Selected topics in

ASTRO-PARTICLE PHYSICS

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Fermilab

Hadron Collider Physics Summer School
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BIG QUESTIONS

Some of the most exciting problems in modern-day High-Energy Physics are identified and/or investigated in astrophysical settings, e.g.:

— What is the origin of cosmic particles?

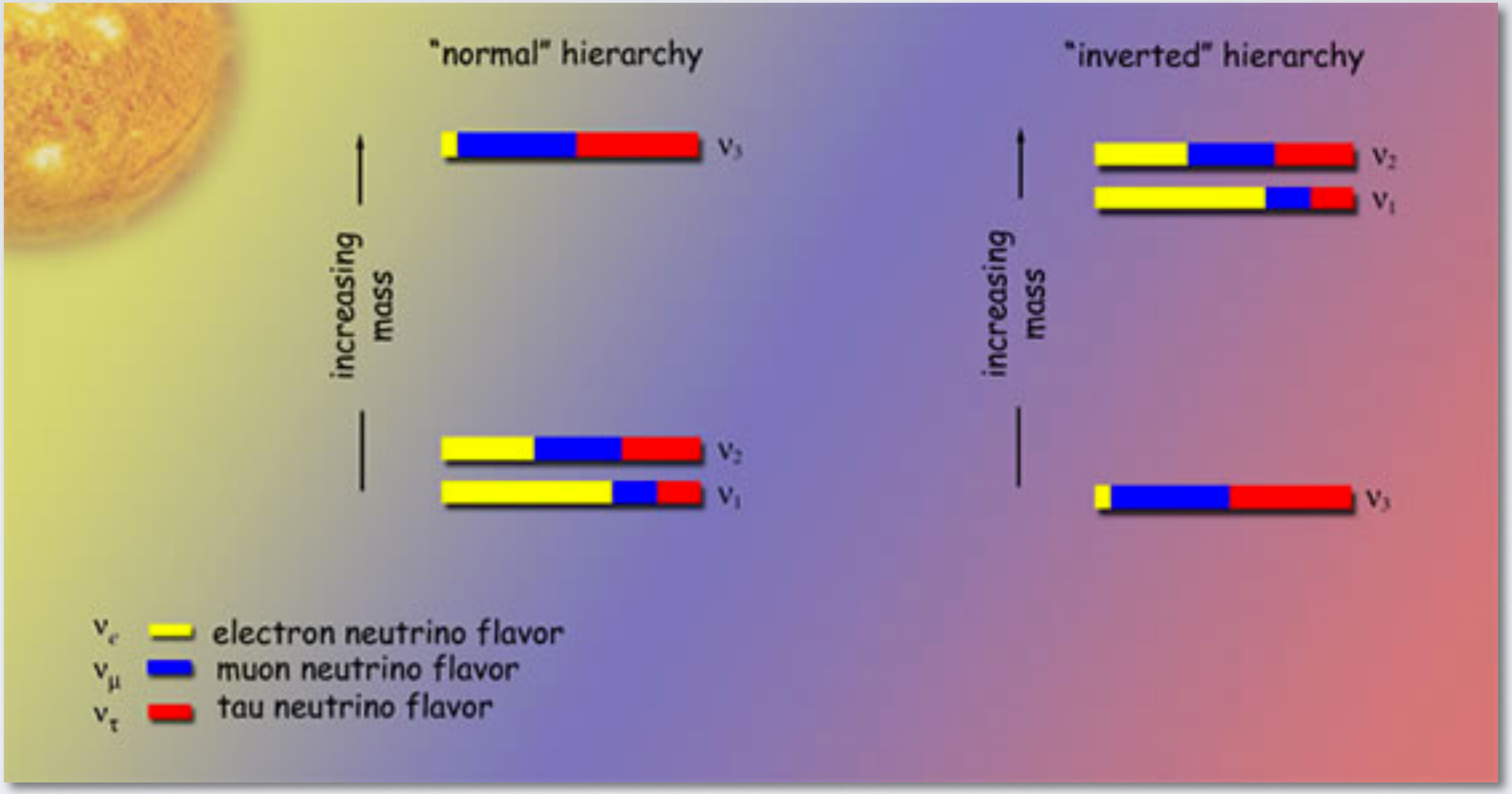
— Are there particles beyond the Standard Model? (Dark Matter?)

— What is the physics underlying the accelerated expansion phases of the universe?

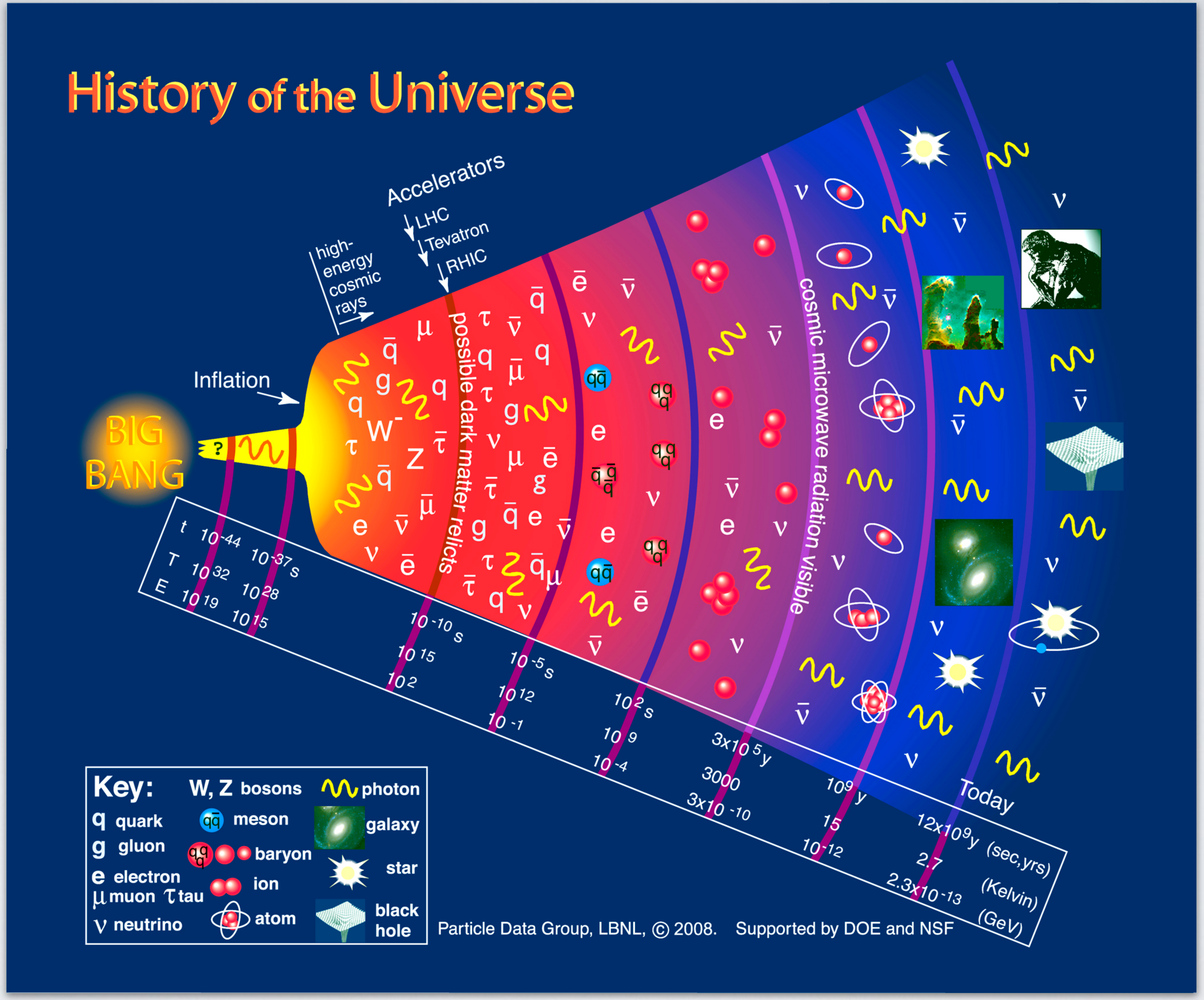
— What are the properties of the neutrinos?

SOLAR NEUTRINOS

Classic example of new physics found at the cosmic frontier.



Discovery of neutrino oscillations (implying mass > 0) led to the development of an entire new research field.


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
µ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

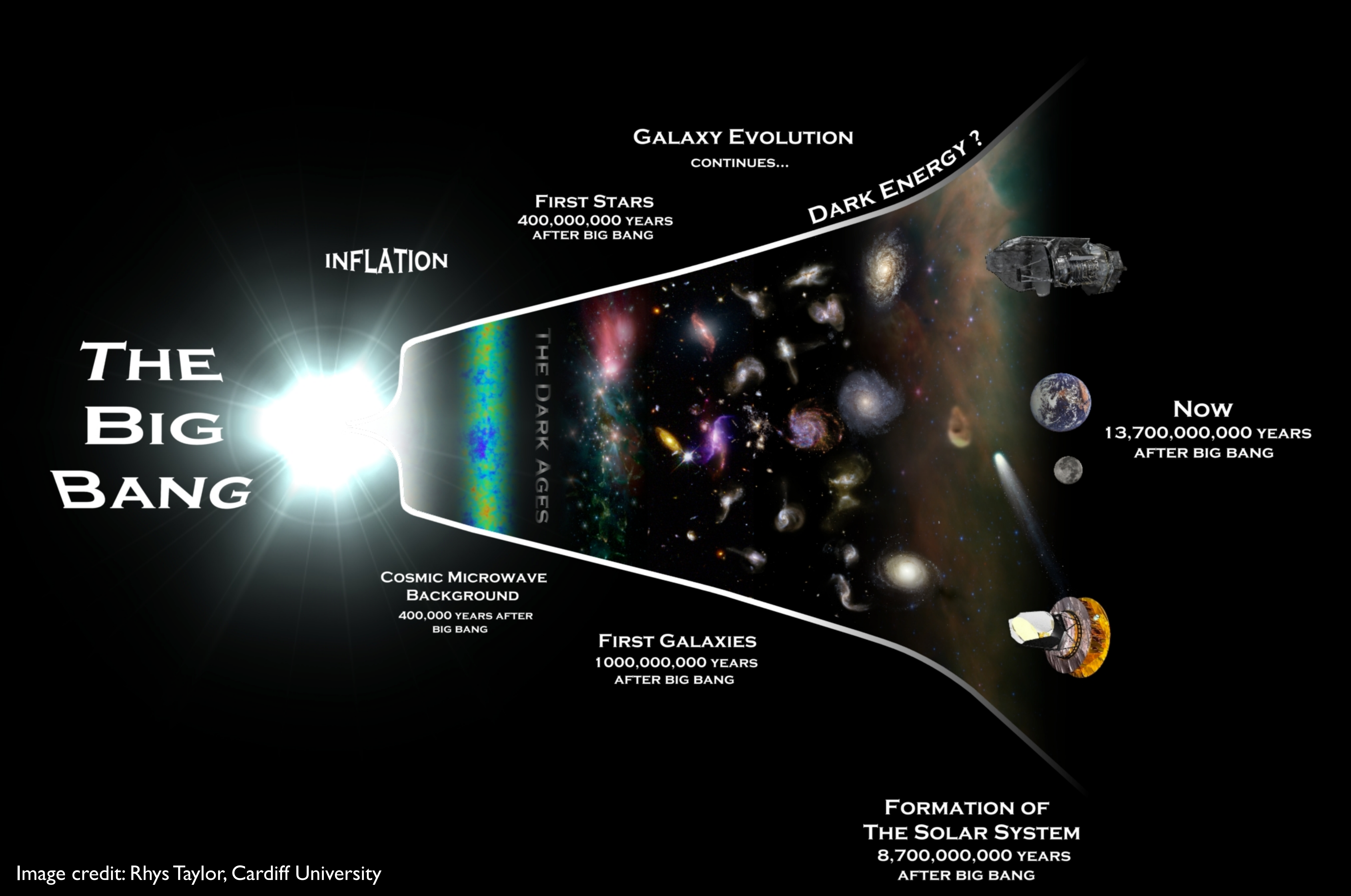
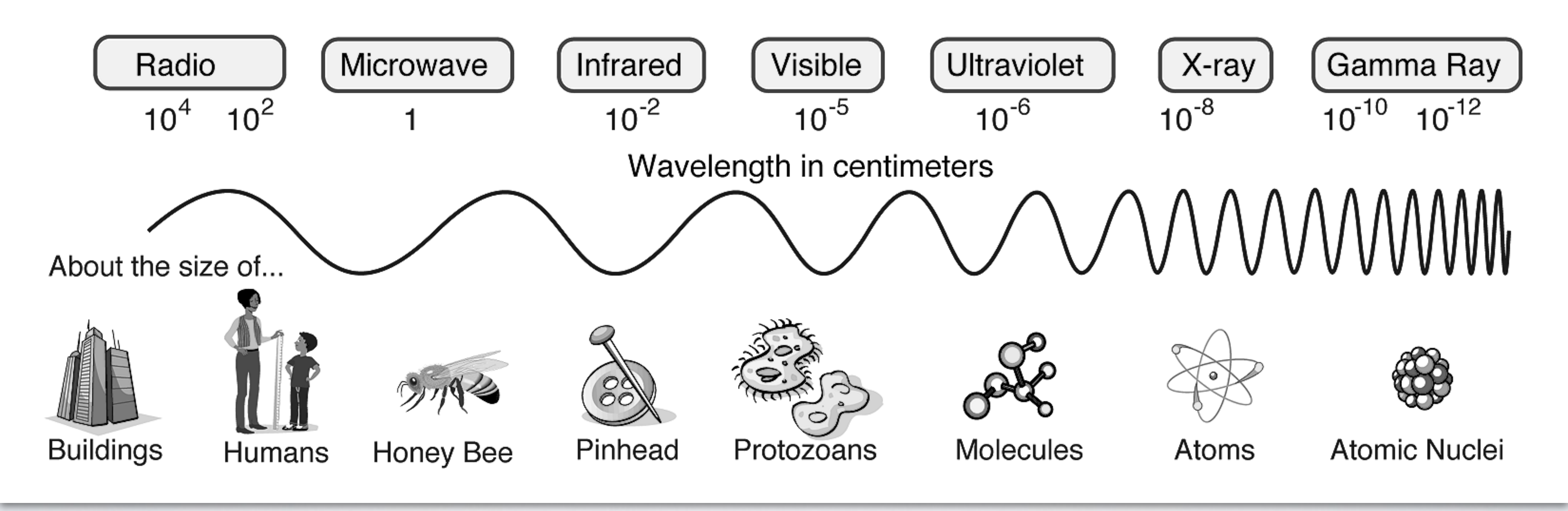


Image credit: Rhys Taylor, Cardiff University

THE 'BRIGHT' SIDE

High-Energy Cosmic Particles (aka Astro-Particles)

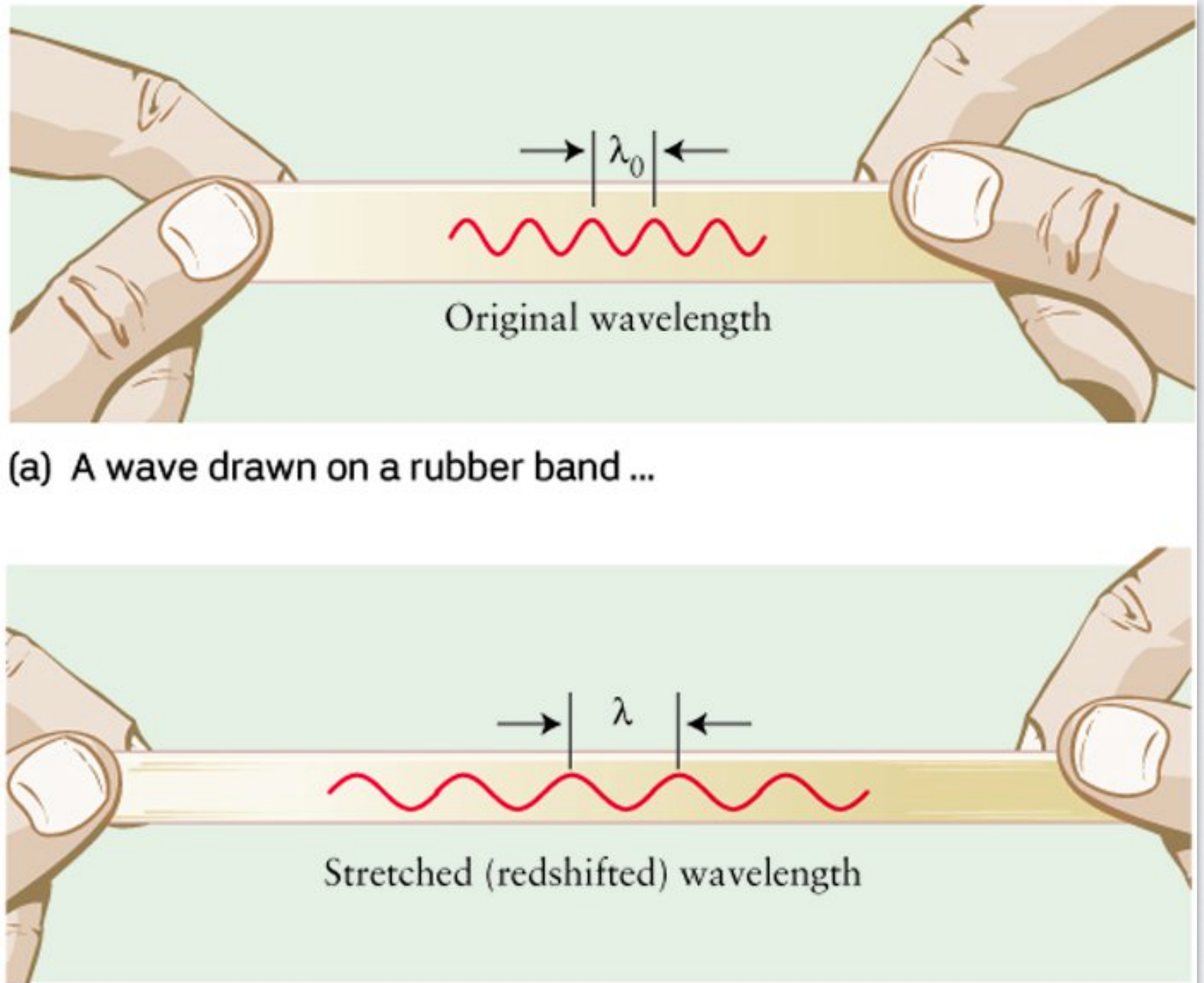
The easiest 'astro-particle' to detect?



Energy range where we observe photons

10^{-9} eV to 10^{14} eV (1 eV = 2.4 10^{14} Hz)

REDSHIFT & SCALE FACTOR



(a) A wave drawn on a rubber band ...

(b) ... increases in wavelength as the rubber band is stretched.

As the universe expands (scale factor **a** increases) photons are redshifted to larger wavelengths.

today: $z = 0$

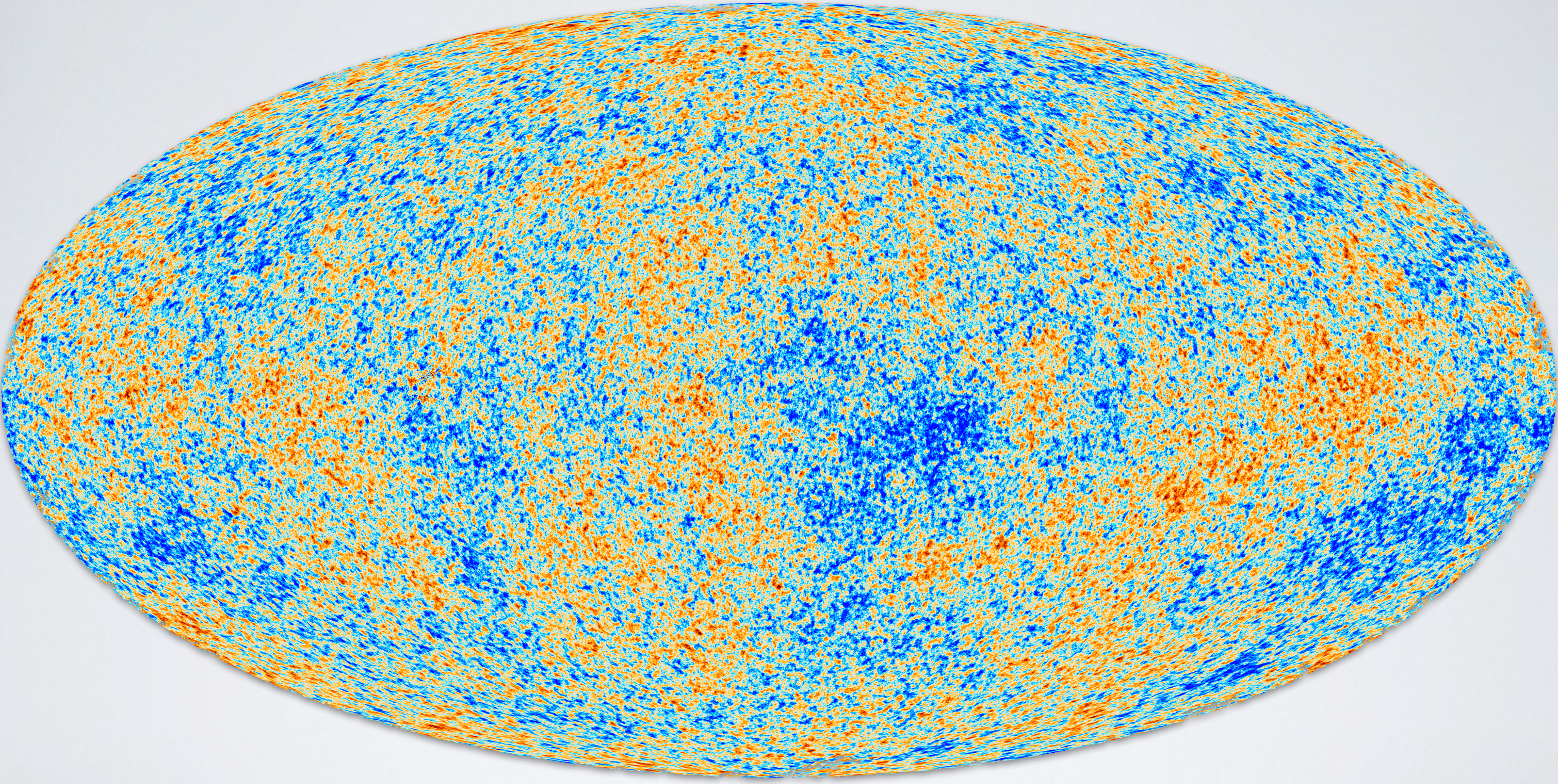
in the past: $z > 0$

$$a = \frac{1}{1+z}$$

$$z = \Delta\lambda/\lambda$$

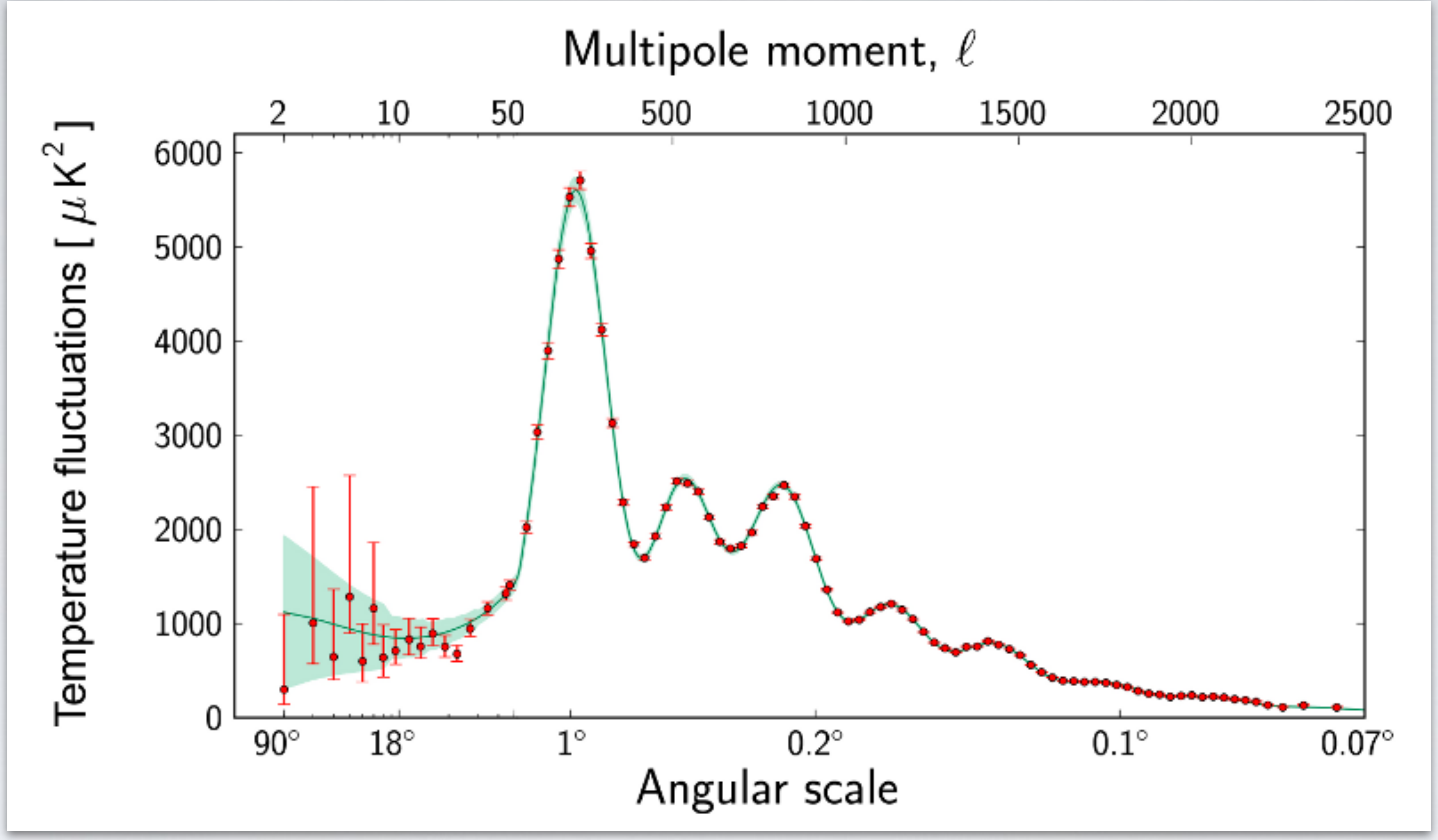
THE OLDEST PHOTONS

Cosmic Microwave Background: z = 1100, t~380,000 yrs, black body @T=2.73K



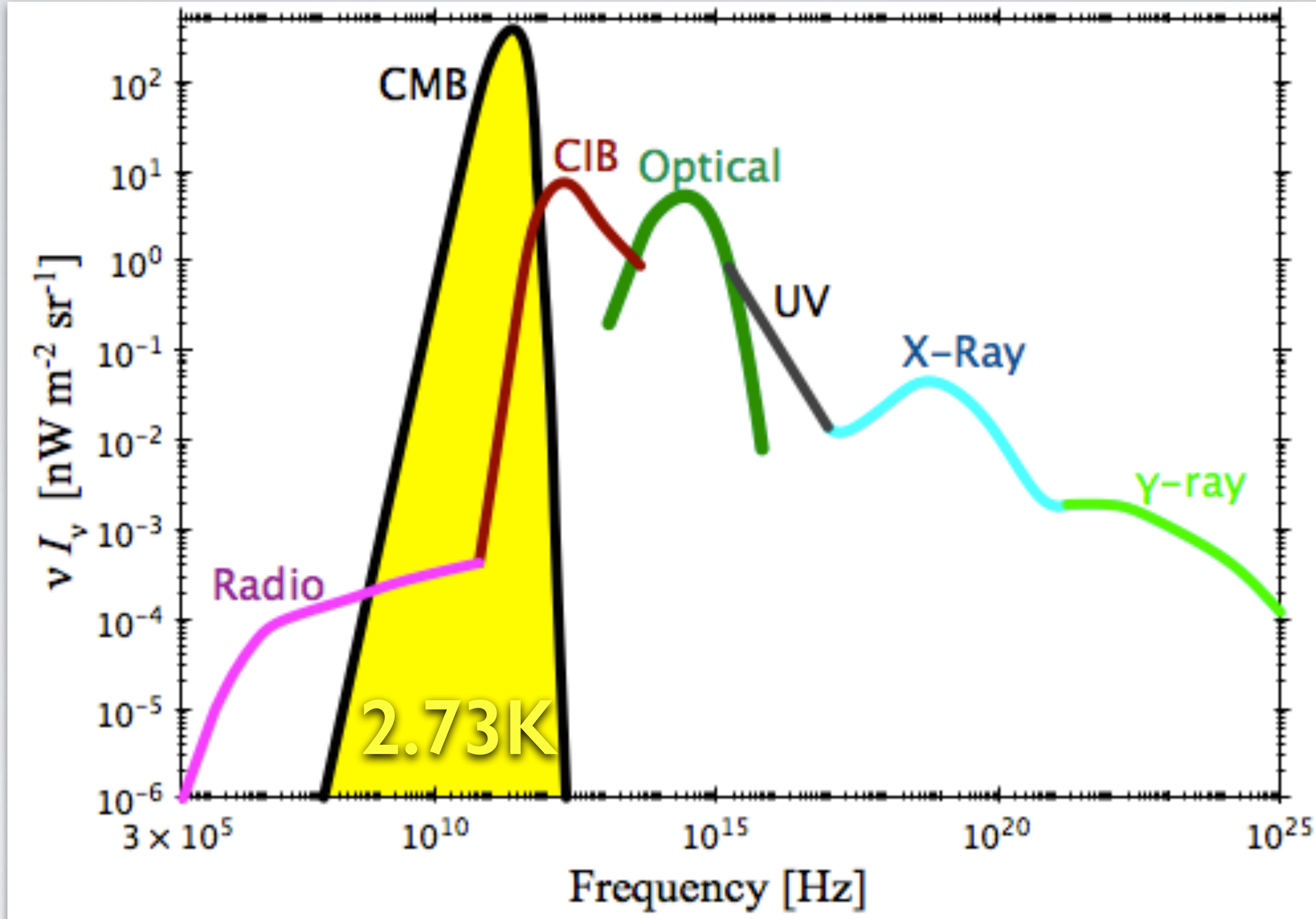
Planck CMB map

CMB ANGULAR SPECTRUM



First peak: mean free path of photons at z~1000

BACKGROUNDS



CMB: black body at 2.73K

What about backgrounds at higher-energies?

HIGH-ENERGY ASTROPARTICLES

HE photons are primarily generated via
charged particle acceleration

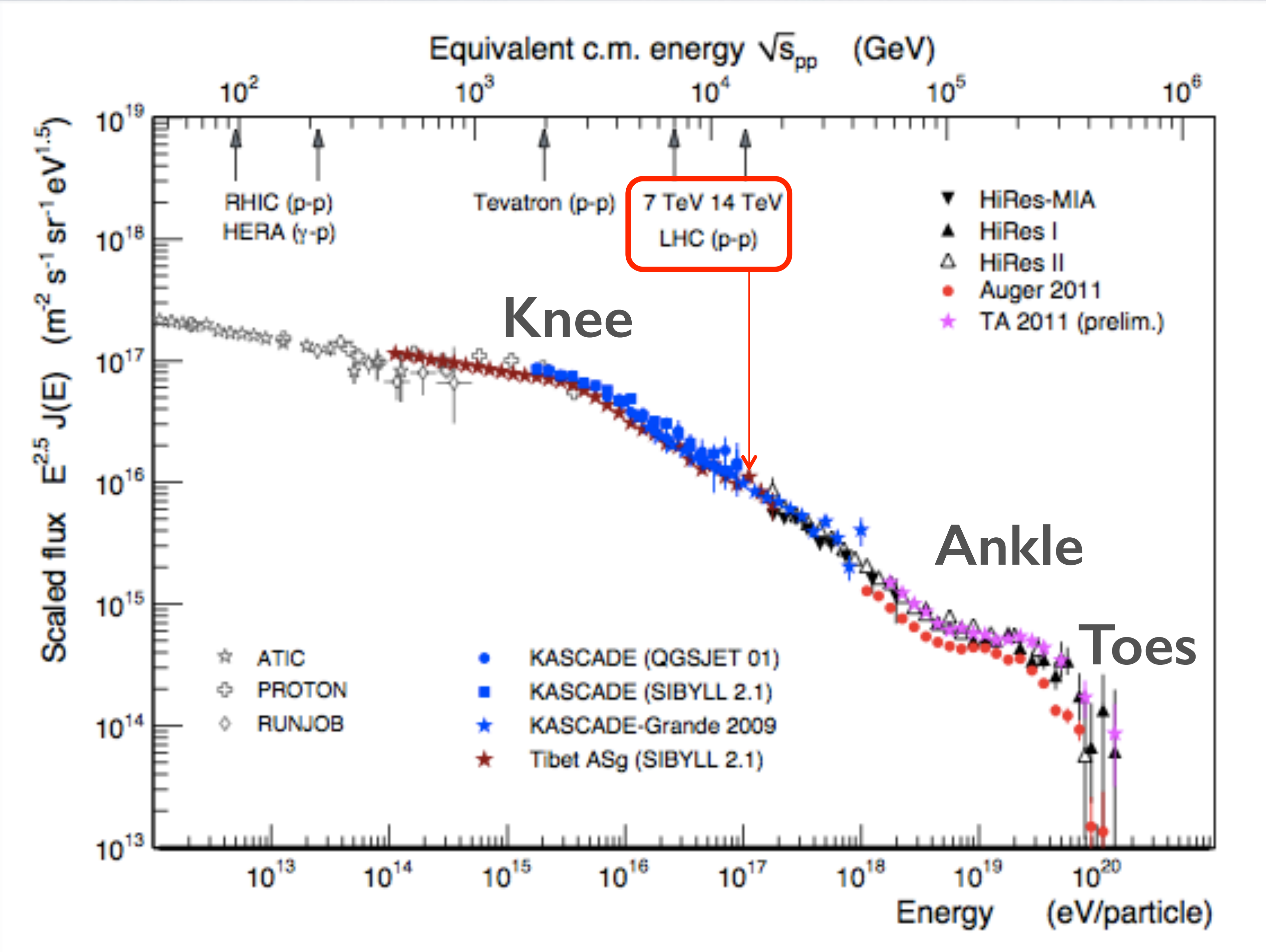
Cosmic Rays

HE charged particles reaching Earth's atmosphere:

~89% **protons**
~ 1% **electrons**
~10% **heavier nuclei** (mostly He)
very few: anti-particles, muons, pions

Energies: 10^8 to 10^{20} eV

COSMIC RAYS



Particle rates:

Knee:
$1/m^2/sec$

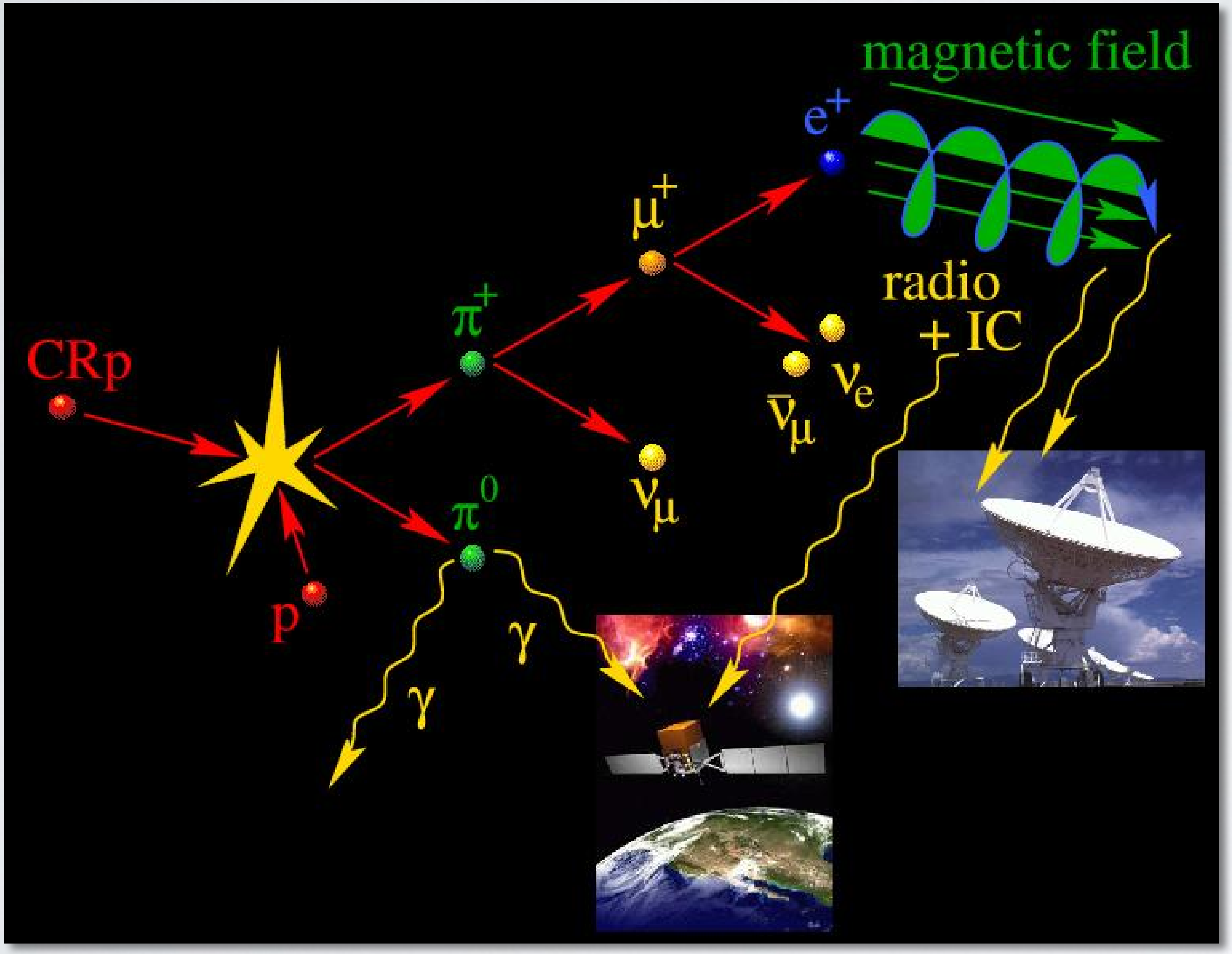
Ankle:
$1/m^2/yr$

Toes:
$1/km^2/century$

MAIN ACCELERATION MECHANISMS

Mechanism	Examples
Cyclotron	Sun
2nd order Fermi	Clouds in the Galaxy Solar winds
1st order Fermi (diffusive shock)	Supernova Remnants Active Galactic Nuclei Galaxy Clusters

DETECTION



Complementary approaches

photons

- gamma-ray
- x-ray
- radio

DETECTION

Complementary approaches

cosmic rays

GALAXY CLUSTER EXAMPLE

Abell 3376

redshfit: $z = 0.046$

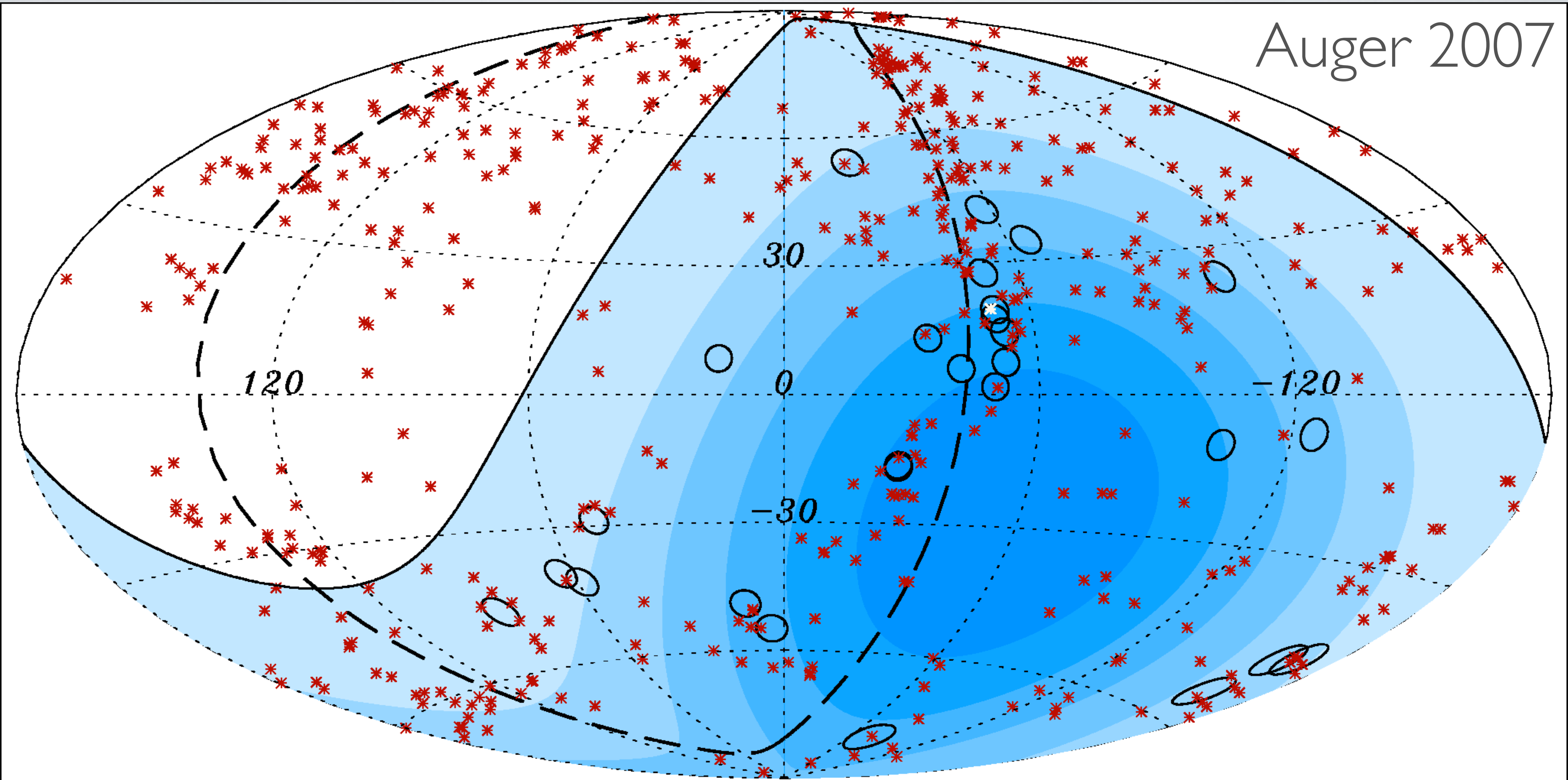
mass: $M = 5 \times 10^{14}$ solar masses

Merger of 2 smaller clusters.

Capable of accelerating cosmic rays!

X-ray
Radio
Optical

CR SOURCES?

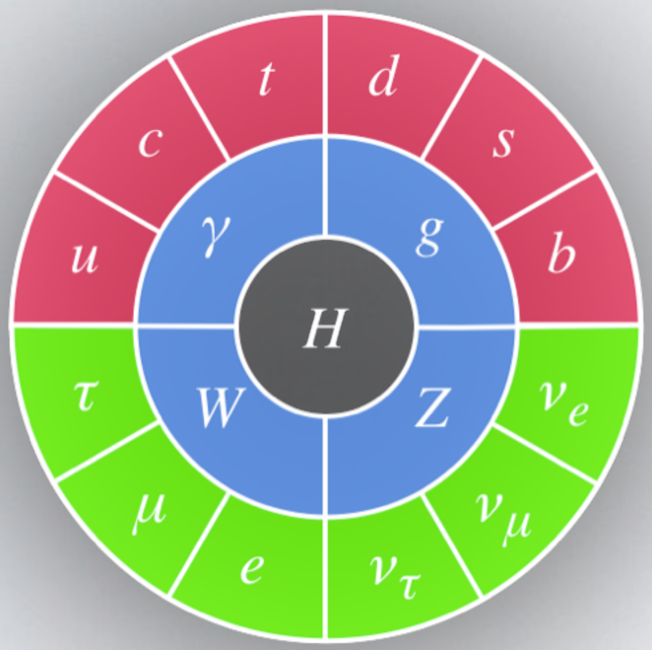


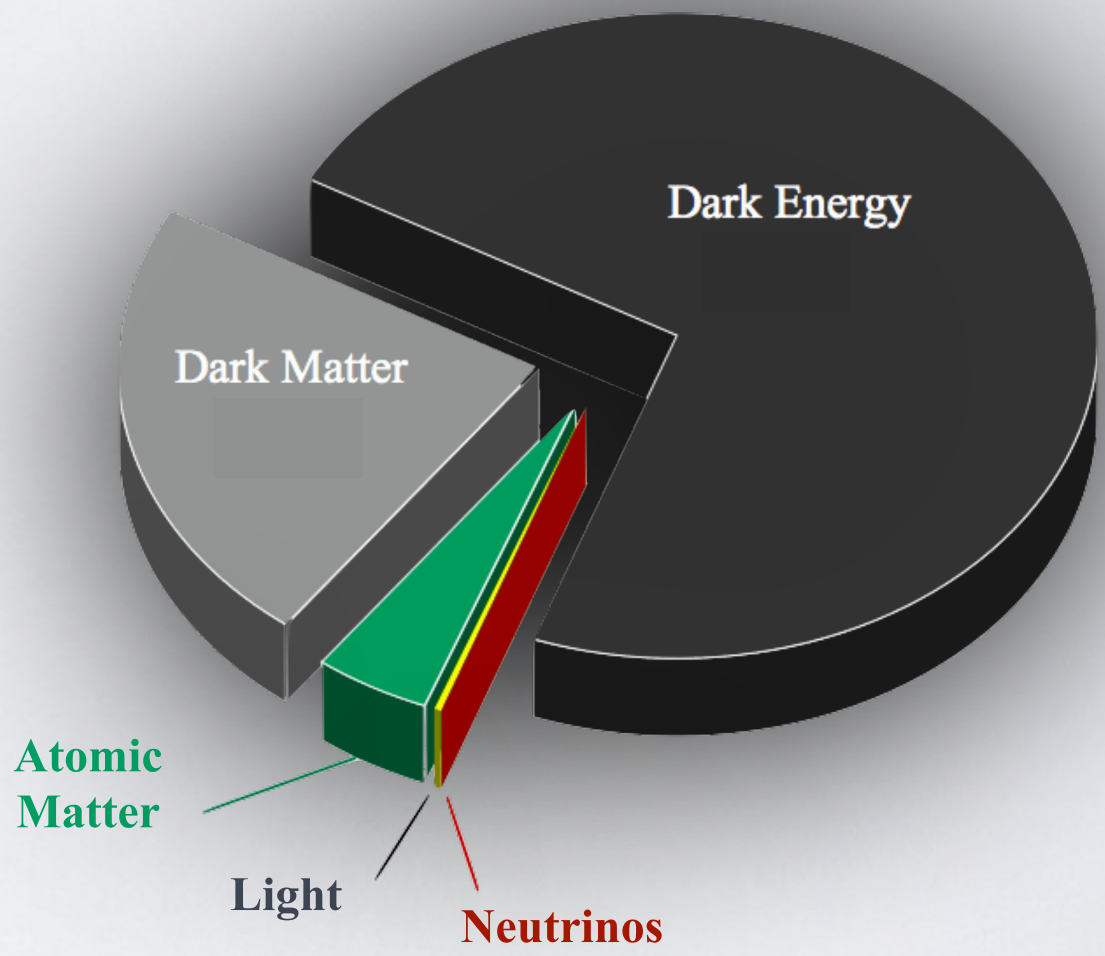
Black: CR events @ E > 60 EeV, Red: AGNs

THE 'DARK' SIDE

It is a great achievement of our research community that we can explain most of the history of the universe with the Standard Model.

That is just the beginning!



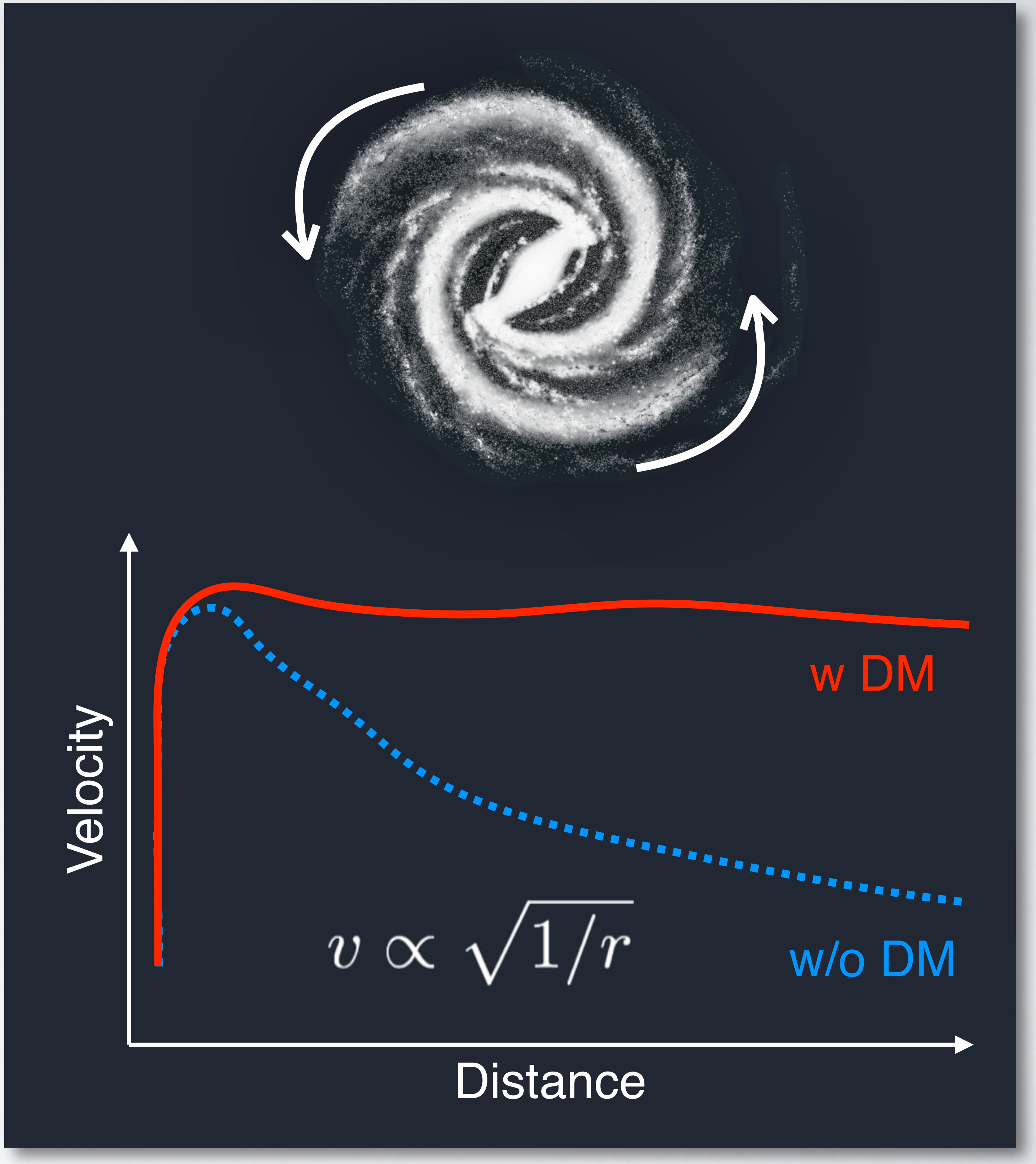


Dark Matter

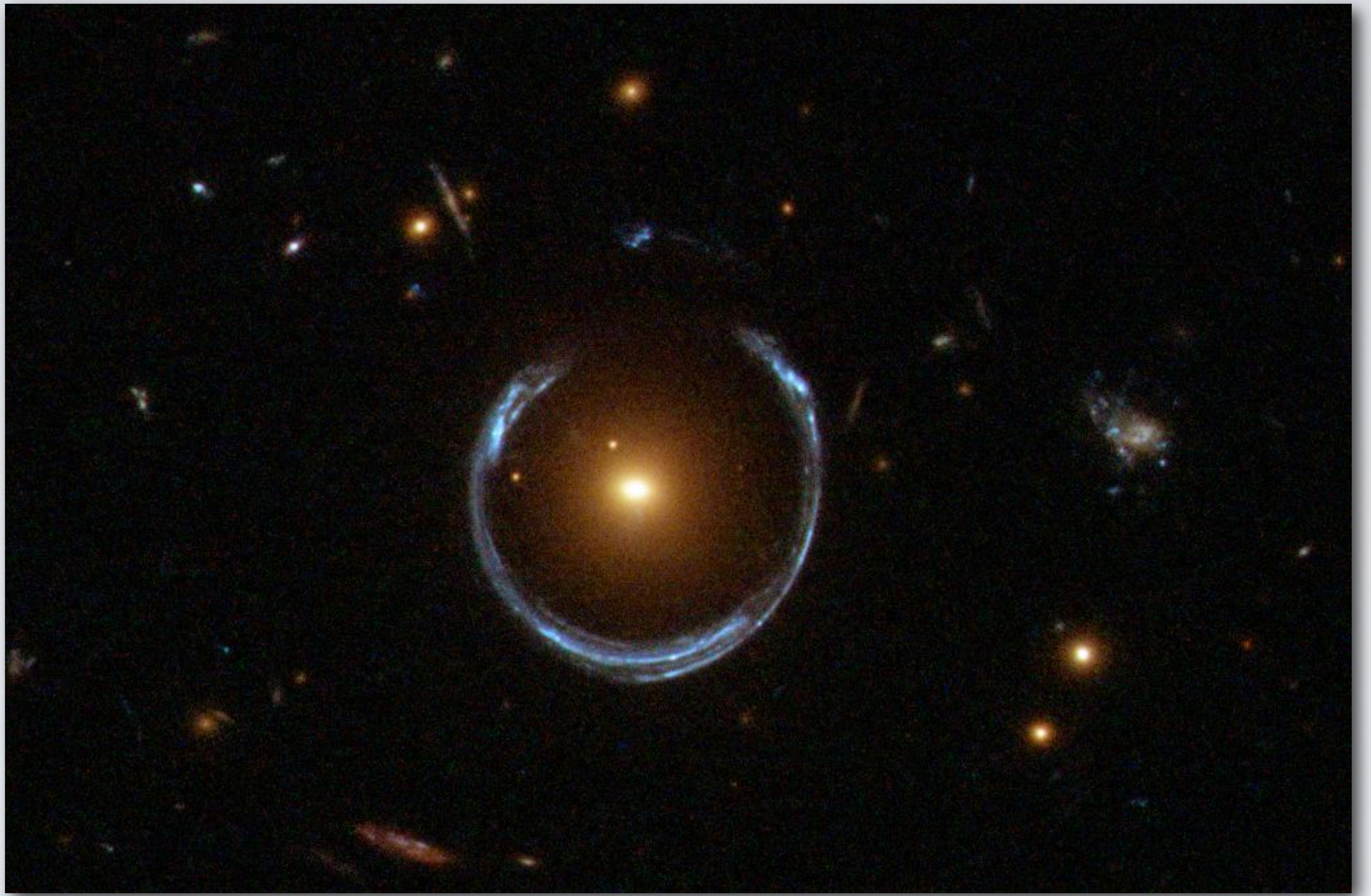
GALAXY ROTATION CURVES

Galaxies rotate faster than they should if luminous matter only is considered.

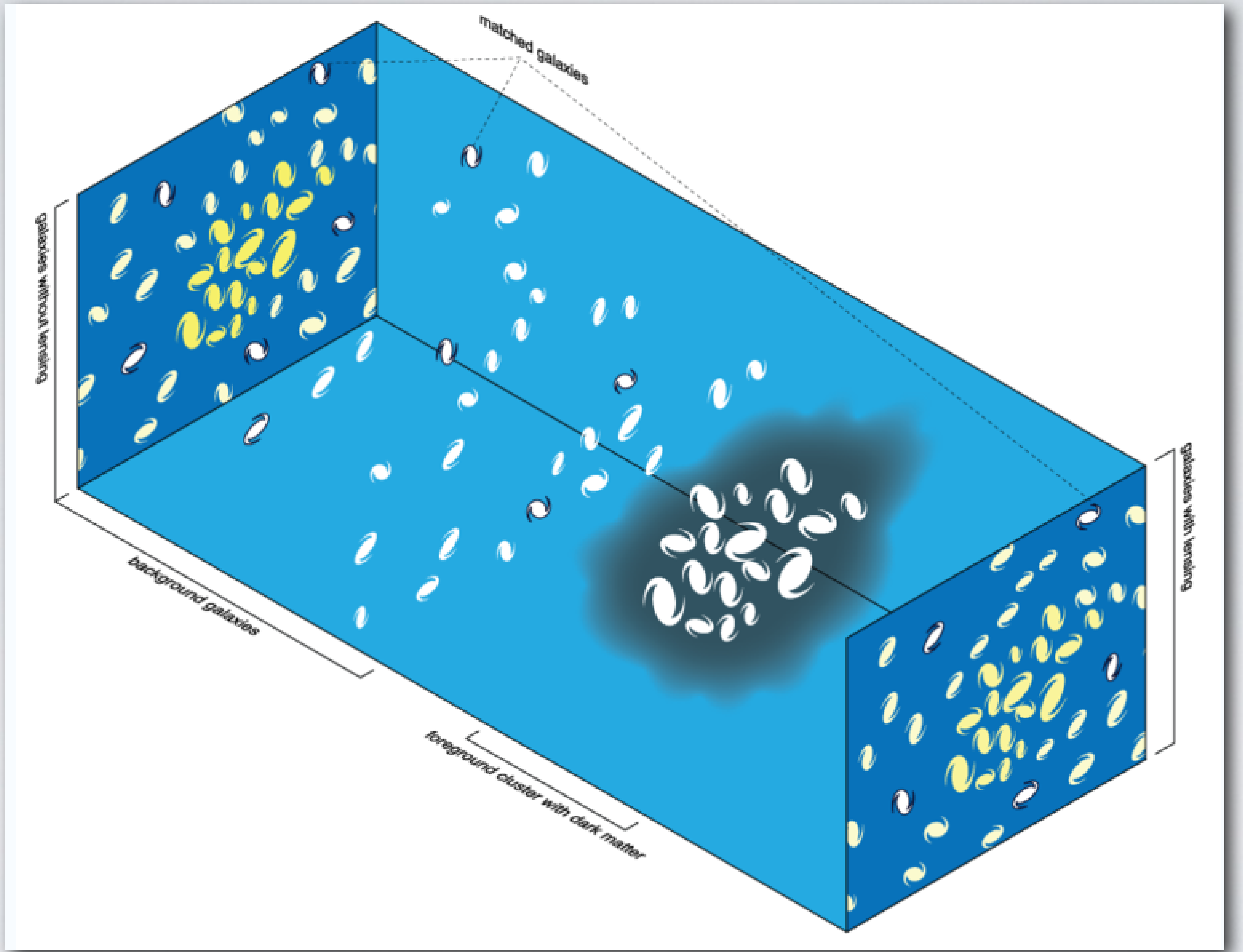
There must be a large amount of non-luminous matter in the galaxy, reaching far outside.



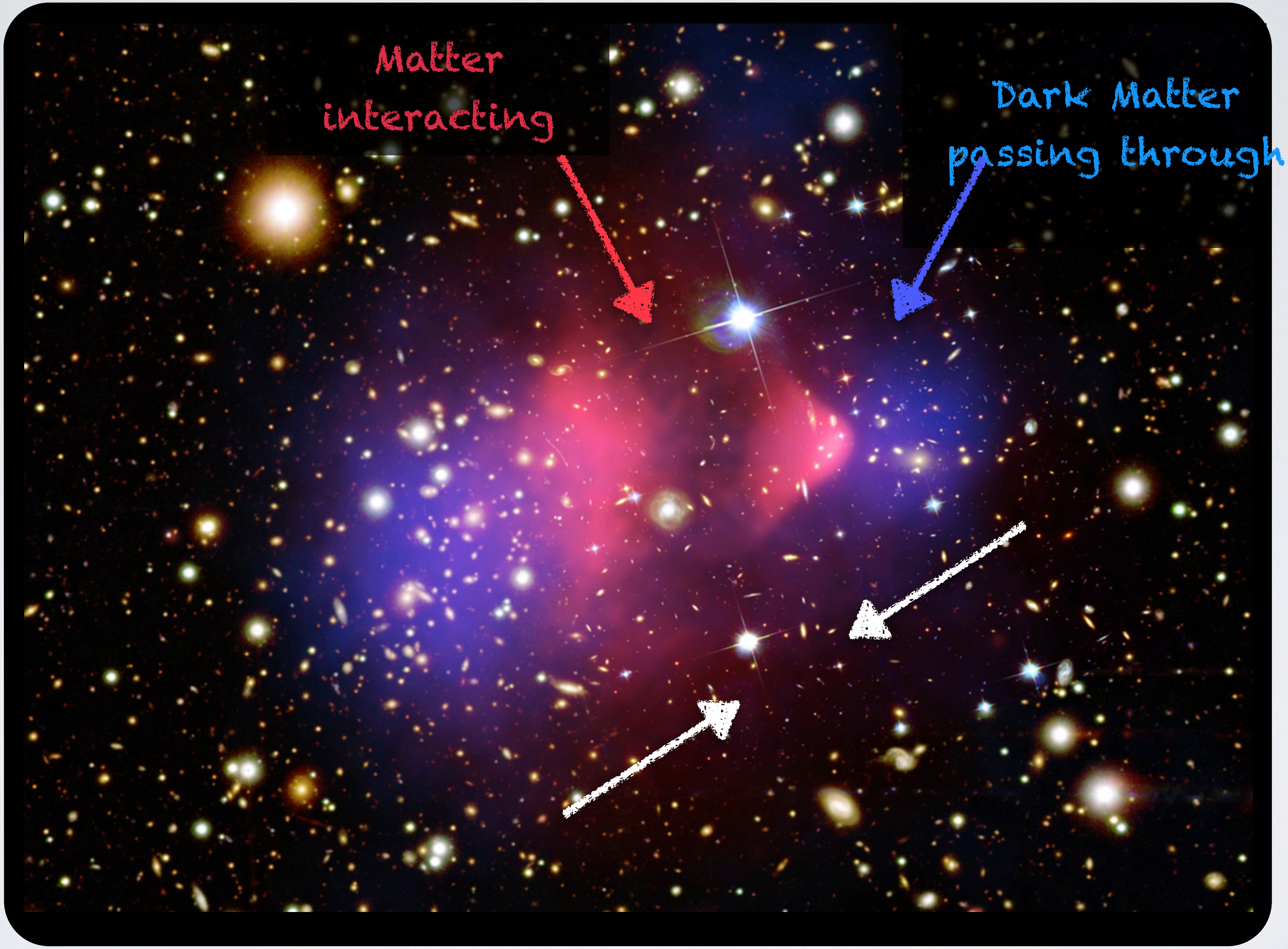
GRAVITATIONAL LENSING



GRAVITATIONAL LENSING

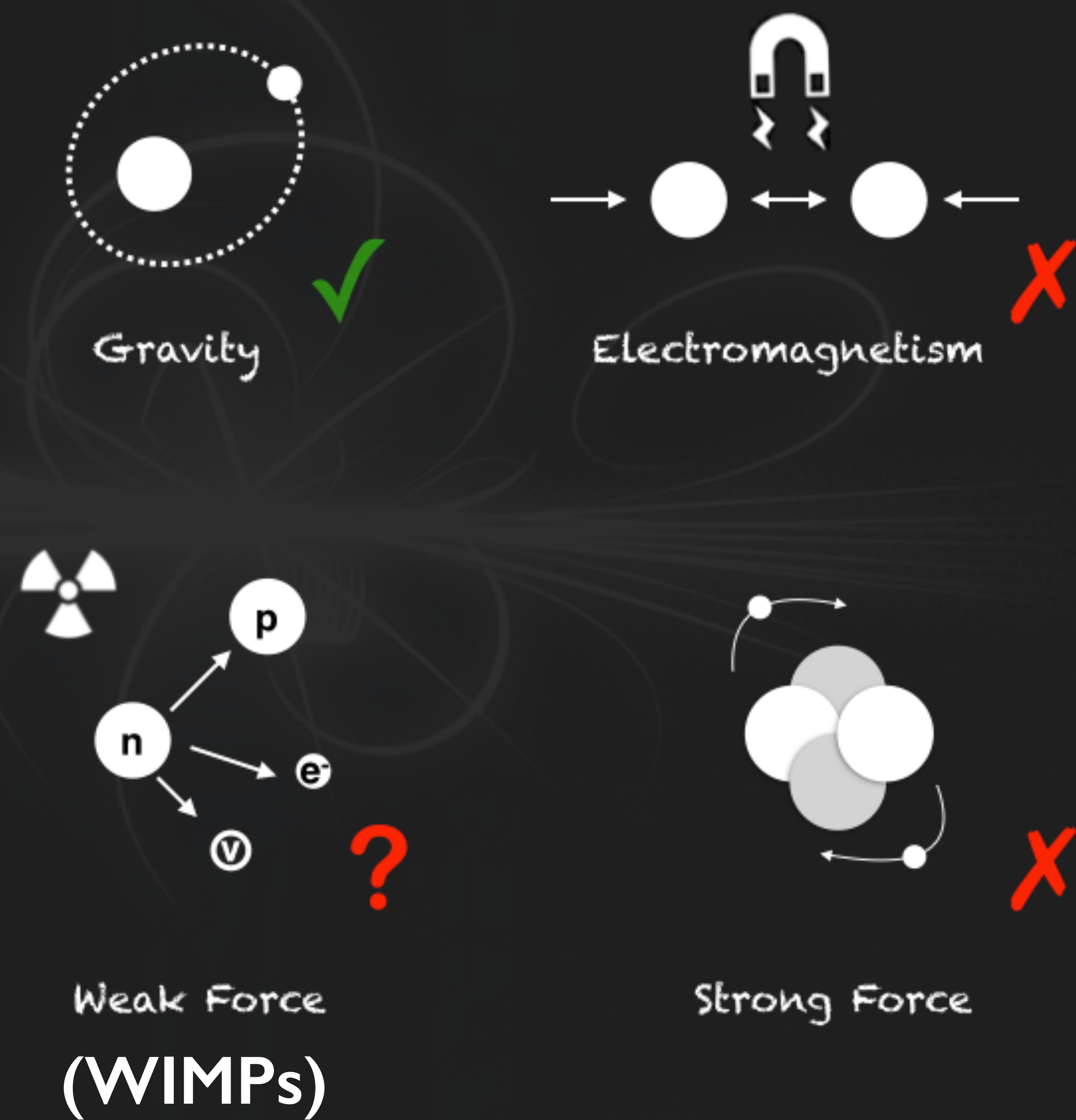


DM IN CLUSTERS

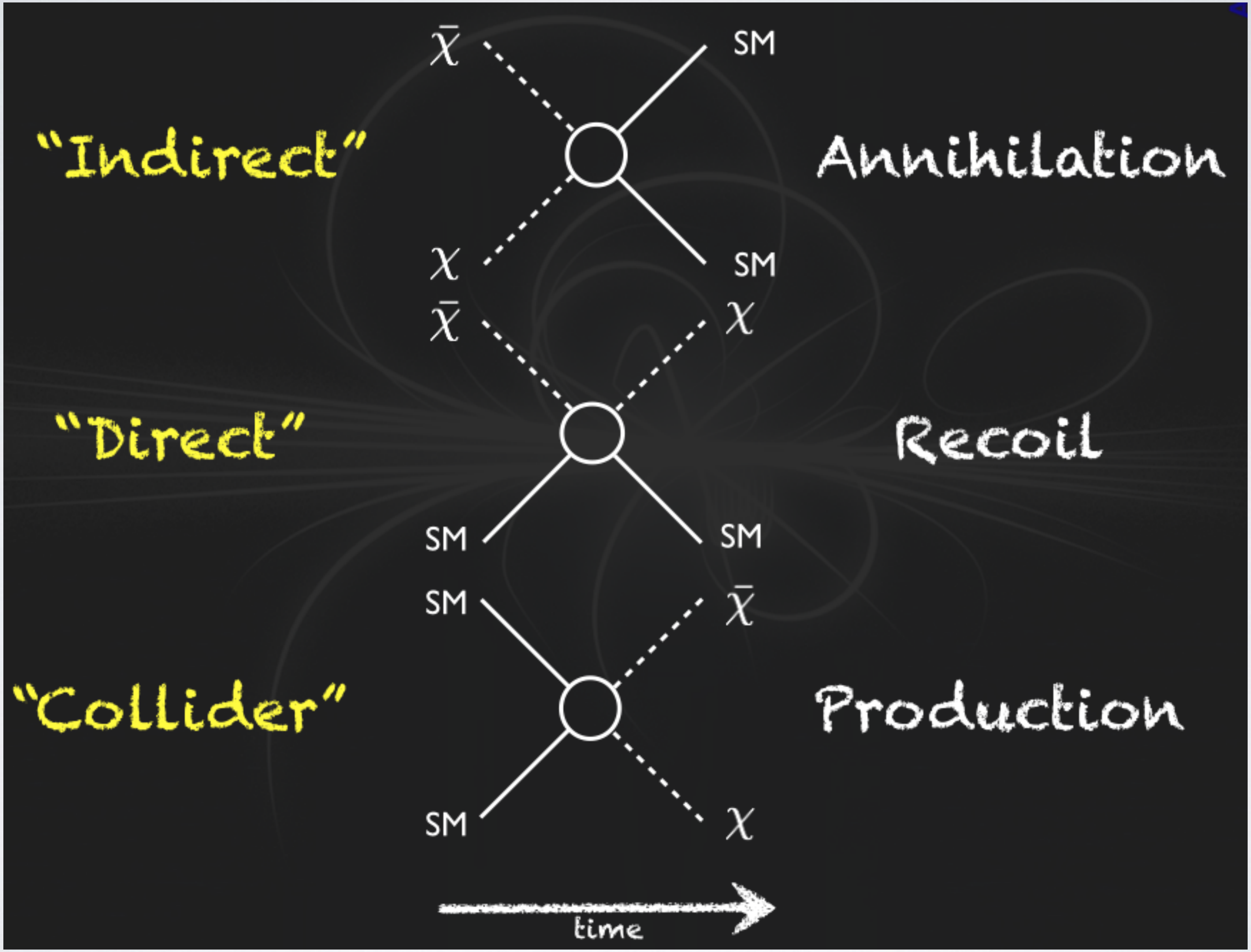


DM INTERACTIONS

- We know of four fundamental interactions
- Dark Matter does
  - interact gravitationally
  - not have any electromagnetic interaction
  - not interact via the strong force (not a baryon)
  - perhaps interact via the weak force but it is not the neutrino

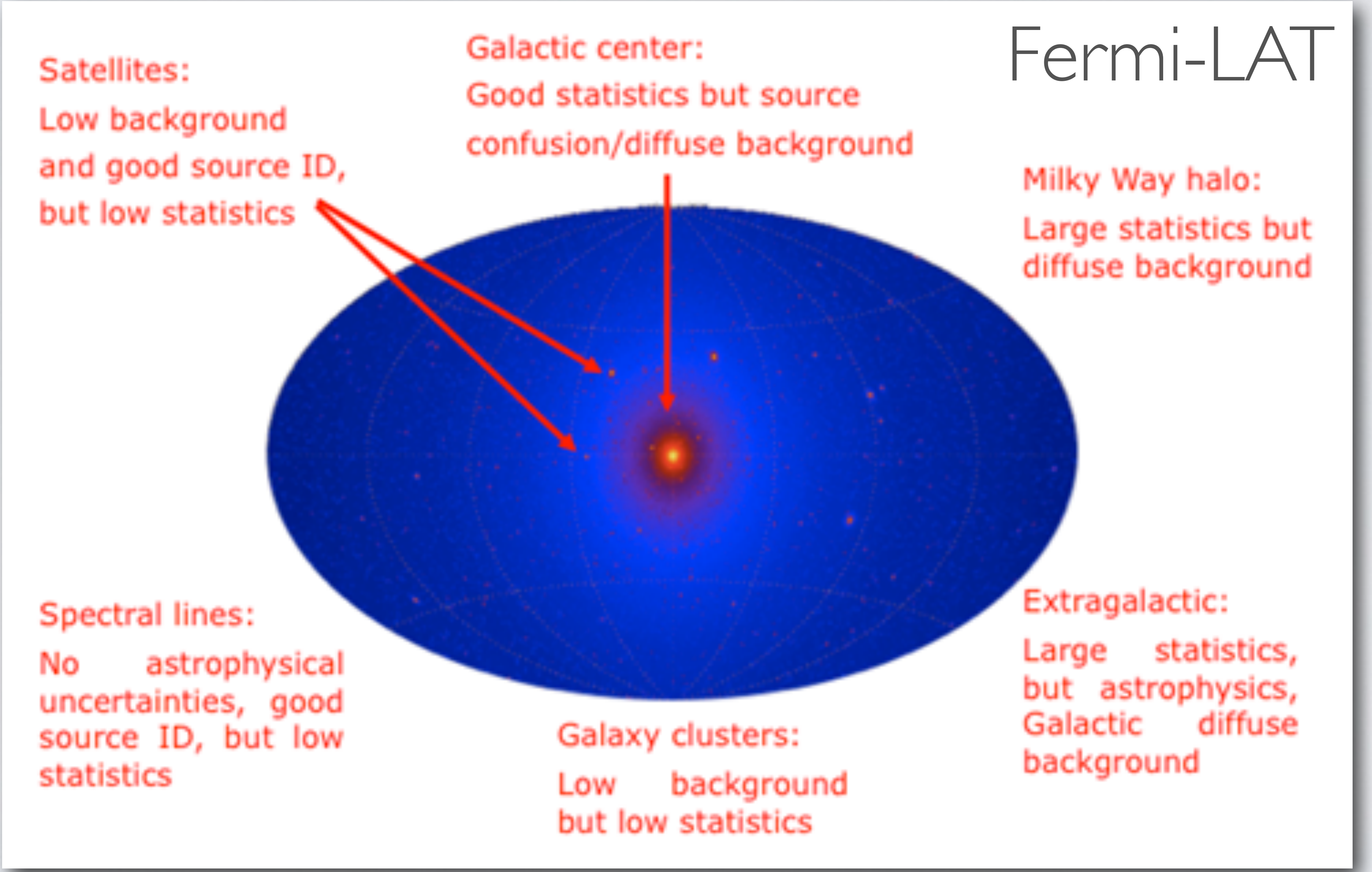


DETECTION APPROACHES



INDIRECT SEARCHES

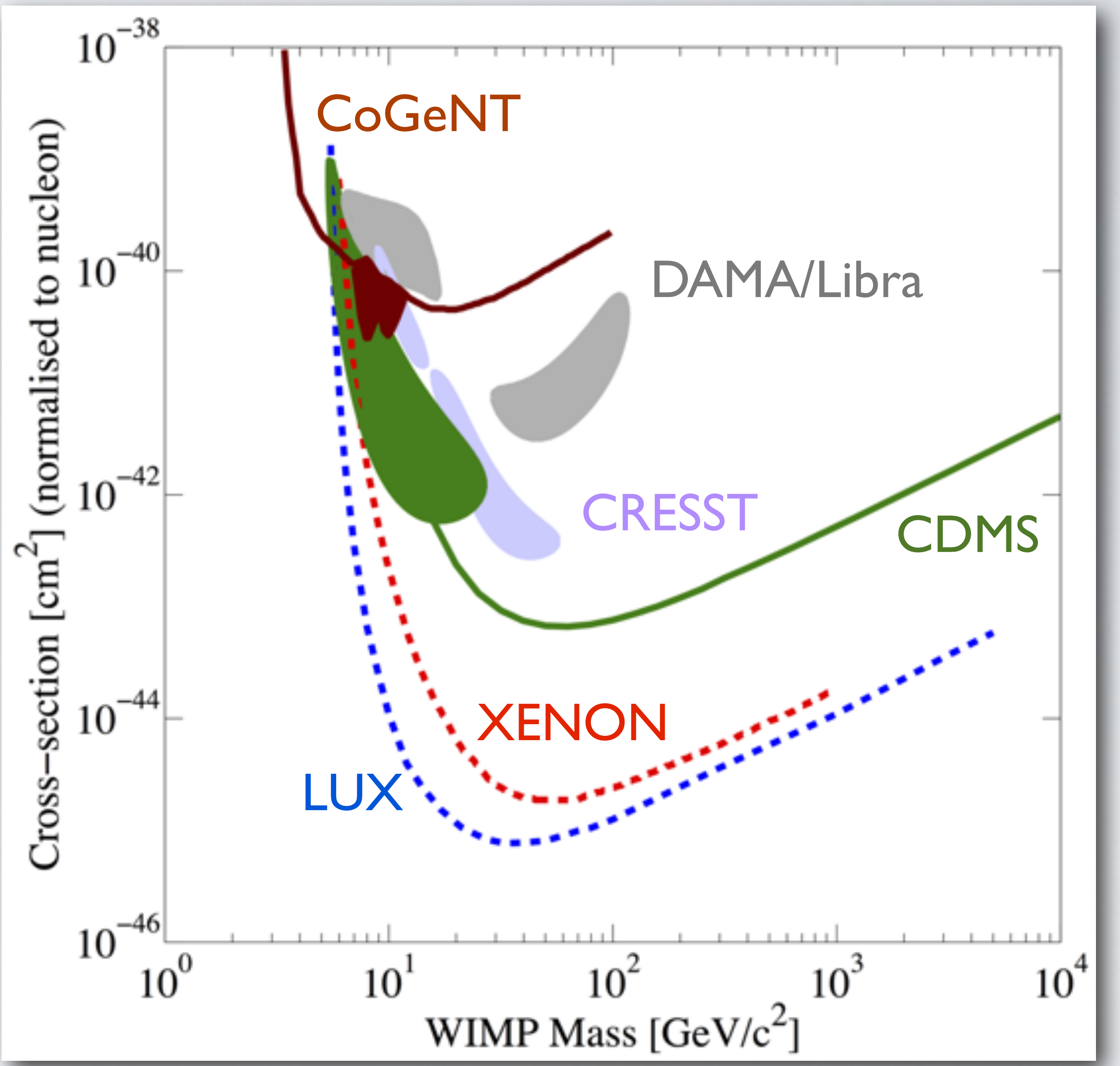
Focus on gamma-ray photons. If there is a signal can we distinguish it from the various other sources of HE photons?



DIRECT SEARCHES

Focus on detecting nuclear recoils. It is hard to detect low-mass candidates.

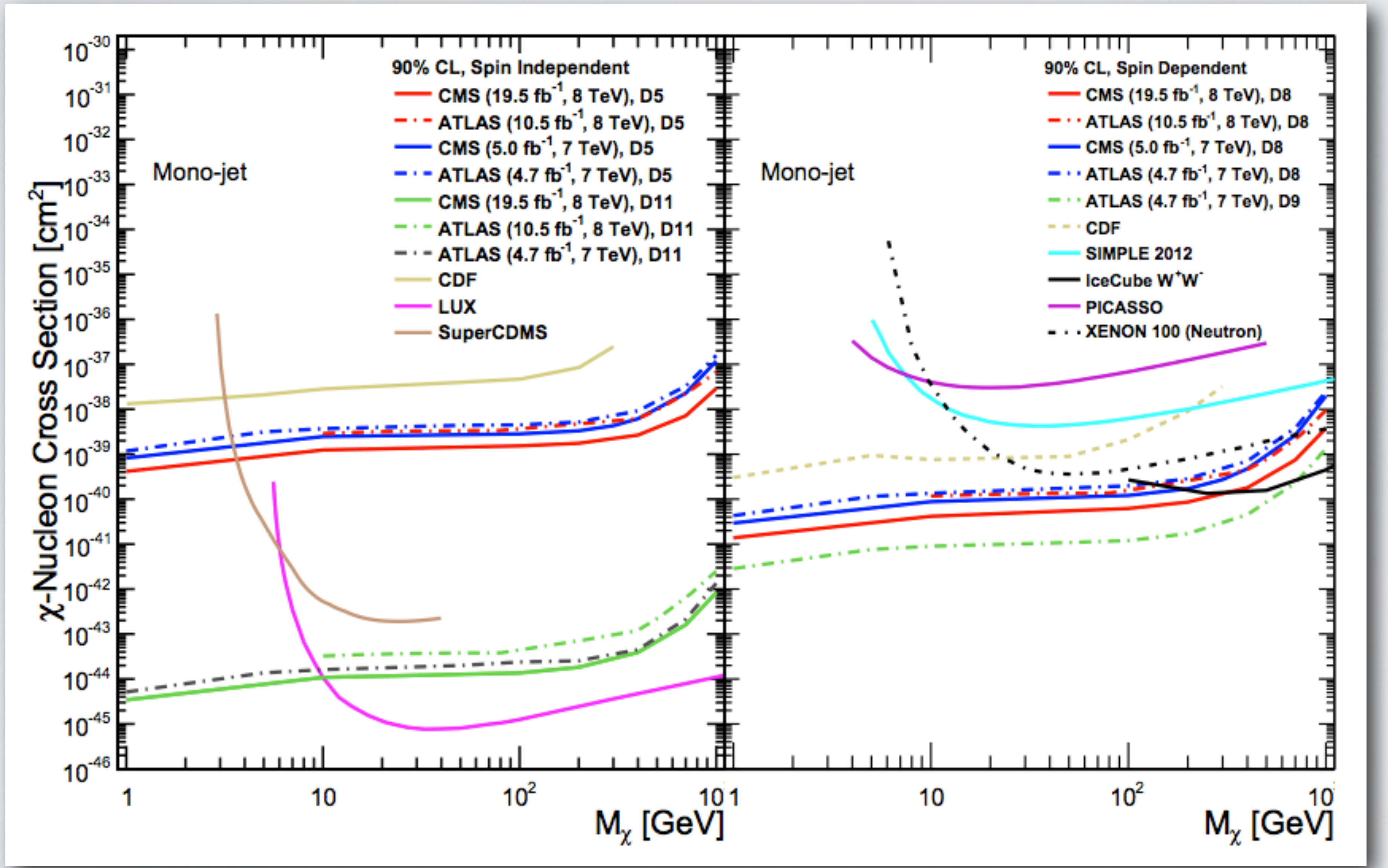
Backgrounds need to be minimized by going underground.



COLLIDER SEARCHES

DM should be produced at colliders in pairs (mediating particle not directly observed).

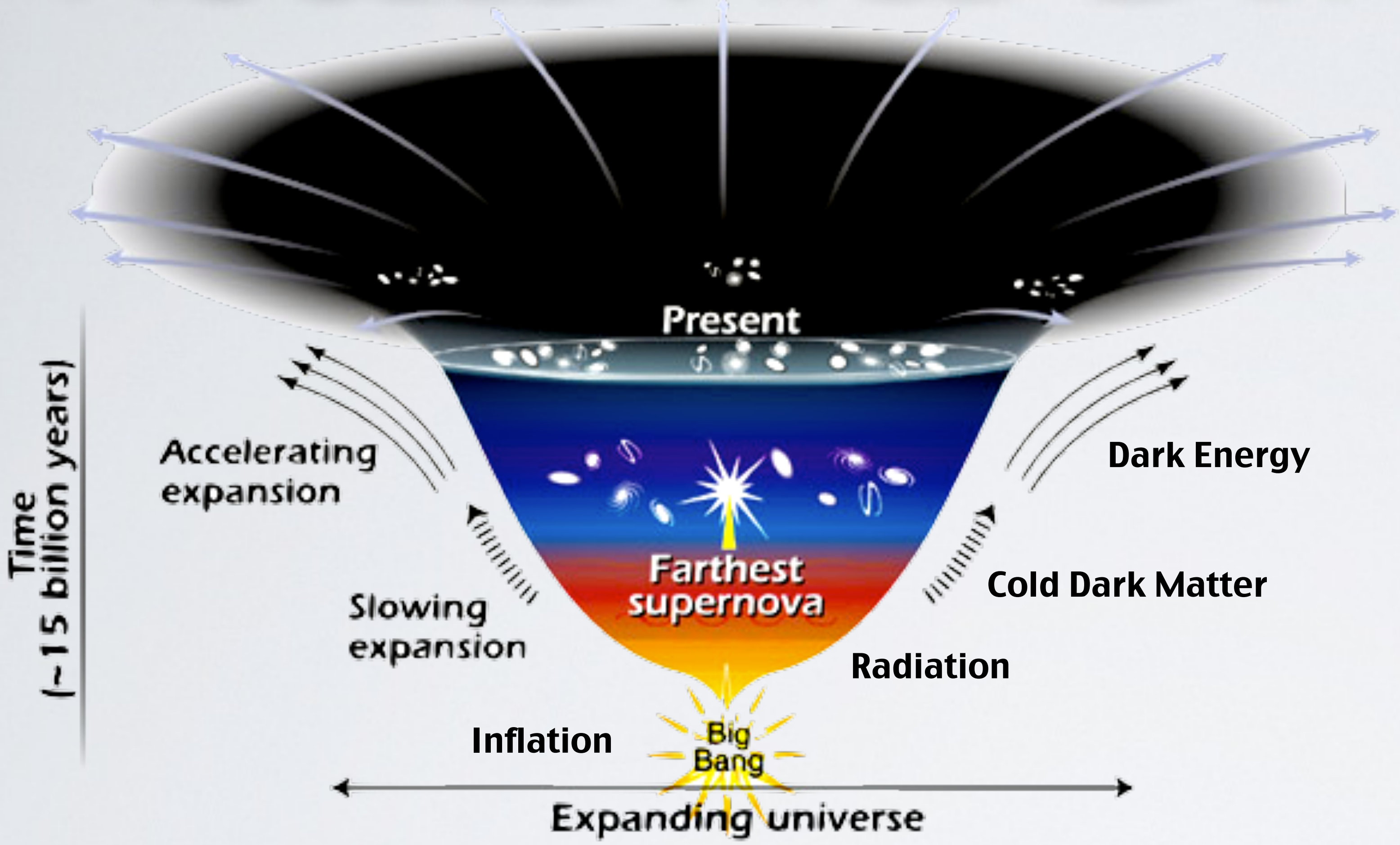
Sensitive to spin-dependent and independent DM and low masses.



arXiv:1406.5662

Dark Energy

DARK ENERGY & ACCELERATED EXPANSION



$$\ddot{a}/a = -(3p + \rho)$$

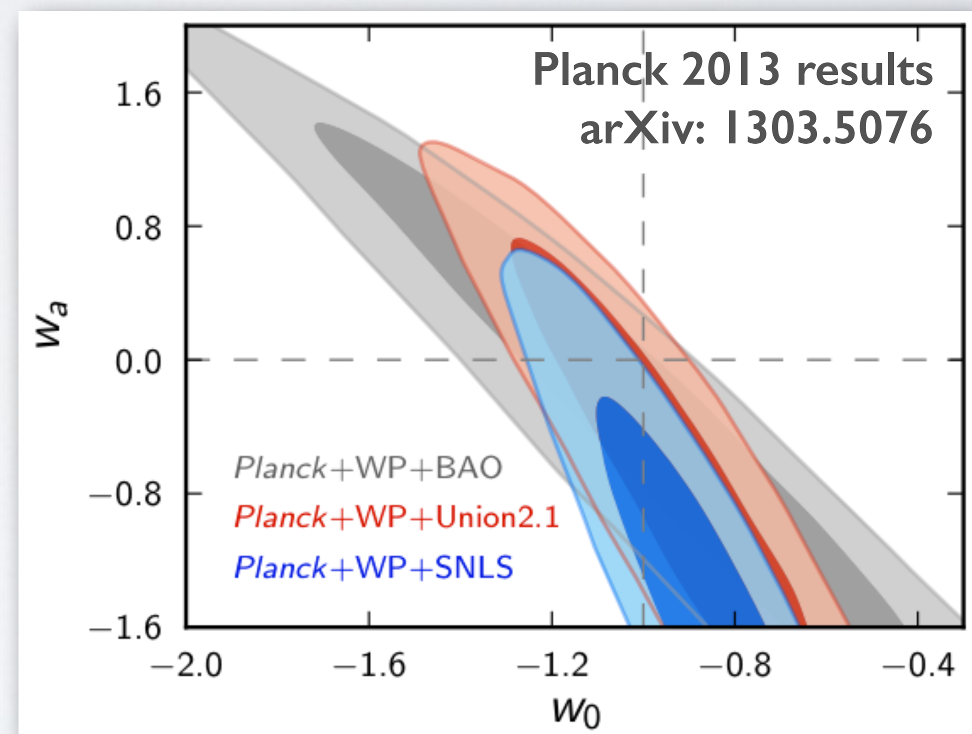
spacetime geometry (scale factor) — **energy content (equation of state)**

$$p = w(a)\rho$$

$$w(a) = w_0 + w_a(1 - a) + \cdots$$

Dark Energy candidate:
Cosmological Constant (Λ)

$$w = -1$$

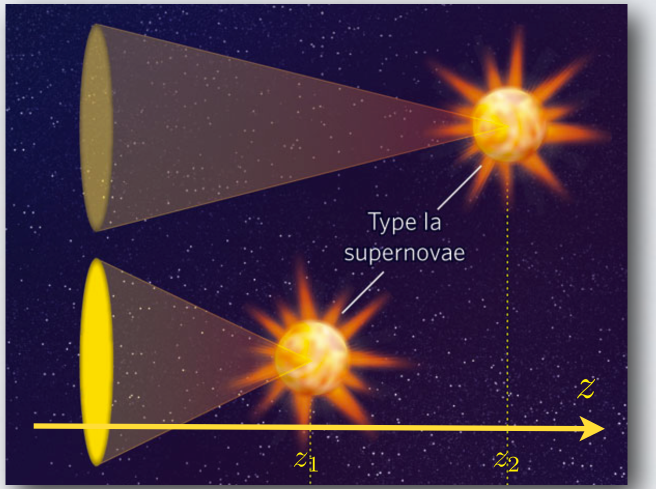


ASTROPHYSICAL OBSERVABLES

$D_L(z)$ Luminosity distance:

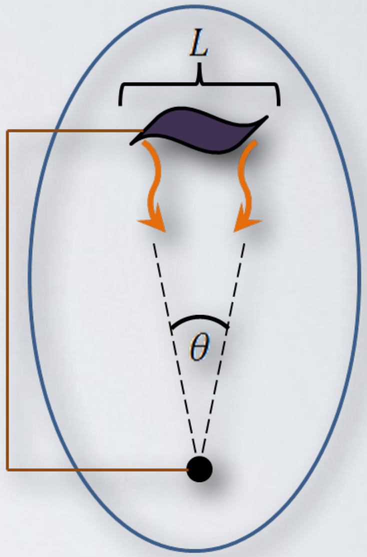
standard candle

1. supernovae (SNe)



$D_A(z)$ Angular diameter distance: **standard ruler**

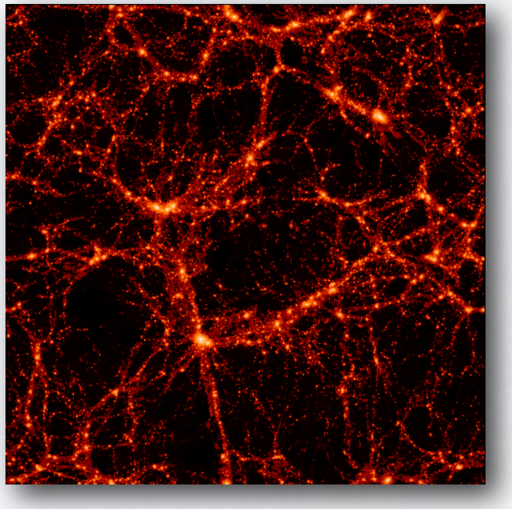
2. baryon acoustic oscillations (BAO) , cosmic microwave background (CMB)
3. weak gravitational lensing (WL)
4. galaxy cluster abundance (Clusters)



$G(\rho, z)$ Growth of structure:

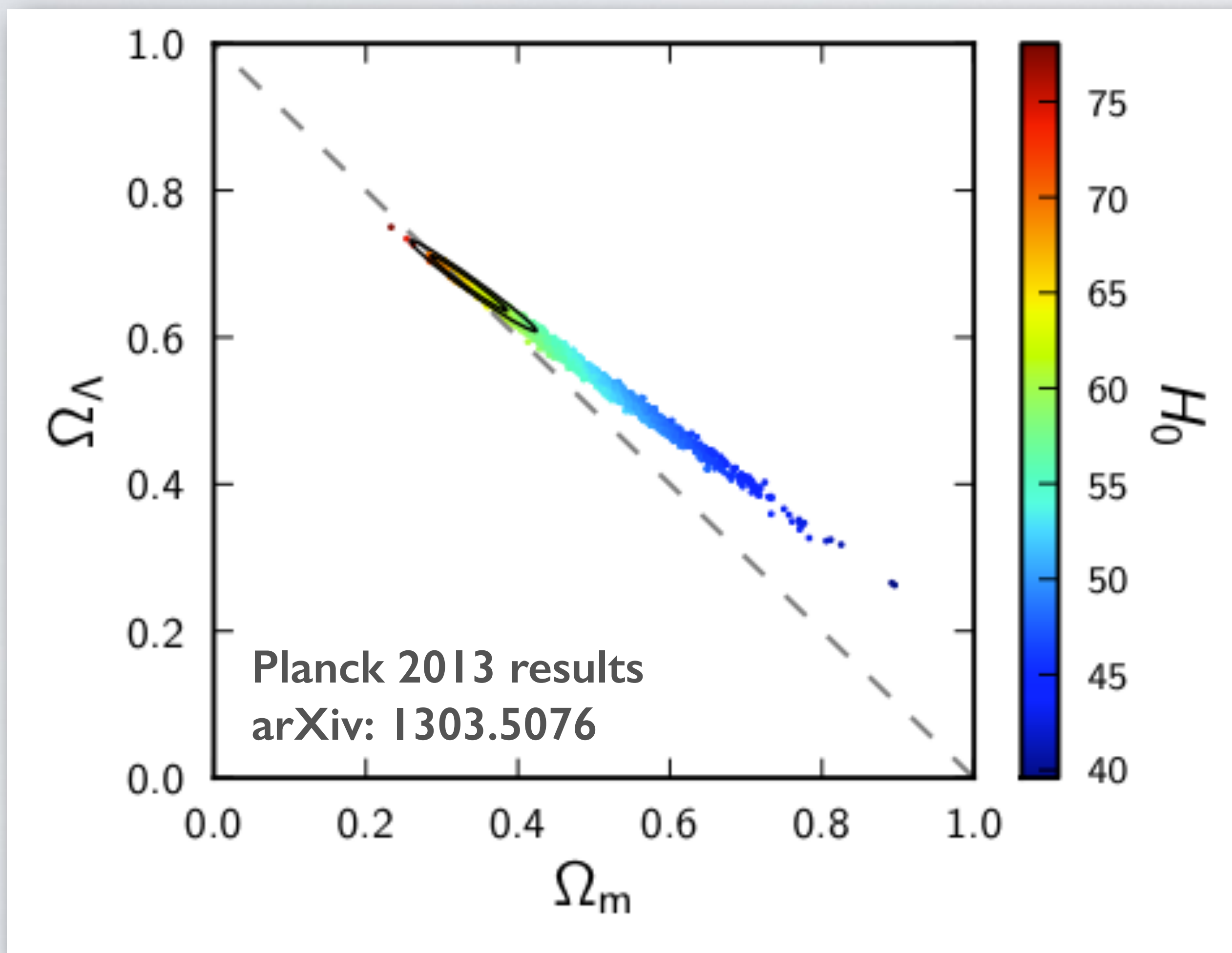
galaxy clustering

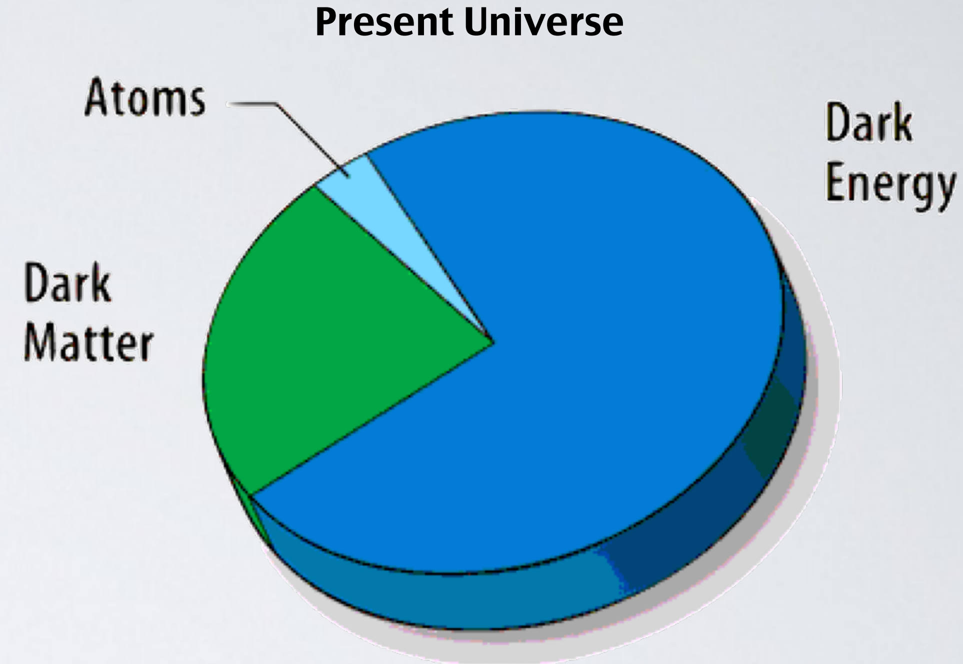
Clusters, WL



DOMINANCE OF NEW PHYSICS

2/3 of today's Universe is Dark Energy
(most of the remaining 1/3 is Dark Matter)





$$\Omega_m \simeq 1/3$$

$$\Omega_\Lambda \simeq 2/3$$

$H_0 \longrightarrow$ **Current expansion rate**

$$h \equiv H_0/100$$

BASIC OBSERVABLES

Positions on the sky (RA, Dec)

correct for distortions

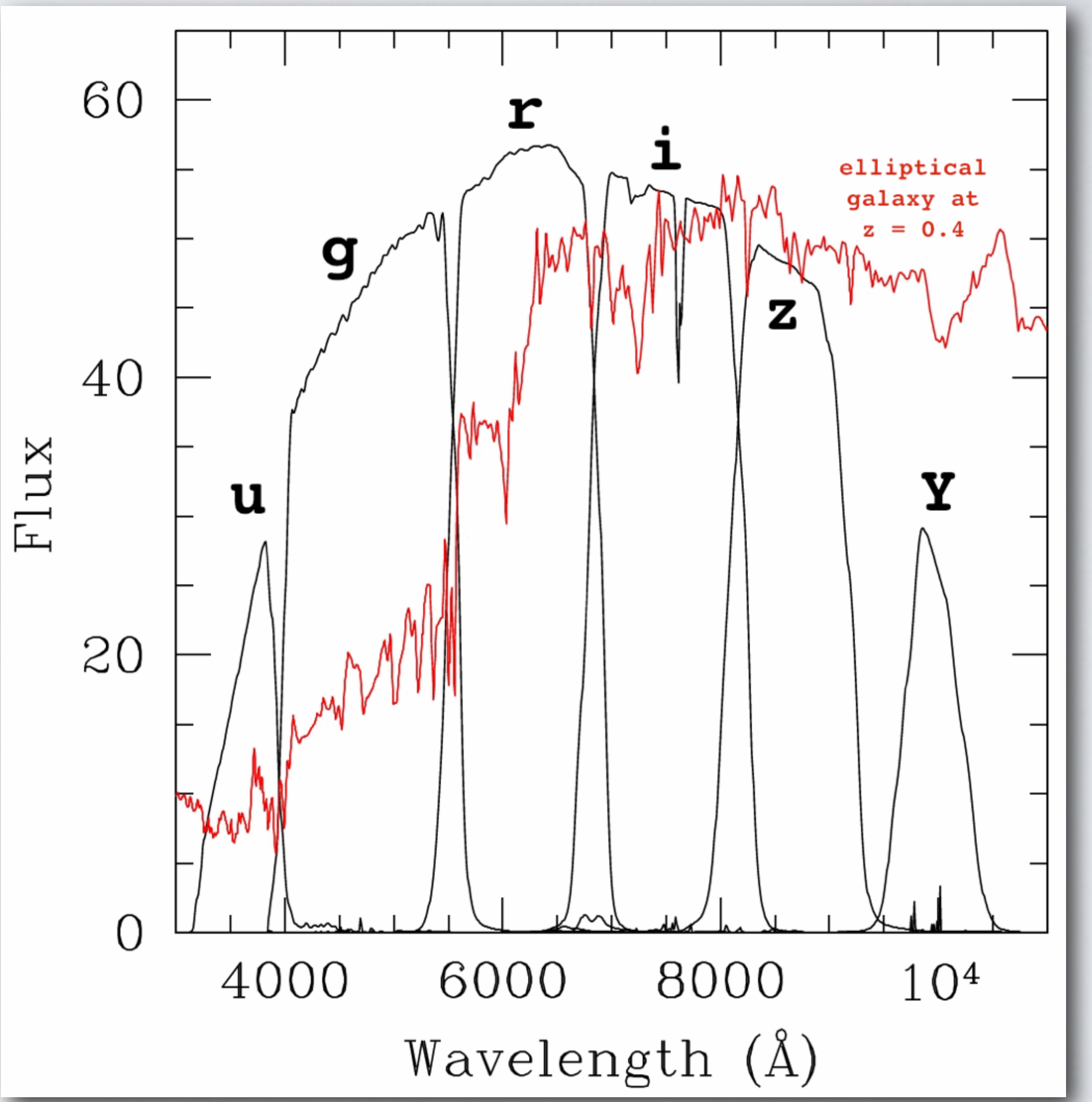
Fluxes (counts/pix/sec)

calibrate from instrumental units to physical units

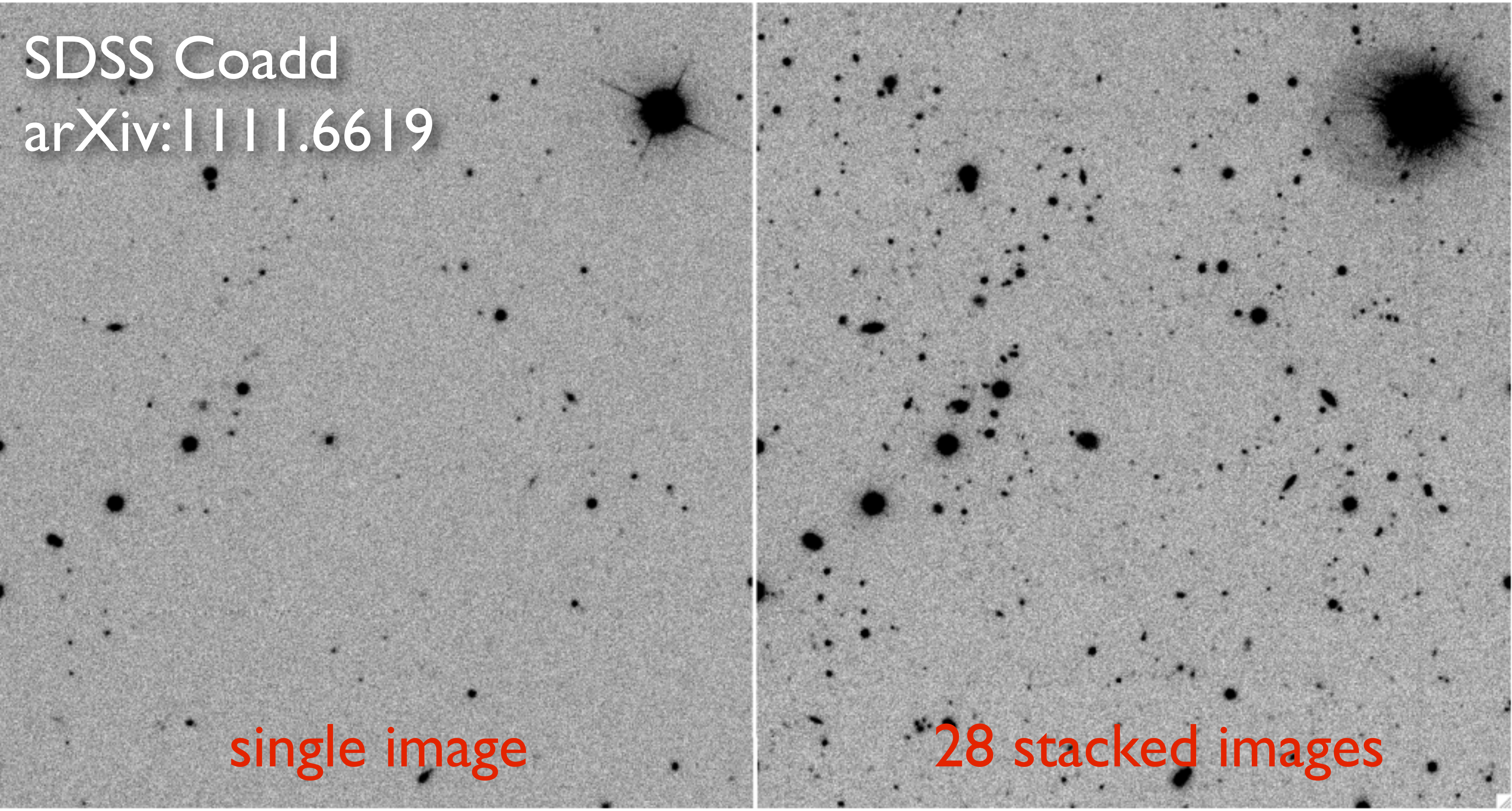
get colors from different **filters** and compute photometric redshifts

Shapes (ellipticity, size)

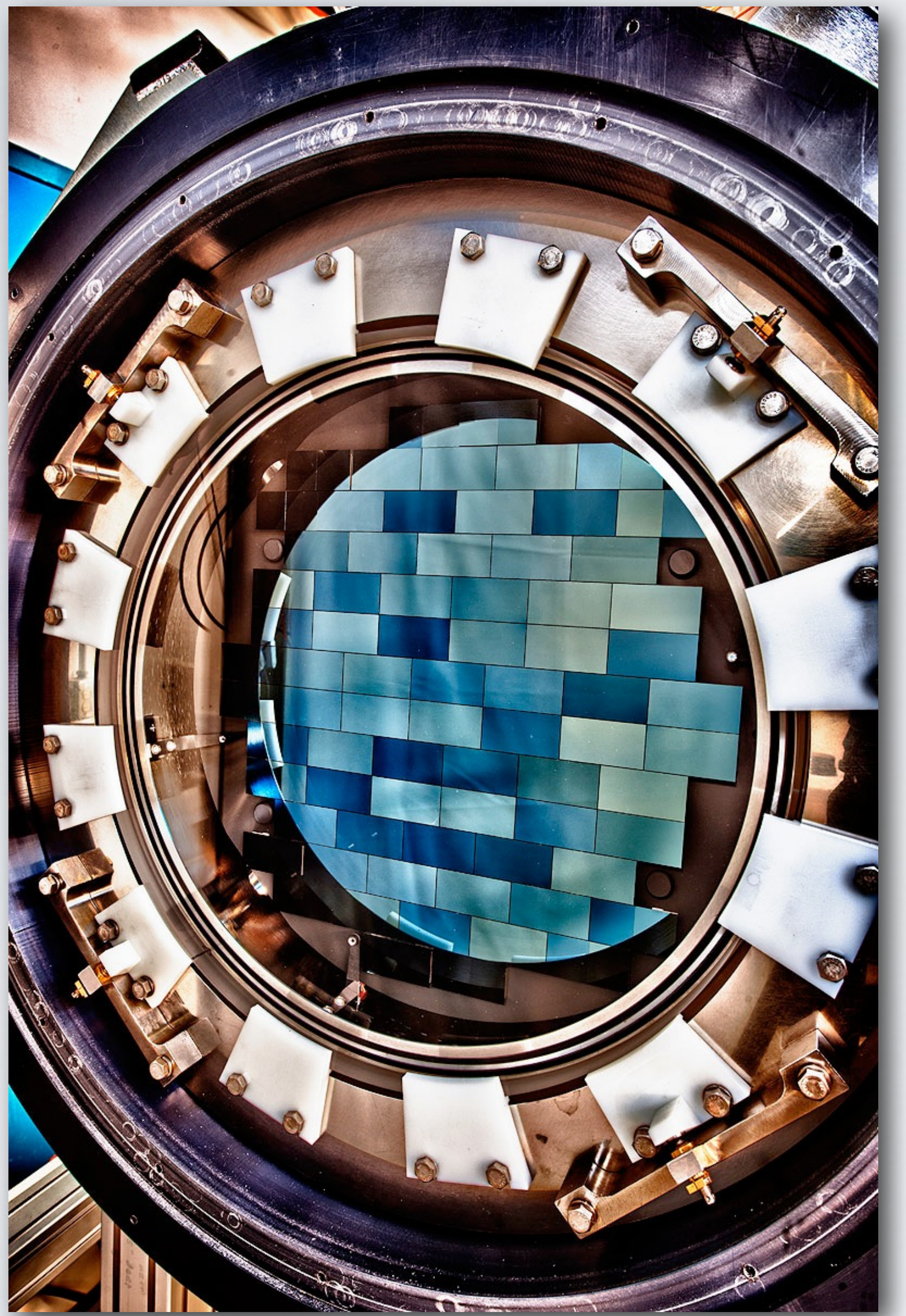
correct for distortions

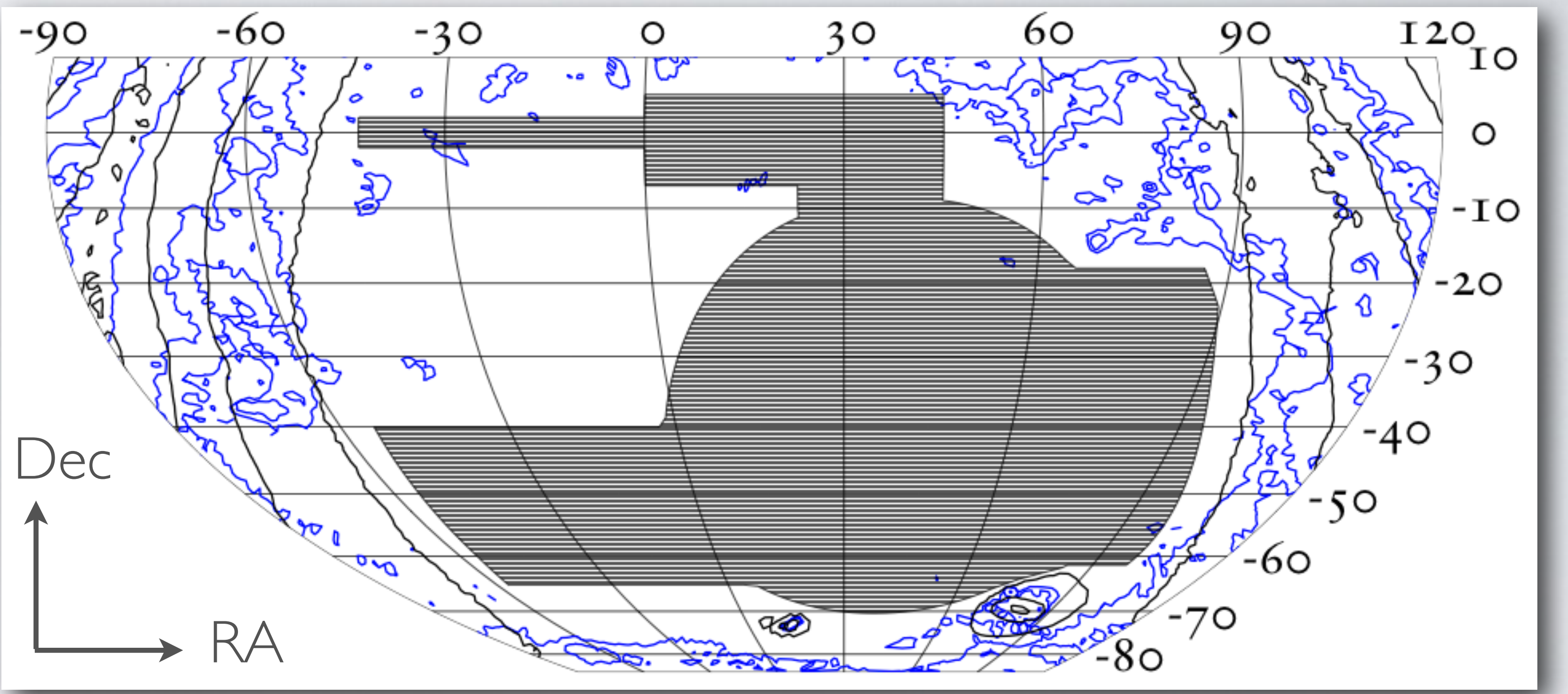


FAINT OBJECTS



DARK ENERGY SURVEY





DEcam

3 sq deg FOV, **570 Mpix** optical CCD camera

Facility instrument at **CTIO Blanco 4-m telescope in Chile**

First light: Sep 2012

Survey

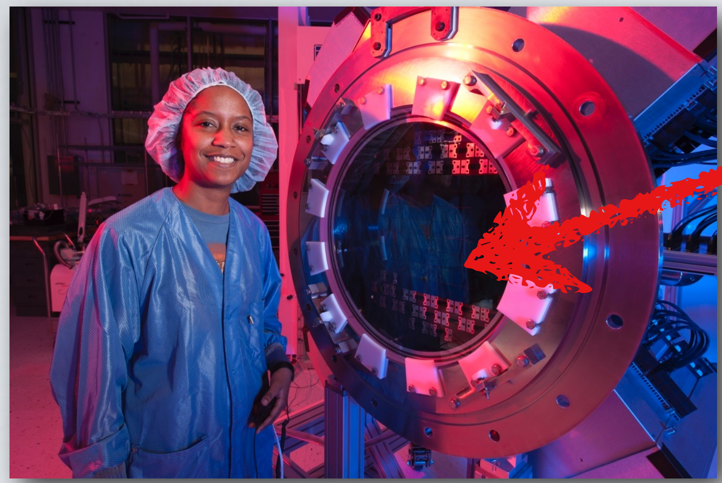
5000 sq deg grizY to **24th mag** overlaping with SPT and VISTA

30 sq deg SNe survey **0.9 arcseconds seeing**

525 nights: 2013-2018

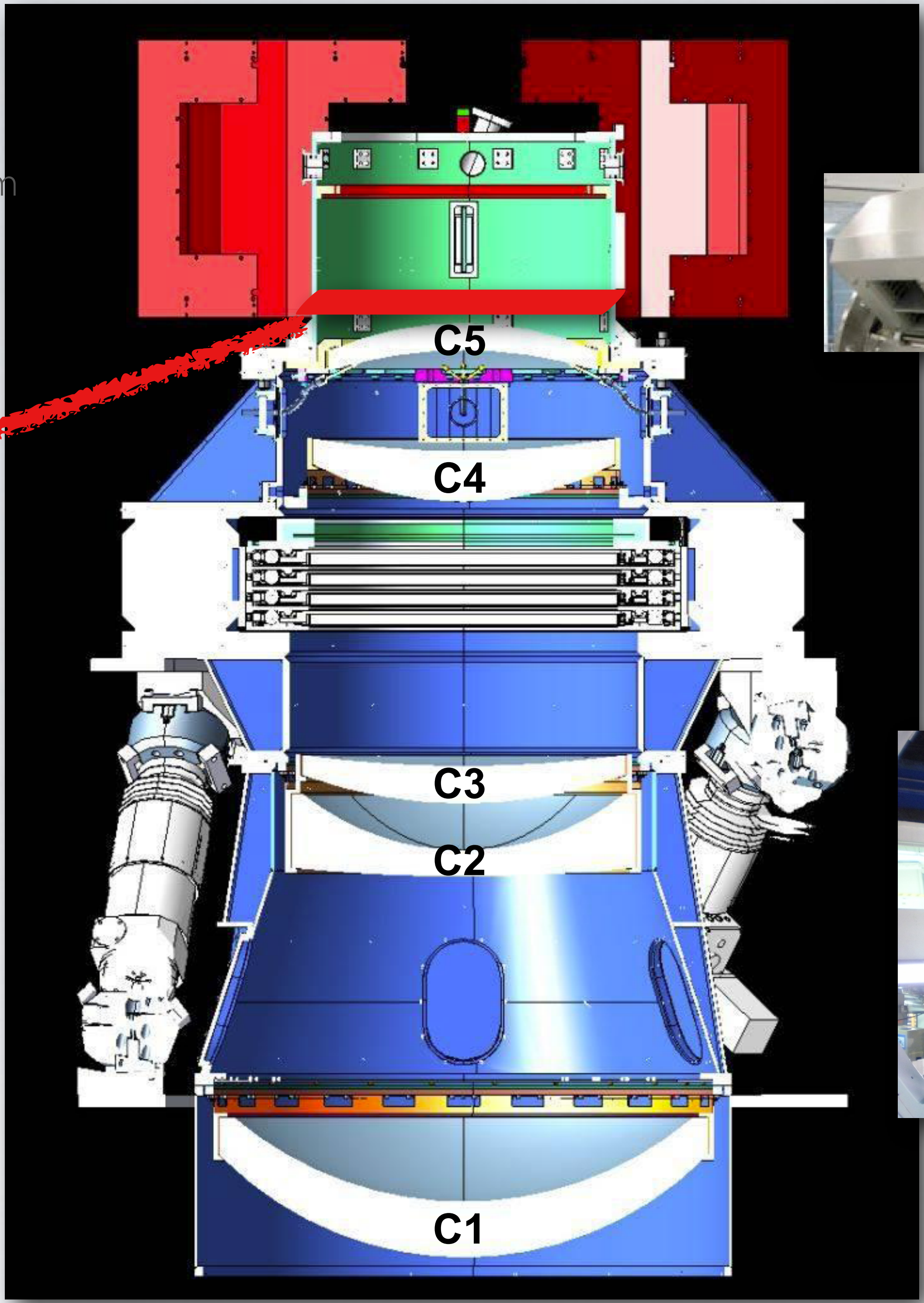
DECAM

CCD focal plane is housed in a vacuum vessel (**the imager**)



Hexapod provides focus and lateral alignment capability for the corrector-imager system

Barrel supports the **5 lenses** and imager



CCD readout electronic crates are actively cooled to eliminate thermal plumes

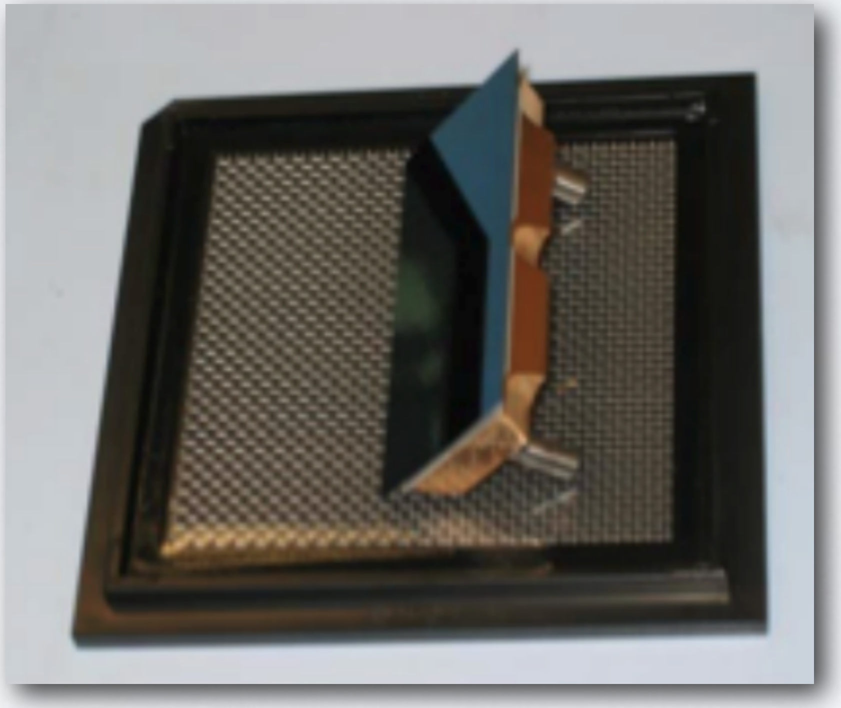
Filter changer with 8 filter capacity and **shutter** fit between lenses **C3** and **C4**

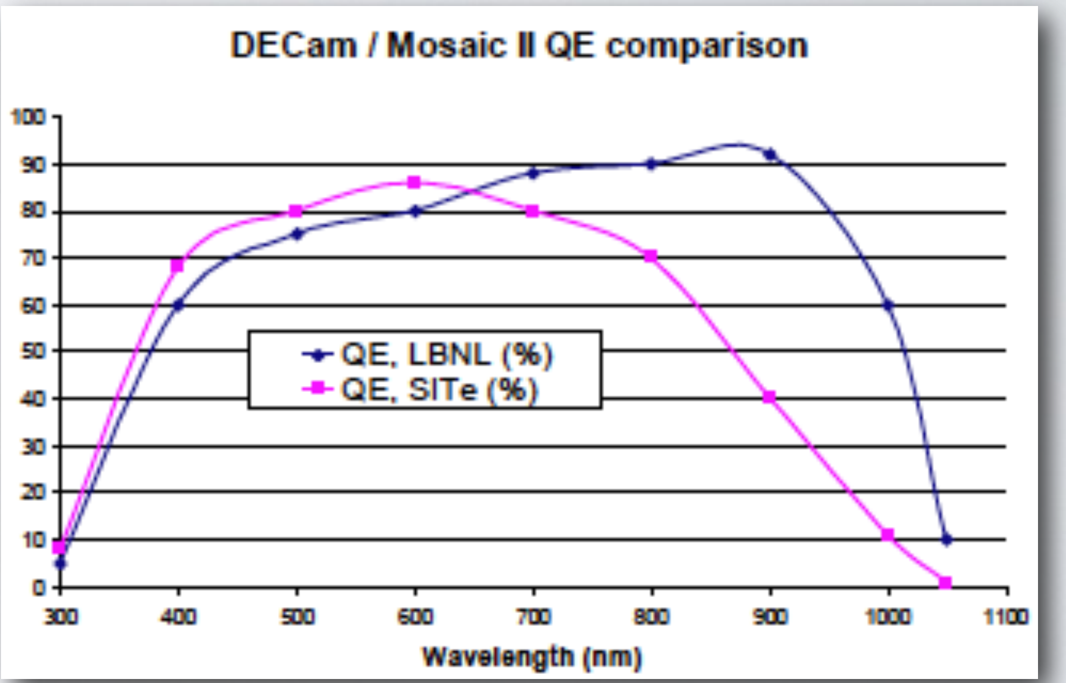
LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C

DECAM CCDS

Red Sensitive CCD wafers, designed by LBNL, processed at DALSA and LBNL:

- QE> 50% at 1000 nm
- 250 microns thick
- readout 250 kpix/sec
- 2 RO channels/device
- readout time ~17sec





CCDs packaged and tested at Fermilab.

DES TIMELINE

Construction:
2008–2011

Installation:
Jan–Aug 2012

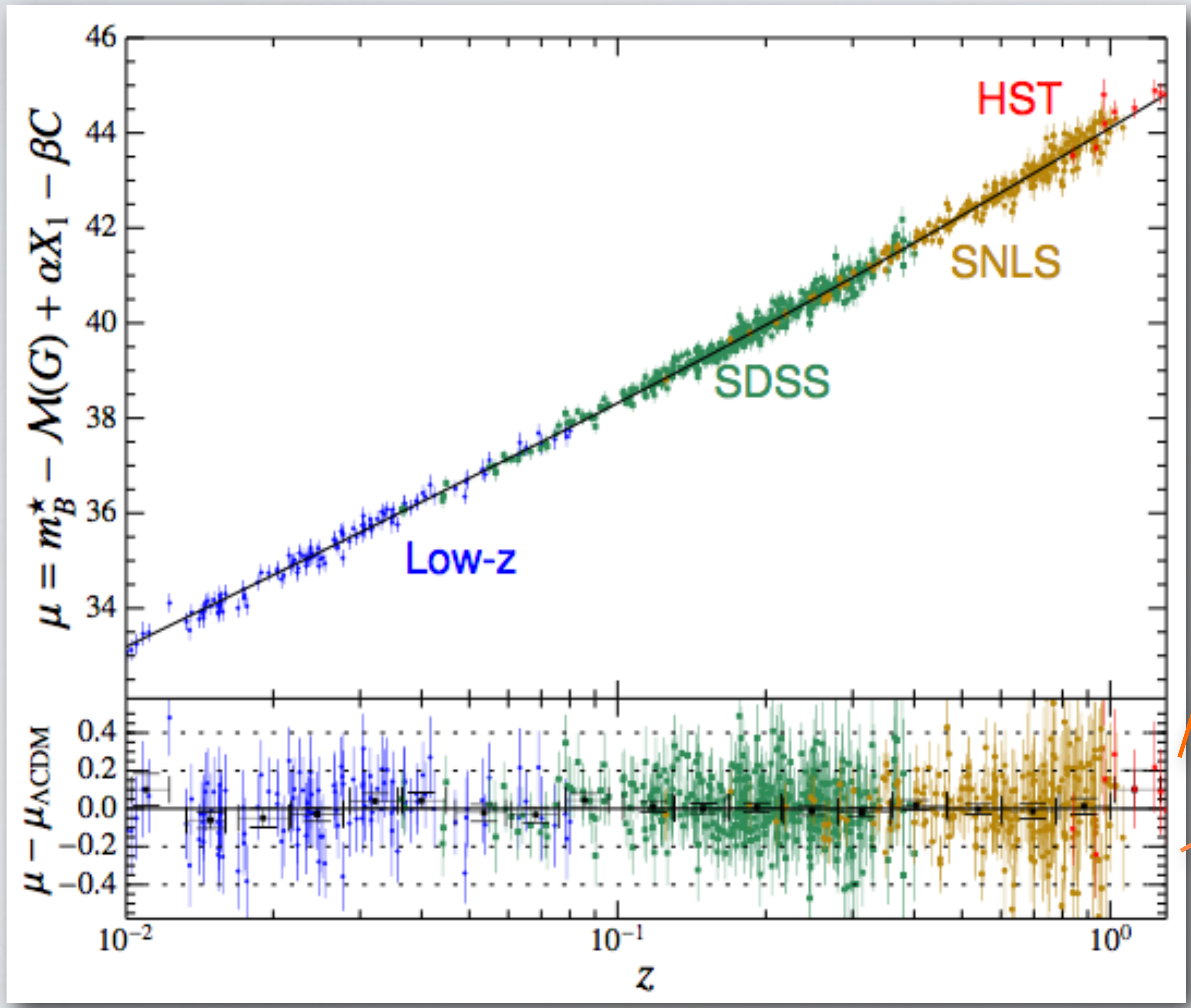
Commissioning:
Sep–Oct 2012

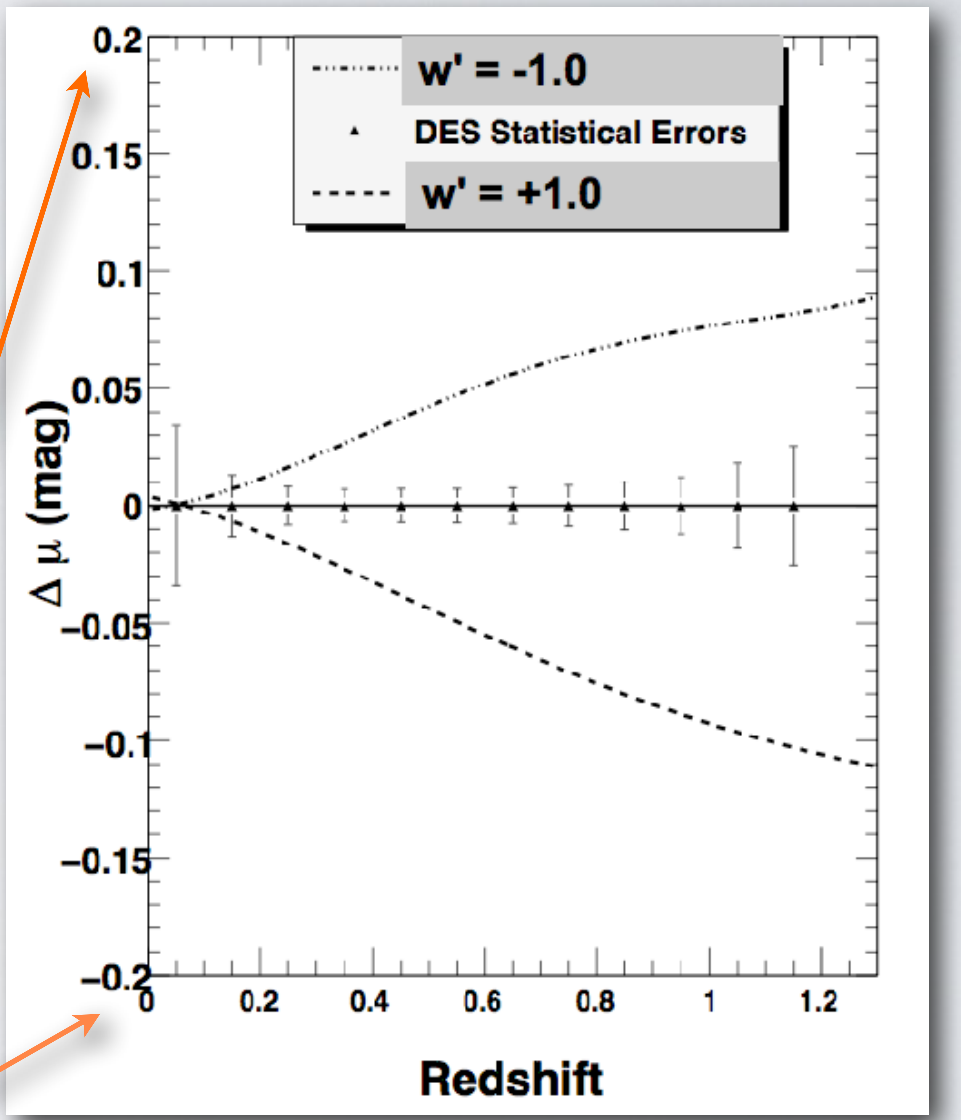
Science Verification:
Nov 2012 – Feb 2013

Operations:
Aug 31, 2013 – Feb 2018

SN SCIENCE

Joint SDSS-II and SNLS results: Hubble diagram using 740 spectroscopically selected SNe (Betoule et al. 2014).





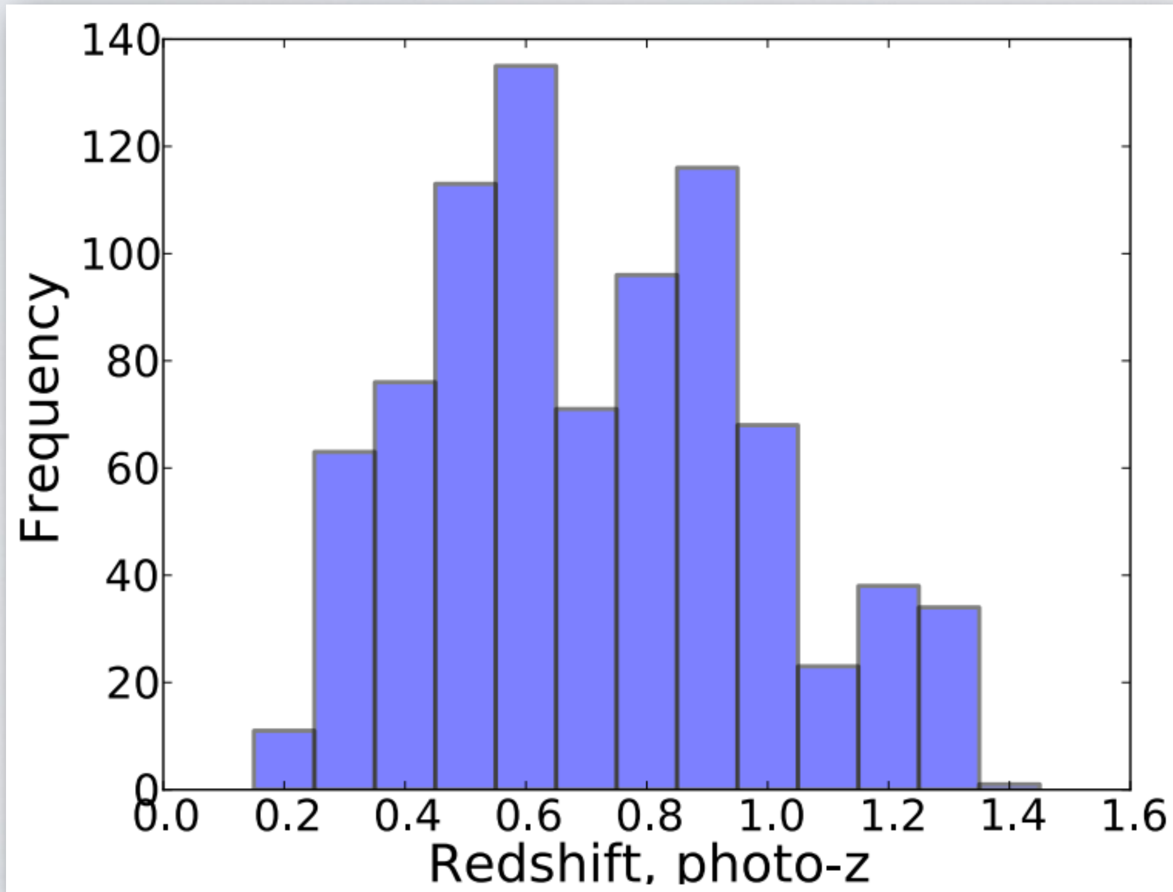
DES expected sensitivity, based on simulations. Assuming 3500 photometrically selected SNe up to z = 1.2 in 30 sq-deg.

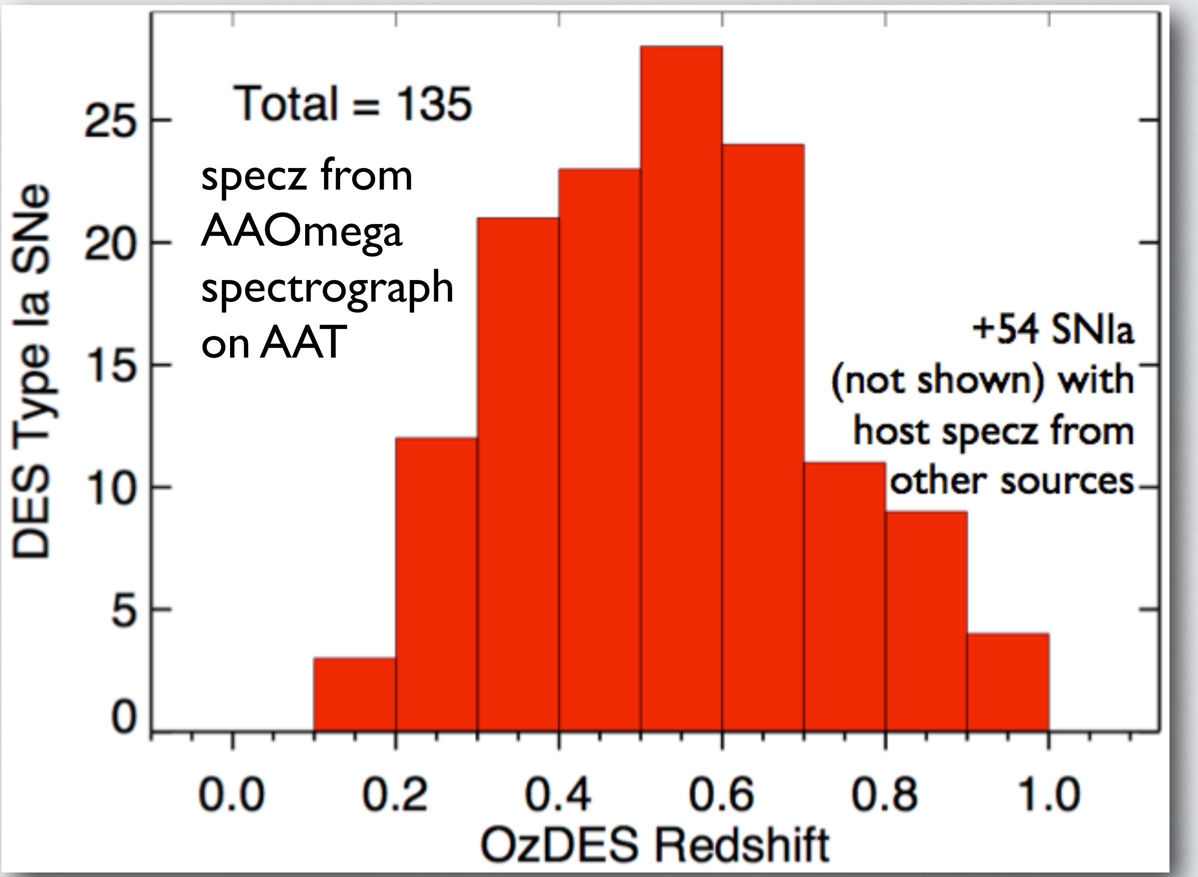
SN SURVEY

Status after Y1:

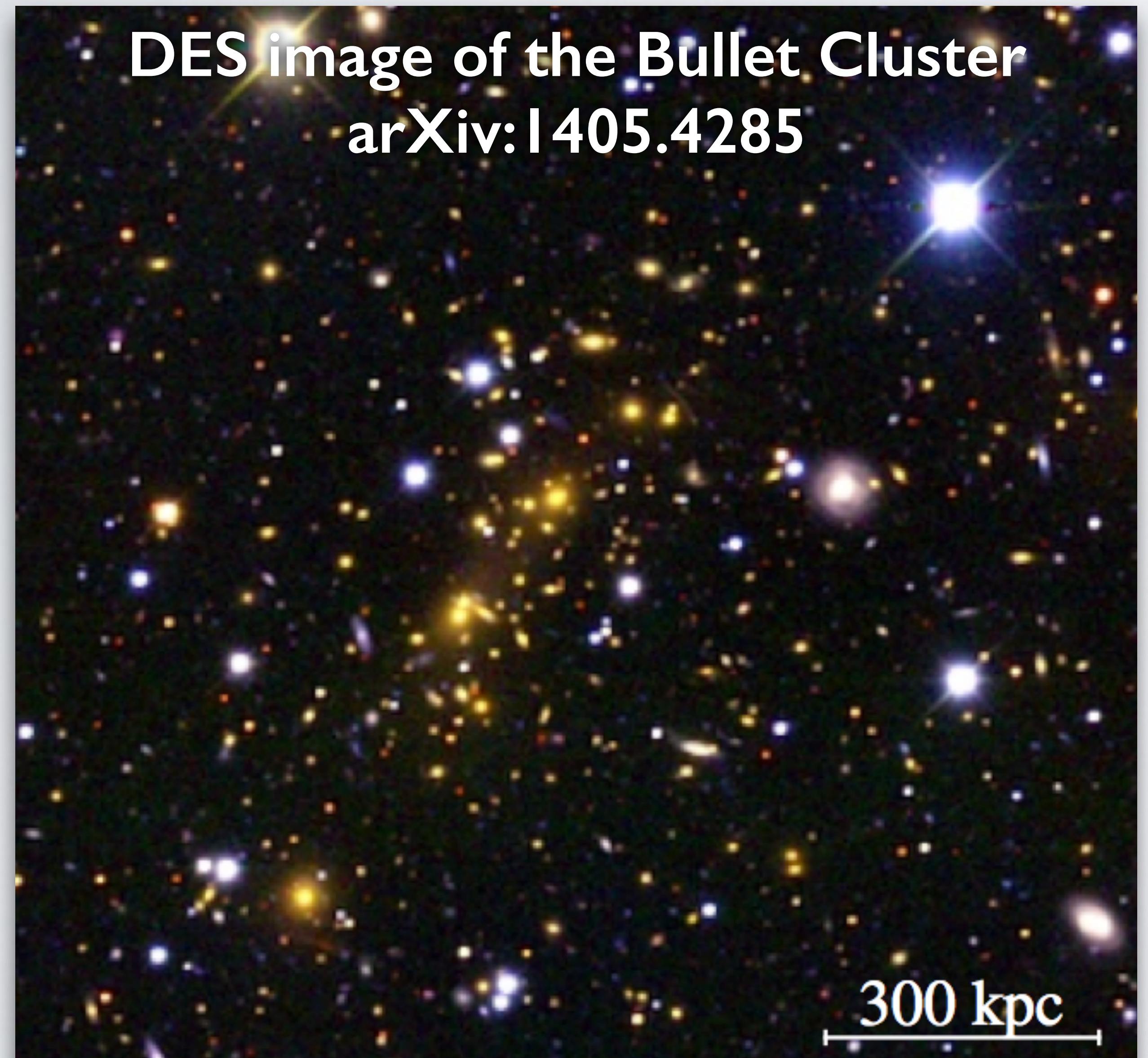
— ~800 candidates selected by DES

— ~200 with host galaxy spectroscopic redshift



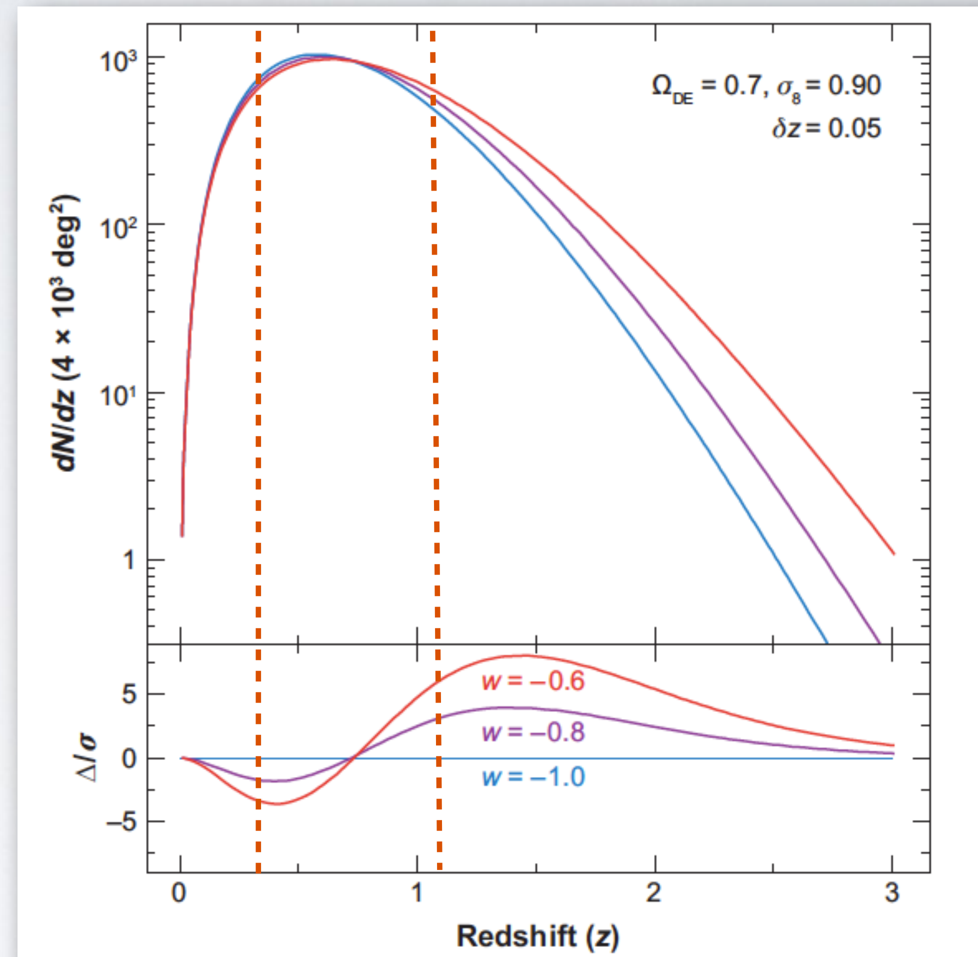


DES SCIENCE: CLUSTERS



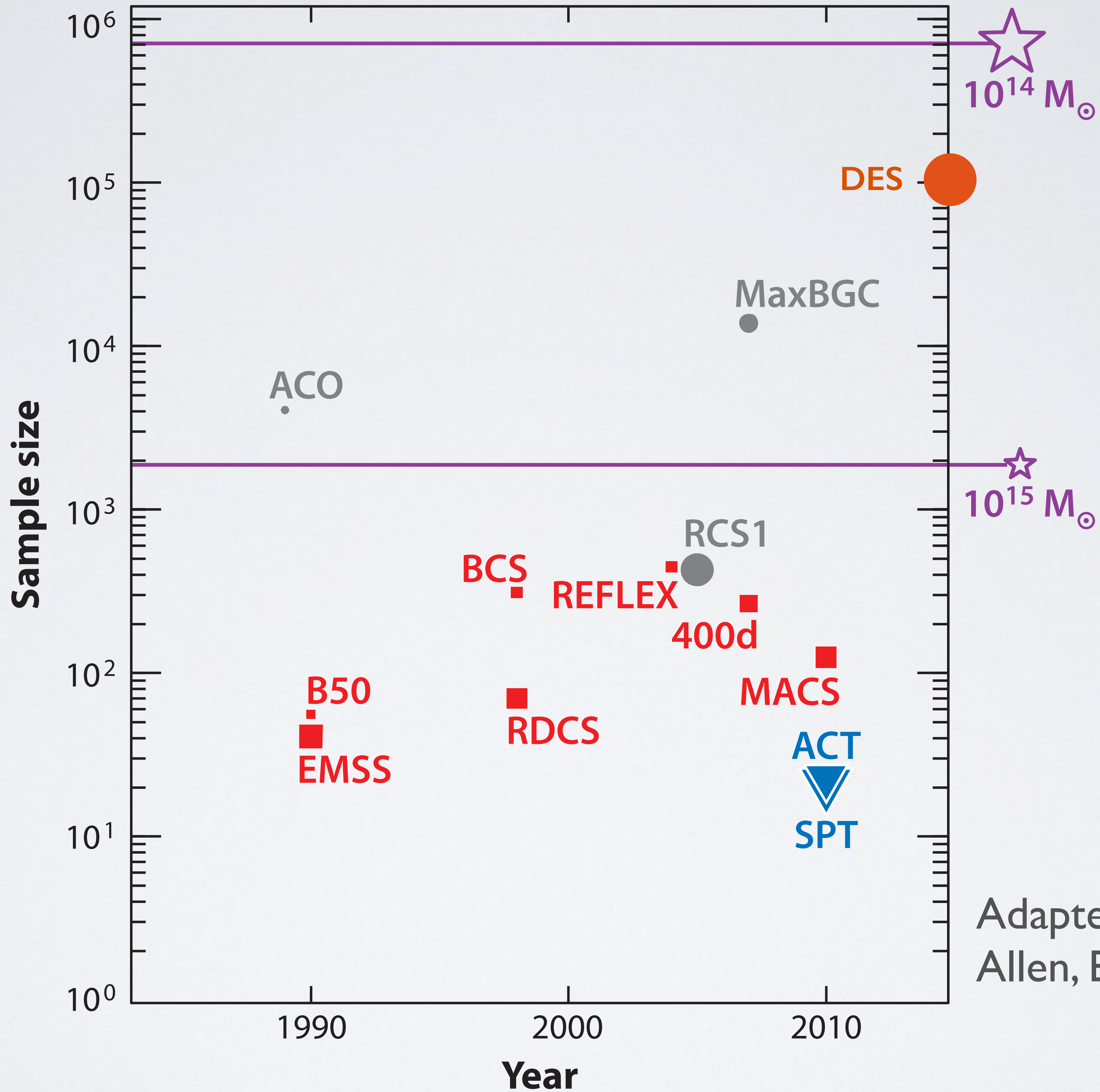
SDSS sample: up to z ~ 0.3

DES sample: up to z ~ 1



Number of clusters above $10^{14.5}$ solar masses as a function of z, for a 4000 sq-deg survey in 3 different cosmologies.

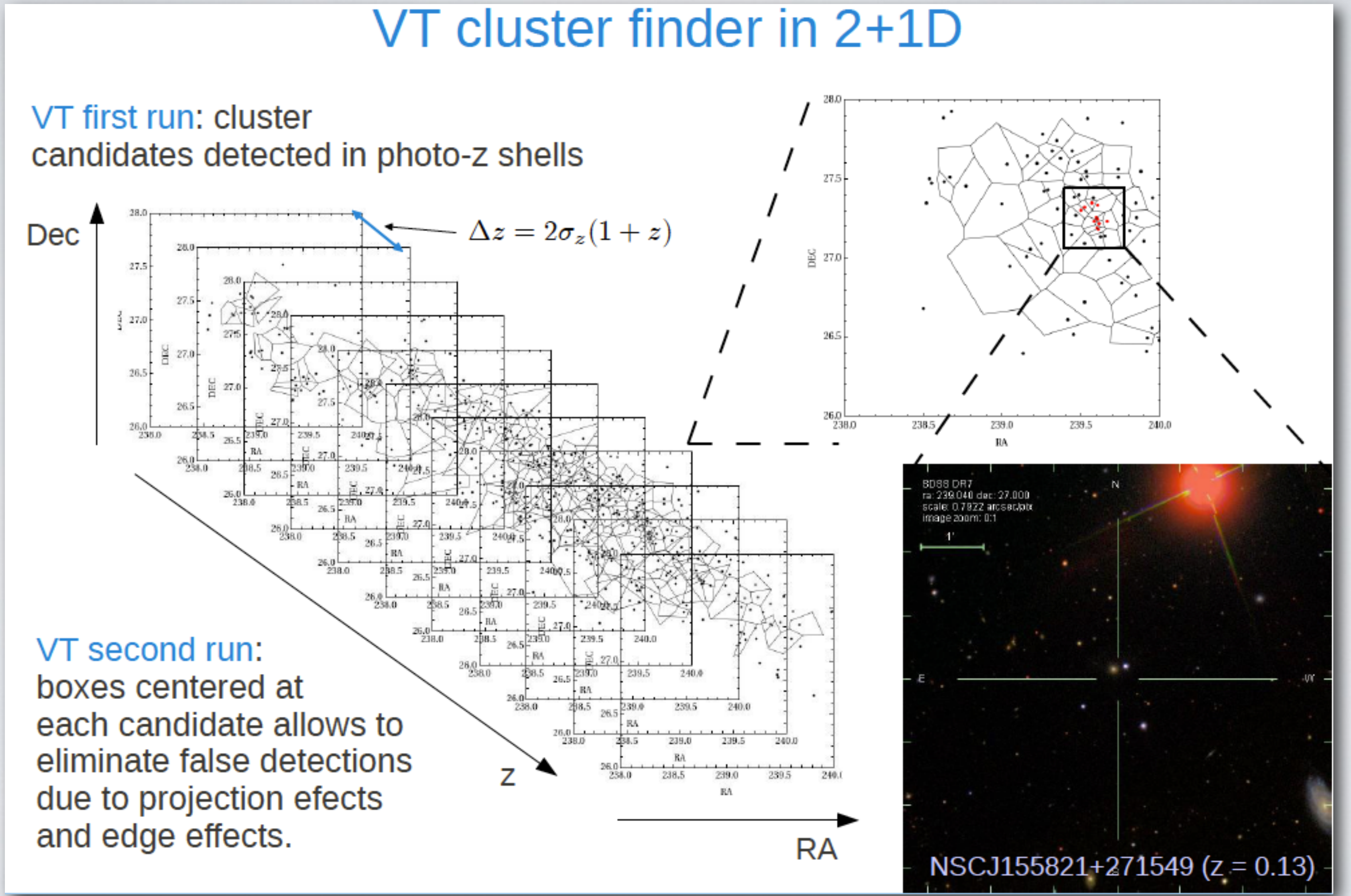
CLUSTER SAMPLES



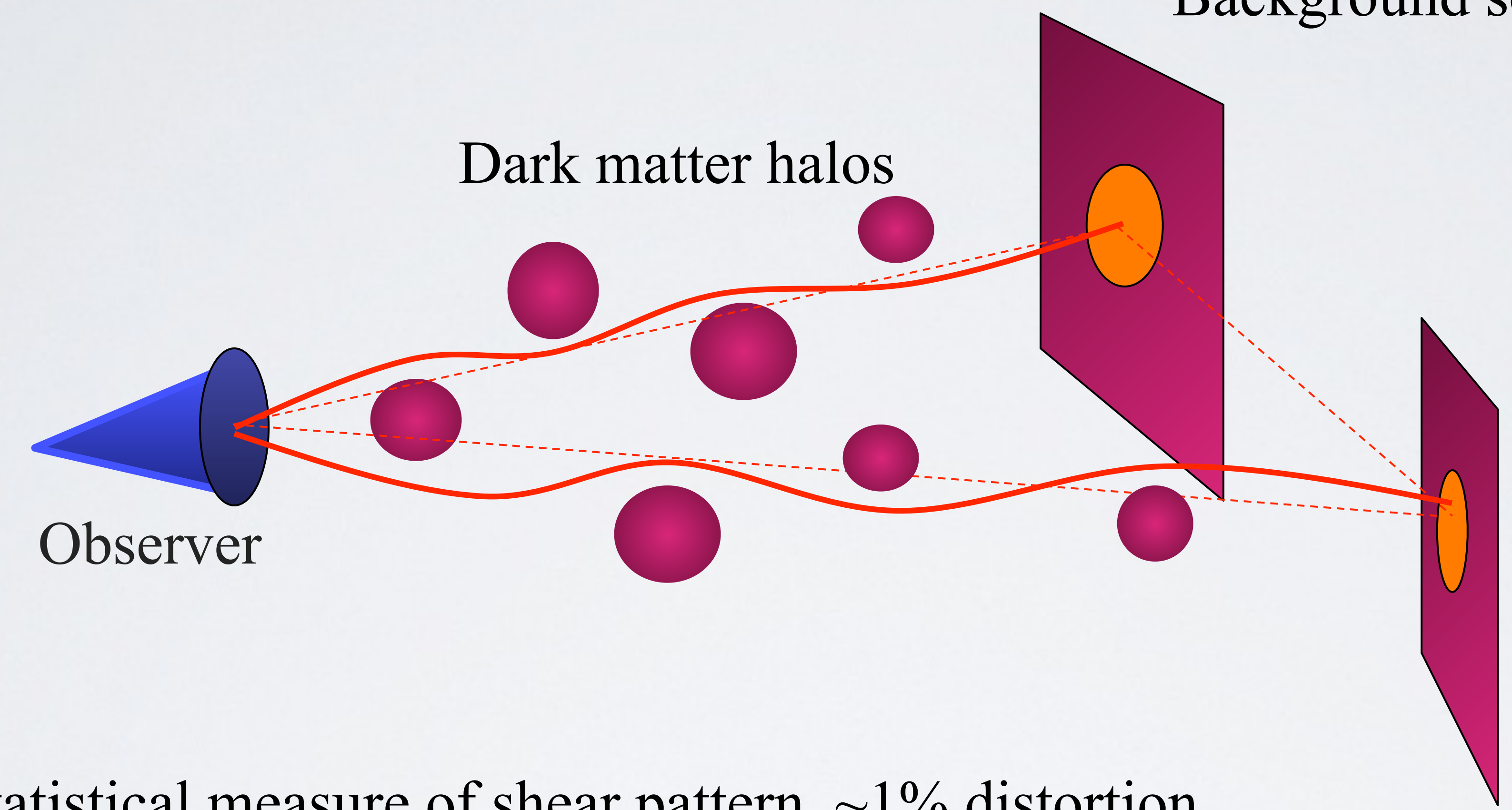
Stars and horizontal lines: Full sky cluster counts expected above this mass threshold in Lambda-CDM cosmology.

Adapted from
Allen, Evrard & Mantz 2011

CLUSTER FINDER



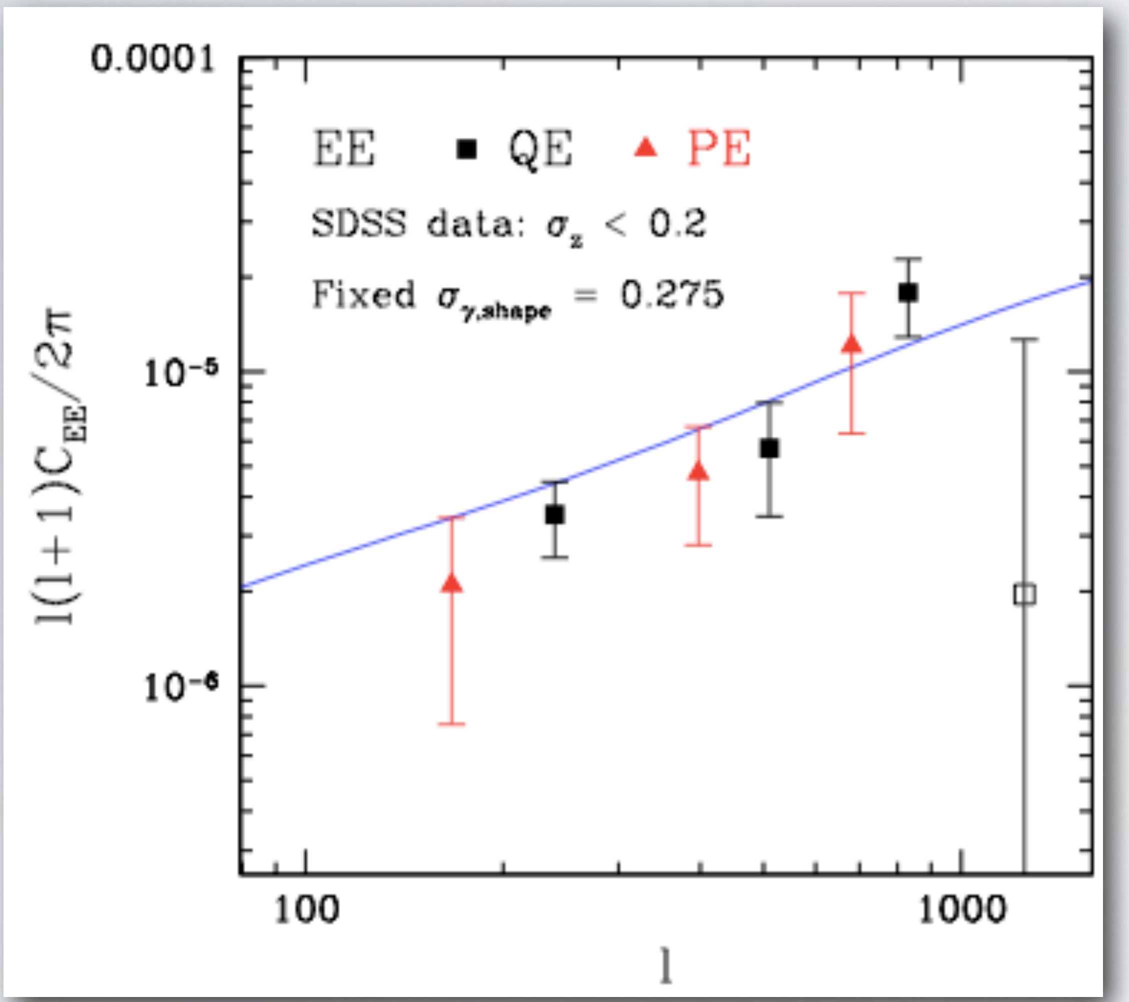
COSMIC SHEAR



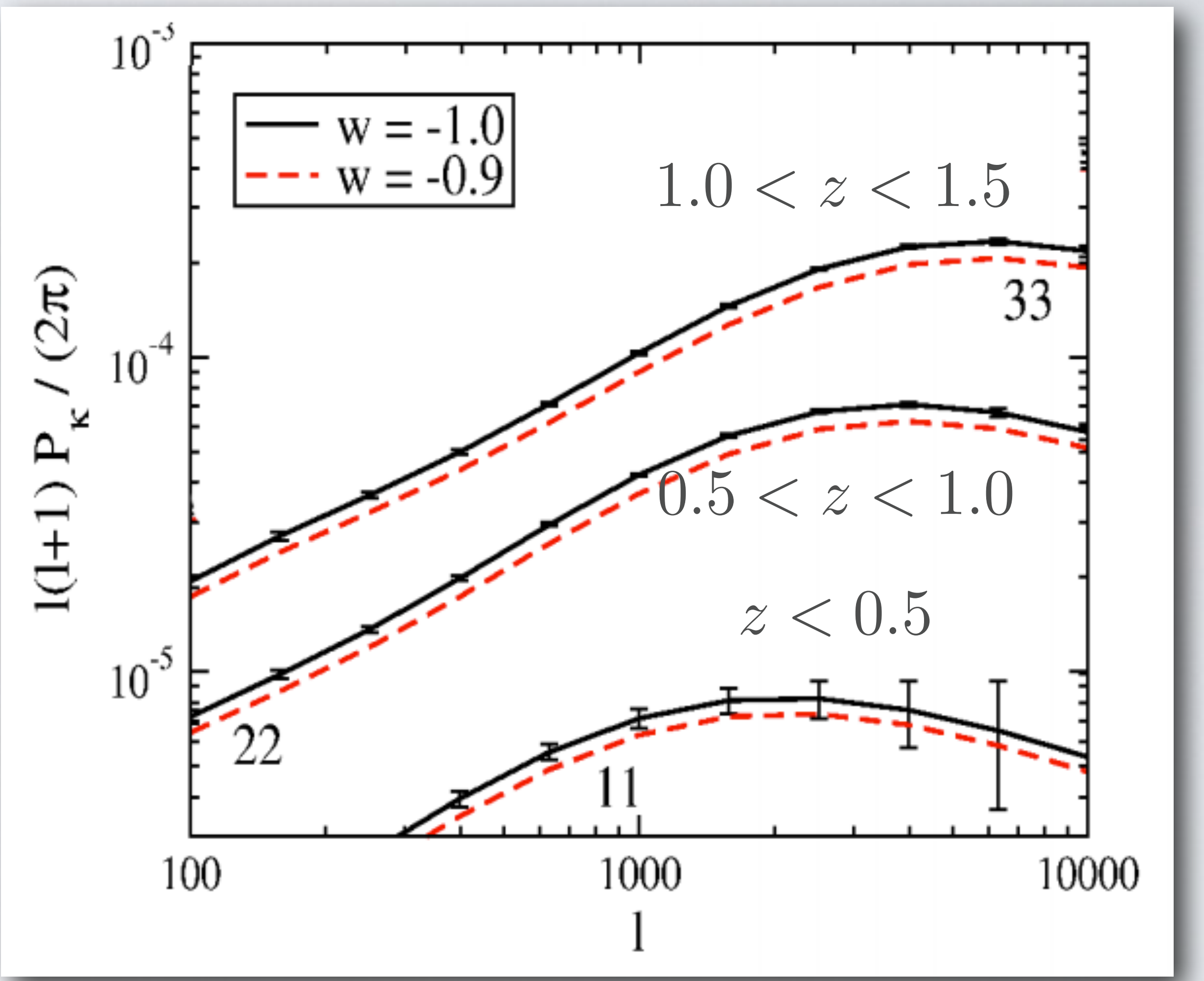
- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on ***geometry*** of Universe
- Foreground mass distribution depends on ***growth*** of structure

Slide from J. Frieman

DES SCIENCE: WL

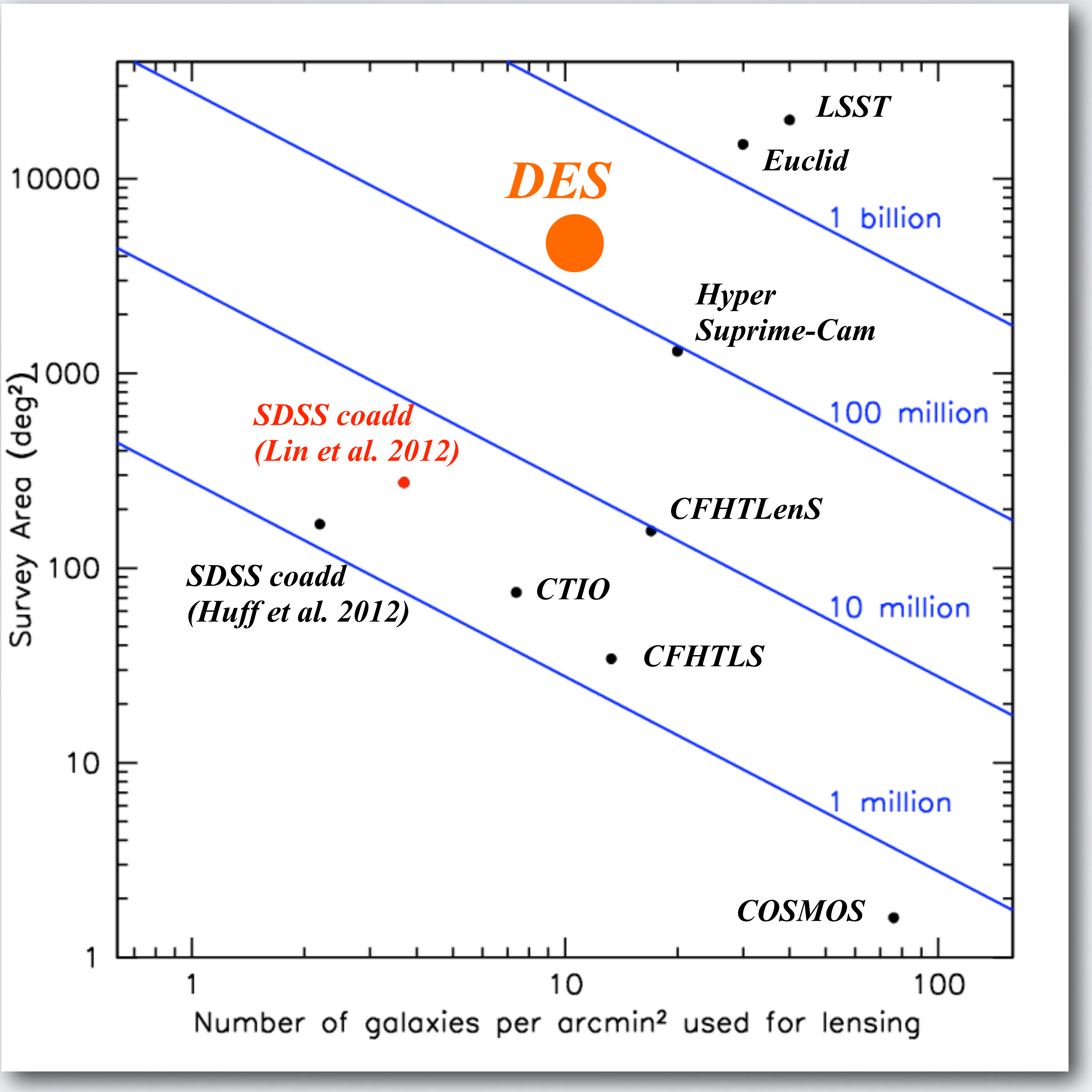


Results based on SDSS data:
275 sq deg, 24th mag, z<0.7
(Lin et al. 2012)



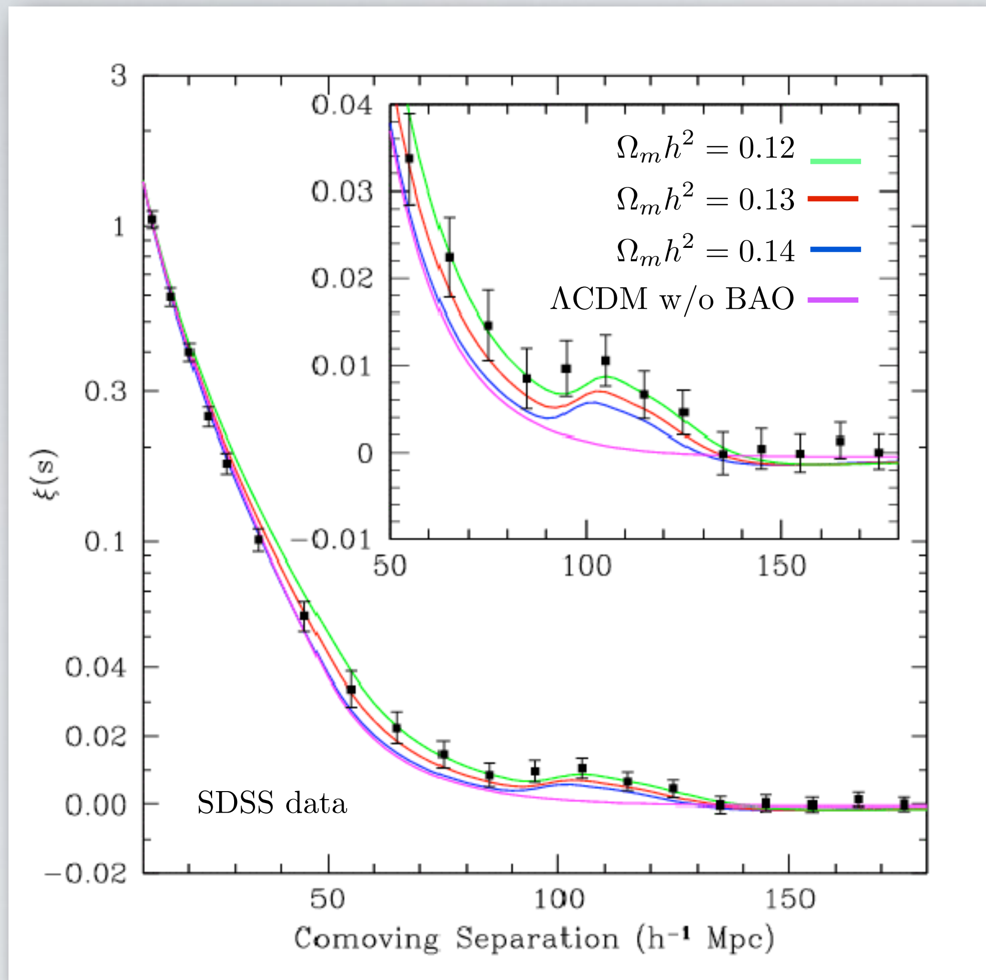
DES expected WL power spectrum assuming 5000 sq-deg, in 3 bins of photot-z width 0.5 out to z = 1.5

CONSTRAINT VS. NUMBER OF GALAXIES



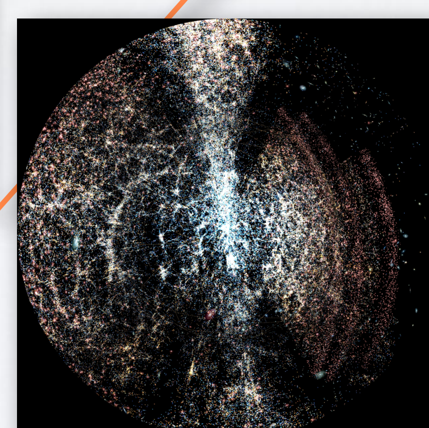
Blue lines indicate constant numbers of galaxies

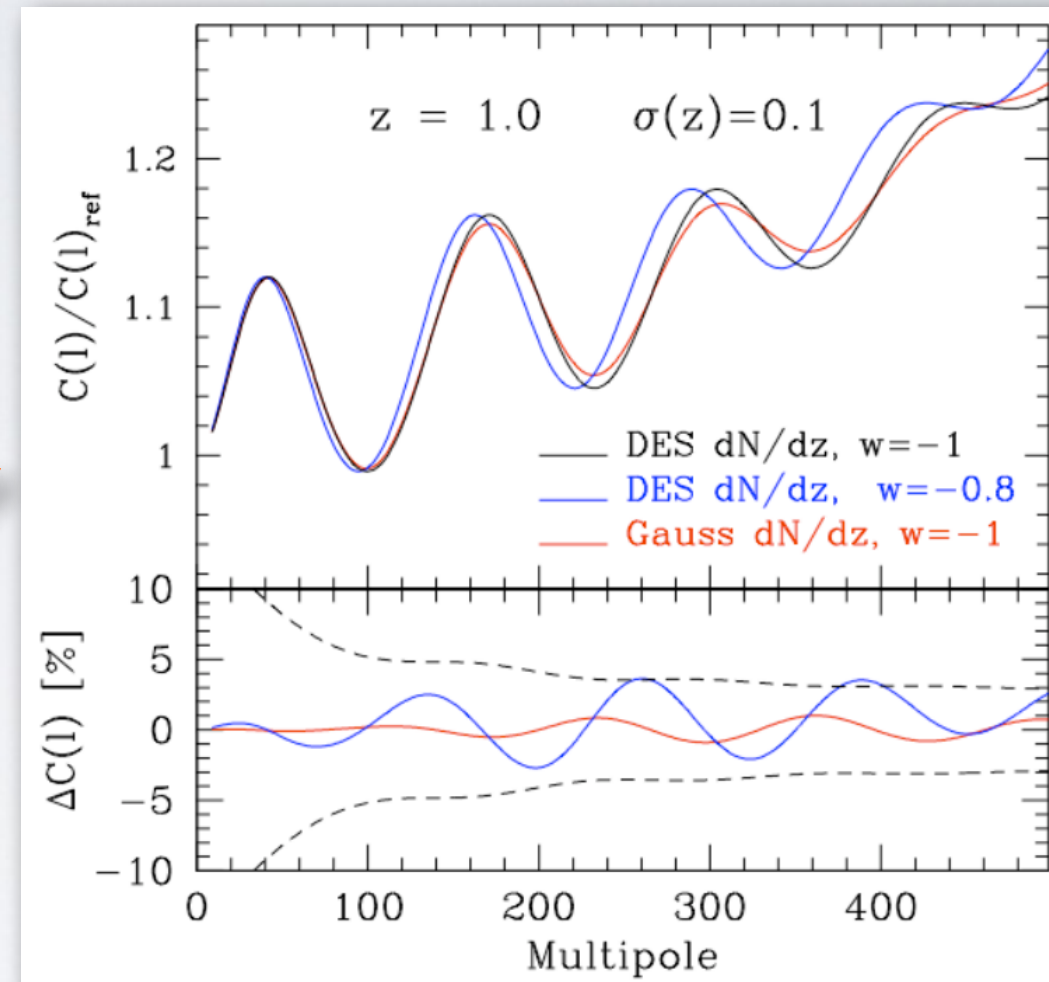
DES SCIENCE: BAO



First results: mean spectroscopic redshift ~ 0.35. Measured Ω_m (Eisenstein et al. 2005)

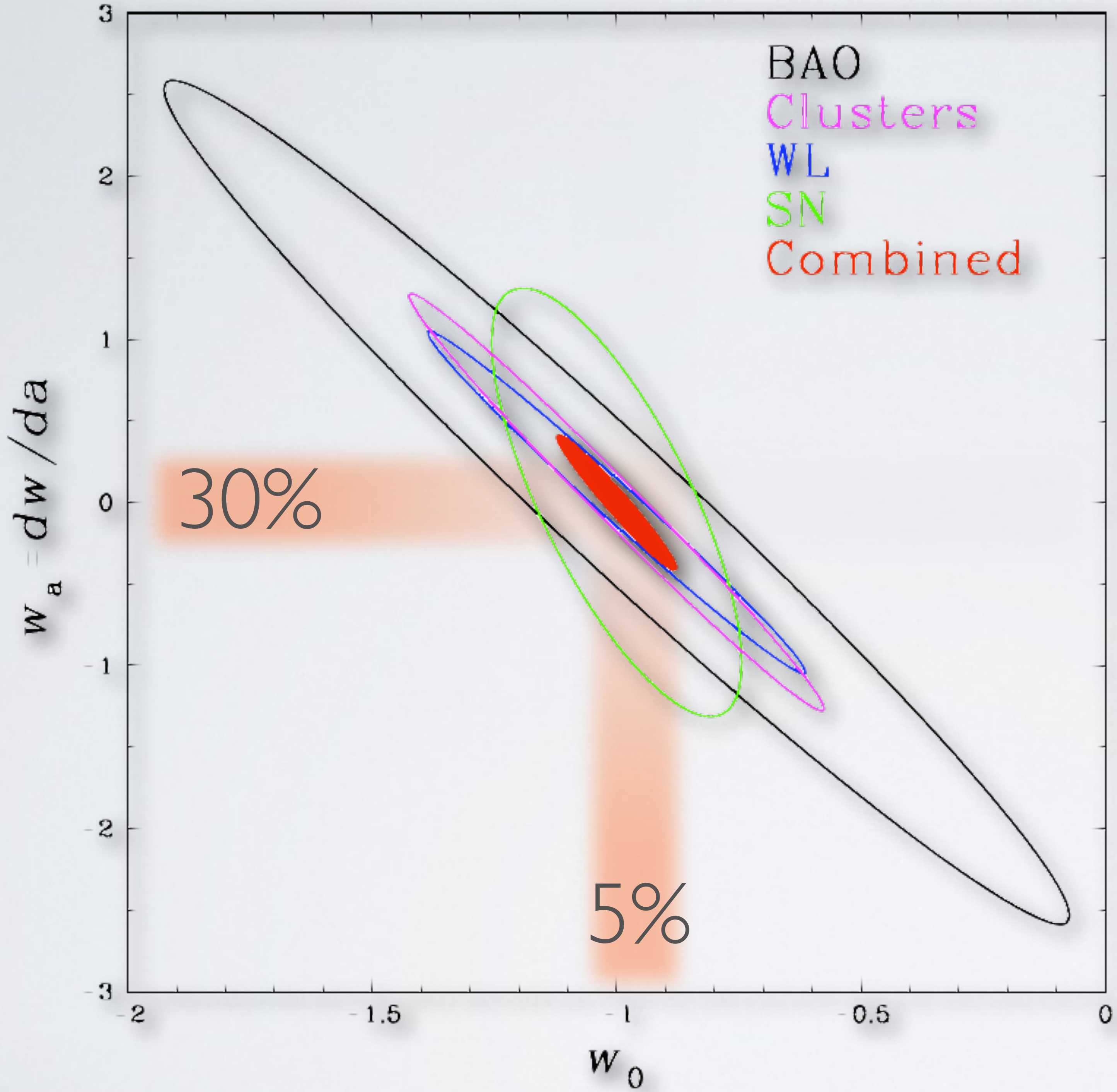
300M glxs up to photometric redshift ~ 1





DES expected sensitivity. Can measure w by probing deeper and slicing in z.

DES PROJECTIONS



5000 deg^2, 0.9" seeing, 24th mag (redshift~1.4)

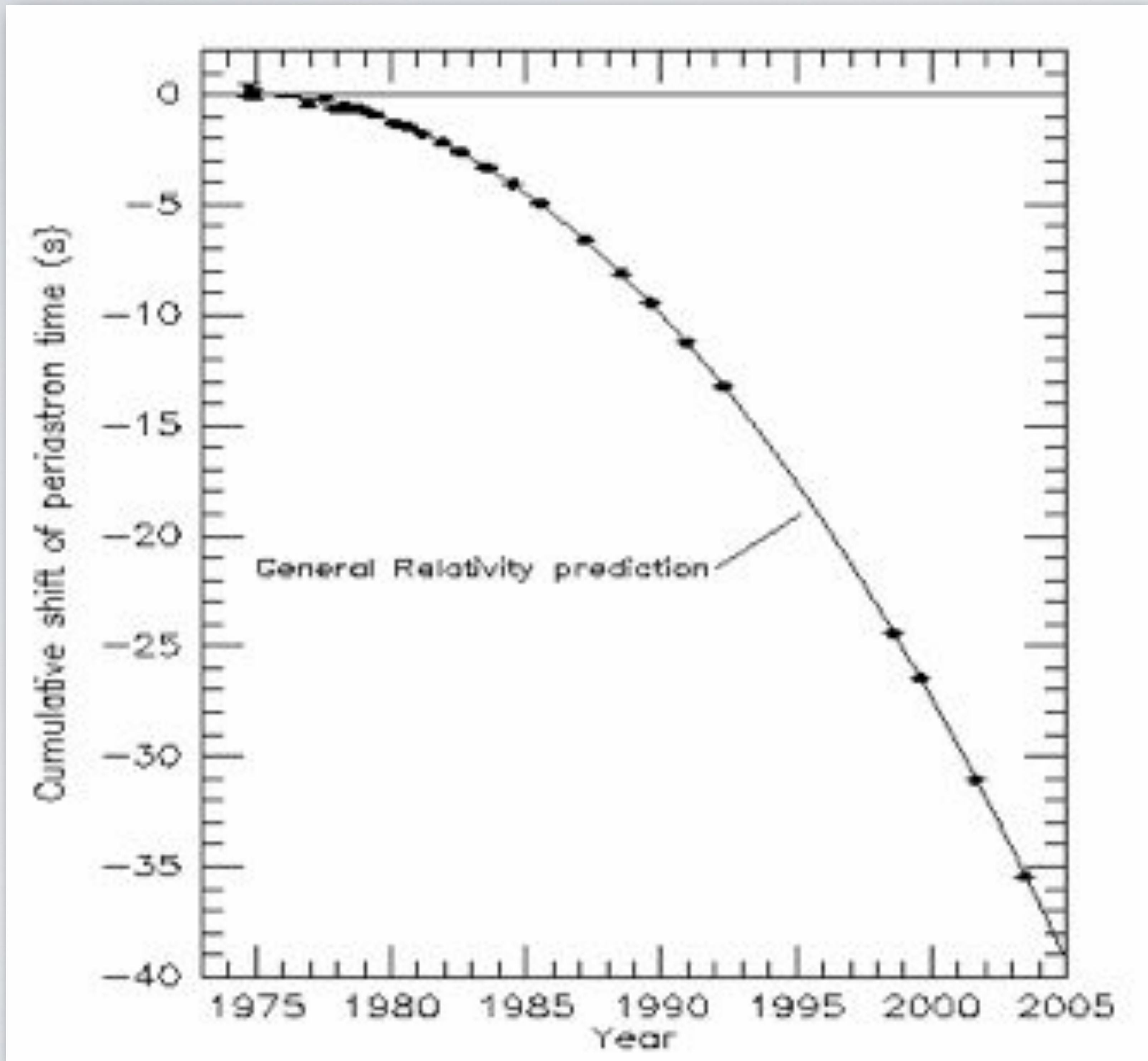
300M galaxies, shapes, 100K clusters, 4K SNe

4 combined probes

3-5x improved Dark Energy measurement

Did we miss any astroparticle?

GRAVITATIONAL WAVES

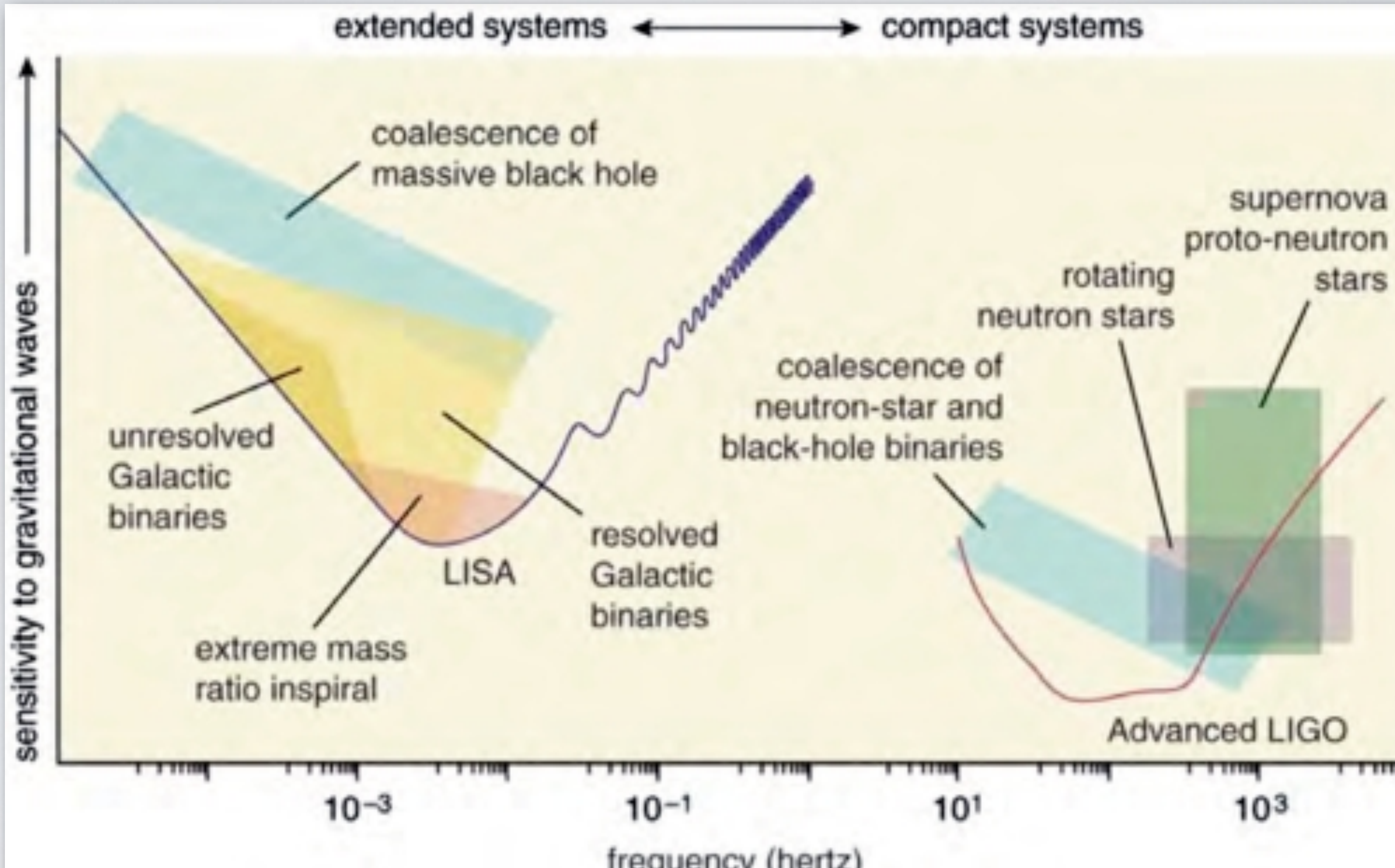


Hulse & Taylor Pulsar

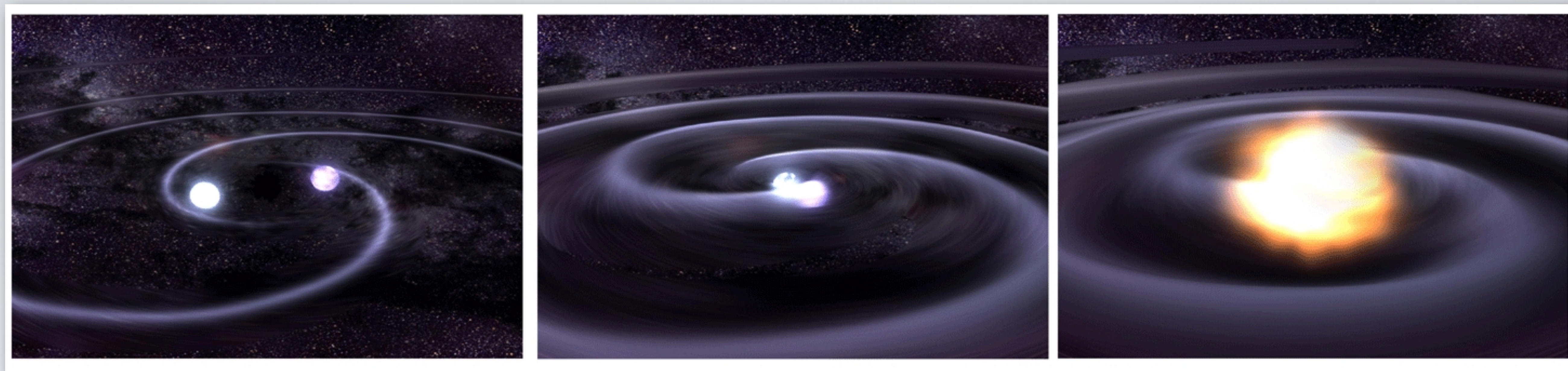
indirect detection of **GW**

DIRECT GW DETECTION?

GW SPECTRUM, SOURCES



NEW INITIATIVE: GRAVITATIONAL WAVES



Coordinated detection of electromagnetic and gravitational radiation from mergers of compact objects (neutron stars, black holes).

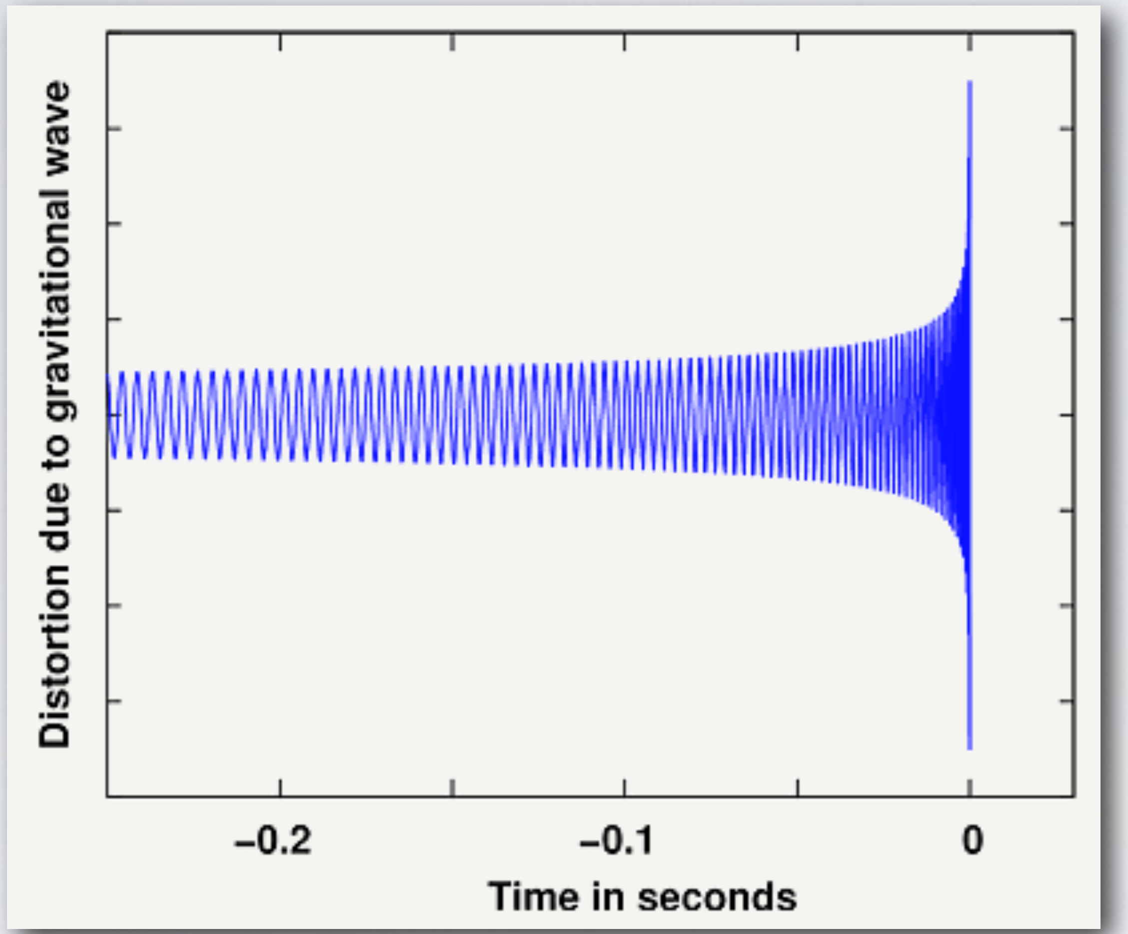
- **Search for optical counterpart of events detected by the advanced LIGO/VIRGO detectors**

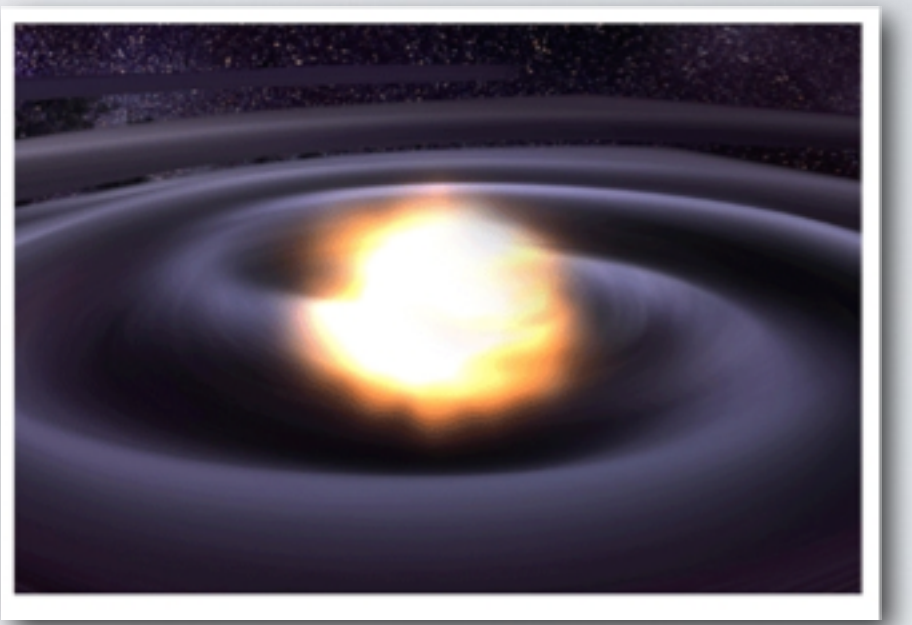
Time of flight experiment: Do gravitons travel at the speed of light?

Standard Sirens: Potentially a new cosmological probe in the future.

Hubble diagram: distance from GW signal, redshift from optical data

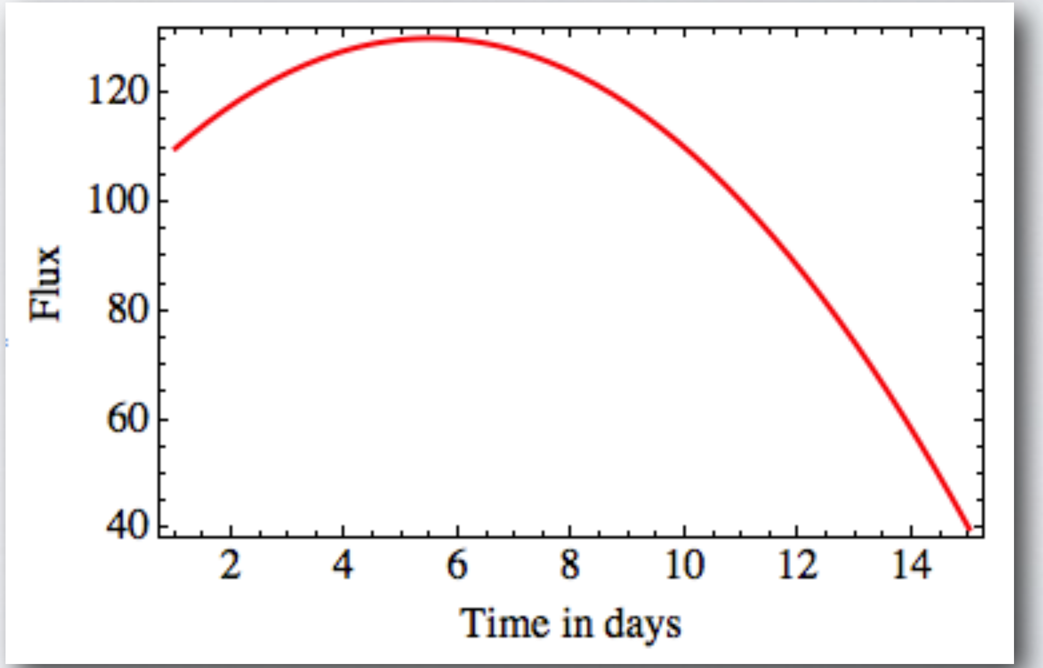
NEW INITIATIVE: GRAVITATIONAL WAVES





GW

EM



ToF experiment

Standard Sirens

SUMMARY

These are great times to be a researcher in High-Energy Physics.

Complementarity between **Astro** and **Collider** approaches is a fact to be explored:

— In search of new physics?
— Need to probe the highest energy scales?
— Want to find new particles, such as Dark Matter?
— Want to understand cosmic acceleration?

— Look up!

SUGGESTED READING MATERIAL

Book:

Grupen, 2005. *Astroparticle Physics*, Springer

Selected review papers:

Askew et al., 2014. *Searching for Dark Matter at Hadron Colliders*, arXiv:1406.5662

Frieman, et al. 2008. *Dark Energy and Accelearting Universe*, arXiv:0803.0982

Kotera & Olinto, 2011. *The Astrophysics of Ultrahigh Energy Cosmic Rays*, arXiv: 1101.4256

Lorentz & Wagner, 2012. *Very-high energy gamma-ray astronomy*, arXiv:1207.6003

Riles, 2013. *Gravitational Waves: sources, detectors, searches*, arXiv:1209.0667