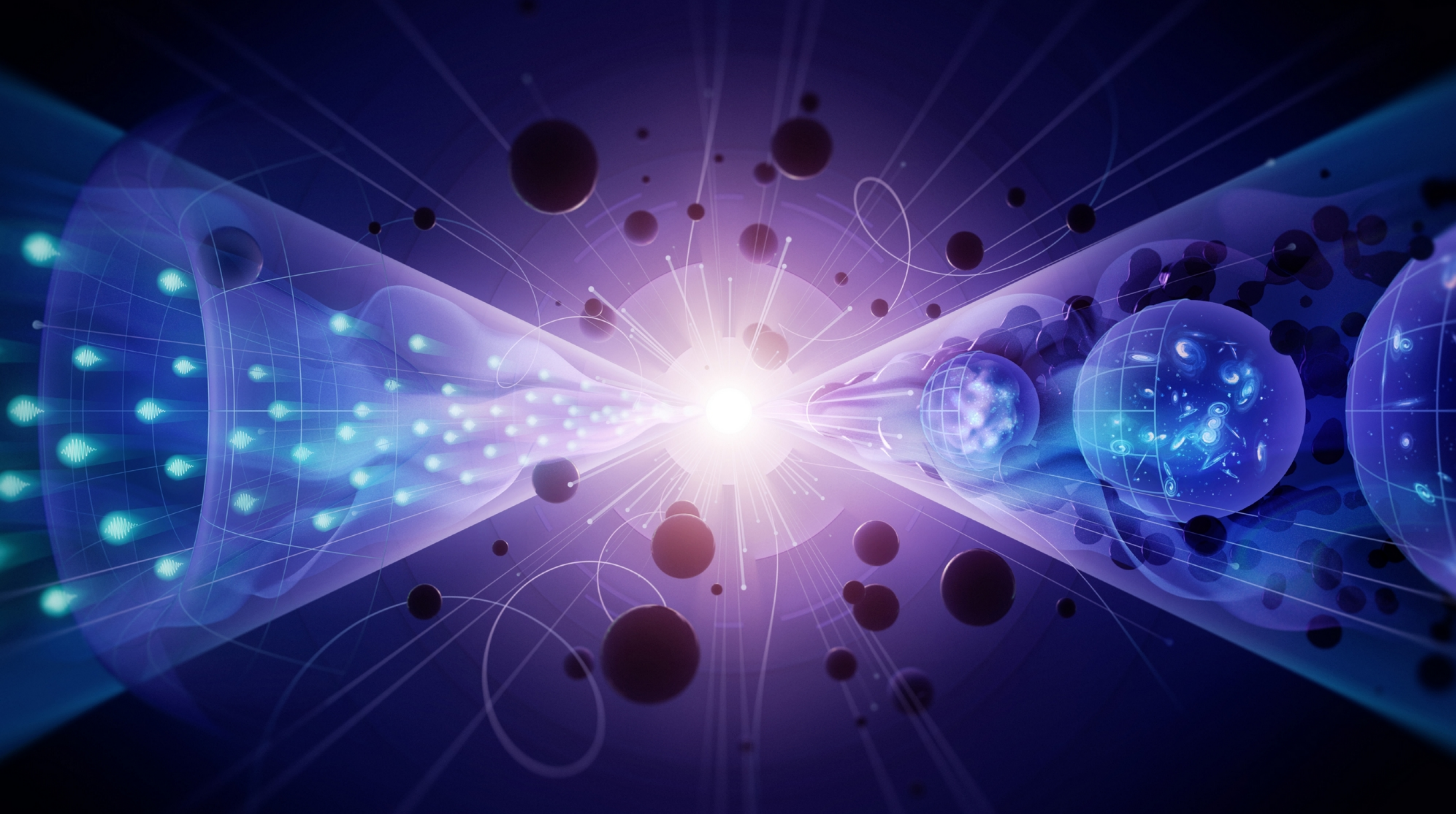
# Community Vision for the Future: Particle Physics and Cosmology in the Next Decade(s)

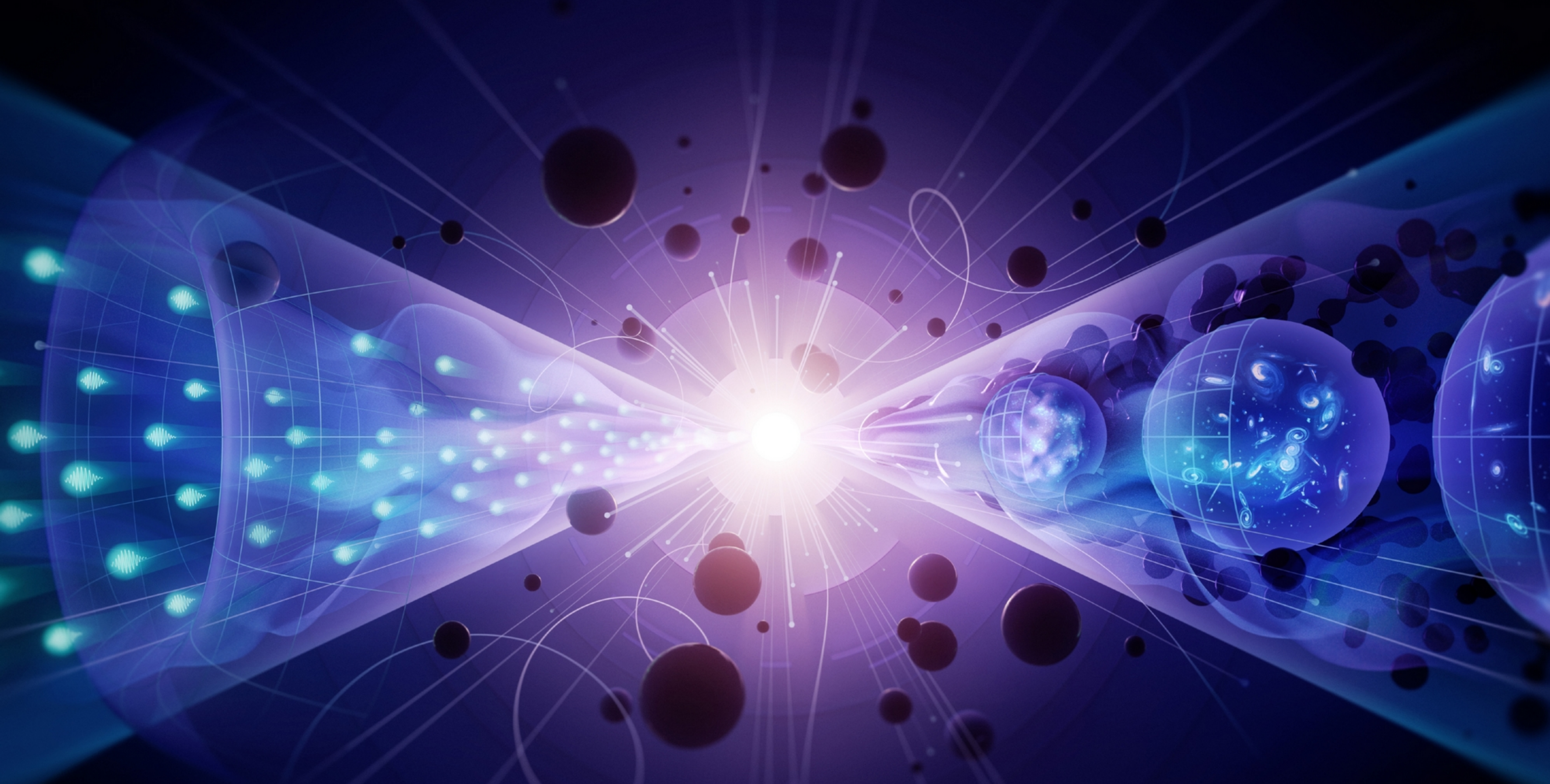

**Benjamin Wallisch**

Stockholm University, Nordita & UT Austin


OKC Colloquium, Stockholm, September 2024

2023 P5 Report





# Exploring the Quantum Universe

## Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

## Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

## Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

# Outline

- Snowmass/P5 Processes and Their Global Relevance
- P5 Recommendations to the US Funding Agencies
- Prioritized Experiments and Their Scientific Goals
- Some Lessons
- Discussion

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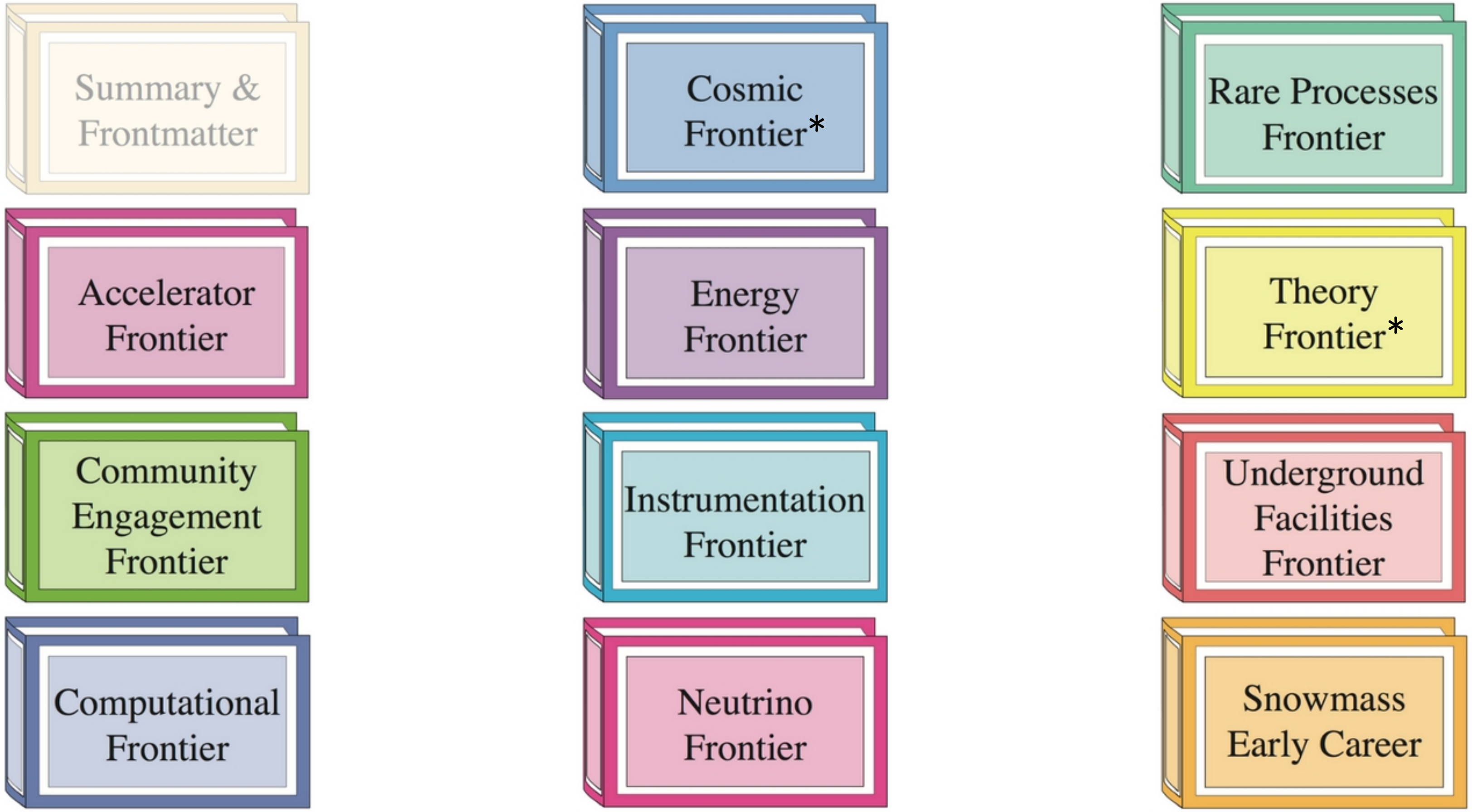
# Snowmass 2021 Community Study

"The US Community Study on the Future of Particle Physics (Snowmass 2021) was a grassroots study to plan for US particle physics in the decade 2025-2035 with an eye towards the following decade."




* BW involved

https://www.slac.stanford.edu/econf/C210711/

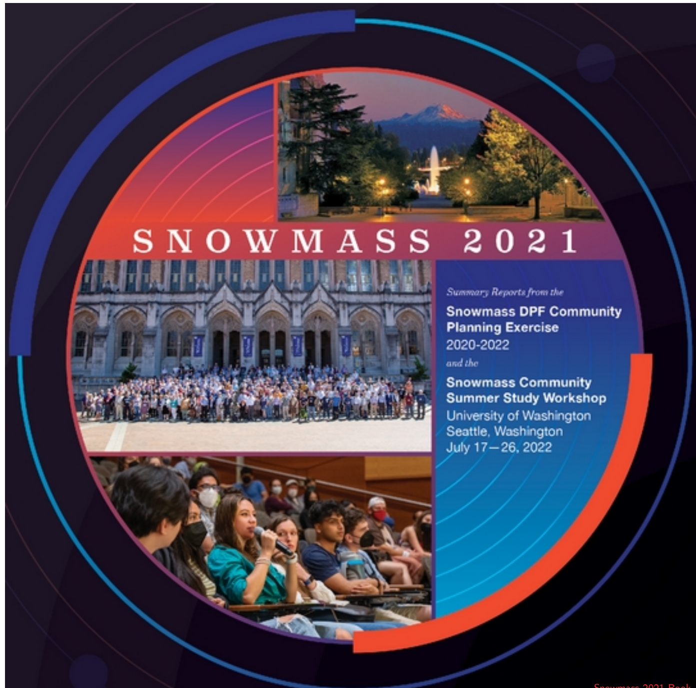
# Snowmass 2021 Community Study

- Several stages, including:
  - August 2020: Letters of intent*
  - October 2020: Community planning meeting*
  - 2021: Pause due to Covid
  - March 2022: White papers on arXiv*
  - July 2022: Ten-day community meeting in Seattle*
  - Fall 2022: Topical group*, frontier and summary reports

- US-based and -organized, but global participation

| | | |
|---|---|---|
| e.g.: | inflation WP: | leads – 2 US*+1 EU, co-authors – 7 US+11 EU+1 Chile; |
| | light relics WP: | leads – 2 US, co-authors – 16 US*+2 EU+1 CA+1 China; |
| | cosmic neutrino WP: | leads – 1 US+2 EU, co-authors – 11 US*+9 EU+1 Japan |

- Review of current state, plans and ‘wish list’ for the future



Snowmass 2021 Book

* BW involved

# P5

- Particle Physics Project Prioritization Panel

- 32 members, including from CERN, DESY and Tokyo
  Chair: Hitoshi Murayama; deputy chair: Karsten Heeger

- Formulate a compelling US high-energy physics program for the next decade(s):
  - Make funding recommendations,
  - Focus on enabling US leadership and unique US facilities in global context,
  - Prioritize experiments within given budget scenarios.

- Report presented in November 2023.

# Global Relevance of Snowmass/P5

- Large number of high-energy physicists.
- US contributions are a sizable fraction of the global high-energy budget, e.g.:
  - Department of Energy, Office of Science, HEP (2023): ca. 1.2 billion USD
  - CERN (2022): ca. 1.2 billion CHF
  - ERC PE2+PE9 (2014–2020): ca. 1.1 billion EUR
  - DESY (2020): ca. 0.3 billion EUR
- Many big projects are mainly funded by or receive sizable contributions from US.
- Other countries/parts of the world perform similar studies, but on a smaller scale.
- Decadal review of state of the field with up-to-date review papers of many aspects.

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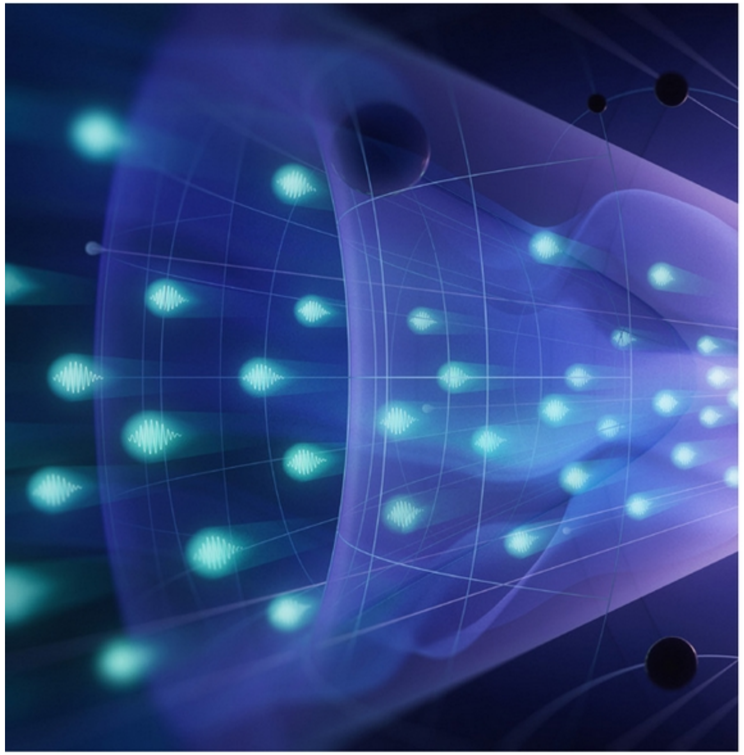

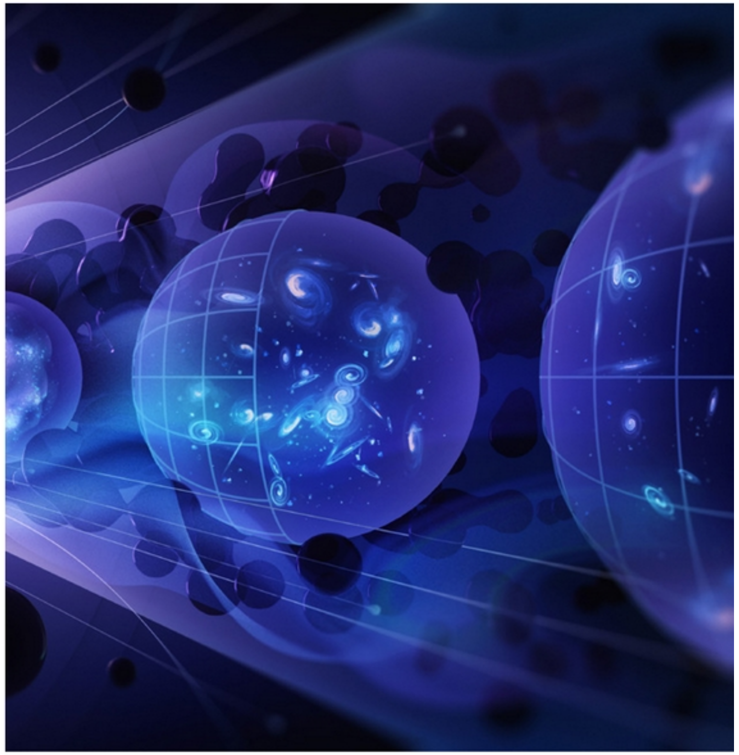

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# P5 Recommendations (Selection)

- Complete construction and support operations of ongoing experiments:
  - HL-LHC
  - DUNE (phase 1)
  - Vera Rubin Observatory/LSST
  - NOvA, SBN, T2K
  - DarkSide-20k, LZ, SuperCDMS, XENONnT
  - DESI
  - Belle II, LHCb, Mu2e
- Construct portfolio of major projects with huge potential for transformations:
  1. CMB-S4†
  2. DUNE (phase 2, smaller)
  3. Higgs factory outside the US
  4. Ultimate dark matter direct detection experiment
  5. IceCube-Gen2†
- Range of small-scale experiments, in particular for dark matter searches
- DESI-II, LHCb upgrade II, Belle II upgrade, Cherenkov Telescope Array (contribution)
- Enhance research in theory
- R&D for the future: muon collider/FCC, Spec-S5, line intensity mapping, AI/ML, ...

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  † no budget cuts

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  (or potentially construct if more money)

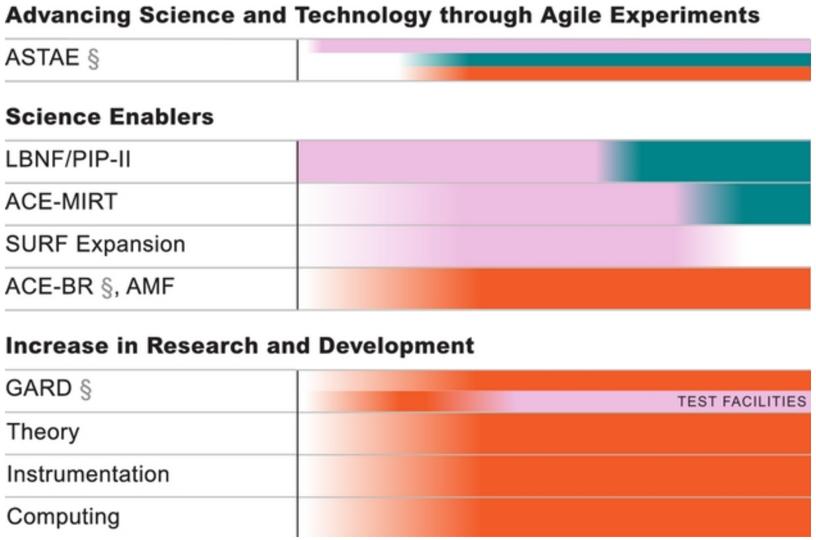
# P5 Program and Timeline

**Science Experiments**


| Science Experiments | Neutrinos | Higgs Boson | Dark Matter | Cosmic Evolution | Direct Evidence | Quantum Imprints | Astronomy & Astrophysics |
|---|---|---|---|---|---|---|---|
| LHC | | P | P | | P | P | |
| LZ, XENONnT | | | P | | | | |
| NOvA/T2K | | | | | S | | |
| SBN | | | | | S | | |
| DESI/DESI-II | S | | S | P | | | P |
| Belle II | | | S | | S | P | |
| SuperCDMS | | | P | | | | |
| Rubin/LSST & DESC | S | | S | P | | | P |
| Mu2e | | | | | | P | |
| DarkSide-20k | | | P | | | | |
| HL-LHC | | P | P | | P | P | |
| DUNE Phase I | P | | | | S | S | S |
| CMB-S4 | S | | S | P | | | P |
| CTA | | | S | | | | P |
| G3 Dark Matter § | S | | P | | | | |
| IceCube-Gen2 | P | | S | | | | P |
| DUNE FD3 | P | | | | S | S | S |
| DUNE MCND | P | | | | S | S | |
| Higgs factory § | | P | S | | P | P | |
| DUNE FD4 § | P | | | | S | S | S |
| Spec-S5 § | S | | S | P | | | P |
| Mu2e-II | | | | | | P | |
| Multi-TeV § | | P | P | | P | S | |
| LIM | S | | P | P | | | P |

Science Drivers

Index: Operation, Construction, R&D, Research  P: Primary  S: Secondary
§ Possible acceleration/expansion for more favorable budget situations



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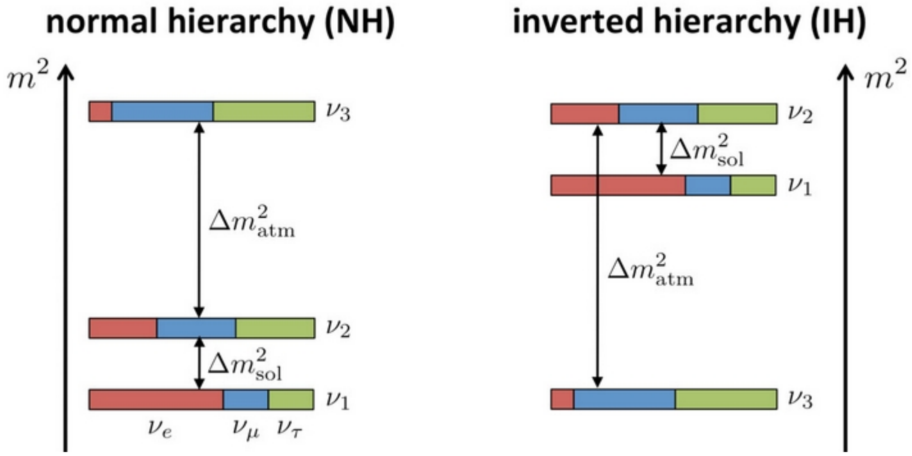
# NOνA and T2K

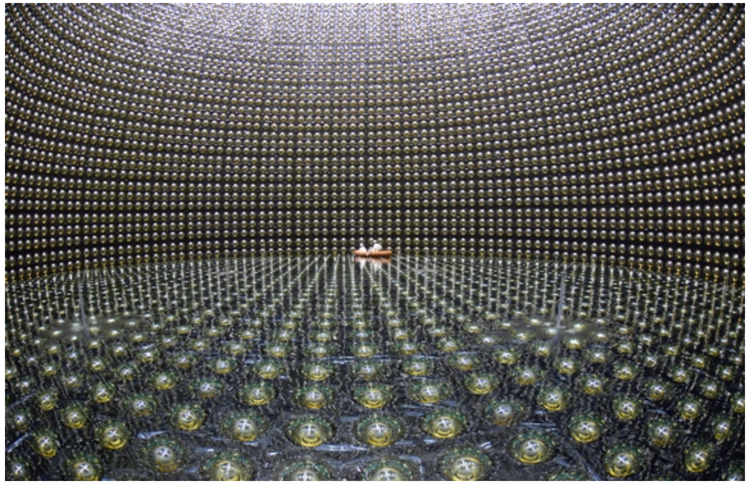
- Accelerator-based neutrino experiments in muon neutrino beam:
  - NOνA: Neutrinos at the Main Injector (NuMI) Off-axis $\nu_e$ Appearance
    $\rightarrow$ Baseline from Fermilab to detectors in Minnesota: ca. 800 km

  - T2K: Tokai to Kamioka
    $\rightarrow$ Baseline from J-PARC to Super-Kamionkande: ca. 300 km


NovA Collaboration



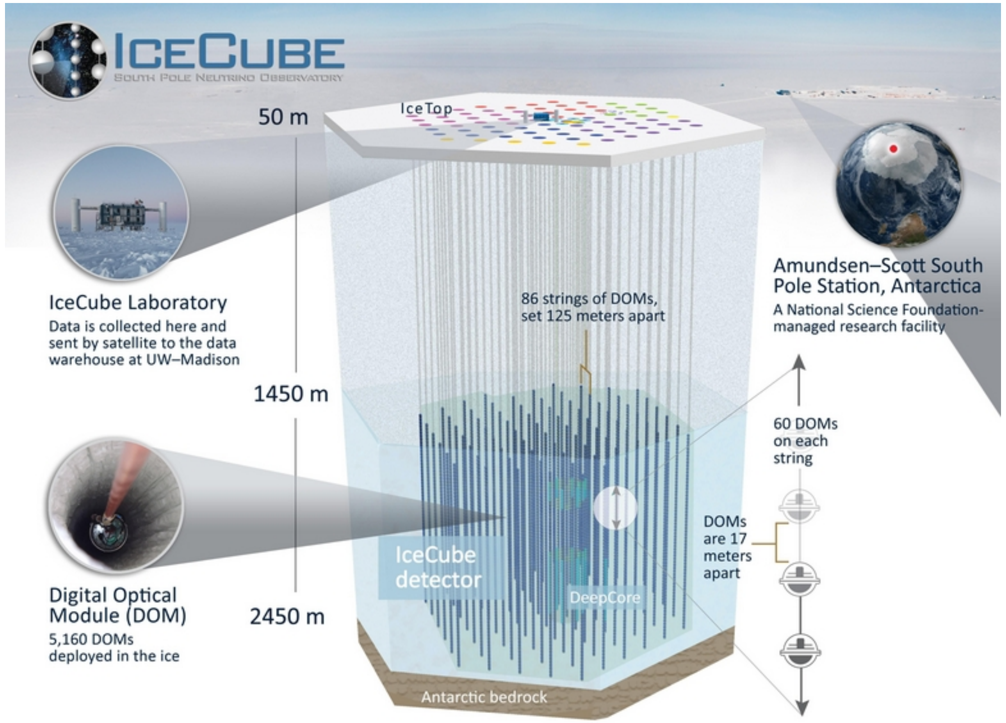
JUNO Collaboration

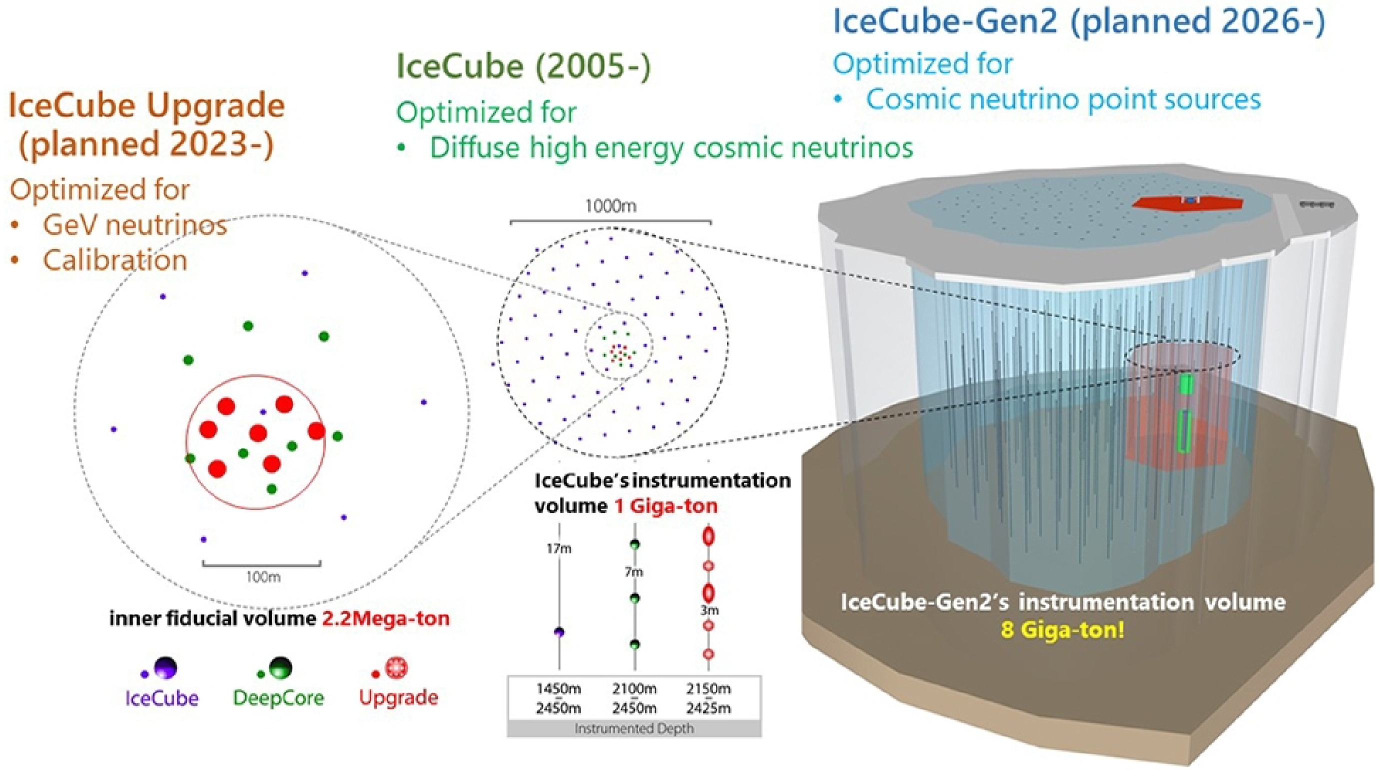

Super-Kamionkande

- Main physics targets:
  - ✔ Neutrino mass hierarchy
  - ✔ Neutrino mixing and CP violation

# IceCube Neutrino Observatory

- Detection of astrophysical neutrinos in the ice at the South Pole




- Main physics targets:
  - ✔ Neutrino oscillations, neutrino astronomy and multimessenger astrophysics
  - ✔ Sterile neutrinos, annihilating and decaying dark matter
  - ✔ Cosmic-ray physics

IceCube Collaboration

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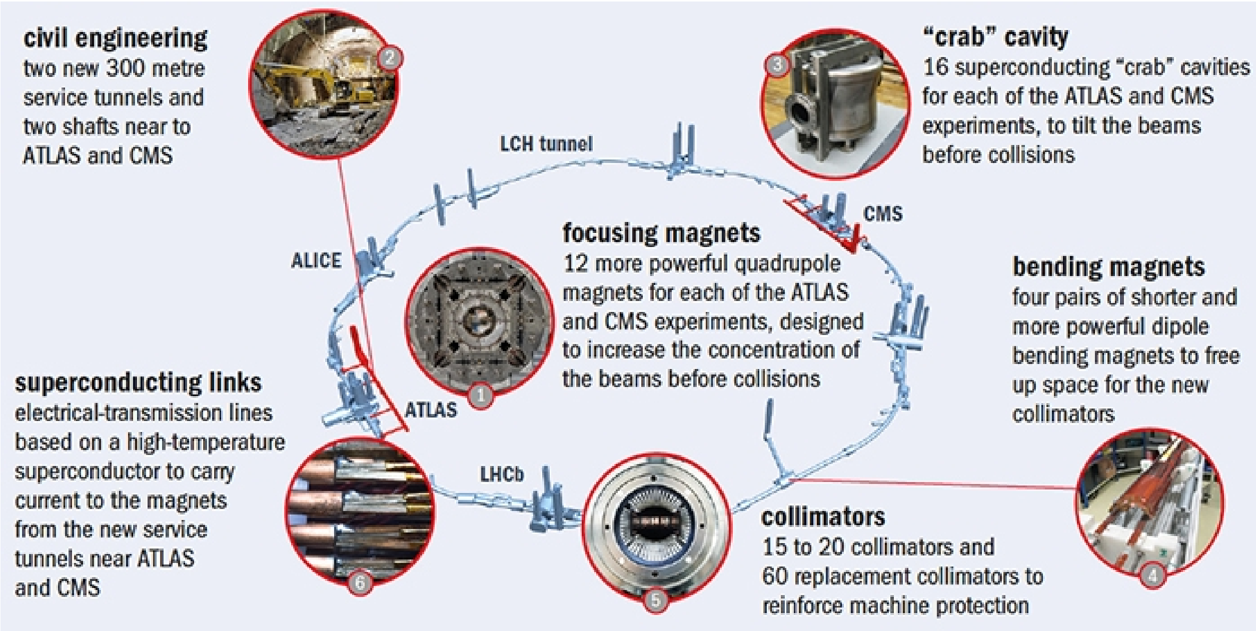
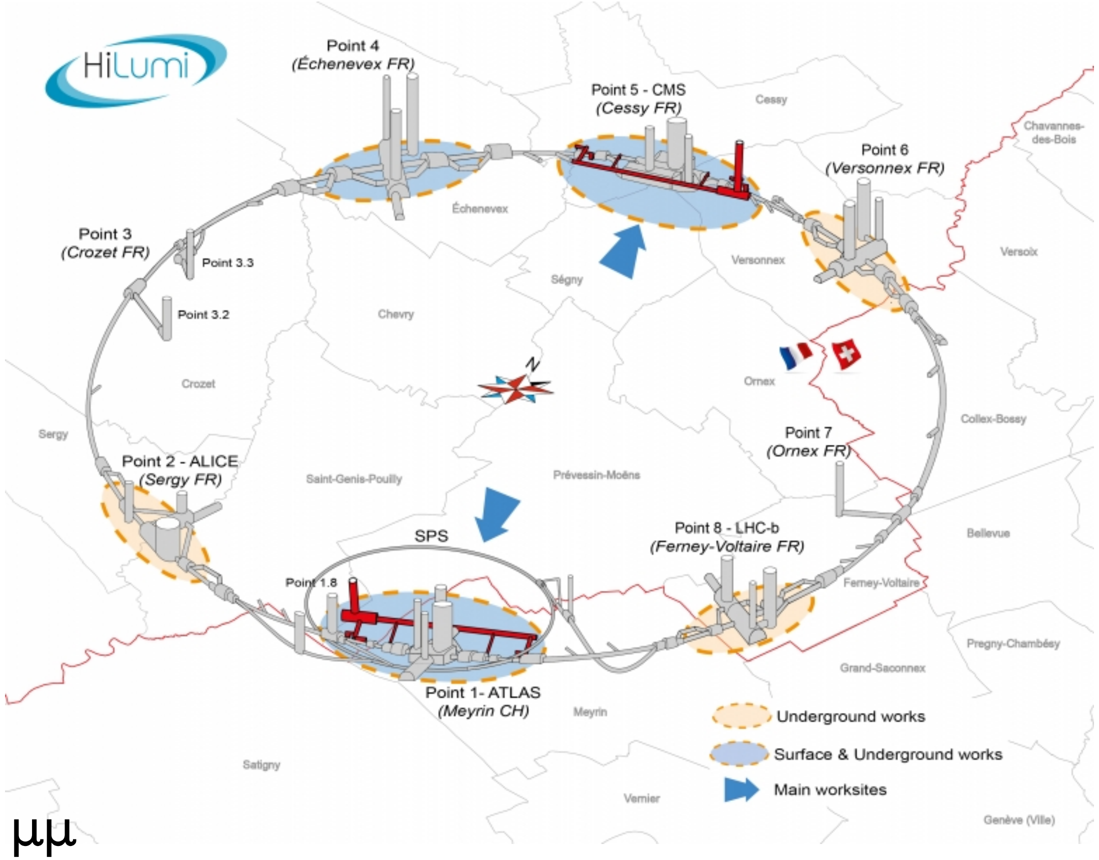
# High Luminosity Large Hadron Collider (HL-LHC)

- Proton-proton collisions at 14 TeV with higher luminosity: around $5 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (peak).
  $\rightarrow$ Production of 180 million Higgs bosons in ATLAS and CMS.



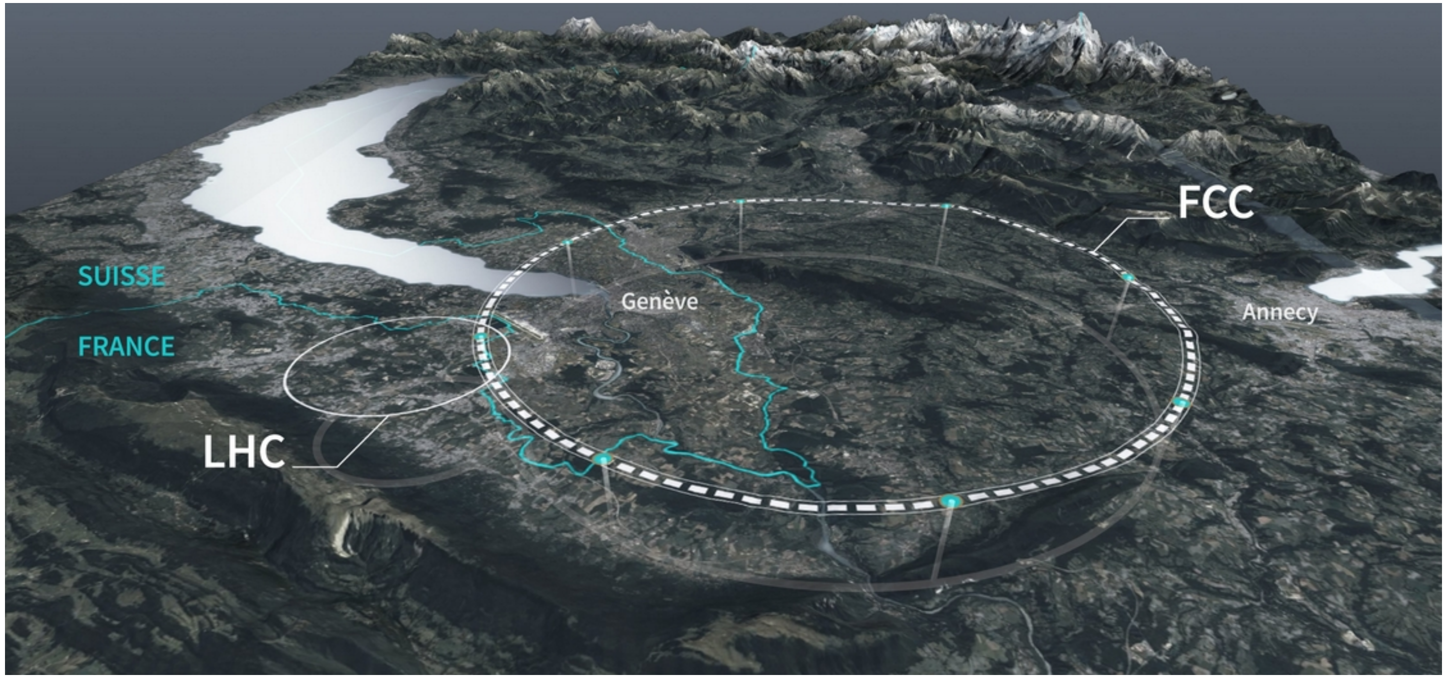

- Main physics targets:
  - ✔ Standard Model precision measurements
  - ✔ Measurement of rare processes, e.g. $H \rightarrow \mu\mu$
  - ✔ Testing the Higgs potential and self-interactions
  - ✔ Physics beyond the Standard Model above TeV masses, ...

HL-LHC Collaboration/CERN

# Higgs Factory and 10 TeV pCM Collider

- Higgs Factory: electron-positron collider with center-of-momentum energy of 90–350 GeV
  - → Very high production rate of Higgs bosons
  - → E.g.: International Linear Collider (ILC) or Future Circular Collider (FCC-ee)

- 10 TeV parton center-of-momentum collider
  - → E.g.: 10 TeV muon collider, FCC-hh




- Main physics targets:
  - ✔ Precision Higgs physics
  - ✔ Very broad tests of physics beyond the Standard Model, including dark matter
  - ✔ Standard Model precision tests, ...

CERN

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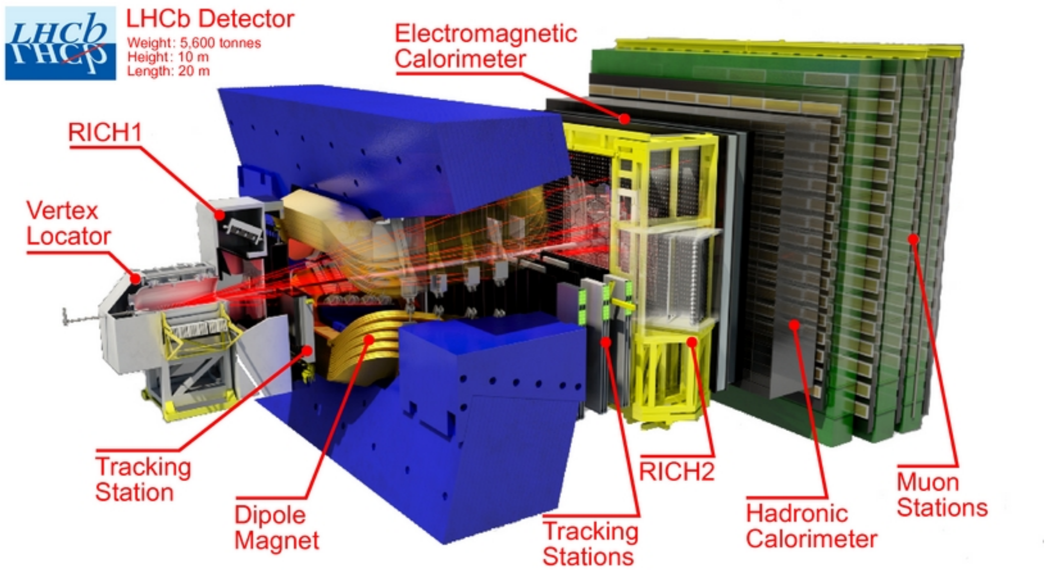
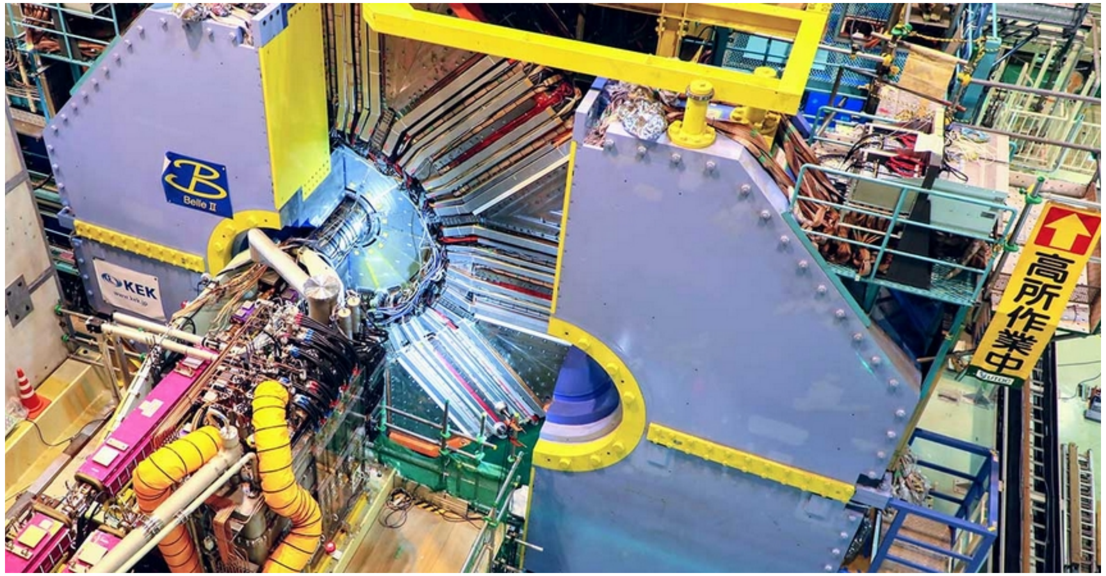
# Belle II and LHCb

- Belle II: detector at electron-positron collider SuperKEKB in Japan
  $\rightarrow$ B-factory: 7 GeV electrons + 4 GeV positrons

- LHCb: detector at LHC



LHCb Collaboration

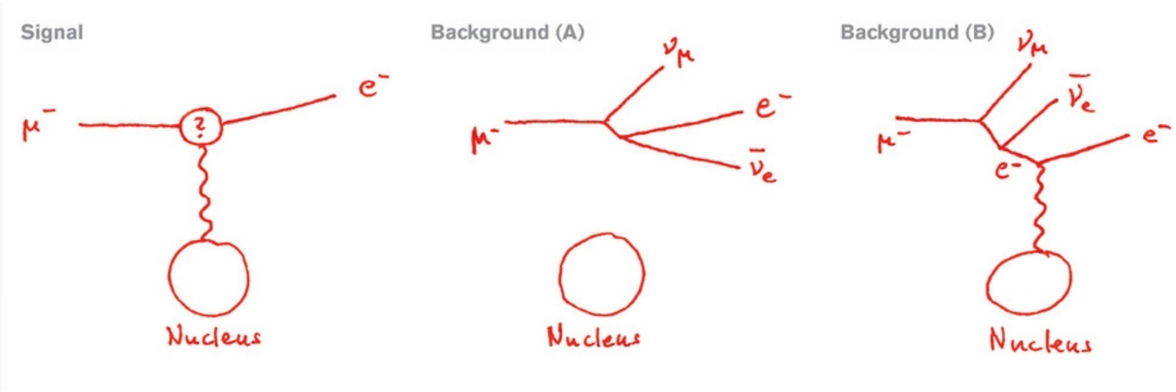


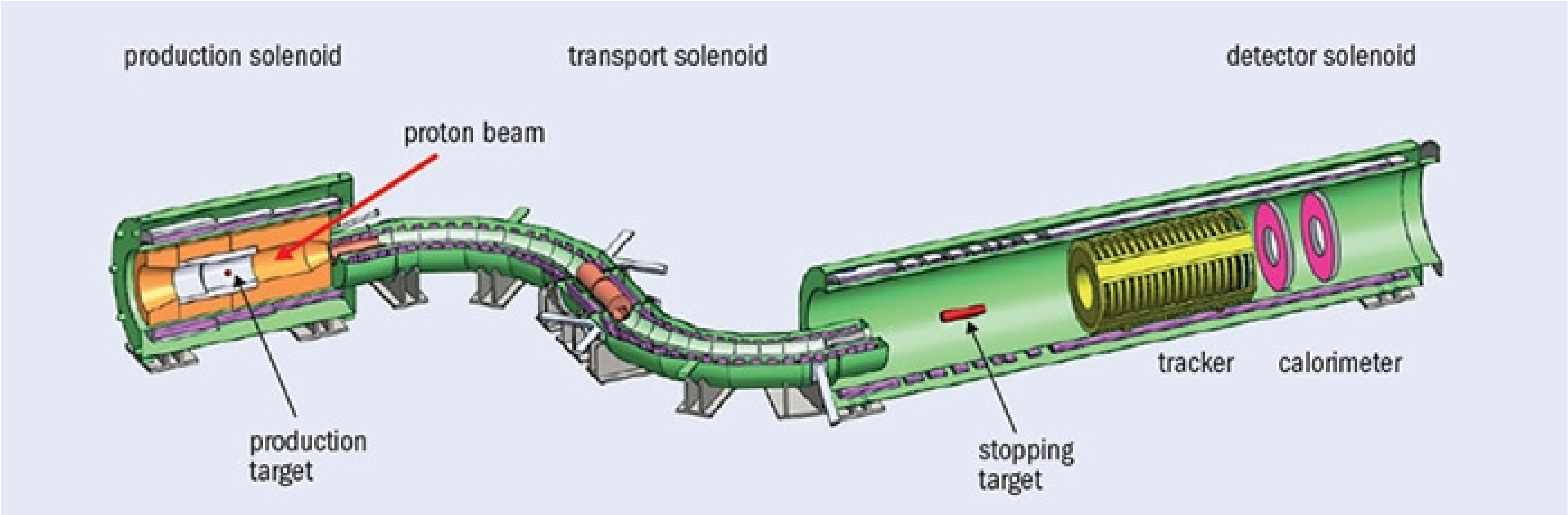
Belle II Collaboration

- Main physics targets:
  - ✔ Decays of bottom, charm and taus
  - ✔ B-physics, esp. rare processes, CP violation and flavor-changing neutral currents
  - ✔ Standard Model precision tests

# Muon-to-Electron Conversion Experiment (Mu2e)

- Neutrinoless conversion of muons captured by a nucleus into an electron at Fermilab




- Main physics target:
  - ✔ Beyond the Standard Model physics: charged lepton flavor violation

Mu2e Collaboration/Fermilab

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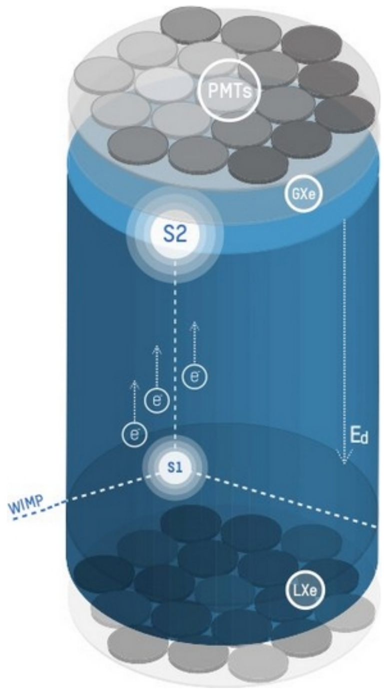
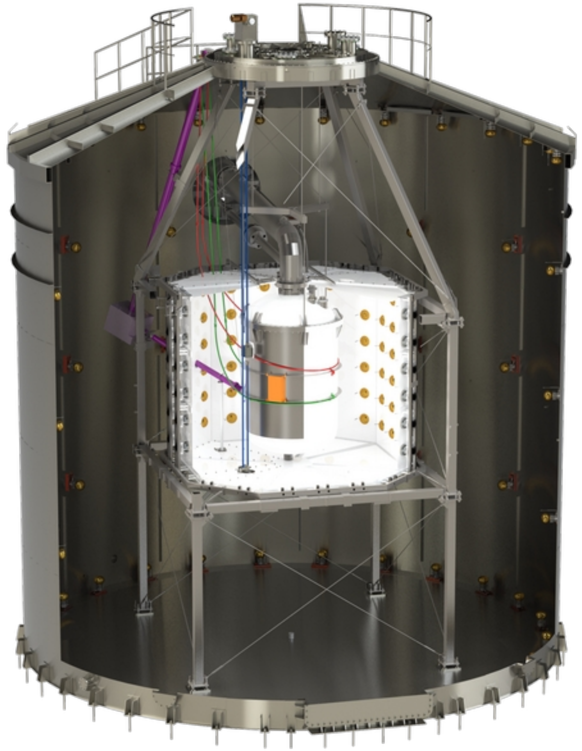
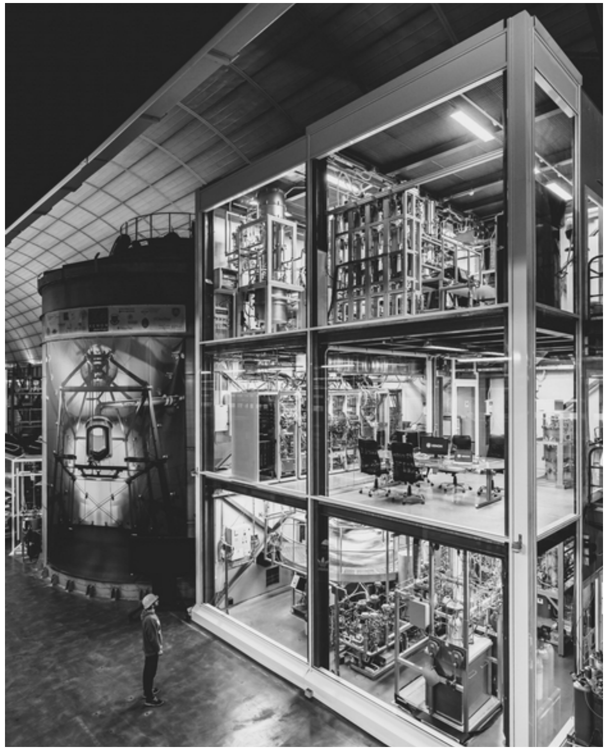
# Current and Near-Term Direct Detection Experiments

- Lux-Zeplin (LZ): Time-projection chamber with 7t liquified Xenon (South Dakota, US)
- XEXONnT: TPC with 8.6t liquified Xenon (Gran Sasso Underground Laboratory, Italy)
- DarkSide-20k: TPC with 20t liquid Argon under construction (Gran Sasso, Italy)



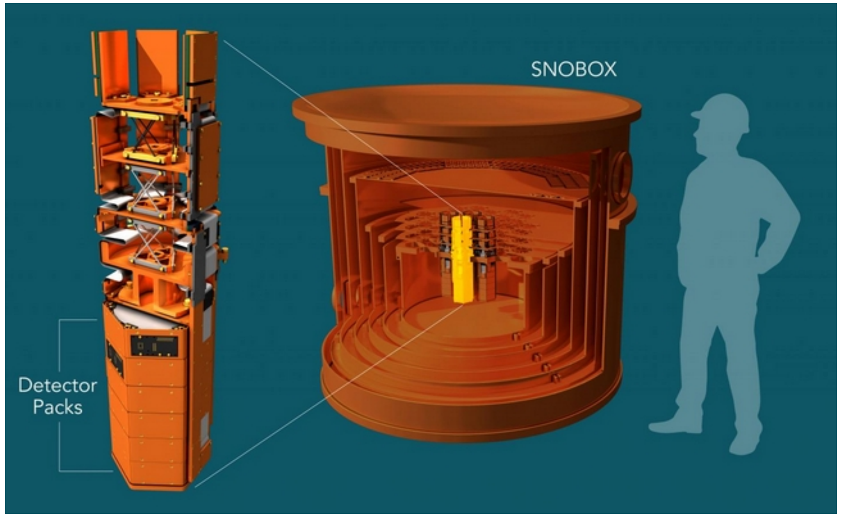


- Main physics target:
  - ✔ Direct detection of weakly-interacting massive particle (WIMP) dark matter

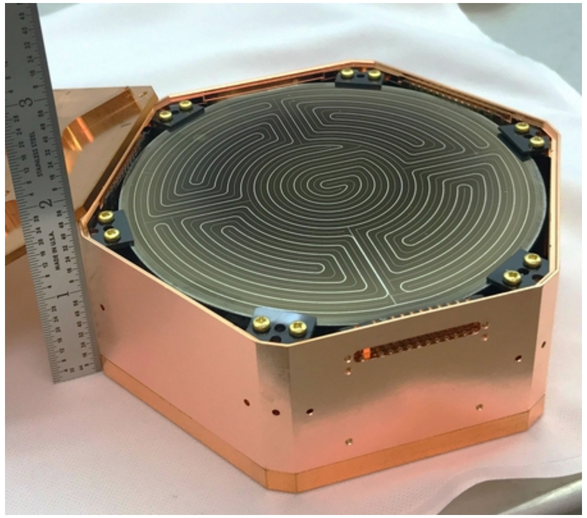
XENONnT Collaboration

# Current and Near-Term Direct Detection Experiments

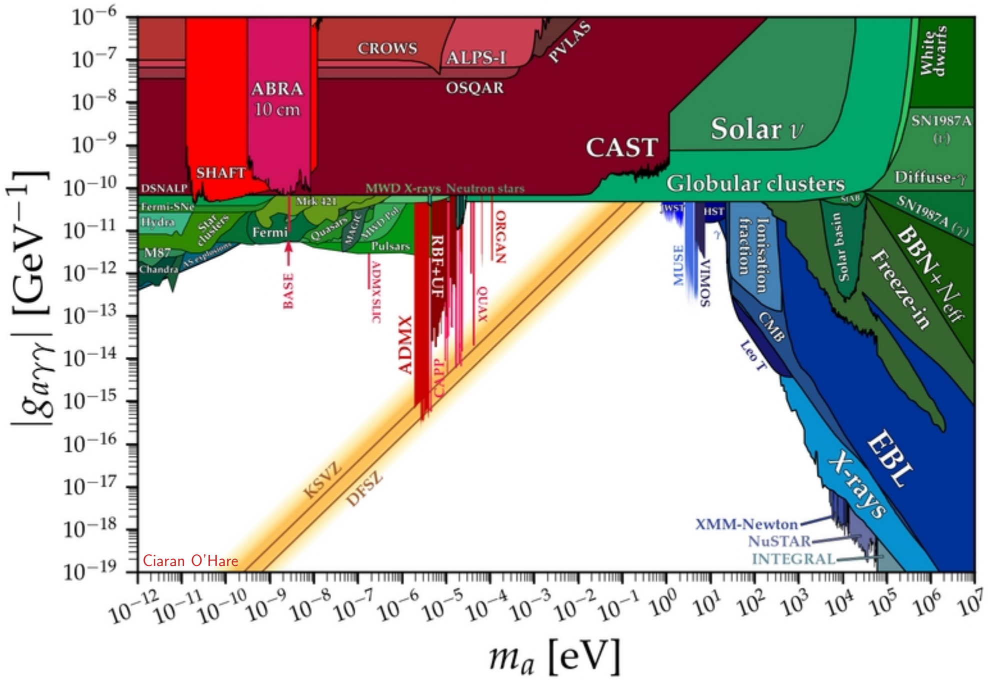
- Super Cryogenic Dark Matter Search (SuperCDMS): phonon detector array based on silicon and germanium crystals at 15 mK; under construction (SNOLAB, Canada)
  - ✔ Direct detection of light particle dark matter



SuperCDMS Collaboration

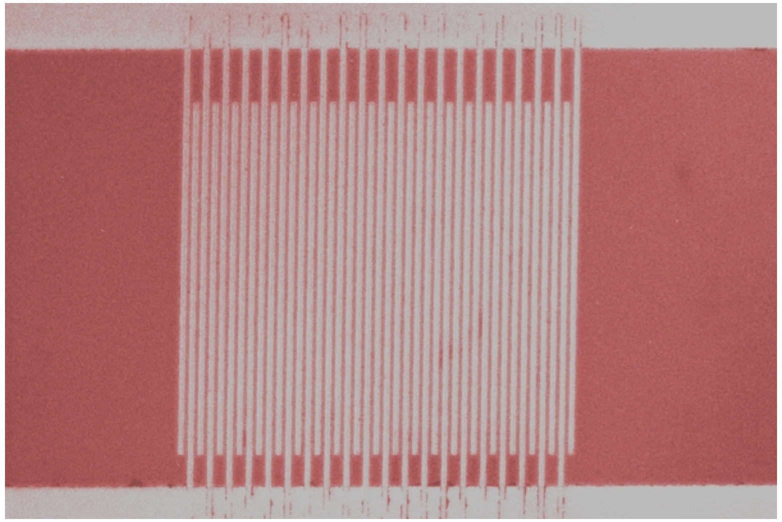

SuperCDMS Collaboration

- Axion Dark Matter eXperiment (ADMX/ADMX-G2): axion-photon conversion haloscope (Seattle, US)
  - ✔ Direct detection of axion dark matter



# Portfolio of Agile Experiments

- Many smaller-scale experiments covering a diverse range of new physics possibilities, e.g.
  - Small detectors based on new technologies
  - Accelerator-based detectors in beam dumps and forward regions
  - Many different axion experiments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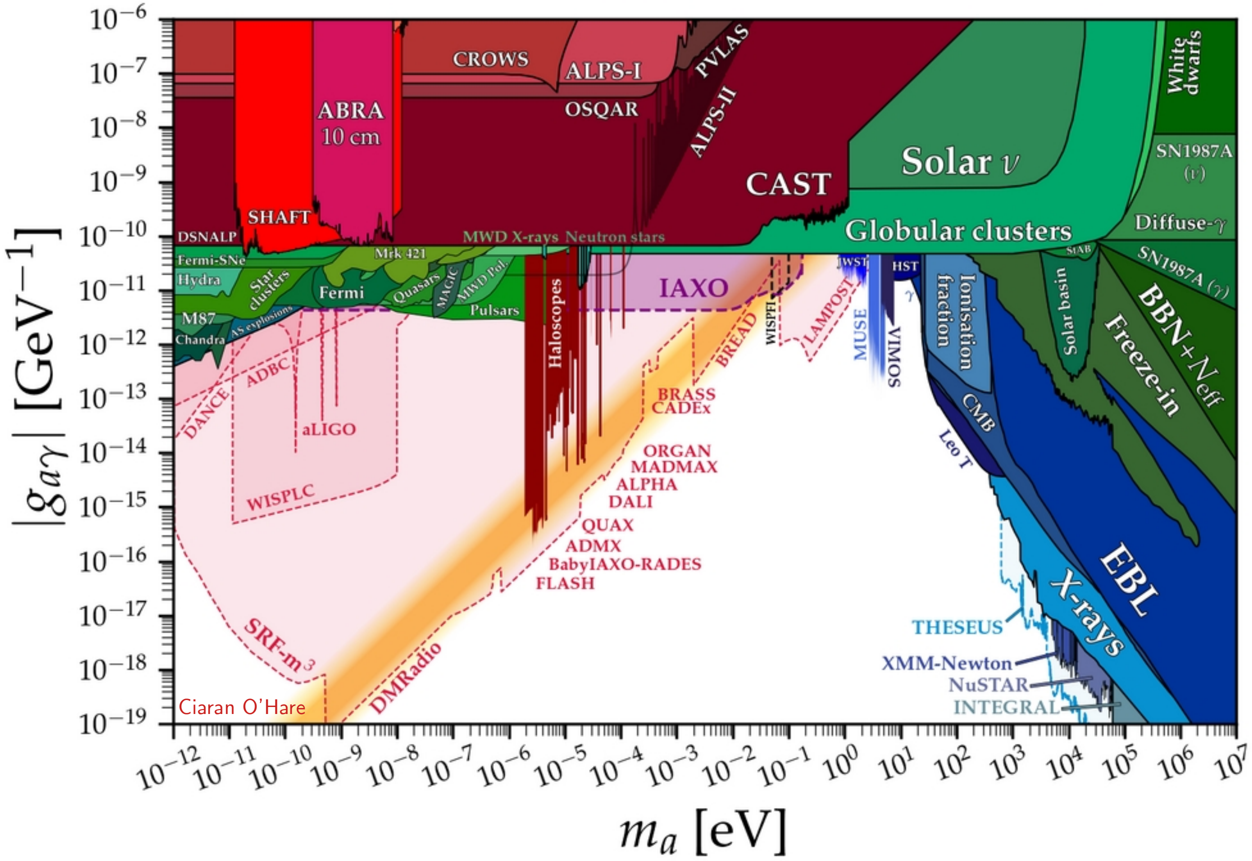
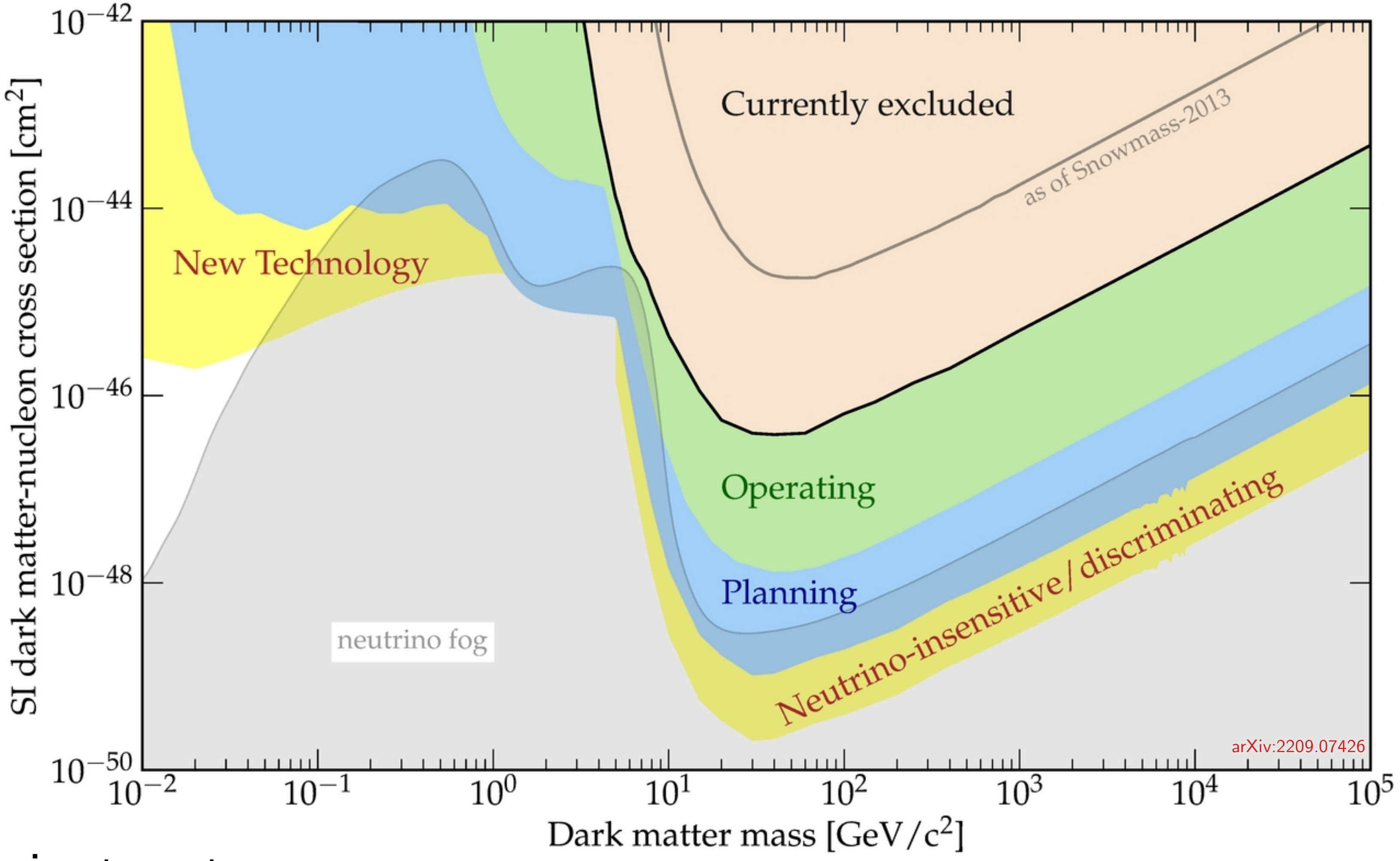



- Main physics target:
  - ✔ Direct detection of dark matter in large parameter & model space

# Ultimate G3 Dark Matter Direct Detection Experiment




- Main physics targets:
  - ✔ Direct detection of WIMP dark matter to the neutrino fog
  - ✔ Solar and supernova neutrinos

## Decipher the Quantum Realm

### Elucidate the Mysteries of Neutrinos

- NOνA & T2K; SBN
- DUNE
- IceCube

### Reveal the Secrets of the Higgs Boson

- (HL-)LHC
- Higgs Factory
- 10 TeV pCM Collider

## Explore New Paradigms in Physics

### Search for Direct Evidence of New Particles

- (HL-)LHC
- Higgs Factory
- 10 TeV pCM Collider
- 'Agile Experiments'

### Pursue Quantum Imprints of New Phenomena

- Belle II
- Mu2e
- (HL-)LHC
- Higgs Factory

## Illuminate the Hidden Universe

### Determine the Nature of Dark Matter

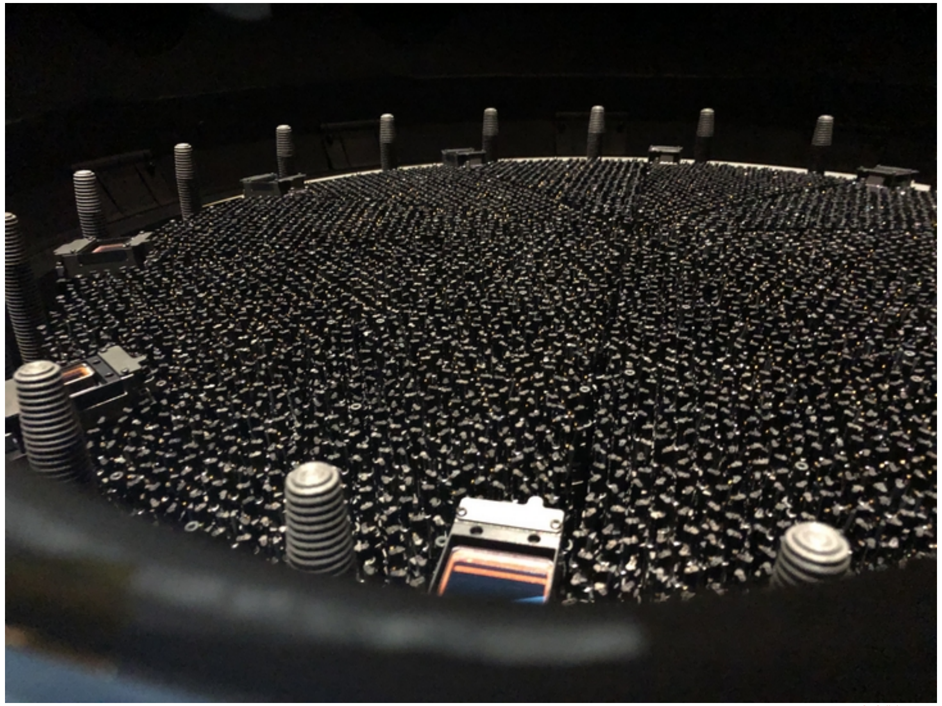
- Direct detection
- 'Agile Experiments'
- IceCube; CTA
- Cosmological surveys

### Understand What Drives Cosmic Evolution

- DESI, VRO/LSST
- CMB-S4
- Spec-S5; LIM

# DESI & Vera Rubin Observatory/LSST

- Dark Energy Spectroscopic Survey: spectroscopic galaxy survey (Arizona, US)
- VRO/Legacy Survey of Space and Time: photometric galaxy survey (Chile)

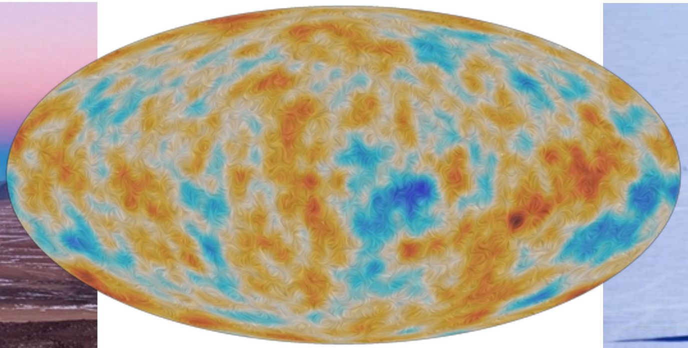
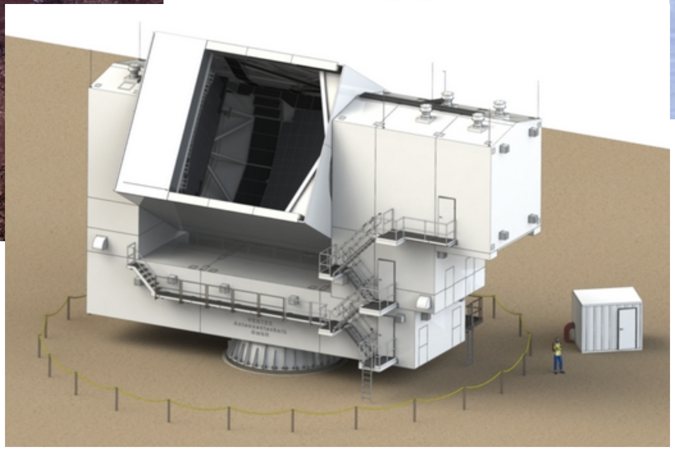

DESI Collaboration

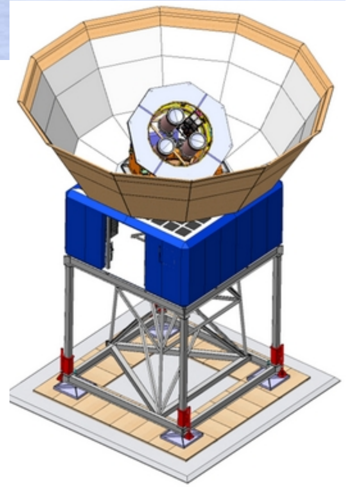

VRO

- Main (fundamental) physics targets:
  - ✔ Dark energy
  - ✔ Neutrino masses, dark matter, early universe

# CMB-S4

- Next-generation cosmic microwave background experiment (Chile + South Pole).*



- Main (fundamental) physics targets:
  - ✔ Primordial gravitational waves
  - ✔ Neutrinos and light thermal particles beyond the Standard Model
  - ✔ Dark matter, dark energy, early universe, ...

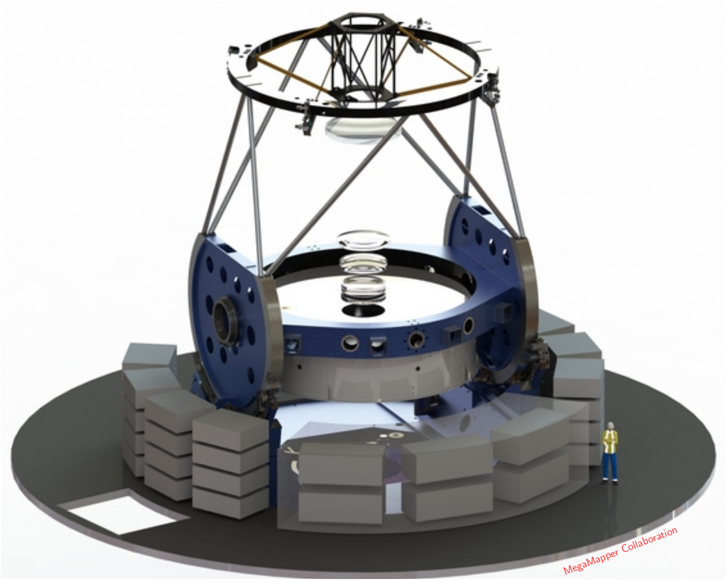
* BW involved

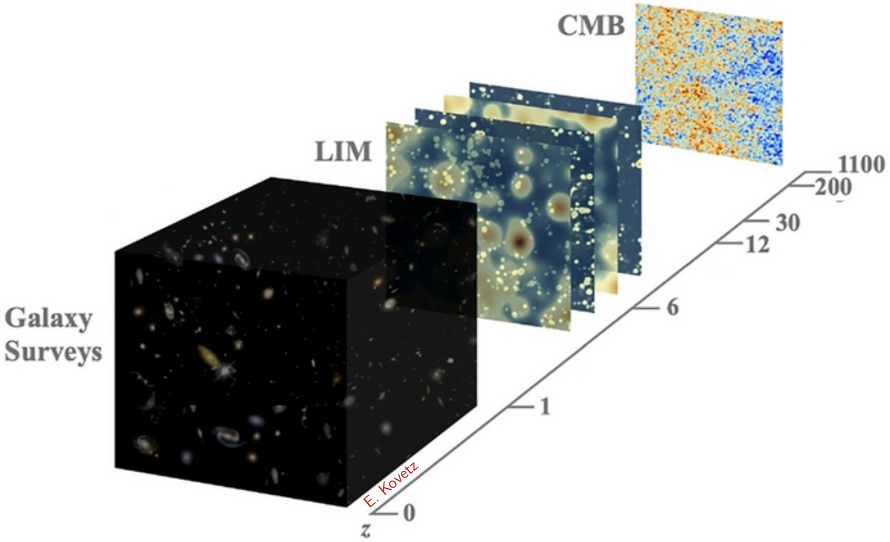
CMB-S4 Collaboration/Planck Collaboration/ESA

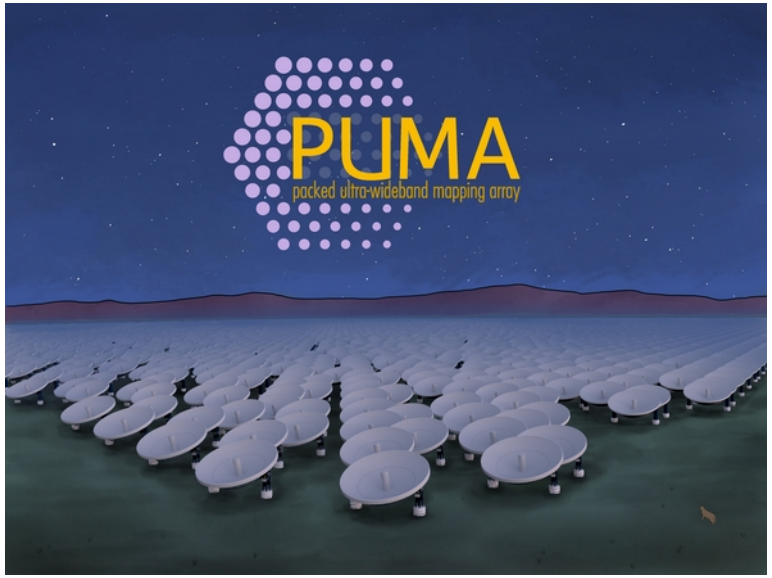
# Spec-S5 & Line Intensity Mapping

- Stage-5 spectroscopic galaxy survey: more galaxies, higher redshifts

- Line intensity mapping: different technique mapping radio emission from gas

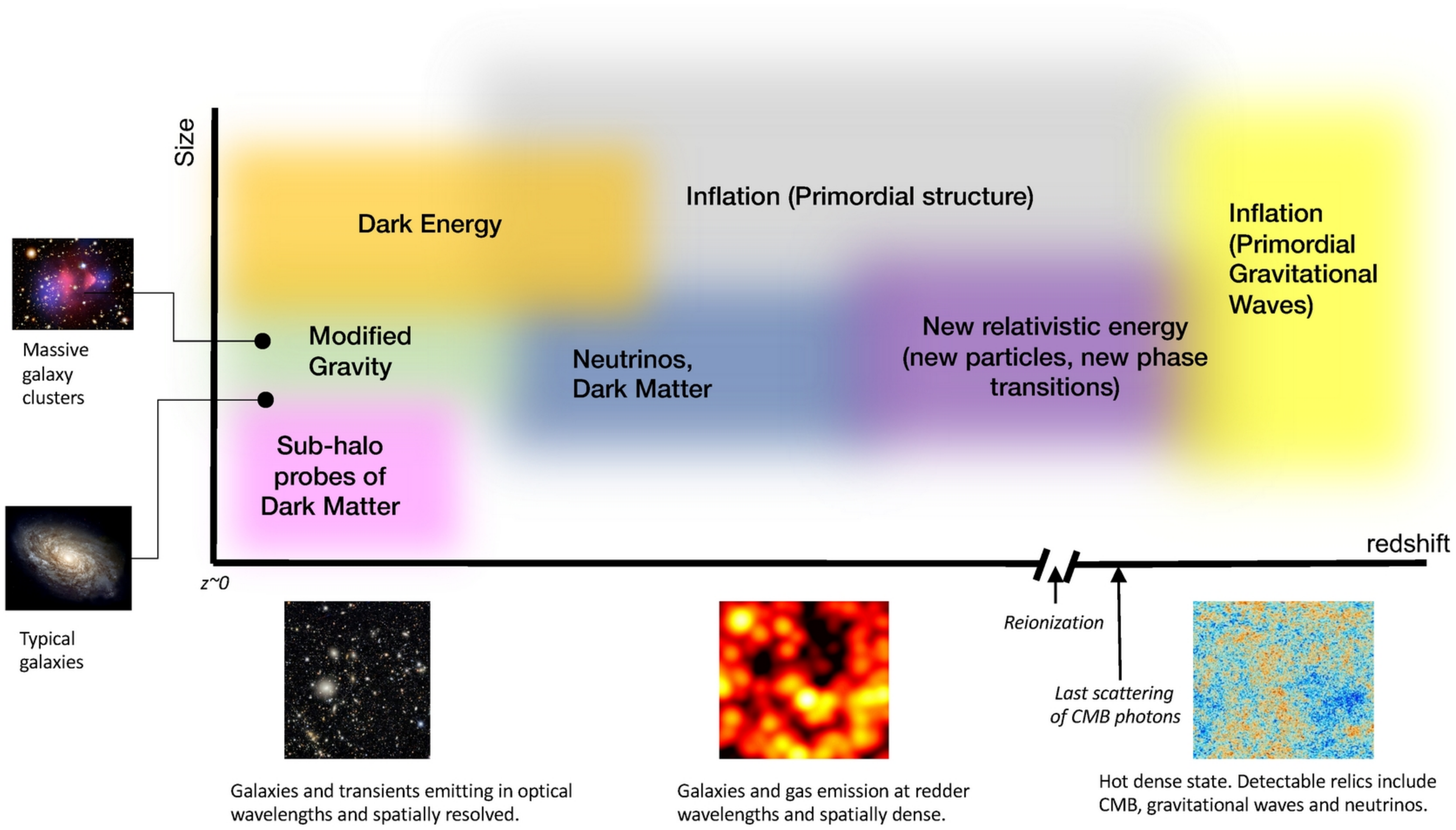


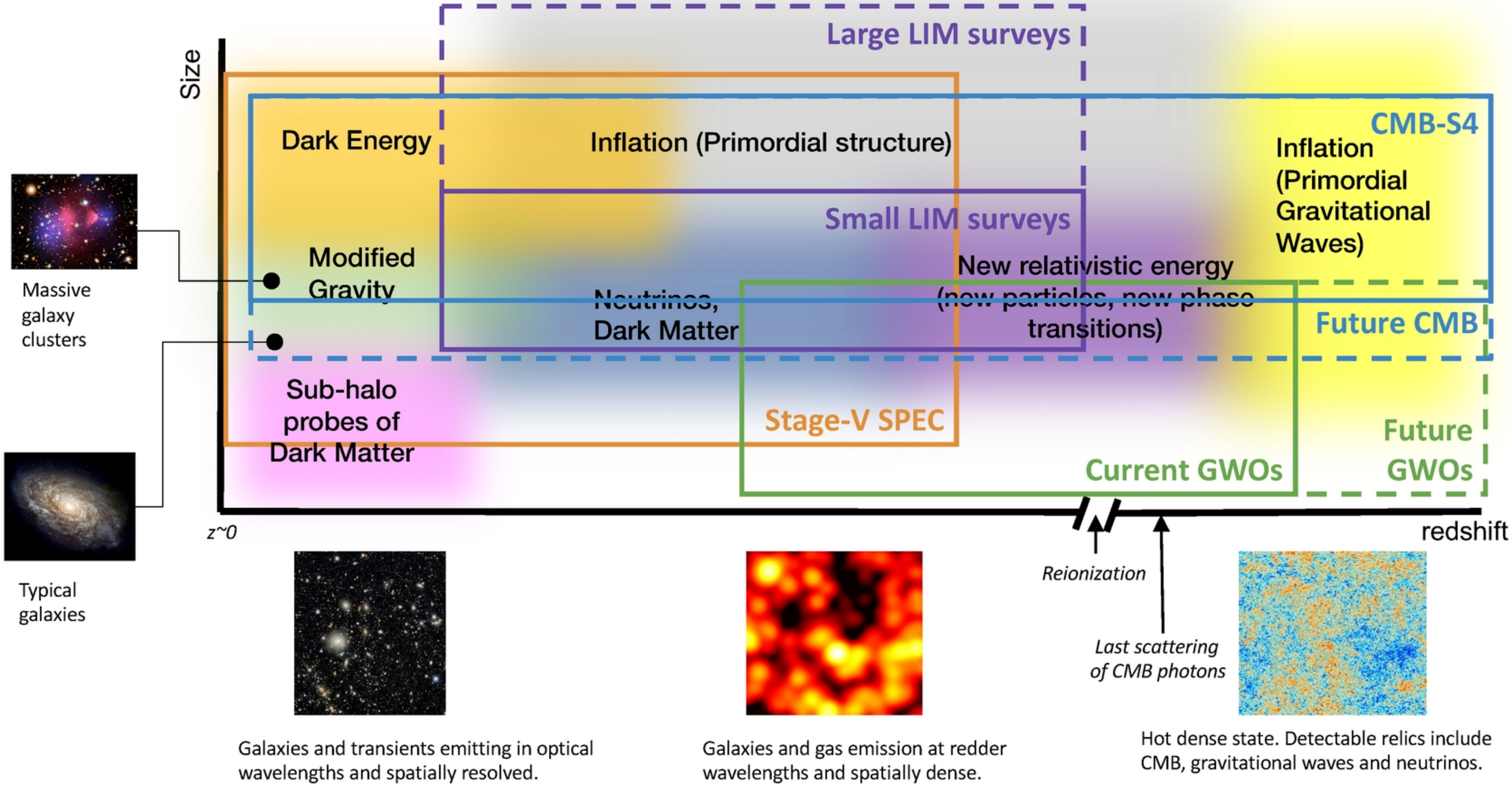




*

- Main (fundamental) physics targets:
  - ✔ Early universe
  - ✔ Physics beyond the Standard Model, neutrinos, dark matter, dark energy, ...


Size
Dark Energy
Inflation (Primordial structure)
Inflation (Primordial Gravitational Waves)
Modified Gravity
Neutrinos, Dark Matter
New relativistic energy (new particles, new phase transitions)
Sub-halo probes of Dark Matter
Massive galaxy clusters
Typical galaxies
redshift
z~0
Reionization
Last scattering of CMB photons
Galaxies and transients emitting in optical wavelengths and spatially resolved.
Galaxies and gas emission at redder wavelengths and spatially dense.
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.


Large LIM surveys
Size
CMB-S4
Dark Energy
Inflation (Primordial structure)
Inflation (Primordial Gravitational Waves)
Small LIM surveys
Massive galaxy clusters
Modified Gravity
New relativistic energy (new particles, new phase transitions)
Neutrinos, Dark Matter
Future CMB
Sub-halo probes of Dark Matter
Stage-V SPEC
Future GWOs
Current GWOs
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z~0
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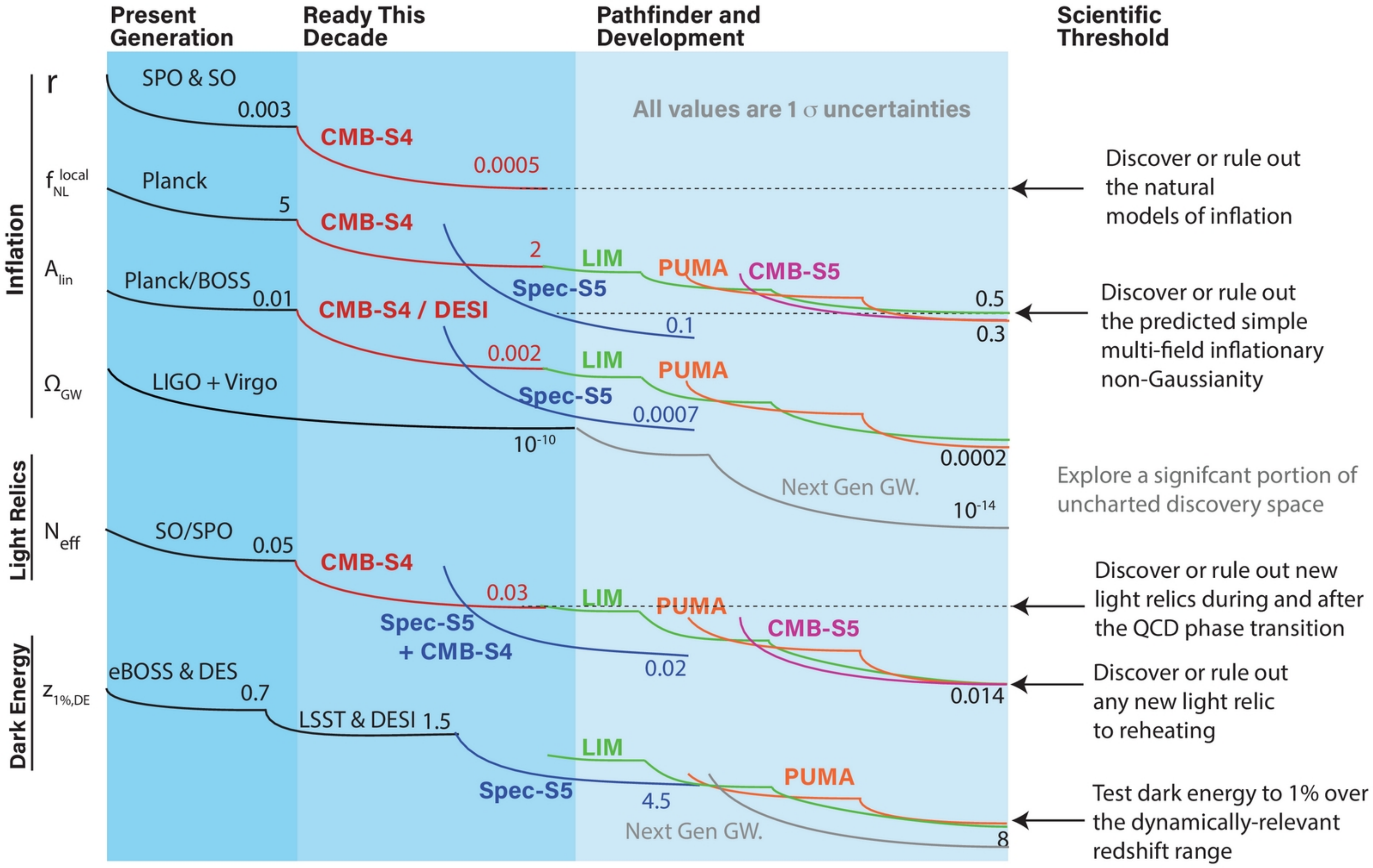

Present Generation
Ready This Decade
Pathfinder and Development
Scientific Threshold
Inflation
r
SPO & SO
0.003
CMB-S4
0.0005
All values are 1 σ uncertainties
Discover or rule out the natural models of inflation
$f_{NL}^{local}$
Planck
5
CMB-S4
2
LIM
PUMA
CMB-S5
Spec-S5
0.1
0.5
0.3
Discover or rule out the predicted simple multi-field inflationary non-Gaussianity
$A_{lin}$
Planck/BOSS
0.01
CMB-S4 / DESI
0.002
LIM
PUMA
Spec-S5
0.0007
0.0002
$\Omega_{GW}$
LIGO + Virgo
$10^{-10}$
Next Gen GW.
$10^{-14}$
Explore a signifcant portion of uncharted discovery space
Light Relics
$N_{eff}$
SO/SPO
0.05
CMB-S4
0.03
LIM
PUMA
CMB-S5
Spec-S5 + CMB-S4
0.02
0.014
Discover or rule out new light relics during and after the QCD phase transition
Discover or rule out any new light relic to reheating
Dark Energy
$z_{1\%,DE}$
eBOSS & DES
0.7
LSST & DESI 1.5
LIM
Spec-S5
4.5
PUMA
Next Gen GW.
8
Test dark energy to 1% over the dynamically-relevant redshift range

## Decipher the Quantum Realm

### Elucidate the Mysteries of Neutrinos

- NOνA & T2K; SBN
- DUNE
- IceCube

### Reveal the Secrets of the Higgs Boson

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# Outline

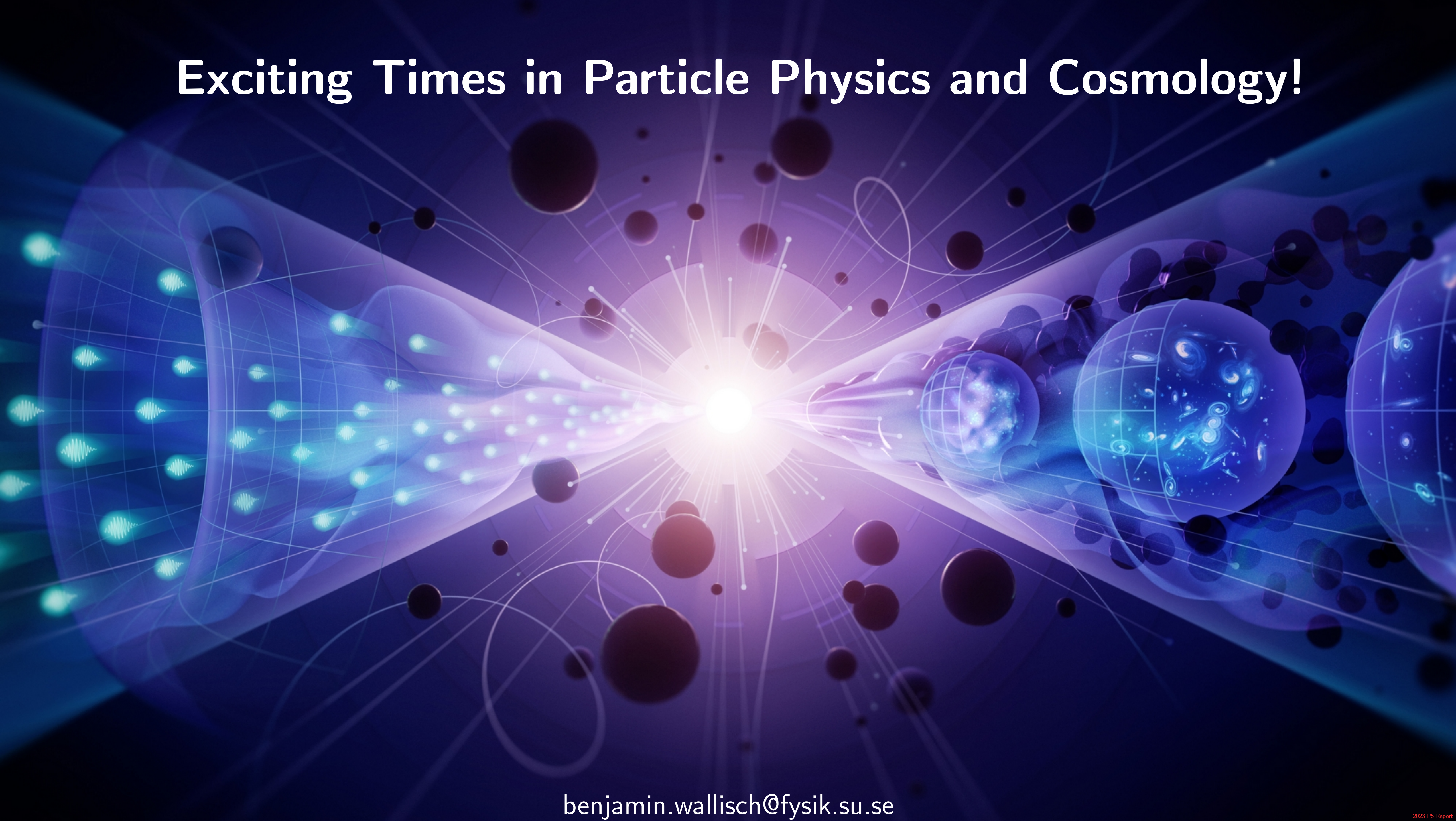
- Snowmass/P5 Processes and Their Global Relevance
- P5 Recommendations to the US Funding Agencies
- Prioritized Experiments and Their Scientific Goals
- Some Lessons
- Discussion

# Some Lessons Learned

- Initial structure is important and can be conducive or hampering in the long term.
- Good leadership open to contributions and new ideas is very beneficial.
- Community organization, mobilization and enthusiasm lead to positive outcomes.
- Coherent message from different sides is very beneficial.
- Can be time consuming for those involved (with limited personal benefit, but broad scientific goals potentially shared more broadly?).
- Exciting and insightful experience.

“By studying the very small and the very large, realms that are beyond the limits of human perception, we expand our understanding of the world around us and begin to grasp our place in the cosmos.”

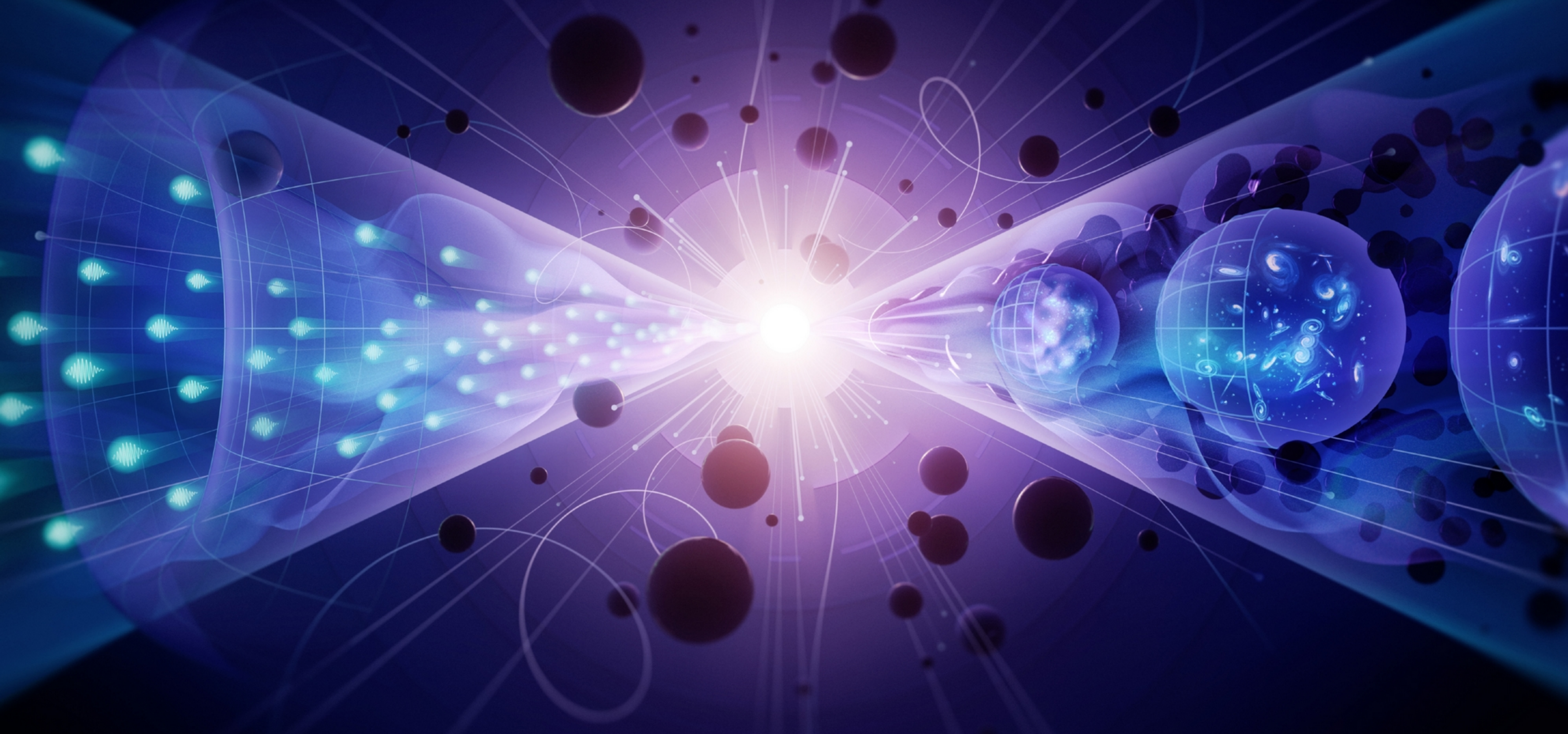
# Exciting Times in Particle Physics and Cosmology!



benjamin.wallisch@fysik.su.se

2023 P5 Report

# More Questions? Discussion?



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2023 P5 Report