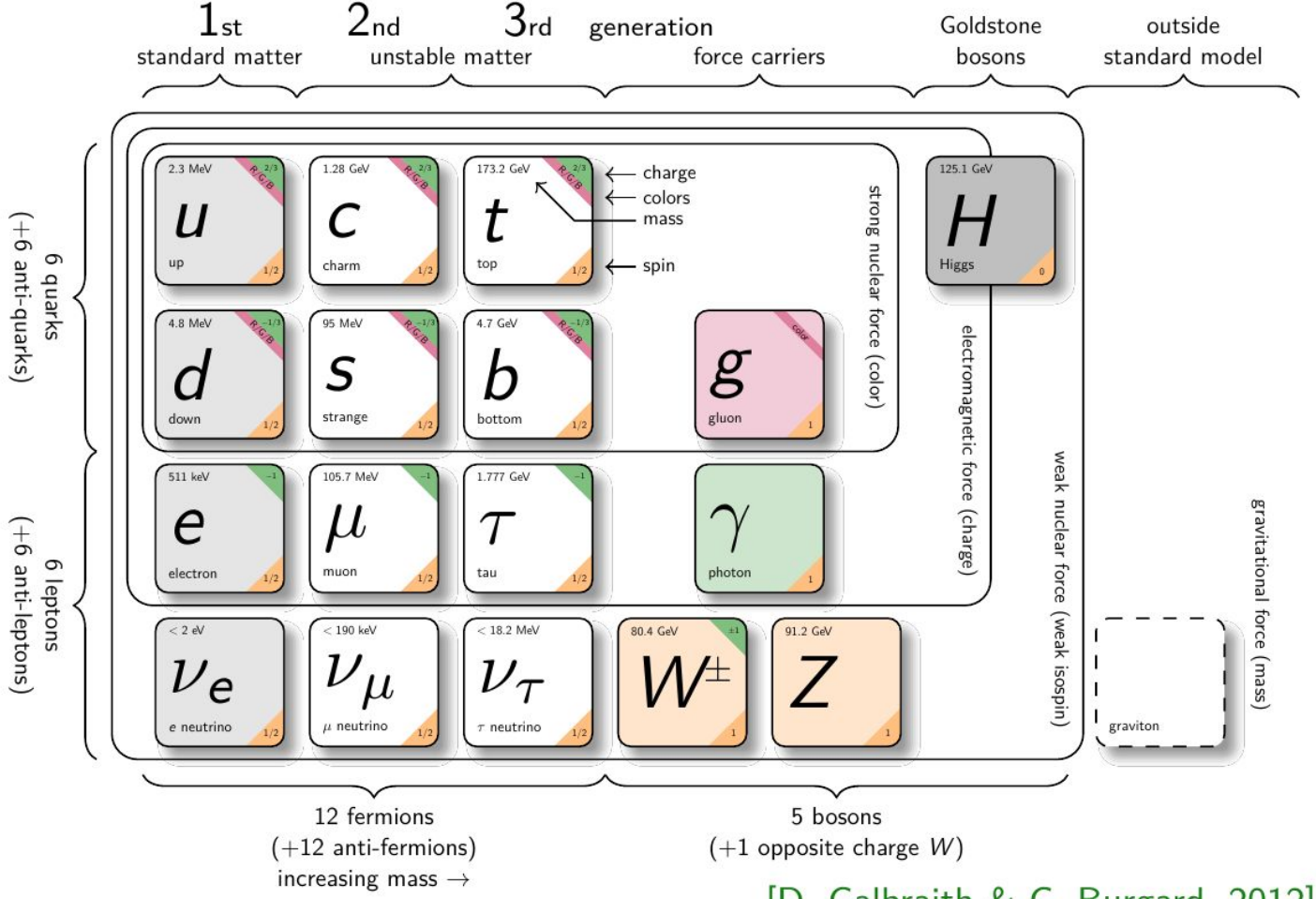
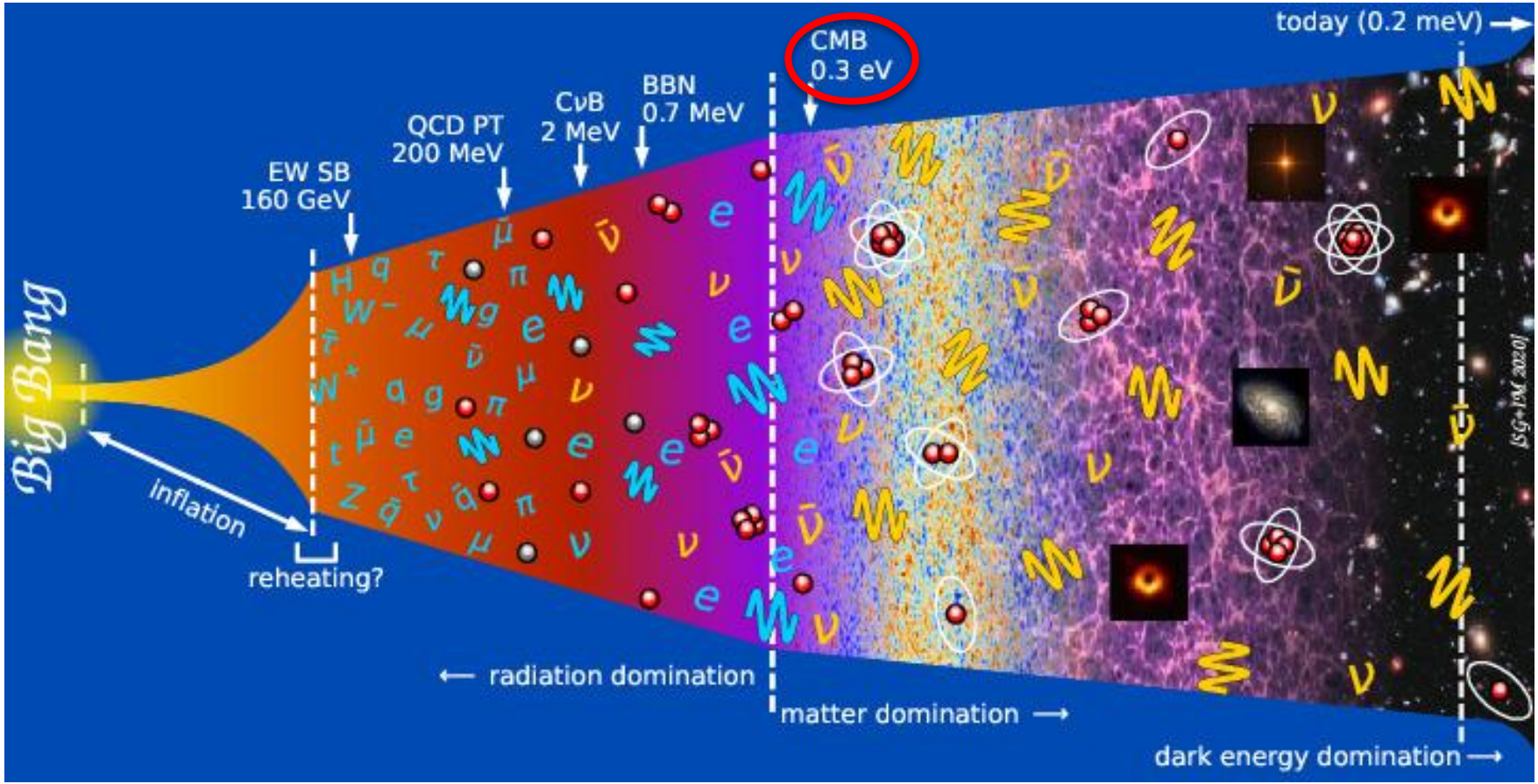
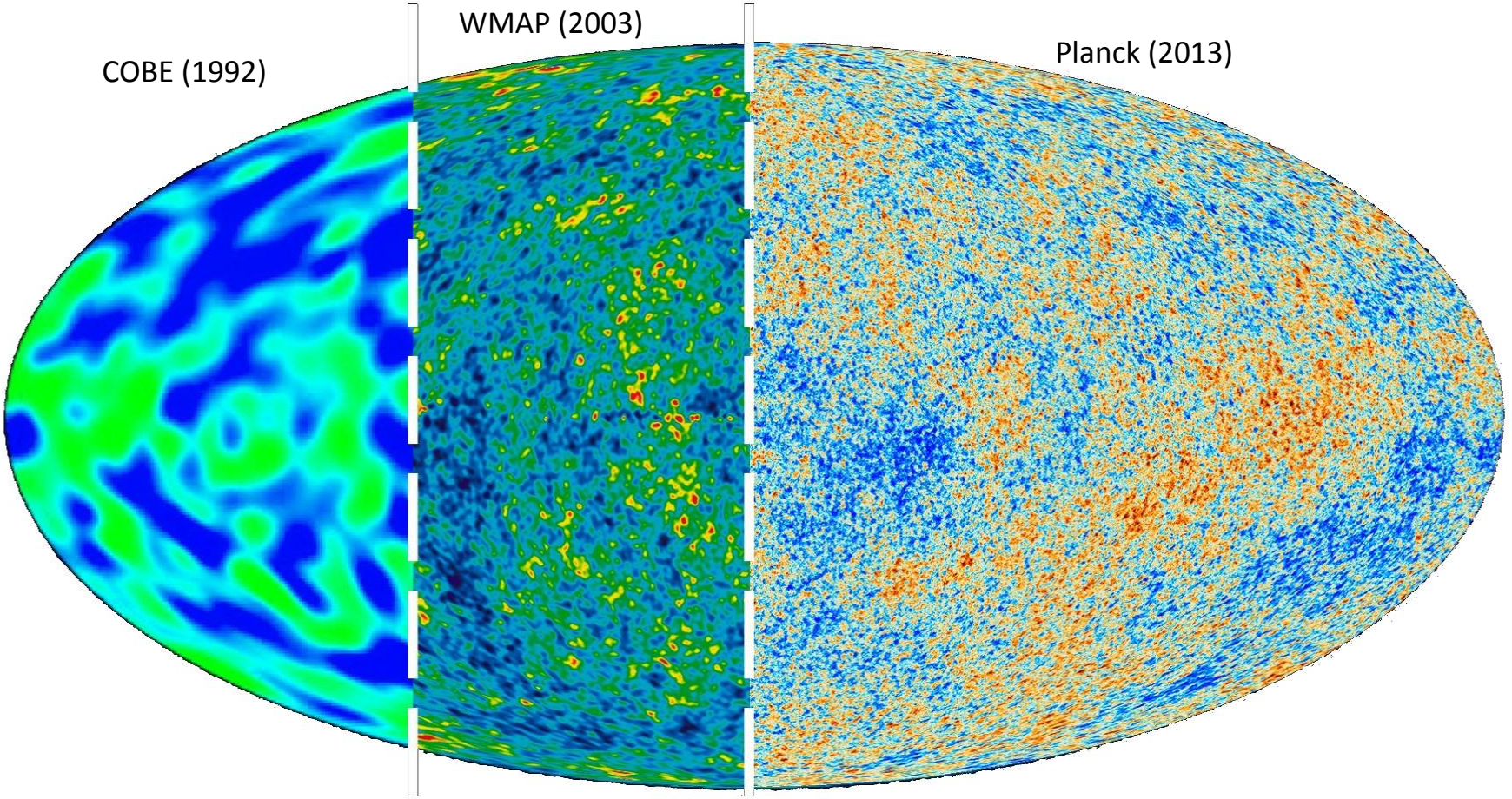
Neutrino Physics and Cryogenic Techniques

Introduction



[D. Galbraith & C. Burgard, 2012]

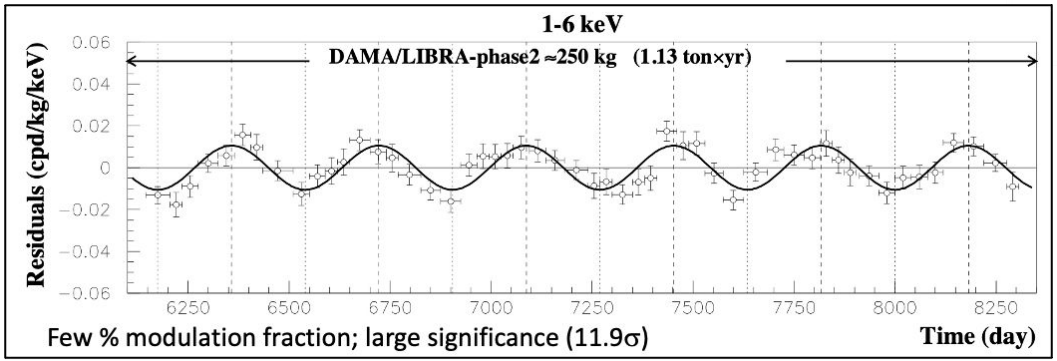

today (0.2 meV)
CMB
0.3 eV
BBN
0.7 MeV
CνB
2 MeV
QCD PT
200 MeV
EW SB
160 GeV
Big Bang
inflation
reheating?
← radiation domination
matter domination →
dark energy domination →

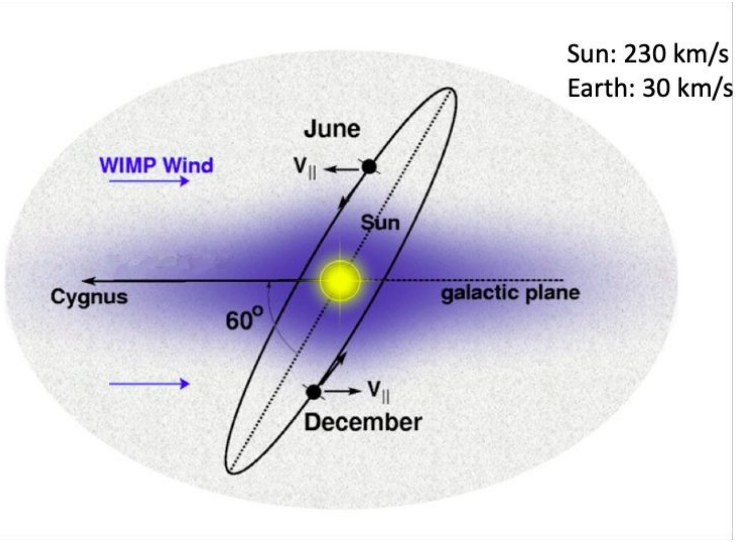

COBE (1992)
WMAP (2003)
Planck (2013)


68.9% DE
4.9% baryons
26.2% DM

DM interaction rate modulation

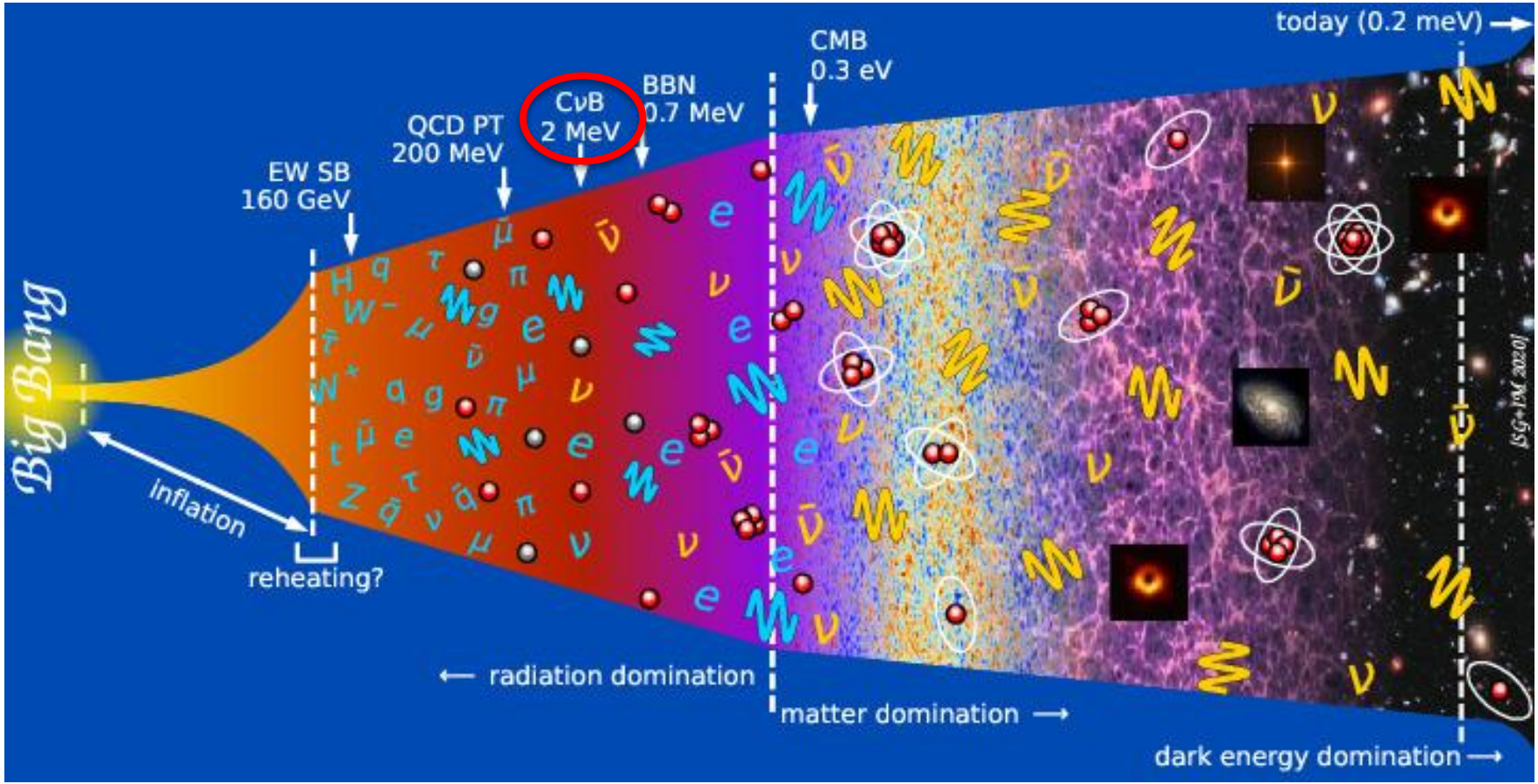
- Combined motion of Earth and Sun around galactic centre through galactic DM Halo
- Expected modulation in interaction rate
- Only DAMA reported positive signal (1-6 keV recoil energy)
- Distinct modulation models could be disentangled below 1 keV





Assumptions: WIMPs, Standard Halo Model

- 1-y period, peak @ June 2nd
- Recoil energy < 50 keV, for DM mass ~ [few GeV - few TeV]
- Interaction rates: 10^{-1} to 10^{-6} events/day/kg.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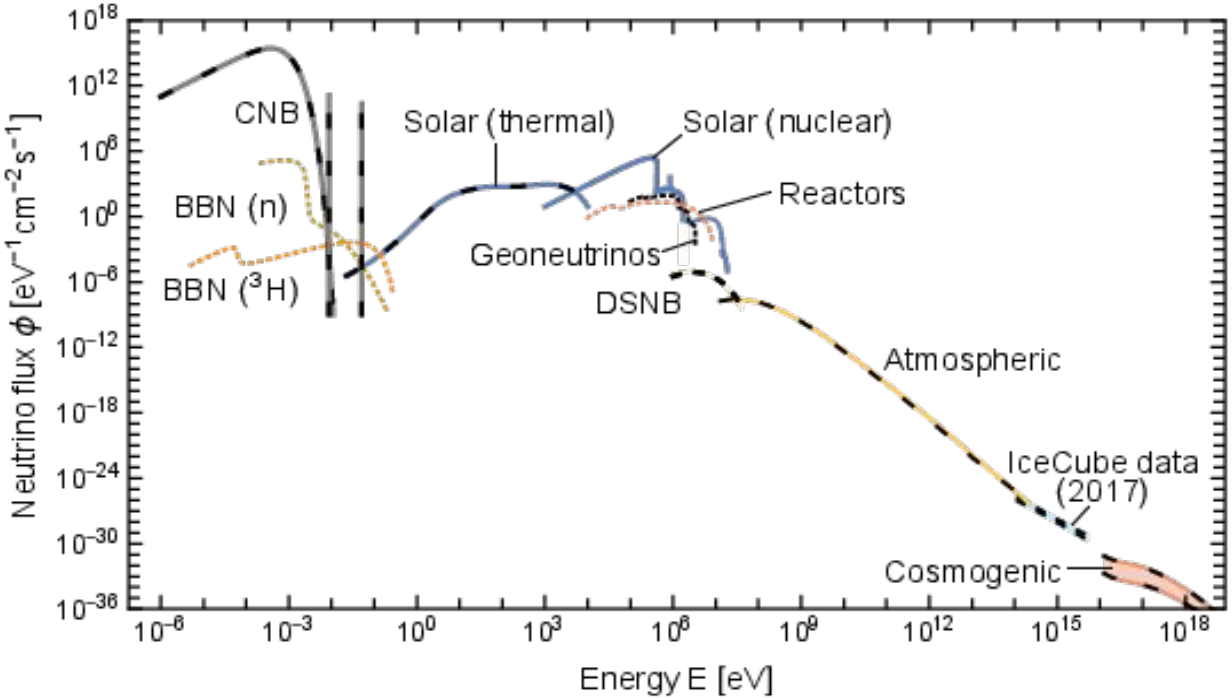
[Vitagliano+, RMP 92 (2020)]



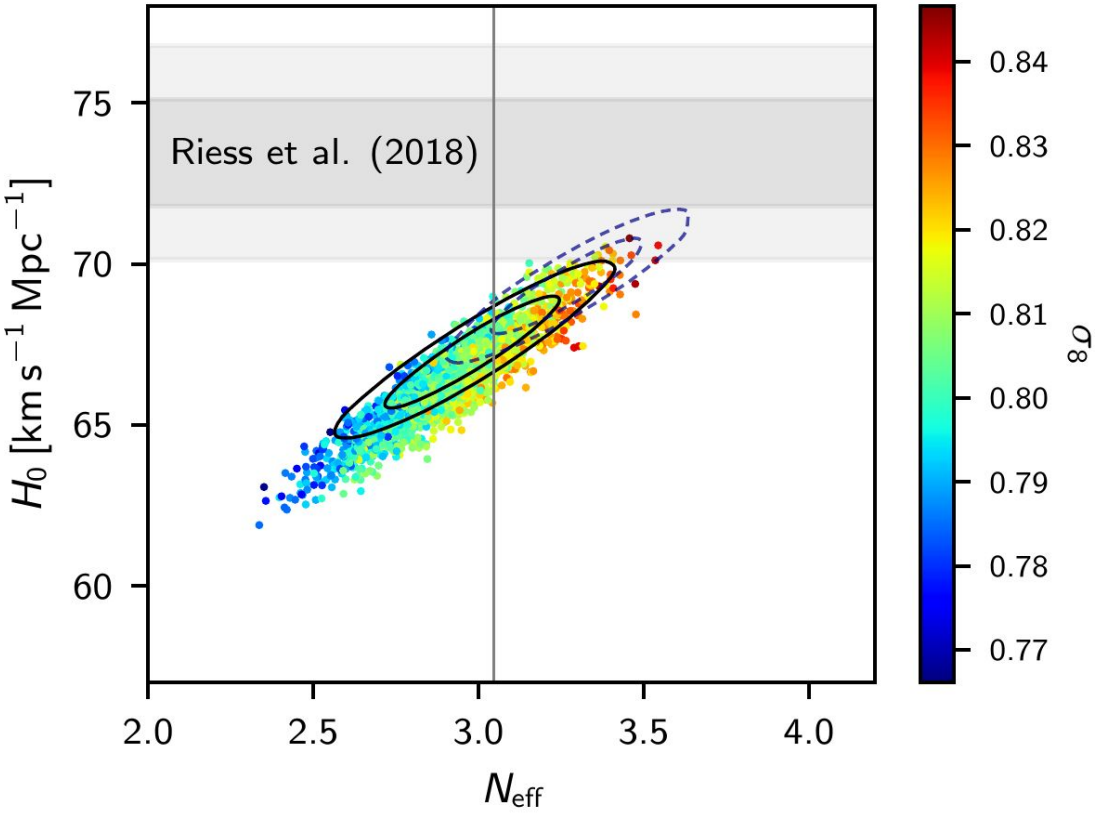
Effective number of neutrinos

Prediction:

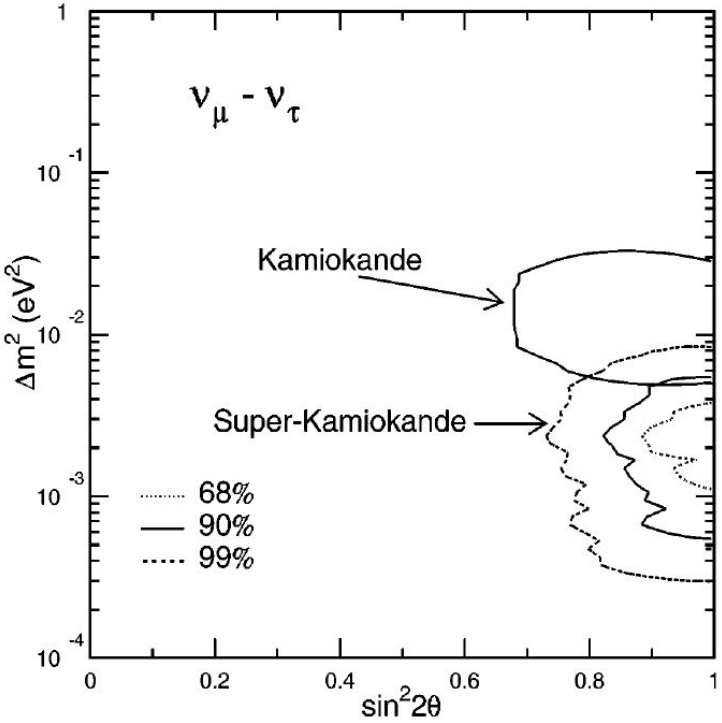
Neff=3.0440
[Bennet, SG+ 2021]
[Froustey+, 2020]

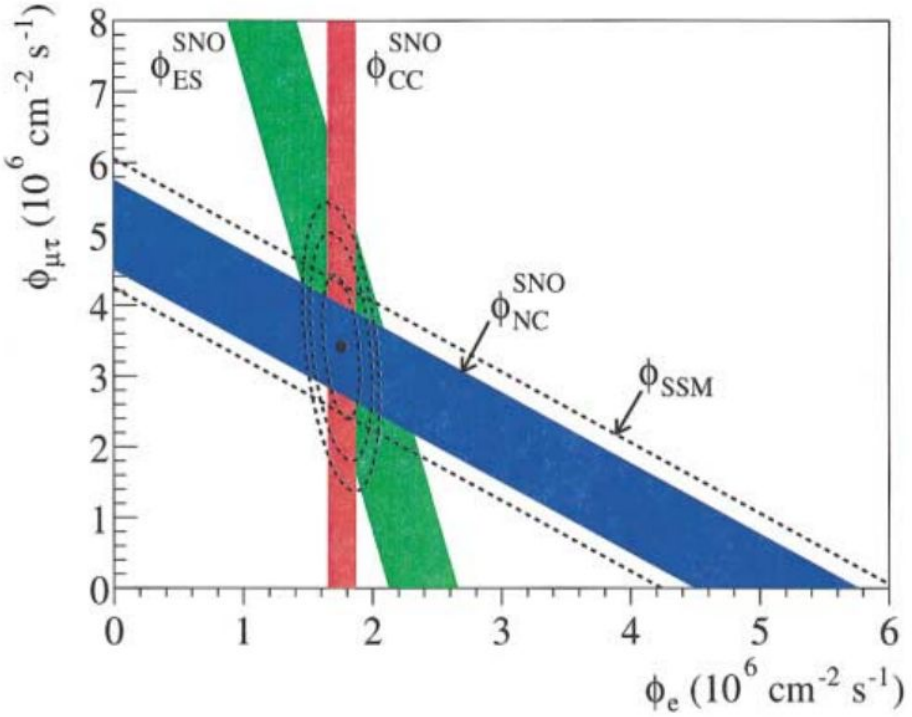
Measurement:

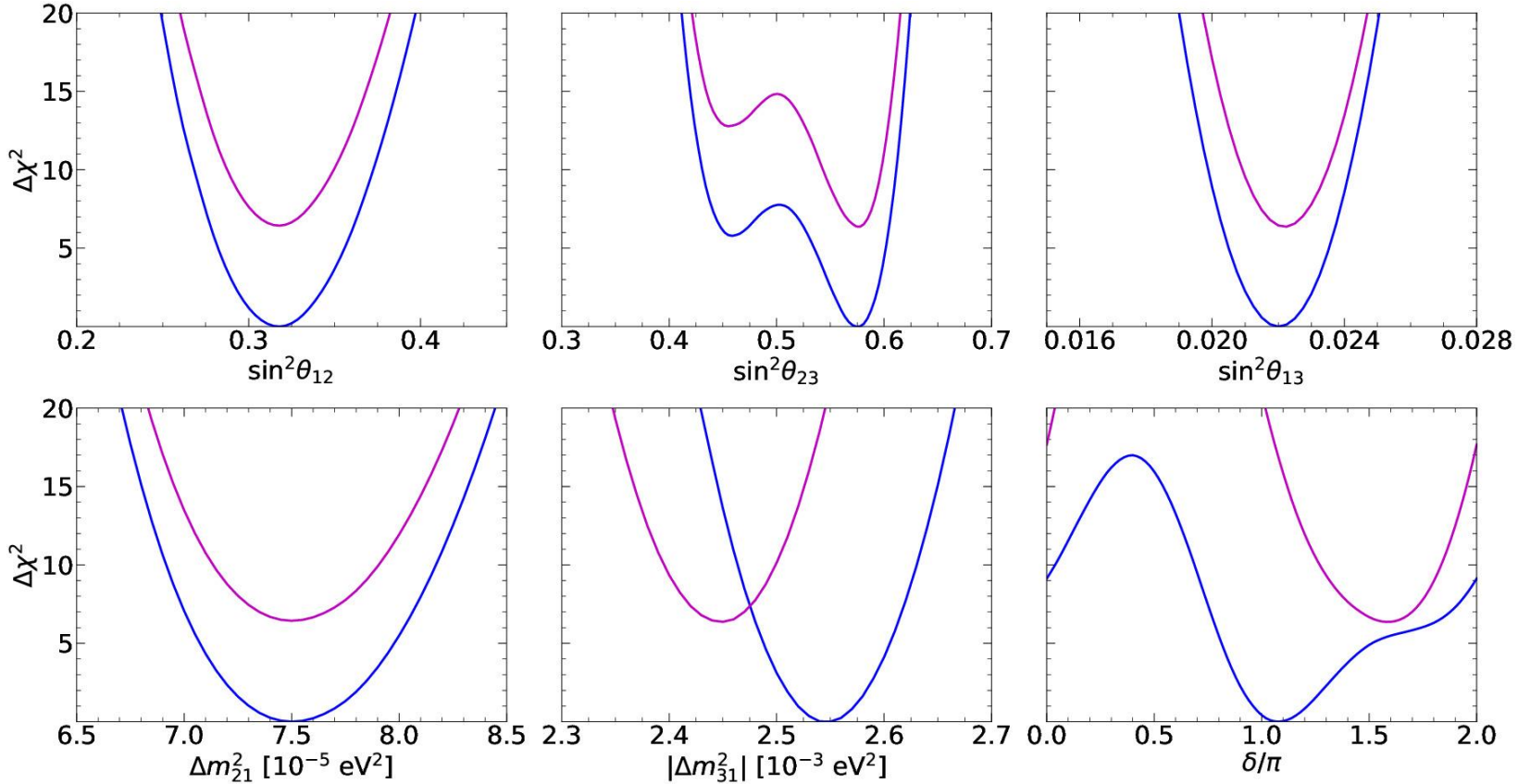
Neff=2.99±0.17
[Planck 2018]

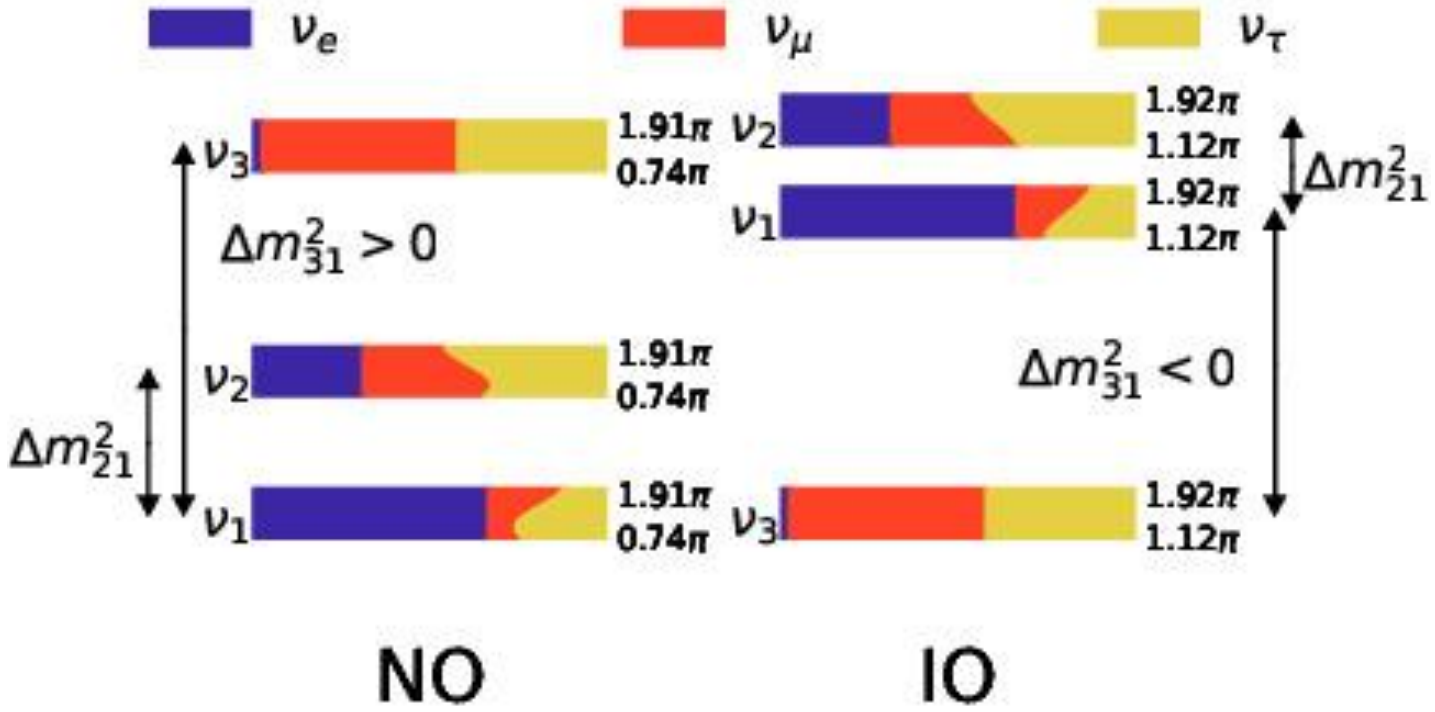


Neutrino oscillations - 2015 Nobel Prize

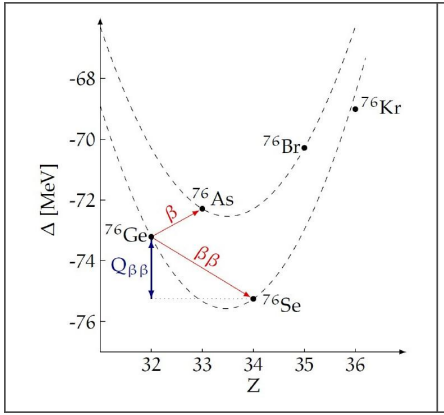


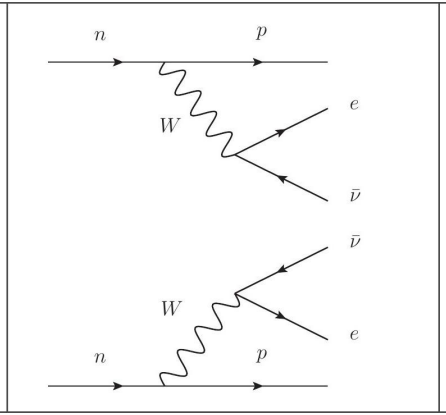


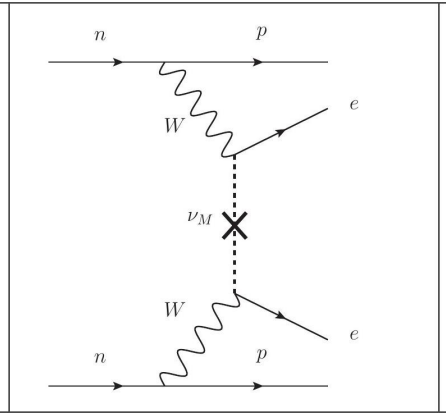

20
15
10
5
$\Delta\chi^2$
0.2
0.3
0.4
$\sin^2\theta_{12}$
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
0.016
0.020
0.024
0.028
$\sin^2\theta_{13}$
20
15
10
5
$\Delta\chi^2$
6.5
7.0
7.5
8.0
8.5
Δm^2_{21} [10^{-5} eV^2]
2.3
2.4
2.5
2.6
2.7
$|\Delta m^2_{31}|$ [10^{-3} eV^2]
0.0
0.5
1.0
1.5
2.0
δ/π

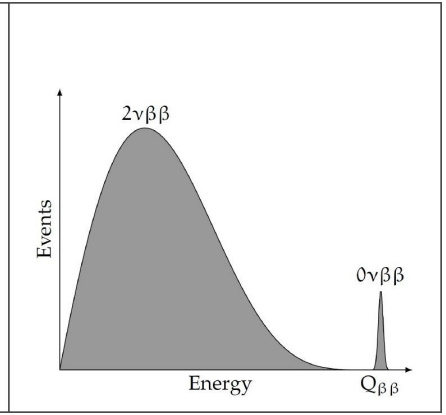

ν_e
ν_μ
ν_τ
ν_3
1.91π
0.74π
$\Delta m^2_{31} > 0$
ν_2
1.91π
0.74π
Δm^2_{21}
ν_1
1.91π
0.74π
NO
ν_2
1.92π
1.12π
ν_1
1.92π
1.12π
Δm^2_{21}
$\Delta m^2_{31} < 0$
ν_3
1.92π
1.12π
IO

Neutrino masses: Dirac or Majorana? 0νββ decay









ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ decay
  ⟹ Energy peak is the only necessary and sufficient signature to claim a discovery
- Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, daughter tagging, …

0νββ decay rate

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2$$

- $T_{1/2}^{0\nu}$ = 0νββ decay halflife
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- f = new physics term

Summary: some big open questions in physics

Neutrino physics

- Neutrinos: are they **Dirac or Majorana** particles?
- What is the absolute neutrino mass scale?
- Is there CP violation in neutrino sector?
- What is the neutrino mass ordering?
- Are there sterile neutrinos? At which mass scale?

Neutrinos in astrophysics and cosmology

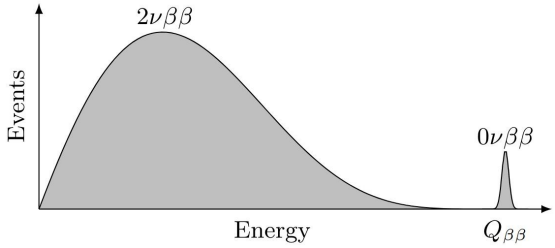
- Is there a **cosmic neutrino background**?
- What are high-energy astrophysical neutrino sources?
- What can we learn from Supernovae neutrinos?

Content of the universe

- What is dark matter?
  - A WIMP?
  - A sterile neutrino?
  - An axion-like particle?
  - Something entirely different?
  - Primordial Black Holes?
- How is Dark Matter distributed in our galaxy?
- How does dark matter interact? **Can we detect it**?
- What is dark energy?

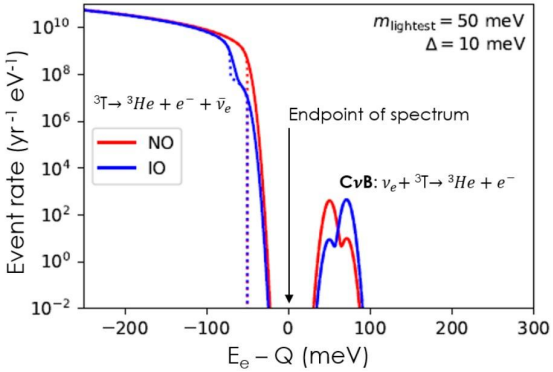
And many more…

How do we answer these open questions?



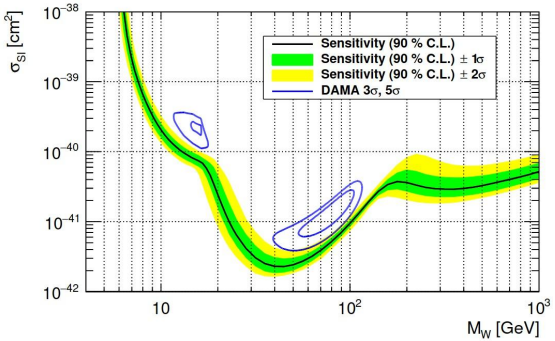
0νββ decay

1. Take a lot of isotope that can decay ββ
2. Make a detector that contains the isotope
3. Minimize radioactive contamination
4. Take data for years and search for a peak at $Q_{\beta\beta}$



Cosmic ν background

1. Take ~100 g of ^{3}H
2. Measure energy of emitted electrons as precisely as possible
3. Distinguish neutrino capture events from β decay events



Dark Matter

1. Take a lot of detectors with low energy threshold
2. Go underground
3. Minimize radioactive contamination
4. Measure for years and look for annual modulated excess

Scientific diffusions

Outlook of Fellini outcomes

Conferences and seminars

- G. Benato, talk @TIPP 2021, @P21O BSM-nu, @LRT 2022
- S. Gariazzo, Seminars @ UAI, Chile; @ PUC, Chile; @ MPI Heidelberg
- S. Gariazzo, plenary talk @ TAUP 2021; talks @ INT 21-79W, @ Rencontres de Blois
- S. Gariazzo, lectures @ GGI; @ EuCAPT Prague
- A. Zani, parallel talk @ TAUP 2021 (before start of FELLINI)

Other scientific outcomes

- S. Gariazzo: FortEPiaNO (code for neutrino oscillations in the early universe, based on DOI:10.1088/1475-7516/2021/04/073 and other papers)
- S. Gariazzo: PArthENoPE 3.0 (code for BBN abundances, DOI:10.1016/j.cpc.2021.108205)

Publications

- G. Benato, Searching for Majorana neutrinos exploiting millikelvin cryogenics with CUORE
- G. Benato, Final result on 0nbb decay half-life of 100Mo from the CUPID-Mo experiment
- G. Benato, Characterization of cubic $Li_2{}^{100}MoO_4$ crystals for the CUPID experiment
- G. Benato, Testing the inverted neutrino mass ordering with neutrinoless double-B decay
- G. Benato, Toward the discovery of matter creation with neutrinoless double beta decay under review at Rev. Mod. Phys.
- S. Gariazzo: Cosmological radiation density with non-standard neutrino-electron interactions
- S. Gariazzo: Most constraining cosmological neutrino mass bounds
- S. Gariazzo: Minimal dark energy: Key to sterile neutrino and Hubble constant tensions?
- S. Gariazzo: Robustness of non-standard cosmologies solving the Hubble constant tension
- S. Gariazzo: Pseudoscalar sterile neutrino self-interactions in light of Planck, SPT and ACT data
- S. Gariazzo: review Two Sides of the Same Coin: Sterile Neutrinos and Dark Radiation, Status and Perspectives
- S. Gariazzo: Neutrino mass and mass ordering: No conclusive evidence for normal ordering
- A. Zani: proceeding @ TAUP2021, The ASTAROTH Project: enhanced low-energy sensitivity to Dark Matter annual modulation
- A. Zani, D. Cortis et al.: engineering paper on test cryogenic chamber in preparation for Adv. Model. and Simul. in Eng. Sci.

Outreach and dissemination activities

Divulgation events

- G. Benato, Sharper 2021 L'Aquila Co-organizzatore dell'astroparticle pavillion
- G. Benato: member of the Asimov Prize scientific commission
- S. Gariazzo - Notte dei Ricercatori 2021

Dissemination activities

- G. Benato, member of the organizing committee of L'Aquila Joint Colloquia
- G. Benato, member of the organizing committee of the Gran Sasso Hands-on Summer School, in program for 2023

Conclusion

Impact and future projects

Secondment plans

- A. Zani @ CERN (dates to be discussed)
- G. Benato @ CEA - Paris (Dec. 2021 - May 2022)
- S. Gariazzo @ Santiago de Chile (12/2021 - 05/2022)

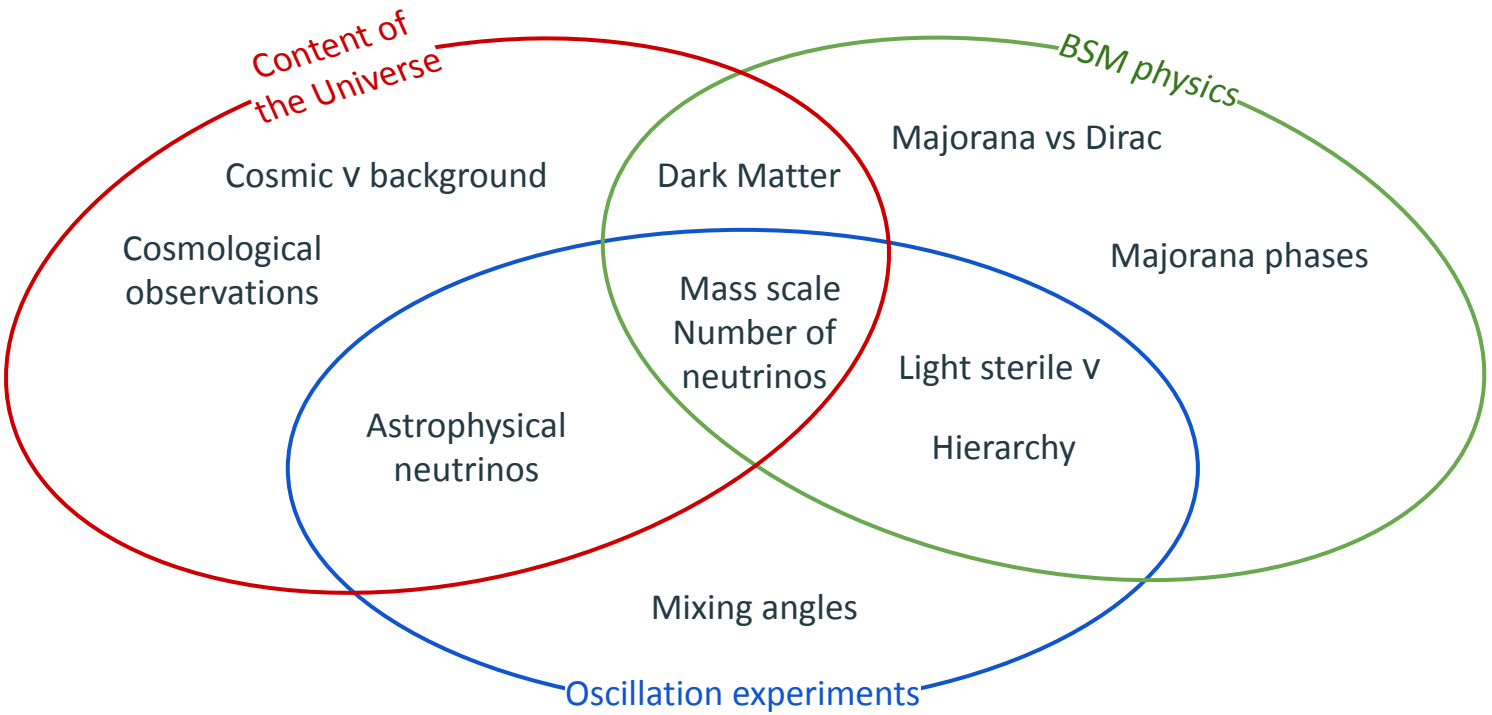
Impact of Fellini projects

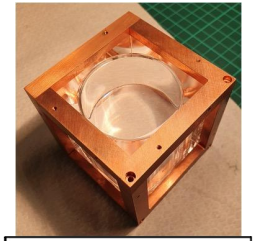
- Success of R&D in LITE-SABRE will lower threshold for DM interaction detection and might change R/O technology
- MC simulation work by G. Benato is fundamental for the design of the CUPID experiment
- PTOLEMY is the only proposed experiment for direct detection of relic neutrinos (S. Gariazzo)

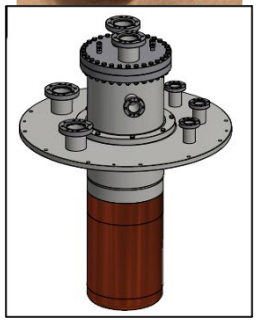
Future projects

- A. Zani: disseminate the use of large SiPM arrays for cryogenic light R/O to other DM/neutrino experiments
- G. Benato: expand the α detector to a screening facility (applied for ERC); develop portable low-background neutron detector (applied for PRIN).
- S. Gariazzo: use machine learning techniques for improving global analyses of neutrino oscillation data

Addressing rare-events questions

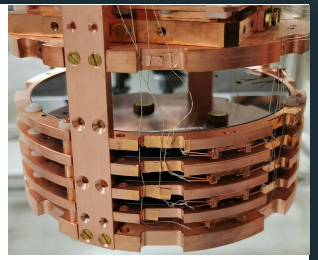






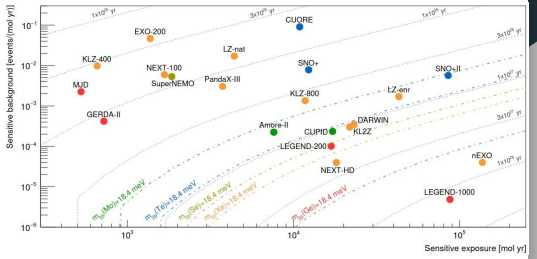
A. Zani

- Development of crystal cooling technology
- Development of cryogenic readout with SiPM arrays
- Commissioning and demonstration



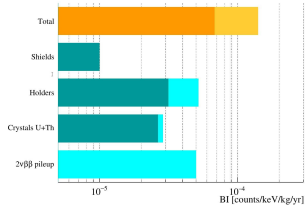
G. Benato

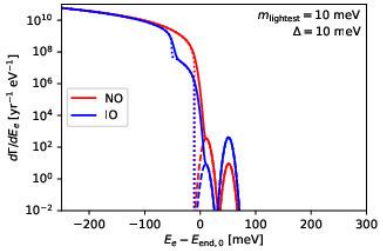
- Optimization of CUPID design
- Screening of α contaminants
- Global 0νββ analyses

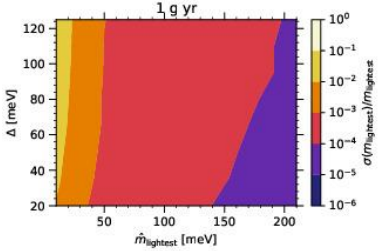


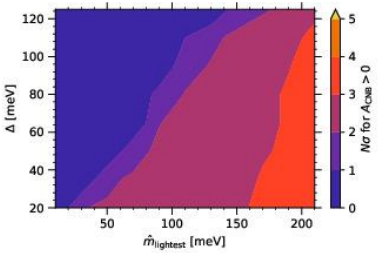
S. Gariazzo

- Cosmic ν background
- PTOLEMY phenomenology









Open questions in astroparticle physics

- What is the nature of neutrino? Dirac or Majorana?
- What is the absolute mass scale? And the mass hierarchy?
- Are there hidden symmetries in their mixings?
- What are their impact in the Early Universe and in cosmology? Baryon asymmetry?
- Does the light sterile neutrino exist? Are there heavy neutrinos?
- What are the astrophysical neutrino sources? How do they participate in SNe explosions?
- Is the cosmic neutrino background out there? Can we detect it?
- What is the nature of Dark Matter?
- How does Dark Matter interact?
- Is the Standard Halo Model reasonably correct?