Working group overview: Astroparticle physics & Cosmology

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WIN 2017, Irvine, June 19 – 24, 2017

What is astroparticle physics and cosmology?

Wikipedia says:

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> **Physical cosmology** is the study of the largest-scale structures and dynamics of the Universe and is concerned with fundamental questions about its origin, structure, evolution, and ultimate fate.

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Astroparticle physics, also called **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology.

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European??

North American??

Astroparticle physics, also called **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology.

A wide range of topics…

Keywords of the
Journal of Cosmology & Astroparticle Physics

Cosmic microwave background : CMB detectors, experiments, polarisation, theory; cosmological parameters from CMB; gravitational waves and CMB polarization; ISW effect; non-gaussianity; reionization; SZ effect

Dark matter and dark energy: cluster counts; dark energy experiments, theory; dark matter detectors, experiments, theory; dark matter simulation; galaxy clustering; rotation curves of galaxies; supernova type Ia - standard candles; weak gravitational lensing

Early universe: alternatives to inflation; axions; baryon asymmetry; big bang nucleosynthesis; cosmic singularity; Cosmic strings, domain walls, monopoles; cosmological applications of theories with extra dimensions; cosmological perturbation theory; cosmological phase transitions; cosmology of theories beyond the SM; cosmology with extra dimensions; inflation; initial conditions and eternal universe; leptogenesis; particle physic/cosmology connection; primordial black holes; primordial magnetic fields; quantum cosmology; quantum gravity phenomenology; recombination; string cosmology; supersymmetry & cosmology; transplanckian physics

High energy astrophysics: X-ray telescopes; absorption and radiation processes; accretion; active galactic nuclei; cosmic ray experiments, theory; detectors; gamma ray burst experiments, theory; gamma ray detectors, experiments, theory; particle acceleration; UHE cosmic rays; X-ray binaries

Large-scale structure of the universe: baryon acoustic oscillations; cosmic flows; cosmic web; cosmological parameters from LSS; cosmological simulations; galaxy clusters; gravitational lensing; intergalactic media; Lyman alpha forest; power spectrum; redshift surveys; superclusters

Neutrinos: cosmological neutrinos; double beta decay; neutrino astronomy; neutrino detectors, experiments; neutrino masses from cosmology; neutrino properties; neutrino theory; solar and atmospheric neutrinos; supernova neutrinos; UHE photons and neutrinos

… plus more

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Topics covered at WIN 2017

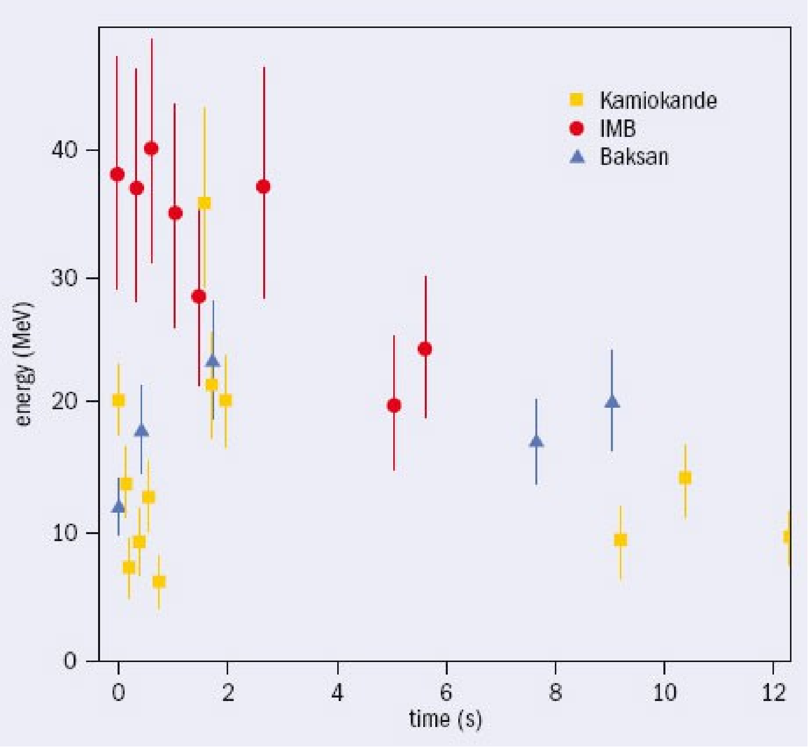
Highlight talks...

Supernova neutrinos	Nakahata, Dasgupta
Dark matter searches and theory	Cooley, Cooley
Multi-messenger astronomy	Murase, Van Elewyck
Synthesising cosmological data	Melchiorri

Highlight 1: Supernova neutrinos...

Nakahata, Dasgupta

Neutrinos carry away ~99% of the energy of a core collapse supernova.



Neutrinos from SN1987A

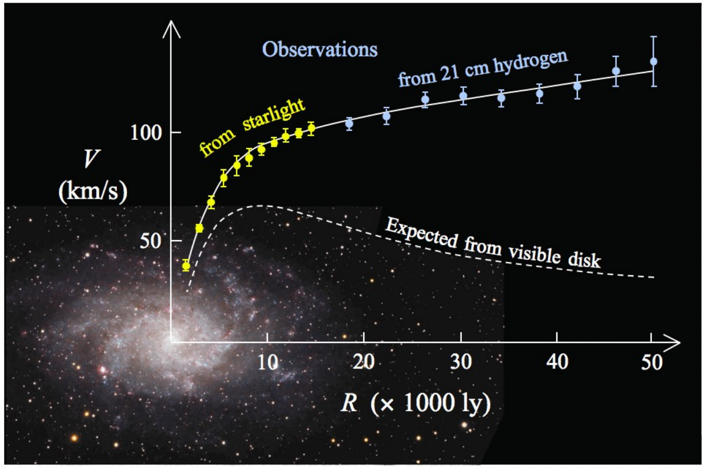
SN1987A

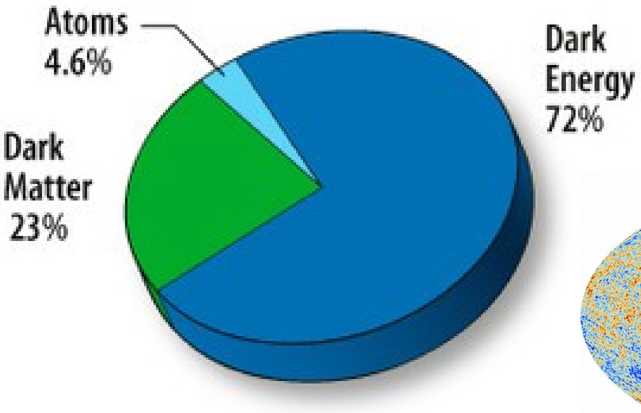
What can the detection of SN neutrinos with current/future technologies tell us about:

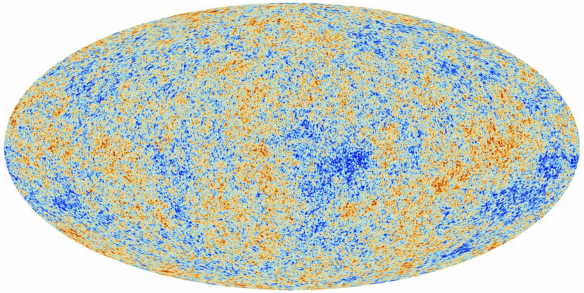
- Supernova explosion mechanism,
- Neutrino properties, e.g., mass hierarchy?

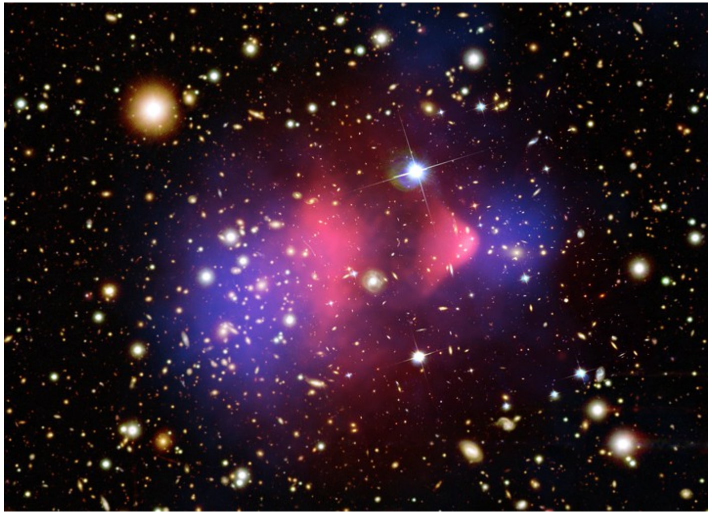
Highlight 2: Dark matter searches & theory...

Cooley, Covi









~23% of the universe's present energy density is in the form of a nonrelativistic, nonbaryonic, electrically neutral, "dark" matter.

- What is it?
- … and what does it imply for BSM theories?

Highlight 3: Multi-messenger astronomy...

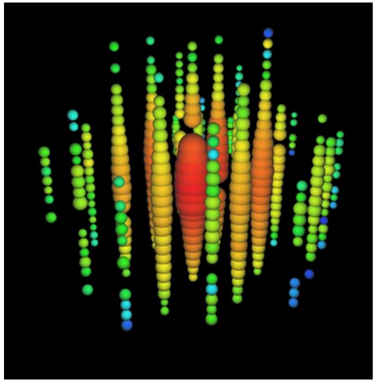
Murase, Van Elewyck

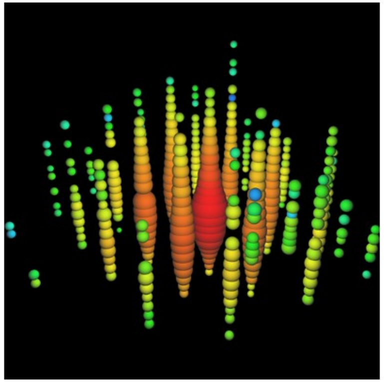
Extra-solar system astrophysical neutrinos have been detected since 2013.

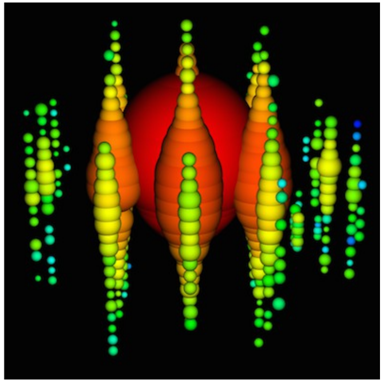
+ Gravitational waves since 2016.

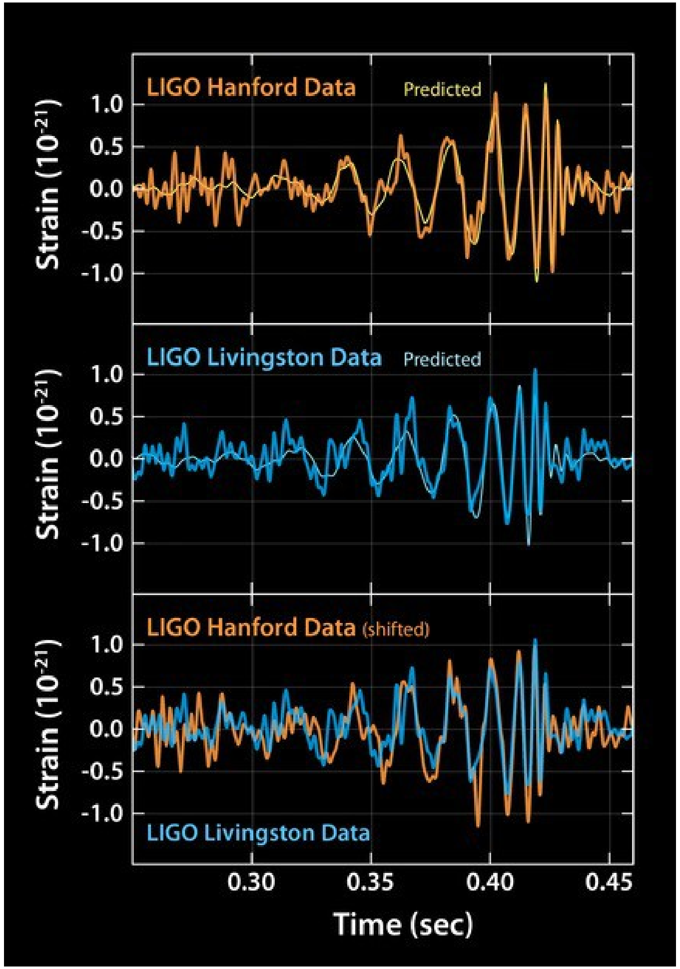
Together with EM and cosmic ray observations how will these add to our understanding of:

- Origin of cosmic rays, cosmic accelerators,
- Gamma-ray bursts?





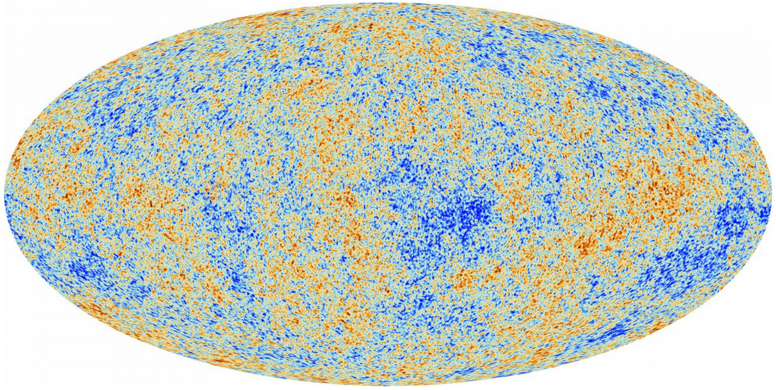


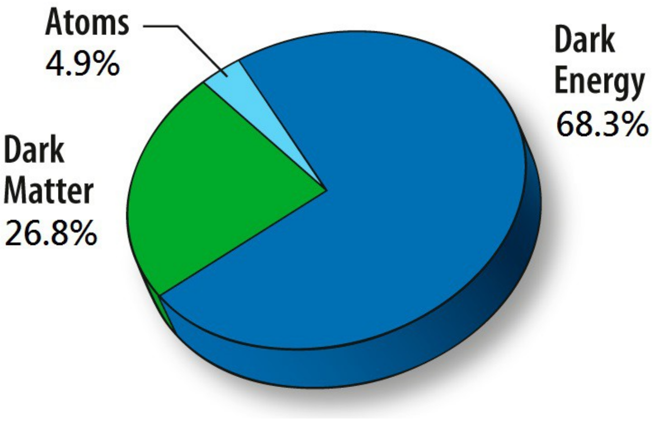


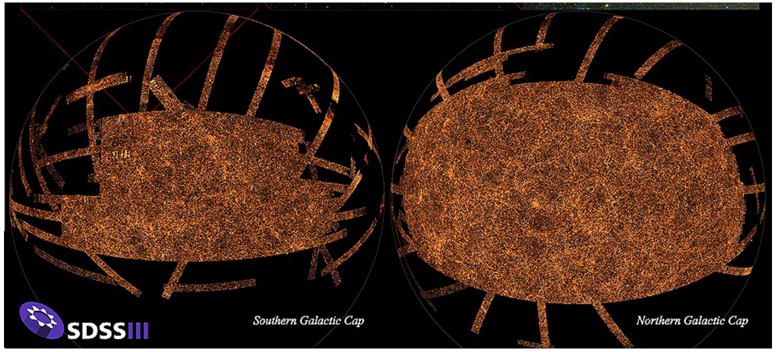
Highlight 4: Synthesising cosmological data...

Melchiorri

The simplest model consistent with current cosmological observations is the ΛCDM model.







- How is the health of ΛCDM? Is there evidence for beyond-ΛCDM cosmology?
- What are the implications for particle physics?

A high degree of complementarity...

“Internal complementarity”

Complementarity between unrelated astrophysical and/or cosmological observations

“External complementarity”

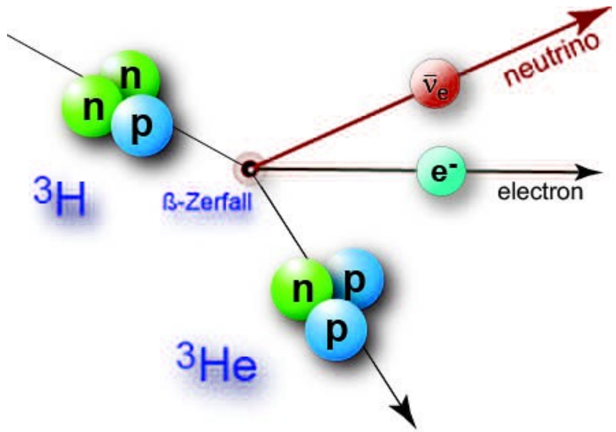
Complementarity with terrestrial laboratory experiments (with man-made sources)

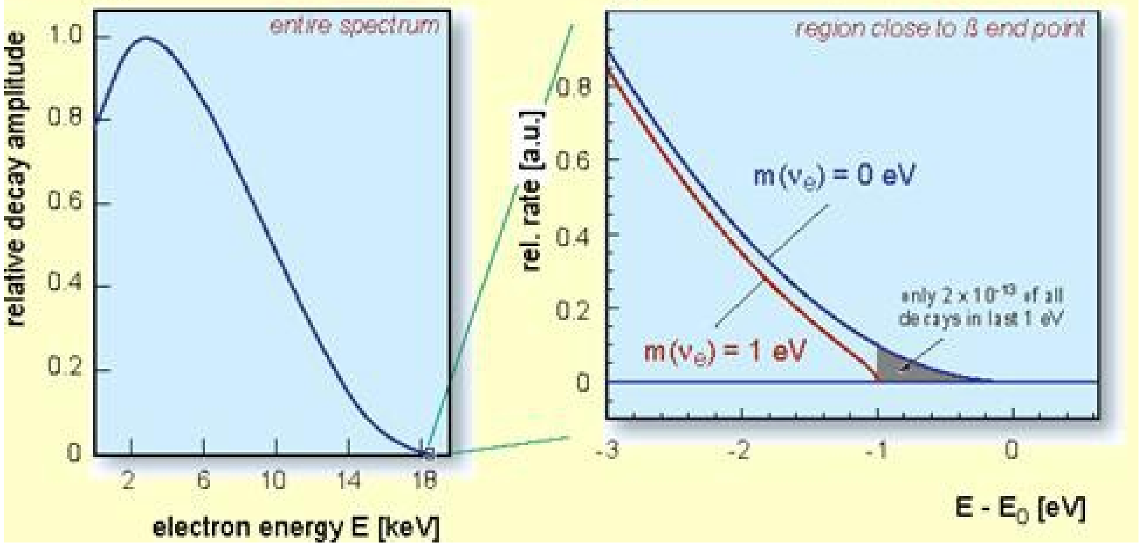
Neutrinos…

Absolute neutrino mass...

See talk of Formaggio

… via **tritium β-decay** end-point spectrum measurements.

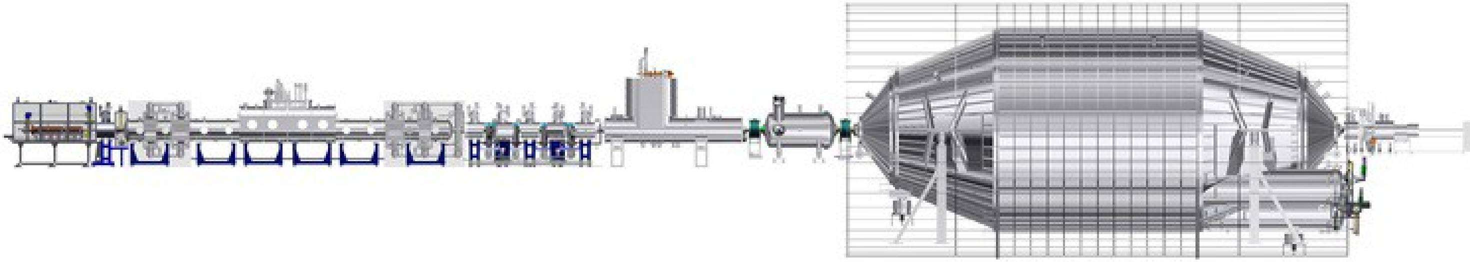


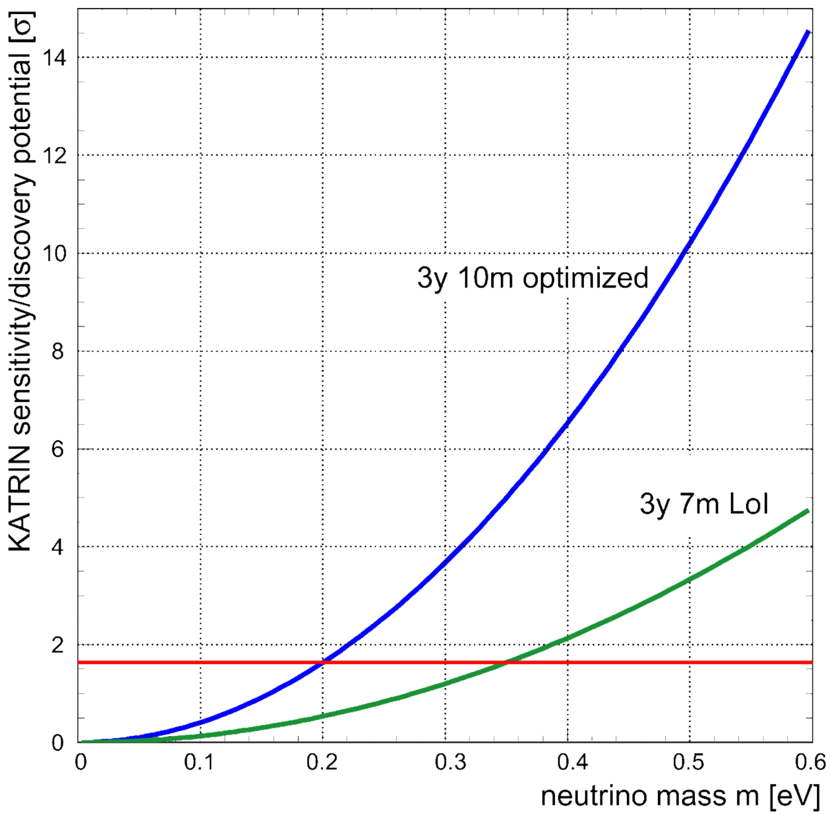


Current upper limit:

$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 2.2 \text{ eV}$$

Lobashev [Troitsk] 2003; Krauss et al. [Mainz] 2005





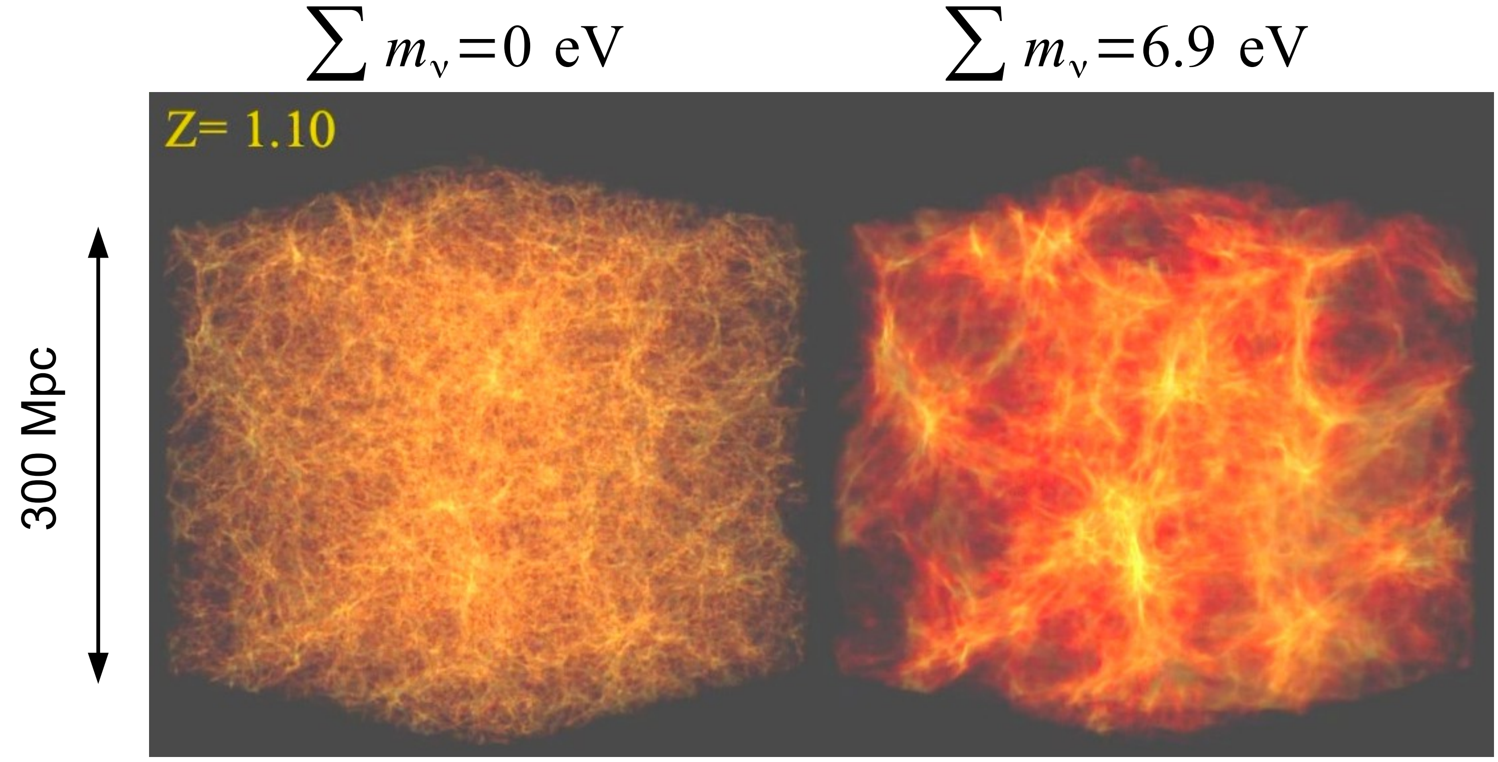
KATRIN projected sensitivity
(90% upper limit if neutrino mass is zero):

$$m_e < 0.2\,\mathrm{eV}$$

(10-fold improvement on current lab limits)

Absolute neutrino mass > from cosmology...

A **sub-eV-mass thermal relic** has too much kinetic energy to cluster efficiently, impeding structure formation on small scales.



Simulation by Troels Haugbølle

Absolute neutrino mass > from cosmology...

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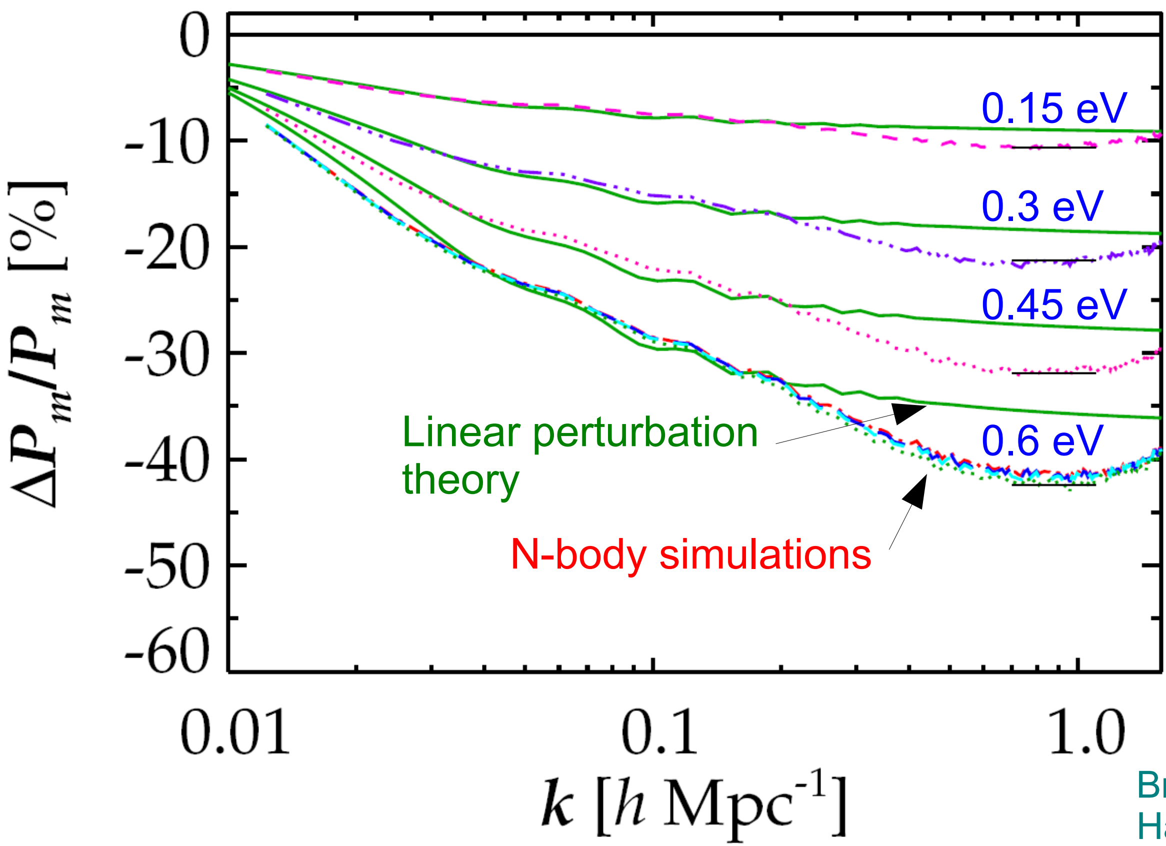


Brandbyge, Hannestad, Haugbolle & Thomsen 2008

Absolute neutrino mass > from cosmology > limits...

See talks of Madhavacheril, Chinone, Reichardt

KATRIN projected sensitivity

$$\sum m_\nu < 0.6 \text{ eV}$$

Planck TT+TE+EE+lowP +lensing+ BAO

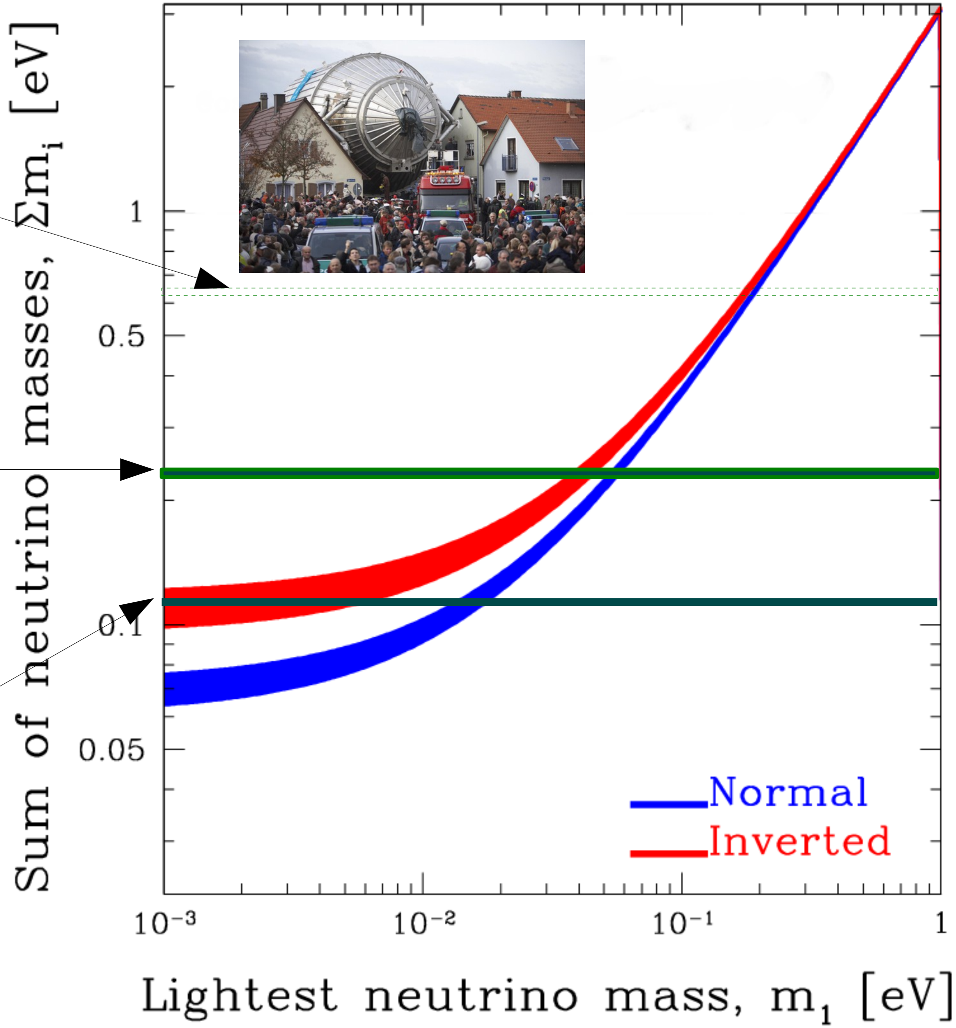
$$\sum m_\nu < 0.23 \text{ eV} \quad (95\% \text{C.L.})$$

Ade et al. [Planck collaboration] 2015

Planck + Lyman-alpha

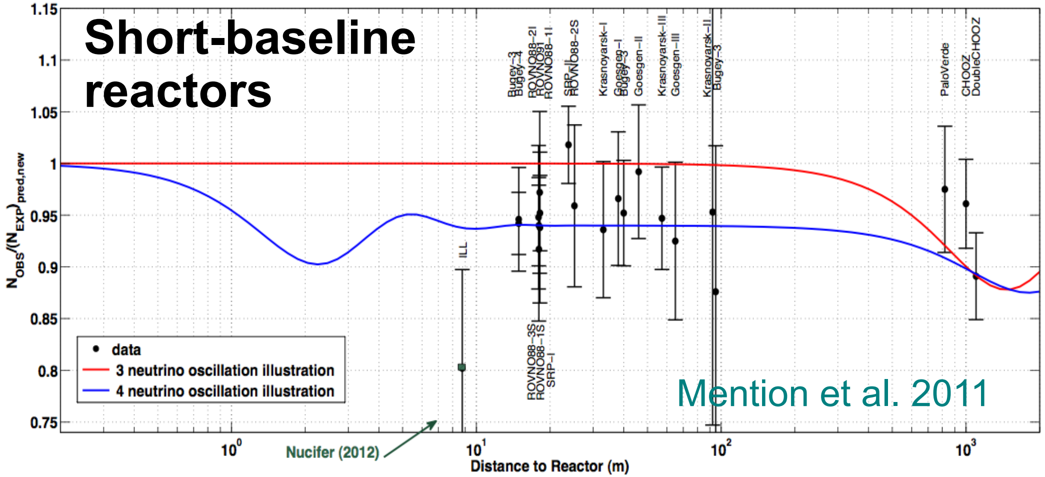
$$\sum m_\nu < 0.12 \text{ eV} \quad (95\% \text{C.L.})$$

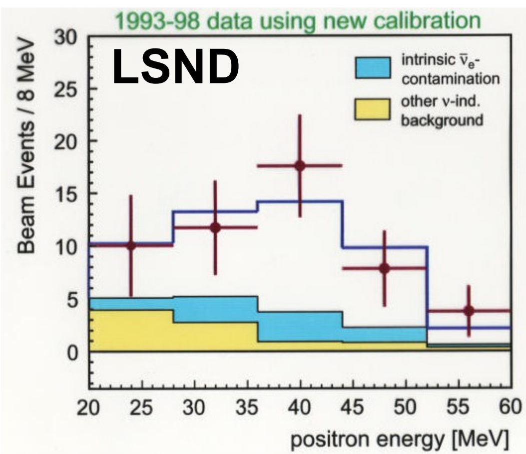
Palanque-Delabrouille et al. 2015

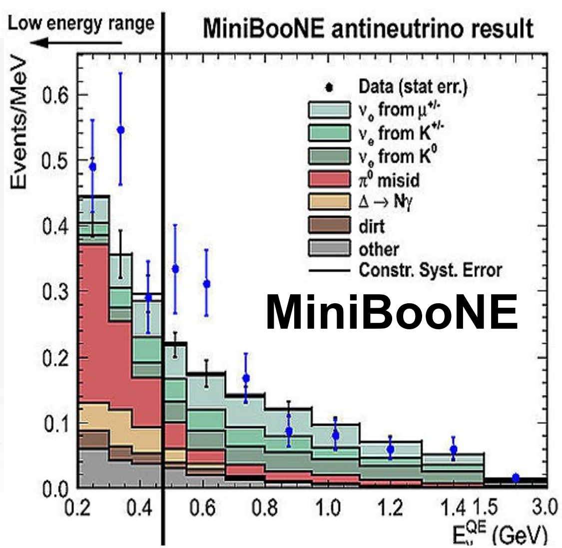


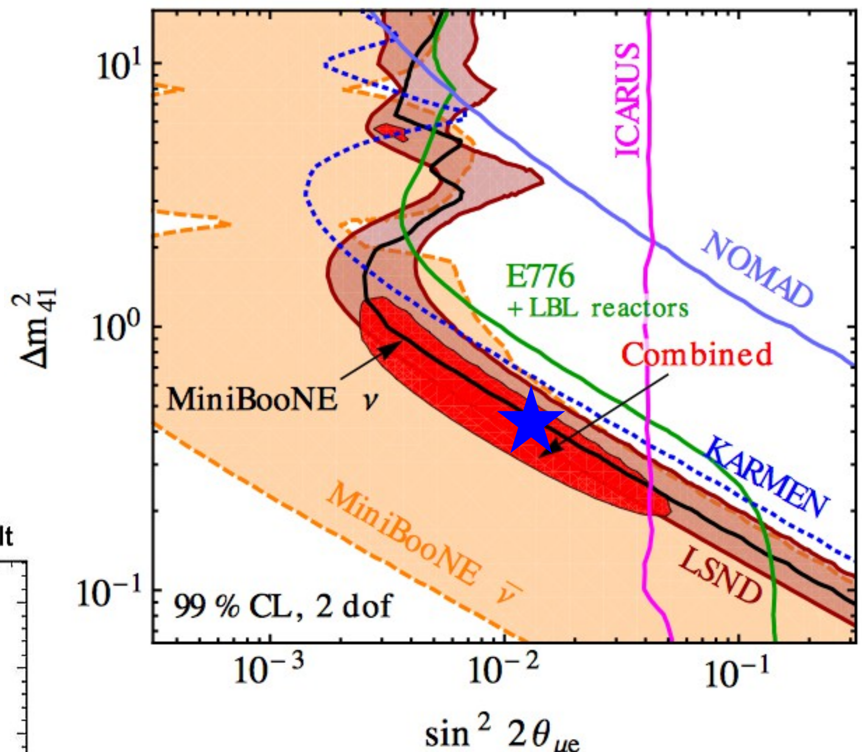
Sterile neutrinos...

See talk of Giunti









$$\Delta m^2_{SBL} \sim 0.5 \ \ eV^2$$
$$\sin^2 2\theta_{SBL} \sim 10^{-2}$$

Kopp, Machado, Maltoni & Schwetz 2012

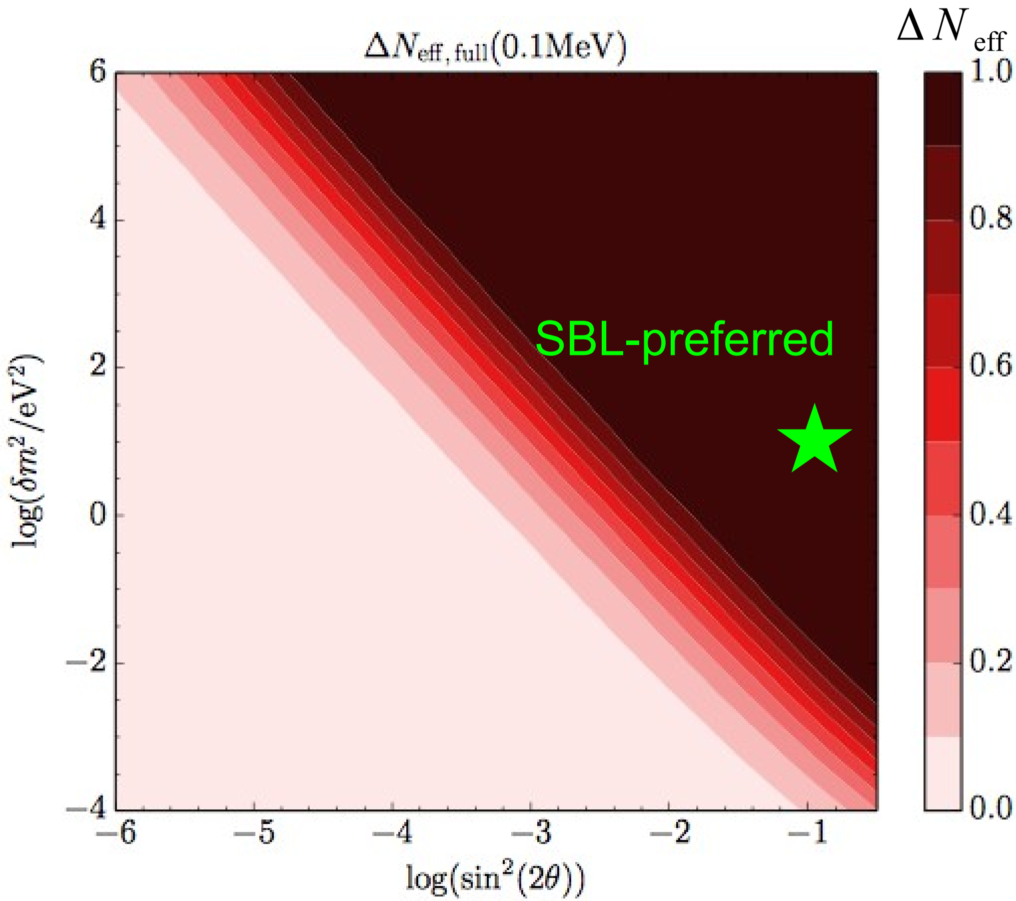
Sterile neutrinos > in cosmology...

The **SBL-preferred mixing parameters** imply thermalisation of the SBL sterile neutrino in the early universe via oscillations+scattering.

$$m_{\rm SBL} \sim \sqrt{\Delta m^2_{\rm SBL}} \sim 0.7 \quad {\rm eV}$$

$$\Delta N_{\rm eff} \sim 1$$

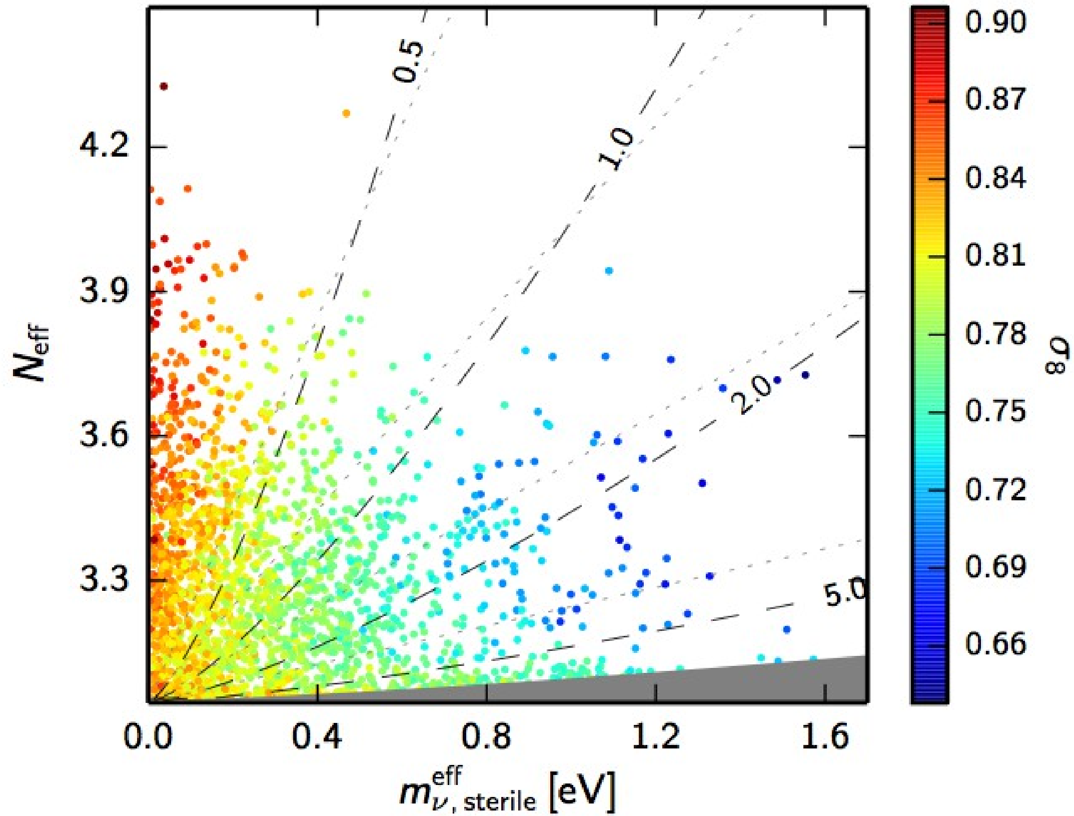
$N_{\rm eff}$ = Effective number of neutrino species



Hannestad, Hansen, Tram & Y[3]W 2015
also older works of Abazajian, Di Bari,
Foot, Kainulainen, etc. from 1990s-early 2000s

Sterile neutrinos > in cosmology > CMB limits...

See talk of Reichardt



Planck TT+lowP+lensing+BAO

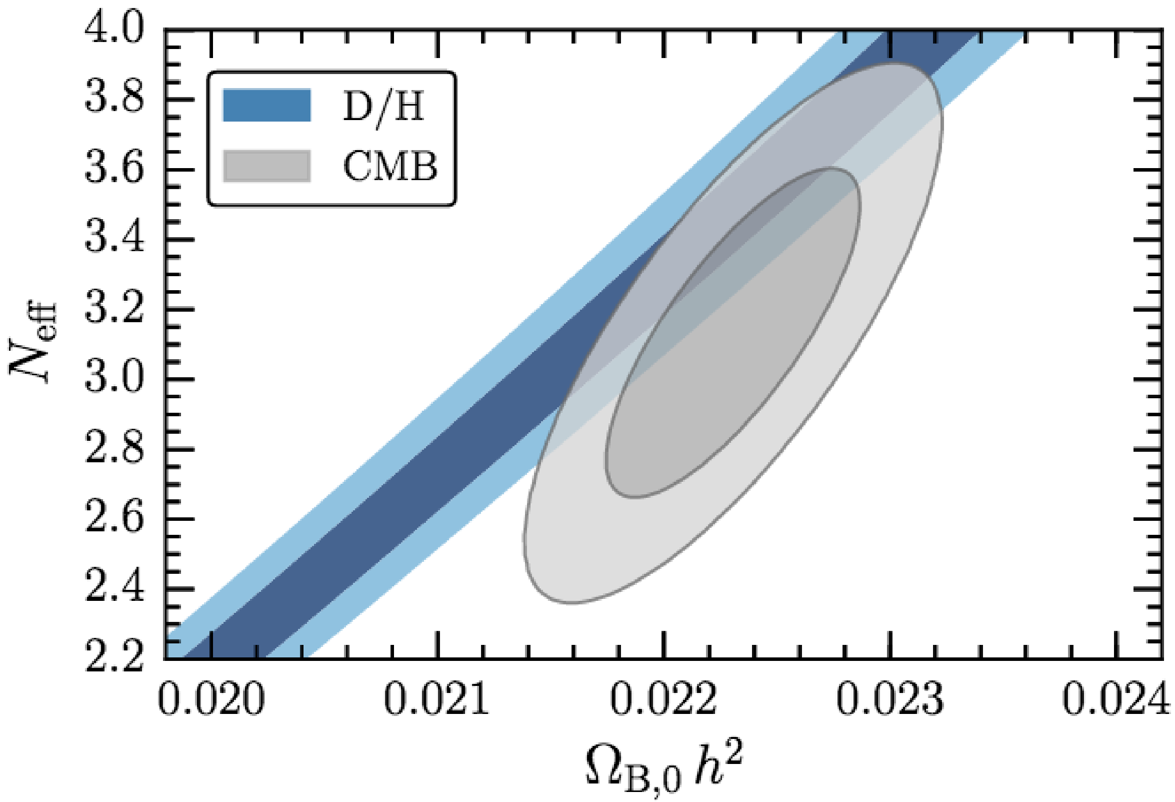
$$N_{\rm eff} = 3.2 \pm 0.5$$
$$\sum m_\nu < 0.32 \text{ eV} \quad (95\%\,\text{C.L.})$$

No evidence for extra neutrinos from CMB+large-scale structure.

Ade et al. [Planck collaboration] 2015

Sterile neutrinos > in cosmology > BBN limits...

See talk of Mangano



Deuterium (D/H) + CMB

$$N_{\rm eff} = 3.44 \pm 0.45 \quad (95\%\,\mathrm{C.L.})$$

Cooke, Pettini, Nollett & Jorgenson 2016

QCD axion…

QCD axion...

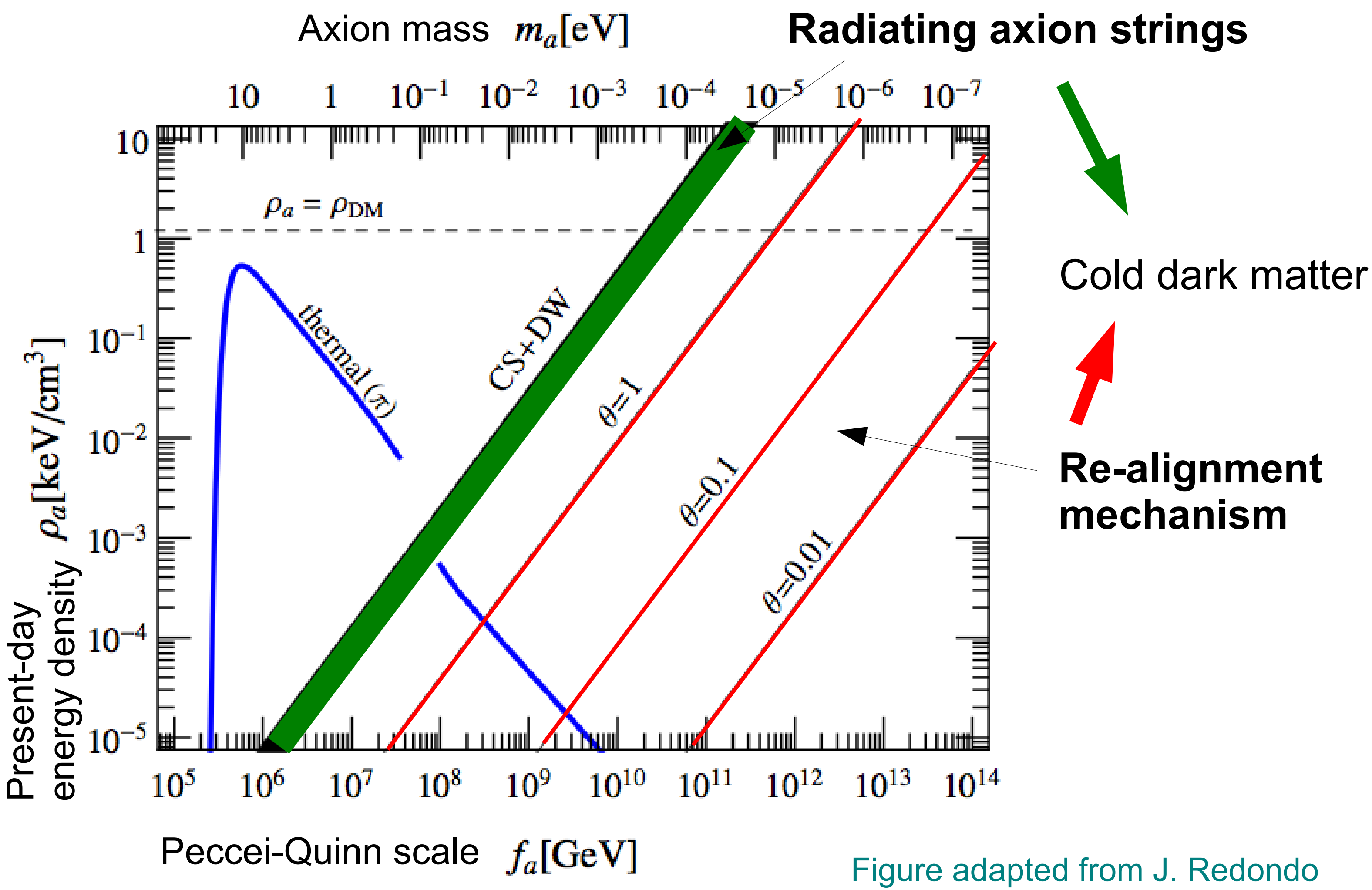


Figure adapted from J. Redondo

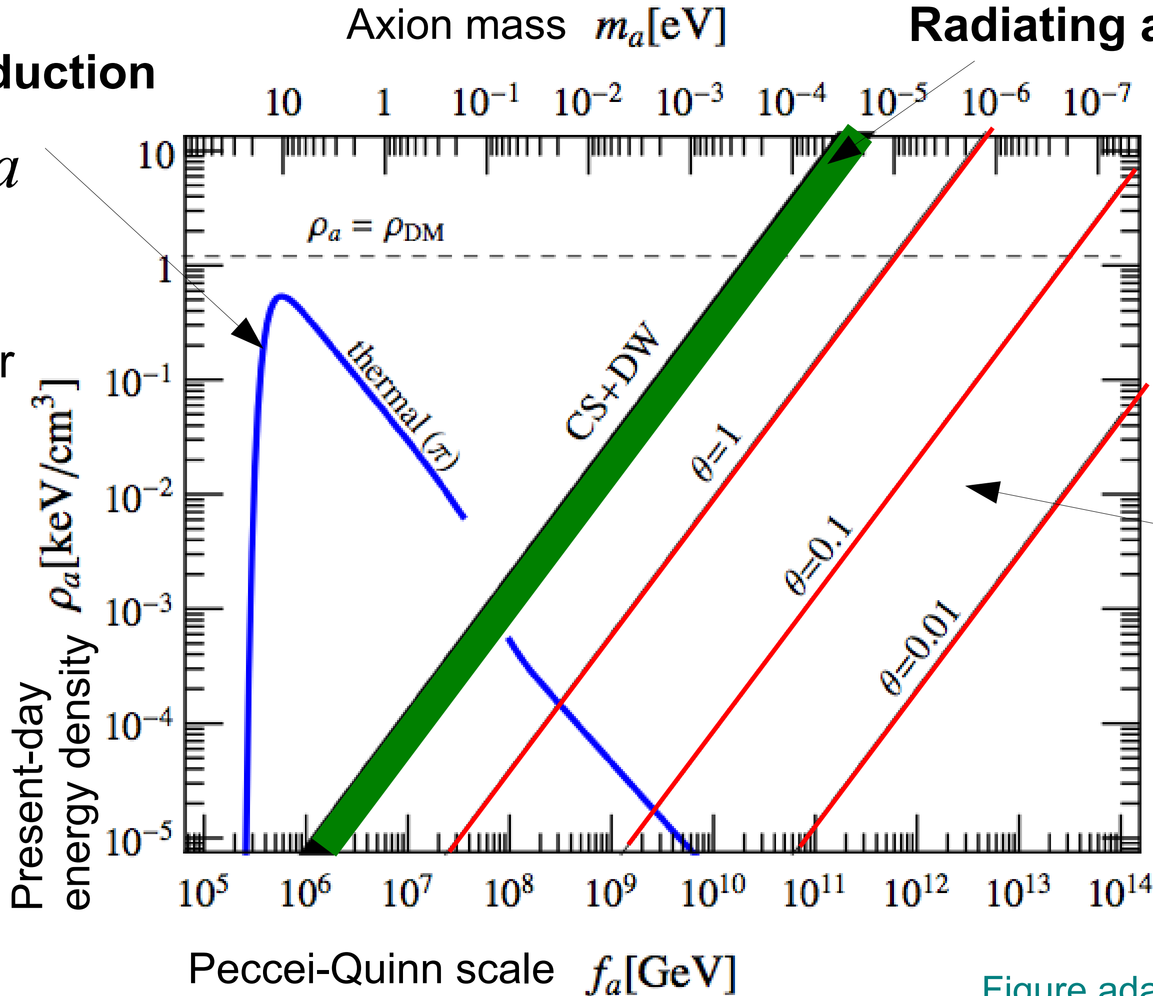
QCD axion...

Thermal production

$\pi + \pi \rightarrow \pi + a$

Hot dark matter

Can be constrained in the same way as we constrain neutrino masses



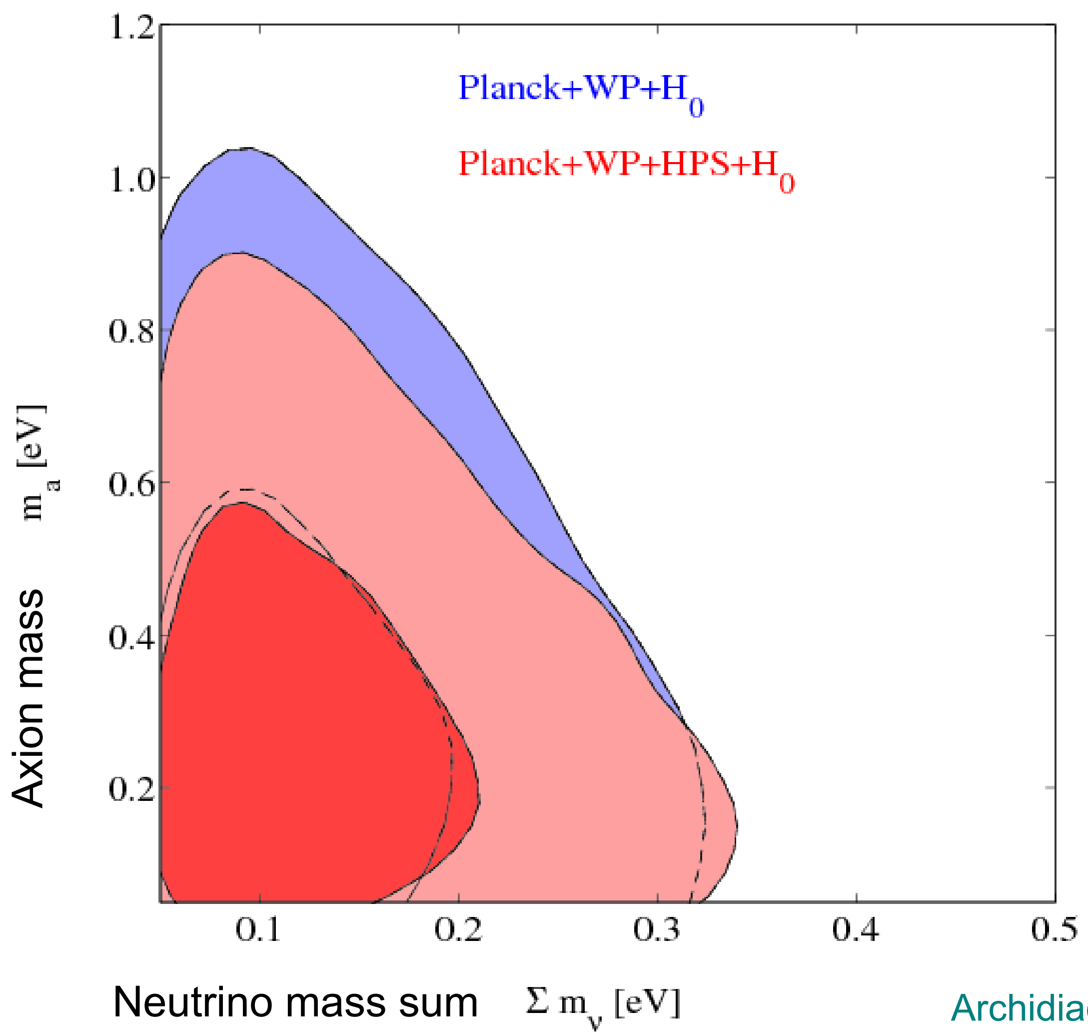
Radiating axion strings

Cold dark matter

Re-alignment mechanism

Figure adapted from J. Redondo

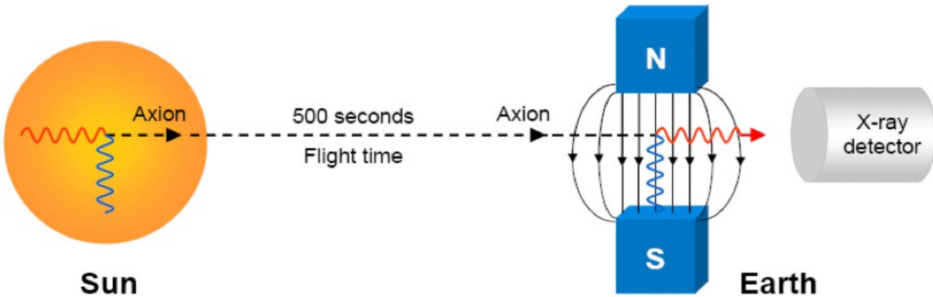
QCD axion > CMB limits...



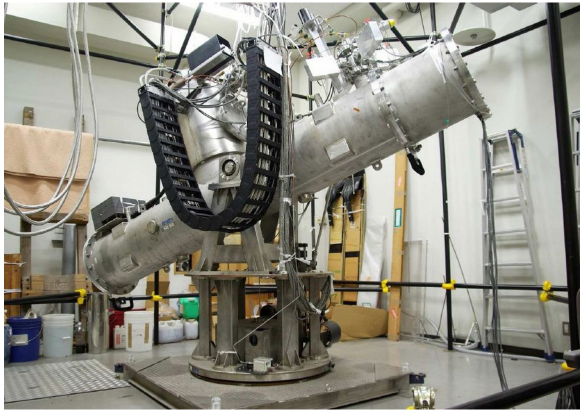
Archidiacono et al. 2013

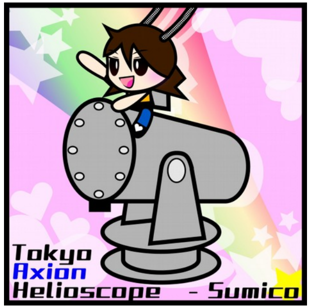
QCD axion > cosmology vs solar axion searches...

The hot dark matter axion parameter space happens to overlap with the search range for **solar axions**.

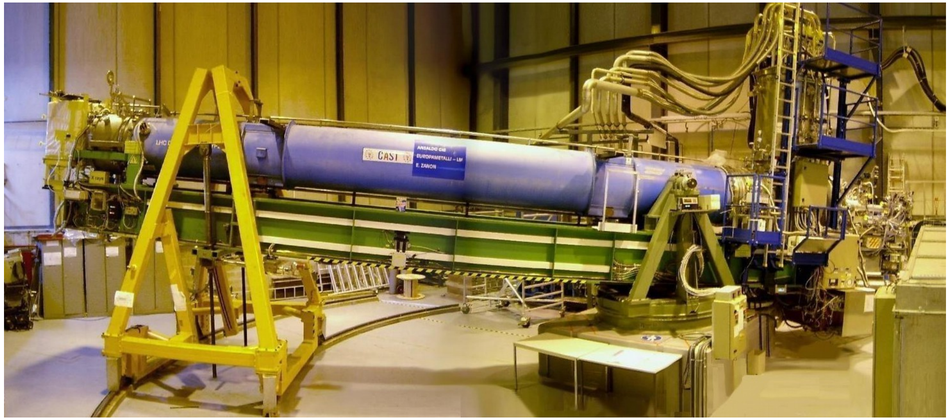


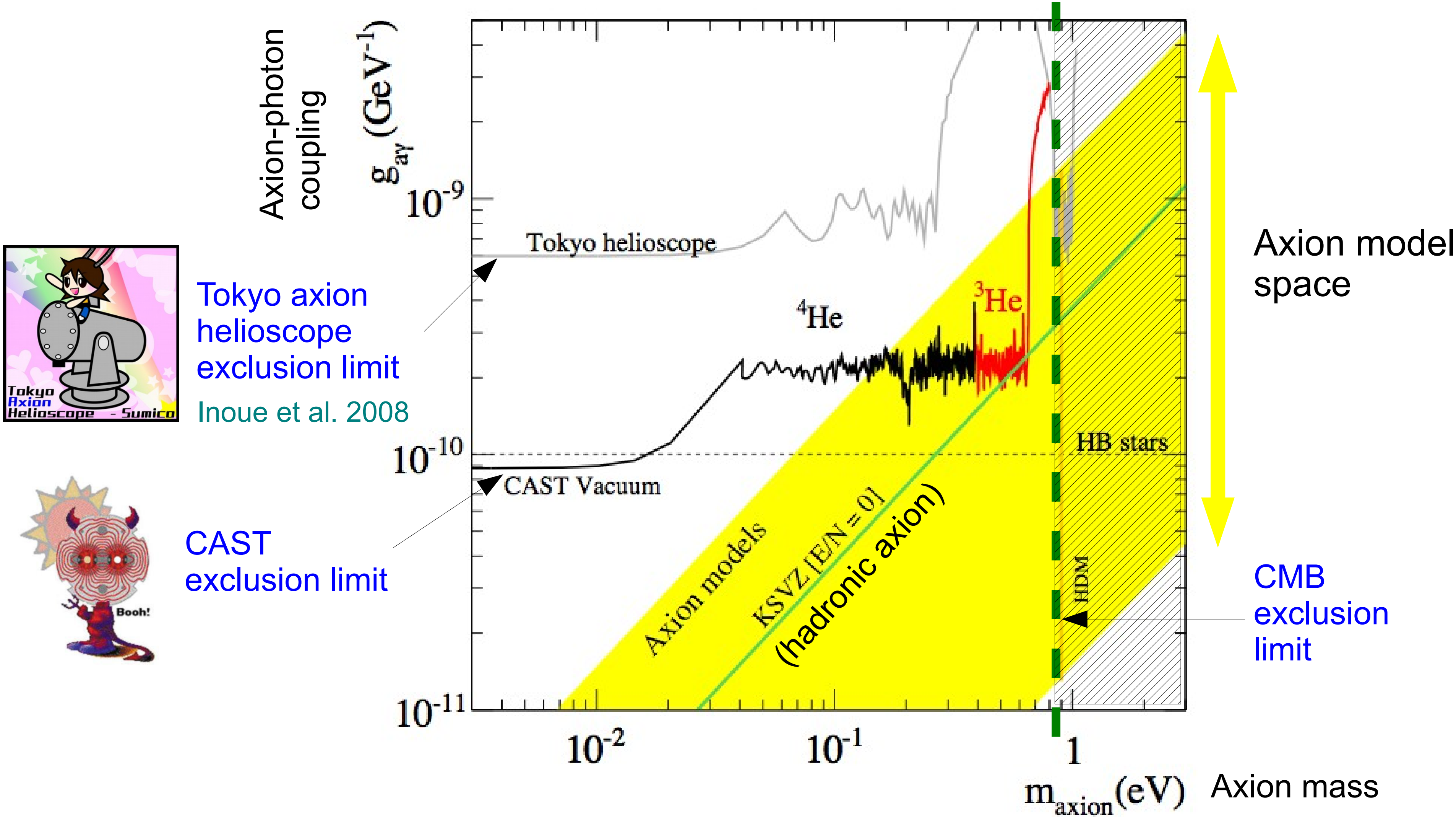
Tokyo Axion Helioscope "Sumico"





CERN Axion Solar Telescope





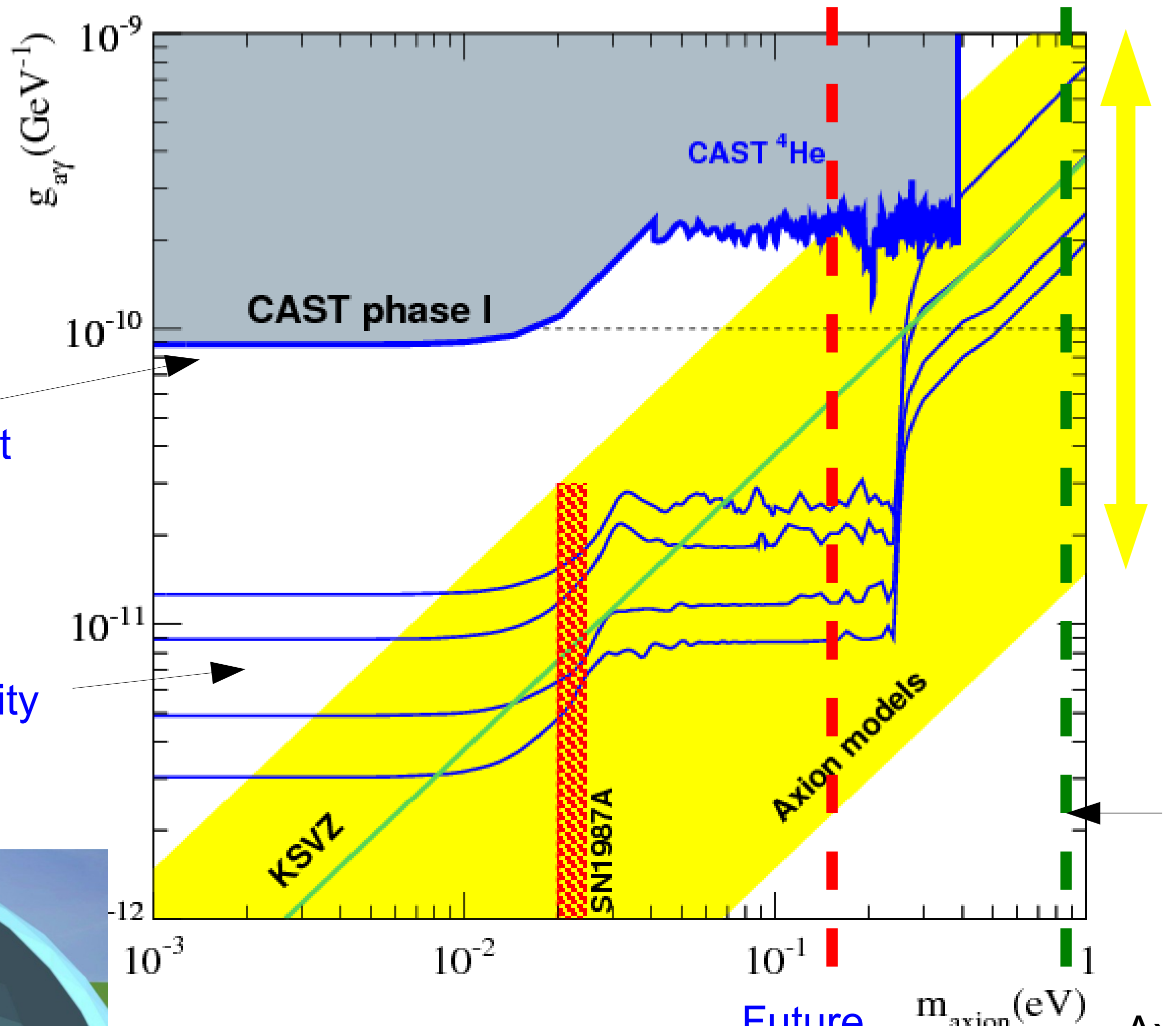
Aune et al. [CAST] arXiv:1106.3919

Axion-photon coupling

CAST exclusion limit

IAXO expected sensitivity

arXiv:1401.3233



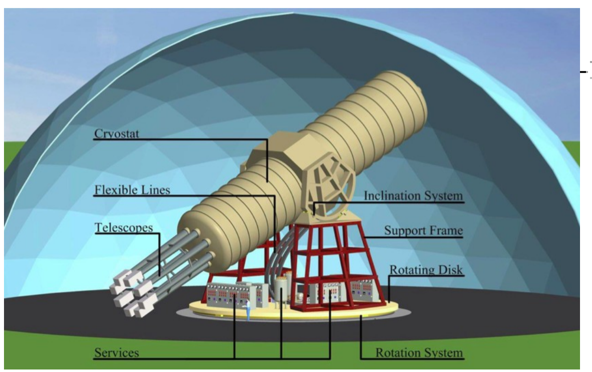
Axion model space

CMB exclusion limit

Future cosmological sensitivity

Archidiacono et al. 2015

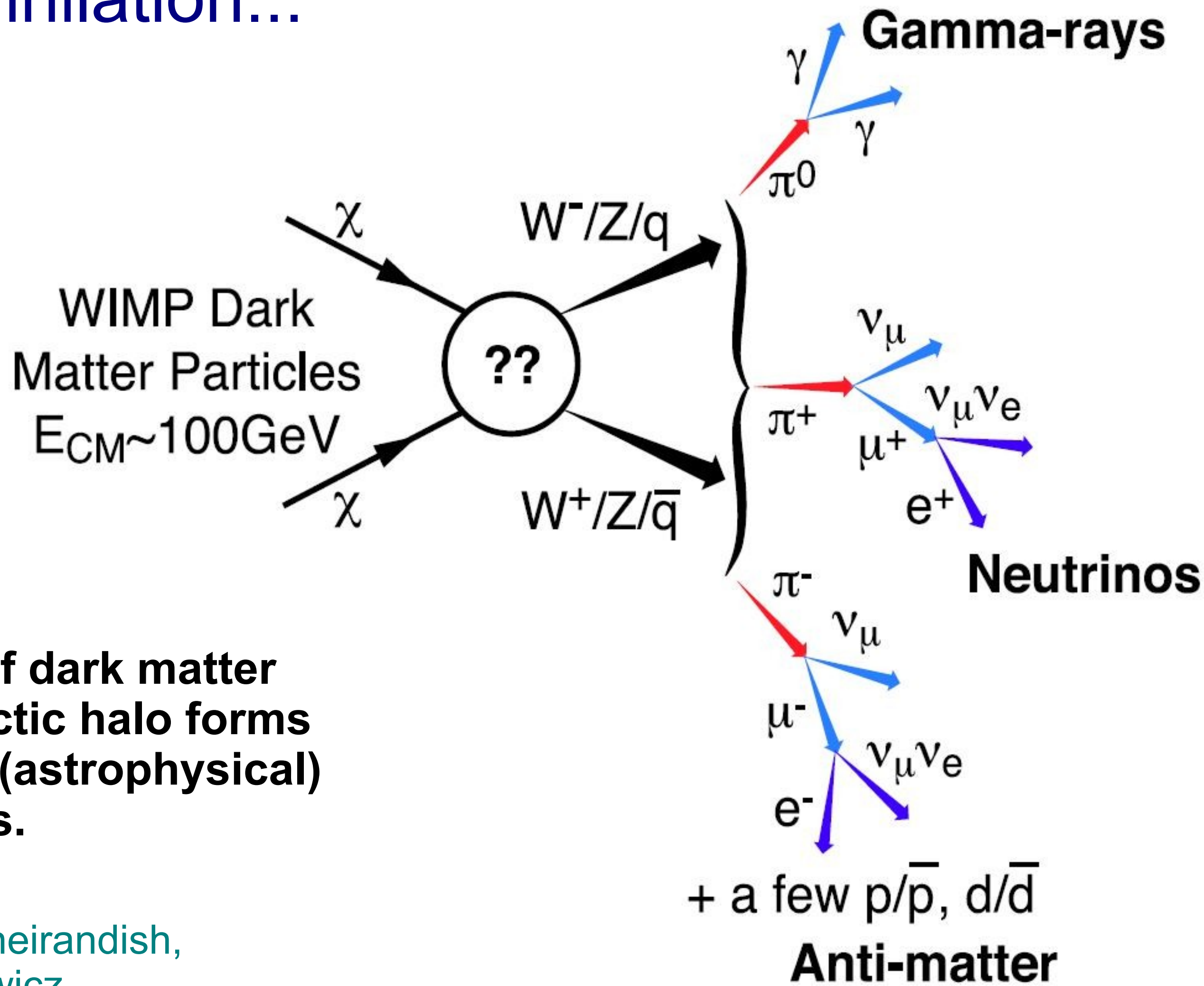
Axion mass



Next generation:
The **I**nternational **AX**ion **O**bservatory (IAXO)

Dark matter...

Dark matter annihilation...



Annihilation/decay of dark matter particles in the Galactic halo forms the basis of indirect (astrophysical) dark matter searches.

See talks of Sarcevic, Kheirandish, Caputo, Medici, Frankiewicz

Vitale et al. [Fermi-LAT collaboration] 2009

Dark matter annihilation > CMB...

Annihilation **injects energy** into the medium, ionises it, thereby delaying photon decoupling.

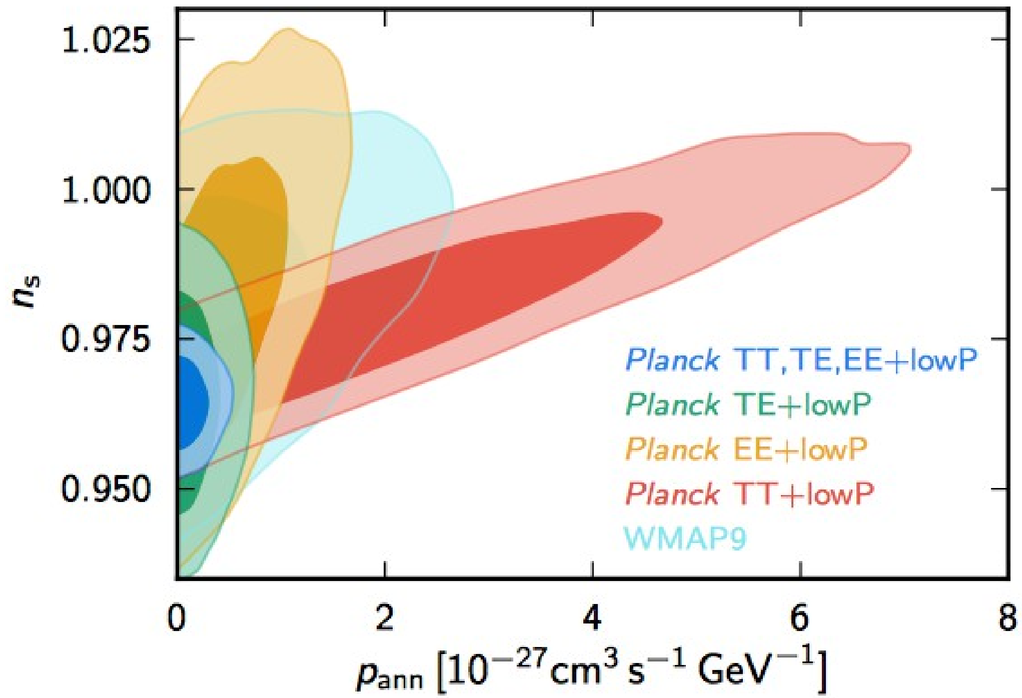
Parameter constrained by the CMB:

Annihilation cross-section

$$p_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi}$$

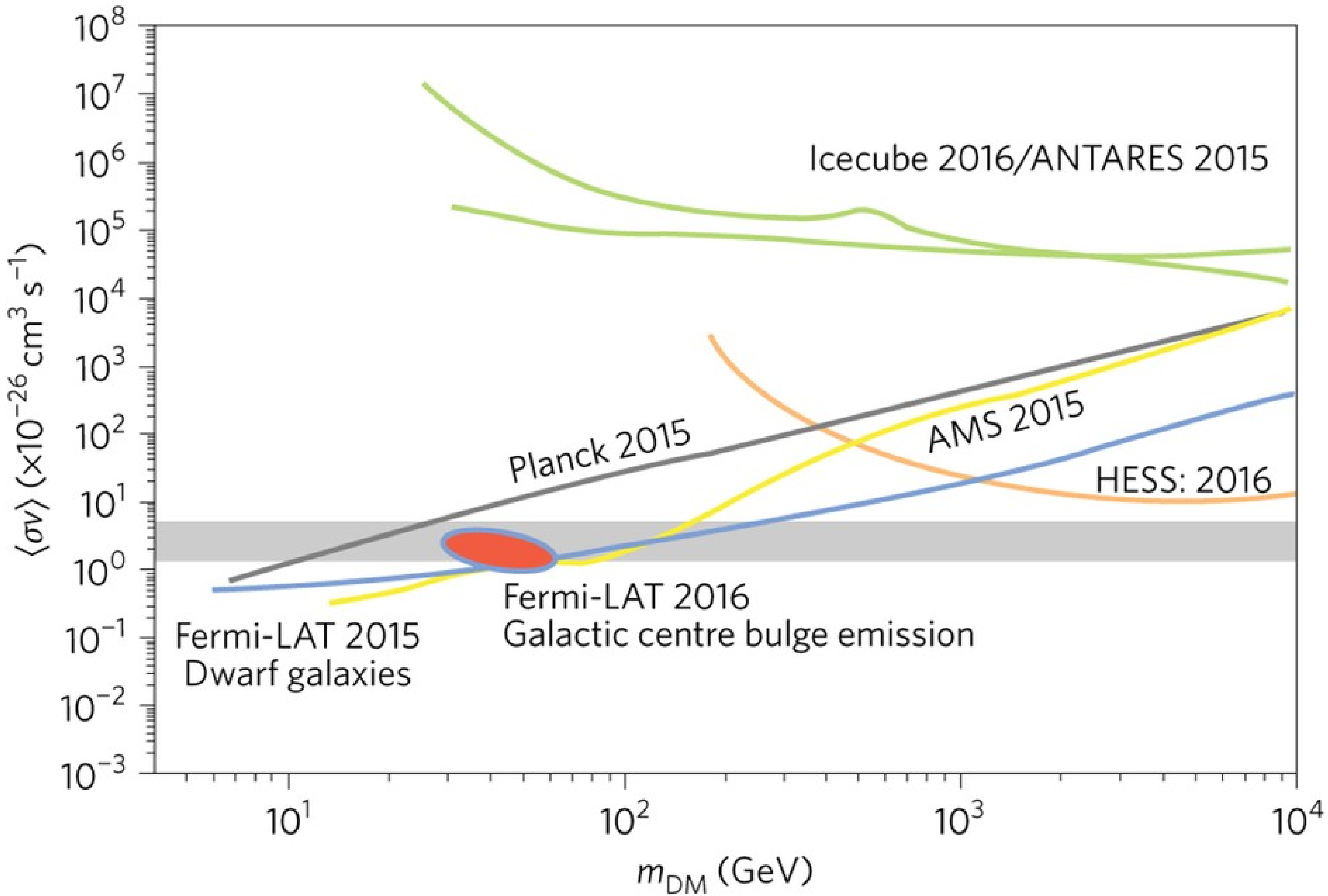
Fraction of energy absorbed by the medium (model-dependent)

DM mass

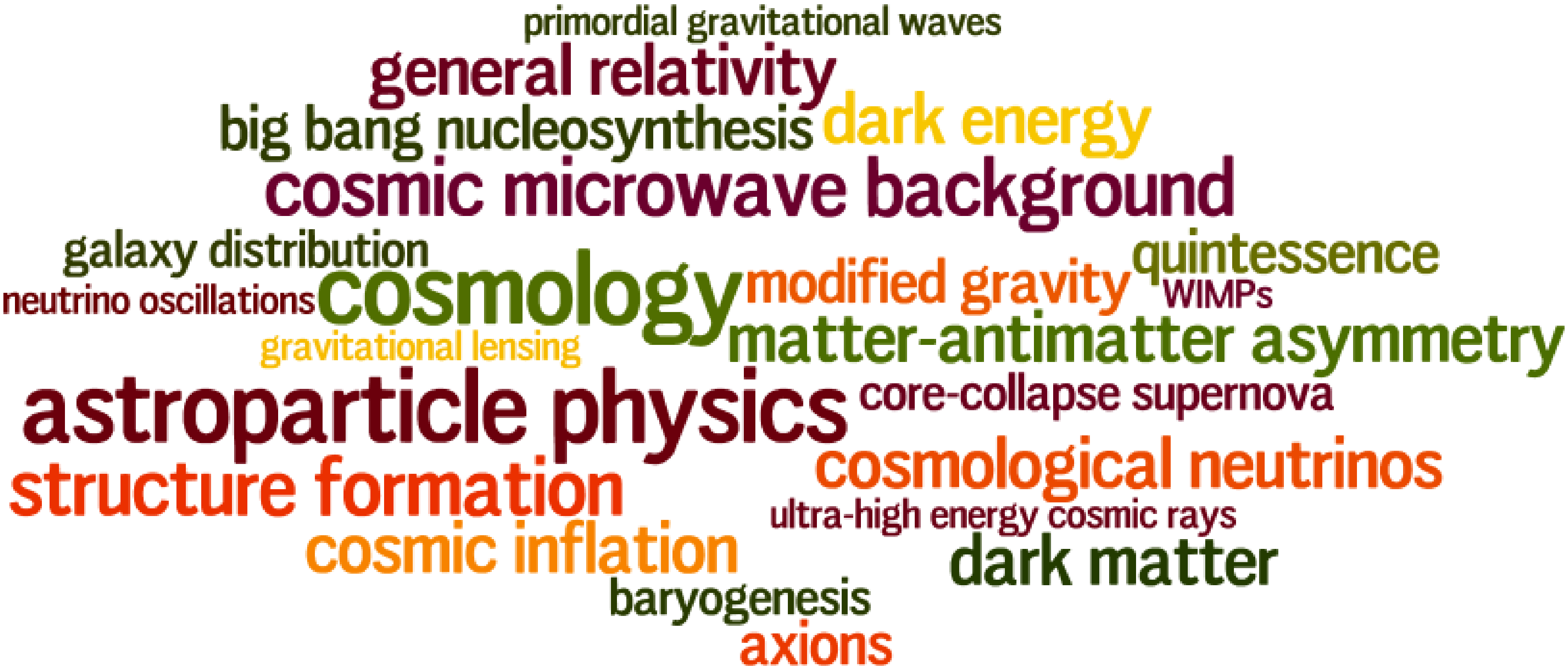


Ade et al. [Planck collaboration] 2015

Dark matter annihilation > CMB vs indirect search...



Conrad & Reimar, Nature Physics, 2017


primordial gravitational waves
general relativity
big bang nucleosynthesis
dark energy
cosmic microwave background
galaxy distribution
quintessence
neutrino oscillations
cosmology
modified gravity
WIMPs
gravitational lensing
matter-antimatter asymmetry
astroparticle physics
core-collapse supernova
cosmological neutrinos
structure formation
ultra-high energy cosmic rays
cosmic inflation
dark matter
baryogenesis
axions