Standard Model & Beyond:
The lessons, puzzles & the way forward

Tao Han @ University of Pittsburgh

Winter Institute of New Physics (WINP2025) in Elementary Particle Physics

Sun Yat-sen University, Shenzhen

The Standard Model:
Triumph in science!

With the Higgs discovery, completion of the SM:

- A relativistic & quantum-mechanical
- Perturbative & unitary
- Renormalizable & ultra-violet (UV) complete

→ potentially valid up to an exponentially high scale, perhaps to the Planck scale!

All known physics

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \; \exp\left\{ \frac{i}{\hbar} \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda \phi \bar{\psi} \psi + |D\phi|^2 - V(\phi) \right] \right\}$$

amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

An eminent physicist remarked:

"... most of the grand underlying principles have been firmly established. The future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiment (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

The Standard Model in the making:
温故知新
Lesson 1: "UV completion"

- QED is UV complete, but doesn't go beyond O(GeV)

  e.g. $(g-2)_e$ versus $(g-2)_\mu$
- QCD is UV complete, could be dynamically extrapolated to an exponentially high scale Q

$$\alpha_s(Q^2) \approx 1/\ln(Q^2/\Lambda^2_{QCD}) \Rightarrow \Lambda_{QCD} \approx Q\exp(-1/2\alpha_s)$$

But new physics comes in at $v \sim 250\ \mathrm{GeV}$

- The SM with the Higgs IS UV complete,

but what confidence do we have to extrapolate it to $O(M_{PL})$?

→UV completion needs NOT to be a completion!

***i.e.* Go for BSM!**

Lesson 2: EFT

"The present educated view of the standard model, and of general relativity, is again that these are the leading terms in effective field theories." S. Weinberg, hep-th/9702027

"We are all Wilsonians now."

- J. Preskill, Quantum Frontier (2013)

In terms of a new physical scale Λ, below which the theory is valid:

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \underbrace{c_0 \Lambda^4 + c_2 \Lambda^2 \mathcal{O}_{\text{dim } 2} + c_3 \Lambda \mathcal{O}_{\text{dim } 3}}_{\text{(relevant operators)}} + \underbrace{c_4 \mathcal{O}_{\text{dim } 4}}_{\text{(marginal operators)}} + \underbrace{\frac{c_6}{\Lambda^2} \mathcal{O}_{\text{dim } 6} + \cdots}_{\text{(irrelevant operators)}}$$

The 1st (most) "relevant operator": $c_0\Lambda^4$

Known physics scales and the observation:

$$(\mathrm{M_{PL}}/\Lambda_{cosm})^4 \sim 10^{120}\,! \quad (\Lambda_{\mathrm{QCD}}/\Lambda_{cosm})^4 \sim 10^{44}\,!$$

Wilsonian argument failed (badly)!

"… I do not understand (quantum) gravity" --- William Bardeen

The 2nd "relevant operator": the Higgs boson mass

$$\mathbf{V = -\mu^2 |\phi|^2 + \lambda |\phi|^4}$$

$$c_2\Lambda^2 \sim m_h^2 : \ \lambda v^2 \sim \mu^2 \sim (100\ \mathrm{GeV})^2 \sim (10^{-16} M_{\mathrm{Planck}})^2$$

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." Ken Wilson, 1970

→We are only in command with "marginal & irrelevant operators"!

Think outside of the box …

Lesson 3: Unification

- Newtonian universal gravitation unified
  the terrestrial & celestial forces & motion
- Maxwell equations unified
  the electricity & magnetism
- Dirac eq. unified Schrodinger eq. & Special rel.
  → electron + positron
- The SM unifies the electromagnetism (**γ**)
  & weak force ($W^{\pm}$, Z^0) to "electroweak"
  → New vacuum structure

→"Unification" reveals deep principles!

Lesson 4: Symmetry principles

- Time translation → energy conservation
- Spatial translation → momentum conservation
- 3D rotation → angular momentum conservation
- Poincare invariance → mass & spin of states
- "higher symmetry" of space-time & S-matrix

Supersymmetry? Bosons ←→ Fermions

→Symmetry governs dynamics;
Symmetry breaking specifies the Nature!

- We have LEARNED A LOT about Nature!
- We have ACCOMPLISHED A LOT in the SM making!
- We have been lucky to have WITNESSED the history, and CONTRIBUTED to it!

Still, there are many **PUZZLES** to contemplate on;

and **PROBLEMS** that need a solution!

Problem 1: Neutrinos ARE massive

ν's: the most elusive/least known particle in the SM:

- How many species: 3 ν_L 's + N_R?
- Absolute mass scale: $m_\nu \sim y_\nu \, v < 1$ eV?

or a new physics scale via "see-saw": $m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$

- Flavor oscillations & CP violation?
- Mixing with sterile/Majorana ν's?
- Portal to dark sector?

Studying neutrino physics has been rewarding:
6^+ Nobel Prizes related to ν's!

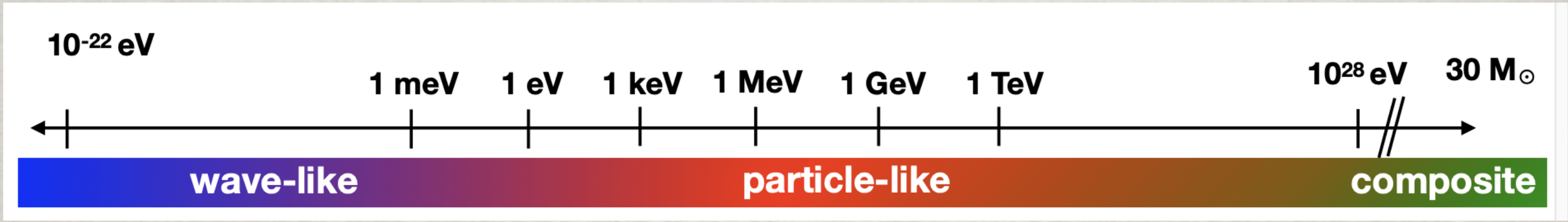
Great playground for theory & experimentation.

→ Determine the masses & their generation mechanism!

Problem 2: Dark Matter exists

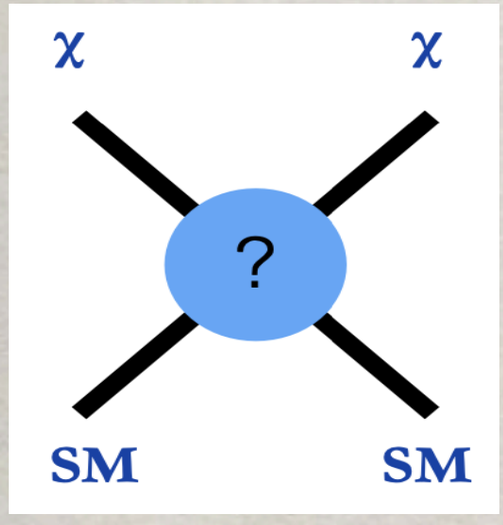
Mounting evidences for DM, thus BSM

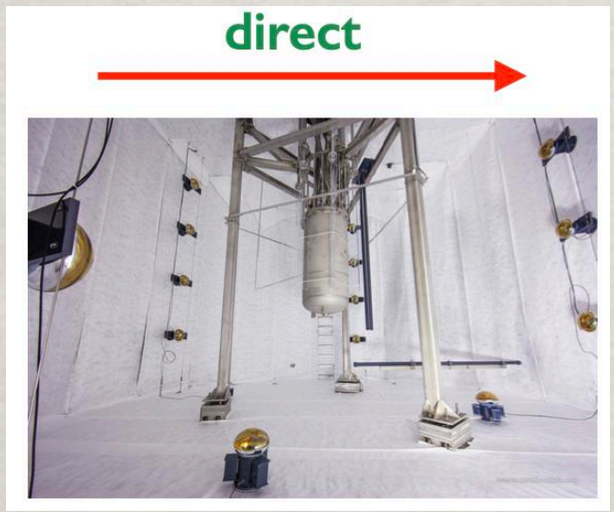
Dark Matter in theory: "embarrassment of riches"

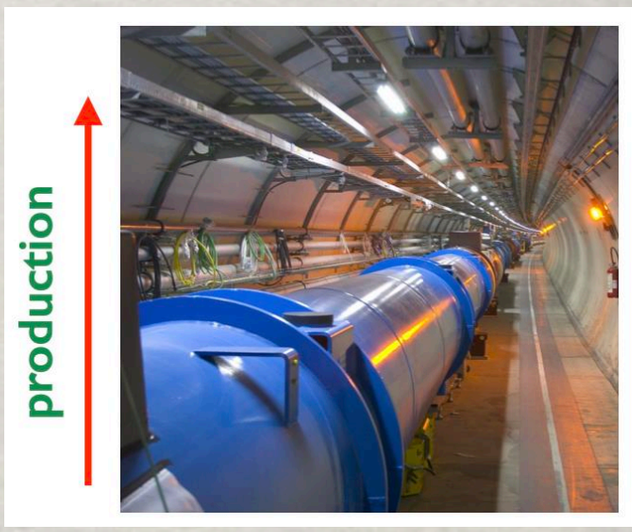


axions, dark photons … sterile ν's WIMPs WIMPzillas PBH?

Dark Matter in practice:







Much more recent activities in light DM detection!

→ **Possible next breakthrough: WIMPs, ALPs …**

Problem 3: Baryogenesis & CPv

The observed baryon dominance → BSM

Sakharov conditions:

- Baryon # violation (EW sphalerons)
- C & CP violation (BSM)
- Out of equilibrium (1st order PT, BSM)

Many BSM theories to accommodate

- Affleck-Dine mechanism (primordial universe)
- Lepto-genesis (ΔB = ΔL via sphalerons)
- EW baryogenegis (1st order PT, BSM)

Observationally,

ΔB ≠ 0 → proton decay, $n - \bar{n}$ oscillation

ΔL ≠ 0 → Majorana neutrinos

Plus extra Higgs bosons to search for

Stochastic gravitational waves …

Puzzles (not "problems")
that may not find a solution

- Mass hierarchy: "Naturalness"?

  why $M_H \ll M_{PL}$ (Large hierarchy)
  and $M_H \ll \Lambda_{NP}$ (Little hierarchy)

- New dynamics: "Composite"?
  - Extended symmetry: SUSY?
  - Unified forces: GUTs?
- Flavors: "minimal flavor violation"?

  Flavor-mixing pattern; mass hierarchy;
  Strong CP phase …
- Extra dimensions / Quantum gravity?
- … …

The Way forward: global context

- **Europe**

European Strategy Process:

2020 Update of European Strategy for Particle Physics

HL-LHC; Fcc-ee, Fcc-hh; R&D in accl., detec, theo.

(Feb. 2, 2024: CERN Council midterm review on Fcc project)

- **Asia**

- Japan: 2017 JAHEP/KEK Roadmap:

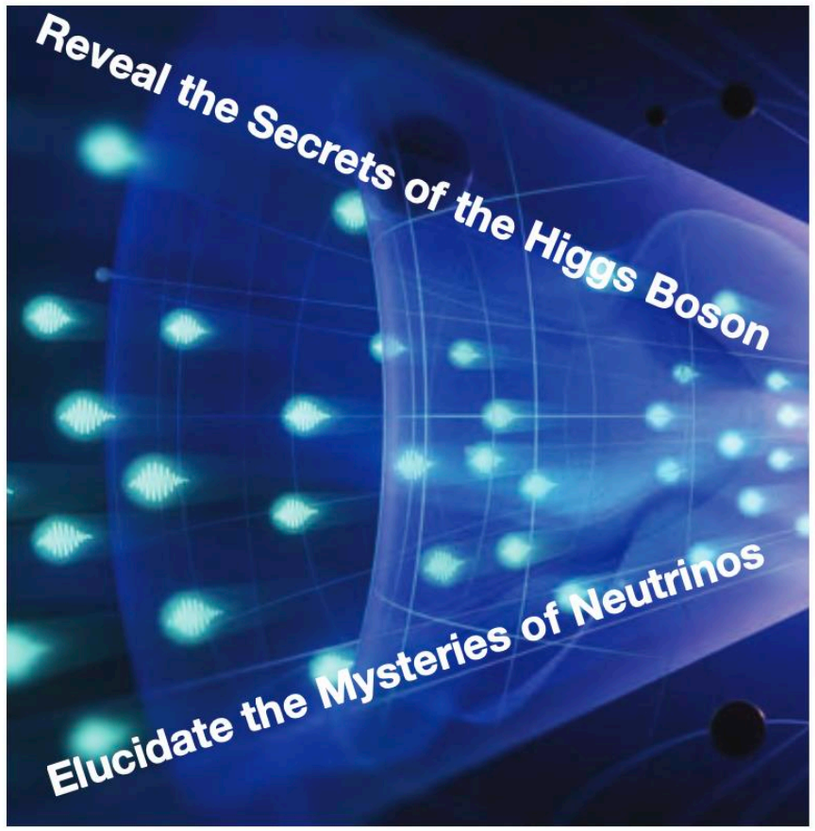
  SuperKEKB; J-PARC; Hyper-K; ILC …
- China: BEPC-II; JUNO; PandaX; LHAASO; AliCPT, CEPC/SppC …

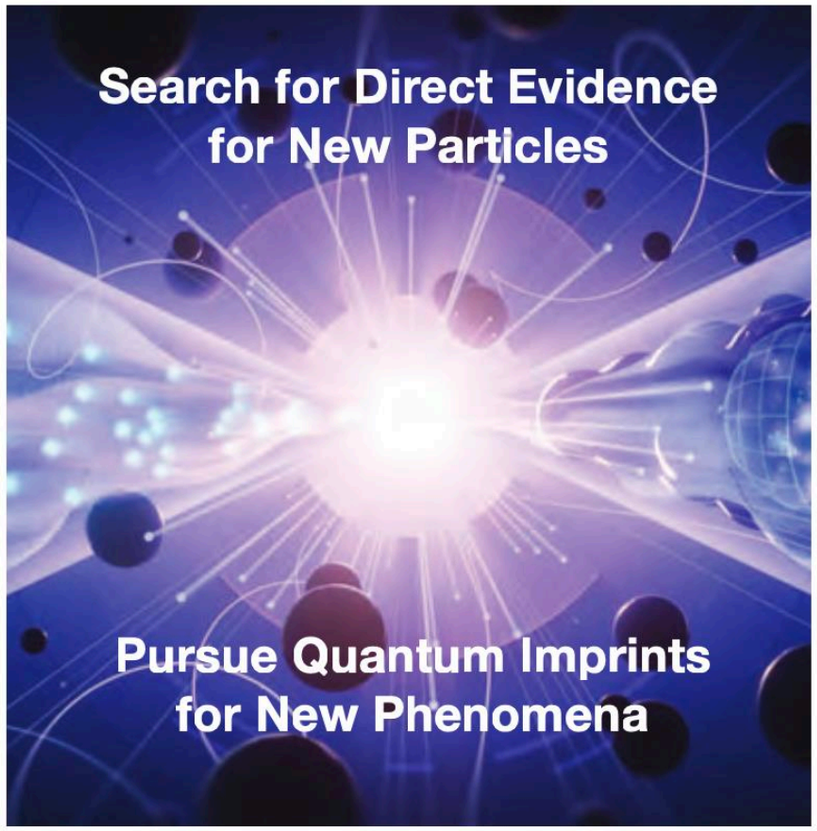
- **United States**

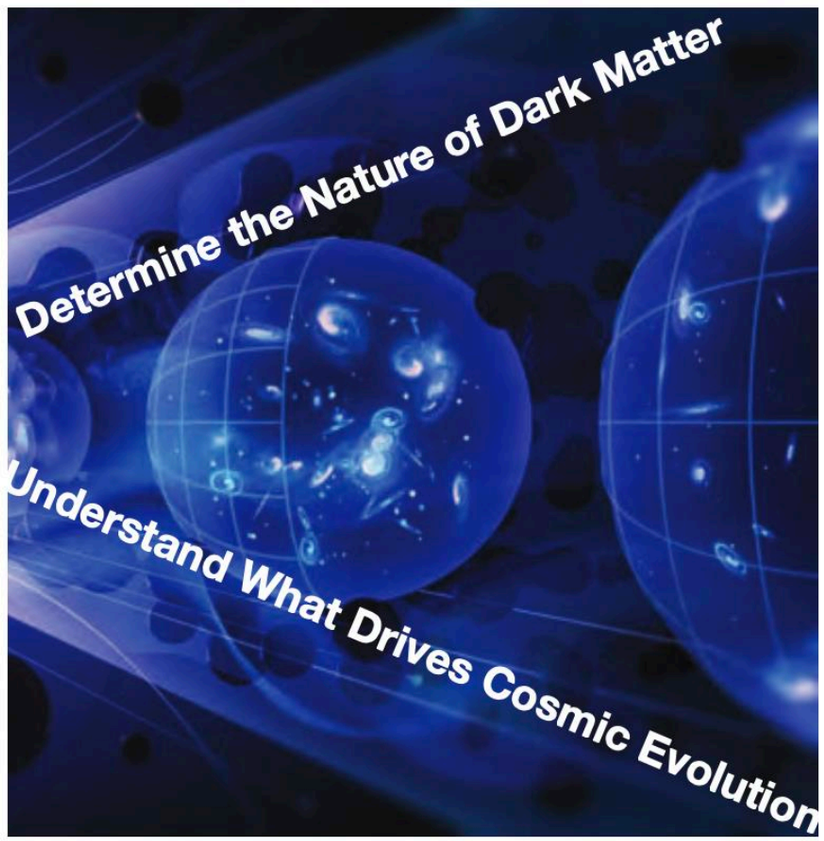
- NAS Decadal survey on Astronomy & Astrophysics (2021)
- NAS Decadal survey on Elementary Particle Physics (2023)
- Snowmass 2021 for a decadal study: two year work
- P5 (Particle Physics Project Prioritization Panel) final report

Explore the Quantum Universe

https://www.usparticlephysics.org/2023-p5-report/





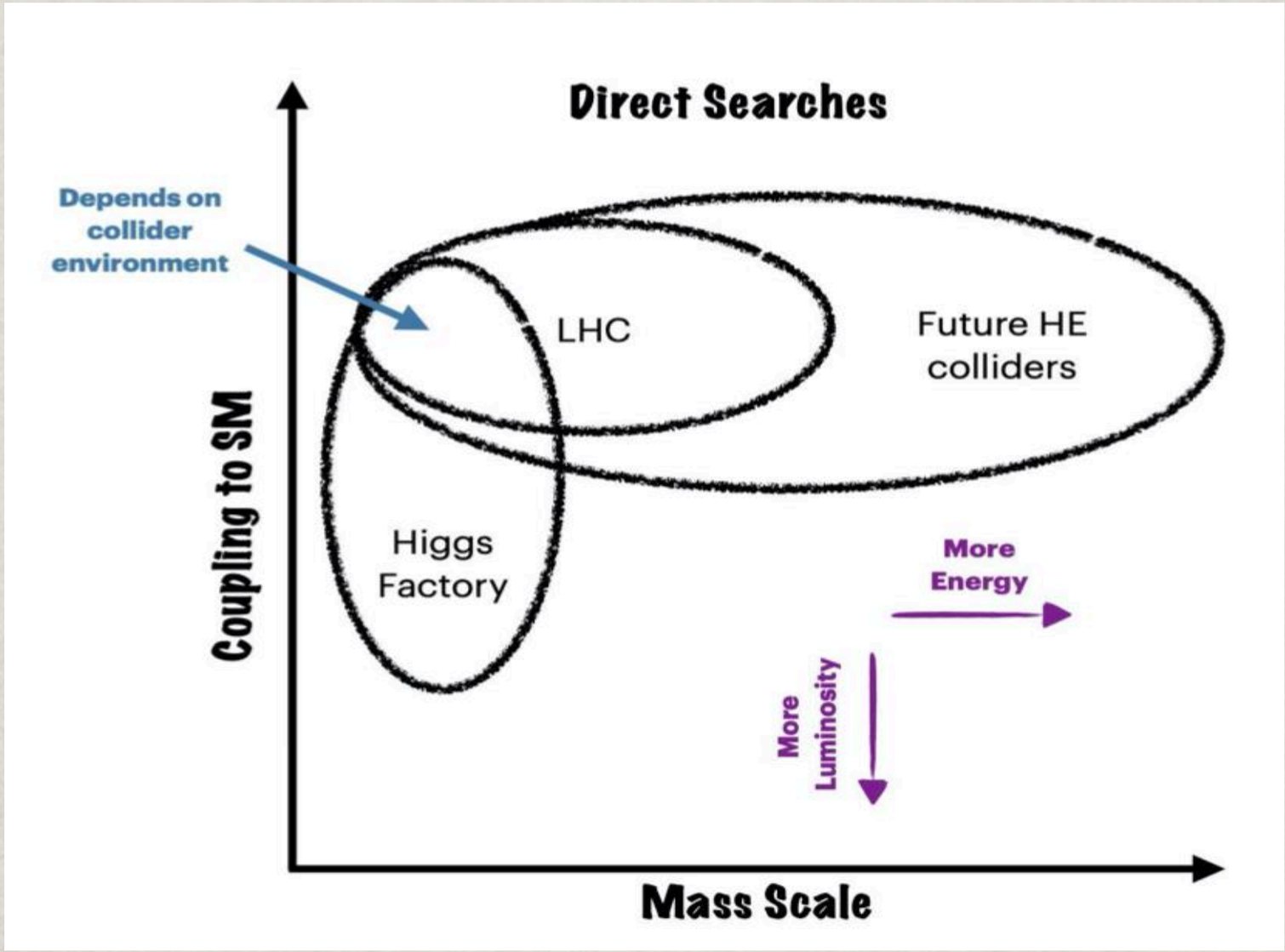


Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

The Energy Frontier Vision:



The energy frontier believes that it is essential to complete the HL-LHC program, to support construction of a Higgs factory, and to ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a Muon Collider or a hadron collider.

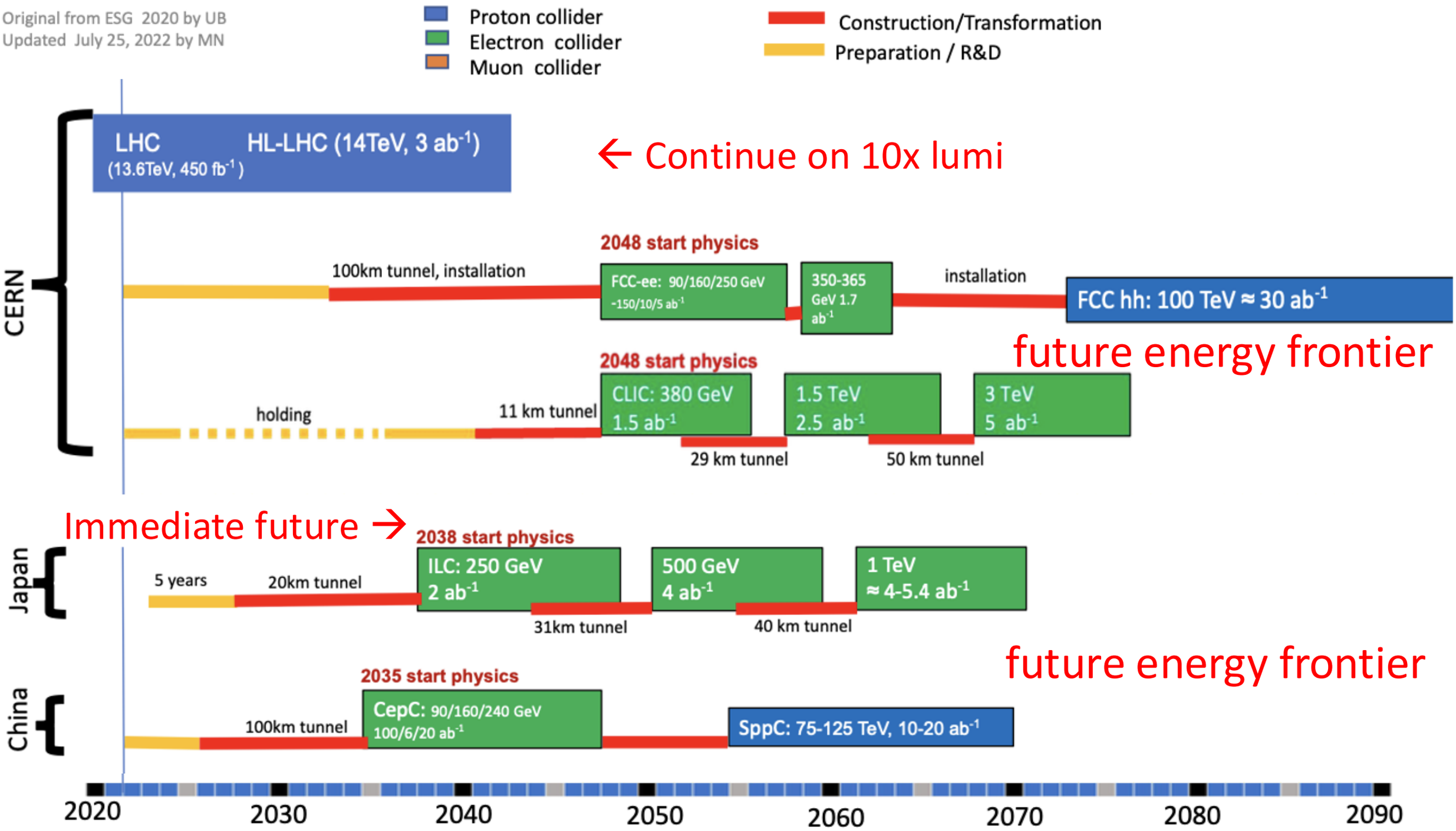
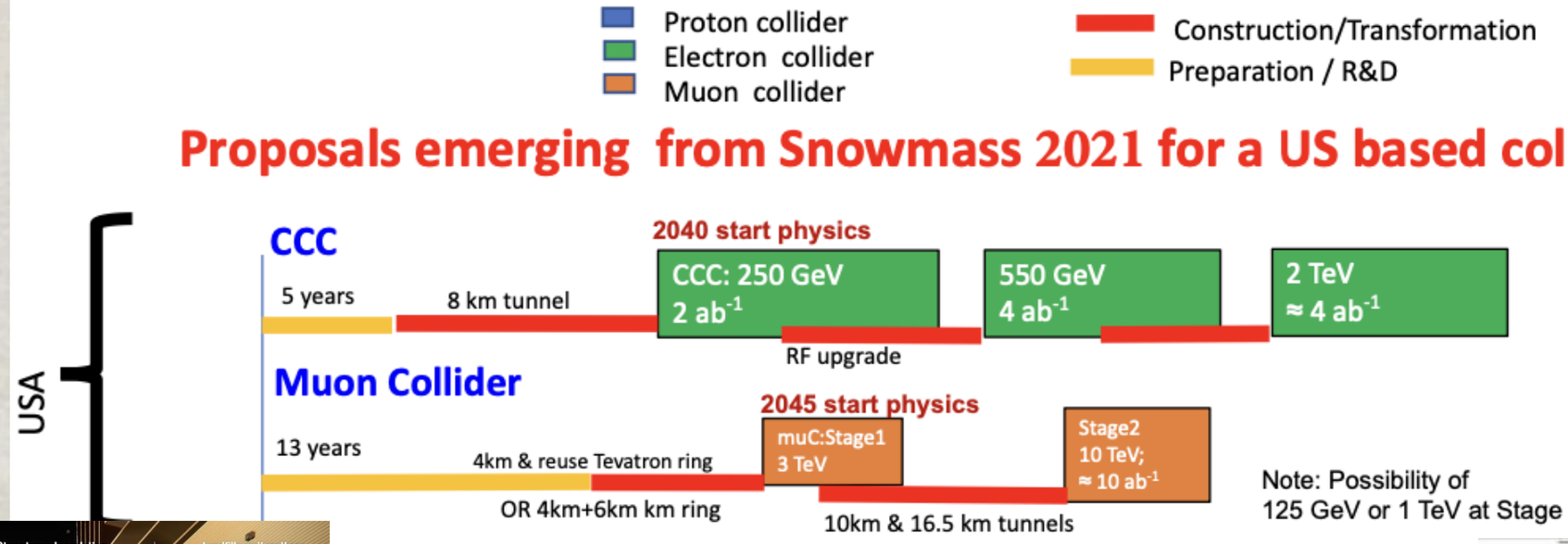


Figure 6-40. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*

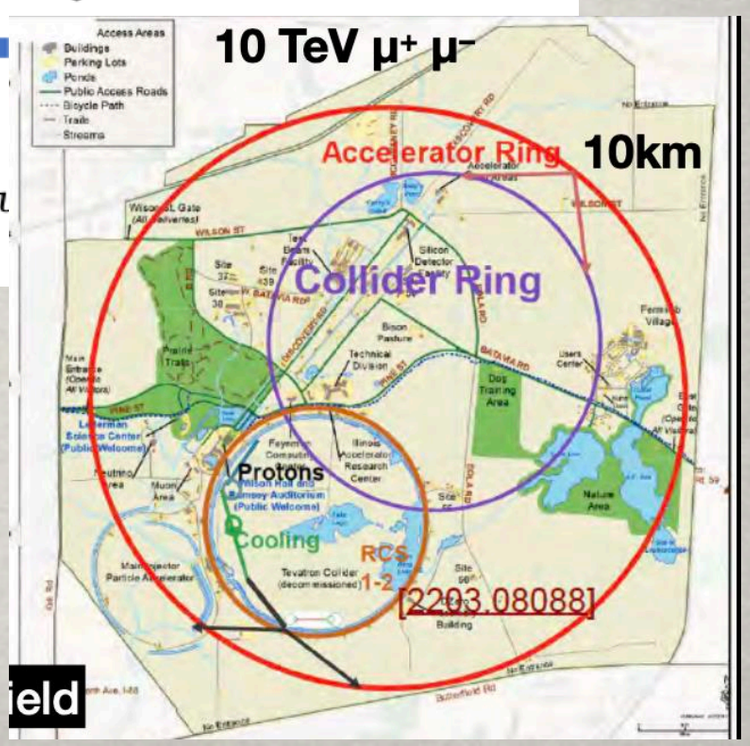
The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**



Approximate timelines for proposals for ILC/CCC and Mu
for a US based collider option.

The "Muon Shot"

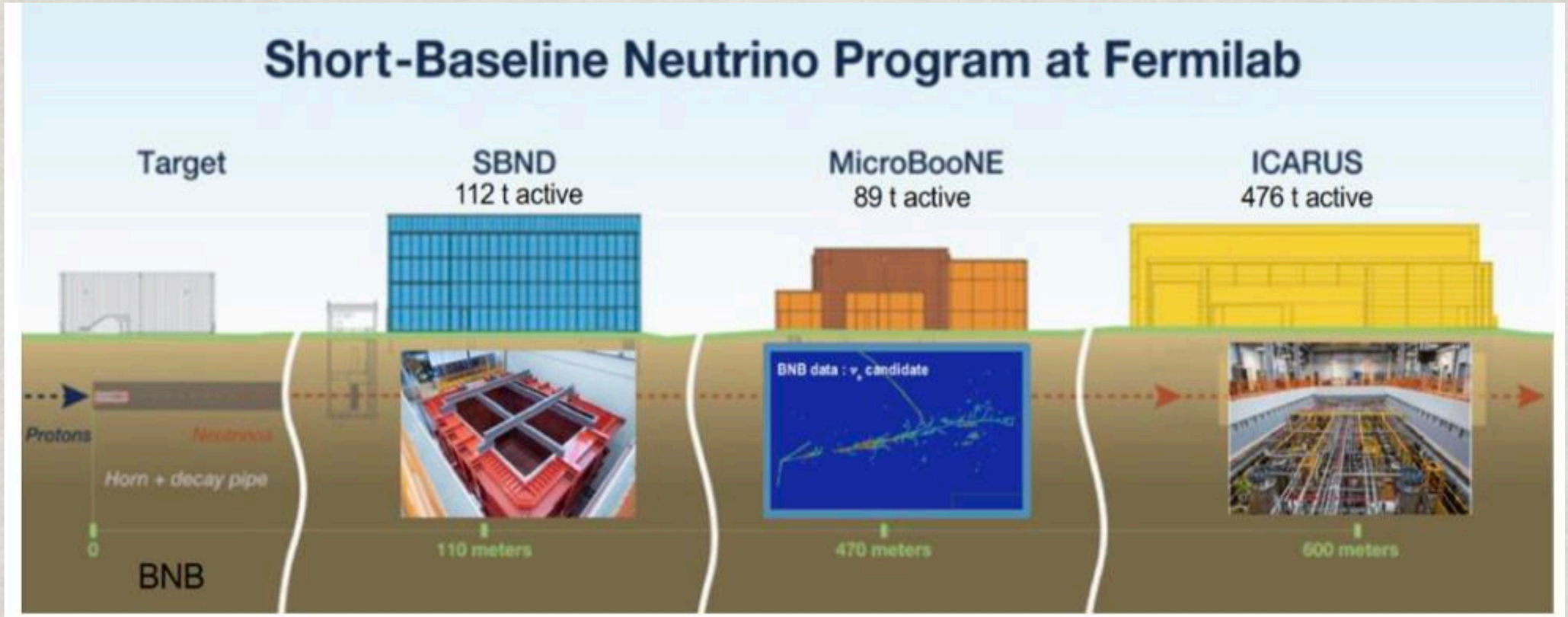


Most wanted coupling: hhh

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

Conclusive test for the Higgs potential & EWPT

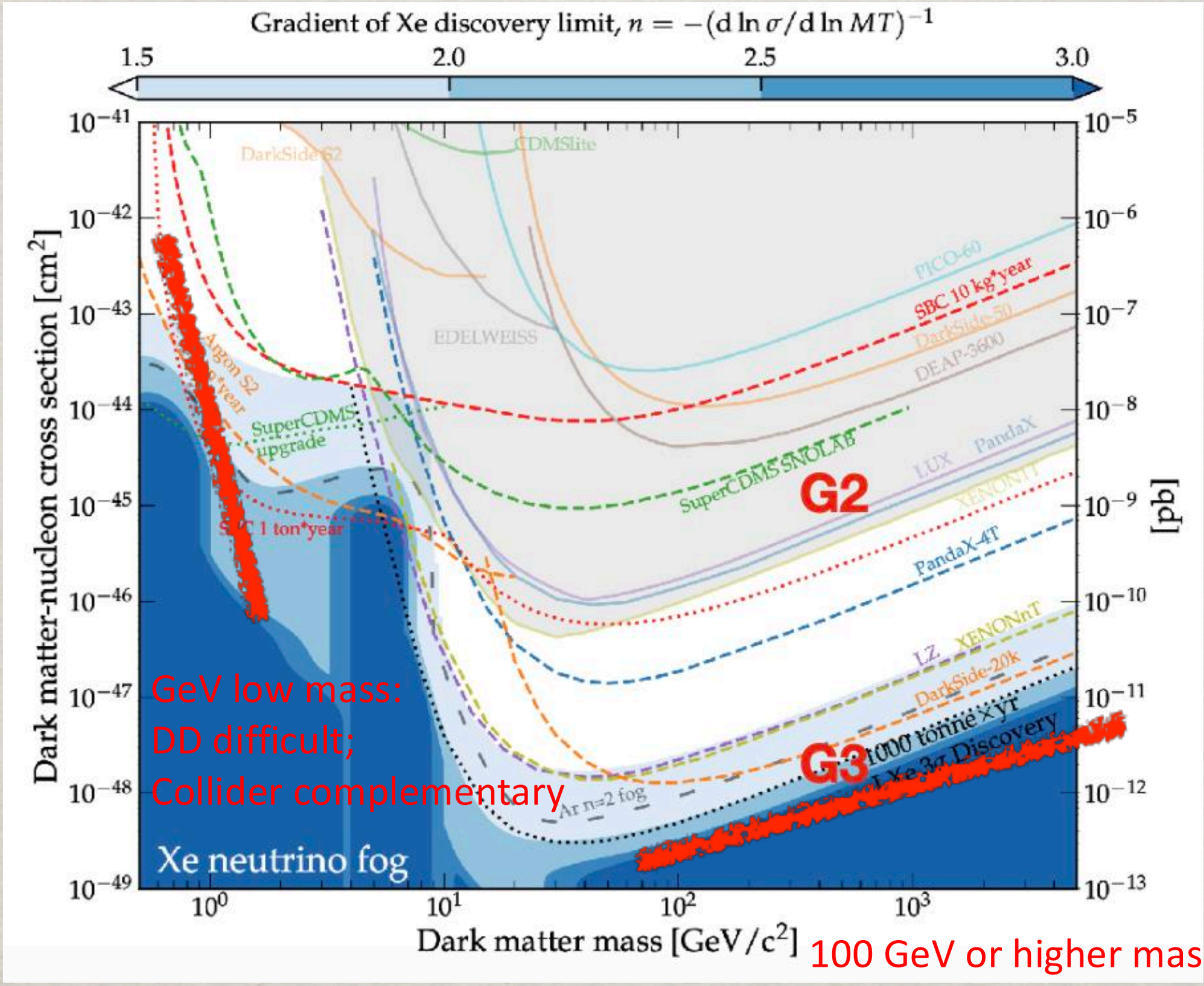
On-going & Upcoming neutrino Experiments



Future LBNE:

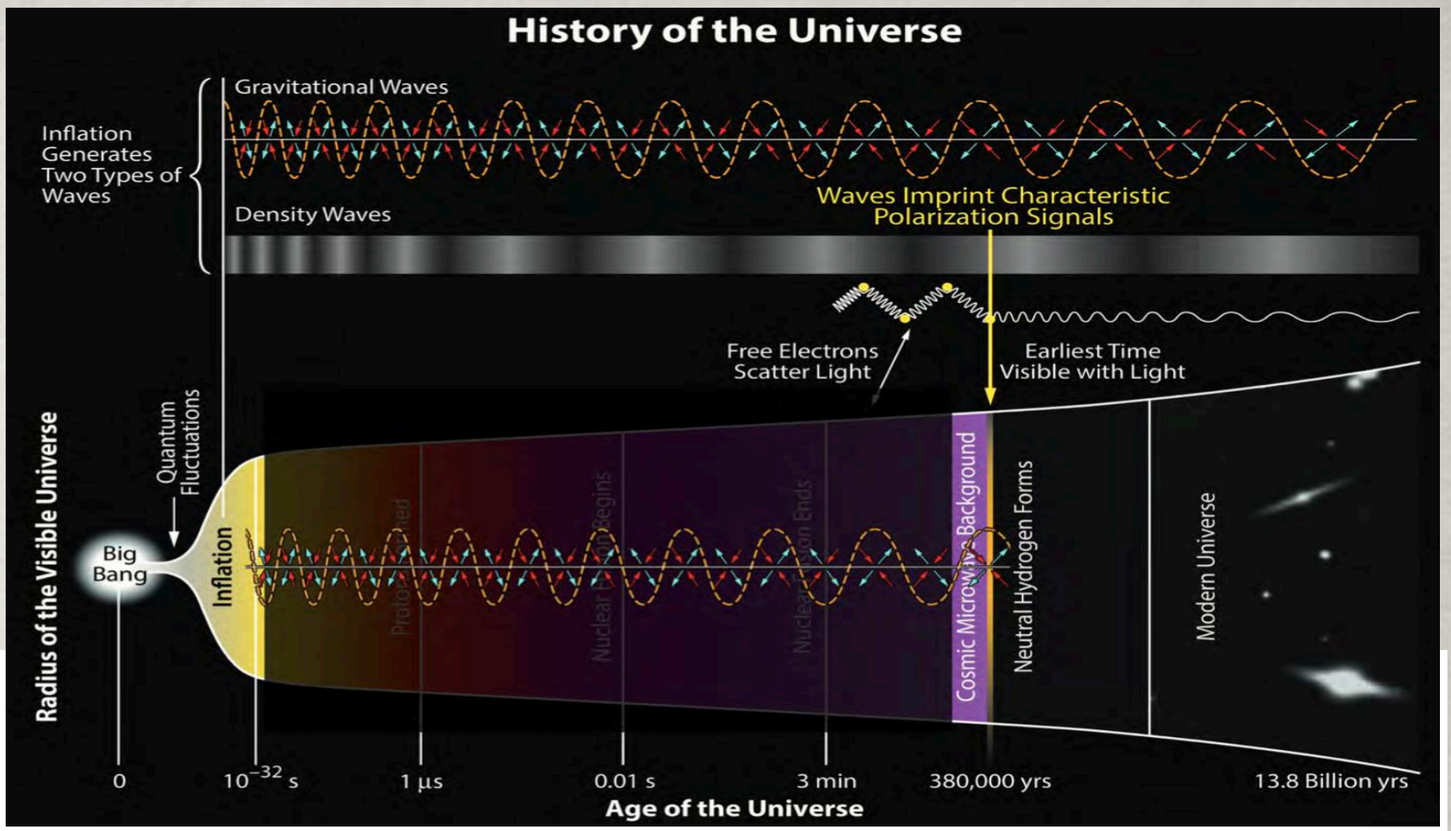
Exp.	Time	Mass ordering	CP phases	Precision Meas.
JUNO (20 kt)	2024	**3-4 σ** *6 y*	—	**$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%),** *6 y*
HyperK (260 kt)	2027	**3-5 σ** *10 y*	**5σ (60%)** *10 y*	Δm^2_{32} ~0.6%, $\sin^2\theta_{23}$~*1.6% *, 10 y*
DUNE (17 kt*4)	2030	**>5 σ** *1-3 y*	5σ (50%) *10 y*	Δm^2_{32} ~0.4%, $\sin^2\theta_{23}$~*1.1% *, 15 y*

G2 to G3 DM Direct Detection

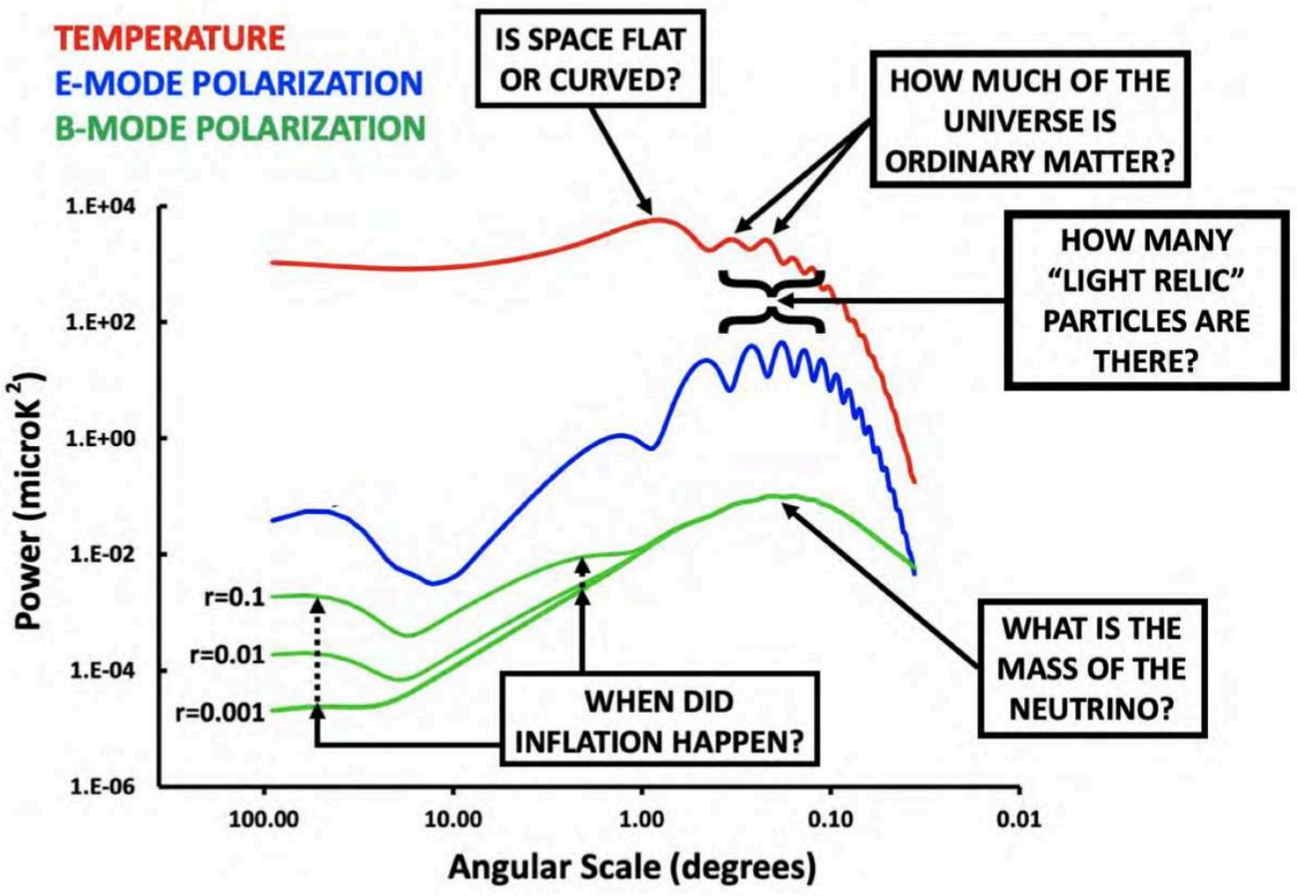


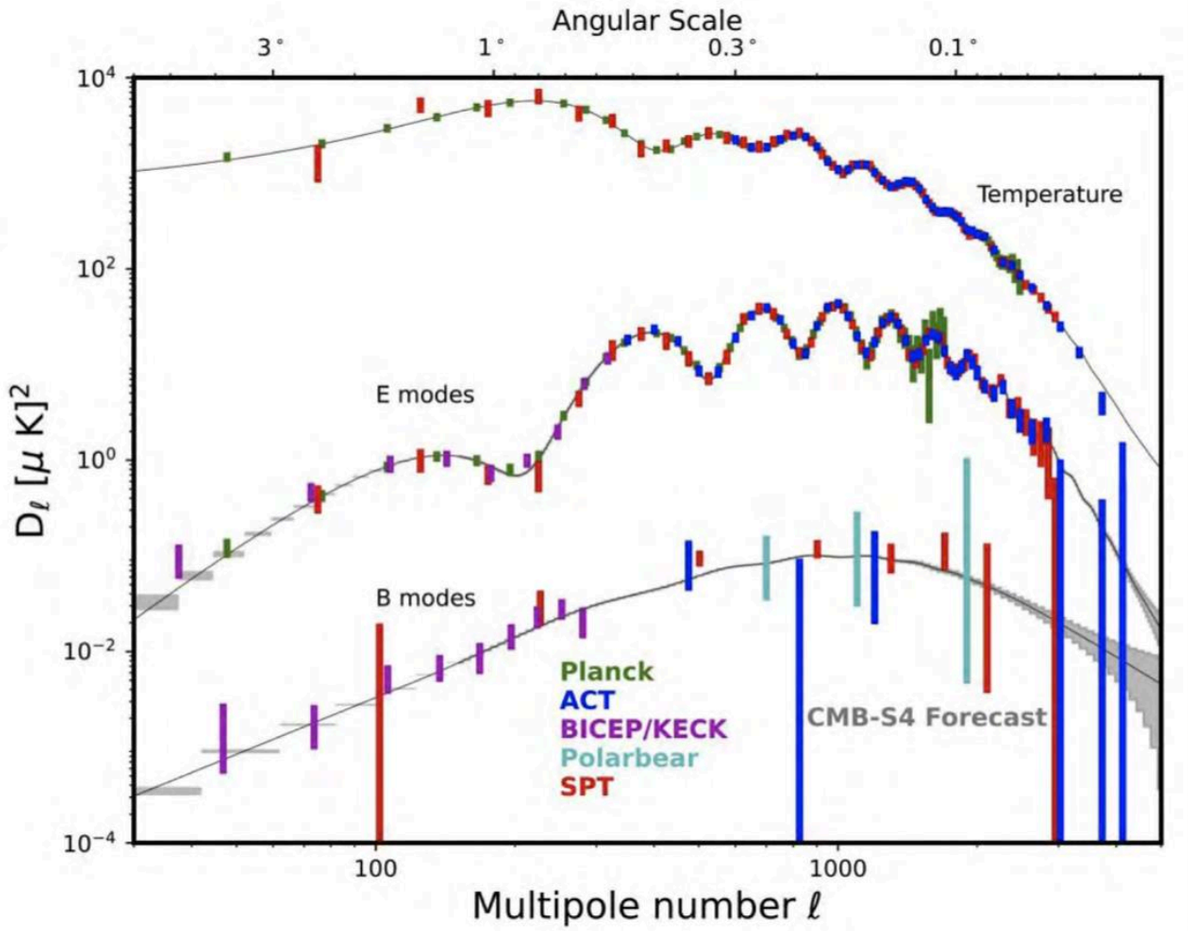
100 GeV or higher mass:
DD + ID + HE Collider

Particle physics & early universe cosmology

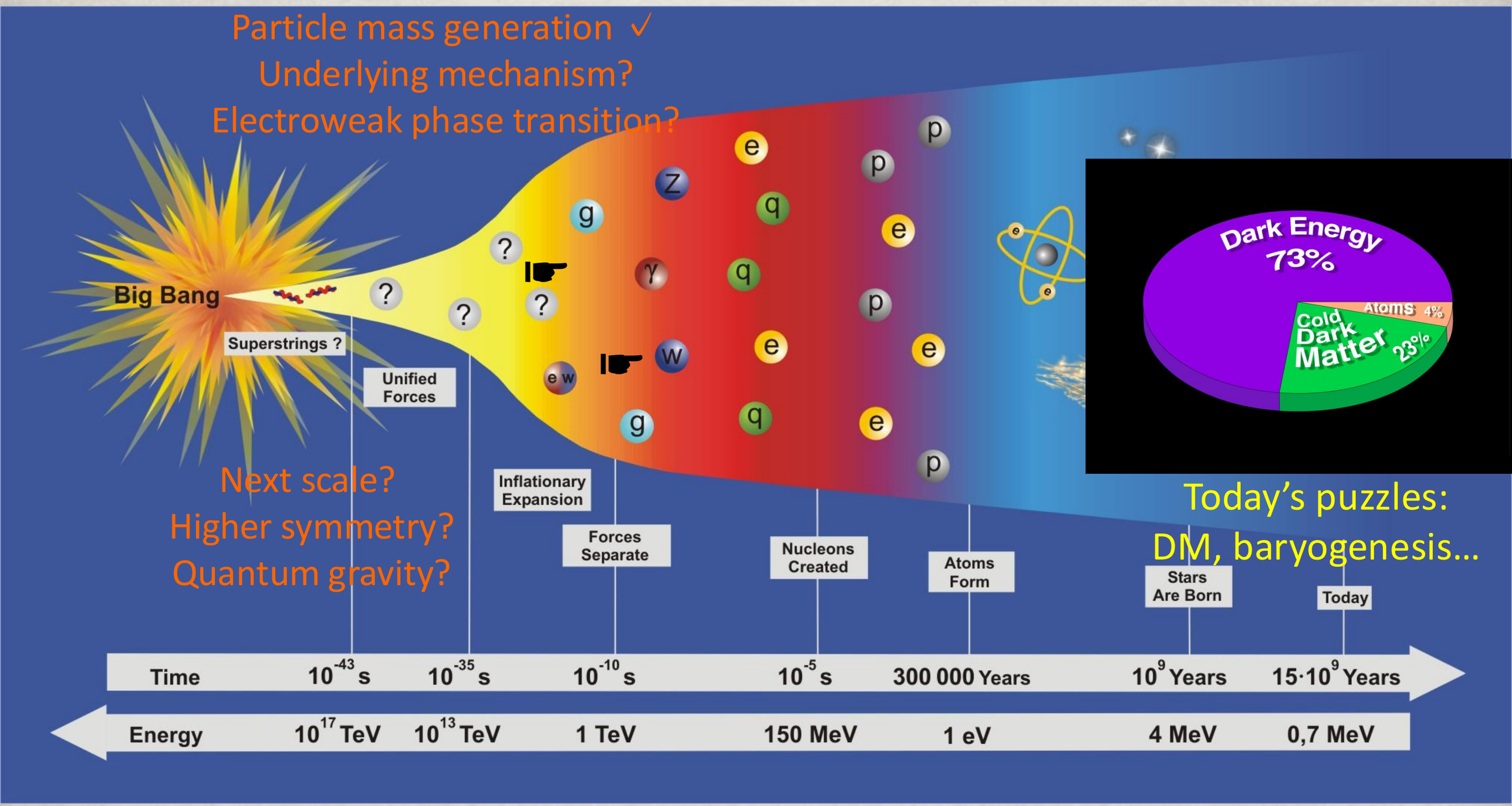


CMB S4





A Grand Picture: SM & BSM



exciting journey ahead!

summary

The Standard Model: A triumph in science!

Lessons from SM in the making, on

UV completion? Naturalness?

Unification; Higher symmetry;

Strong dynamics; Quantum Gravity

Problems that need a BSM solution

Dark matter; Neutrino mass;

Baryon asymmetry & CP violation

Challenging model-building &
exciting experimental programs ahead!