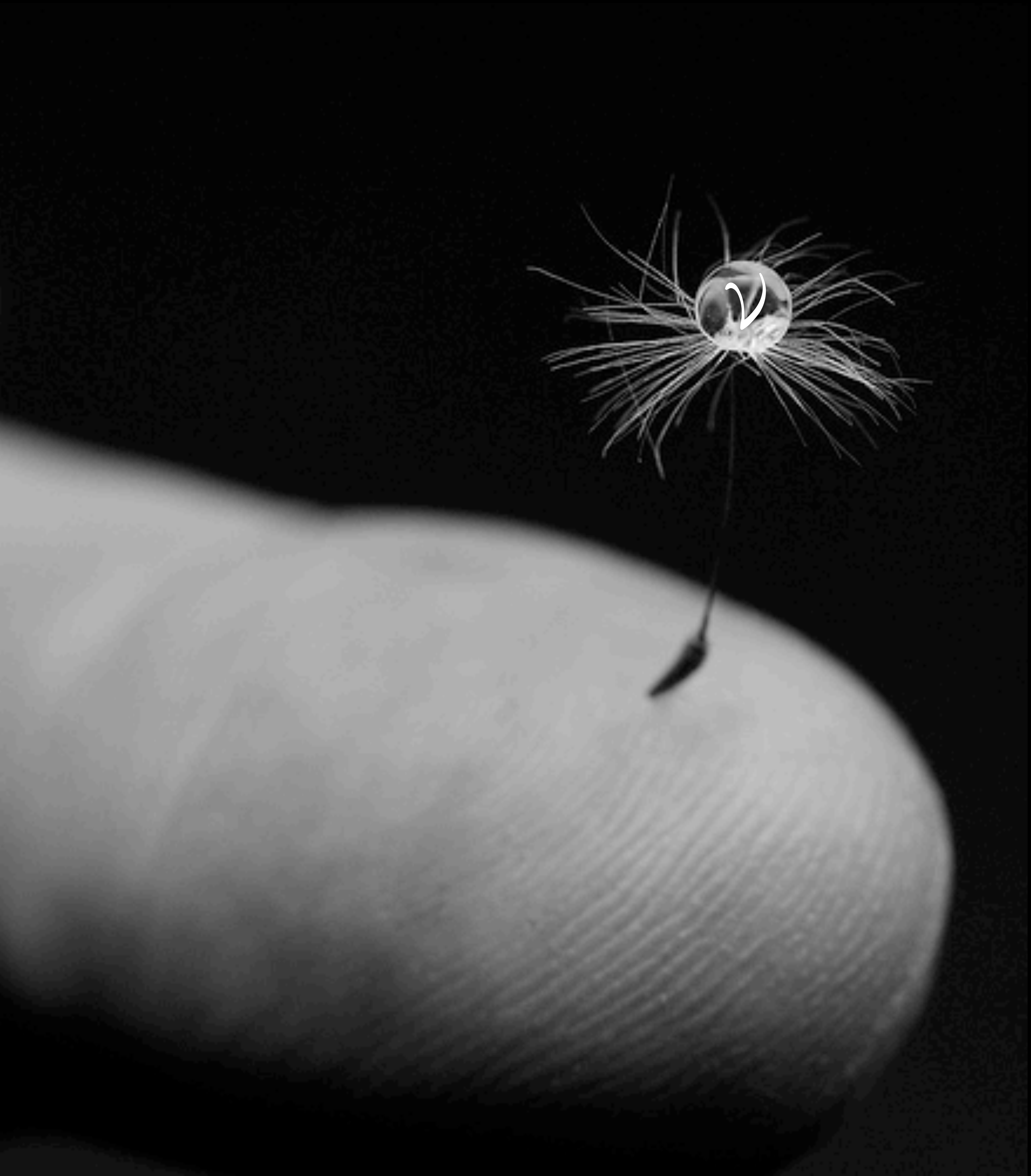
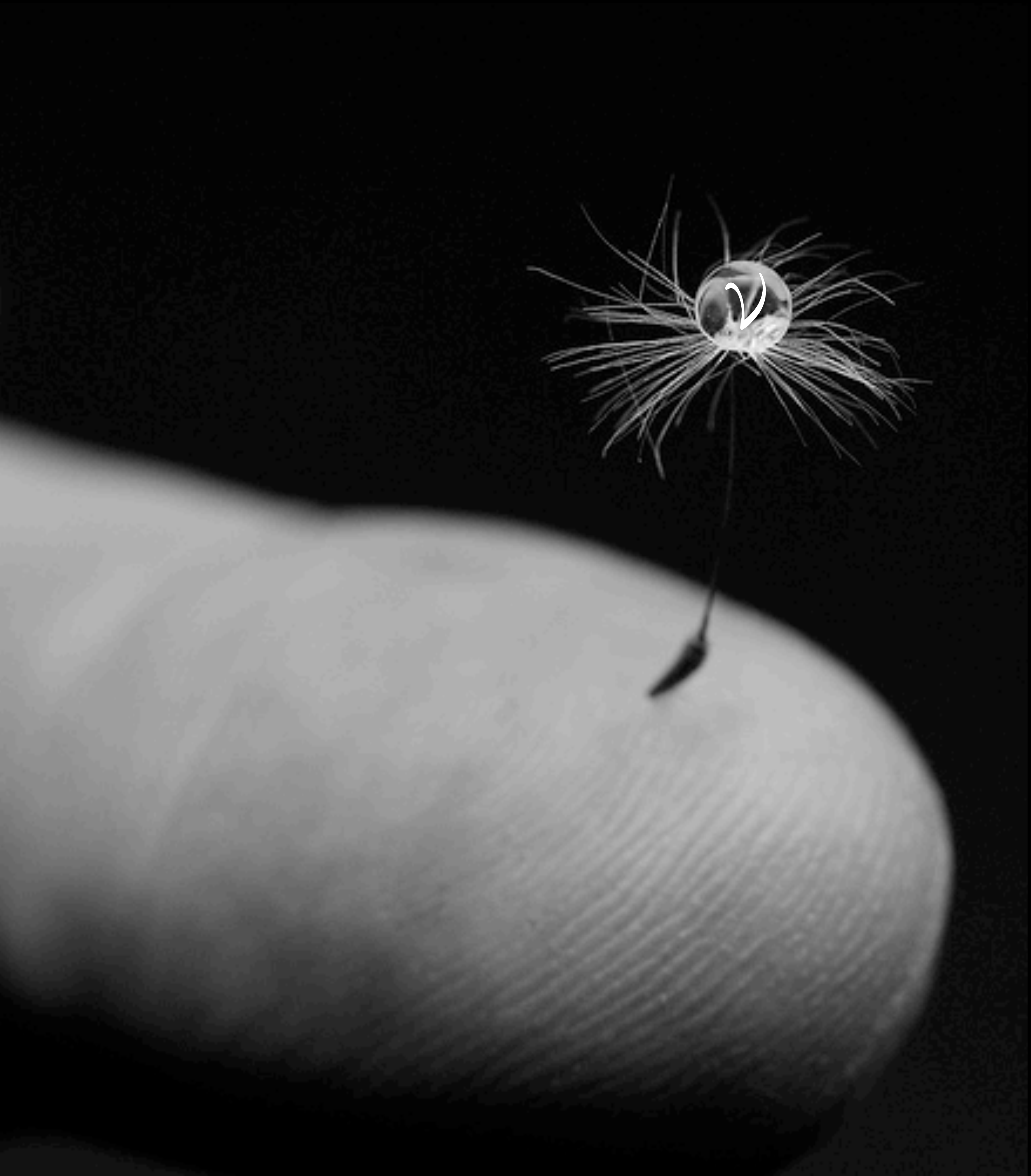




Weighing

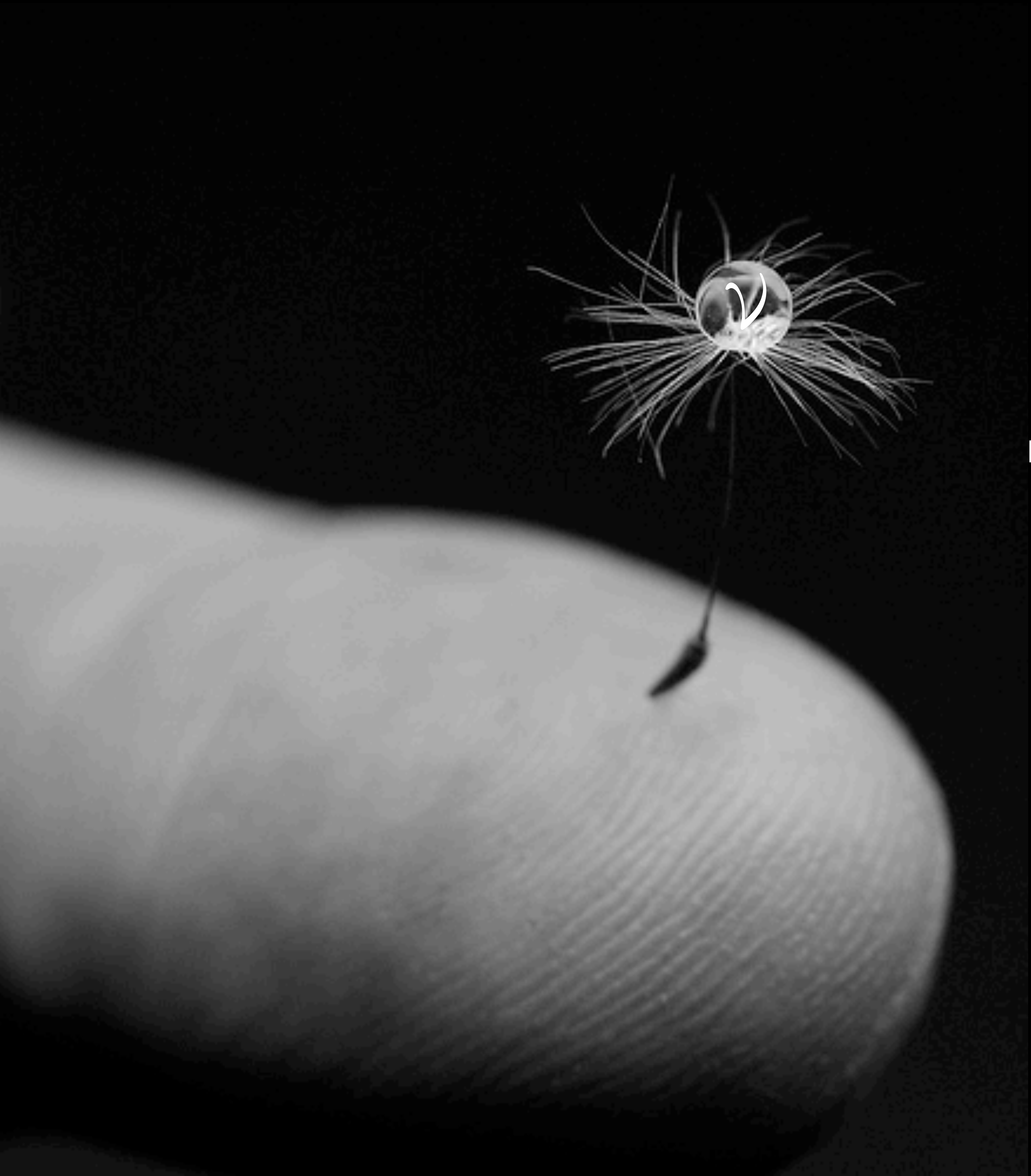
Neutrinos

APS "April" Meeting

May 1st, 2011

J. A. Formaggio

Massachusetts Institute of Technology



Measuring ν masses

(the framework)

Measuring neutrinos from the Heavens

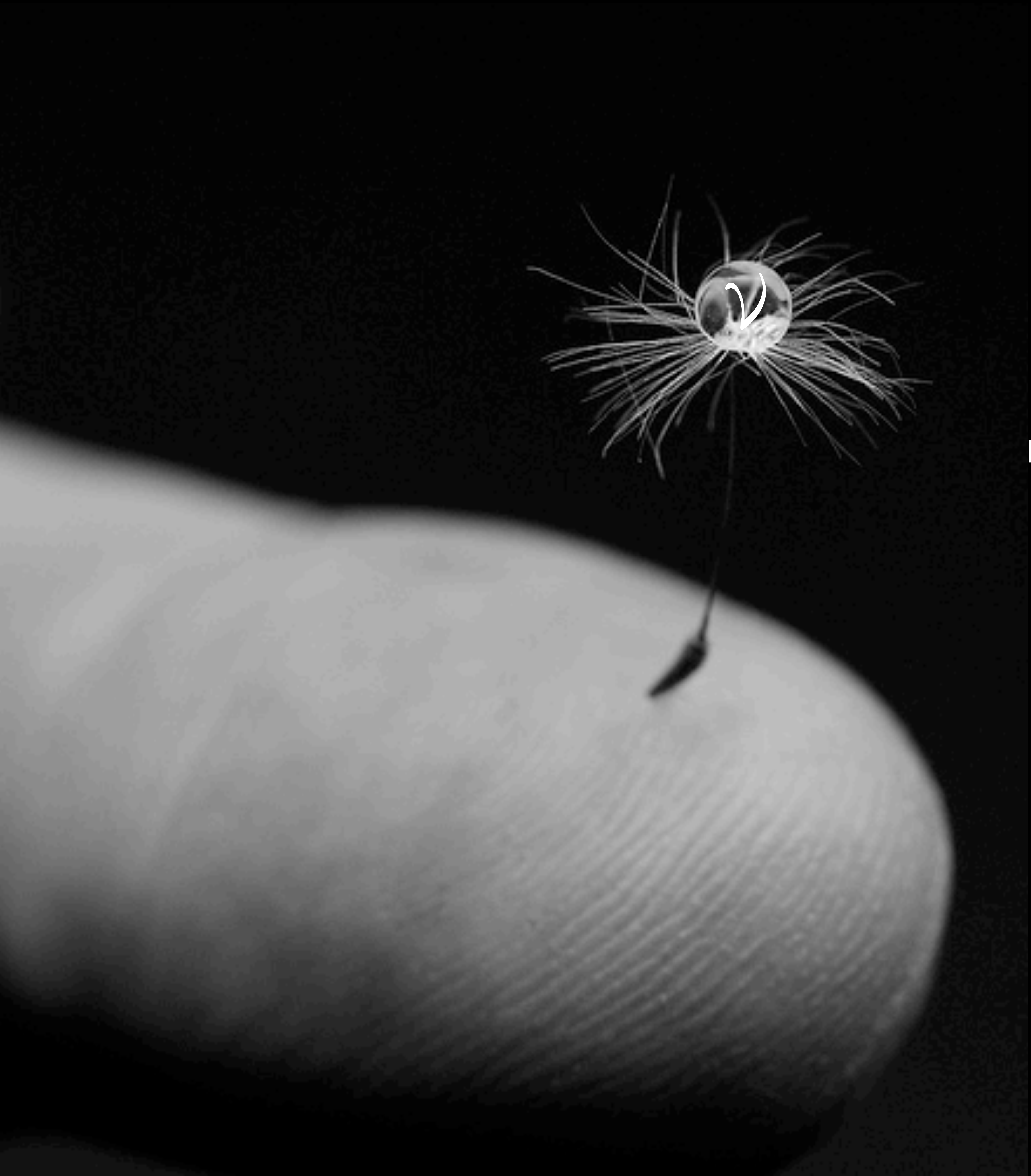
(cosmology)

Measuring neutrinos on Earth

(beta decay)

Patient measurements

(Neutrinoless double beta decay)



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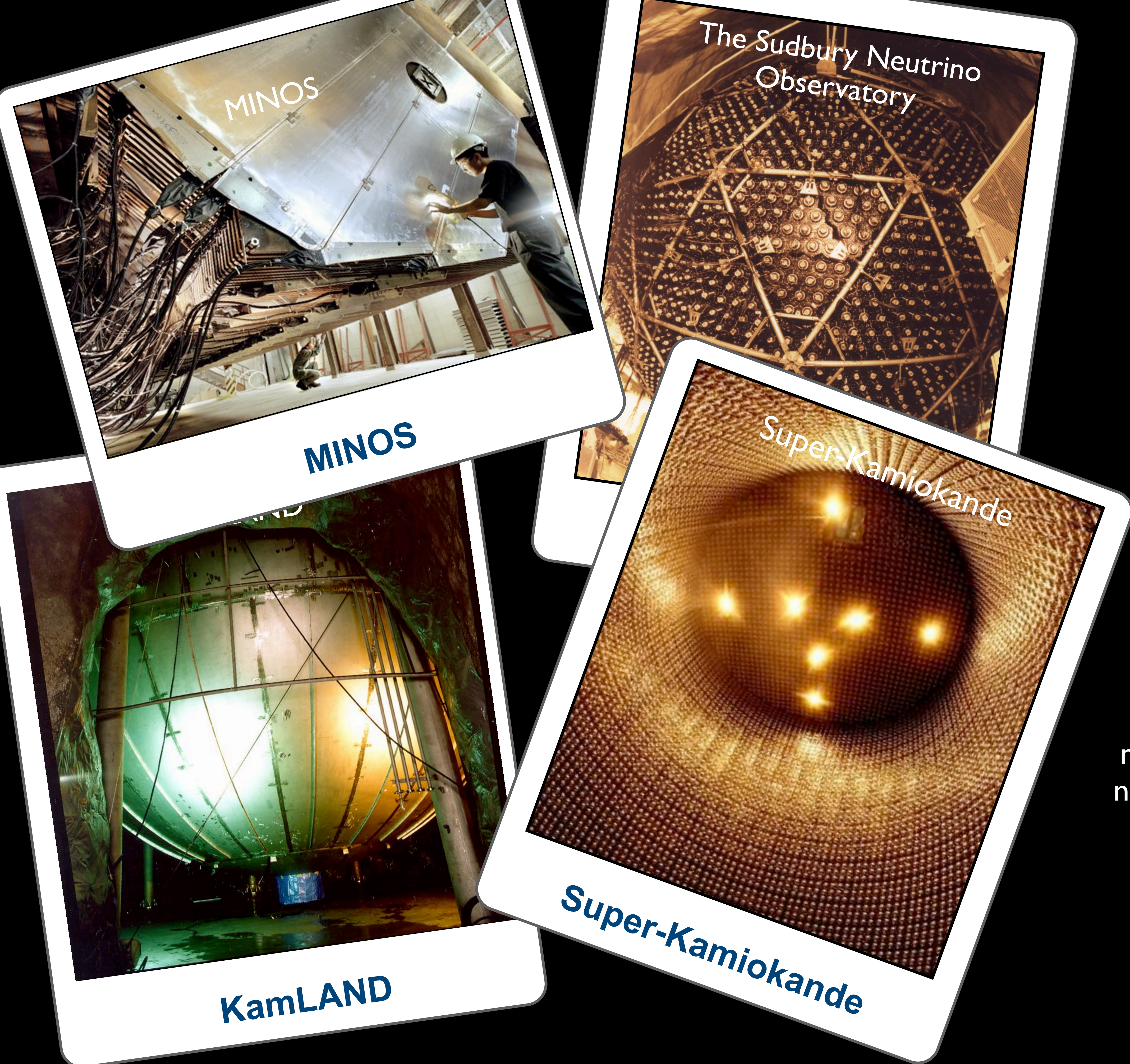
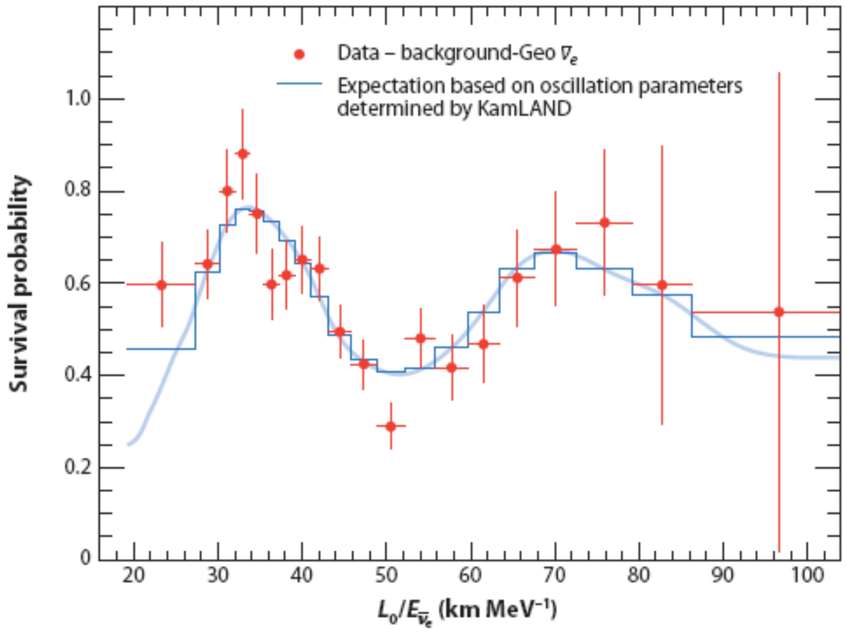


Body of Evidence

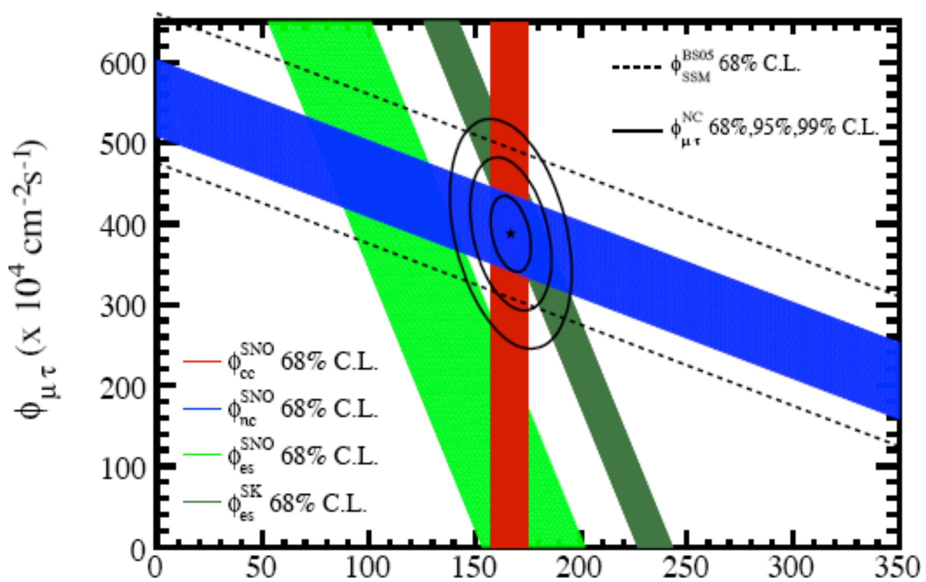
The phenomena of neutrino oscillations is now firmly established.

Neutrinos have mass. Period.

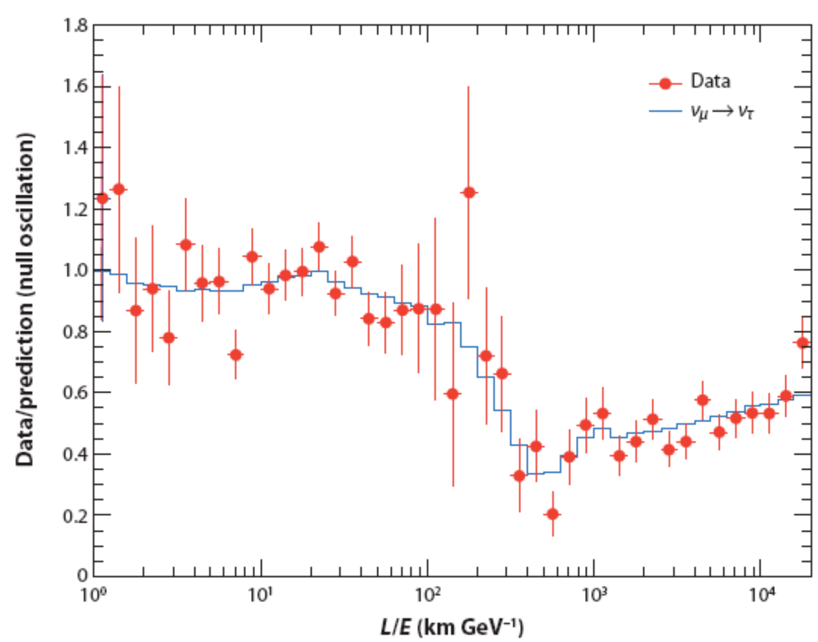
Body of Evidence



Reactor

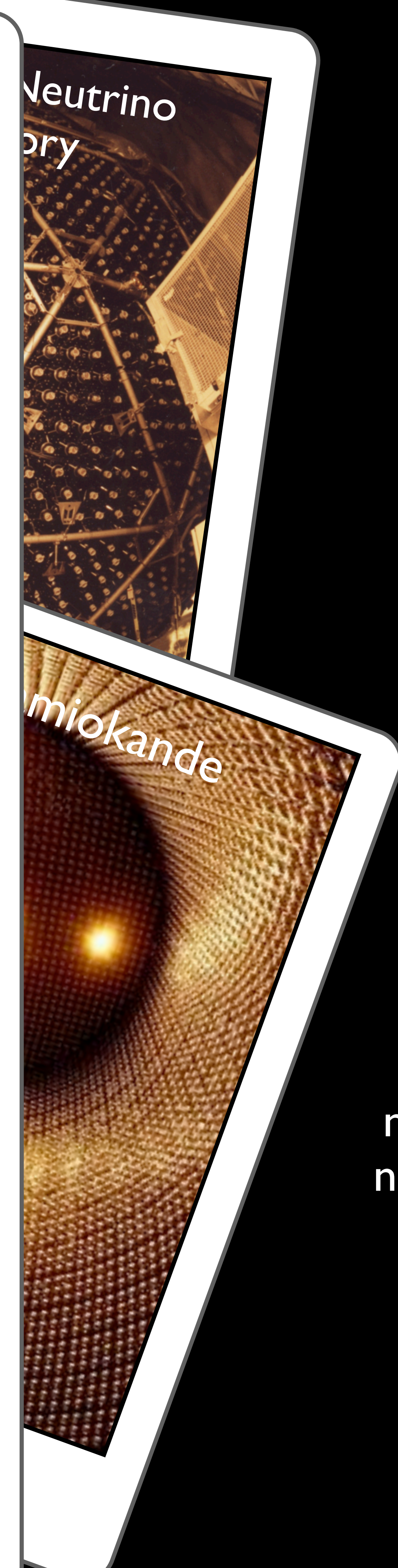


Solar



Atmospheric

Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).



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More Questions

<u>What We Don't Know</u>

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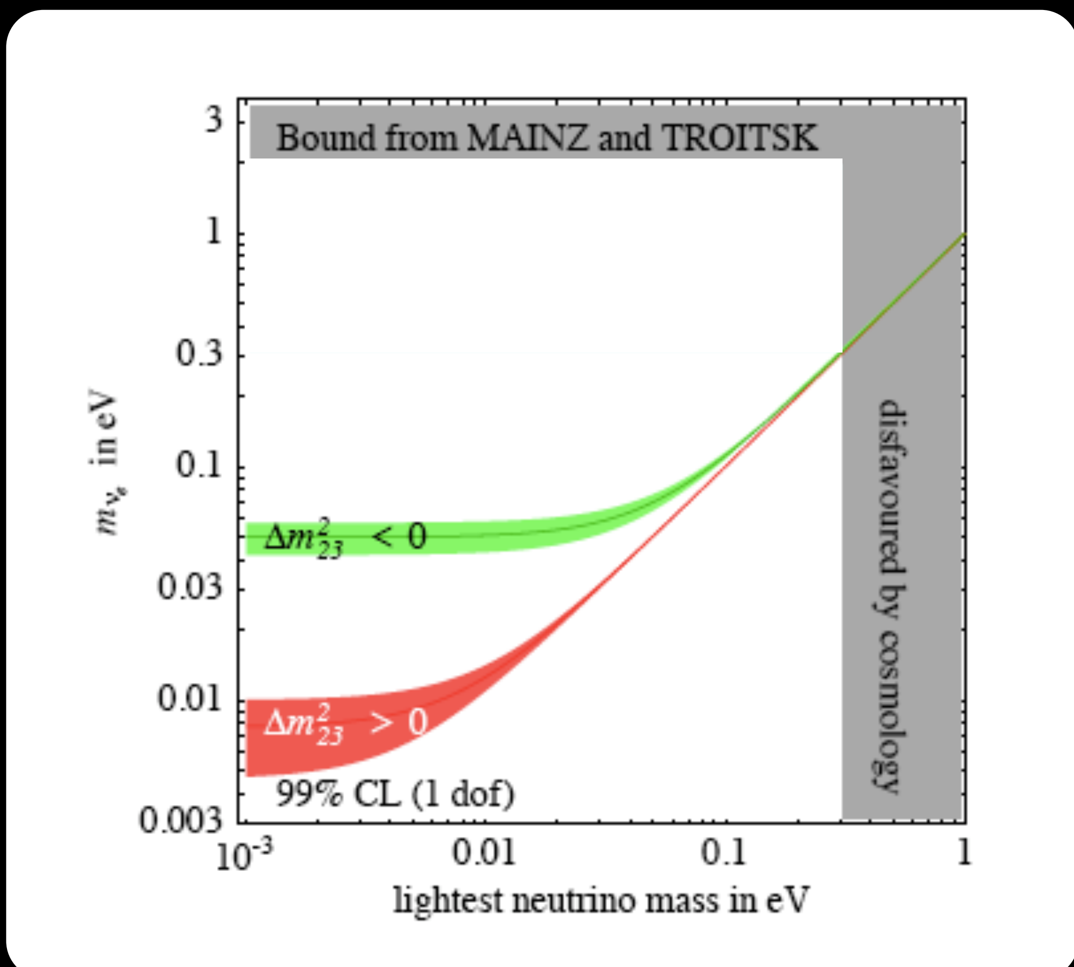
(2) What is the mass hierarchy?

(3) What is the nature of neutrino mass?



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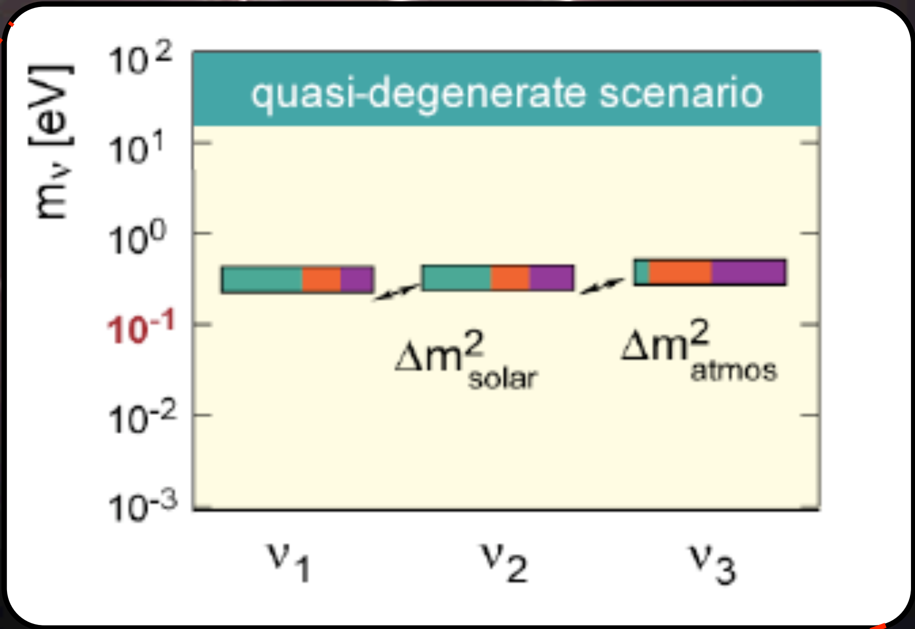

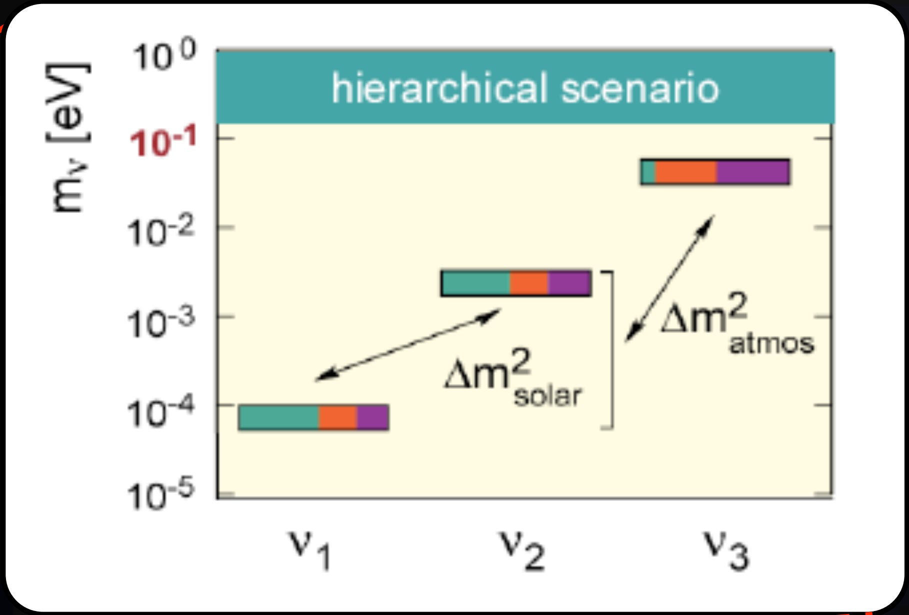

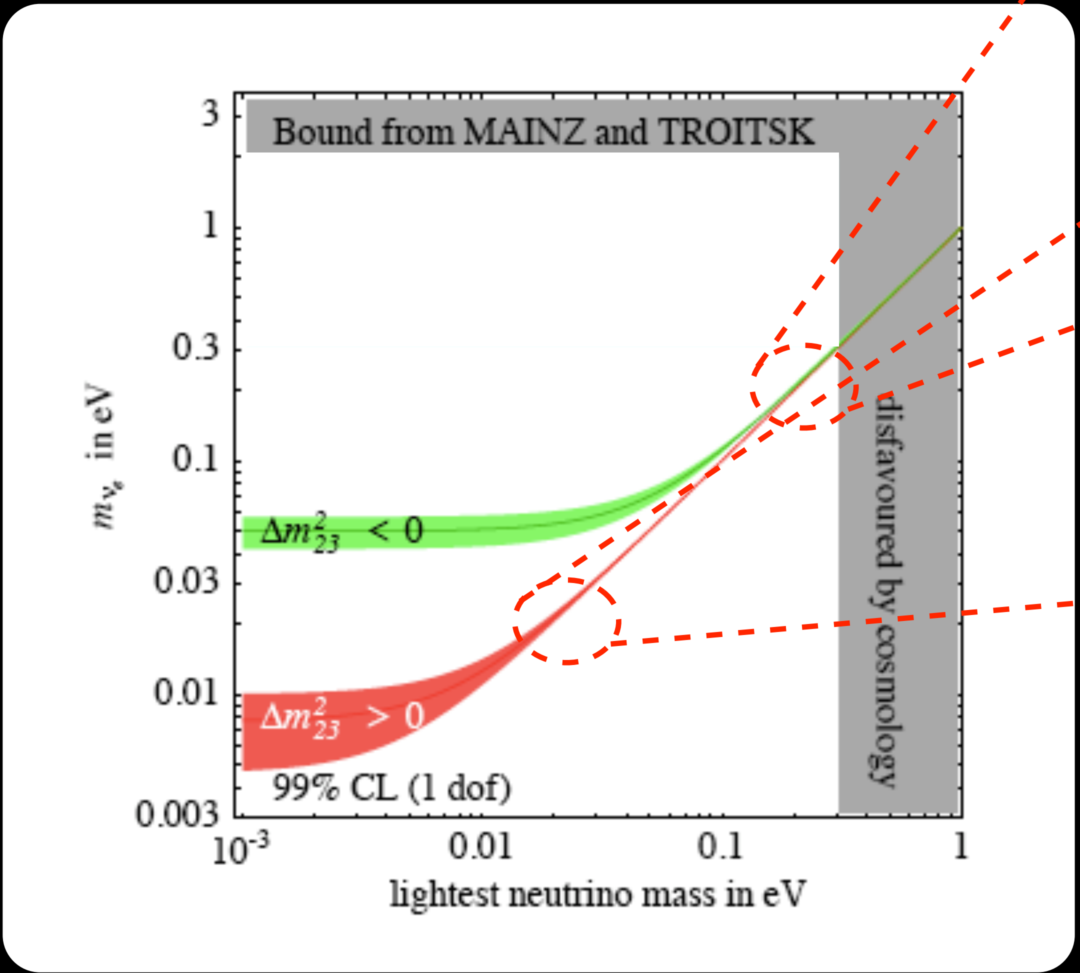

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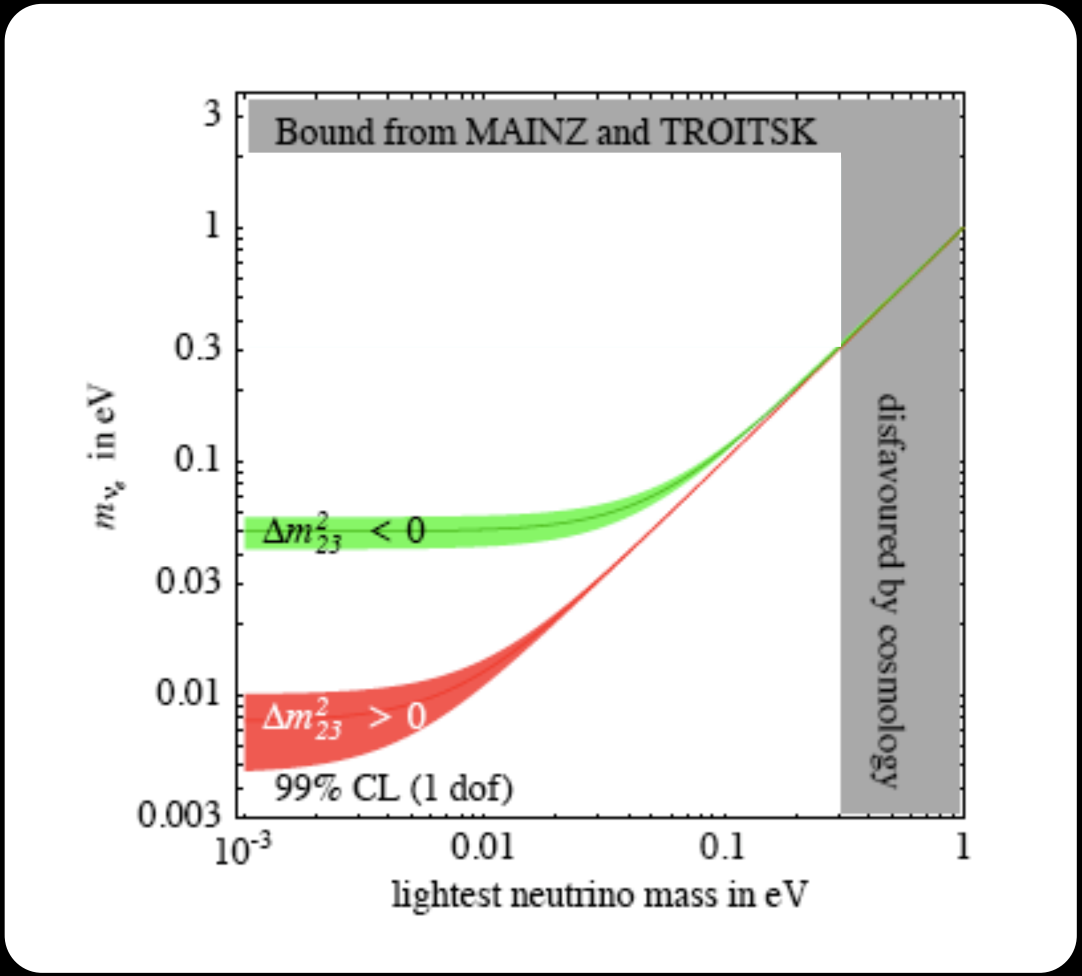

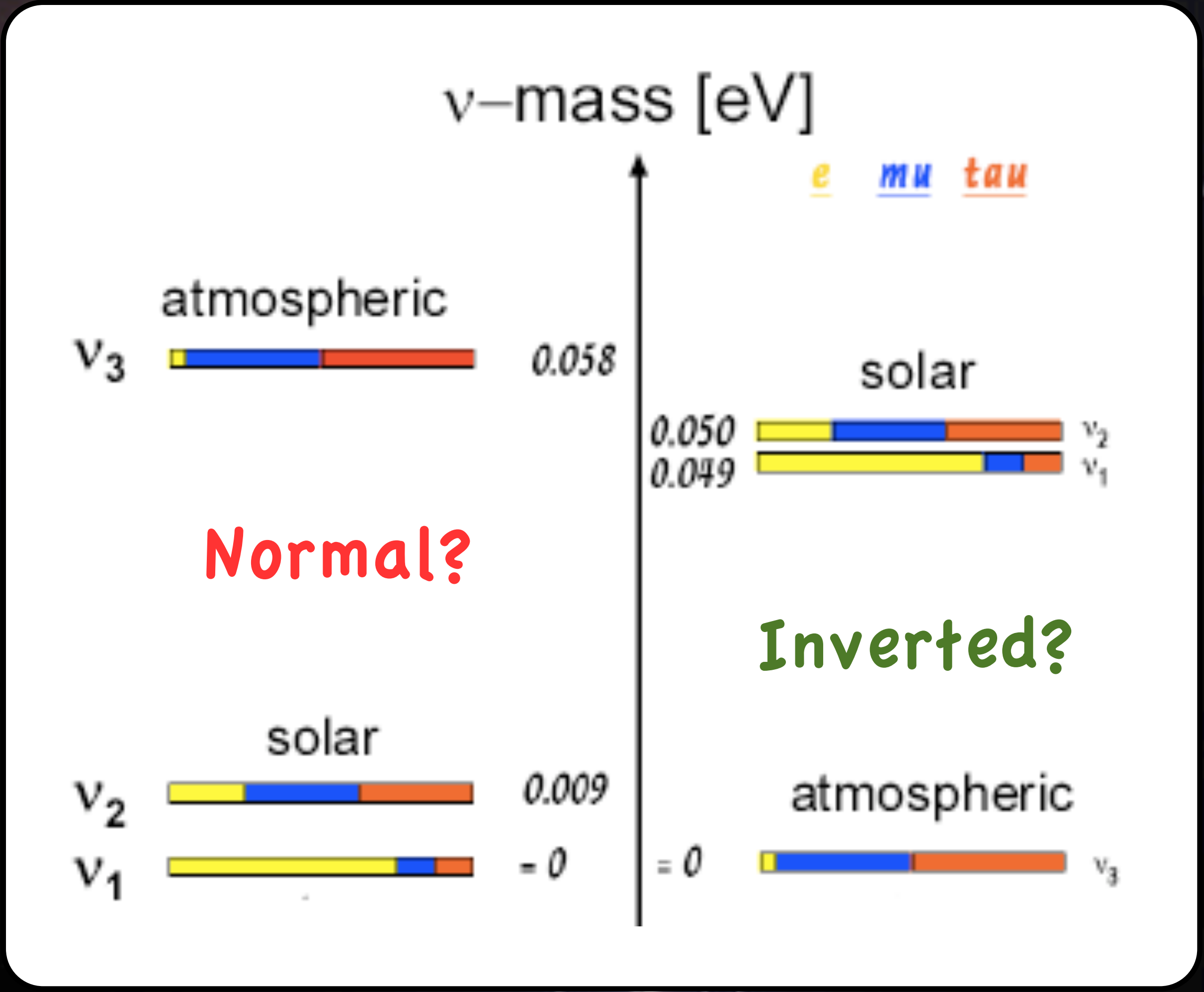

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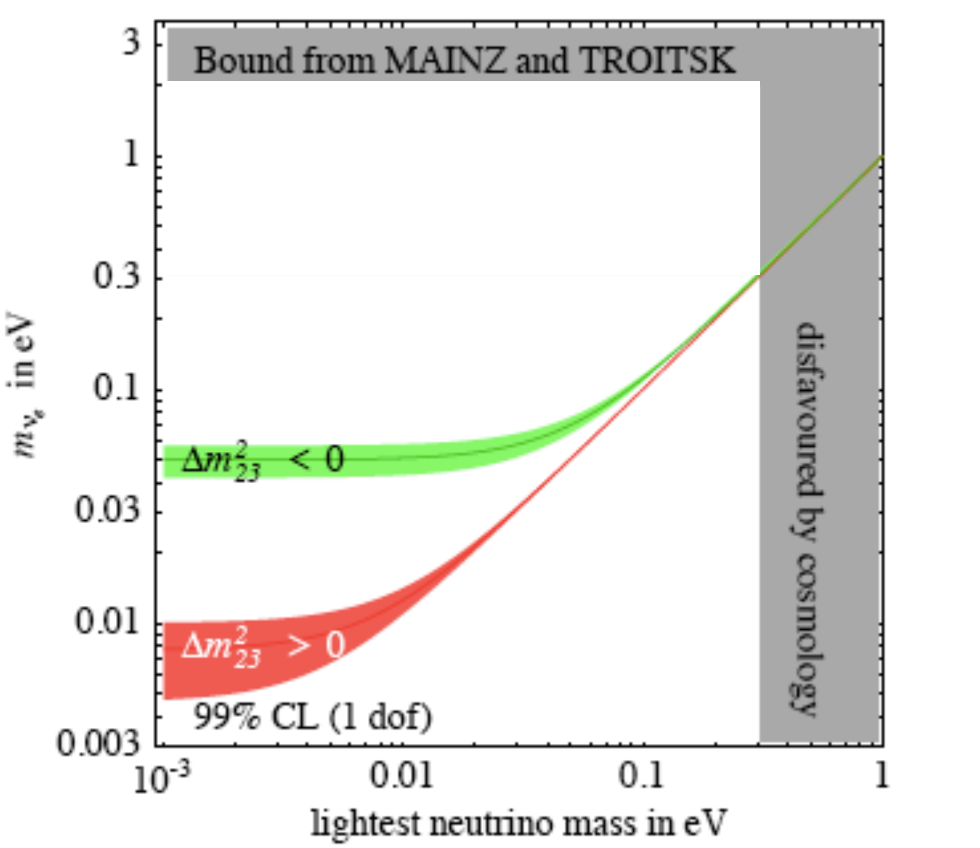

Dirac

Majorana?

More Questions

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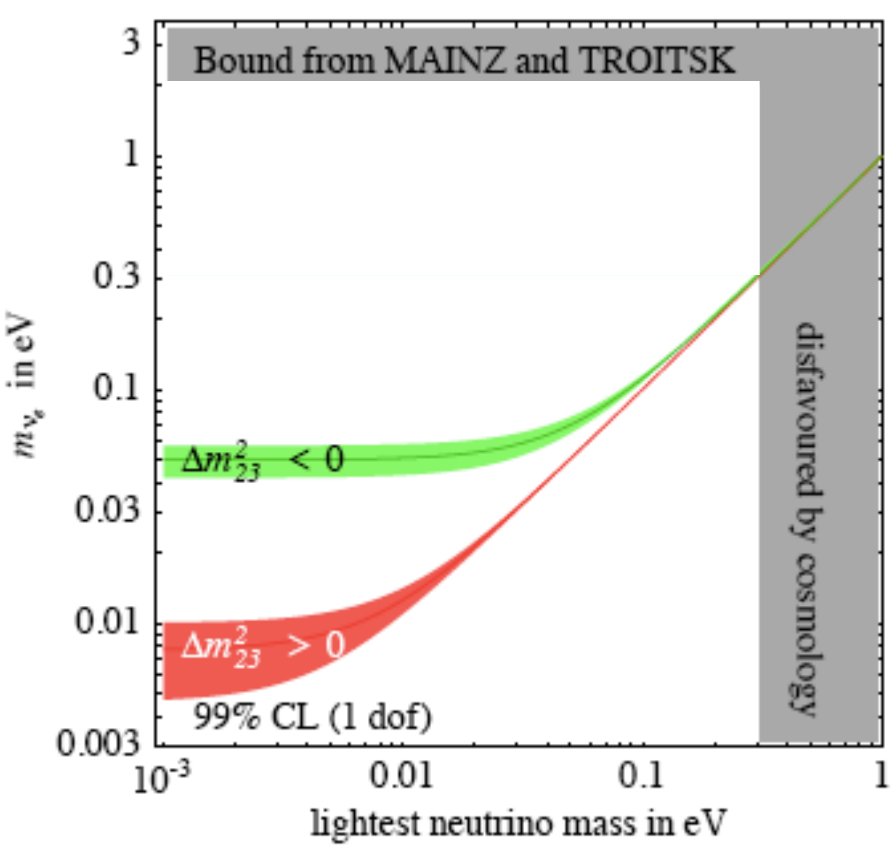

Dirac Majorana?

Generally...
Know << Don't Know

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(the framework)

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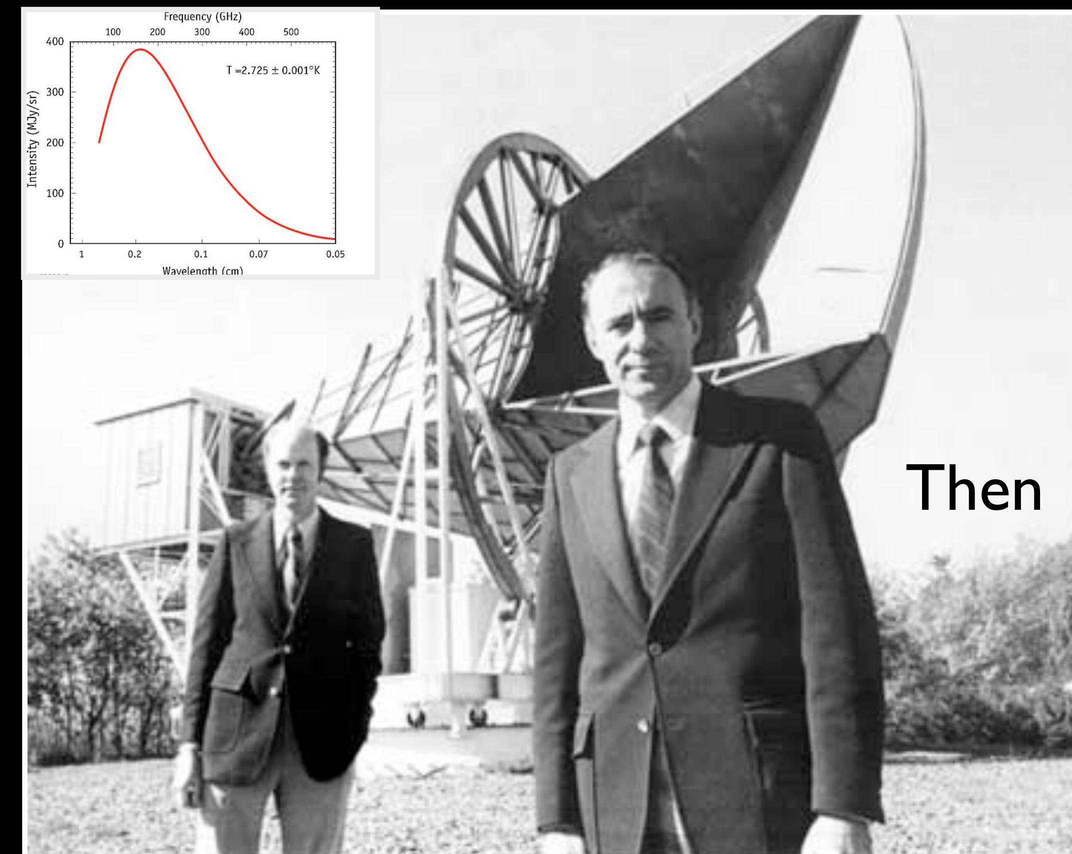
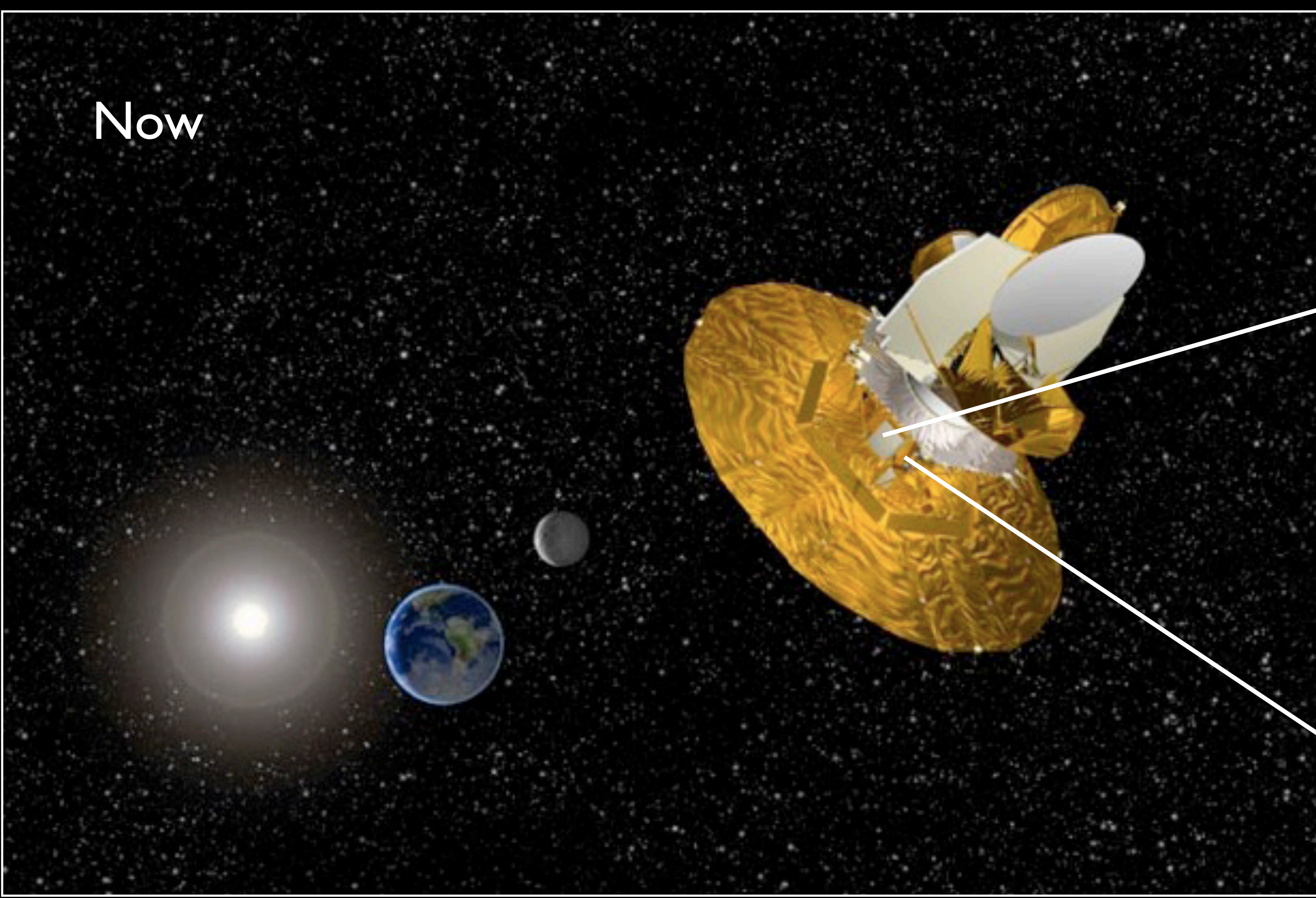
Precision Cosmology

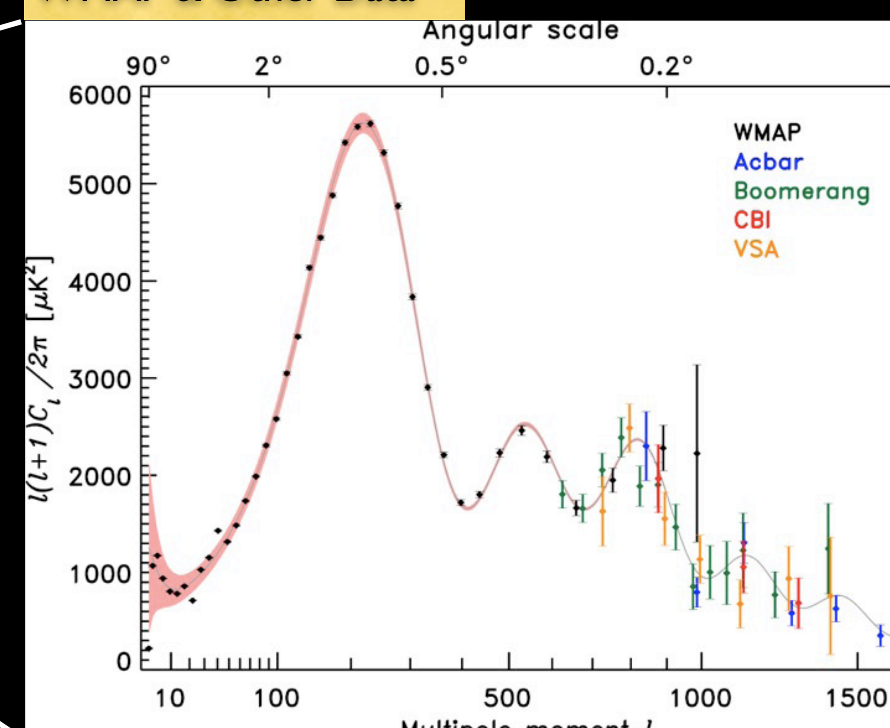
- Mapping the cosmic microwave background has reach unprecedented precision and, along with that, great predictive power.



Wilson and Penzias

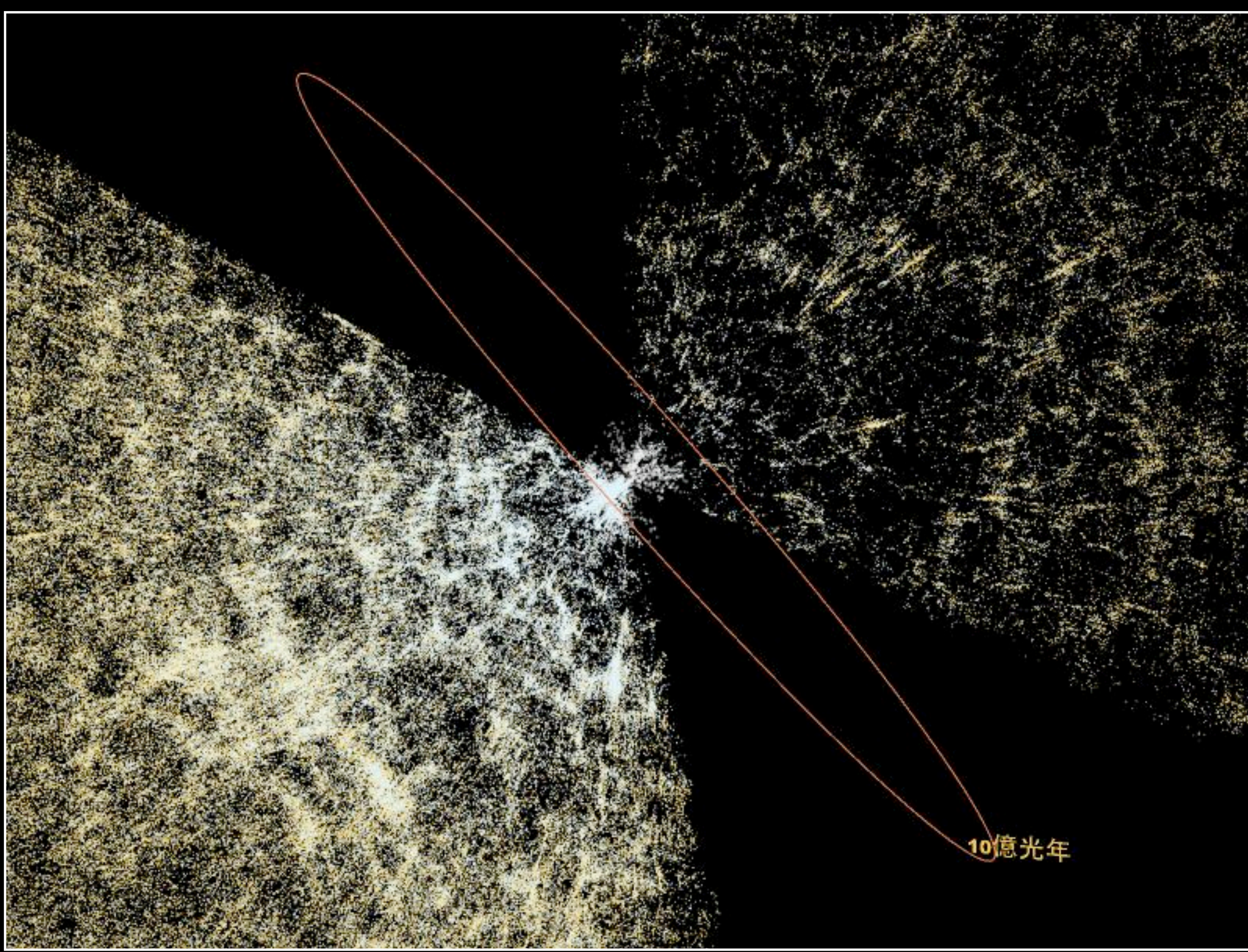


WMAP & Other Data



Neutrino Masses from Cosmology

- Cosmology looks at the *sum* of neutrino masses (their gravitational effect)



Large Scale Sctructure

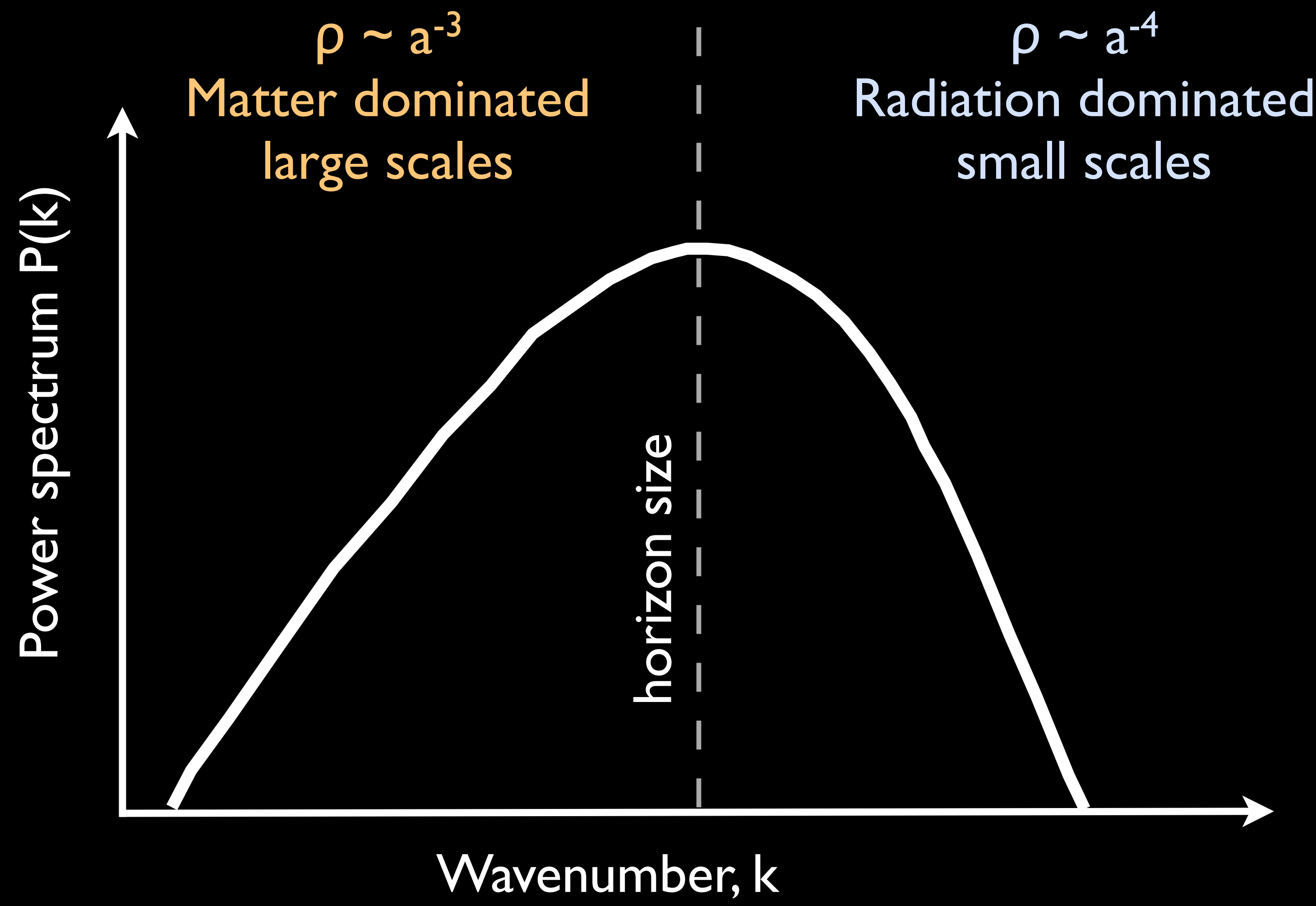
Just cold dark matter

Cold dark matter with neutrino mass

Colombi, Dodelson, & Widrow 1995

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\text{critical}}}$$

The Strategy
(a naive view)



$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

$$P(k) = \left\langle |\delta(k)|^2 \right\rangle$$

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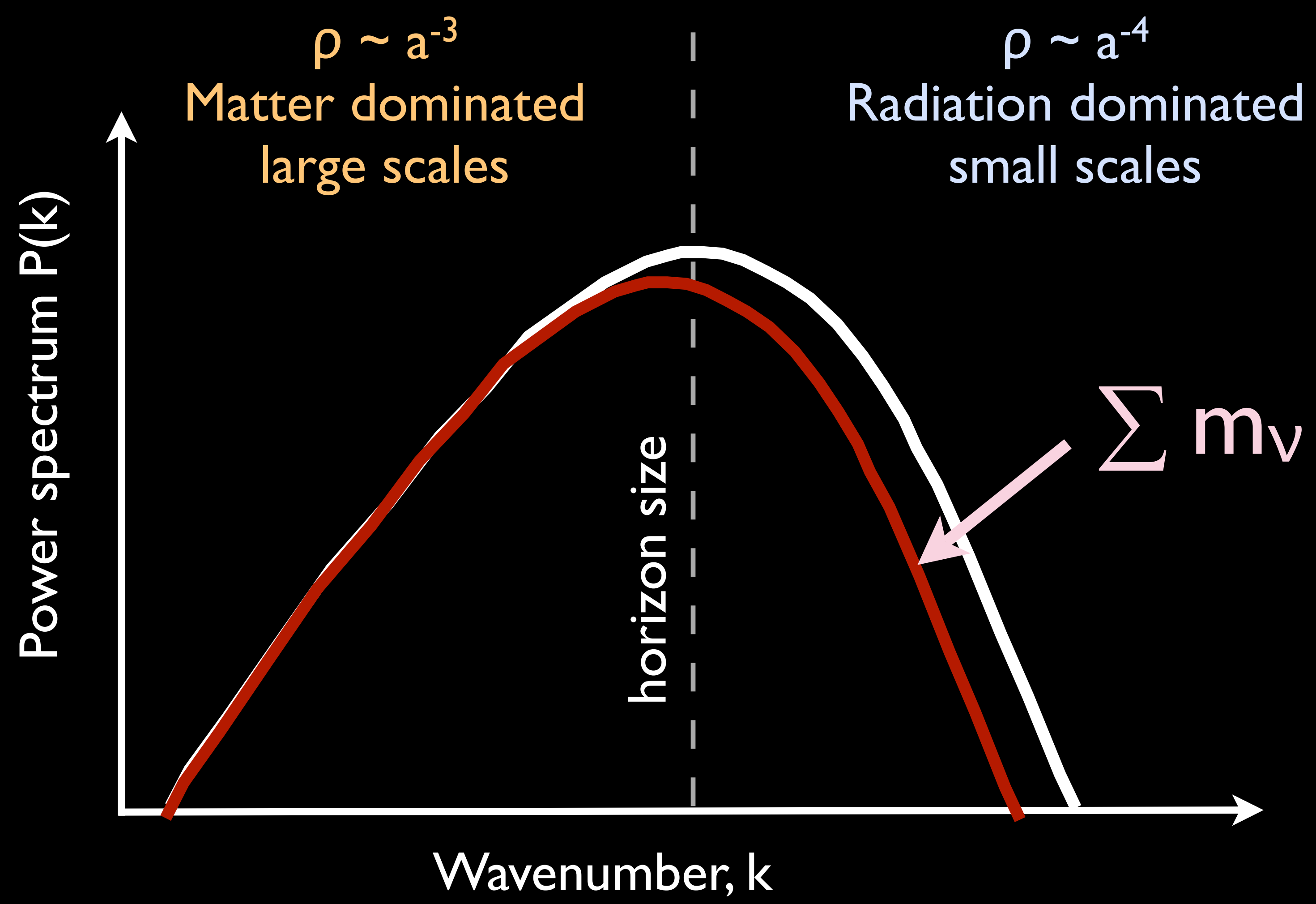
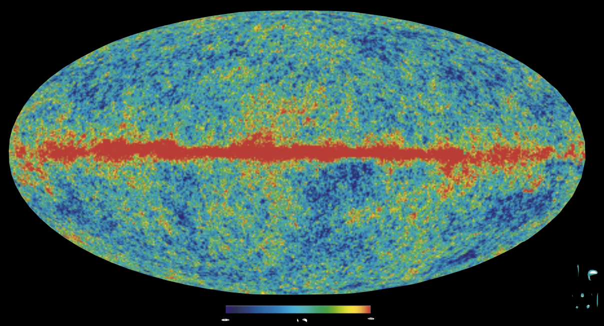


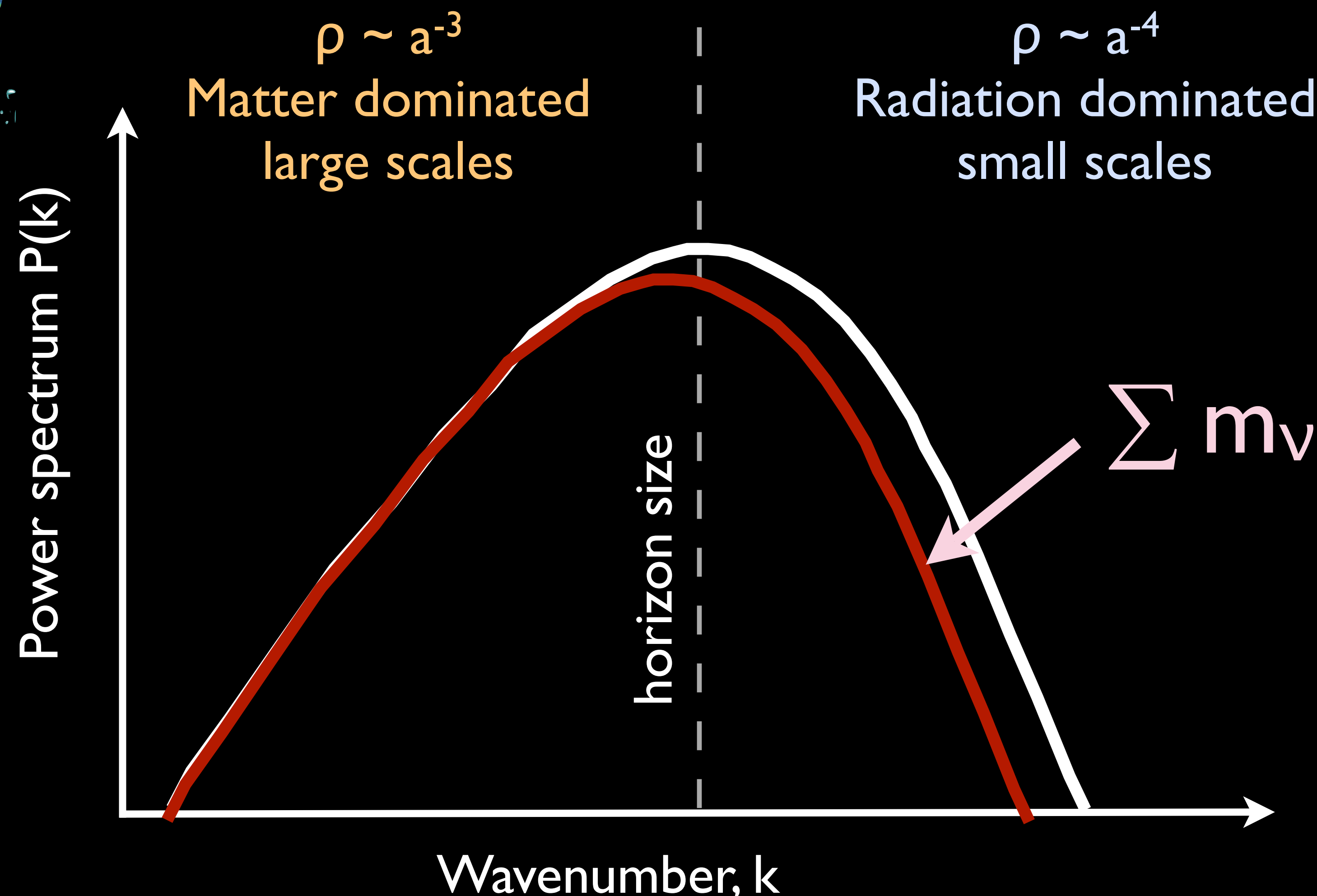
Neutrinos come to affect the power spectrum,

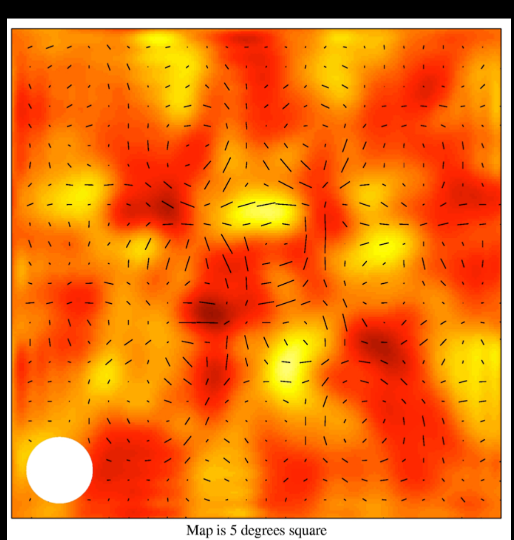
particularly at small distance scales

The Strategy
(a naive view)

WMAP Temperature Map







CMB Polarization

Neutrinos come to affect the power spectrum,

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The Strategy
(a naive view)

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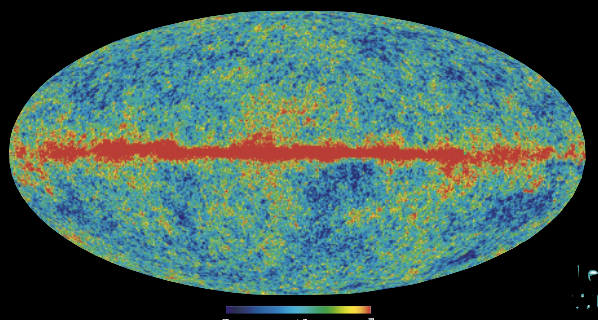
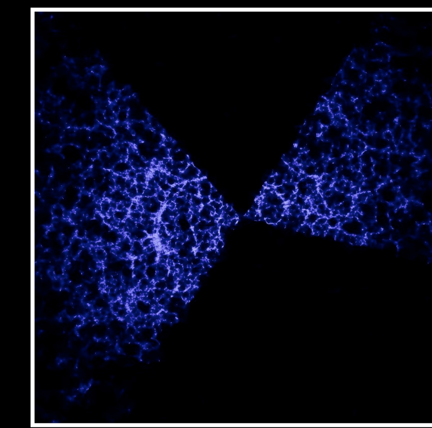
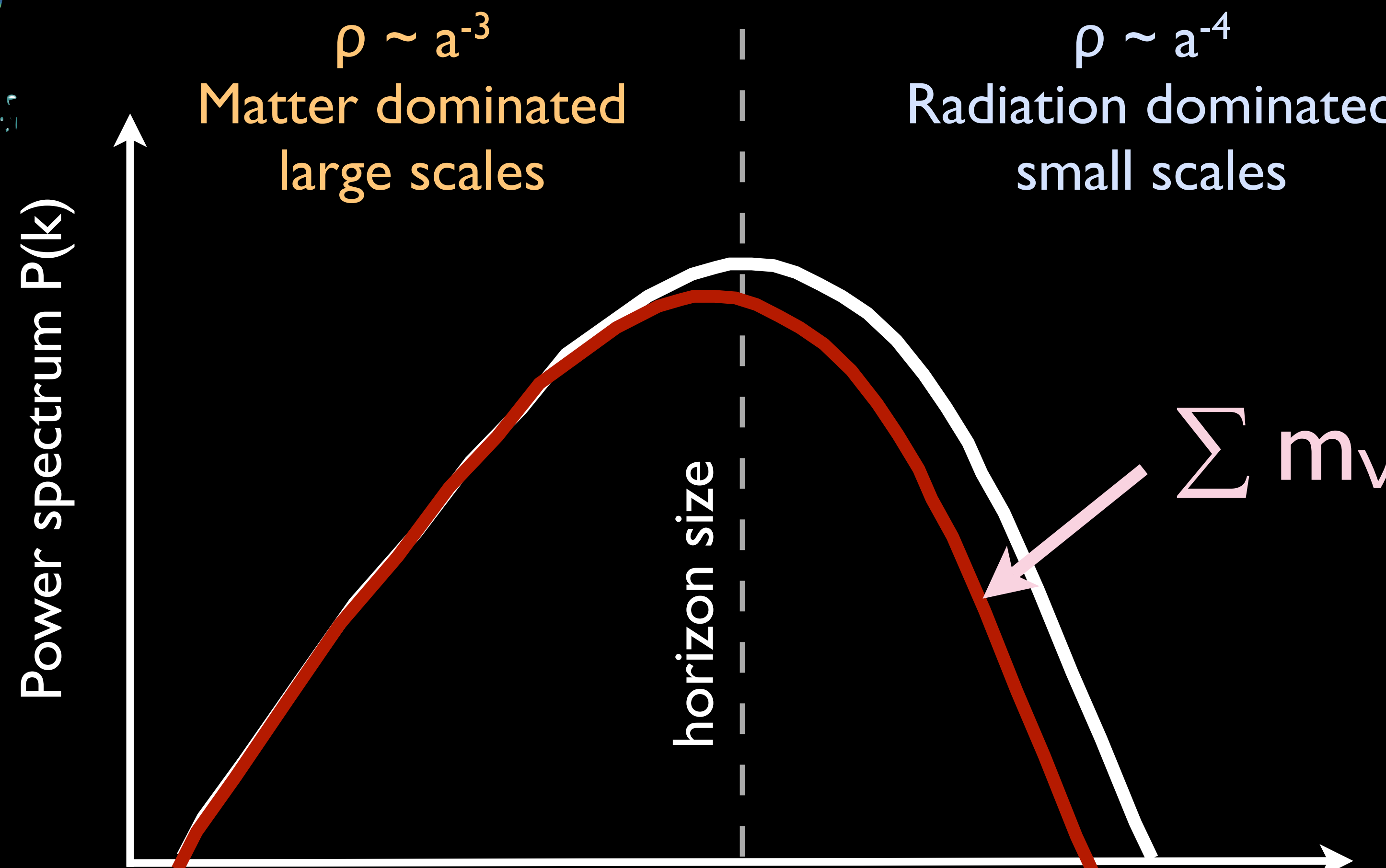
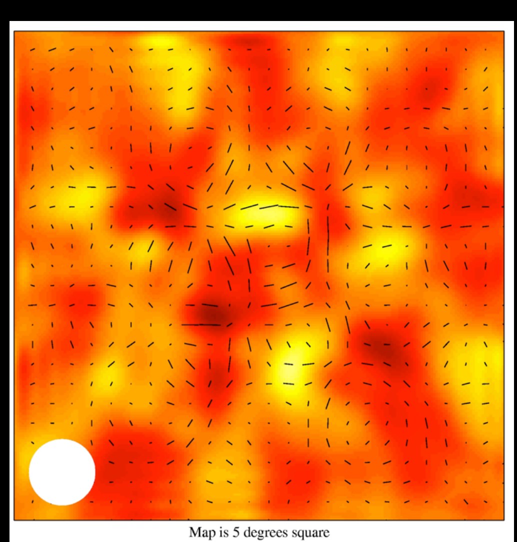


Galaxy Surveys





Weak lensing



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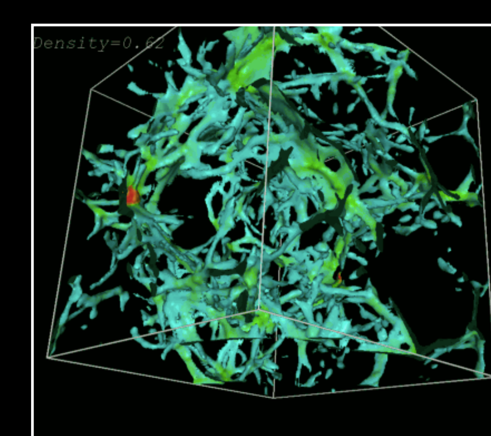

Lyman α

Neutrinos come to affect the power spectrum, particularly at small distance scales

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(a naive view)

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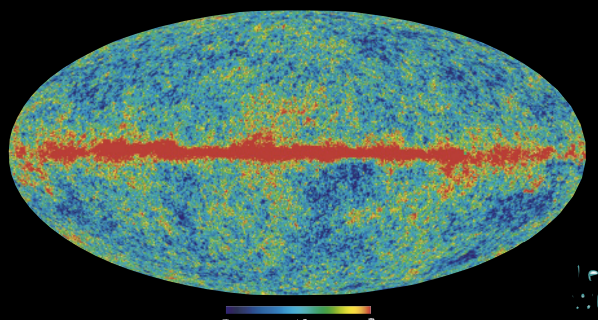

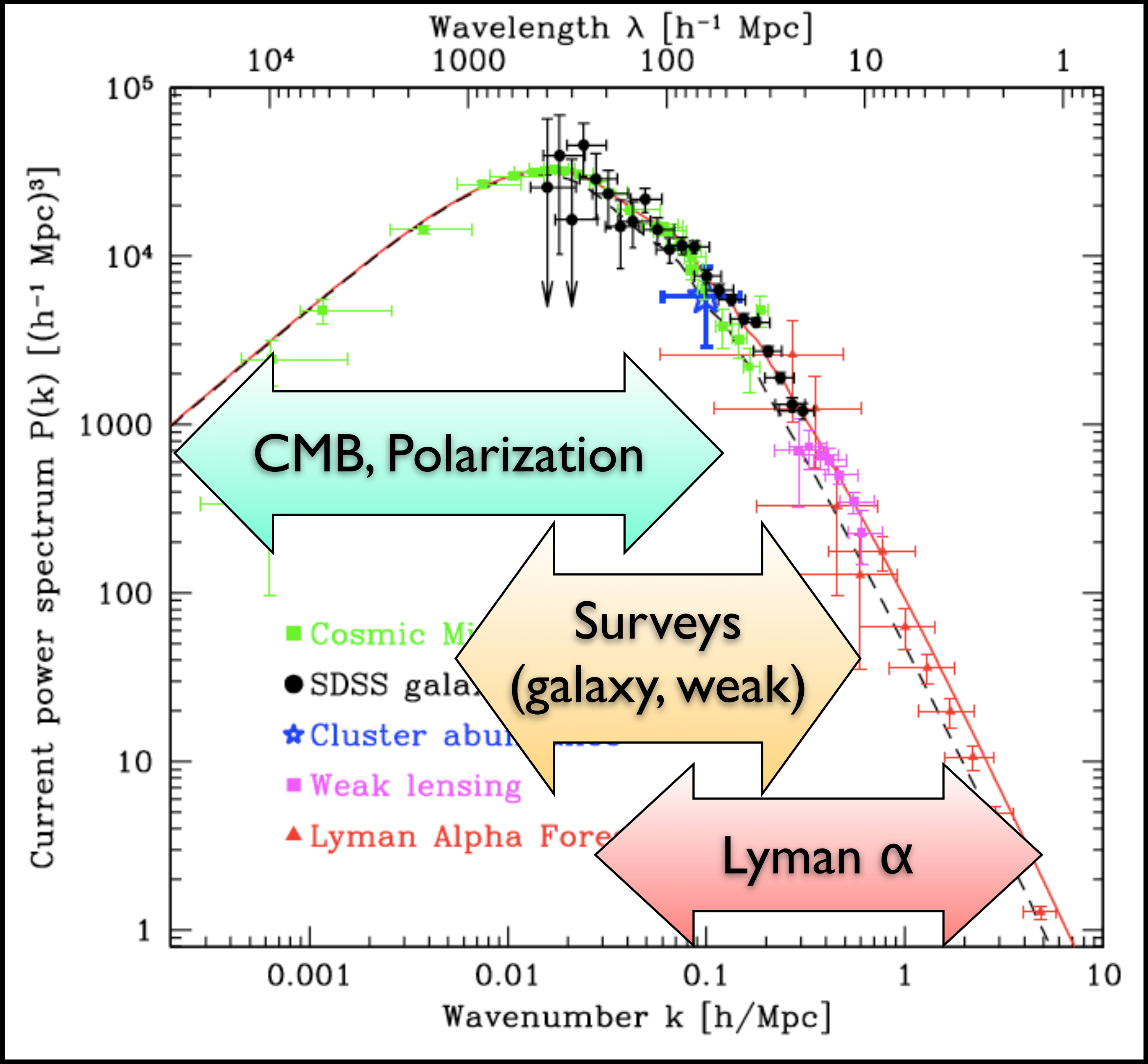

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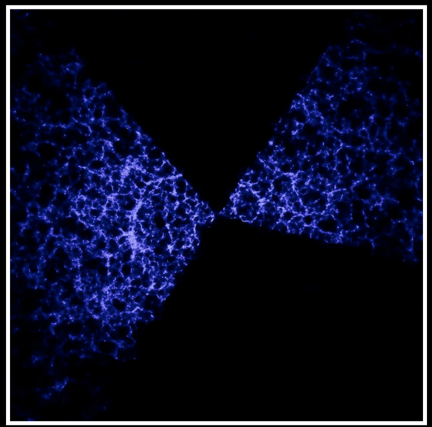

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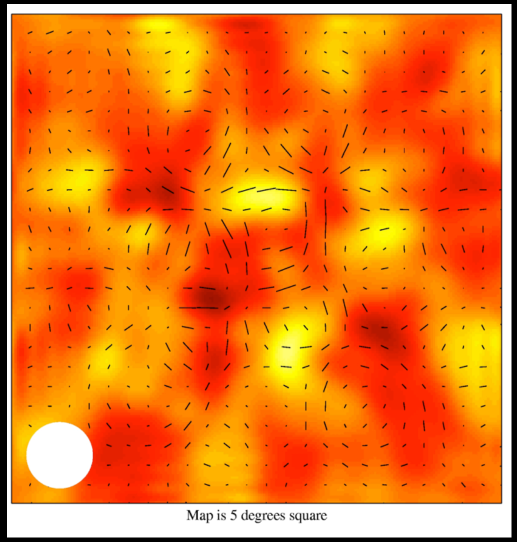
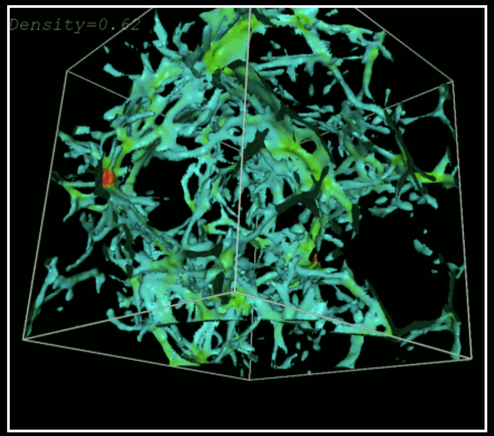


CMB Polarization

Max Tegmark, 2005

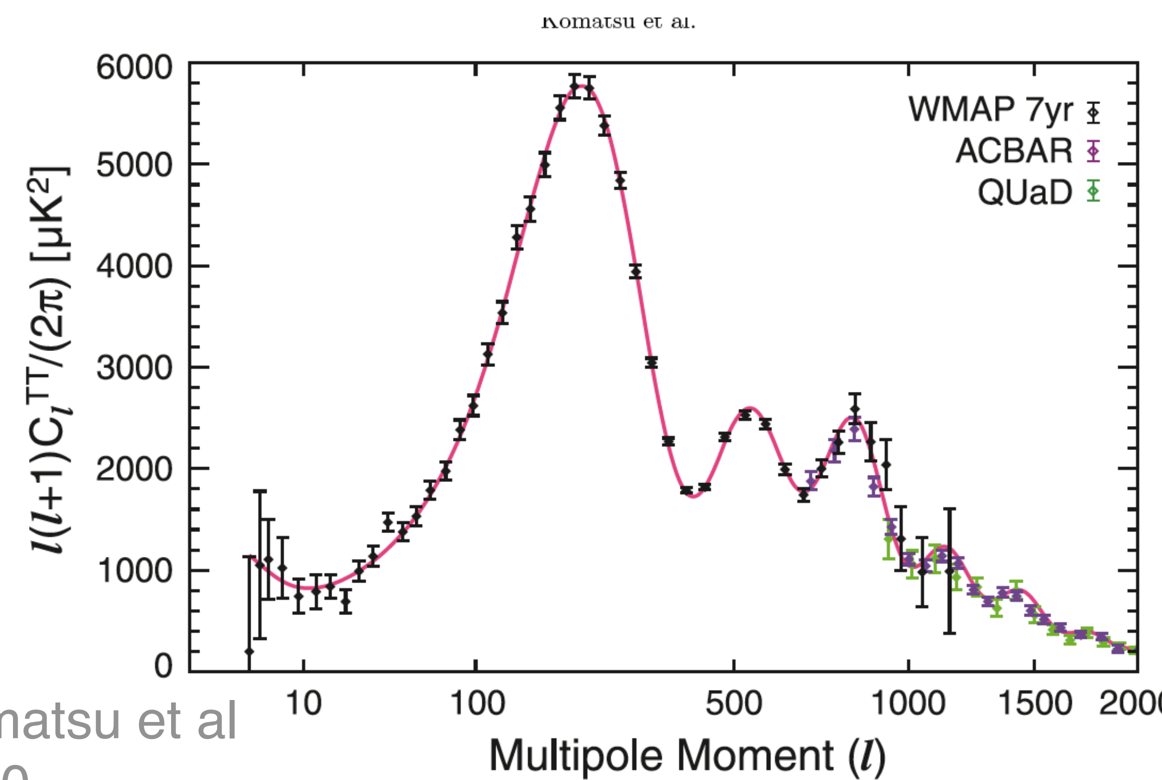


Lyman α

Current Limits

- Limits for neutrino masses depend in part on:
  - Which data is used, and...
  - ...what assumptions are made.

Set	$w = -1$	$w \neq -1$
WMAP 7 only	$\Sigma m_\nu < 1.3$ eV	$\Sigma m_\nu < 1.4$ eV
WMAP7 + BAO + H0	$\Sigma m_\nu < 0.58$ eV	$\Sigma m_\nu < 1.3$ eV
WMAP7 + BAO + SN	$\Sigma m_\nu < 0.7$ eV	$\Sigma m_\nu < 0.9$ eV



Komatsu et al 2010

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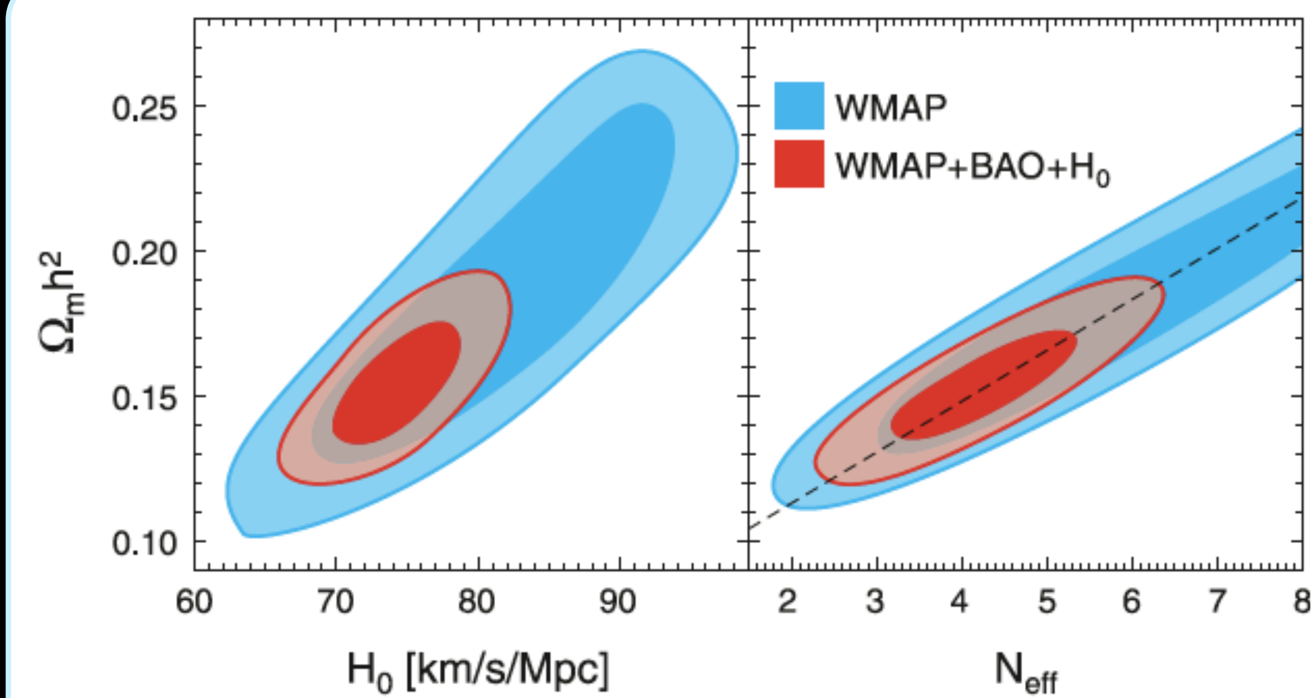

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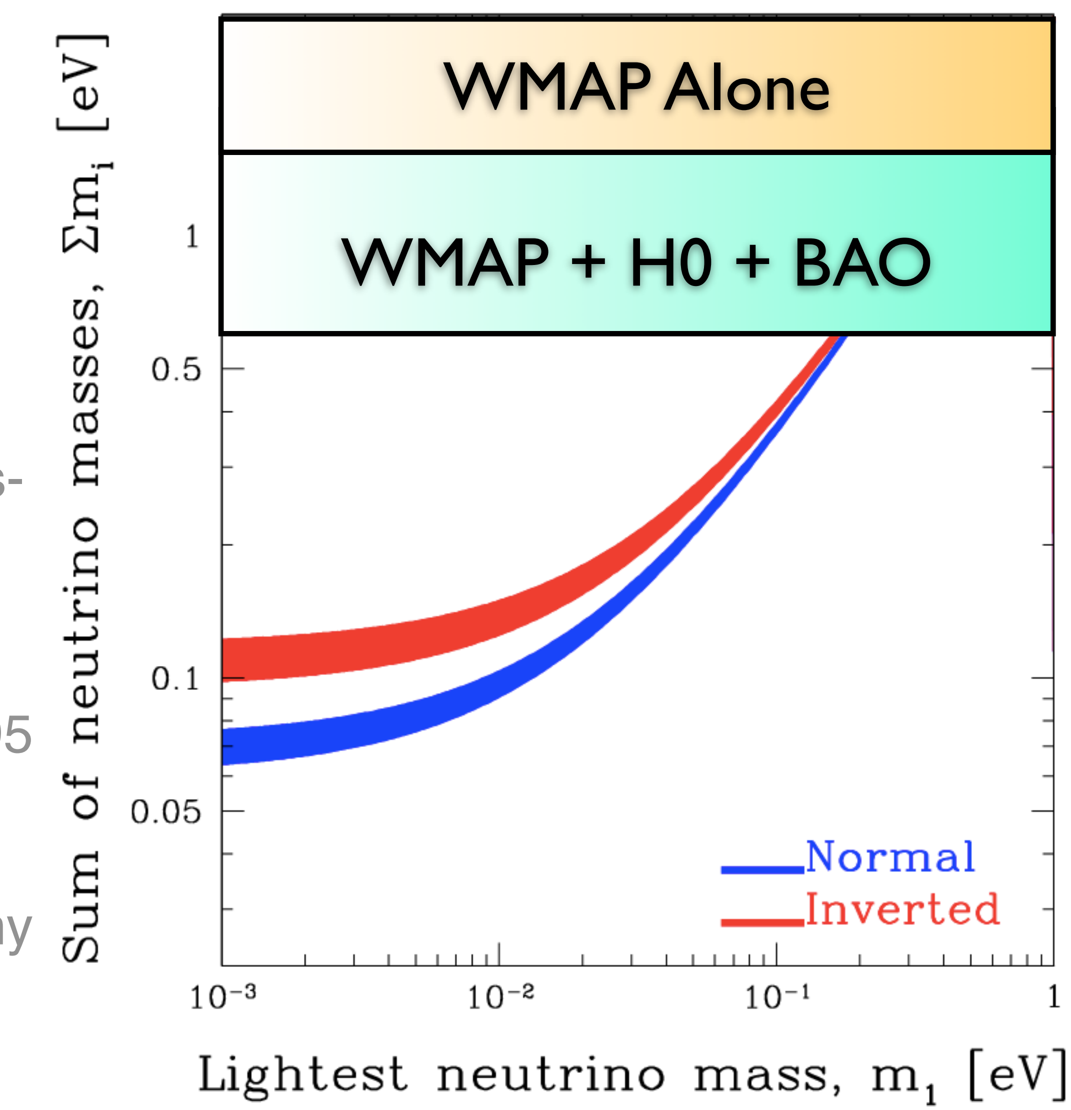

Gonzales-Garcia

arXiv: 1006.3795 v2

(and many others)

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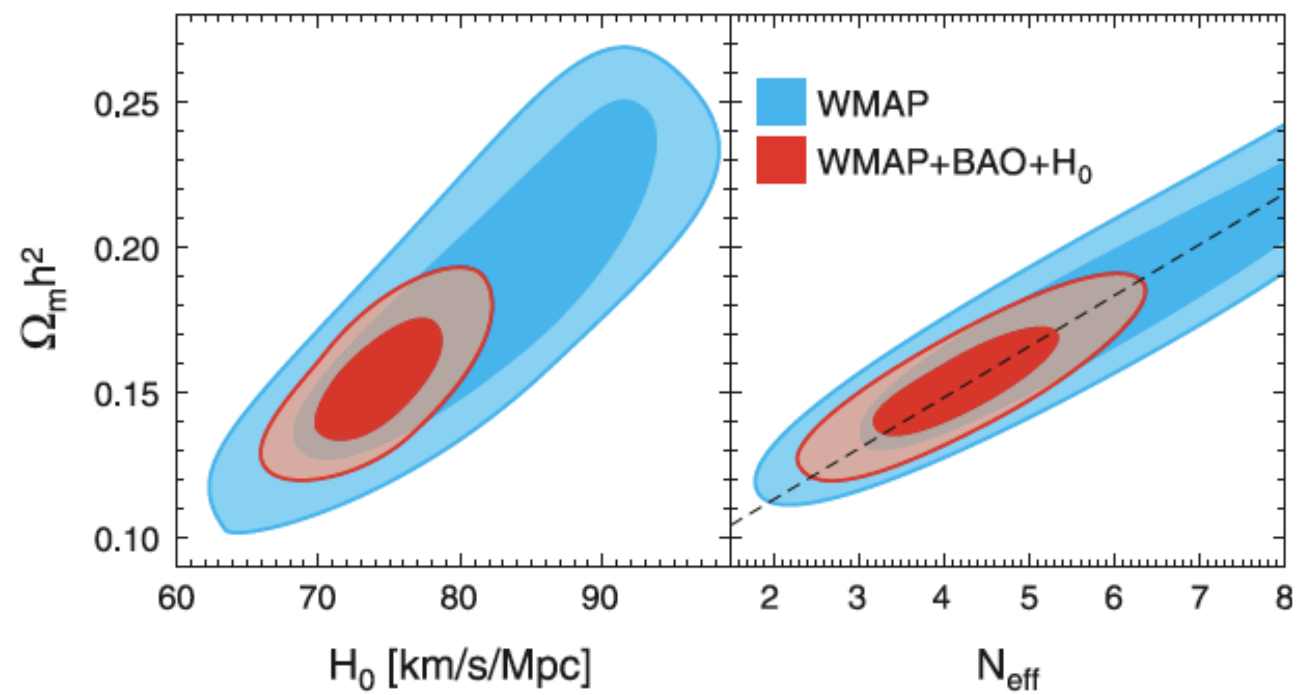

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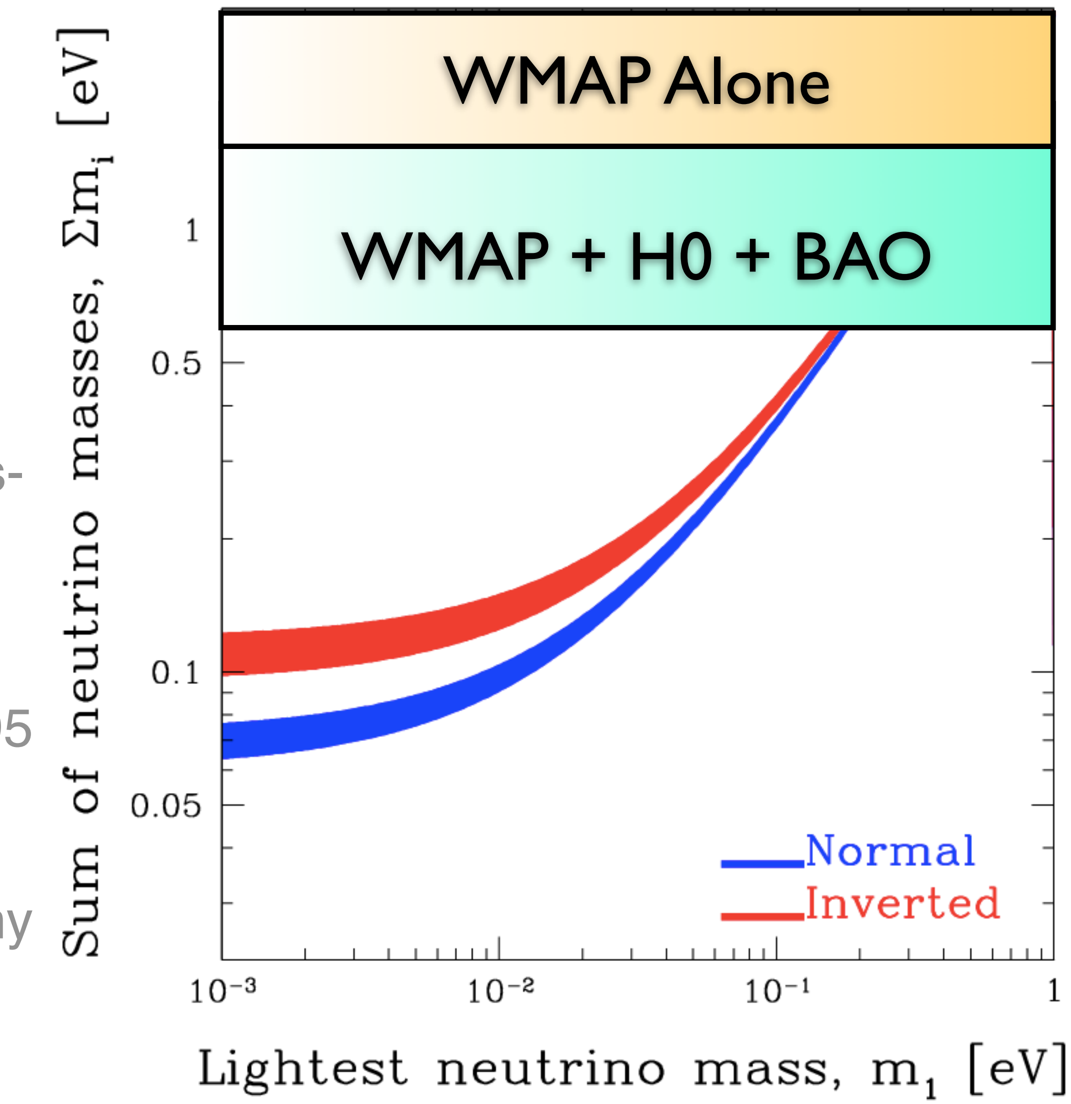

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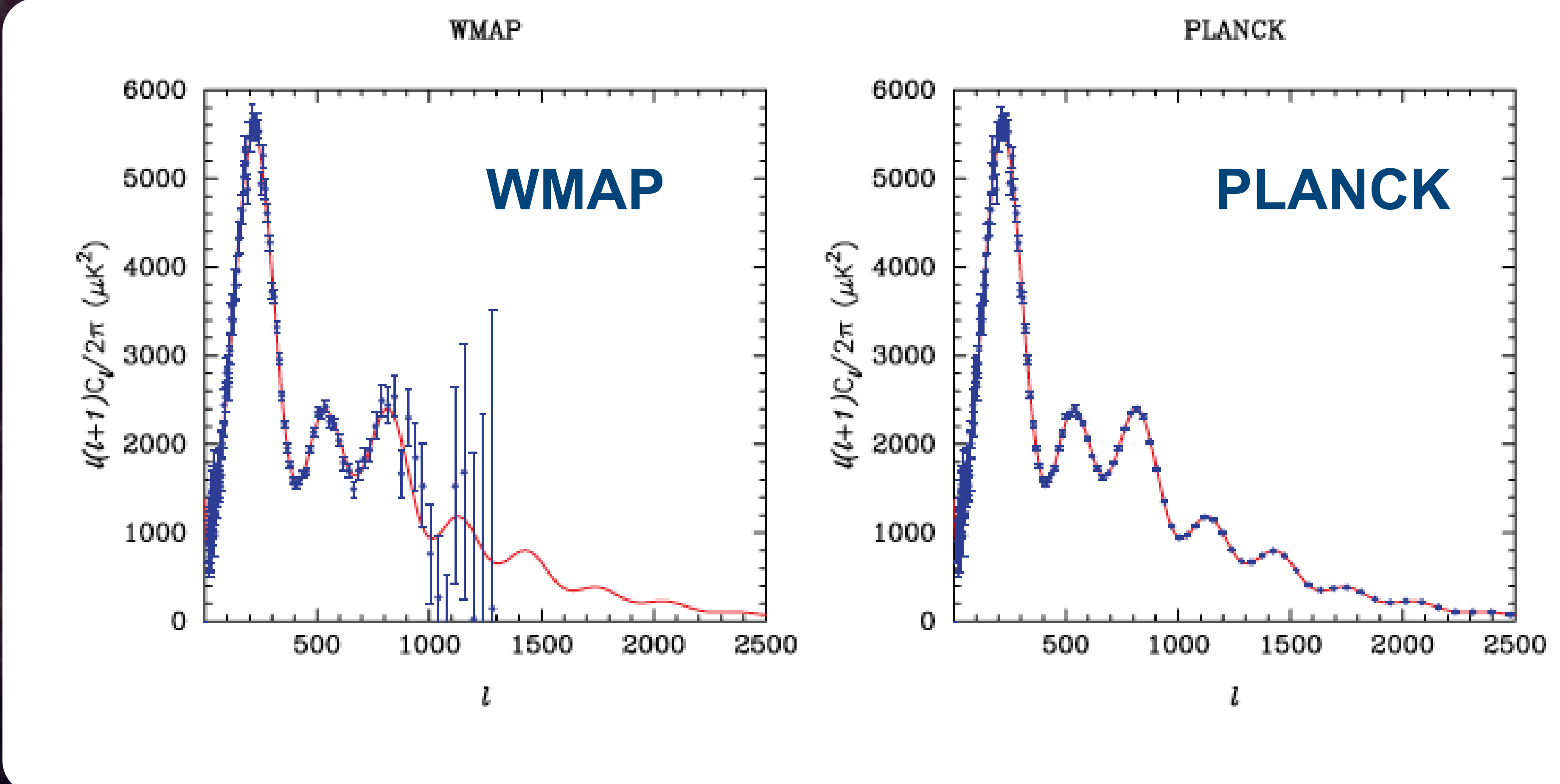
(and many others)

New Frontiers

Planck Satellite:

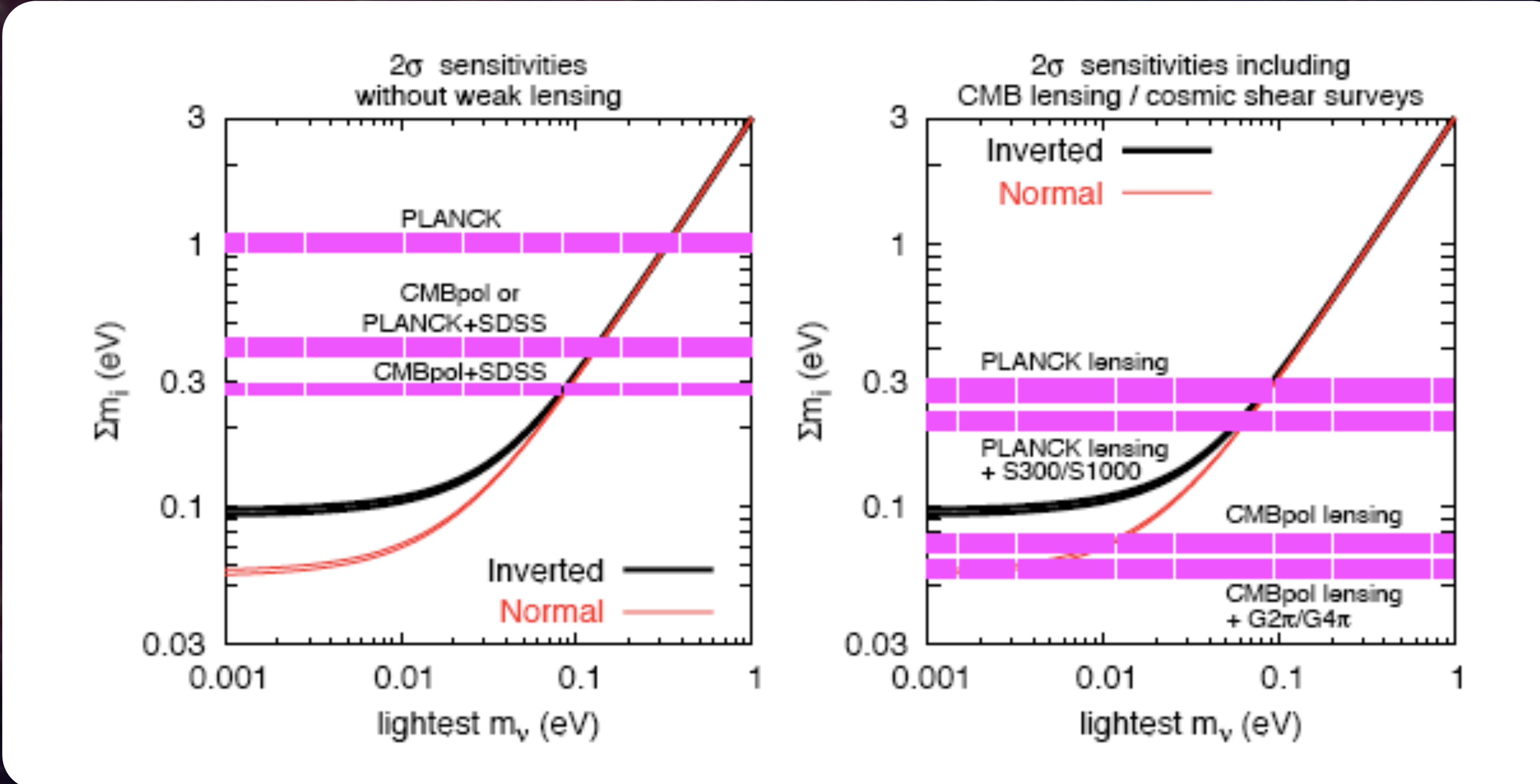
Launched May 14th, 2009

Upcoming Data



- Planck alone can push neutrino limits down 1 eV.
- Host of new experiments coming to the forefront.

Upcoming Data



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CMB Lensing	None	CMBPol	0.05 eV
Galaxy Distribution	0.6 eV	LSST	0.1 eV
21 cm	None	SKA	0.05 eV

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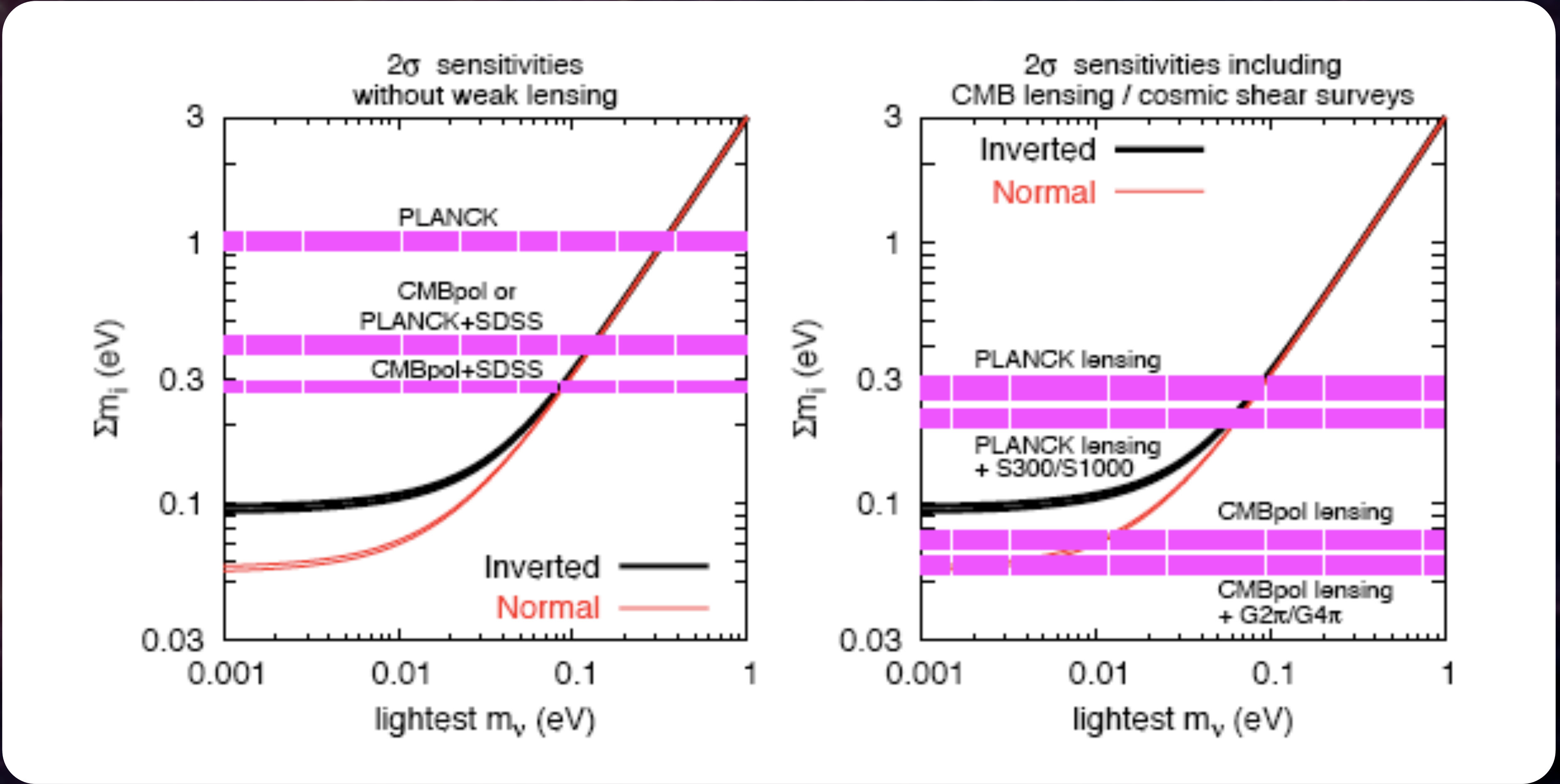

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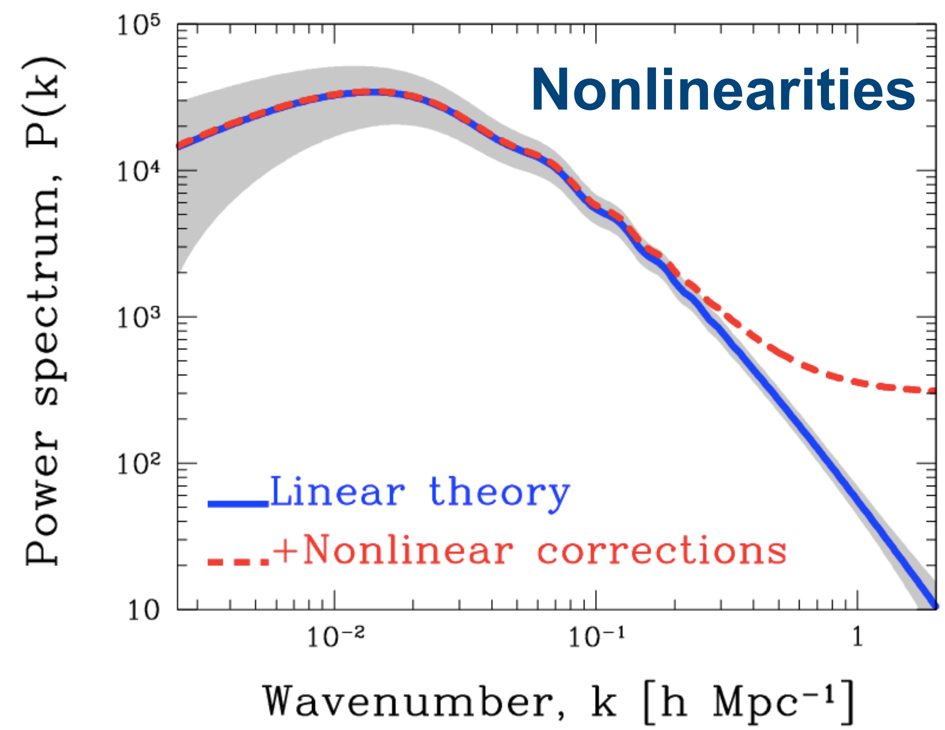
Moving Forward...

Moving to the normal hierarchy scale now requires 1% precision on the power spectrum.

$$\frac{\Delta P}{P} \simeq -12\frac{\Omega_\nu}{\Omega_m} \simeq 1\%$$

Systematic Effects

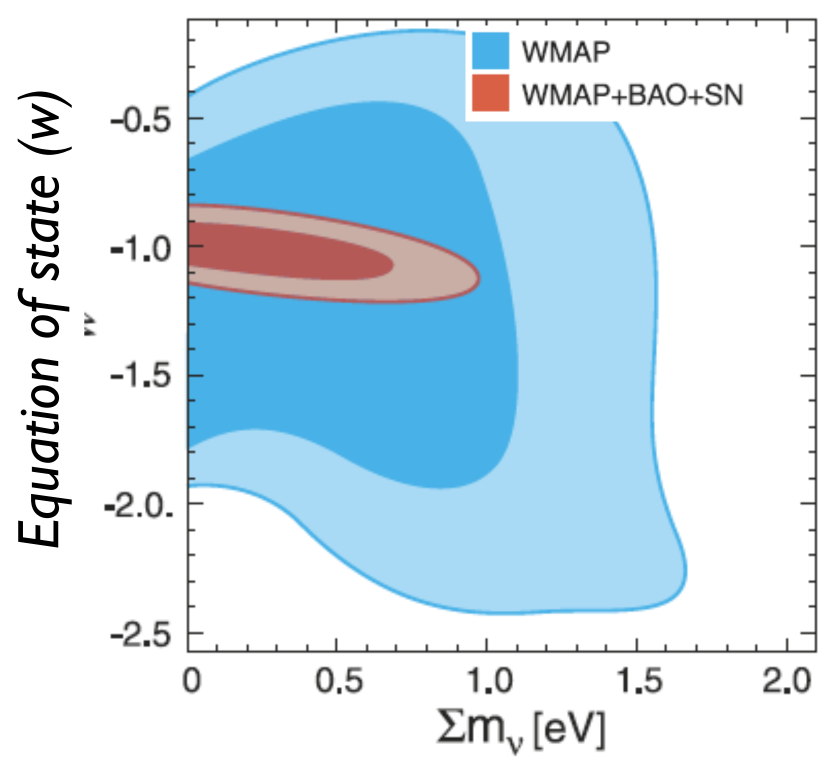
- As precision demands moves to 1%, non-linear effects, degeneracies, baryons, etc. all begin to play a role.
- Numerical simulations and semi-analytical techniques used to address.



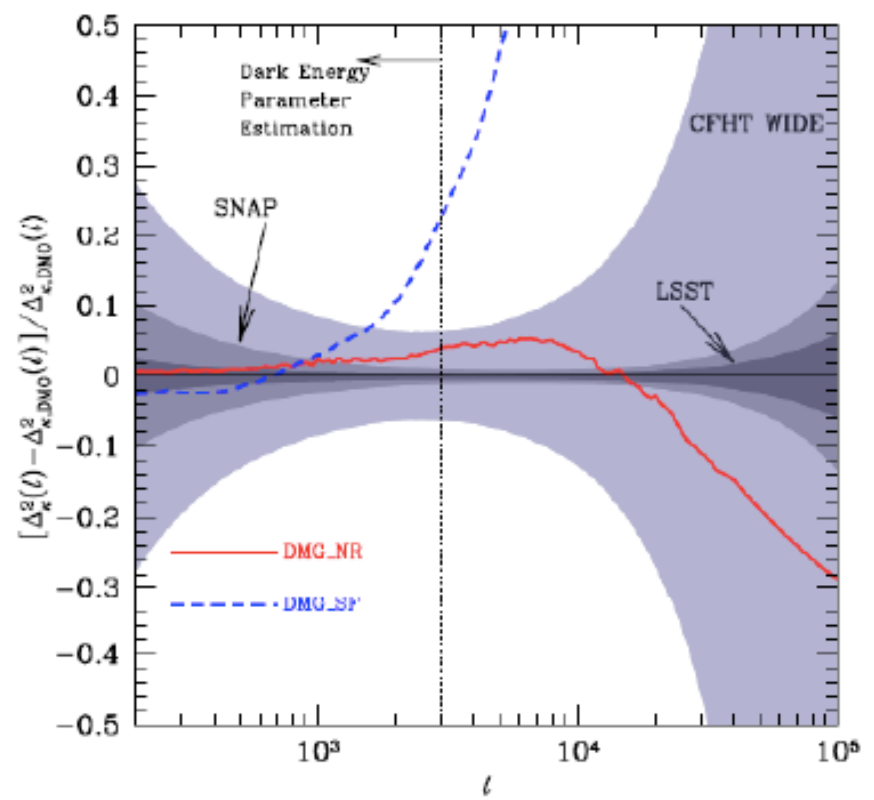
Y. Y. Y. Wong, 2010

Degeneracies

S. Hannestad
Phys. Rev. Lett 95 221301



Baryon Effects



Rudd, Zentner & Kravtsov, 2007

"...down they fell, driven headlong from the pitch of heaven, down into this deep...", Paradise Lost

Measuring ν masses

(the framework)

Measuring neutrinos from the Heavens

(cosmology)

Measuring neutrinos on Earth

(beta decay)

Patient measurements

(Neutrinoless double beta decay)

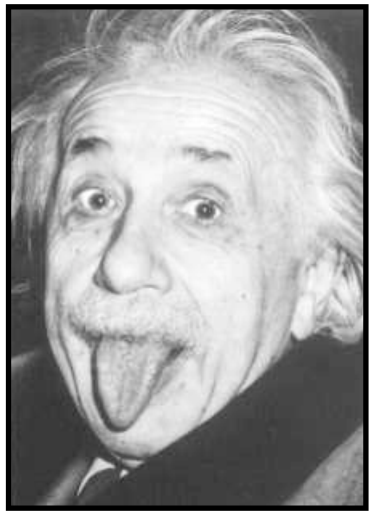
Beta Decay Experiments

Beta decay allows a *kinematic* determination of the neutrino mass

Sensitive to the incoherent sum of masses and mixings

$$m_\beta^2 \simeq \sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2$$

Beta Decay Experiments



From E= mc^2

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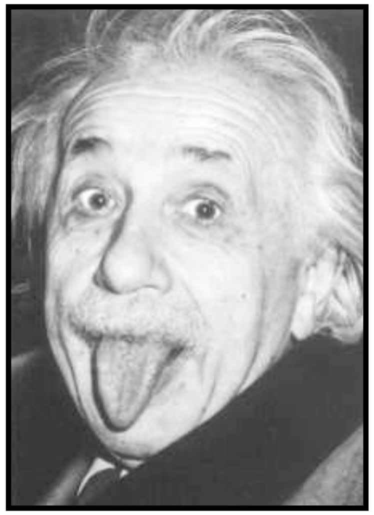
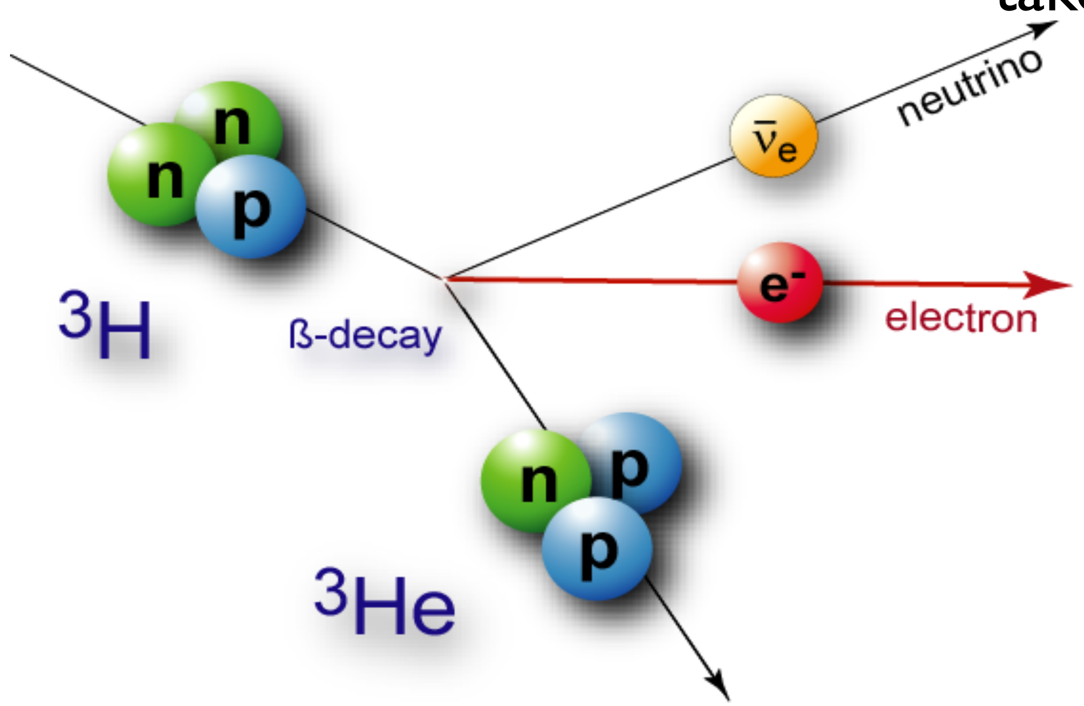


From $E = mc^2$



If massive, the neutrino takes away some energy...

...from the electron (which we detect)

$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

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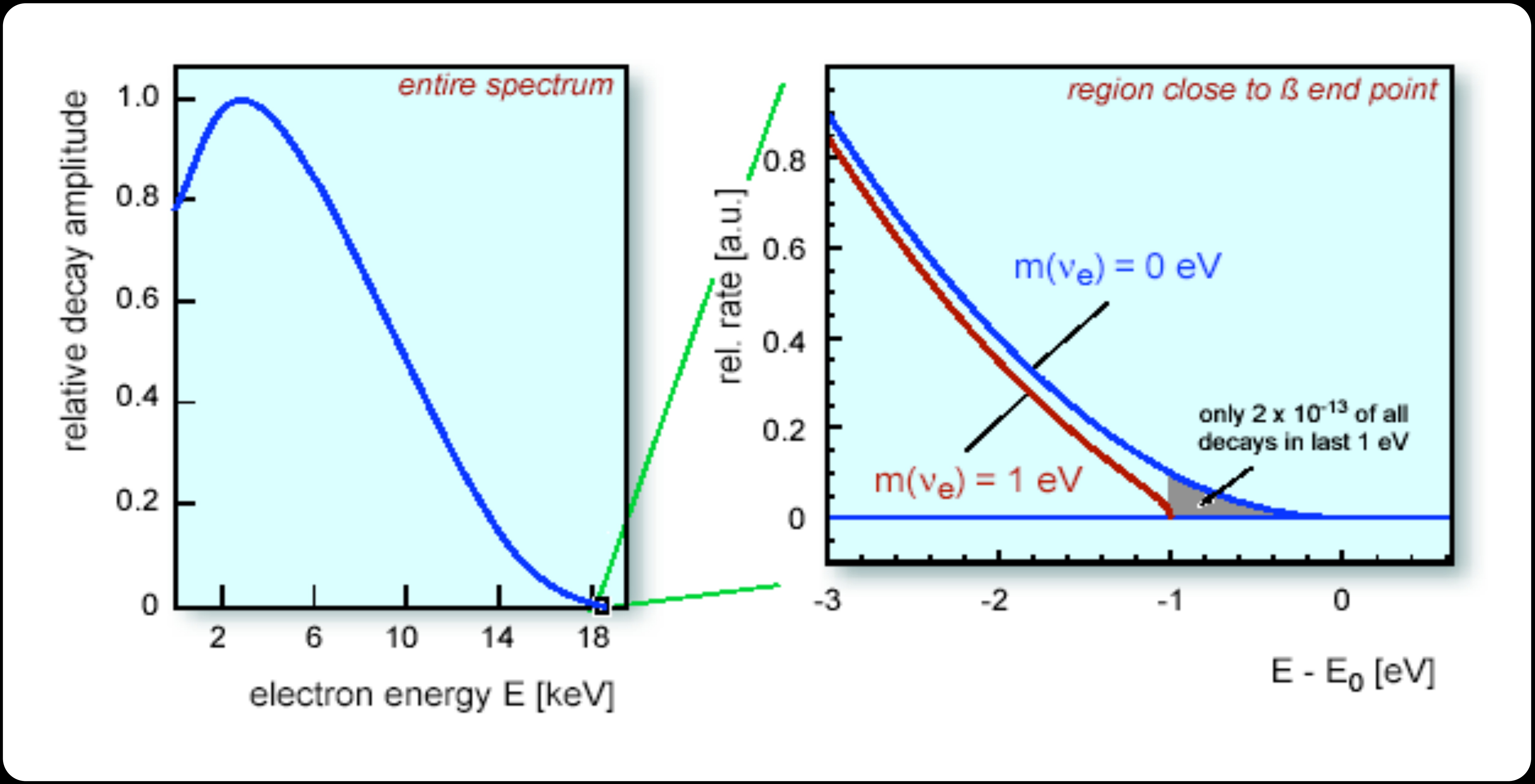

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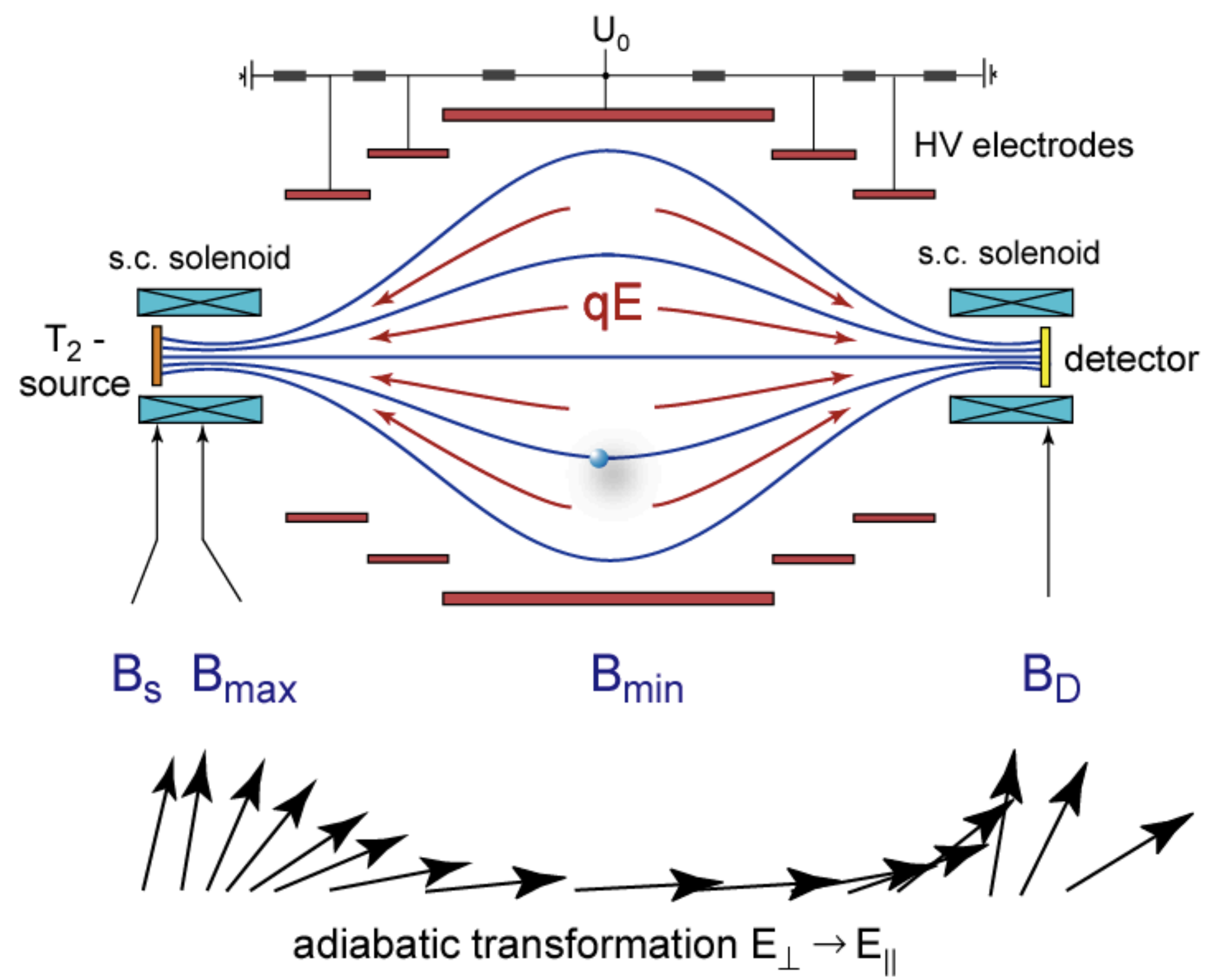
State-of-the-Art: KATRIN

KATRIN

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter

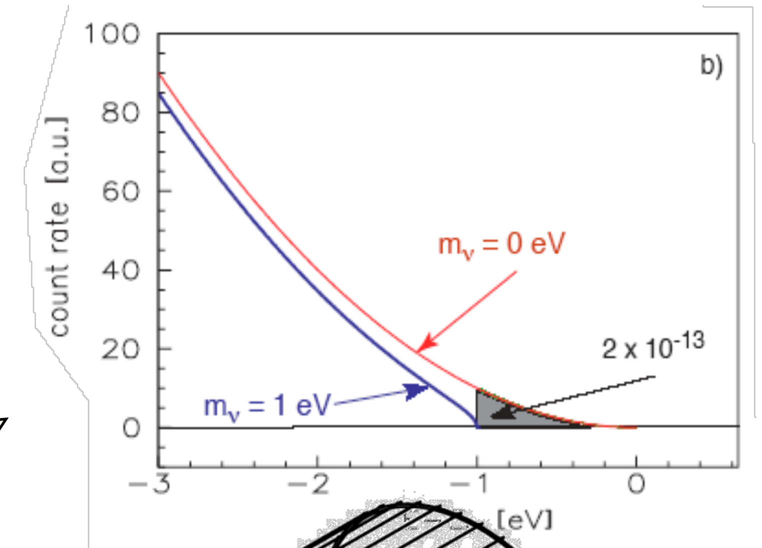


Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution ($\Delta E/E = B_{min}/B_{max}$ = 0.93 eV)

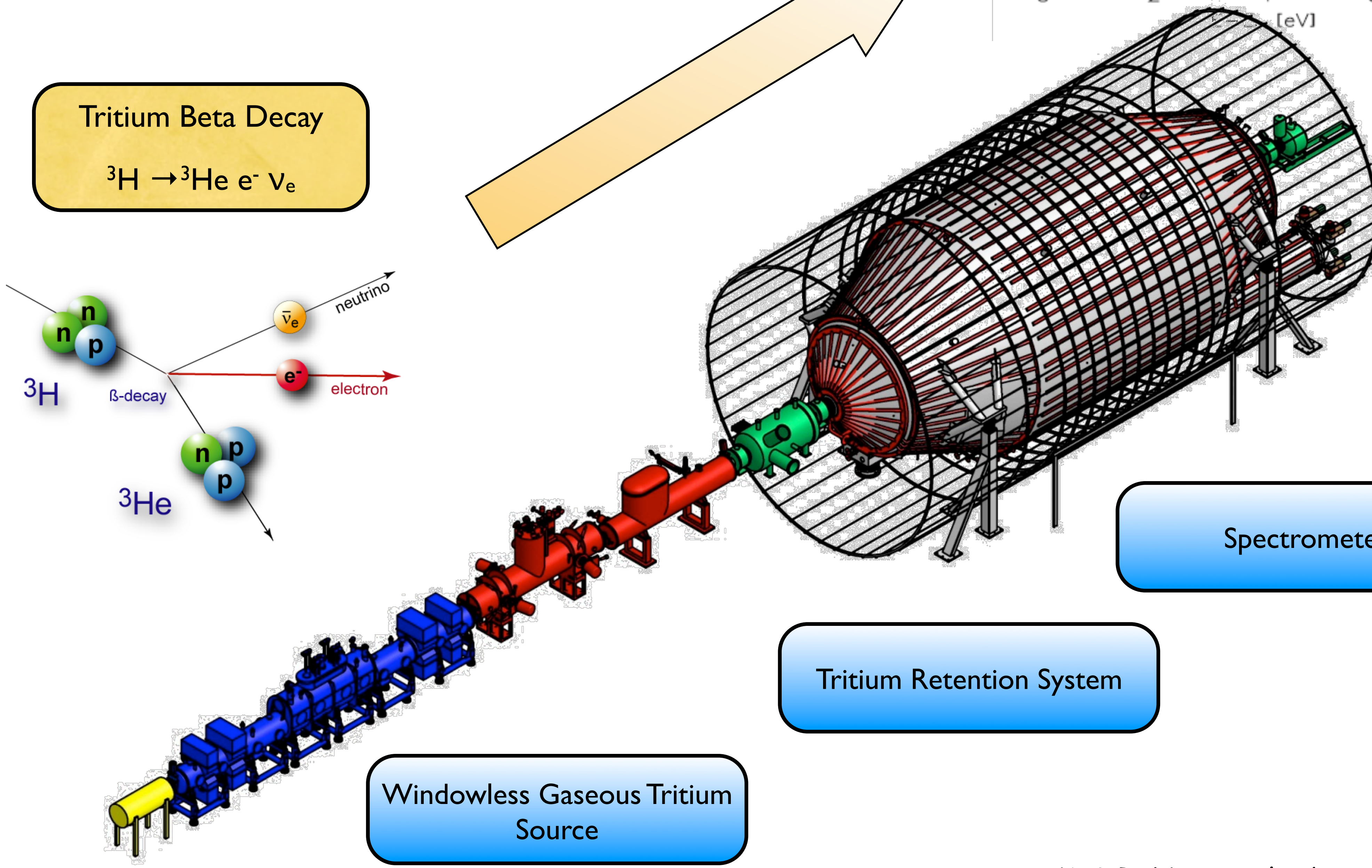
The KATRIN Experiment



Electron Beta Decay Spectrum

Tritium Beta Decay

$^3H \rightarrow {}^3He\ e^-\ \nu_e$



Electron Detector

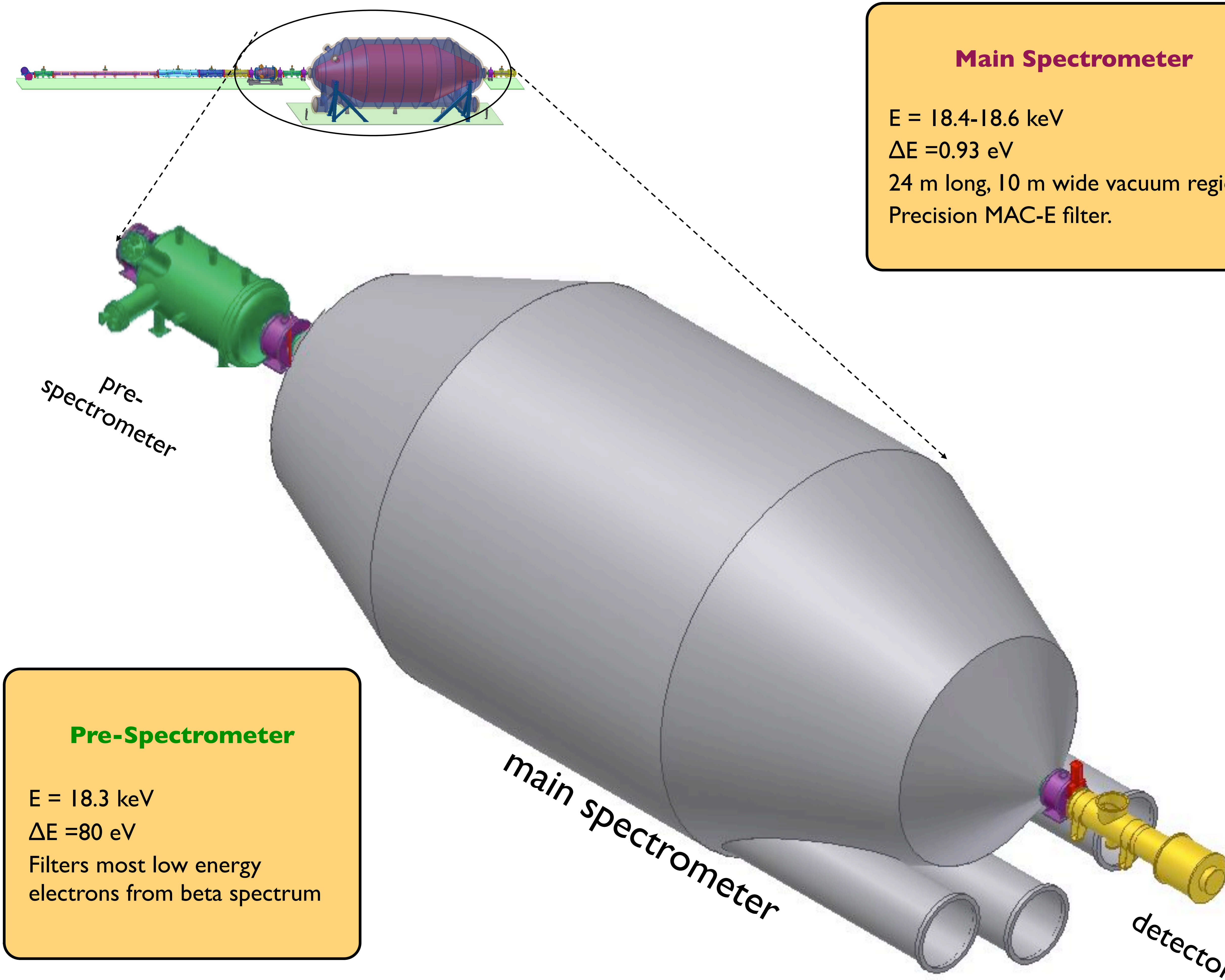
Spectrometer

Tritium Retention System

Windowless Gaseous Tritium Source

Rear Calibration & Monitoring

- KATRIN uses the beta decay from (gaseous) tritium to probe the absolute neutrino mass scale.



Main Spectrometer

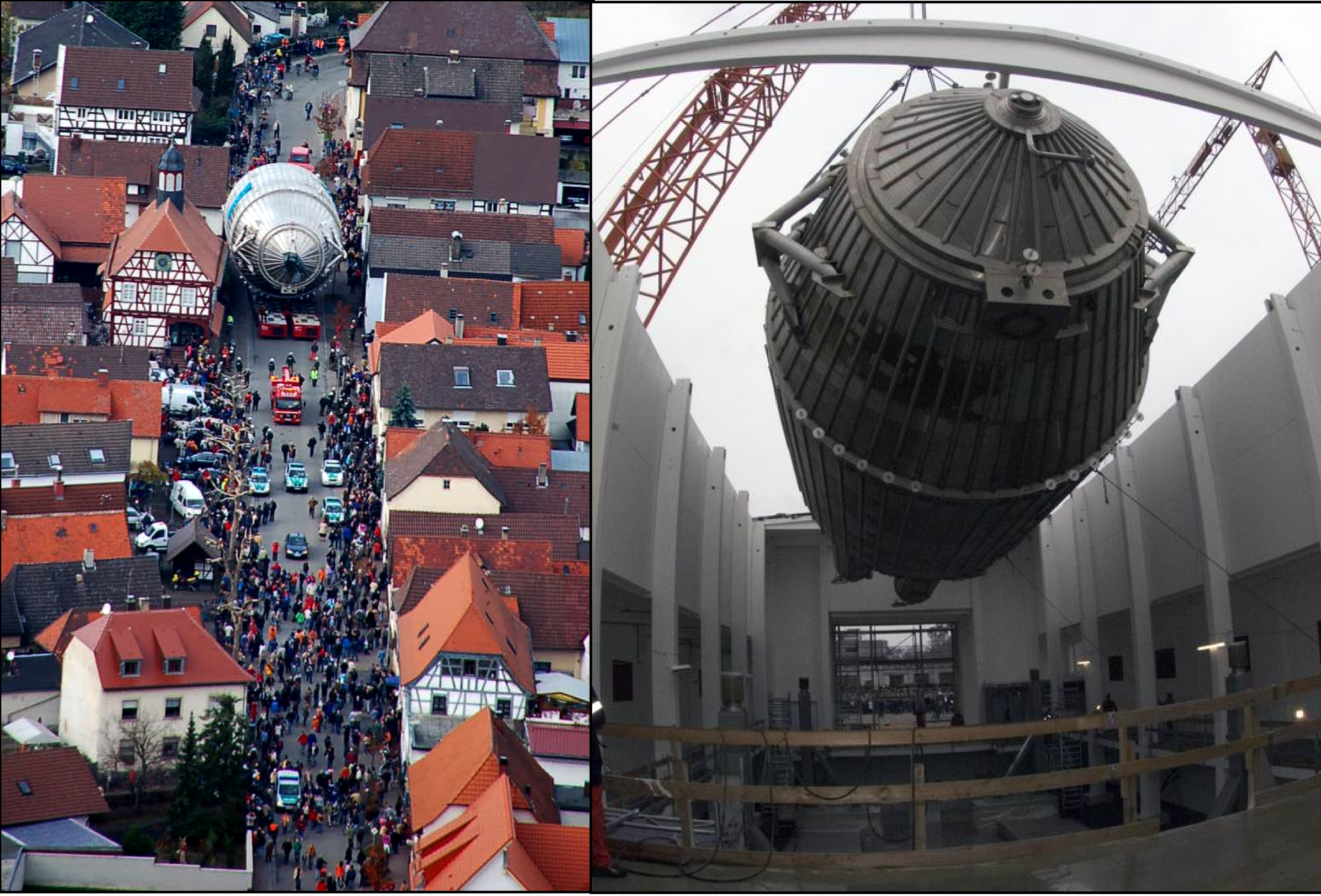
E = 18.4-18.6 keV
ΔE =0.93 eV
24 m long, 10 m wide vacuum region.
Precision MAC-E filter.

Pre-Spectrometer

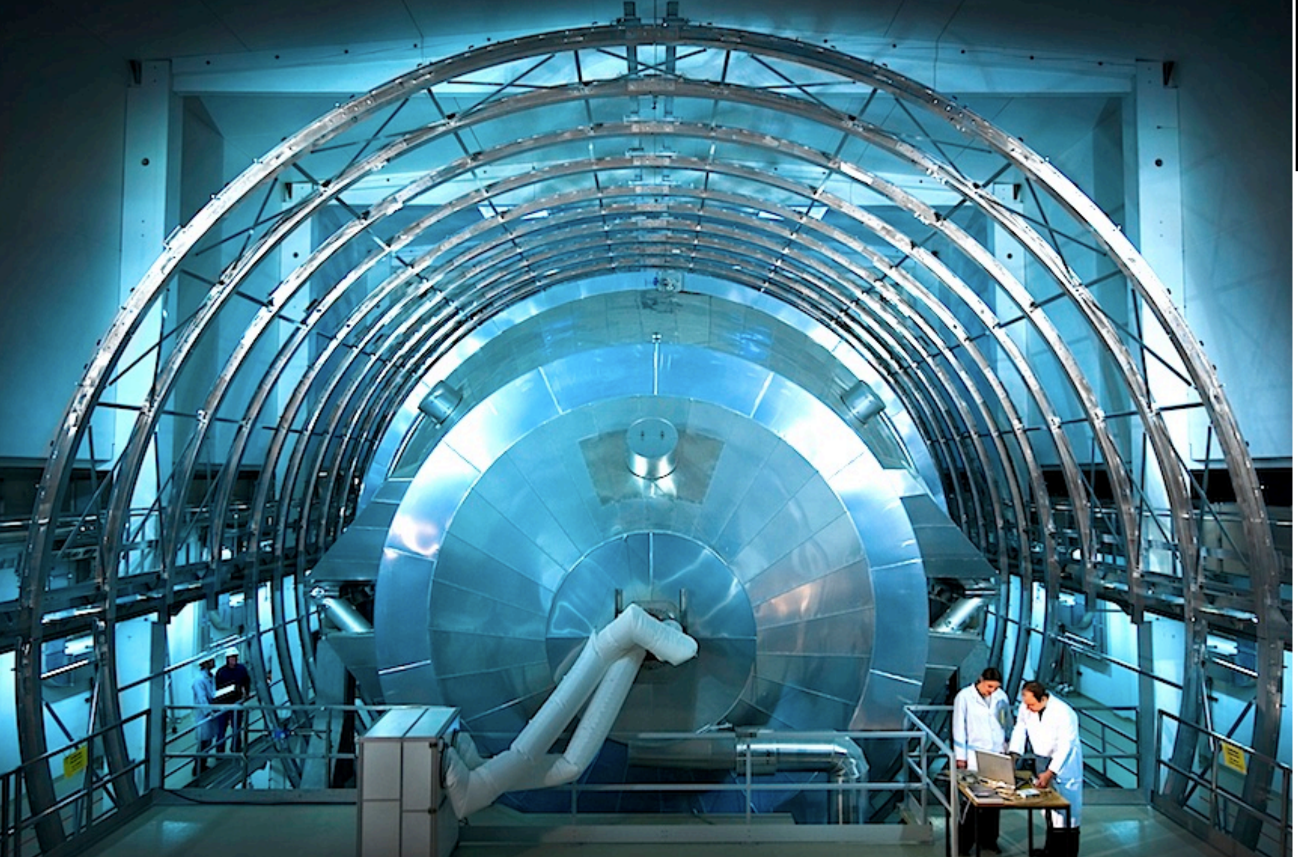
E = 18.3 keV
ΔE =80 eV
Filters most low energy
electrons from beta spectrum

UNITED KINGDOM
IRELAND
Belfast
Dublin
Irish Sea
Isle of Man (U.K.)
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
DENMARK
Copenhagen
Malmö
Kaliningrad
RUSSIA
Bornholm
Gdańsk
Hamburg
Bremen
Berlin
NETH.
Amsterdam
Rotterdam
Essen
Cologne
Bonn
Leipzig
GERMANY
Frankfurt am Main
Brussels
Lille
BEL.
Guernsey (U.K.)
Jersey (U.K.)
Luxembourg
LUX.
Paris
Stuttgart
Munich
Strasbourg
Nantes
Loire
Bay of Biscay
FRANCE
Zürich
Bern
SWITZ.
Vaduz
LIECH.
Geneva
Lyon
MASSIF CENTRAL
Bordeaux
Toulouse
MONACO
Marseille
Andorra la Vella
ANDORRA
PYRENEES
Bilbao
Porto
Zaragoza
Barcelona
PORTUGAL
Madrid
Lisbon
SPAIN
Valencia
Balearic Sea
BALEARIC ISLANDS
Sevilla
Gibraltar (U.K.)
Málaga
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Melilla (SPAIN)
Oran
Algiers
Rabat
Casablanca
MOROCCO
ALGERIA
Tunis
TUNISIA
Valletta
MALTA
Mediterranean Sea
Corsica
Sardinia
Cagliari
Ligurian Sea
Tyrrhenian Sea
Palermo
Sicily
Ionian Sea
Turin
Milan
Venice
Genoa
Florence
SAN MARINO
ITALY
Rome
VATICAN CITY
Naples
Adriatic Sea
Vilnius
LITHUANIA
Minsk
Mahilyow
BELARUS
Hrodna
Homyel'
Brest
Warsaw
Poznań
POLAND
Łódź
Wrocław
Oder
Elbe
Vistula
Kraków
Prague
CZECH REPUBLIC
Brno
SLOVAKIA
Bratislava
Vienna
AUSTRIA
Danube
Budapest
HUNGARY
Ljubljana
SLOVENIA
Zagreb
CROATIA
BOSNIA AND HERZEGOVINA
Sarajevo
Belgrade
Serbia
Montenegro
Podgorica
Tirana
ALB.
Skopje
F.Y.R.O.M.
Thessaloniki
GREECE
Athens
Aegean Sea
Crete
Rhodes
Sofia
BULGARIA
Varna
ROMANIA
Bucharest
Cluj-Napoca
CARPATHIAN MTS.
Iași
MOLDOVA
Chișinau
Constanța
Black Sea
Kiev
Rivne
L'viv
Chernivtsi
UKRAINE
Mykolayiv
Odesa
Dnipro
Istanbul
Bursa
İzmir
TURKEY
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles


S"
RVICE
udios
SYSTEMS
44
PHOTO

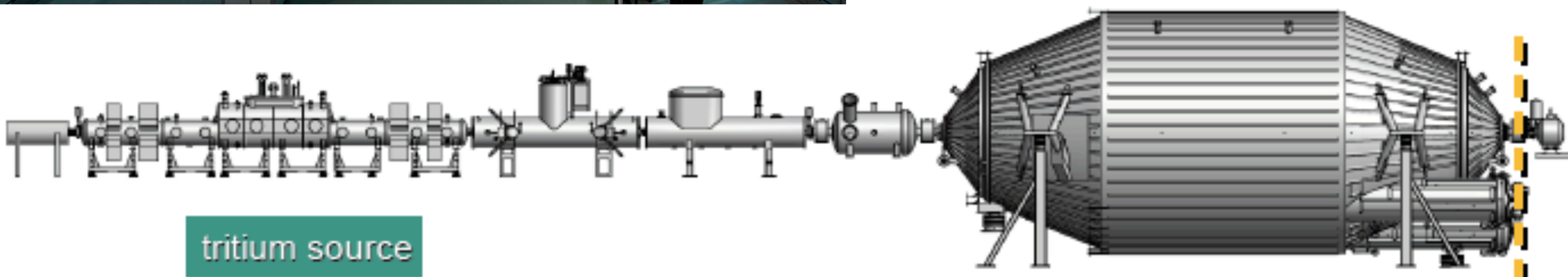


KATRIN landing...



Spectrometer and air coils

Detector

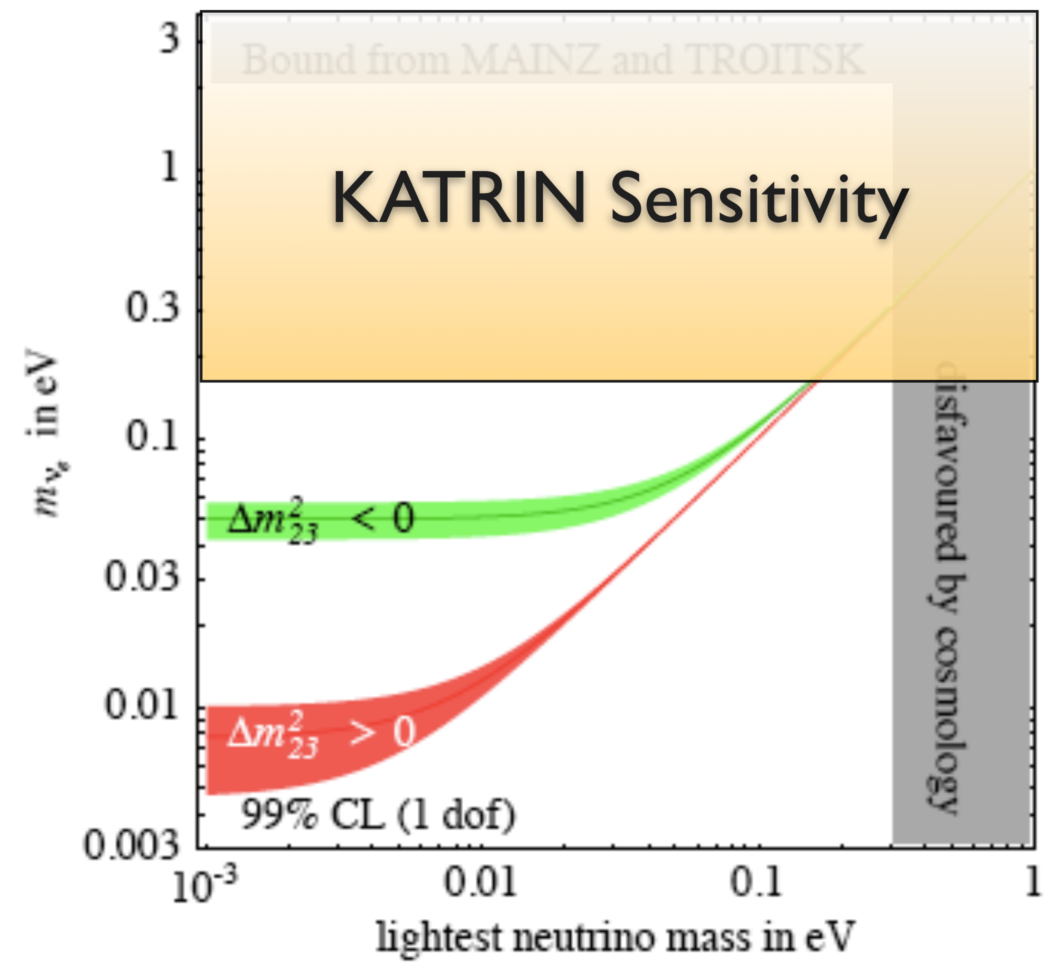


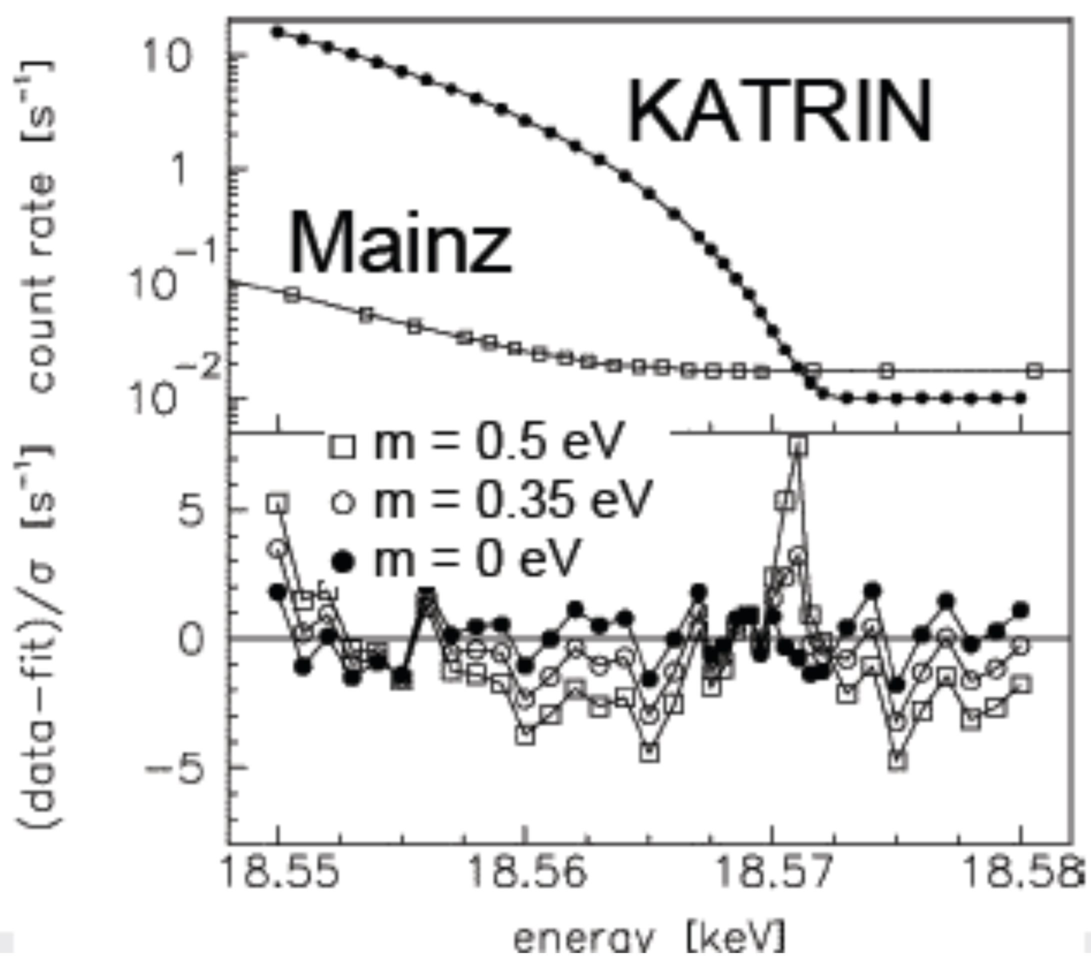
tritium source

Projected Sensitivity

$\Delta m_{\beta,stat}^2 = 0.018\ eV^2$ → Assumes 3 yr running

$\Delta m_{\beta,sys}^2 = 0.017\ eV^2$ → Major systematics include source purity, HV stability, source stability and T_2 final states





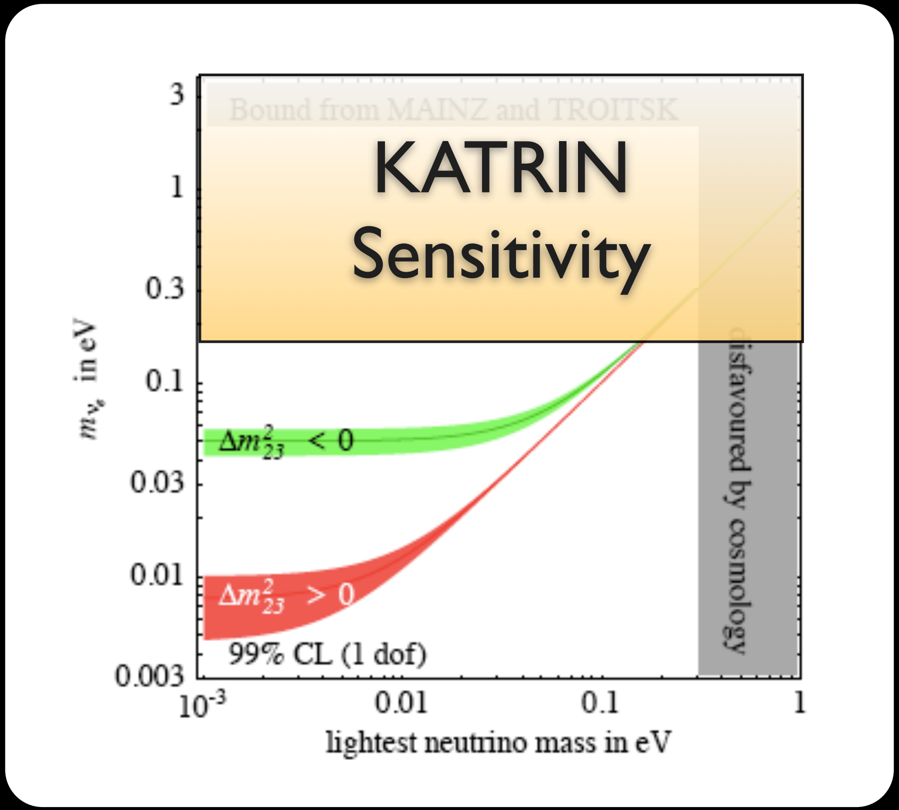
Neutrino Mass Goals

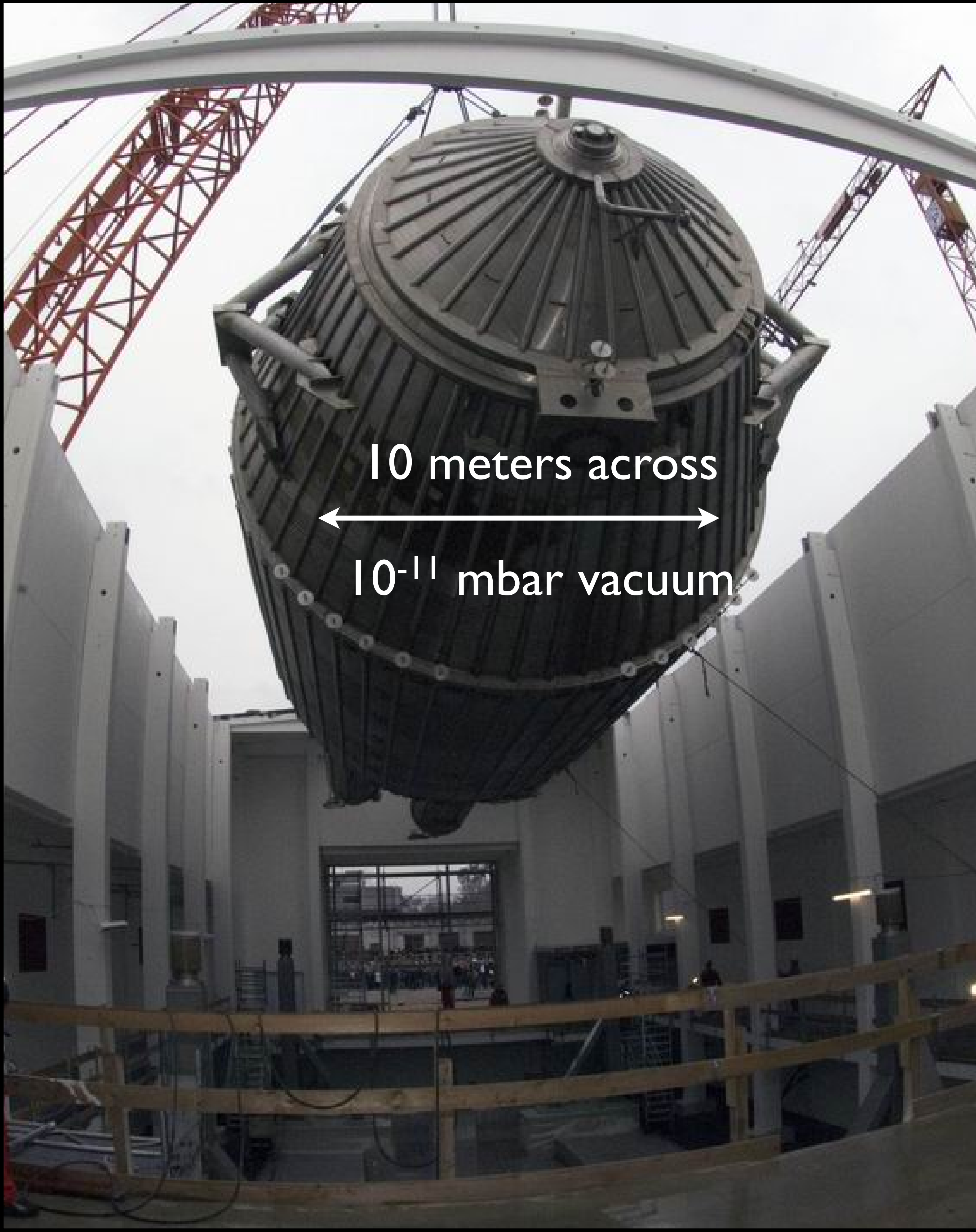
Discovery: 350 meV (at 5σ)

Sensitivity: 200 meV (at 90% C.L.)

Can we push further?

- KATRIN will achieve 200 meV scale. Can direct measurements push lower to the normal hierarchy scale?
- Any future experiment needs to be able to (a) have a better scaling law for increased target mass and (b) improve its energy resolution.

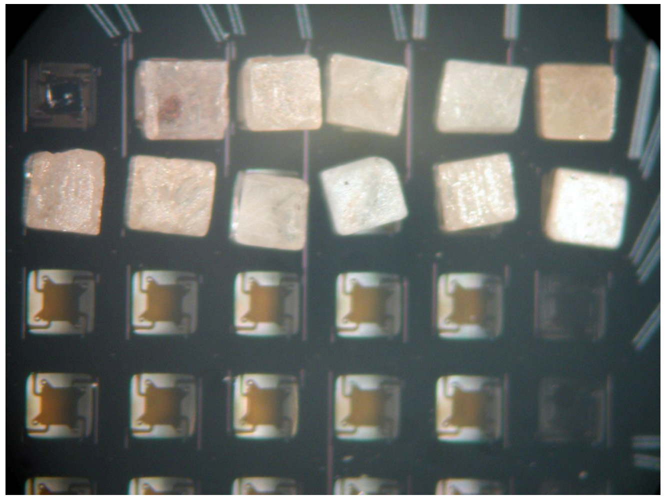




MARE

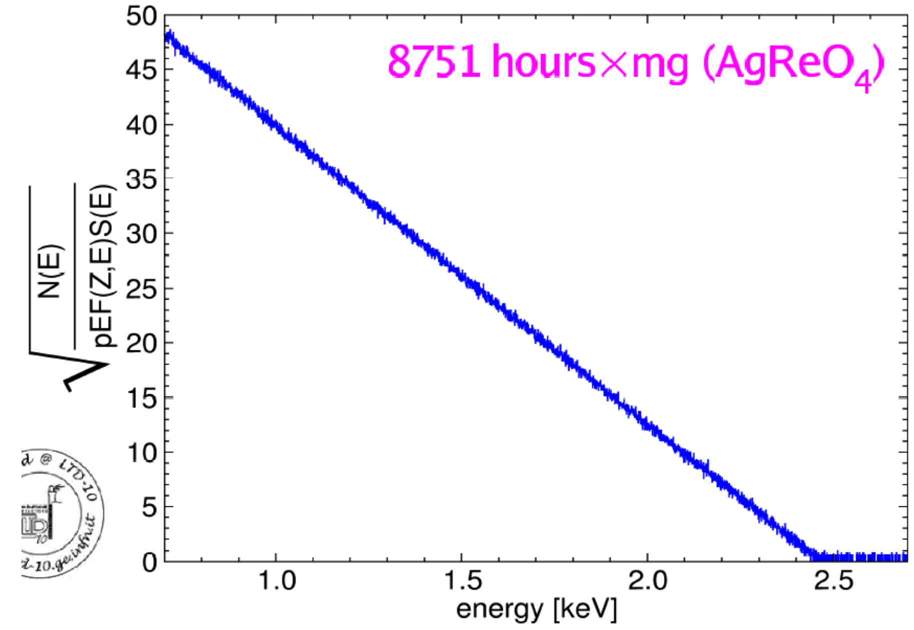
Bolometric:

MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

- Uses ^{187}Re as its beta source (one of the lowest endpoints, 2.3 keV)
- Advantages:
  - No backscattering
  - No atomic or molecular final state effects.
- Disadvantages:
  - Extremely long half-life.
  - Pileup backgrounds.

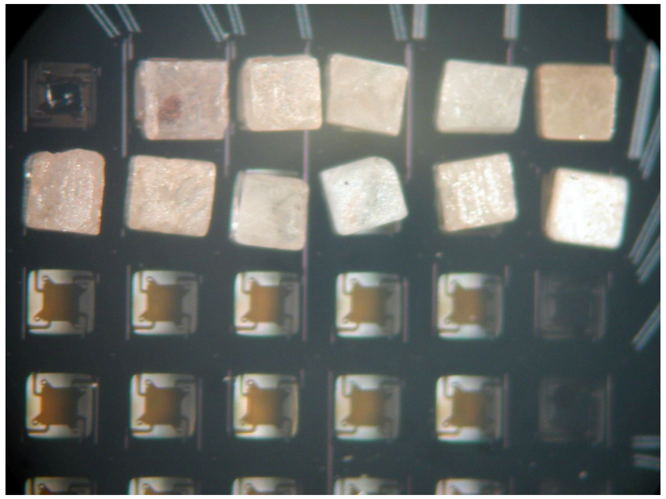


$m_\nu^2 = (-112 \pm 207 \pm 90)\ \mathrm{eV}^2$

MARE

Bolometric:

MARE



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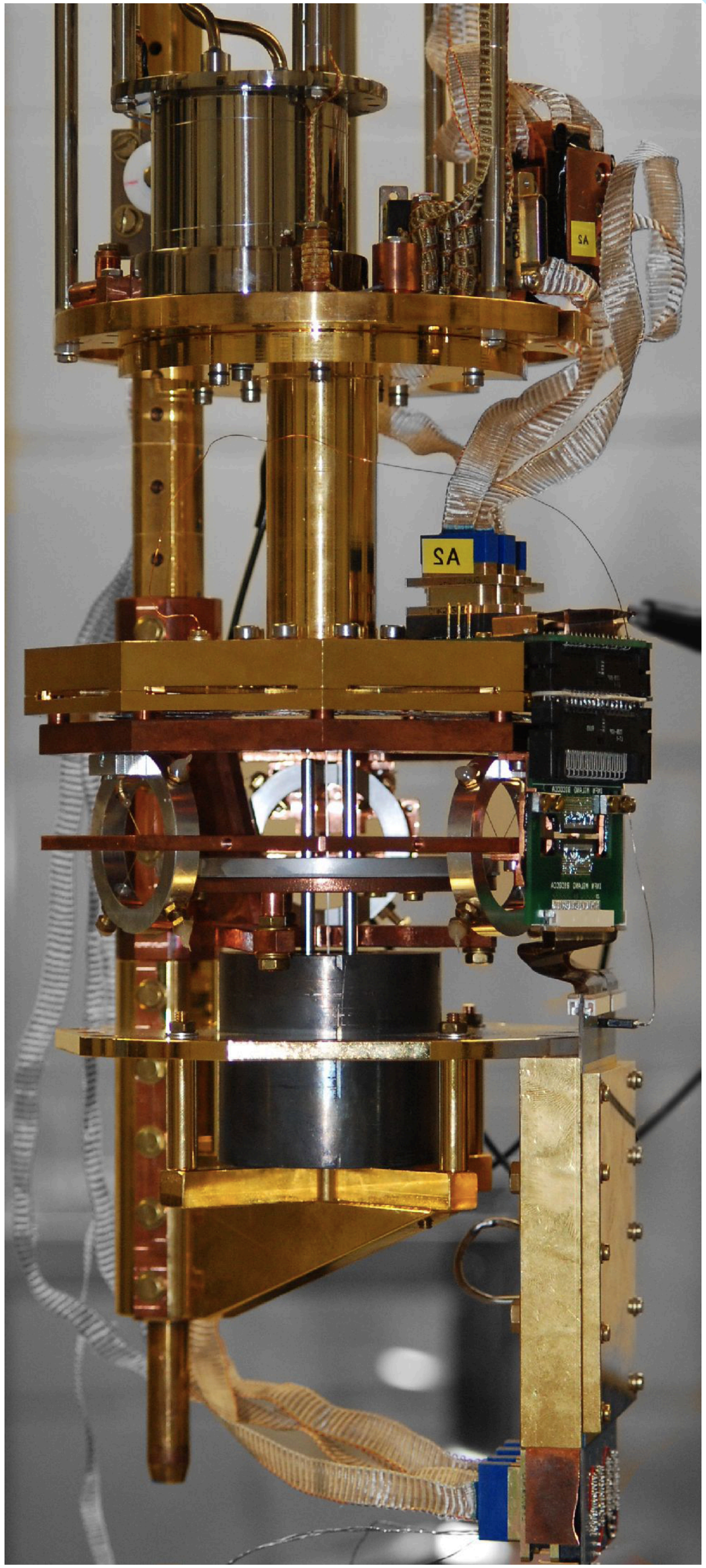
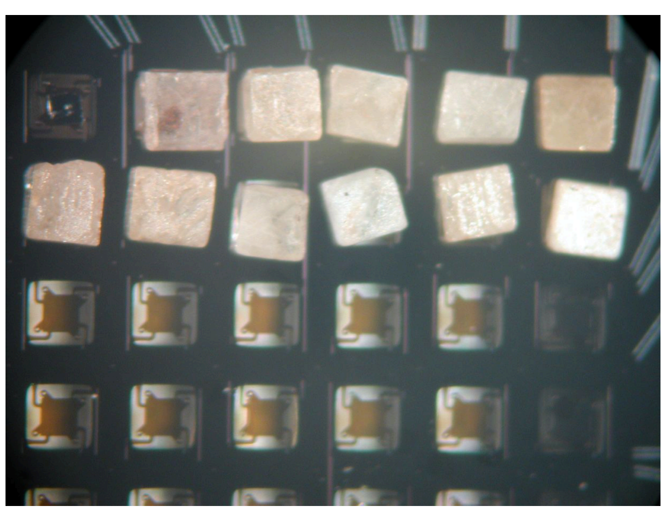
Cryogenic setup in Milan



MARE R&D

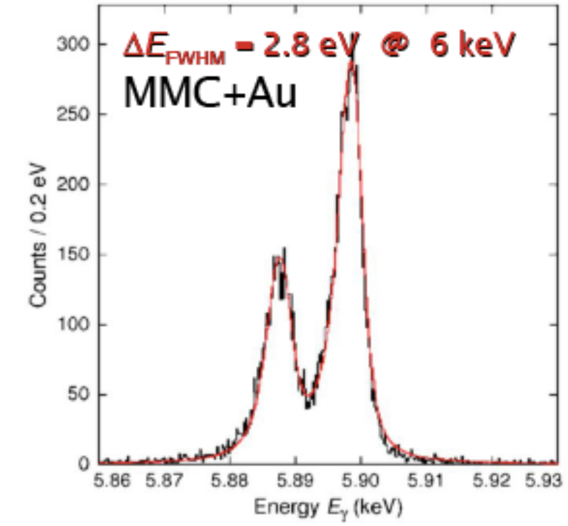
Bolometric:

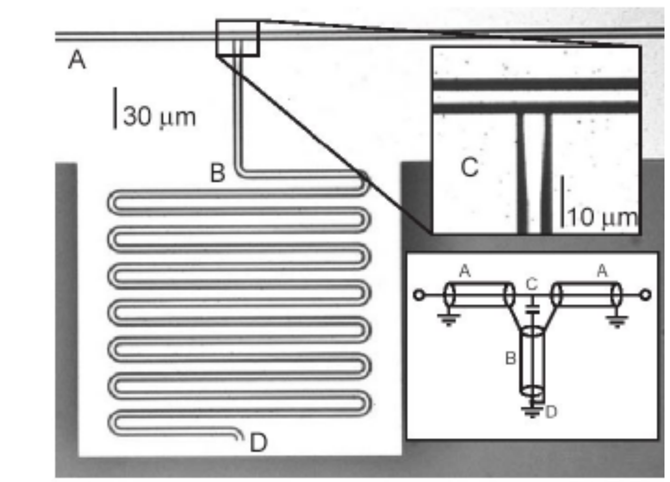
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

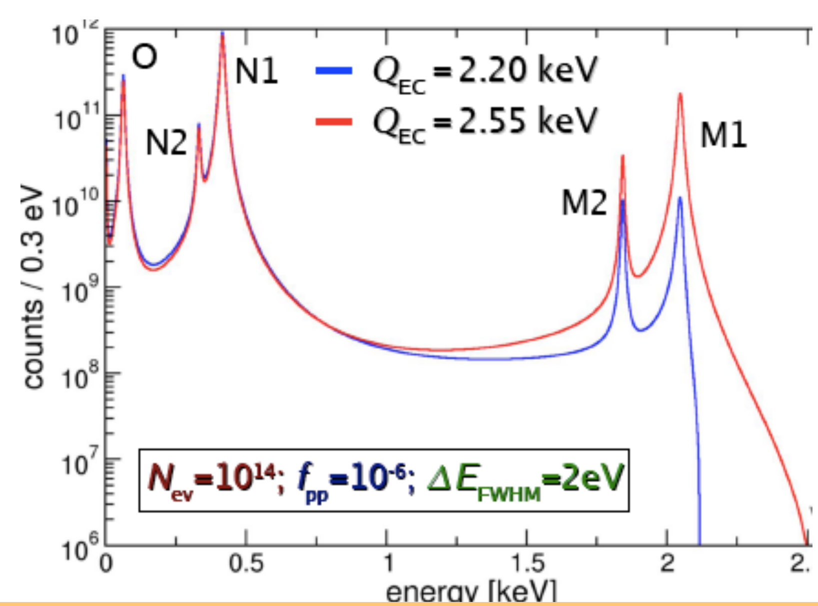
- New Technology:
  - Use of magnetic micro calorimeters. Minimize rise time and energy resolution.
  - MKID devices (1-10 GHz) resonating super-conductors.
  - Reduces pileup, increases pixelation and energy resolution





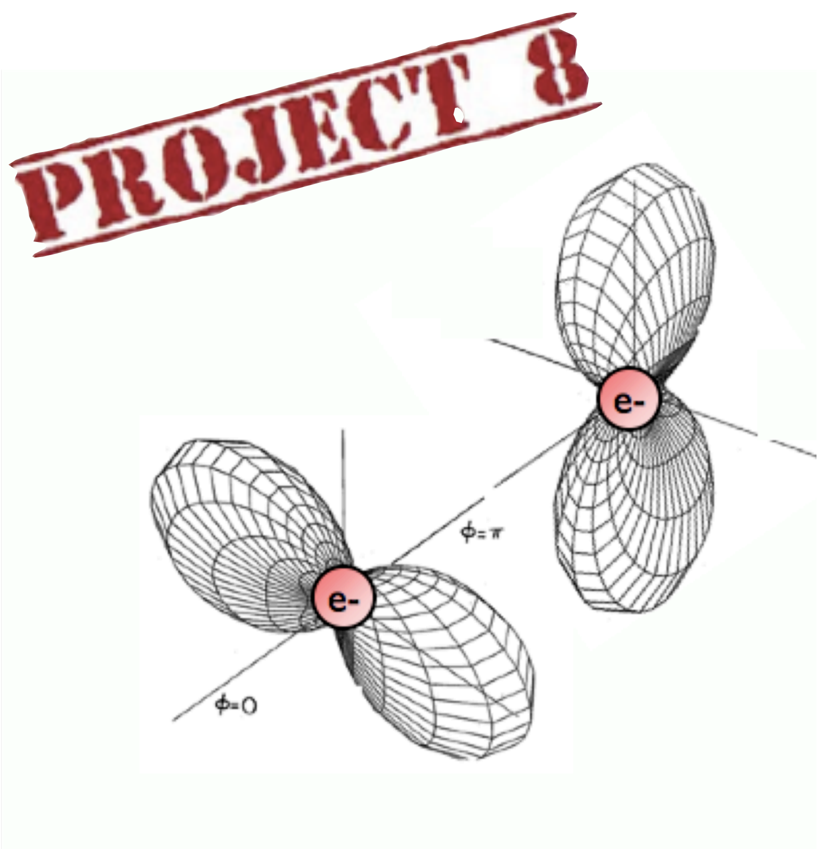
- New Isotopes:
  - Also exploring ^{183}Ho electron capture

$$^{183}Ho + e^{-} \rightarrow {}^{163}Dy* + \nu_e$$



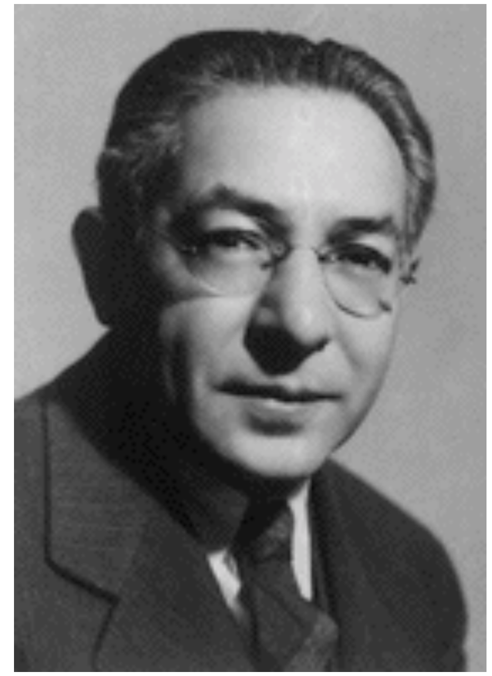
R&D to lead to MARE 2 (0.2 eV sensitivity)

Project 8



Frequency

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$



"Never measure anything but frequency."

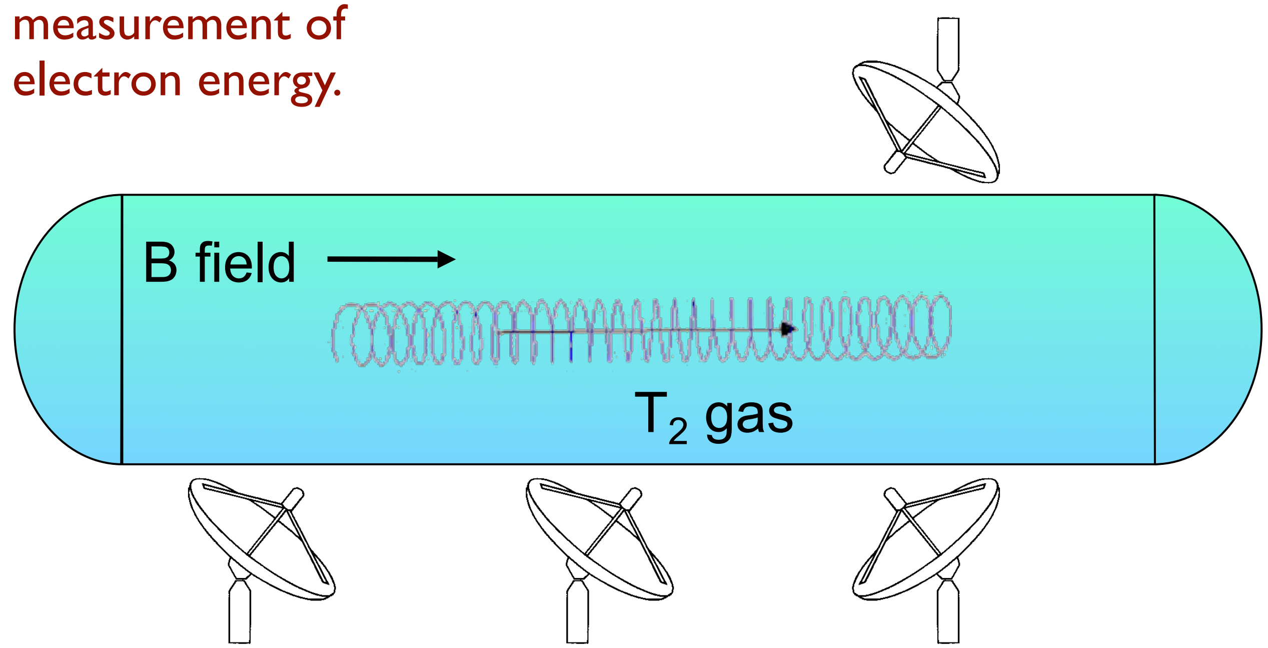
I. I. Rabi

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

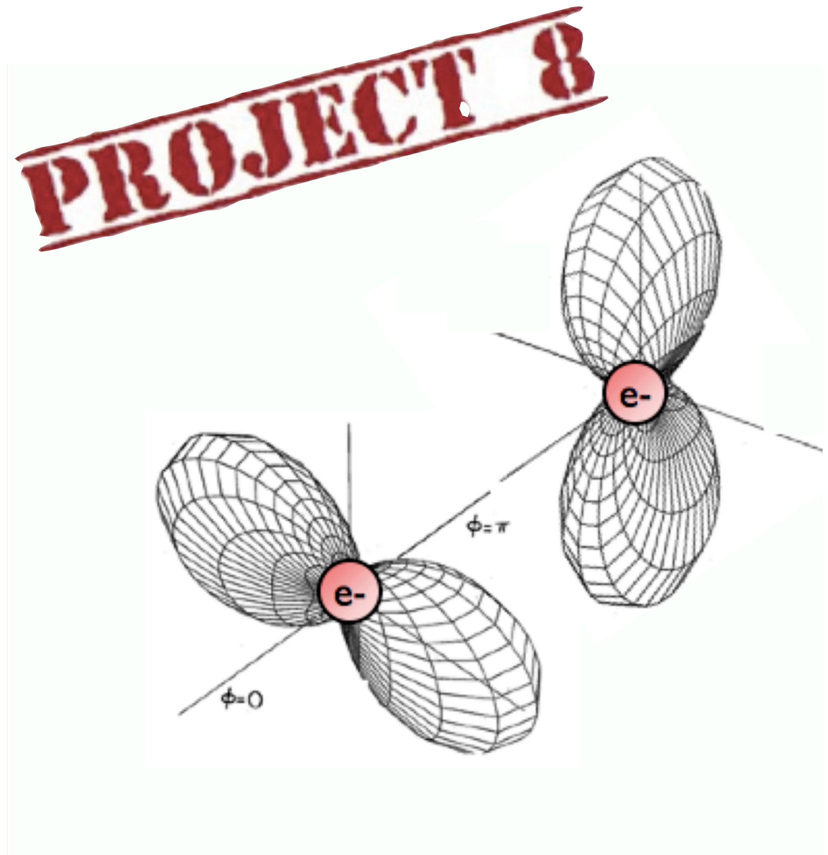
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Non-destructive measurement of electron energy.



B. Monreal and J. Formaggio, Phys. Rev D80:051301

Project 8



Frequency

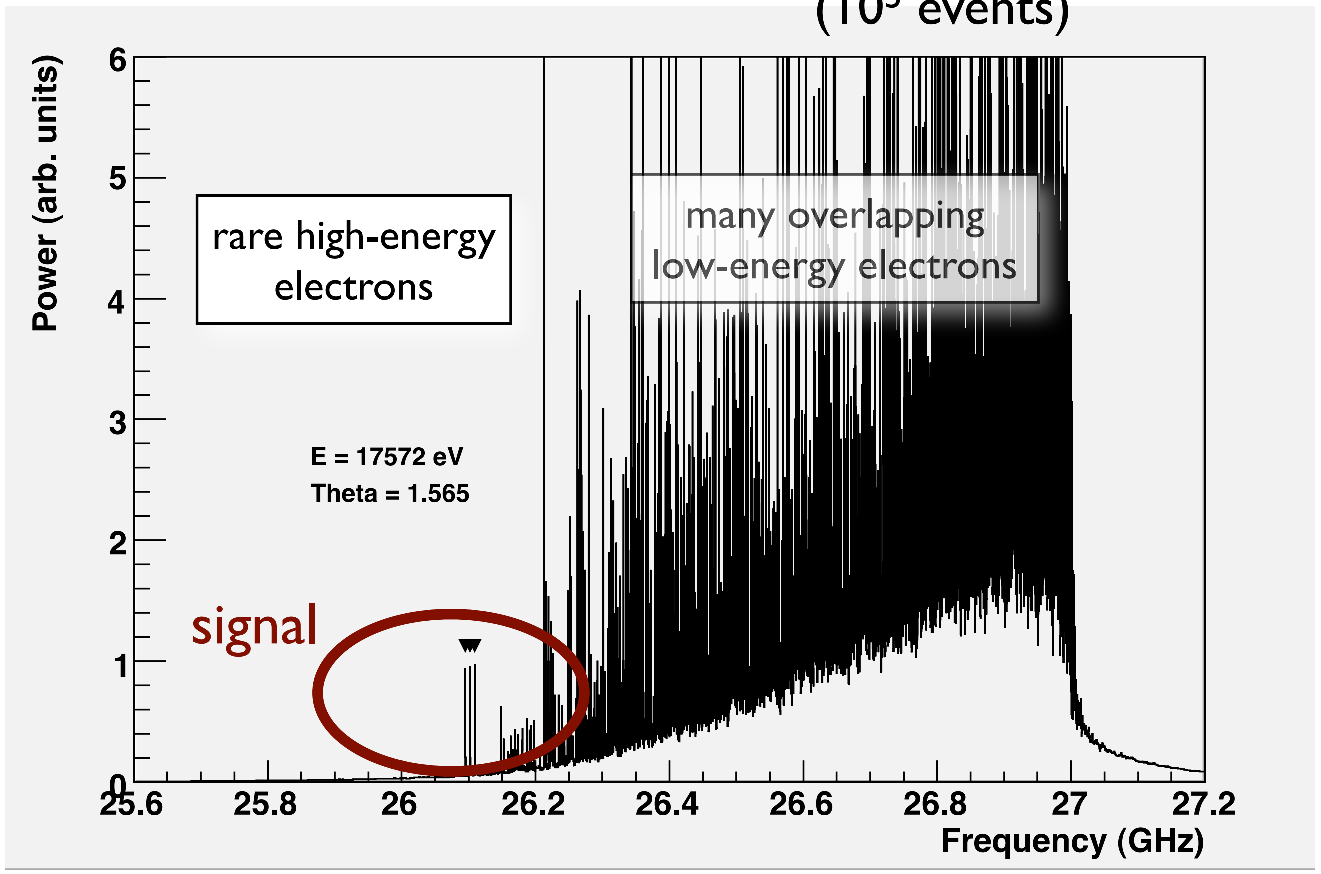
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

I. I. Rabi

"Never measure anything but frequency."

A. L. Schawlow

Simulation run (10^5 events)



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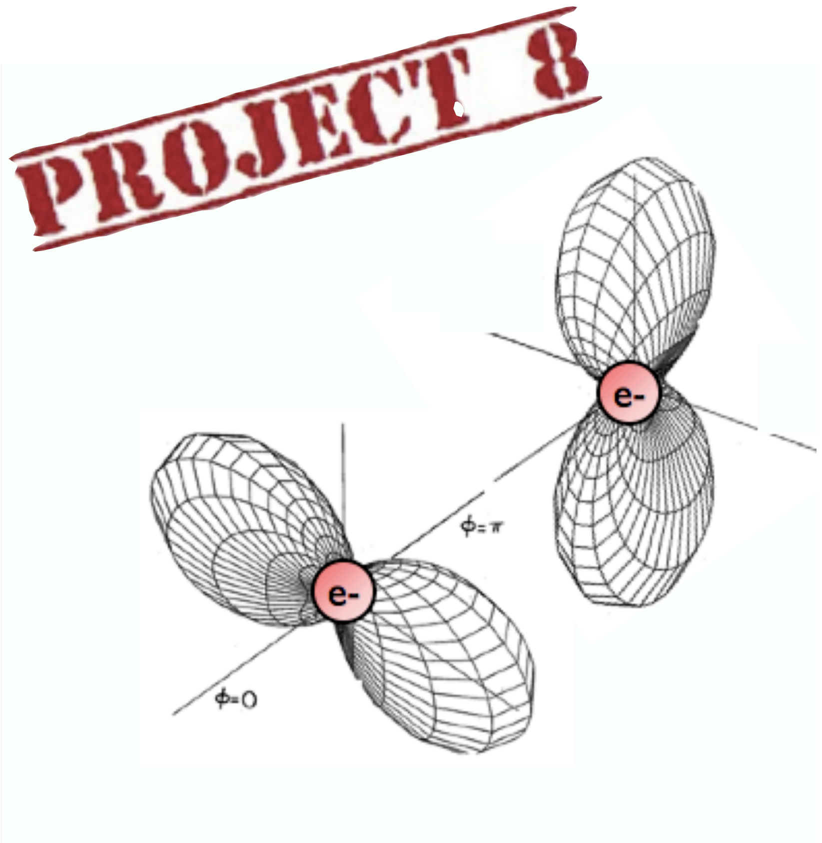

Frequency

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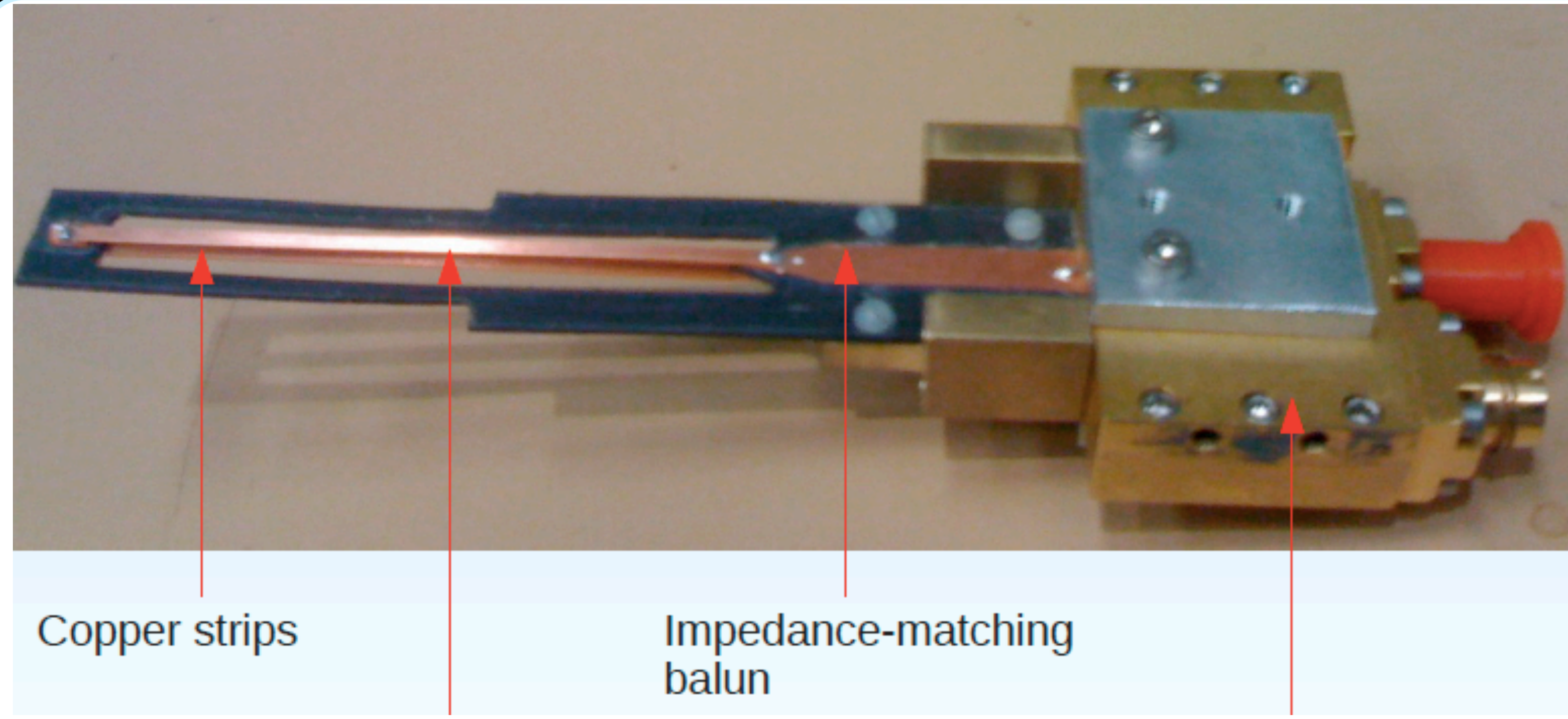
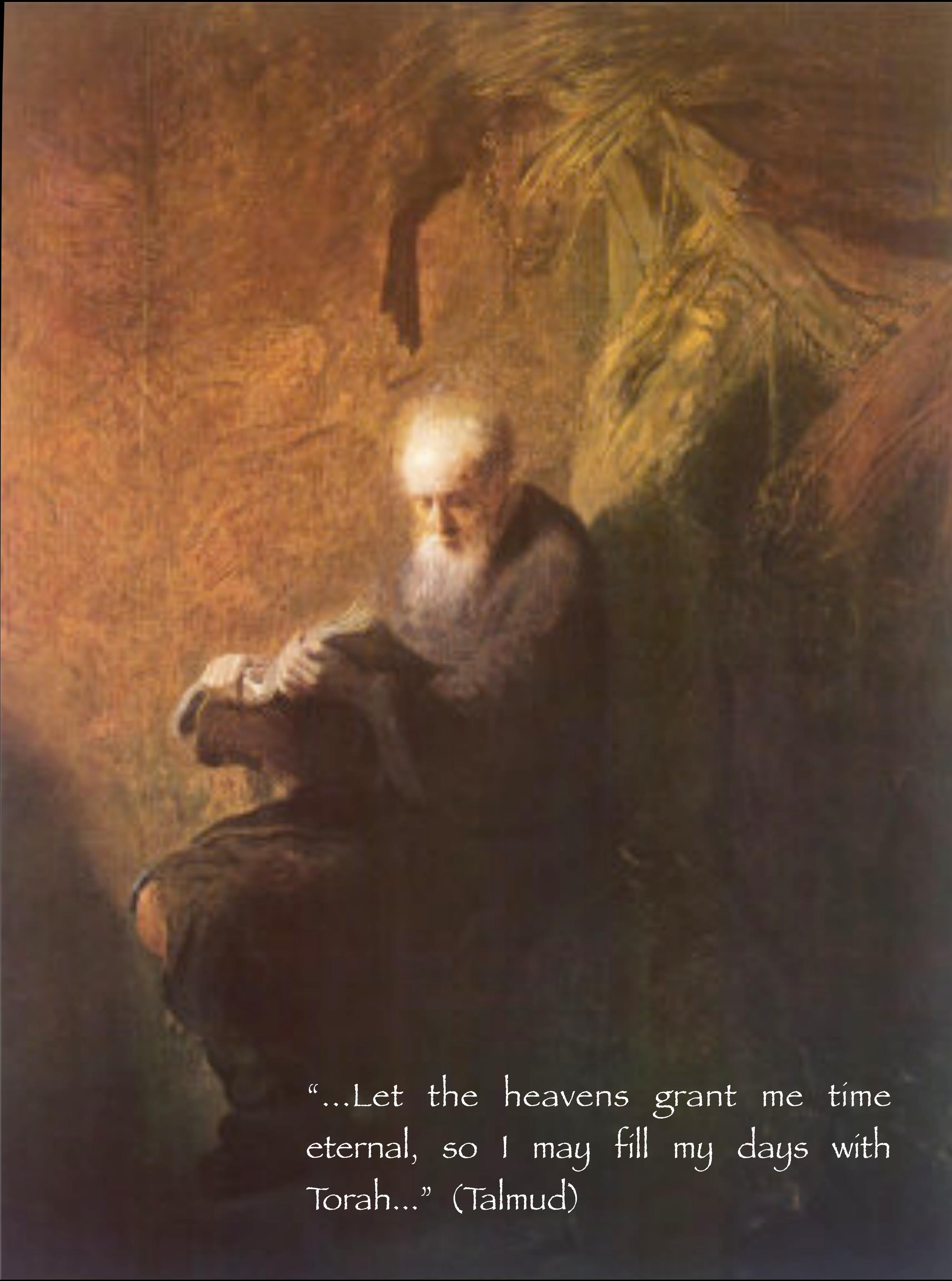


Wire antenna

Low noise GHz amplifier

Magnetic bottle
1 T field (27 GHz)



Measuring ν masses

(the framework)

Measuring neutrinos from the Heavens

(cosmology)

Measuring neutrinos on Earth

(beta decay)

Patient measurements

(Neutrinoless double beta decay)

Neutrinoless Double Beta Decay

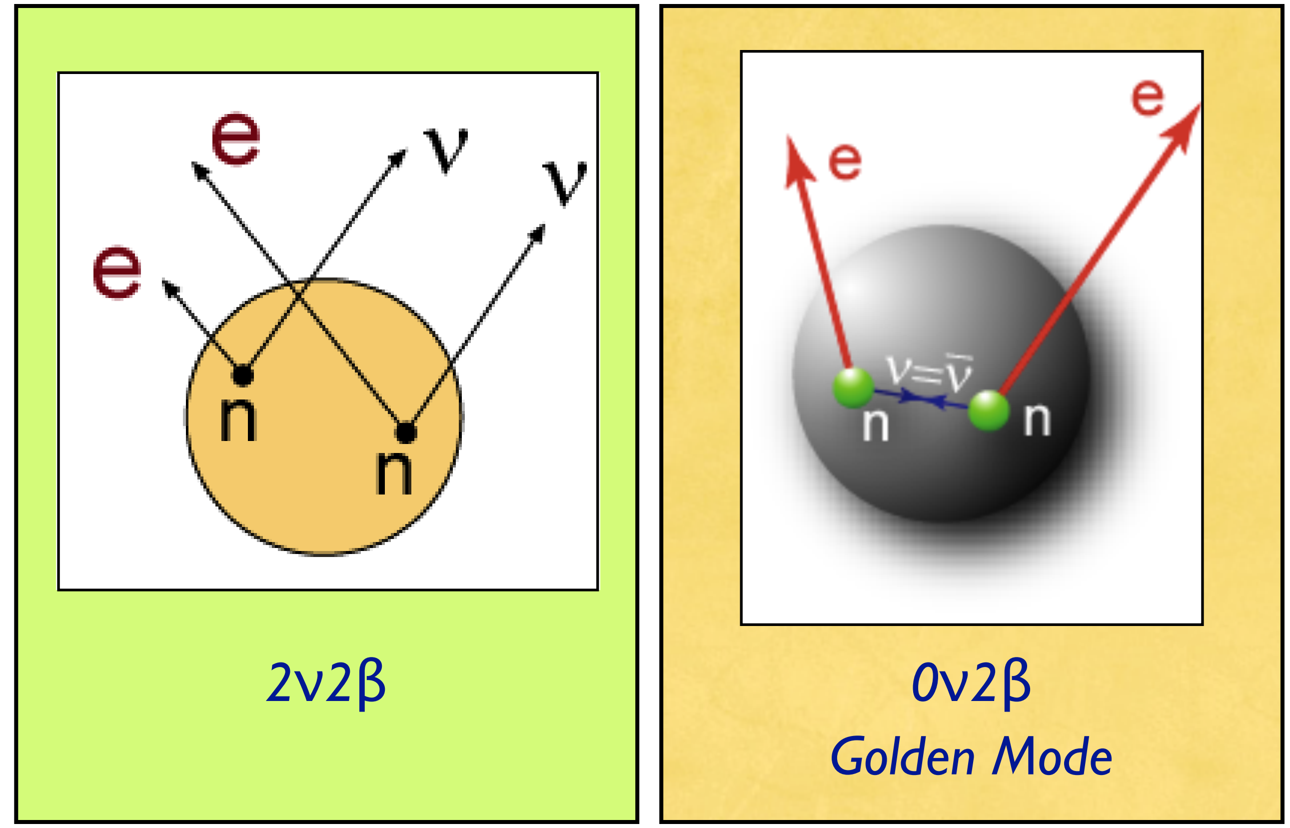
- Clear decay signature (peak at endpoint) sensitive to Majorana neutrino masses.

- To be seen, two conditions must hold:

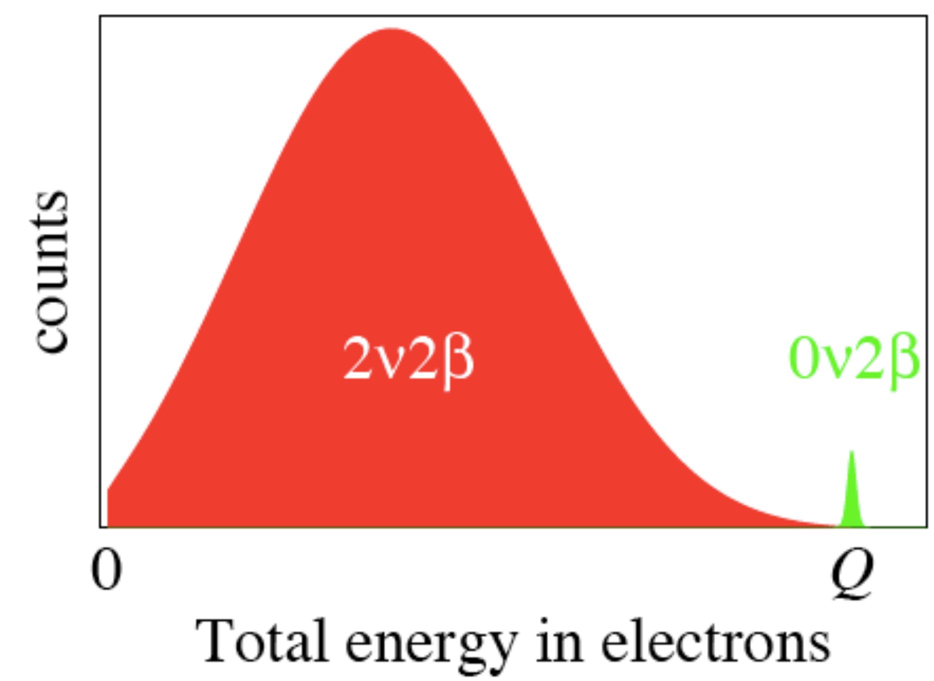
  (1) Non-zero neutrino mass.

  (2) Lepton number violation.

- Currently a strong focus of the experimental neutrino community.



$$m_{\beta\beta} = |\sum_{i=1}^{n_\nu} U_{ei}^2 m_i|$$



Lifetime and Masses

$$(T^{0\nu}_{\frac{1}{2}})^{-1} = G^{0\nu}|M^{0\nu}|^2 m^2_{\beta\beta}$$

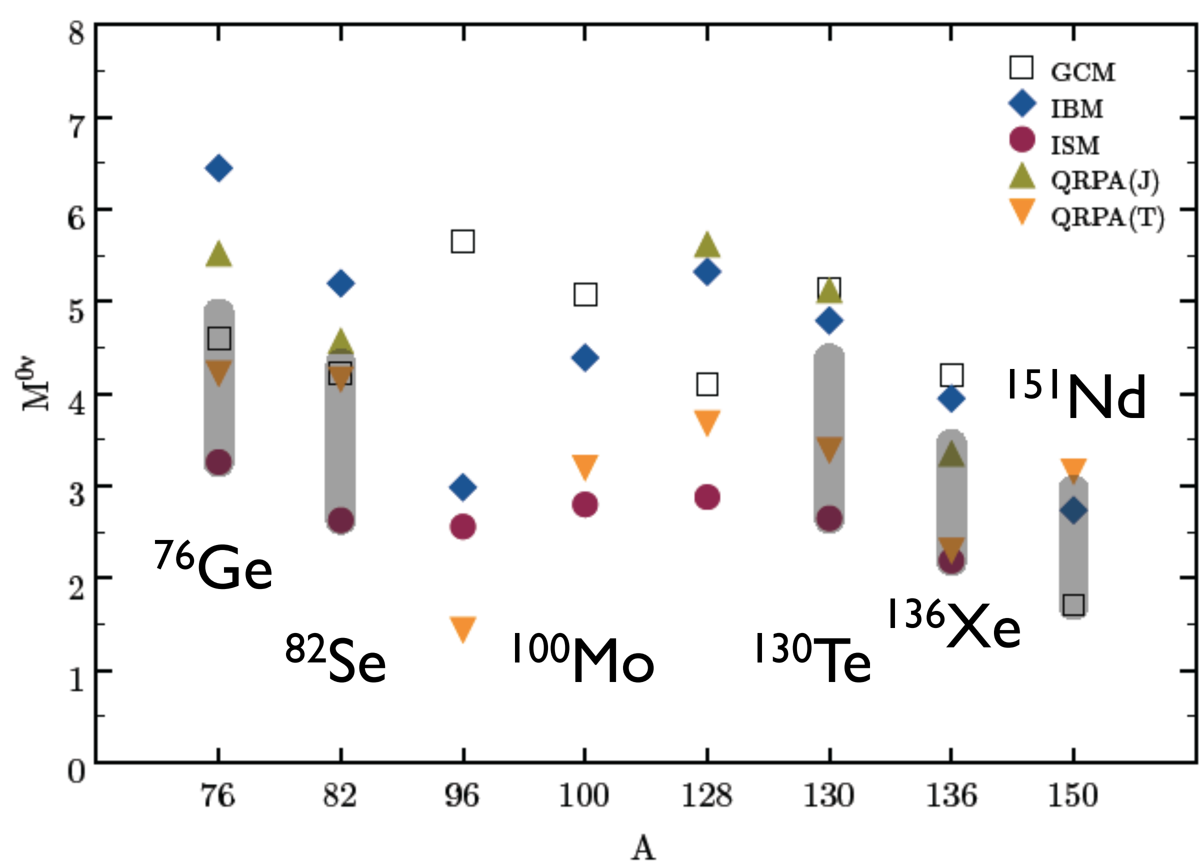
Phase space term

Matrix element

Majorana mass term

- Technology often dictated by the isotope selected.
- Positive signal establishes Majorana property of lepton violation. Neutrino mass amplitude a bit harder to extract.
- Calculations of matrix elements have seen better agreement (Interacting Shell Model, Quasi Random Phase Approximation, etc.)

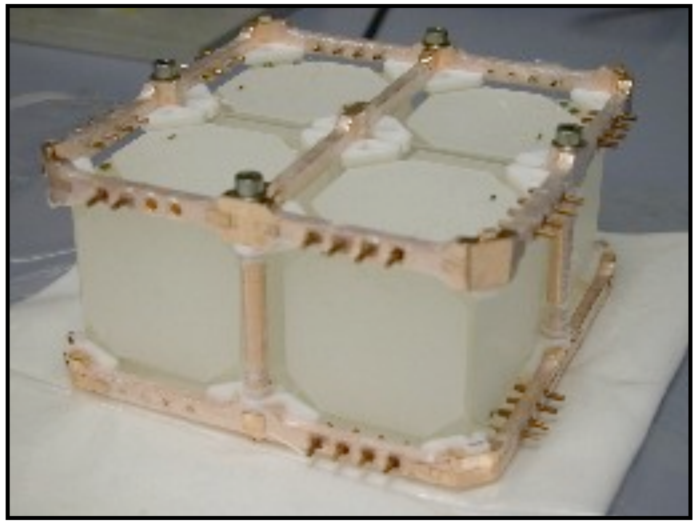
J. J. Gomez-Cadenas et al
arXiv:1010.5112v4



Methods

Methods

Bolometric:



Excellent energy resolution

Current experiments:

CUORICINO, CUORE, LUCIFER

Methods

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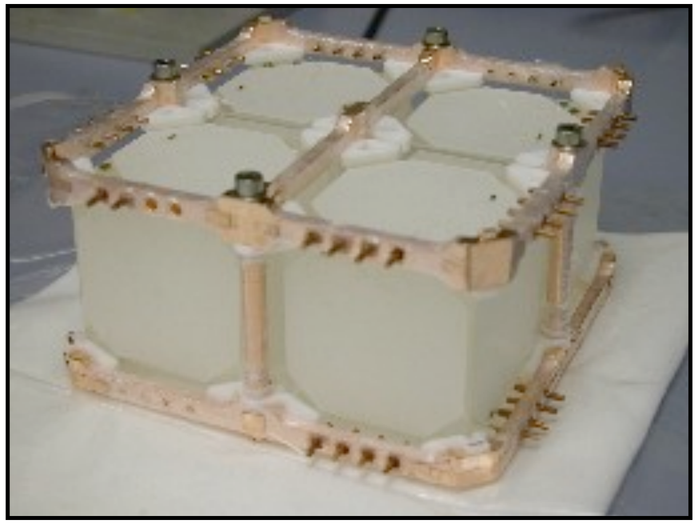

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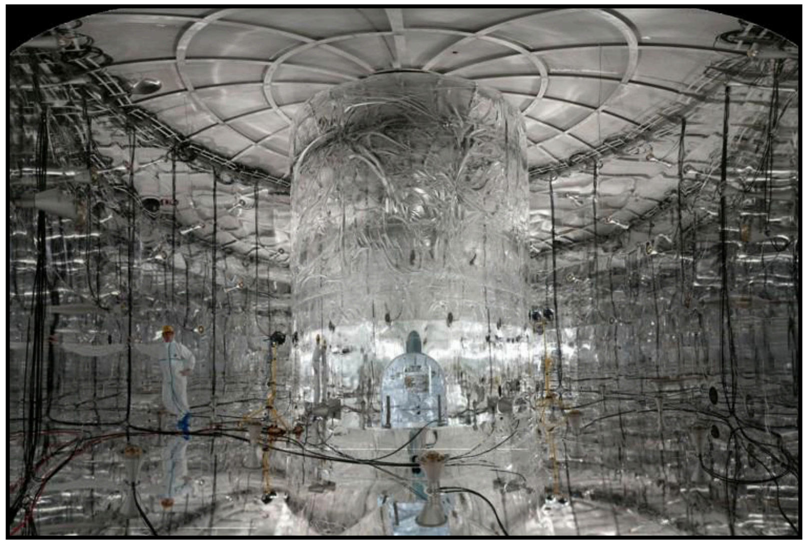

Excellent energy resolution and background rejection

Current experiments:

MAJORANA, GERDA, COBRA

Methods

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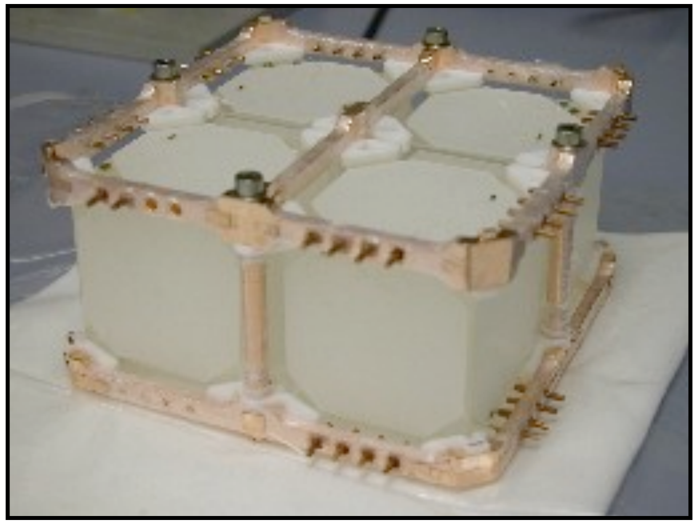

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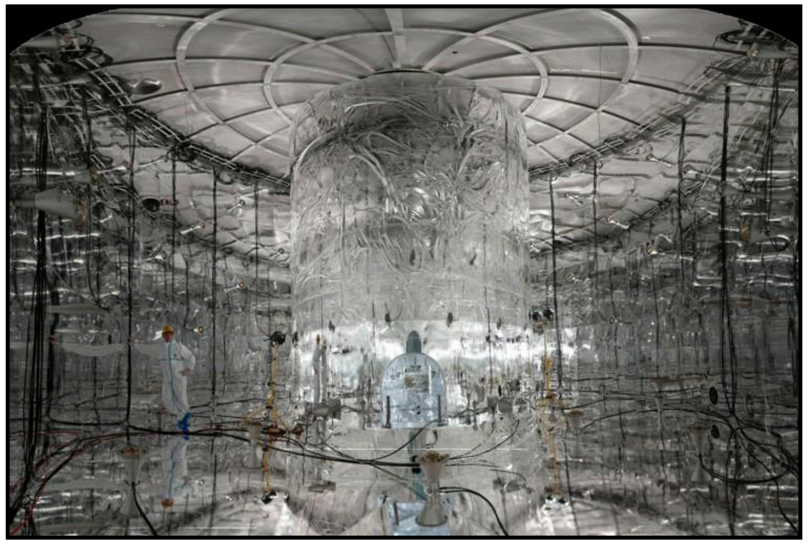

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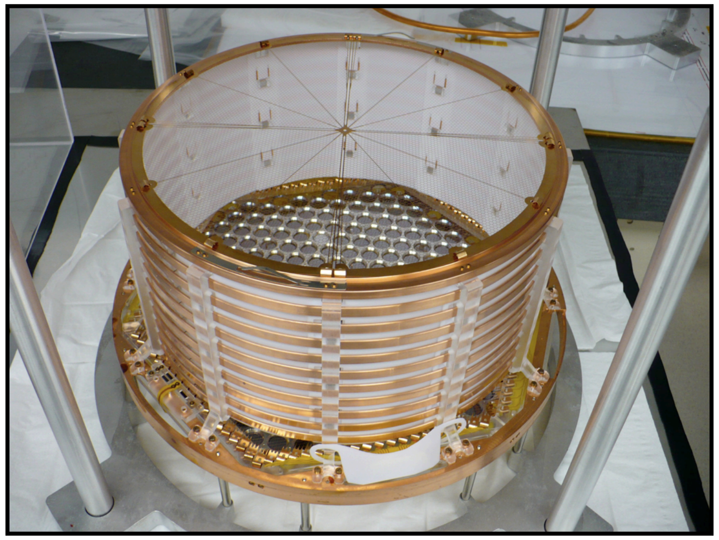
Tracking & Calorimetry:



Allows for track reconstruction or large volumes

Current experiments:

EXO, SuperNEMO, SNO+, NEXT, KamLAND-Zen

Methods

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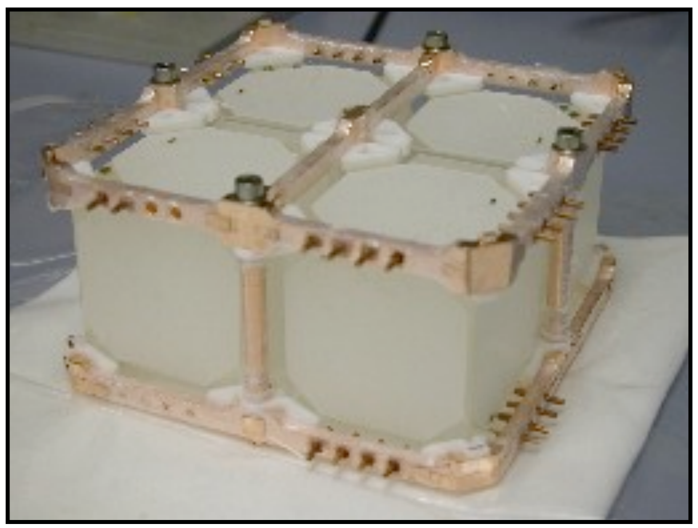


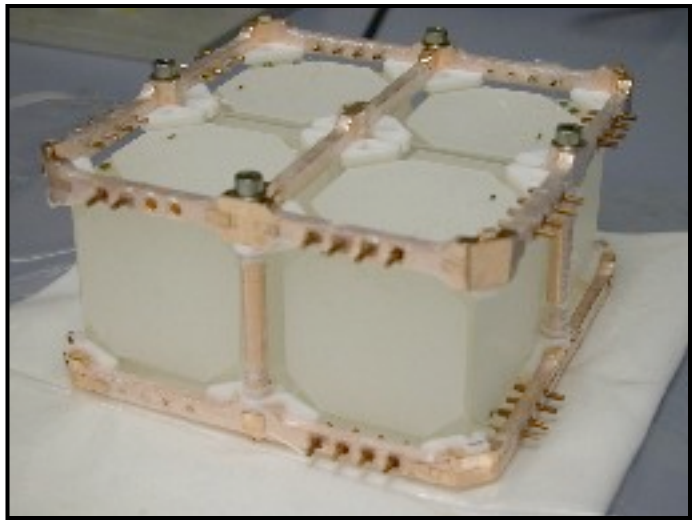
Excellent energy and radiopurity

Current experiments:

CUORICINO, CUORE, LUCIFER

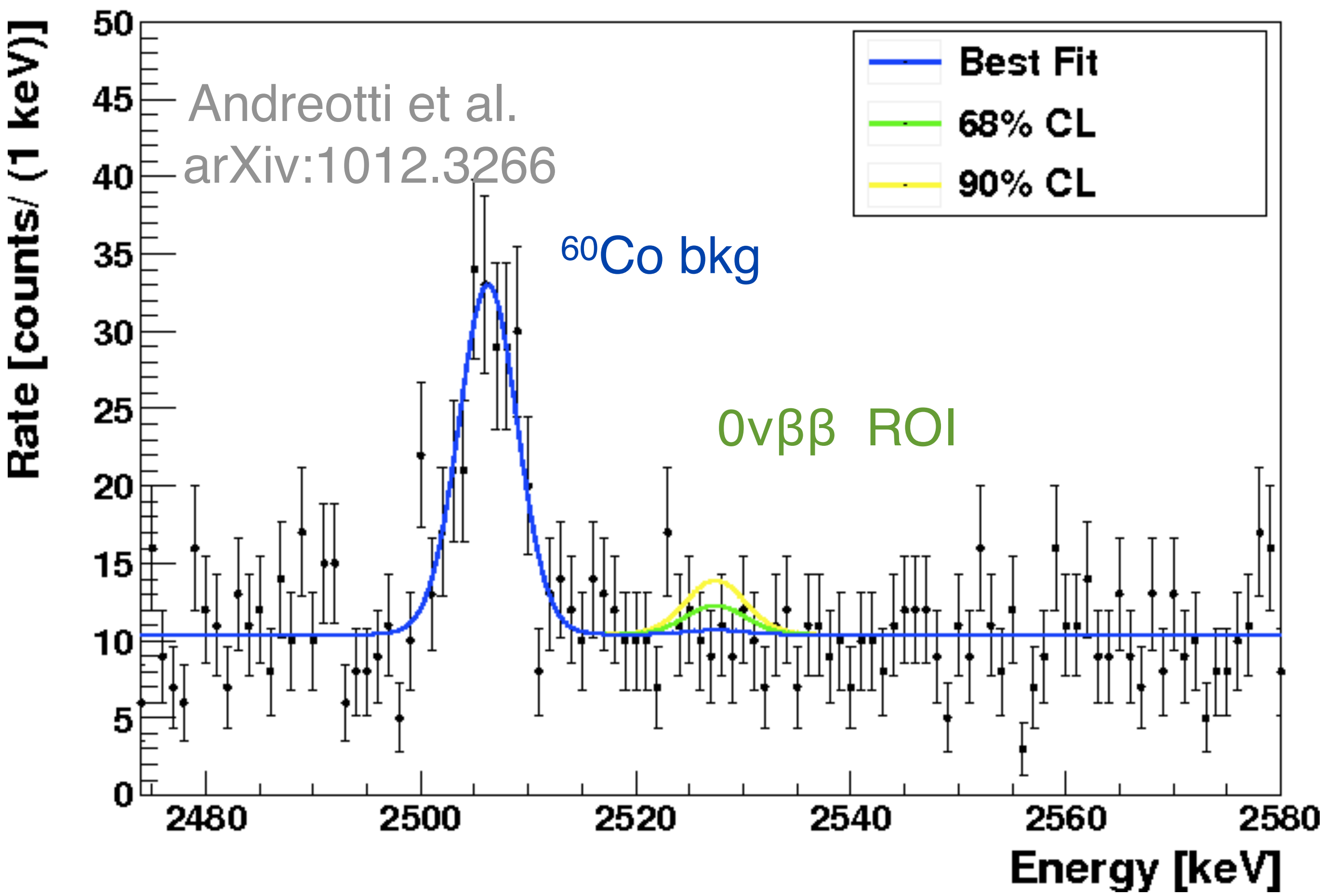
CUORE & CUORICINO

- Uses 20 kg ^{130}Te (very high natural abundance ~30%)
- High endpoint for background suppression.
- Cuoricino results, upgrade to CUORE.



$T_{1/2}$ (0ν) $>2.8 \times 10^{24}$ yr

$m_{\beta\beta} >\approx$ (300-710 meV)



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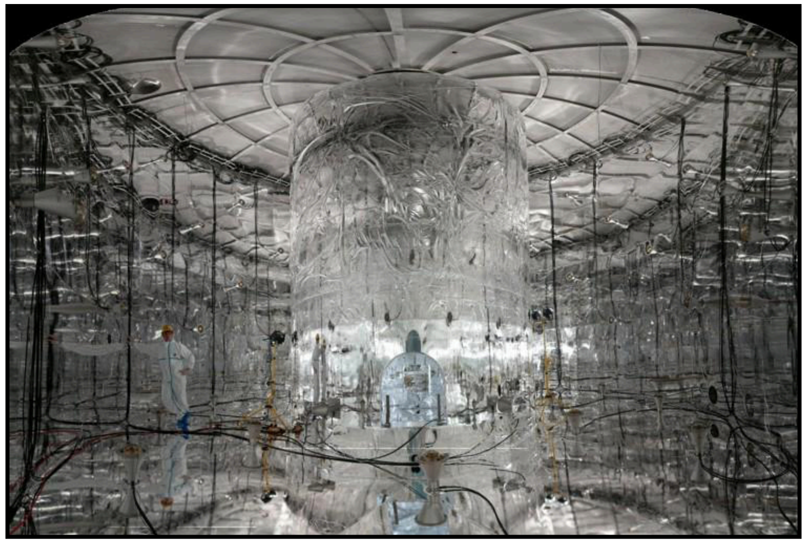

Excellent energy resolution and background rejection

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MAJORANA, GERDA, COBRA

Germanium Experiments

- Two major endeavors underway: MAJORANA (US) and GERDA (EUROPE).
- Superb energy resolution (0.2% FWHM at Q-value).
- Excellent background purities:

  GERDA I 10^{-2} cnt/kg/keV/yr;

  MAJORANA: 10^{-3} cnt/kg/keV/yr
- New developments:
  - Pulse shape discrimination
  - LAr shield

Methods

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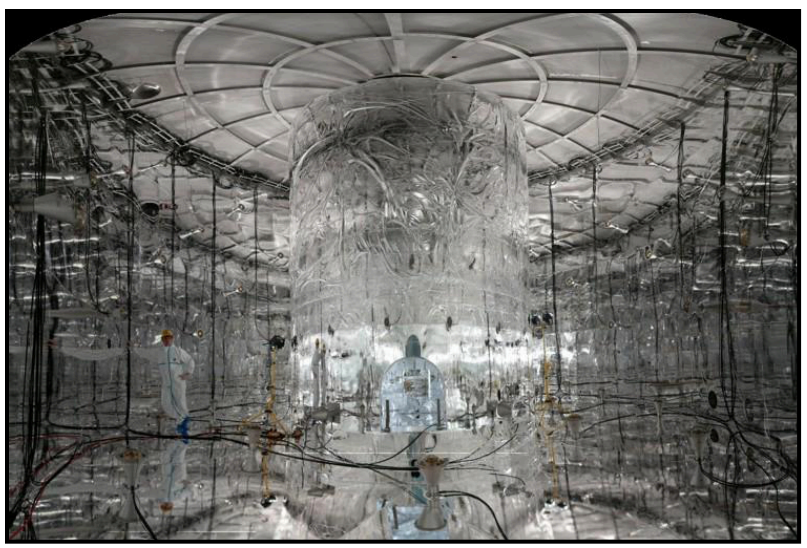

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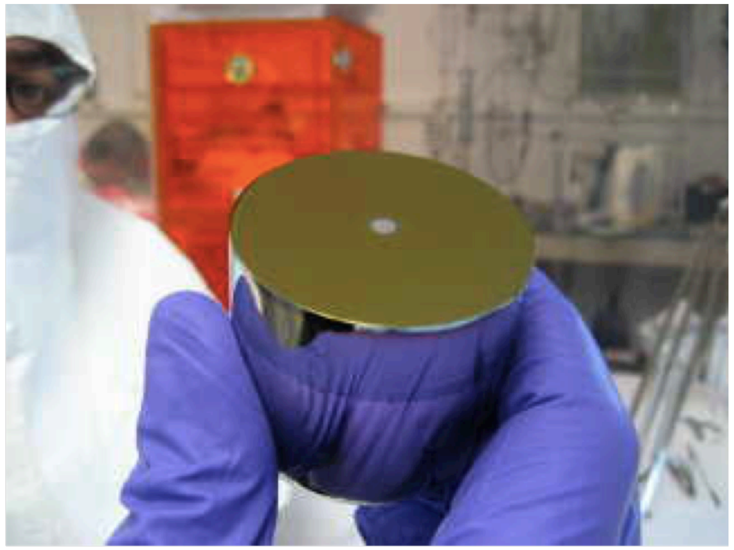

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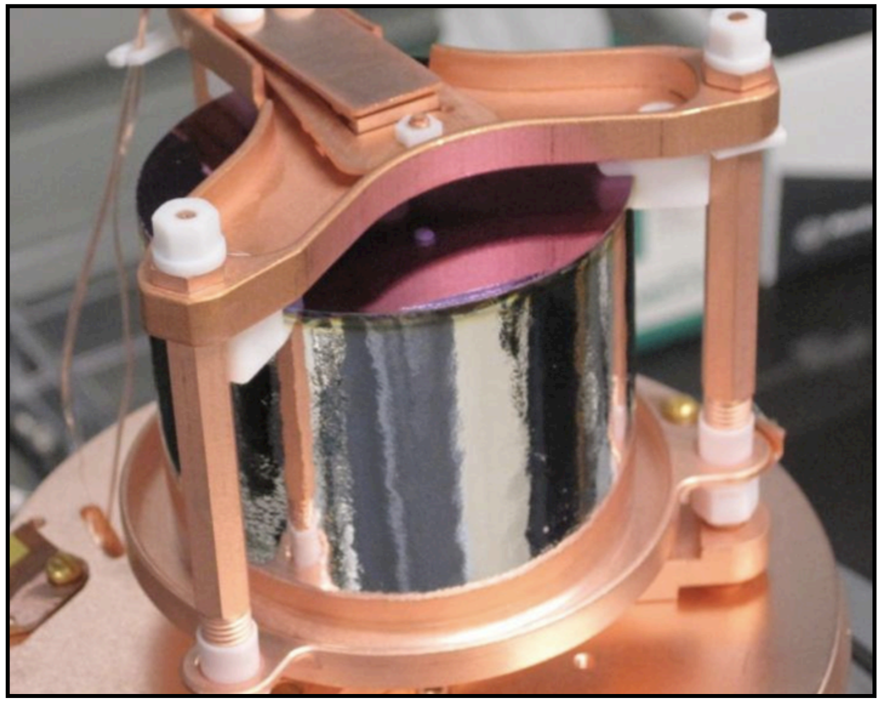

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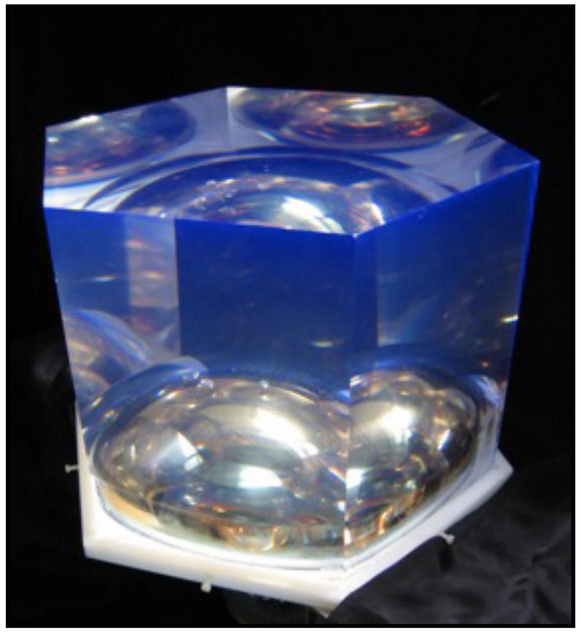


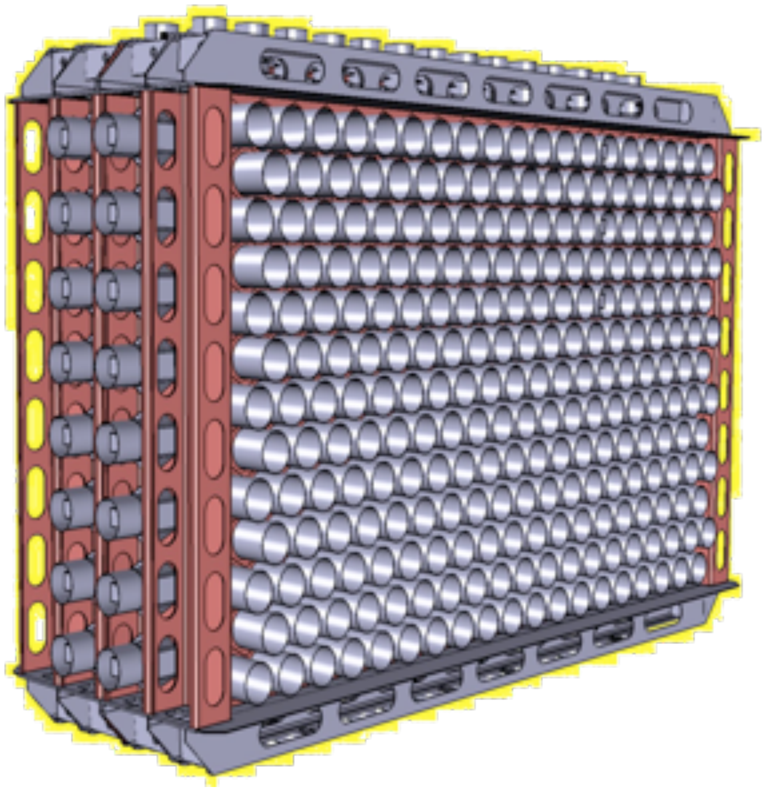
Allows for track reconstruction or large volumes

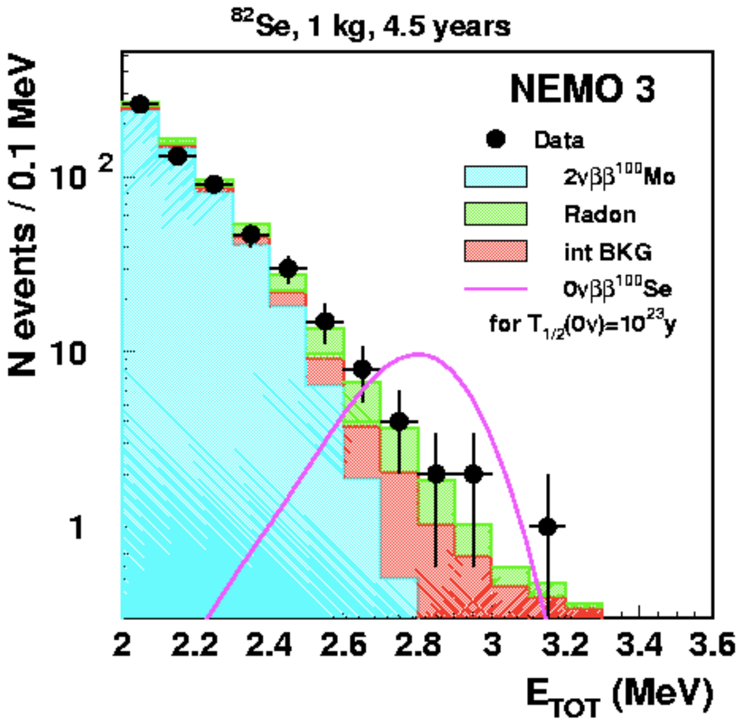
Current experiments:

EXO, SuperNEMO, SNO+, NEXT, KamLAND-Zen

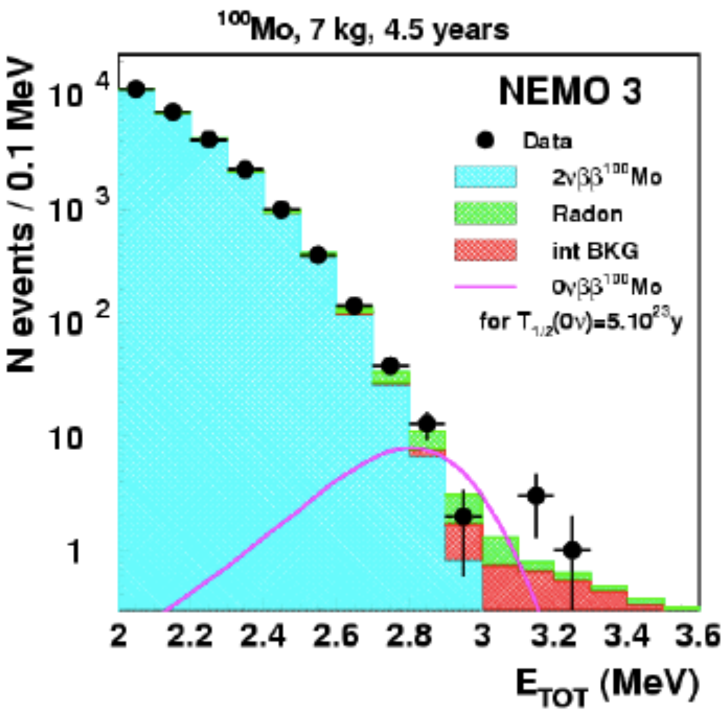
NEMO3 & SuperNeMO

- Full electron track reconstruction (use tracking & calorimetry).
- Multiple isotopes in use (in particular, ^{100}Mo and ^{82}Se).
- Excellent sample of $2\nu\beta\beta$ events collected.





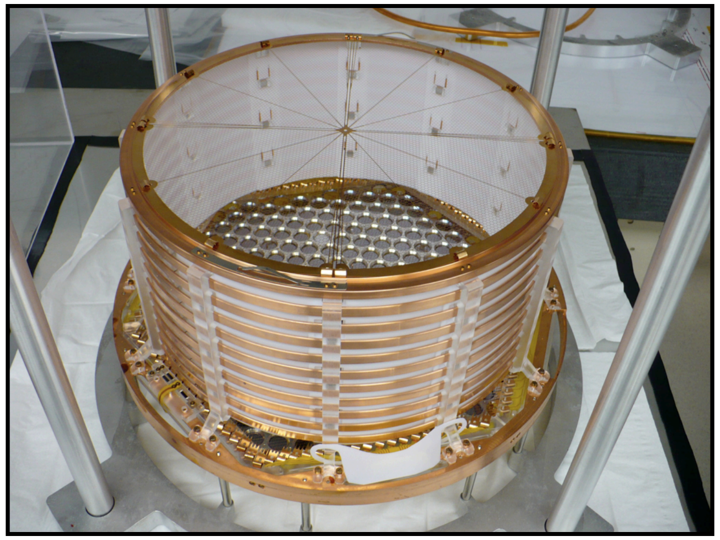
$T_{1/2}$ $(0\nu\beta\beta)$ $>3.2\times10^{23}$ yr



$T_{1/2}$ $(0\nu\beta\beta)$ $>10^{24}$ yr

Methods

Tracking & Calorimetry:



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Current experiments:

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EXO-200

- EXO-200 to use 200 kg of enriched ^{136}Xe (80%).
- Liquid Xe TPC with ionization and scitillation energy determination (1.4% resolution).
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- Possibility of Ba tagging.

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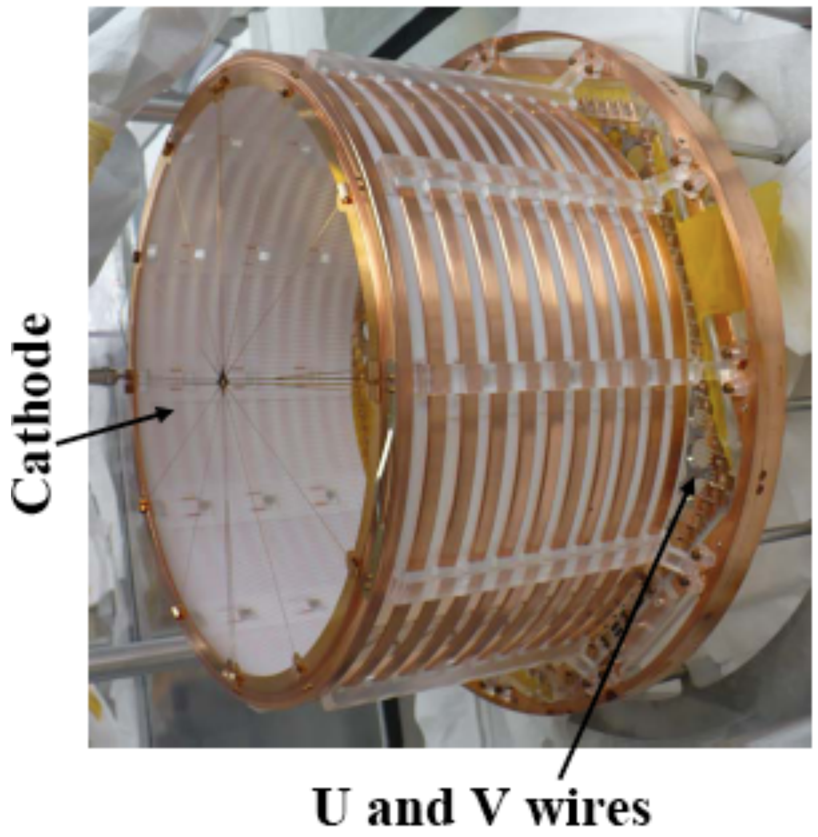
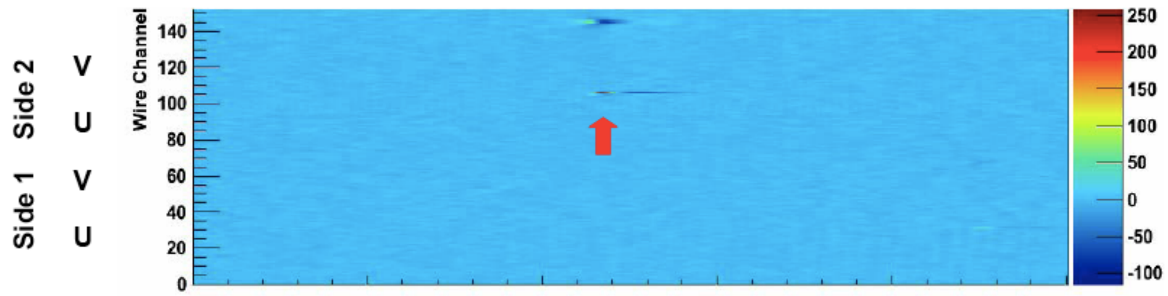
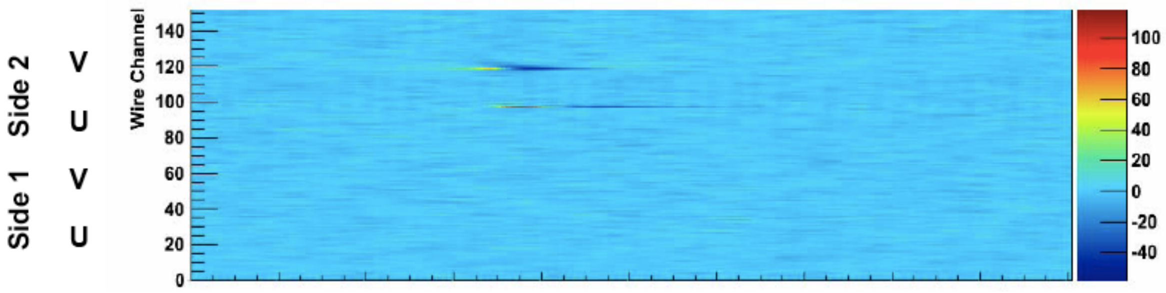




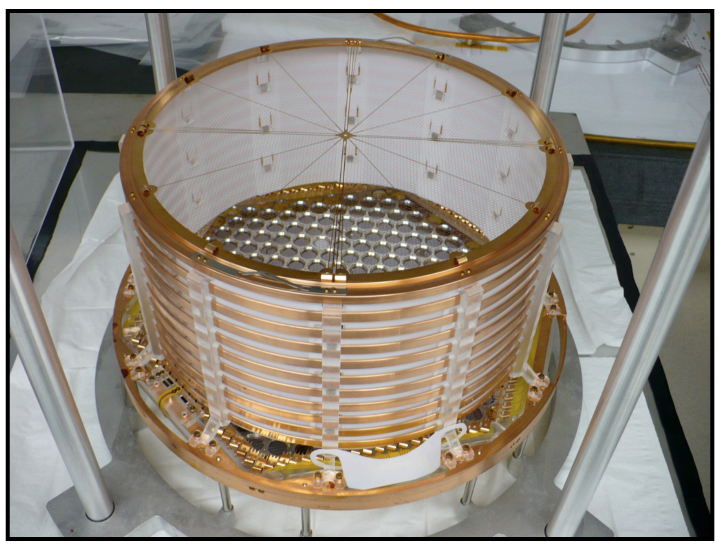
^{214}Bi candidate



Single site Compton

Methods

Tracking & Calorimetry:



Allows for track reconstruction or large volumes

Current experiments:

EXO, SuperNEMO, SNO+, NEXT, KamLAND-Zen

EXO-200

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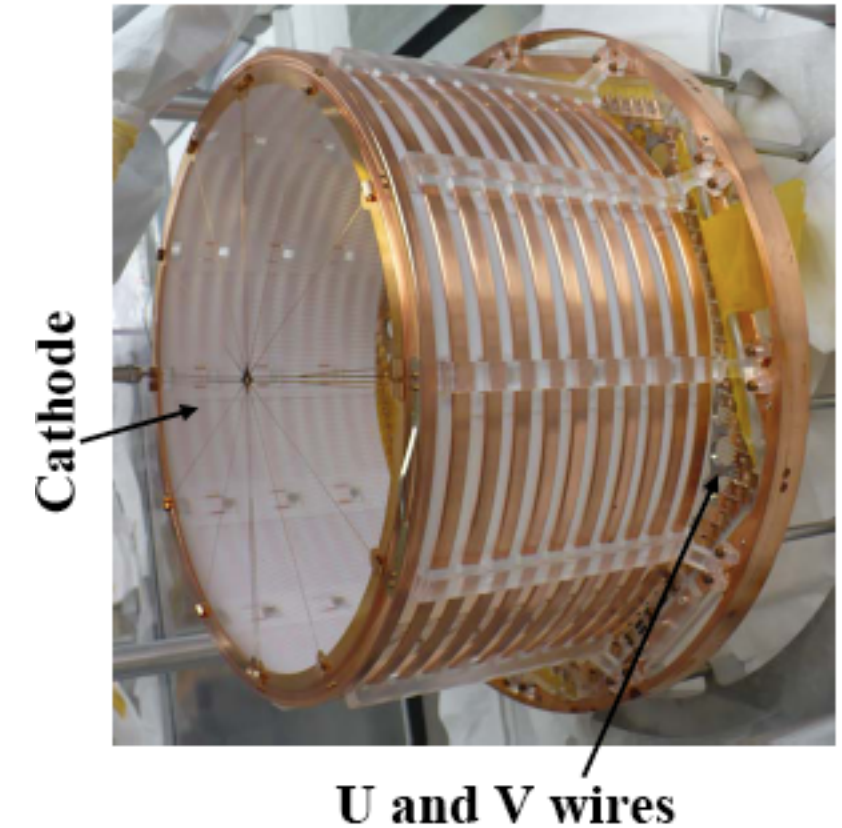

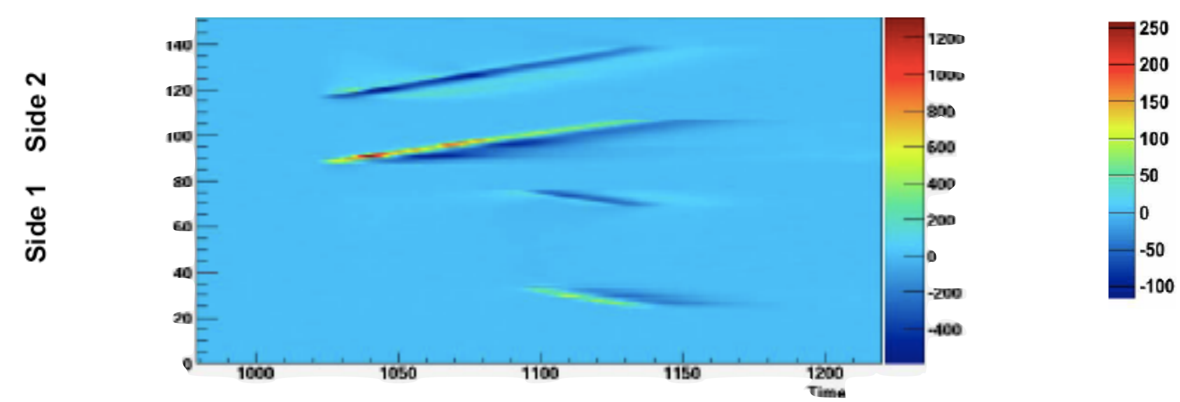

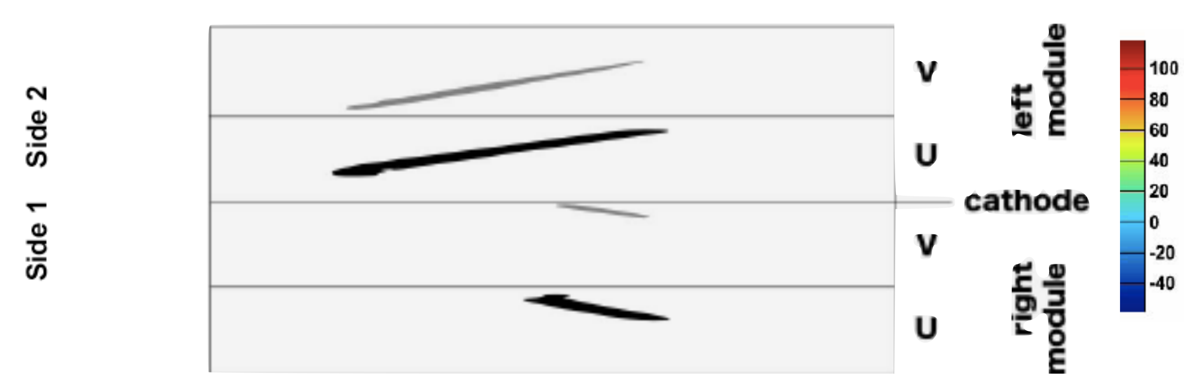

Muon event

The Next Level

- Current generation should be able to reach the 100 meV scale within the decade.
- If a signal, then the community will naturally require further confirmation:
  - Seen in other isotope/technique?
  - Daughter isotope tagging?
  - Observe excited state decays?
- If not, need to push to normal hierarchy scale. This implies:
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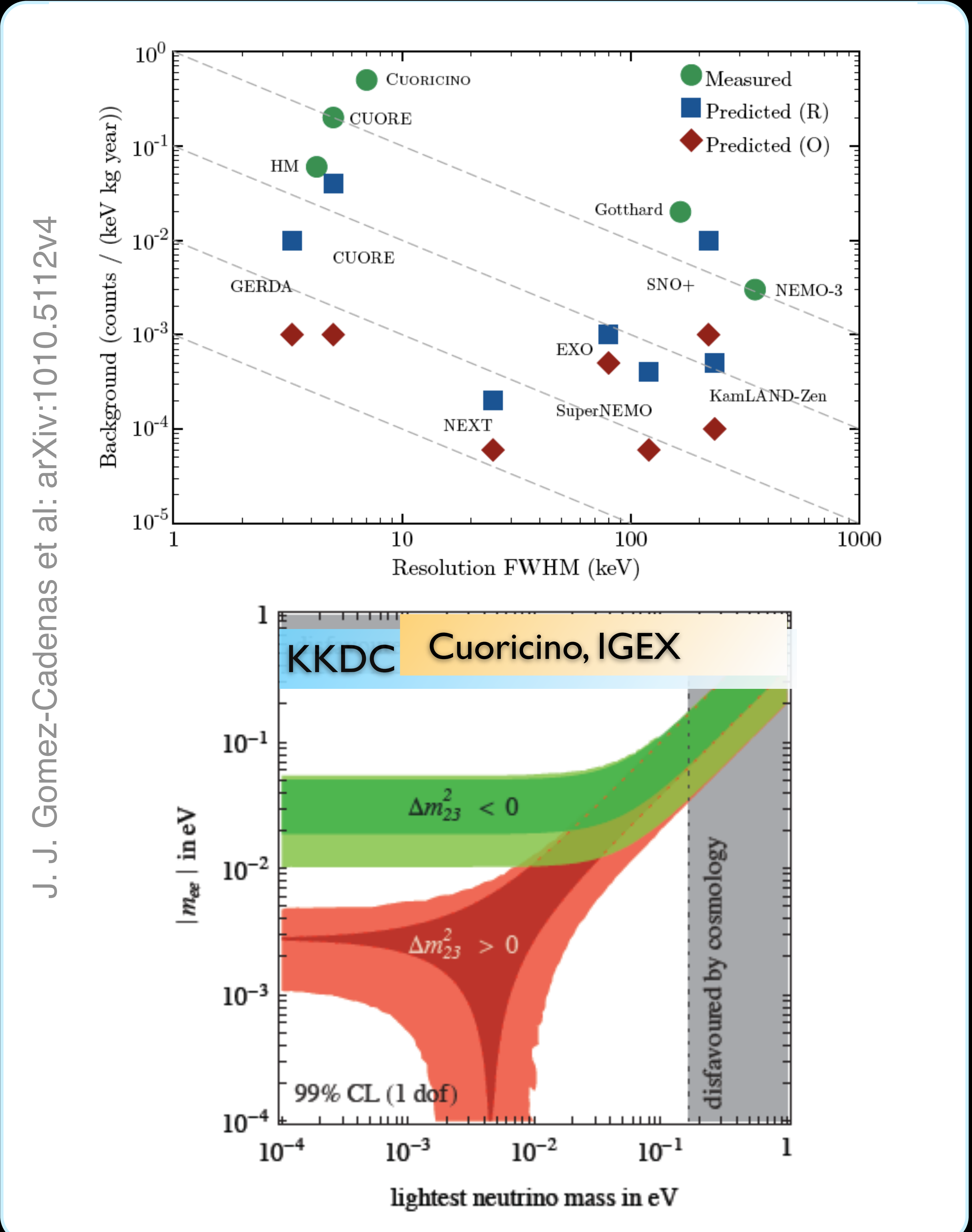
  - Ton scale detectors.



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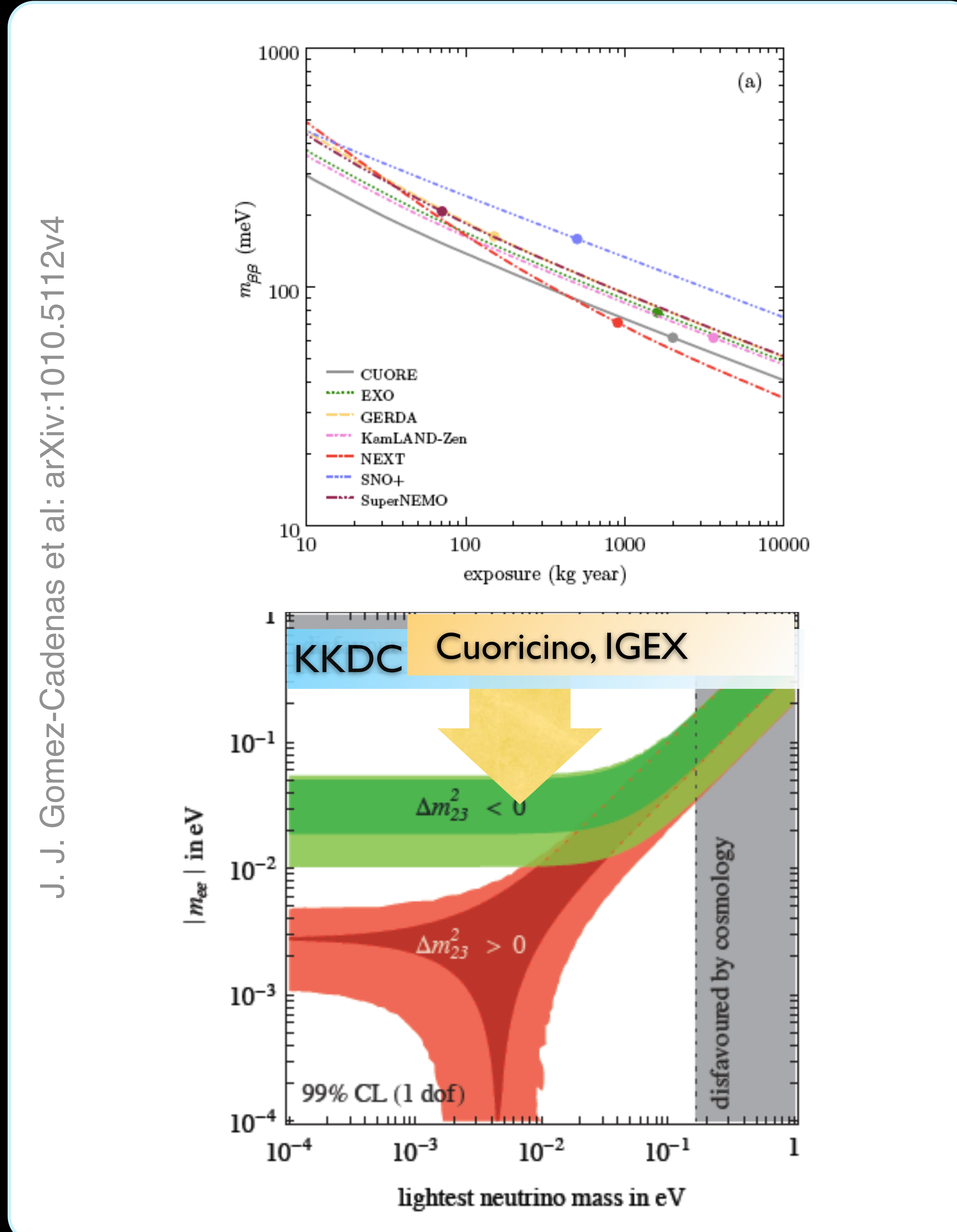

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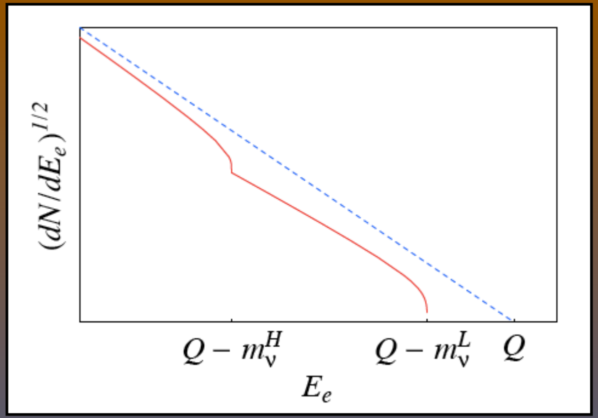

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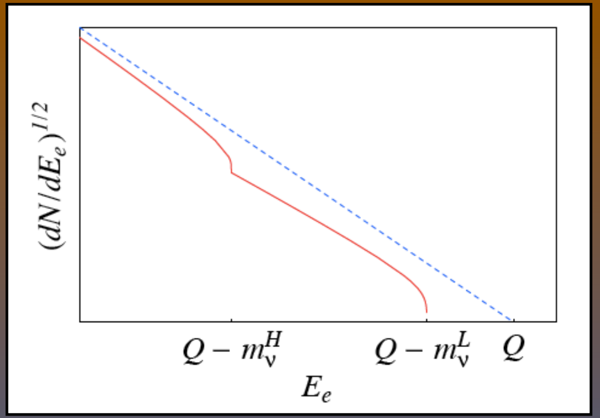
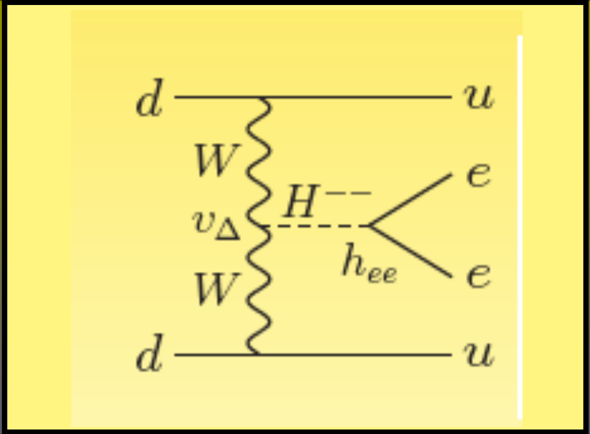
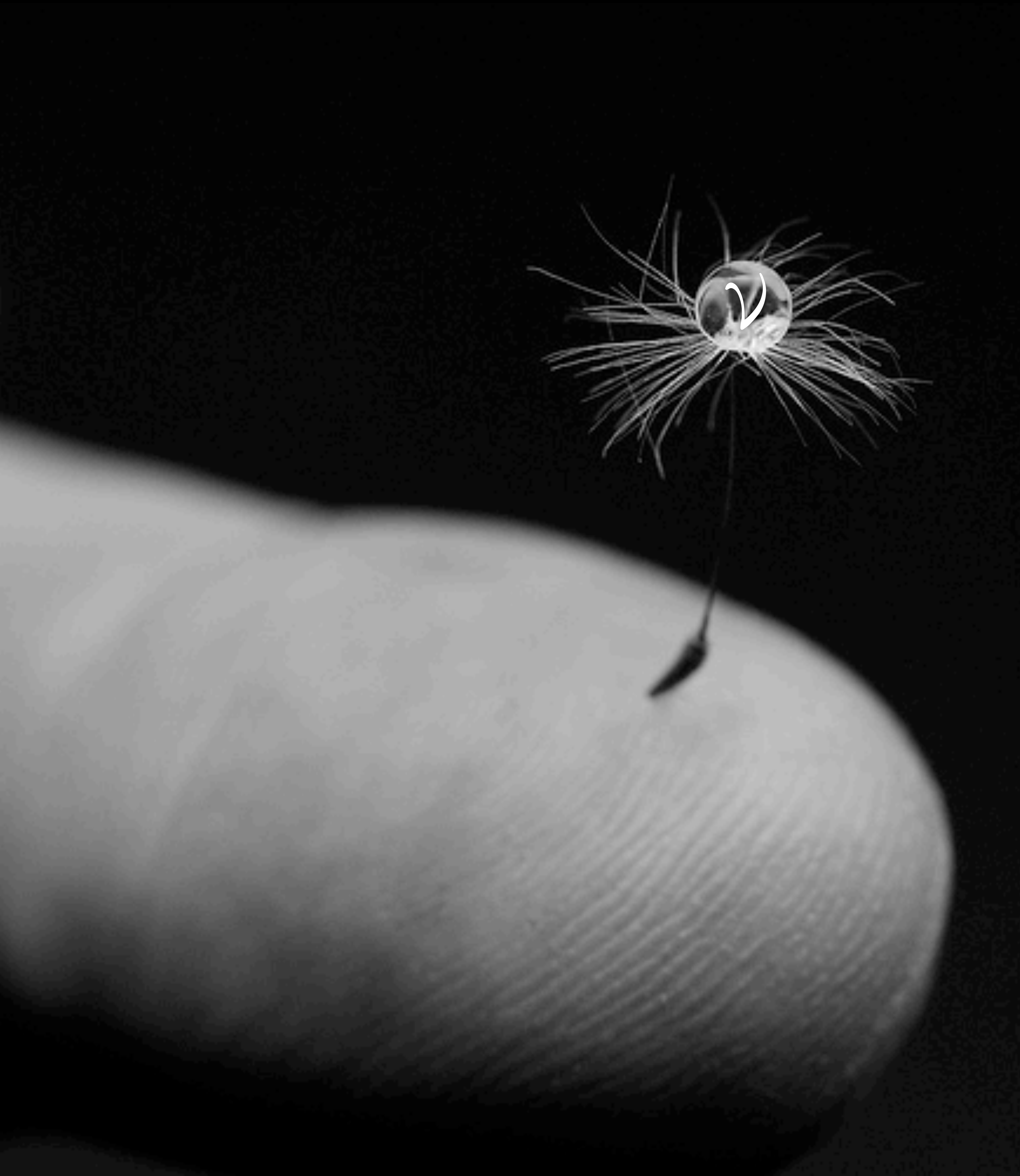
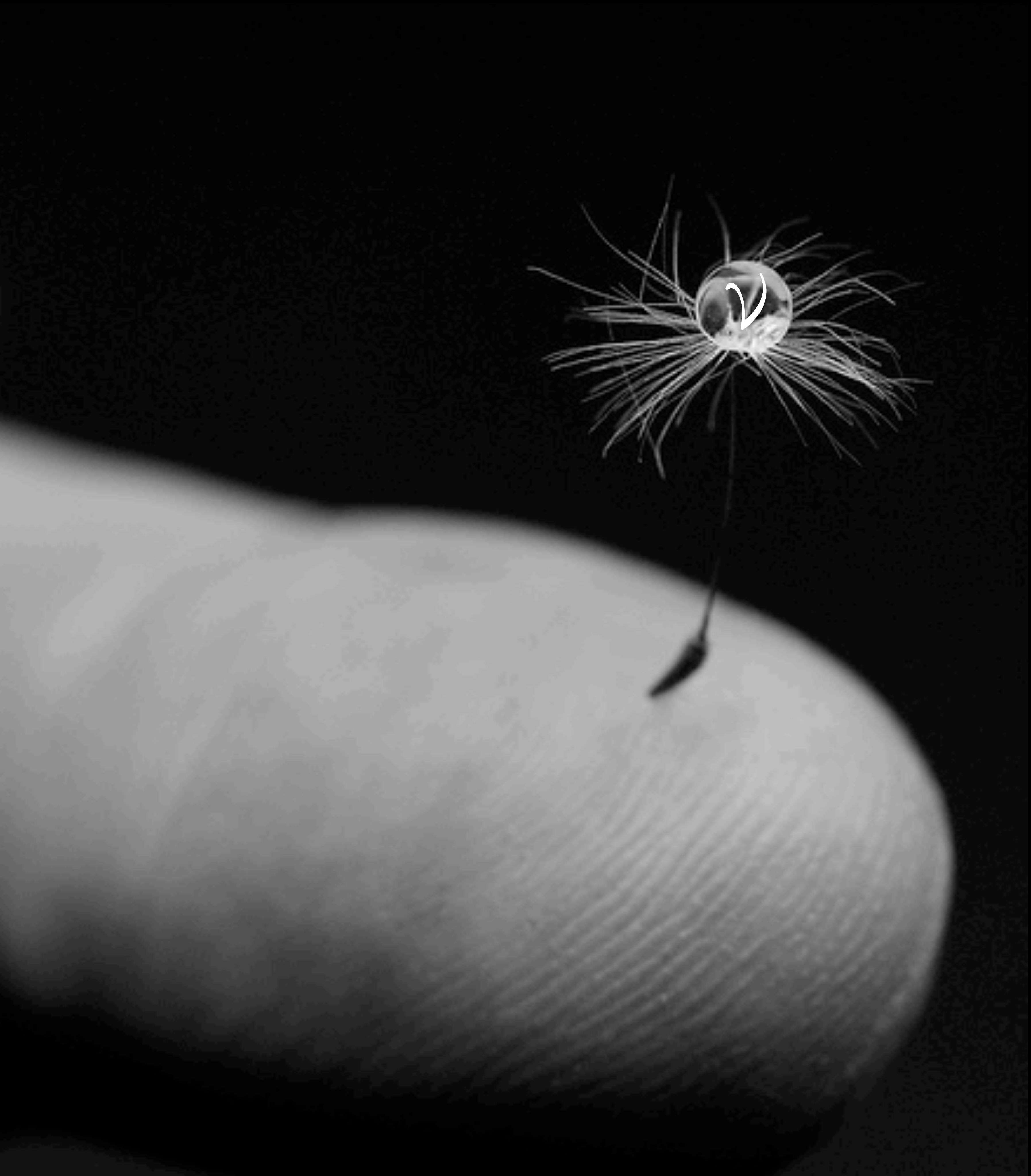


Neutrinoless double beta decay

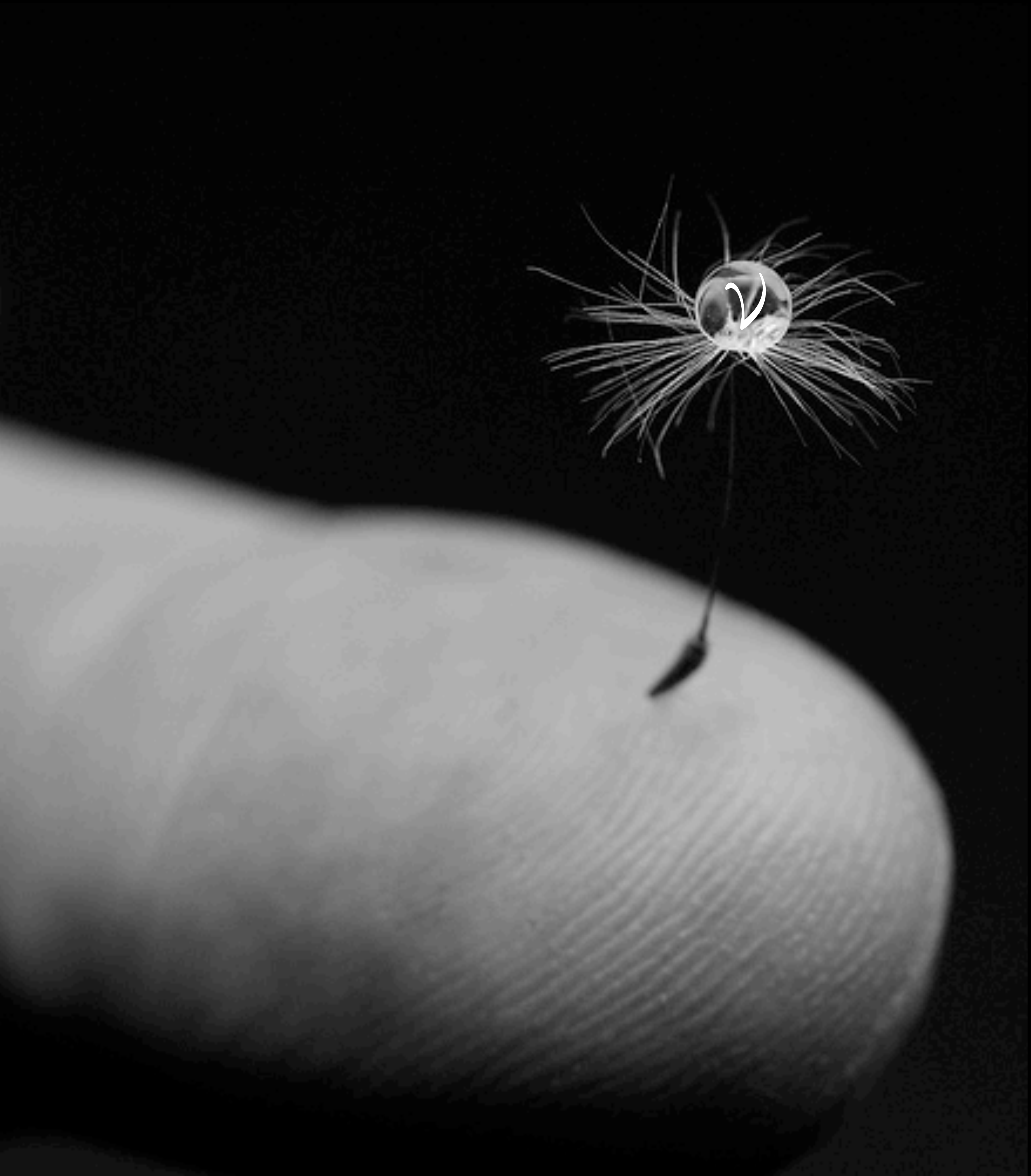
(Majoran particles, supersymmetry, etc.)







Neutrino masses still play a key role in our current experimental program.



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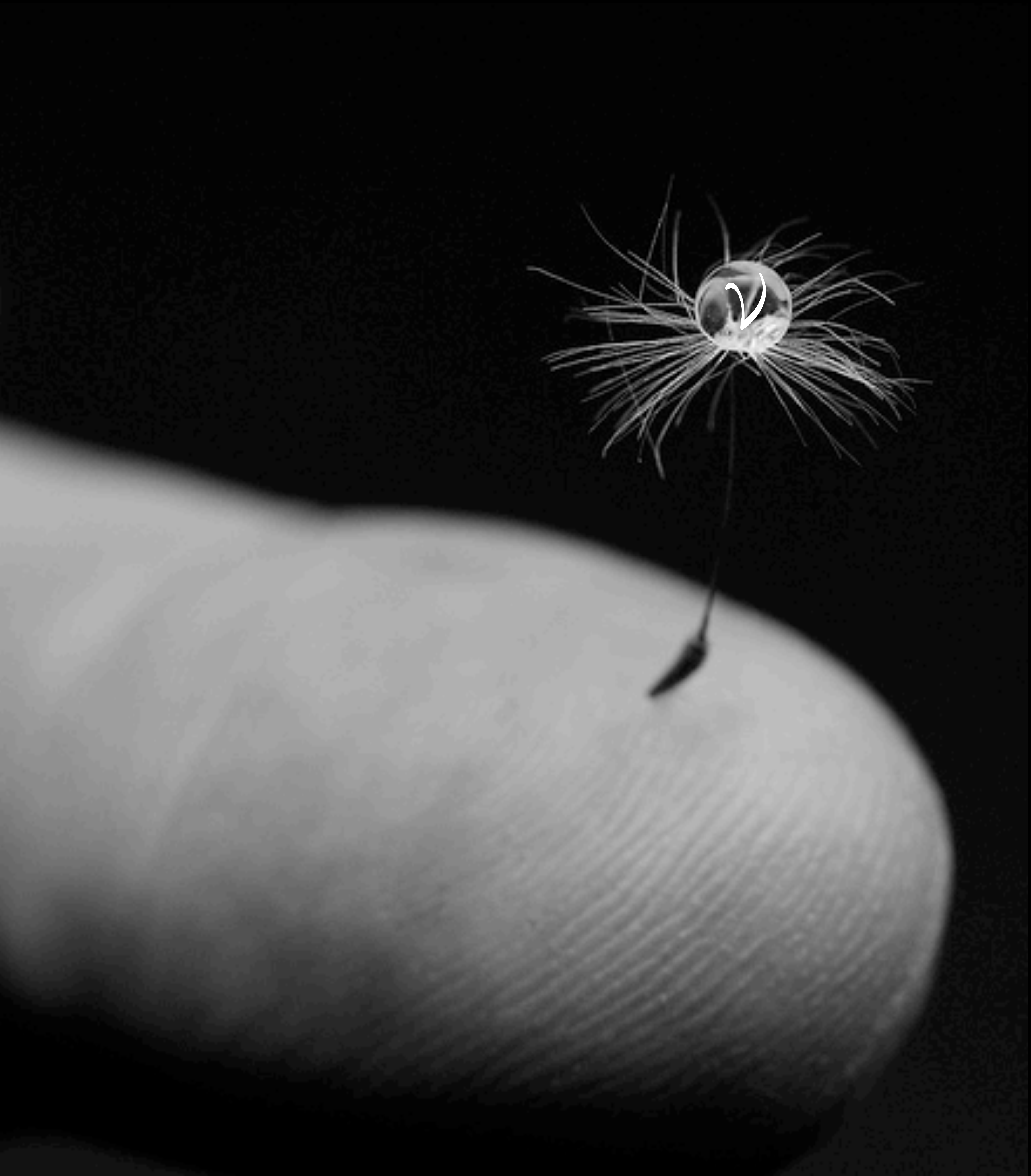

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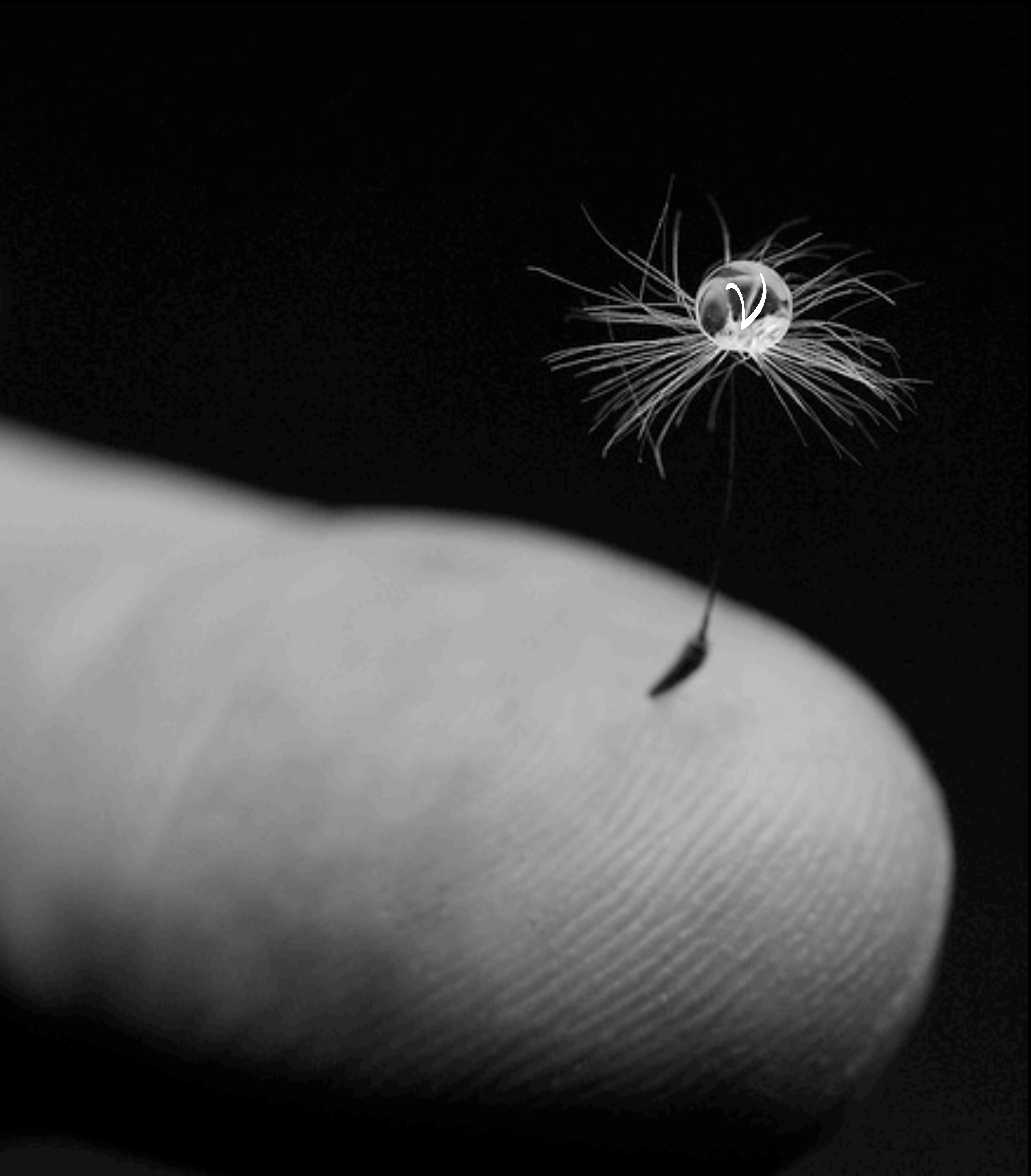

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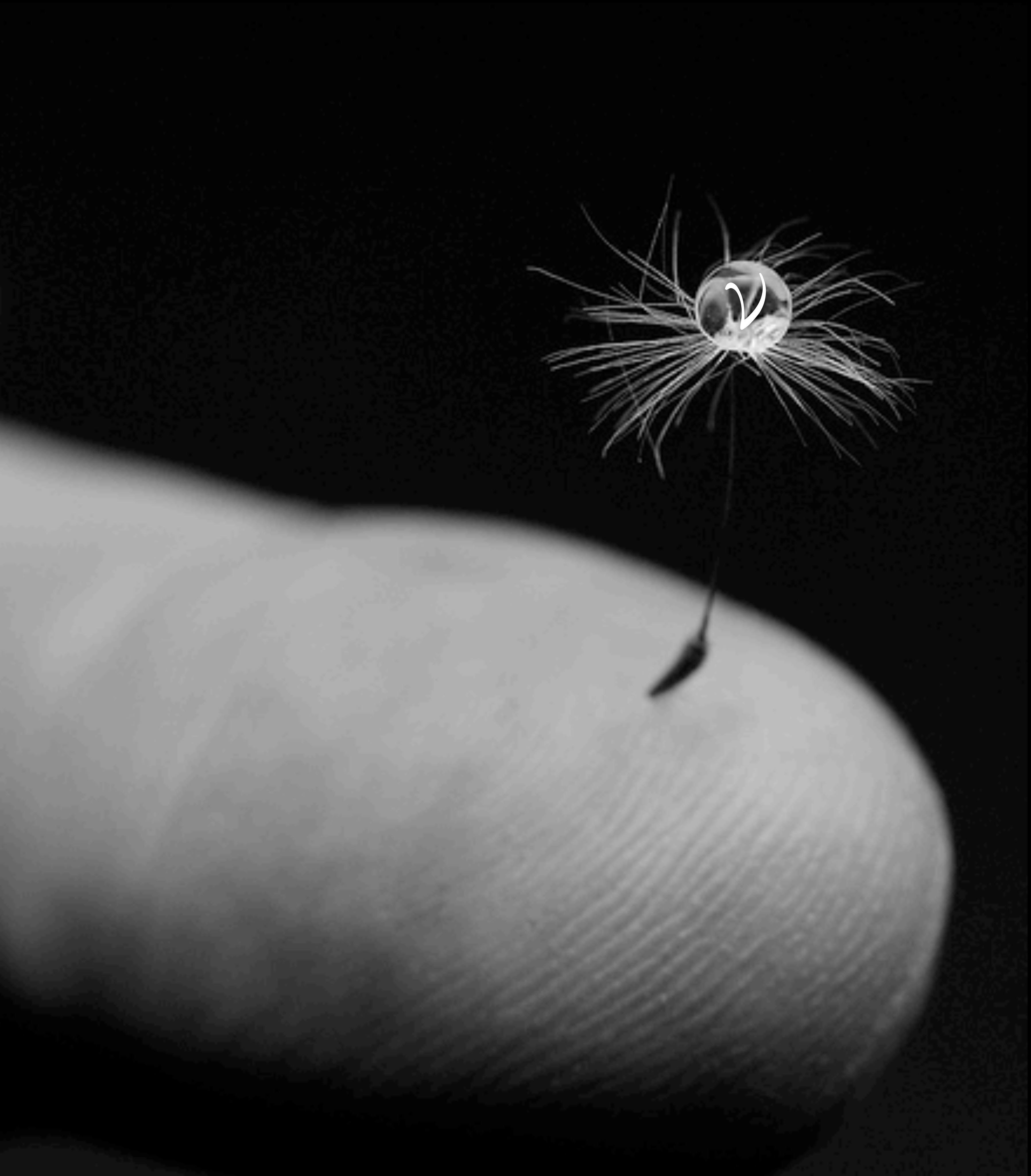
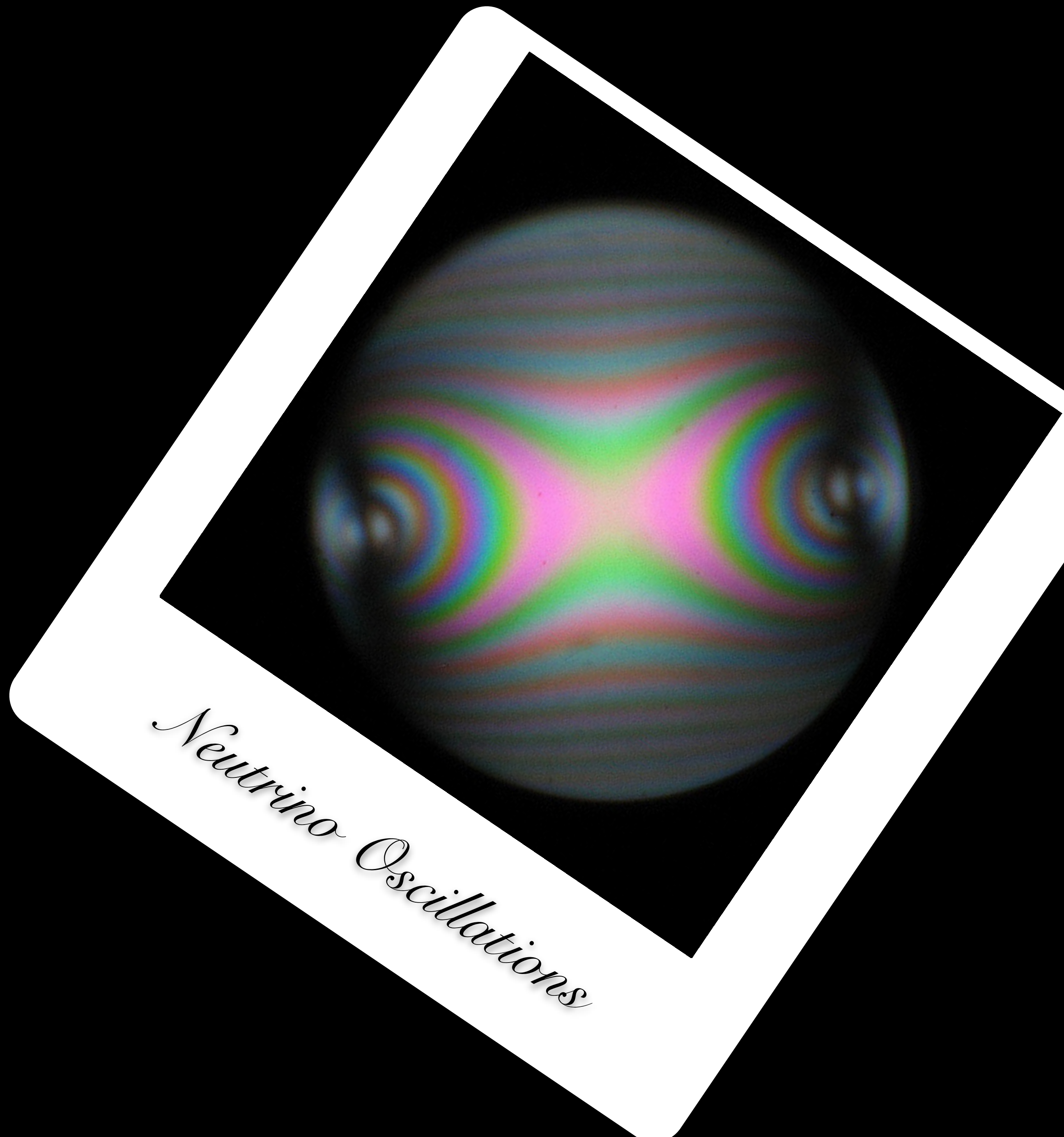
A complementary approach across vastly different techniques should strengthen a positive signal.



Thank you for your attention

How do we measure masses?

Neutrino mass can be measured using several different but complimentary techniques.



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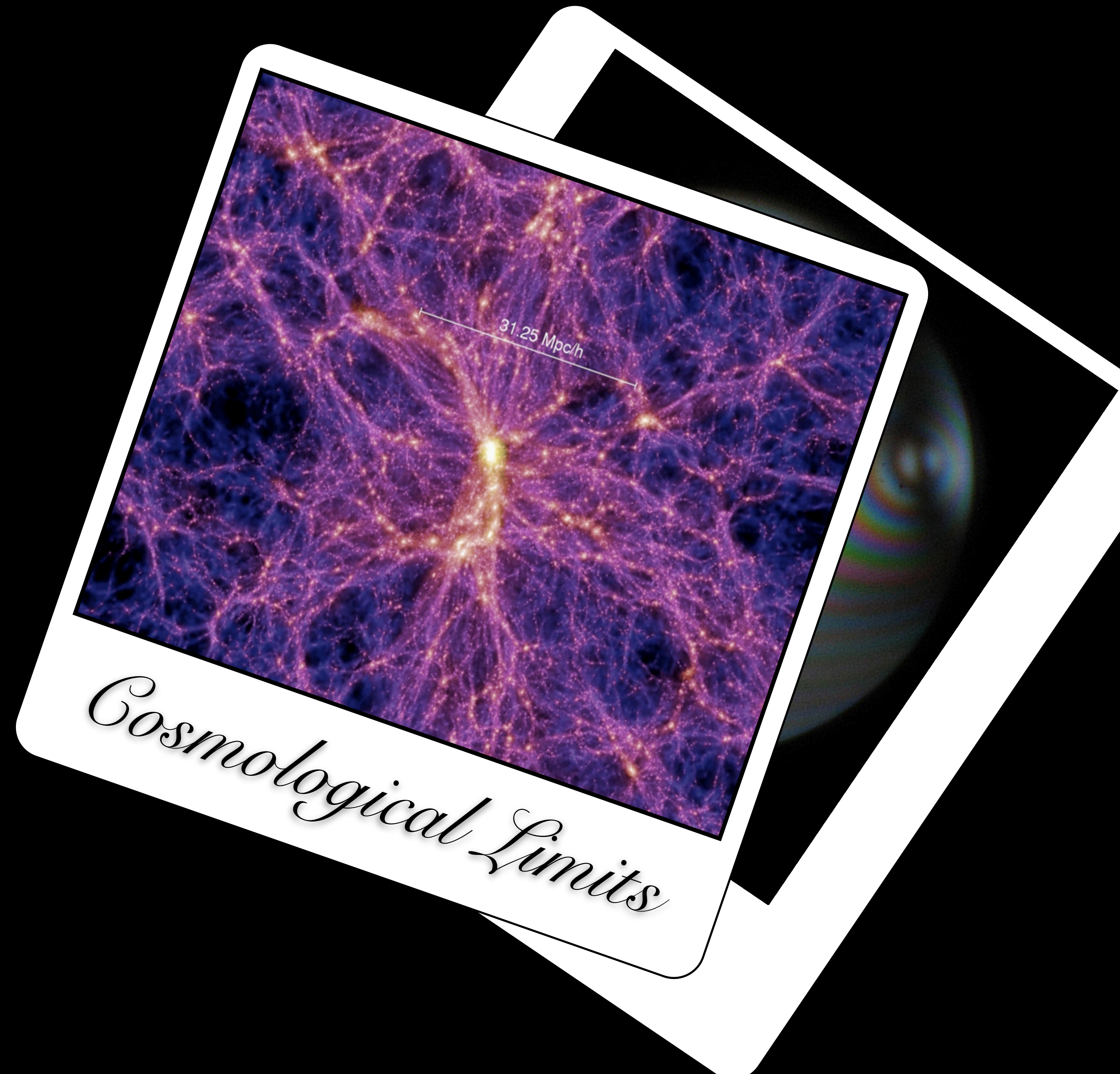

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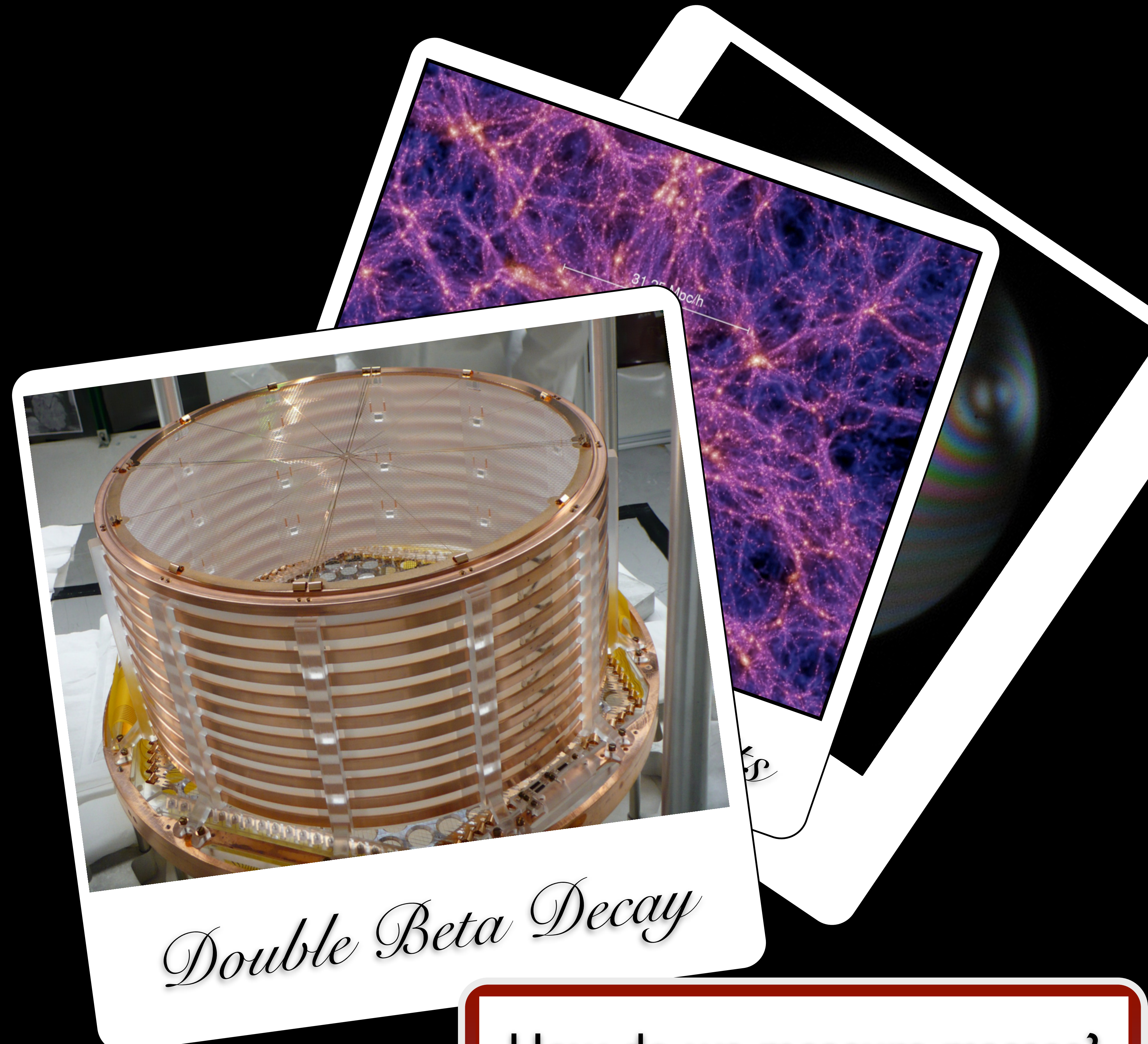

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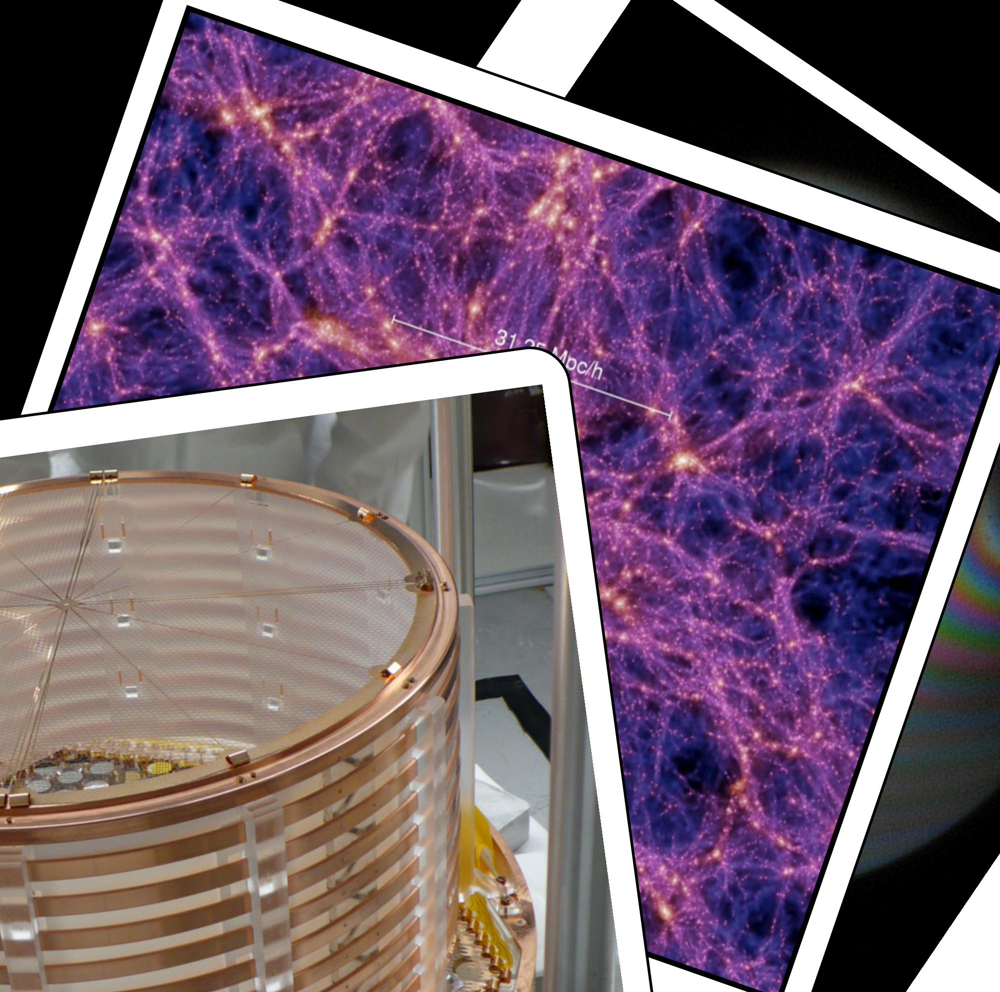
Direct Mass Probes



Double Beta Decay

How do we measure masses?

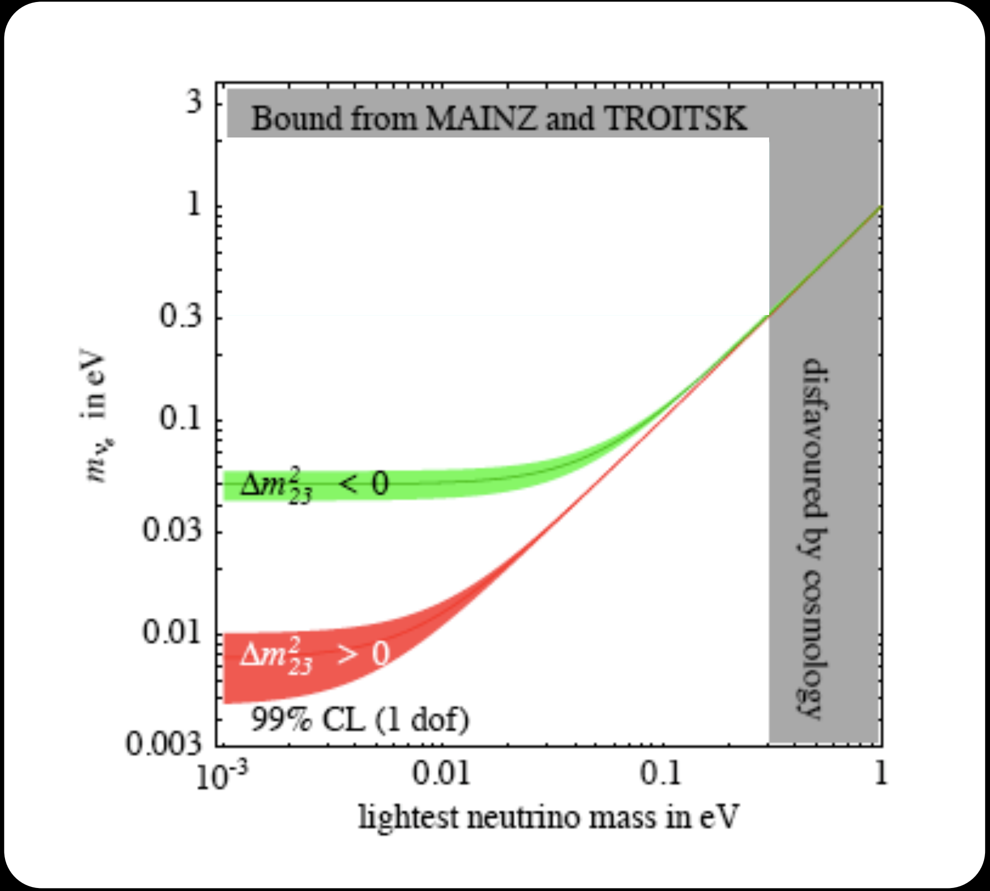
Neutrino mass can be measured using several different but complimentary techniques.

Q & A

<u>What We Know</u>

(1) Neutrinos *do* have mass (and we measure these mass differences very well).

(2) Neutrinos mix (and we know most of those mixing constants very well)



The Triumph of Cosmology

- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.
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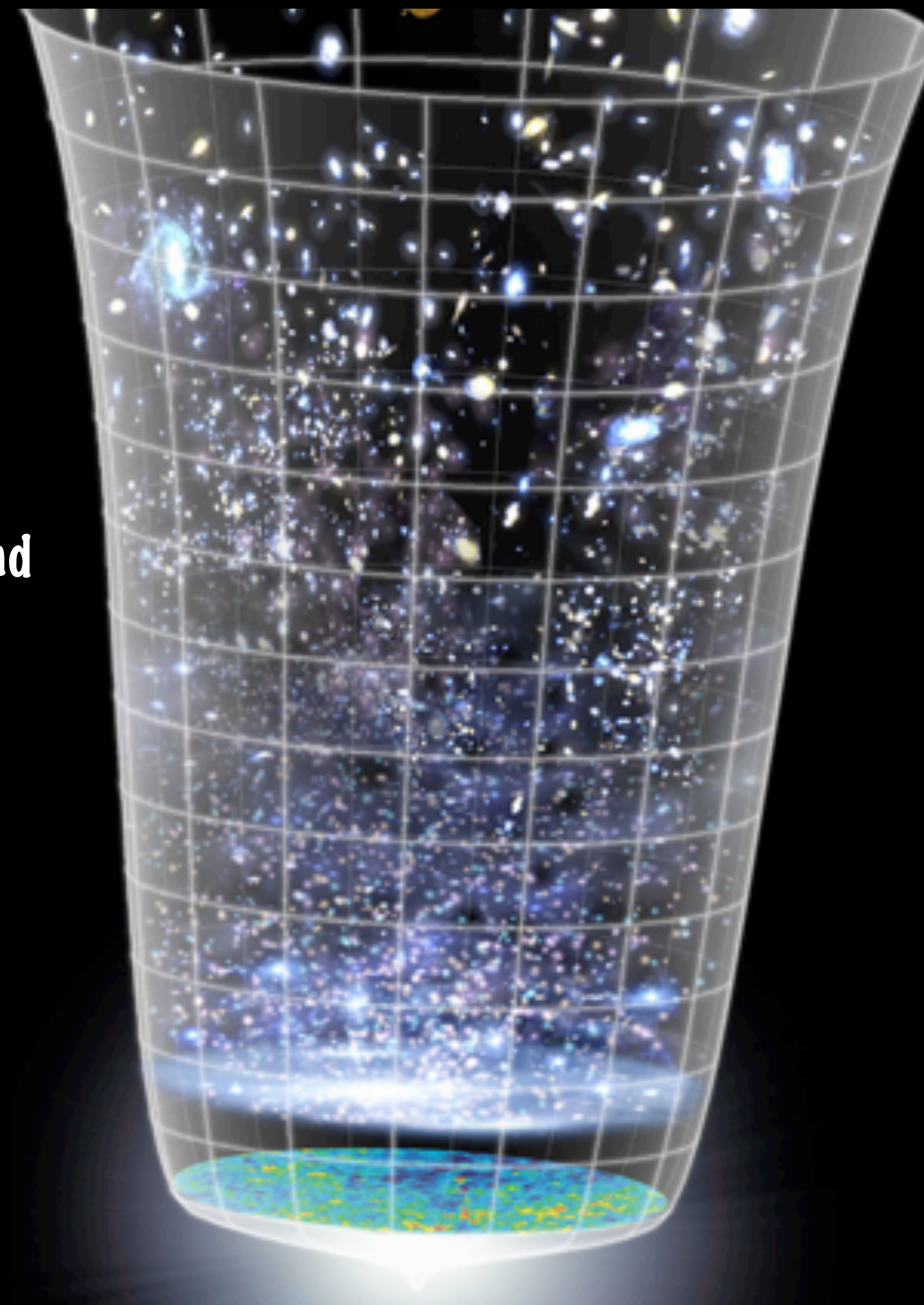


Microwave Background

400 kyr
z =1100

Nucleosynthesis

3-30 min
$z = 5 \times 10^8$

Relic Neutrinos

0.18 s
$z = 1 \times 10^{10}$

Experimental Effort

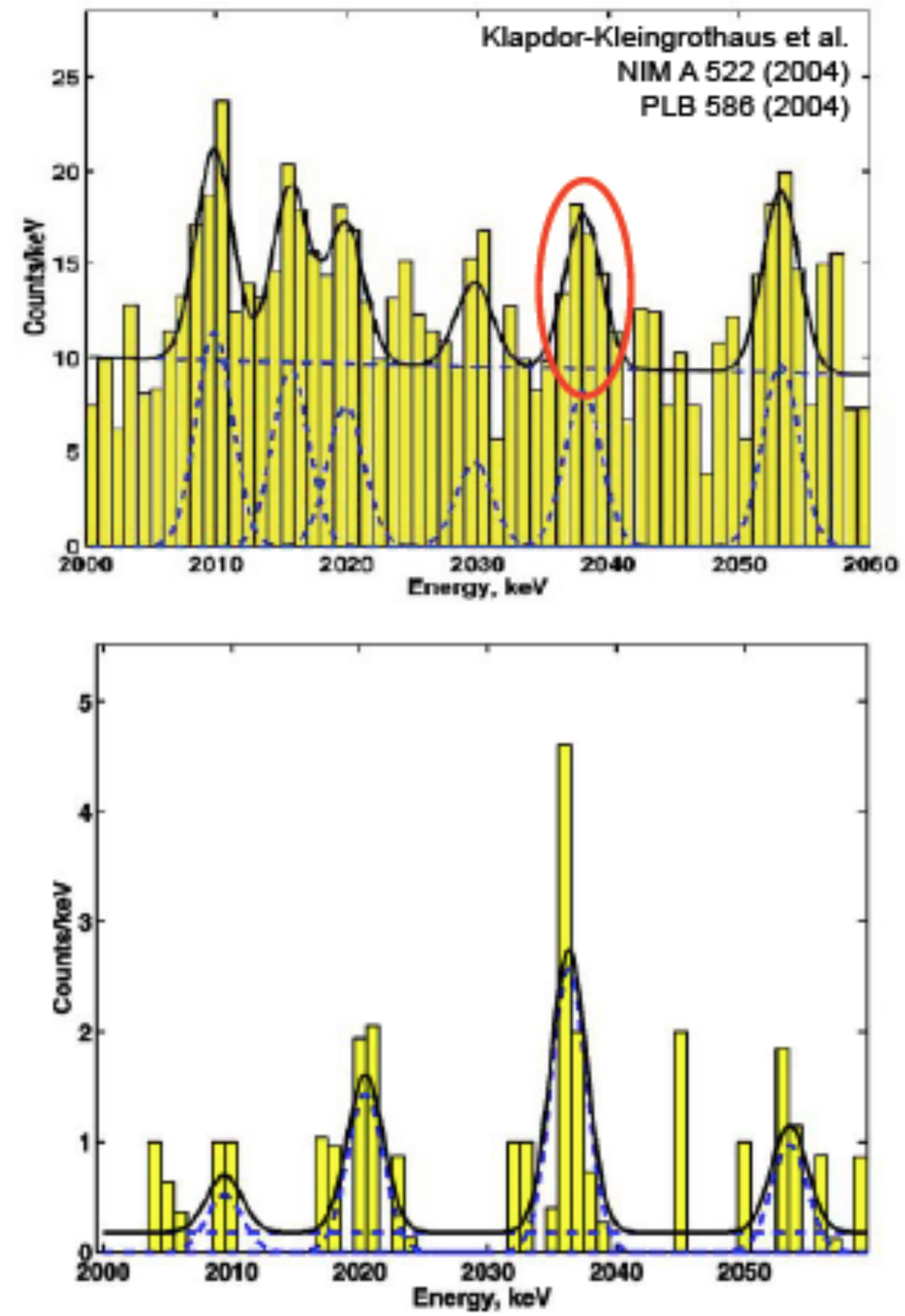
- Future experiments hope to push the sensitivity of $0\nu\beta\beta$ decay limits in order to probe whether the neutrino is its own anti-particle.

- Recent improvements seen in many experiments:

  1. Increased target mass
  2. Finer energy resolution
  3. Material screening and purity
  4. Depth
  5. Isotope tagging

- Possible hint of signal ?

Possible Hint ?



$T_{1/2} = (1.19 +2.99/-0.5) \times 10^{25}$ y
$0.24 < m_\nu < 0.58$ eV (3σ)