Physics with Future e+e- Colliders: Inter-frontier Connections

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- UMass Amherst
- Caltech

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
MeToo

CEPC International Conference, Nanjing, October 23, 2023

Goals for this Talk: What I Won't Do

- ***Reiterate the "familiar story"***

CEPC Snowmass Report

2205.08553

The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

CONTENTS

Goals for this Talk: What I Won't Do

- ***Reiterate the "familiar"***
- ***Report on incremental physics updates since the last CEPC meeting & Snowmass white paper***
- ***Provide a menu of new processes and observables to put on the CEPC "bucket list"***

Goals for this Talk: What I'll Try to Do

- ***Challenge** us to think more deeply and broadly about implications of e+e- physics for other fundamental physics frontiers*
- ***Illustrate** a subset of these connections drawn from my own scientific experience*
- ***Highlight** developments in other sub-fields of fundamental physics that may bear on CEPC inter-frontier connections*
- ***Invite** discussion, other ideas, and future explorations*

Key Ideas for this Talk

- *Scalar fields play a significant theoretical role in the physics of other frontiers→ an e+e- Higgs factory provides a unique inter-frontier laboratory*
- *The next generation e+e- colliders live at the interface of the high energy and "intensity" frontiers → the large number of H and Z bosons make the CEPC/FCC-ee/ILC precision tools at this interface*
- *The theoretical interpretation of these precision e+e- measurements can connect early universe cosmology, astrophysics, underground science, and "table top" condensed matter and AMO physics*

Disclaimer

- ***Apologies for omissions of references to other important work***
- ***Focus will be CEPC-centric but much of the discussion pertains to FCC-ee and ILC***

Outline

I. *Questions & Frontiers*

II. *Was there an electroweak phase transition ?*

III. *What is the scale of lepton number violation ?*

IV. *Outlook*

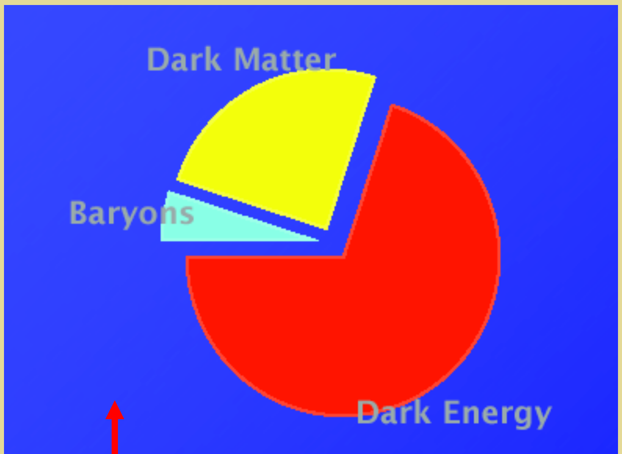
V. *Where is the CP-violation needed to explain the matter-antimatter asymmetry ?*

Time permitting

I. Questions & Frontiers

Fundamental Questions

MUST *answer*



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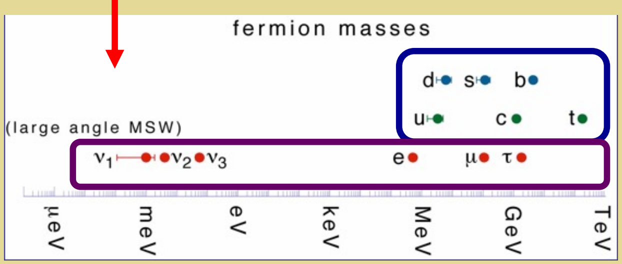
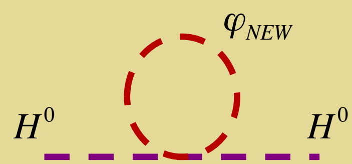


Origin of m_ν

SHOULD *answer*

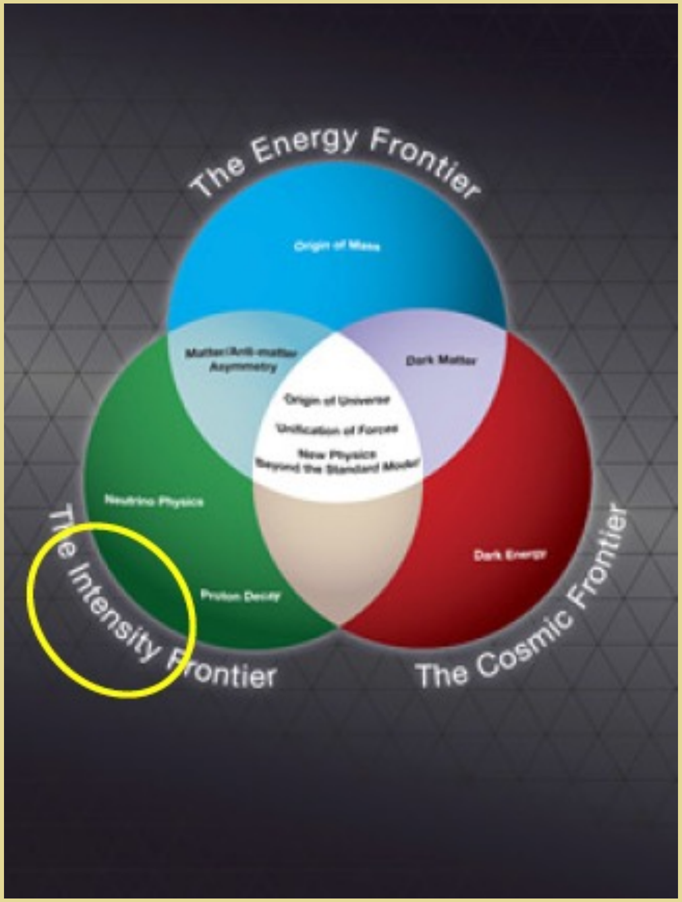


$\Delta m^2 \sim \lambda \Lambda^2$

?

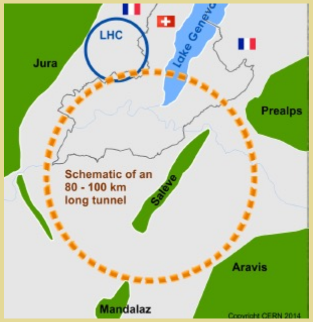
$\Lambda_{Cosmological}$

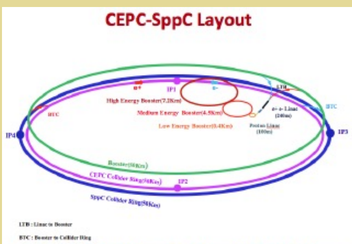
Frontiers



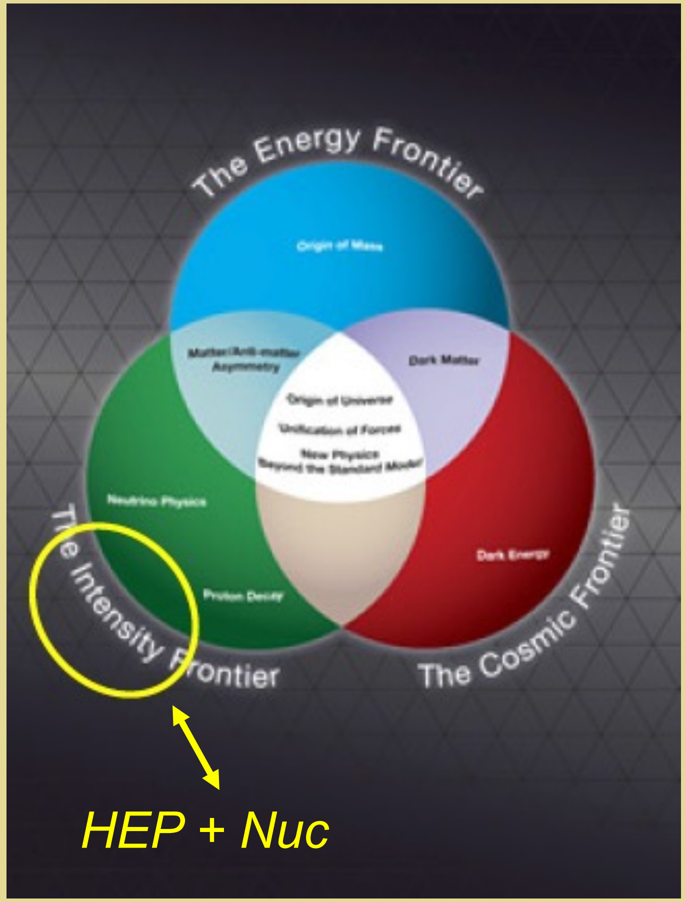
Historical artifact: US HEP vision → still useful mnemonic

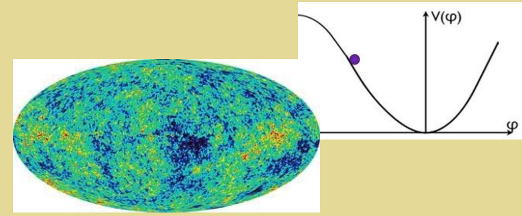
Frontiers

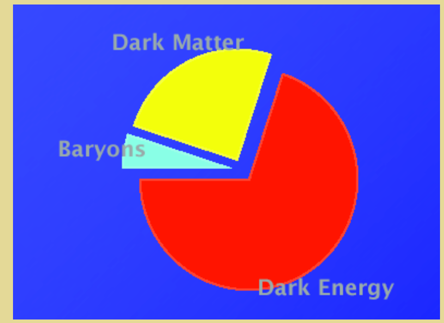


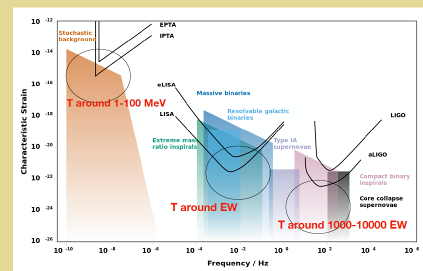


- *Precision tests: muon g-2, PV ee…*
- *Fundamental symmetry tests (CP, Lepton number…)*
- *Neutrino properties*
- *Flavor physics*









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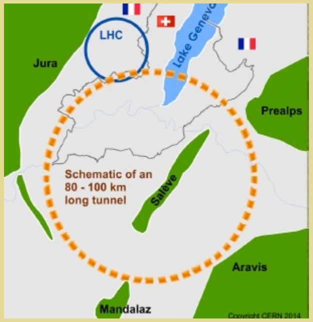

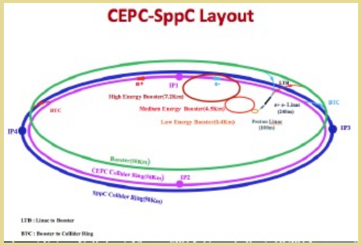

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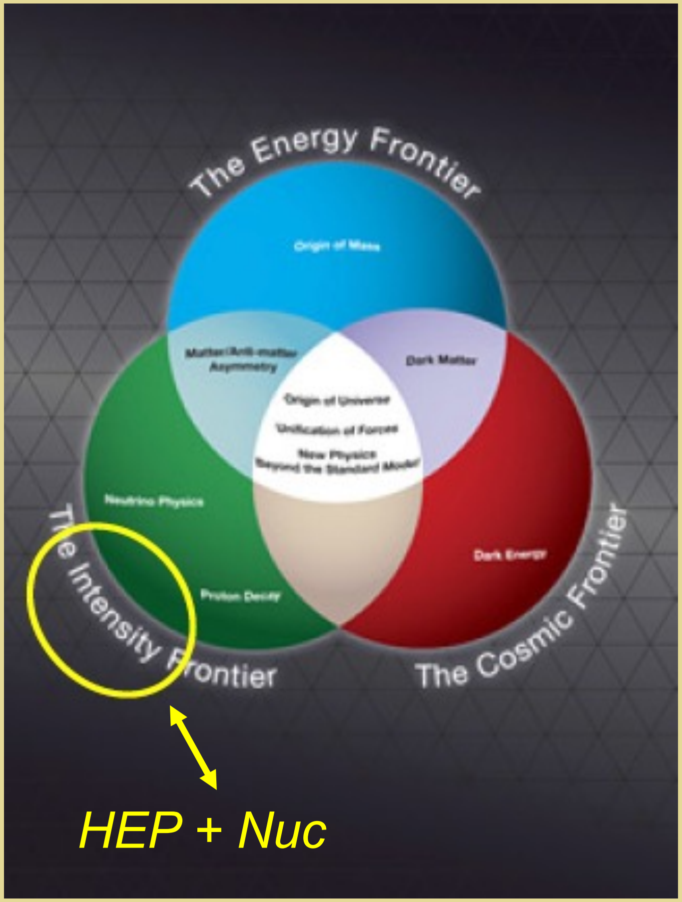

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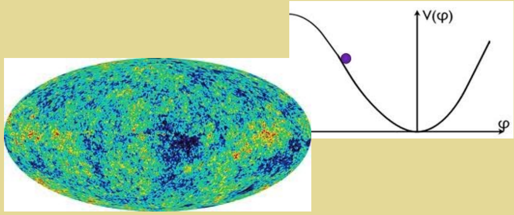
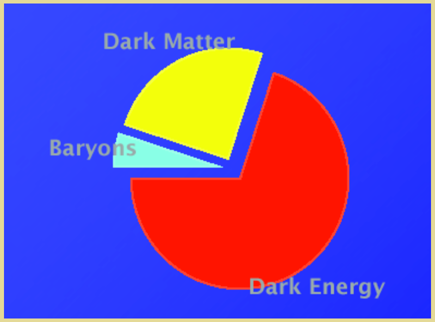
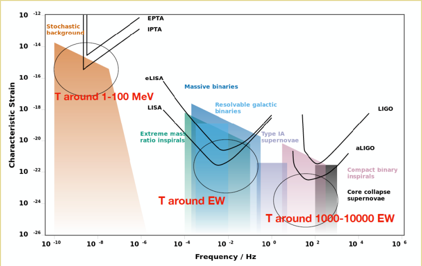
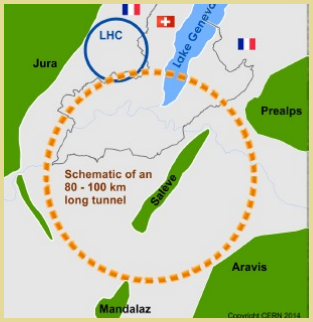


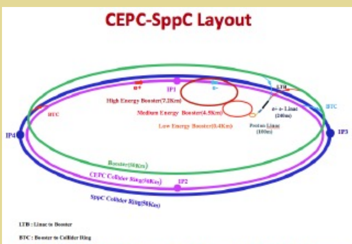




- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

Frontiers





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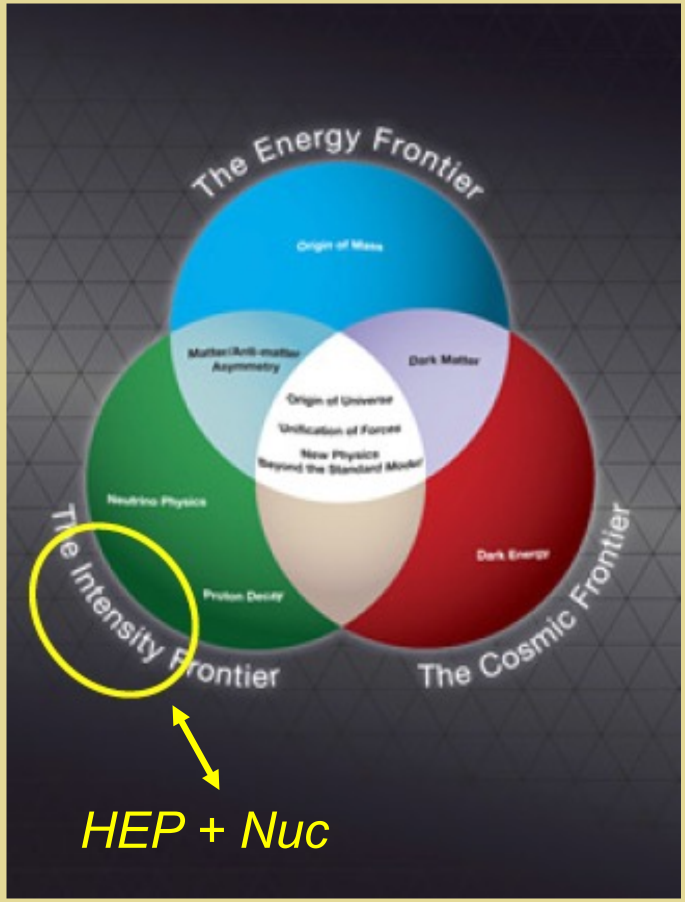

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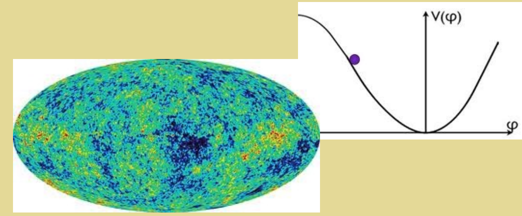

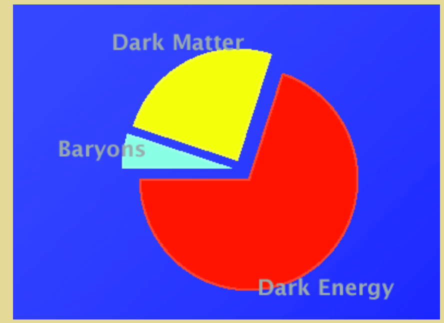

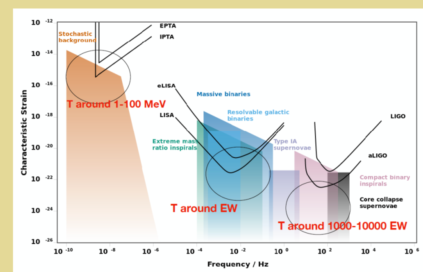

- ***Atomic, Molecular, Optical***
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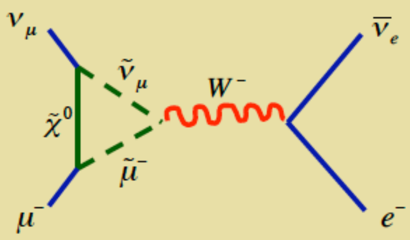
Intensity Frontier: BSM Footprints

New Symmetries

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



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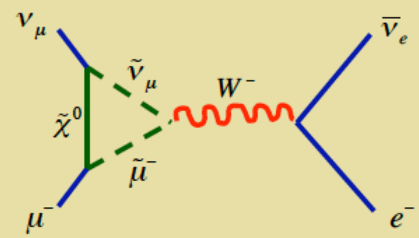

Fundamental symmetry & precision tests: draw inferences about BSM scenarios from a variety of measurements

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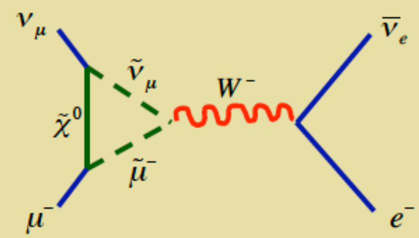

New particle searches: does the observed BSM "species" fit the footprints ?

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

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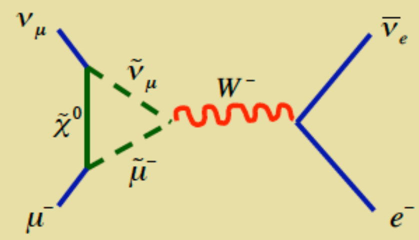


Discovery

Discovery

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

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

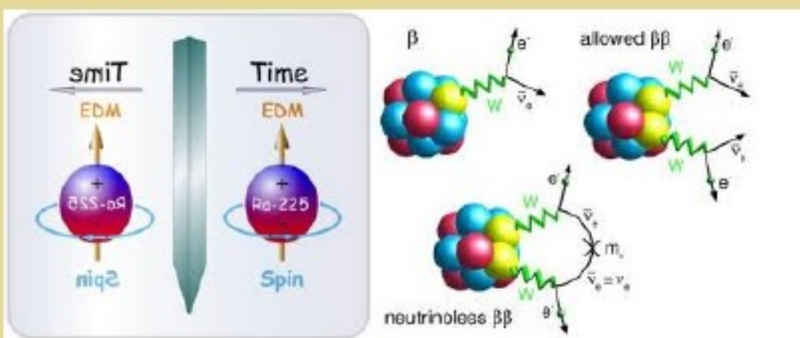
Nuclear Physics Connections

Lepton number

$0\nu\beta\beta$ Decay

EDMs

CP & T



Fundamental symmetries & neutrinos: "Intensity Frontier"

Precision tests

Muon g-2, PV ee, β decay…

More Matter than Antimatter ?

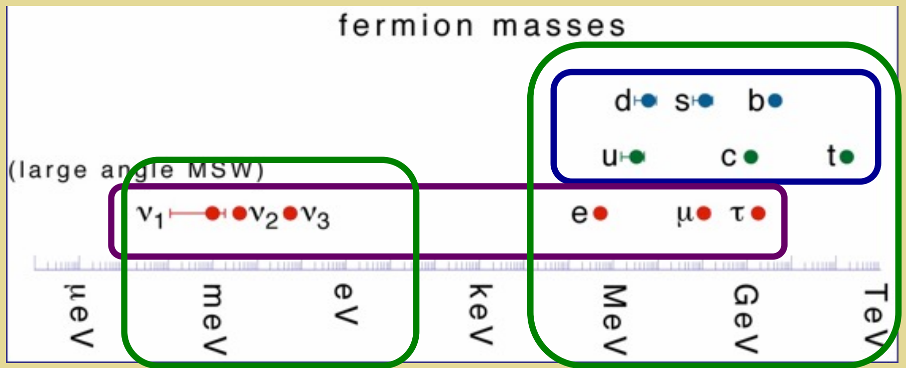
Paradigmatic inter-frontier challenge

Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✓	✓
• *C & CP violation*	✗	✓
• *Out-of-equilibrium or CPT violation*	✗	✓

Fermion Masses & Baryon Asymmetry



Partners

Partners

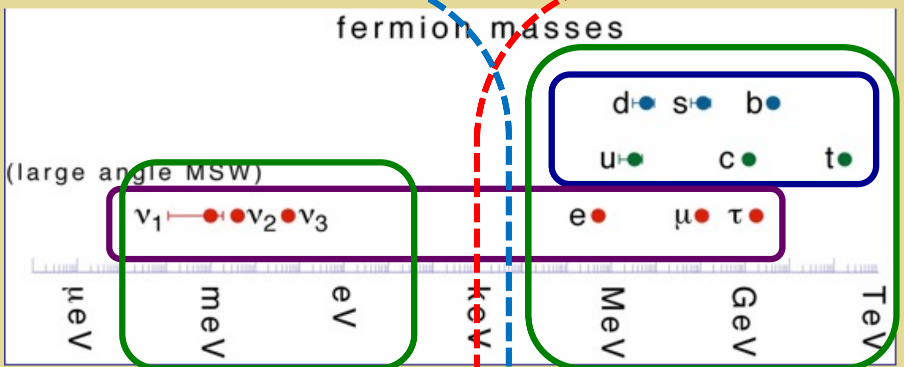
Something else ?

Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Fermion Masses & Baryon Asymmetry



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This talk

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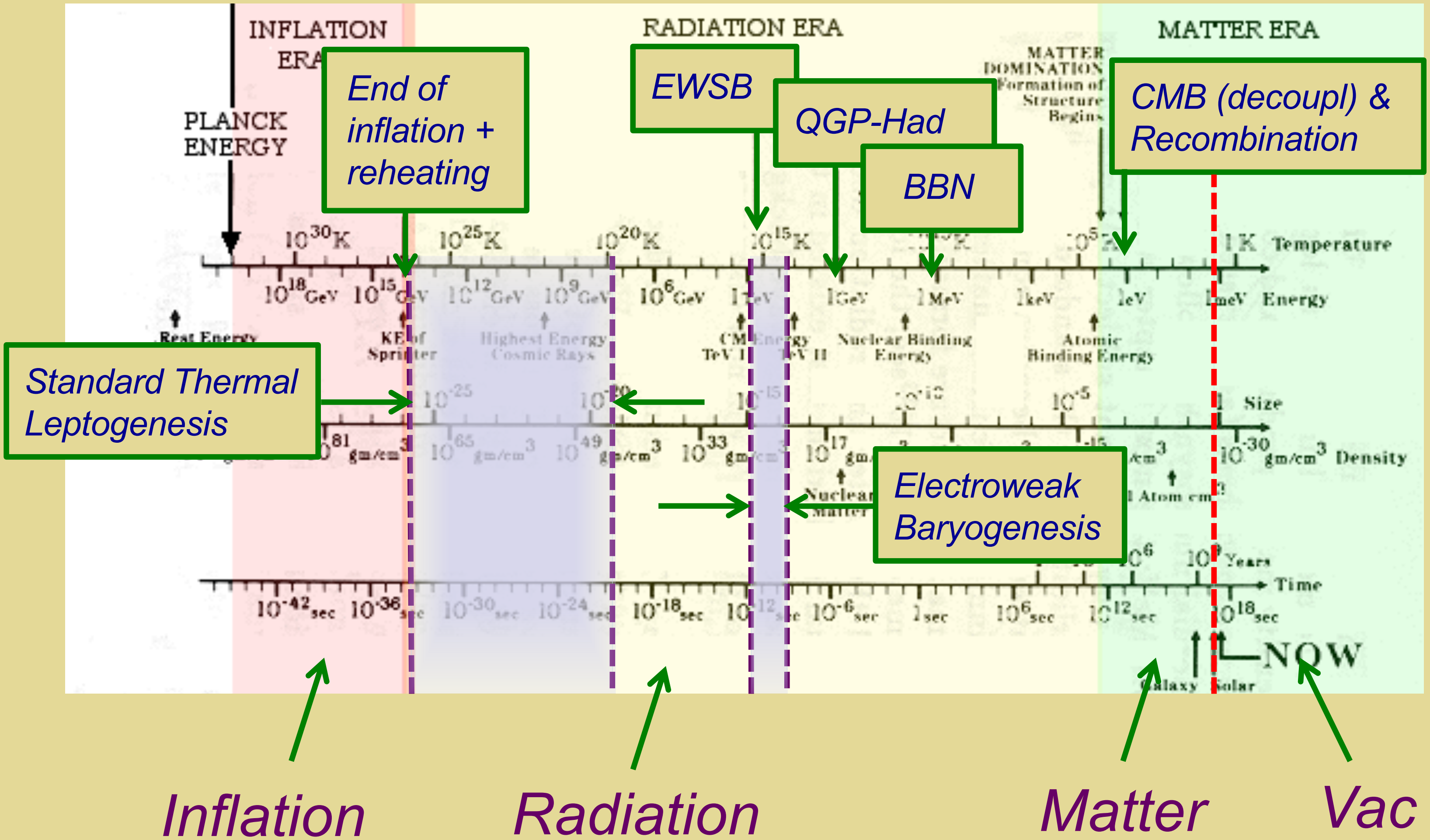
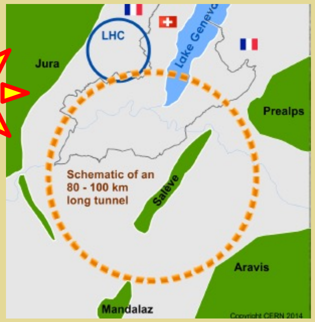
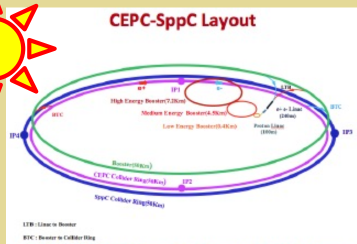
Cosmic History



Frontiers





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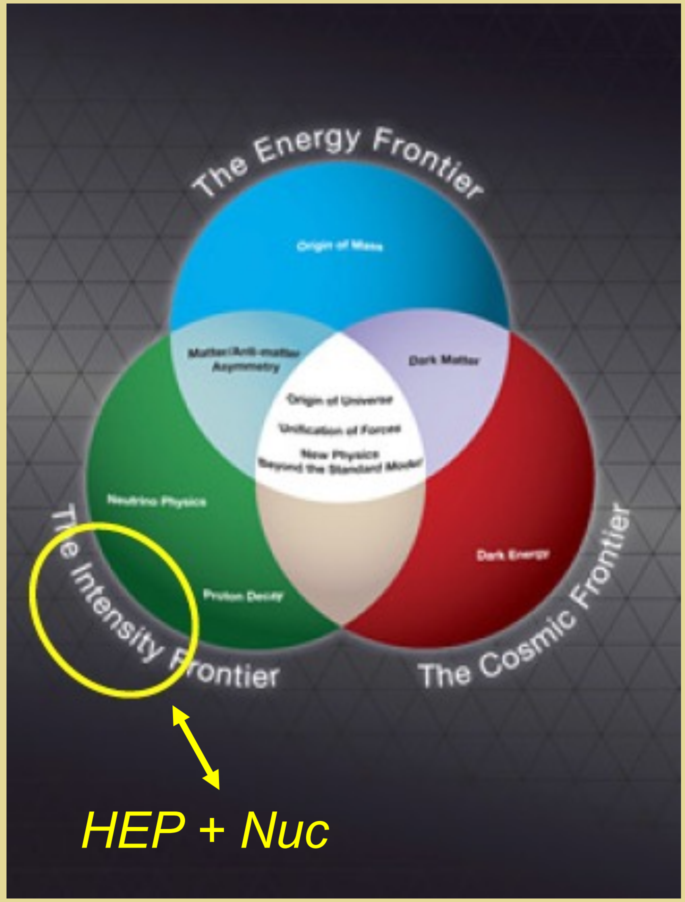

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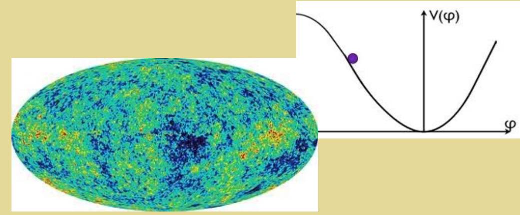
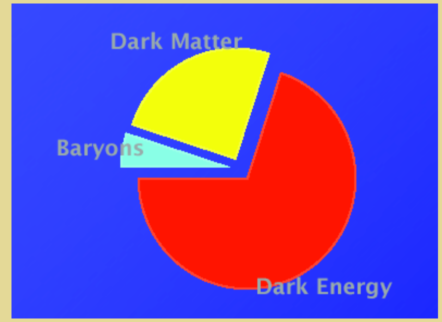
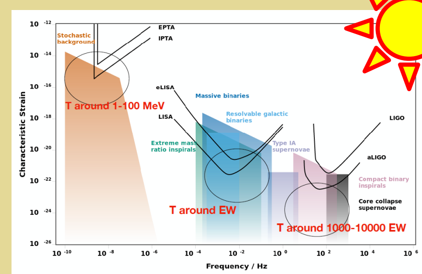






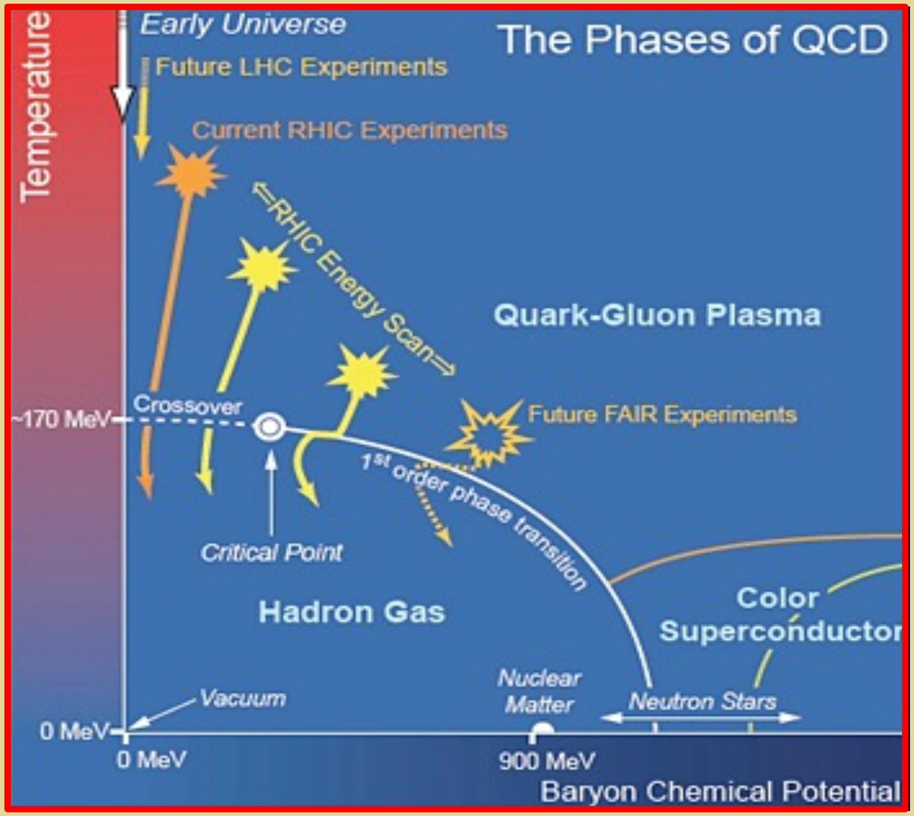
- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

II. Was There an Electroweak Phase Transition ?

Was There an Electroweak Phase Transition ?

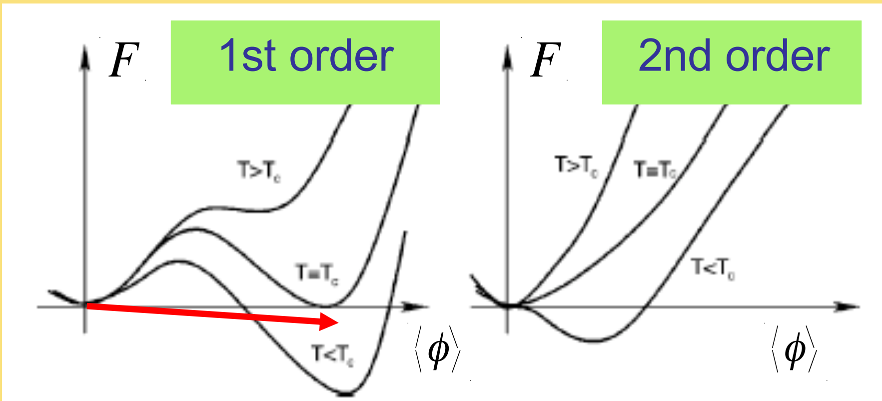
- *Interesting in its own right*
- *Key ingredient for EW baryogenesis*
- *Source of gravitational radiation*

Thermal History of Symmetry Breaking

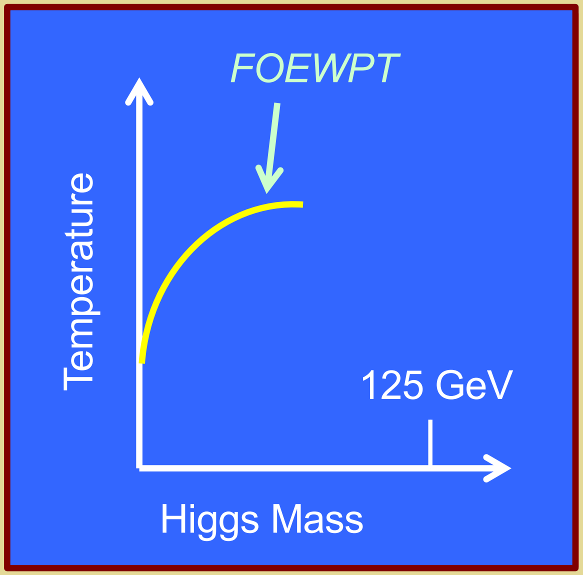


QCD Phase Diagram → EW Theory Analog?

Was There an EW Phase Transition?



Increasing m_h →



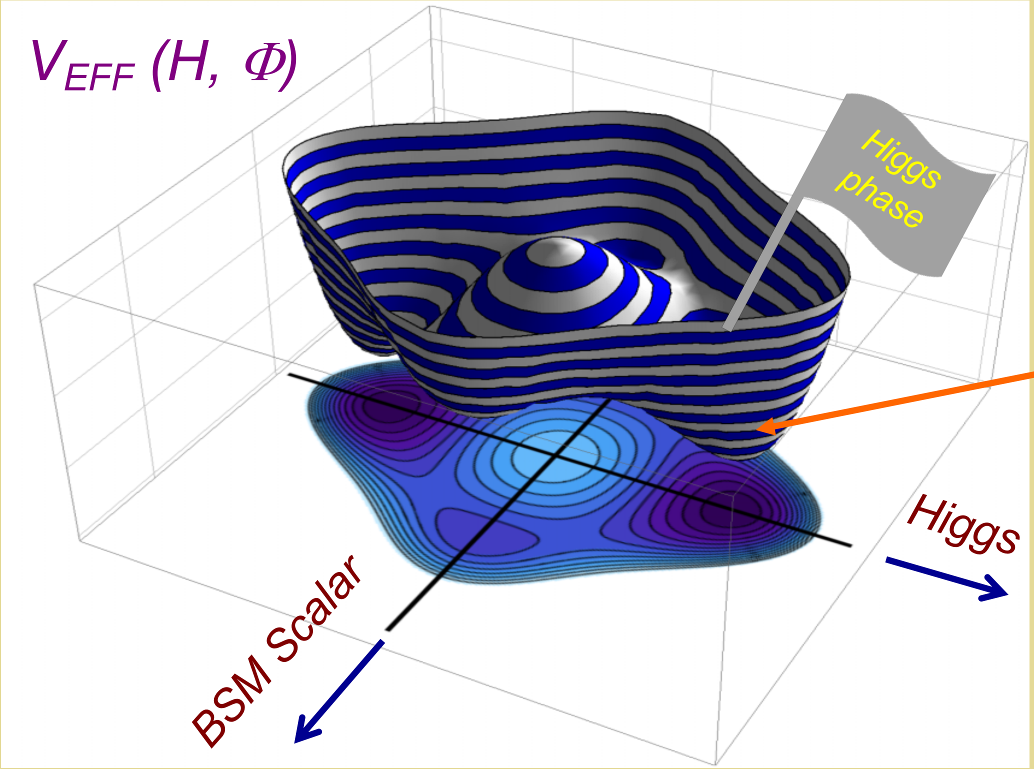
EW Phase Diagram

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

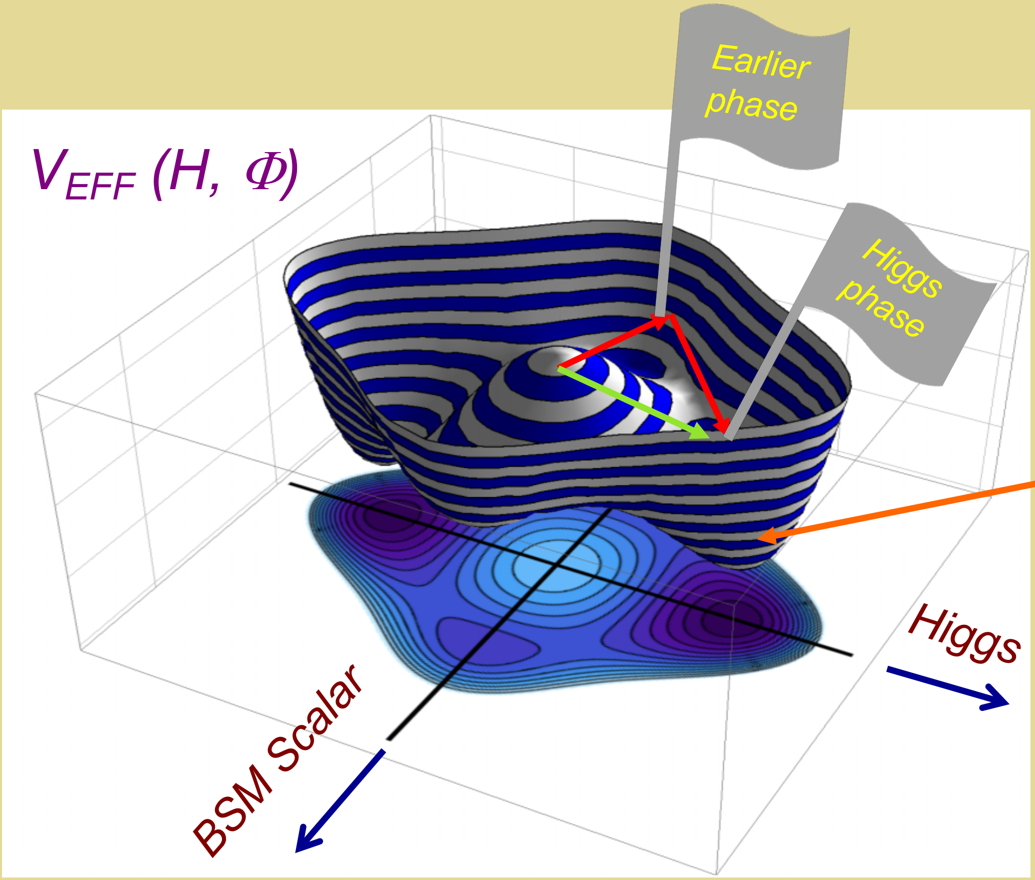
Patterns of Symmetry Breaking



How did we end up here ?

Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Patterns of Symmetry Breaking



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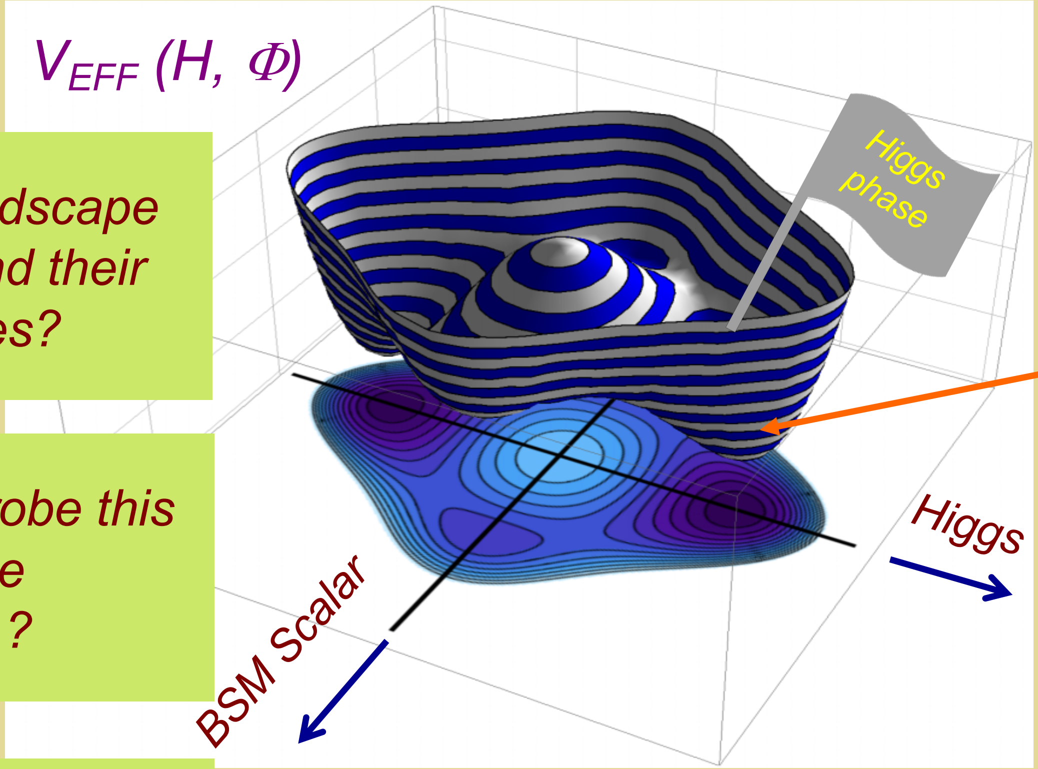


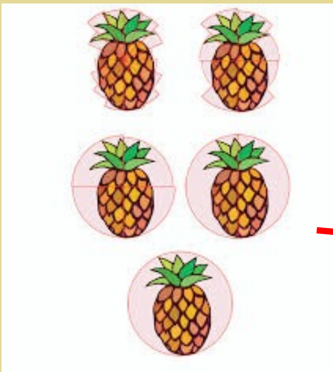
- *What is the landscape of potentials and their thermal histories?*
- *How can we probe this T > 0 landscape experimentally ?*
- *How reliably can we compute the thermodynamics ?*

How did we end up here ?

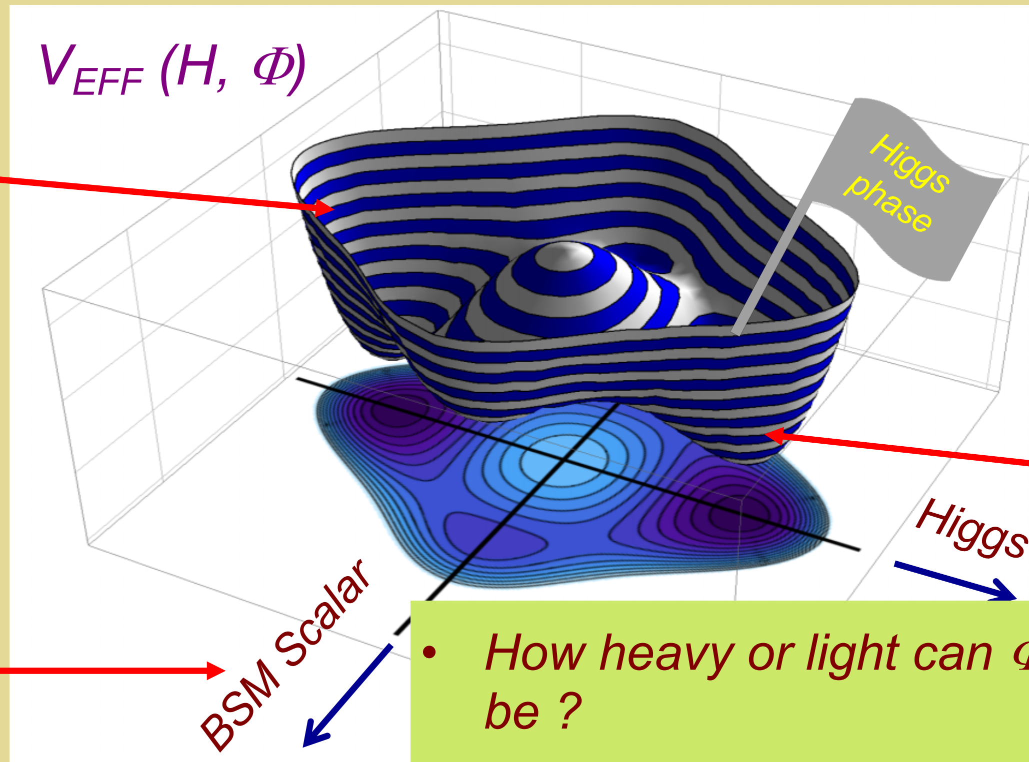
n evolve differently as T evolves → ilities for symmetry breaking

Was There an EW Phase Transition?

Bubble Collisions



Grav Radiation



Higgs precision tests

Direct Production

BSM Higgs

- *How heavy or light can Φ be ?*
- *How coupled to H ?*
- *Can it be discovered at the LHC or beyond ?*

Extrema can evolv →
rich possibilities f

MJRM: 1912.07189

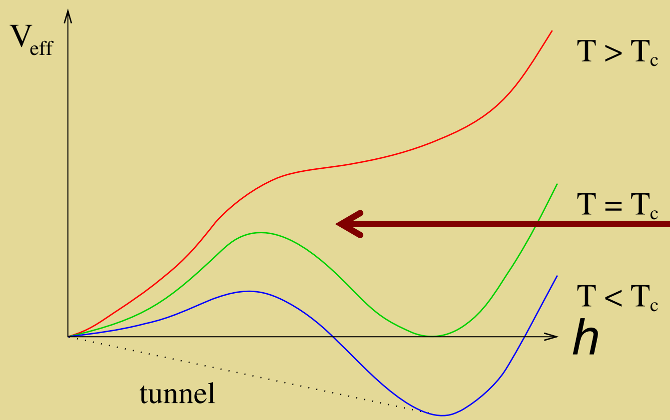
T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

$$\boxed{V(h,T)_{\rm SM} = D(T^2 - T_0^2)\,h^2 + \lambda\,h^4 \quad + \ldots}$$

$\boxed{T_0 \sim 140 \text{ GeV}}$ $\boxed{\equiv \quad T_{EW}}$

First Order EWPT from BSM Physics

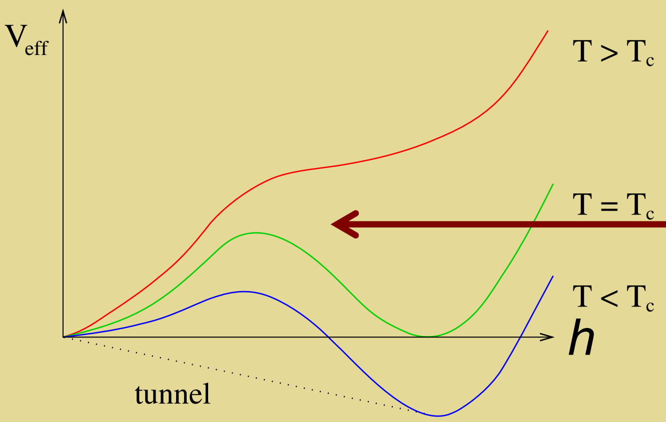


Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

- ***$M_\phi \lesssim 700$ GeV***
- ***h-ϕ mixing: $|\sin\theta| \gtrsim 0.01$***

First Order EWPT from BSM Physics



Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

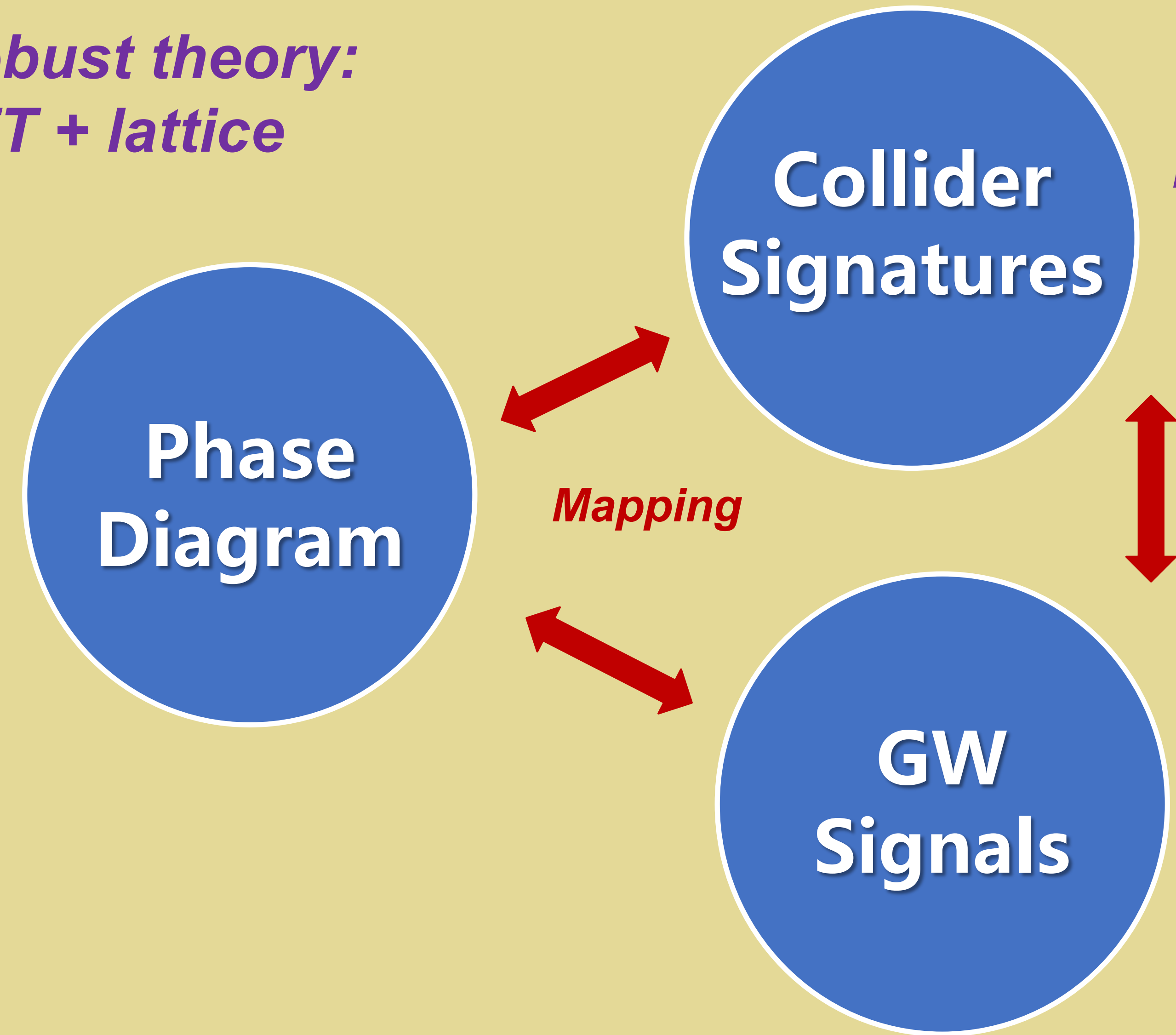
Collider target

- $M_\phi \lesssim 700$ GeV
- h-ϕ mixing: $|\sin\theta| \gtrsim 0.01$

BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

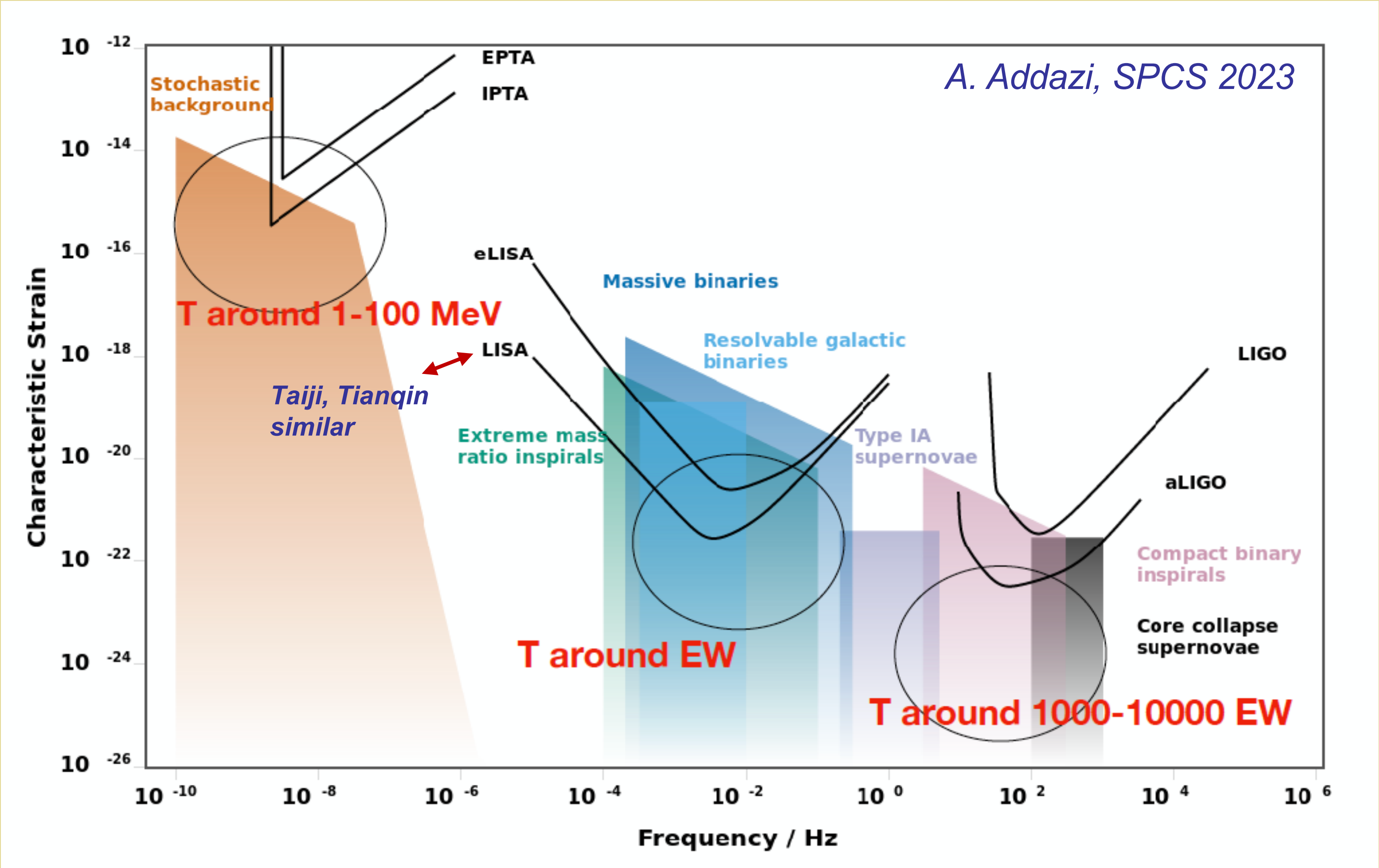
Observables:
model specific



Combined reach

Hydro:
$\alpha\,,\ \beta / H_*$

Gravitational Waves



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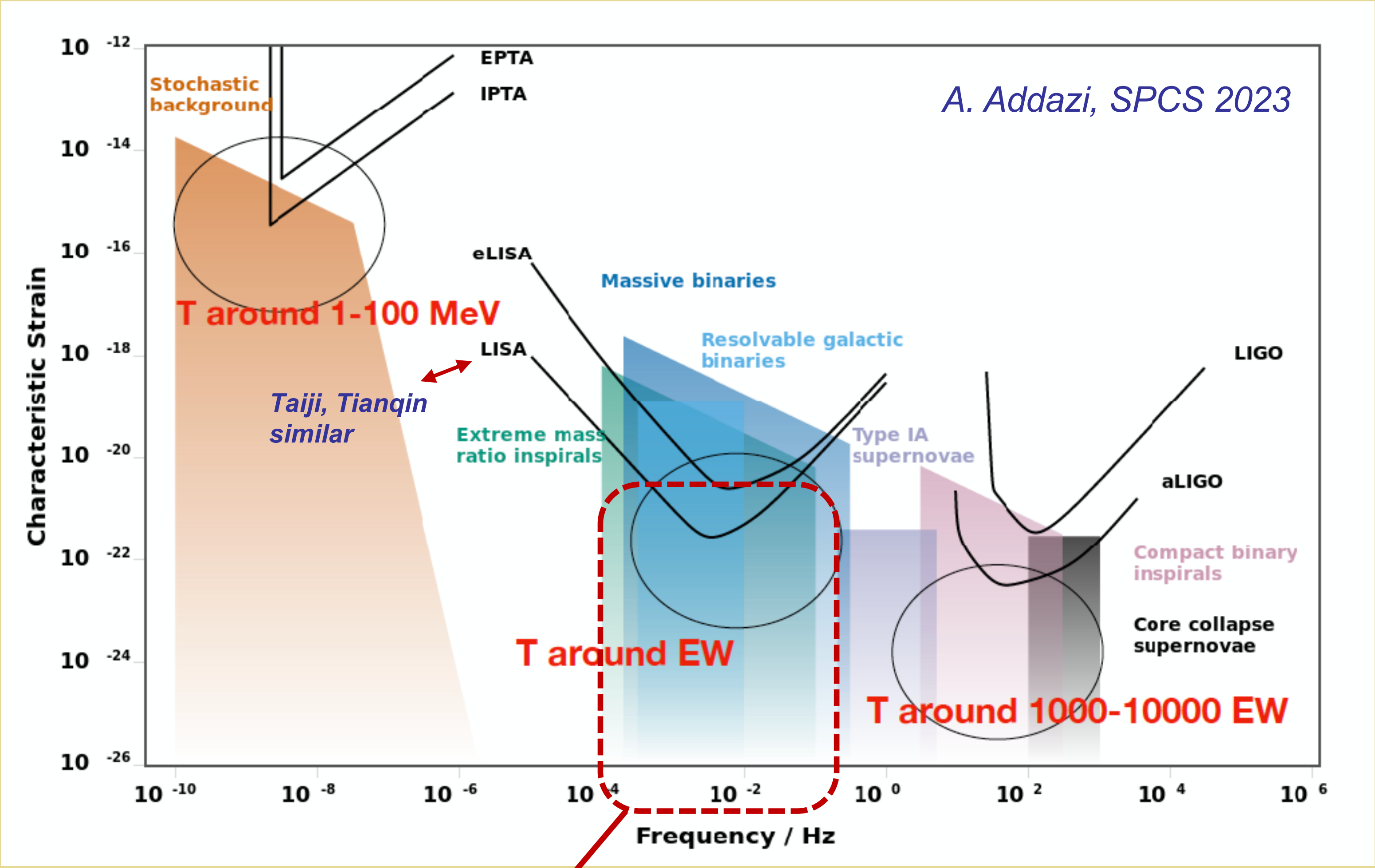
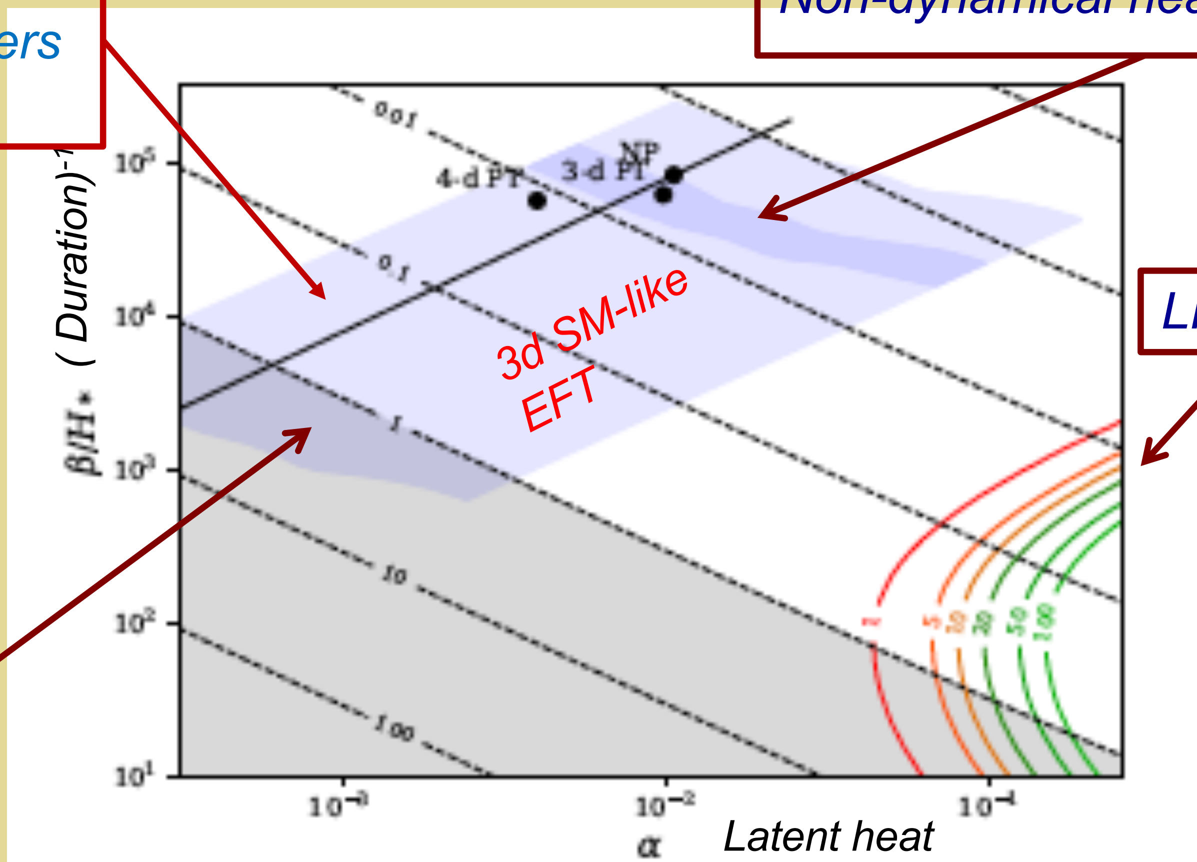


EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

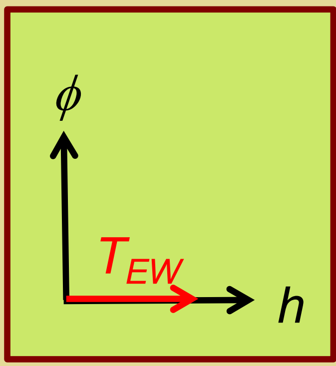
BSM Scalar: EWPT & GW

Collider probes of BSM parameters in $\mathcal{L}_{full}$

Non-dynamical heavy BSM scalars



LISA SNR



- *One-step*
- *Non-perturbative*

Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

BSM Scalar: EWPT & GW

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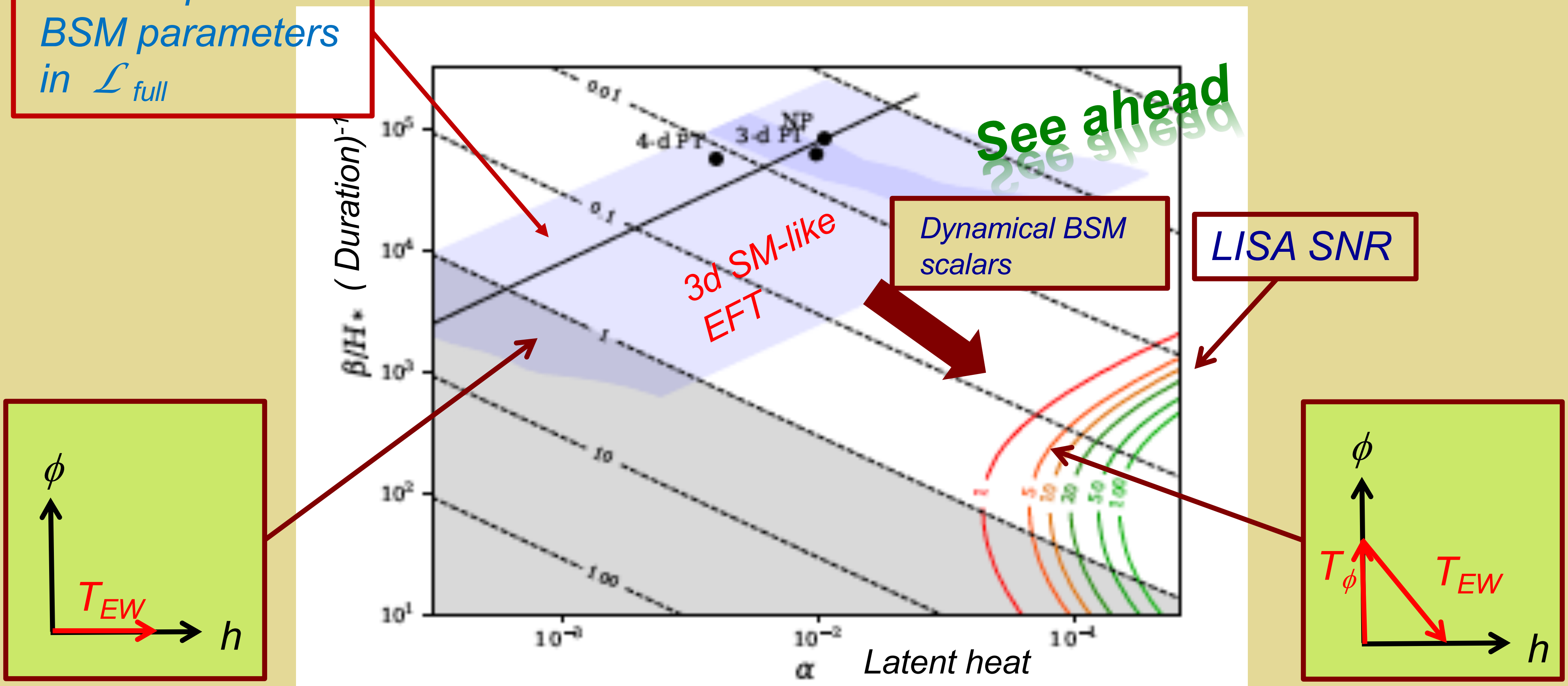


Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- One-step
- Non-perturbative

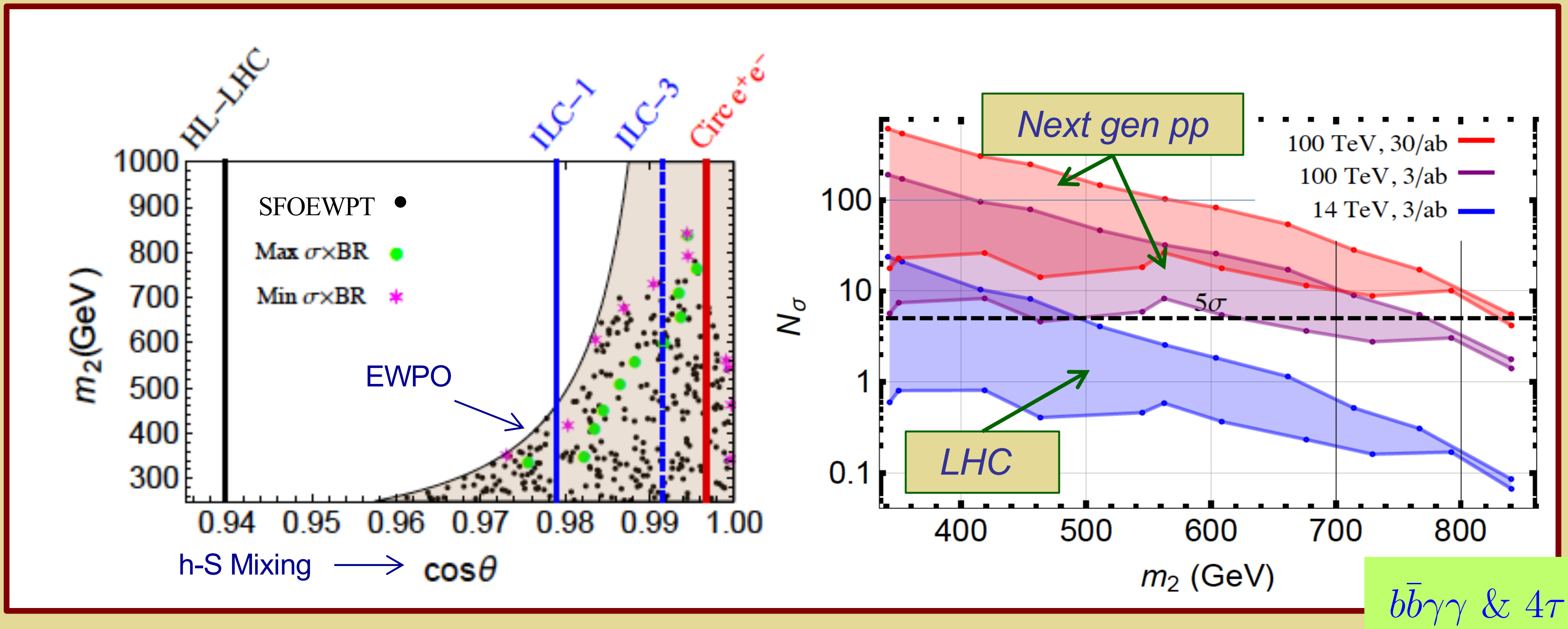
Model Illustrations

Simple Higgs portal models:

- *Real gauge singlet (SM + 1)*
- *Real EW triplet (SM + 3)*

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Precision Higgs studies & resonant di-Higgs



Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442;
Li et al, 1906.05289

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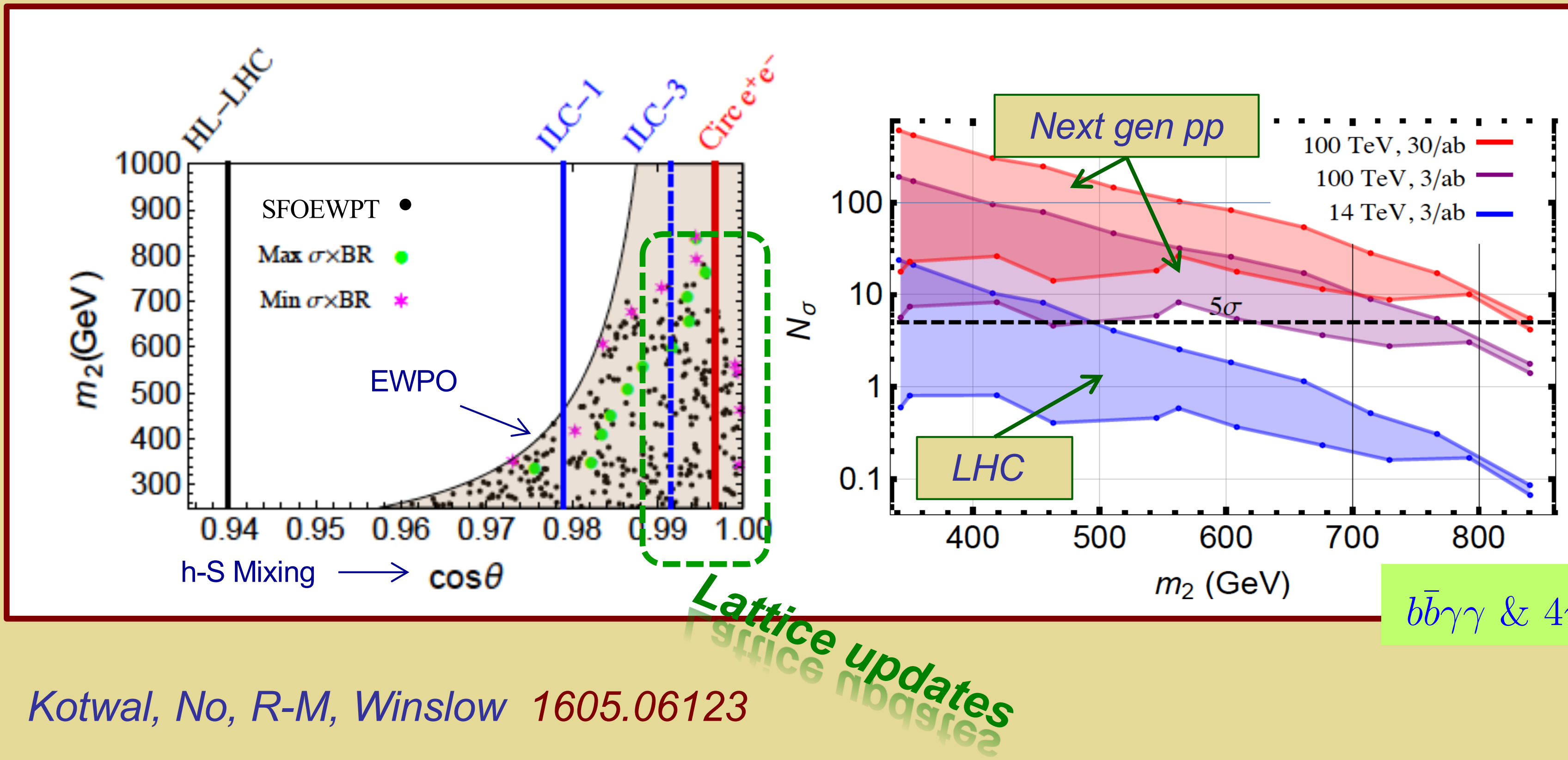

$b\bar{b}\gamma\gamma$ & 4τ

Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442;
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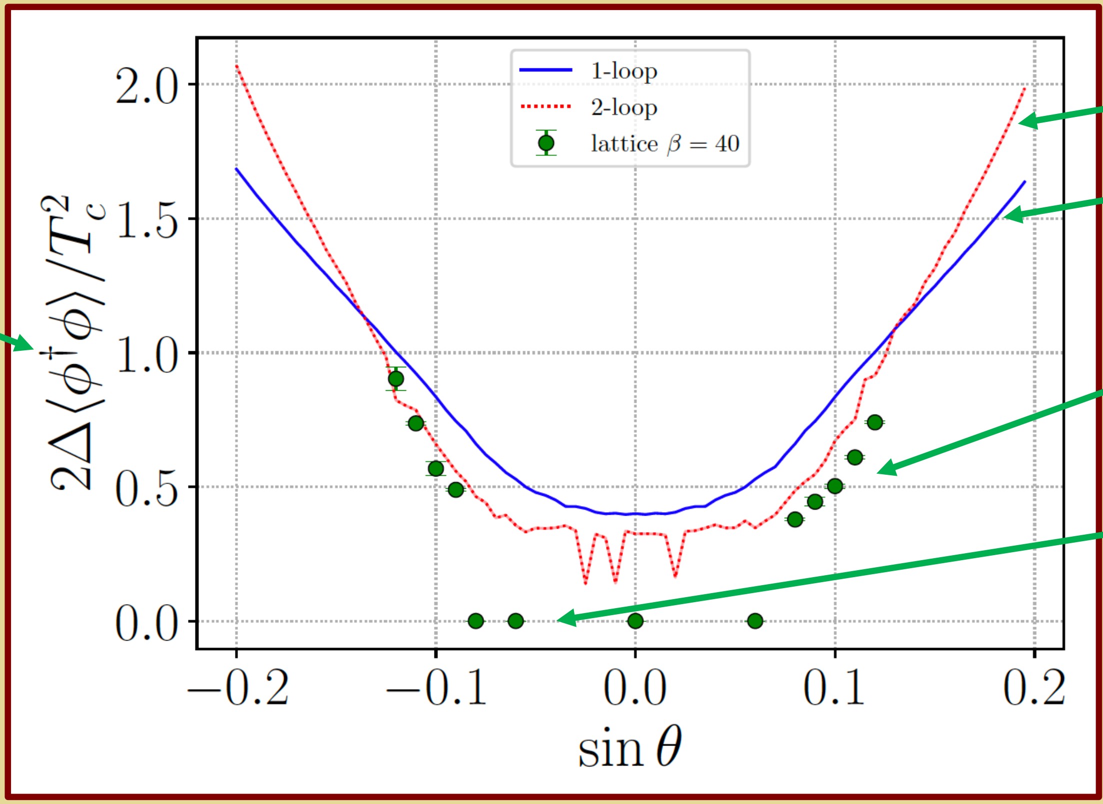
Lattice Benchmarking

L. Niemi, MRM, G. Xia in 2311.NNNN

M_{h2} = 350 GeV

Change in condensate at T_C



2 loop PT

1 loop PT

Lattice: FOEWPT

Lattice: Crossover

Lattice Benchmarking

L. Niemi, MRM, G. Xia in 2311.NNNN

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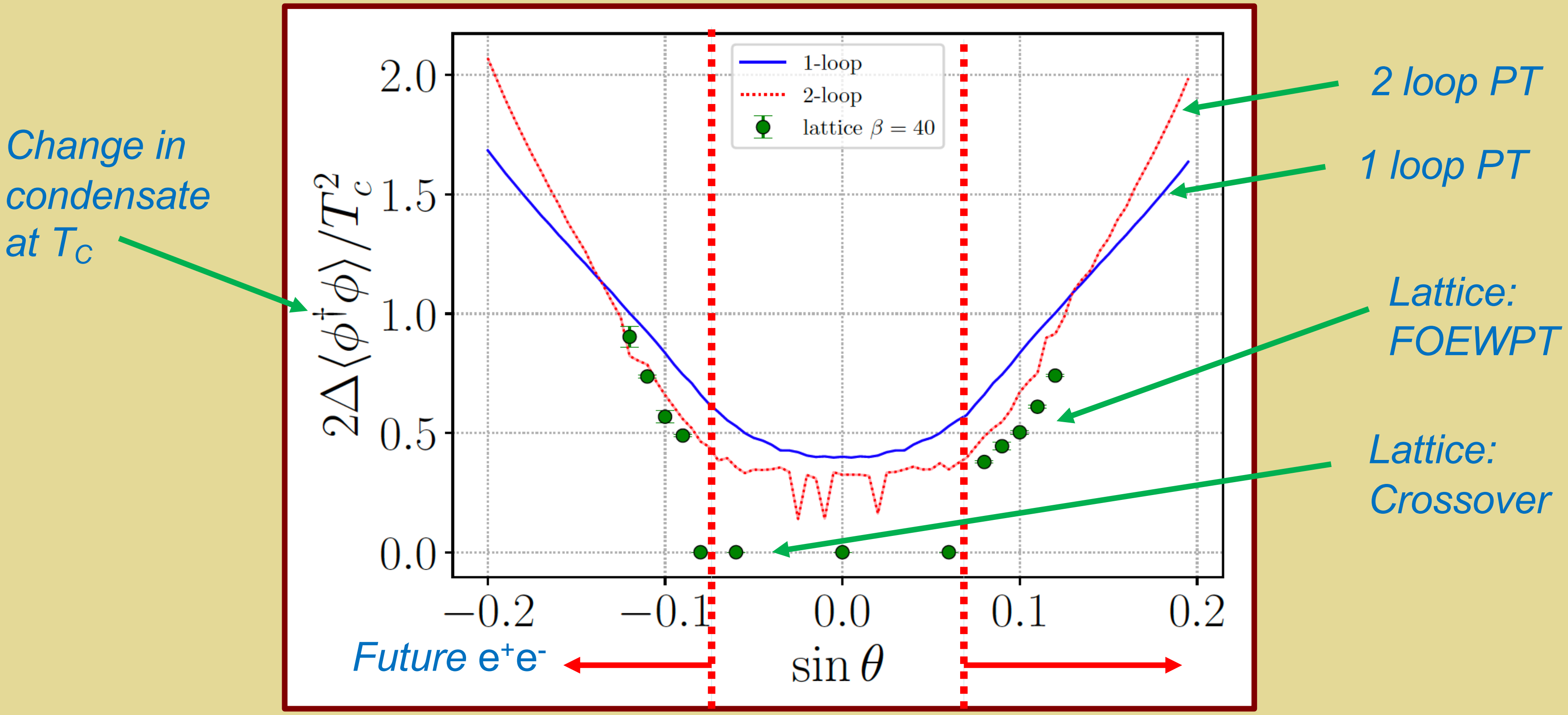
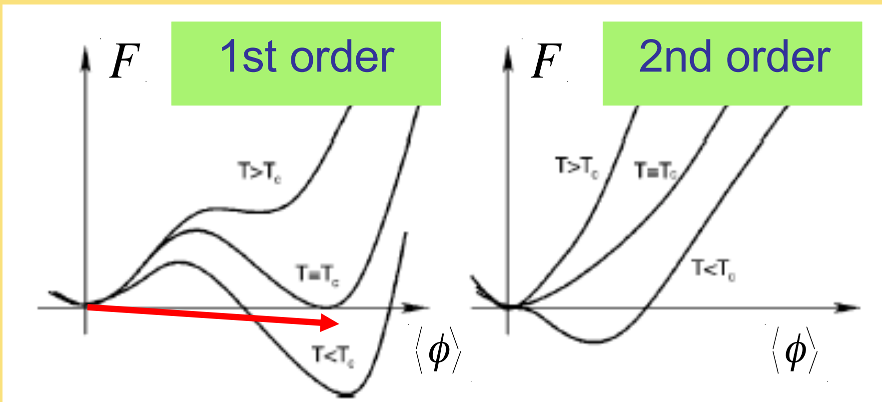
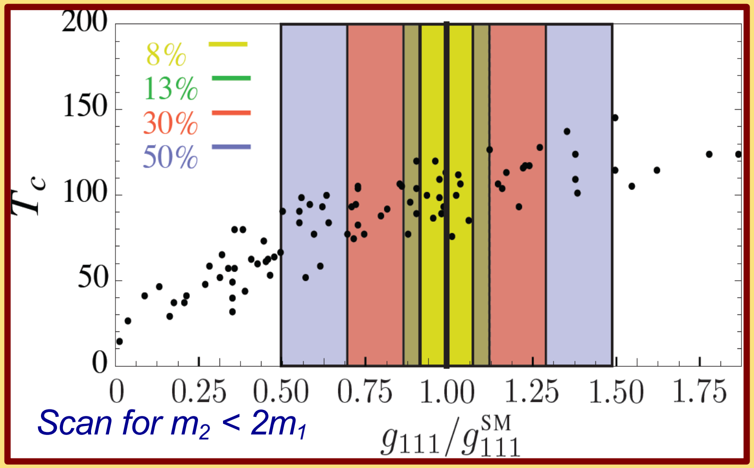


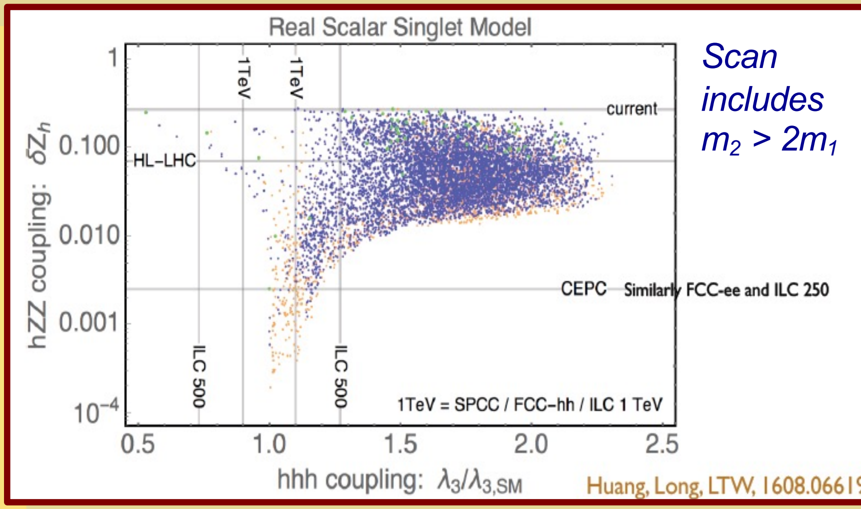
- *When a FOEWPT occurs, 2 loop PT gives a good description*
- *Lattice needed to determine when onset of FOEWPT occurs*
- *Future precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

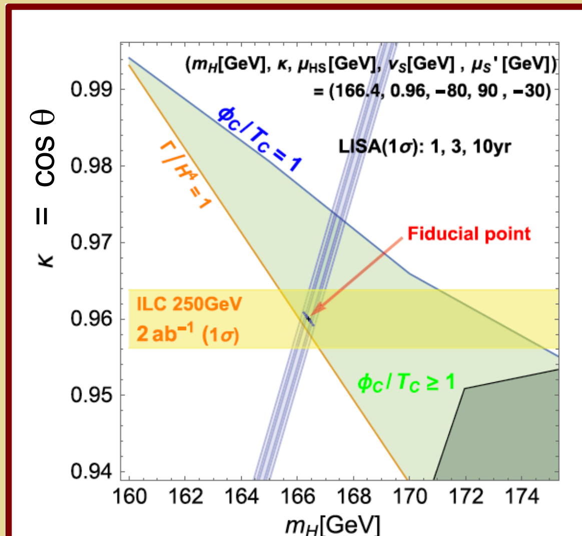
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling







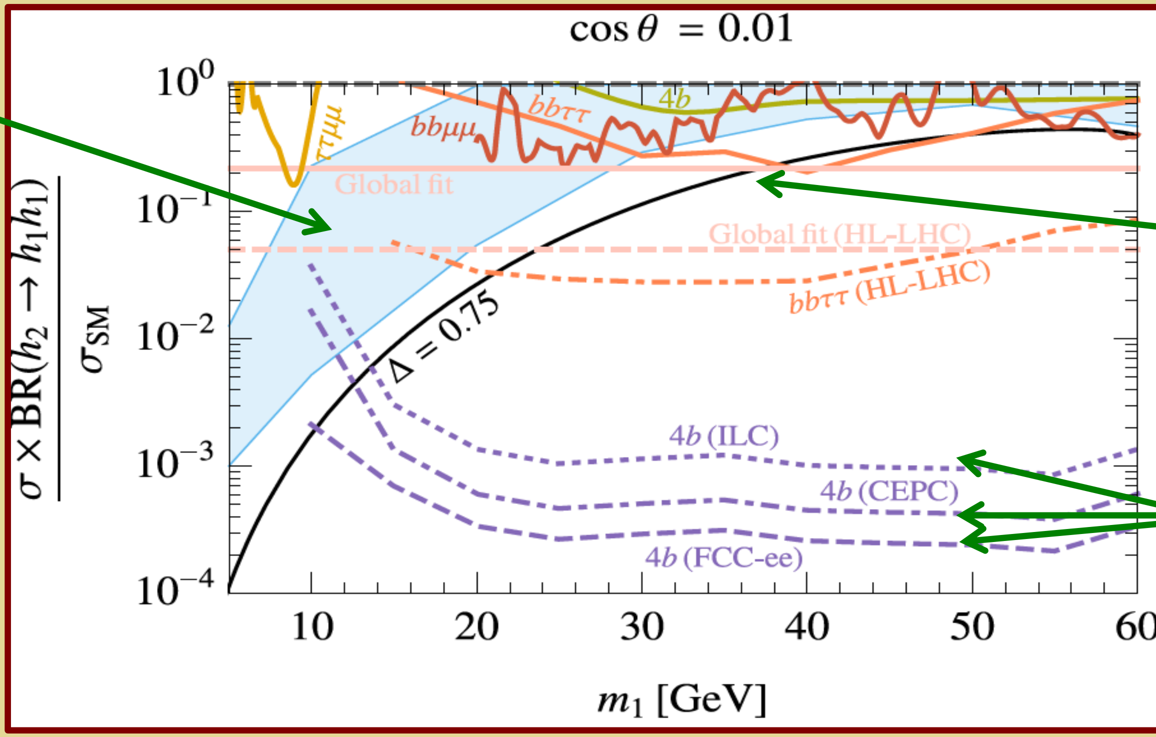
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

K. Hasino et al, PRD 99 (2019) 075011

Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

Future e^+e^-

Global LHC update: Snowmass white paper 2206.08326

J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

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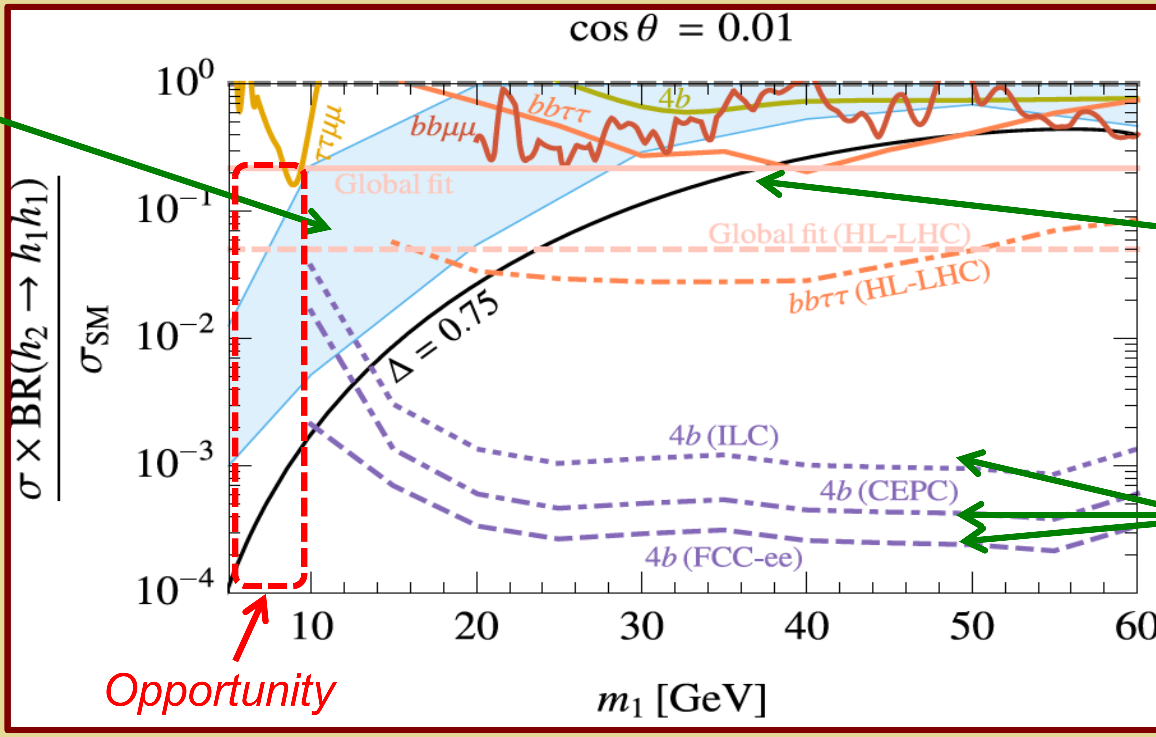

Opportunity

EWPT viable: Semi analytic

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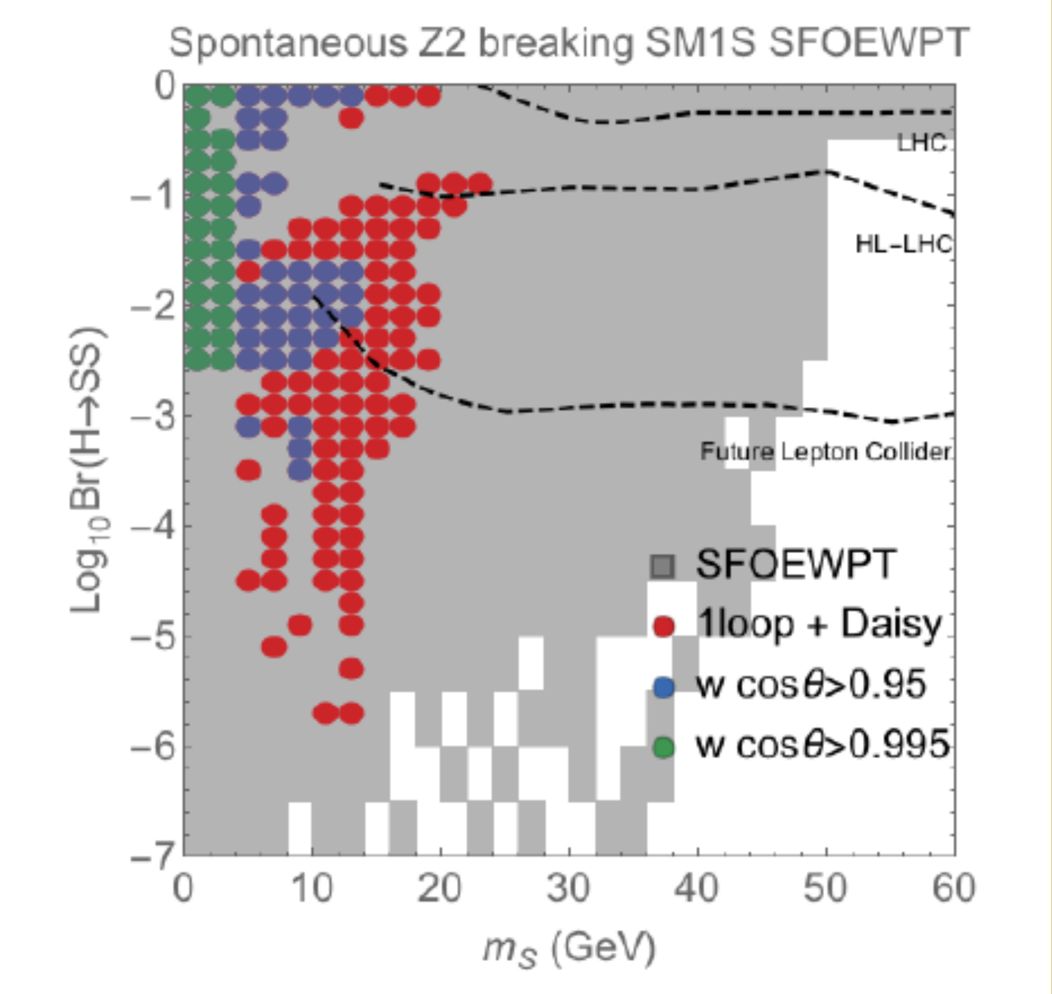
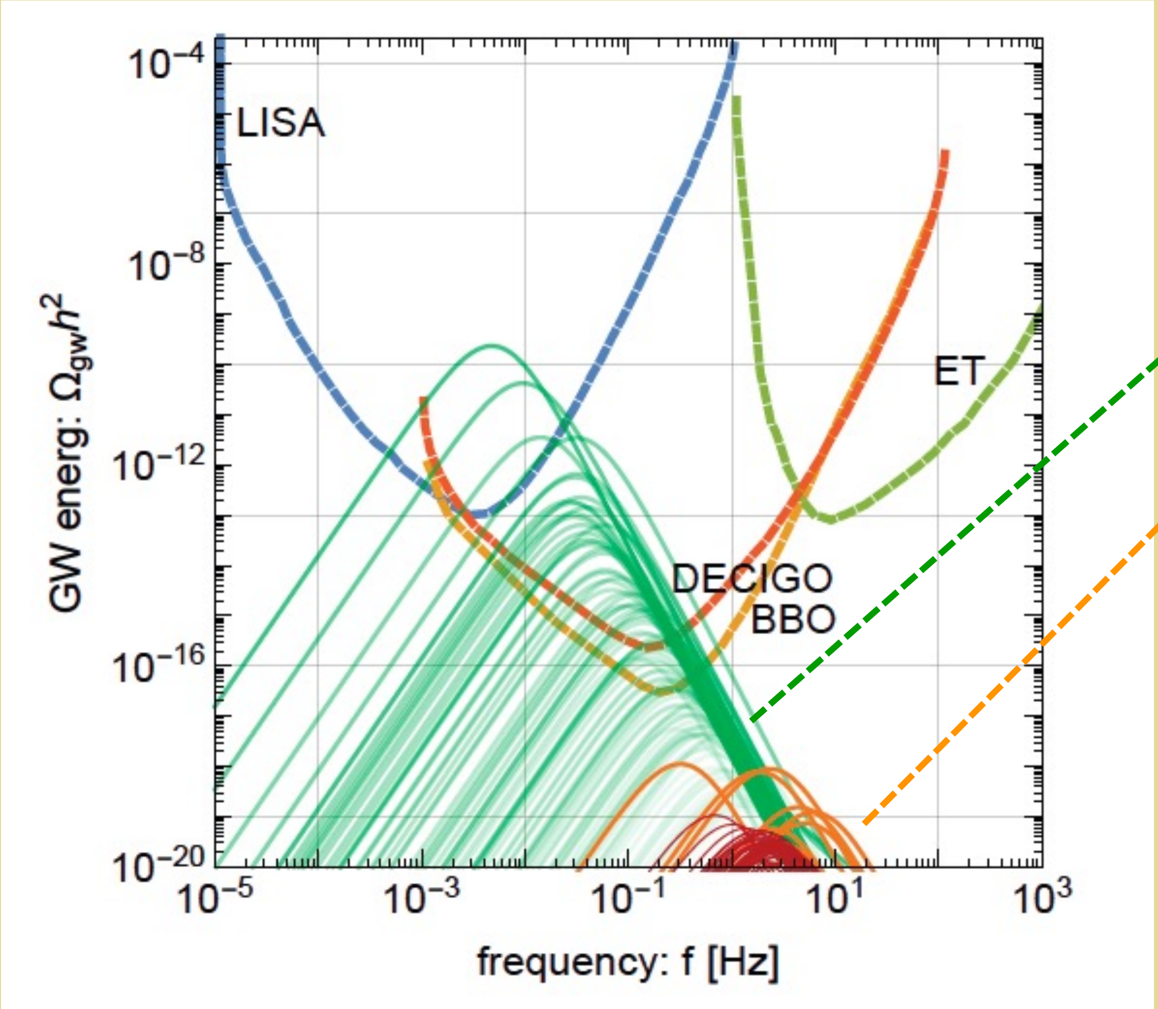
J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

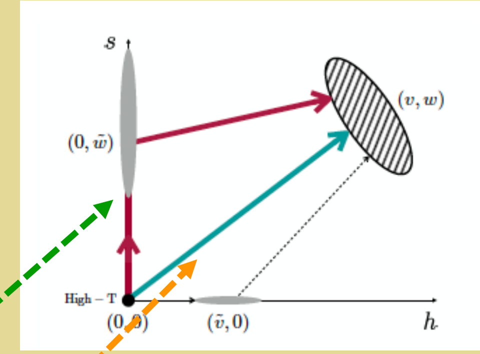
Spontaneous Z_2 Breaking



Carena, Liu, Wang 1911.10206

Spontaneous Z_2 Breaking





Carena, Liu, Wang 1911.10206

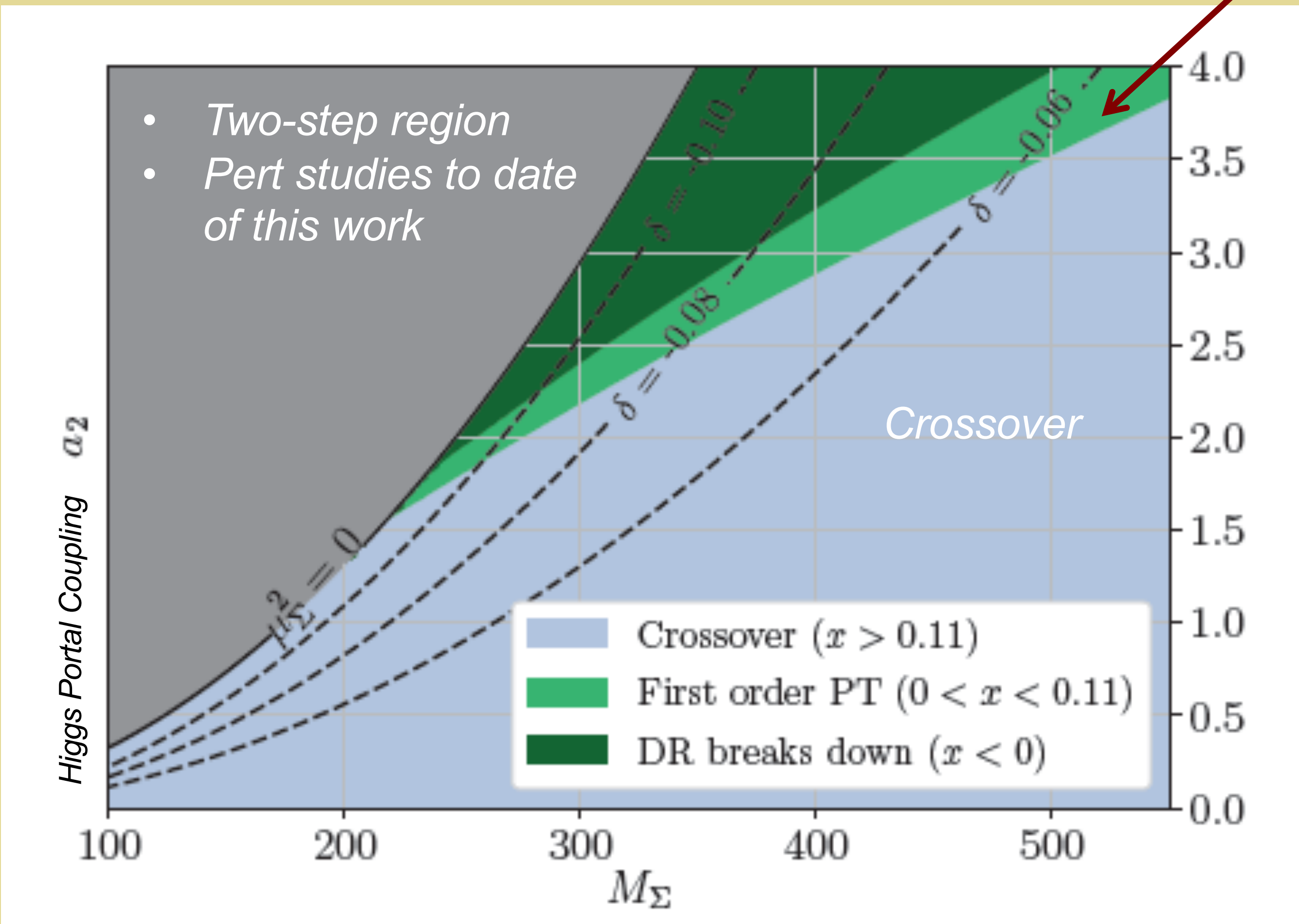
Model Illustrations

Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Non-Dynamical Real Triplet: One-Step EWPT

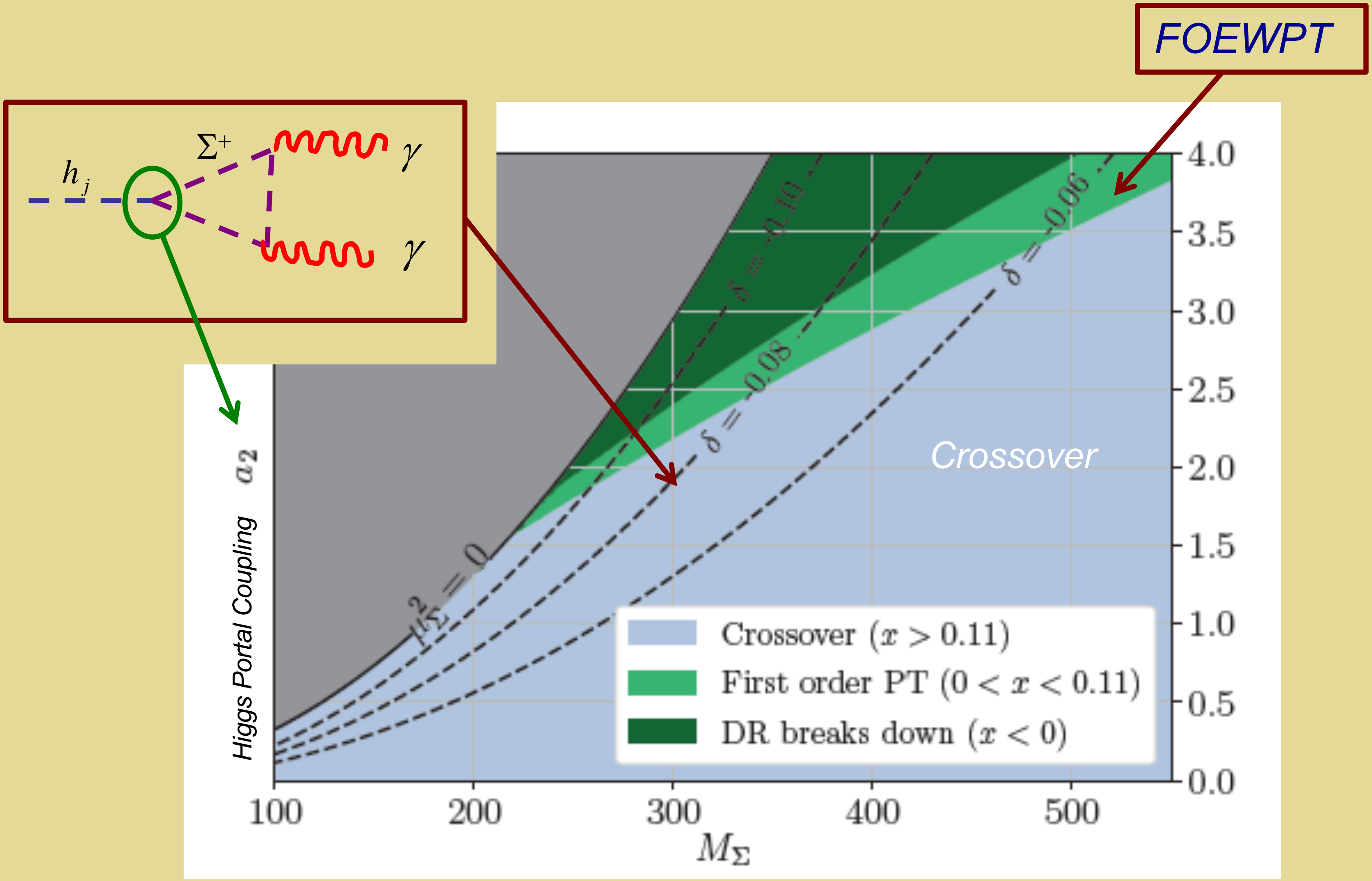
FOEWPT



- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Non-Dynamical Real Triplet: One-Step EWPT



Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

- *One-step*
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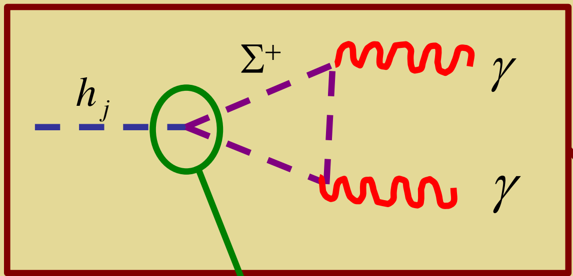
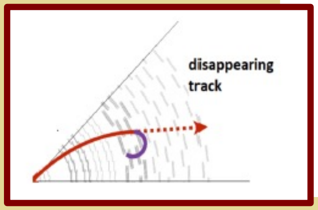
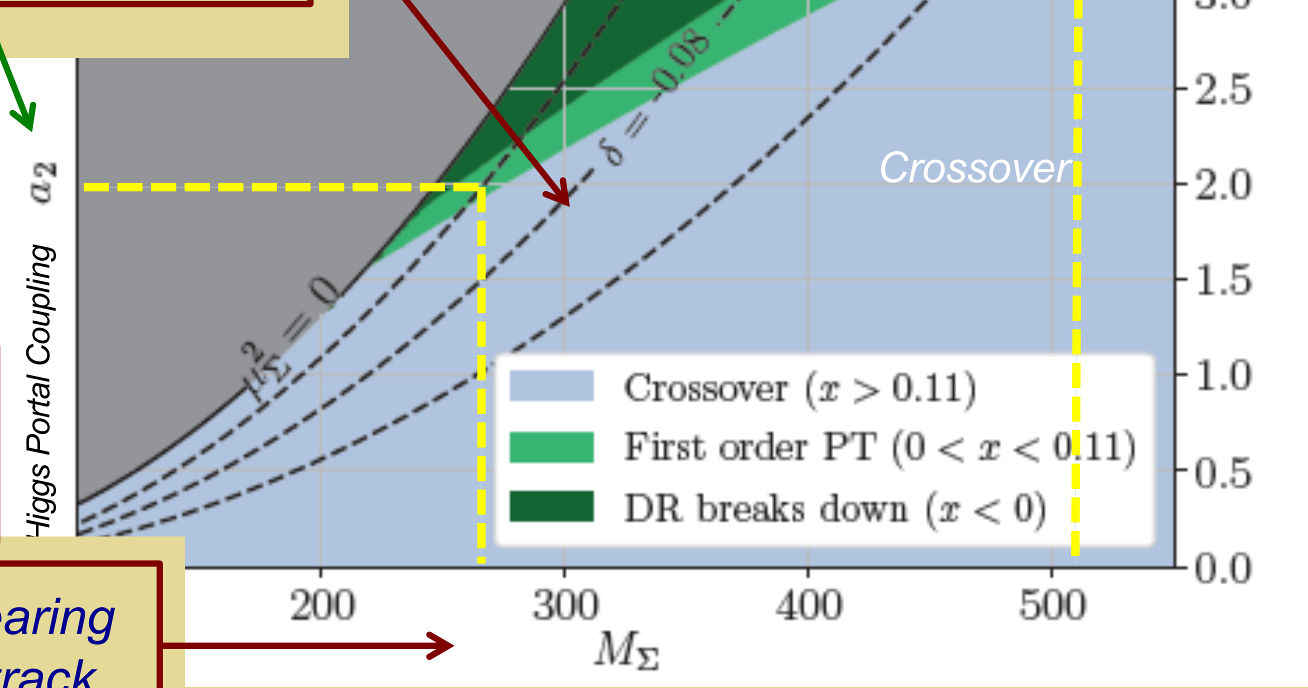






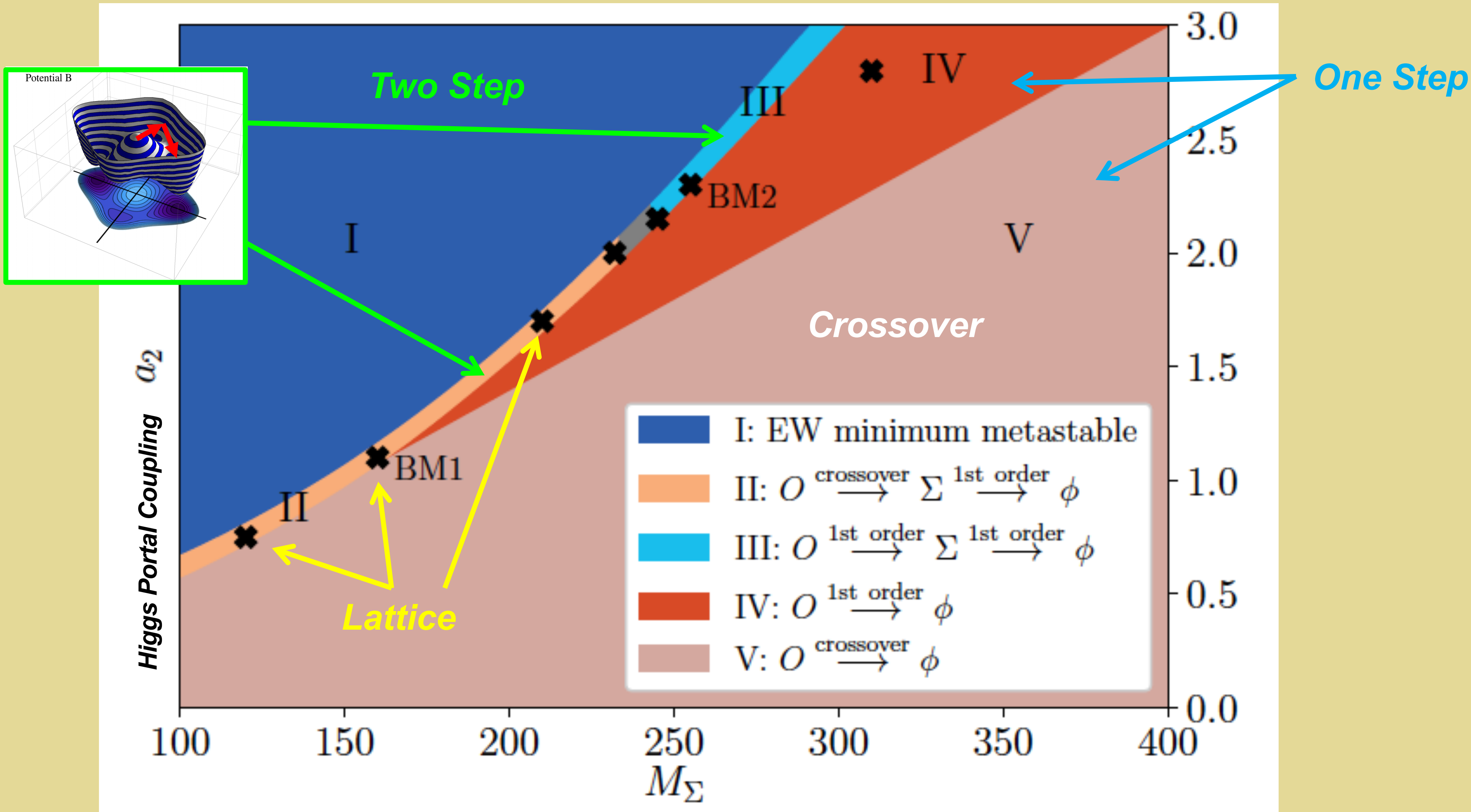
FOEWPT

Disappearing charge track

- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

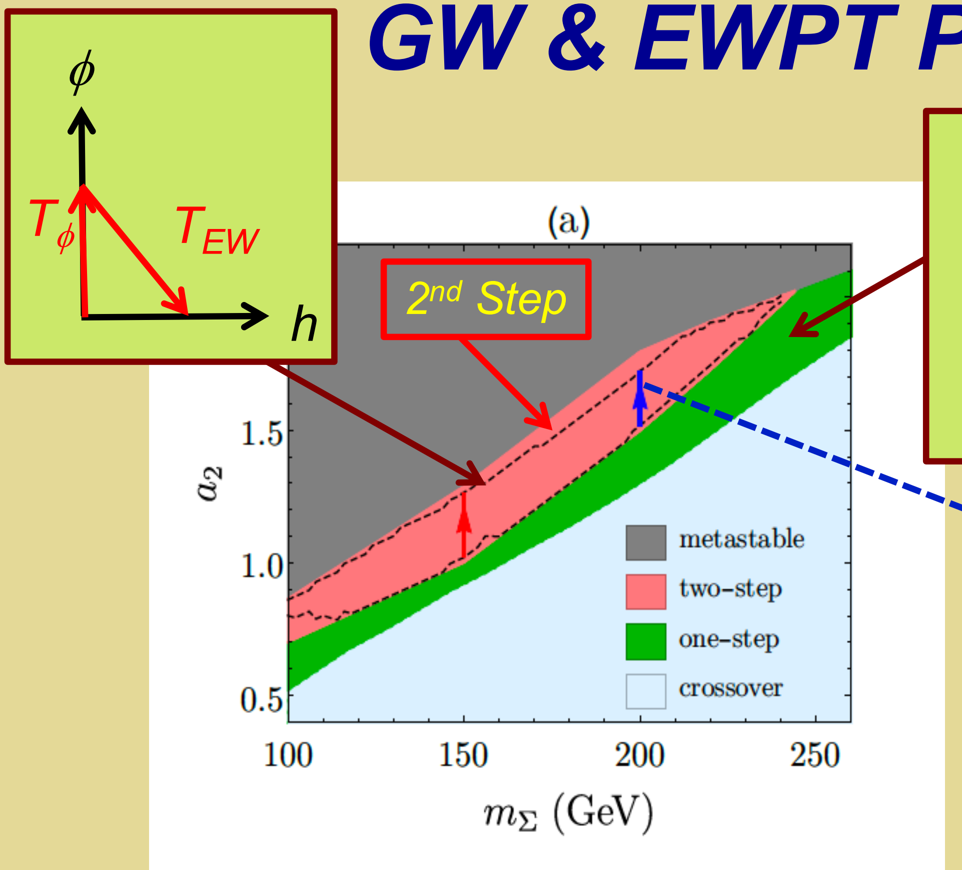
Real Triplet & EWPT: Novel EWSB

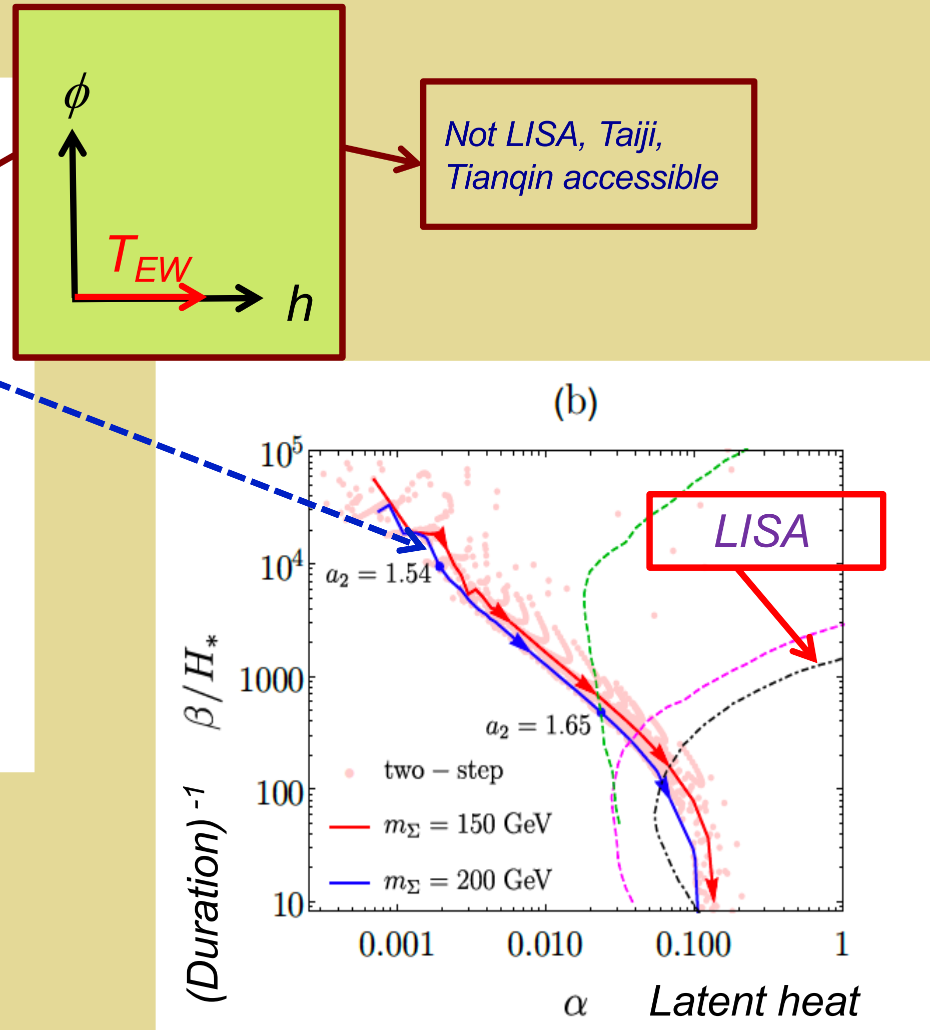


Niemi, R-M, Tenkanen, Weir 2005.11332

- *1 or 2 step*
- *Non-perturbative*

GW & EWPT Phase Diagram

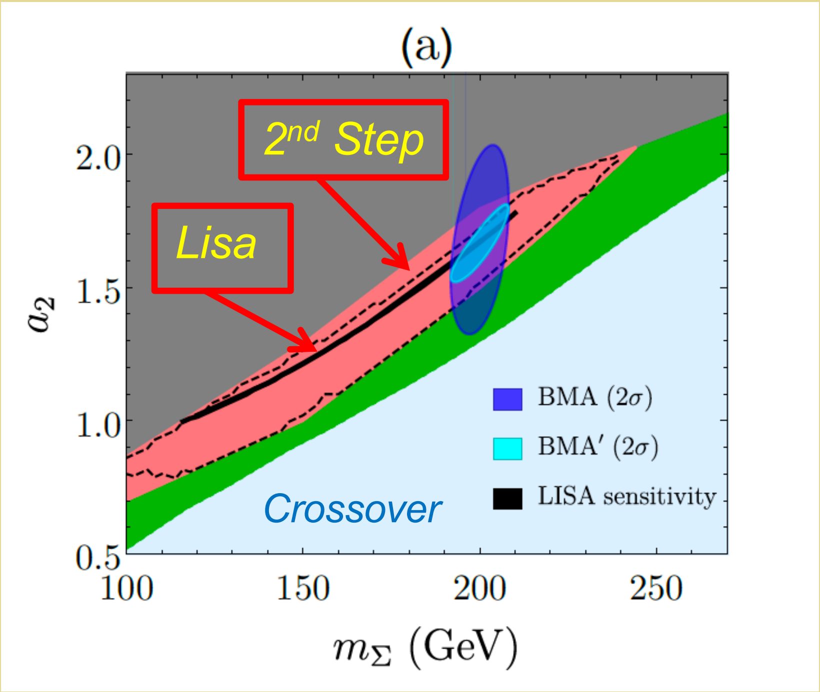


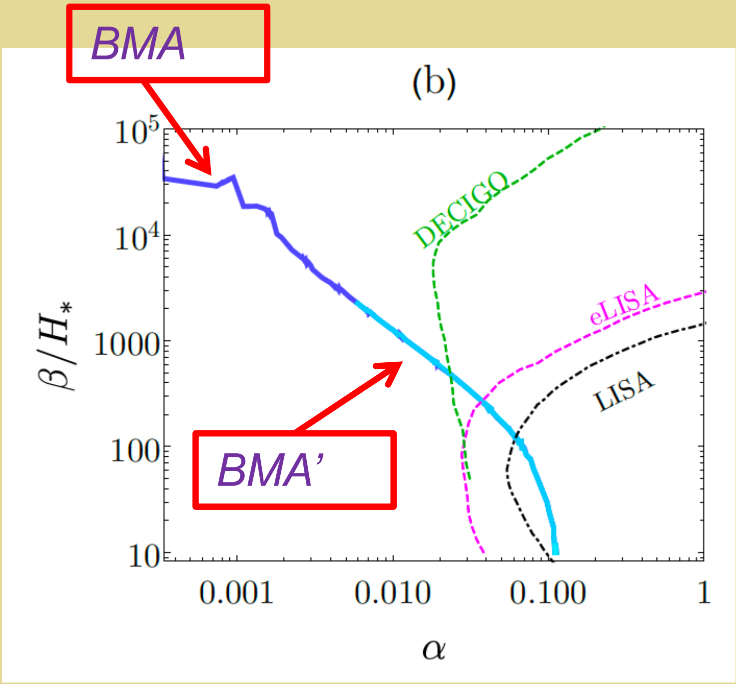


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





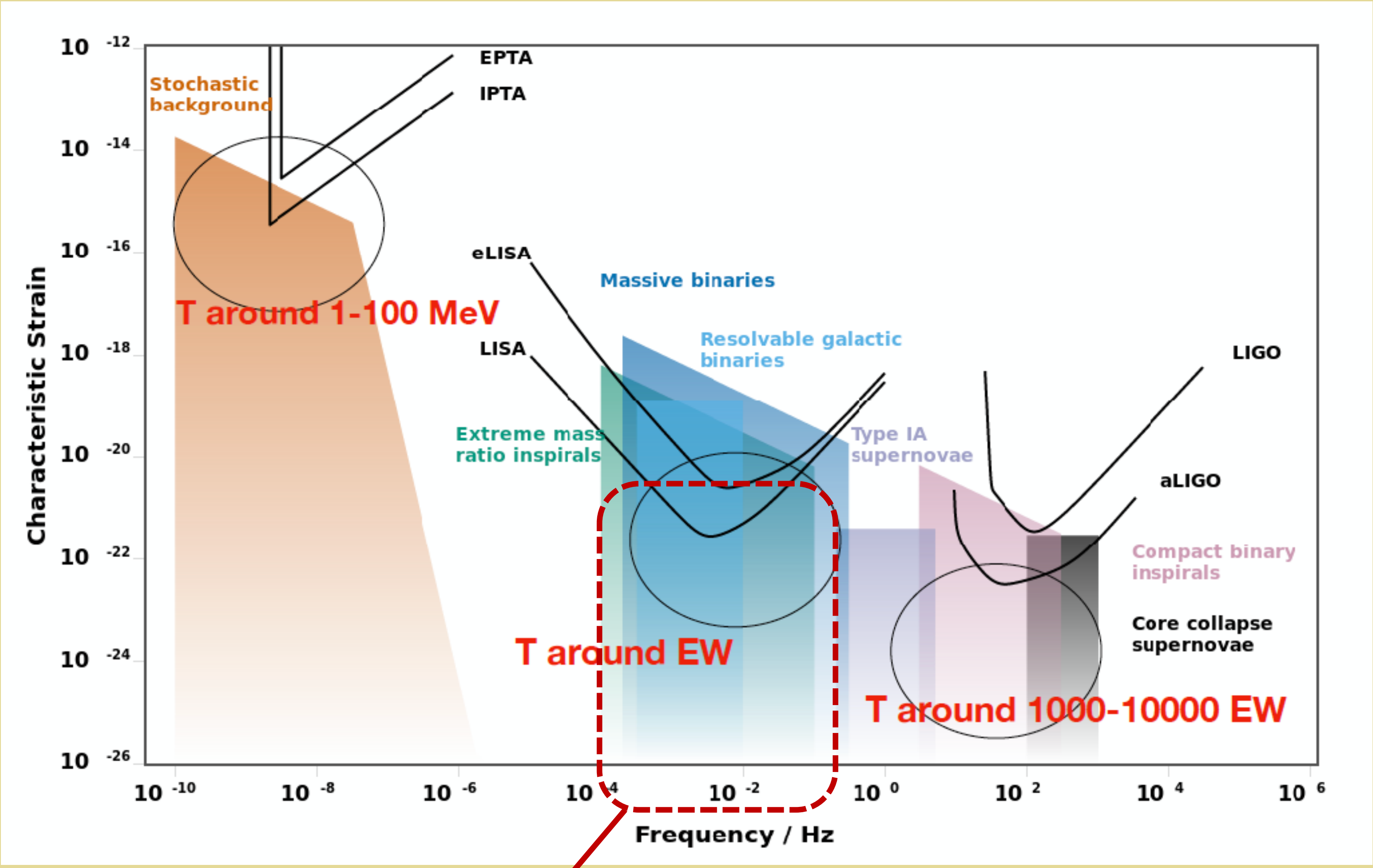
BMA: m_Σ + h → $\gamma\gamma$

BMA' : BMA + Σ^0 → ZZ

Friedrich, MJRM, Tenkanen, Tran 2203.05889

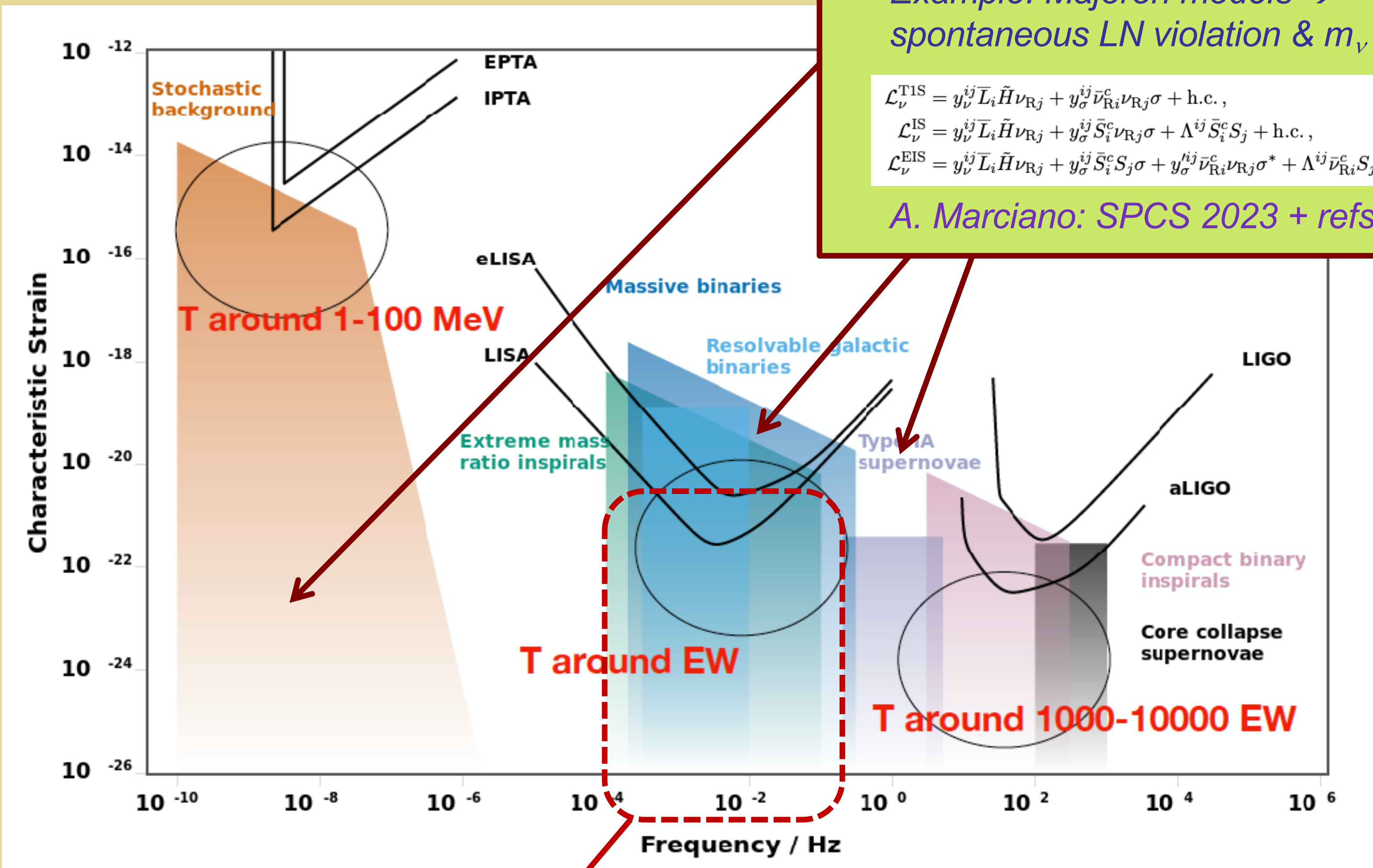
- *Two-step*
- *EFT+ Non-perturbative*

Gravitational Waves



EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

Gravitational Waves



Example: Majoron models → spontaneous LN violation & m_ν

$$\mathcal{L}_\nu^{\mathrm{T1S}} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{\mathrm{R}j} + y_\sigma^{ij}\bar{\nu}_{\mathrm{R}i}^c\nu_{\mathrm{R}j}\sigma + \mathrm{h.c.}\,,$$

$$\mathcal{L}_\nu^{\mathrm{IS}} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{\mathrm{R}j} + y_\sigma^{ij}\bar{S}_i^c\nu_{\mathrm{R}j}\sigma + \Lambda^{ij}\bar{S}_i^c S_j + \mathrm{h.c.}\,,$$

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A. Marciano: SPCS 2023 + refs

EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

Gravitational Waves

LNV: see ahead

Example: Majoron models →
spontaneous LN violation & m_ν

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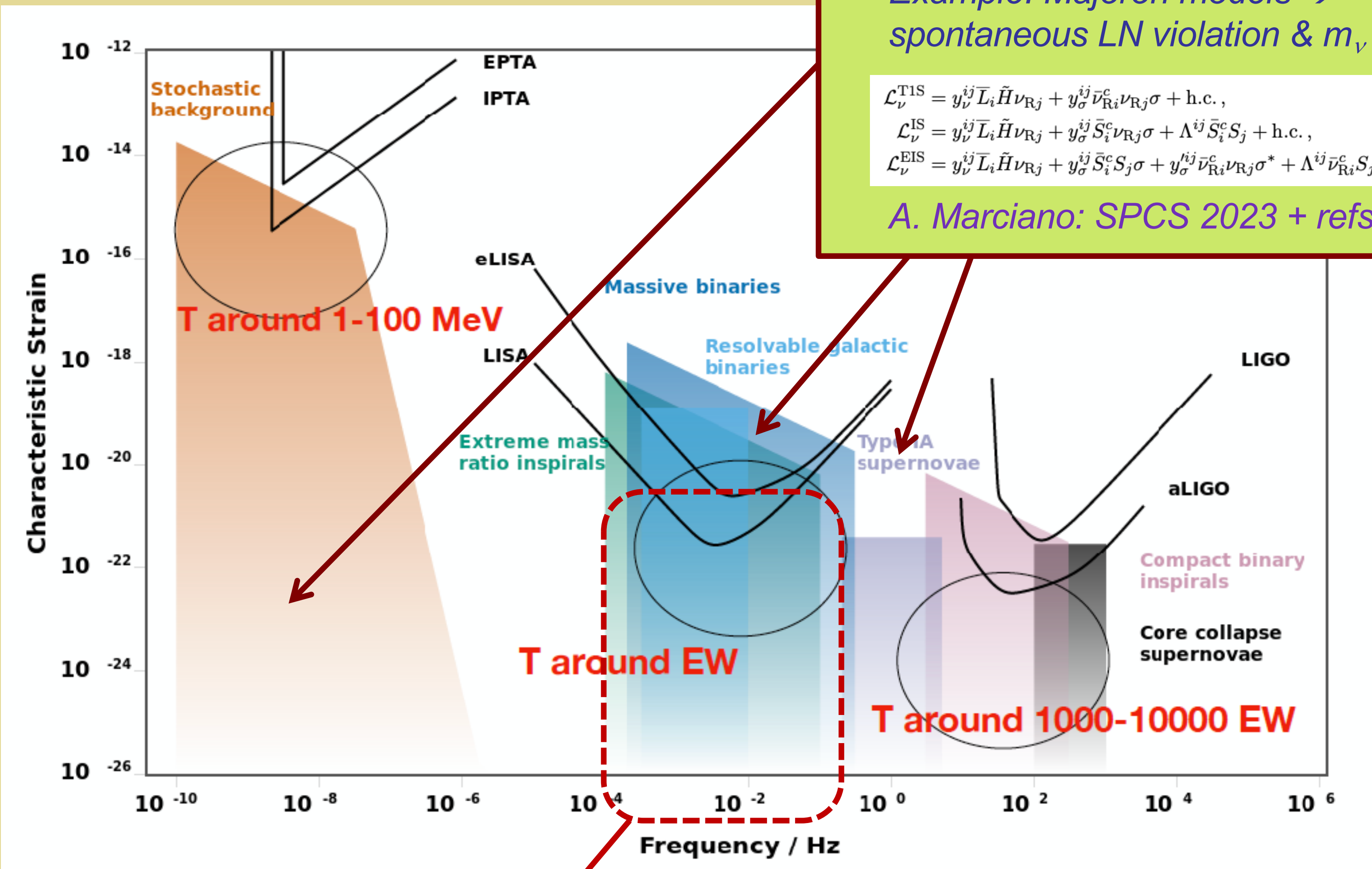

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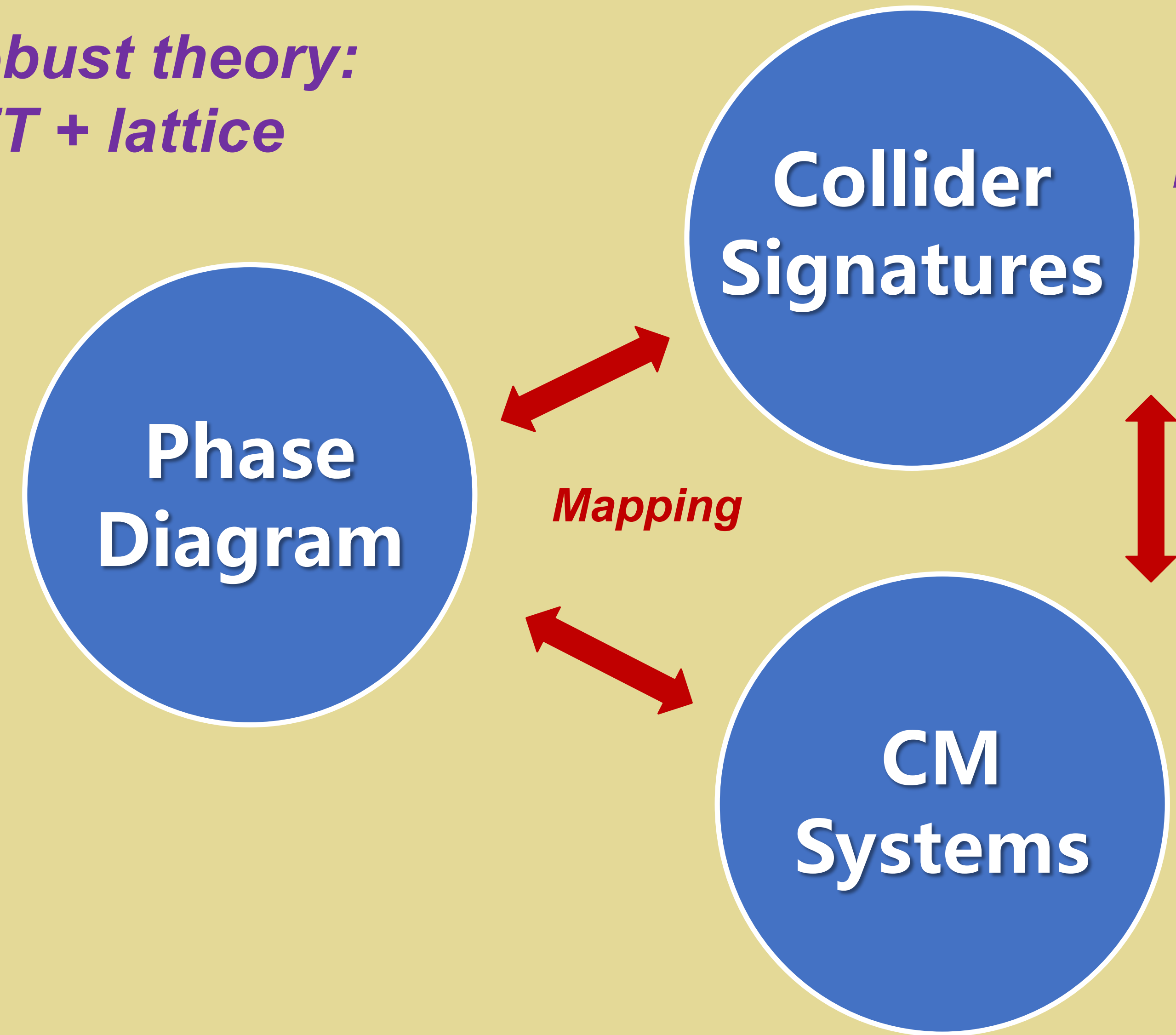
BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

Observables:
model specific



"Table top" tests ?

Supercond, superfluids …

First Order Phase Transitions

VOLUME 32, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1974

First-Order Phase Transitions in Superconductors and Smectic-*A* Liquid Crystals

B. I. Halperin
Bell Laboratories, Murray Hill, New Jersey 07974

and

T. C. Lubensky*
Department of Physics and Laboratory for Research in the Structure of Matter, University of Pennsylvania, Philadelphia, Pennsylvania 19174

and

Shang-keng Ma†
University of California at San Diego, La Jolla, California 92037

(Received 30 November 1973)

Abelian Higgs model (non-rel)

$$F\{\psi,\vec{A}\} = \int d^3r\Big[a|\psi|^2 + \tfrac{1}{2}b|\psi|^4 + \gamma|(\nabla - iq_0\vec{A})\psi|^2 + (8\pi\mu_0)^{-1}\sum_{i>j}(\nabla_j A_i - \nabla_i A_j)^2\Big]. \qquad (1)$$

$$\frac{1}{2\Omega}\frac{dF}{d|\psi|} = a|\psi| + b|\psi|^3 + q_0^2\gamma|\psi|\langle A^2\rangle_\psi,$$

$$\langle A^2\rangle_\psi = 4\mu_0 T_c \Lambda\pi^{-1} - (32\pi\gamma q_0^2\mu_0)^{1/2}\mu_0 T_c|\psi|.$$

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Cubic term → barrier → FO phase transition

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Rich opportunity for future synergy

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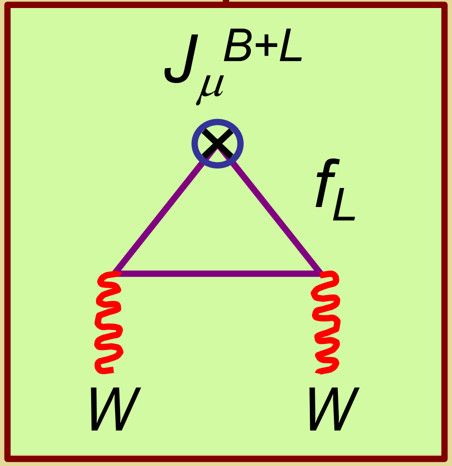
Cubic term → barrier → FO phase transition

III. What is the LN Violation Mass Scale ?

SM: B+L Not Conserved

B+L Anomaly

$$\boxed{\partial^\mu J_\mu^{B+L} = \frac{2N_F}{32\pi^2} \times \left\{ g^2 W_{\mu\nu}^a \widetilde{W}^{\mu\nu\, a} - g'^{\,2} B_{\mu\nu} \widetilde{B}^{\mu\nu} \right\}}$$



SM B+L Violation & Sphalerons

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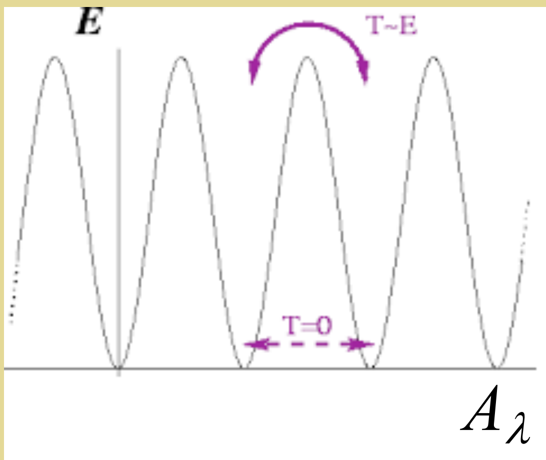

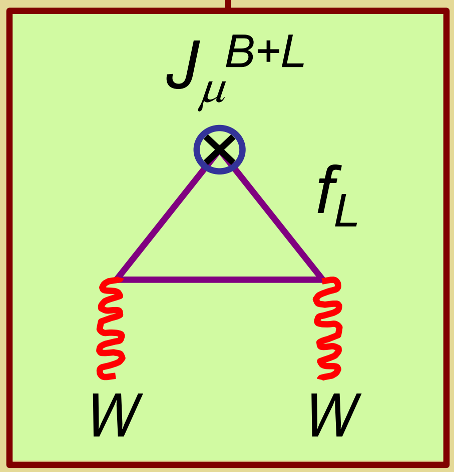

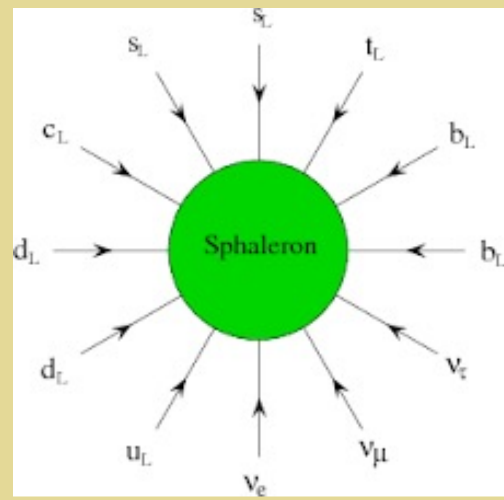

Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

SM B+L Violation & Sphalerons

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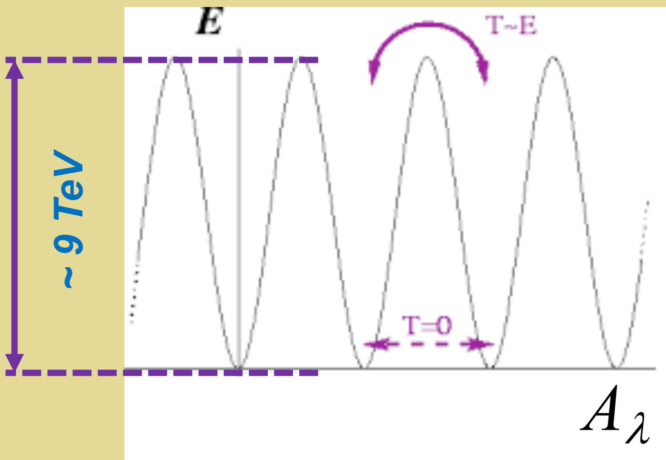
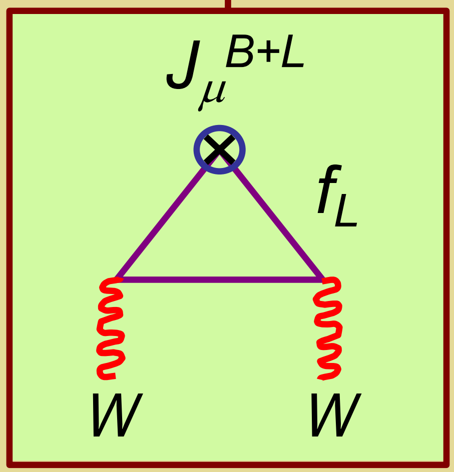
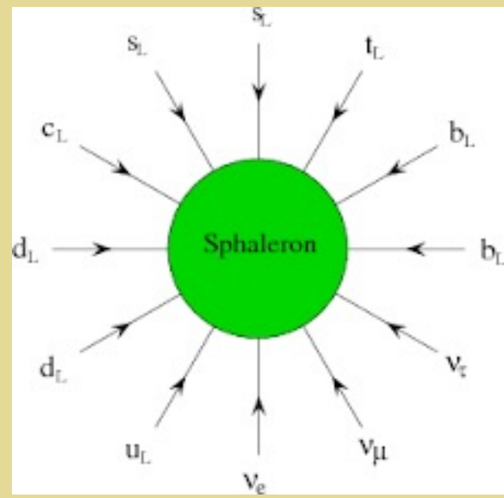






Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

Additional LN Violation: Questions

- *Are there additional sources of LN violation at the classical (Lagrangian) level?*
- *If so, what is the associated LNV mass scale ?*
- *What is the sensitivity of ton-scale $0\nu\beta\beta$-decay searches under various LNV scenarios ?*
- *What are the inter-frontier implications?*

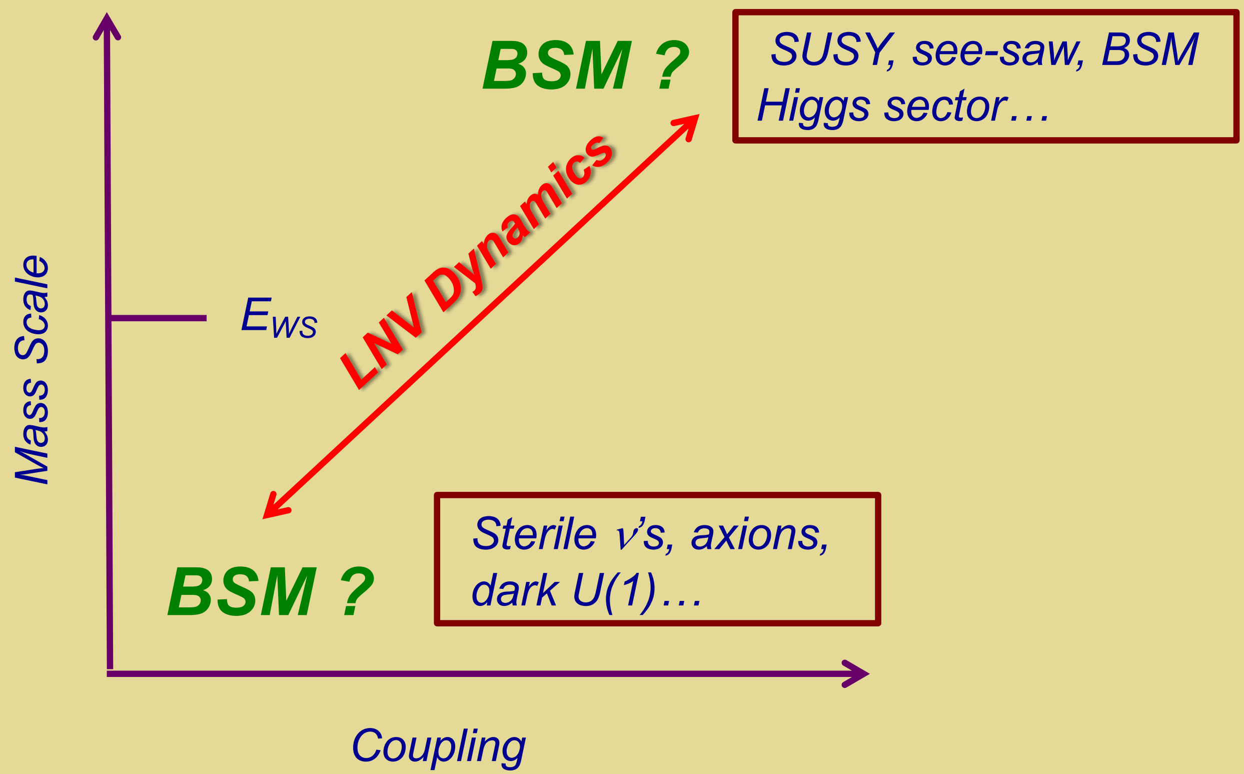
Origin of m_ν

Cosmology:
- **BAU**
- **Σm_ν**

ν Pheno
- **$0\nu\beta\beta$ decay**
- **μ_ν**

Colliders

LNV Physics: Where Does it Live ?



Is the BSM LNV scale (associated with m_ν) far above E_{WS} ? Near E_{WS} ? Well below E_{WS} ?

Lepton Number: ν Mass Term?

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

0νββ-Decay: LNV? Mass Term?

$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \mathrm{h.c.}$$

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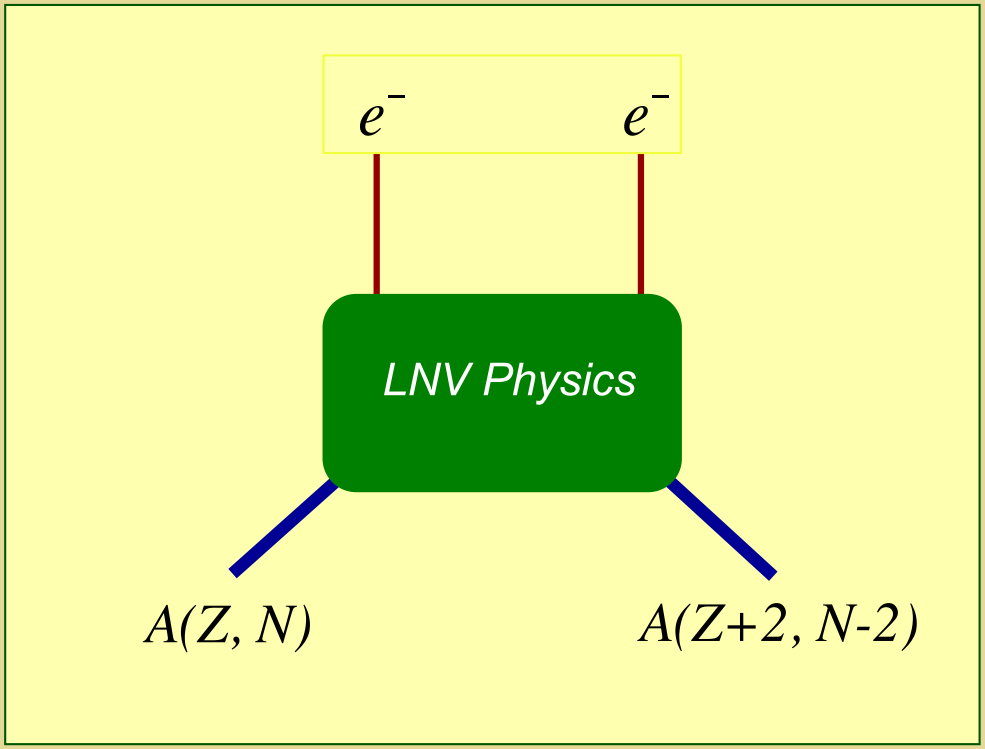

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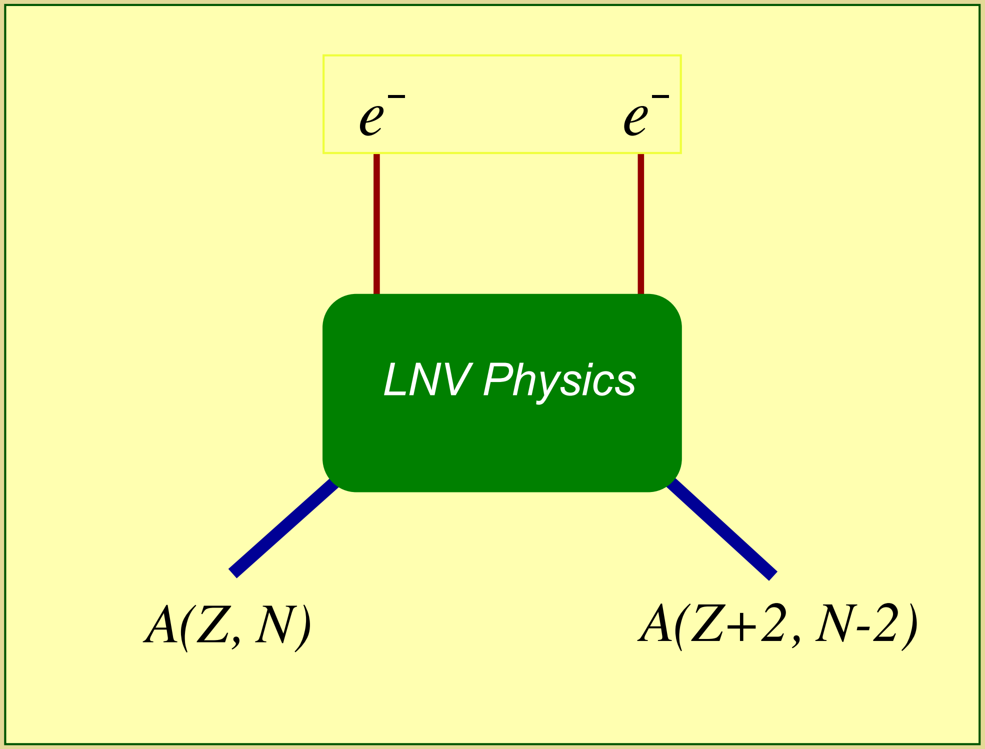
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



0νββ-Decay: LNV? Mass Term?

$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \mathrm{h.c.}$$

Dirac

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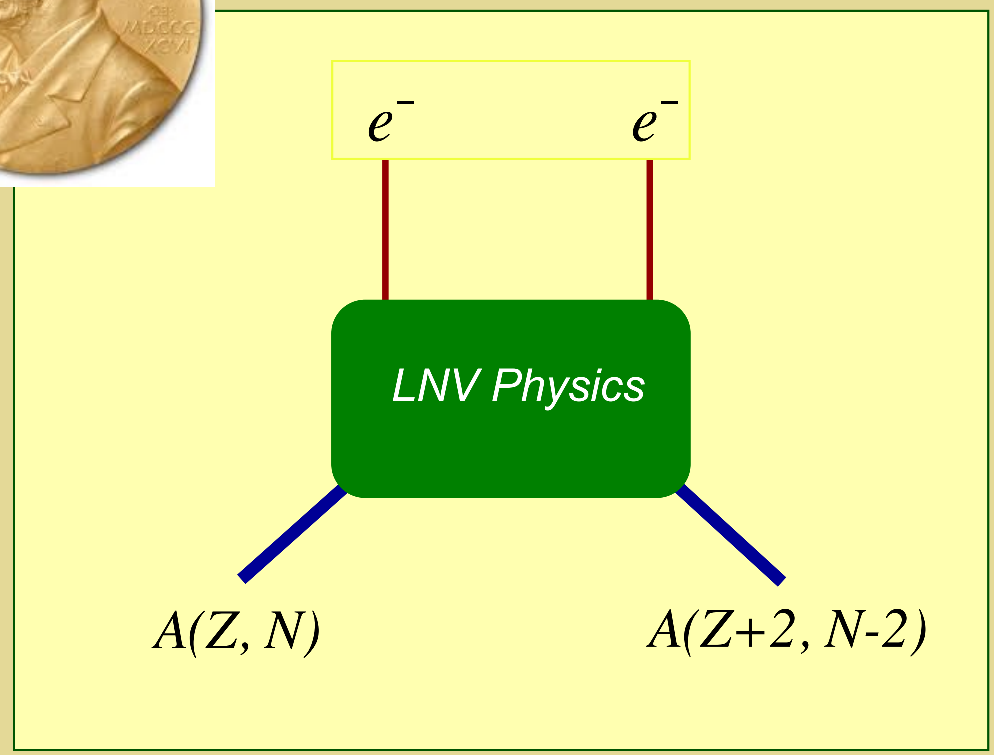
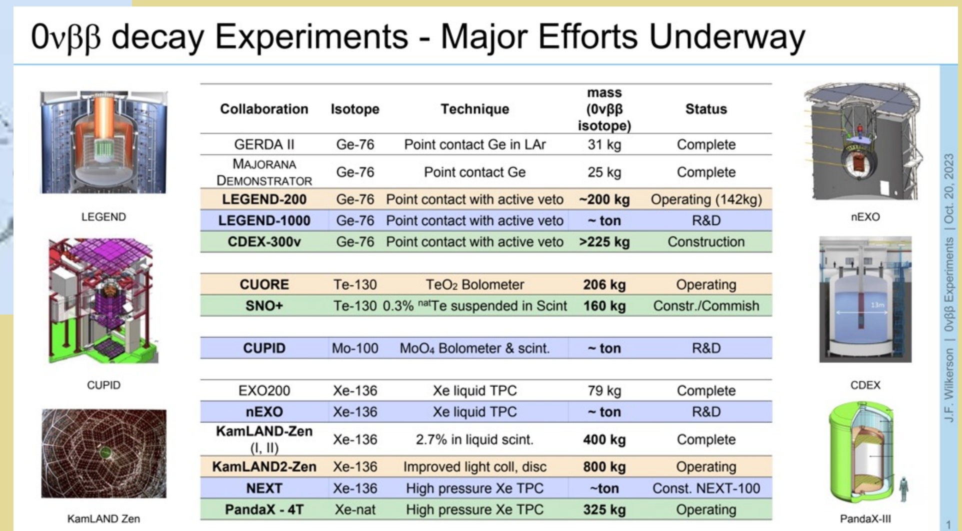


NLDBD Experimental Horizons

Thanks: J. Wilkerson



0νββ decay Experiments - Major Efforts Underway

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
GERDA II	Ge-76	Point contact Ge in LAr	31 kg	Complete
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Complete
LEGEND-200	Ge-76	Point contact with active veto	**~200 kg**	Operating (142kg)
LEGEND-1000	Ge-76	Point contact with active veto	**~ ton**	R&D
CDEX-300ν	Ge-76	Point contact with active veto	**>225 kg**	Construction
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Constr./Commish
CUPID	Mo-100	MoO_4 Bolometer & scint.	**~ ton**	R&D
EXO200	Xe-136	Xe liquid TPC	79 kg	Complete
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**400 kg**	Complete
KamLAND2-Zen	Xe-136	Improved light coll, disc	**800 kg**	Operating
NEXT	Xe-136	High pressure Xe TPC	**~ton**	Const. NEXT-100
PandaX - 4T	Xe-nat	High pressure Xe TPC	**325 kg**	Operating

- ***Global effort to deply "ton scale" expt's → 100 x better lifetime sensitivity***
- ***Top priority for U.S. nuclear science***

$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

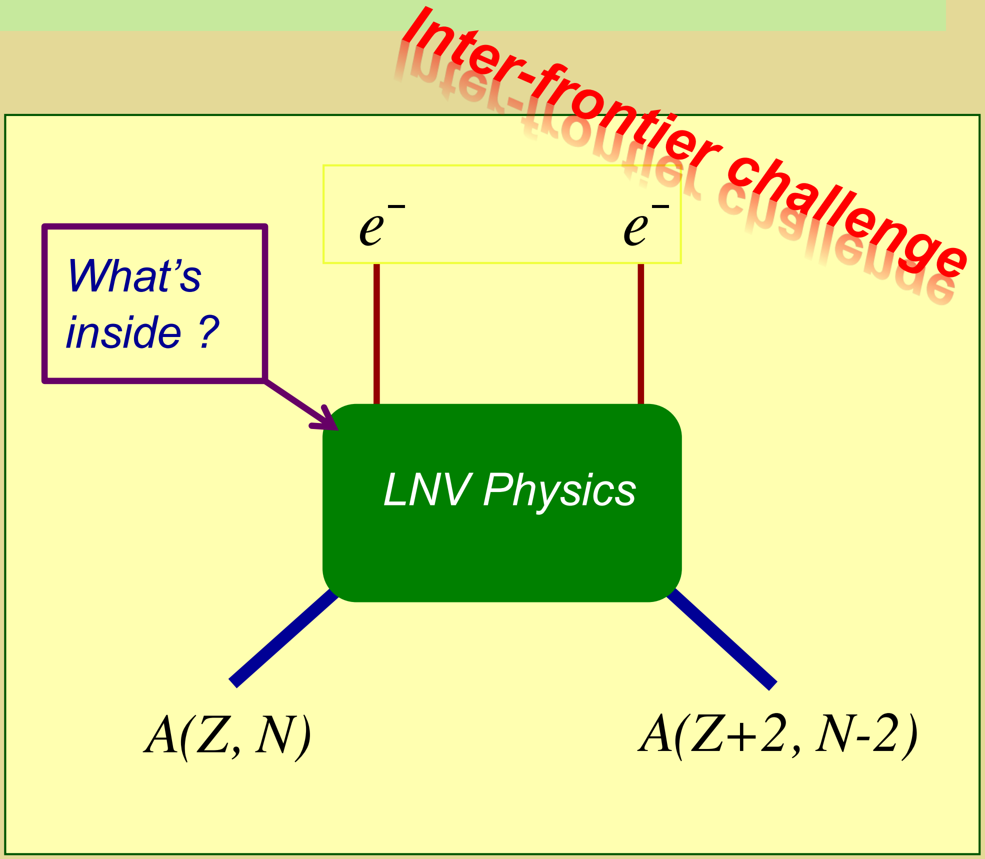
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



LNV Mass Scale & $0\nu\beta\beta$-Decay

A(Z,N) $\rightarrow$ *Underlying Physics* $\rightarrow$ *A(Z+2, N-2) +* $e^- e^-$

- *3 light neutrinos only : source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale LNV*
- *> 3 light neutrinos*

How can we determine the underlying LNV physics?

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ Underlying Physics $\rightarrow A(Z+2, N-2) + e^- e^-$

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The "Standard Mechanism"

0νββ-Decay: LNV? Mass Term?

$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \mathrm{h.c.}$$

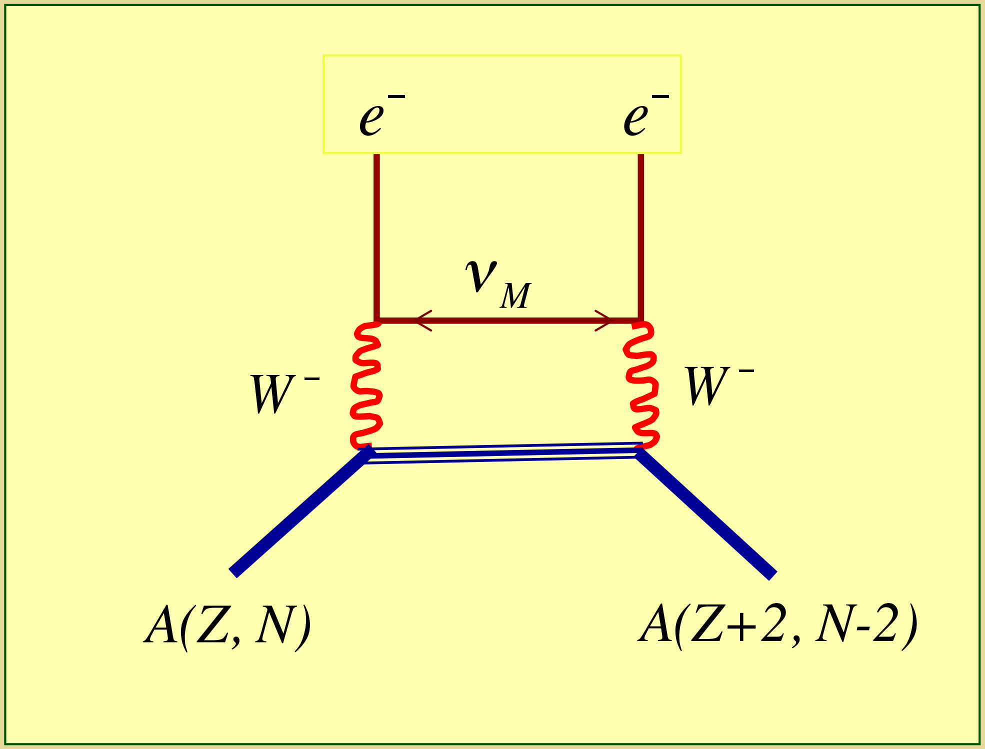
Dirac

$$\mathcal{L}_{\mathrm{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \mathrm{h.c.}$$

Majorana

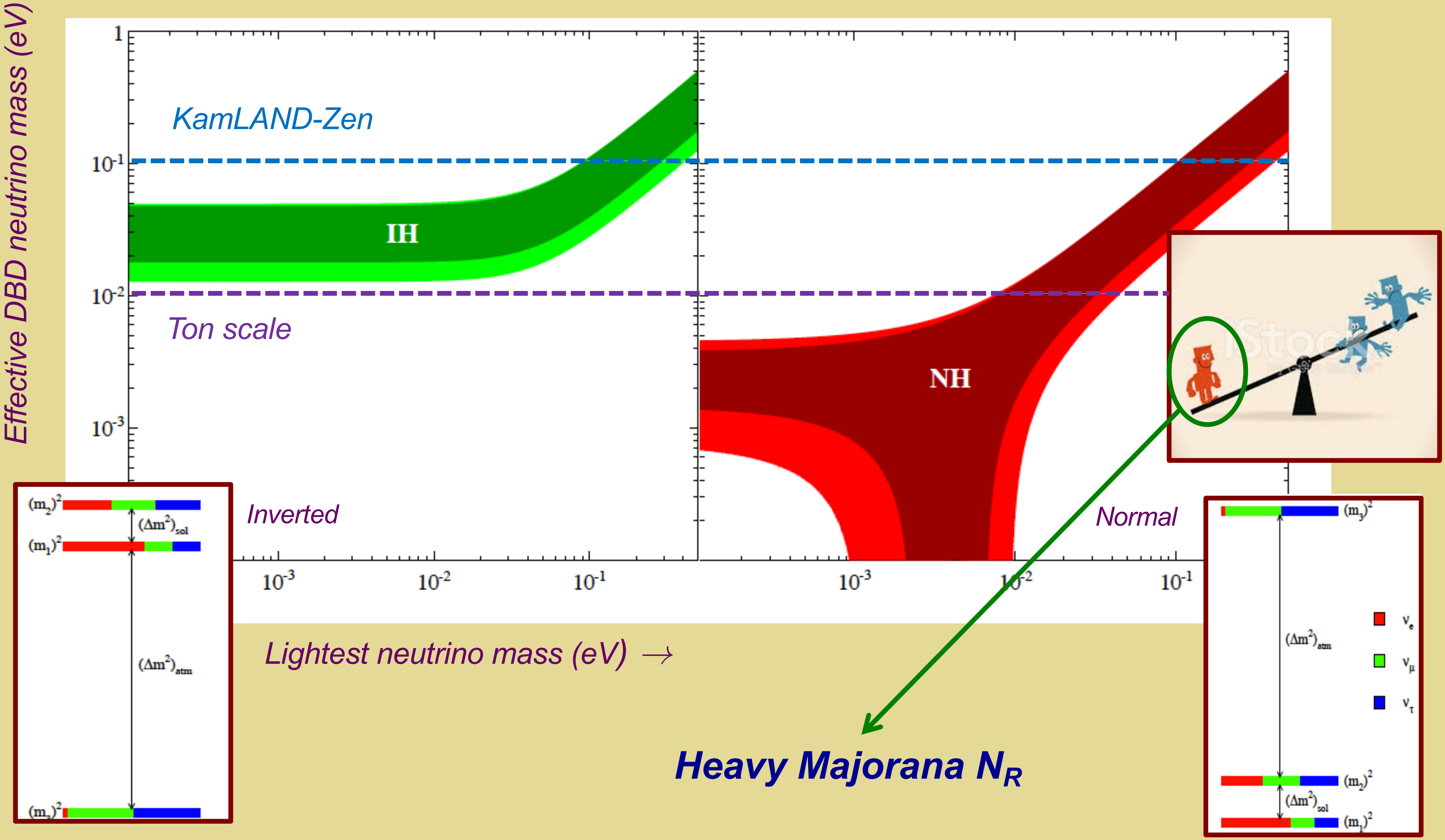
"Standard" Mechanism

- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



$0\nu\beta\beta$-Decay: “Standard” Mechanism

Three active light neutrinos



LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ Underlying Physics $\rightarrow A(Z+2, N-2) + e^- e^-$

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0νββ-Decay: LNV? Mass Term?

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \mathrm{h.c.}$$

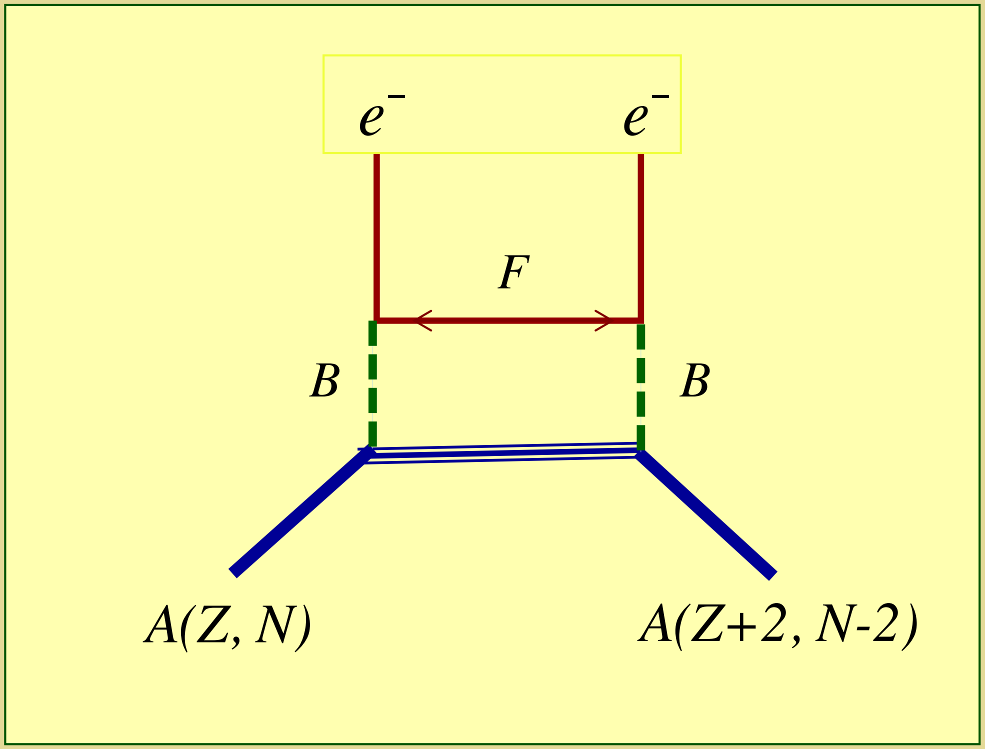
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \mathrm{h.c.}$$

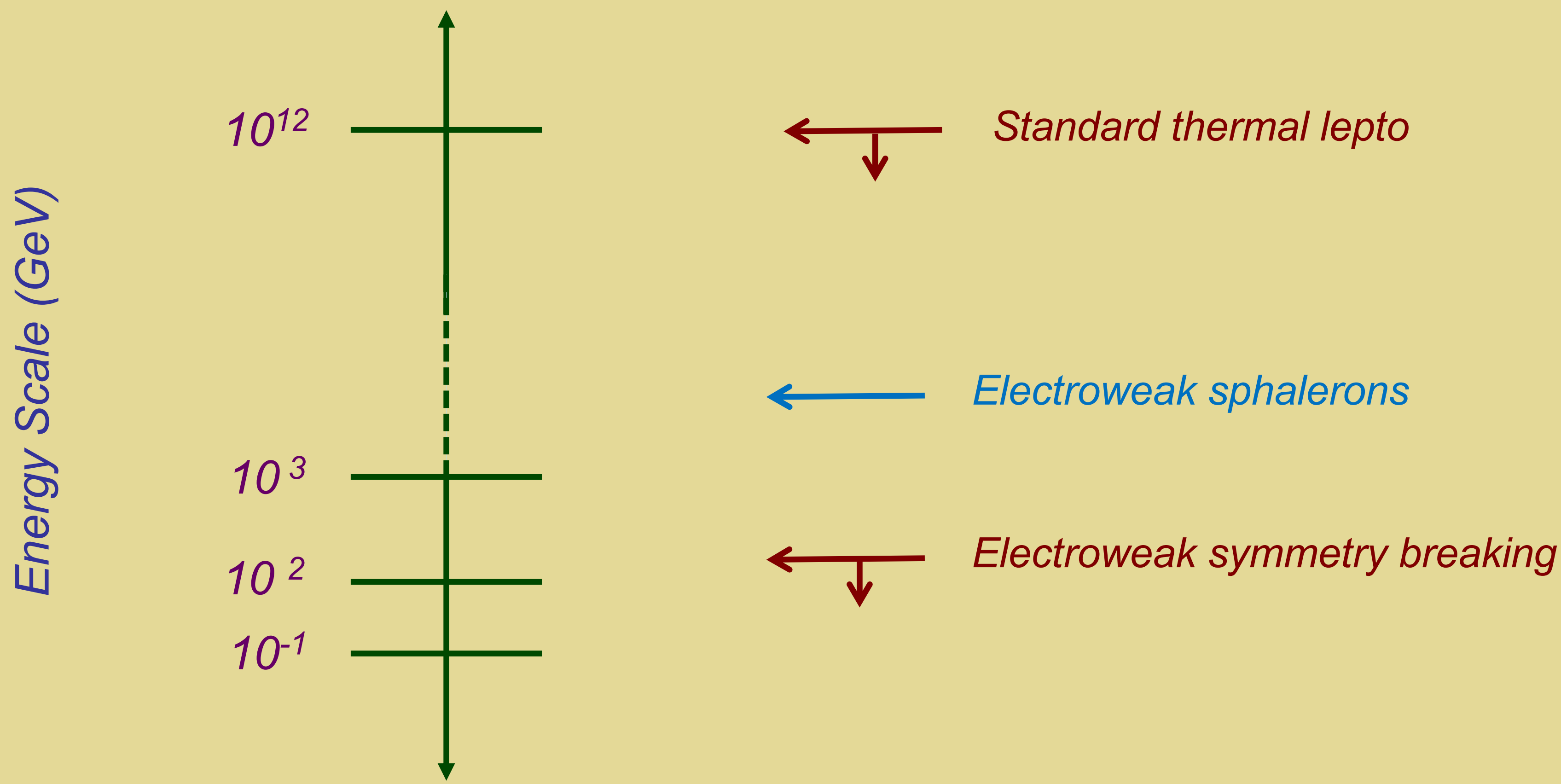
Majorana

TeV LNV Mechanism

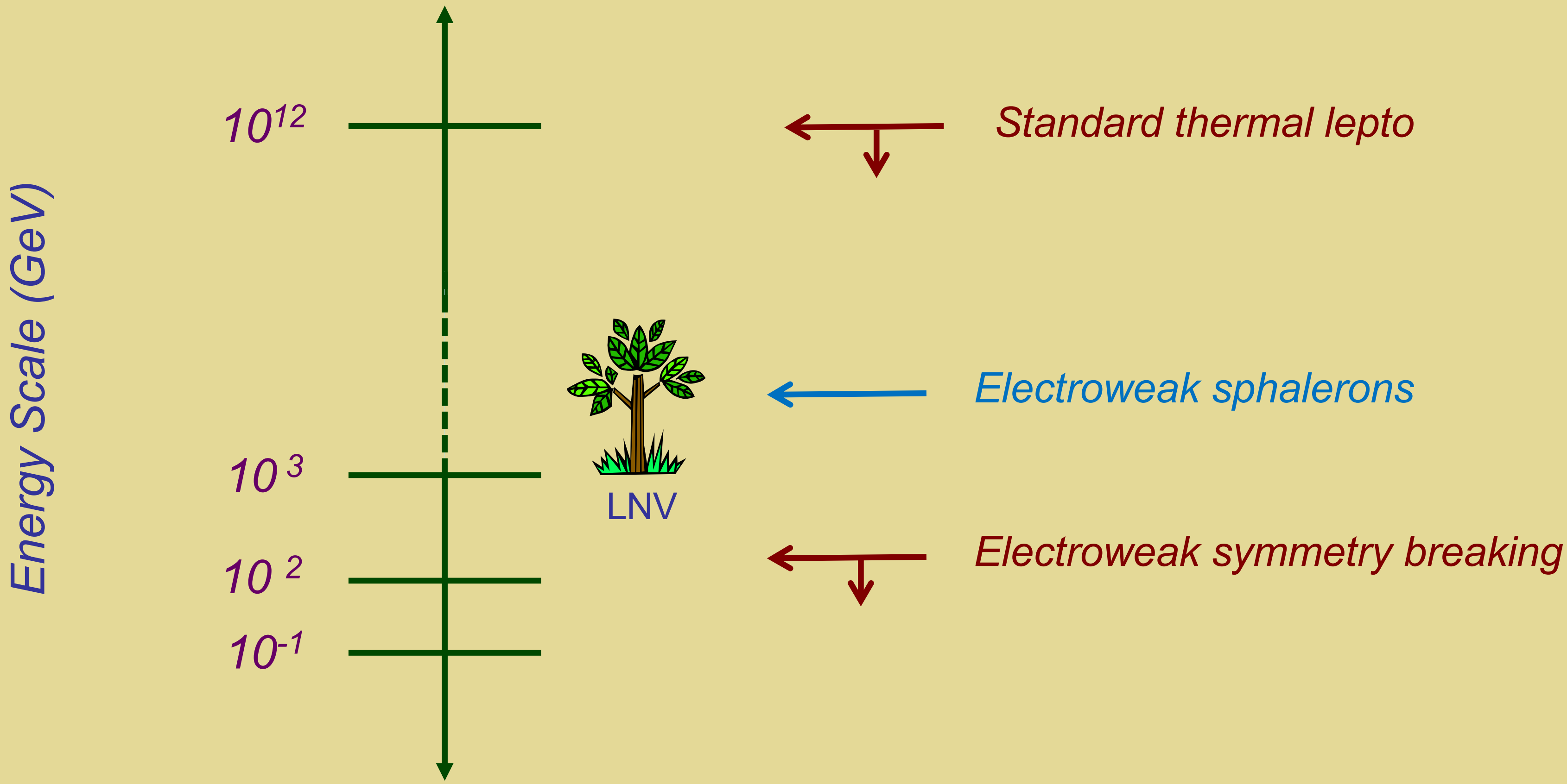
- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but 0νββ-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



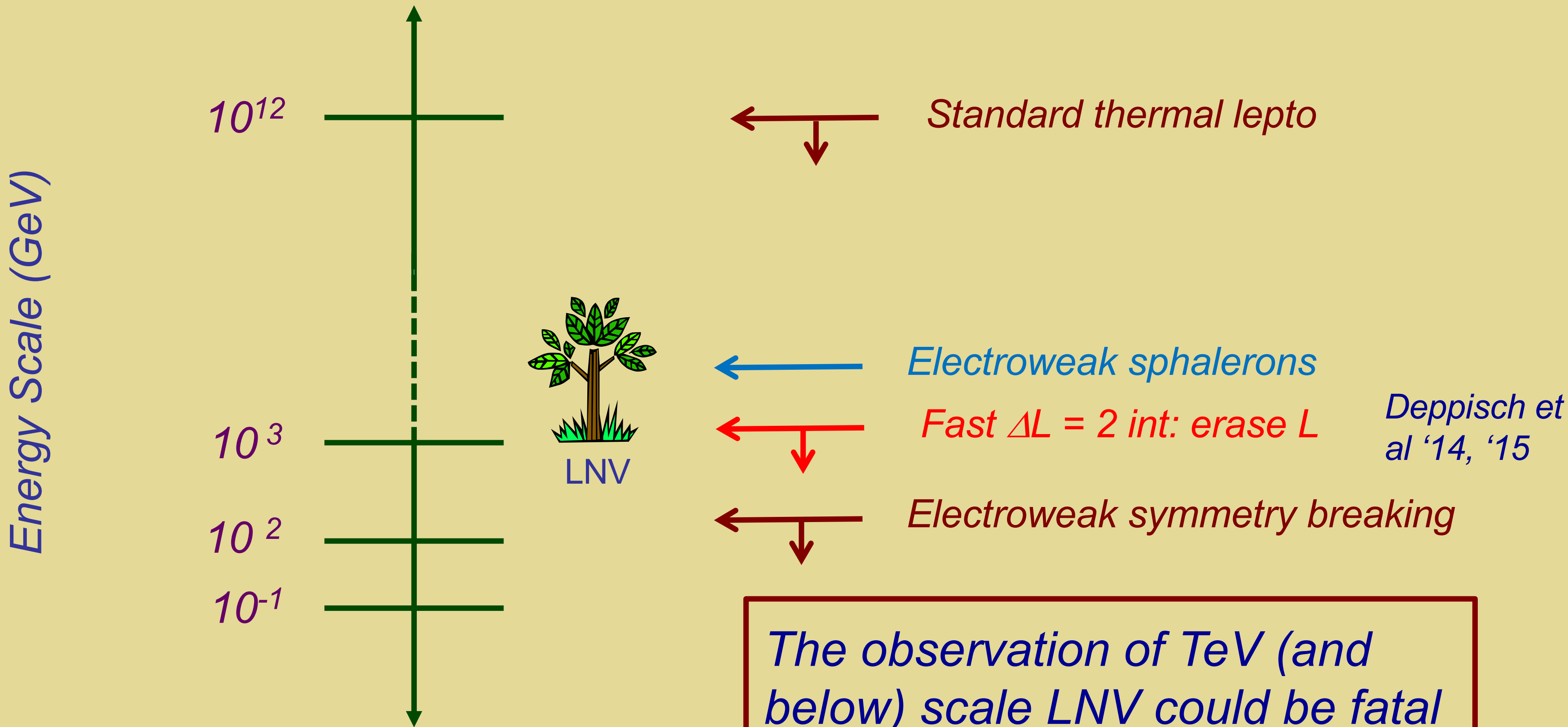
High Scale LNV & Leptogenesis



High Scale LNV & Leptogenesis



Low Scale LNV & Leptogenesis



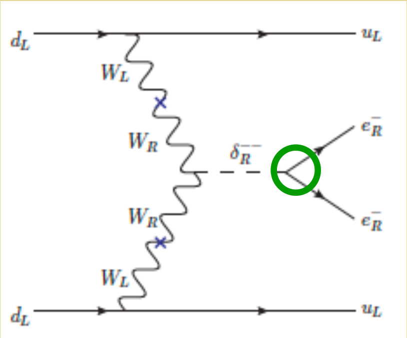
The observation of TeV (and below) scale LNV could be fatal to the leptogenesis paradigm

Low Scale LNV Probes

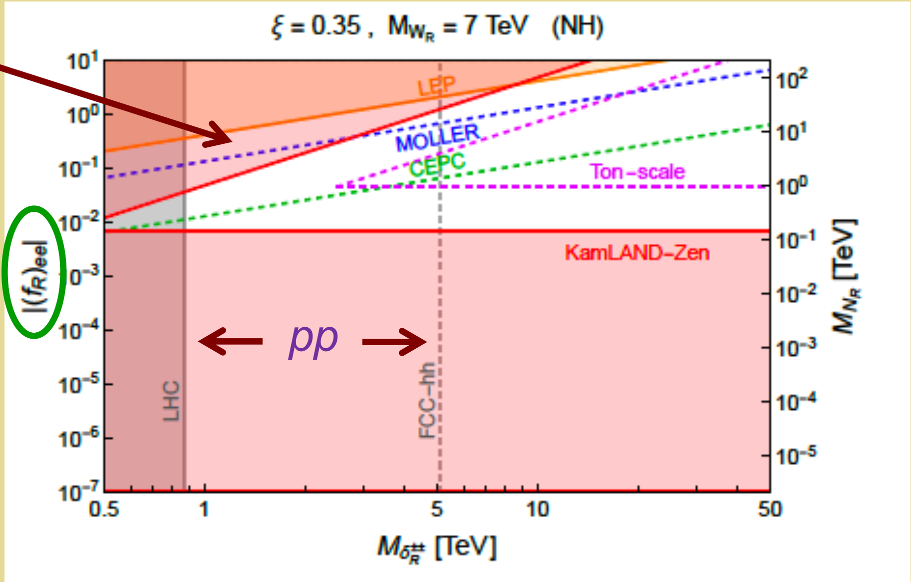
- ***New scalars (type II see saw)***
- ***Heavy neutral leptons (sterile neutrinos…)***

LNV: Scalar Fields & m_ν

$0\nu\beta\beta$ Decay, PV $e^-e^- \rightarrow e^-e^-$, $e^+e^- \rightarrow e^+e^-$ & pp collisions



MLRM type II Seesaw: δ^{--}



G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez

LNV: Scalar Fields & m_ν

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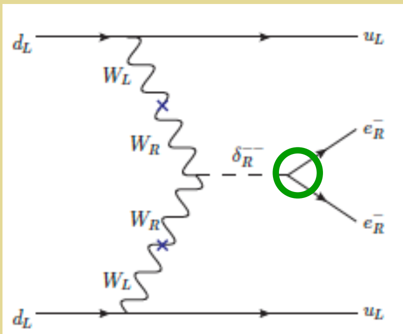
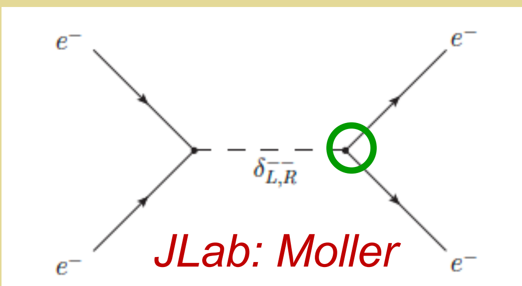
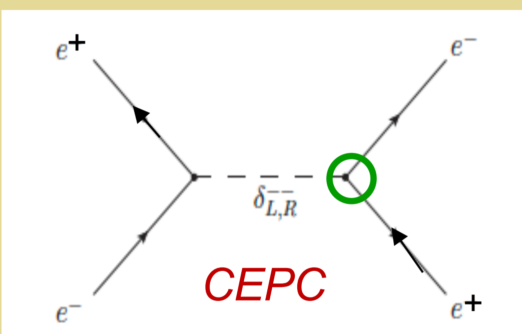
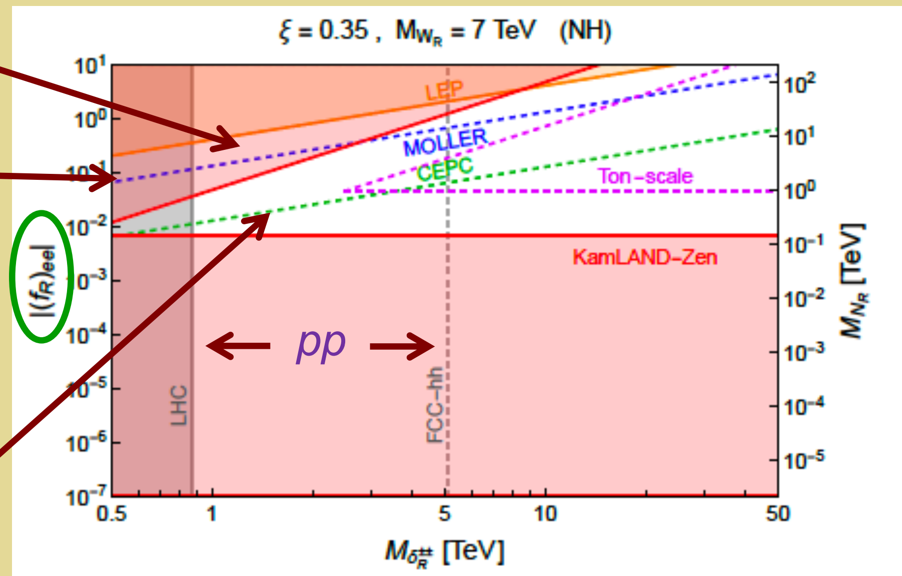






MLRM type II Seesaw: δ^{--}



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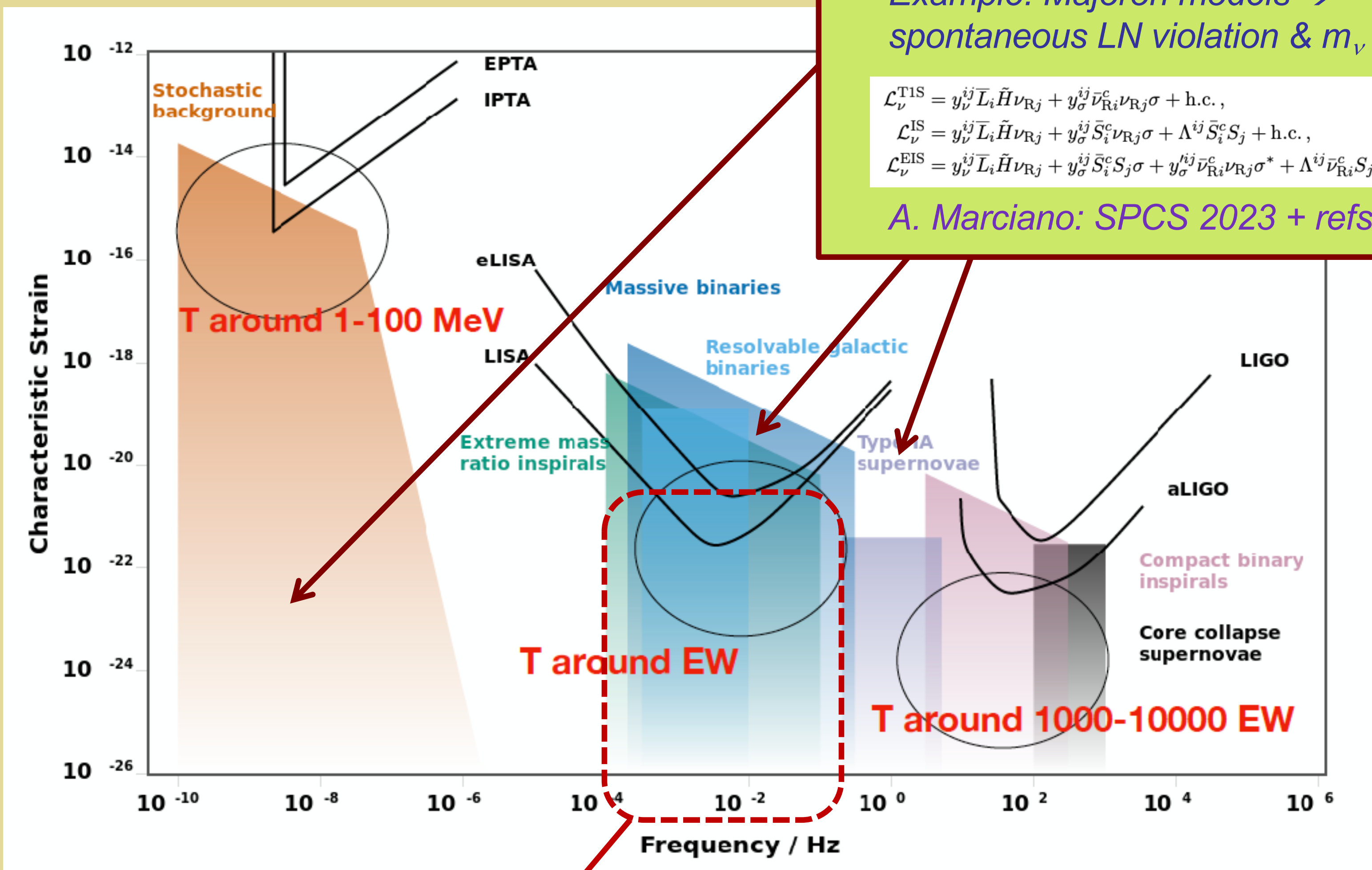
LNV Scalar Field & GW



Example: Majoron models → spontaneous LN violation & m_ν

$$\mathcal{L}_\nu^{\rm T1S} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{\nu}^c_{{\rm R}i}\nu_{{\rm R}j}\sigma + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm IS} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}^c_i\nu_{{\rm R}j}\sigma + \Lambda^{ij}\bar{S}^c_i S_j + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}^c_i S_j\sigma + y'^{ij}_\sigma\bar{\nu}^c_{{\rm R}i}\nu_{{\rm R}j}\sigma^* + \Lambda^{ij}\bar{\nu}^c_{{\rm R}i}S_j + {\rm h.c.}$$

A. Marciano: SPCS 2023 + refs

EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

BSM LNV: *0νββ*-Decay & pp Colliders

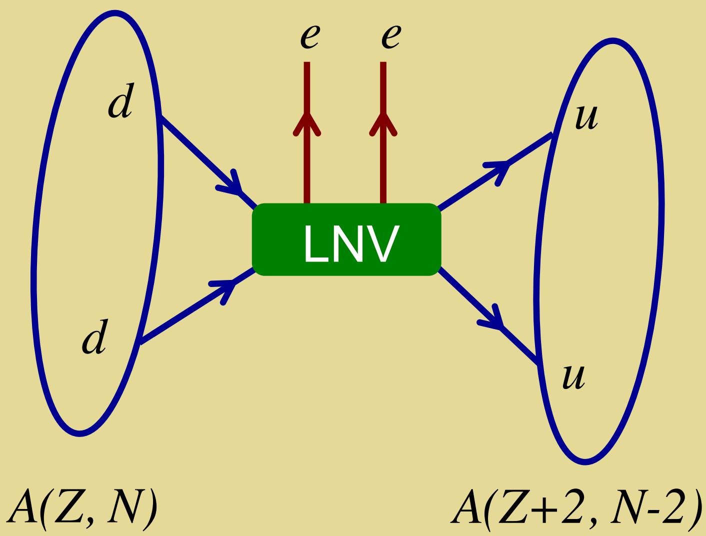
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; {\rm h.c.}$$

Dirac

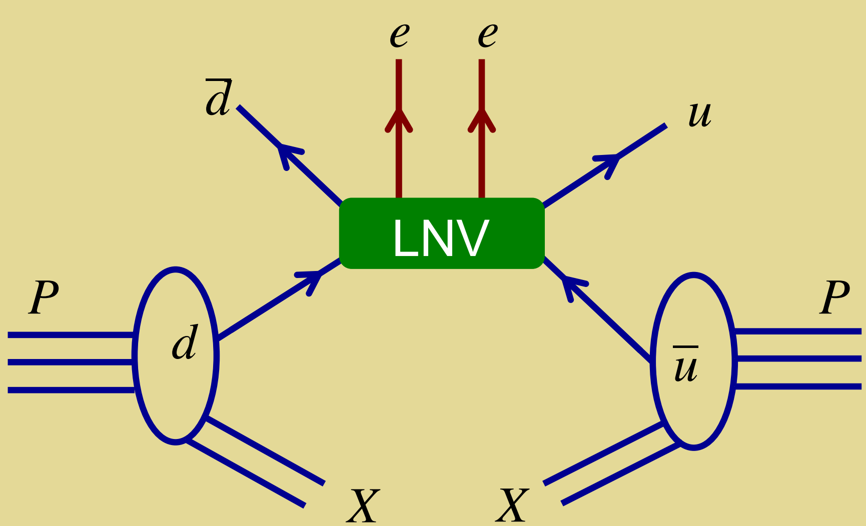
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; {\rm h.c.}$$

Majorana

0νββ-Decay



pp Collisions



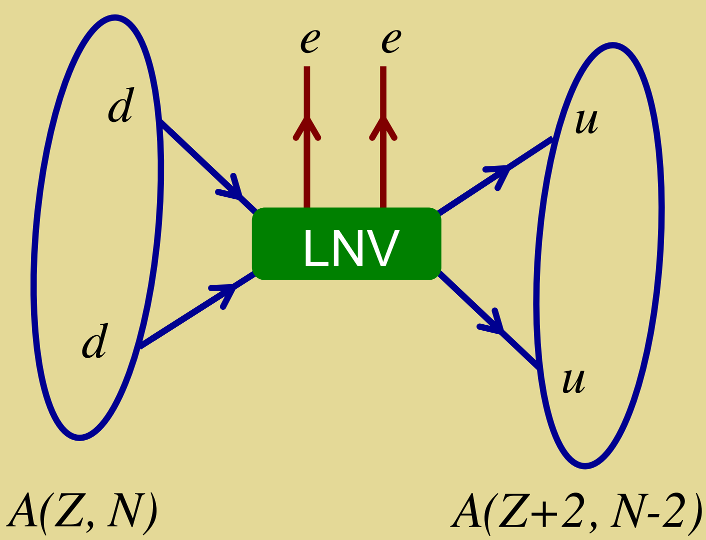
BSM LNV: *0νββ*-Decay & pp Colliders

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; {\rm h.c.} \qquad\qquad \mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^{c} H H^{T} L \; + \; {\rm h.c.}$$

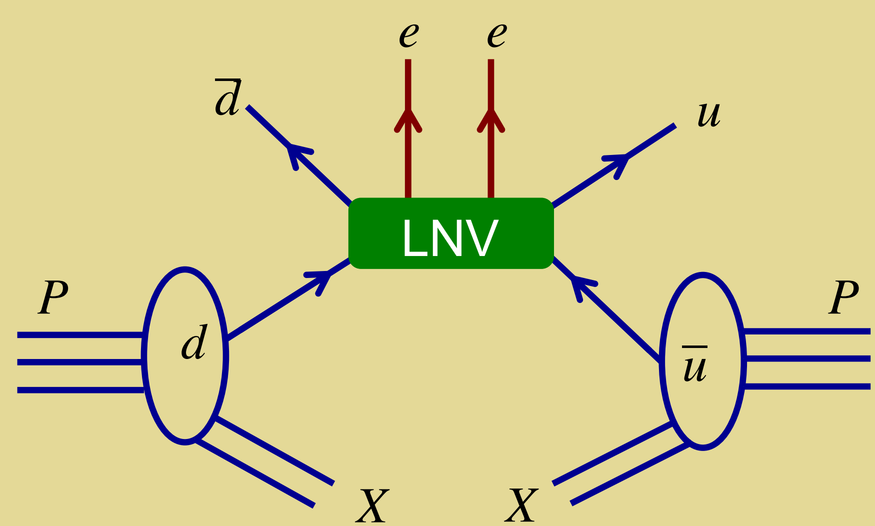
Dirac — *Majorana*

LHC: SS Dilepton + Dijet

0νββ-Decay



pp Collisions

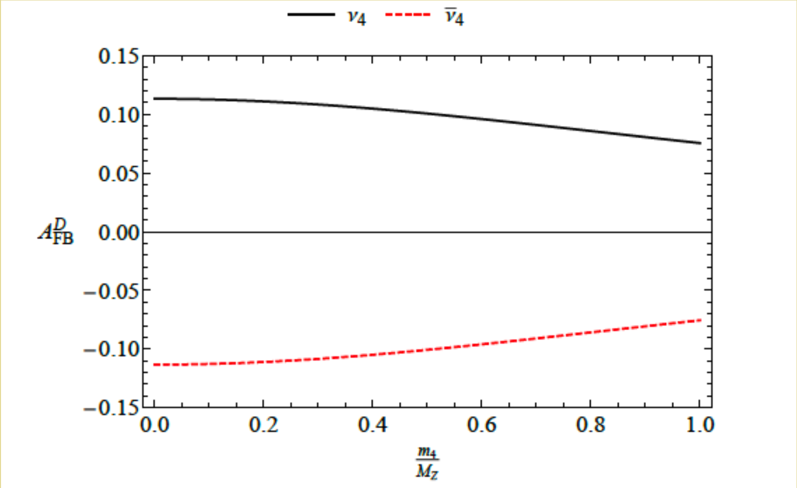


Numerous studies: another talk…

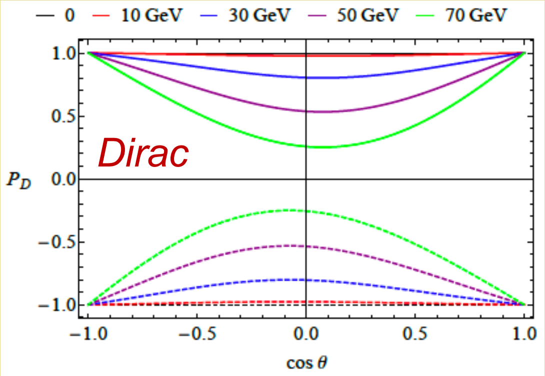
Lepton Collider Probes

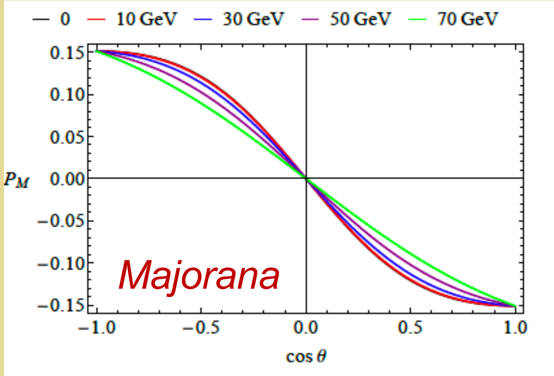
$e^+ e^- \rightarrow Z^0 \rightarrow N\, N$ vs $e^+ e^- \rightarrow Z^0 \rightarrow N\, \bar{N}$

Lepton FB Asymmetry



N Polarization





A_{FB} : vanish for Majorana N

M. Drewes 2210.17110 (mini-review)
Blondel, de Gouvea, Kayser 2105.06576

Lepton Collider Probes

$e^+ e^- \rightarrow Z^0 \rightarrow N\, N$ vs $e^+ e^- \rightarrow Z^0 \rightarrow N\, \bar{N}$

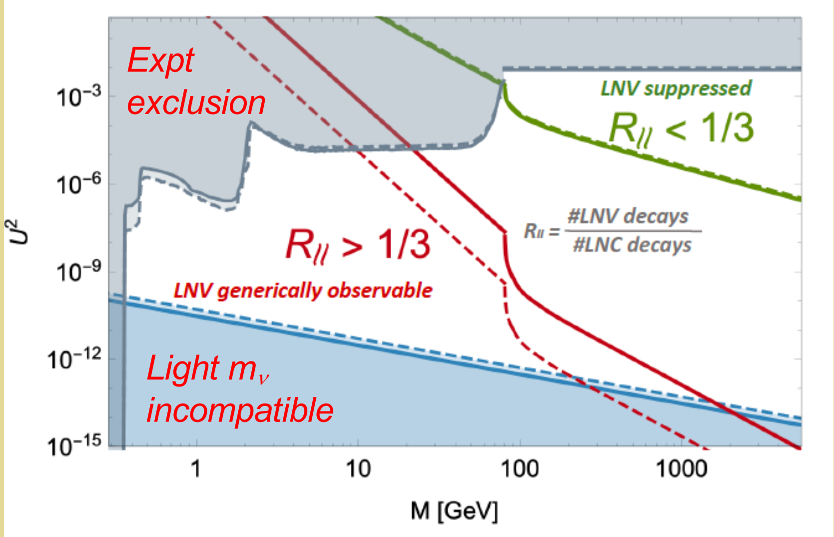
Displaced decays (LLPs)

$$N_{\rm obs} \simeq u_\beta^2 N_{{\rm HNL}\alpha} \left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right] \epsilon_{\alpha\beta},$$

$\lambda_N^{Majorana} = 2 \times \lambda_N^{Dirac}$

Active-HNL Mixing

LLP LNV Observability

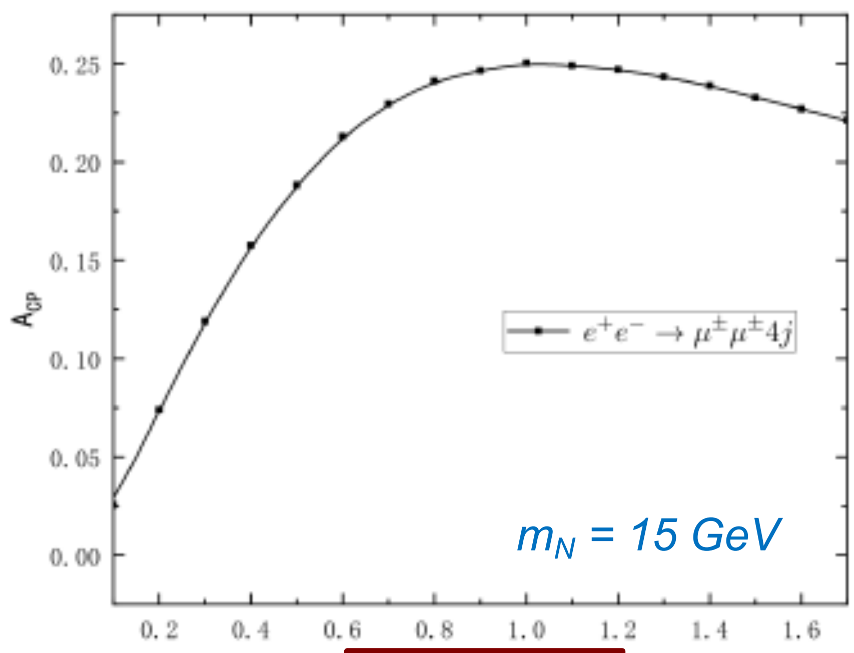


M. Drewes 2210.17110 (mini-review)
Blondel, de Gouvea, Kayser 2105.06576

W Pair Production

LNV + CPV

$$\mathcal{A}_{CP} = \frac{Br(\ell^+\ell^- \to \mu^+\mu^+4j) - Br(\ell^+\ell^- \to \mu^-\mu^-4j)}{Br(\ell^+\ell^- \to \mu^+\mu^+4j) + Br(\ell^+\ell^- \to \mu^-\mu^-4j)}$$



$$h = \Delta m/\Gamma_{N_a}$$

IV. Outlook

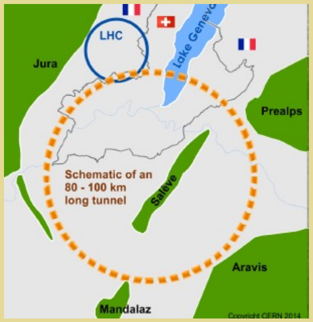
Future e+e- Colliders: Frontier Interface

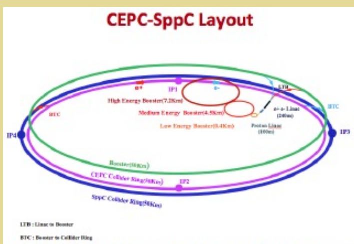
- *The particle physics of an e+e- Higgs factory is compelling in its own right and the scientific opportunities of a next generation e+e- collider must be realized*

- *The large number of H and Z bosons make the CEPC/FCC-ee/ILC precision tools at the interface of the high energy and intensity frontiers*

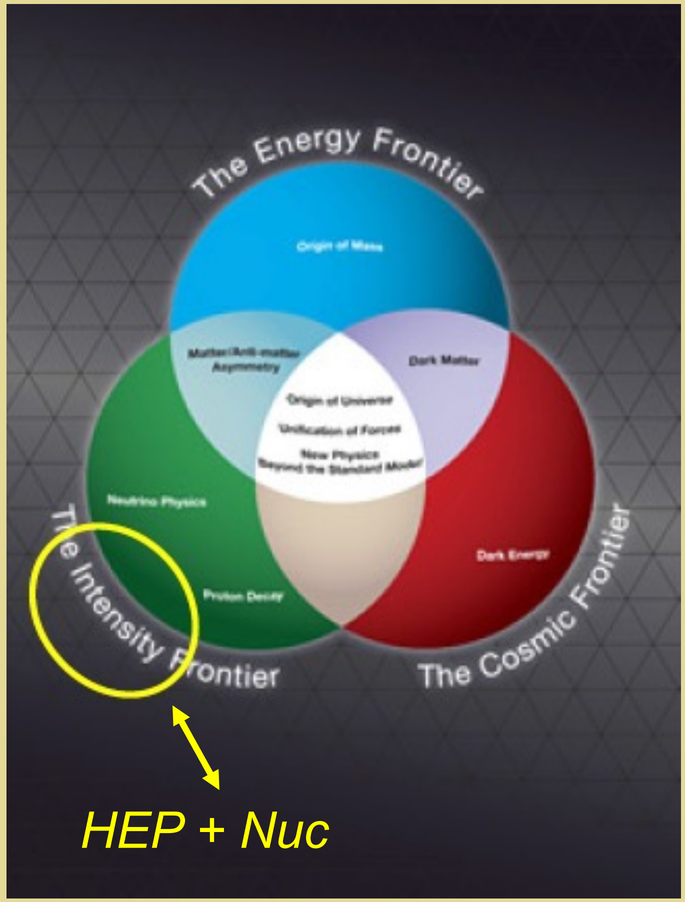
- *There exist exciting opportunities for inter-frontier synergy on fundamental questions involving e+e- colliders and cosmology/astrophysics, nuclear physics, condensed matter and AMO physics → let's pursue these synergies vigorously and communicate the inter-frontier opportunities to our colleagues enthusiastically*

Frontiers

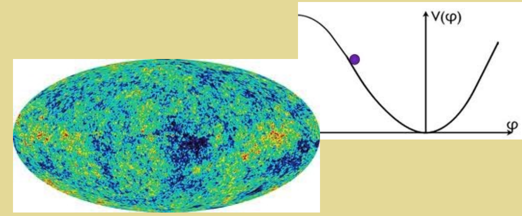


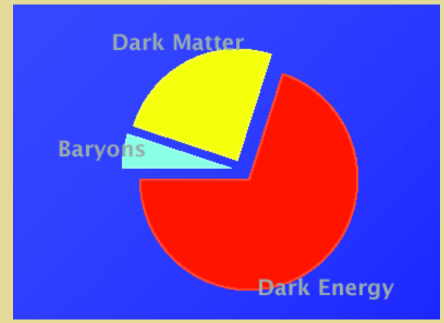


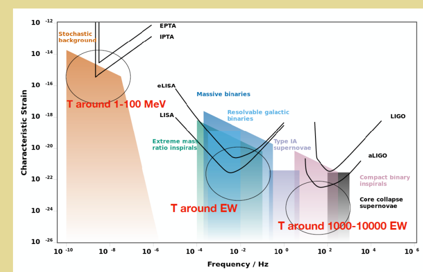
- *Precision tests: muon g-2, PV ee…*
- *Fundamental symmetry tests (CP, Lepton number…)*
- *Neutrino properties*
- *Flavor physics*



Historical artifact: US HEP vision → still useful mnemonic







- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

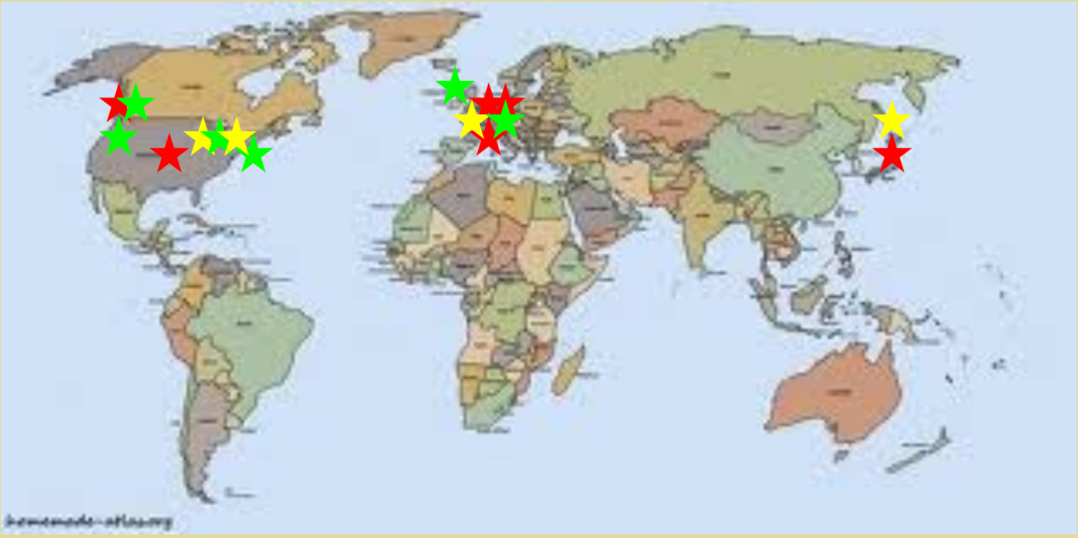
Back Up Slides I

V. Where is the CPV for Baryogenesis ?

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
HfF^{+}	4.1×10^{-30} **	10^{-38}	10^{-29}
n	1.8×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^{-} equivalent



★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

EDMs: New CPV?

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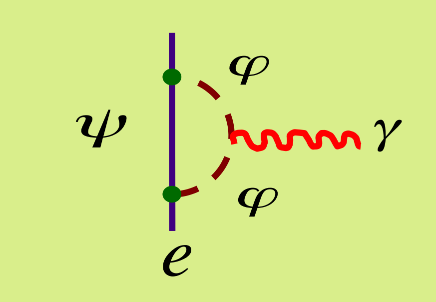
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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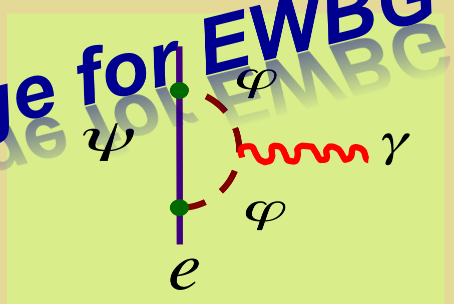
Mass Scale Sensitivity

Challenge for EWBG



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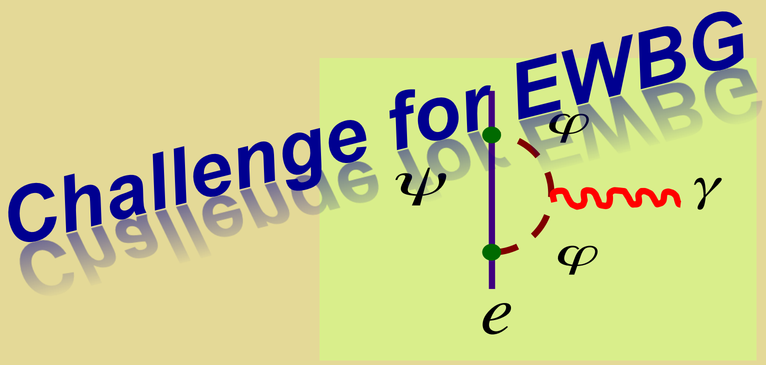
Mass Scale Sensitivity



- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
- ***CPV is "partially secluded"***

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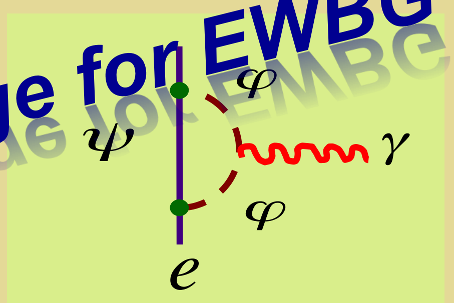
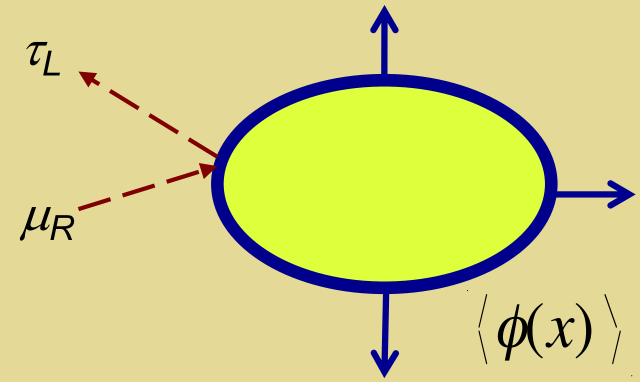
Mass Scale Sensitivity

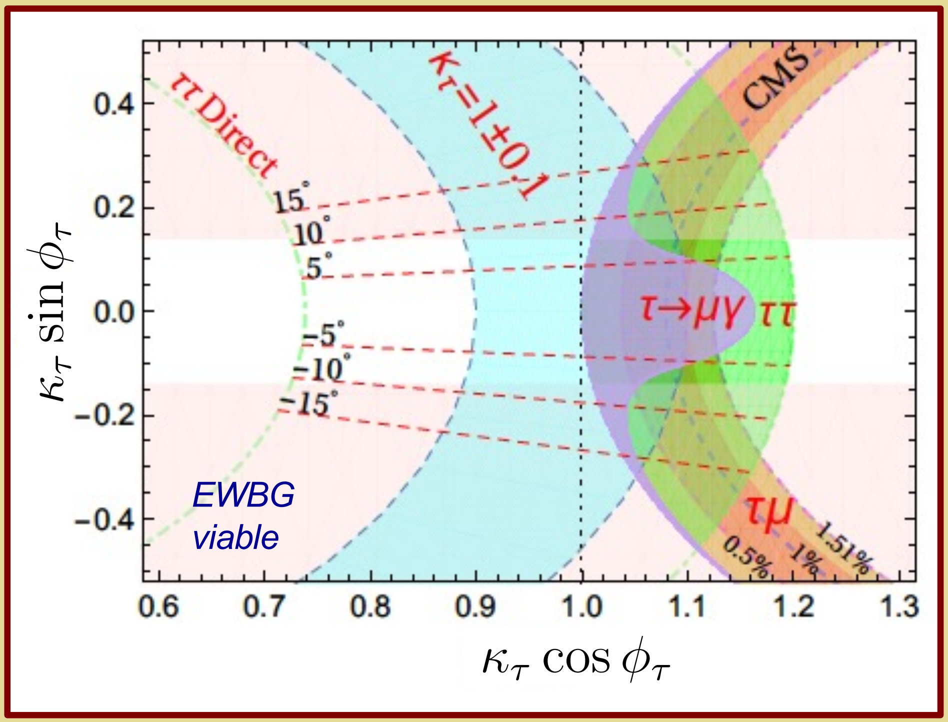
Challenge for EWBG



- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
- ***CPV is "partially secluded"***

Flavored EW Baryogenesis





Flavor basis (high T)

$$\mathscr{L}_{\text{Yukawa}}^{\text{Lepton}} = -\overline{E_L^i}\left[(Y_1^E)_{ij}\Phi_1 + (Y_2^E)_{ij}\Phi_2\right] e_R^j + h.c.$$

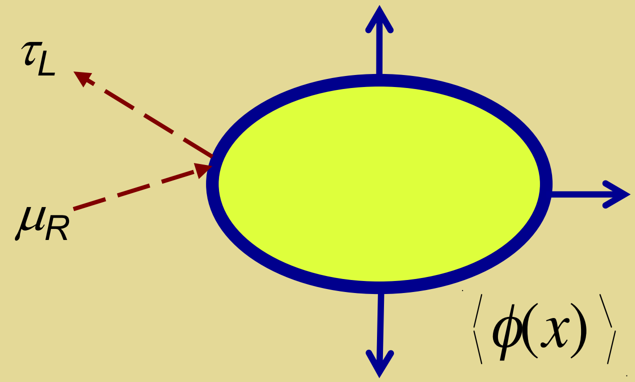
Mass basis (T=0)

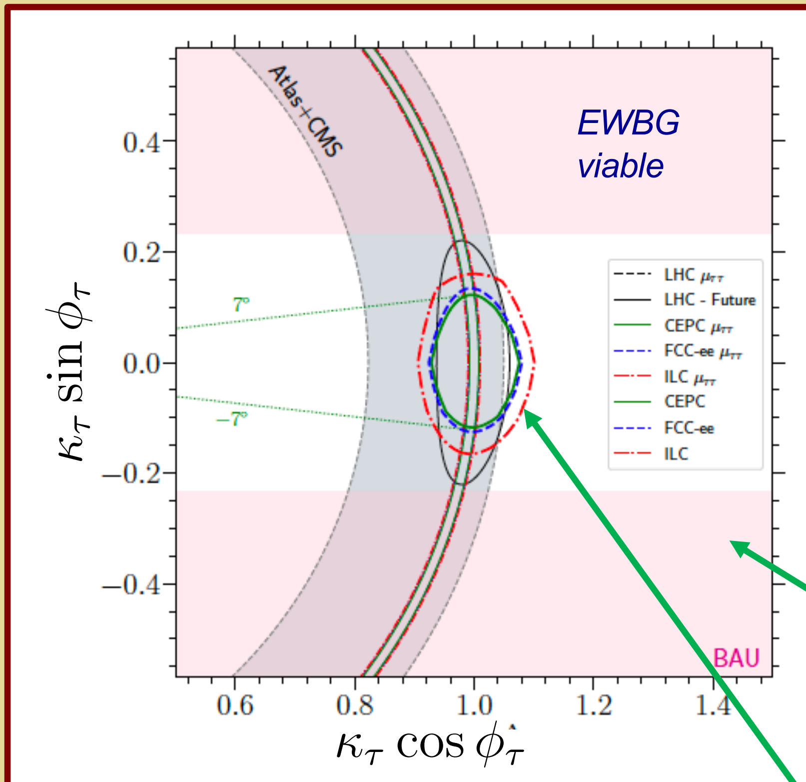
CPV $h \to \tau\tau$

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \boxed{\sin\phi_\tau \bar{\tau} i\gamma_5 \tau)h}$$

Guo, Li, Liu, R-M, Shu 1609.09849

Flavored EW Baryogenesis





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Mass basis (T=0)

CPV $h \to \tau\tau$

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \boxed{\sin\phi_\tau\bar{\tau}i\gamma_5\tau)h}$$

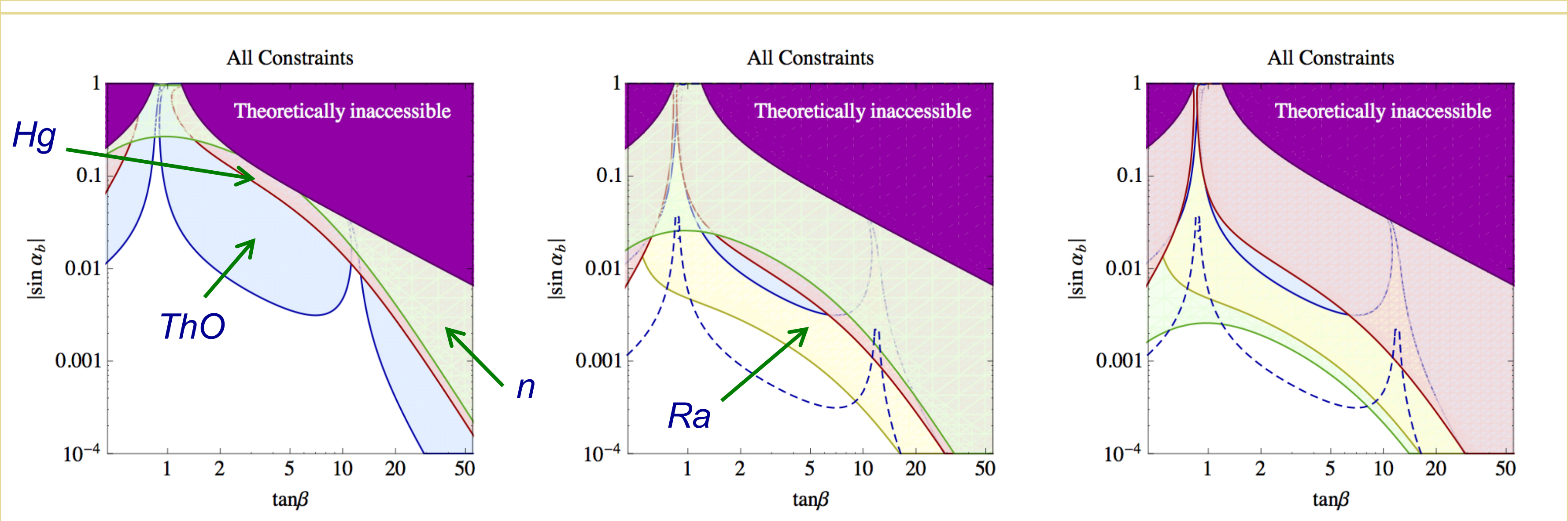
Guo, Li, Liu, R-M, Shu 1609.09849

Ge, Li, Pasquini, R-M, Shu 2012.13922

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present — *New ThO: ACME*

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra) [10^{-27} e cm]

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

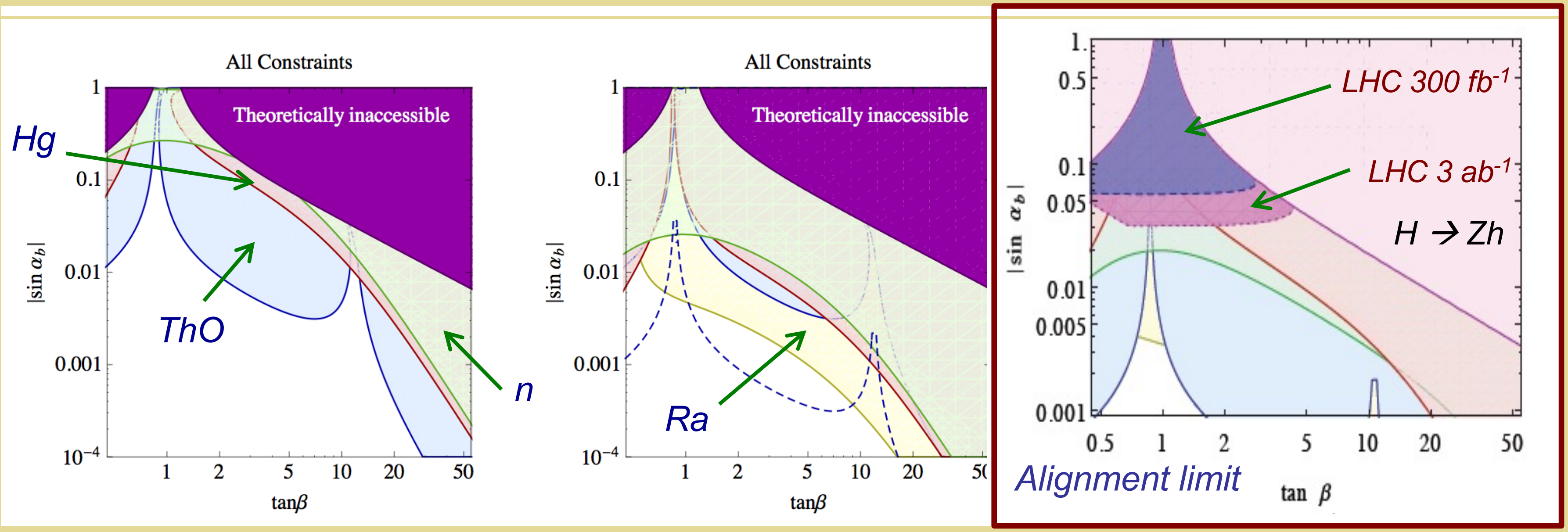
$\sin \alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Chen, Li, R-M: 1708.00435

Present

New ThO: ACME

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

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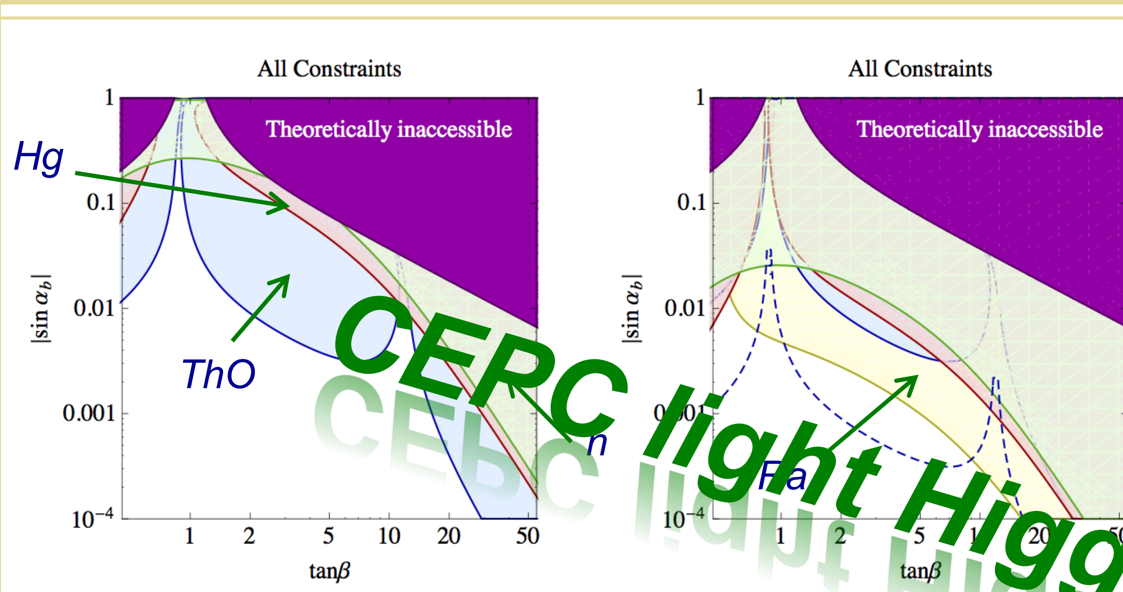
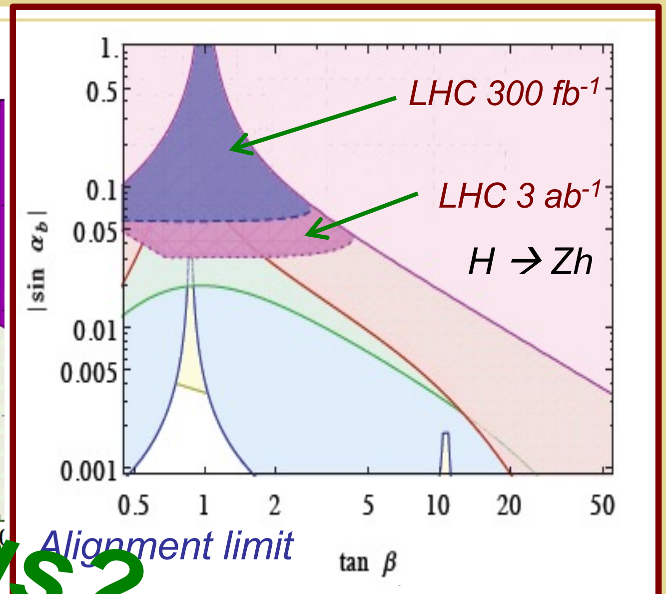




CEPC light Higgs?

Alignment limit

Chen, Li, R-M: 1708.00435

Present — *New ThO: ACME*

Future:	*Future:*
d_n x 0.1	d_n x 0.01
d_A(Hg) x 0.1	d_A(Hg) x 0.1
d_{ThO} x 0.1	d_{ThO} x 0.1
d_A(Ra) [10^{-27} e cm]	d_A(Ra)

$\sin\alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

The Top Quark Portal

CPV Top Quark Interactions?

- *3rd generation quarks often have a special role in BSM scenarios, given m_t >> all other m_f*
- *If BSM CPV exists, d_t may be enhanced*

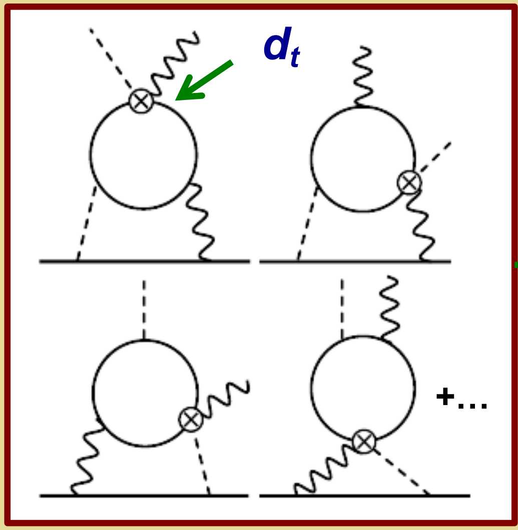
- *Top EDMs difficult to probe experimentally*

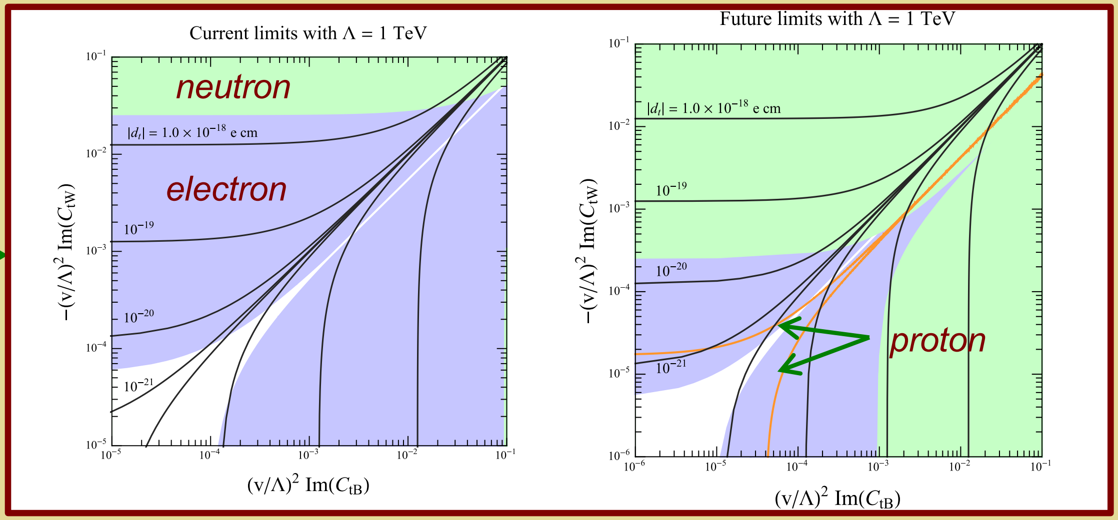
- *Light fermion EDMs to the rescue !*

CPV Top Quark Interactions?

Cordero-Cid et al '08, Kamenik et al '12, Cirigliano et al '16, Fuyuto & MRM in 1706.08548

Model-indep: independent $SU(2)_L$ & $U(1)_Y$ dipole operators: C_{tB} , C_{tW} $\rightarrow$ Tree level d_t & loop level d_e , $d_{light\ q}$





Induced d_e , $d_{light\ quark}$

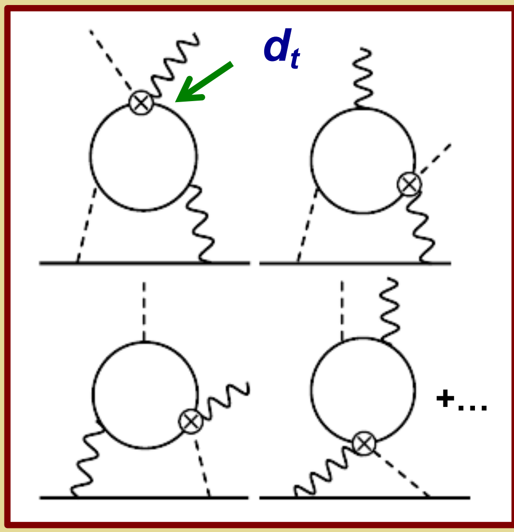
Fuyuto & MRM '17
Fuyuto '19: Updated for new ThO

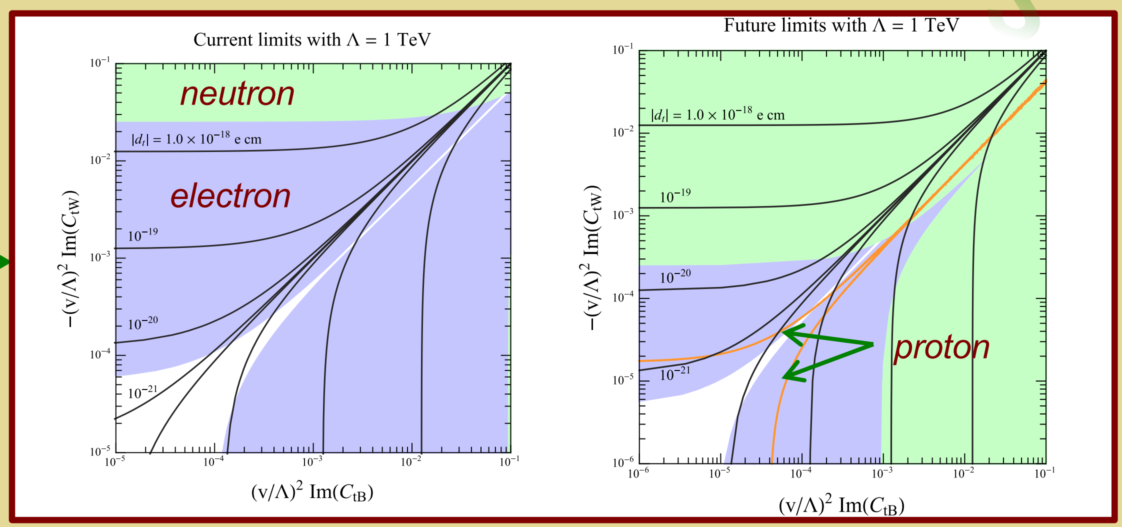
CPV Top Quark Interactions?

Cordero-Cid et al '08, Kamenik et al '12, Cirigliano et al '16, Fuyuto & MRM in 1706.08548

CEPC $t\,\bar{t}$ studies ?

Model-indep: independent $SU(2)_L$ & $U(1)_Y$ dipole operators: C_{tB}, C_{tW} $\rightarrow$
Tree level d_t & loop level d_e, $d_{light\ q}$





Induced d_e, $d_{light\ quark}$

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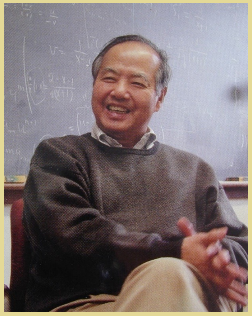
Fuyuto '19: Updated for new ThO

Back Up Slides II

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



Director

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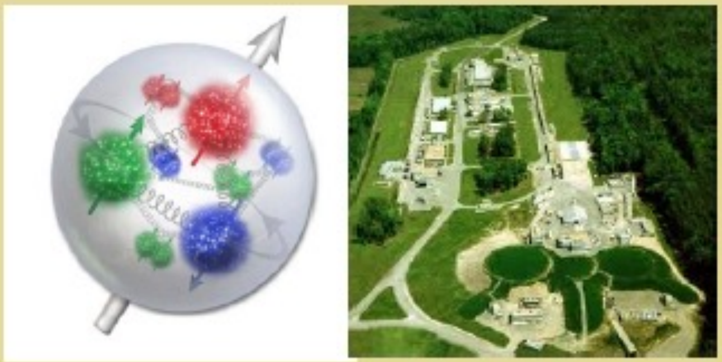
Theory & Experiment

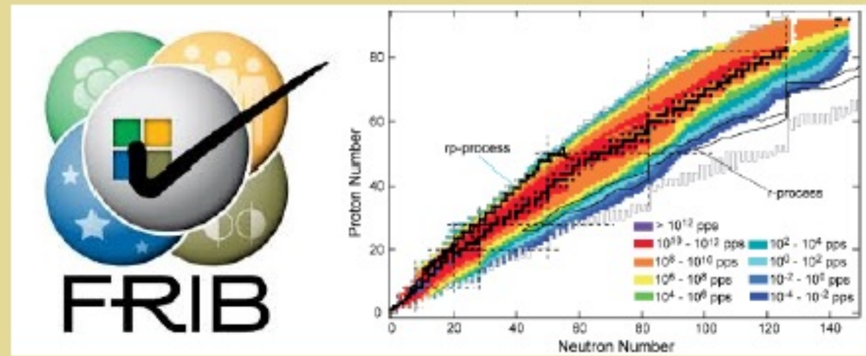
Particle & Nuclear Physics	Astronomy & Astrophysics	Quantum Science
Dark Matter & Neutrino	Laboratory Astrophysics	Topological Quantum Computation

https://tdli.sjtu.edu.cn/EN/

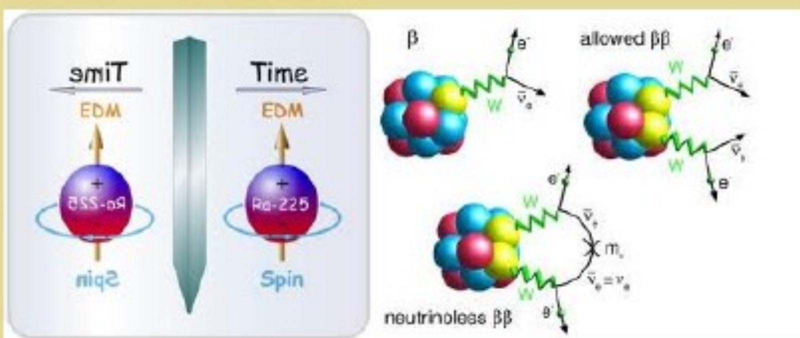
Nuclear Physics Today



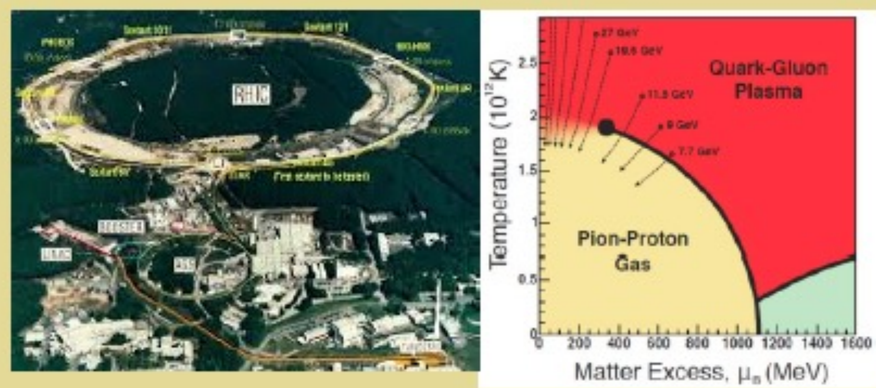
Hadron structure & dynamics: "cold QCD"



Rare isotopes: nuclear structure & astrophysics

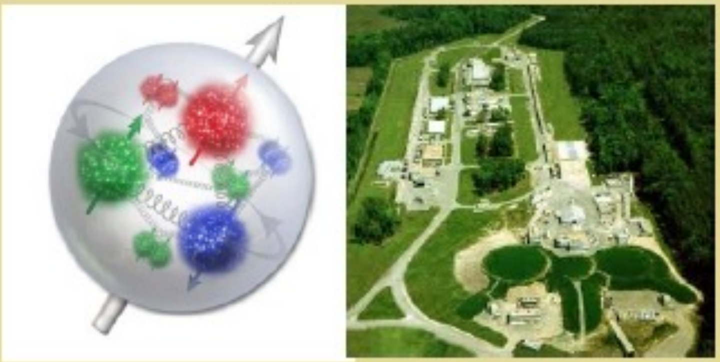


Fundamental symmetries & neutrinos: "Intensity Frontier"

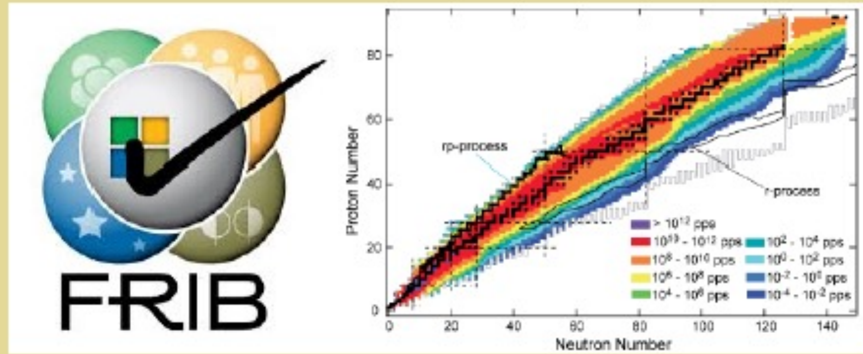


Relativistic heavy ions: "hot & dense QCD"

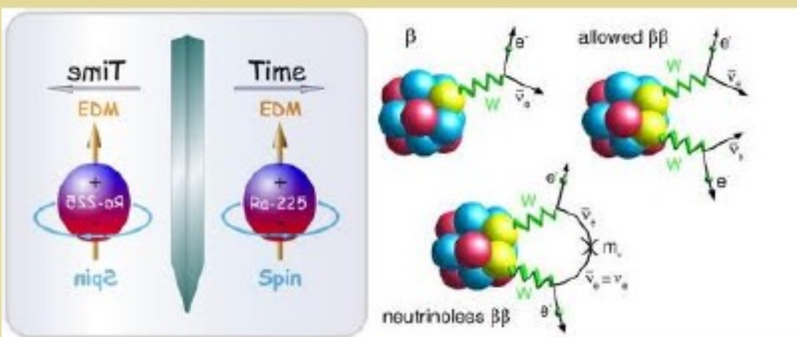
Nuclear Physics Today



Hadron structure & dynamics: “cold QCD”



Rare isotopes: nuclear structure & astrophysics



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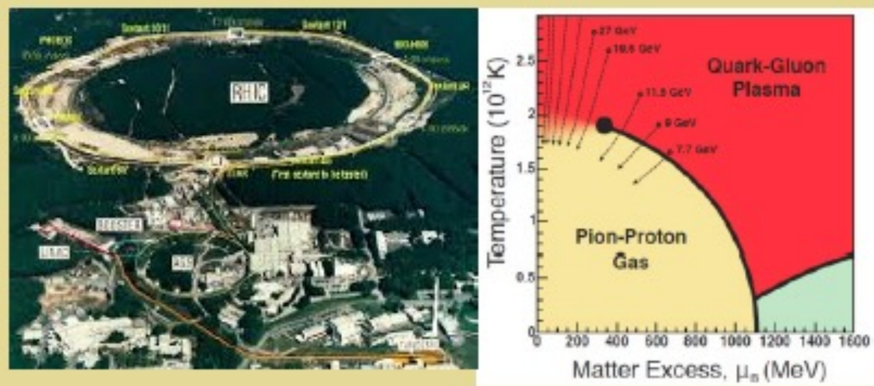


Relativistic heavy ions: “hot & dense QCD”

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

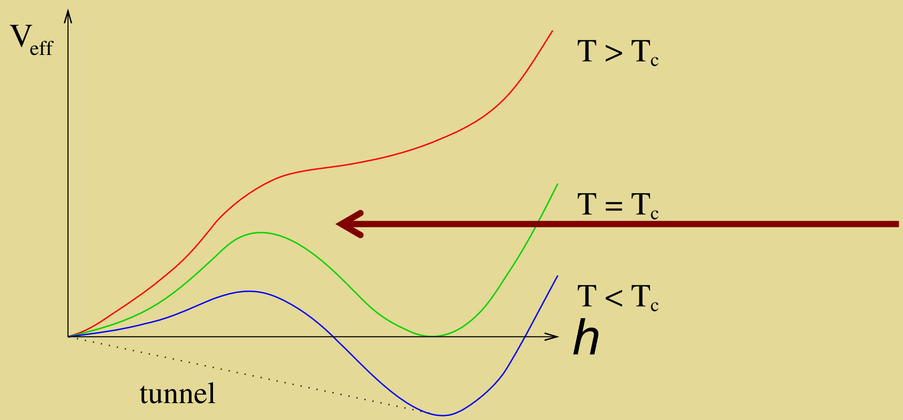
$$\boxed{V(h,T)_{\rm SM} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \; + \ldots}$$

$$\boxed{T_0^2 = (8\lambda + \text{ loops})\left(4\lambda + \frac{3}{2}g^2 + \frac{1}{2}g'^{\,2} + 2y_t^2 + \cdots\right)^{-1} v^2}$$

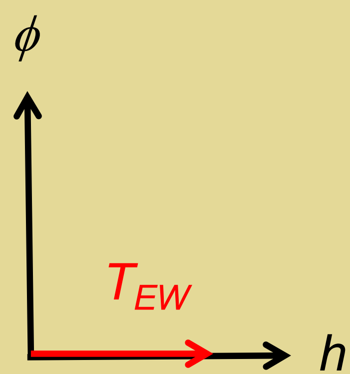
$\boxed{T_0 \sim 140\ \text{GeV}}$ $\boxed{\equiv \quad T_{EW}}$

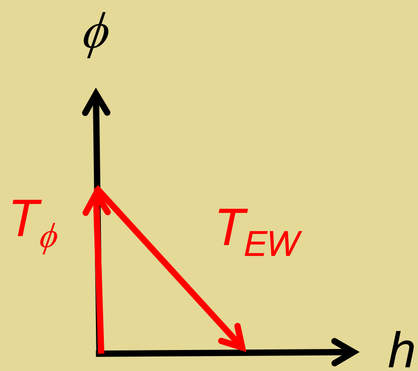
MJRM: 1912.07189

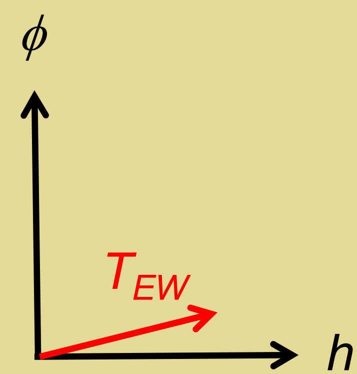
First Order EWPT from BSM Physics



Generate finite-T barrier







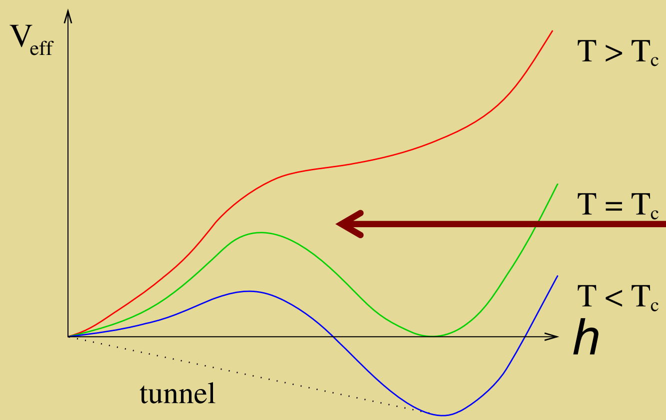
$a_2\, H^2\phi^2$: $T > 0$
loop effect

$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

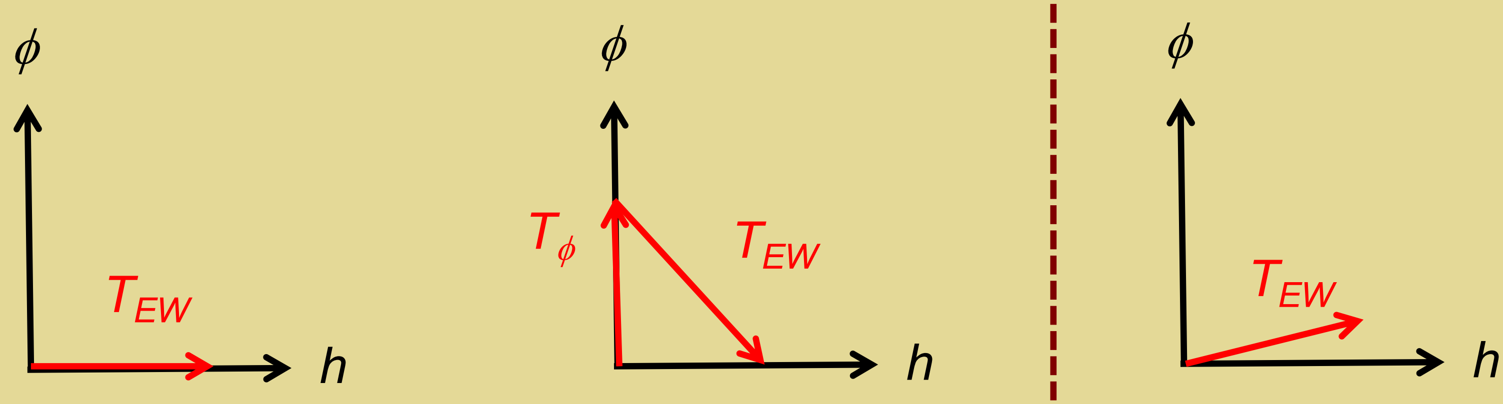
$a_1\, H^2\phi$: $T = 0$
tree-level effect

MJRM: 1912.07189

First Order EWPT from BSM Physics



Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV



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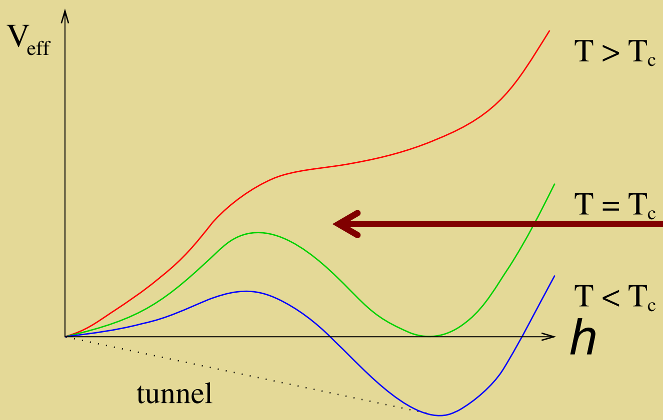
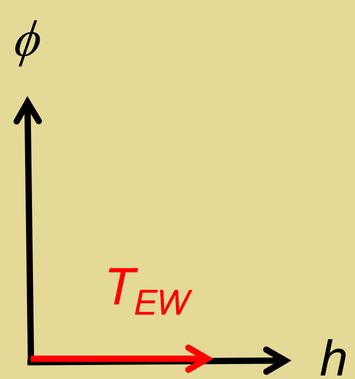
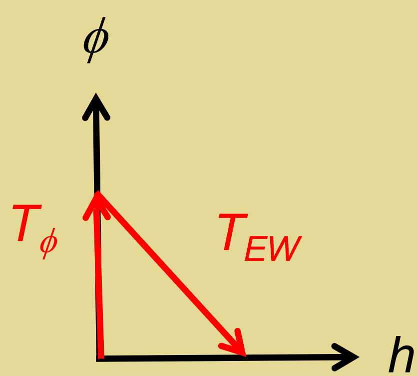
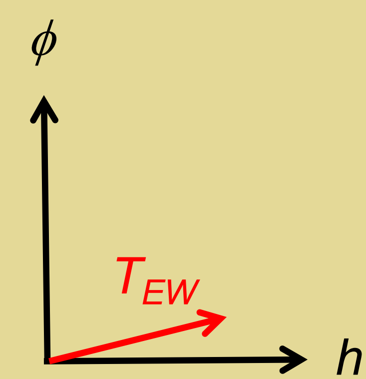


Higgs – ϕ^0 Mixing







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tree-level effect

$a_1\, H^2\phi$: $T = 0$
tree-level effect

MJRM: 1912.07189

Strong First Order EWPT

- **Prevent baryon number washout**
- **Observable GW**

Collider Target: Precision and single ϕ production

$$\boxed{\frac{|a_1|}{2\lambda T_{\mathrm{EW}}} \gtrsim 1} \longrightarrow \boxed{\begin{array}{l} |\sin\theta| \gtrsim 0.01 \\ |\Delta\lambda/\lambda| \gtrsim 0.003 \end{array}}$$

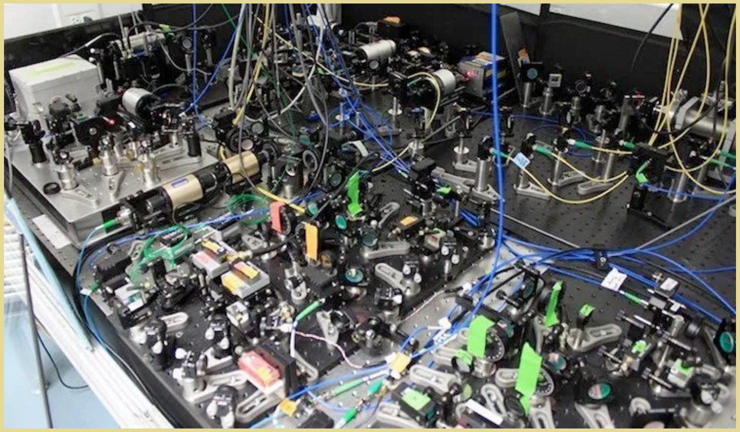
EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + \boxed{d_n^{CKM}}$$

$$\boxed{d_n^{CKM} = (1 - 6) \times 10^{-32}\ e\ cm}$$

C. Seng arXiv: 1411.1476

BSM CPV: Electric Dipole Moments



Electron EDM experiment:
on a table top

Neutron EDM experiment:
a bigger "table"

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \boxed{\sin\phi}\ x\ y_f\, F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ \mathrm{cm})\ \times\ \boxed{(\upsilon / \Lambda)^2}\ \times\ \sin\phi\ \times\ y_f\, F$$

BSM mass scale: TeV ? Much higher ?

υ = 246 GeV   Higgs vacuum expectation value
Λ > 246 GeV   Mass scale of BSM physics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ \ x\ \ \sin\phi\ \ x\ \boxed{y_f F}$$

BSM dynamics: perturbative? Strongly coupled?

y_f Fermion f Yukawa coupling
F Function of the dynamics

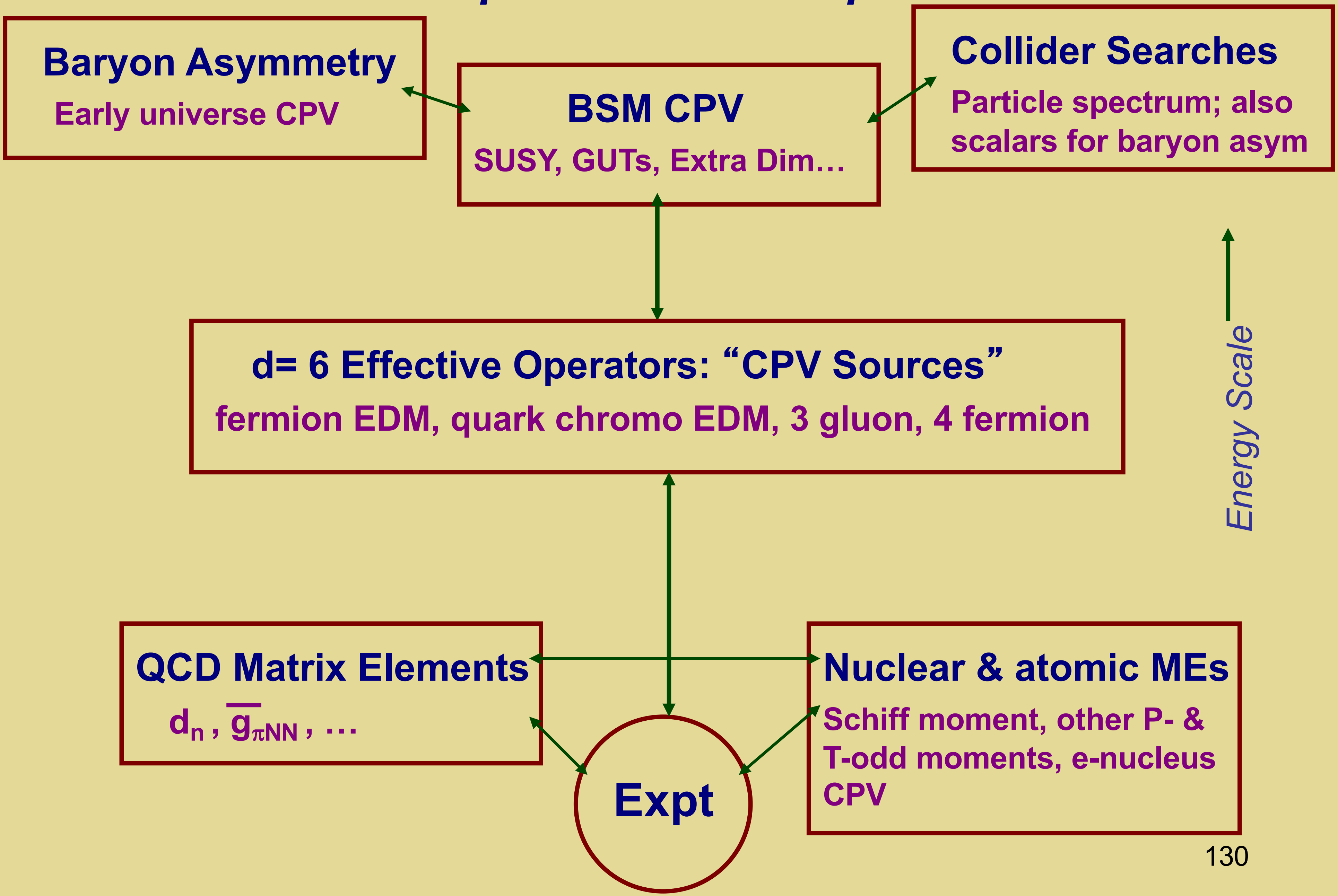
EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ \mathrm{cm}) \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

- Baryon asymmetry — Cosmic Frontier
- High energy collisions — Energy Frontier
- EDMs — Intensity Frontier

EDM Interpretation & Multiple Scales



The Higgs Portal

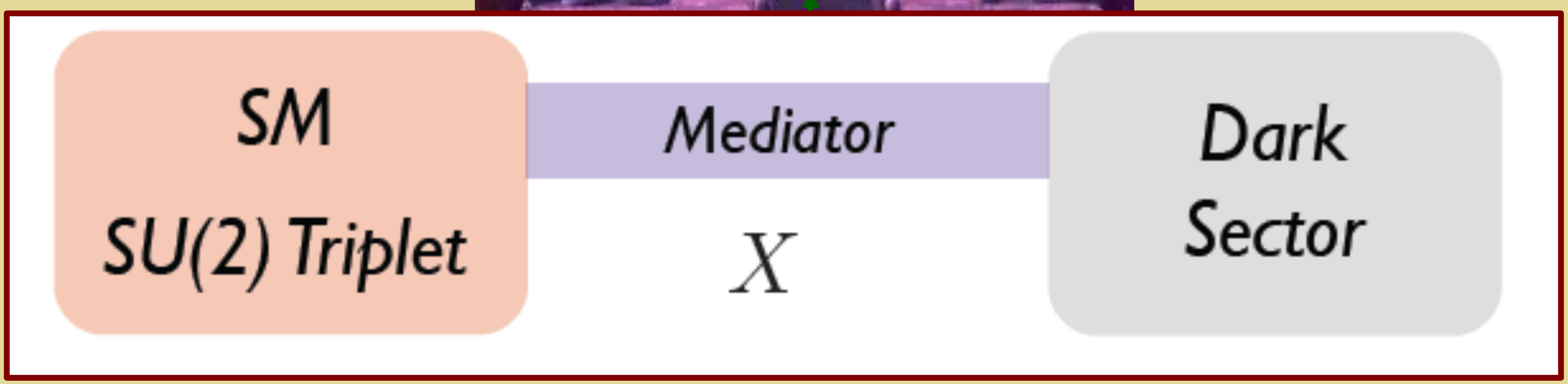
Dark Photon Portal

Dark Photon Portal

Standard Model ⟷ *Hidden Sector*

New CPV ?

Dark Photon Portal



Thanks: K. Fuyuto

CPV Dark Photon

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving CP-violating

Thanks: K. Fuyuto

K. Fuyuto, X.-G. He, G. Li, MJRM 1902.XXXXX

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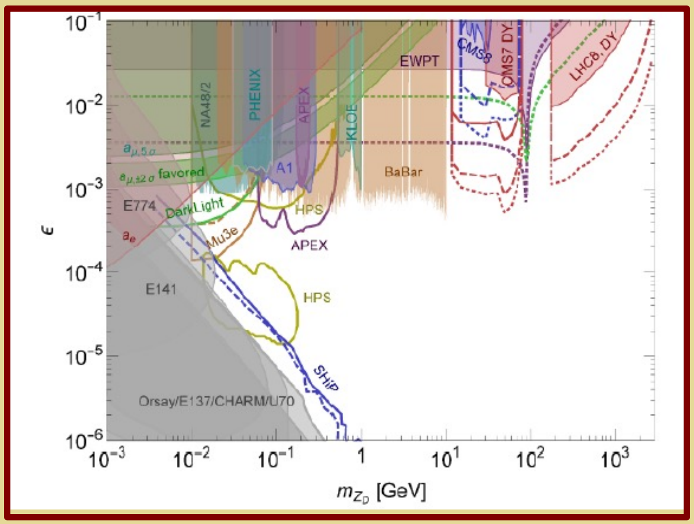
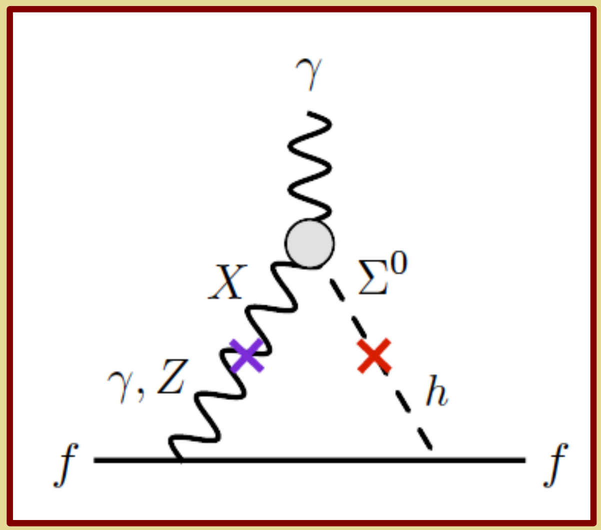
X – γ Mixing



EDM



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CP-conserving

CP-violating

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EDM