What's next in fundamental and particle physics in space

Bologna
INAF-OABO
Octobre 1th 2015

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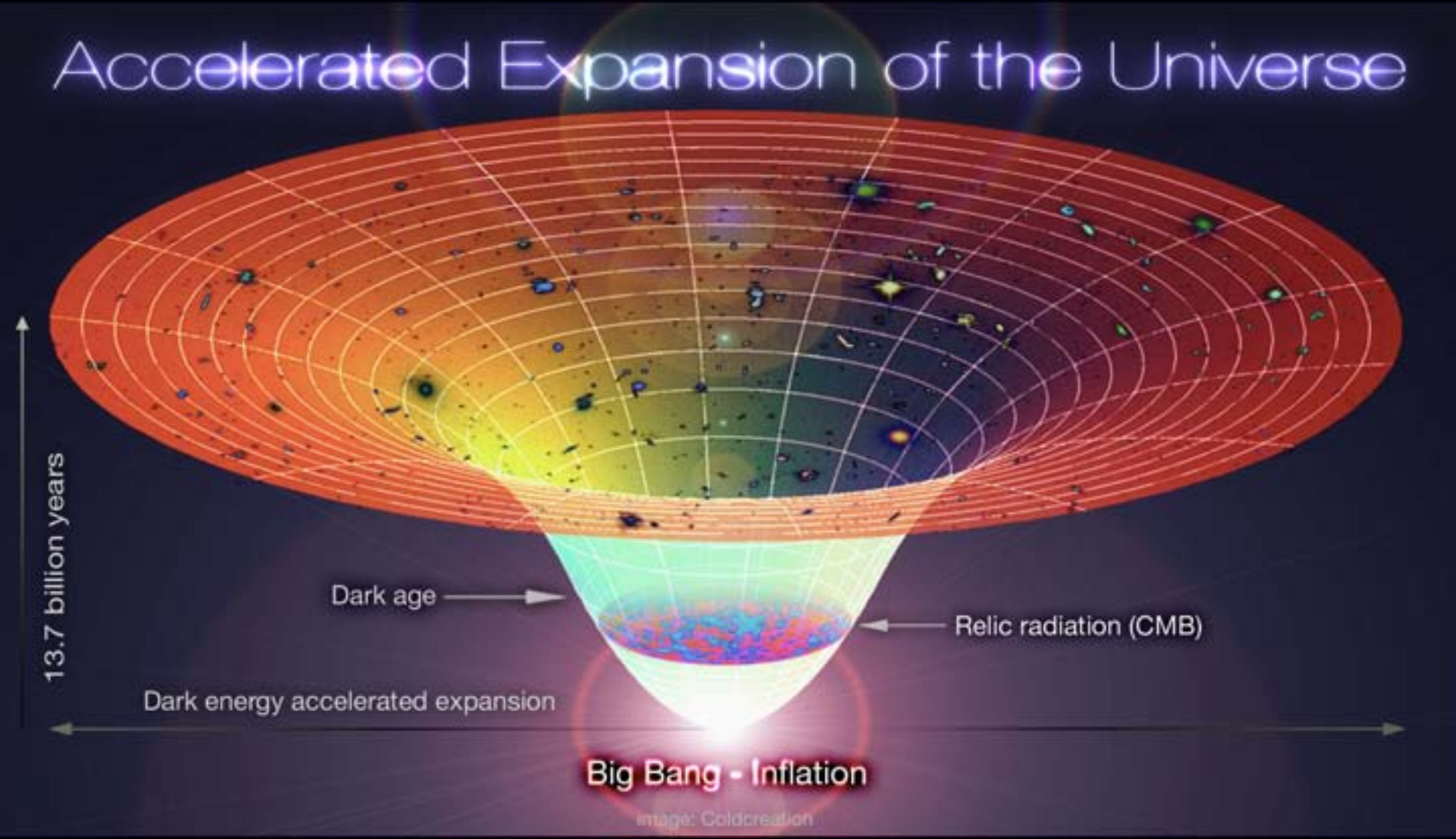
Italian Space Agency
University and INFN-TIFPA, Trento

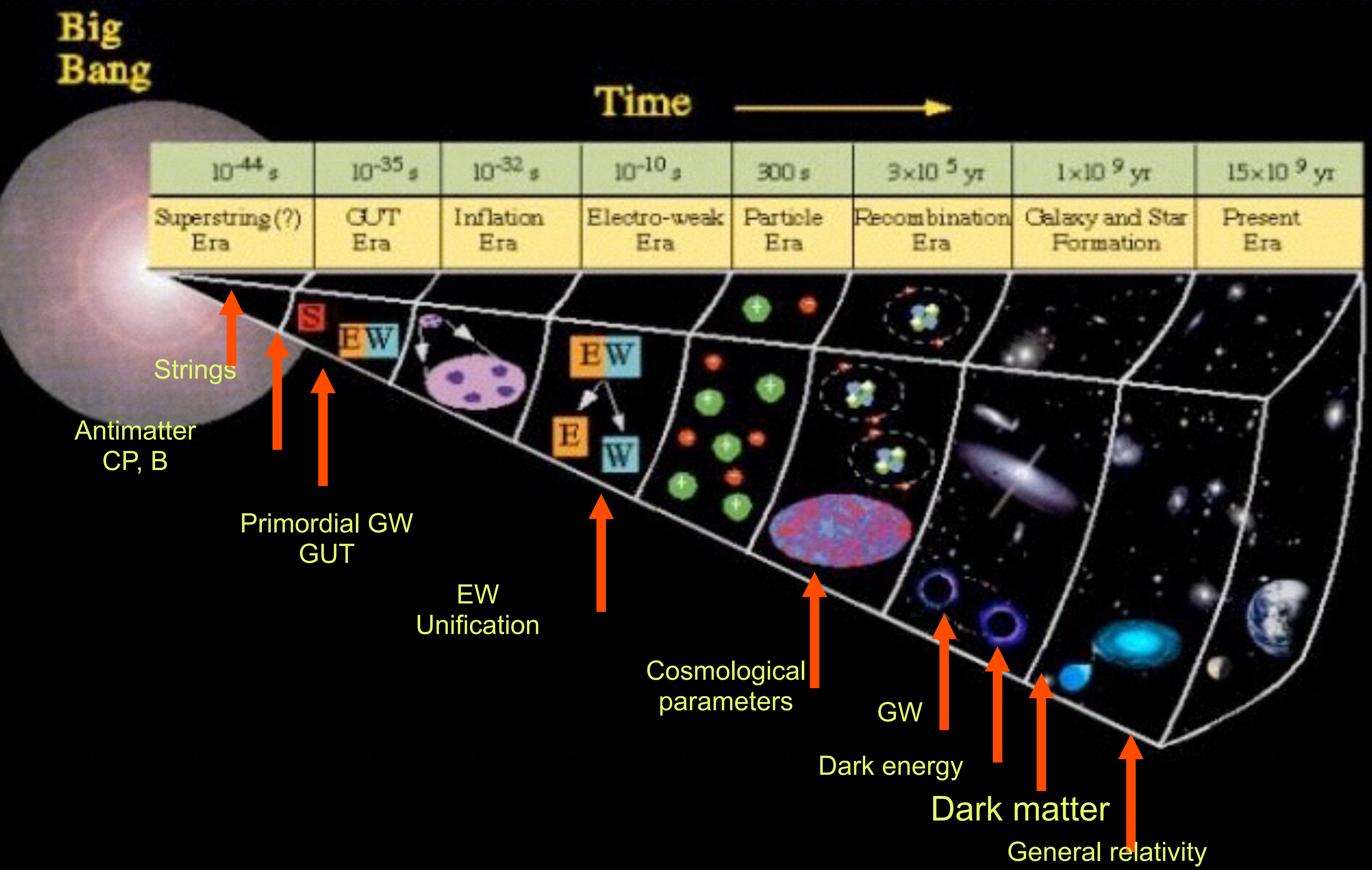
- Content

- Space, time and gravity
- Quantum origins and the CMB bonanza
- The dark side of the universe
- Dark Matter search at accelerators, underground and in space

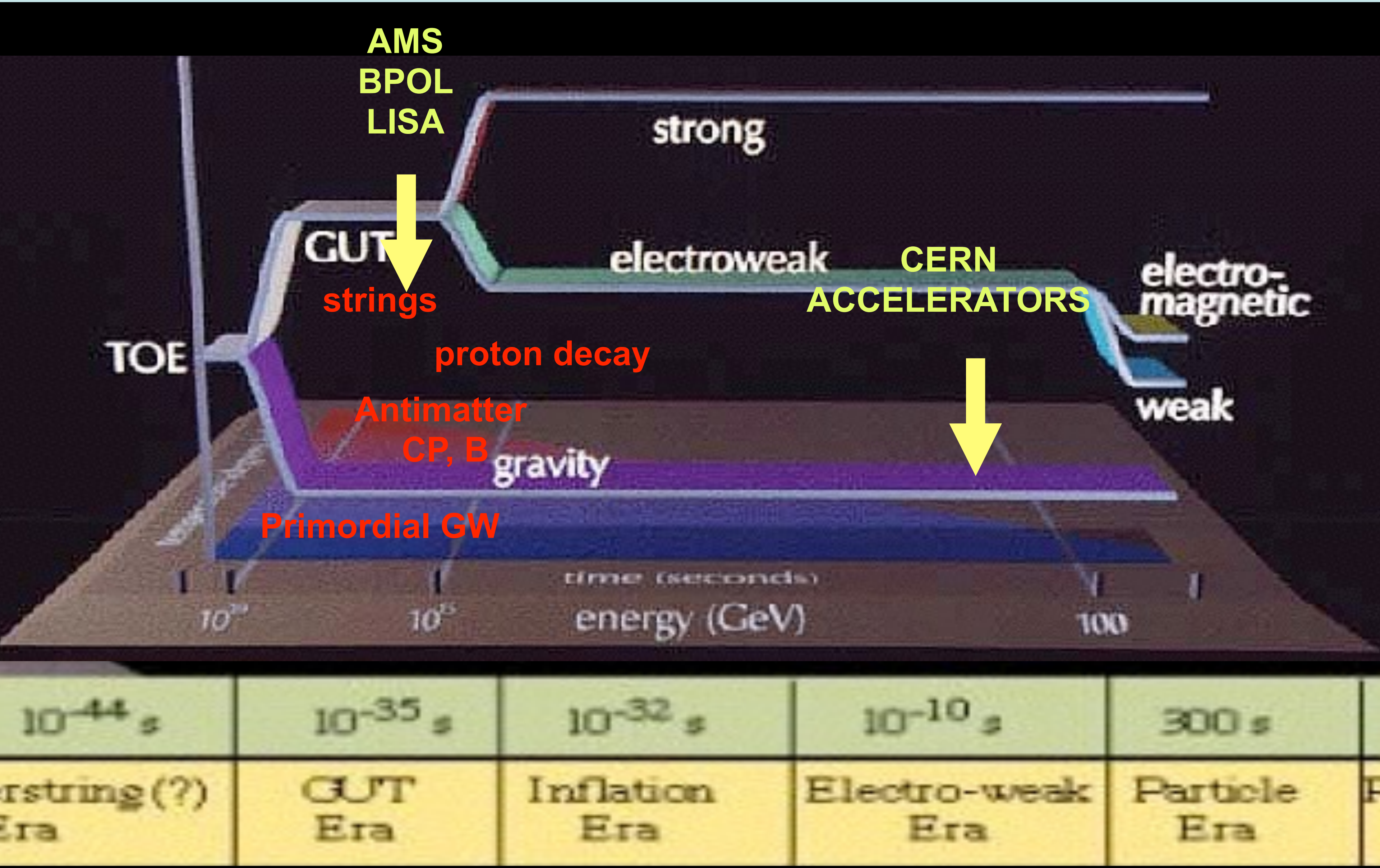

Accelerated Expansion of the Universe
13.7 billion years
Dark age
Relic radiation (CMB)
Dark energy accelerated expansion
Big Bang - Inflation
image: Coldcreation

ΛCDM model

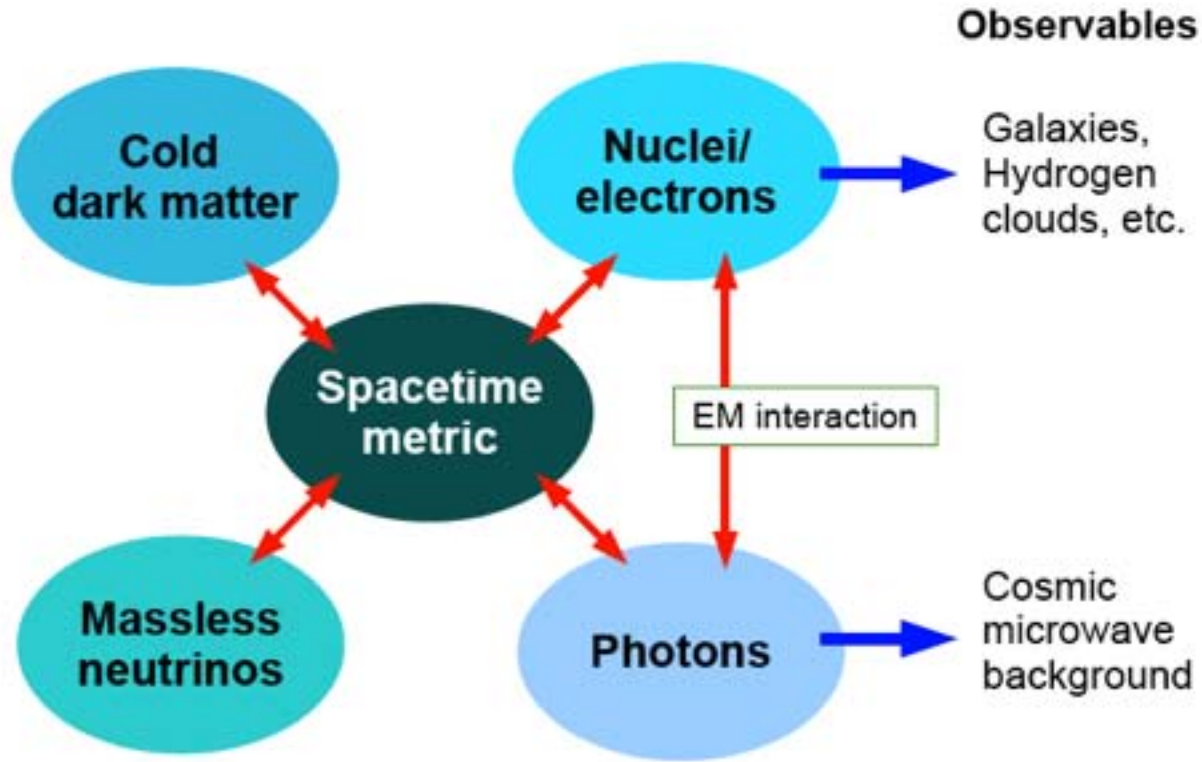
The Universe is the ultimate laboratory to test fundamental physics.....



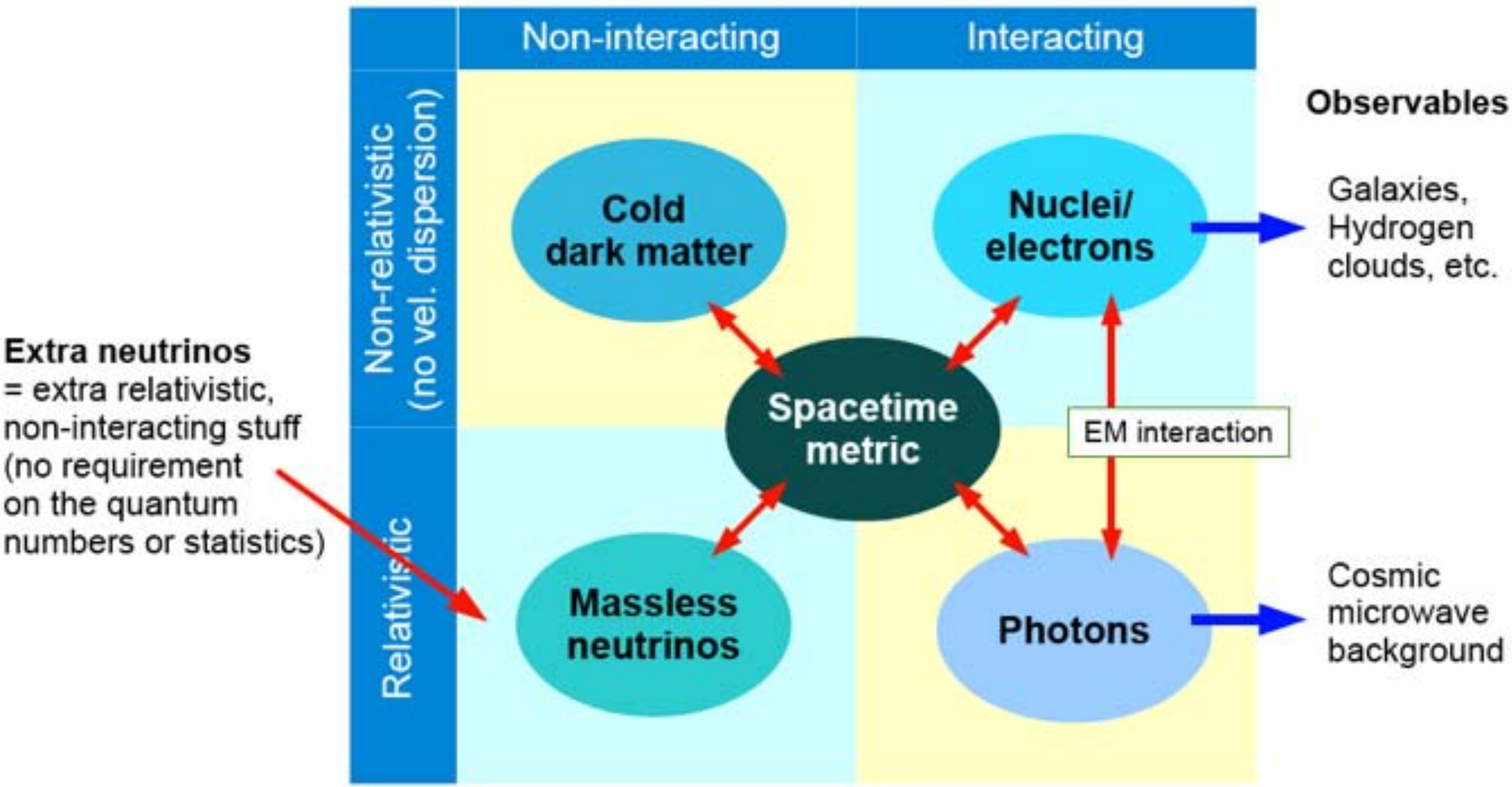
.......to scales which cannot be reached by the most powerful accelerators....



Particle content of the concordance ΛCDM model...

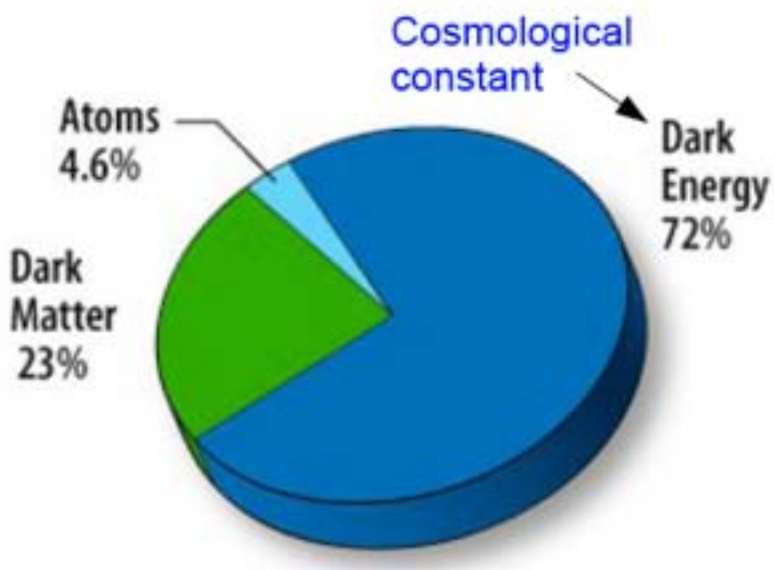


Particle content of the concordance ΛCDM model...

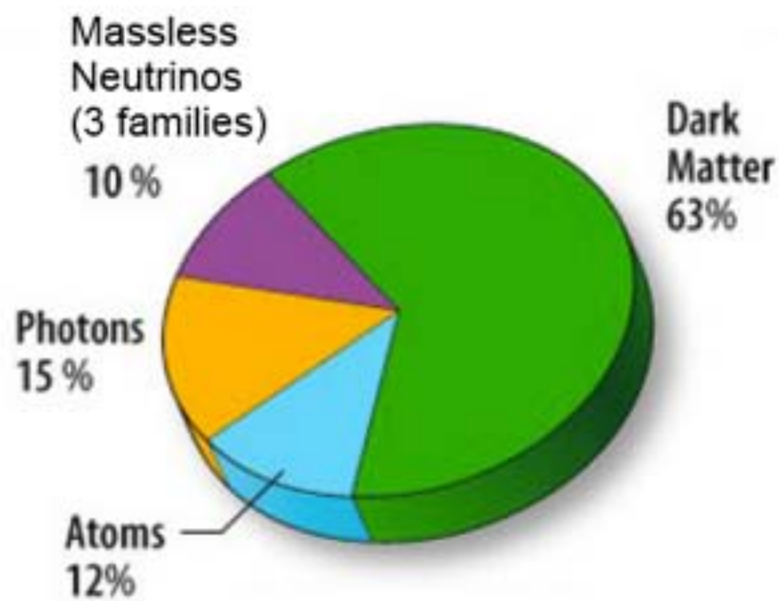


The concordance flat ΛCDM model...

- The simplest model consistent with **observations**.



Composition today



13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions
from single-field inflation

......and space - time

Theoretical Landscape of the 20th Century:

Competing Theories of Gravity

not a complete list…

Newton 1686	Poincaré 1890			
Einstein 1912	Nordstrøm 1912	Nordstrøm 1913	Einstein & Fokker 1914	Einstein 1915
Whitehead 1922	Cartan 1923	Kaluza & Klein 1932	Fierz & Pauli 1939	Birkhoff 1943
Milne 1948	Thiry 1948	Papapetrou 1954	Jordan 1955	Littlewood & Bergmann 1956
Brans & Dicke 1961	Yilmaz 1962	Whitrow & Morduch 1965	Kustaanheimo & Nuotio 1967	
Page & Tupper 1968	Bergmann 1968	Deser & Laurent 1968	Nordtvedt 1970	Wagoner 1970
Bollini et al. 1970	Rosen 1971	Will & Nordtvedt 1972	Ni 1972	Hellings & Nordtvedt 1972
Ni 1973	Yilmaz 1973	Lightman & Lee 1973	Lee, Lightman & Ni 1974	Rosen 1975
Belinfante & Swihart 1975	Lee et al. 1976	Bekenstein 1977	Barker 1978	Rastall 1979
Coleman 1983	Hehl 1997	Overlooked (20th century)		

- Some authors proposed more than one theory, e.g. Einstein, Ni, Lee, Nordtvedt, Papapetrou, Yilmaz, etc.
- Some theories are just variations of others
- Some theories were proposed in the 1910s/20s; many theories in the 1960s/70s
- Overlooked: this is <u>not a complete list</u>!

Theory must be:

- **Complete**: not a law, but a theory. Derive experimental results from first principles
- **Self-consistent**: get same results no matter which mathematics or models are used
- **Relativistic**: Non-gravitational laws are those of Special Relativity
- **Newtonian**: Reduces to Newton's equation in the limit of low gravity and low velocities

Theoretical Landscape of the 20th Century:
Competing Theories of Gravity

"Aesthetics-Based" Conclusion for 20th Century

Newton 1686 | Poincaré 1890
Einstein 1912 | Nordstrøm 1912 | Nordstrøm 1913 | Einstein & Fokker 1914 | **Einstein 1915**
Whitehead 1922 | Cartan 1923 | Kaluza & Klein 1932 | Fierz & Pauli 1939 | Birkhoff 1943
Milne 1948 | Thiry 1948 | Papapetrou 1954 | Jordan 1955 | Littlewood & Bergmann 1956
Brans & Dicke 1961 | Yilmaz 1962 | Whitrow & Morduch 1965 | Kustaanheimo & Nuotio 1967
Page & Tupper 1968 | Bergmann 1968 | Deser & Laurent 1968 | Nordtvedt 1970 | Wagoner 1970
Bollini et al. 1970 | Rosen 1971 | Will & Nordtvedt 1972 | Ni 1972 | Hellings & Nordtvedt 1972
Ni 1973 | Yilmaz 1973 | Lightman & Lee 1973 | Lee, Lightman & Ni 1974 | Rosen 1975
Belinfante & Swihart 1975 | Lee et al. 1976 | Bekenstein 1977 | Barker 1978 | Rastall 1979
Coleman 1983 | Hehl 1997 | Overlooked (20th century)

- "Among all bodies of physical law none has ever been found that is simpler and more beautiful than Einstein's geometric theory of gravity"

  – Misner, Thorne and Wheeler, 1973

- "[...] Unfortunately, any finite number of effects can be fitted by a sufficiently complicated theory. [...] Aesthetic or philosophical motives will therefore continue to play a part in the widespread faith in Einstein's theory, even if all tests verify its predictions."

  – Malcolm MacCallum, 1976

JPL

Theoretical Landscape of the 21st Century:

Competing Theories of Gravity

NASA

First decade of 21'st century… they are back!

Newton 1686 | Poincaré 1890

Einstein 1912 | Nordstrøm 1912 | Nordstrøm 1913 | Einstein & Fokker 1914 | **Einstein 1915**

Whitehead 1922 | Cartan 1923 | **Kaluza & Klein 1932** | Fierz & Pauli 1939 | Birkhoff 1943

Milne 1948 | Thiry 1948 | Papapetrou 1954 | Jordan 1955 | Littlewood & Bergmann 1956

Brans & Dicke 1961 | Yilmaz 1962 | Whitrow & Morduch 1965 | Kustaanheimo & Nuotio 1967

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Ni 1973 | Yilmaz 1973 | Lightman & Lee 1973 | Lee, Lightman & Ni 1974 | Rosen 1975

Belinfante & Swihart 1975 | Lee et al. 1976 | Bekenstein 1977 | Barker 1978 | Rastall 1979

Coleman 1983 | Hehl 1997 | Overlooked (20th century) | **Scalar-Tensor Theories**

Arkani-Hamed, Dimopoulos & Dvali 2000 | **Dvali, Gabadadze & Poratti 2003** | **Strings theory?**

Bekenstein 2004 | **Moffat 2005** | **Multiple f(R) models 2003-10** | **Bi-Metric Theories**

Need for new theory of gravity:

- Classical GR description breaks down in regimes with large curvature
- If gravity is to be quantized, GR will have to be modified or extended

Other challenges:

- Dark Matter
- Dark Energy

Motivations for new tests of GR:

- GR is a fundamental theory
- Alternative theories & models
- New ideas & techniques require comprehensive investigations

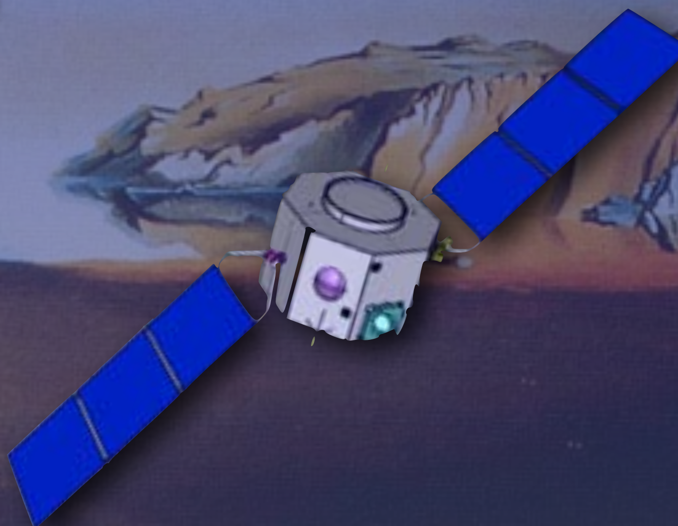
ACES

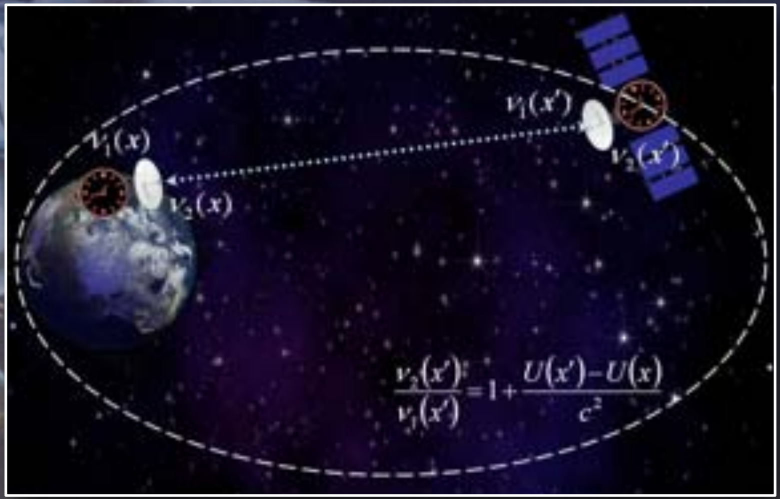
- Atomic Clock Ensemble in Space
  - PHARAO: Cs atomic clock (CNES)
  - SHM: Hydrogen maser (ESA)
  - Microwave link to ground terminals
- Science goals:
  - Measurement of gravitational redshift
    - Precision 50 x 10^{-6} in 300 s; 2 x 10^{-6} in 10 days
  - Time variations in fine structure constant
    - $\alpha^{-1} . d\alpha/dt < 10^{-17}$ 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,

ESA (Human Spaceflight programme)-CNES

STE-QUEST

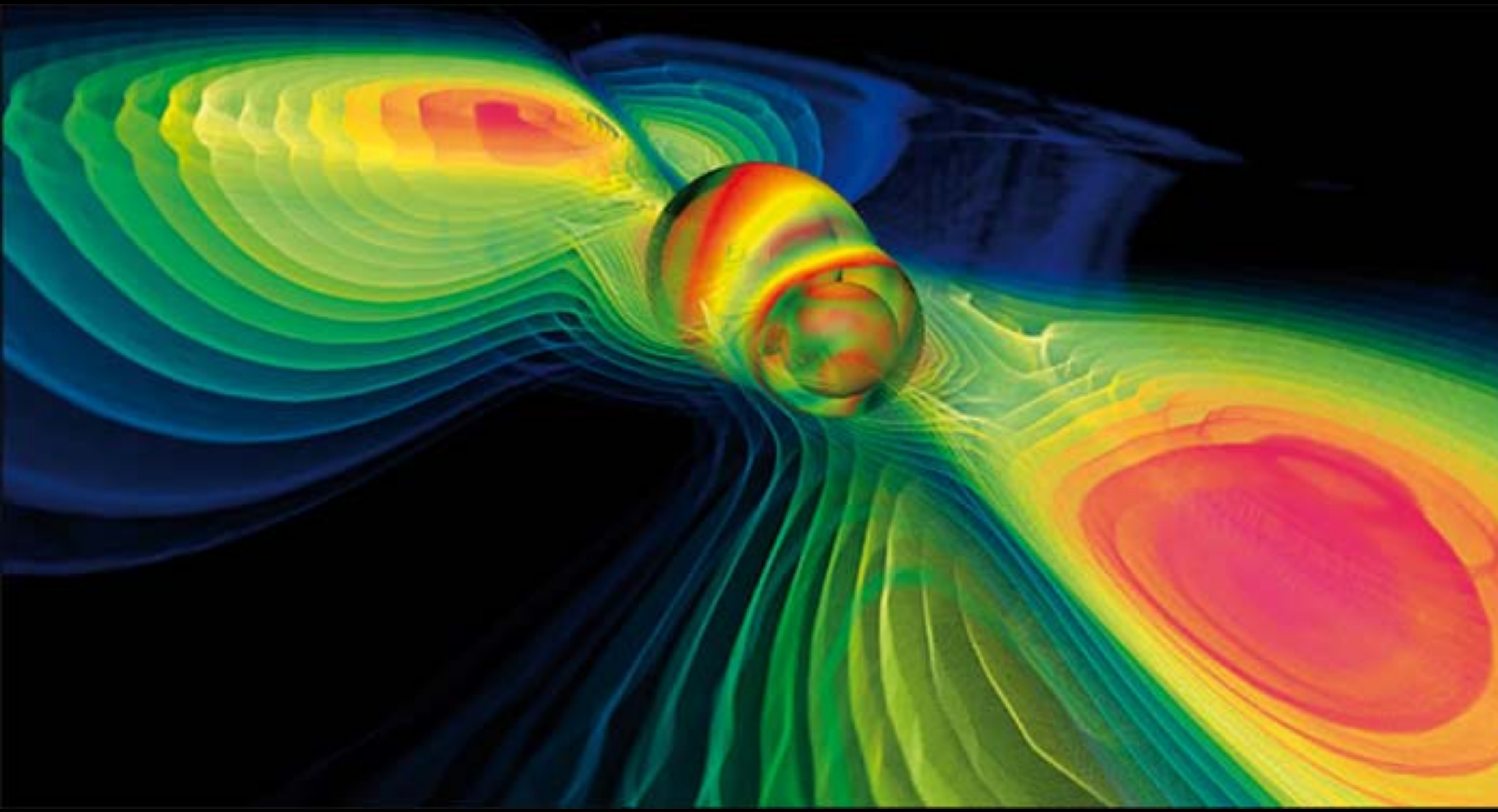
- Space Time Explorer and Quantum Equivalence Space Test
  - Laser-cooled Rb microwave atomic clock
  - ^{85}Rb/^{87}Rb differential matter interferometer
  - Microwave/optical links to ground terminals
- Science goals:
  - Earth gravitational redshift
    - Precision 2 x 10^{-7}; ultimate aim 4 x 10^{-8}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





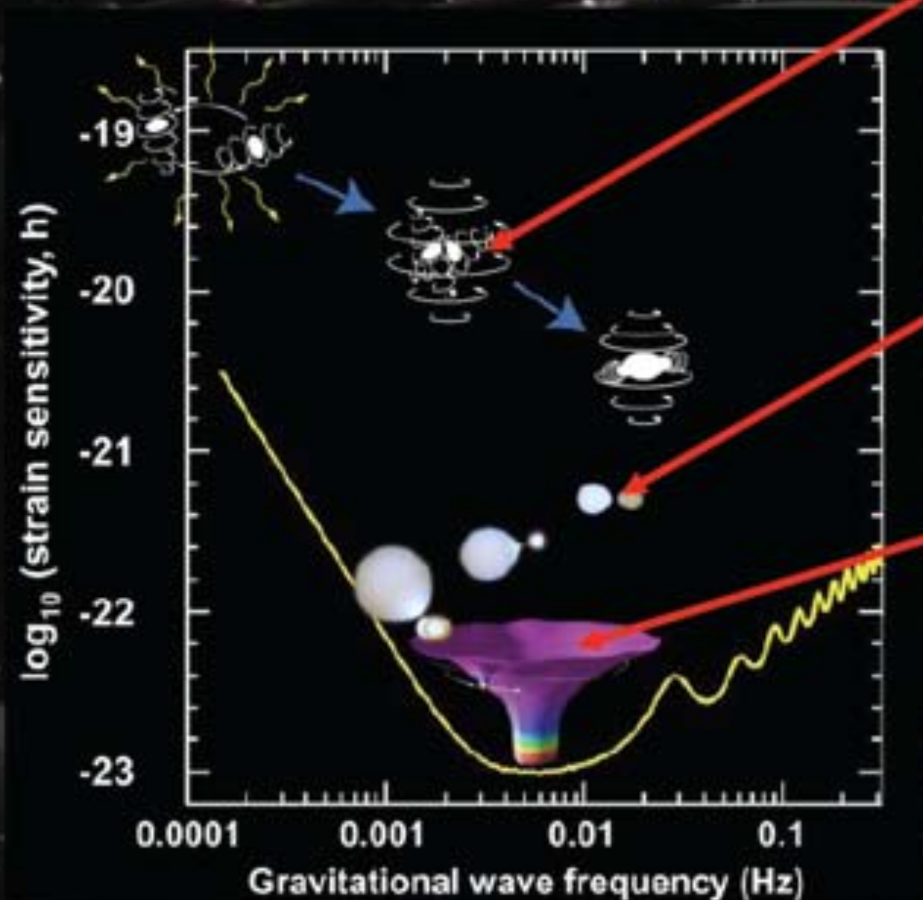
Mission to provide high precision test of Einstein Equivalence Principle, nominal launch in 2022–2024

Gravitational waves



World-Wide Laser Interferometric Gravitational Wave Detector Network

At Low Frequencies: A Universe full of Strong GW Sources



Massive Black Hole Binary (BHB) inspiral and merger

Ultra-compact binaries

Extreme Mass Ratio Inspiral (EMRI)

Cosmic backgrounds, superstring bursts?

LISA Pathfinder

Launch date 2015

ESA gravitational wave detection technology testbed, scheduled launch 2014

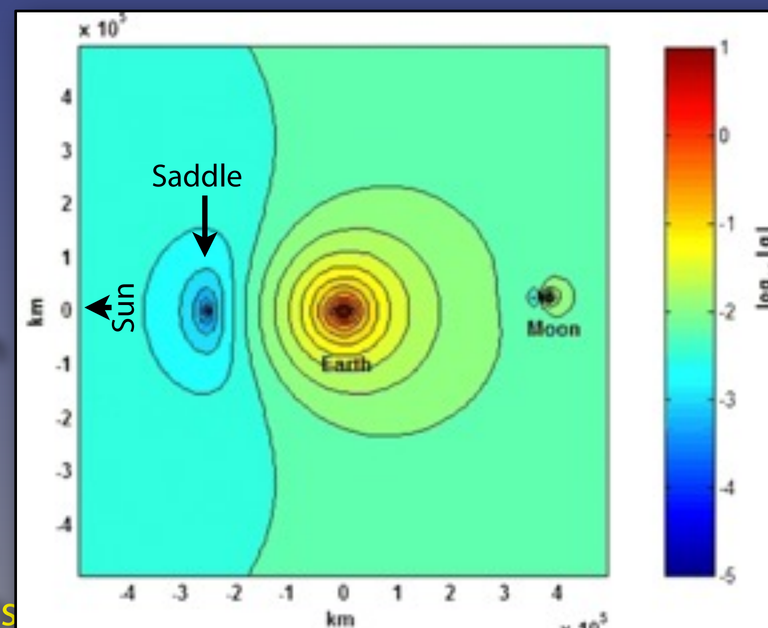
NGO: Revealing a Hidden Universe

Presentation to SSAC for the L1 selection, Paris, April 2, 2012

Bernard Schutz and Karsten Danzmann
for the NGO Study Team

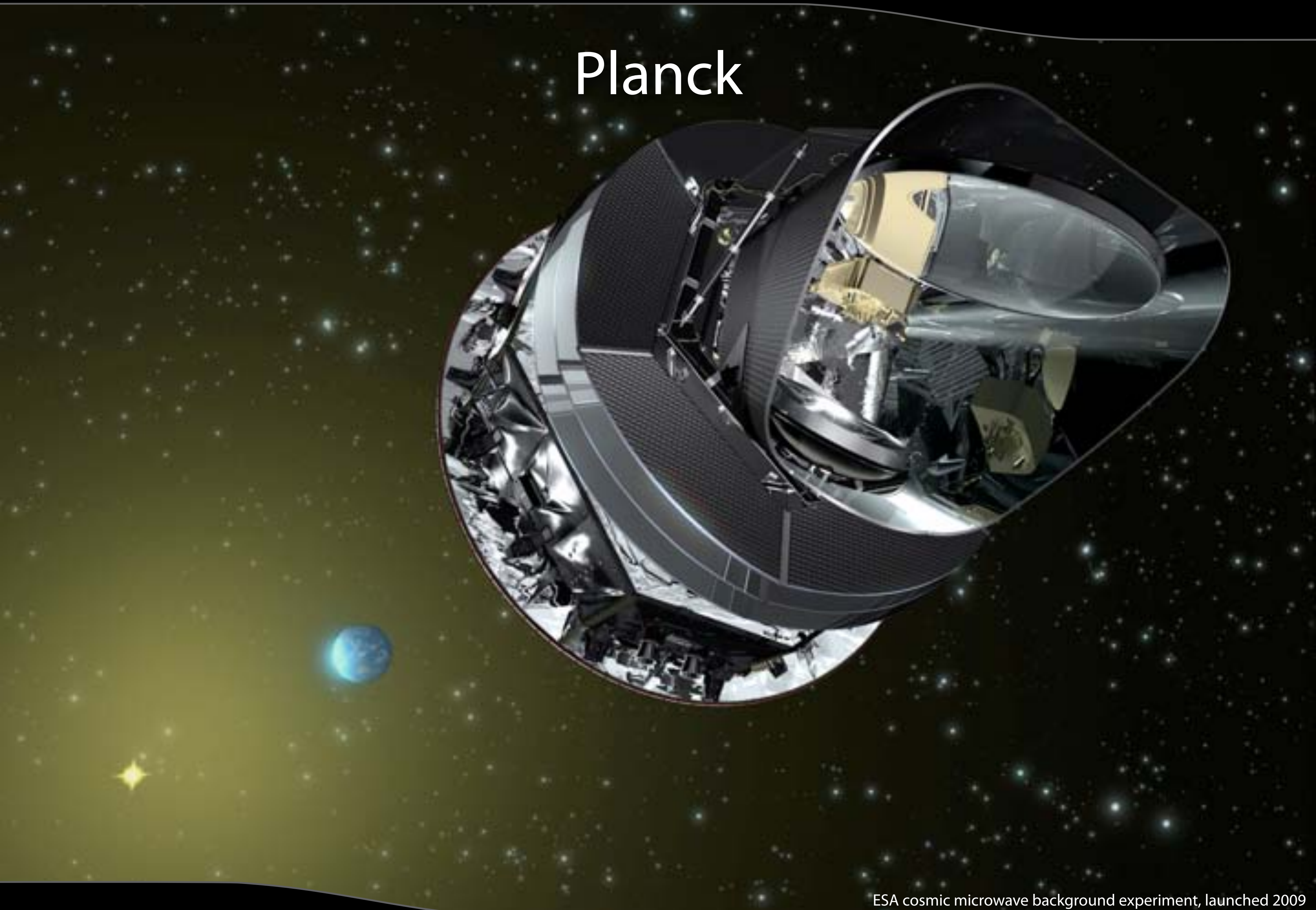
Testing alternative theories of gravity

- 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

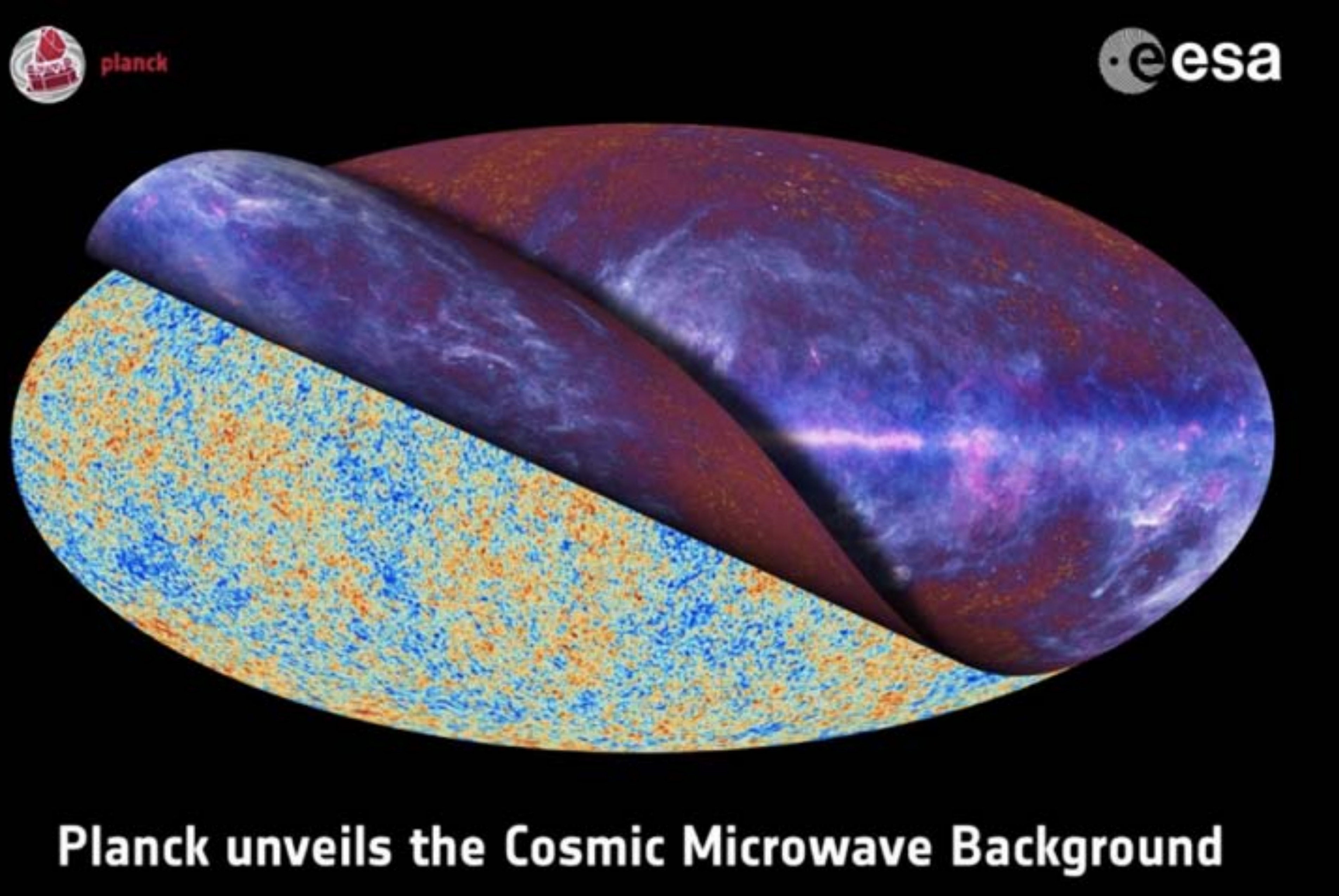



ORIGINS
or
the CMB bonanza

Planck



ESA cosmic microwave background experiment, launched 2009



WMAP, Jarosik et al. (2010) / NASA

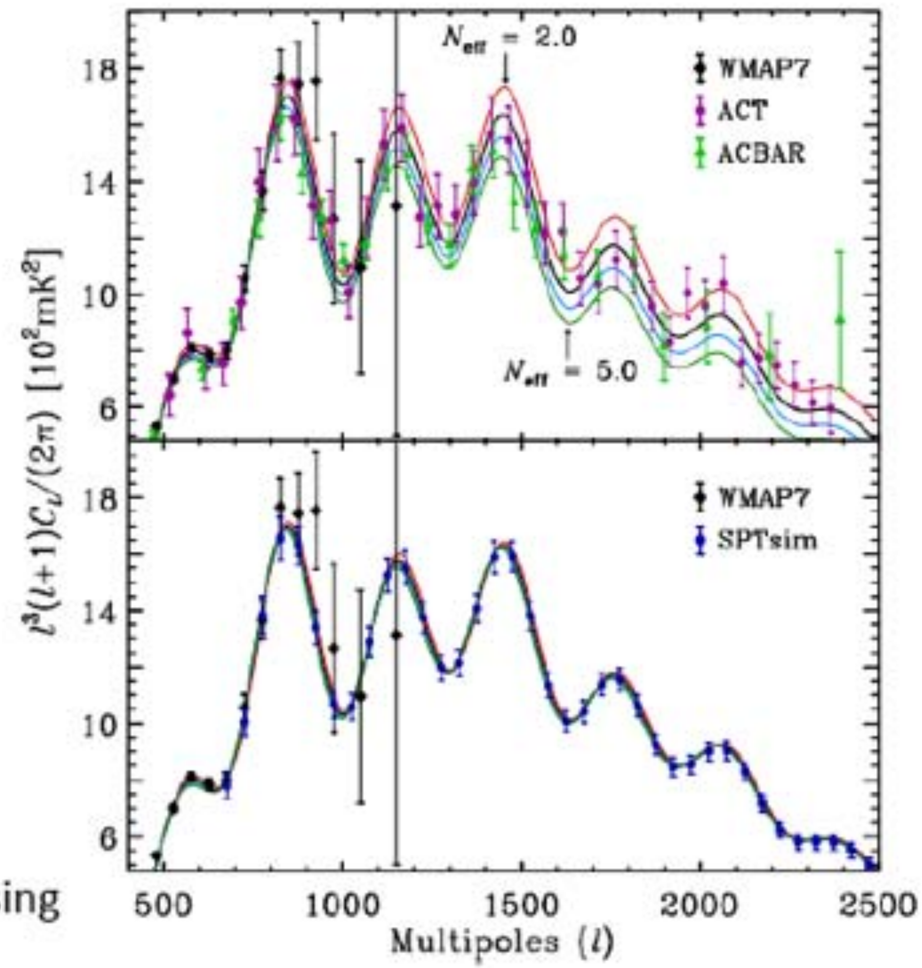
Probing the Neutrino Number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

and the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$



Once the sound horizon scale is fixed, increasing N_{eff} decreases the damping scale and the result is an increase in the small angular scale anisotropy.
We expect degeneracies with the Hubble constant and the Helium abundance.
(see e.g. Hou, Keisler, Knox et al. 2013, Lesgourgues and Pastor 2006).

Constraints from Planck and other CMB datasets (95% c.l.)

Planck alone (no pol.)	$N_{eff}^{\nu} = 4.53_{-1.4}^{+1.5}$
Planck + WP	$N_{eff}^{\nu} = 3.51_{-0.74}^{+0.80}$
Planck + WP + Lensing	$N_{eff}^{\nu} = 3.39_{-0.70}^{+0.77}$
Planck + WP + highL	$N_{eff}^{\nu} = 3.36_{-0.64}^{+0.68}$
Planck + WP + highL + Lensing	$N_{eff}^{\nu} = 3.28_{-0.64}^{+0.67}$

Conclusions:

- Neff=0 is excluded at high significance (about 10 standard deviations). We need a neutrino background to explain Planck observations !

- **No evidence** (i.e. > 3 σ) for extra radiation from CMB only measurements.

- Neff=4 is also consistent in between 95% c.l.

- Neff=2 and Neff=5 excluded at more than 3 σ (massless).

A. Melchiorri

Should we care about a 2.7 σ signal ?

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be 3.5° ± 1.0° K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

Discovery of the CMB was made at 3.5 σ !

Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant

of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8σ

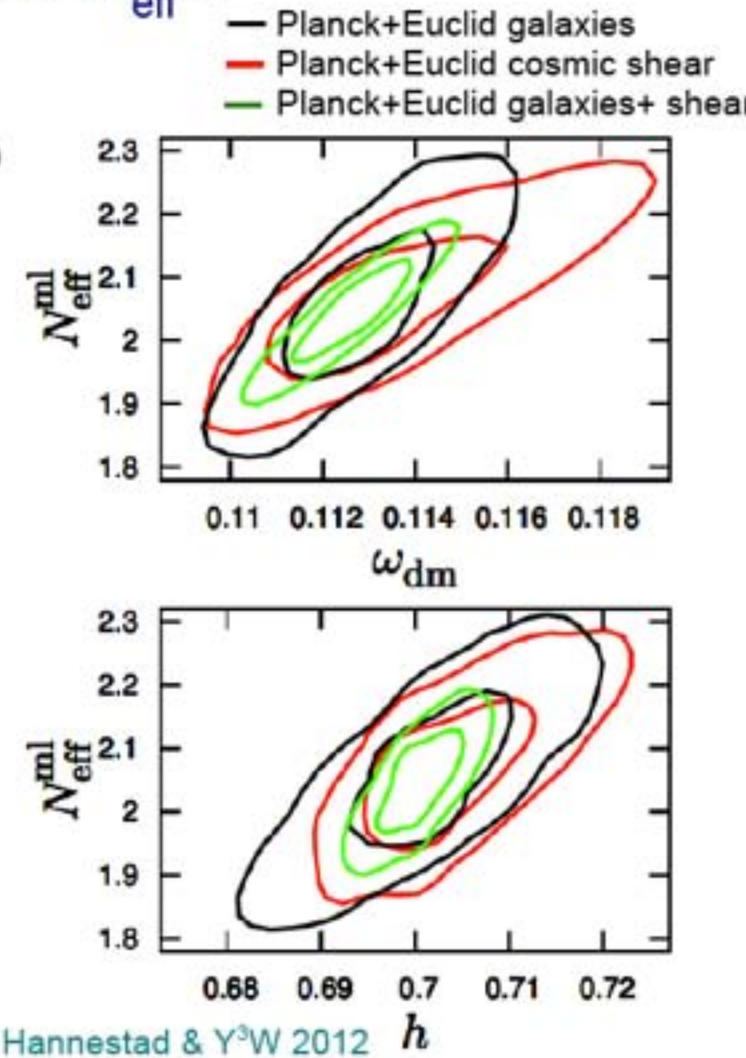
Discovery of the accelerating universe was made at 2.8 σ !

A. Melchiorri

Further down the road: Euclid and N_{eff}…

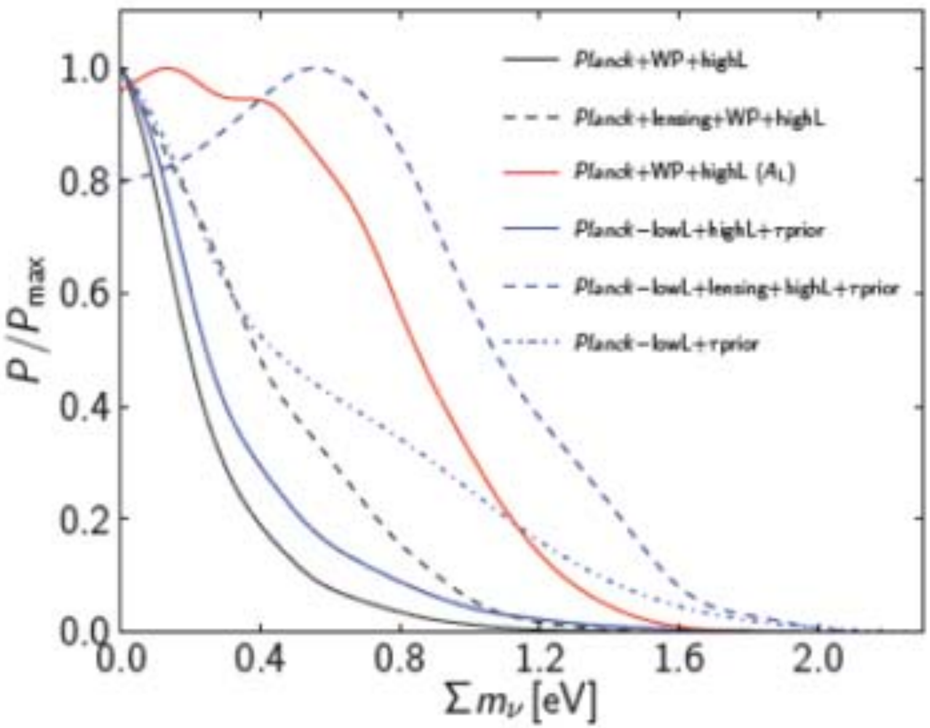
- **Euclid** will improve Planck's sensitivity to N_{eff} by a factor of ~4 [$\sigma(N_{eff})$ ~ 0.055].

2 Euclid spacecraft concepts



Hamann, Hannestad & Y[3]W 2012

Constraints on Neutrino Mass (standard 3 neutrino framework)



$$\sum m_\nu < 0.66\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}).$$

$$\sum m_\nu < 1.08\,\mathrm{eV} \quad [95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}\ (A_\mathrm{L})],$$

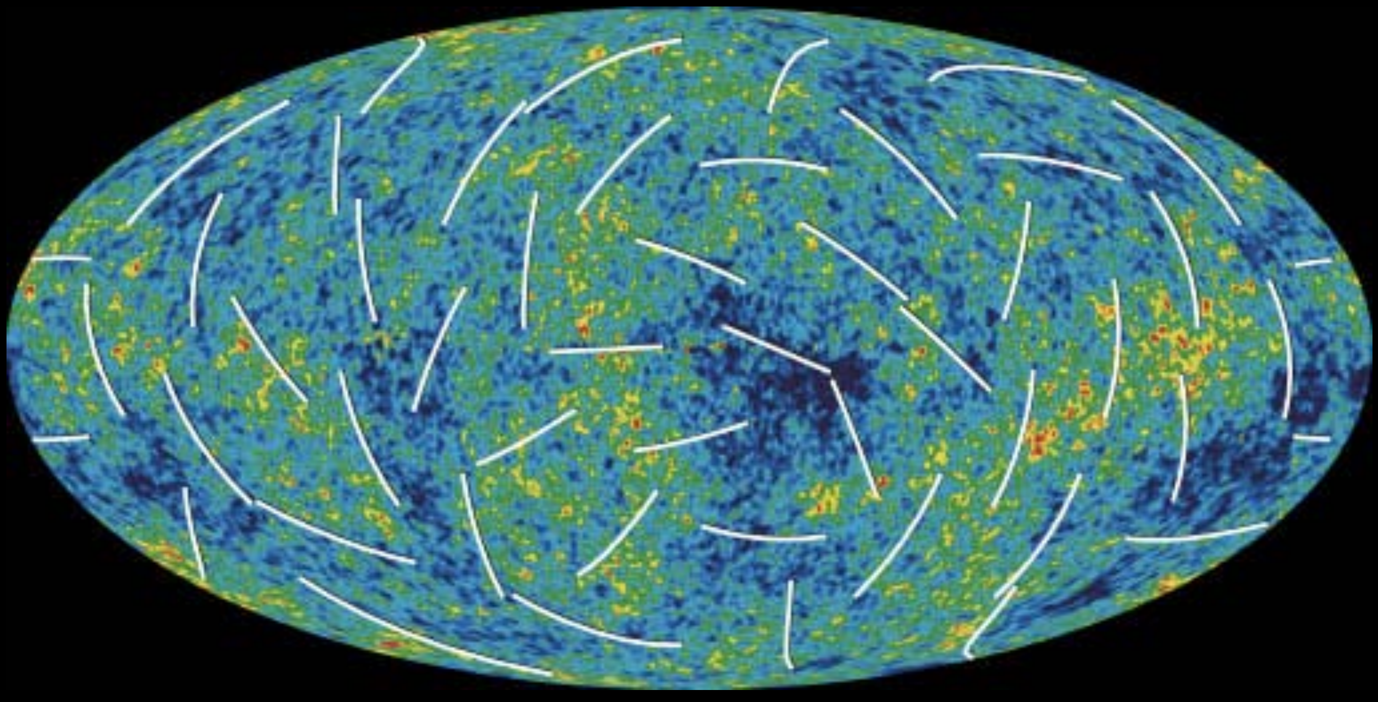
$$\sum m_\nu < 0.85\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{lensing}+\mathrm{WP}+\mathrm{highL}),$$

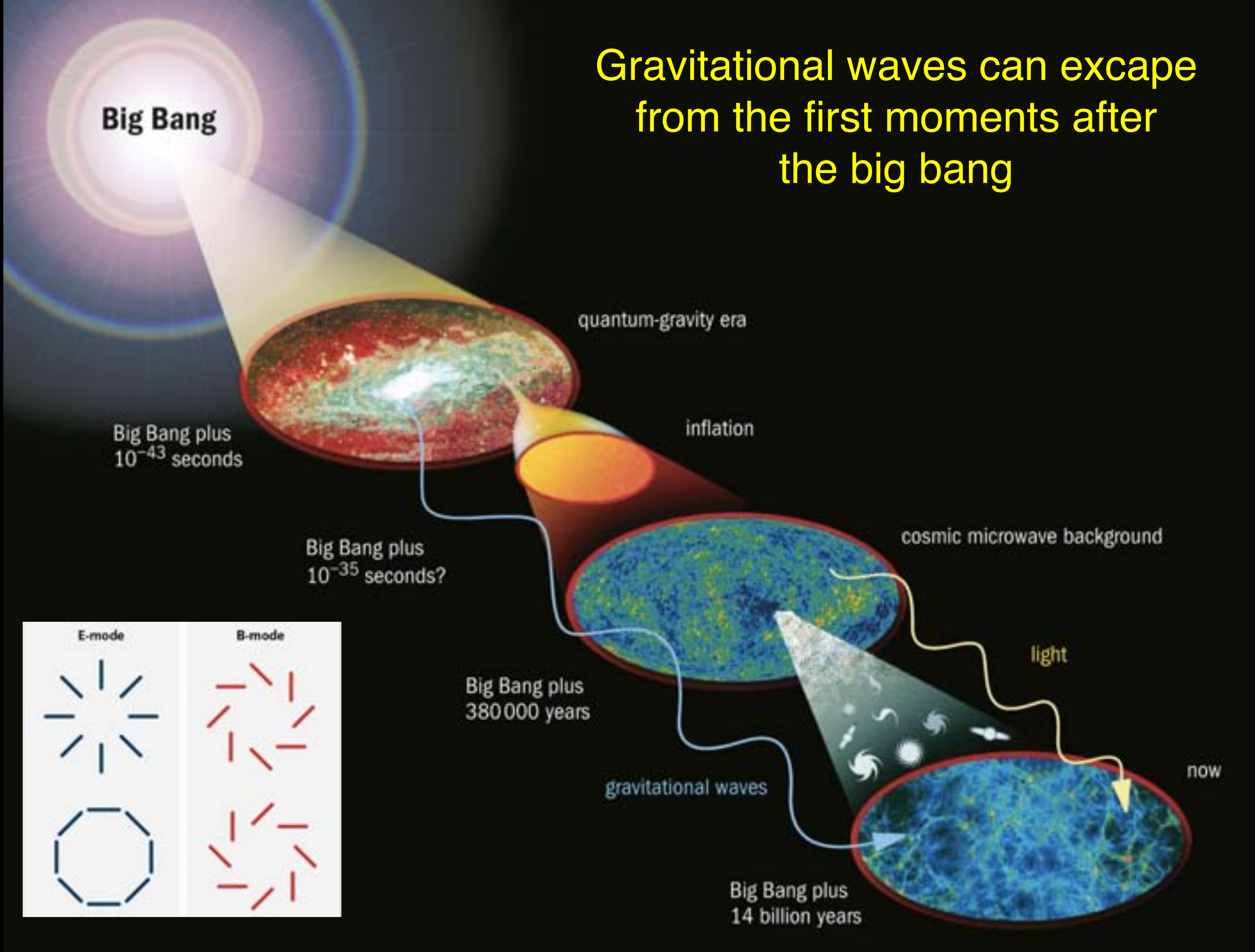
$$\sum m_\nu < 0.23\,\mathrm{eV} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO}).$$

- Planck strongly improves previous constraints on neutrino masses.
- Planck TT spectrum prefers a lensing amplitude higher than expected (A_{LENS}=1.2).
- Inclusion of lensing from TTTT weakens the Planck constraint by 20%
- Including BAO results in the best current constraint on neutrino masses of 0.23 eV

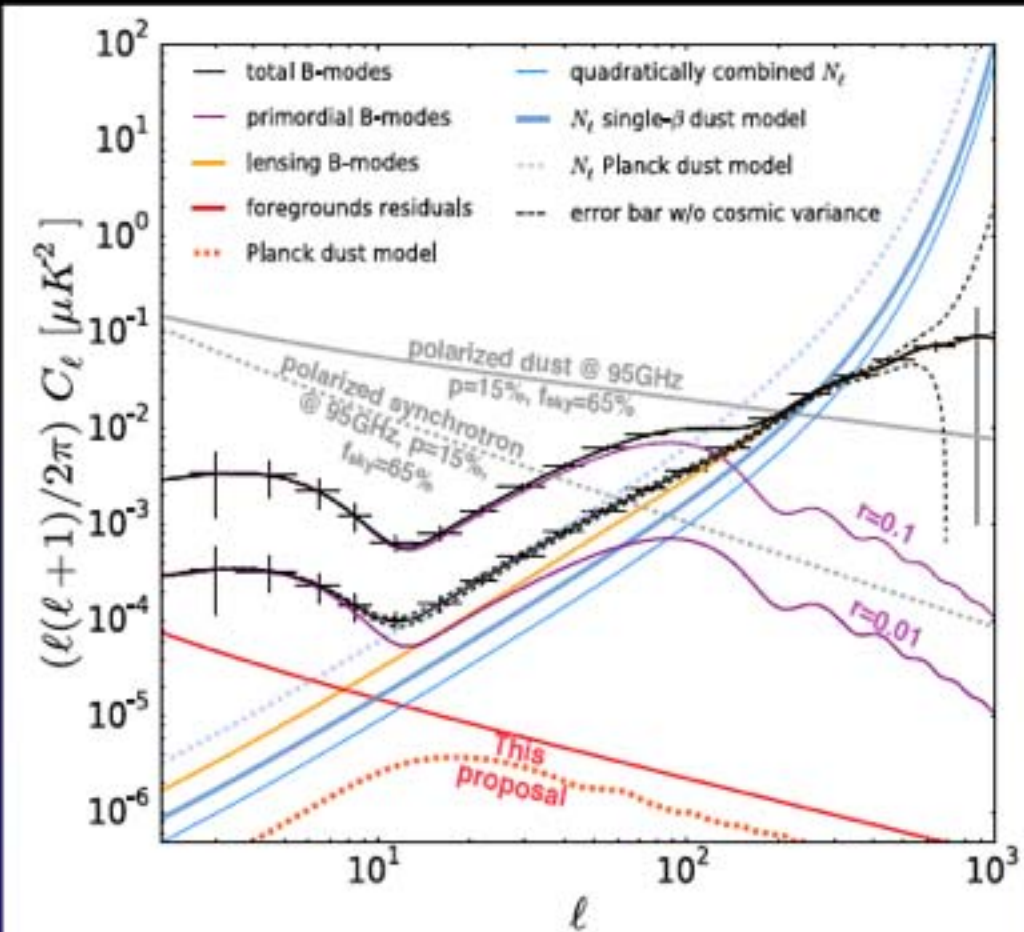
CMB POLARIZATION

testing the quantum, inflationary universe at the beginning of space and time




Gravitational waves can excape from the first moments after the big bang
Big Bang
quantum-gravity era
Big Bang plus 10^-43 seconds
inflation
Big Bang plus 10^-35 seconds?
cosmic microwave background
light
Big Bang plus 380 000 years
gravitational waves
now
Big Bang plus 14 billion years
E-mode
B-mode

Sensitivity w/ foreground subtraction



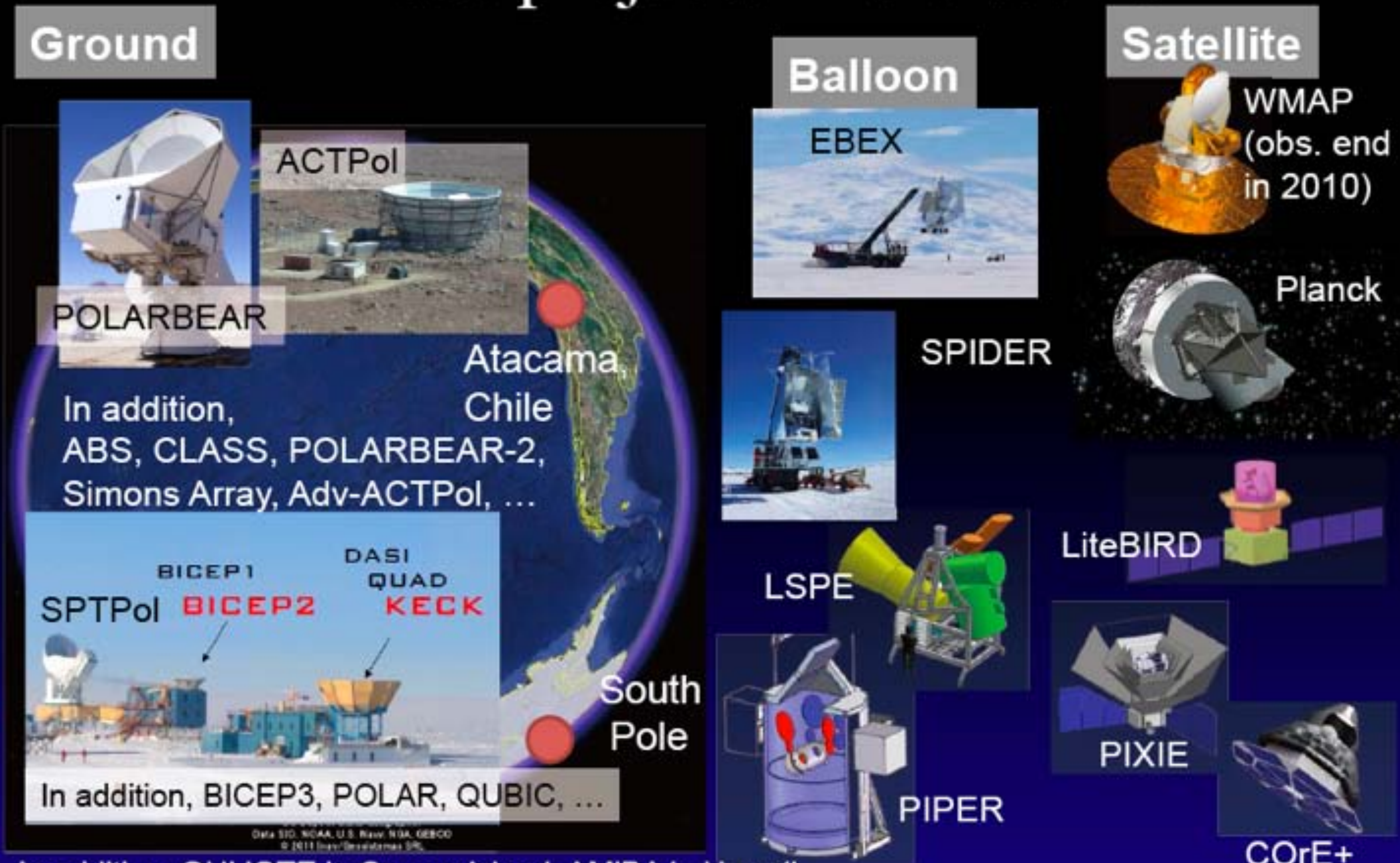
$\sigma(r) = 0.45 \times 10^{-3}$

for r = 0.01, including foreground removal and cosmic variance

$r < 0.4 \times 10^{-3}$
(95% C.L.)
for undetectably small r

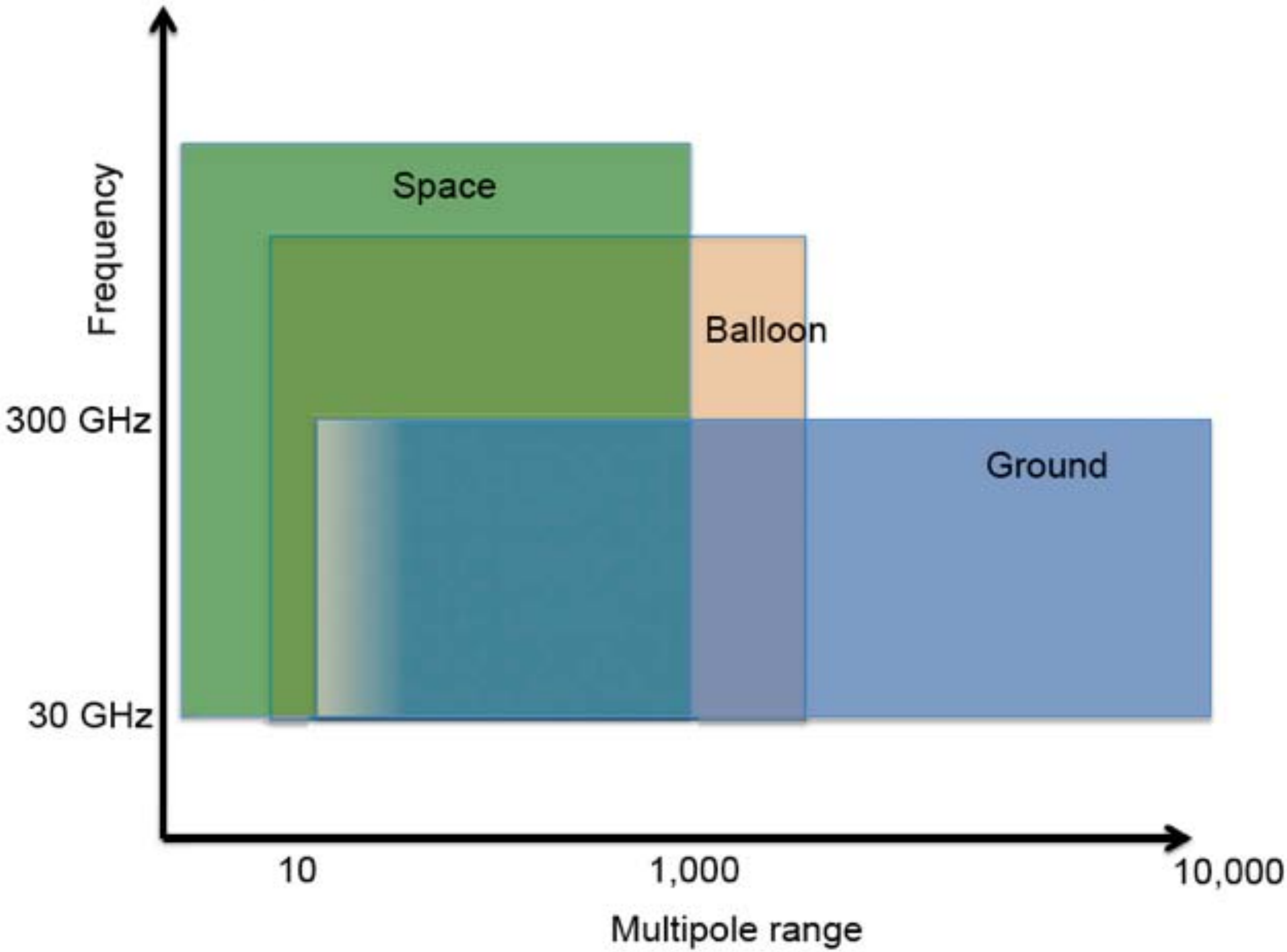
Residual computation method: Errard et al. 2011, Phys. Rev. D 84, 063005 and another paper in preparation

B-mode projects in the world



In addition, QUIJOTE in Canary island, AMiBA in Hawaii

Complementarity of Observations

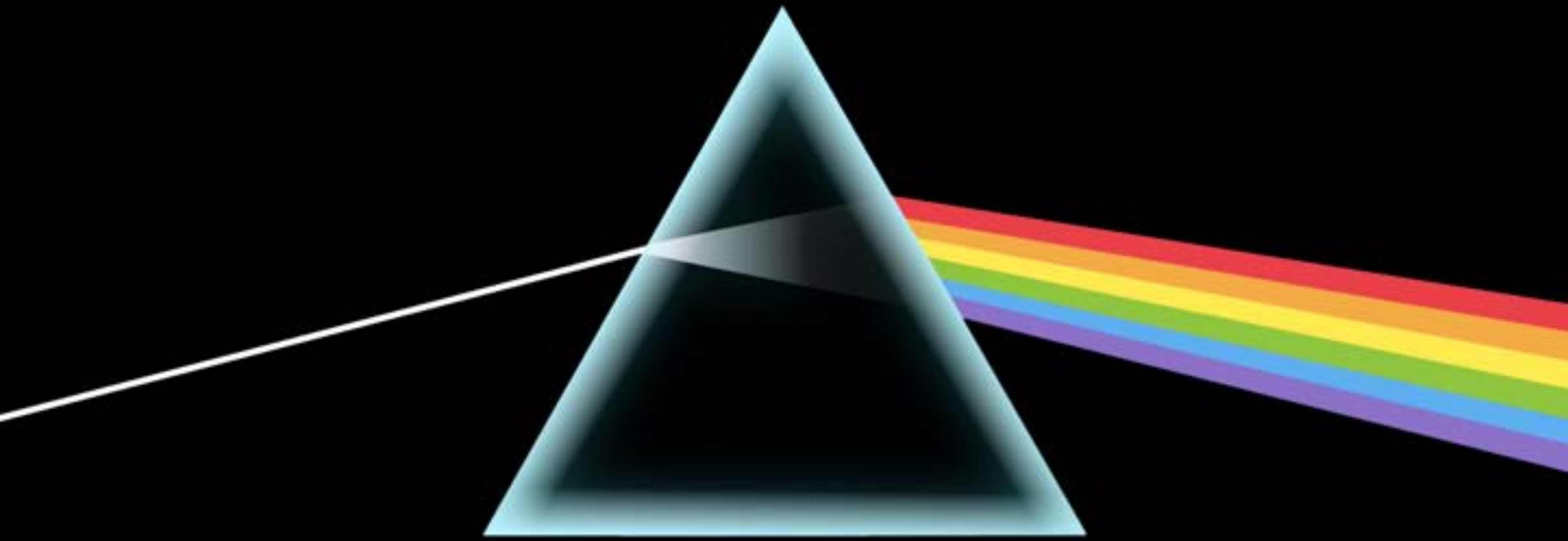


Take-home messages

$\sigma(r) \sim 0.01$ in ~5 years

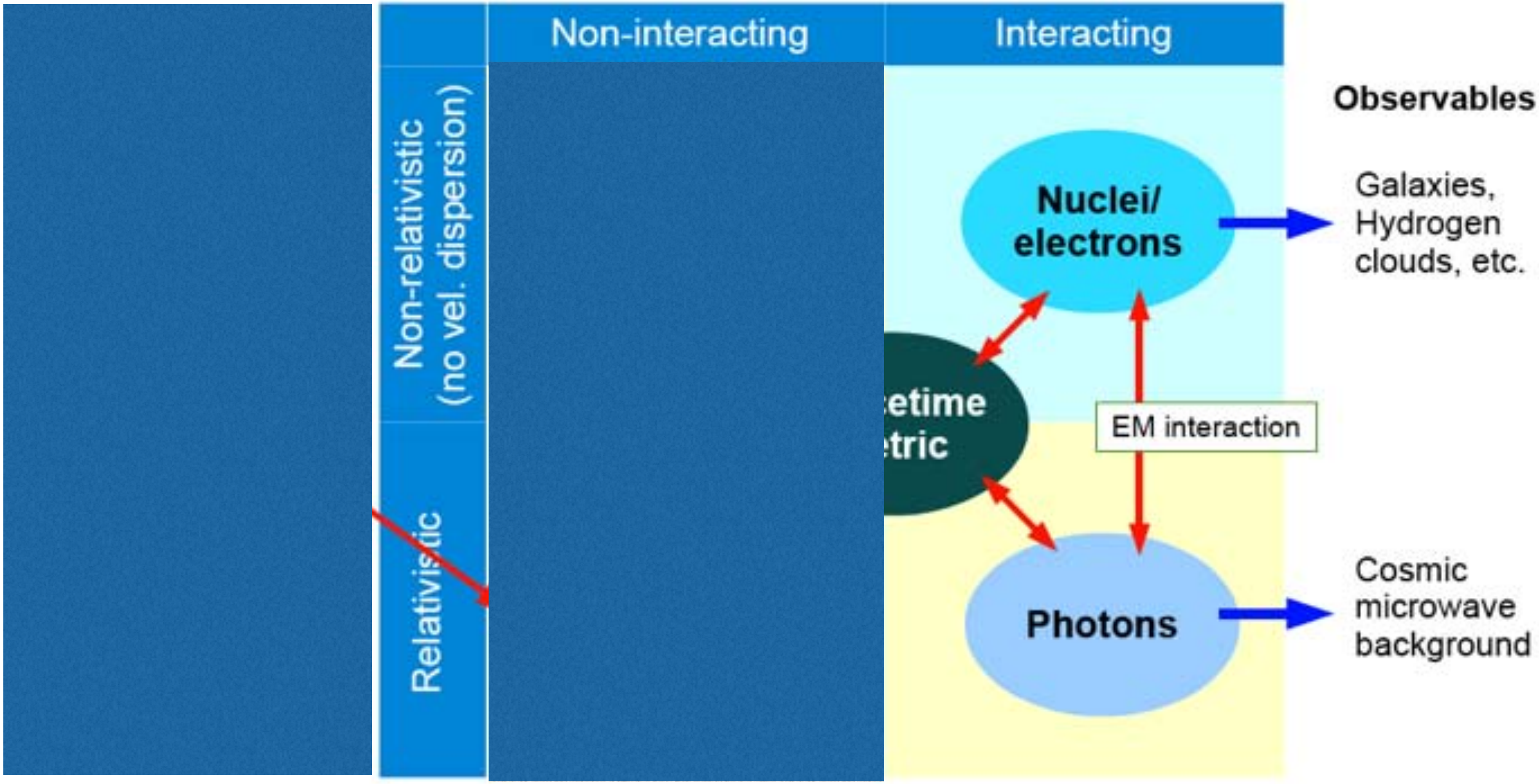
$\sigma(r) \sim 0.001$ in 2020s

Exciting period ahead of us !



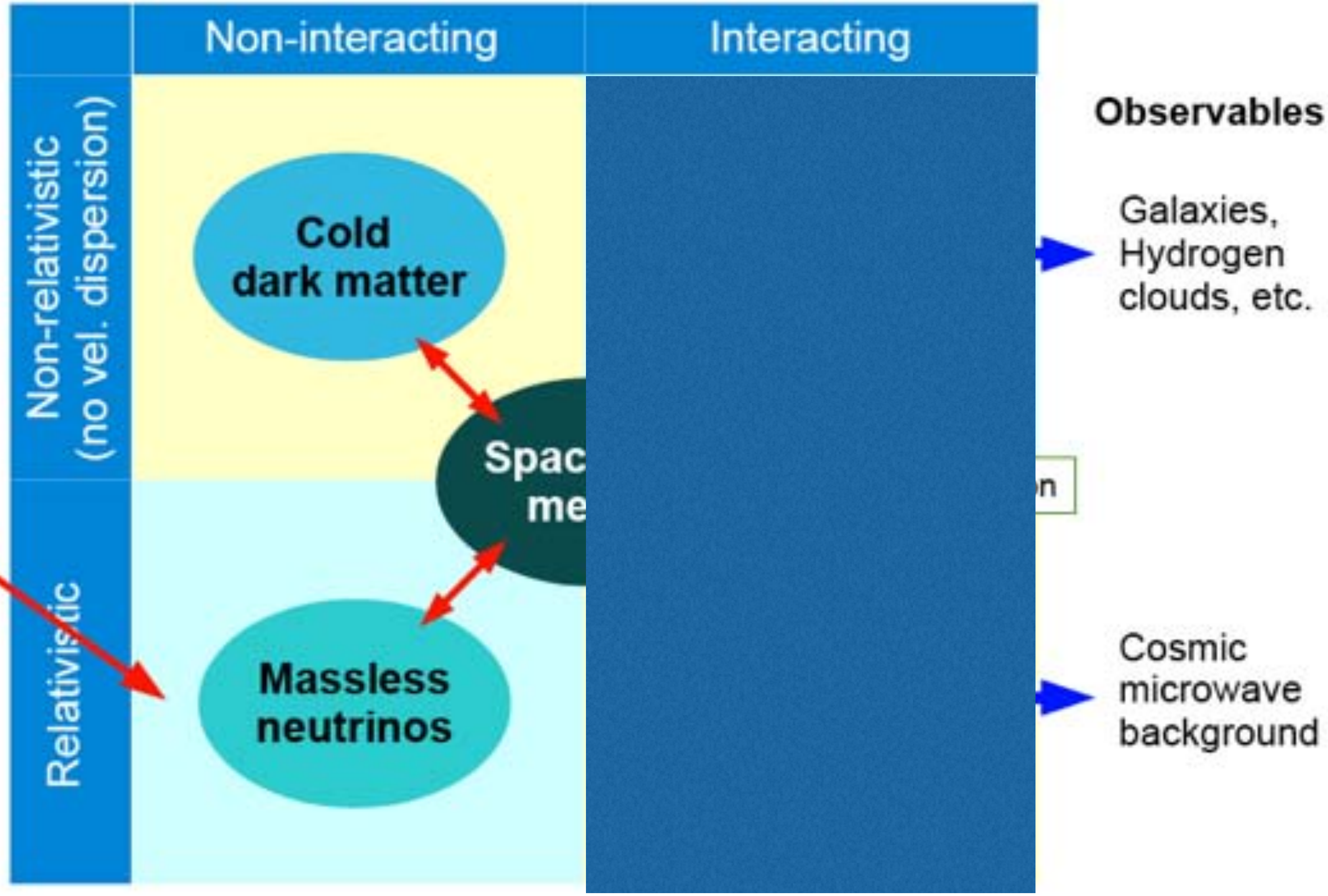
The dark side of the universe

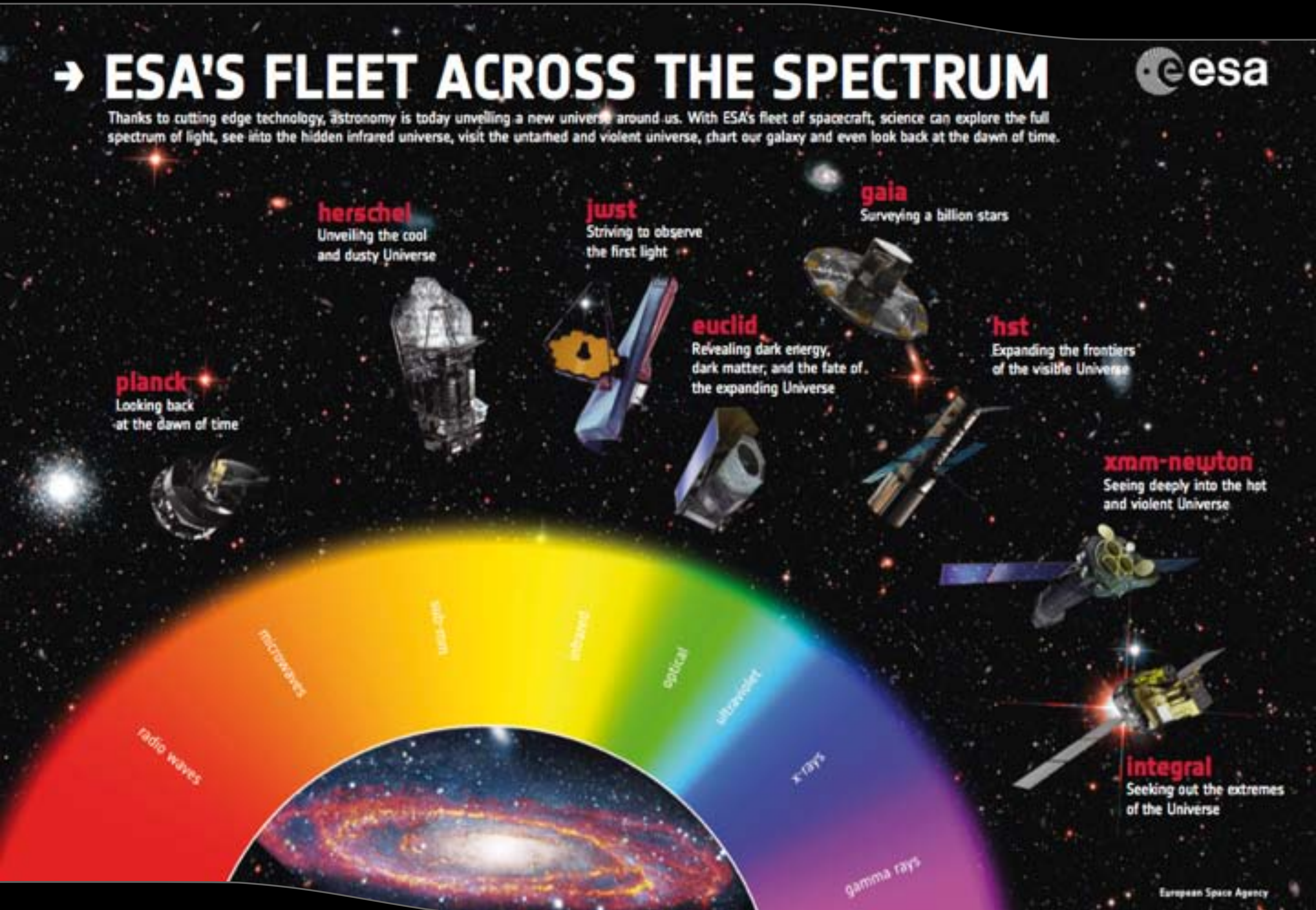
We need light (QED and interactions)….



….to study the dark side of the universe

Extra neutrinos
= extra relativistic,
non-interacting stuff
(no requirement
on the quantum
numbers or statistics)




→ 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

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

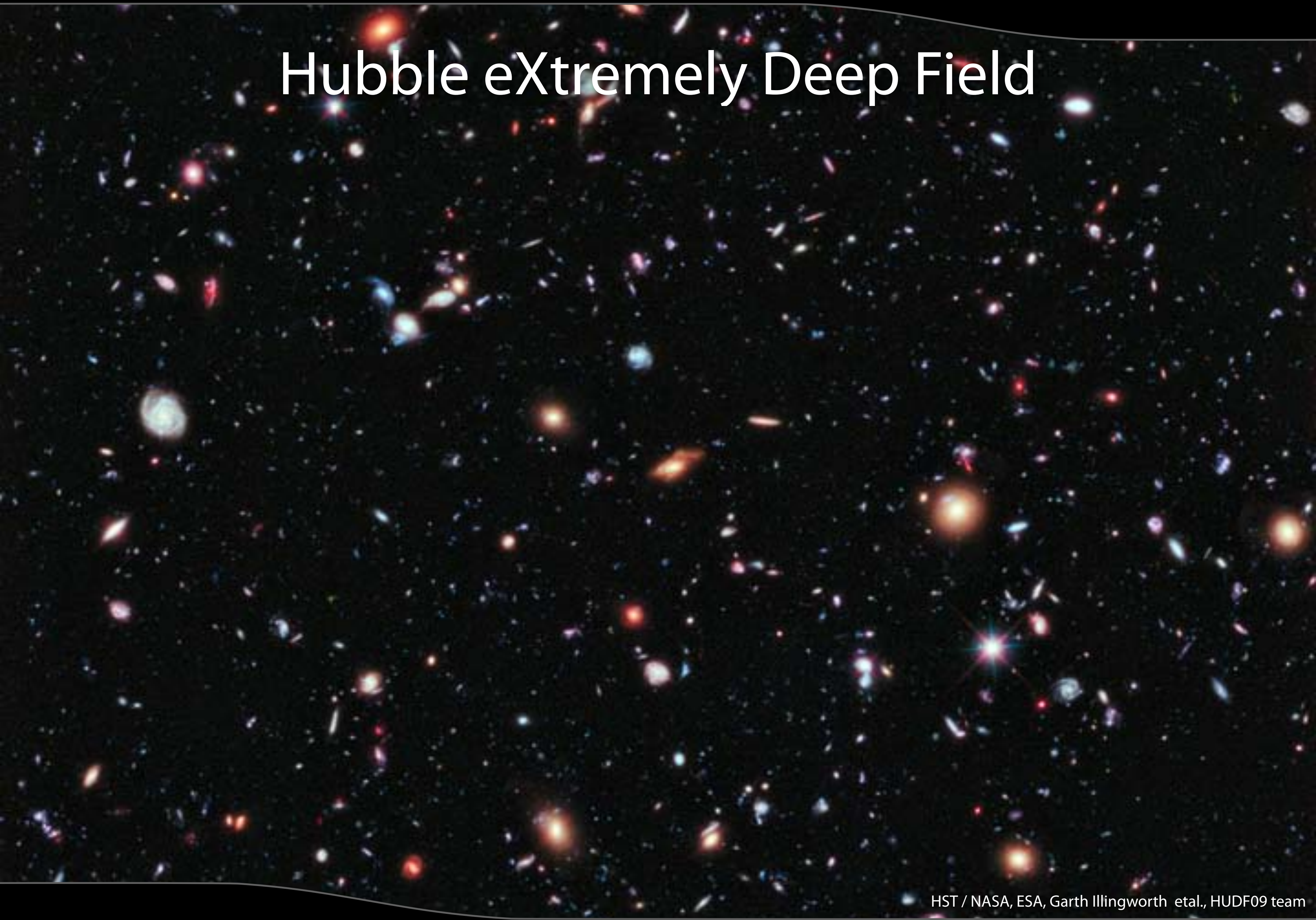
Carina Nebula in the visible: ionised gas

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

Hubble Space Telescope

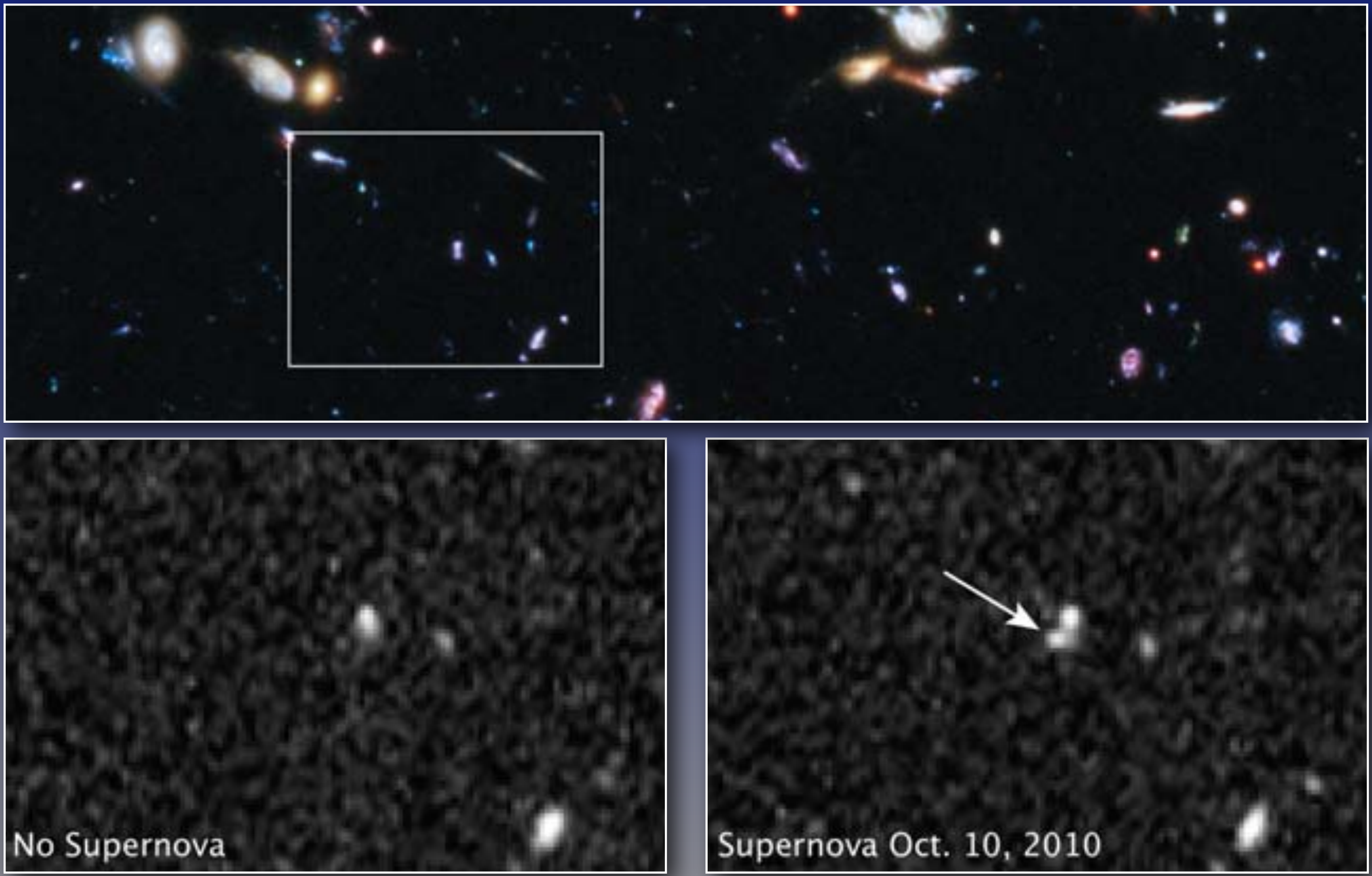
NASA-ESA UV-optical-near-IR astrophysical observatory, launched 1990, last servicing May 2009

Hubble eXtremely Deep Field



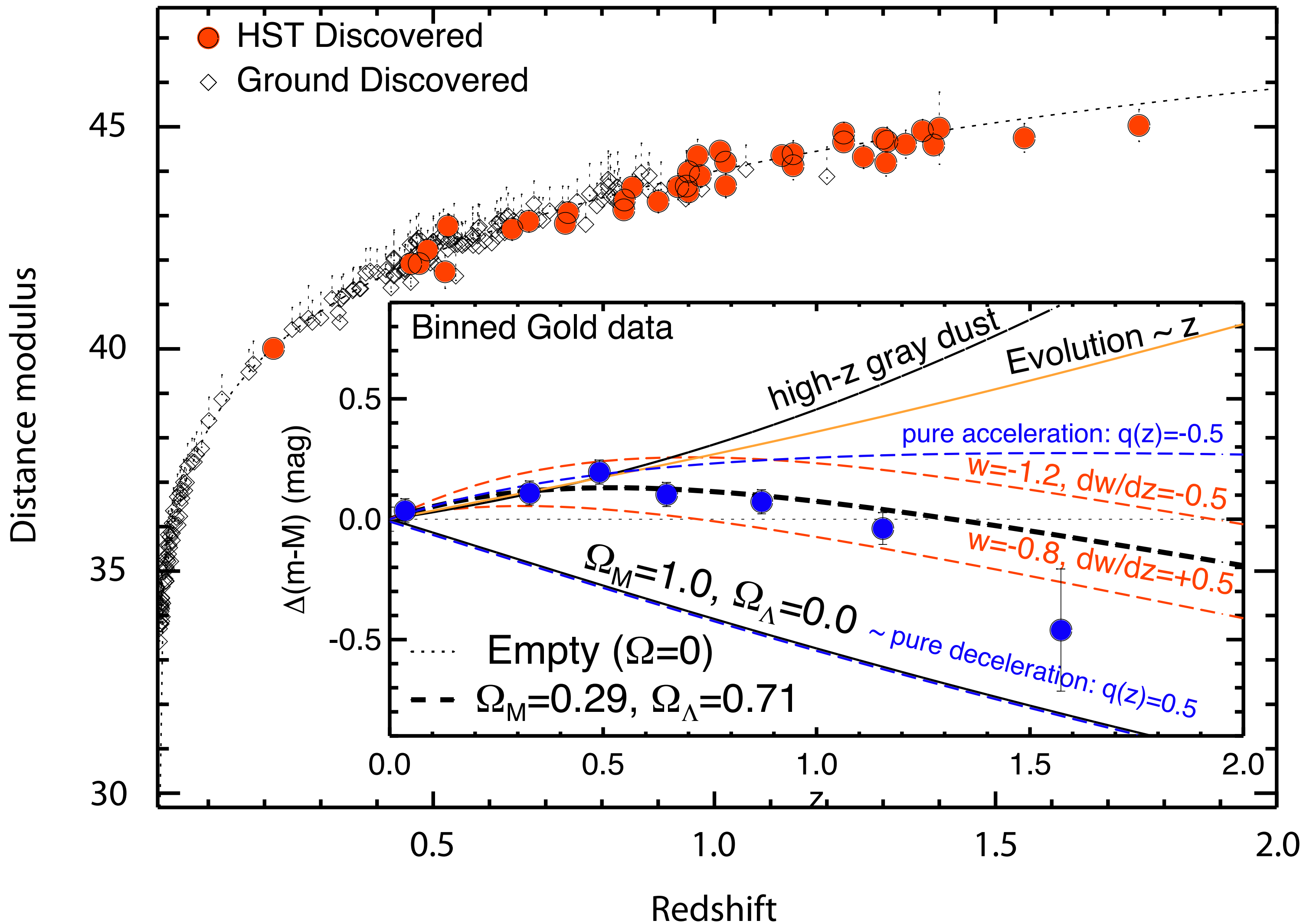
HST / NASA, ESA, Garth Illingworth etal., HUDF09 team

A very distant Type 1a supernova



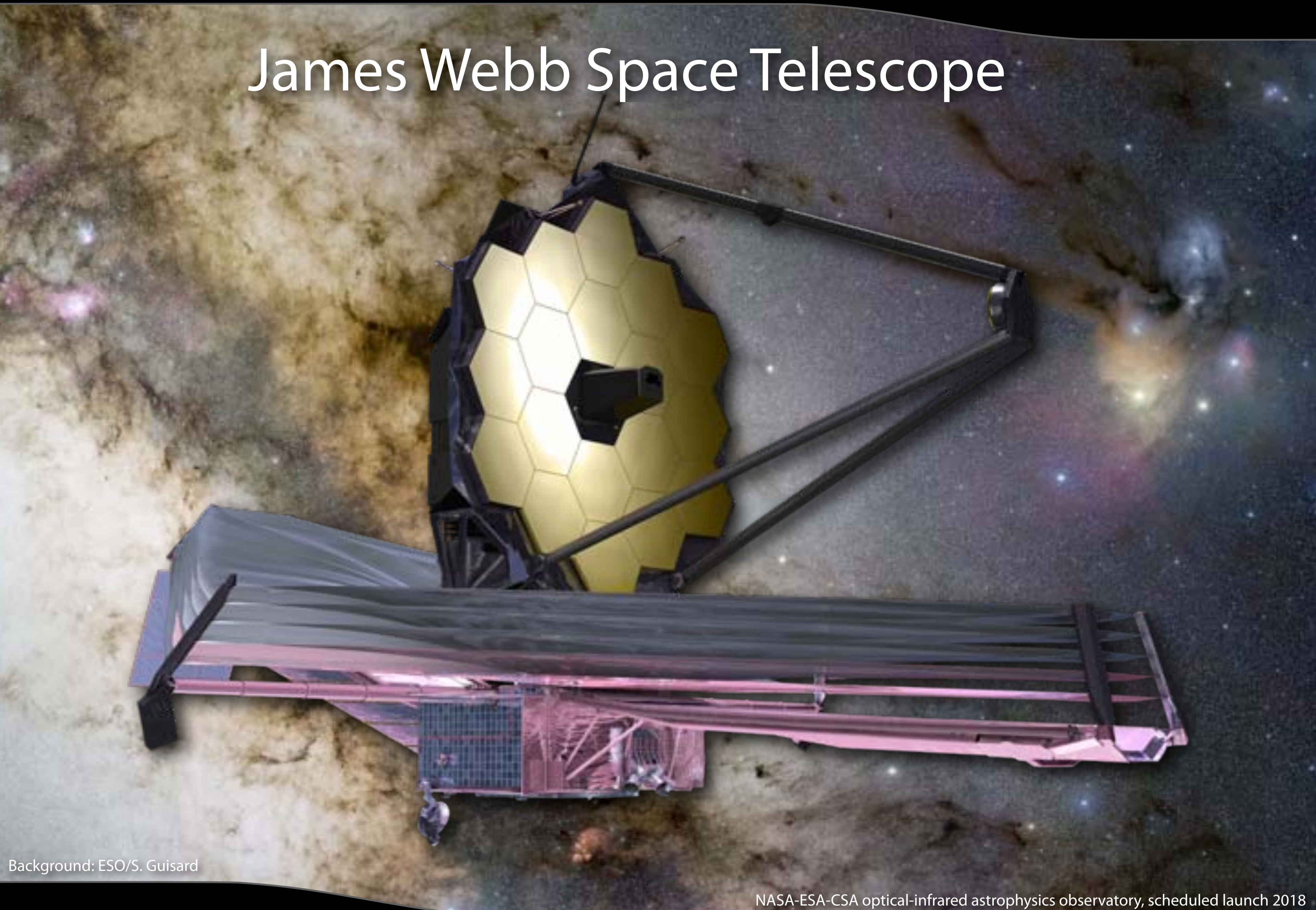
HST WFC3 / Supernova in Hubble Ultradeep Field / ESA, NASA, Adam Riess, Steven Rodney

Evidence for an accelerated expansion



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

James Webb Space Telescope

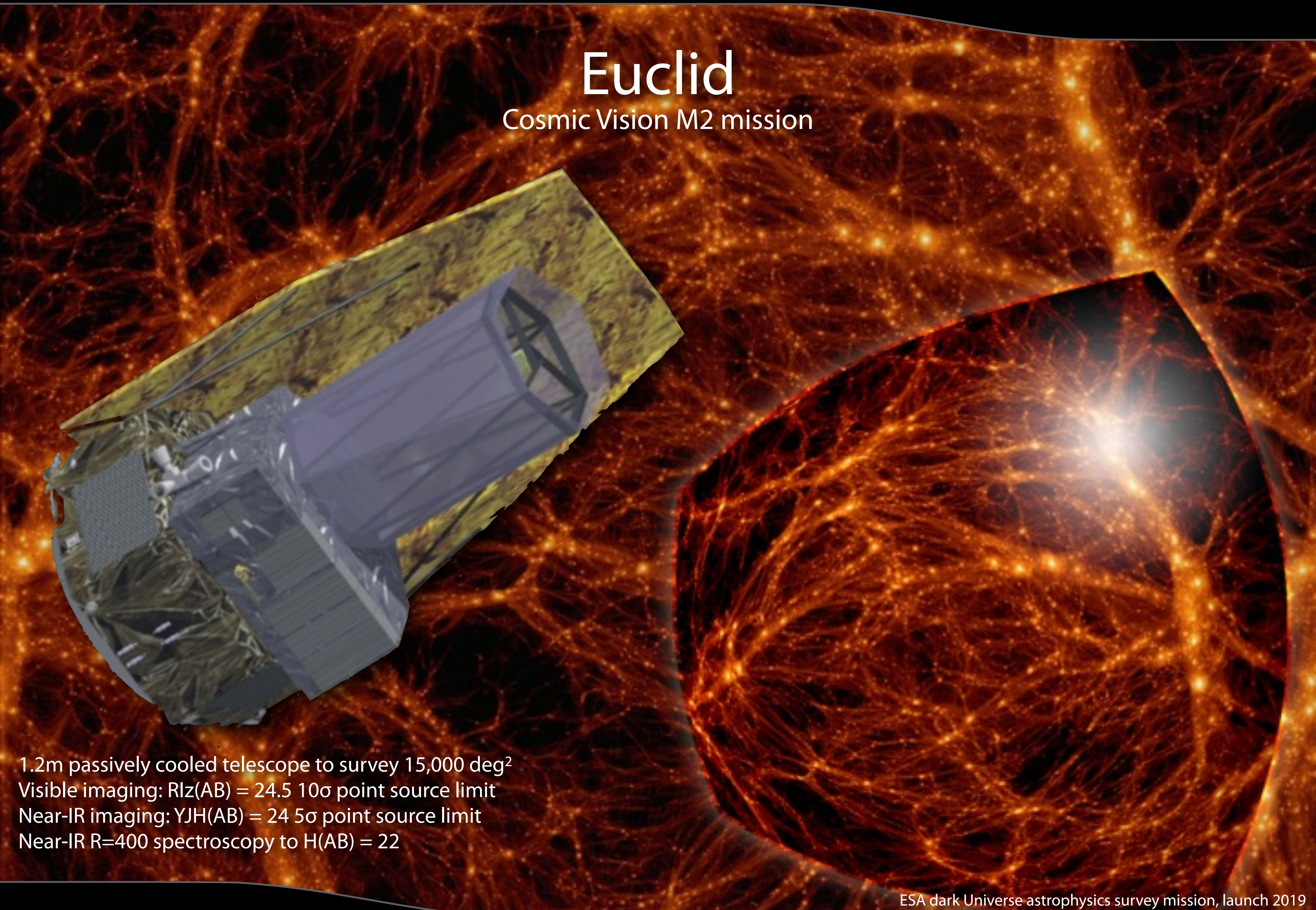


Background: ESO/S. Guisard

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

Euclid

Cosmic Vision M2 mission

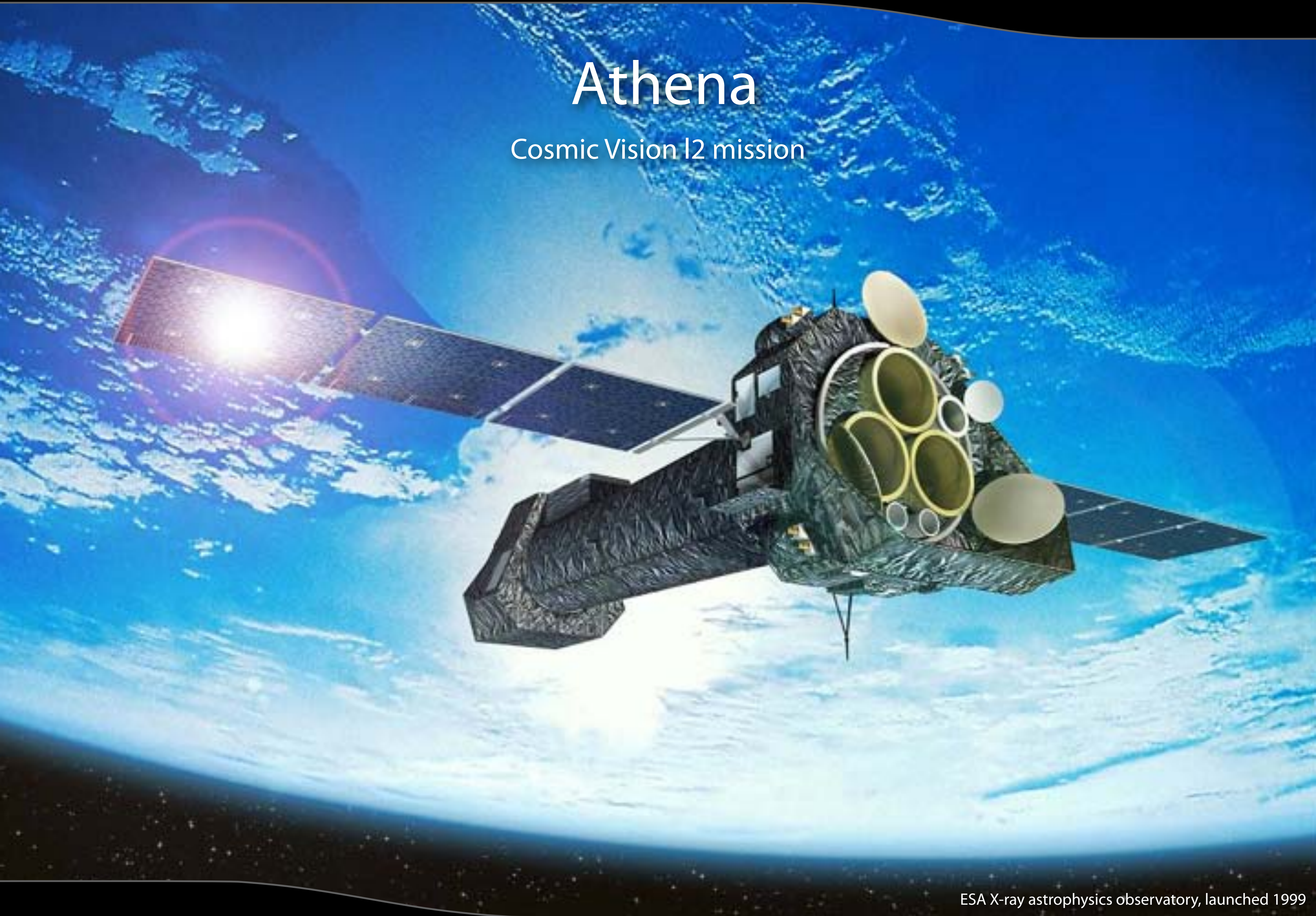


1.2m passively cooled telescope to survey 15,000 deg^2
Visible imaging: RIz(AB) = 24.5 10σ point source limit
Near-IR imaging: YJH(AB) = 24 5σ point source limit
Near-IR R=400 spectroscopy to H(AB) = 22

ESA dark Universe astrophysics survey mission, launch 2019

Athena

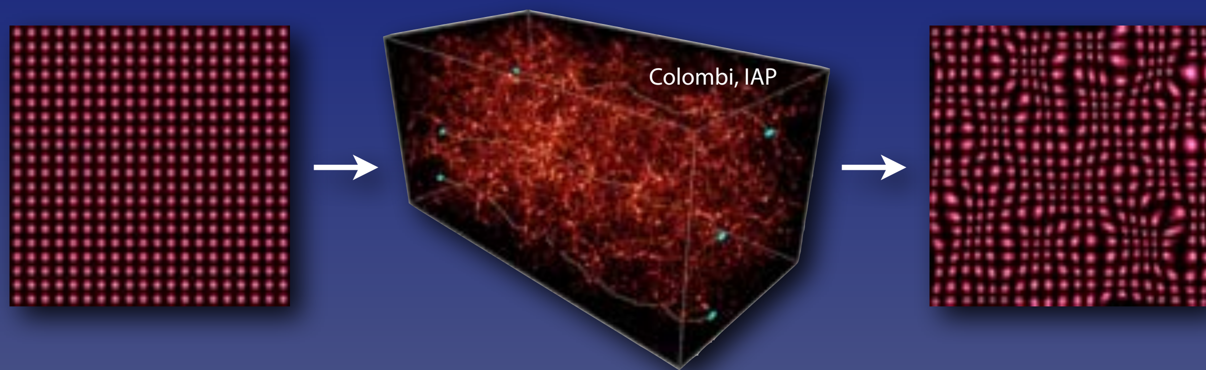
Cosmic Vision l2 mission



ESA X-ray astrophysics observatory, launched 1999

Multiple probes of evolving cosmic structure

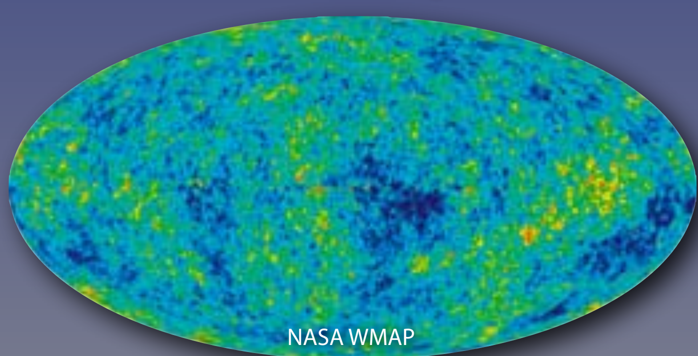
Weak lensing

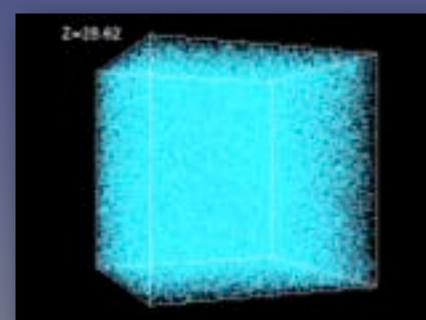


Galaxy shapes systematically distorted by intervening matter (baryonic and dark)

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

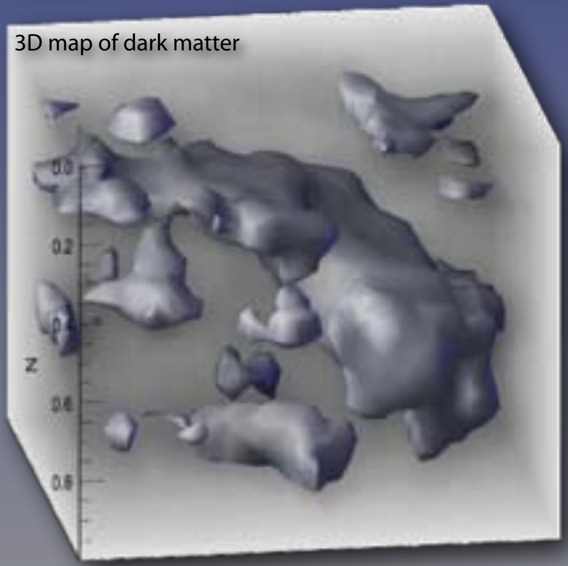
Initial structure imprinted on Universe at recombination has characteristic scale; follow its evolution as standard ruler to present epoch (now ~ 150 Mpc)

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

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



Massey et al. (2007, Nature)

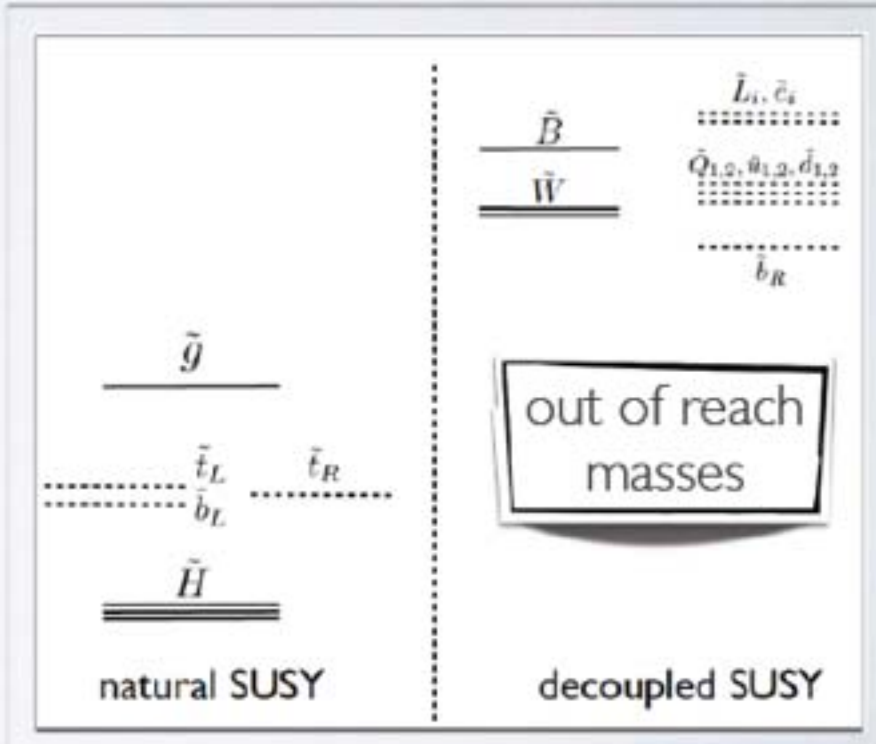
Dark Matter

NATURAL SUSY

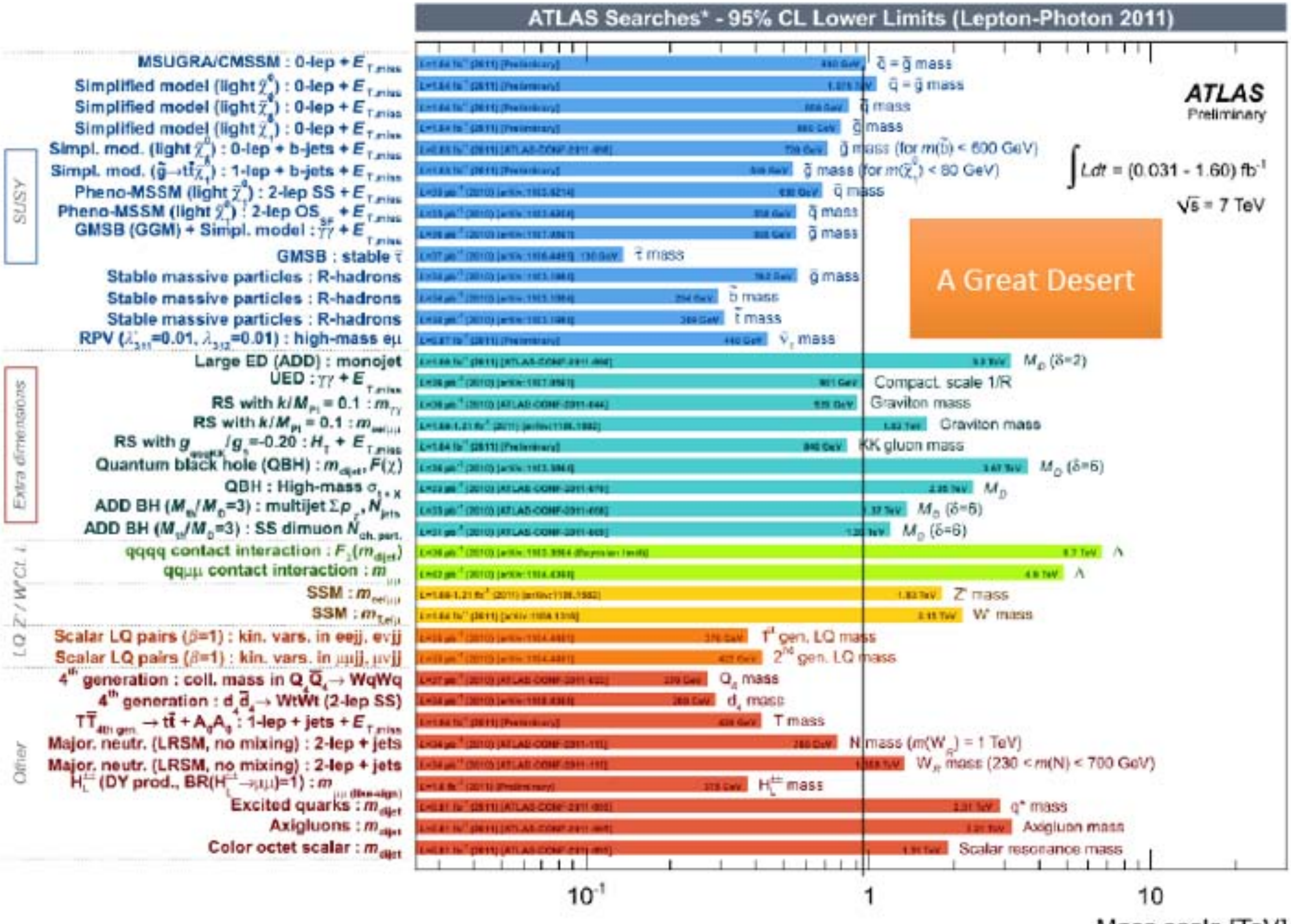
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2.$$

If SUSY is natural LHC is capable of discovering it

- Stop < 700 GeV
- Gluino < 1500 GeV
- Higgsino < 350 GeV



arxiv: 1110.6926



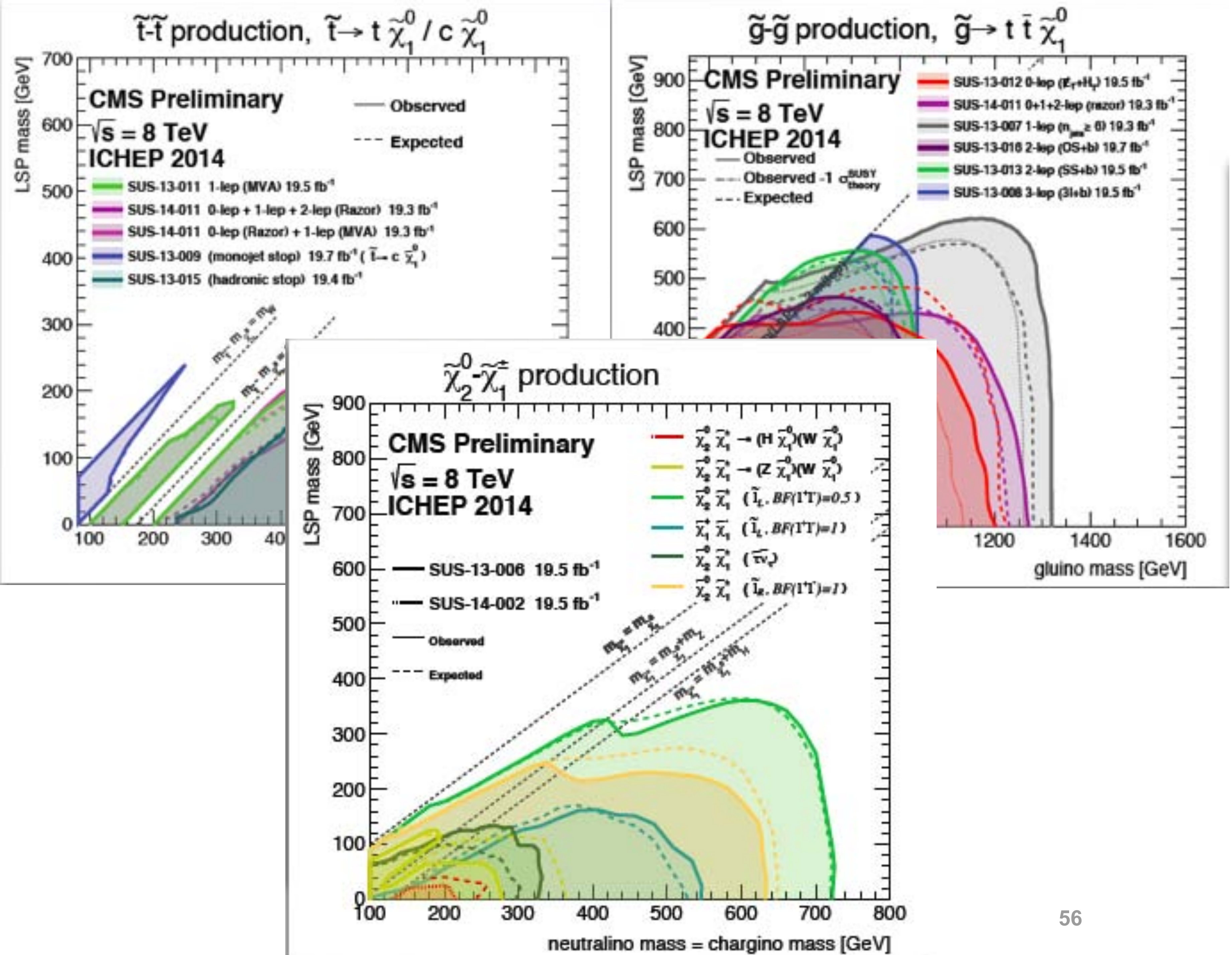
*Only a selection of the available results leading to mass limits shown

BEFORE LHC RUN 1

F. Giordano, IFAE 2015

AFTER LHC RUN 1

F. Giordano, IFAE 2015


t̃-t̃ production, t̃→ t χ̃₁⁰ / c χ̃₁⁰
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Expected
SUS-13-011 1-lep (MVA) 19.5 fb⁻¹
SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb⁻¹
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb⁻¹
SUS-13-009 (monojet stop) 19.7 fb⁻¹ (t̃ → c χ̃₁⁰)
SUS-13-015 (hadronic stop) 19.4 fb⁻¹
LSP mass [GeV]
g̃-g̃ production, g̃→ t t̄ χ̃₁⁰
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ theory SUSY
Expected
SUS-13-012 0-lep (E_T+H_T) 19.5 fb⁻¹
SUS-14-011 0+1+2-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep (n_jets ≥ 6) 19.3 fb⁻¹
SUS-13-016 2-lep (OS+b) 19.7 fb⁻¹
SUS-13-013 2-lep (SS+b) 19.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
LSP mass [GeV]
gluino mass [GeV]
χ̃₂⁰-χ̃₁± production
CMS Preliminary
√s = 8 TeV
ICHEP 2014
SUS-13-006 19.5 fb⁻¹
SUS-14-002 19.5 fb⁻¹
Observed
Expected
χ̃₂⁰ χ̃₁± → (H χ̃₁⁰)(W χ̃₁⁰)
χ̃₂⁰ χ̃₁± → (Z χ̃₁⁰)(W χ̃₁⁰)
χ̃₂⁰ χ̃₁± (l̃_L, BF(l⁺l⁻)=0.5)
χ̃₁± χ̃₁∓ (l̃_L, BF(l⁺l⁻)=1)
χ̃₂⁰ χ̃₁± (τ̃ν_τ)
χ̃₂⁰ χ̃₁± (l̃_R, BF(l⁺l⁻)=1)
LSP mass [GeV]
neutralino mass = chargino mass [GeV]

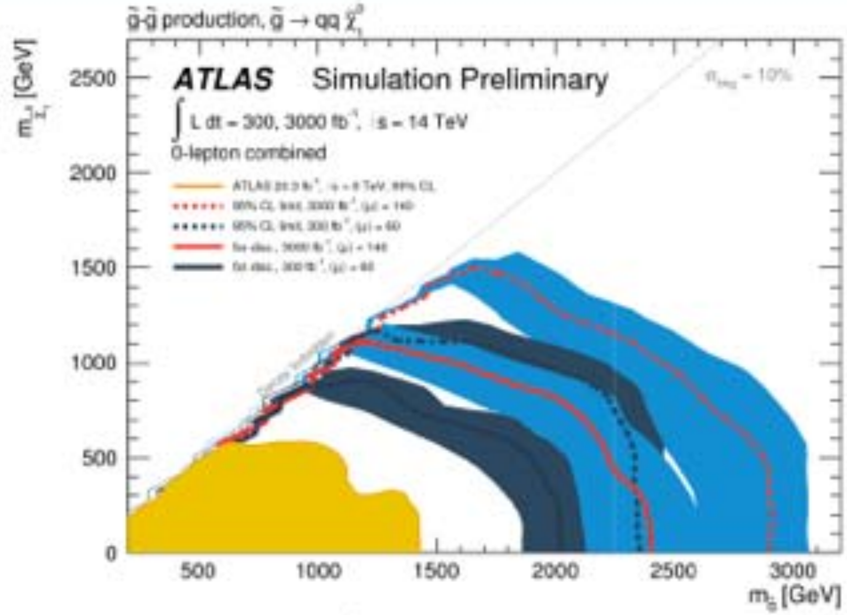
SO WHAT IS NEXT?

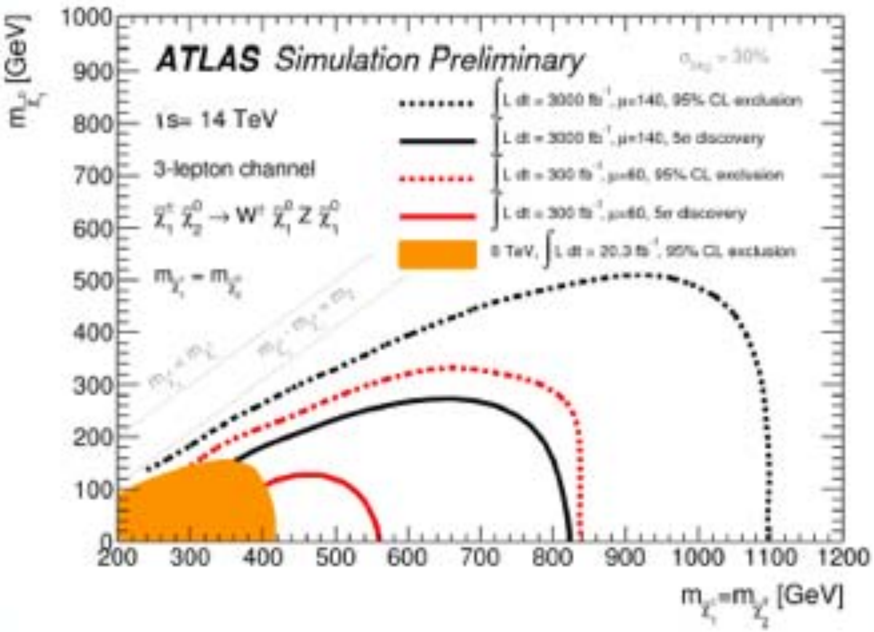
- LHC so far has found no evidence of SUSY particles
- Run1 data are still being exploited to turn every stone
- Nonetheless SUSY is still far from being dead
- Surprises can still happen in RUN2

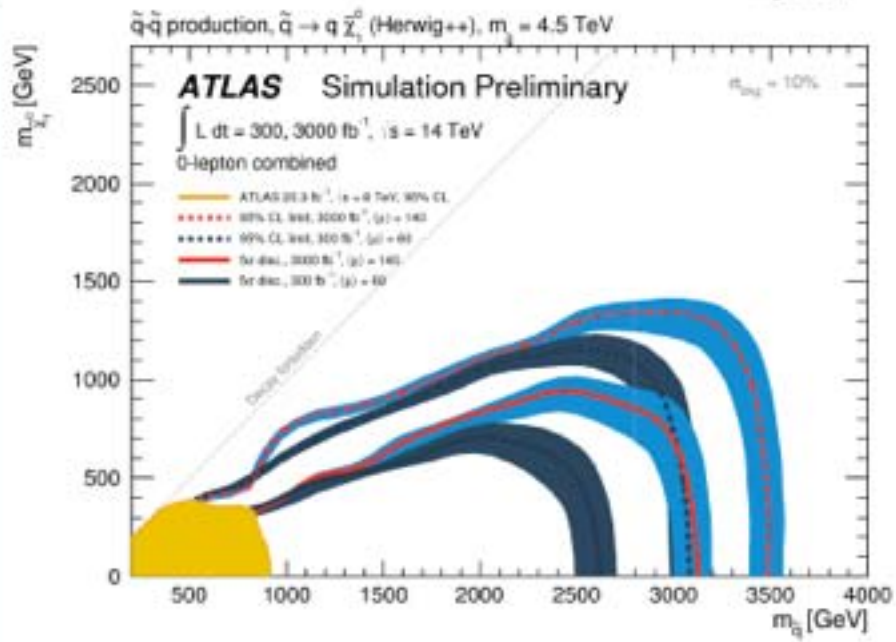
F. Giordano, IFAE 2015

13 TEV !


Cross section ratios: 14 (13) TeV / 8 TeV
Minimum bias 1.2
ZZ 2.1
WH 2.1
t (s-channel) 2.2
H (ggF) 2.6
H (VBF) 2.6
t (t-channel) 2.8
tt 3.9
ttH 4.7
stop pair (0.7 TeV) 11 (for 13 TeV / 8 TeV: 8.4)
stop pair (0.9 TeV) 16 (for 13 TeV / 8 TeV: 12)
gluino pair (1.5 TeV) 72 (for 13 TeV / 8 TeV: 46)
gluino pair (2.5 TeV) 5700 (13 / 8: 2700)
Z' SSM (3 TeV) 13
Q* (4 Tev) 87
QBH (6 TeV) 12000
1
10
100
1000
10000
100000

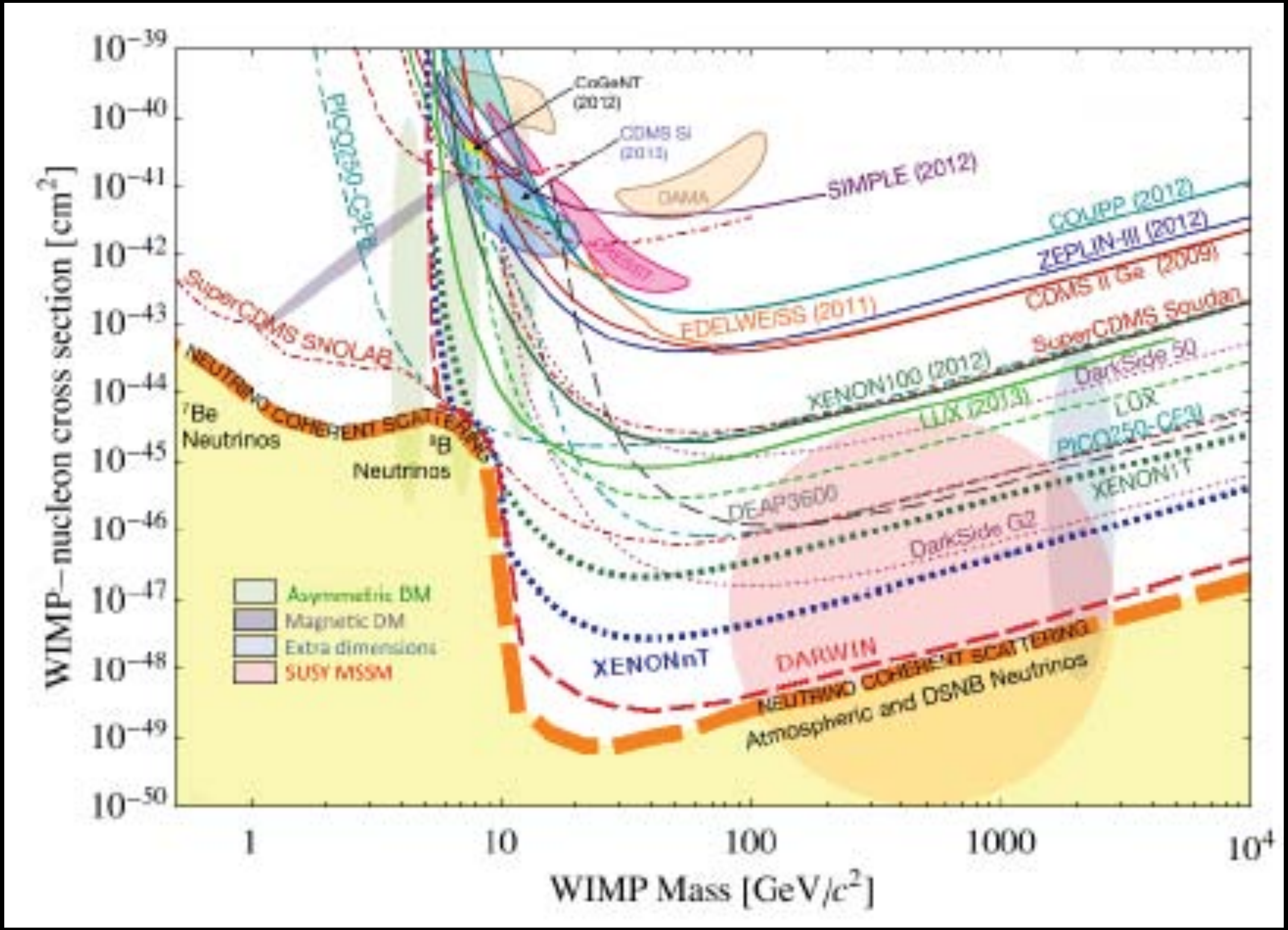

$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow qq\,\tilde{\chi}_1^0$
ATLAS Simulation Preliminary
$\int L\,dt$ = 300, 3000 fb^{-1}, $\sqrt{s}$ = 14 TeV
0-lepton combined
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]


ATLAS Simulation Preliminary
$\sqrt{s}$= 14 TeV
3-lepton channel
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W^\pm \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$
$\int L\,dt$ = 3000 fb^{-1}, μ=140, 95% CL exclusion
$\int L\,dt$ = 3000 fb^{-1}, μ=140, 5σ discovery
$\int L\,dt$ = 300 fb^{-1}, μ=60, 95% CL exclusion
$\int L\,dt$ = 300 fb^{-1}, μ=60, 5σ discovery
8 TeV, $\int L\,dt$ = 20.3 fb^{-1}, 95% CL exclusion
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}=m_{\tilde{\chi}_2^0}$ [GeV]


$\tilde{q}$-$\tilde{q}$ production, $\tilde{q} \rightarrow q\,\tilde{\chi}_1^0$ (Herwig++), $m_{\tilde{g}}$ = 4.5 TeV
ATLAS Simulation Preliminary
$\int L\,dt$ = 300, 3000 fb^{-1}, $\sqrt{s}$ = 14 TeV
0-lepton combined
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}}$ [GeV]

F. Giordano, IFAE 2015

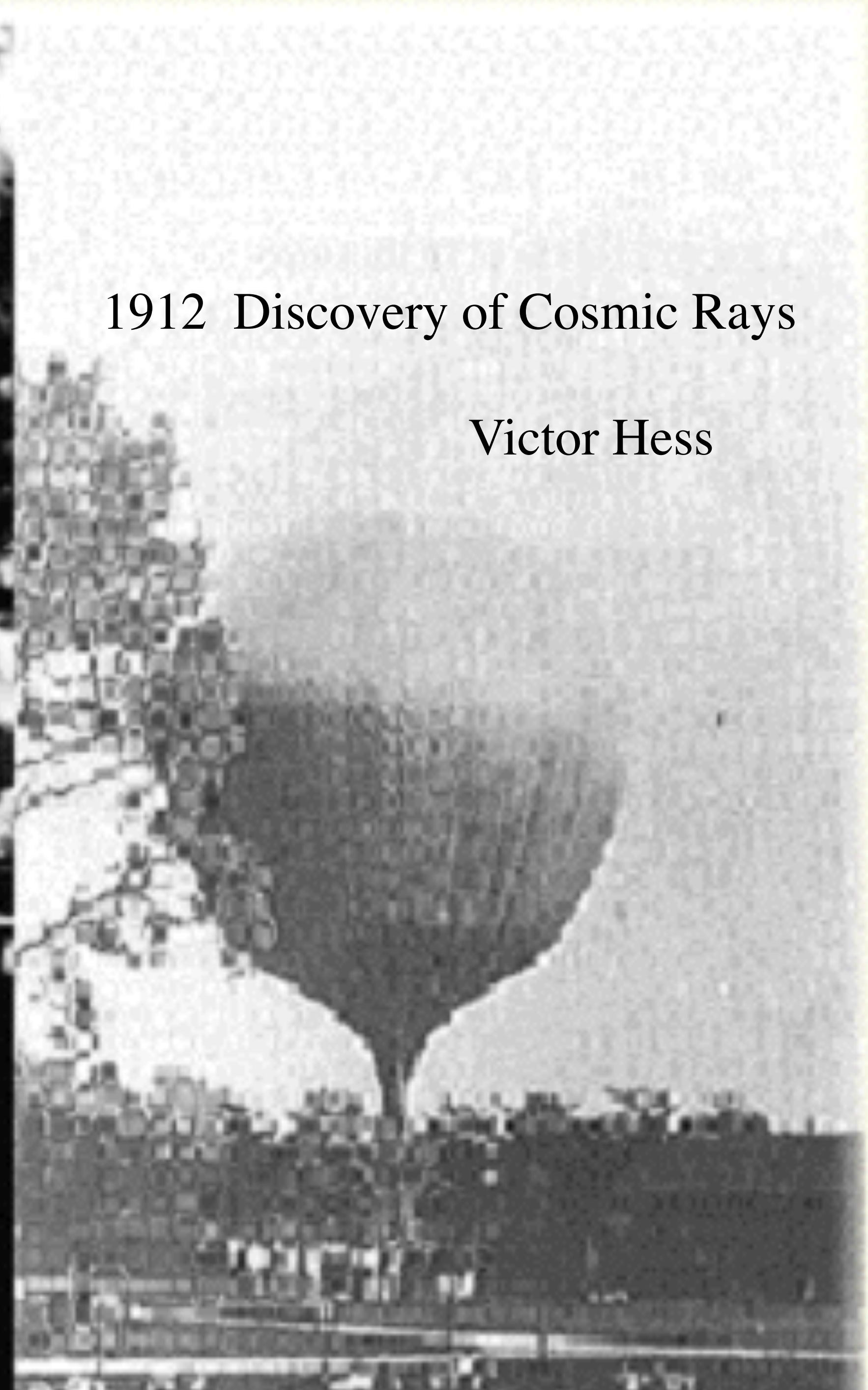
DIRECT SEARCHES

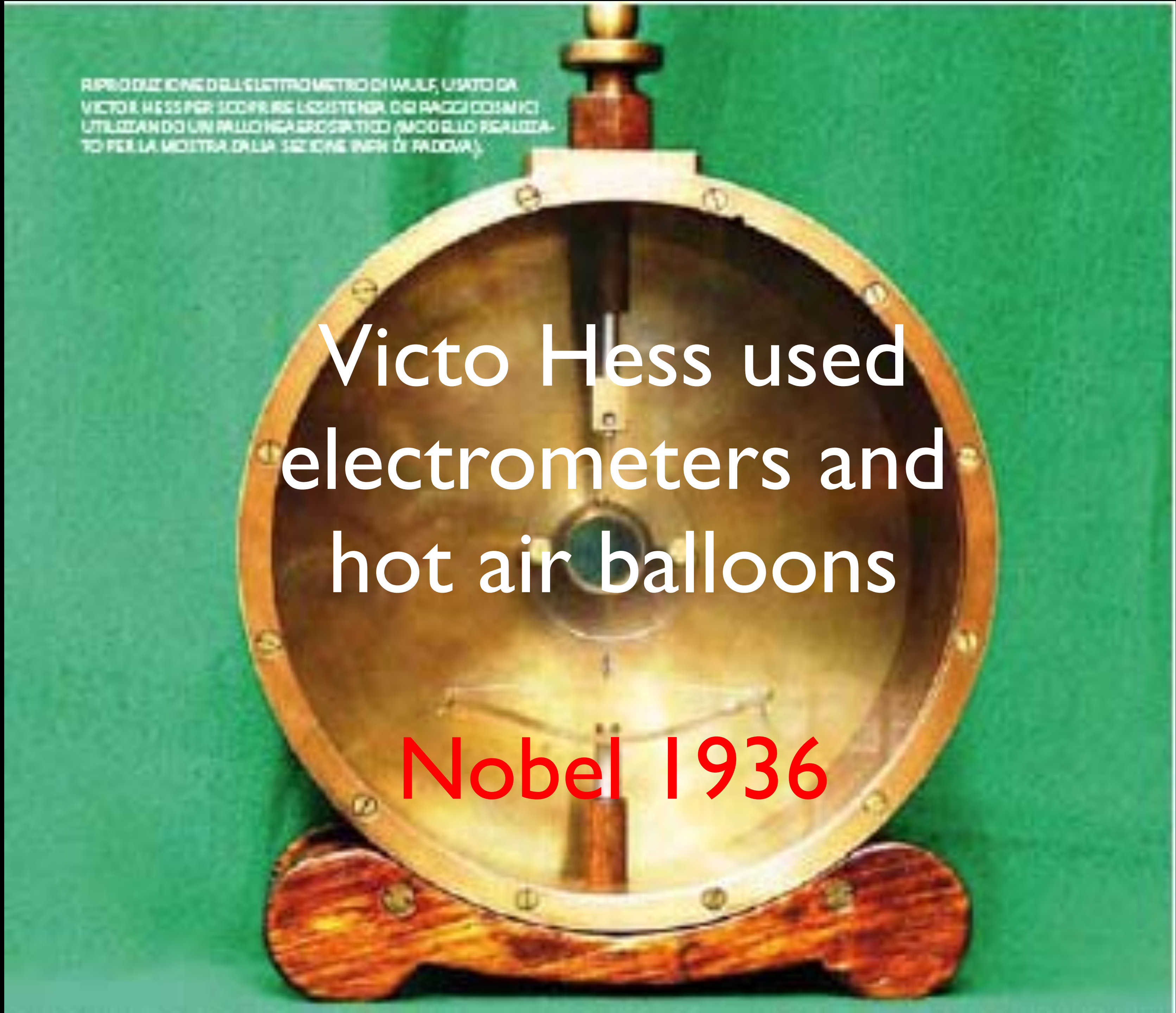


DM and Cosmic Rays

1912 Discovery of Cosmic Rays

Victor Hess




Victo Hess used electrometers and hot air balloons
Nobel 1936


e+
1932
μ+ μ−
1937
π+ π-
1947
K+K-
1949
π°
1950
K°
1950
Λ° Δ
1952
Σ+ Σ-
1953
Ξ-
1953
Symposium on Cosmic Ray, 1939 (The University of Chicago, U.S.A.)

Exitence of antimatter

Paul A.M. Dirac

Theory of electrons and positrons, 1928

Nobel Lecture, December 12th, 1933

Relativity:

$$\frac{W^2}{c^2} - p_r^2 - m^2c^2 = 0$$

Quantum mechanics

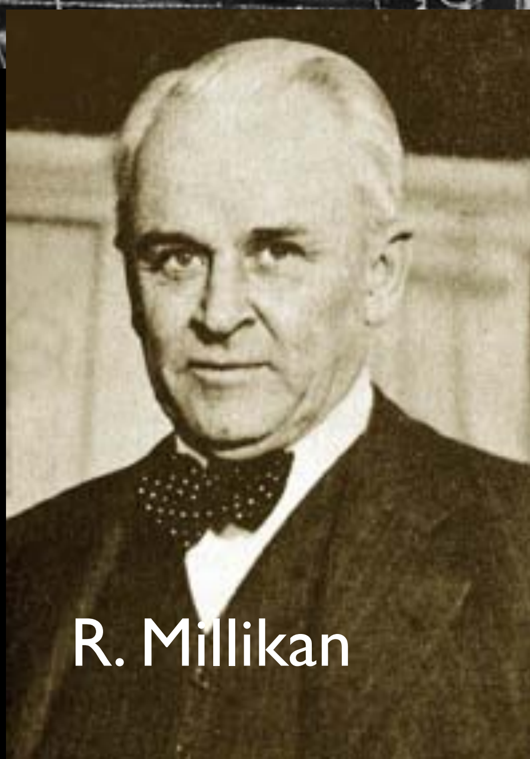
$$\left[\frac{W^2}{c^2} - p_r^2 - m^2c^2 \right]\Psi = 0$$

$$m^2 = (m)(m) = (-m)(-m)$$

Dirac asked himself: what's (-m) ➡ antimatter theory

Positron adventure

Dmitri Skobeltzyn



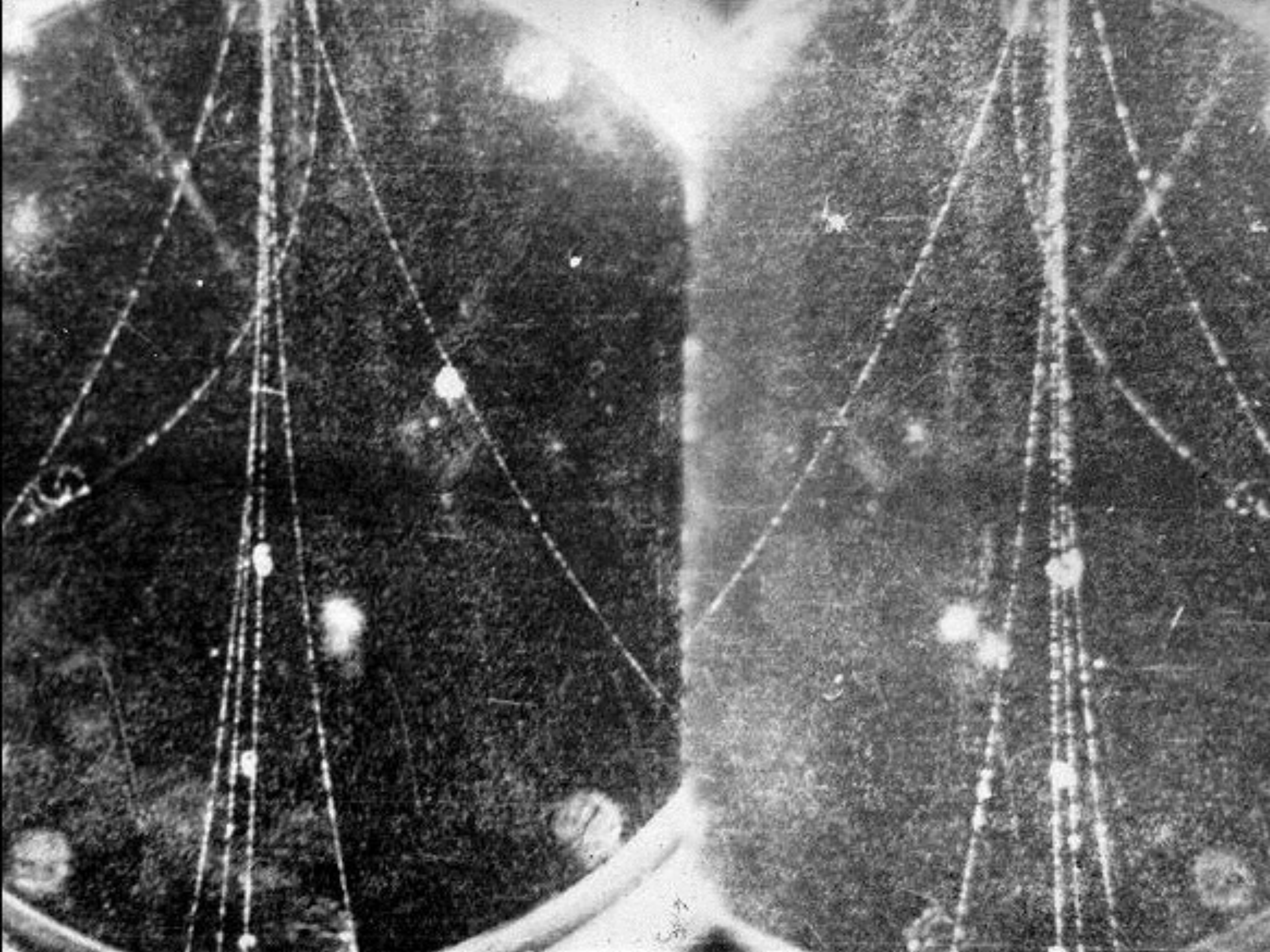
R. Millikan

P.A.M. Dirac

Patrick M.S. Blackett

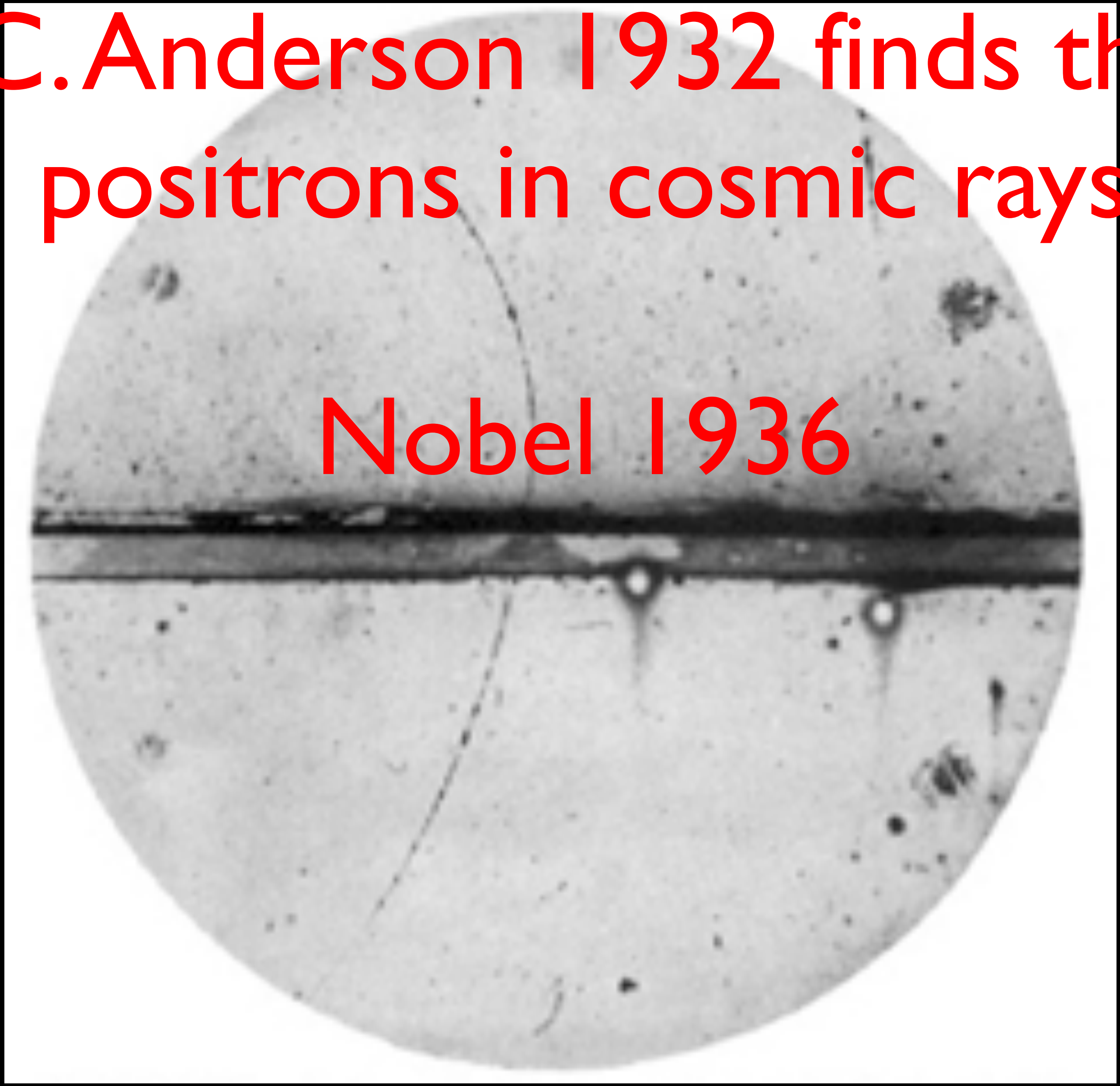
Giuseppe “Beppo” Occhialini


Positron adventure
C.Anderson



C. Anderson 1932 finds the positrons in cosmic rays

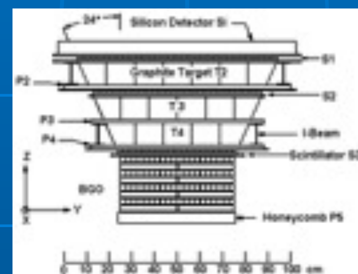
Nobel 1936



Space Missions and LDF

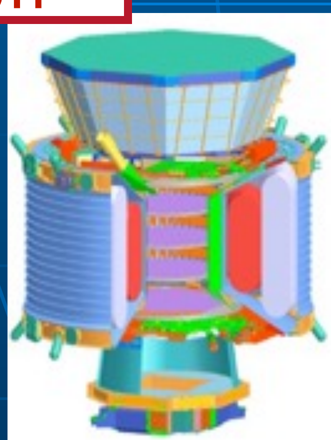
PAMELA
15-06-2006

ATIC
2002 - 2007



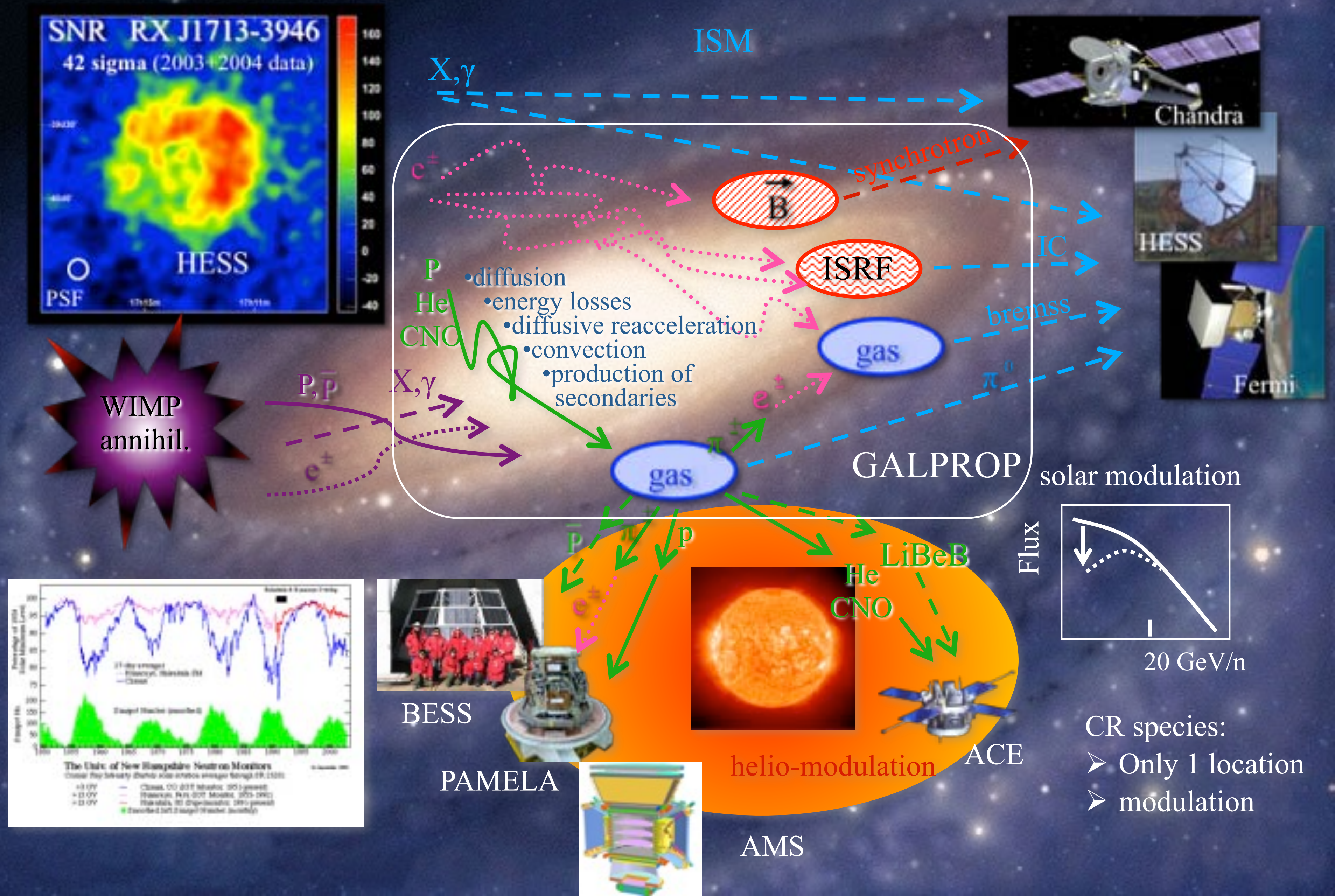
BESS
13-12-2004
23-12-2007

AMS-02
16 -5-2011



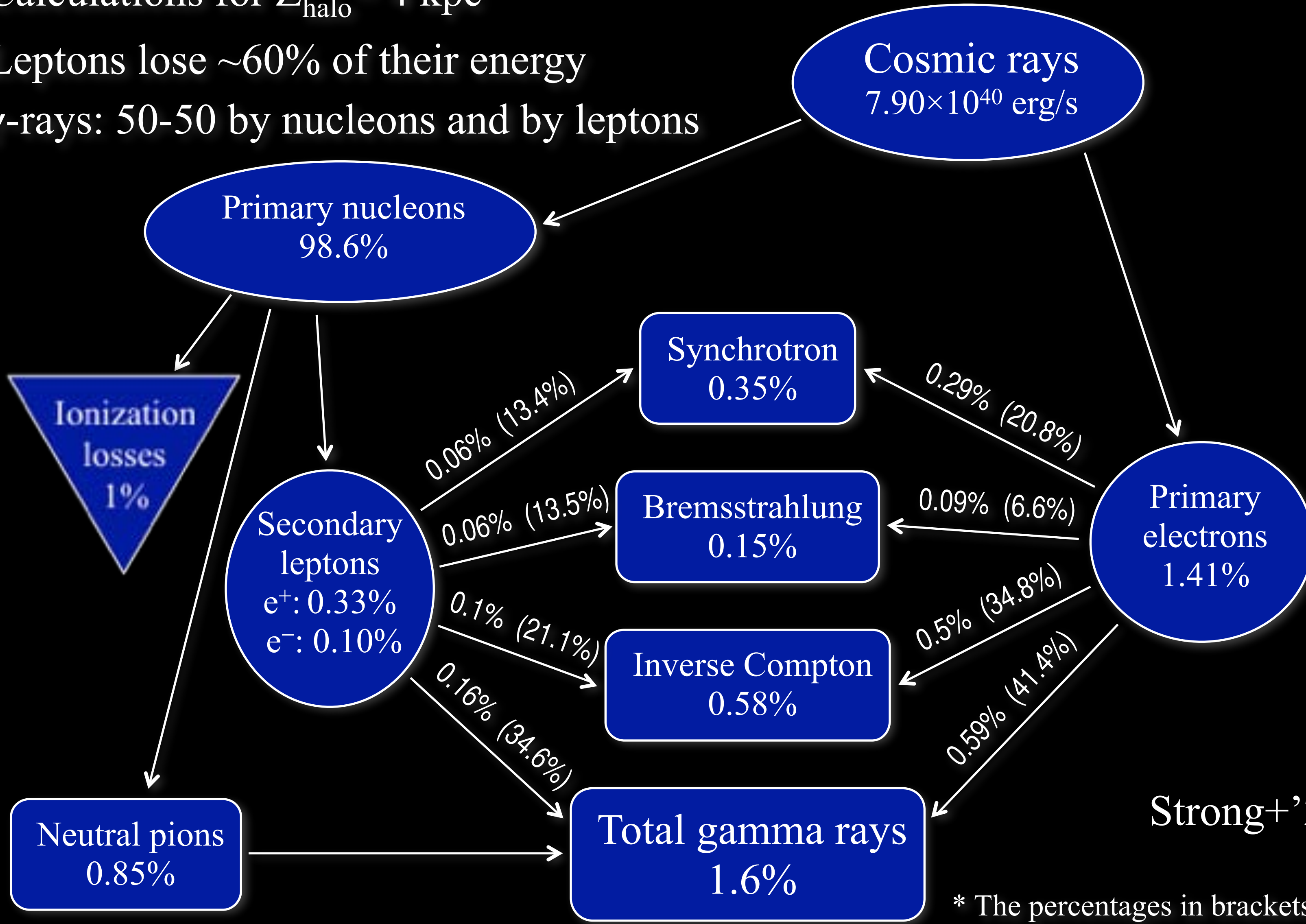
Fermi/GLAST
11-6-2008

CRs in the interstellar medium



Milky Way as an electron calorimeter

- Calculations for Z_{halo}= 4 kpc
- Leptons lose ~60% of their energy
- γ-rays: 50-50 by nucleons and by leptons



Strong+'2011

* The percentages in brackets show the values relative to the luminosity of their respective lepton populations

AMS-02 since May 16th 2011 collecting cosmic ray data on the ISS

Nuclear Instruments and Methods in Physics Research A 350 (1994) 351–367
North-Holland

NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

An antimatter spectrometer in space

Antimatter Study Group

S. Ahlen [f], V.M. Balebanov [a], R. Battiston [l], U. Becker [g], J. Burger [g], M. Capell [g],
H.F. Chen [p], H.S. Chen [o], M. Chen [g], N. Chernoplekov [b], R. Clare [g], T.S. Dai [g],
A. De Rujula [f,*], P. Fisher [d], Yu. Galaktionov [c], A. Gougas [d]. Gu Wen-Oi [n].
M. He [q], V. Koutsenko [c], A. Lebedev [c], T.P. Li [o], Y.S. Lu
Y. Ma [o], R. McNeil [e], R. Orava [j], A. Prevsner [d], V. Plyask
R. Sagdeev [h], M. Salamon [i], H.W. Tang [o], S.C.C. Ting [g],
Xia Ping-Chou [n], Z.Z. Xu [p], J.P. Wefel [e], Z.P. Zhang [p], B.

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[b] *Kurchatov Atomic Institute, Moscow, 123182 Russian Federation*
[c] *Institute of Theoretical and Experimental Physics, ITEP, Moscow, 117259, Russi*
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[f] *Boston University, Boston, MA 02215, USA*
[g] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[h] *East-West Center for Space Science, University of Maryland, College Park, MD*
[i] *University of Utah, Salt Lake City, UT 84112, USA*
[j] *SEFT Research Institute for High Energy Physics, Helsinki, 00014 Finland*
[k] *University of Bologna and INFN Sezione di Bologna, 40126 Bologna, Italy*
[l] *Perugia University and INFN Sezione di Bologna, 06100 Perugia, Italy*

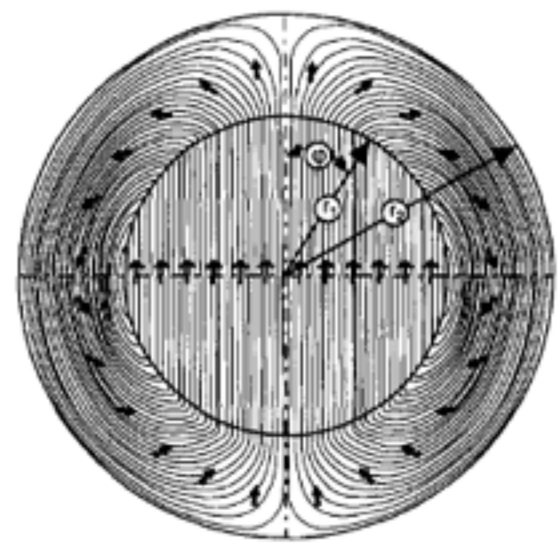


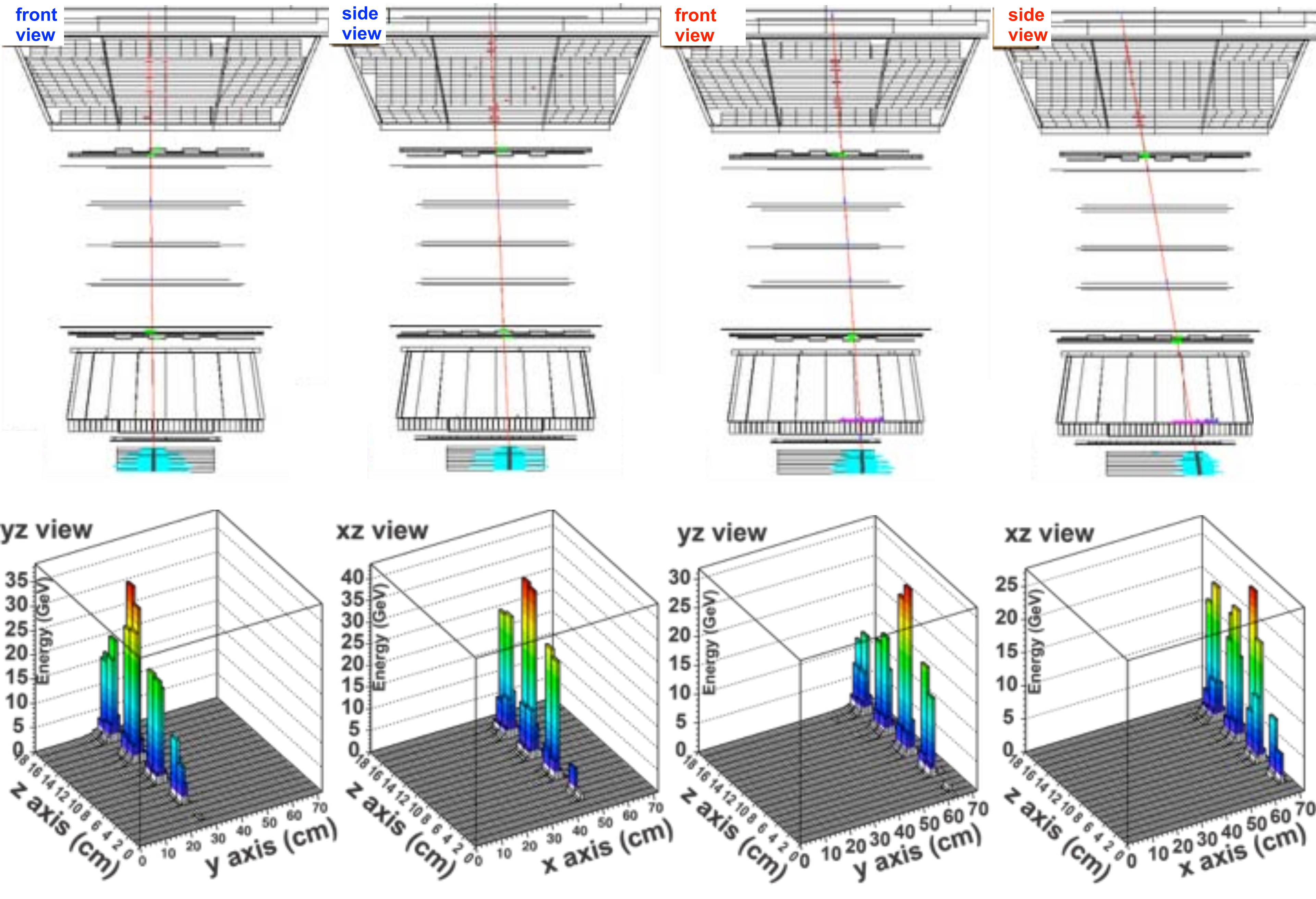
Fig. 6. Magnetic field distribution at a cross-section of the center of the magnet.

Electron E=982 GeV

Run/Event 1329775818/ 60709

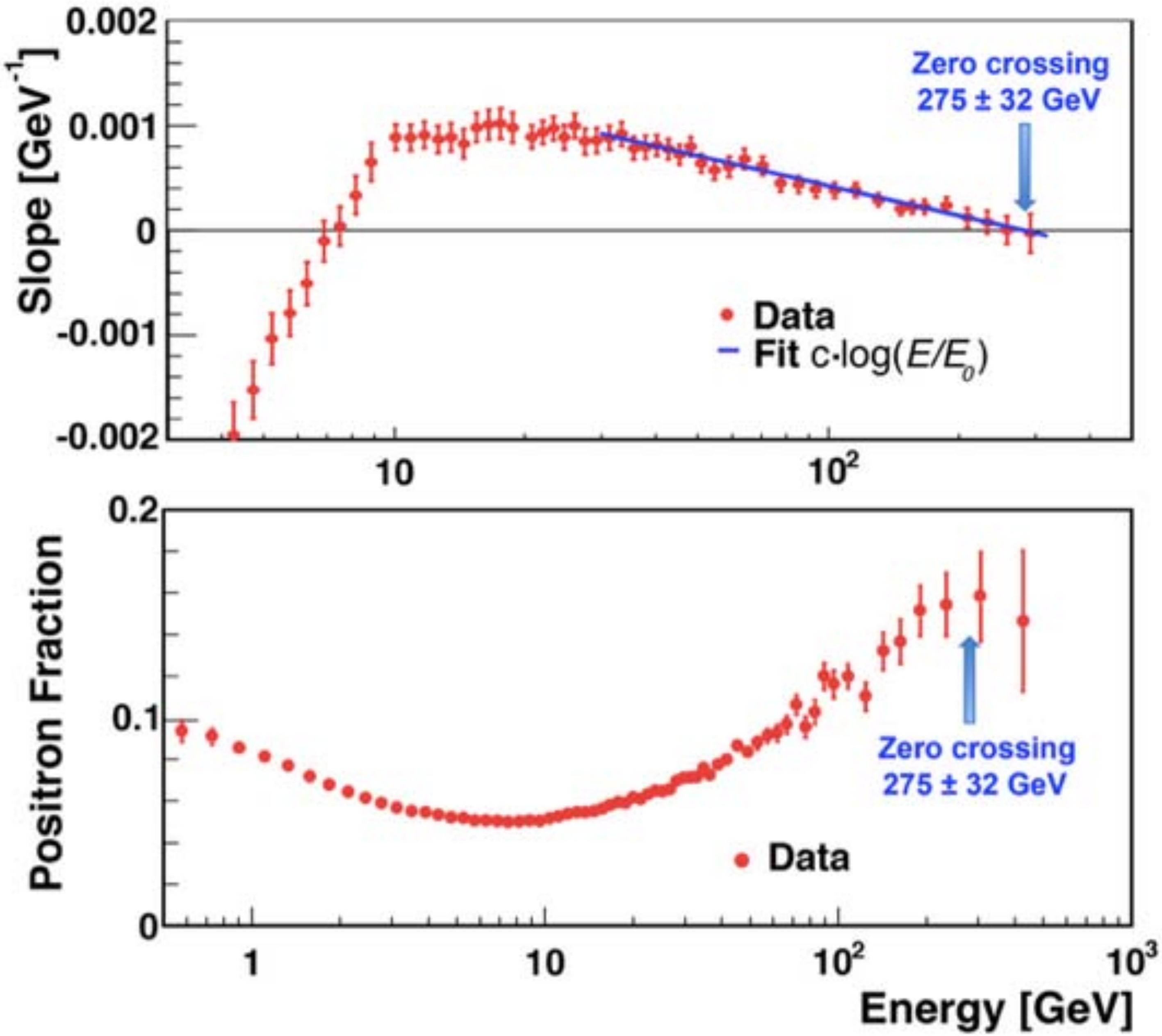
Positron E=636 GeV

Run/Event 133119-743/ 56950

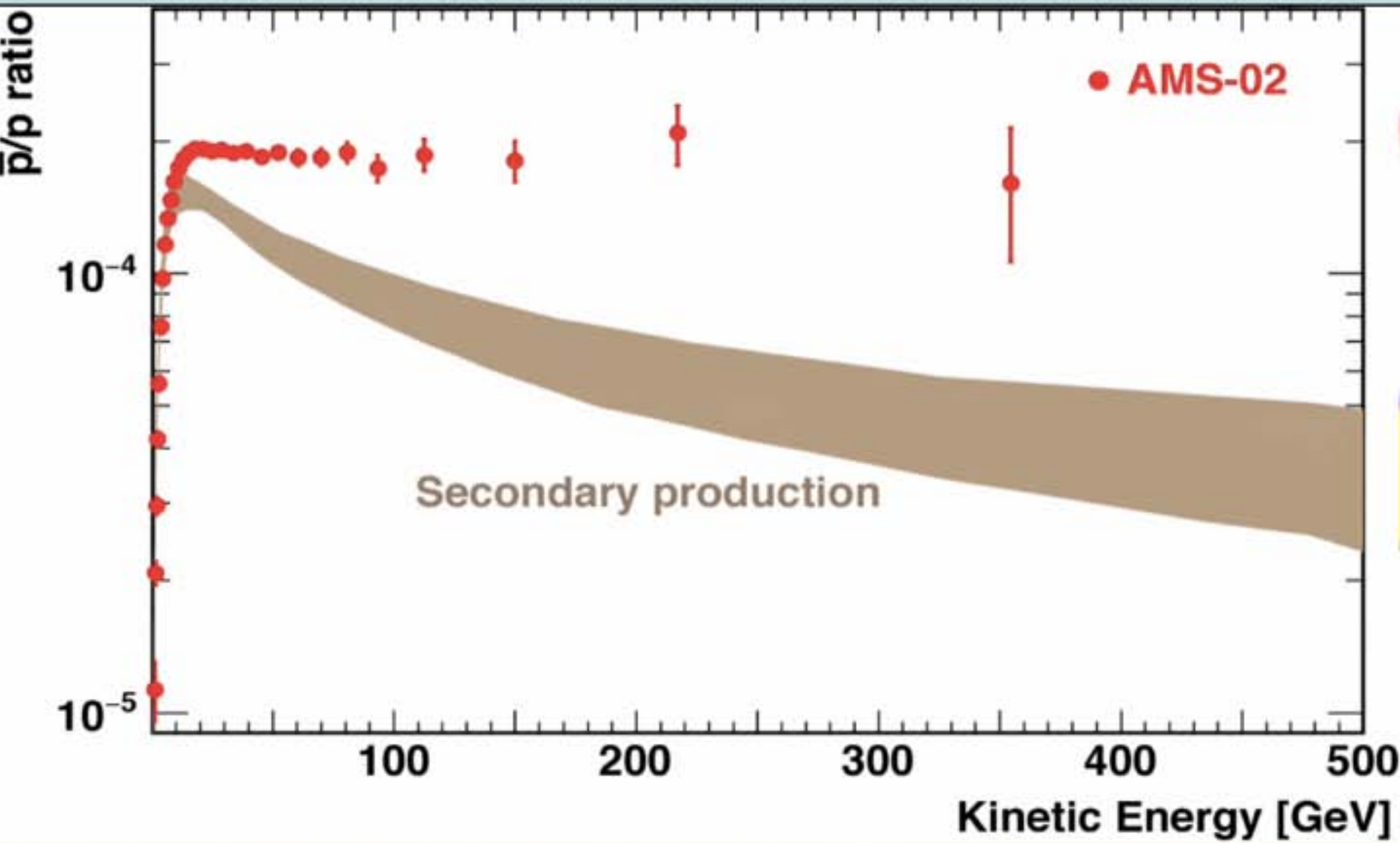


AMS-02: entering the era of precision cosmic ray measurement

e+ / e+ + e- ratio



New Antiproton/Proton Ratio



Above previous estimate of secondary production


Will the DM mistery will be
solved through CR ?
Stay tuned !

Open issues after AMS-02

- Dark matter (LHC will not be able to explore mχ> few 100 GeV)
  - Positrons at the 1-10 TeV scale
  - Antiprotons at the 1 TeV scale
  - Gamma rays at the TeV scale
  - Antideuterons at the GeV scale
- Spectral features at the knee scale
  - Protons at the PeV scale
  - Helia at the PV scale
  - Ions at the 100 TV scale

How to reach the O(10 TeV) scale ?

- Exposure : increase by a factor O(100) for e+

  From 0.05 to 5 m2sr

- Detector : capable to deal with 10 TeV particles
  - Tracker + Magnet → MDR > 20 TV
  - ECAL → ECAL+HCAL

AMS-03 : expected rates detection tools/limitations

ELECTRON AND POSITRON PHYSICS @ AMS-03

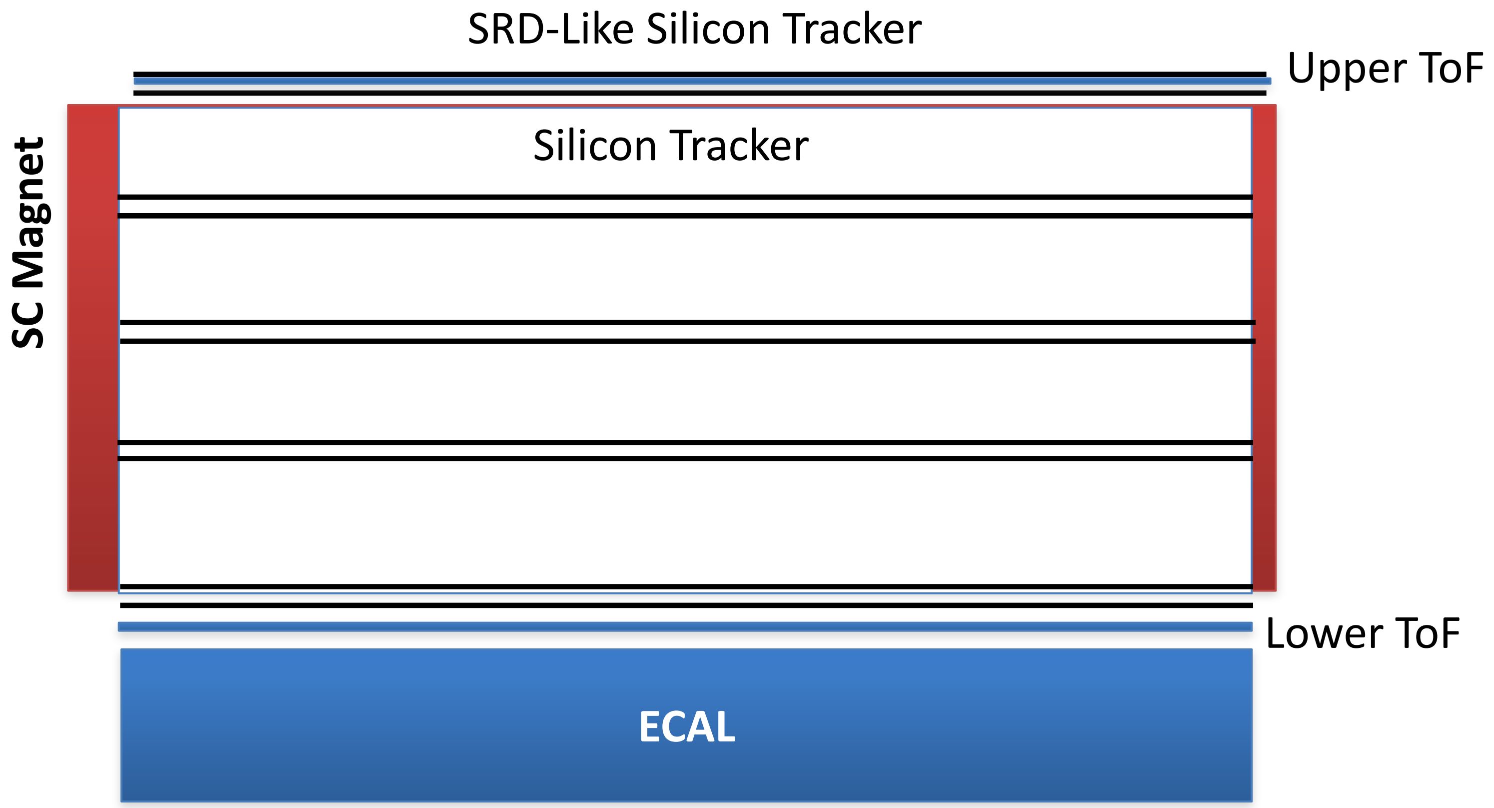
5	m2 sr		3,14E+07	s/y		ACCESSIBLE	EXCLUDED	EXCLUDED
eV	10^8	10^9	10^10	10^11	10^12	10^13	10^14	10^15
scale	100MeV	GV			TV			PV
Integral . 1/y	**.@ 0,1-1**	**.@ 1-10**	**.@ 10-100**	**.@ 100-1000**	**.@ 1.000 ->**	**.@ 10.000 ->**	**.@ 100.000 ->**	**.@ 1.000.000 ->**
e-	4,99E+10	3,11E+09	1,56E+08	9,33E+05	7,78E+03	7,78E+01	7,78E-01	7,78E-03
e+	2,50E+09	1,56E+08	1,56E+07	1,40E+05	1,17E+03	1,17E+01	1,17E-01	1,17E-03
Detectors	tracker, TOF, TRD, ECAL	tracker, TOF, TRD, ECAL	Tracker, TRD, ECAL	Tracker, TRD, ECAL	Tracker,SRD,ECAL	Tracker,SRD,ECAL		
Variables	R, beta, gamma, energy	R, beta, gamma, energy	R, gamma, energy	R, gamma, energy	R,Energy, Syncrotron Radiation	R, Energy, Synchroton Radiation		
Physics	Van Allen, solar, subcutoff	solar, geomagnetic, galactic	DM, galactic, asymmetries	DM, galactic, asymmetries	DM, galactic	DM, galactic, moon shadow, sun shadow	DM, galactic	DM, extragalactic, knee
Tools	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, TRD calibration, backtracing (near Earth)	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, TRD calibration, backtracing (near Earth)	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, TRD calibration, backtracing (near Earth)	acceptance vs R, live time, efficiency, MC, inner/outer tracker, TRD, alignement, backtracing (Earth-Moon, Earth- Sun)	acceptance vs R, live time, efficiency, MC, outer tracker, alignement, SRD calibration, ECAL calibration, backtracing Earth-Moon, Earth-Sun	acceptance vs R, live time, efficiency, MC, tracker, alignement, SRD calibration, ECAL calibration, backtracing Earth-Moon, Earth-Sun		
Background e-	-	-	-	p	p	p	p	p
Background e+	p	p	p	p	p	p	p	p
Limitations	multiple, scattering, acceptance,AMS02 magnetic field		-		SRD Acceptance, MDR Tracker, ECAL must be in accceptance	SRD acceptance, MDR Tracker, ECAL must be in accceptance	no statistics	no statistics

AMS-03 : expected rates and detection tools/limitations

PROTON (ANTIPROTON) and HELIUM PHYSICS @ AMS-03

5	m2 sr	3,14E+07	s/y			ACCESSIBLE	ACCESSIBLE	ACCESSIBLE
	10^8	**10^9**	**10^10**	**10^11**	**10^12**	**10^13**	**10^13**	**10^13**
	100MeV	**GV**			**TV**			**PV**
Integral . 1/y	**.@ 0,1-1**	**.@ 1-10**	**.@ 10-100**	**.@ 100-1000**	**.@ 1.000 ->**	**.@ 10.000 ->**	**.@ 100.000 ->**	**.@ 1.000.000 ->**
p	4,99E+10	9,96E+10	1,99E+10	3,97E+08	7,19E+06	1,44E+05	2,86E+03	5,71E+01
He	1,80E+09	1,79E+10	3,58E+09	7,14E+07	1,29E+06	2,58E+04	5,15E+02	1,03E+01
Detectors	tracker, TOF, RICH	Tracker, (RICH)	Tracker	Tracker	Tracker	Tracker+ HCAL	Tracker+ HCAL	Tracker+ HCAL
Variables	R, beta	R	R	R	R	R, Energy	Energy	Energy
Physics	Van Allen, solar, subcutoff	solar, geomagnetic, galactic	galactic	galactic	galactic, moon shadow, sun shadow	galactic, moon shadow, sun shadow	galactic	extragalactic, knee
Tools	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing(near Earth)	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, , RICH calibration, backtracing (near Earth)	acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing near Earth)	acceptance vs R, live time, efficiency, MC, inner/outer tracker, alignement, backtracing Earth-Moon, Earth- Sun)	acceptance vs R, live time, efficiency, MC, outer tracker, alignement, , ECAL calibration, backtracing Earth-Moon, Earth-Sun	acceptance vs R, live time, efficiency, MC, tracker, alignement, HCAL calibration, backtracing Earth-Moon, Earth- Sun	acceptance vs R, live time, efficiency, MC, tracker, alignement, HCAL calibration, backtracing Earth-Moon, Earth- Sun	HCAL calibration, backtracing Earth-Moon, Earth- Sun
Background p	-	-	-	-				
Background He	He3/He4	He3/He4	He3/He4	He3/He4	-	-	-	
Limitations	multiple, scattering, acceptance,AMS02 magnetic field	-	-	different tracker acceptances, alignement	MDR	MDR+ HCAL	HCAL	HCAL

AMS-03-SC concept



PRELIMINARY DESIGN **with HT-MgB2 SC magnet**

ToF + Tracker + Ecal/HCAL + SRD-Like

SRD-like: 2D X-ray detector to be installed on the top of the magnet on the space station

Magnet: (B) MgB2 double helix (perfect dipole) : Inner radius 130 cm, Height 100 cm,
B-field 1 Tesla
Weight: < 1 Ton , **MDR 56 TV,**
Acceptance 6 times AMS-02-Magnet

ECAL: Radius 130cm, tungsten absorber, scintillating fibers with SiPM readout,
Thickness 32 cm, 37 Radiation Length,
Weight ~15 Tons Acceptance 75 times AMS-02 ECAL

Hadronic energy resolution of the ECAL : to be calculated , expected 30-40% @ TV scale

Tracker: 5 carbon fiber disks in a carbon fiber support structure with a top and bottom silicon layer on each disk.
Single Point resolution < 0.002 mm. Technology : CMOS camera arrays being developed for LHC during the last 10 years (record resolution 600 nanometers)
Acceptance: 9 m^2 sr
MDR: 56 TV

High mass DM could justify the physics case for a precision post-AMS-02 large acceptance, high resolution CR space spectrometer to explore the 10 TeV energy range


Conclusions

Conclusions 1

One hundred years after the discovery of Cosmic Rays, in the era of the Higgs boson, multimessenger observation of the Universe continues to provide outstanding physics results

The Universe reveal itself through the interaction of mass and energy deforming the space-time texture

A modern class of space observatories is pushing the limits of sensitivities to the edge of space and time, using most sophisticated technologies and Europe is playng a key role in these global scientific enterprises

Current generation of space instruments compete in cost and complexity with the largest LHC experiments

Conclusions 2

The links between astrophysics, cosmology, astroparticle physics and the physics at the accelerators are stronger and deeper than ever

The detailed study of the CMB, light, gamma rays, cosmic rays and gravitational waves are providing extraordinary experimental insights in the early phases of the universe, testing fundamental concepts in particle physics like number of neutrino species, dark matter, symmetry breaking, inflation, phase transitions......

Still most of the Universe remain unexplained : dark matter, dark energy, absence of antimatter are striking examples of how long is our journey to understand the place we live


Thanks !