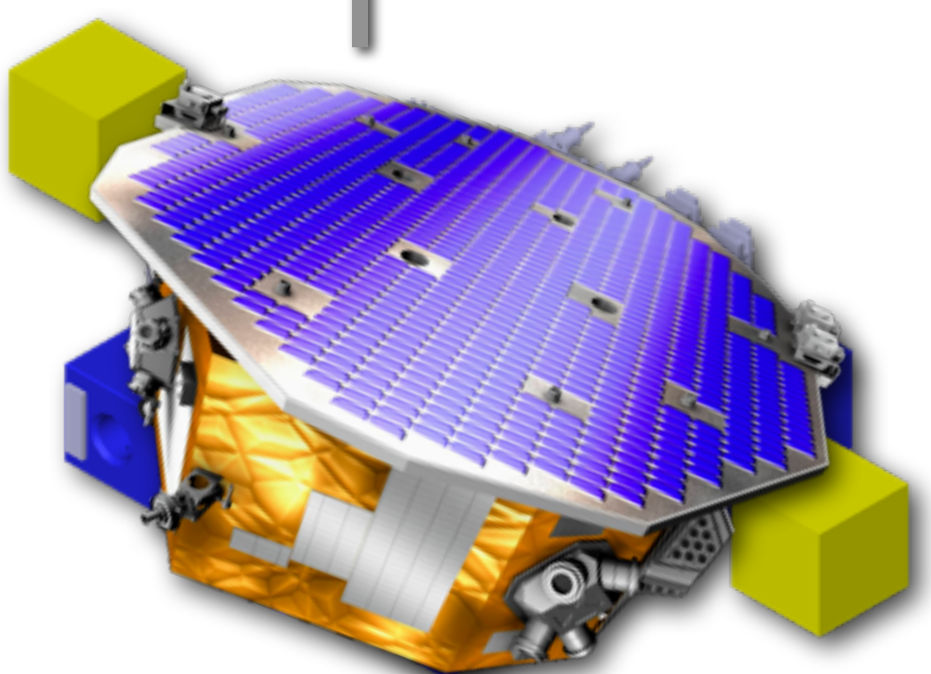
- LISA Pathfinder will provide the most accurate test yet of assumption that free particles follow geodesics
  - Two free-floating test masses within a drag-free spacecraft, linked interferometrically to measure relative displacements
  - Tests of technology for future gravitational wave detection missions
- Provides a near-perfect environment for fundamental physics
  - Spacecraft jitter w.r.t. inertial frame ~ 2 nm/√Hz at 1 mHz

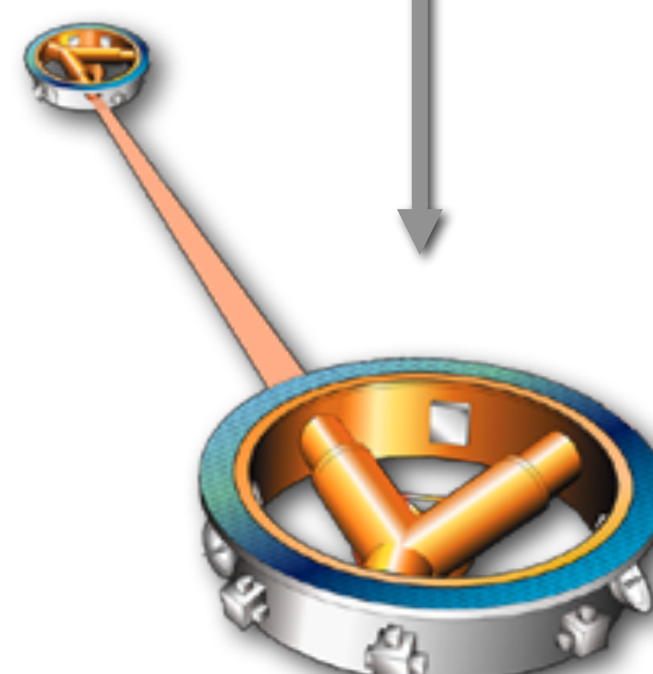
From LISA to LISA Pathfinder



$$\frac{1}{\omega_{light}} \frac{d\omega_{light}}{dt} \approx c\, R^{1}{}_{010} \Delta x^{1}$$

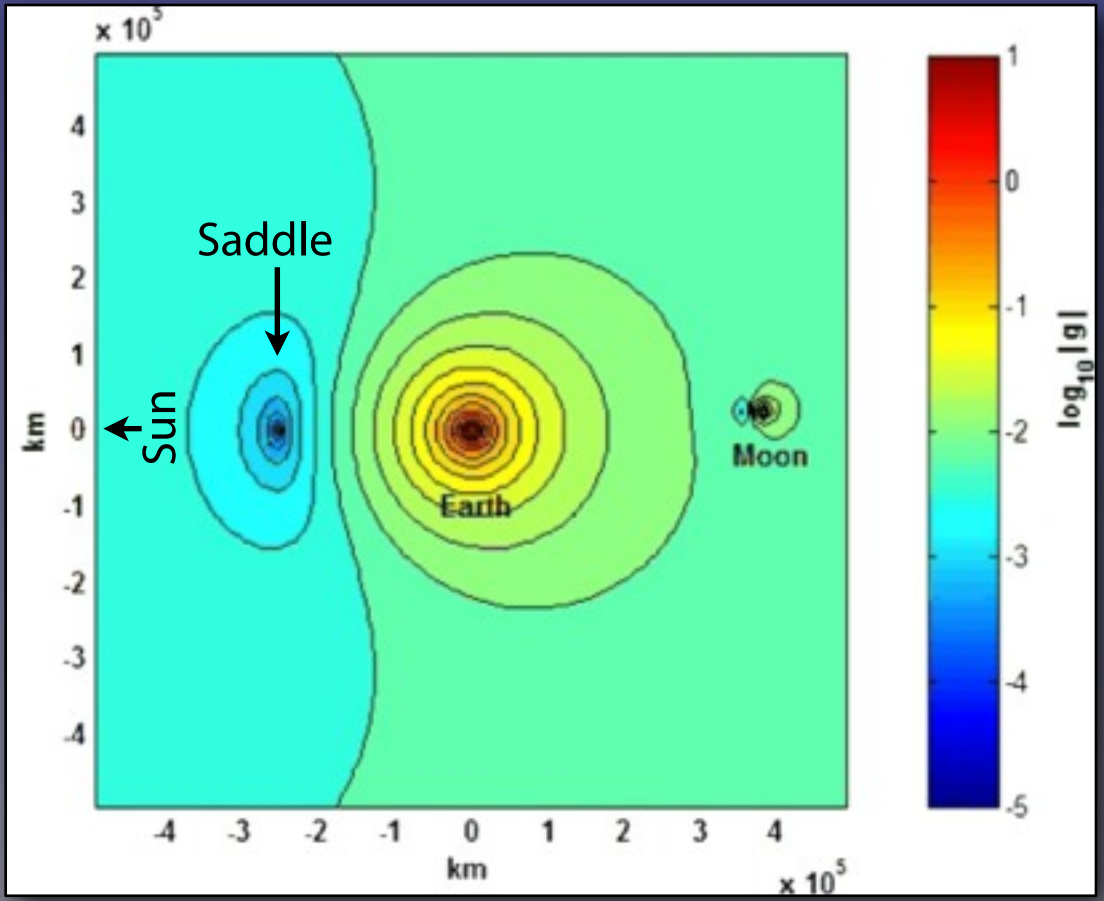






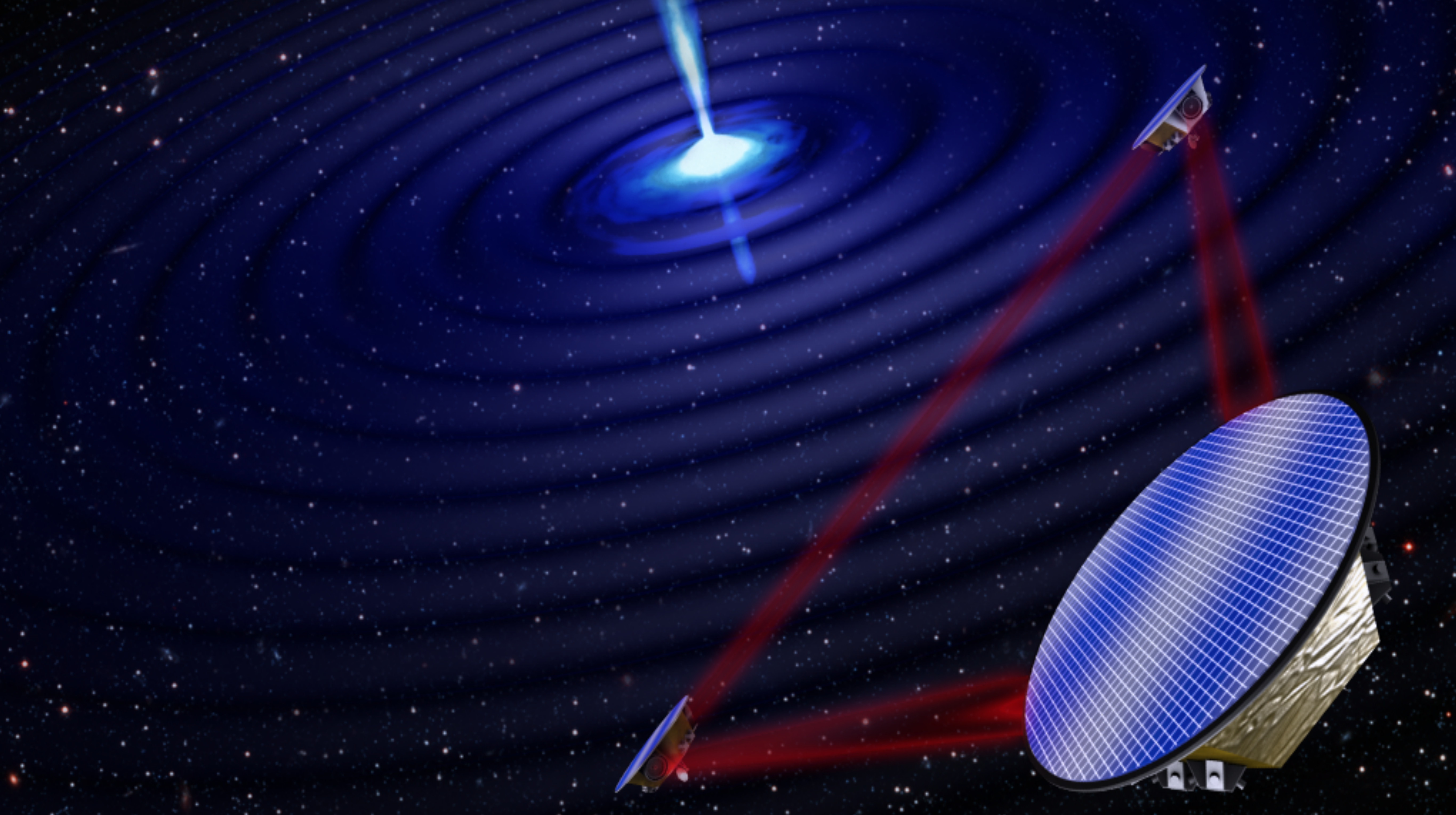
Testing alternative theories of gravity

- Galaxies seen to have flat rotation curves
  - Standard solution is that they are embedded in massive dark matter haloes
- Alternative: breakdown in Newtonian dynamics when background gravitational field drops below threshold ~ 10^{-10} m s^{-2}
  - MOND (Millegrom), TeVeS (relativistic version of MOND, Bekenstein), and others
- Direct test of modified gravity difficult
  - e.g. at LISA Pathfinder station at L1, background acceleration ~ 6 x 10^{-3} m s^{-2}
- But there are saddle points ("bubbles") where fields should cancel
  - e.g. Sun-Earth saddle, ~ 250,000 km from Earth
- After nominal mission, LISA Pathfinder could fly through "MOND bubble"
  - Monitor gravity gradient between test masses
  - Predicted MOND "signal": ~10^{-13} m s^{-2} for ~300s
  - Only mission planned with required sensitivity



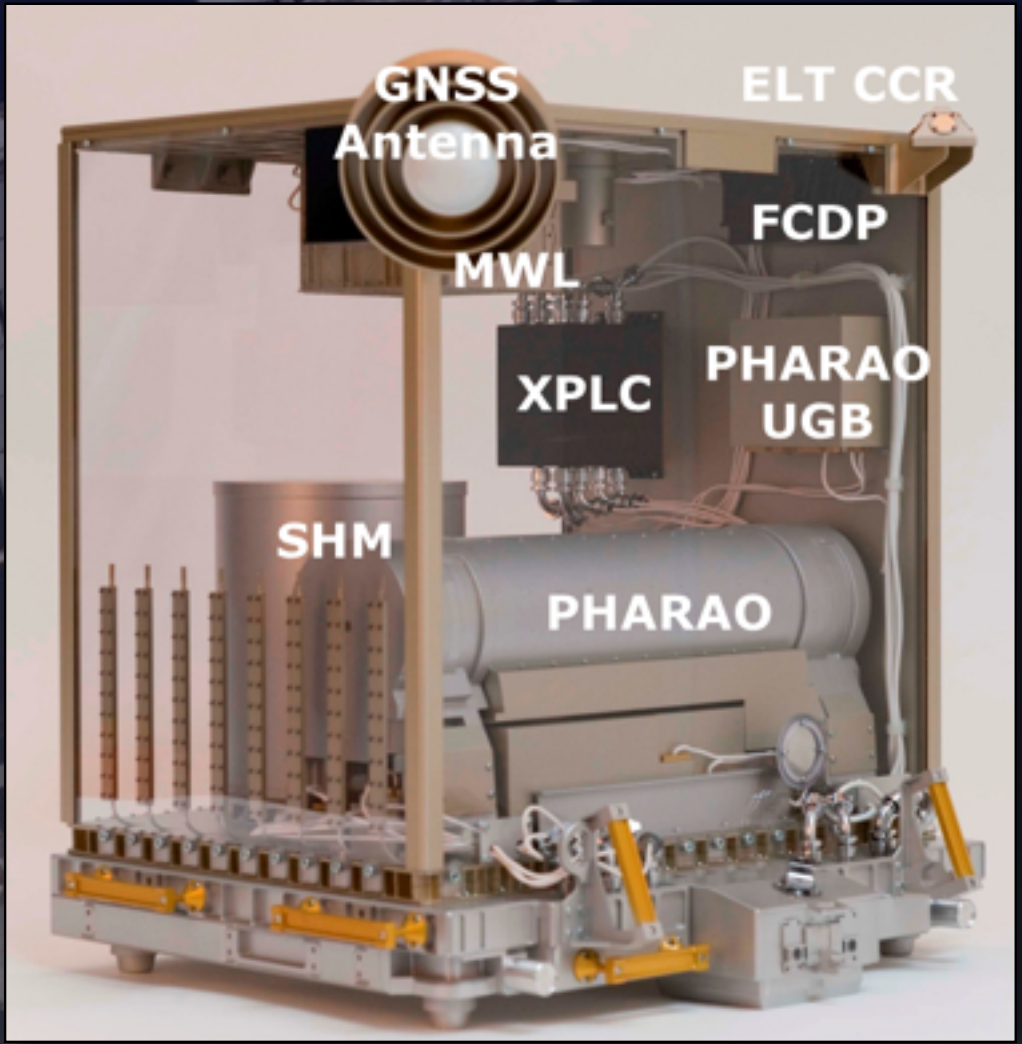
Future gravitational wave mission

LISA, NGO



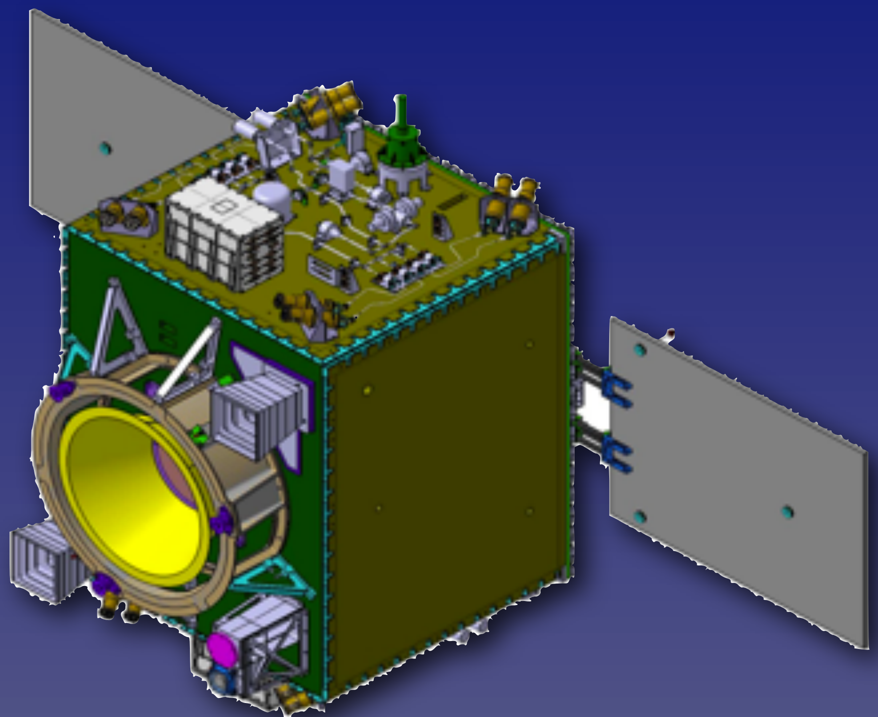
ACES

- Atomic Clock Ensemble in Space
  - PHARAO: Cs atomic clock (CNES)
  - SHM: Hydrogen maser (ESA)
  - Microwave link to ground terminals
- Science goals:
  - Measurement of gravitational redshift
    - Precision 50 x 10^{-6} in 300 s; 2 x 10^{-6} in 10 days
  - Time variations in fine structure constant
    - $\alpha^{-1} . d\alpha/dt < 10^{-17}$ yr^{-1}
  - Search for anisotropies in speed of light
    - $\Delta c/c \sim 10^{-10}$
  - Relativistic geodesy at 10 cm level
- Low-Earth orbit
  - To be installed on ISS in 2015
  - Ground-terminals: Europe, US, Asia, Australia

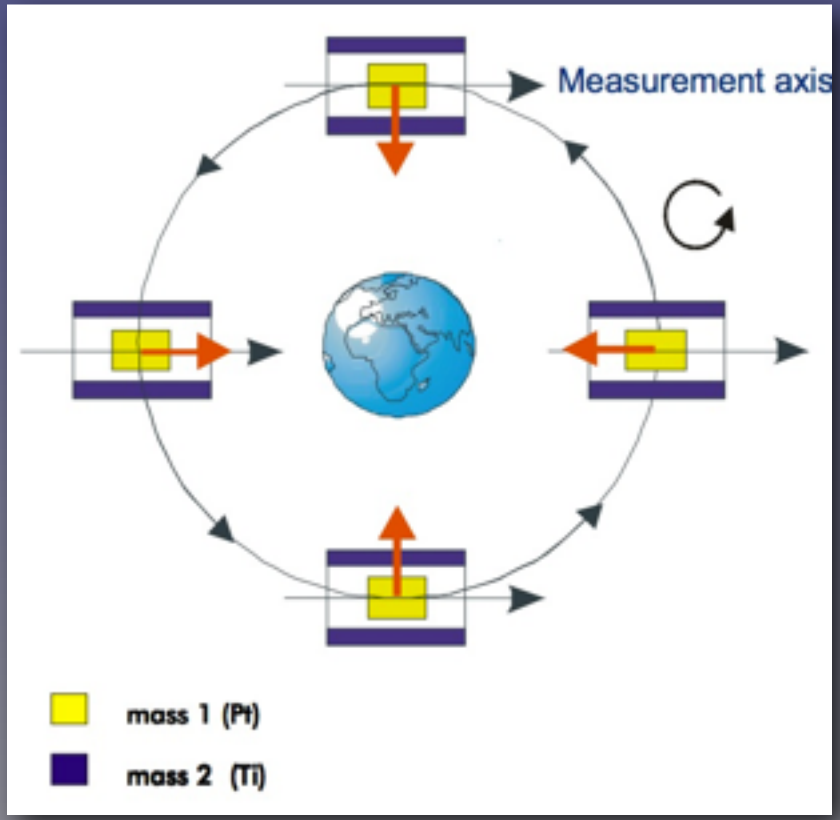


ESA (Human Spaceflight programme)-CNES

Microscope



- CNES-led mission
  - ESA contributes cold gas thruster system
  - Similar to Gaia, LISA Pathfinder propulsion system
- Science goal:
  - Test Weak Equivalence Principle to 1 part in 10^{15}
- Measure relative free-fall of two test masses
  - Concentric cylinders of platinum and titanium
- Low-Earth orbit
  - Sun synchronous, altitude 730–790 km
- Launch date: 2016

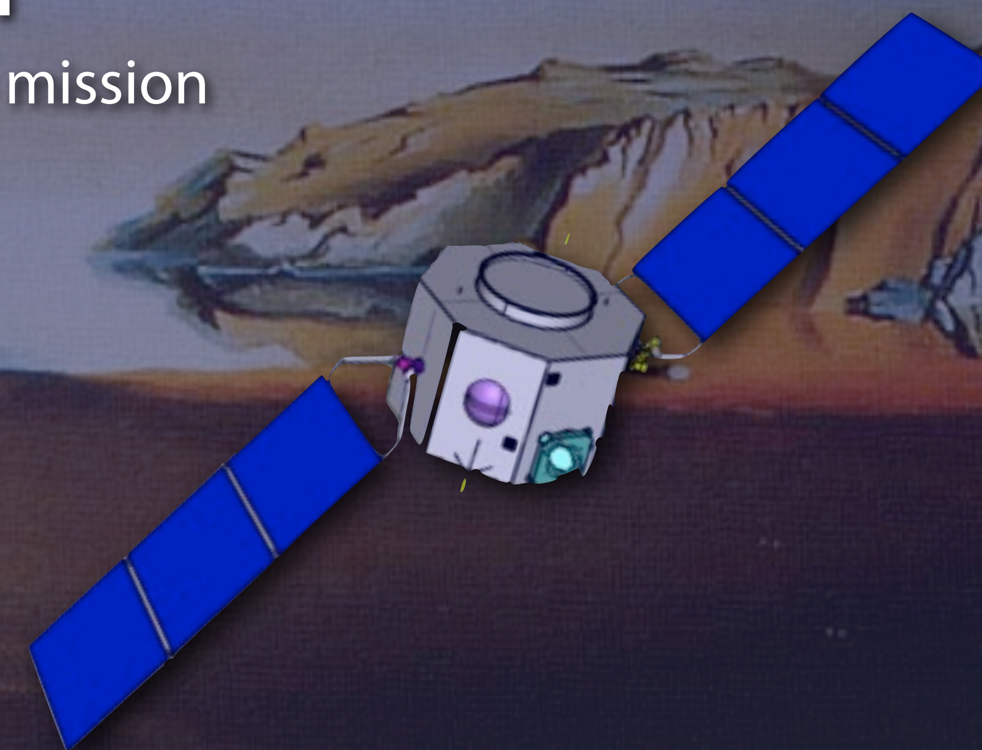


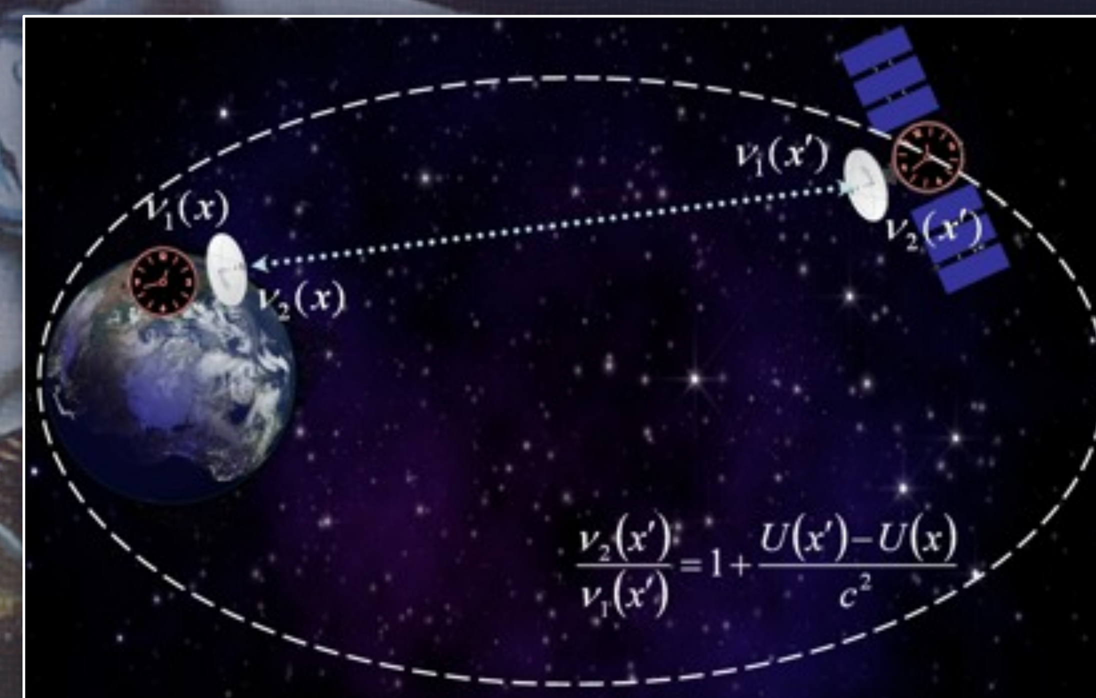
CNES-ESA

STE-QUEST

Cosmic Vision M3 candidate mission

- Space Time Explorer and Quantum Equivalence Space Test
  - Laser-cooled Rb microwave atomic clock
  - $^{85}Rb/^{87}Rb$ differential matter interferometer
  - Microwave/optical links to ground terminals
- Science goals:
  - Earth gravitational redshift
    - Precision 2×10^{-7}; ultimate aim 4×10^{-8}
  - Sun gravitational redshift
    - Precision 2×10^{-6}; ultimate aim 6×10^{-7}
  - Universality of propagation of matter waves
    - Measurement of Eötvös parameter to $< 10^{-15}$
- Highly-elliptical Earth orbit





Mission to provide high precision test of Einstein Equivalence Principle, nominal launch in 2022–2024