Das Rätsel der Dunklen Materie

Auf der Suche nach der unsichtbaren Materie im Universum

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https://xenon.physik.uni-mainz.de

https://www.staff.uni-mainz.de/pschwal/

Bachelor-Vortragsreihe

JGU Mainz

Nov. 15, 2021

Image credit: NASA, ESA, M. J. Jee & H. Ford et al. (Johns Hopkins Univ.)

Bundesministerium für Bildung und Forschung

PRISMA+

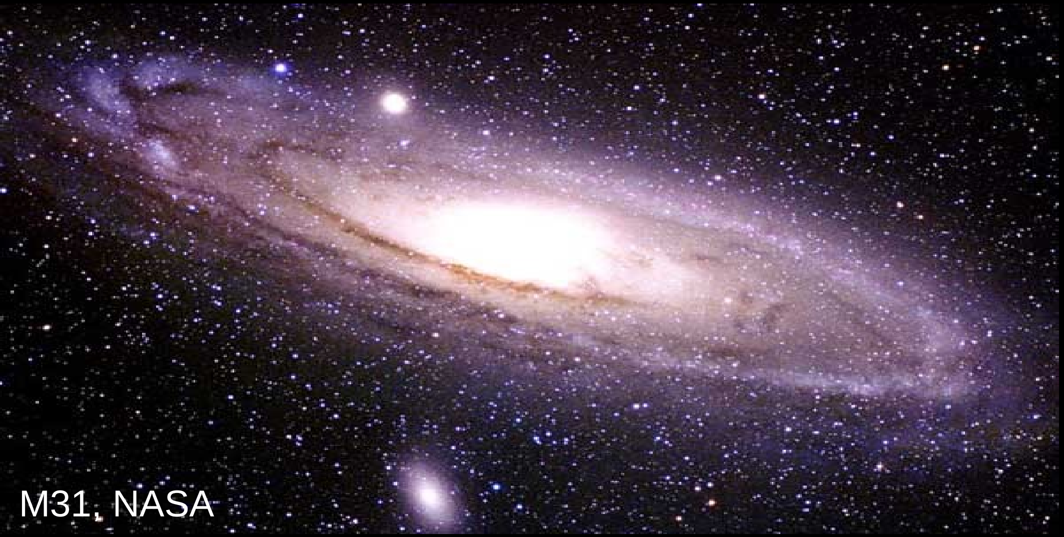
Outline

- Evidence for Dark Matter → Uwe Oberlack
  - The Problem of Missing Mass
  - In galaxies
  - In galaxy clusters
  - In the universe as a whole
- DM Direct Searches
  - Detection principle
  - Example experiment & results
  - Outlook
- DM Candidates → Pedro Schwaller
  - The DM particle zoo
  - Models of DM and their creation in the early universe

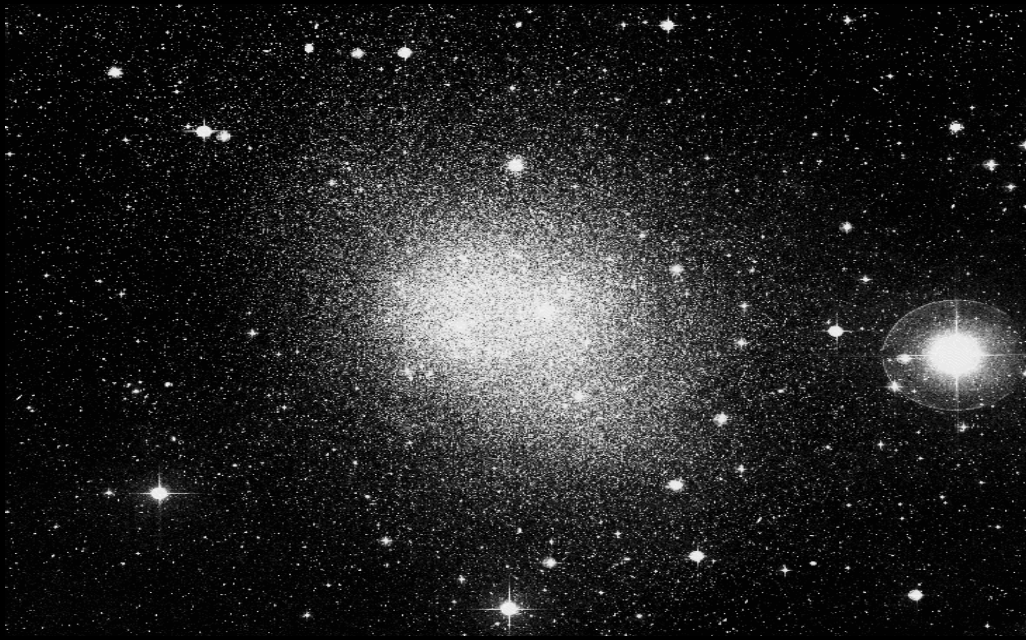
Evidence for Dark Matter In Galaxies

Scale: 10^{21} m (~10^{5} lightyears)

Spiral galaxies

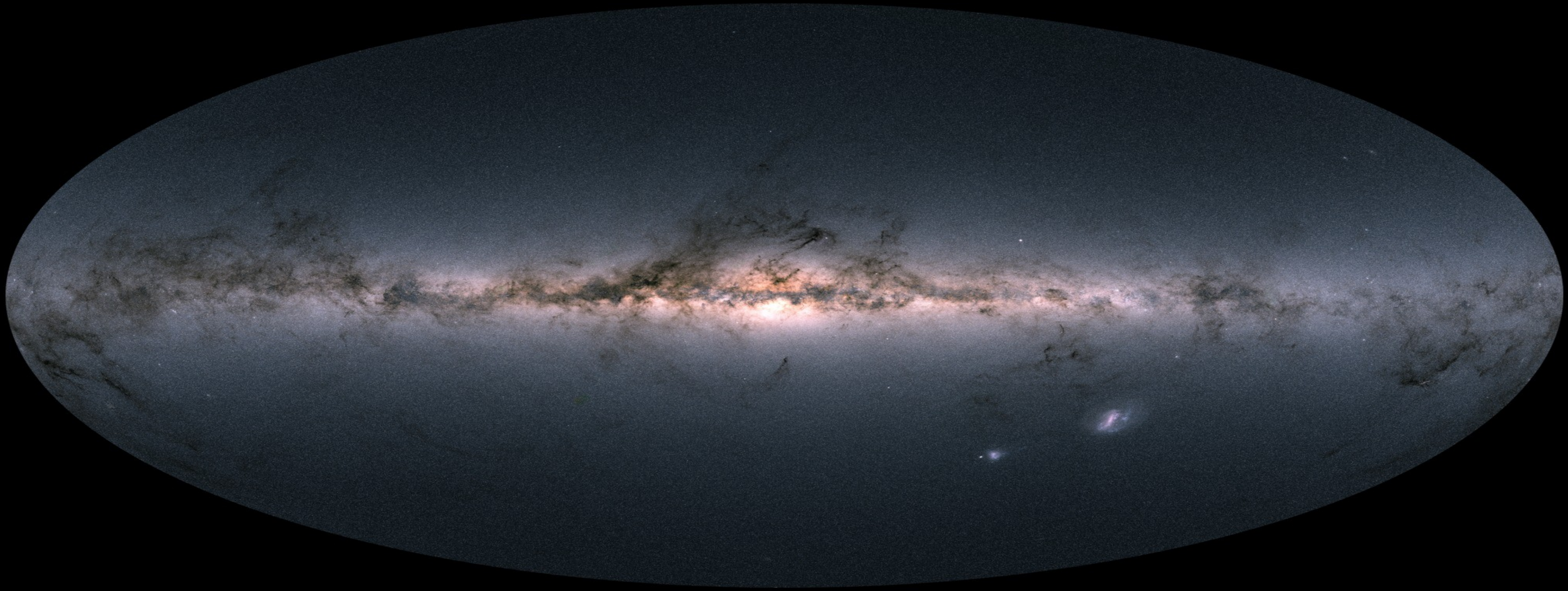


Dwarf Spheroidal galaxies



Fornax
David Malin, Anglo-Australian Observatory.

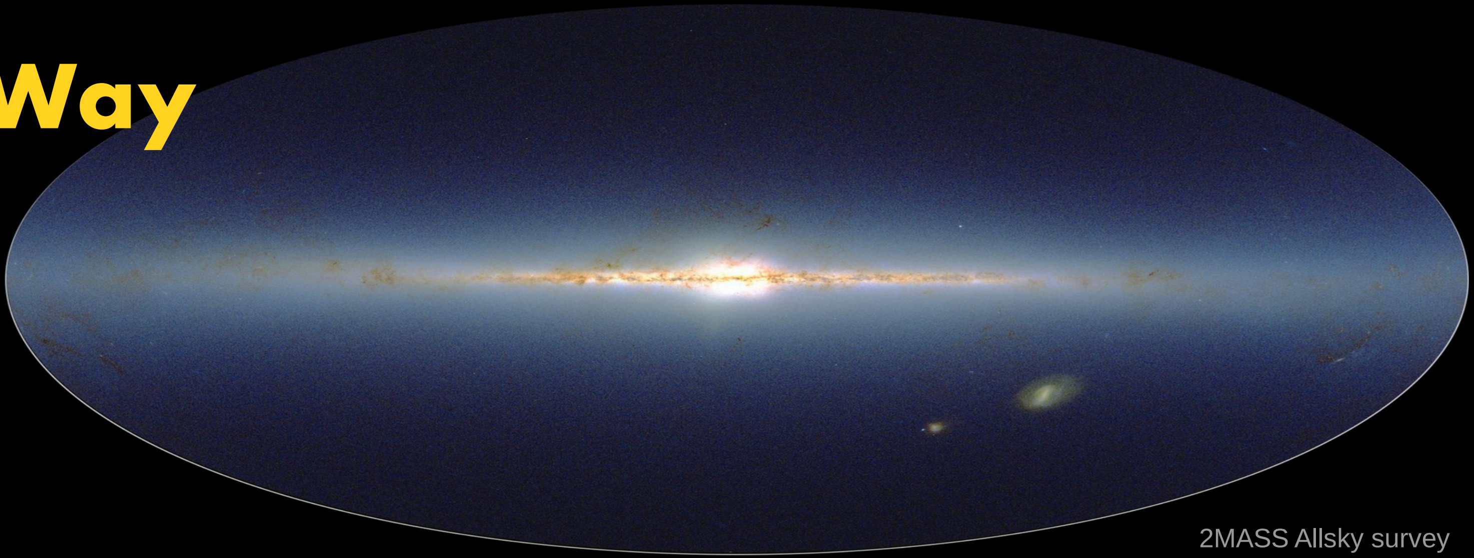
The Milky Way in the optical wavelength range



GAIA (2018) ESA

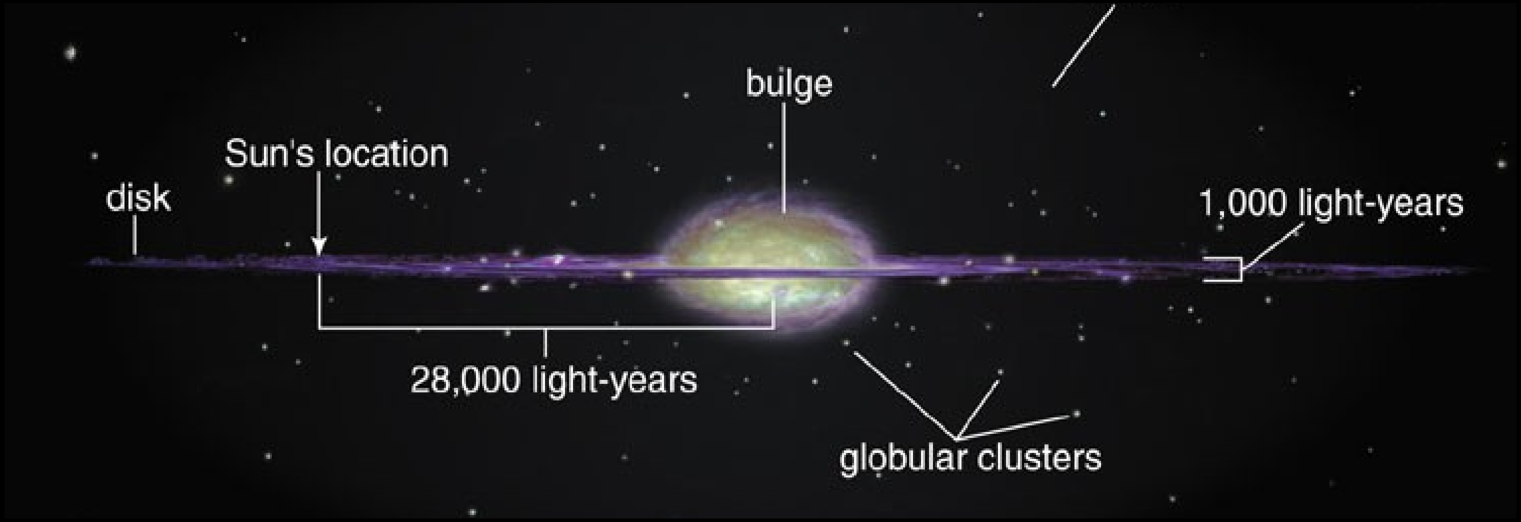
The Milky Way

Our view from inside the disk (in near infrared radiation)

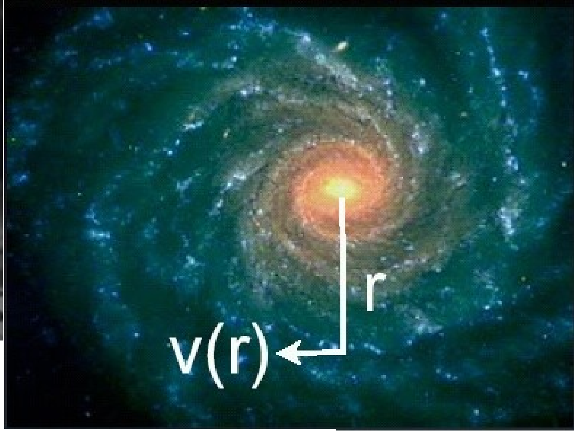


2MASS Allsky survey

Edge-on view (sketch)

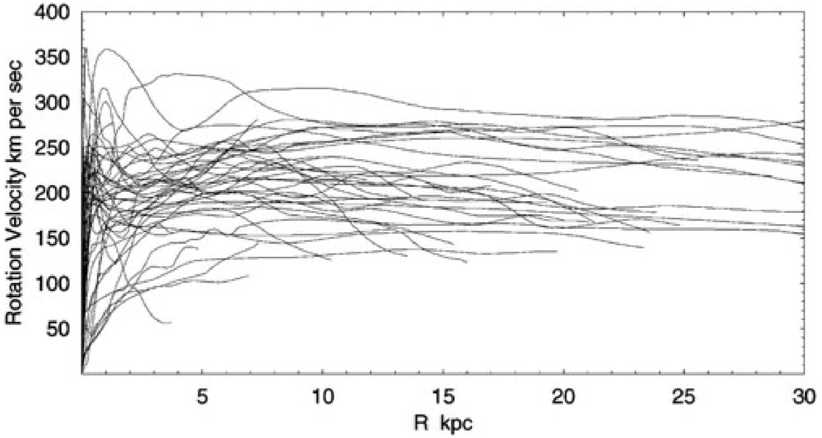


Evidence for Dark Matter in Spiral Galaxies

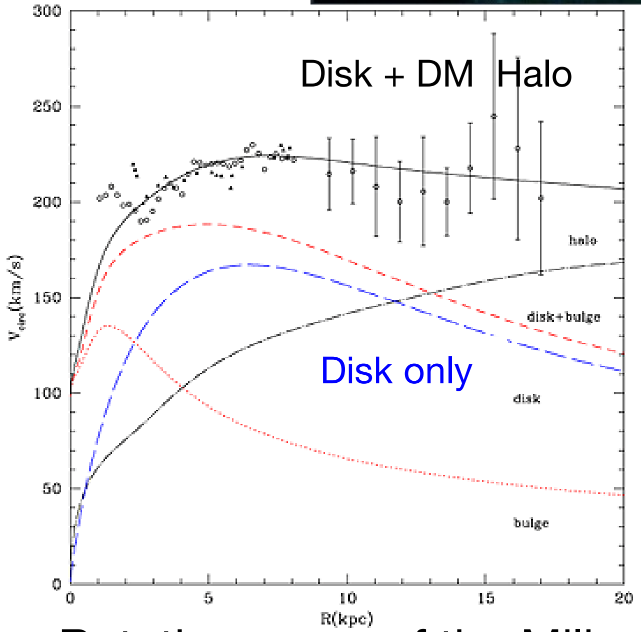


Rotation curves (orbital velocity vs. galactocentric radius) remain flat well beyond the edge of the visible disk in spiral galaxies.

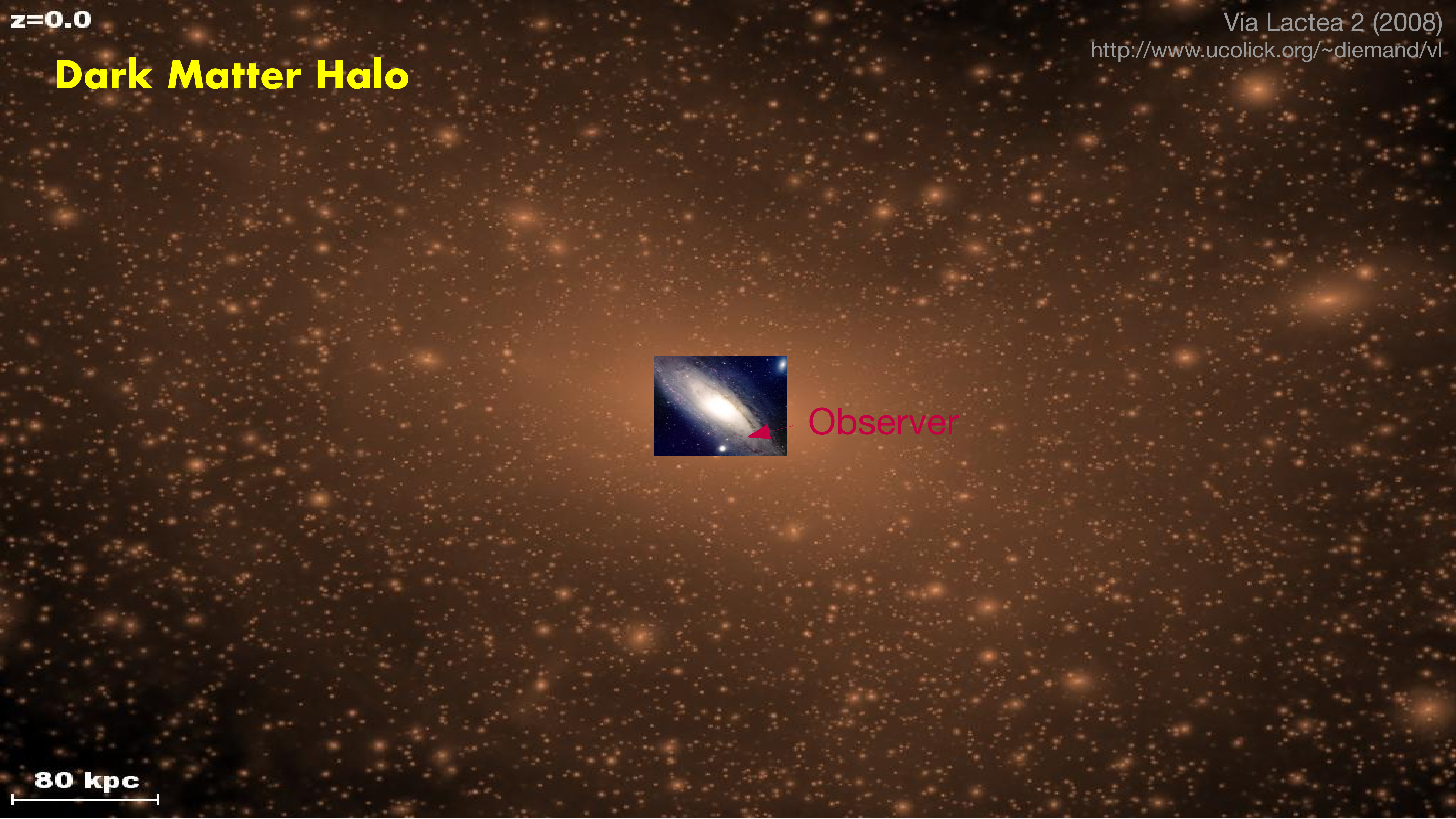
$$\left.\begin{array}{lcl} v(R) & = & \sqrt{GM(R)/R} \\ v(R) & \approx & const \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} M(R) & \propto & R \\ \rho(R) & \propto & R^{-2} \end{array}\right.$$



Rotation curves of nearby galaxies
(Sofue & Rubin ARAA 2001)



Rotation curve of the Milky Way
(A. Klypin et. al, ApJ. 573, 2002)

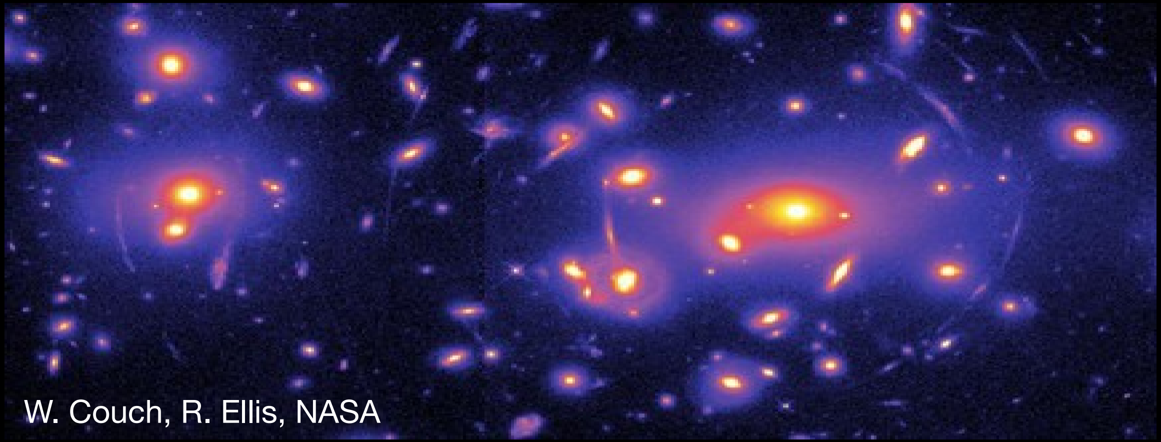

z=0.0
Dark Matter Halo
Via Lactea 2 (2008)
http://www.ucolick.org/~diemand/vl
Observer
80 kpc

Evidence for Dark Matter in Galaxy Clusters

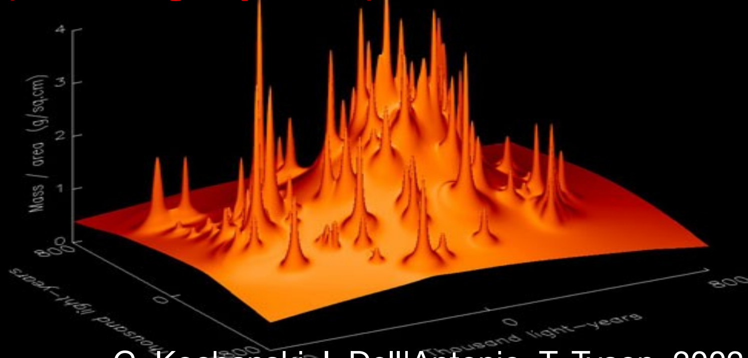
- Orbital velocities of galaxies exceed escape velocity estimated from visible mass in galaxies (Zwicky 1933).
- X-ray gas: pressure too great for visible mass. Traces gravitational potential.
- Gravitational lensing: measures total mass distribution in galaxy clusters.

NOAO/Kitt Peak: Uson, Dale
NASA/CXC/IoA: Allen et al.

Scale: ~10^{22} m
(~10^{6} lightyears)



W. Couch, R. Ellis, NASA

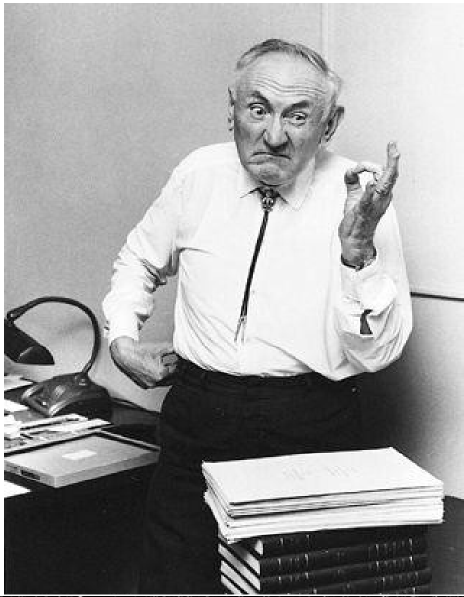


G. Kochanski, I. Dell'Antonio, T. Tyson, 2002

Velocity dispersion in galaxy clusters

Fritz Zwicky (1933) used the velocity dispersion of galaxies in the Coma cluster and the virial theorem to estimate the mass of the cluster $M_{cluster}$.

$$E_{kin} = -\frac{1}{2} E_{pot}$$



Comparing this mass to the luminosity of the galaxies in the cluster, using empirical relations between luminosity and mass for stars, he found:

$$M_{lum} \sim 1/400\ M_{cluster}$$

Something is missing : **Dark Matter ?**

Die Rotverschiebung von extragalaktischen Nebeln

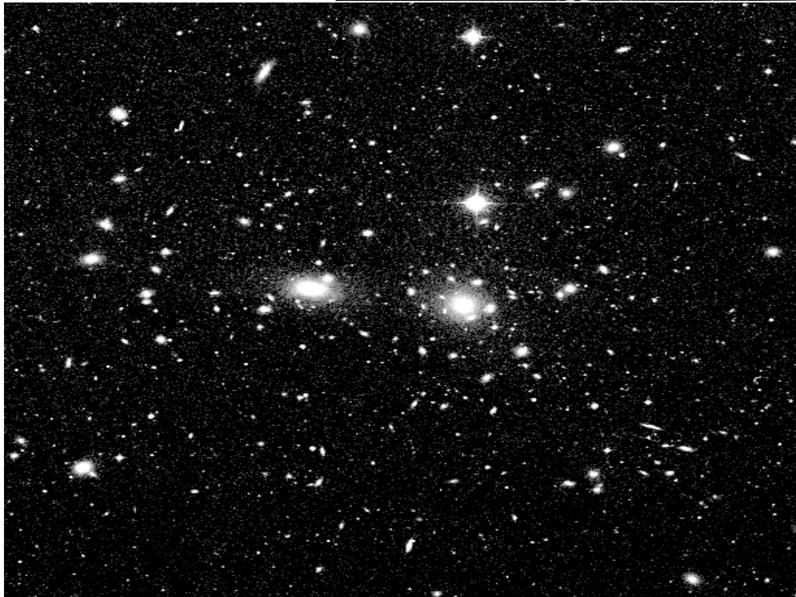
von **F. Zwicky.**

(16. II. 33.)

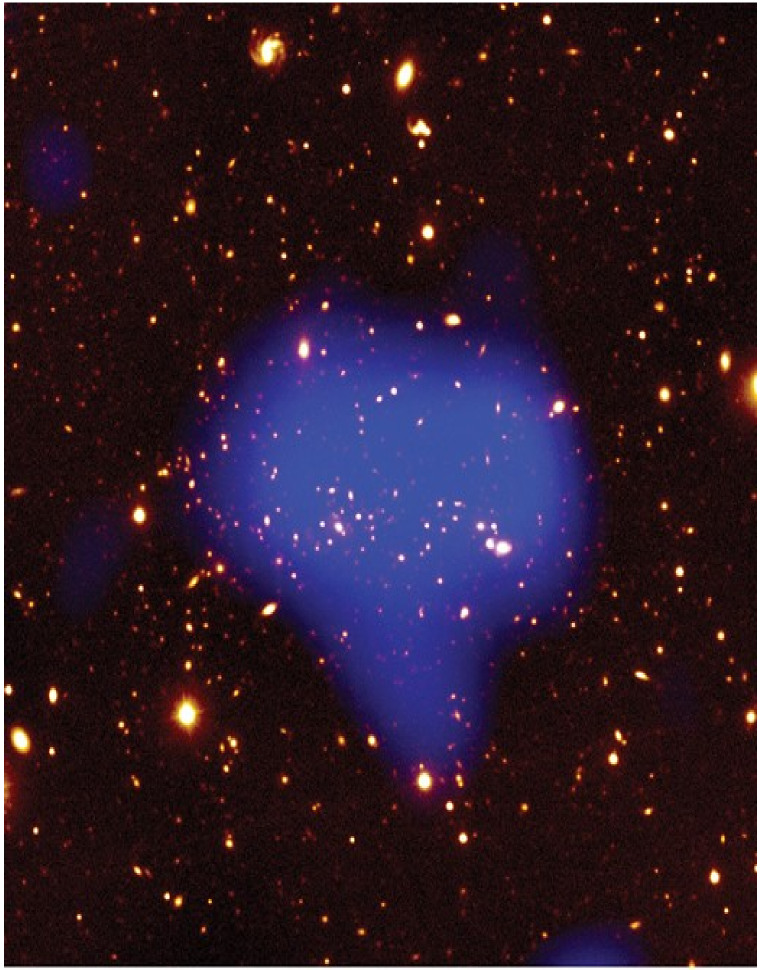
Helvetica Physica Acta
6 (1933), 110

125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.



X-Ray Observations of Galaxy Clusters



Baryonic matter in galaxy clusters is dominated by **X-ray emitting hot gas**. Temperature of the hot gas tells us the total cluster mass.

85% dark matter
13% hot gas
2% stars ← Zwicky knew only about this!

This results from the assumption that the observed clusters are virialized, i.e., $|E_{pot}| = 2\,E_{kin}$

Kinetic energy = thermal energy

$$\frac{1}{2}\bar{m}\langle v^2\rangle = \frac{3}{2}kT_{\text{virial}}$$

with avg. particle mass $\bar{m} \approx 1.23\, m_H$

Boltzmann constant:

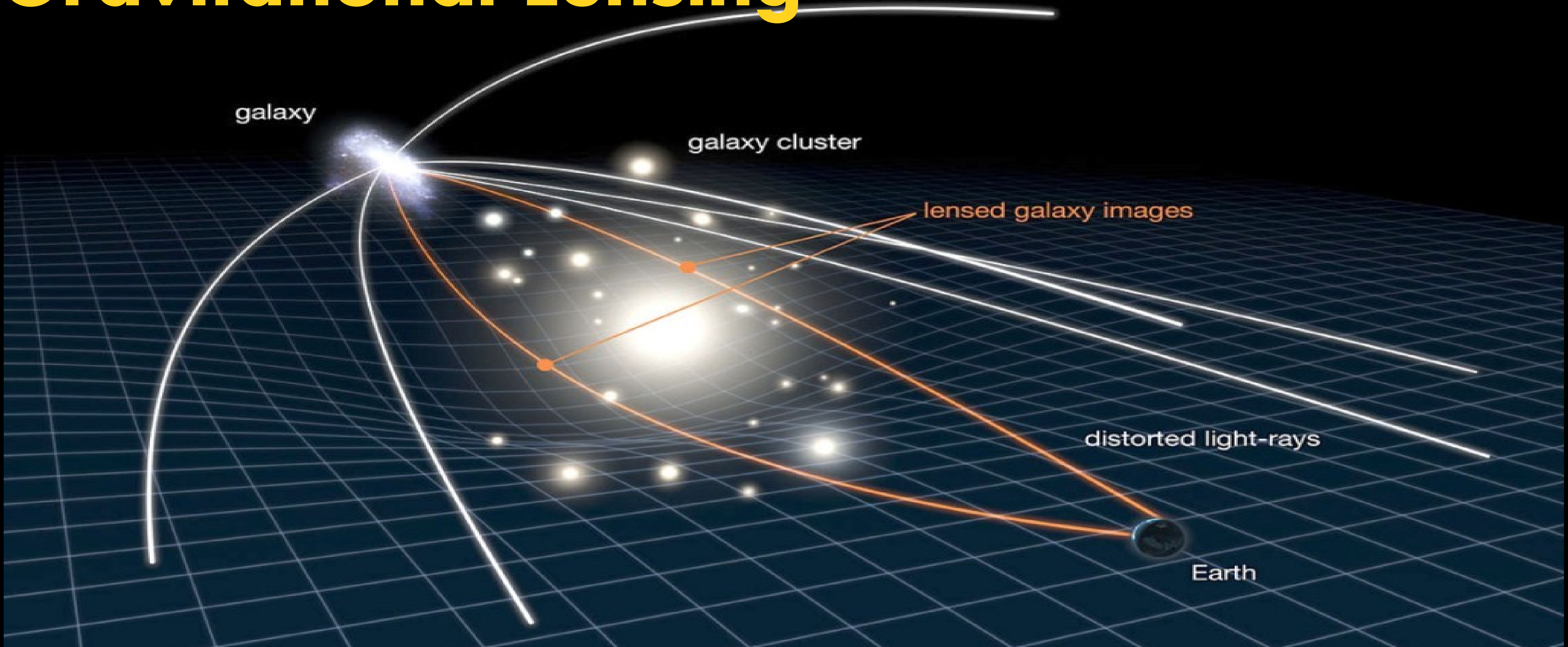
$k = 1.38065 \times 10^{-23}\, J/K$

$\Rightarrow$ Velocity dispersion: $\sigma = \sqrt{\langle v^2\rangle}$

$$\sigma = \sqrt{\frac{3kT}{\bar{m}}} \approx 1.4 \times 10^3\,\text{km s}^{-1}\sqrt{\frac{T}{10^8\,\text{K}}}$$

$$\sigma \sim 10^3\,\text{km s}^{-1},\ T \sim (2-11) \times 10^7\,\text{K}$$

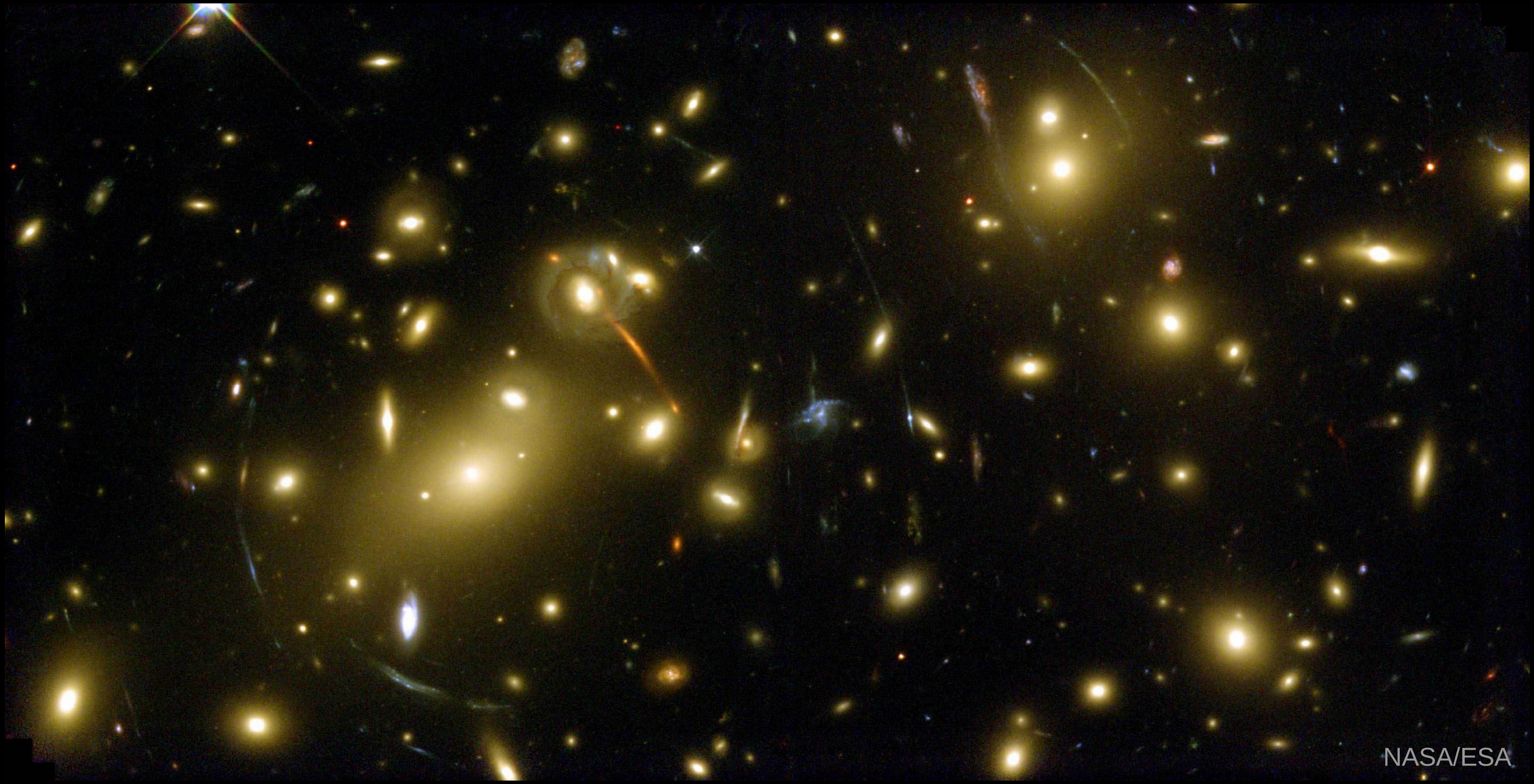
Gravitational Lensing



General Relativity: A massive object (e.g., a galaxy cluster) curves spacetime.
Light follows geodesics.
→ A massive object acts as a gravitational lens for light from a distant source.

NASA/ESA

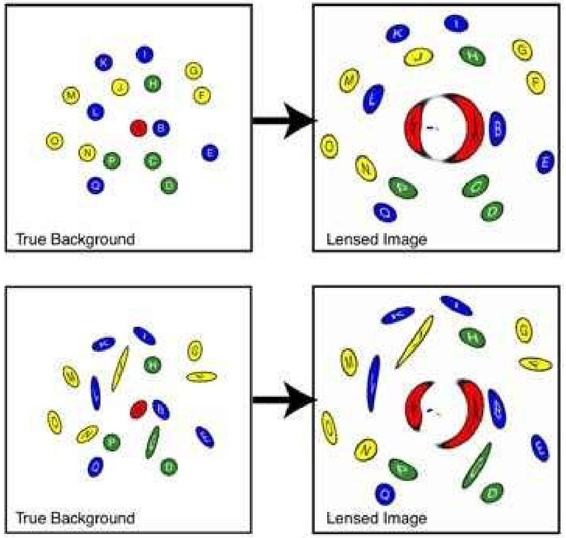
Gravitational Lensing: Strong Lensing

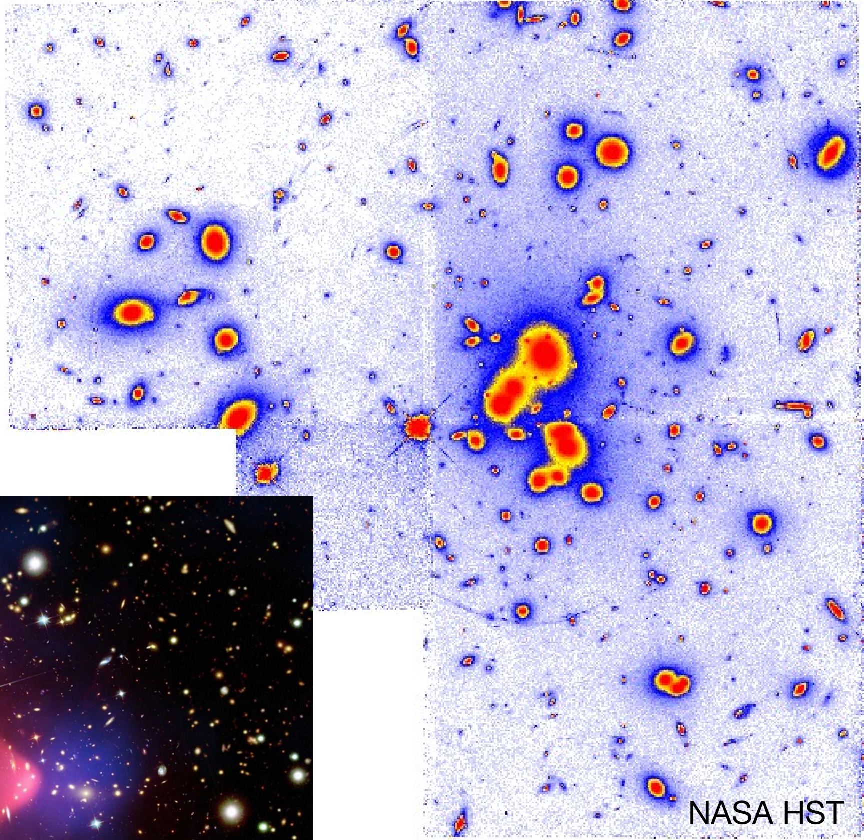


Gravitational lensing measures the total mass enclosed by the light rays, independent of the type of matter.

Weak Lensing

- Line of sight near galaxy cluster: strong lensing (long arcs)
- Further out: weaker distortions, but more abundant. → weak lensing
- Measure **total** mass distribution in galaxy clusters

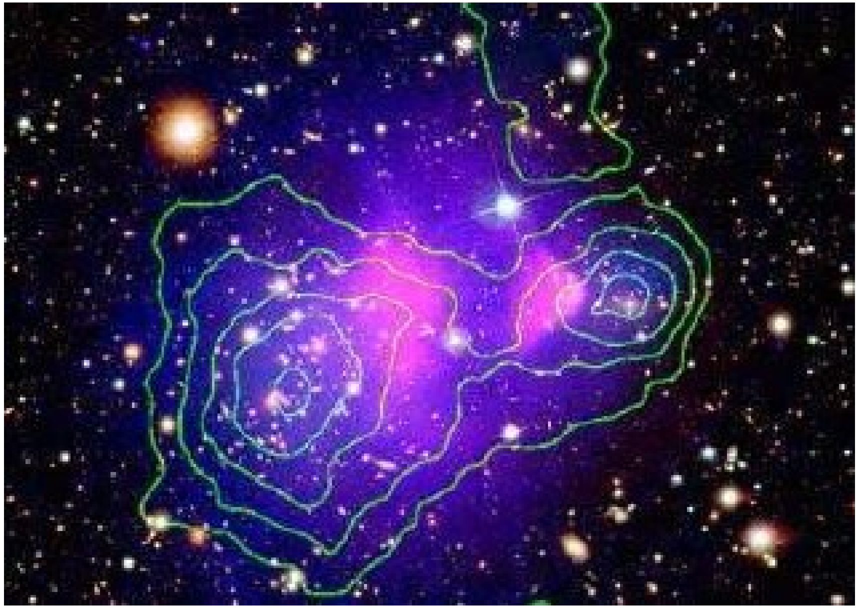




Bullet cluster
pink: X-rays – hot gas
blue: total mass distribution from weak lensing

The Bullet Cluster

- “Bullet cluster” (z~0.3) is an ongoing merger of two galaxy clusters.
- Cores passed through each other ~100 million years ago (recent!).
- Weak lensing observations (blue) trace the total mass distribution.
- Known property of clusters: bulk of regular (baryonic) matter consists of hot intra-cluster gas. Stars contribute just a little.
- Chandra X-ray observations (pink) trace hot intracluster gas, i.e., most baryons.
- Stars and Dark Matter are collisionless, whereas gas (plasma) experiences ram pressure.



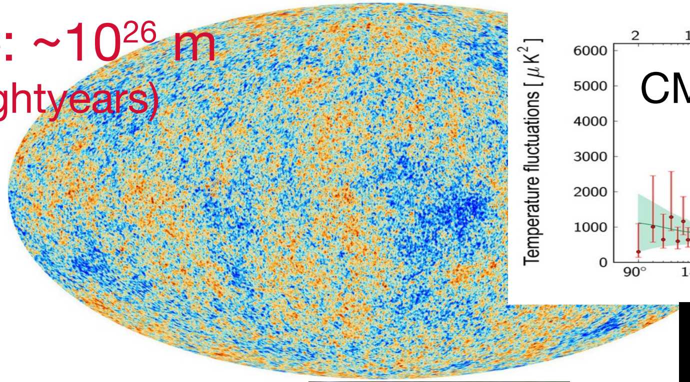
D. Clowe et al., Astrophys. J. 648 (2006) L109

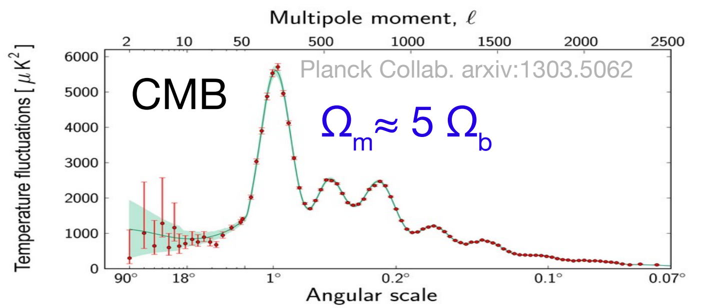
- Gas is offset with respect to total matter distribution.
  ⇒ **Dark Matter!**
  ... and not modified gravity.

- Mass of cluster >> Mass of gas
- Bulk of total mass offset with respect to bulk of baryonic matter.
- **But:** these systems are rare, dynamics complicated, possible counter example, etc.

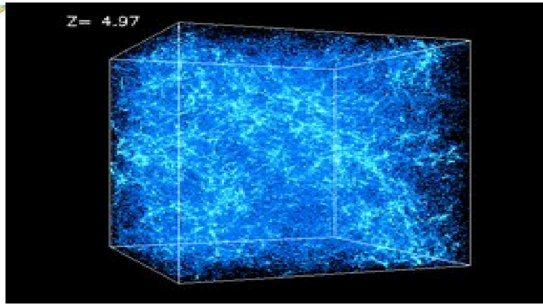
Evidence for Dark Matter from Cosmology

Scale: ~10^{26} m
(10^{10} lightyears)

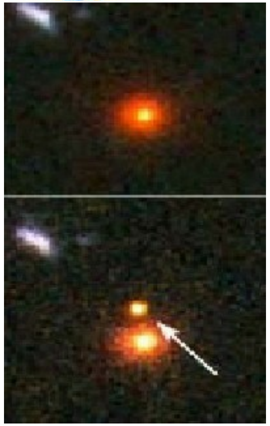




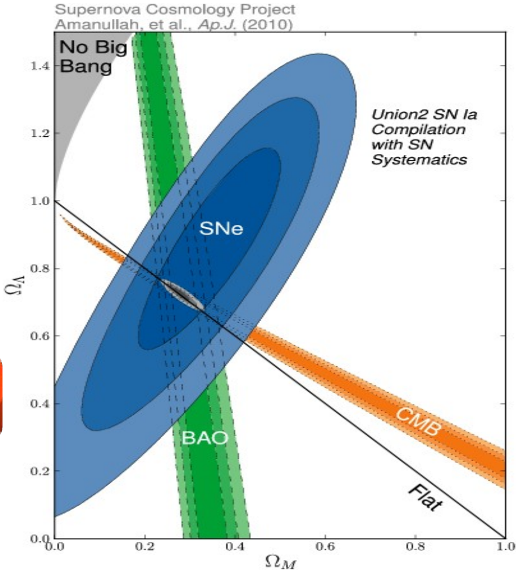
- Cosmic Microwave Background.
  - Uniformity at age 380,000 yr.
  - Flatness of the universe
  - Baryon density, etc.



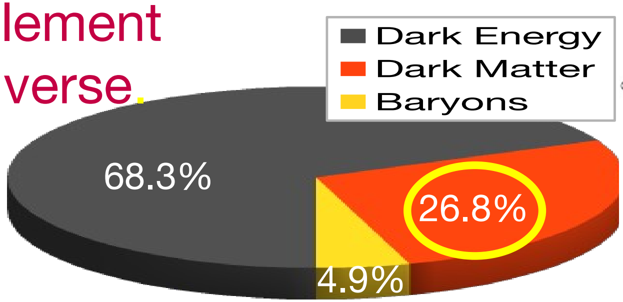
- Supernovae as standard candles.
  - Expansion history of the universe.



- Galaxy surveys (wide or deep) and Simulations of structure formation.
  - Large scale structure.
  - Early structure formation.
    First stars. Quasars and galaxies.



- Big Bang Nucleosynthesis and light element abundances observed in the early universe.
  - Limit on baryon density, consistent with CMB.



- Baryon Acoustic Oscillations …
  - standard ruler

Multipole Expansion of CMB
WMAP after dipole subtraction

Expansion in spherical harmonics:

$$T(\vec{n}) = T_0 \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=+\ell} a_{\ell m} Y_{\ell m}$$

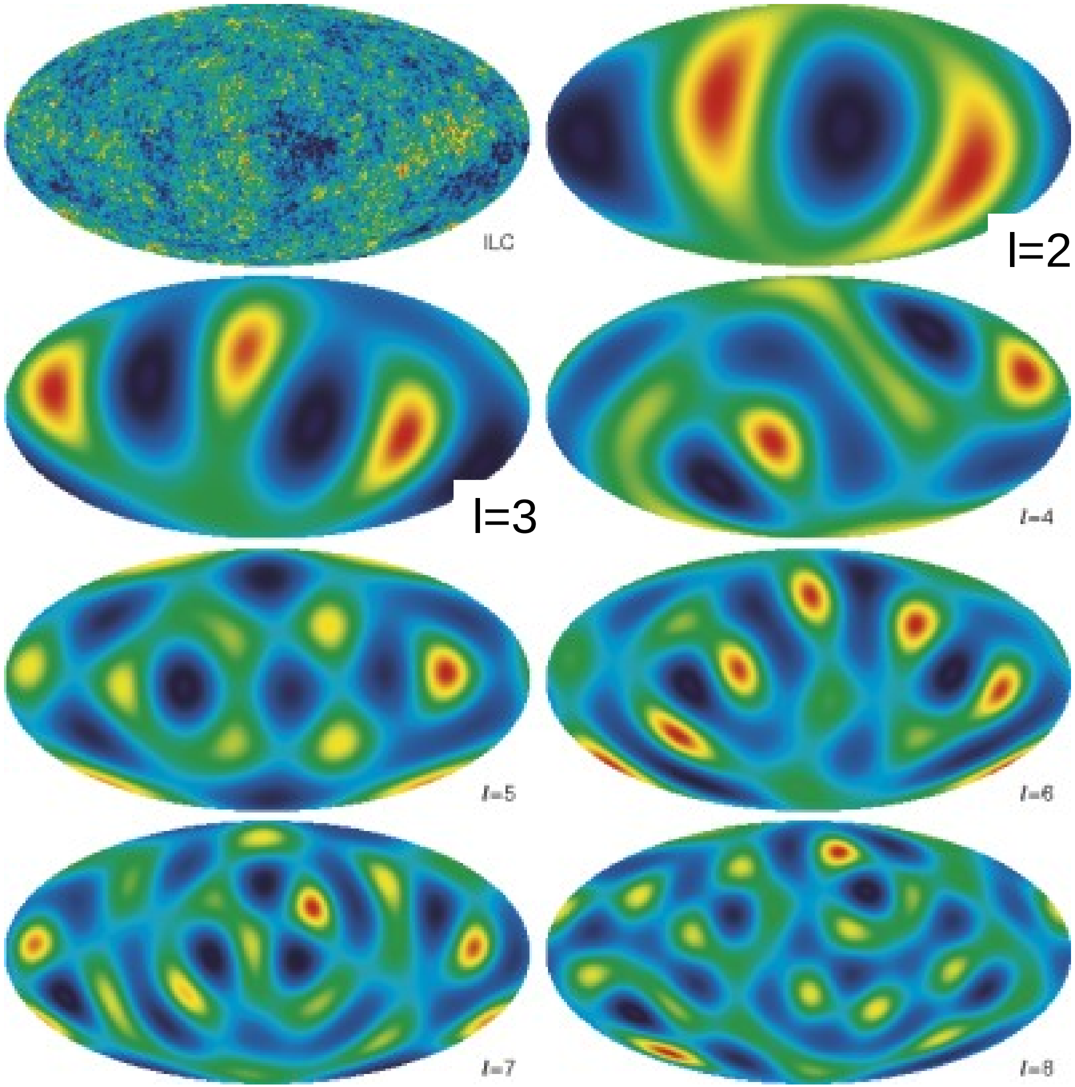
Pair correlation function:

$$C(\theta) = \left\langle \left(\frac{\Delta T(\vec{n})}{T_0} \right) \left(\frac{\Delta T(\vec{m})}{T_0} \right) \right\rangle$$

$$C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\theta)$$

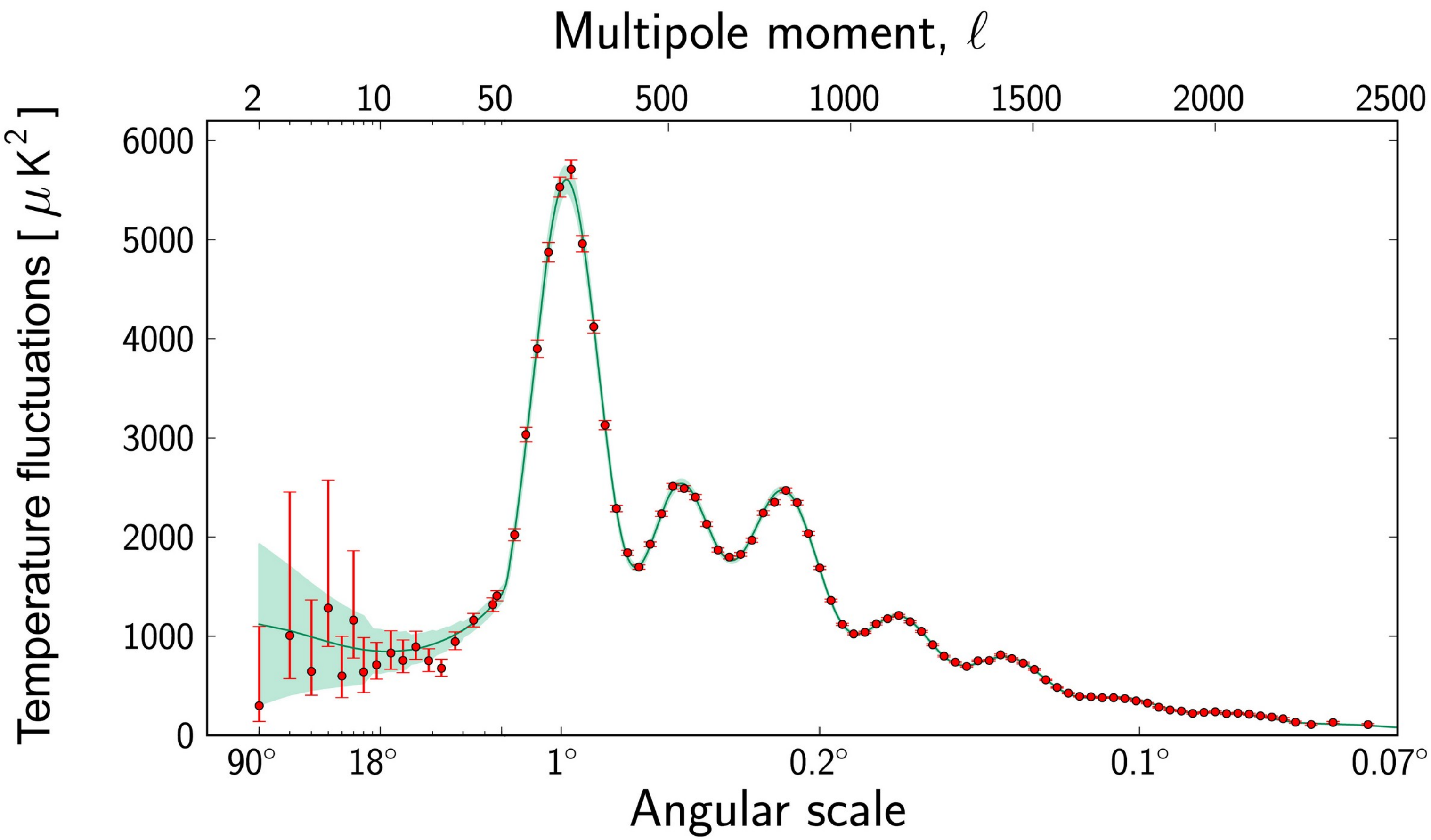
$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

$$(\Delta T)^2 = l\,(l + 1)\,\frac{C_l}{2\,\pi}$$



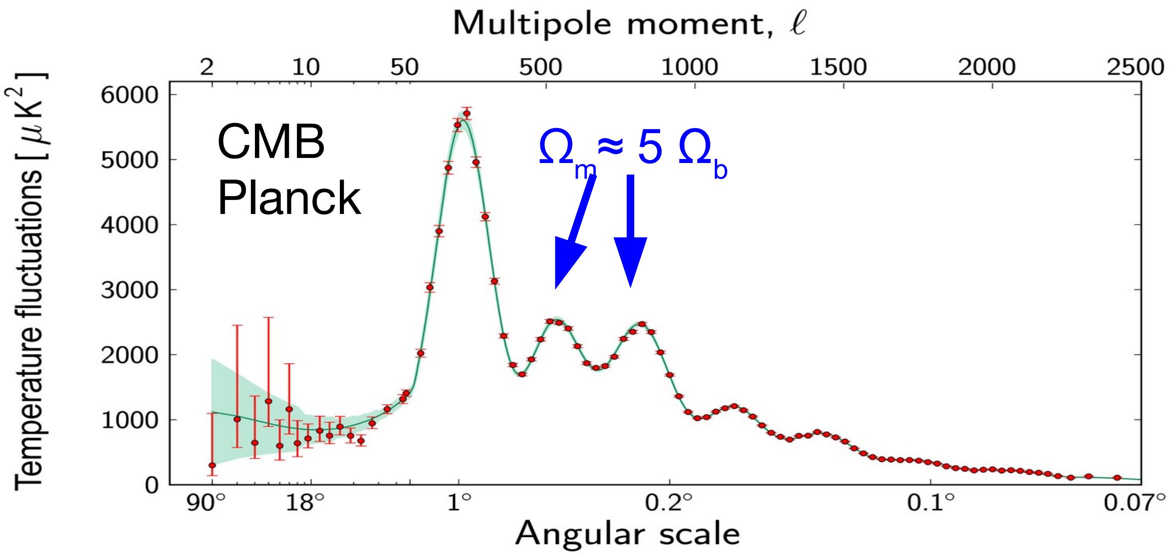
NASA/WMAP

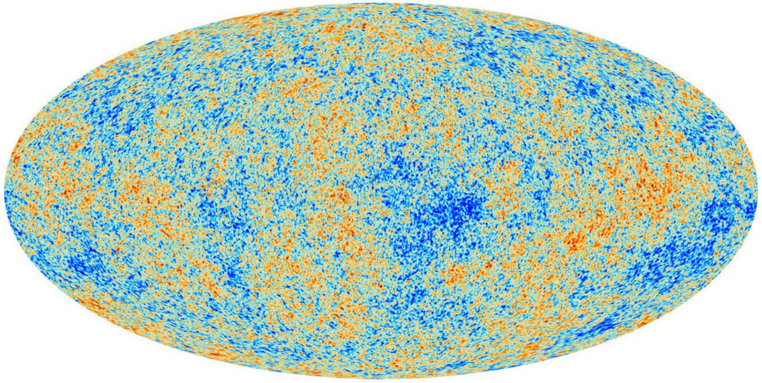
CMB as seen by Planck: Power Spectra



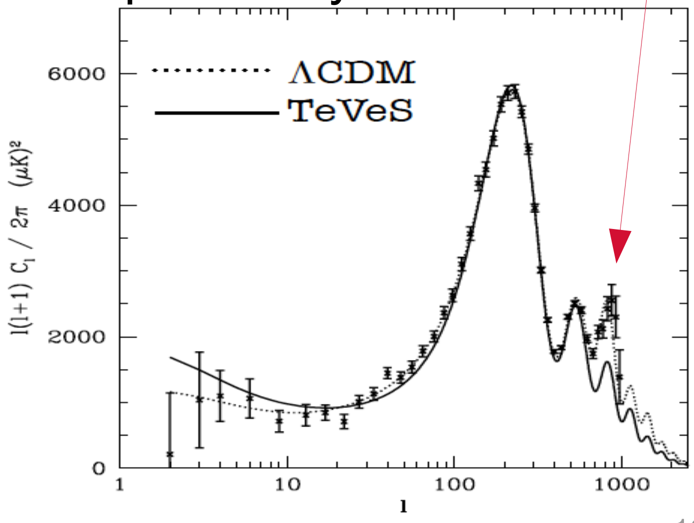
Planck Collaboration, arxiv:1303.5062

Non-baryonic Dark Matter or Alternative Theories of Gravity?





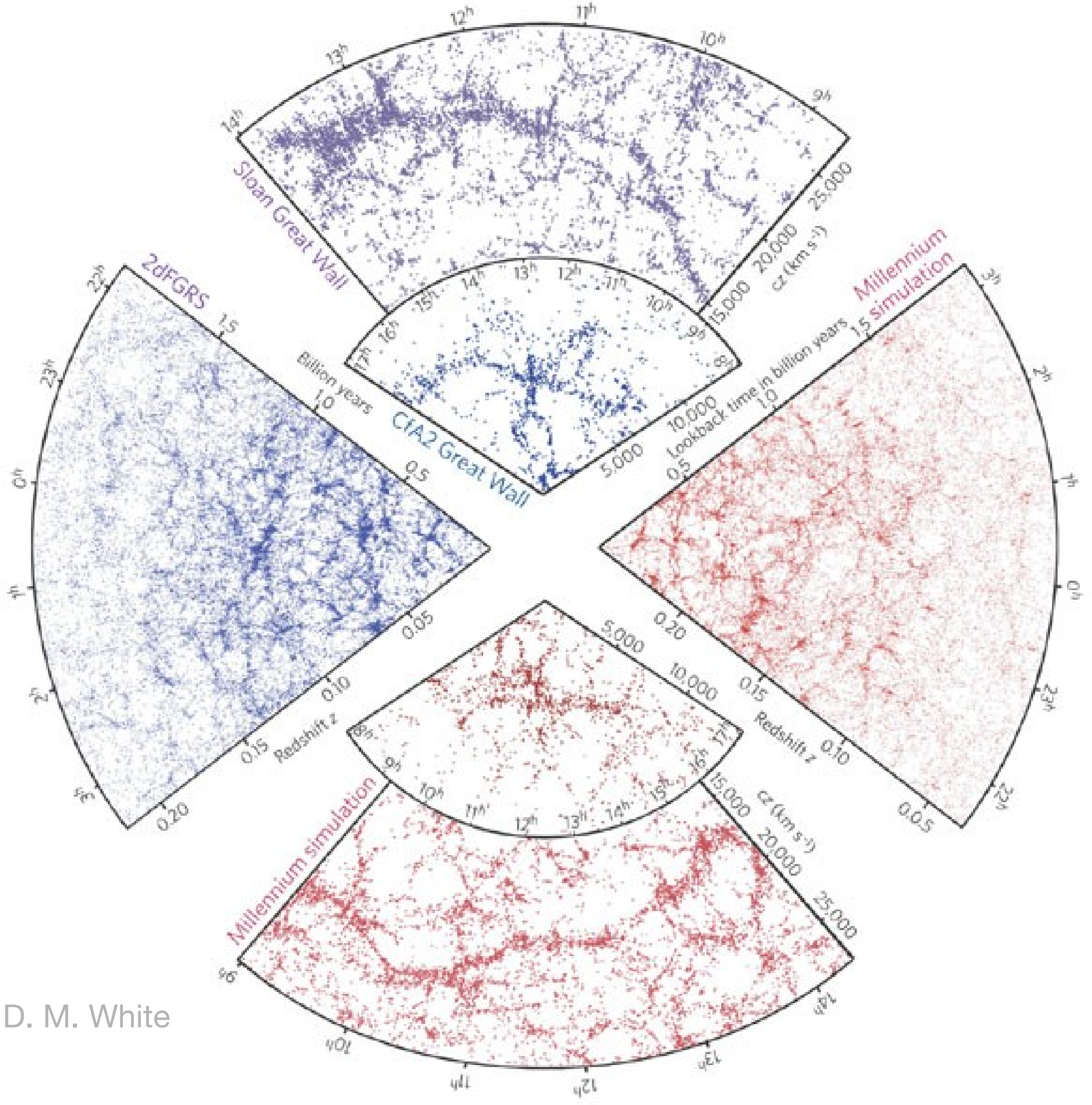
3[rd] peak only with Dark Matter



- Relative strength of acoustic peaks provides Ω_m and Ω_b independently.
- One can also test for alternative theories of gravitation (e.g., TeVeS): no alternative theory can do without Dark Matter.

→ Dark Matter is non-baryonic.

Cold Dark Matter Structure Formation

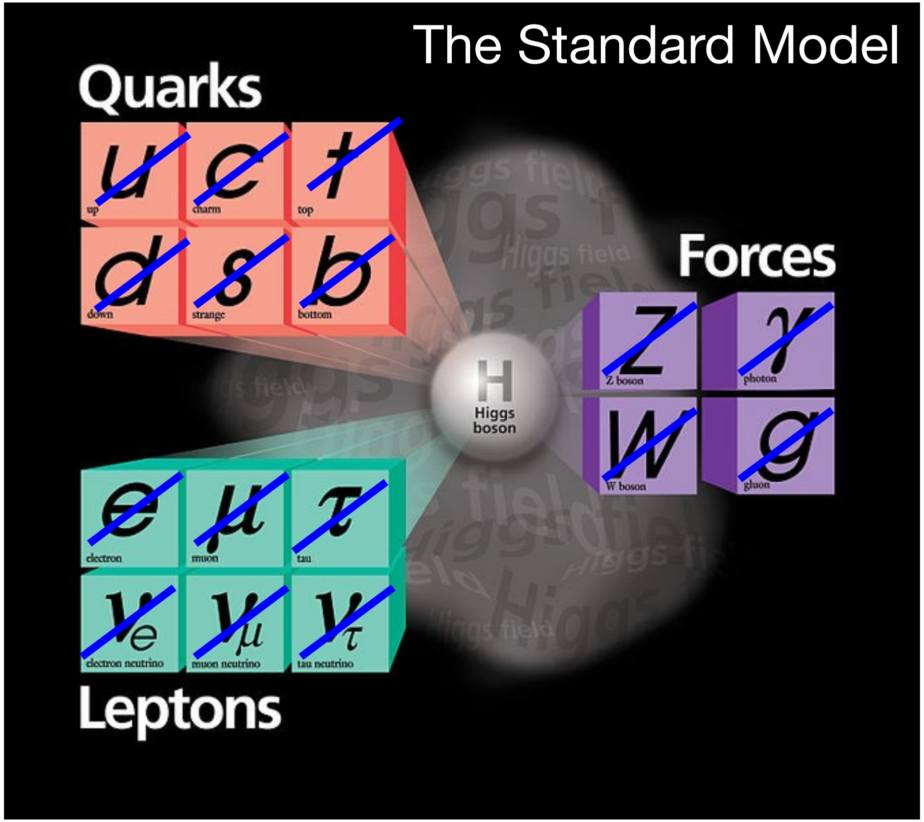


V. Springel, C. S. Frenk, S. D. M. White
Nature 440, 1137 (2006)

→ Dark Matter is non-relativistic:
cold, or at least not hot.

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.27$
- Electrically neutral
  - Dark Matter
- Non-baryonic
  - does not couple with plasma
  - CMB, Big Bang nucleosynthesis
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Constraints from
  - accelerator searches
  - direct searches
  - indirect searches



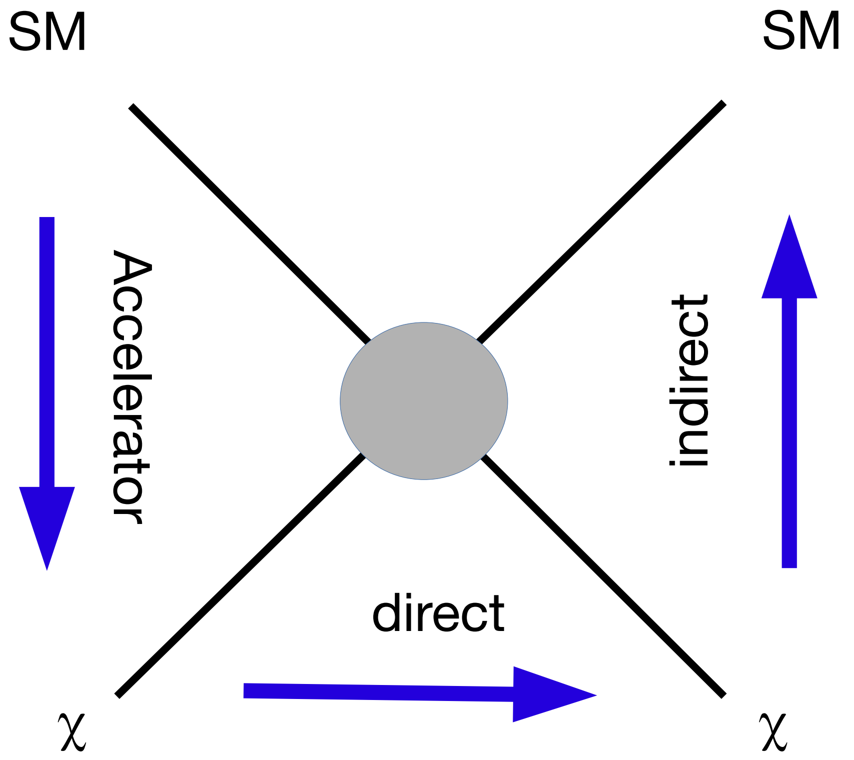
Dark Matter requires physics beyond the Standard Model!

Dark Matter Candidates

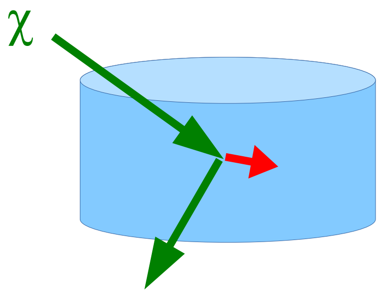
Bertone & Tait
Nature 2018

Searching in all directions:

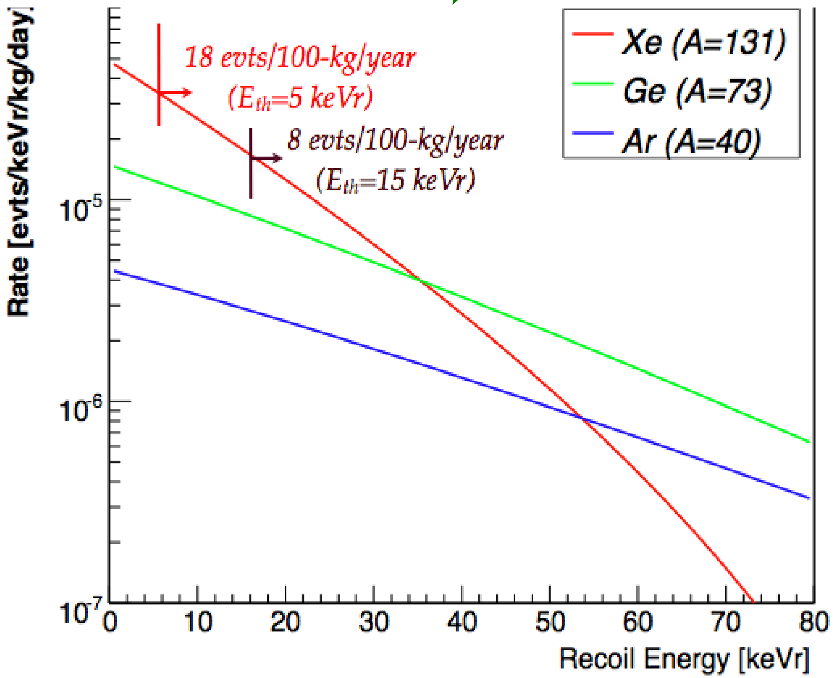
Direct Searches, Indirect Searches, Searches at Accelerators



WIMP Dark Matter Direct Detection



- Elastic scattering of WIMPs χ off nuclei A.
  → **nuclear recoil**
  - spin-independent (~A^2) or spin-dependent? (… EFT op's)
- Mass range
  - m_χ ~ 10 – few 10^3 GeV/c^2 ("traditional")
  - < 1 GeV/c^2 to 10^4 GeV/c^2 (extended)
- Energy spectrum:
  - "Standard" spherical halo
  - DM relative velocity: v_χ ~ 230 km/s
    → exponential recoil spectrum
    <E> ~ O(10 keV)
  - large nuclei: coherence ~A^2 for small q
  - nuclear form factor reduction at higher q
  - Local number density of WIMPs: ρ_χ/m_χ
    ρ_χ ~ 0.3 GeV/c^2/cm^3
  - ρ_χ/m_χ ~ 100 / L * (30 GeV/c^2/m_χ)



Rate < 10^{-4} events / kg / day

Backgrounds in Direct DM Search

Cross-sections are *very* small: <10^{-46} cm^2 (spin-independent).
Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$
With background subtraction $\propto$ $(M\ t)^{-1/2}$ until limited by systematics.

Backgrounds by origin:

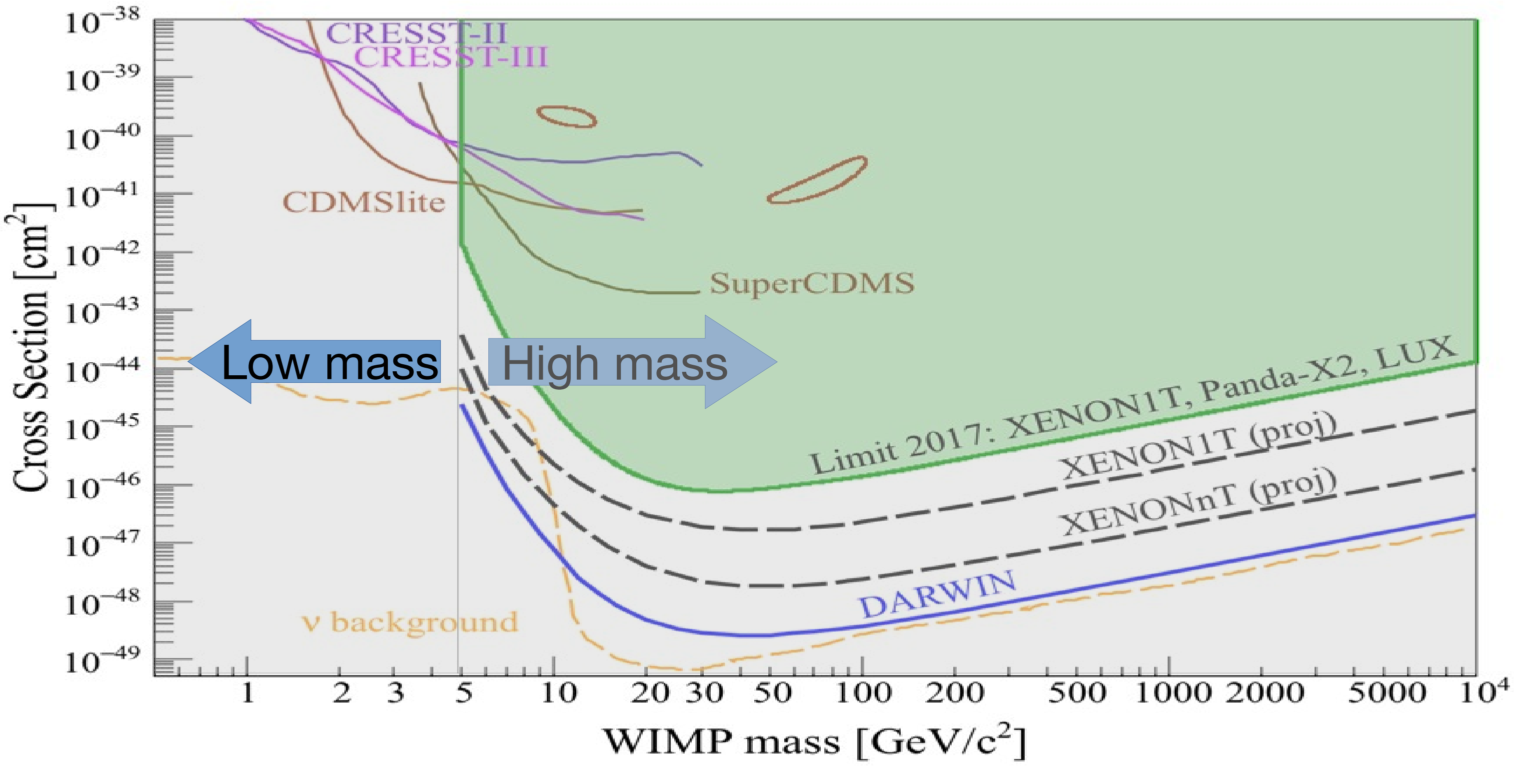
- external
  - cosmic → depth, veto
  - radiogenic → shielding, self-shielding, veto, material selection
- surface → localization, veto
- internal → minimize!

→ **discrimination**

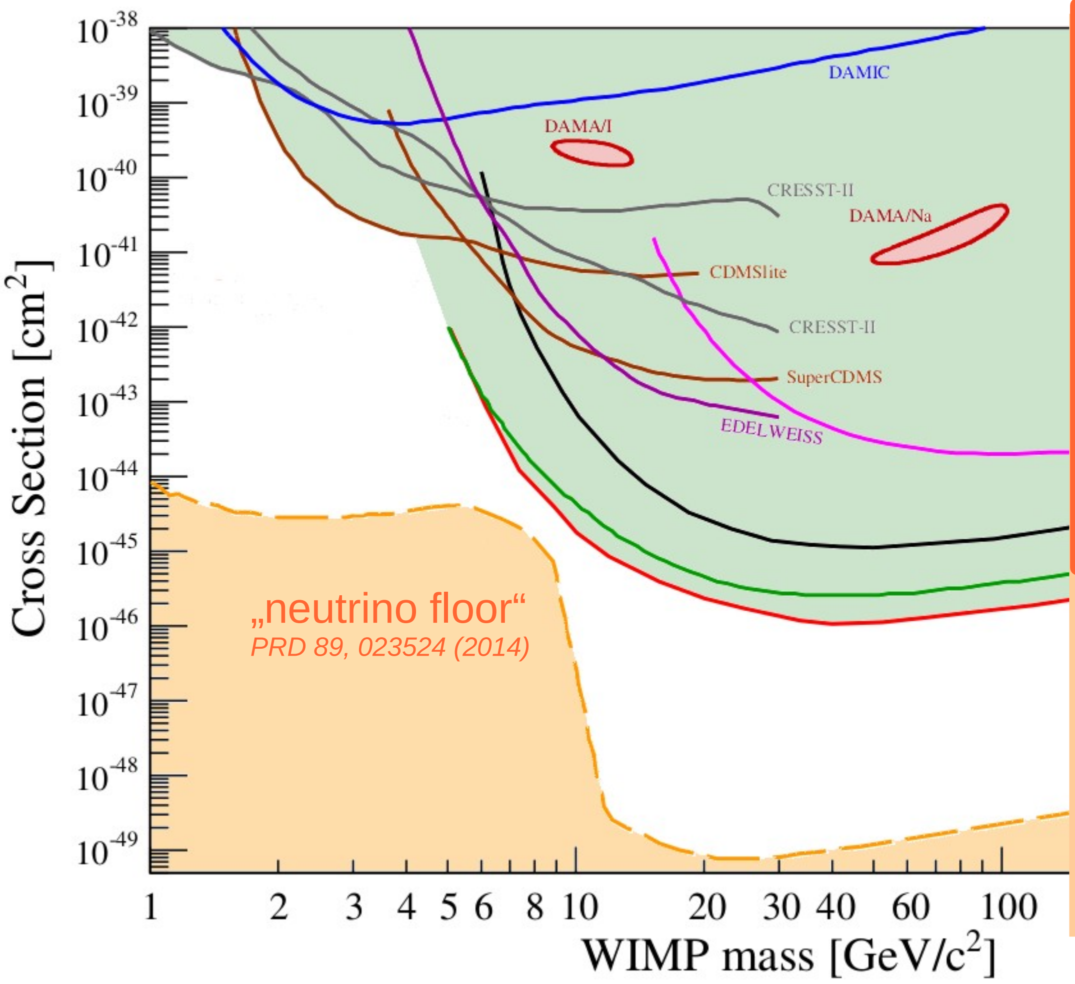
Backgrounds by radiation type:

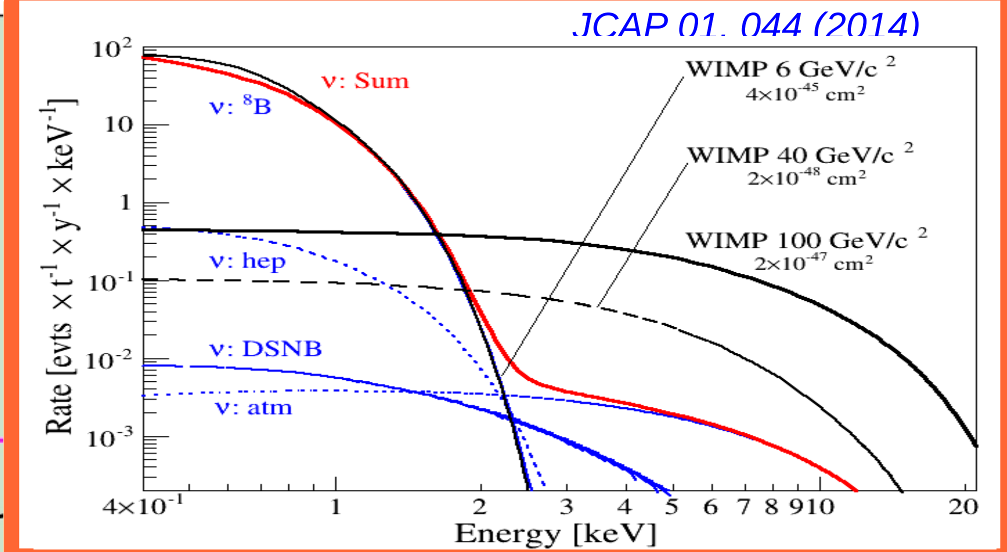
- gamma rays: long range
- beta decays
- α decays from natural decay chains + nuclear recoils
- neutrons from (α, n) reactions and spontaneous fission (up to ~10 MeV)
- neutrons from cosmic ray muons >~ 100 MeV
- neutrinos!

Dark Matter Searches: Status

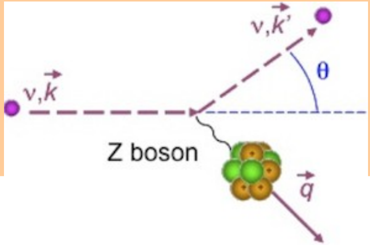


Neutrino Floor:
Nuclear Recoils from Solar, Supernova, and Atmospheric ν's





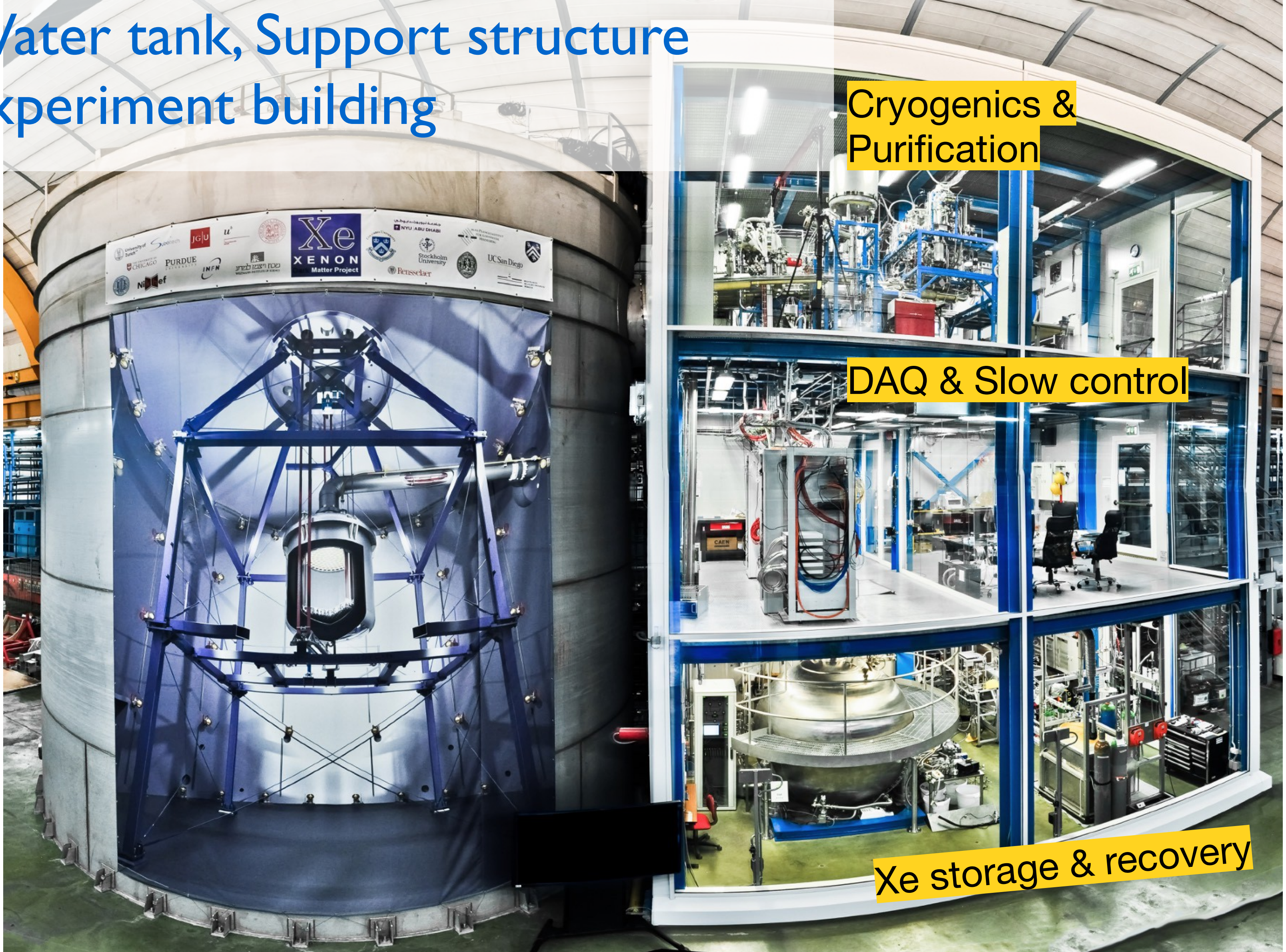
Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



The XENON Experiment at LNGS

- ~170 scientists
- ~ 29 institutions

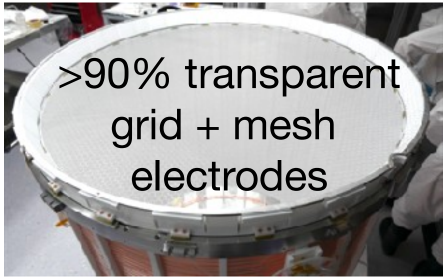
Water tank, Support structure
Experiment building



Kr distillation column & Xe analytics

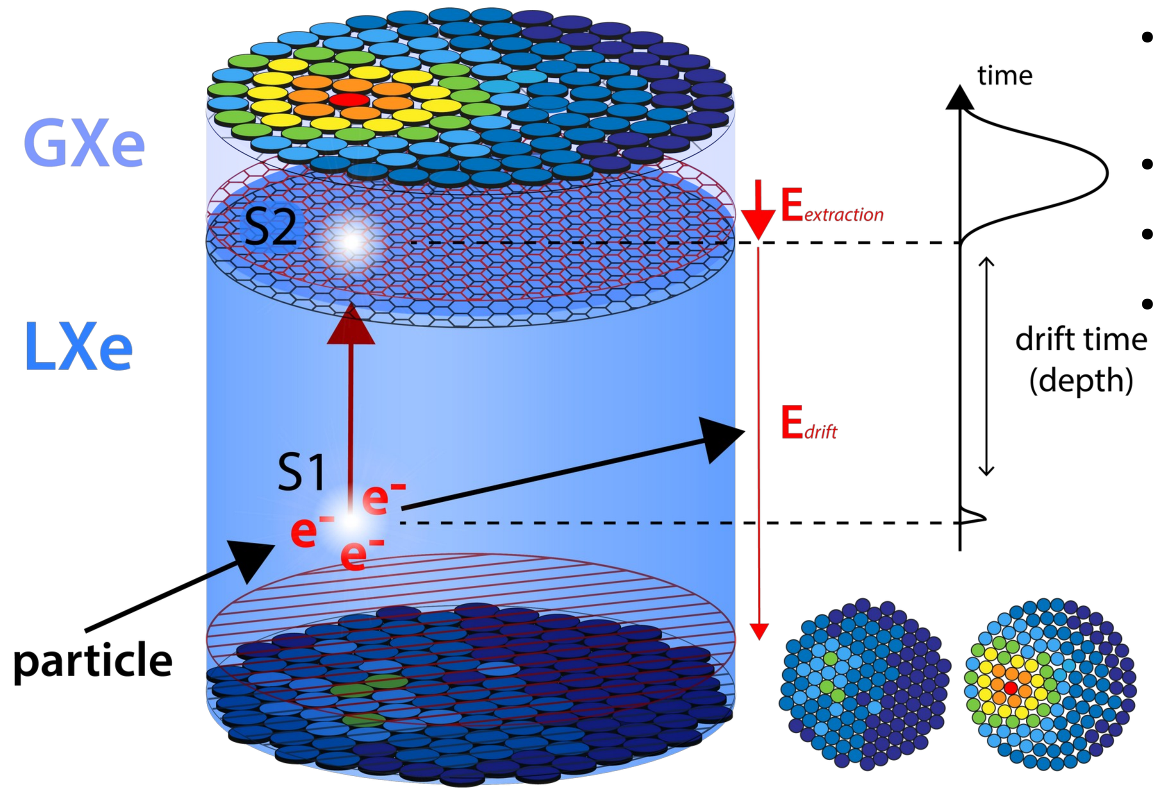
The Time Projection Chamber (LXe TPC)

127 Top
PMTs

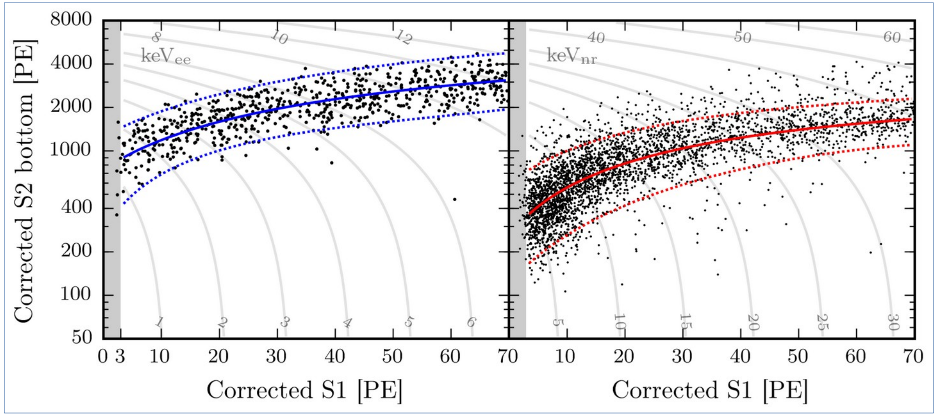


121 Bottom
PMTs

Dual Phase TPC – Time Projection Chamber



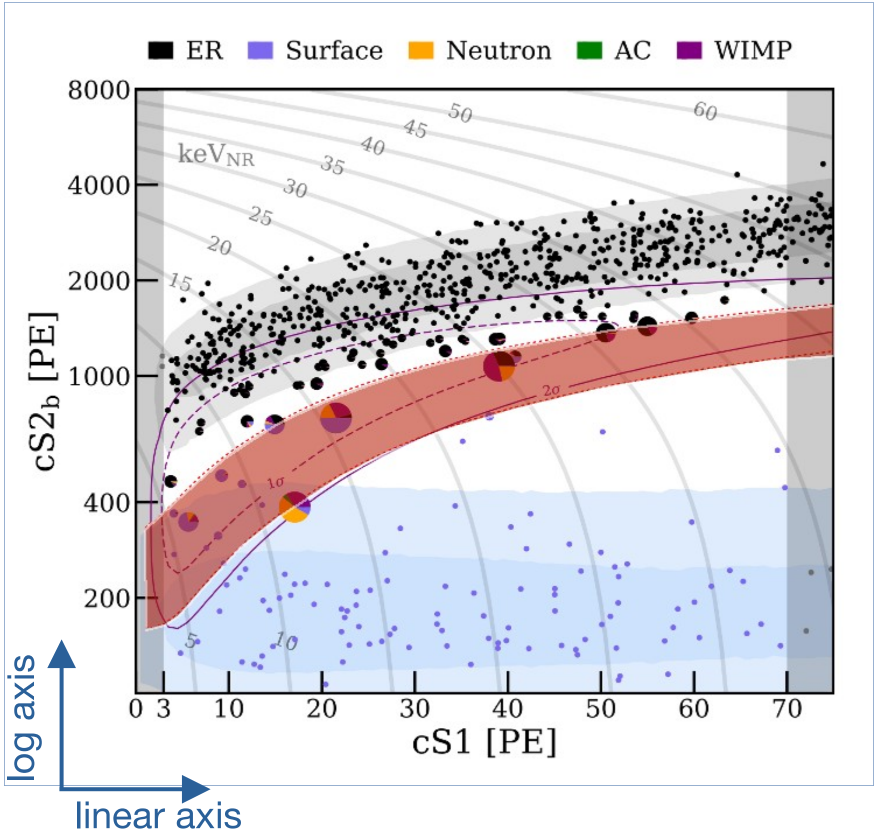
- Prompt scintillation photons give first signal (S1)
- Ionized e⁻ drift up to the anode and amplified, giving S2
- Time difference gives Z position
- S2 Hit pattern on top gives XY position
- Ratio S2/S1 indicates type of interaction



ER: γ, β

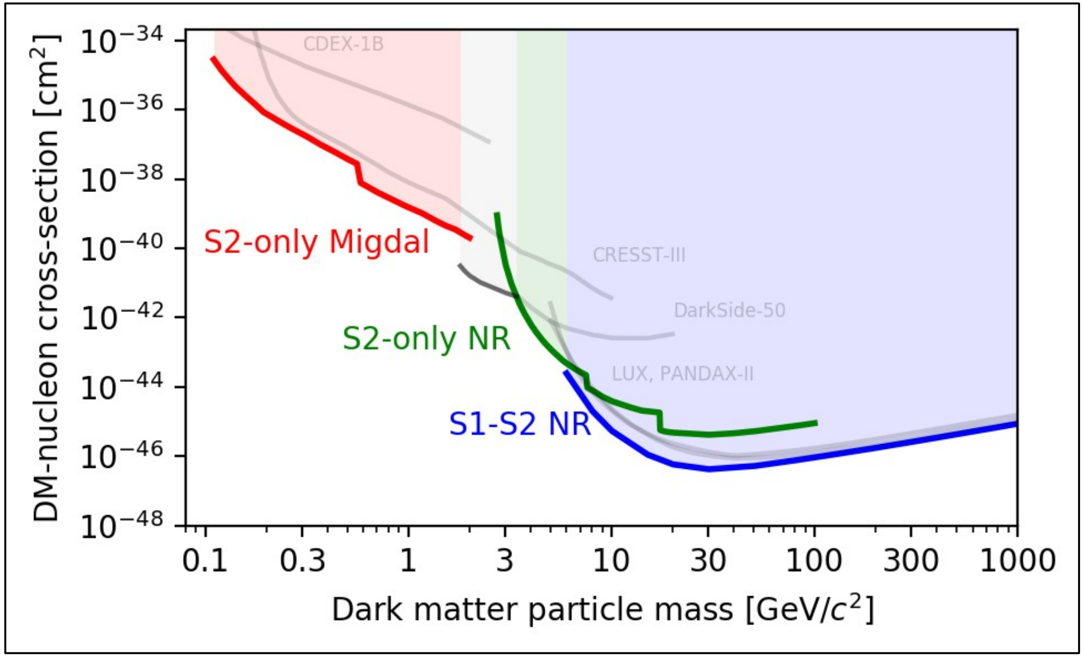
NR: n, χ

Nuclear Recoil Searches



ER “leakage” in the NR band < 0.3 %

Best constraints on WIMP dark matter with masses > 3 GeV/c^2

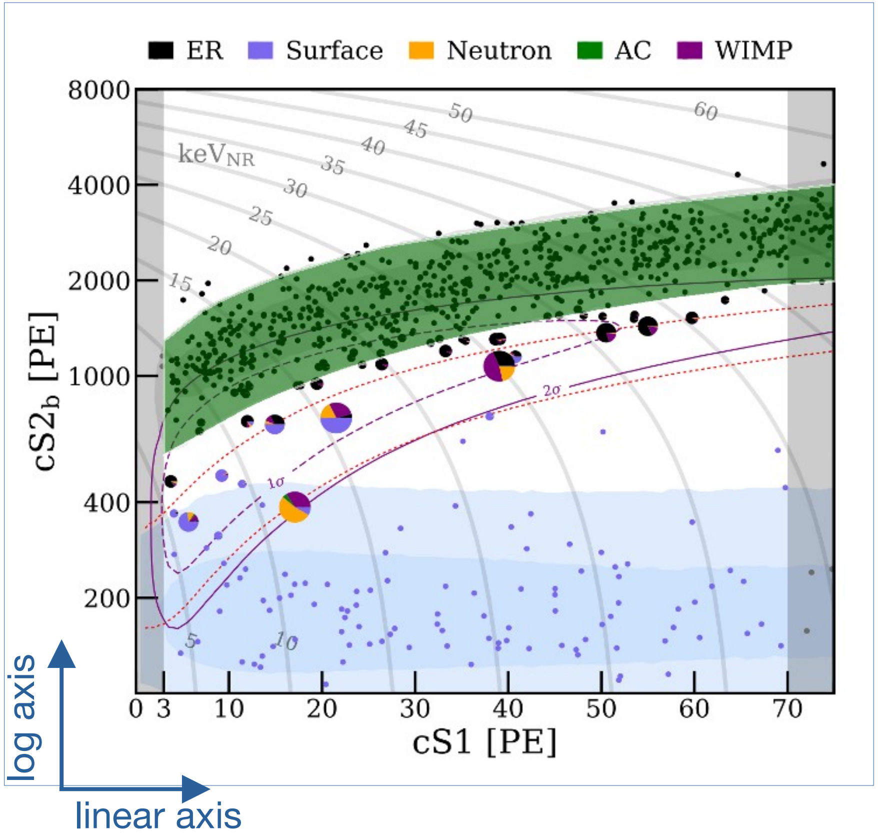


PRL 123, 241803 - Migdal effect

PRL 123, 251801 - Light dark matter

PRL 121, 111302 - Main WIMP search

Electronic Recoil Search

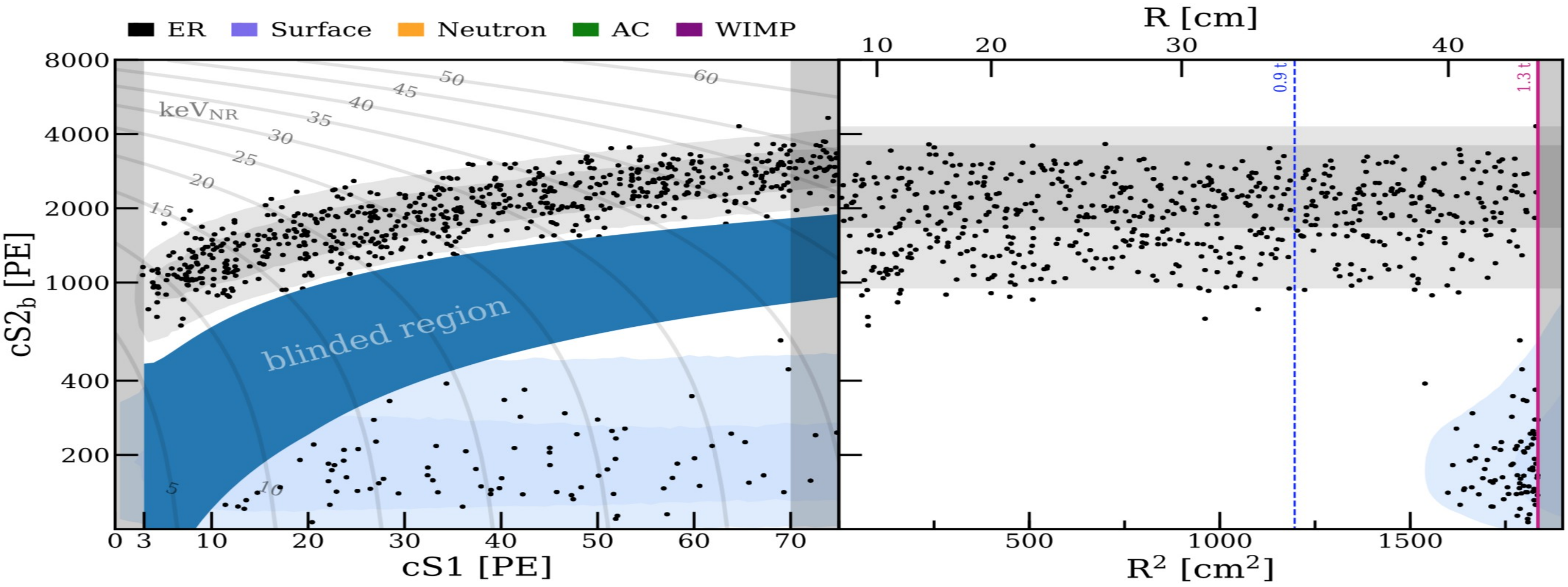


- **ER band** search for excess above known, flat-like backgrounds
- A "dedicated" Dark Matter experiment can do much more!

arxiv:2006.09721

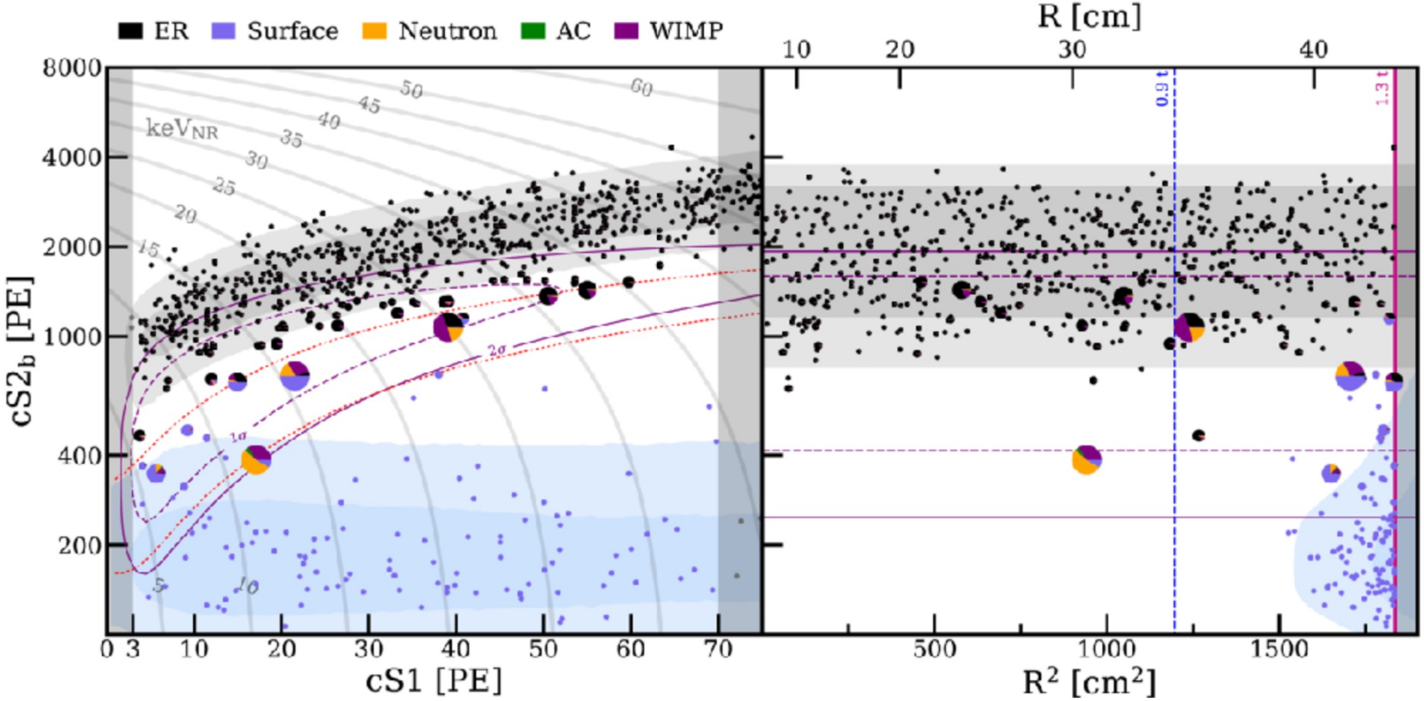
XENON1T Dark Matter Search

- Blinding: to avoid potential bias in event selection and the signal/background modeling the nuclear recoil ROI (S2 vs S1 only) was blinded from the start of SR1 analysis (and SR0 re-analysis).
- Salting: to protect against post-unblinding tuning of cuts and background models, an undisclosed number and type of event was added to data



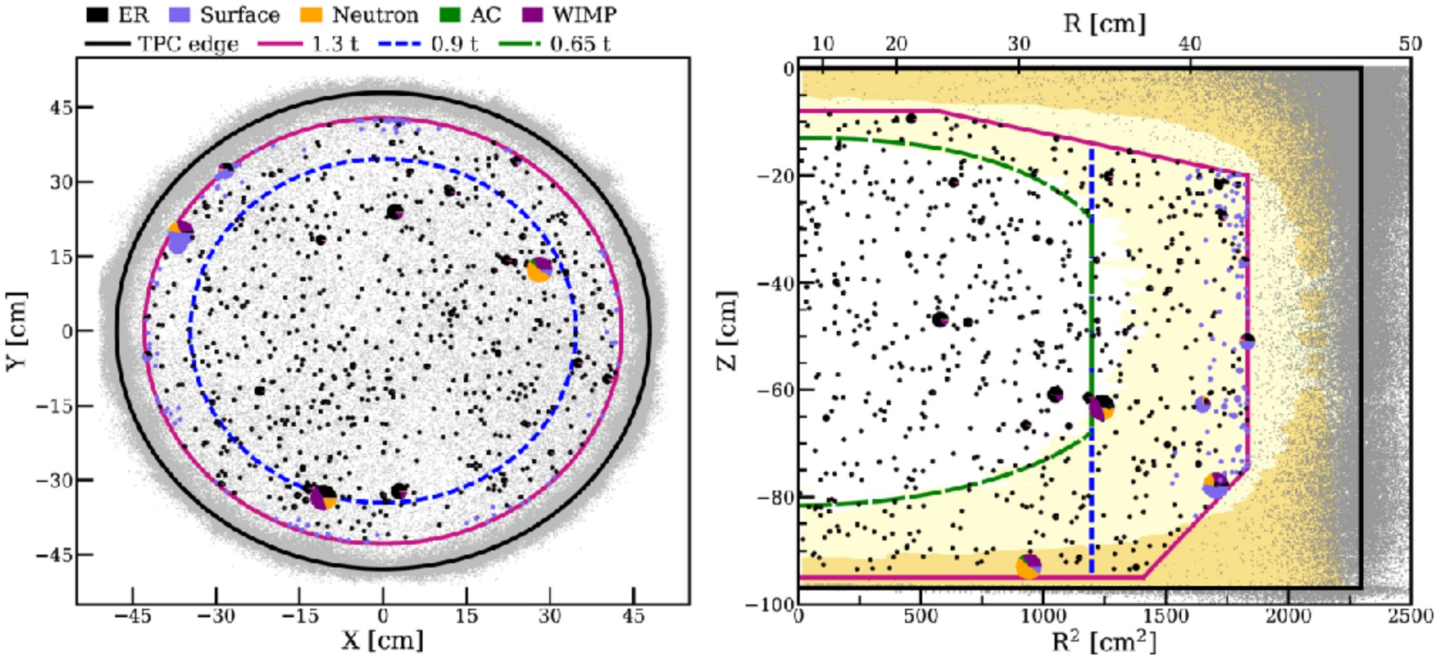
XENON1T Result from 1 ton x year exposure

- Results interpreted with unbinned profile likelihood analysis in cs1, cs2, r space
- piechart indicate the relative PDF from the best fit of 200 GeV/c^2 WIMPs with a cross-section of 4.7×10^{-47} cm^2



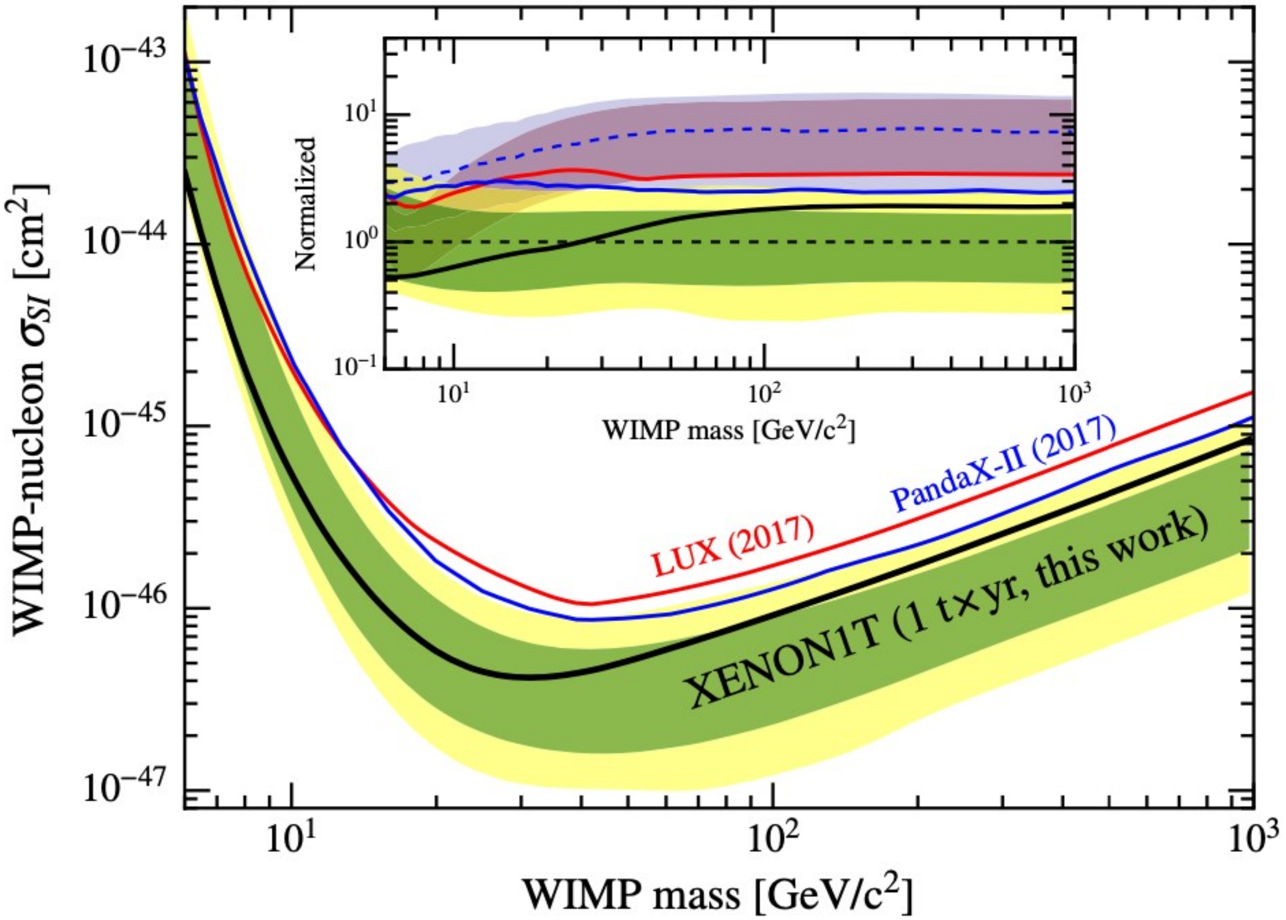
Spatial Distribution of DM Search Data

- Results interpreted with unbinned profile likelihood analysis in cS1, cS2, r space
- **Core volume** to distinguish WIMPs over neutron background

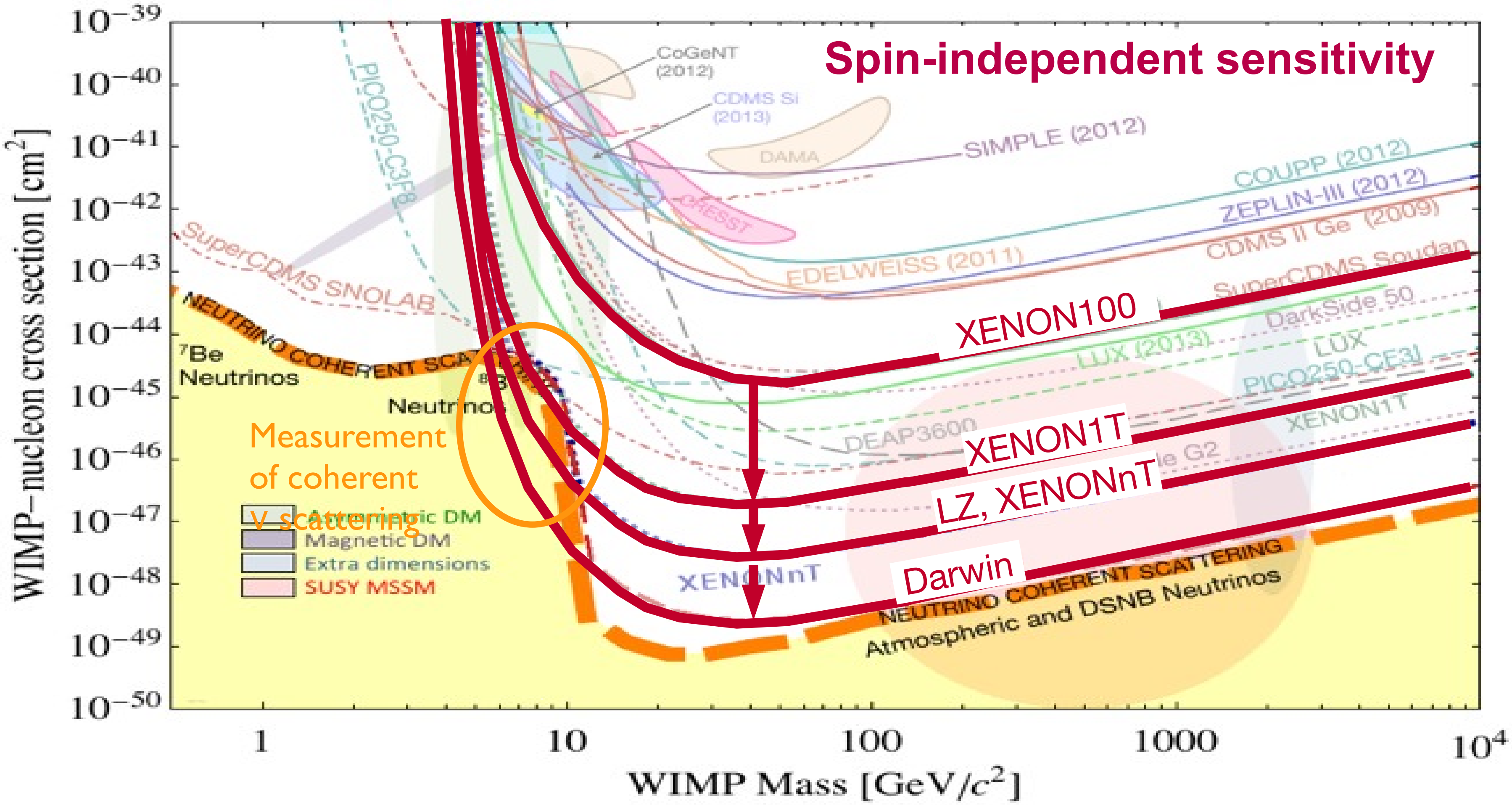


XENON1T DM Search Result (2018)

Phys. Rev. Lett 121, 111302



Current Status and Future Goals

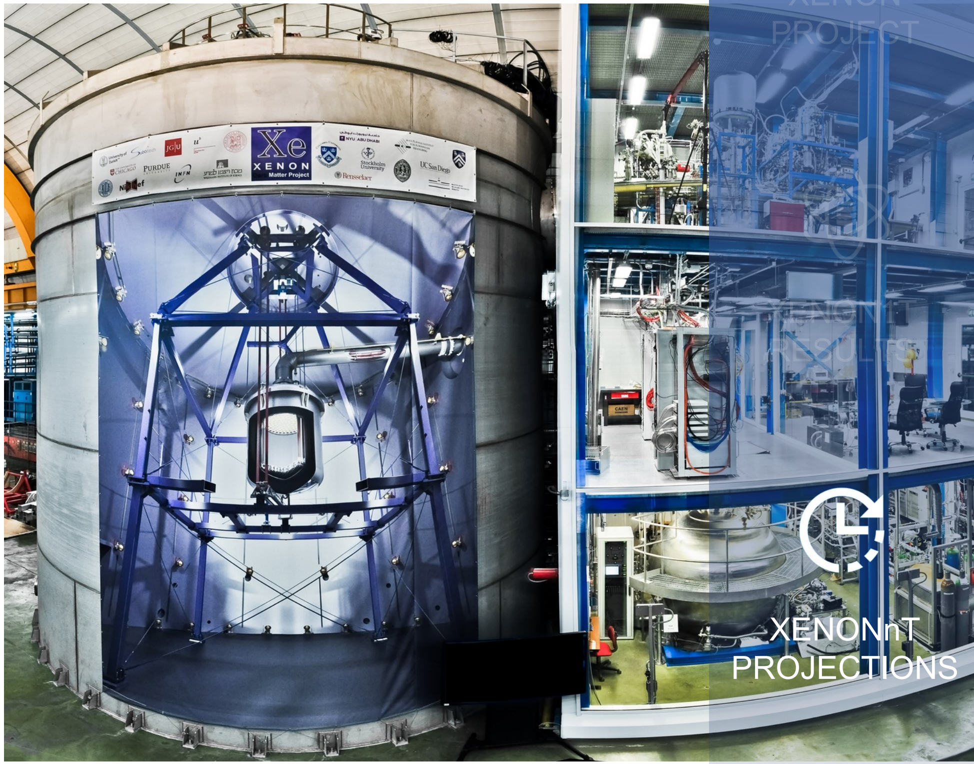


Conclusions

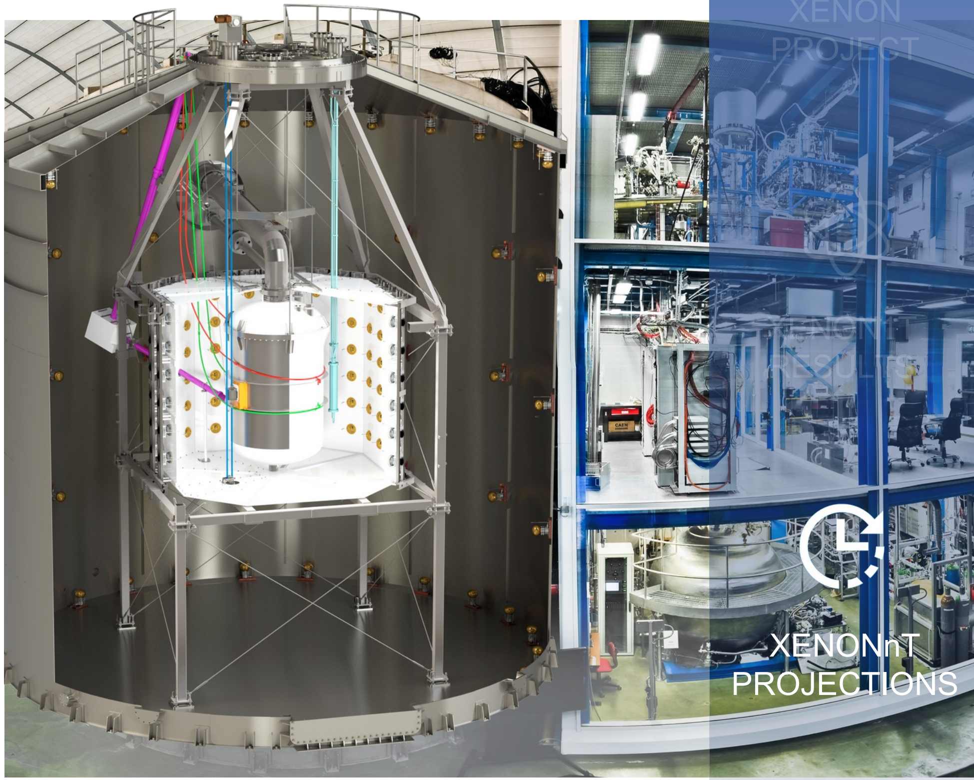
- Important question
- Exciting Progress
- We are still looking!
- Time for input from theory?

Backup Slides

Recontres de Moriond EW | 27 March 2021



XENON1T @ LNGS (Hall B)



XENONnT @ LNGS (Hall B)

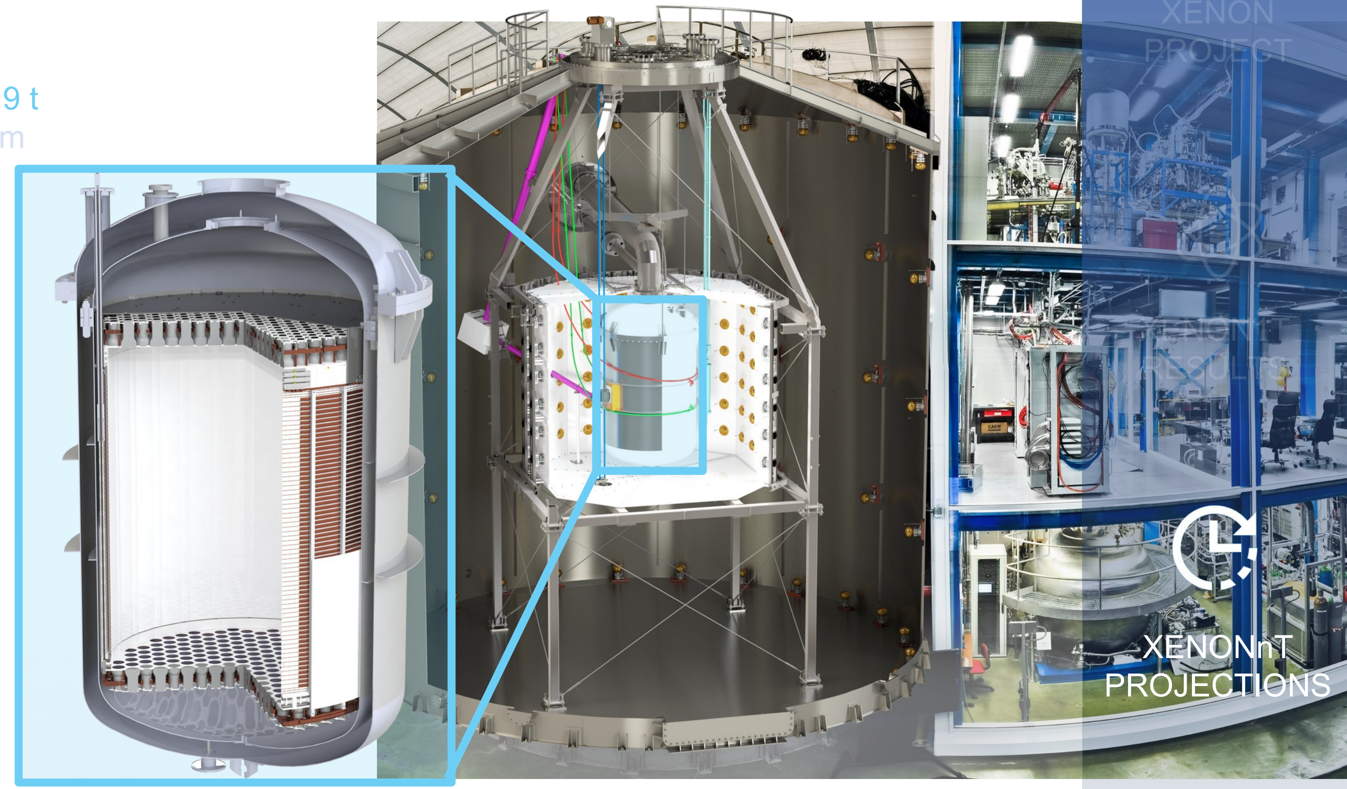
Recontres de Moriond EW | 27 March 2021

▲ Size

NEW LARGER TPC

x3 LXe target mass: 2.0 t → 5.9 t

- 8.6 t total LXe in the system
- x2 PMTs: 248 → 494
- 1.5 m drift length

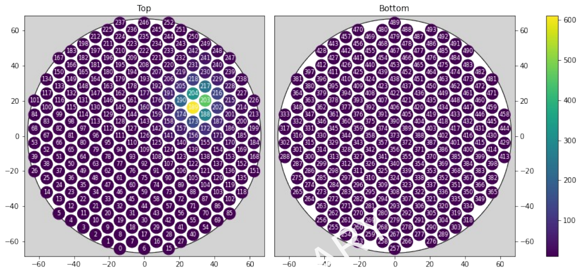


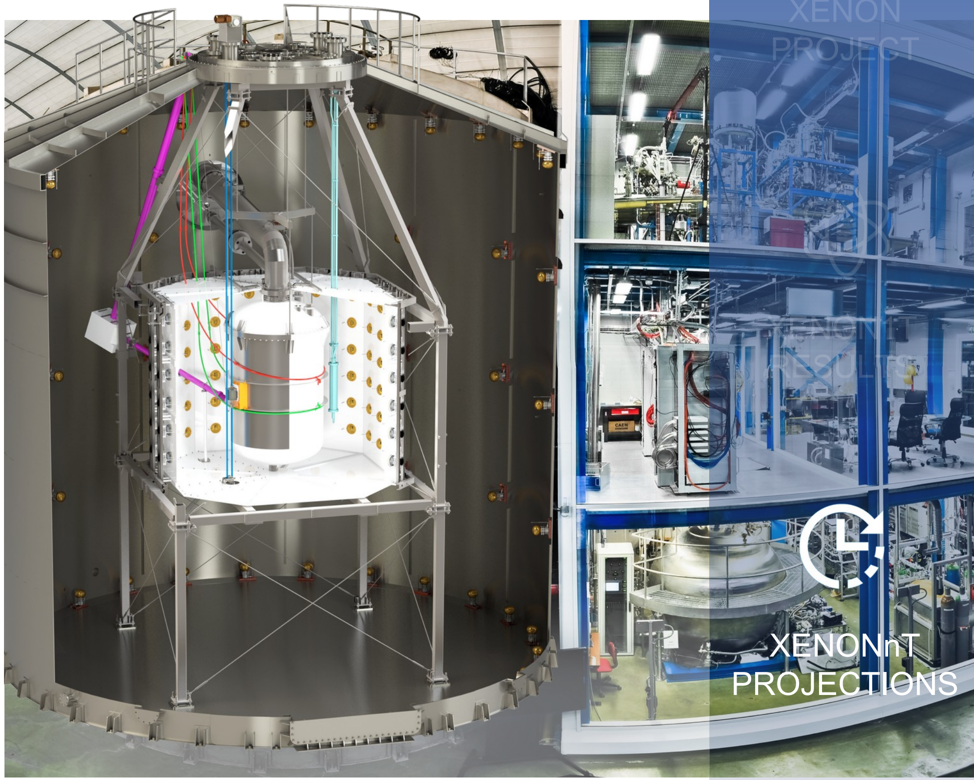
XENONnT @ LNGS (Hall B)

▲ Size

NEW LARGER TPC

Under commissioning …





XENONnT @ LNGS (Hall B)

XENON PROJECT

XENONnT RESULTS

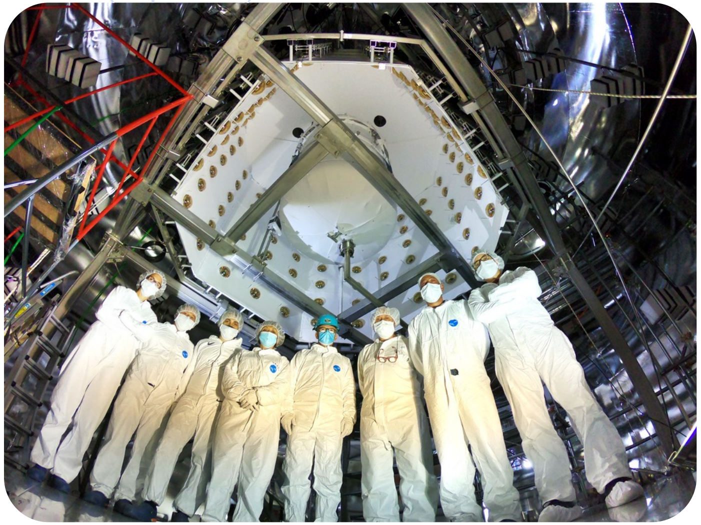
XENONnT PROJECTIONS

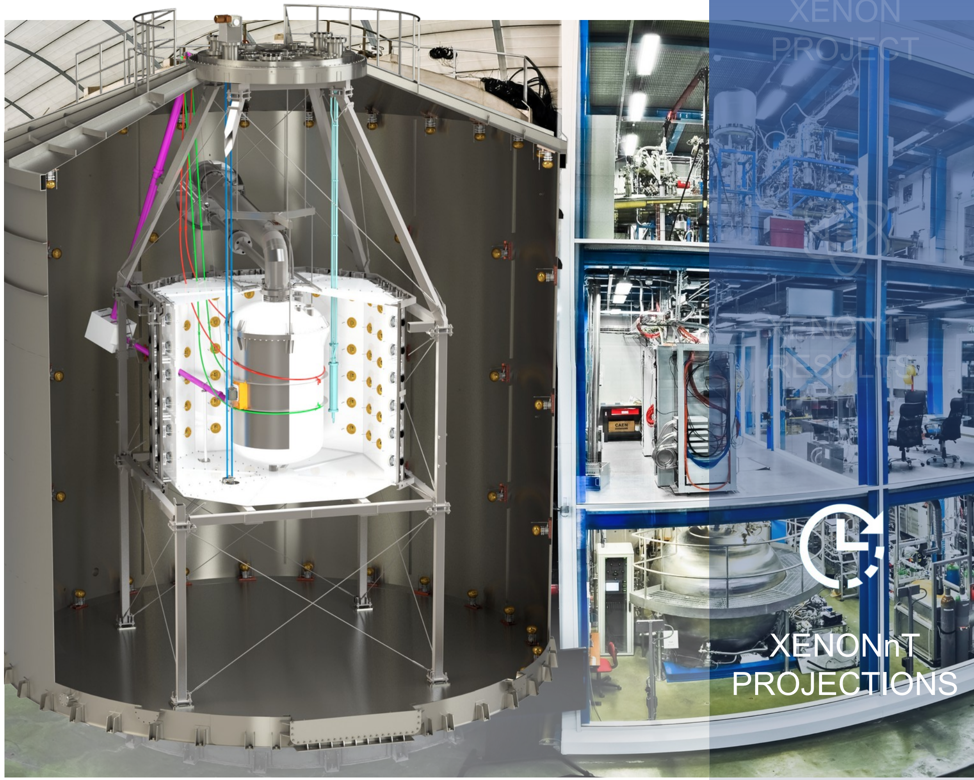
▼ NR bkg

NEW NEUTRON VETO DETECTOR

Neutron background suppression

- Gd-doped water Cherenkov detector
- 120 PMTs, highly reflective
- 87% neutron tagging efficiency (expected)





XENONnT @ LNGS (Hall B)

▼ NR bkg

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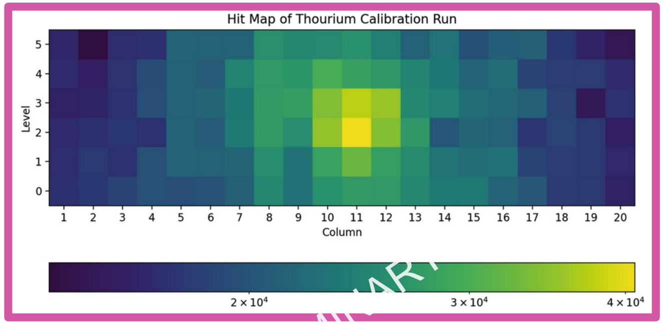
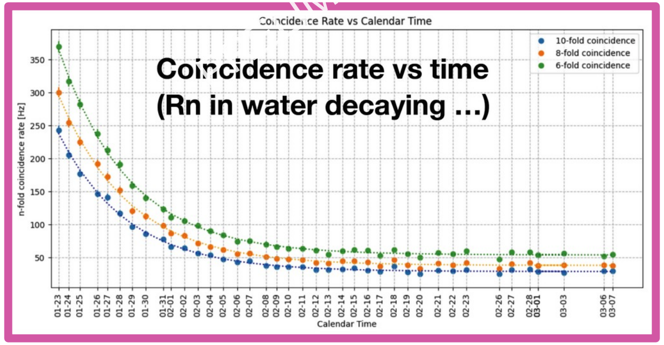
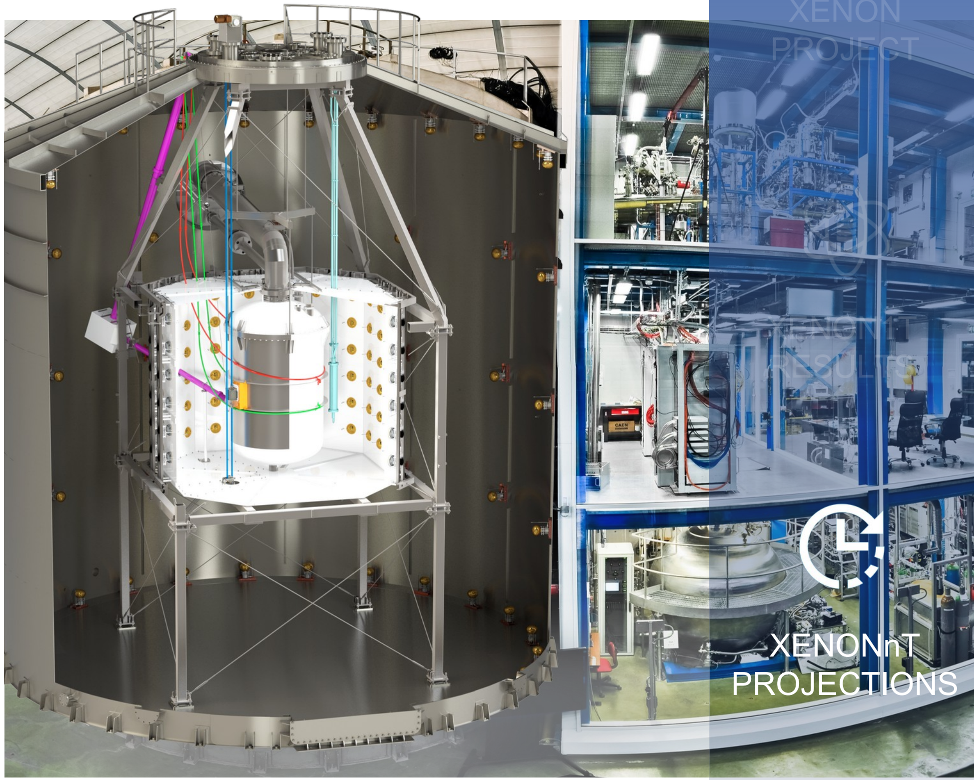






XENONnT @ LNGS (Hall B)

Recontres de Moriond EW | 27 March 2021

▲ Purity

NEW LIQUID Xe PURIFICATION

Improve signal detection and target purity

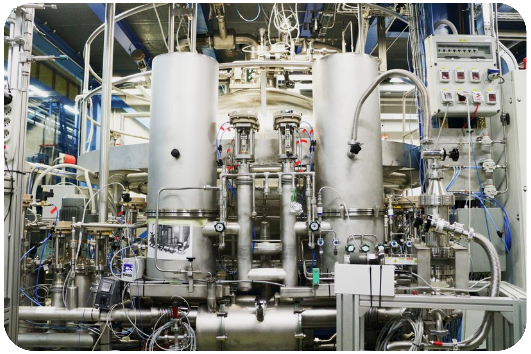
- ~1000 slpm flux purification
- Ultra-low Rn emanation system
- >7 ms electron lifetime (achieved)

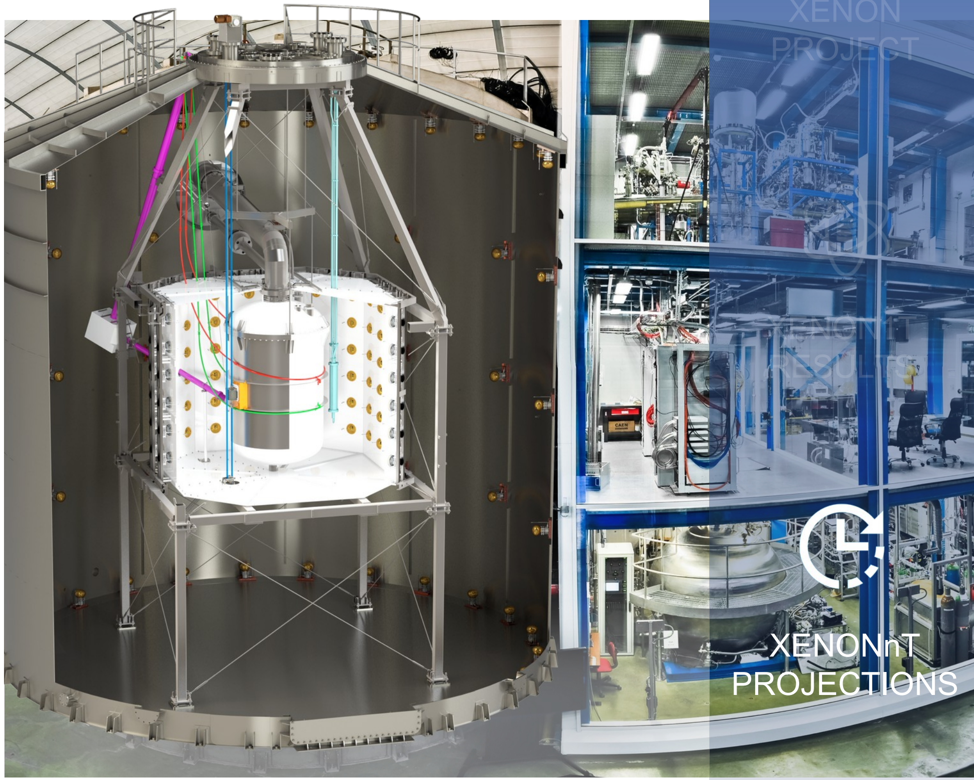
▼ ER bkg

NEW RADON REMOVAL SYSTEM

ER background reduction

- Dedicated Rn cryogenic distillation column
- 1 μBq/kg ^{222}Rn level (goal)
- In XENON1T was 13 μBq/kg (science run)
  4.5 μBq/kg (latest R&D run)





XENONnT @ LNGS (Hall B)

XENON PROJECT

XENONnT RESULTS

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Under commissioning …

▼ ER bkg

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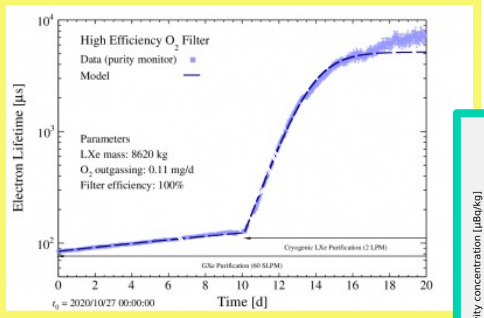
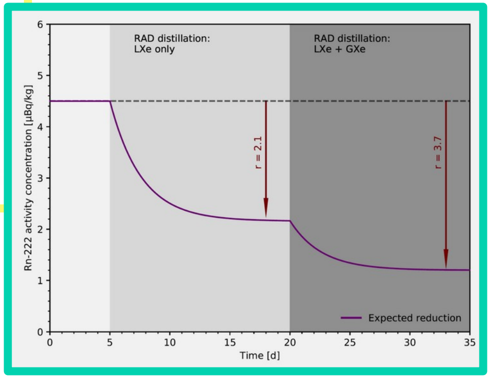
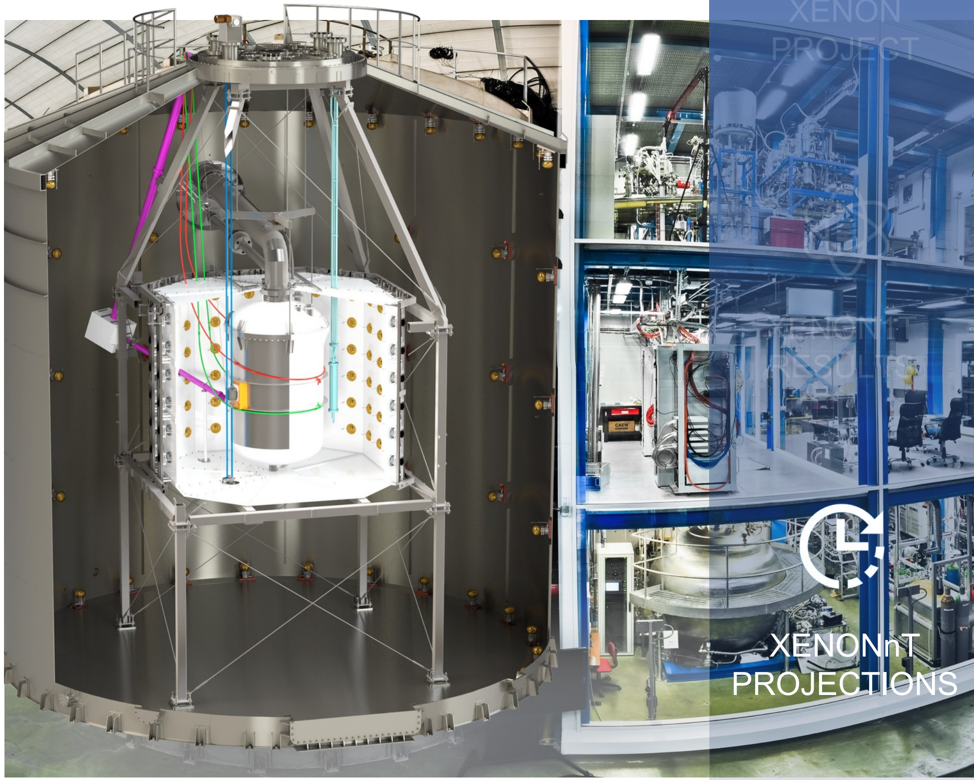
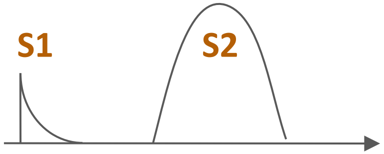






XENONnT @ LNGS (Hall B)

Combined Energy Scale as Analysis Space

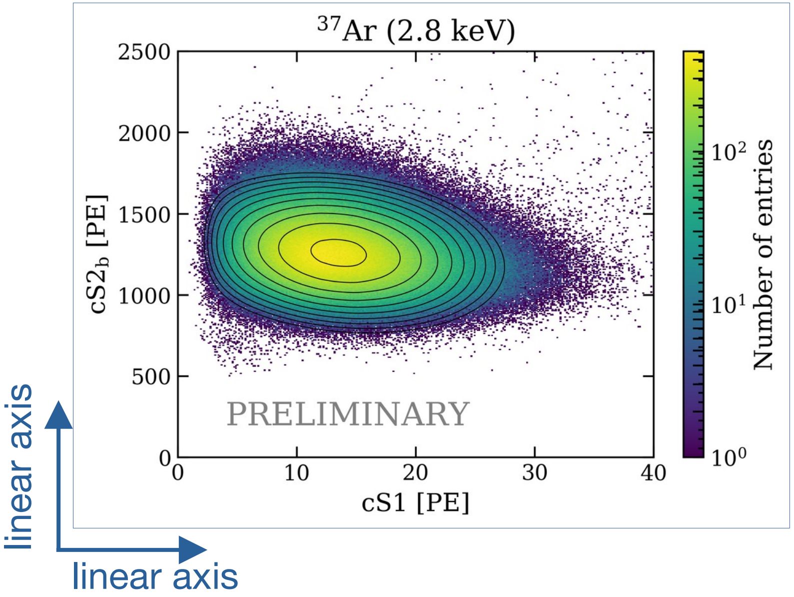


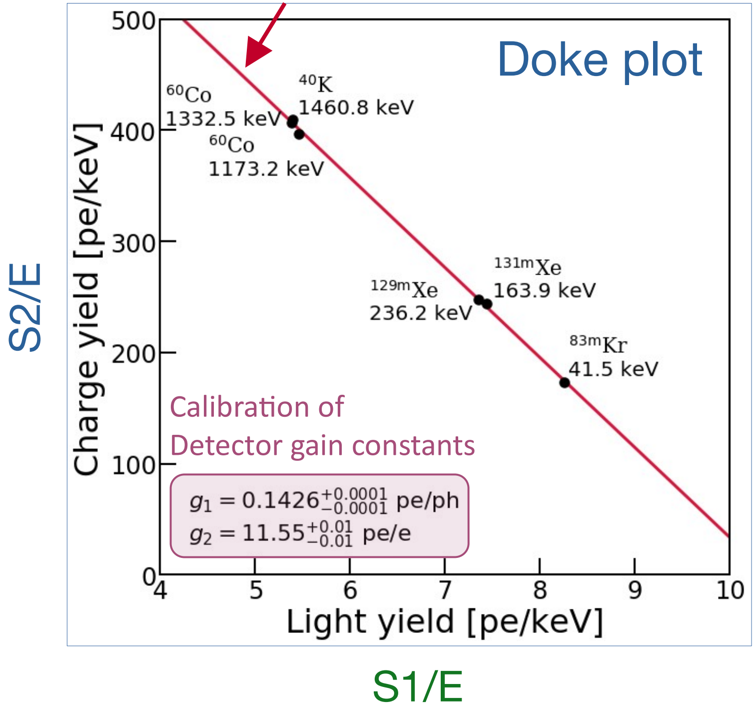
$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

$$W = 13.7\ eV/quanta$$

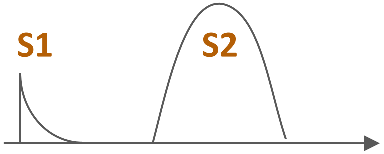
$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$

offset slope





Combined Energy Scale as Analysis Space

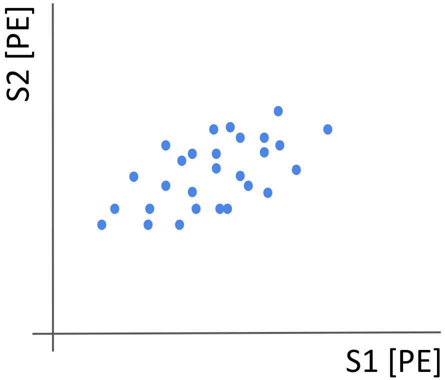


$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

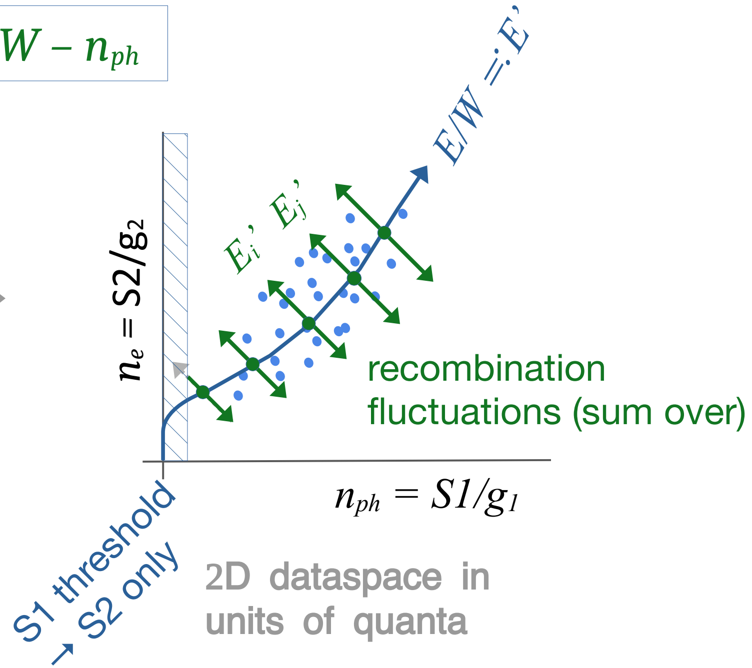
$W = 13.7\ eV/quanta$

$\Leftrightarrow \quad n_e = E/W - n_{ph}$

$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$

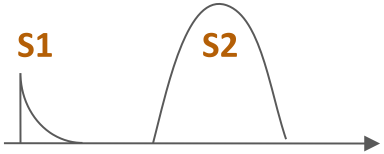


2D analysis



2D dataspace in units of quanta

Bundesministerium für Bildung und Forschung



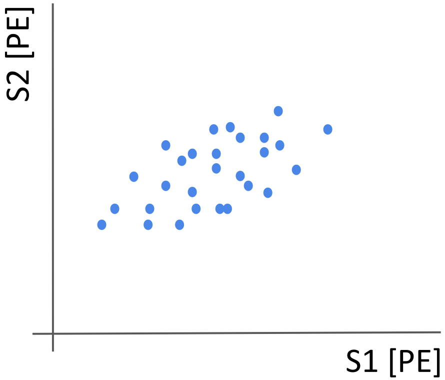
Combined Energy Scale as Analysis Space

$$E = (n_{ph} + n_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

$$W = 13.7\ eV/quanta$$

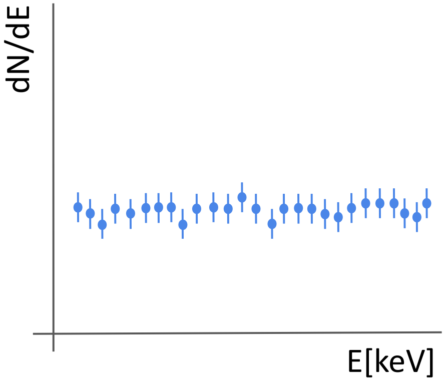
↔

$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$



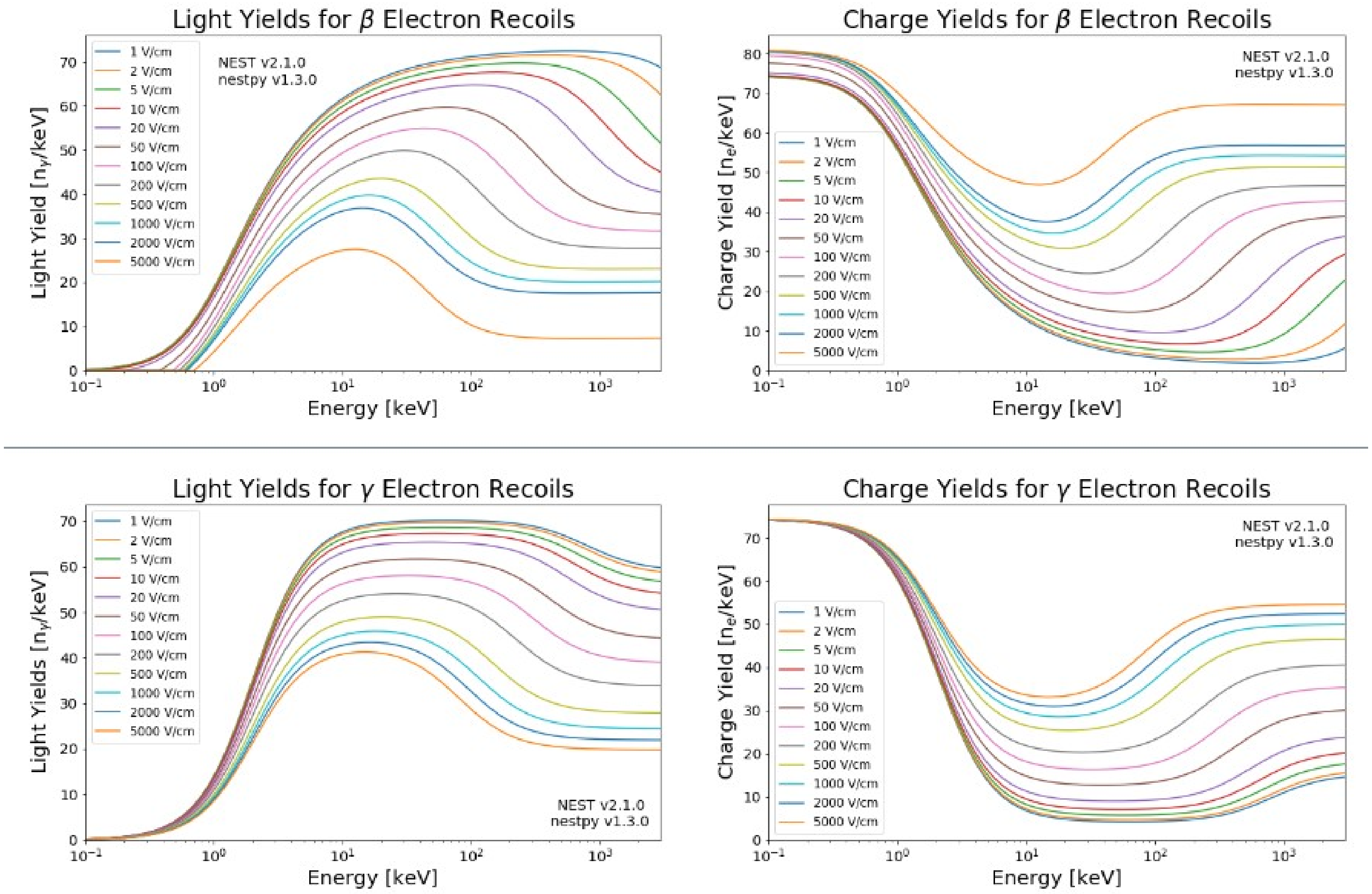
2D analysis

→



1D analysis

Theory / Phenomenology: LXe Charge and Light Yield - ER

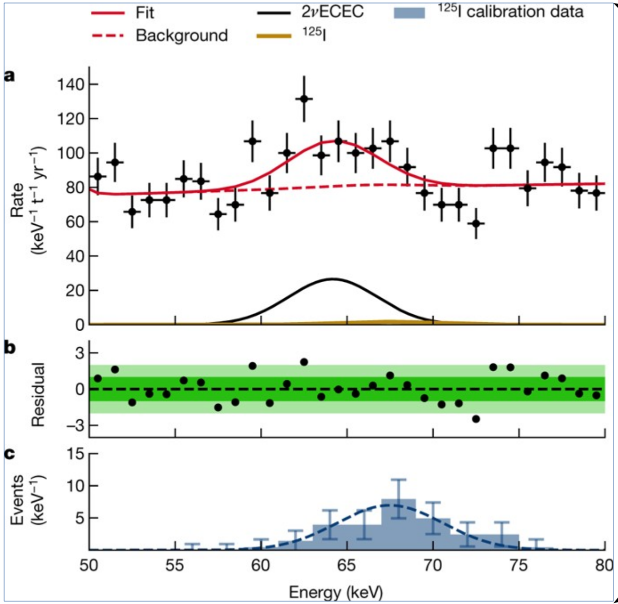


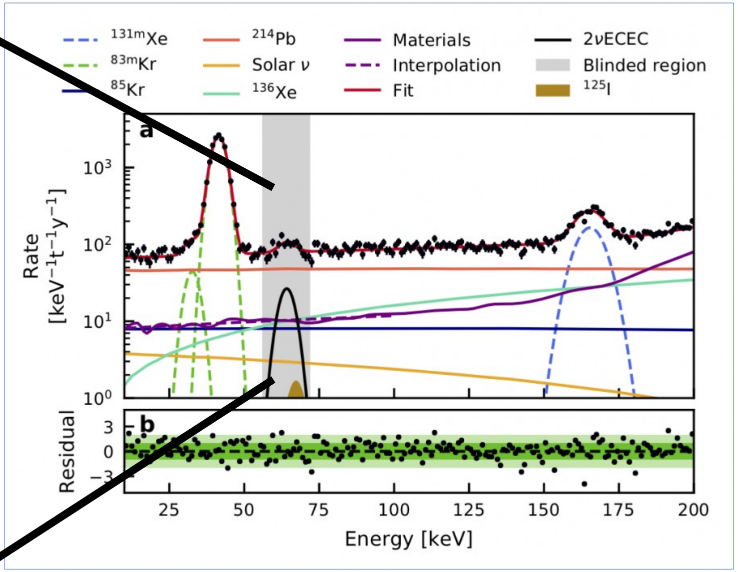
NEST

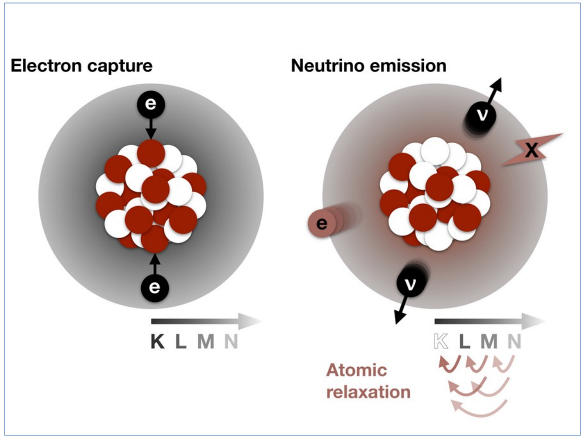
http://nest.physics.ucdavis.edu/benchmark-plots

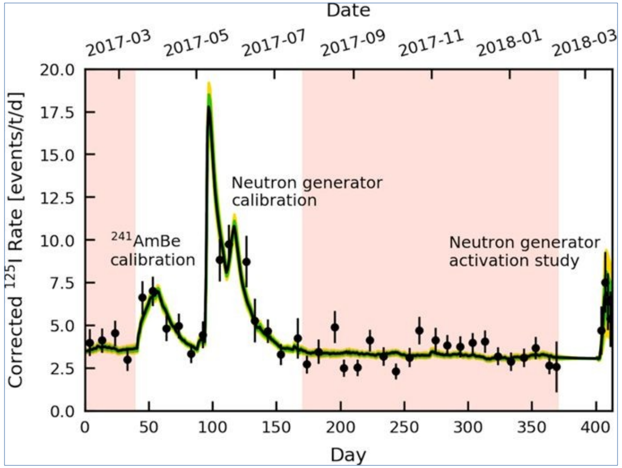
Double Electron Capture in ^{124}Xe

Nature 568, 532–535 (2019)









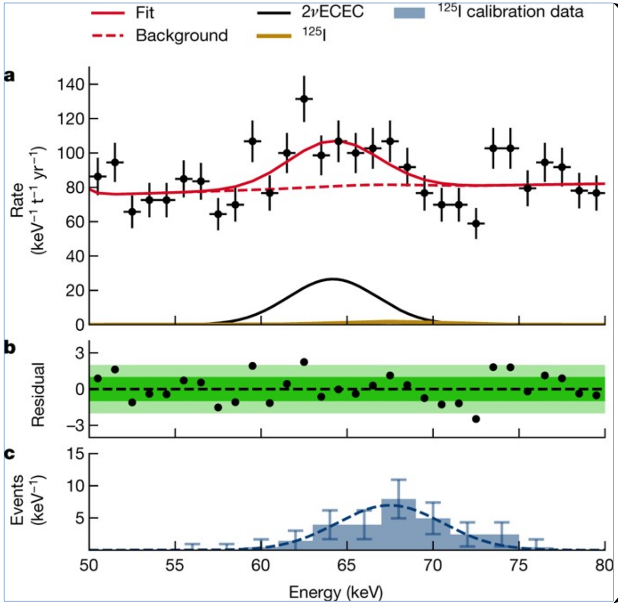
Half-life of (1.8 ± 0.6) x 10^{22} years,

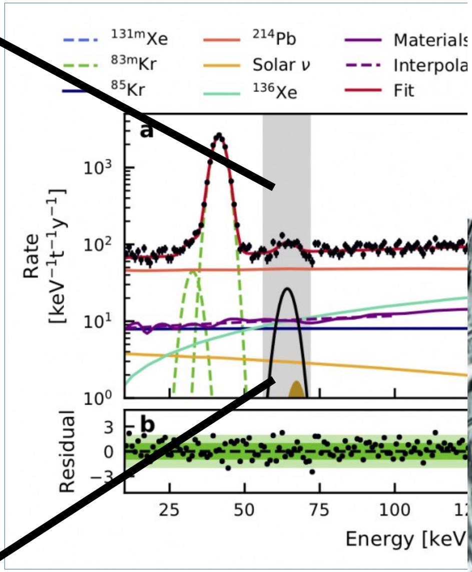
→ **longest directly measured half-life to date**

Modeled nearby background ^{125}I from activation during neutron calibration

Double Electron Capture in ^{124}Xe

Nature 568, 532–535 (2019)



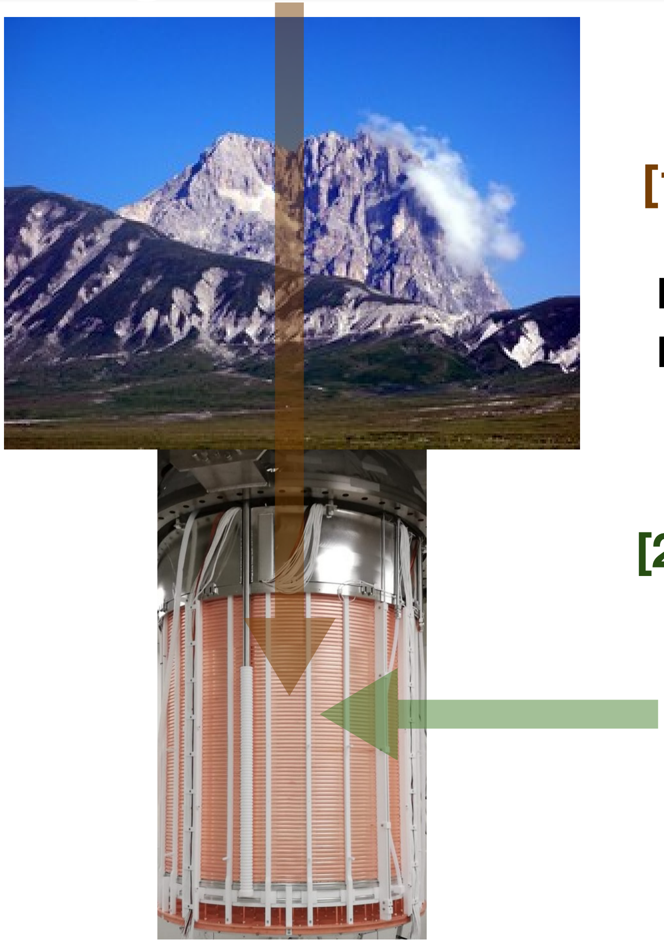


Half-life of (1.8 ± 0.6) x 10^{22} years,

→ **longest directly measured half-life to date**

Modeled nearby background ^{125}I from activation during neu

Potential background events in XENON1T



[1] Go through > km of rock

Muons: too high energy

Neutrinos, dark particles

[2] Go through many cm of metal and xenon

Neutrons: different S1/S2

β, γ: Energy and spectrum incompatible

[3] Infiltrate the LXe

$^{222}Rn \rightarrow {}^{214}Pb$,

^{85}Kr, ^{136}Xe, ^{133}Xe, ^{124}Xe (!)

- Accounted for, different energies

^{127}Xe, ^{37}Ar

- $t_{1/2}$ ~ month, too short
- Requisite air leak ruled out by Kr measurements.

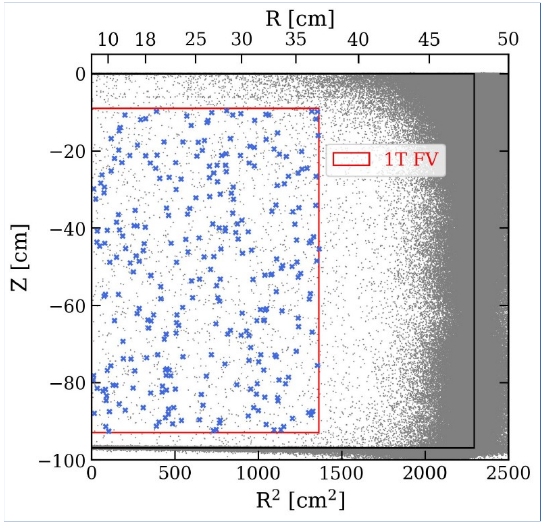
Tritium

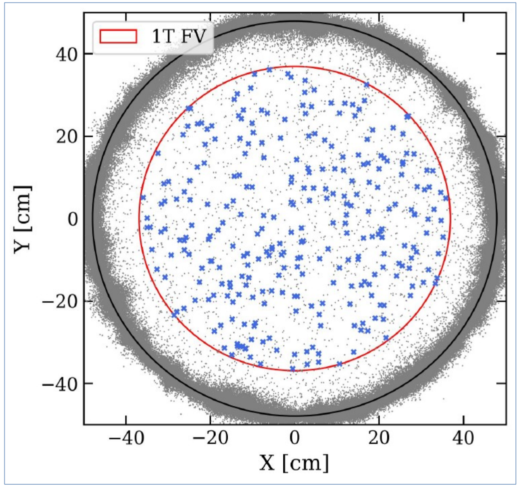
...

Time or space dependence?

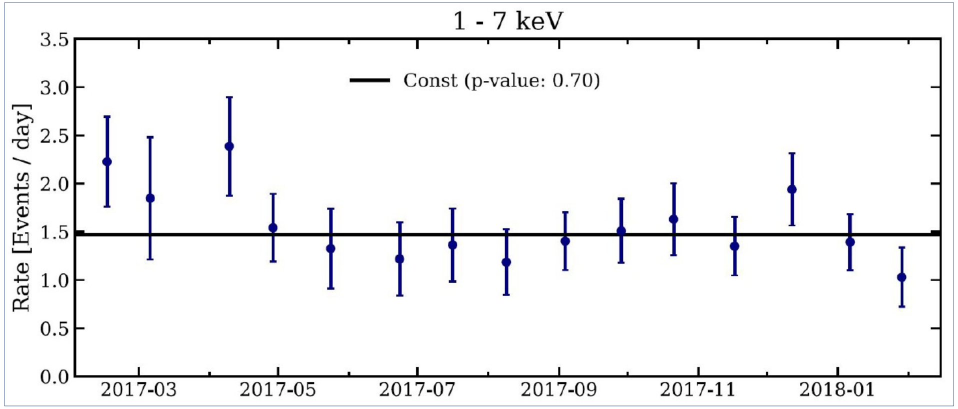
Spatial distribution

[1, 210 keV] [1, 7] keV





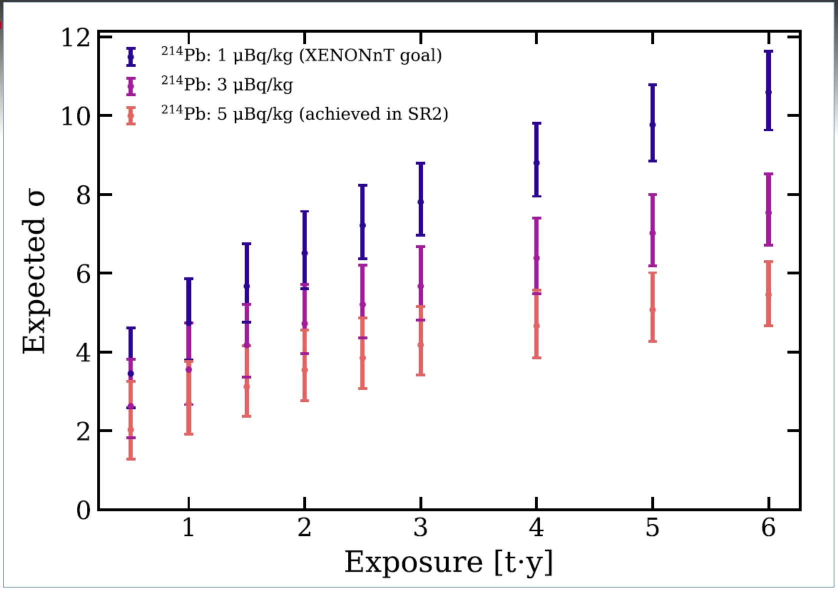
Temporal evolution



- Events are seemingly **uniformly distributed** in the fiducial volume
- Rate rather **constant in time** during SR1 (but limited statistics)

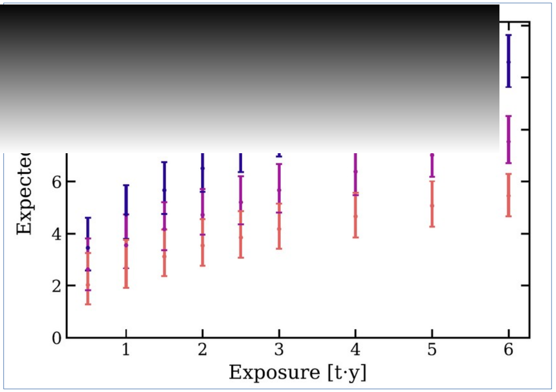
Upgrading: XENONnT

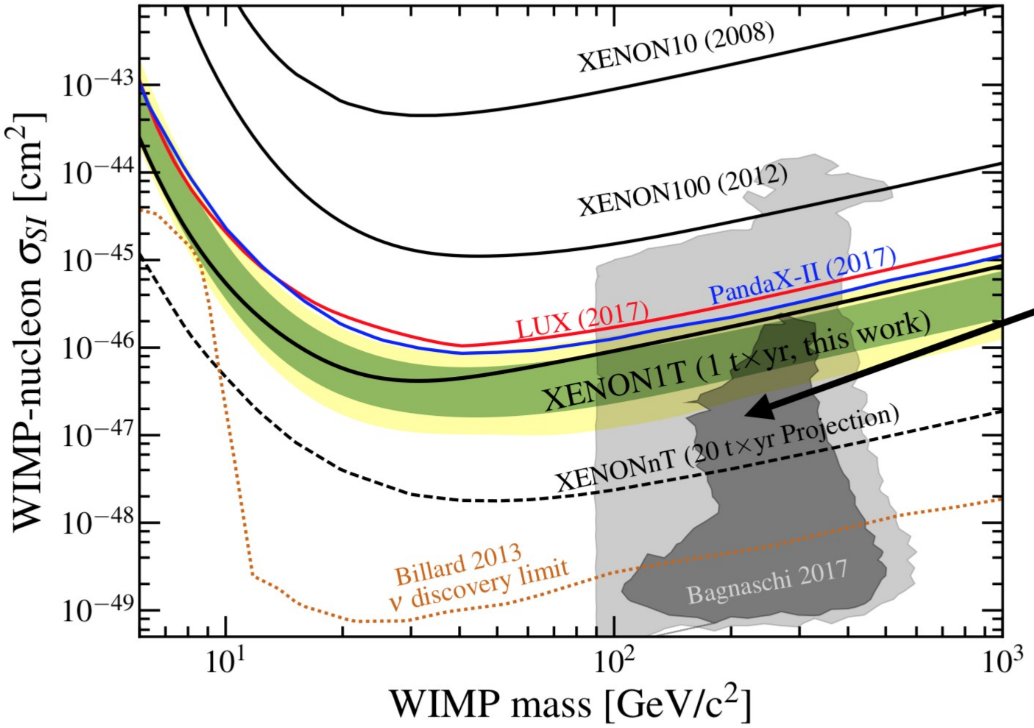
- Right now being commissioned at LNGS
- Factor 5-10 lower background
- Factor ~4 larger fiducial mass
  - ▻ Good chances to distinguish T from “shaped signal”



Upgrading: XENONnT

- Right now being commissioned at LNGS
- Factor 5-10 lower background
- Factor ~4 larger fiducial mass
  - Good chances to distinguish T from “shaped signal”
  - And, of course, most sensitive WIMP searches ever!





Summary

- A low-energy ER analysis of XENON1T full exposure found an excess in the 1-7 keV range.
- A number of signal models are significant at >3σ (global).
- Tritium, left unconstrained, lowers the significance to 2.x σ at most.
  - We do not have a separate way to estimate the T content.
  - It remains a possibility.
- The excess is robust to most assumptions, including threshold, energy reconstruction, microphysics. We continue to study new suggestions.
- We are continuing our studies for improved low-energy response modeling using a ^{37}Ar source developed at Mainz. Yet, the energy scale looks robust.
- Higher exposure with lower background would allow XENONnT to distinguish between T and several signal models.

Thanks to …

- the XENON low-E ER team for a great job on analysis
- everyone on XENON for putting together and operating a fantastic detector and for working hard on the XENONnT upgrade
- Ranny Budnik, Matteo Alfonsi, Evan Shockley, Jelle Aalbers for reuse of slides & plots

The Low-Energy Electronic-Recoil Excess observed by XENON1T

Uwe Oberlack

Institute of Physics and
PRISMA⁺ Excellence Cluster
Johannes Gutenberg Univer...
Mainz

Mainz P...
Retr...

NEUE PHYSIK IN SICHT?

Mysteriöses Signal im Dunkle-Materie-Detektor

VON MANFRED LINDINGER - AKTUALISIERT

Frankfurter Allgemeine ZEITUNG • FAZ.NET

CORRIERE DELLA SERA / SCIENZE

GLI ESPERIMENTI SOTTO IL GRAN SASSO

Laboratorio del Gran Sasso, registrati segnali anomali nella caccia alla materia oscura: so... gli assioni?

Cauti gli scienziati, che tra le spieg... dati e impurità nei materiali del... neutrini e particelle mai risco... ...a fluttuazione statistica dei ...nuove proprietà dei ...odello della fisica

di Paolo Virtuani

OUT THERE

The New York Times

Seeking Dark Matter, They Detected Another Mystery

Do signals from beneath an Italian mountain herald a revolution in physics?

By Dennis Overbye

June 17, 2020

arxiv:2006.09721