

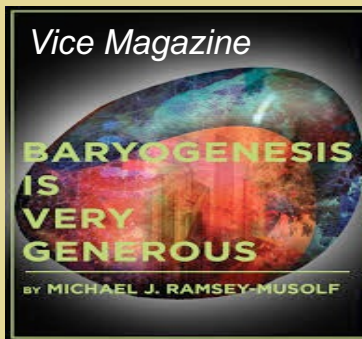
# More Matter Than Anti-Matter: When and How ?

## M.J. Ramsey-Musolf

- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst*
- *Caltech*

### *About MJRM:*

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- [mjrm@sjtu.edu.cn](mailto:mjrm@sjtu.edu.cn)
- 微信 : mjrm-china
- <https://michaelramseymusolf.com/>



*Science*



*Family*

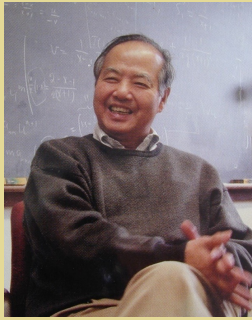


*Friends*

*My pronouns: he/him/his*  
*# MeToo*

USTC Lectures June 4-6, 2023

# T. D. Lee Institute / Shanghai Jiao Tong U.



Director



Prof Jie Zhang

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world famous source of original innovation



Founded 2016

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

## Theory & Experiment

Particle & Nuclear Physics

Astronomy & Astrophysics

Quantum Science

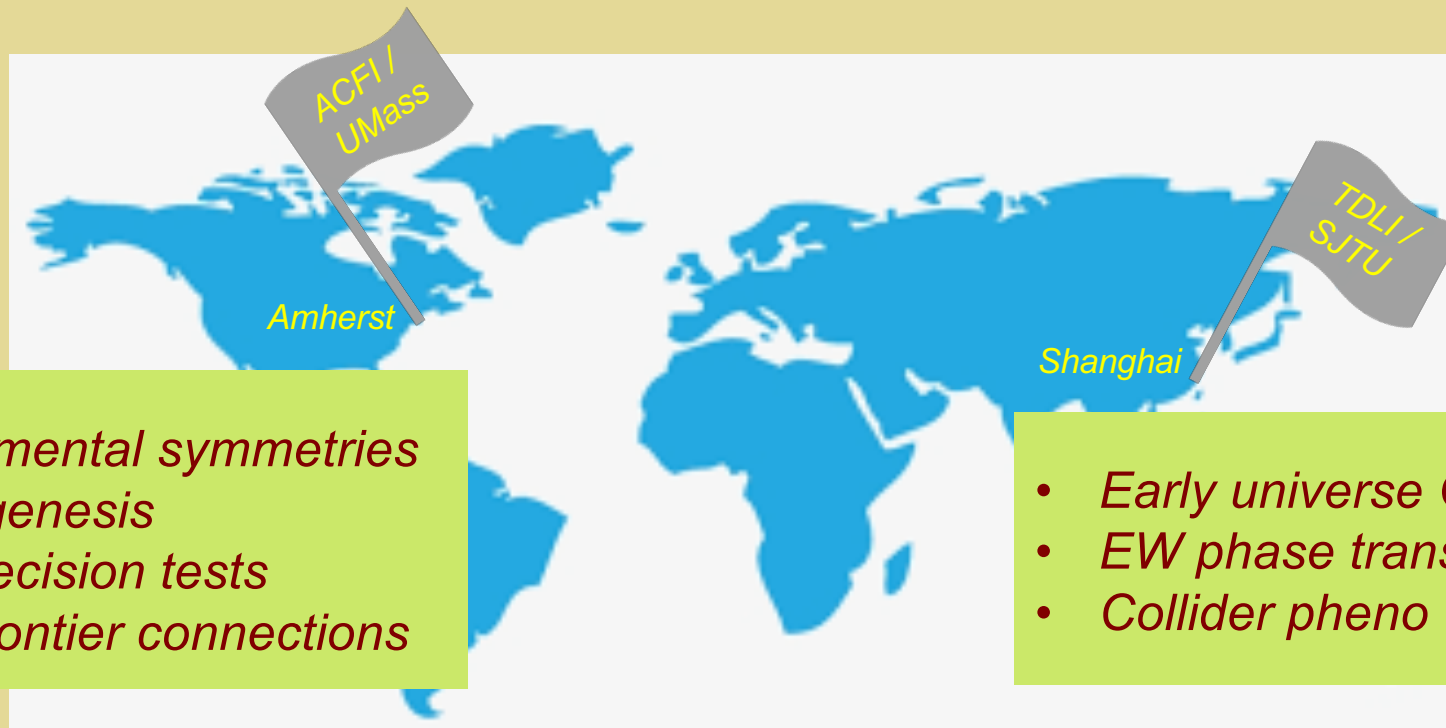
Dark Matter & Neutrino

Laboratory Astrophysics

Topological Quantum Computation

<https://tdli.sjtu.edu.cn/EN/>  
<https://www.youtube.com/watch?v=z0awD6q8FTI> 19.1

# ***MJRM: Scientist & “Ambassador”***

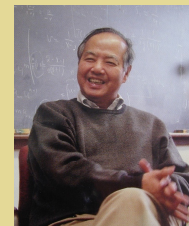


- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

- *Early universe QFT*
- *EW phase transition*
- *Collider pheno & Higgs*



- ***Global effort: 18 researchers***
- ***Foster scientific connections***
- ***Science First ! 科学第一 !***



## ***Goals for this Talk***

- ***Introduce the matter-antimatter challenge and its connection with other open questions in particle physics***
- ***Highlight the opportunities for experimental discoveries and insights addressing this challenge***
- ***Illustrate recent theoretical developments***
- ***Invite you to engage in the quest to solve the origin of matter problem***

## ***Key Ideas for this Talk***

- ***Explaining the origin of matter – “why we exist” -- is one of the key challenges at the forefront of fundamental interaction physics***
- ***Addressing this challenge requires BSM physics and violations of fundamental symmetries beyond the known SM violations***
- ***The origin of matter problem presents rich opportunities for experimental discoveries and theoretical insights***
- ***Exploiting inter-frontier connections is vital***

## ***Three Lectures***

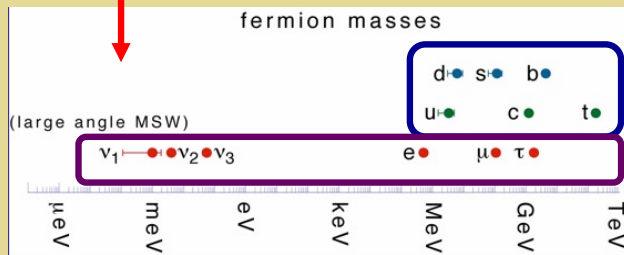
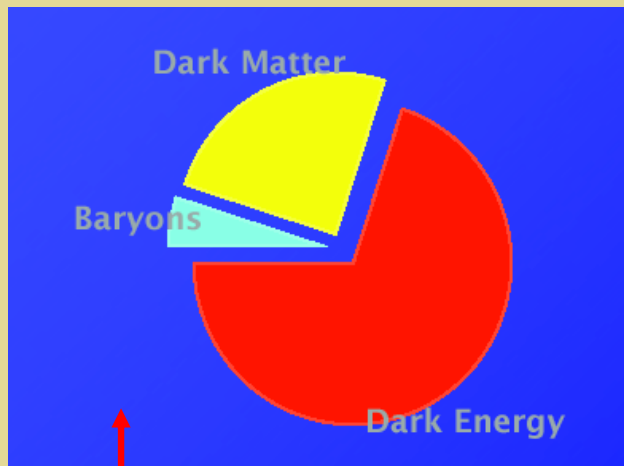
- ***Was There an Electroweak Phase Transition ?***
- ***BSM CPV: Electric Dipole Moments & More***
- ***BSM LNV Two-for-One:  $m_\nu$  &  $Y_B$  ?***

# ***This Introduction***

- ***Fundamental questions in particle physics***
- ***Experimental Probes & Inter-frontier Connections***
- ***The Origin of Matter Problem***

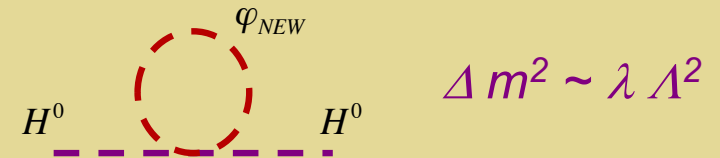
# Fundamental Questions

**MUST** answer



Origin of  $m_\nu$

**SHOULD** answer



$\Lambda$  Cosmological



# Experimental Probes: Energy Frontier

LHC

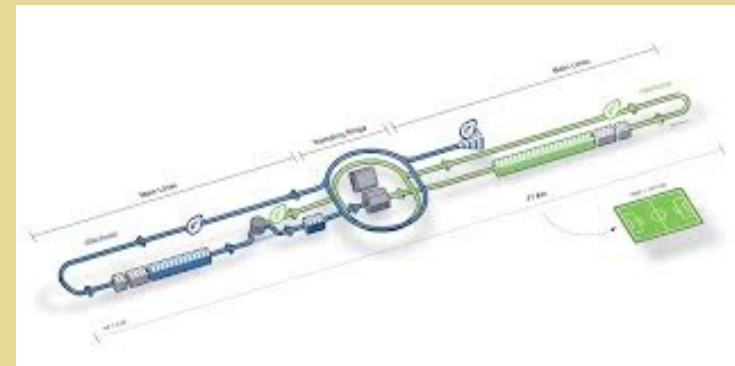


ATLAS

CMS

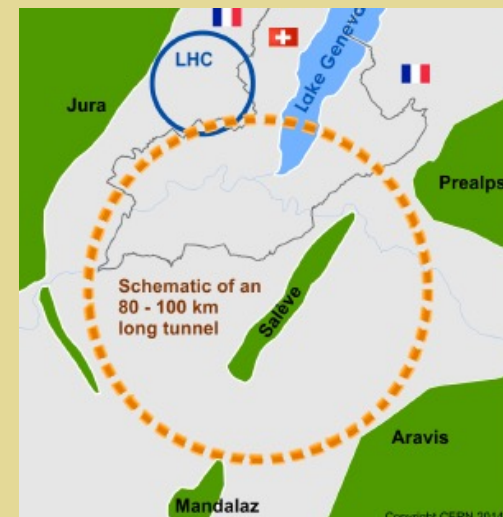
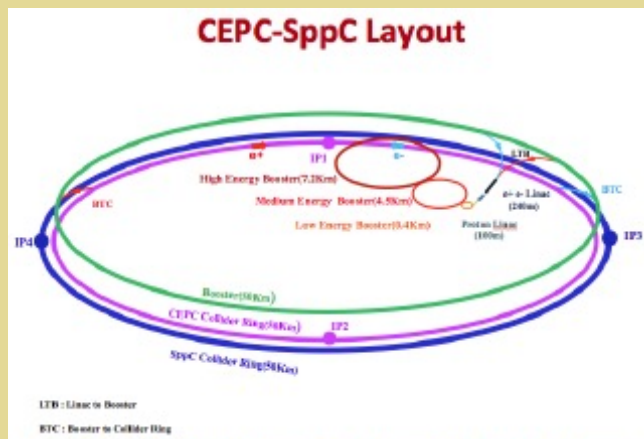


International Linear Collider



Future Circular  $e^+e^-$  &  $pp$

Future Circular  $e^+e^-$  &  $pp$

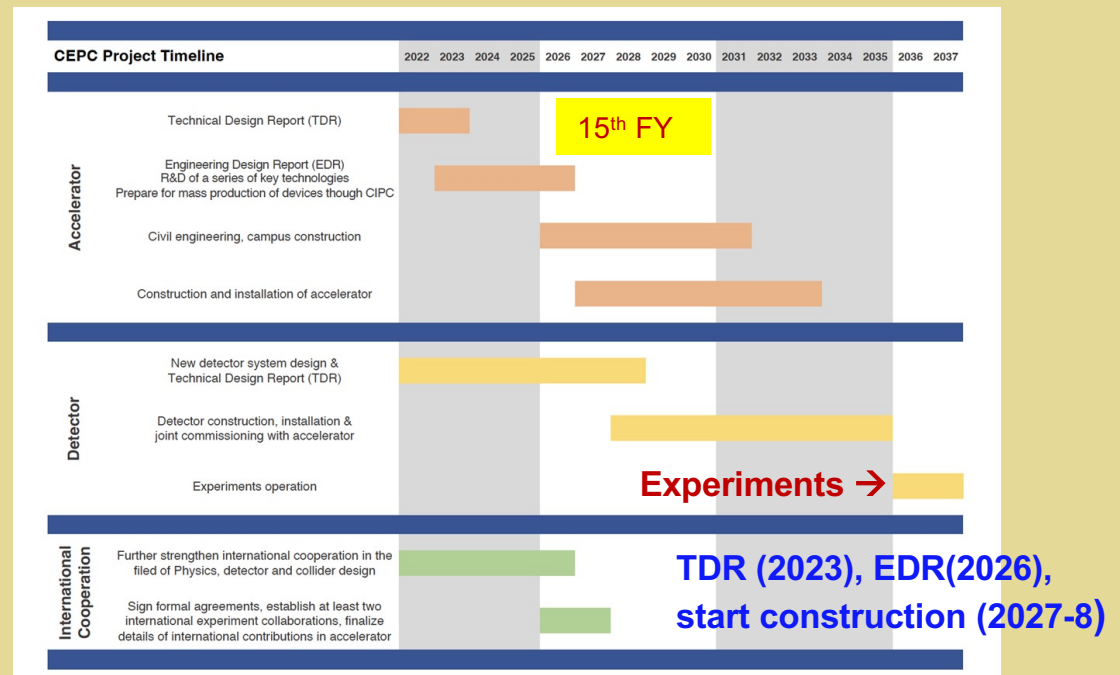


# Future Colliders: CEPC

- ❑ The idea of CEPC was proposed in Sep. 2012, and quickly gained the momentum in IHEP and in the world.
- ❑ The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- ❑ To run at  $\sqrt{s} \sim 240$  GeV, above the **ZH** production threshold for  $\geq 1$  M Higgs; at the **Z** pole for  $\sim$ Tera Z; at the **W<sup>+</sup>W<sup>-</sup>** pair and then **t $\bar{t}$**  pair production thresholds.
- ❑ Higgs, EW, flavor physics & QCD, probes of physics BSM.
- ❑ Possible *pp* collider (SppC) of  $\sqrt{s} \sim 50\text{--}100$  TeV in the far future.



Yuhui Li, CEPC 2023, Nanjing

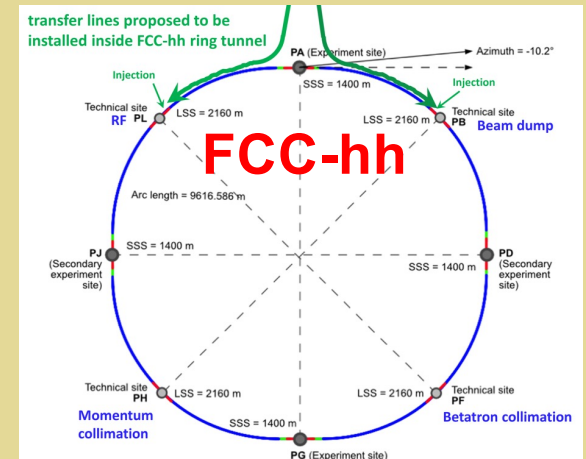
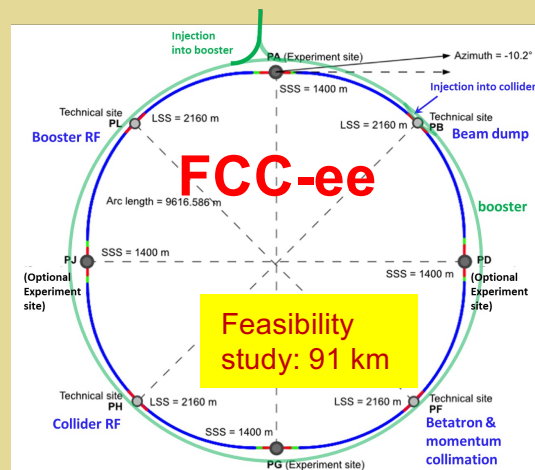


# Future Colliders: FCC

*European Strategy for Particle Physics 2020*

comprehensive long-term program maximizing physics opportunities

- stage 1: FCC-ee (Z, W, H,  $t\bar{t}$ ) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



2020 - 2040

2045 - 2063

2070 - 2095



# Future Colliders: ILC & CLIC

## Linear Colliders

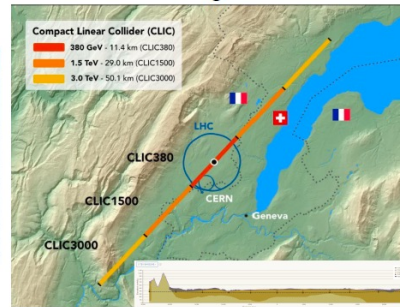
ILC & CLIC specs



- Energy extendability to TeV scale lies in the heart of linear colliders: ILC focuses on  $\sqrt{s}$  from 250 GeV to 1 TeV; CLIC 380 GeV to 3 TeV; keeping options to run at Z-pole (“GigaZ”)
- Complementary approaches: “Warm” & “Cold” accelerating technologies; 72MeV/m @ CLIC380; 31.5MeV/m @ ILC250
- Polarized beams: both offering 80% for electron; 30% for positron in ILC default design



ILC250 ~ 20km



- MEXT (represents Japanese government) didn't approve the original Pre-Lab proposal [newsline]
- Not entirely negative: pointed out what directions to move forward [“hosting is not the problem”, S.Asai]
- Support to carry out time-critical R&D that was in the Pre-Lab proposal
- A really encouraging sign from this April: a fact of 2 increase on KEK funding for ILC R&D by MEXT
- ILC Technology Network (ITN) is launched: memorandum between KEK & CERN signed
- Promotion under leadership by International Development Team (IDT), KEK and ILC-Japan



# Future Colliders: Specs

## CEPC

### New Physics ~10 TeV

- ✓ Dark Matter
- ✓ Extended Higgs
- ✓ Composite Higgs
- ✓ Supersymmetry
- .....

### High Precision ~1%

- ✓ Higgs: 1%-0.1%
- ✓ EW:  $O(10^2-10^3)$  vs current
- ✓ Flavor
- .....

### Detector

#### Particle Flow

- ✓ High Granularity
- ✓ Good Resolution
- ✓ Reliable PID
- .....

### High Lumi.

~ $10^{34-36} \text{cm}^{-2}\text{s}^{-1}$

- ✓ Higgs: 20  $\text{ab}^{-1}$
- ✓ Z: 100  $\text{ab}^{-1}$
- ✓ W: 6  $\text{ab}^{-1}$
- ✓ Top: 1  $\text{ab}^{-1}$

Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP ( $10^{34} \text{cm}^{-2} \text{s}^{-1}$ )	115	16.0	5.0
Integrated luminosity ( $\text{ab}^{-1}$ , 2 IPs)	60	3.6	12
Event yield (30 MW)	$2.5 \times 10^{12}$	$1.0 \times 10^8$	$2.5 \times 10^6$
Event yield (50 MW)	$4.0 \times 10^{12}$	$1.6 \times 10^8$	$4.0 \times 10^6$

## FCC-ee

double ring  $e^+e^-$  collider, with full-energy booster

2 or 4 interaction points

efficient  $\mathcal{L}$  from Z to  $t\bar{t}$

thanks to twin-aperture magnets, high-Q SRF, efficient RF power sources, top-up injection, etc.

>2.5  $\text{ab}^{-1}$  / IP with  $\sim 0.5 \times 10^6$  H / IP (3y)

>75  $\text{ab}^{-1}$  / IP with  $\sim 2 \times 10^{12}$  Z / IP (4y)

## ILC

LEP:  $17 \times 10^6$  Z

	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L} (\text{ab}^{-1})$	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization ( $e^-/e^+$ ; %)	80/30	80/30	80/30	80/30	80/20
(LL, LR, RL, RR) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
$\delta_{ISR}$ (%)	10.8	11.7	12.0	12.4	13.0
$\delta_{BS}$ (%)	0.16	2.6	1.9	4.5	10.5

[arXiv:2203.07622]

## CLIC

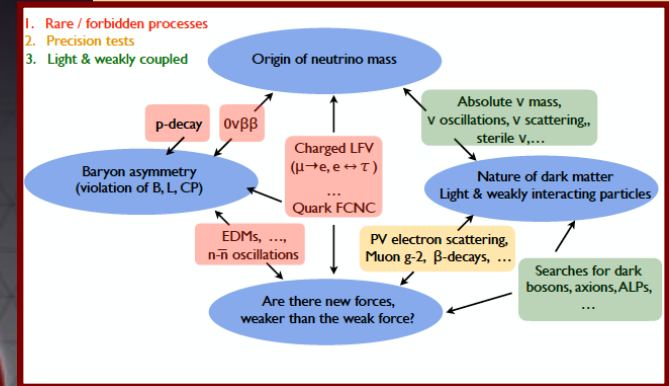
	380 GeV	1.5 TeV	3 TeV
$\int \mathcal{L} (\text{ab}^{-1})$	1	2.5	5
P( $e^-, e^+$ ; %)	80/0	80/0	80/0
(LR, RL)	(50,50)	(80,20)	(80,20)

[arXiv:2203.07622]

# Frontiers

Lifetime Frontier

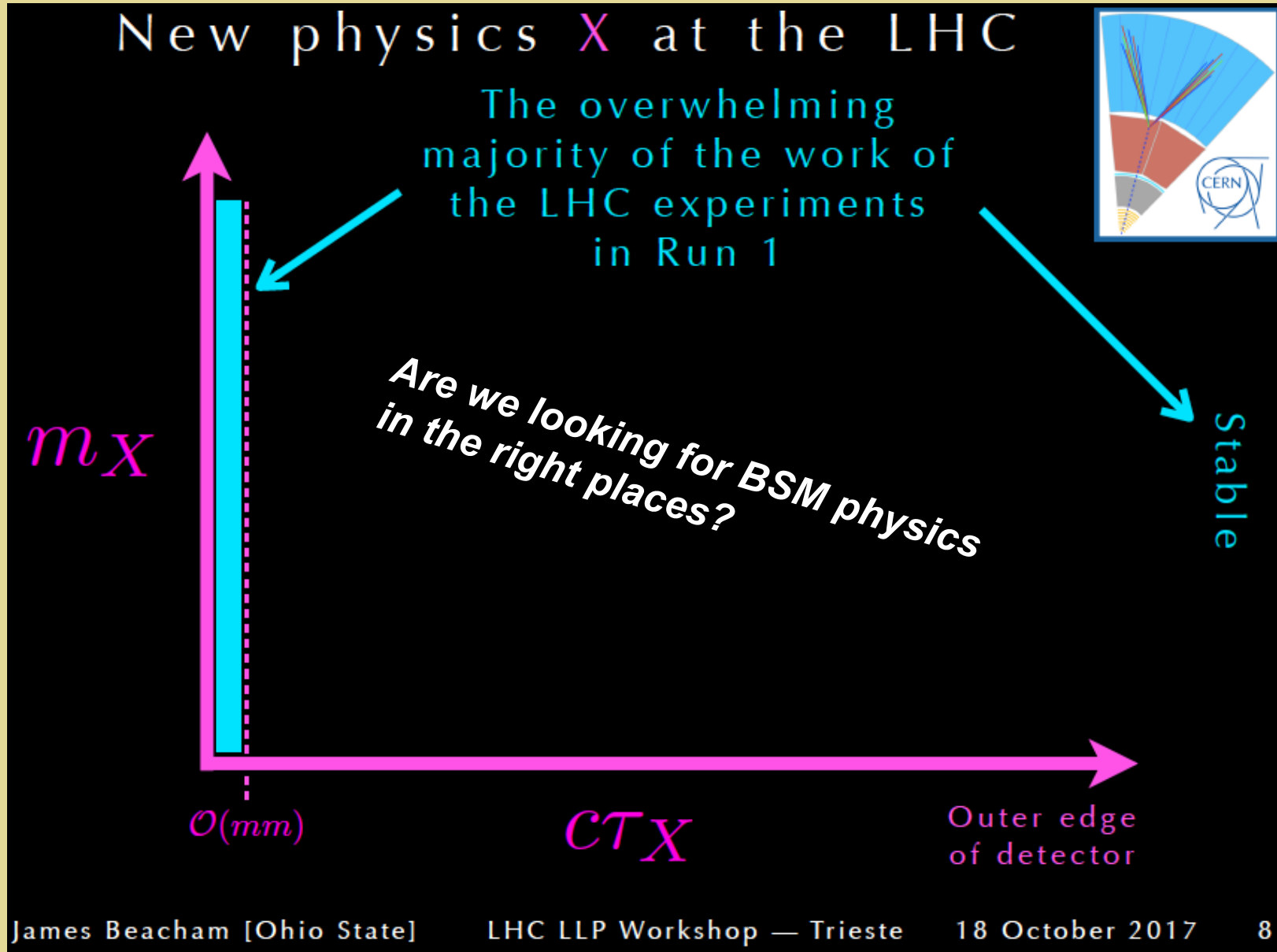
HEP : New (heavy) particles



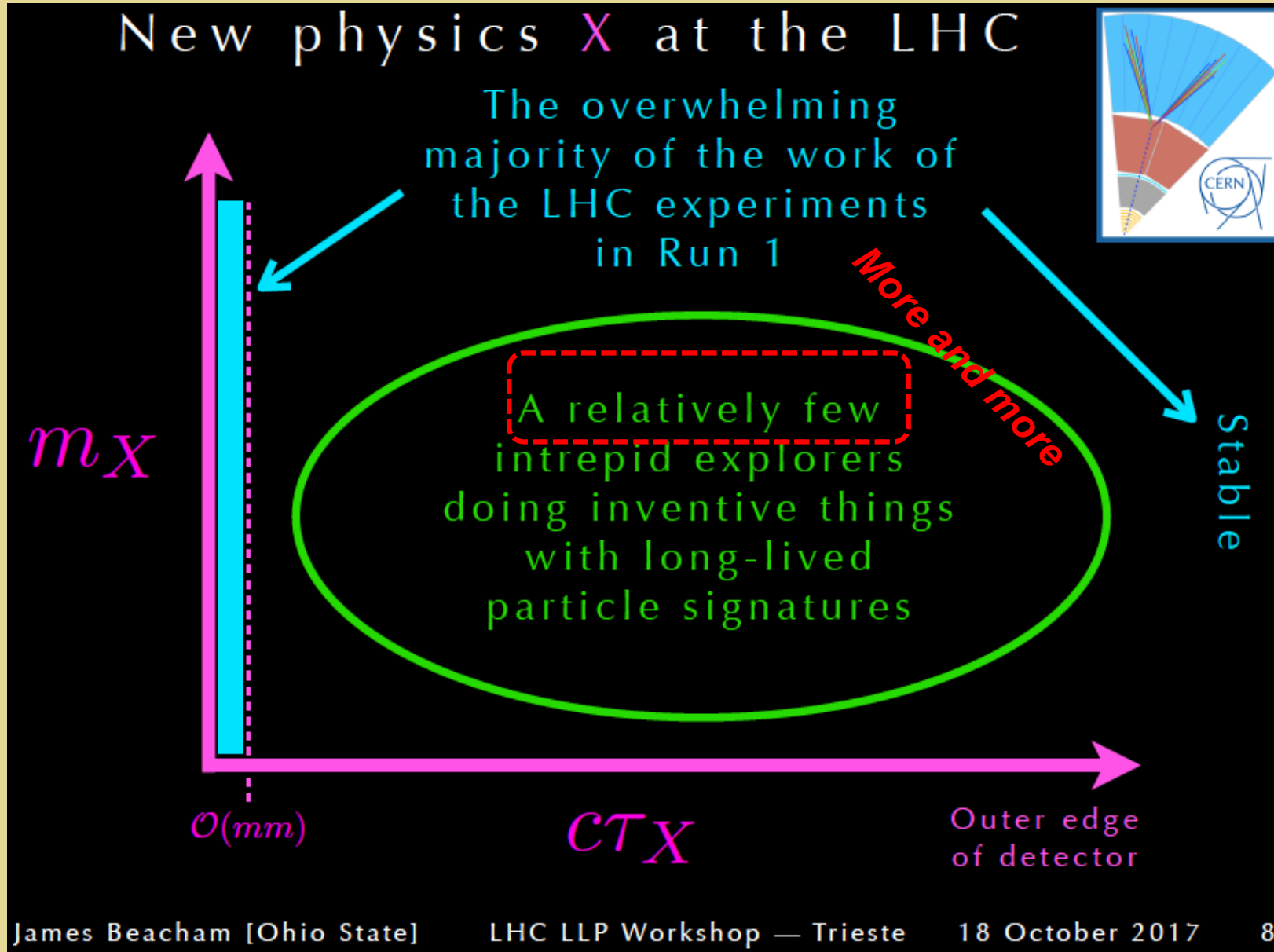
V. Cirigliano, INT workshop '24

Historical artifact: US HEP vision → still useful mnemonic

# A New LHC Emphasis: Lifetime Frontier



# A New HEP Emphasis: Lifetime Frontier





# Why Should BSM LLP's Exist ?

*Large scale hierarchies & broken symmetries*

$$C\tau \longleftrightarrow \left( \frac{M_X}{M_Y} \right) \gg 1$$

- Heavy (off shell) mediator:  
Hidden valley

$$C\tau \longleftrightarrow \left( \frac{M_X}{\Delta M} \right) \gg 1$$

- Compressed spectrum :  
Stealth SUSY

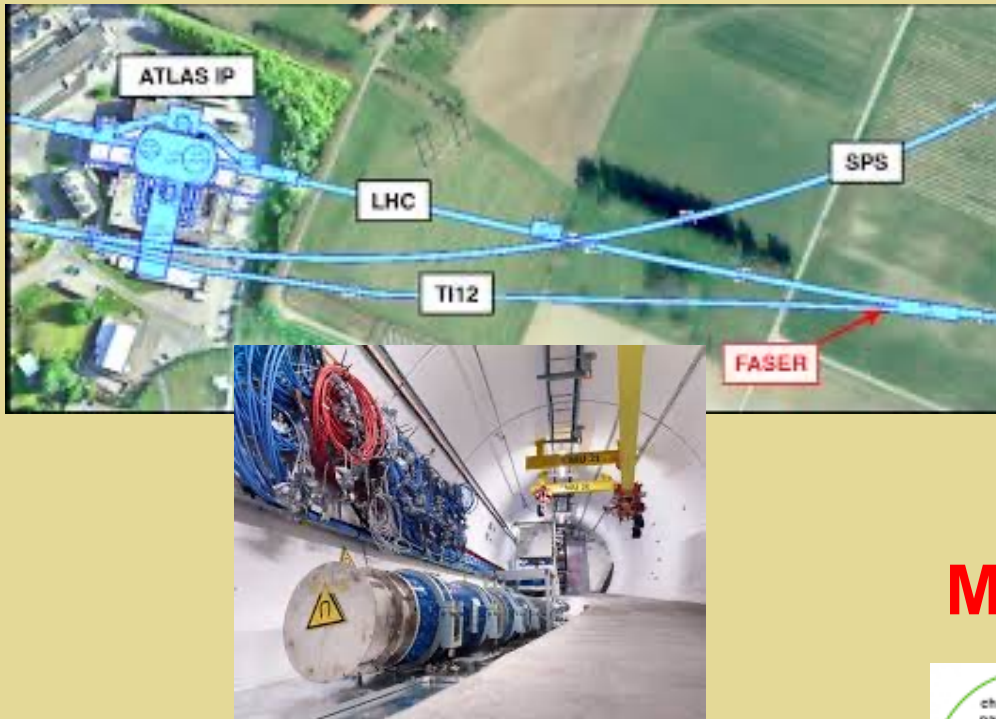
$$(C\tau)^{-1} \longleftrightarrow g_X \ll 1$$

- Broken symmetry:  
RPV SUSY
- Scale ratio:  $N_R, Z_D$

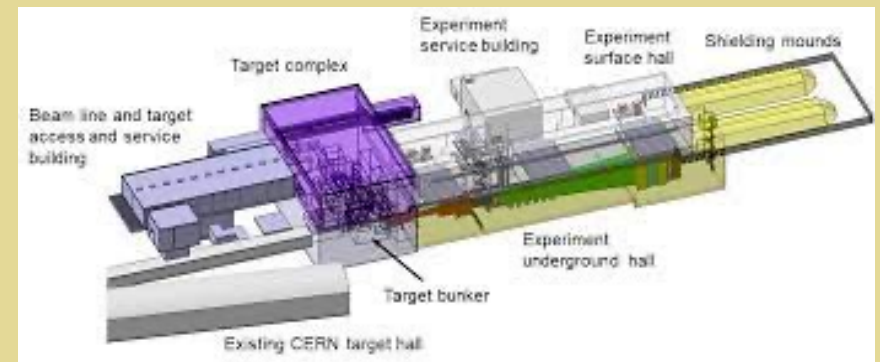


# A New HEP Emphasis: Lifetime Frontier

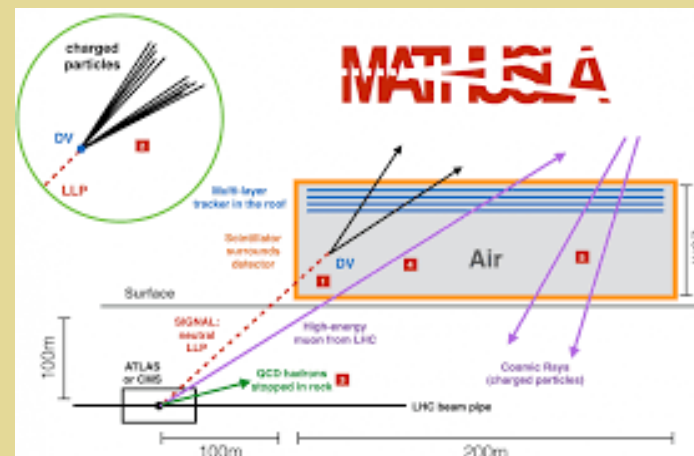
## FASER



## SHiP (proposed)



## MATHUSLA (proposed)



+ ATLAS, CMS, LHCb

# Energy Frontier: LHC

**ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits**  
Status: March 2023

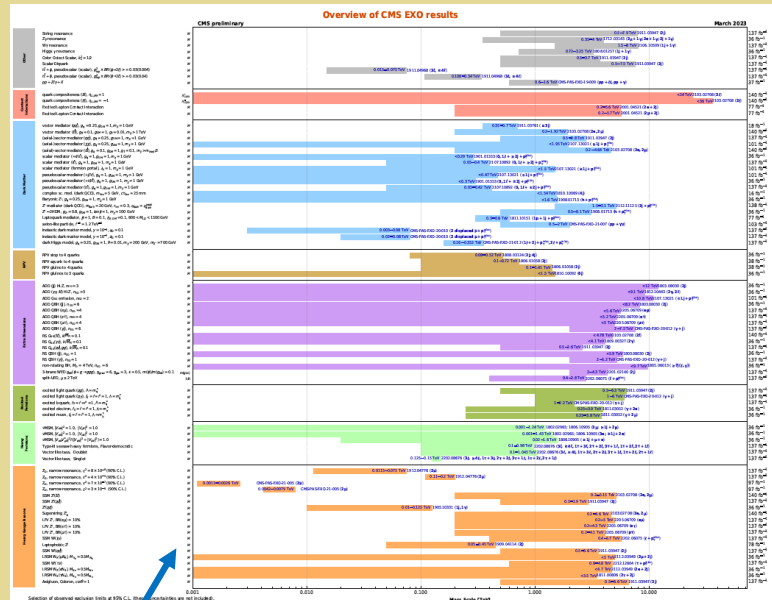
ATLAS Preliminary  $\sqrt{s} = 13$  TeV

Model	$L, \gamma$	Jets <sup>†</sup>	$E_{miss}^{min}$	$f_{cut}(p_{T1})$	Limit	Reference
<b>Extra dim.</b>	ADD $G_{\mu\nu} \rightarrow G_{\mu\nu}$	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025
<b>Charge bound.</b>	SSM $Z \rightarrow \mu\mu$	2 $\mu$	1	Yes	13 TeV	ATLAS CONF-2022-025
<b>CP</b>	CP even	2 $\mu$	1	Yes	13 TeV	ATLAS CONF-2022-025
<b>DM</b>	Scalar	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025
<b>LO</b>	Scalar	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025
<b>Vector-like fermions</b>	Vector	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025
<b>Exotic fermions</b>	Exotic	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025
<b>Other</b>	Other	0 $\mu$ , 1 $\gamma$	1-4	Yes	13 TeV	ATLAS CONF-2022-025

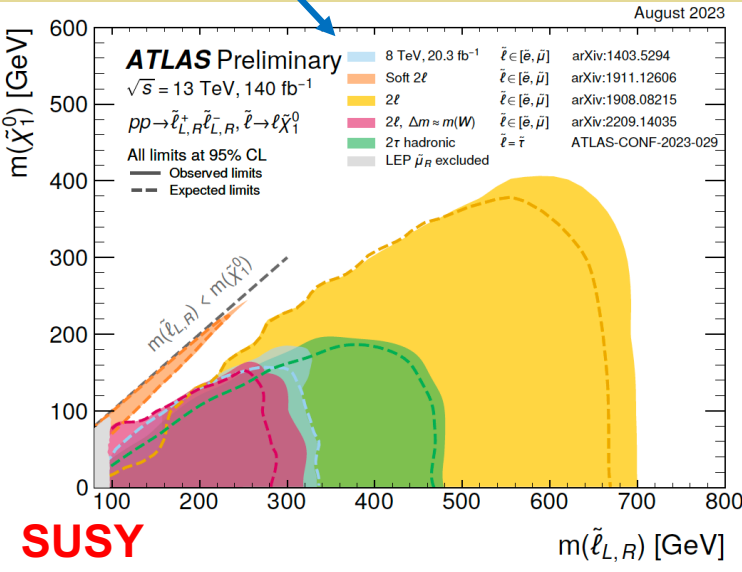
\*Only a selection of the available mass limits on new states or phenomena is shown.  
†Small-radius (large-radius) jets are denoted by the letter (s) (l).

**Non-SUSY**

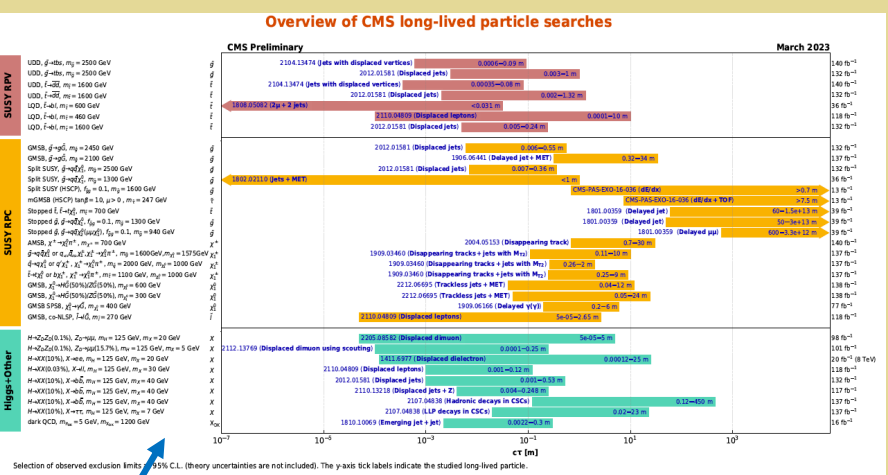
## ATLAS: Heavy BSM (prompt)



## MS: Heavy BSM (prompt)

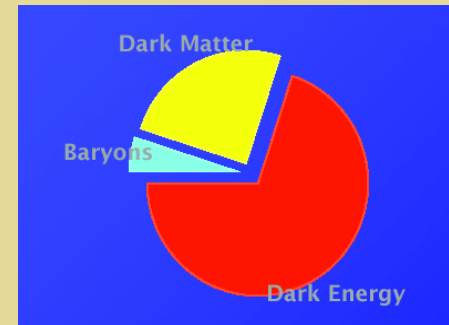
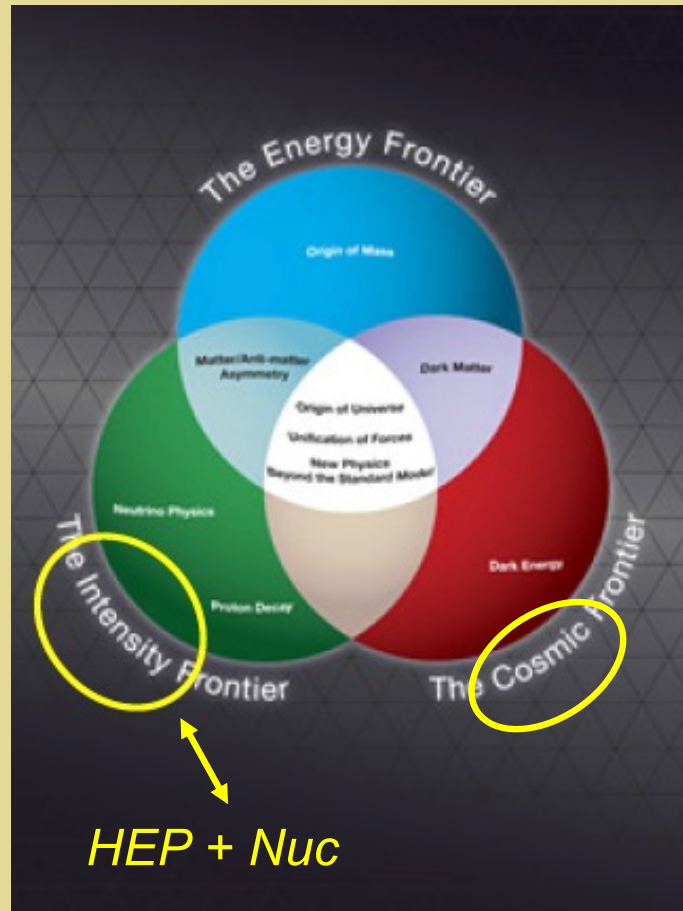
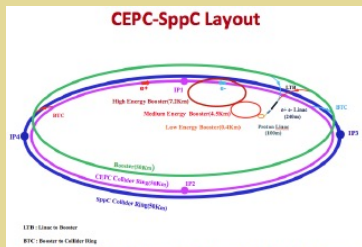
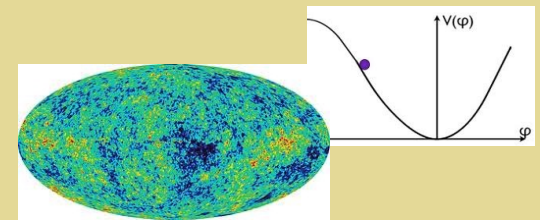
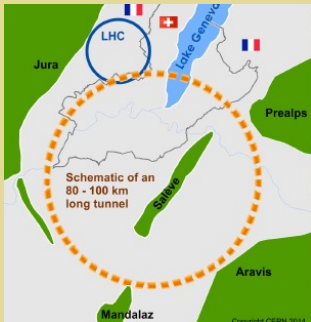


**SUSY**

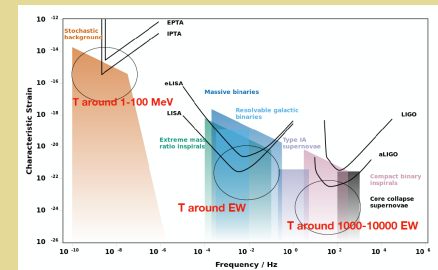


**CMS: LLP**

# Frontiers



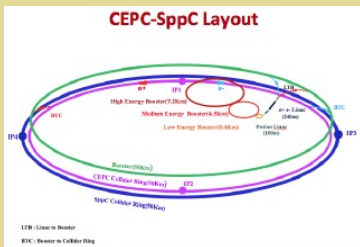
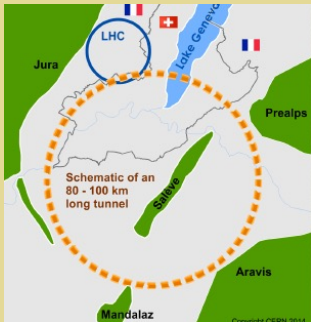
- Precision tests: muon  $g-2$ , PV  $ee...$
- Fundamental symmetry tests (CP, Lepton number...)
- Neutrino properties
- Flavor physics



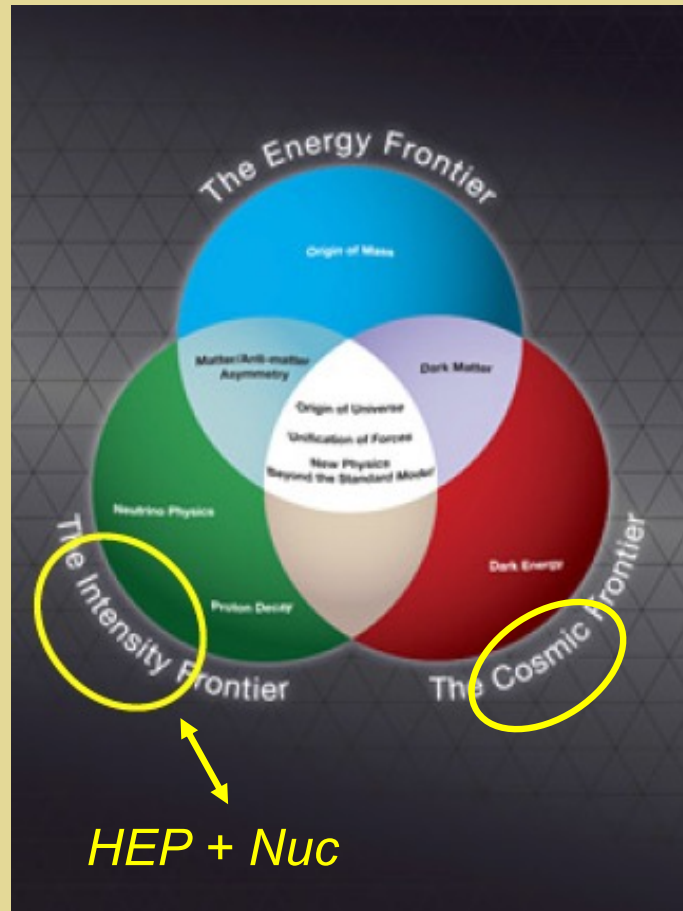
**Historical artifact: US HEP vision → still useful mnemonic**



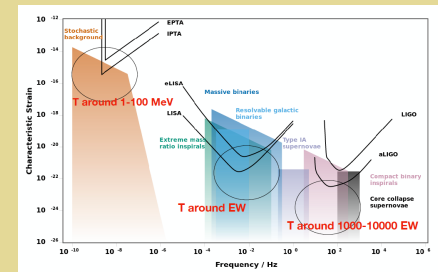
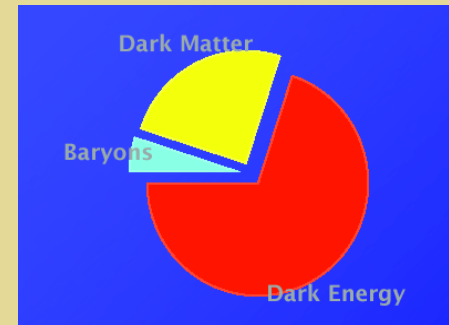
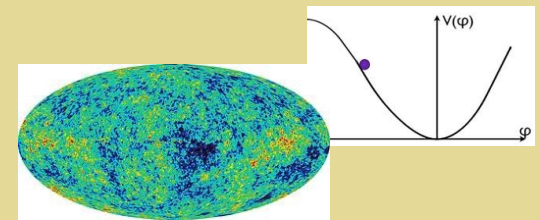
# Frontiers



- Precision tests: muon  $g-2$ , PV  $ee\dots$
- Fundamental symmetry tests (CP, Lepton number...)
- Neutrino properties
- Flavor physics

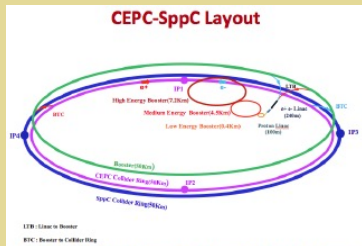
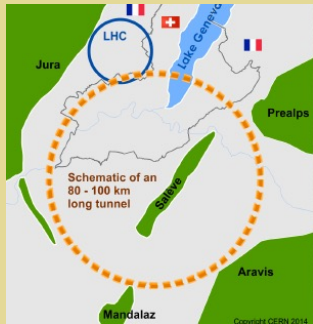


**Historical artifact: US HEP vision  $\rightarrow$  still useful mnemonic**

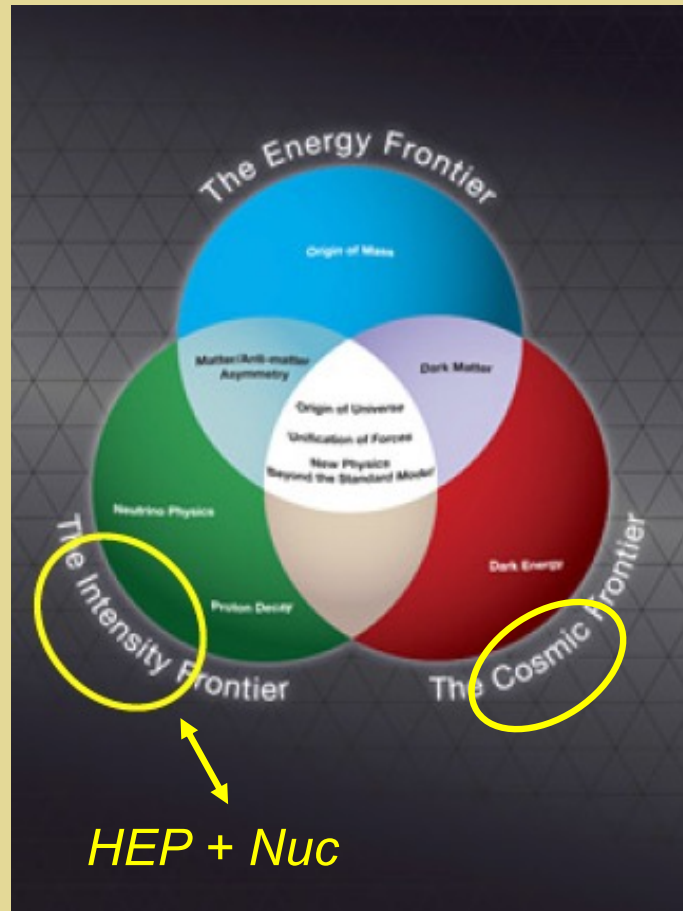


- Atomic, Molecular, Optical
- Condensed Matter

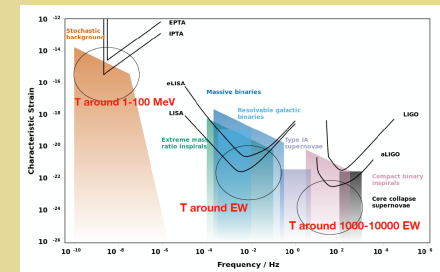
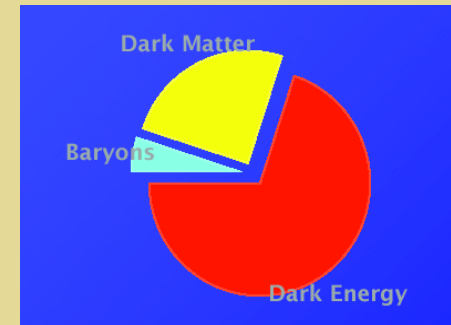
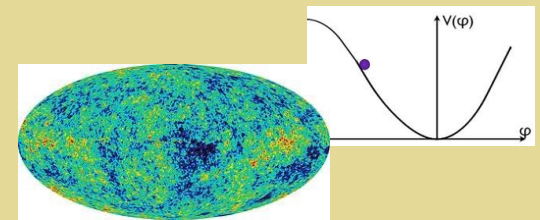
# Frontiers



- Precision tests: muon  $g-2$ , PV  $ee$ ...
- Fundamental symmetry tests (CP, Lepton number...)
- Neutrino properties
- Flavor physics



Historical artifact: US HEP vision  $\rightarrow$  still useful mnemonic

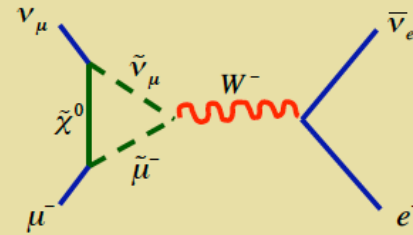


- Atomic, Molecular, Optical
- Condensed Matter

# Intensity Frontier: BSM Footprints

## New Symmetries

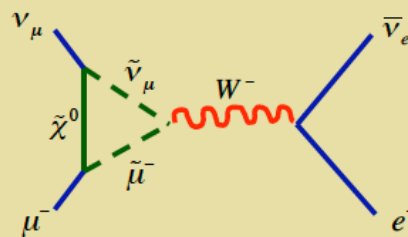
1. Origin of Matter
2. Unification & gravity
3. Weak scale stability
4. Neutrinos



# Intensity Frontier: BSM Footprints

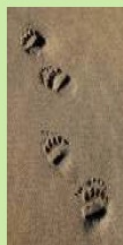
## New Symmetries

1. Origin of Matter
2. Unification & gravity
3. Weak scale stability
4. Neutrinos



Discovery

Discovery



New particle searches:  
does the observed BSM  
“species” fit the footprints ?

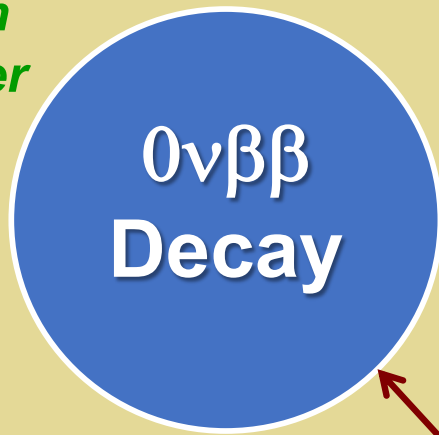


Fundamental symmetry & precision  
tests: draw inferences about BSM  
scenarios from a variety of  
measurements

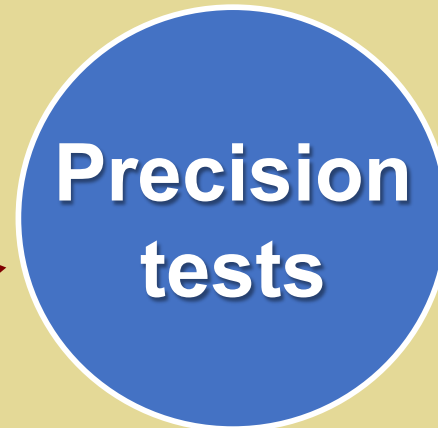
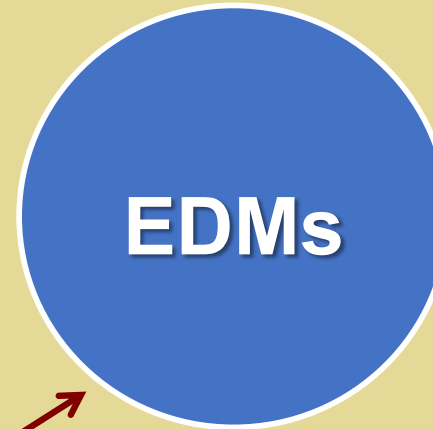


# Nuclear Physics Connections

Lepton number



CP & T



Precision tests

Muon  $g-2$ , PV  $ee$ ,  $\beta$  decay...

*Fundamental symmetries & neutrinos: "Intensity Frontier"*

# ***More Matter than Antimatter ?***

***Paradigmatic inter-frontier challenge***

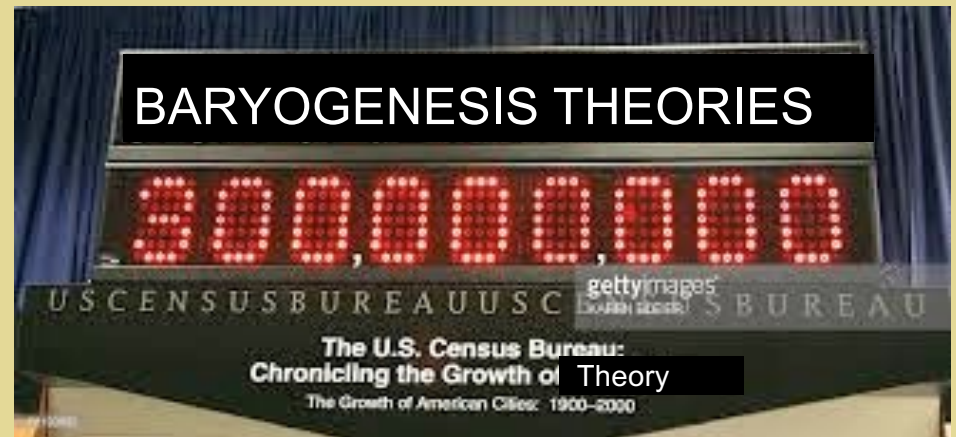
# Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.66 \pm 0.04) \times 10^{-11}$$

*One number* → ~~!!!~~ ~~!!!~~ ~~!!!~~ ... *Explanations*

*Experiment can help:*

- *Discover ingredients*
- *Falsify candidates*



# Ingredients for Baryogenesis



Scenarios: leptogenesis, EW baryogenesis, Affleck-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis...

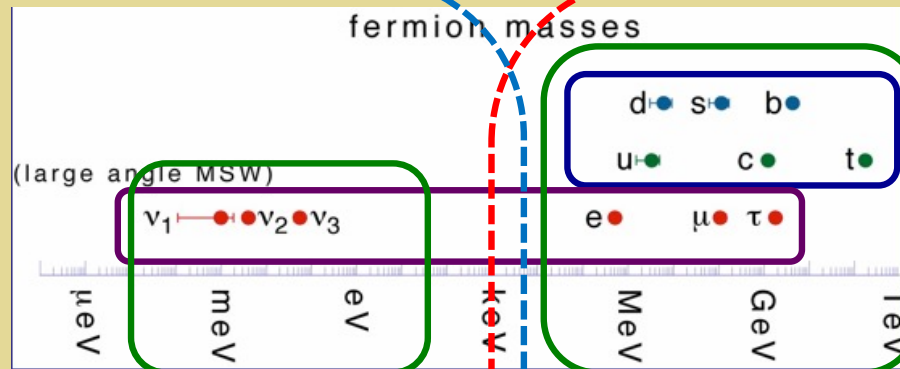
- *B violation (sphalerons)*
- *C & CP violation*
- *Out-of-equilibrium or CPT violation*

Standard Model

BSM



# Fermion Masses & Baryon Asymmetry



*Partners*

*Partners*

*Something else ?*

*Higgs Mechanism*

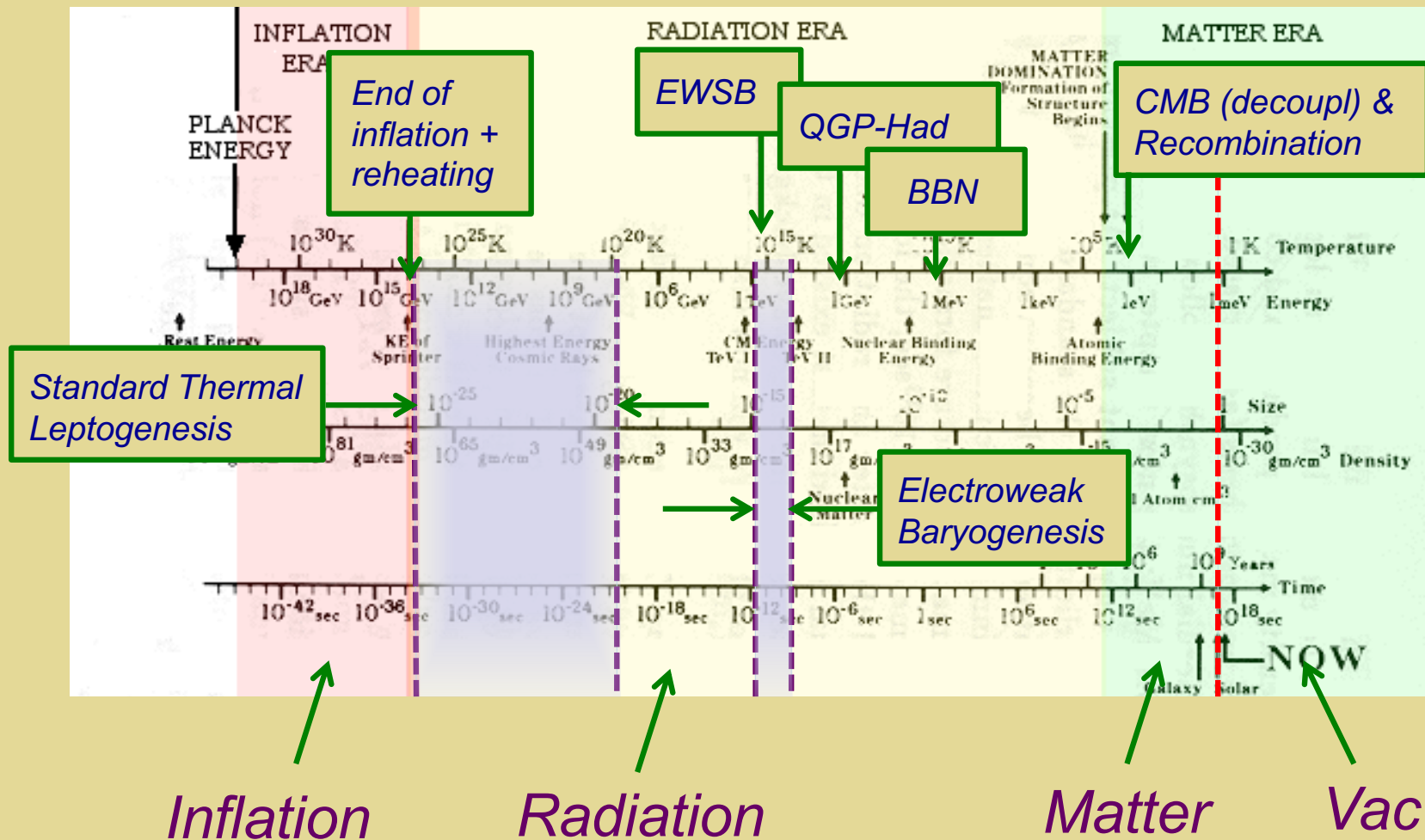
**Leptogenesis: Baryon asymmetry &  $m_\nu$  from lepton number violation**

**Electroweak baryogenesis: Baryon asymmetry &  $m_f$  from EW symmetry breaking**

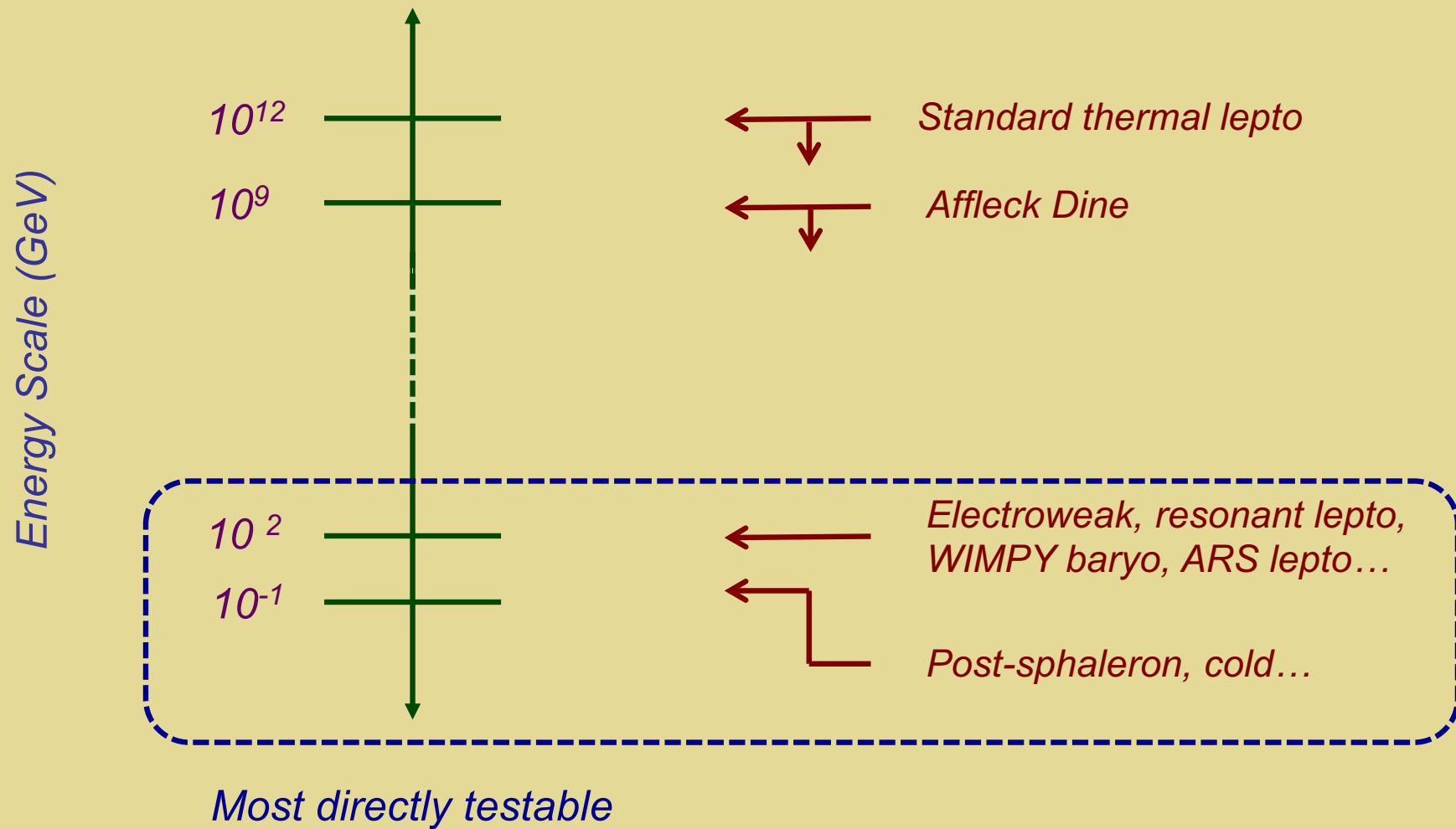
***This talk***

***This talk***

# Cosmic History

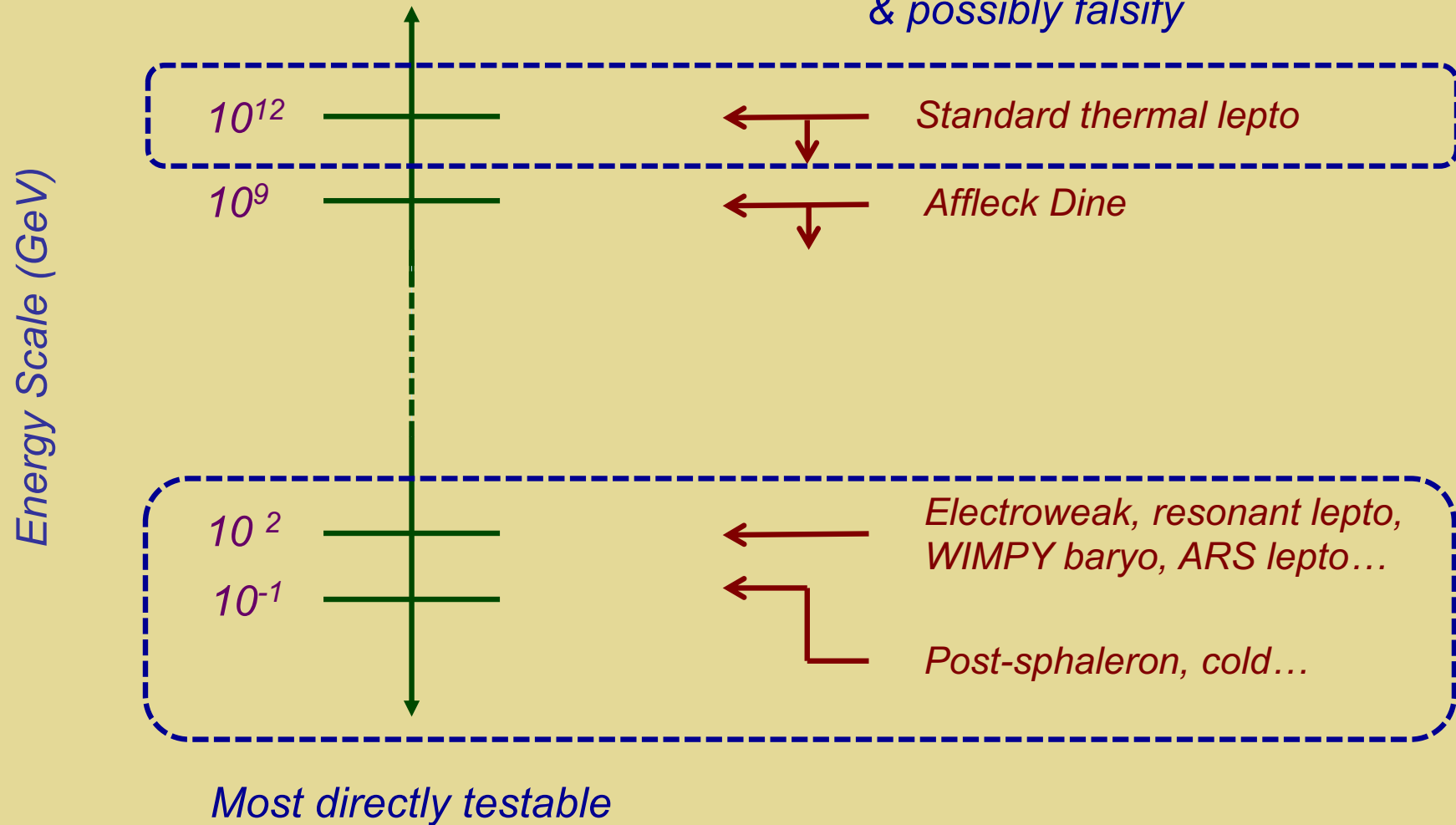


# Baryogenesis Scenarios



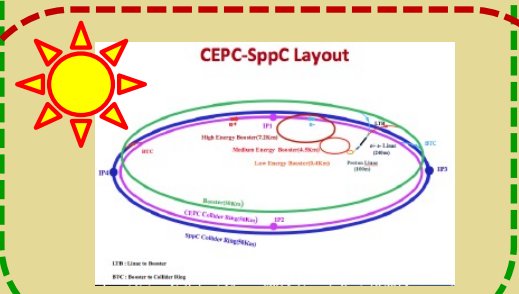
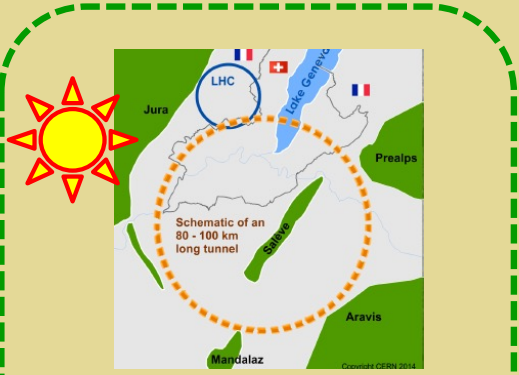
# Baryogenesis Scenarios

*Discover (some) ingredients  
& possibly falsify*





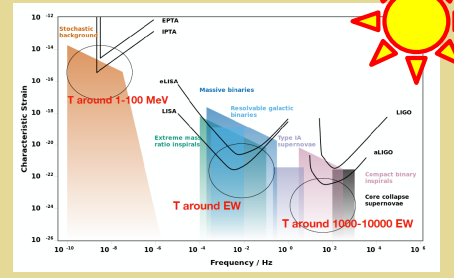
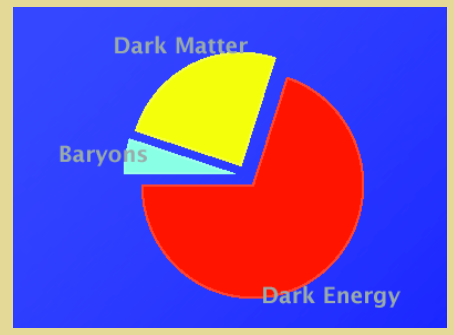
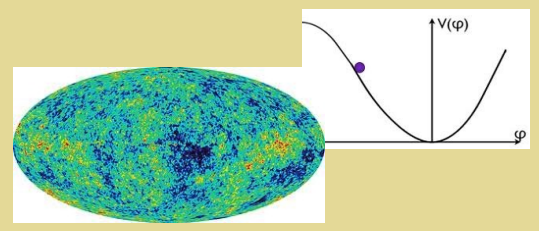
# Frontiers



- Precision tests: muon  $g-2$ , PV  $ee...$
- Fundamental symmetry tests (CP, Lepton number...)
- Neutrino properties
- Flavor physics



Historical artifact: US HEP vision  $\rightarrow$  still useful mnemonic



- Atomic, Molecular, Optical
- Condensed Matter