Fundamental Interactions: Inter-frontier Connections

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- *Caltech*

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About MJRM:

Science

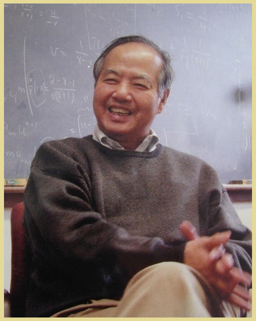
Family

Friends

My pronouns: he/him/his
 # MeToo

PASCOS 2024 Quy Nhon
July 13, 2024

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



Director

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

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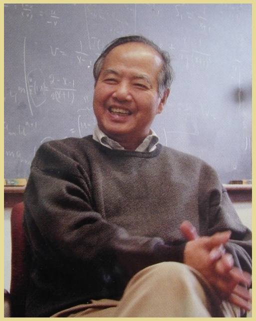

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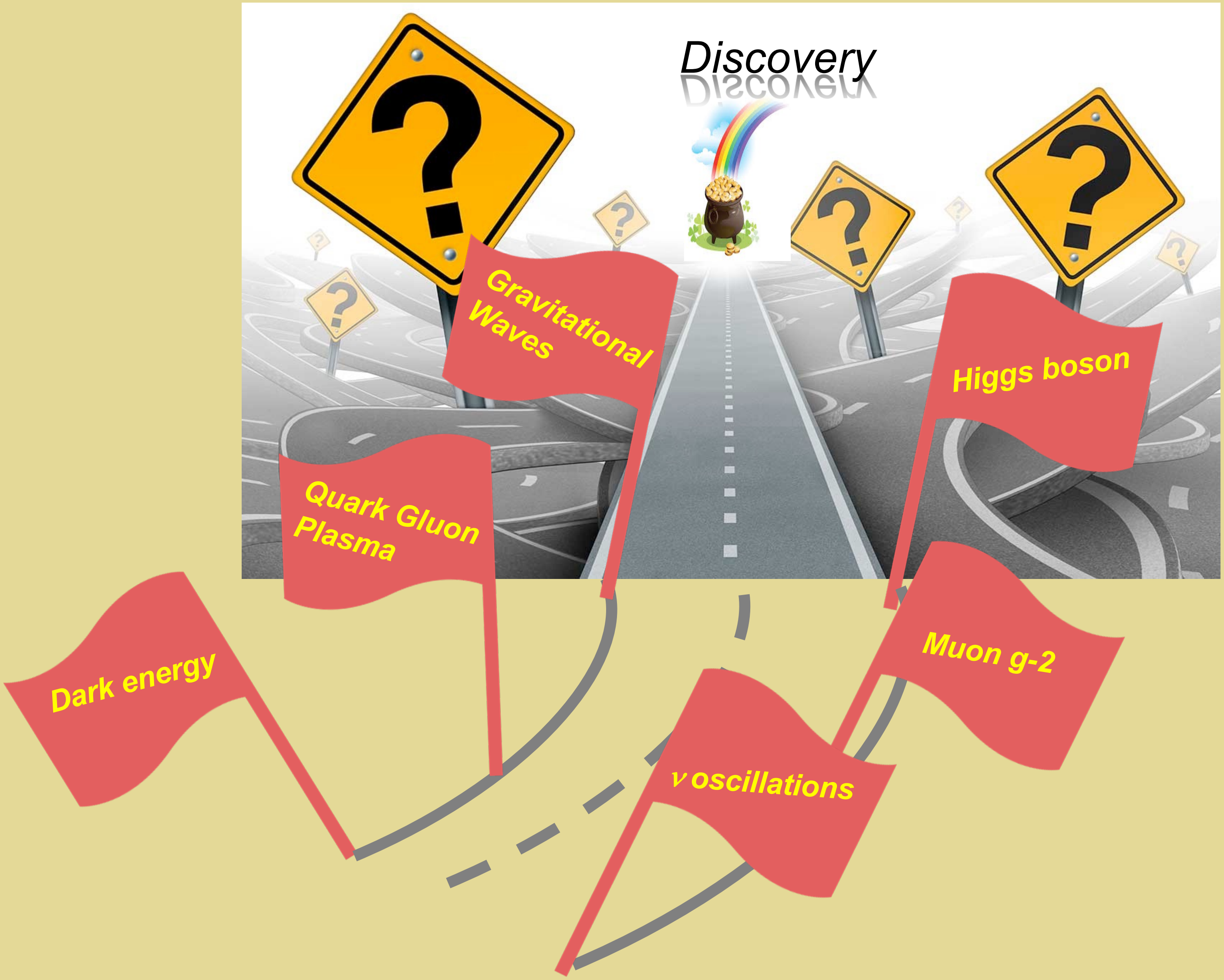
Goals for this Talk

- ***What I won't do:*** ***Give a theoretical summary overview***

- ***What I will do:*** ***Share my perspective on two themes***

Fundamental Physics: Past & Future



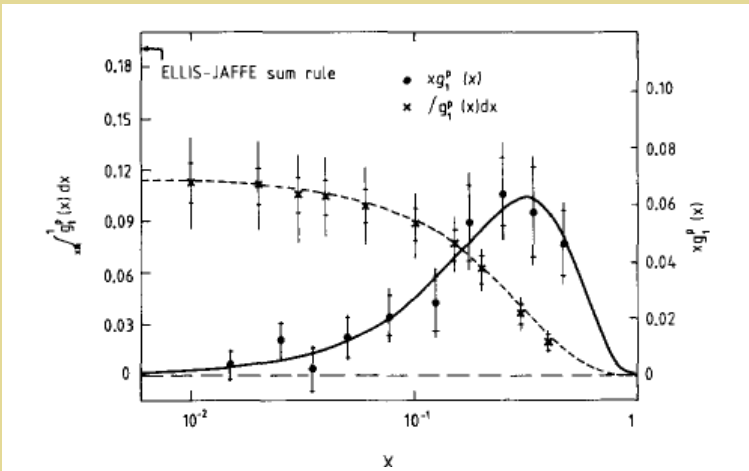
Two Themes

- ***Progress will come from focusing on well-posed scientific questions → potential for insights and/or discoveries***

"Historical" Examples

"Spin Crisis"

EMC '88



$$\langle S_z \rangle_{\mathrm{u}} = 0.373 \pm 0.019 \pm 0.039 \,,$$

$$\langle S_z \rangle_{\mathrm{d}} = -0.254 \pm 0.019 \pm 0.039 \,,$$

$$\langle S_z \rangle_{\mathrm{s}} = -0.113 \pm 0.019 \pm 0.039 \,,$$

$$\langle S_z \rangle_{\mathrm{u+d+s}} = 0.006 \pm 0.058 \pm 0.117$$

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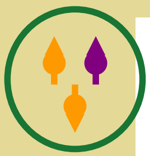
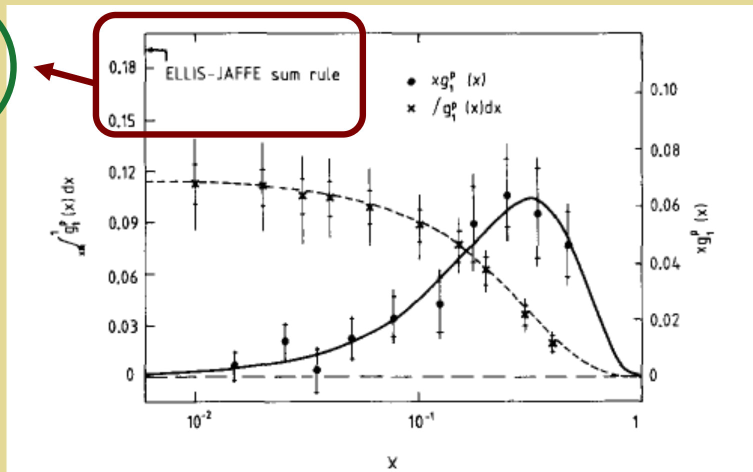


Δs = 0



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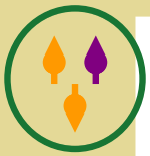
Large negative strange sea polarization & small ΔΣ

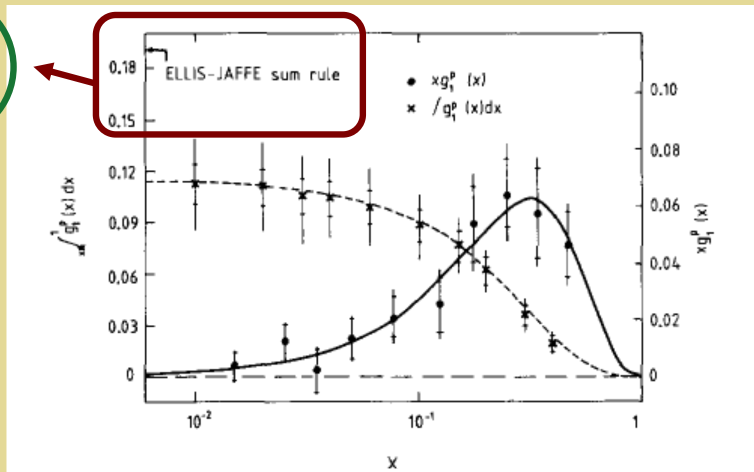
"Historical" Examples

"Spin Crisis"

EMC '88



$\Delta s = 0$



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Large negative strange sea polarization & small $\Delta\Sigma$

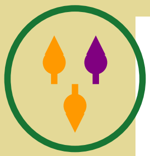
What is the s-quark component of the nucleon magnetic moment and charge distribution ?

- *Kaplan & Manohar '88*
- *Jaffe '89*
- *McKeown & Beck '89*
- *Holstein & MJRM '90*

"Historical" Examples

"Spin Crisis"

EMC '88



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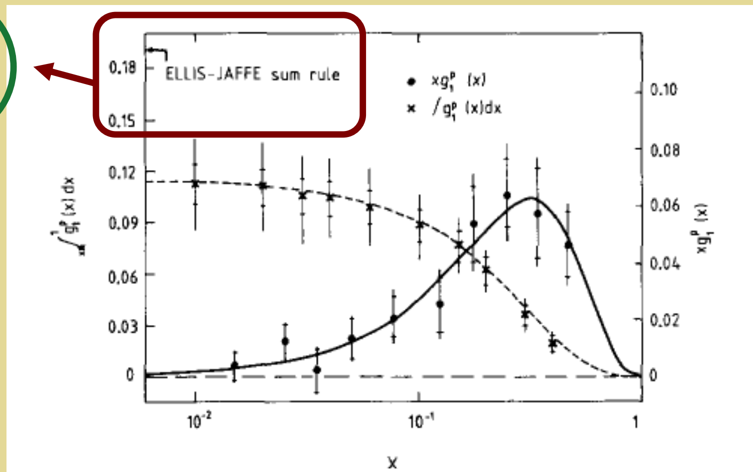

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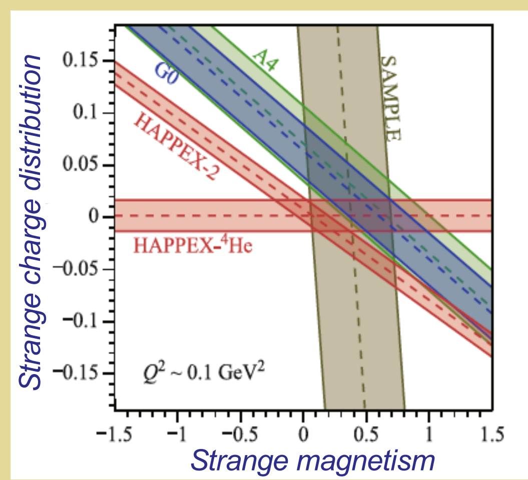
25 years of PV ep, eA scattering



P. Souder & K. Paschke, Front Phys 11 (2016) 111301

Two Themes

- ***Progress will come from focusing on well-posed scientific questions → potential for insights and/or discoveries***

- ***It's important to think beyond boundaries of funding agency priorities and conventional sub-field categories → rich opportunities from inter-frontier connections***

“Historical” Examples

Nuclear Science Long Range Plan
Pre-Town Meeting: Los Alamos 2006

Hamish Robertson

$V_{\rm PMNS}$ =

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times\, {\rm diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

“Atmospheric” *“Reactor”* *“Solar”*

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“High Energy” ??? “Nuclear”

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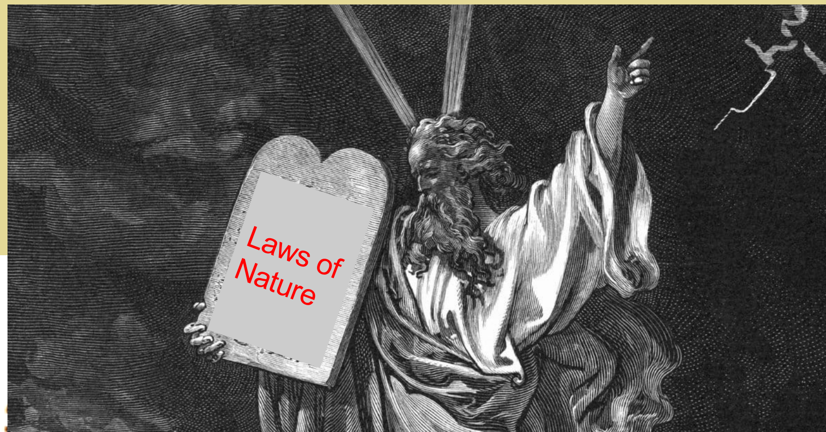

$$\begin{bmatrix} c_{12}c_{13} & \cdots & \cdots e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{1}\cdots & \cdots & \cdots \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & \cdots \end{bmatrix}$$

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“Atmospheric” *“Reactor”* *“Solar”*

The BSM Dog Race

This talk: I'll focus on a problem I'm particularly immersed in to illustrate → other areas of inquiry equally important & interest

Outline

I. Questions & Frontiers

II. Origin of matter: EW scale

III. Outlook

IV. Origin of matter & neutrino physics

V. Electroweak precision tests

Another day

I. Questions & Frontiers

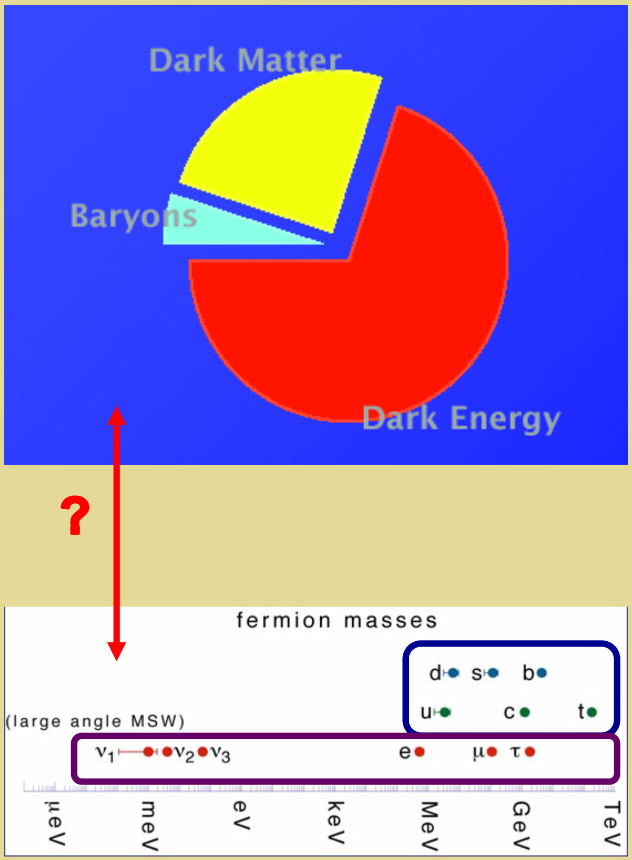
Fundamental Questions

***MUST** answer*

***SHOULD** answer*

Fundamental Questions

***MUST** answer*

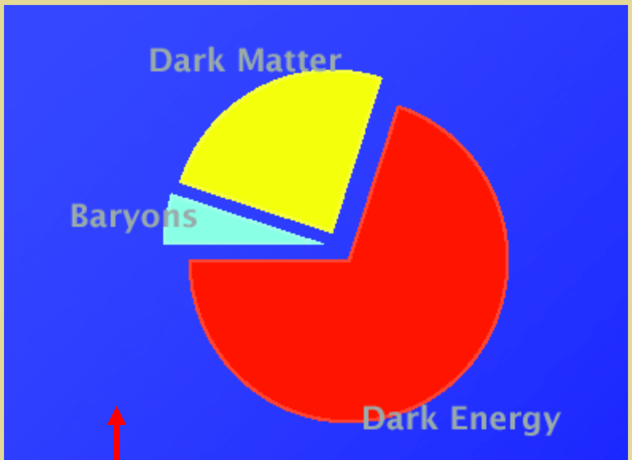


Origin of m_ν

***SHOULD** answer*

Fundamental Questions

MUST *answer*



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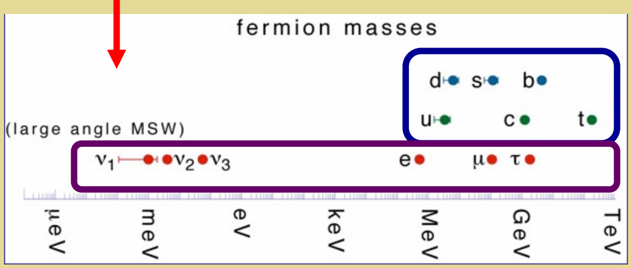

Origin of m_ν

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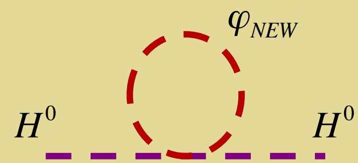
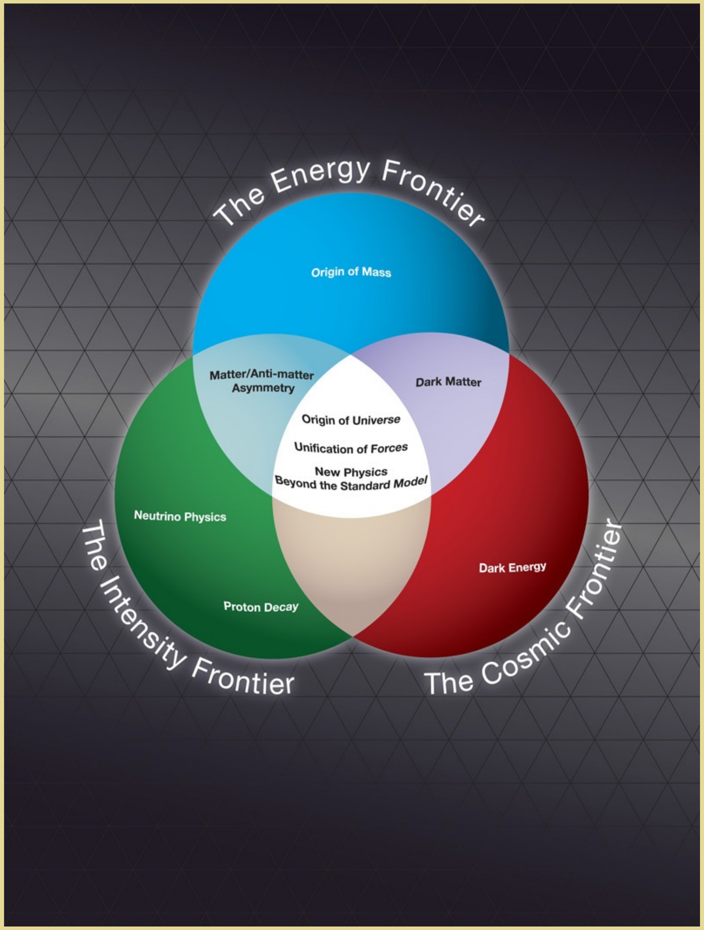


$\Delta m^2 \sim \lambda \Lambda^2$

?

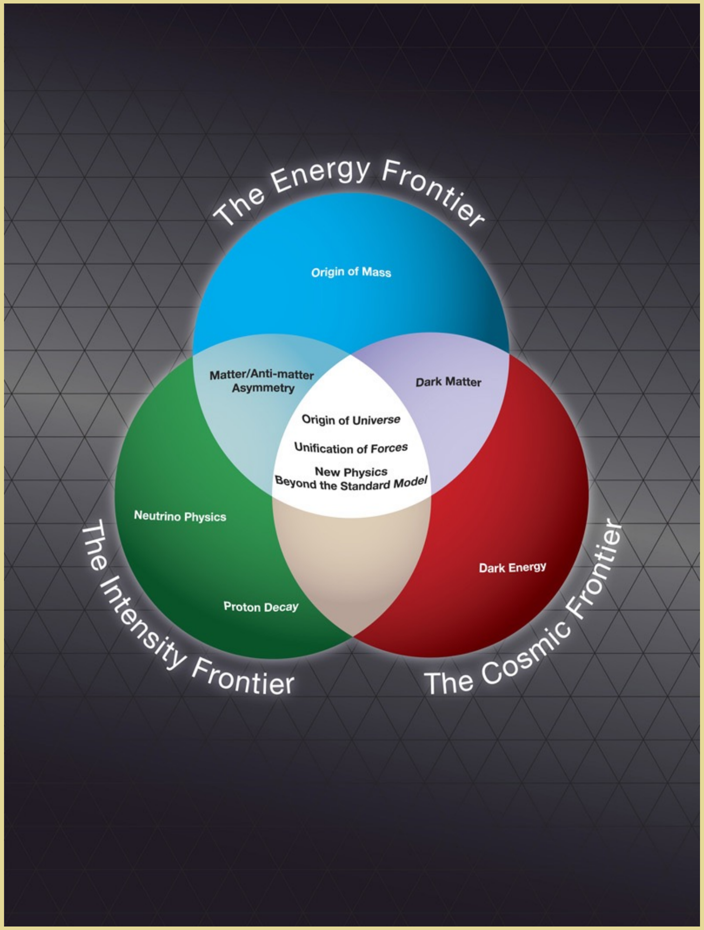
$\Lambda_{Cosmological}$

Frontiers



Historical artifact: US HEP vision → still useful mnemonic

Frontiers



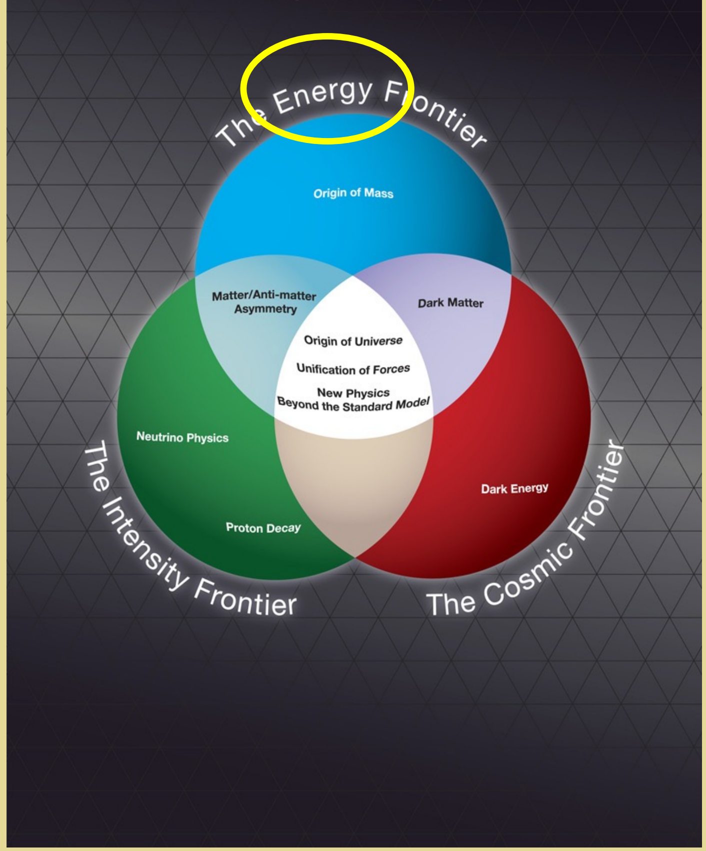
Lifetime Frontier

Historical artifact: US HEP vision → still useful mnemonic

Frontiers

HEP : New (heavy) particles

Lifetime Frontier



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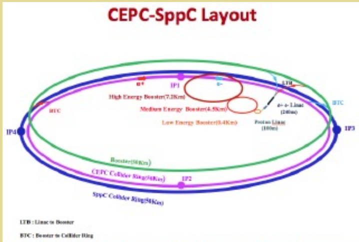
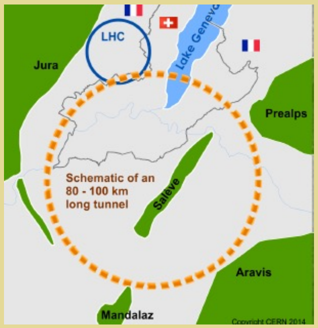
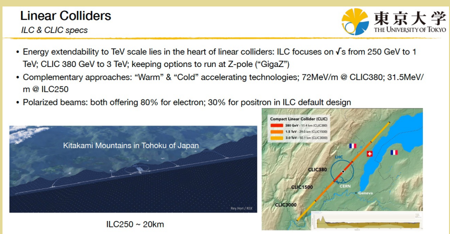
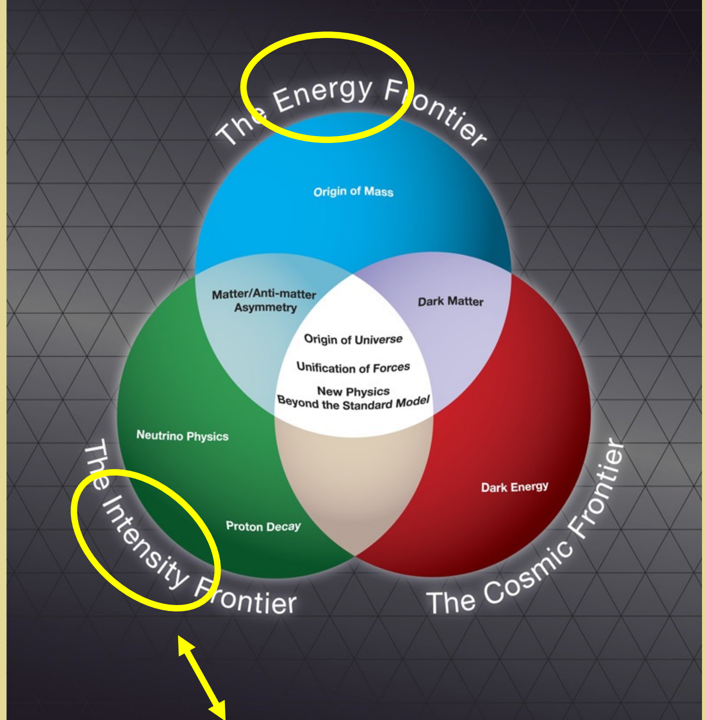






HEP : New (heavy) particles

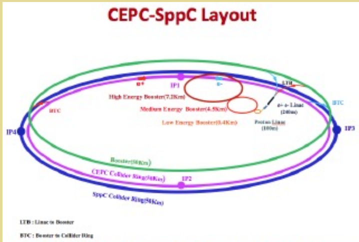
Lifetime Frontier

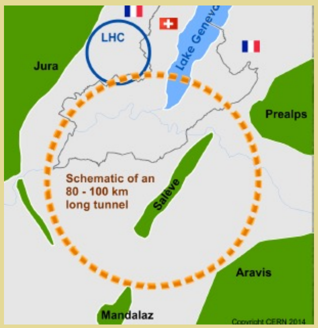


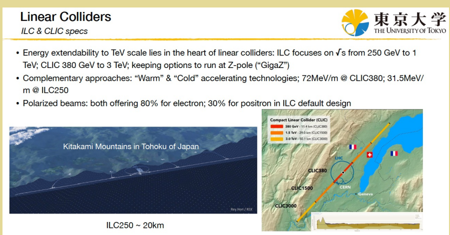
HEP : H & Z factories

Historical artifact: US HEP vision → still useful mnemonic

Frontiers

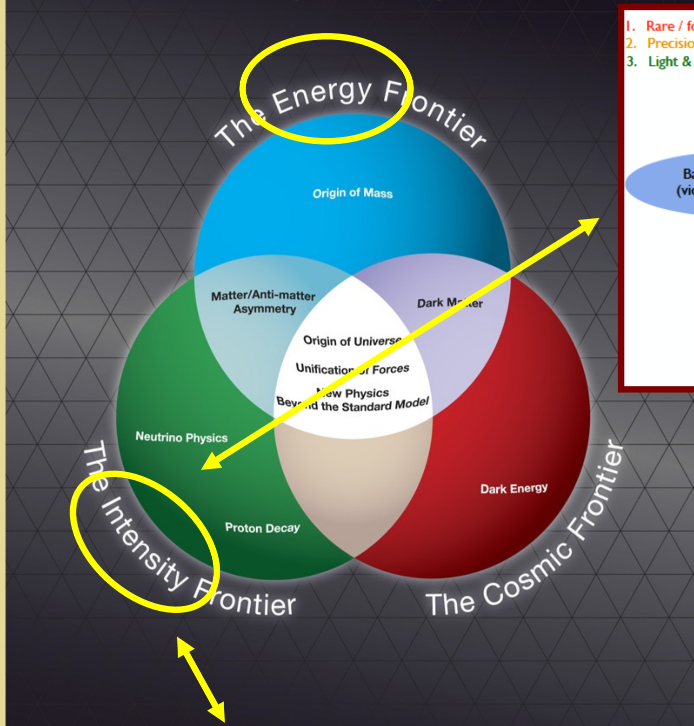




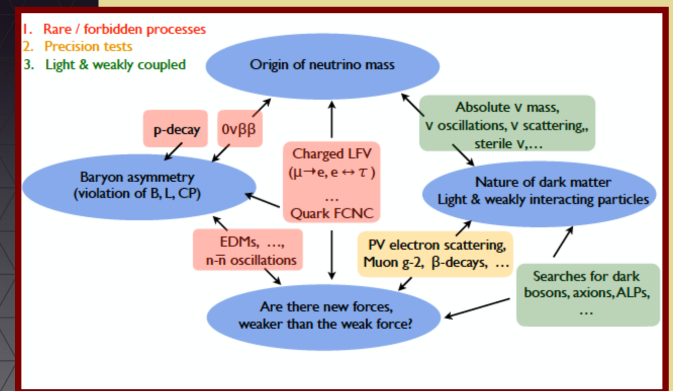


Lifetime Frontier

HEP : New (heavy) particles



HEP + Nuc



V. Cirigliano, INT EIC '24

- *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

Nuclear Physics Connections

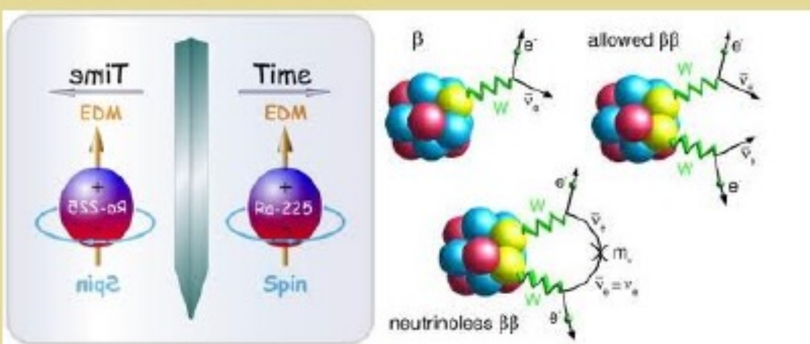
Lepton number

$0\nu\beta\beta$ Decay

EDMs

CP & T

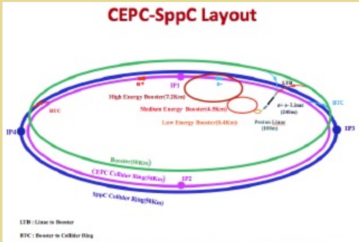
Precision tests

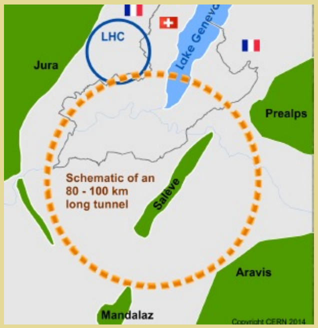


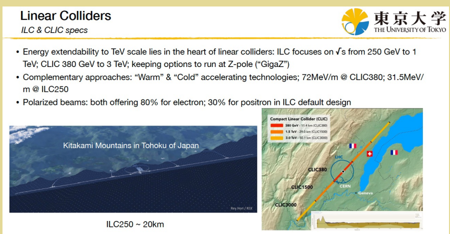
Fundamental symmetries & neutrinos: "Intensity Frontier"

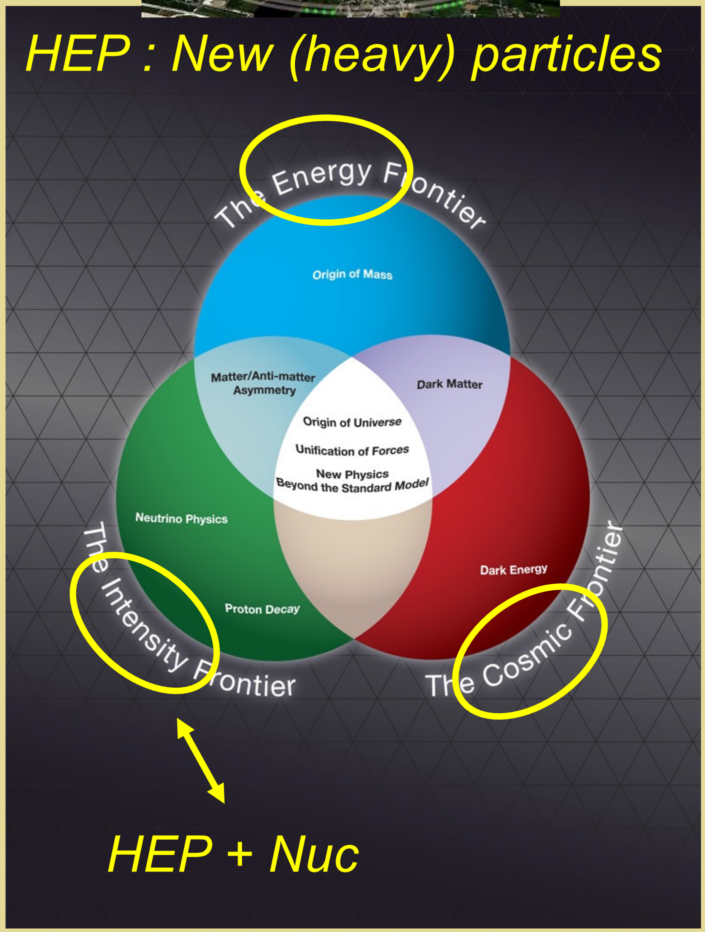
Muon g-2, PV ee, β decay…

Frontiers

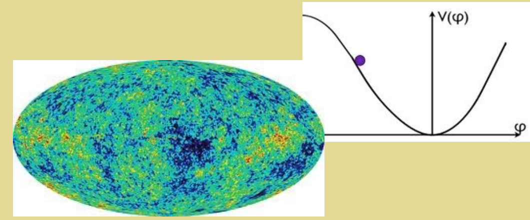


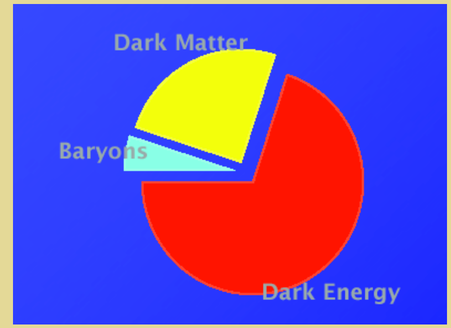


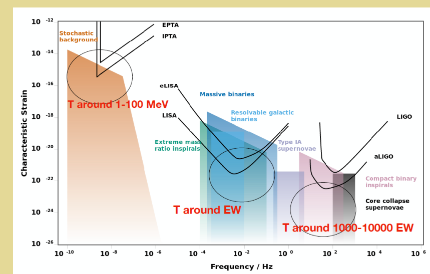




Lifetime Frontier







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- *Neutrino properties*
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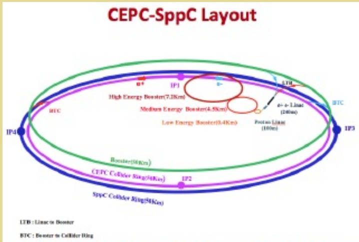
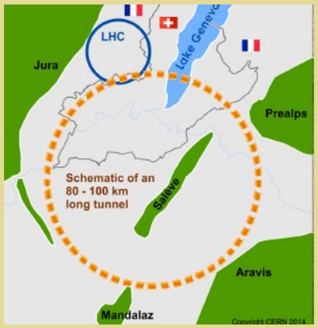
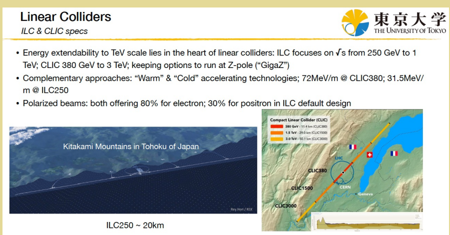
Historical artifact: US HEP vision → still useful mnemonic

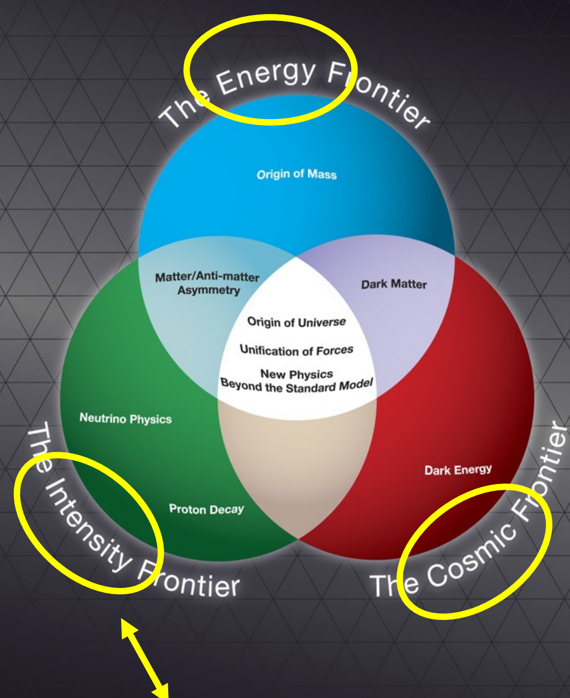
Frontiers





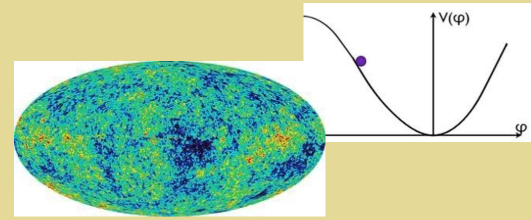


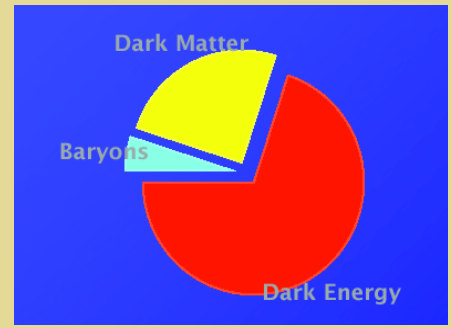
HEP : New (heavy) particles

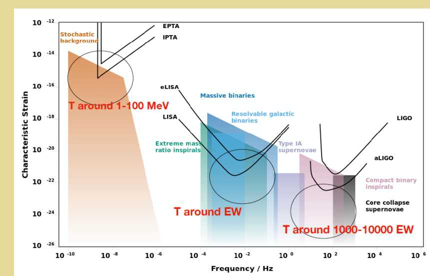


HEP + Nuc

Lifetime Frontier







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

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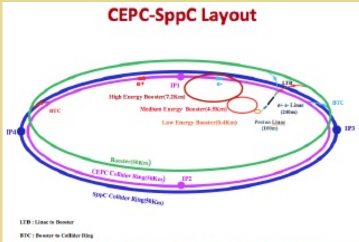
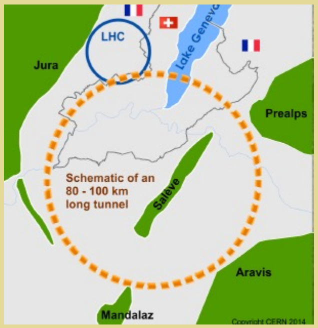
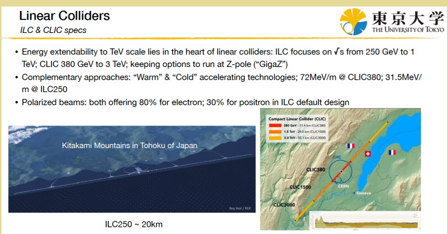
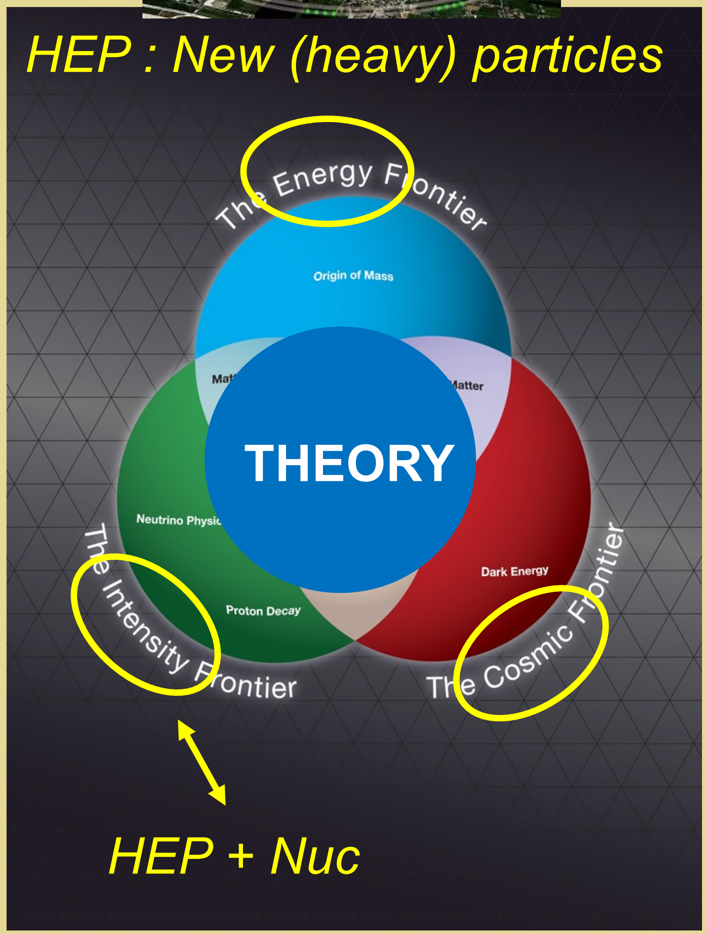
Frontiers

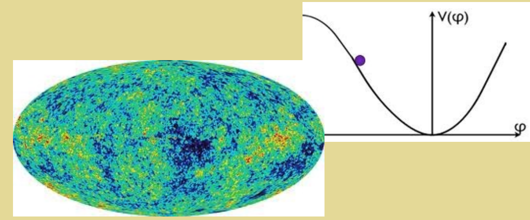


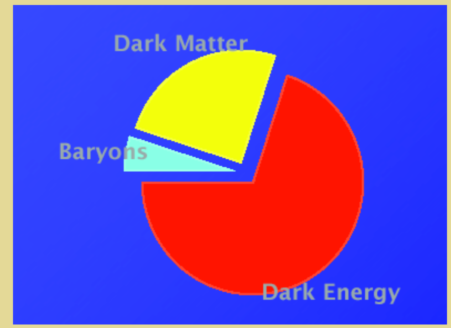


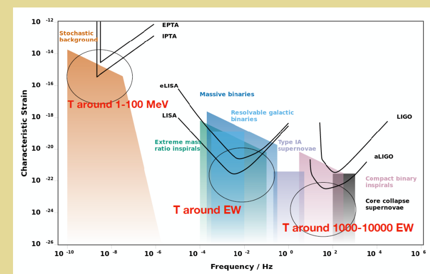


Lifetime Frontier









- *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***

More Matter than Antimatter ?

When & how was the baryon asymmetry generated ?

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*	✗	✓

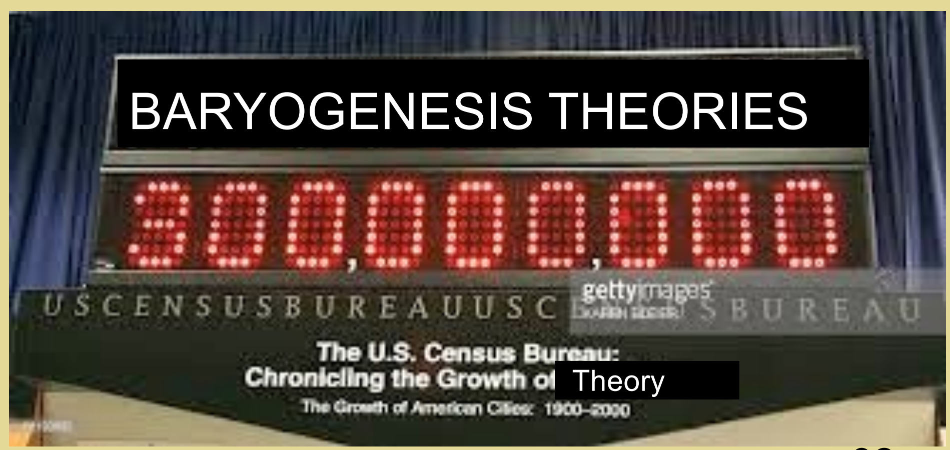
Cosmic Baryon Asymmetry

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

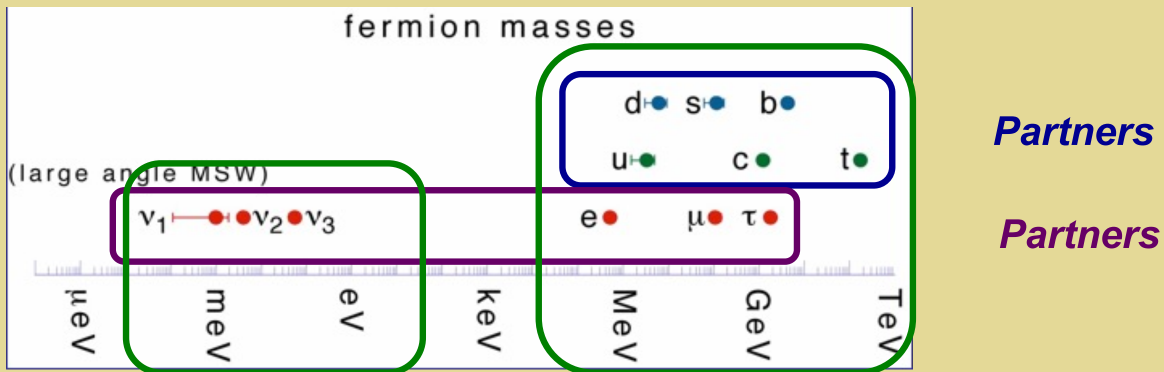
One number → ~~||||~~ ~~||||~~ ~~||||~~ … Explanations

Experiment can help:

- *Discover ingredients*
- *Falsify candidates*



Fermion Masses & Baryon Asymmetry



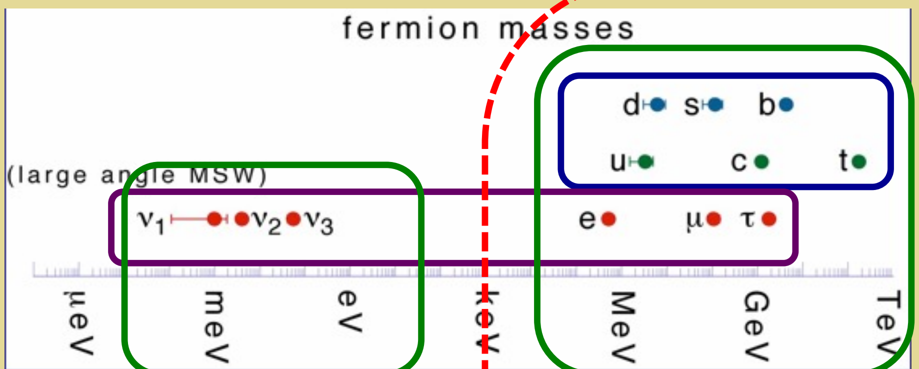
Something else ?

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



Partners

Partners

Something else ?

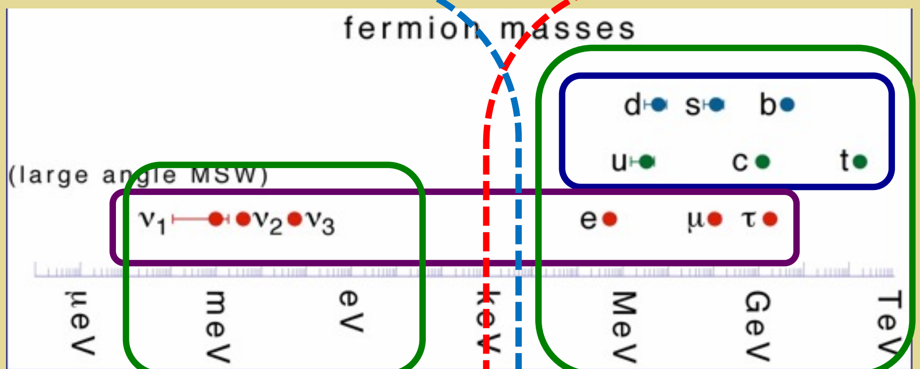
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This talk

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

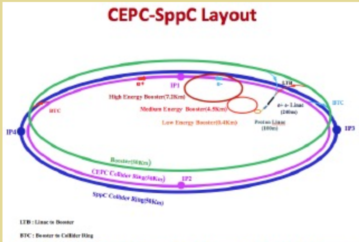
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

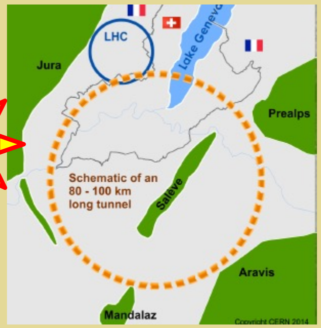
Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

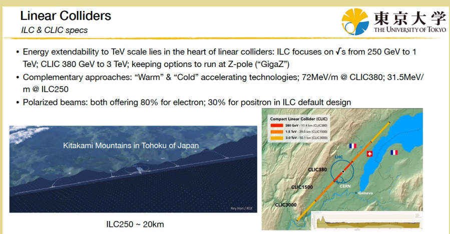
Another day

This talk

Frontiers






Linear Colliders
ILC & CLIC specs
東京大学 THE UNIVERSITY OF TOKYO

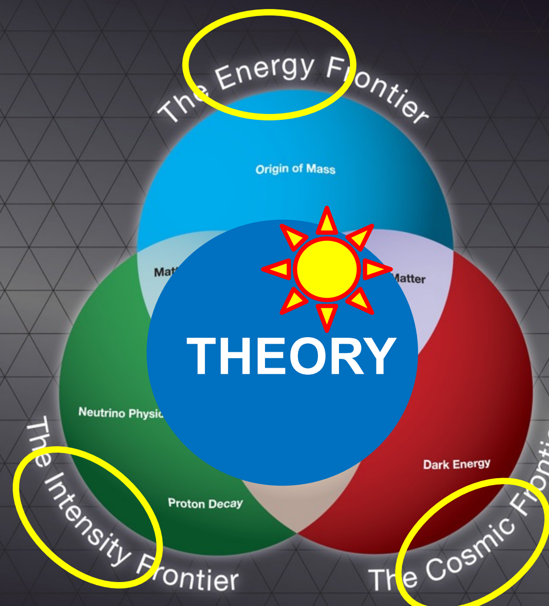
- Energy extendability to TeV scale lies in the heart of linear colliders: ILC focuses on √s from 250 GeV to 1 TeV; CLIC 380 GeV to 3 TeV; keeping options to run at Z-pole ("GigaZ")
- Complementary approaches: "Warm" & "Cold" accelerating technologies; 72MeV/m @ CLIC380; 31.5MeV/m @ ILC250
- Polarized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

ILC250 ~ 20km

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

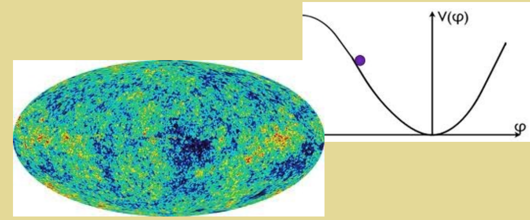
Lifetime Frontier

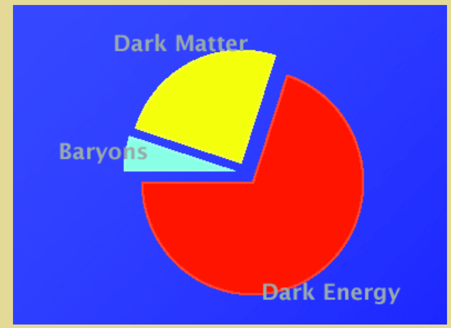
HEP : New (heavy) particles

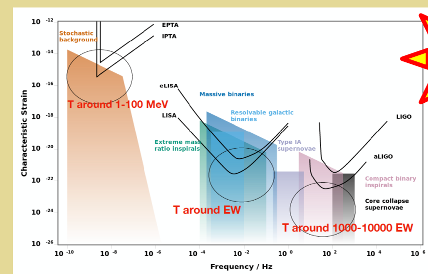


HEP + Nuc

Historical artifact: US HEP vision → still useful mnemonic







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

II. Origin of Matter: EW Scale

Was the baryon asymmetry generated in conjunction with spontaneous EW symmetry breaking ?

EWBG Ingredients

- *EW Sphalerons*
- *Strong 1st Order EW Phase Transition*
- *Left-handed number density*

EWBG Ingredients

- *EW Sphalerons* ✔
- *Strong 1st Order EW Phase Transition* → **BSM Higgs**
- *Left-handed number density* → **BSM CPV**

EWBG Ingredients

- *EW Sphalerons* ✔
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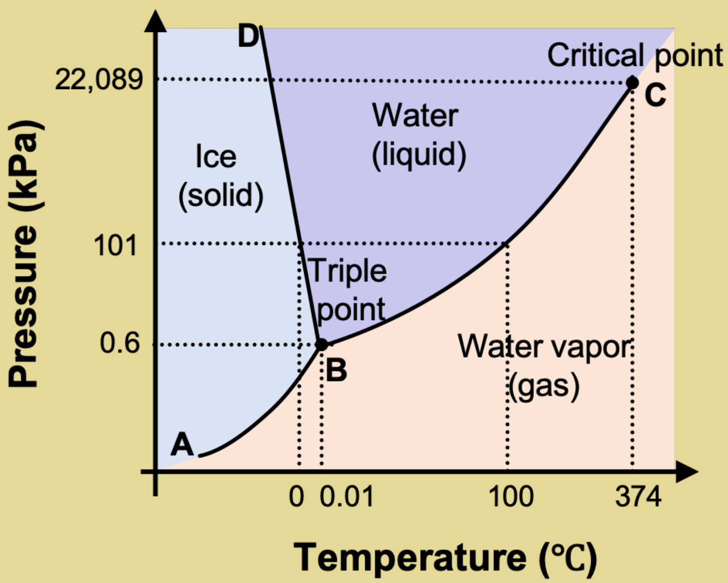
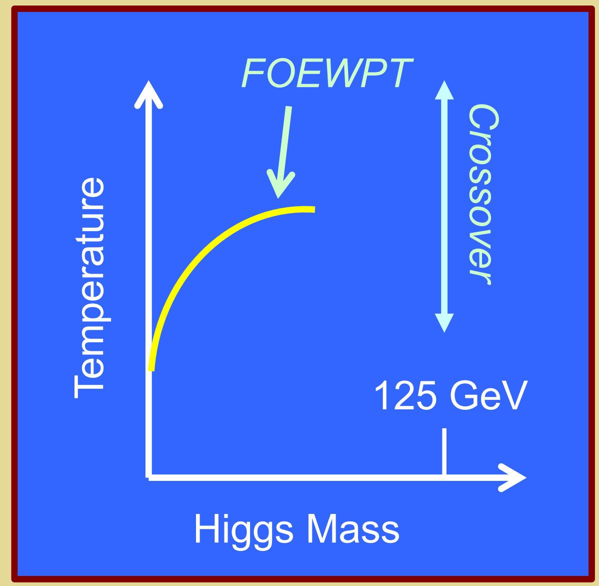
- *Left-handed number density* → *BSM CPV*

Was There an Electroweak Phase Transition ?

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

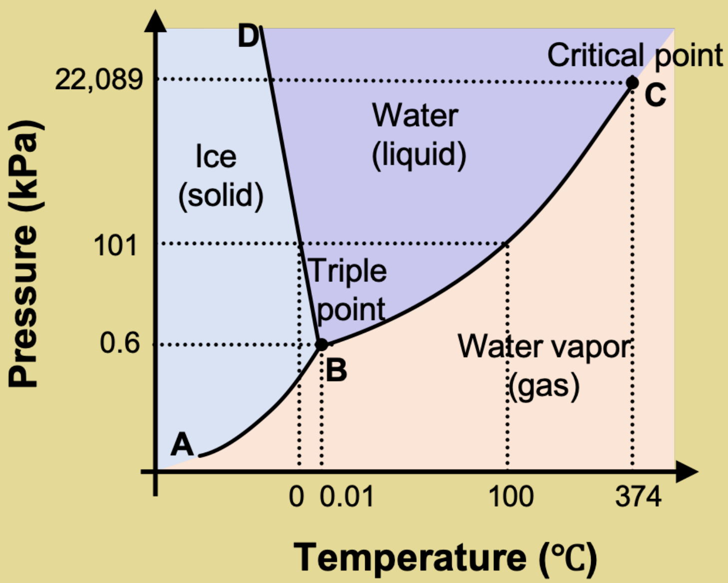
Was There an Electroweak Phase Transition ?

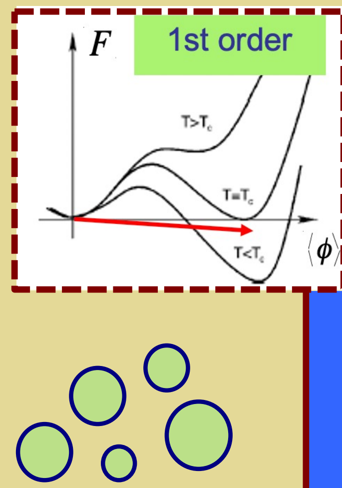


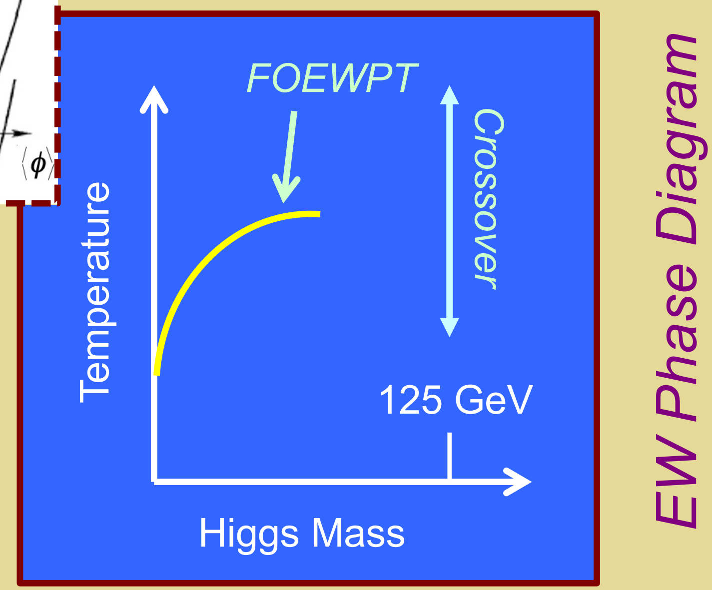


EW Phase Diagram

Was There an Electroweak Phase Transition ?







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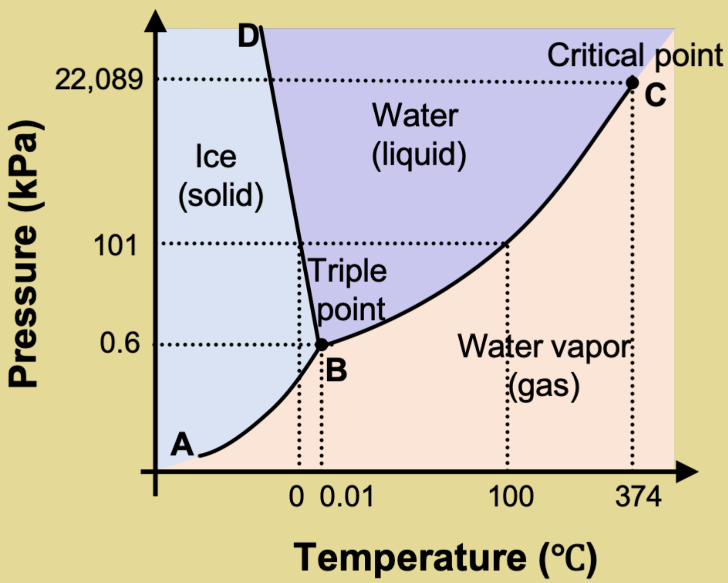
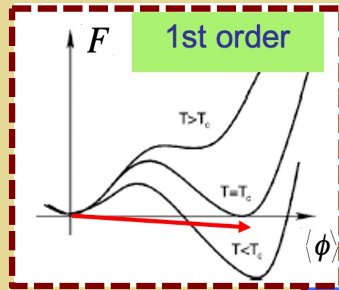
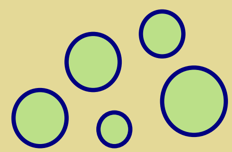
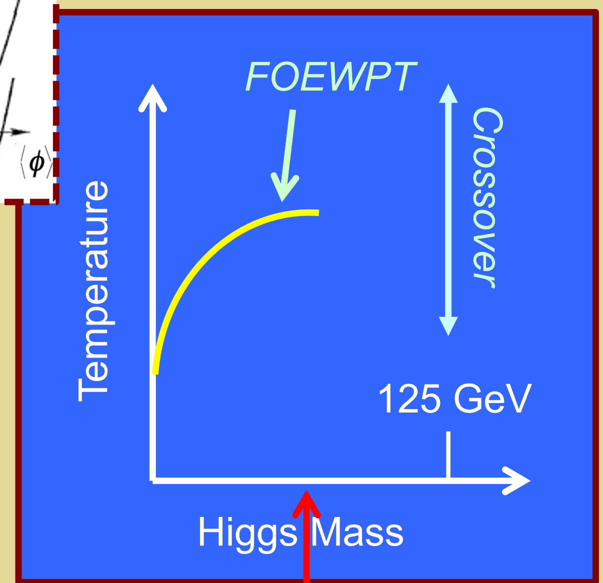




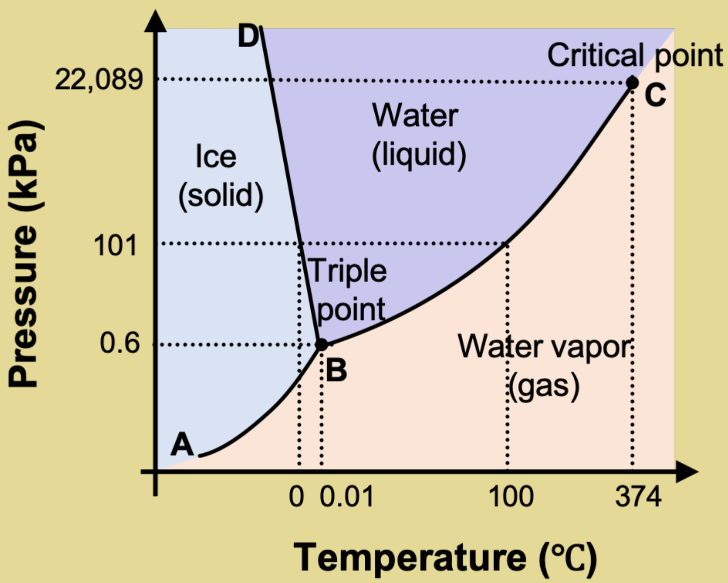


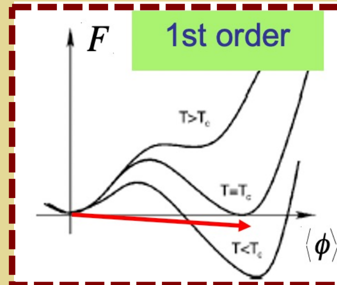


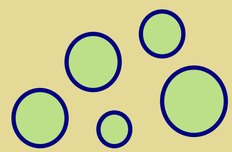
EW Phase Diagram

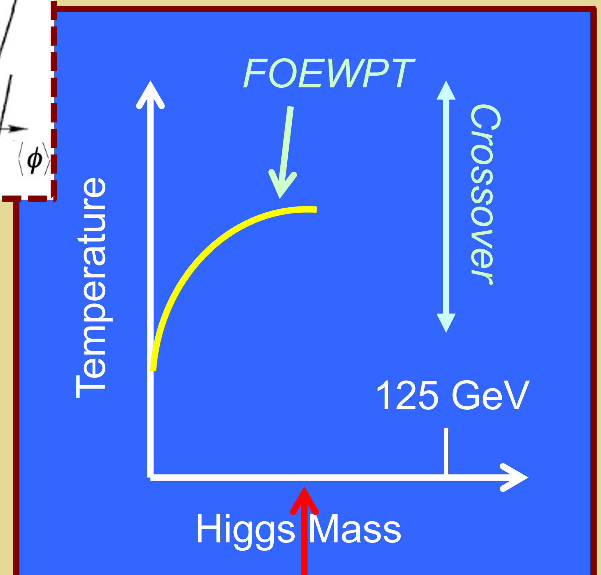
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

Was There an Electroweak Phase Transition ?









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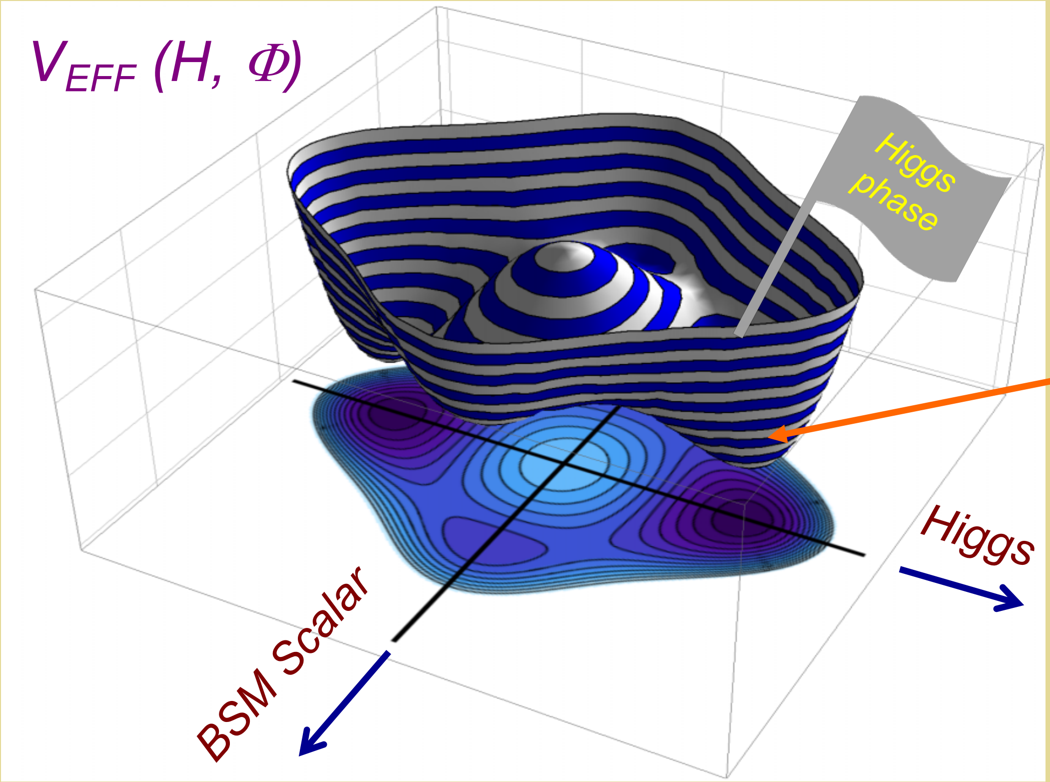
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

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

What Was the EWSB Thermal History ?



How did we end up here ?

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

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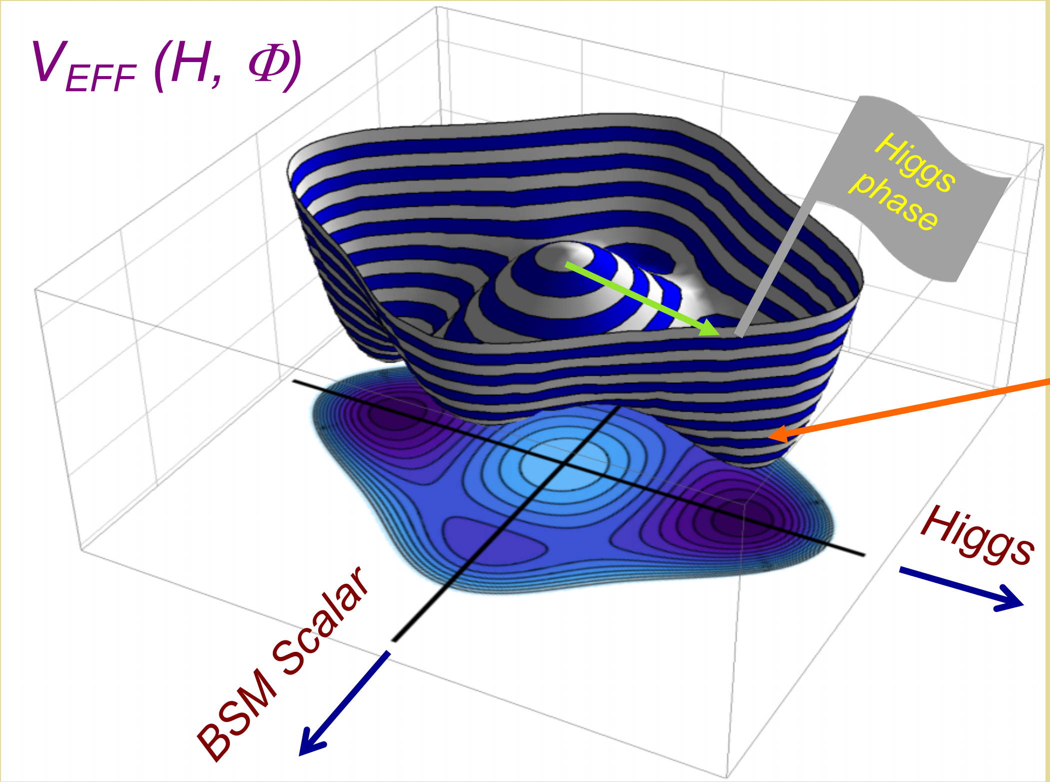

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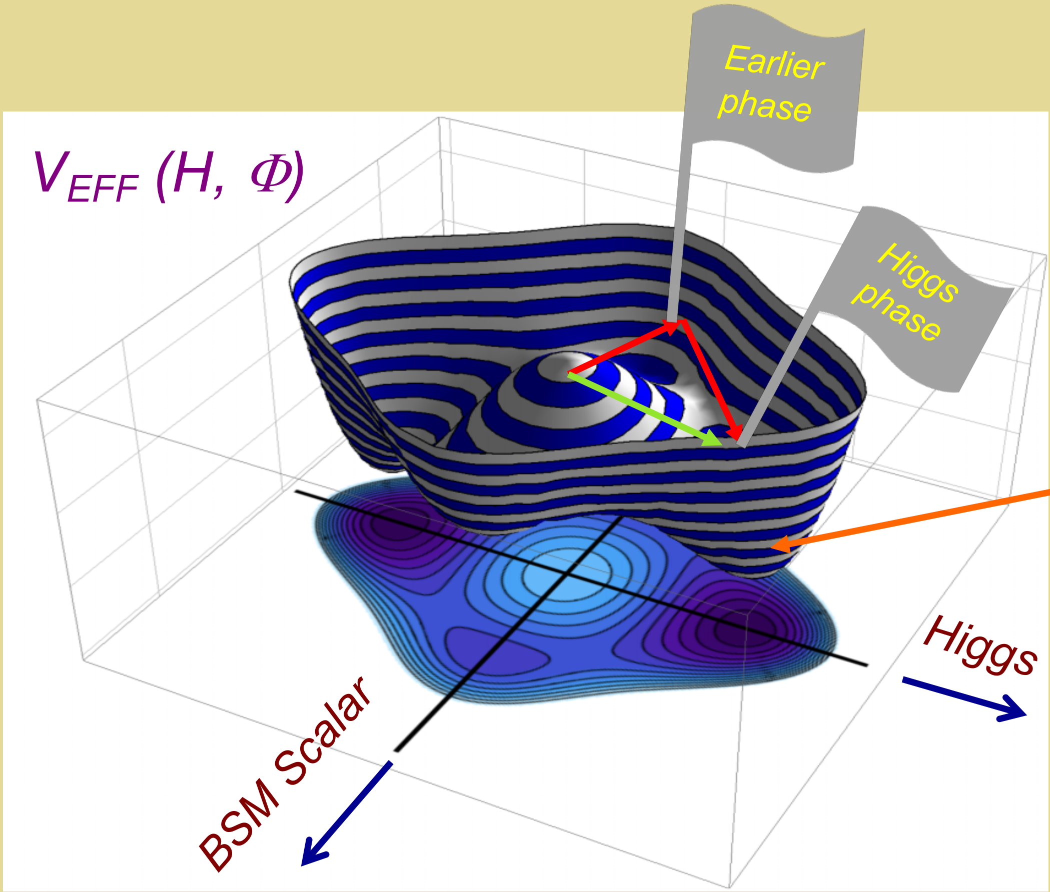

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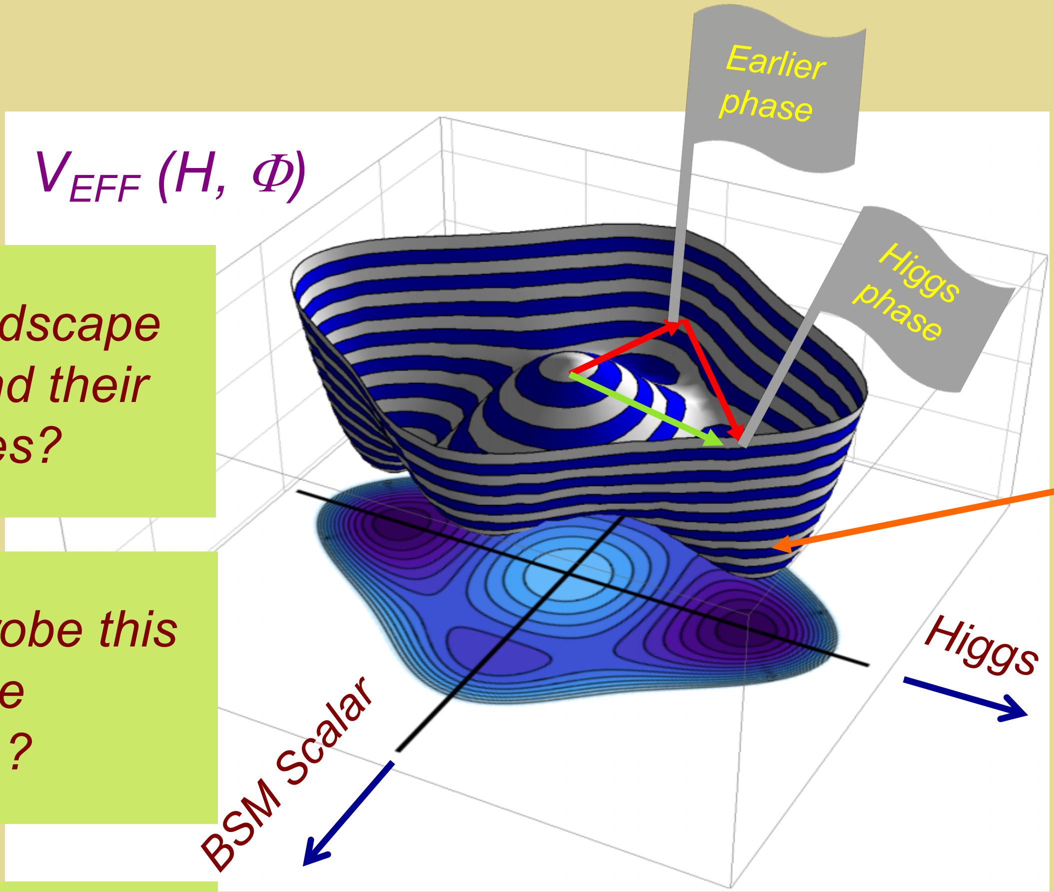


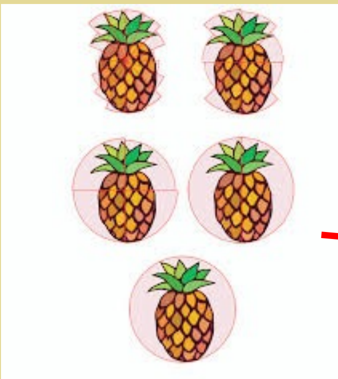
How did we end up here ?

- 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 ?

n evolve differently as T evolves →
ilities for symmetry breaking

Was There an EW Phase Transition?

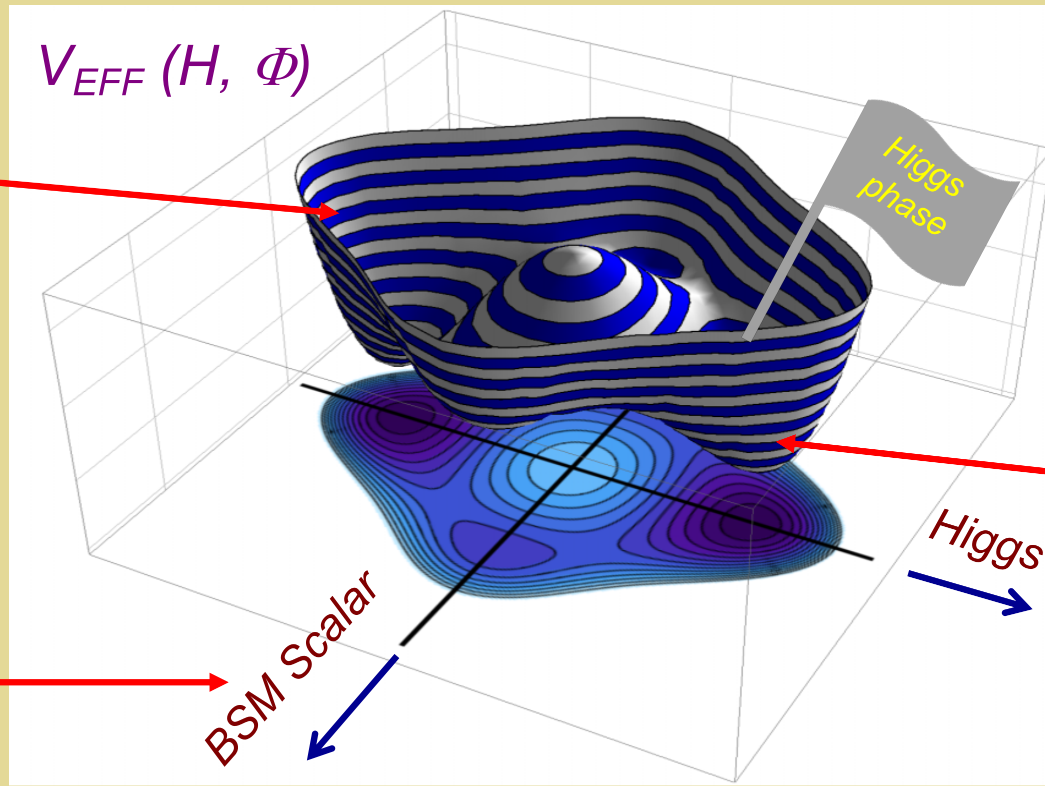
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs

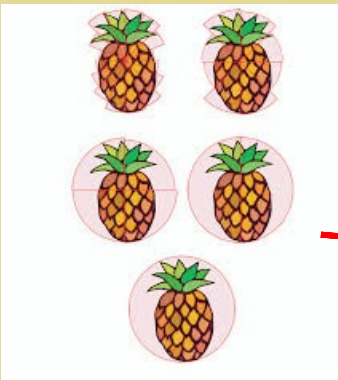


Higgs precision tests

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

Was There an EW Phase Transition?

Bubble Collisions



Grav Radiation

Direct Production

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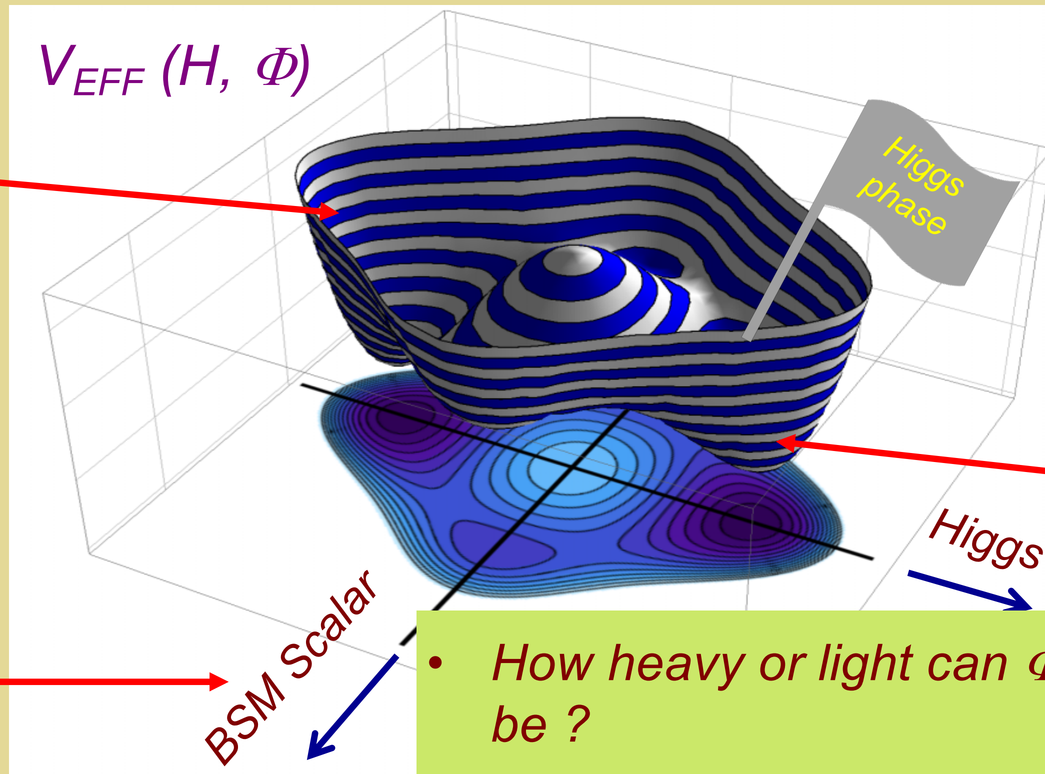


Higgs precision tests

- *How heavy or light can Φ be ?*
- *How coupled to H ?*
- *Can it be discovered with colliders & GW probes ?*

Extrema can evolv →
rich possibilities fo

MJRM: 1912.07189

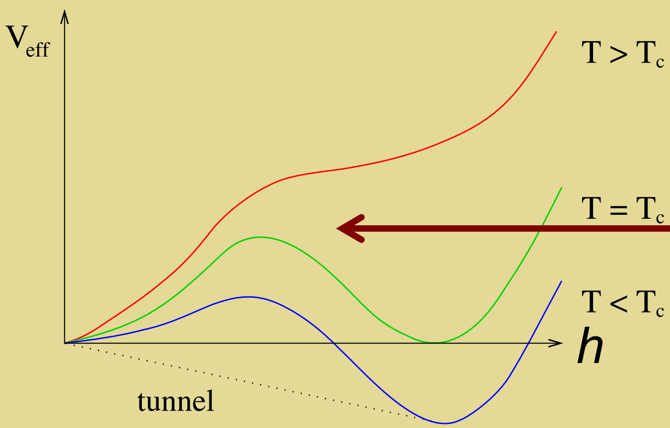
T_{EW} → Scale for Colliders & GW probes

High-T SM Effective Potential

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

$T_0 \sim$ 140 GeV $\equiv$ T_{EW}

First Order EWPT from BSM Physics

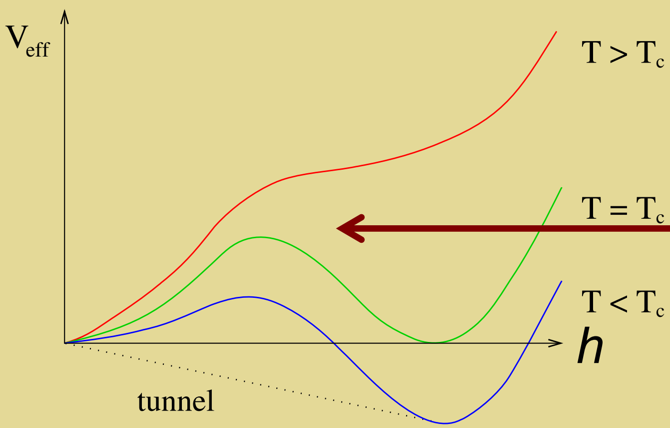


Generate finite-T barrier

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



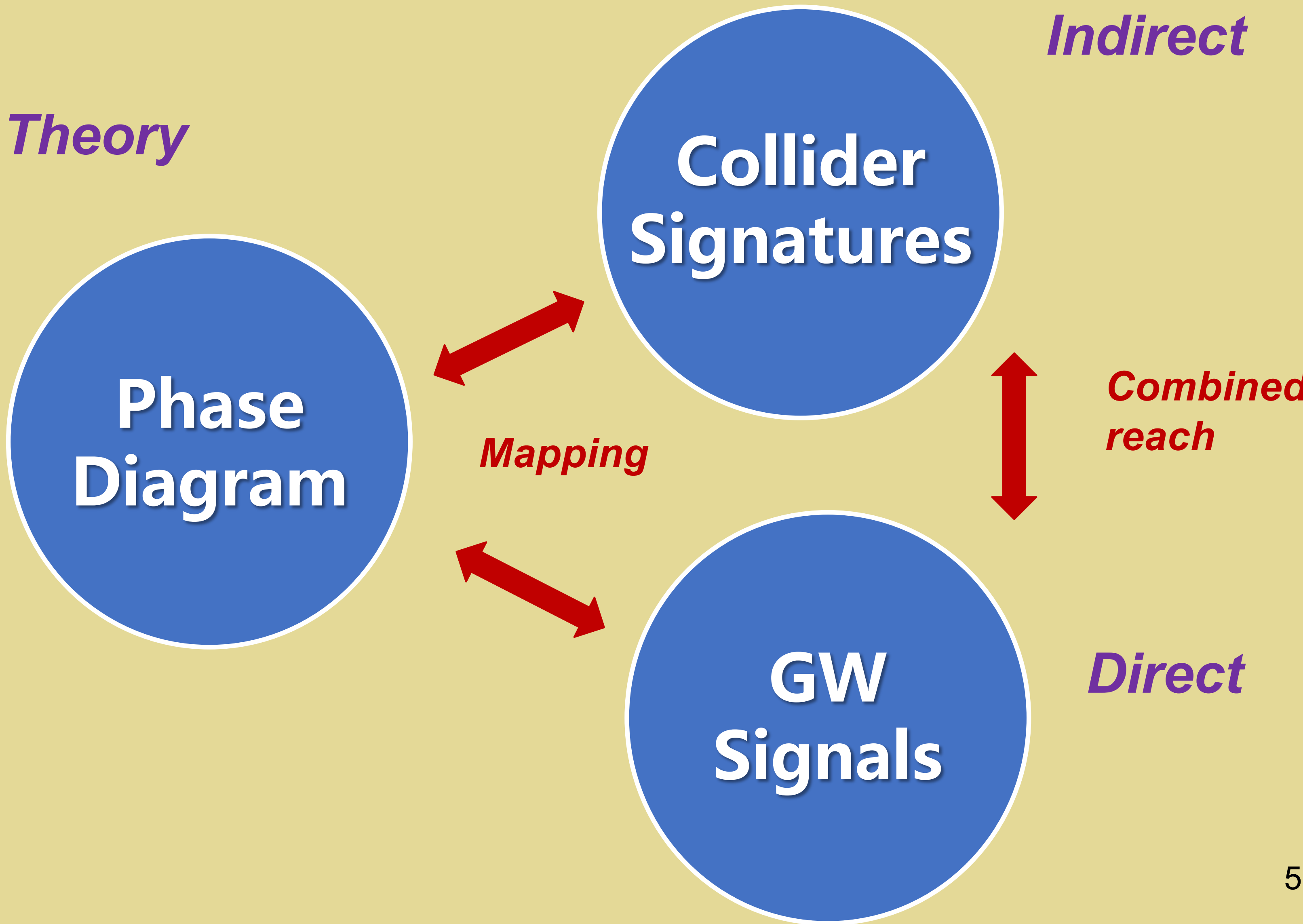
Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

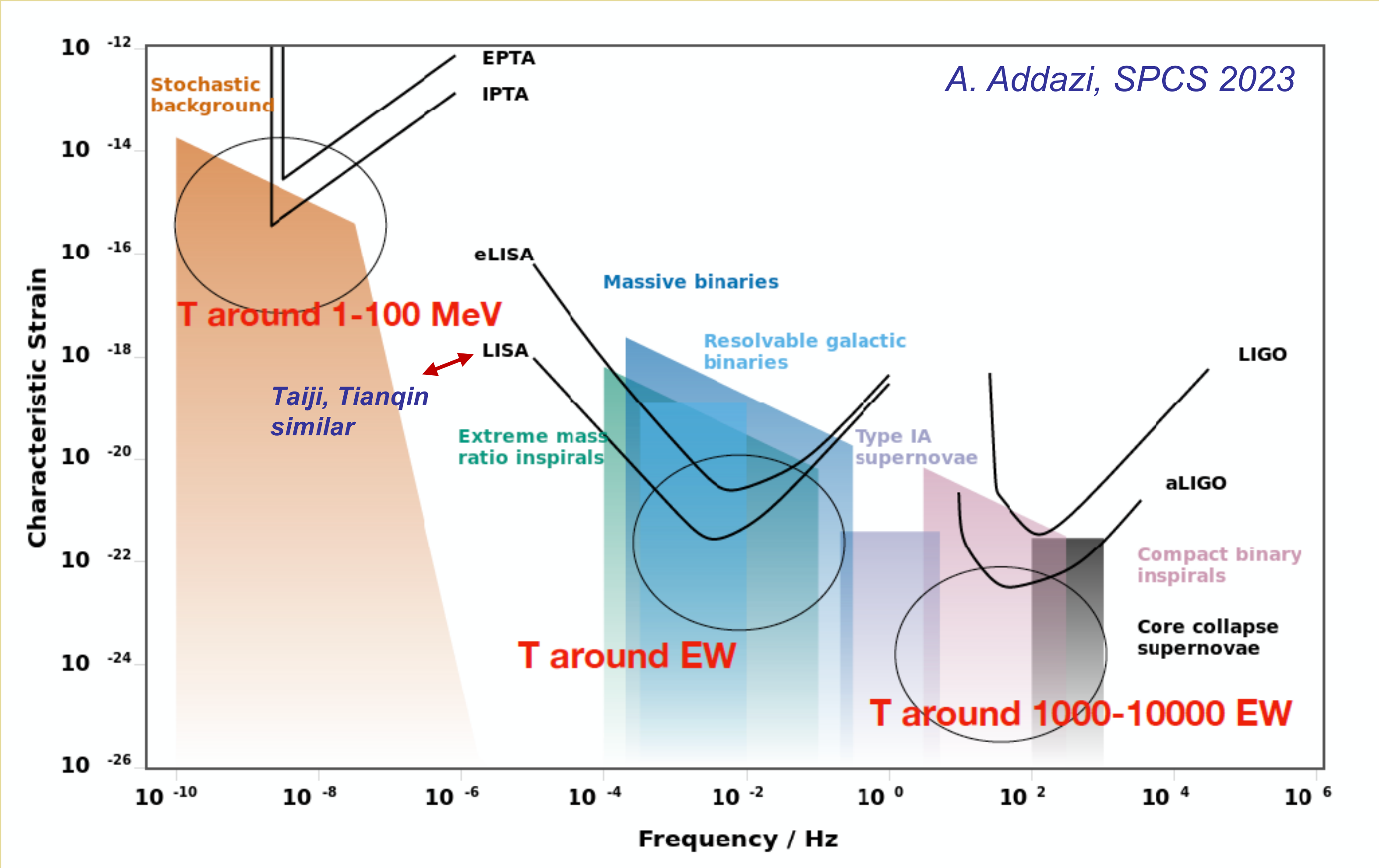
Collider target

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

BSM EWPT: Inter-frontier Connections



Gravitational Waves



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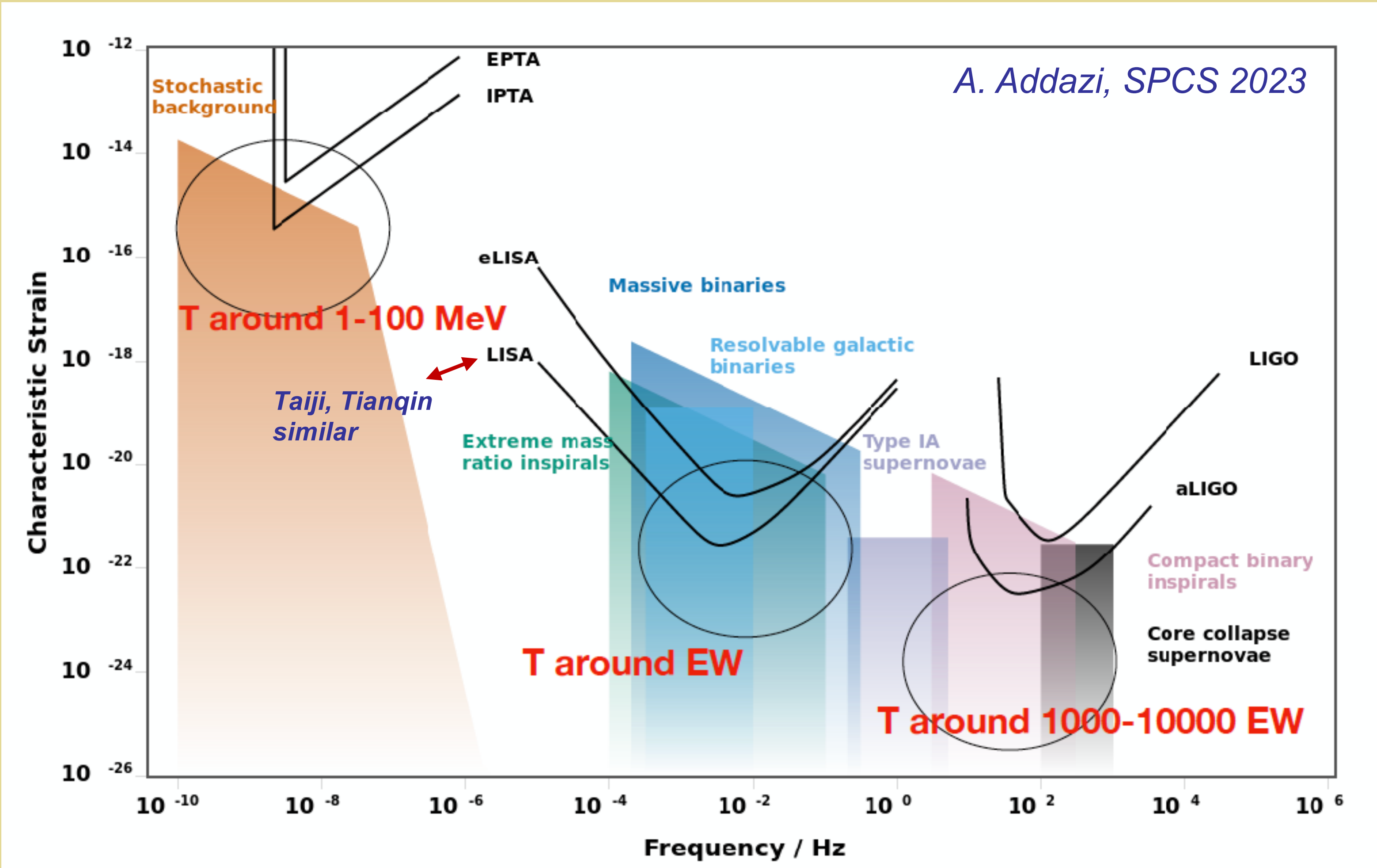
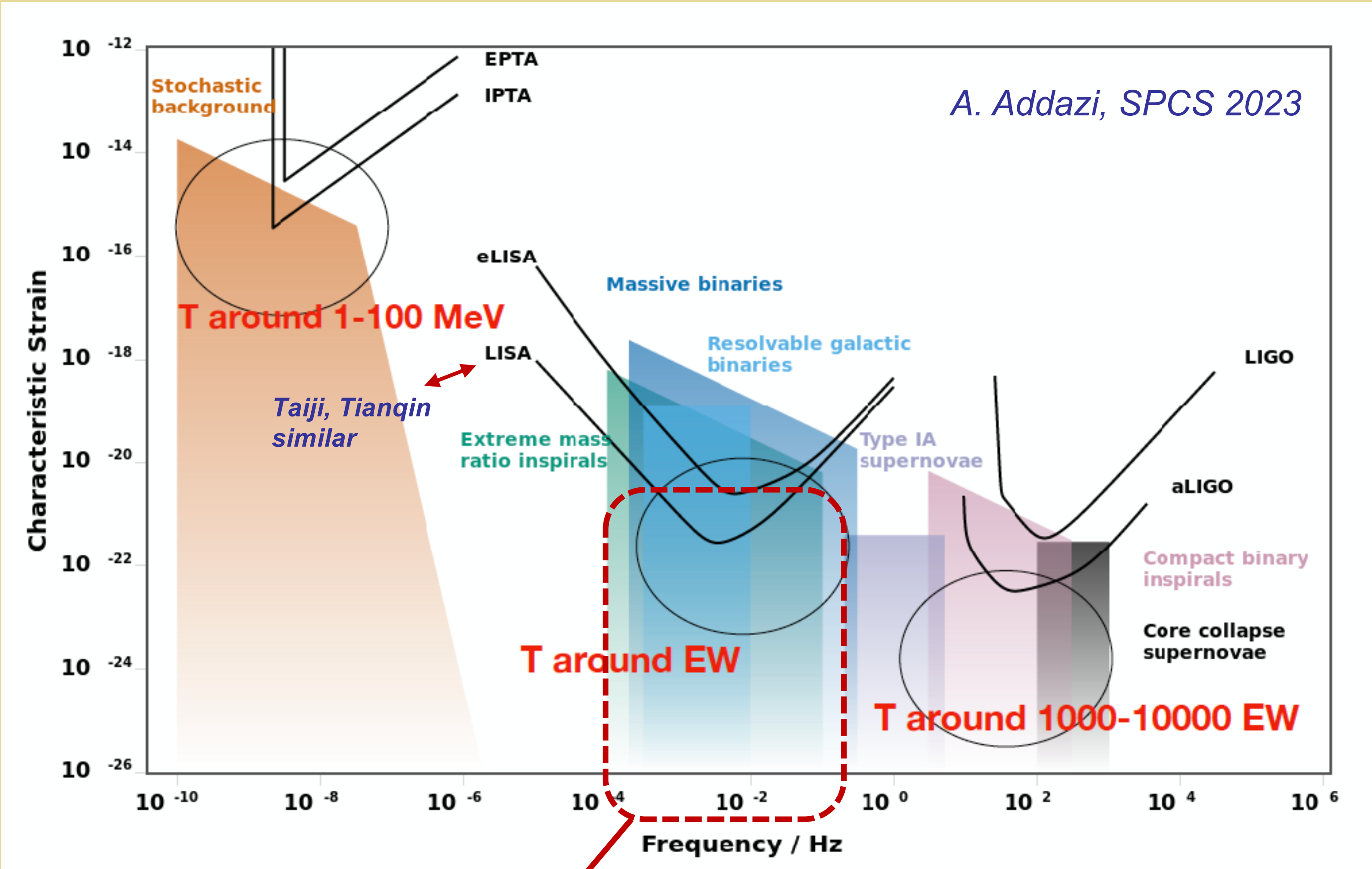


Particle physics (phase transitions, domain walls…)
→ possible GW sources at range of frequencies

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

EWPT: Theory-Pheno Interface

Theoretical developments → phenomenological implications

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...
SM + Scalar Doublet (2HDM)	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...
NMSSM...	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

Models & Phenomenology

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Models & pheno: how reliable ?

Thanks: J. M. No

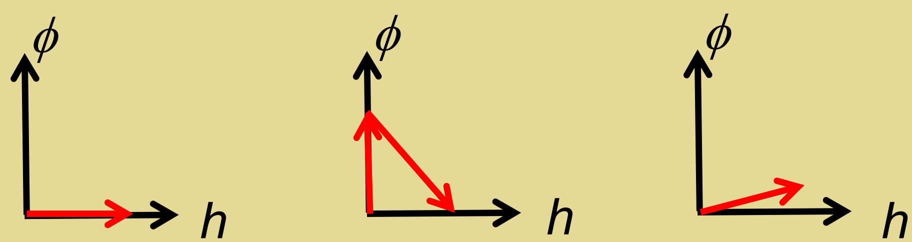
Extensive references in MJRM: 1912.07189

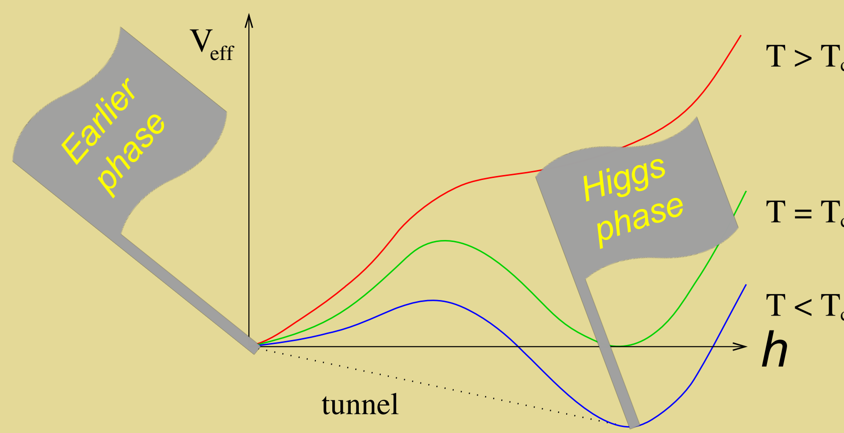
Theory-Pheno Interface

Simple Higgs portal models:

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

$$V \supset a_1 H^2 \phi + a_2 H^2 \phi^2$$





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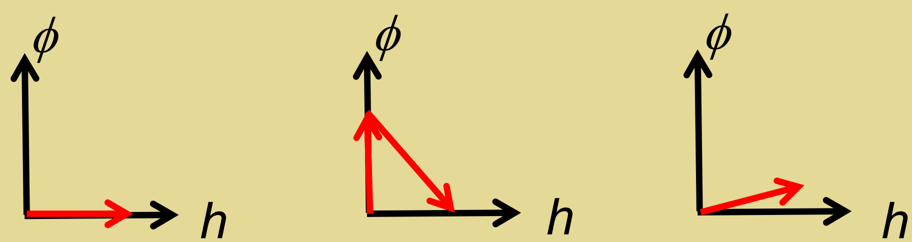

Phenomenology

$$h_1 = \sin\theta\ s + \cos\theta\ h$$
$$h_2 = \cos\theta\ s - \sin\theta\ h$$

$m_{1,2}$; θ ; $h_i\, h_j\, h_k$ couplings

Collider Probes

- *Resonant di-Higgs (h_1 h_1) production* *
- *Heavy h_2 production* *
- *Associated production (Z h_1) and non-resonant di-Higgs production* *
- *Exotic Higgs decays* **

* *Heavy h_2*

** *Light h_2*

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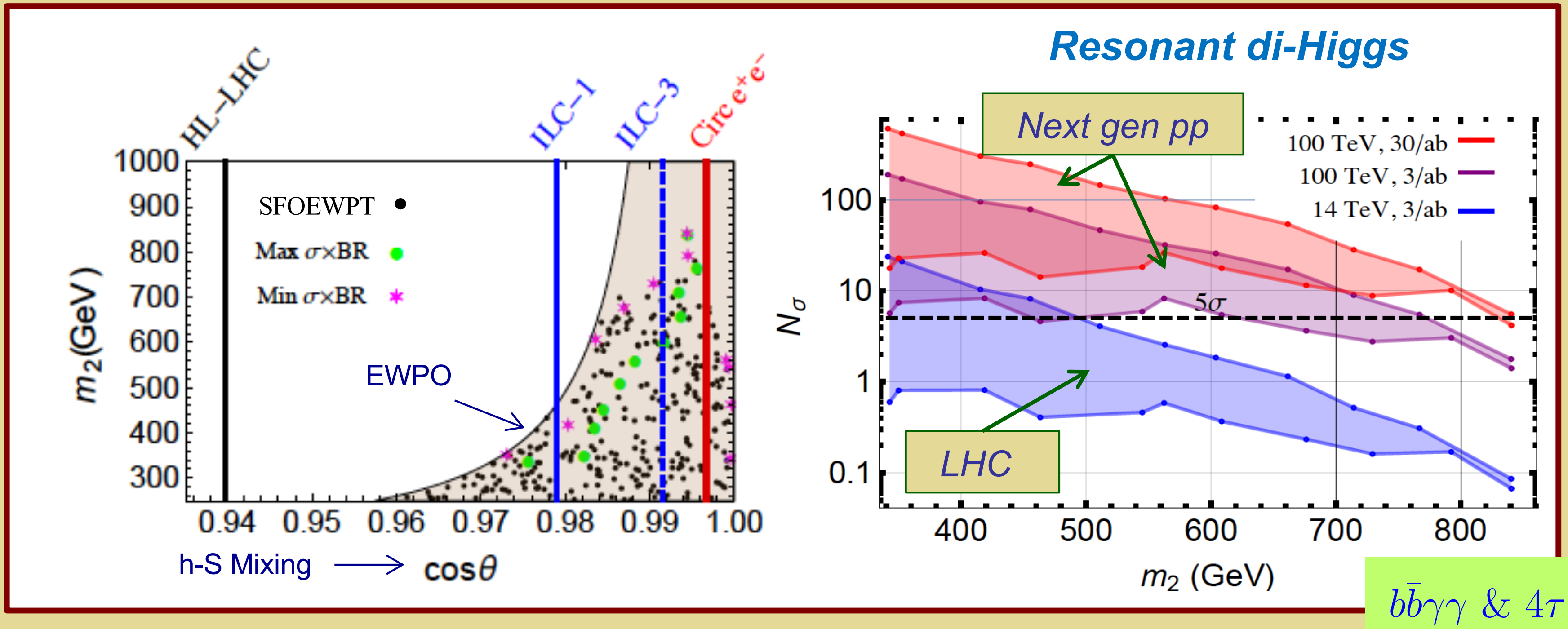
Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Kotwal, No, R-M, Winslow 1605.06123

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

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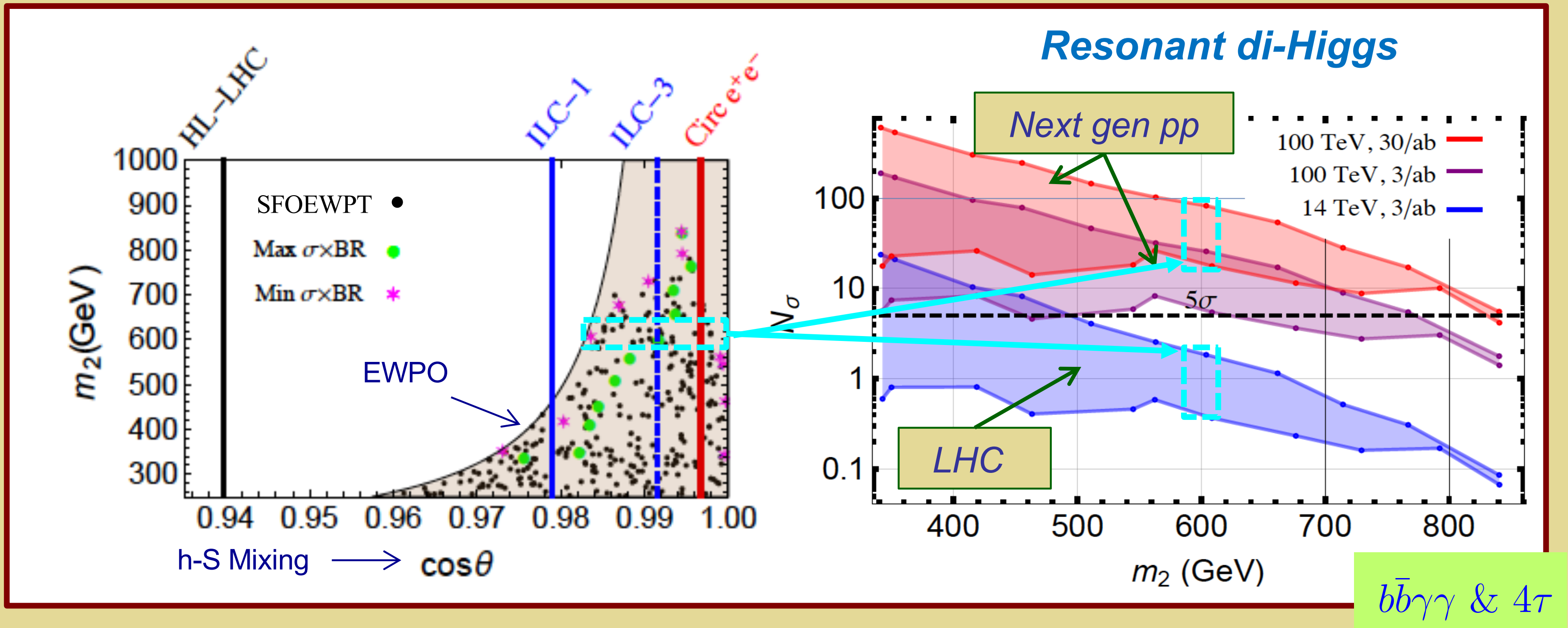

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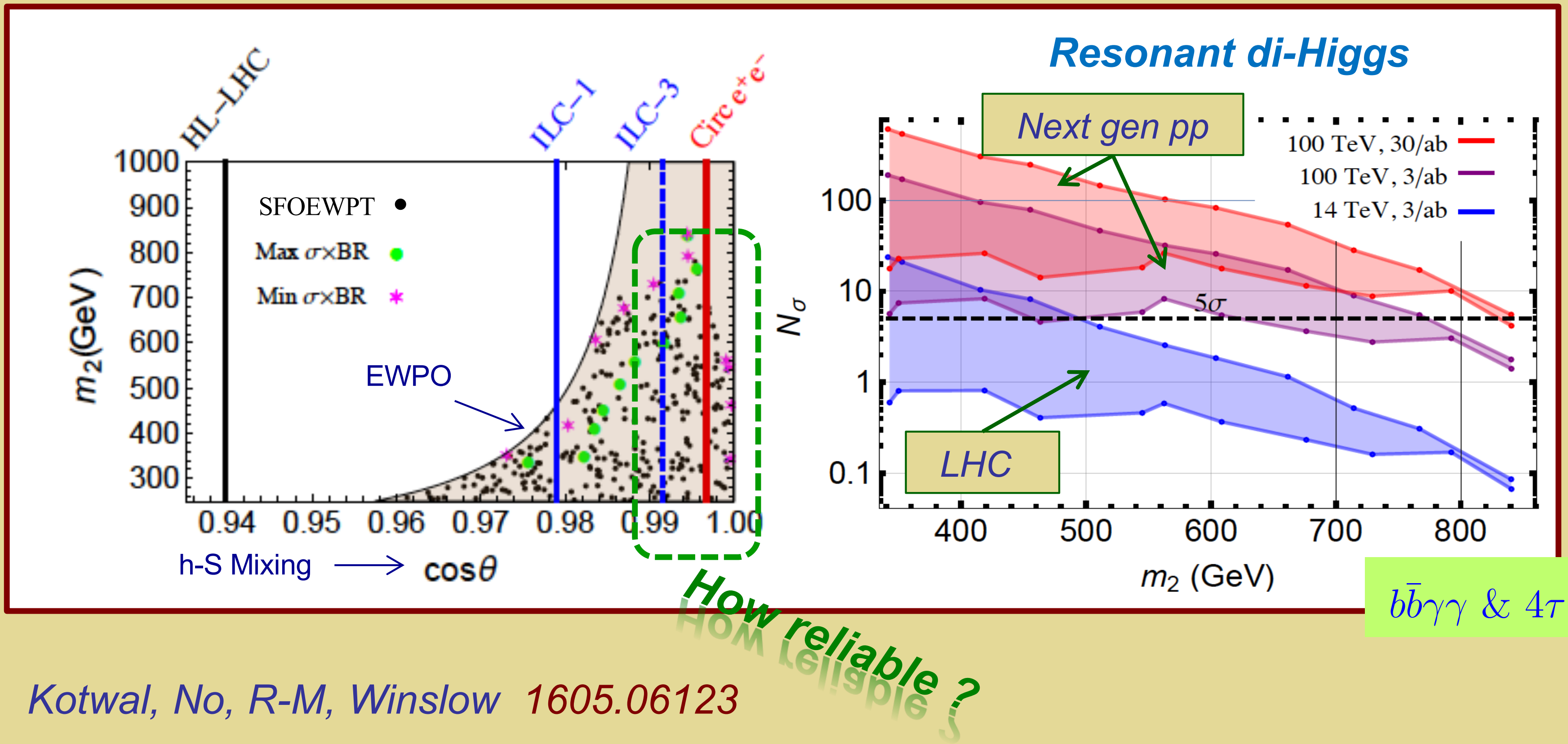

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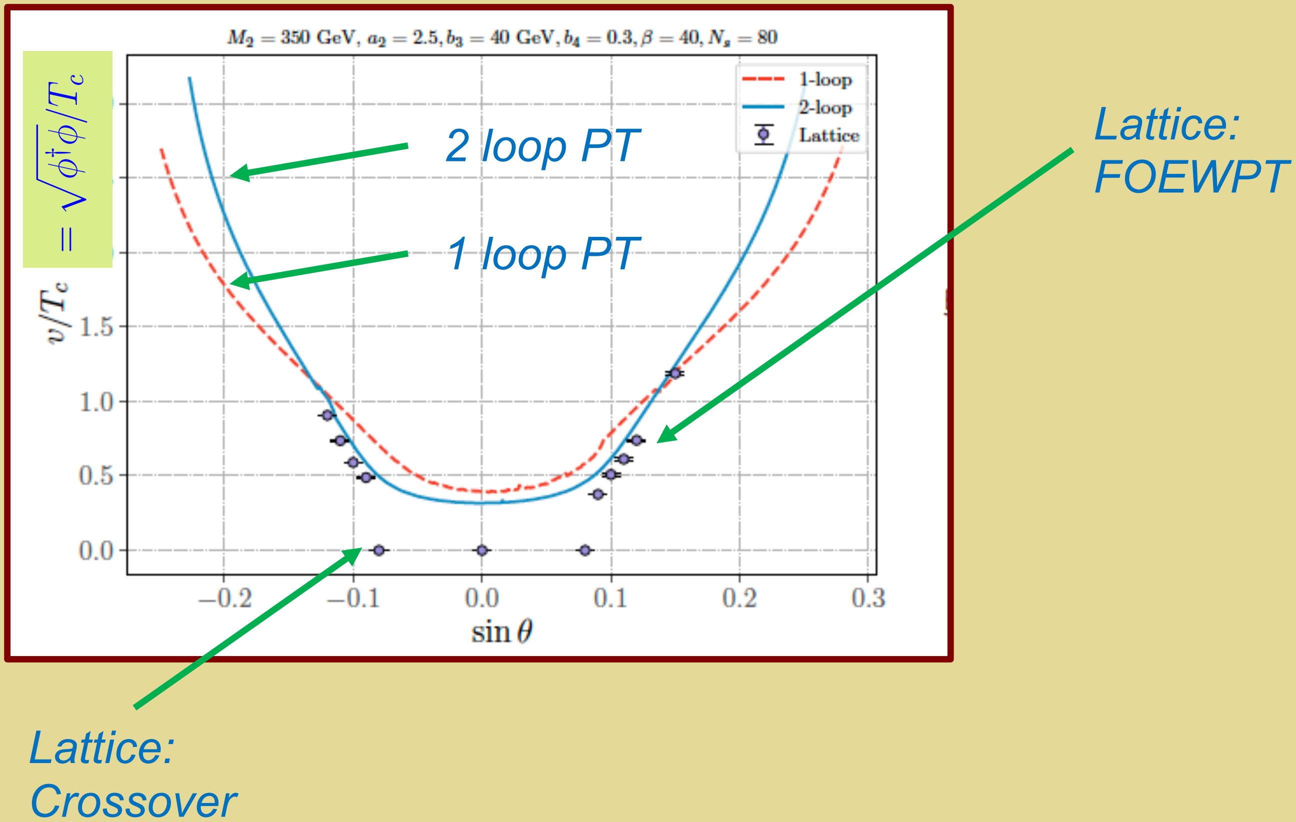
Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



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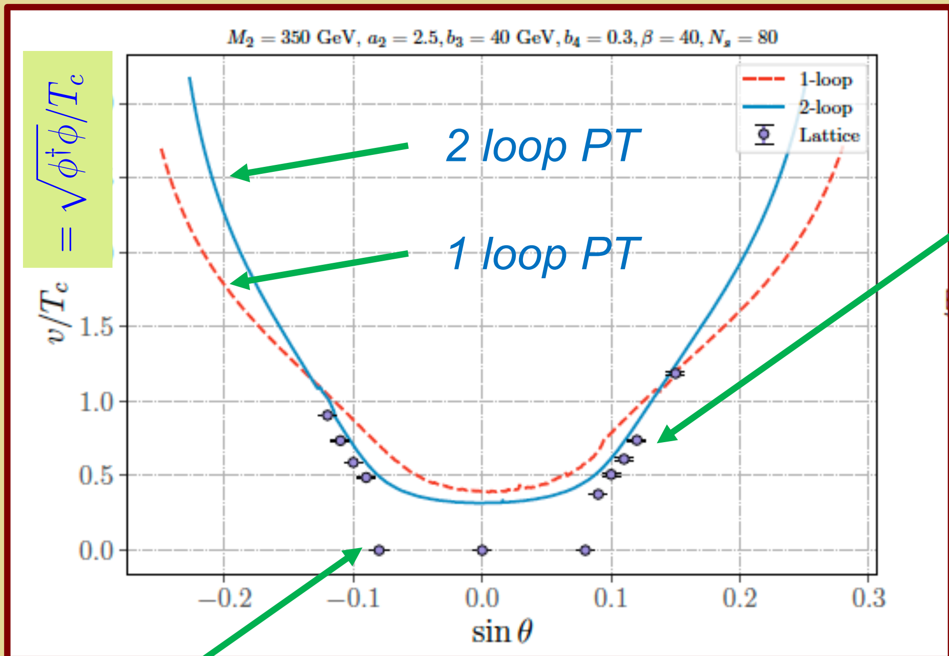
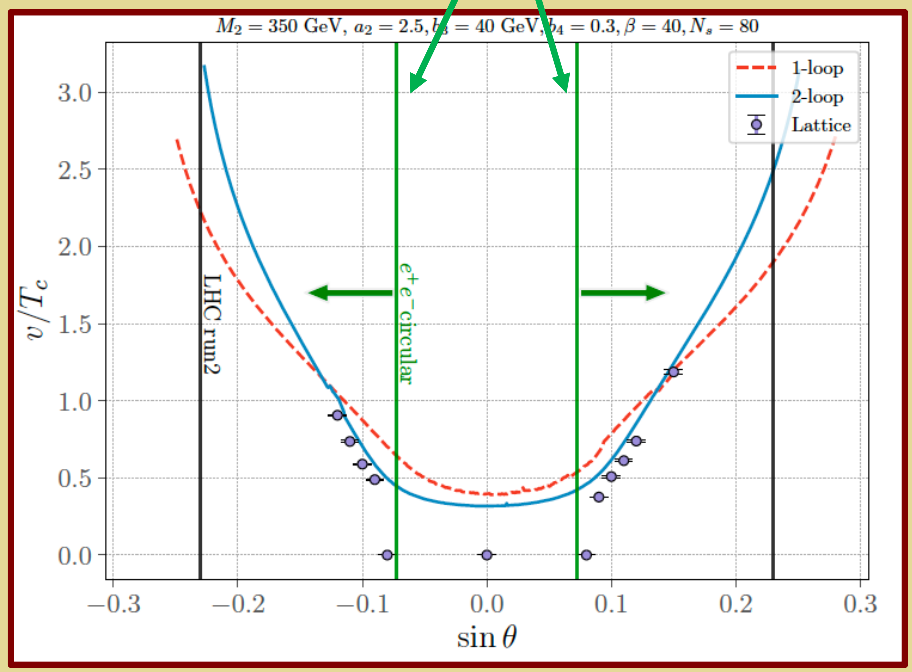


Lattice: FOEWPT

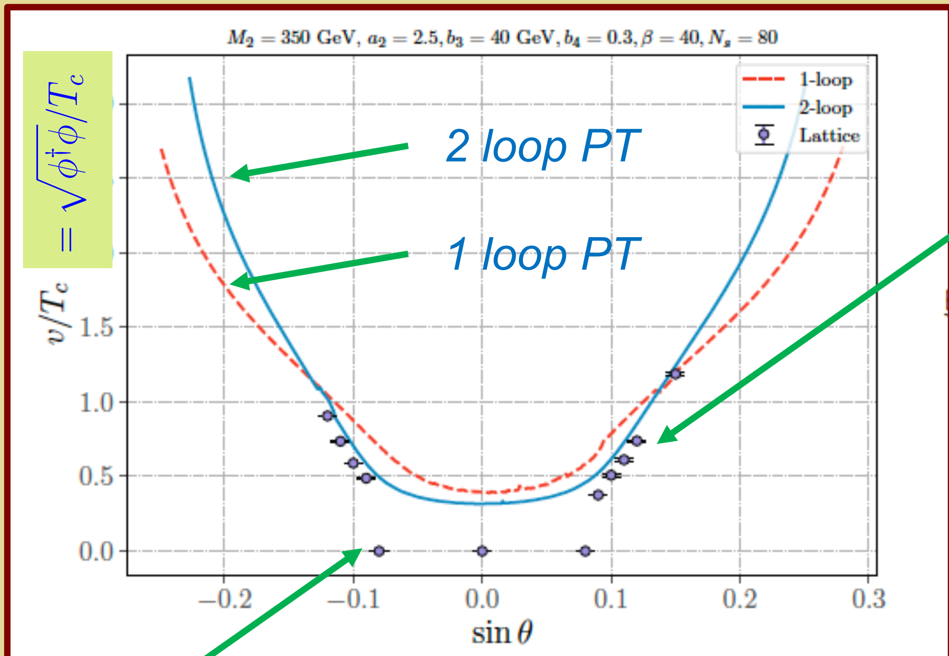
Future e^+e^-



Lattice: Crossover

Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



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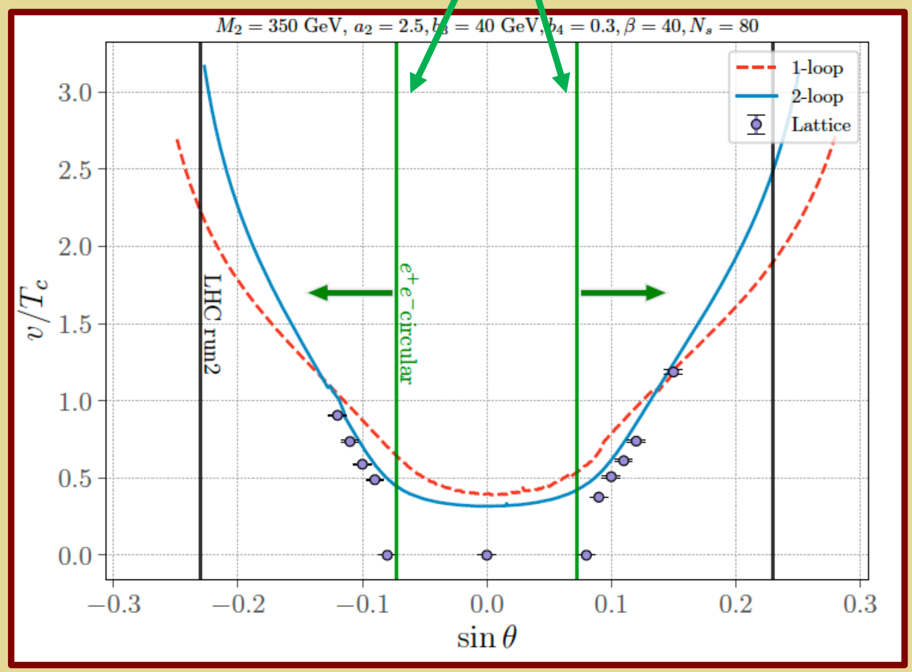

- *Lattice: crossover-FOEWPT boundary*
- *FOEWPT region: PT-lattice agreement*
- *Pheno: precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

Collider Probes

- *Resonant di-Higgs (h_1 h_1) production* *
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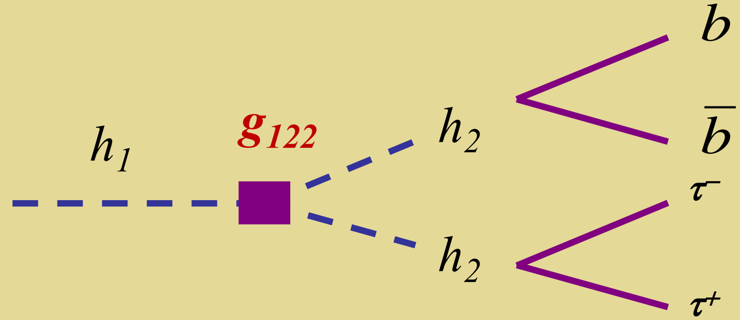
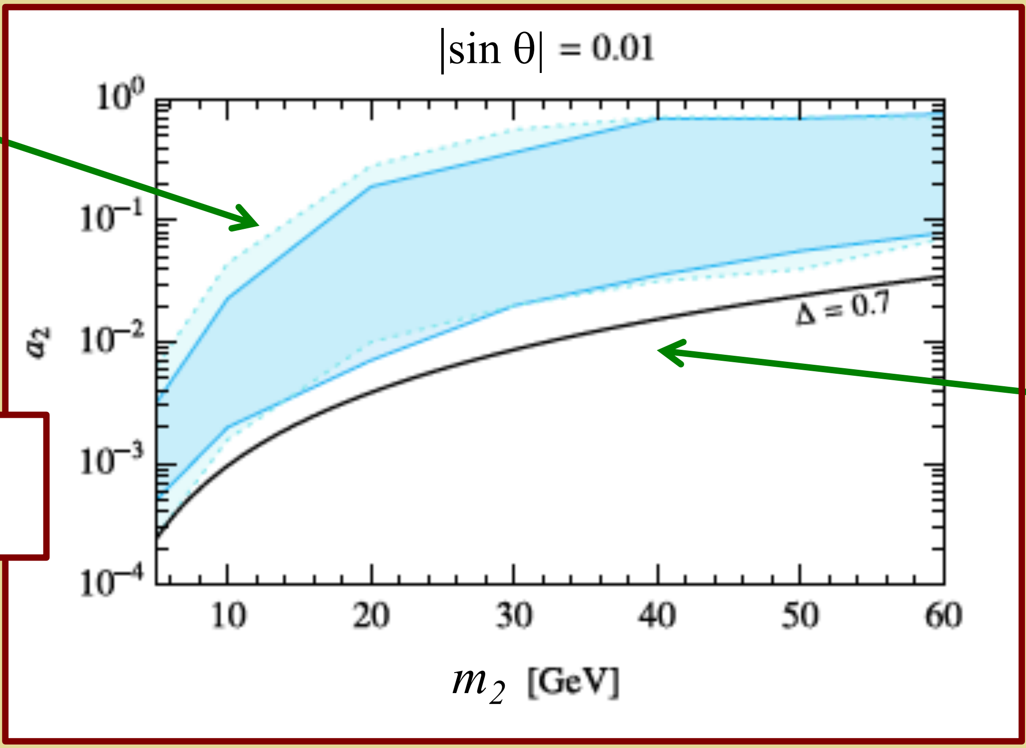


Light Singlets: Exotic Higgs Decays

One loop perturbation theory

EWPT viable: numerical



EWPT viable: Semi analytic
→ nucleation decisive

$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

$h_1 \rightarrow h_2 h_2$

J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206, Carena et al 2203.08206, Wang et al 2203.10184

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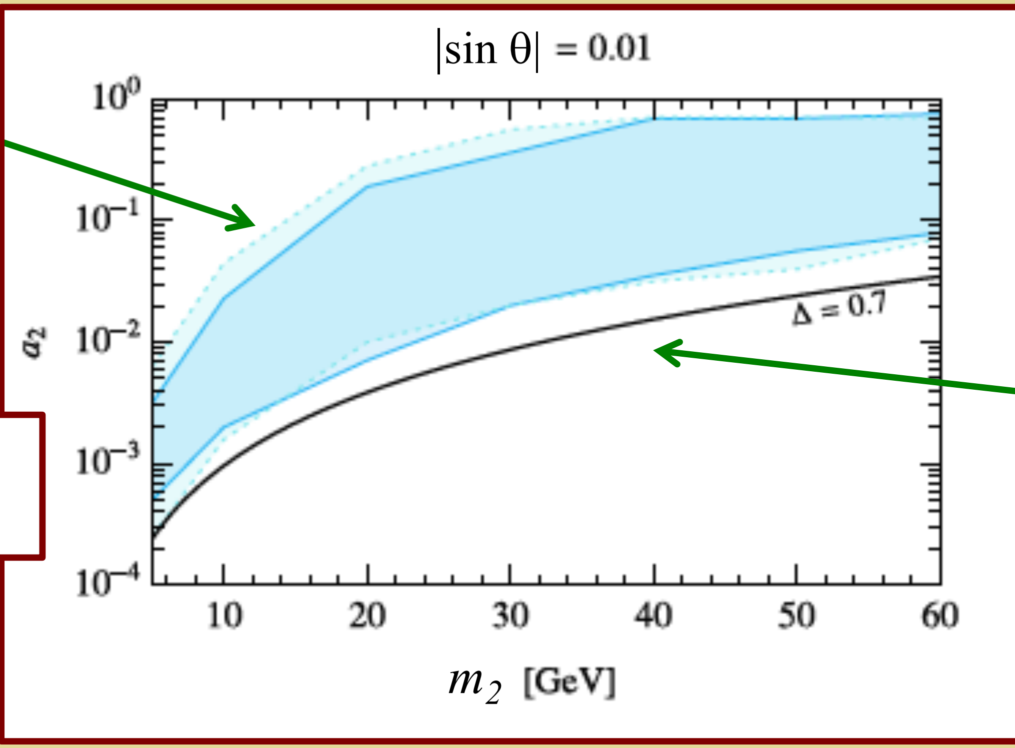

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$$\Gamma(h_2, m_2) = \sin^2\theta \, \Gamma(h_{SM}, m_2)$$

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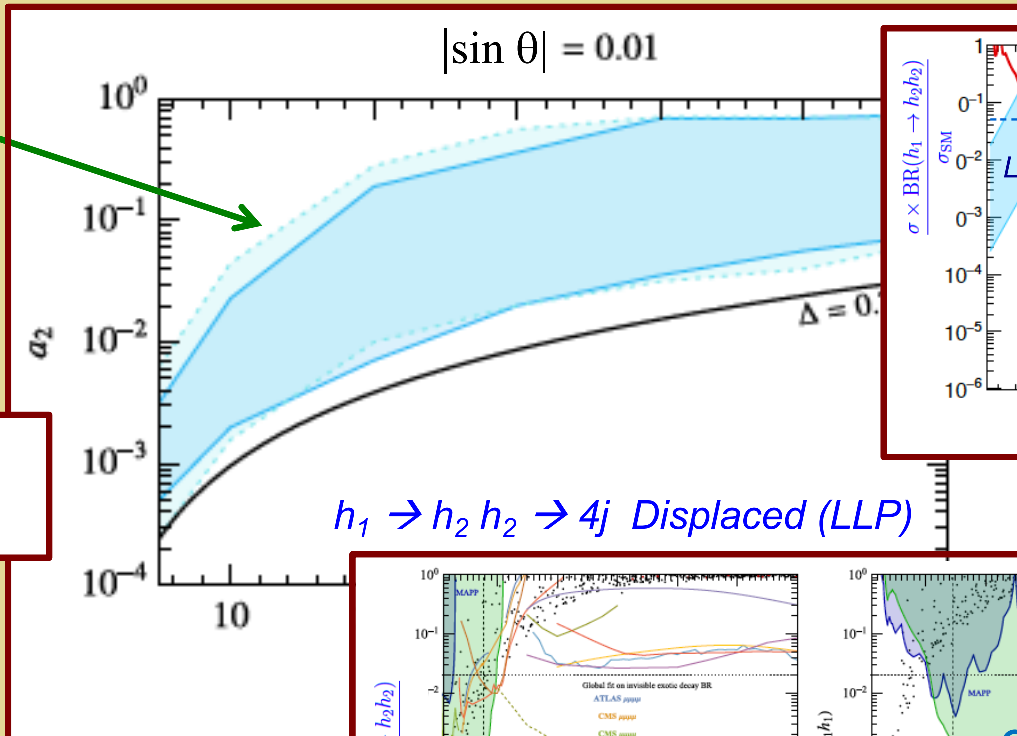
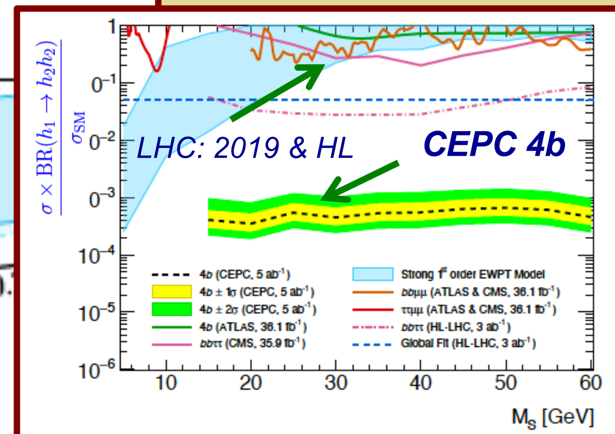


$h_1 \rightarrow h_2\, h_2 \rightarrow 4b$ (prompt)



J. Wang et al (Snowmass) 2203.10184

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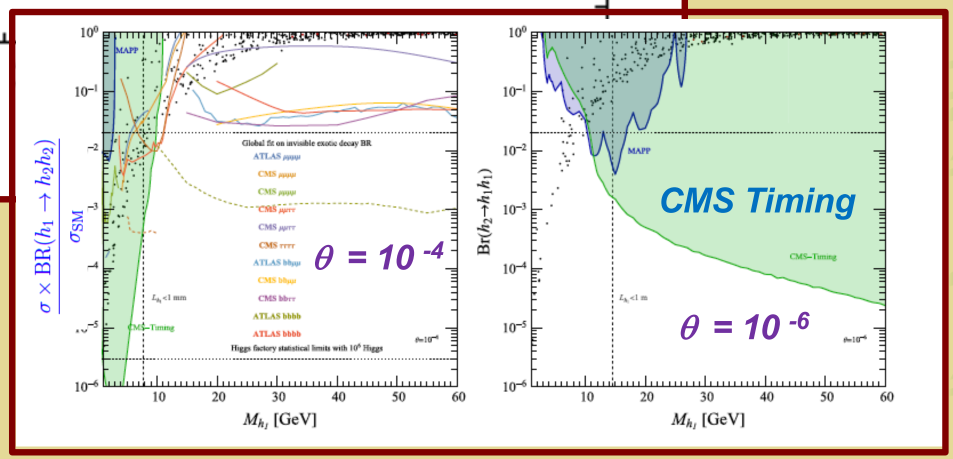
$h_1 \rightarrow h_2\, h_2 \rightarrow 4j$ Displaced (LLP)



Lifetime frontier

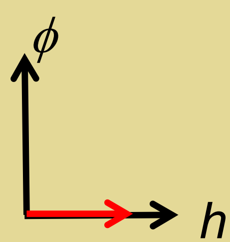
W. Liu, A. Yang, H. Sun, PRD 105 (2022) 115040

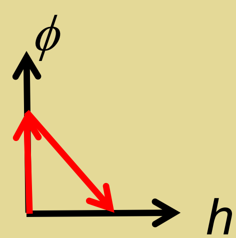
Theory-Pheno Interface

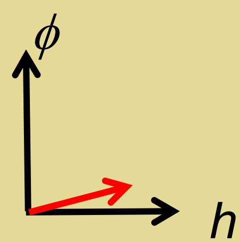
Simple Higgs portal models:

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

$$V \supset a_1 H^2\phi + a_2 H^2\phi^2$$







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Small

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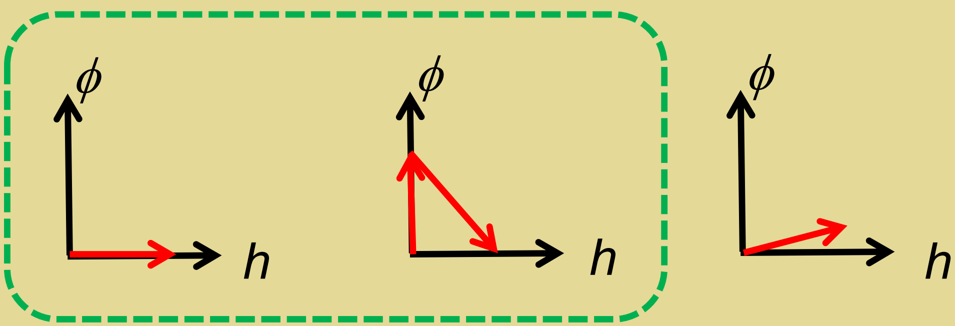

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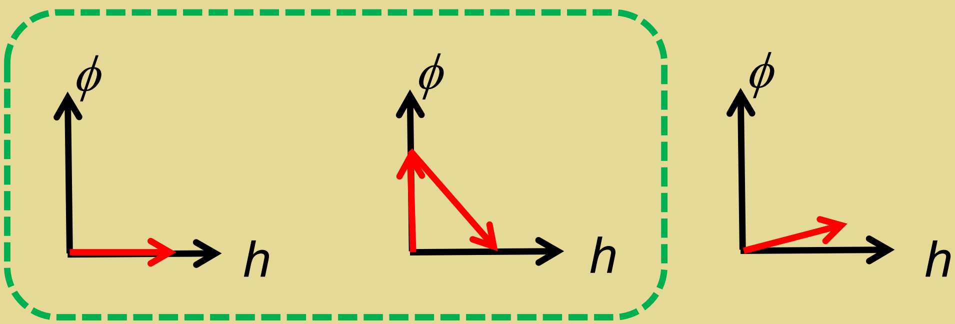
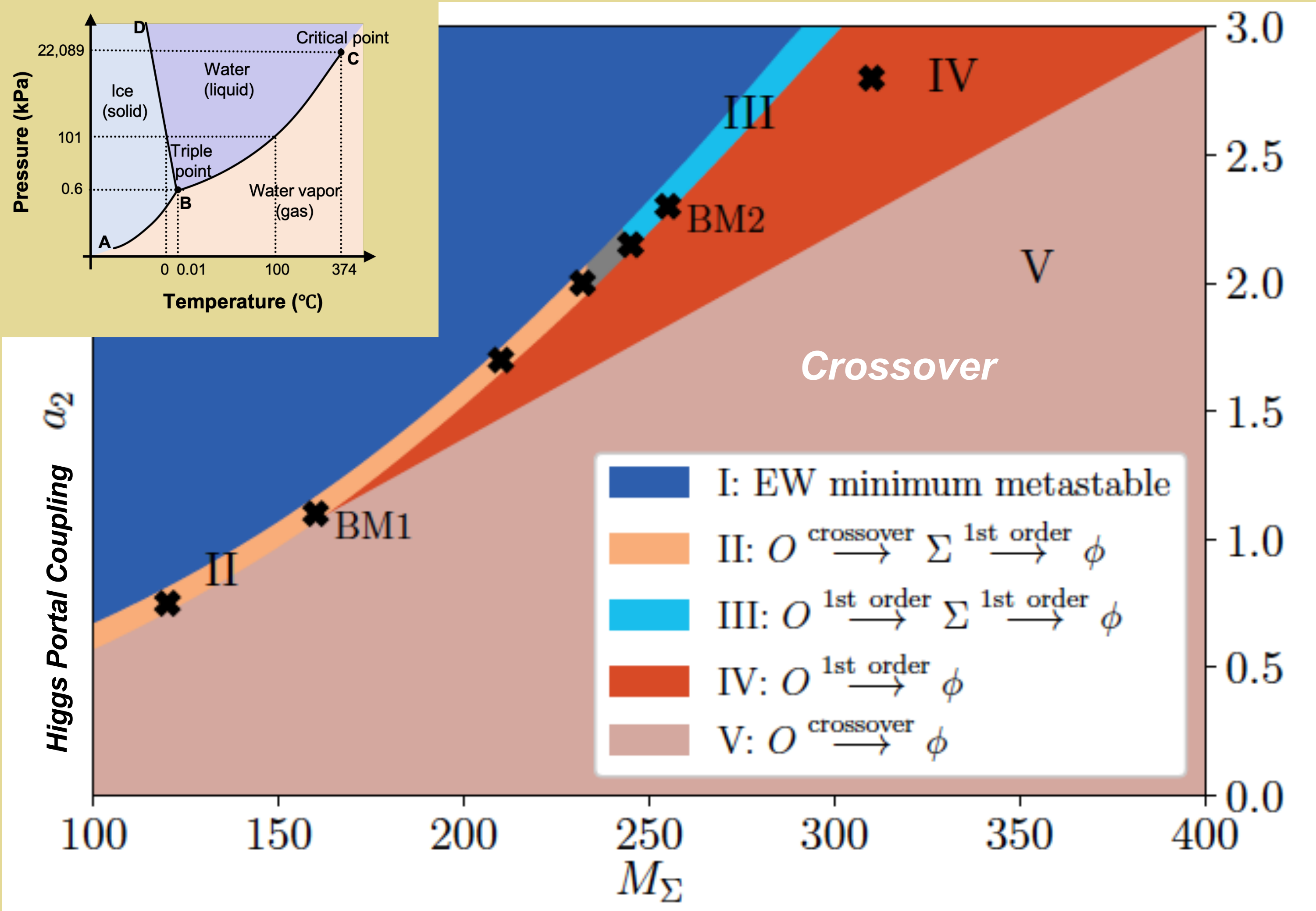


Phenomenology

- *Gravitational waves*
- *Collider: $h \to \gamma\gamma$, dis charged track, NLO $e^+e^- \to Zh$…*

Real Triplet & EWPT: Novel EWSB



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

Niemi, R-M, Tenkanen, Weir 2005.11332

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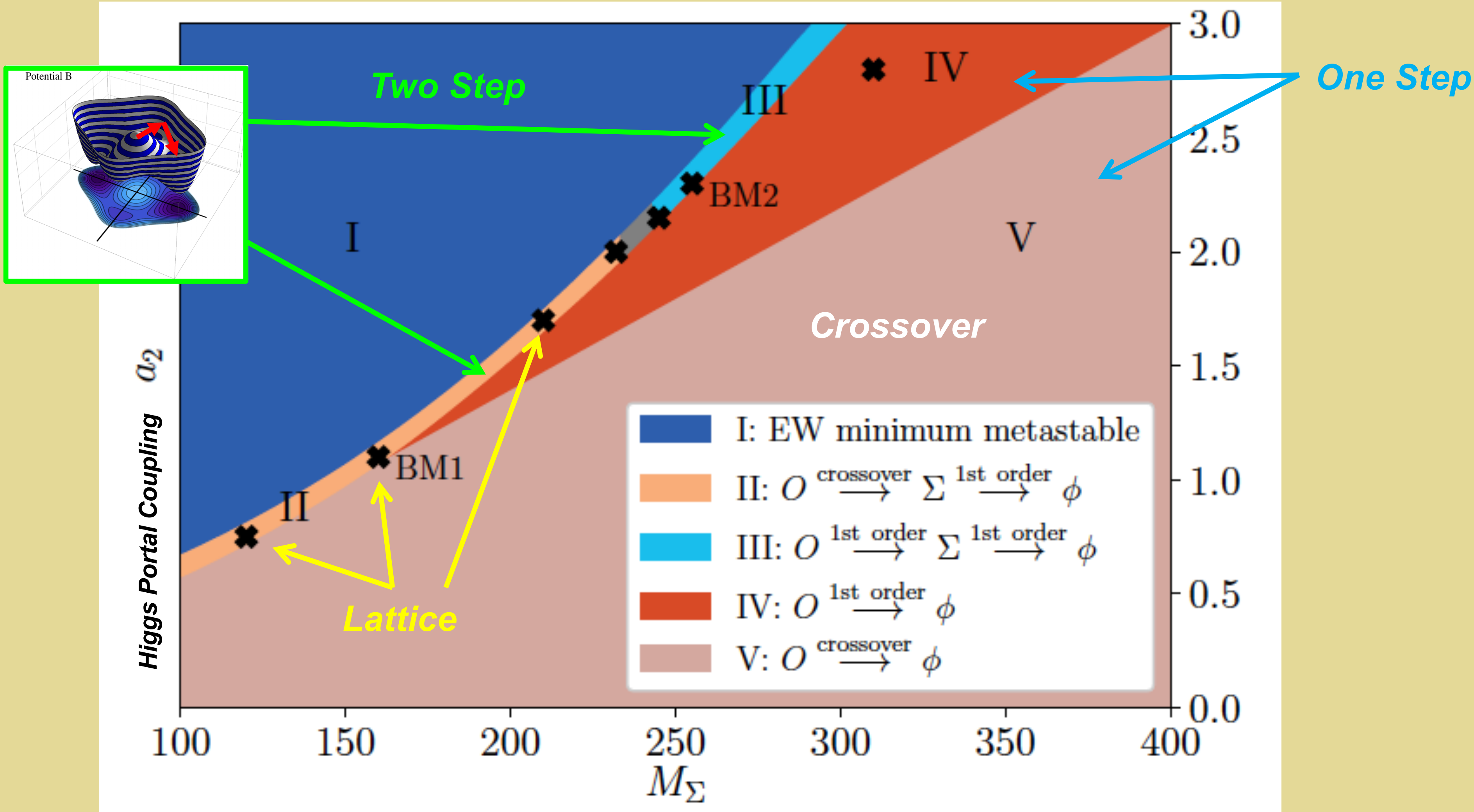

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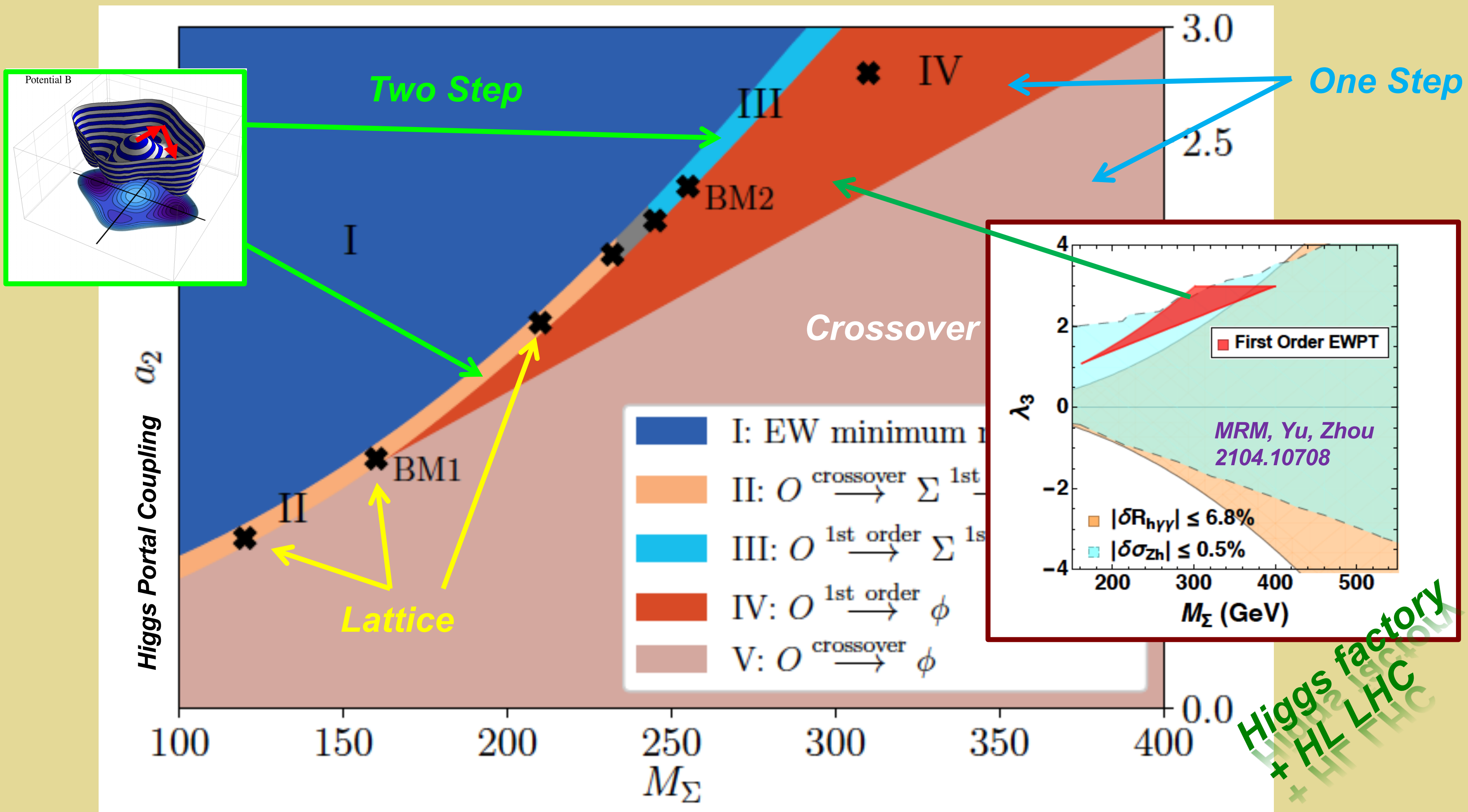

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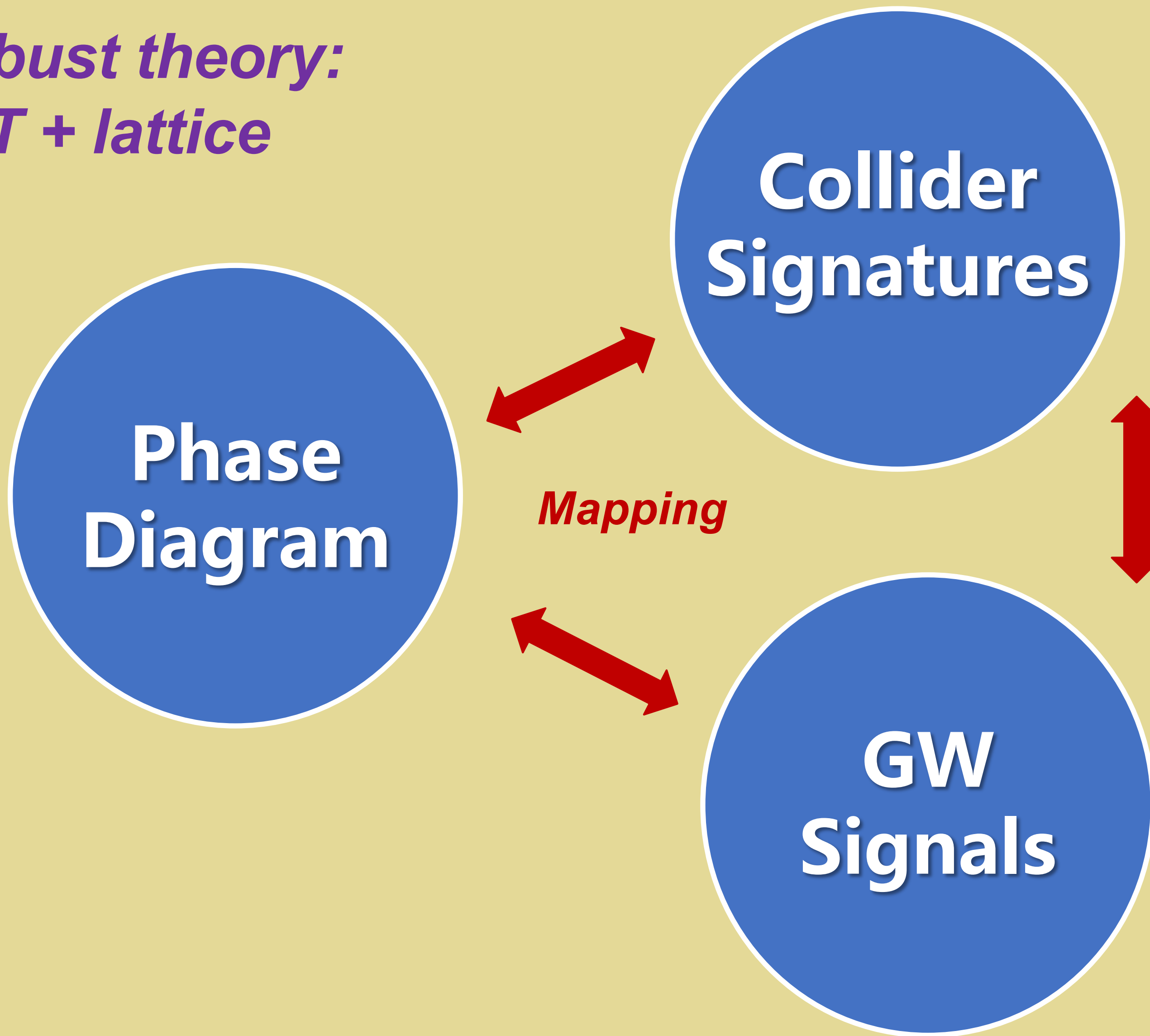
Niemi, R-M, Tenkanen, Weir 2005.11332

BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

Observables:
model specific



Combined reach

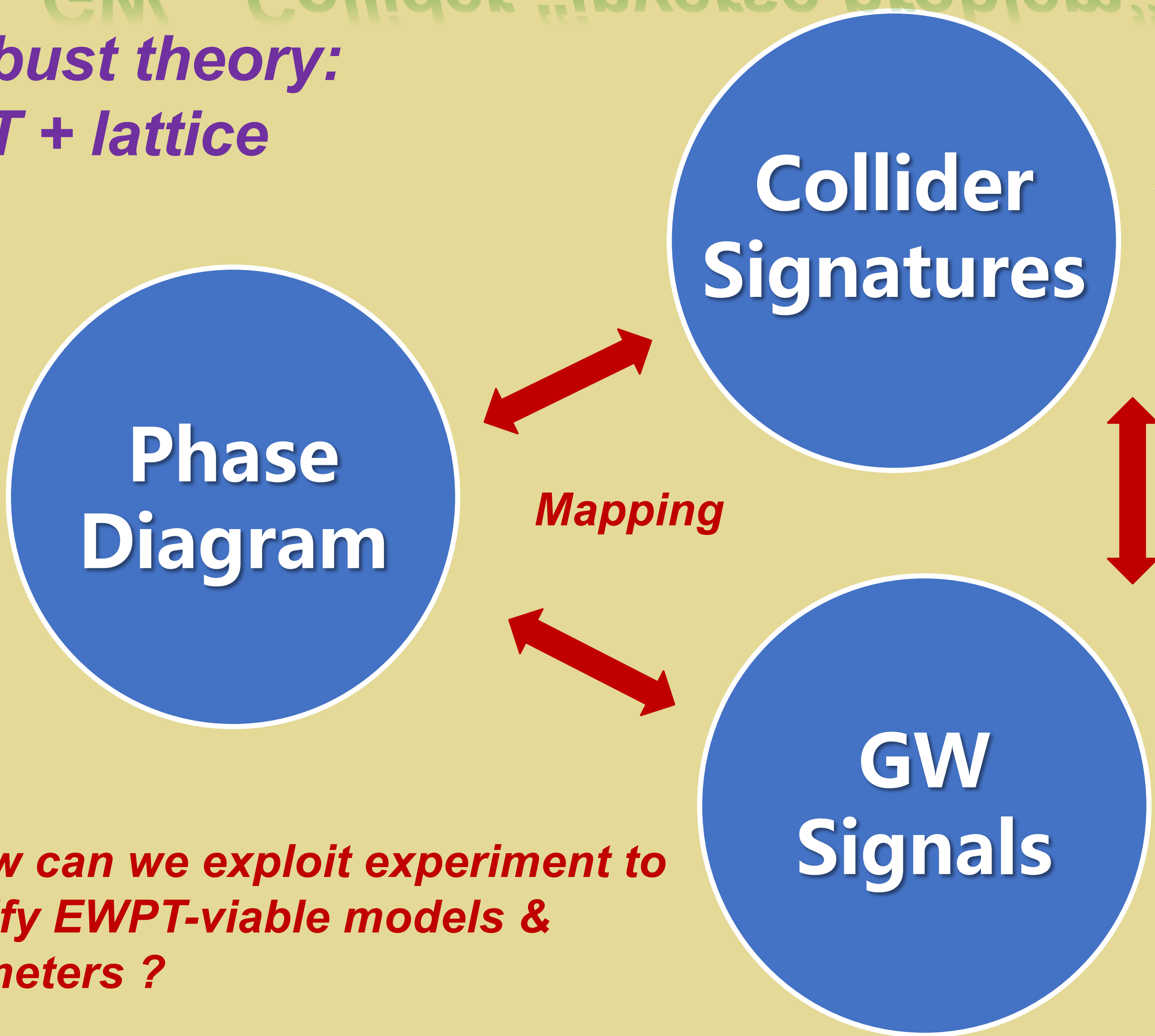
Hydro:
α , β / H_*

BSM EWPT: Inter-frontier Connections

GW – Collider "inverse problem" **

Robust theory:
EFT + lattice

Observables:
model specific

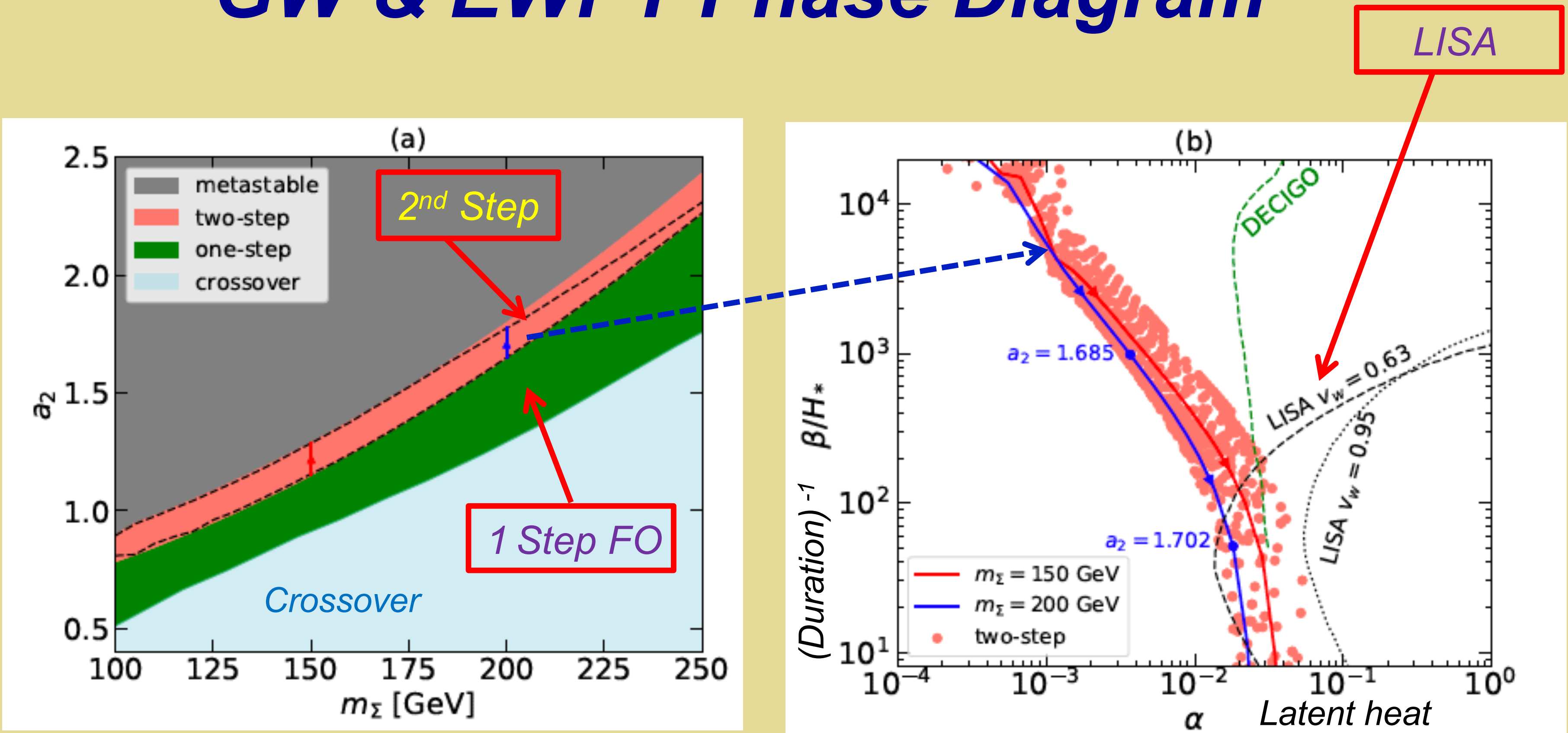


Combined reach

Hydro:
α , β / H_*

*** How can we exploit experiment to identify EWPT-viable models & parameters ?*

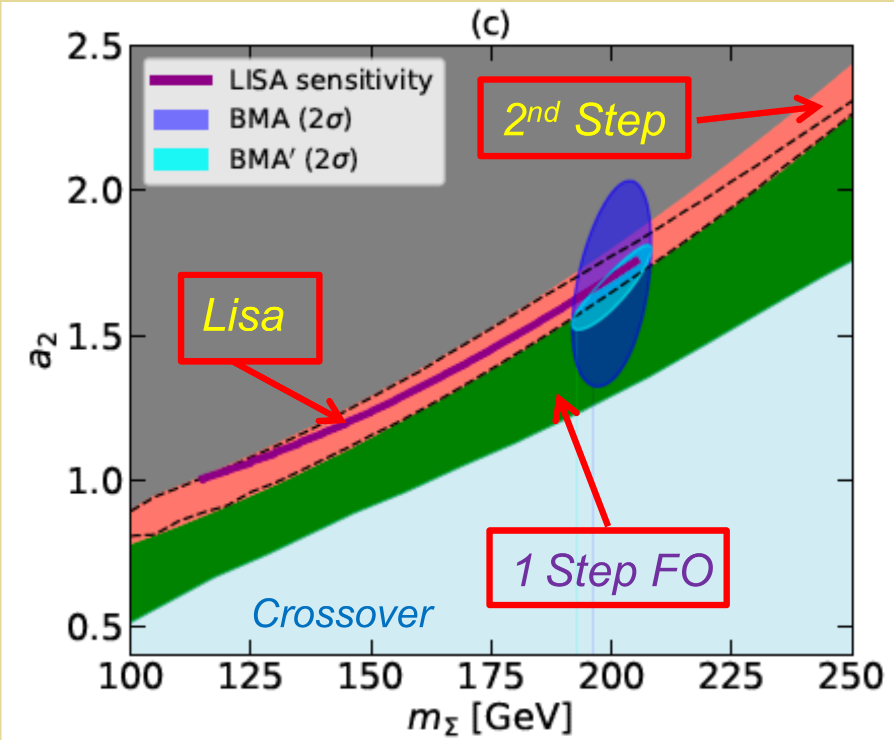
GW & EWPT Phase Diagram

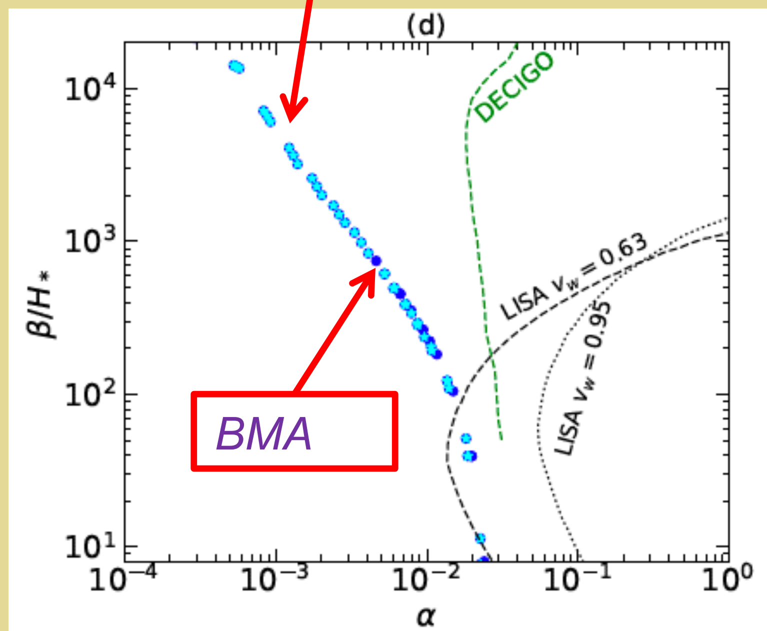


- *Single step transition: GW well outside LISA sensitivity*
- *Second step of 2-step transition can be observable*
- *Significant GW sensitivity to portal coupling*

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





BMA: m_Σ + h→ $\gamma\gamma$

BMA' : BMA + Σ^0→ ZZ

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

Friedrich, MJRM, Tenkanen, Tran 2203.05889

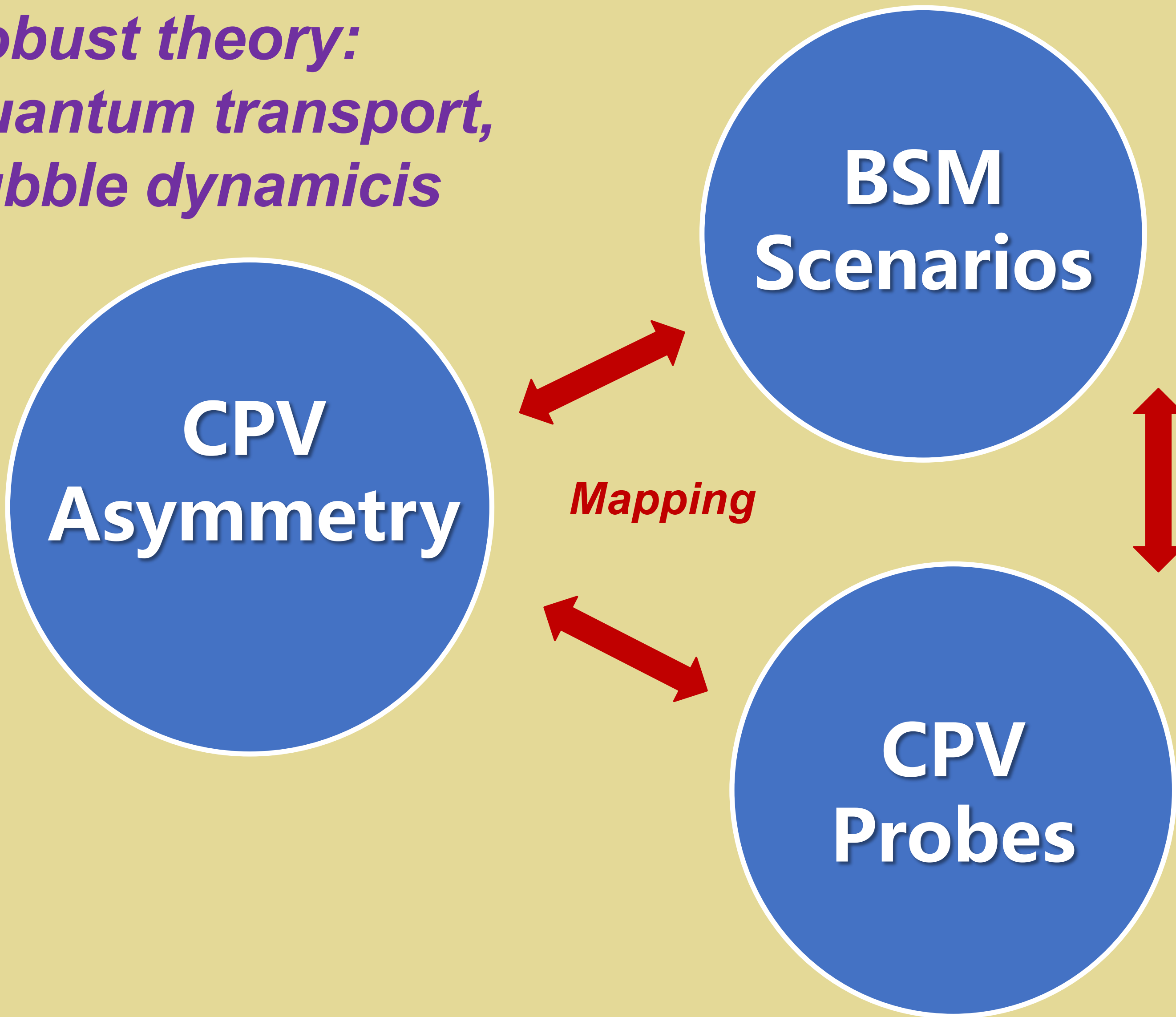
EWBG Ingredients

- *EW Sphalerons* ✓
- *Strong 1st Order EW Phase Transition* → **BSM Higgs**
- *Left-handed number density* → **BSM CPV**

BSM CPV: Inter-frontier Connections

Robust theory: Quantum transport, bubble dynamicis

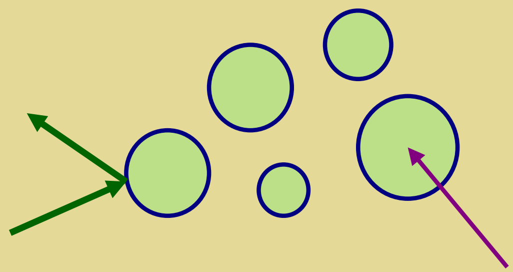
Models, other pheno…



EDM, heavy flavor…

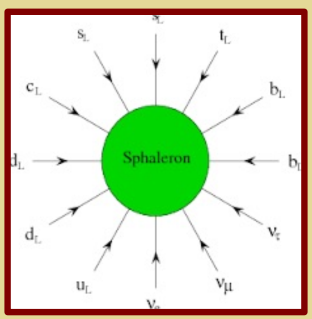
CPV for EWBG

1st order EWPT

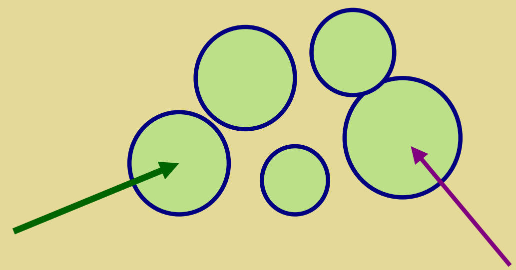


Y_B : CPV &
EW sphalerons

EWSB



1st order EWPT →
"strong" to preserve Y_B

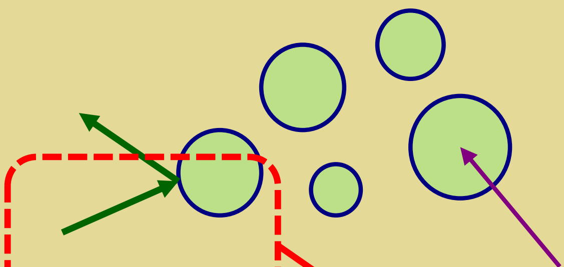


Y_B : diffuses
into interiors

EWSB

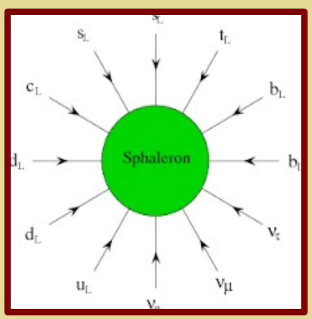
CPV for EWBG

1st order EWPT



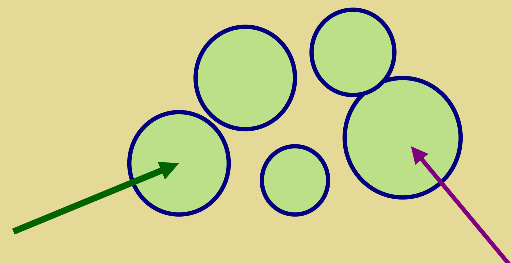
Y_B : CPV & EW sphalerons

EWSB



- *Electric dipole moments*
- *Heavy flavor CPV*
- *Higgs CPV*

1st order EWPT →
"strong" to preserve Y_B



Y_B : diffuses into interiors

EWSB

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^{-30}
n	1.8×10^{-26}	10^{-31}	10^{-26}

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

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

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Challenge for nuc & AMO

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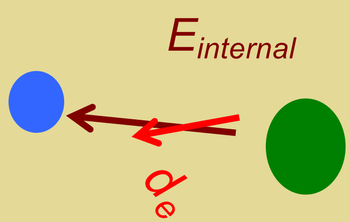
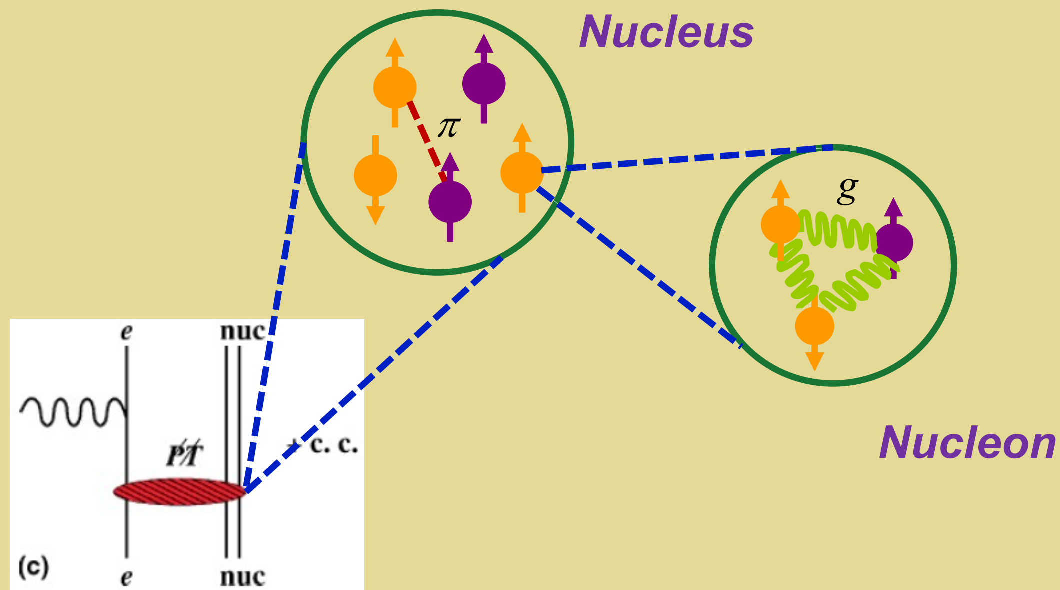


Polar molecules: paramagnetic



Diamagnetic atom

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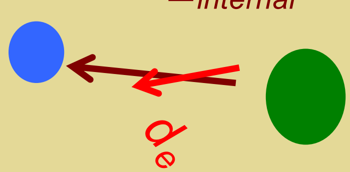
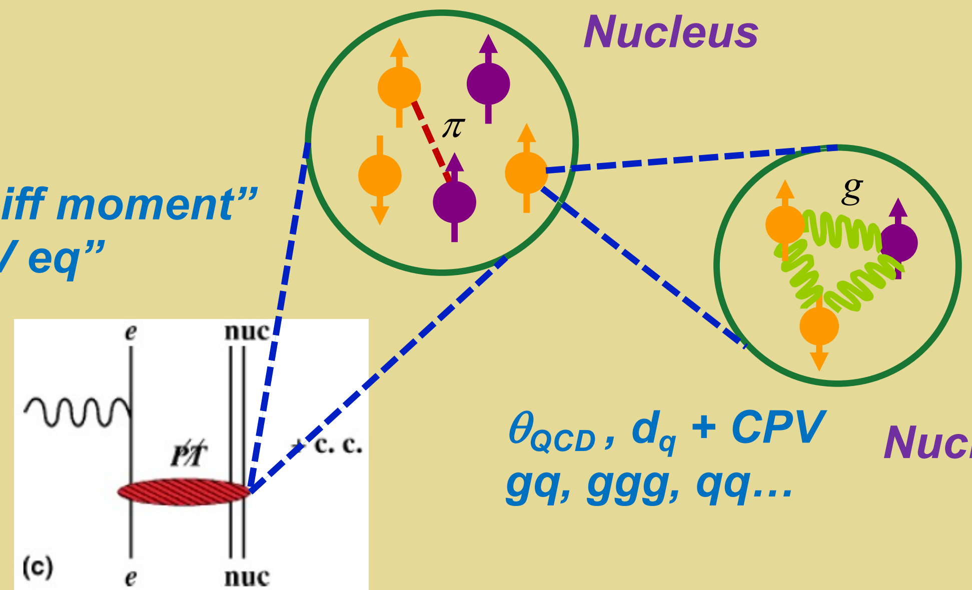


Polar molecules: paramagnetic

d_e + CPV eq

"Schiff moment" + CPV eq"



θ_{QCD} , d_q + CPV gq, ggg, qq…

Nucleon

Diamagnetic atom

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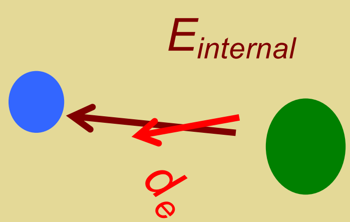
THEORY



Polar molecules: paramagnetic

d_e + CPV eq

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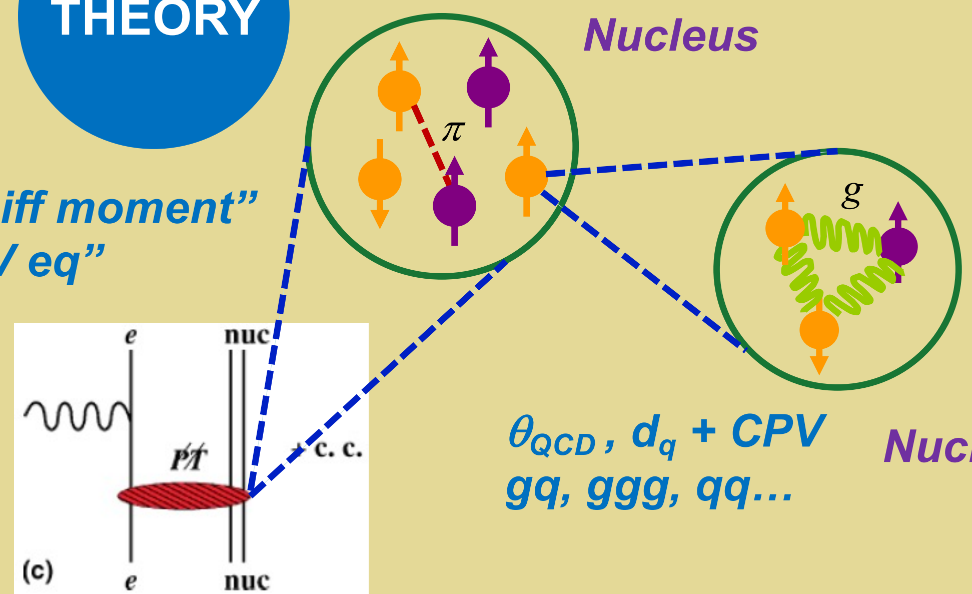
Nucleus



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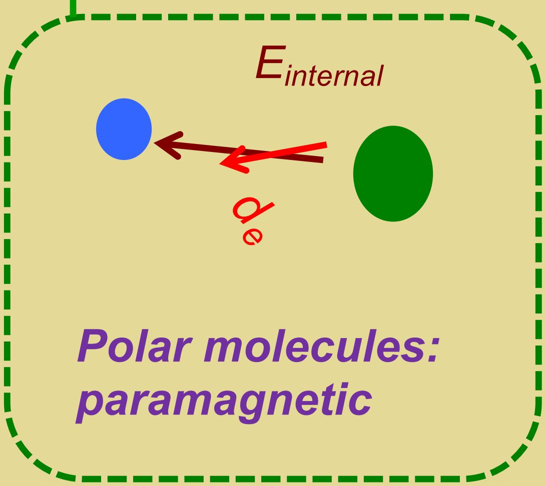
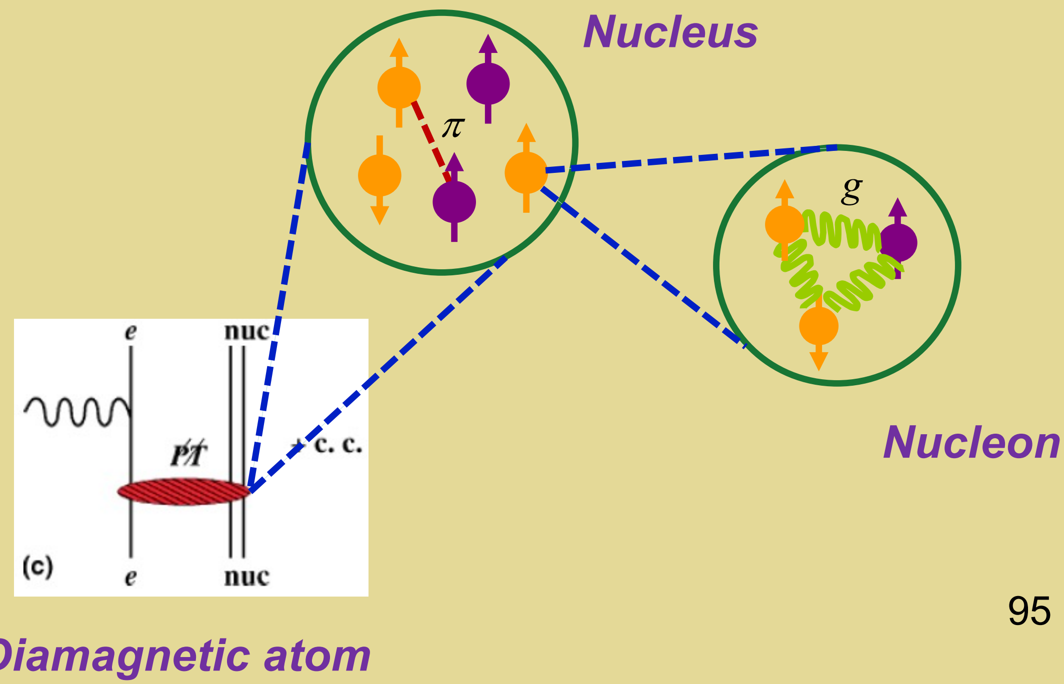
AMO





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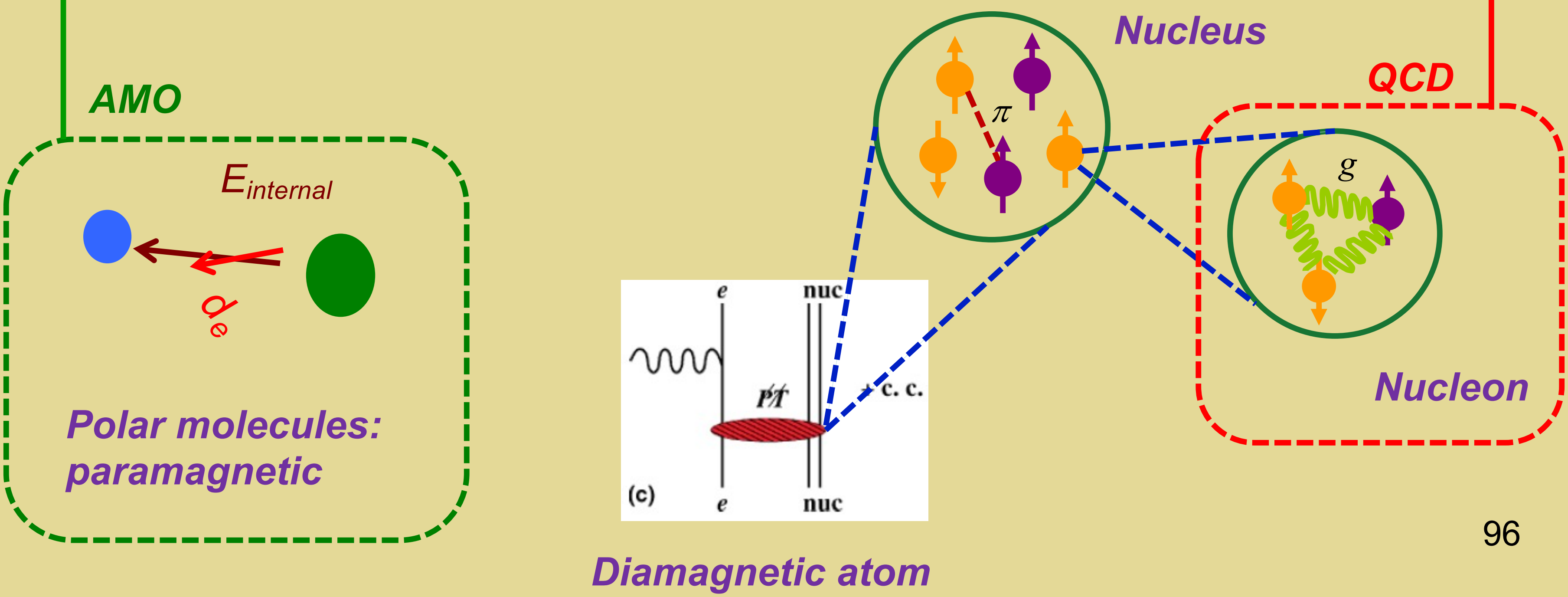

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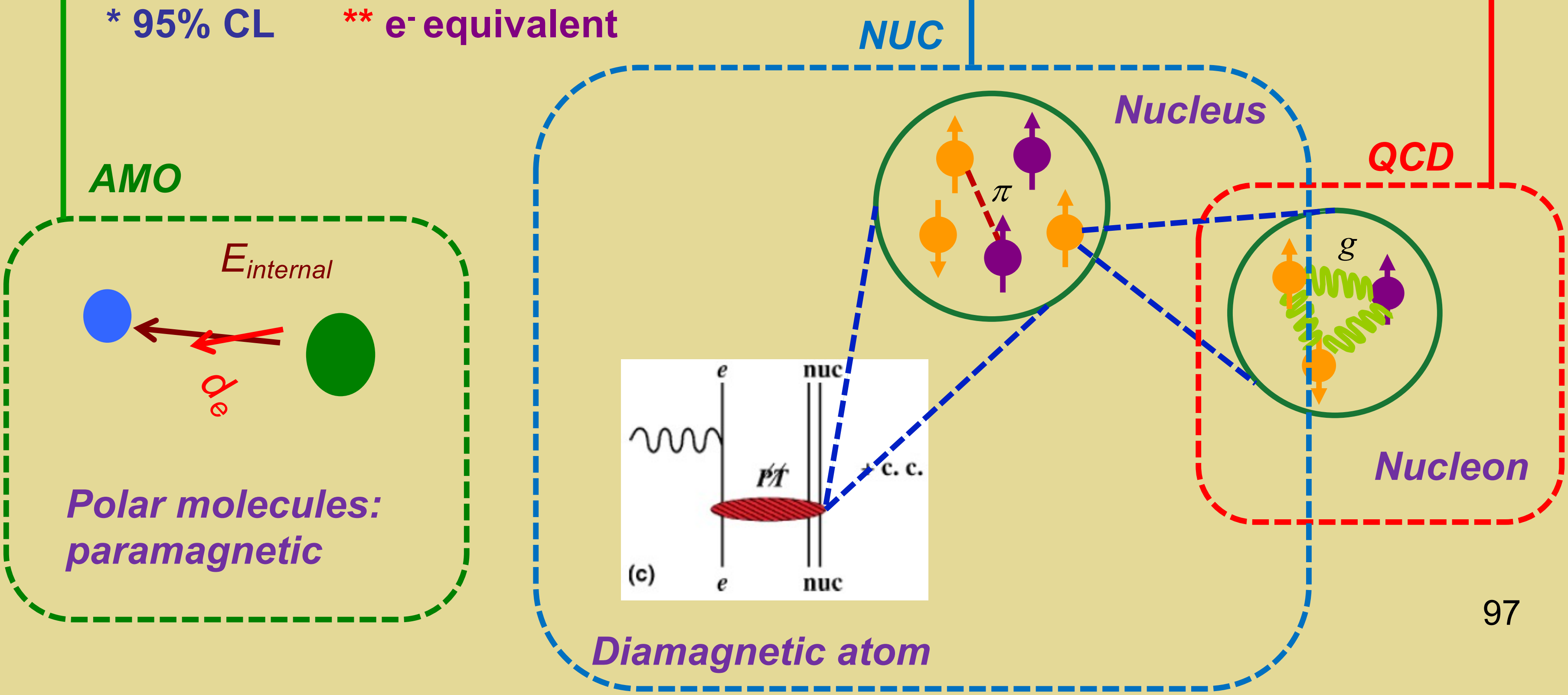

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HfF^{+}	4.1×10^{-30} **	10^{-38}	10^{-30}
n	1.8×10^{-26}	10^{-31}	10^{-26}

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

Challenge for EWBG

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

EDMs: New CPV?

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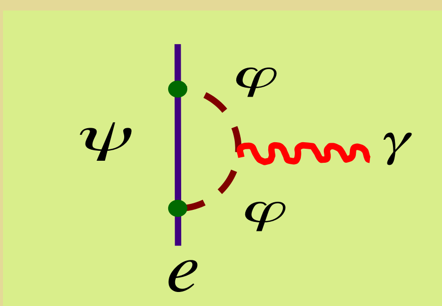
Challenge for EWBG

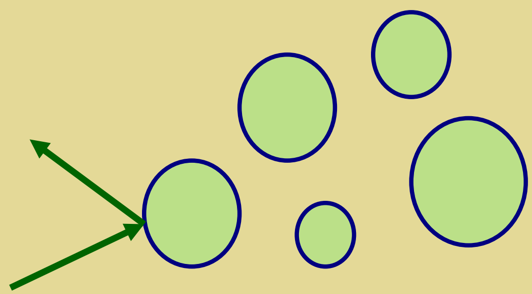
Mass Scale Sensitivity



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

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

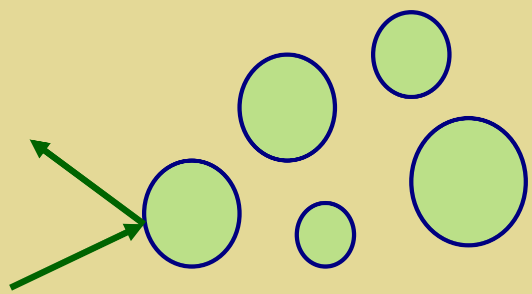
CPV for EWBG



Y_B : CPV, diffusion & EW sphalerons

- ***Can the CPV interactions be sufficiently "large" ?***
- ***Reliable quantum transport computations ?***

CPV for EWBG



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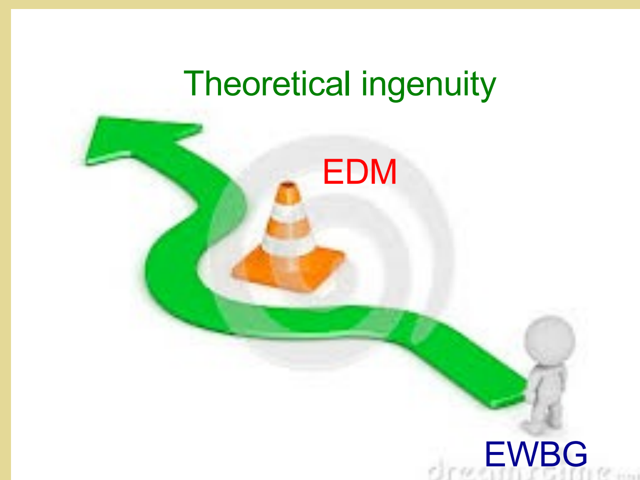


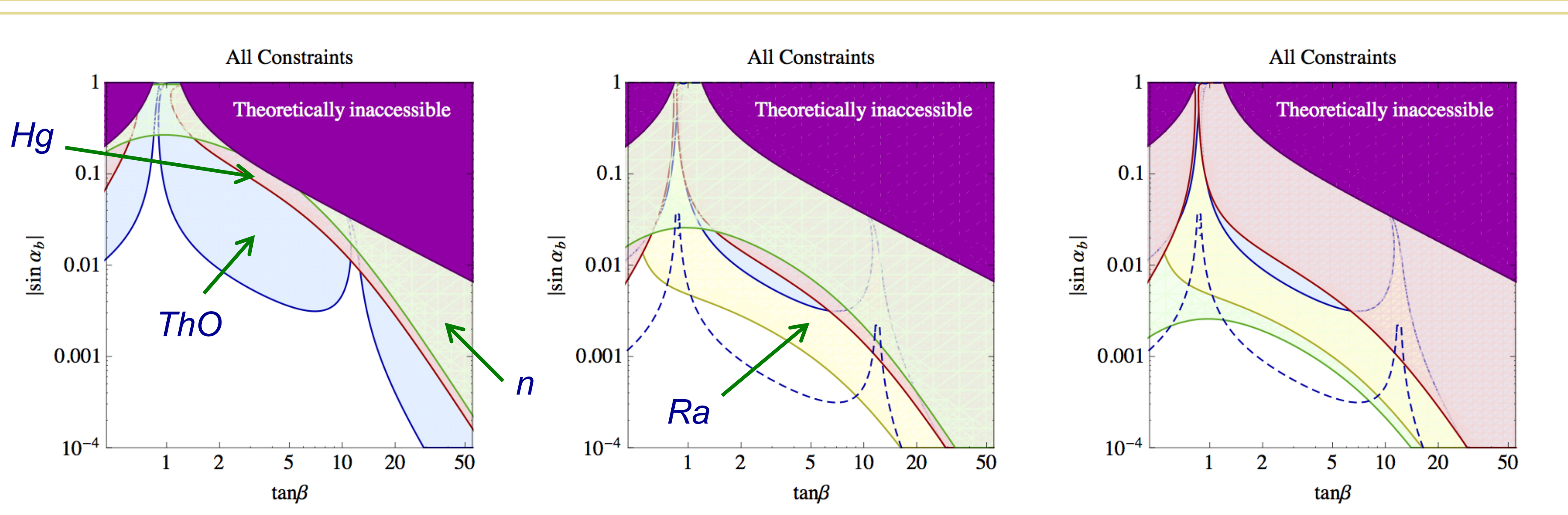
- ***Can the CPV interactions be sufficiently "large" ?***
- ***Reliable quantum transport computations ?***

Illustrations

2HDM CPV : EDMs 2014

CPV & 2HDM: Type II illustration

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



2014 → New HfF+

Present & 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
- $d_A(Ra)$

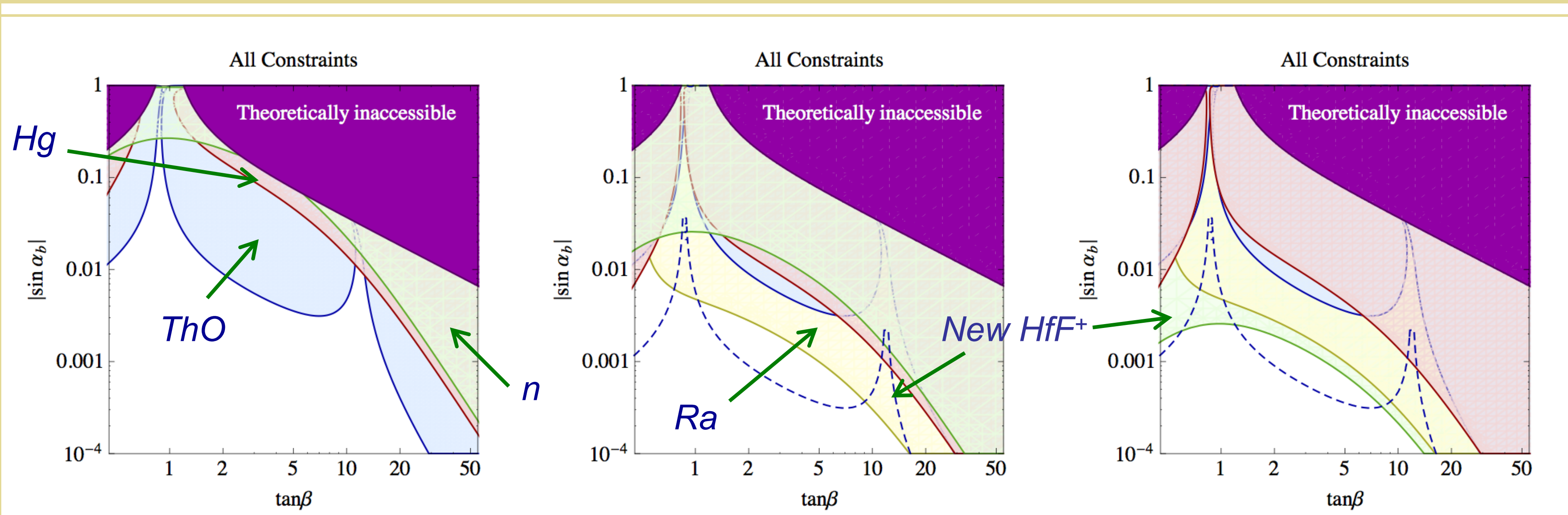
$\sin\alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

2HDM CPV : EDMs & LHC 2024

CPV & 2HDM: Type II illustration

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



Present

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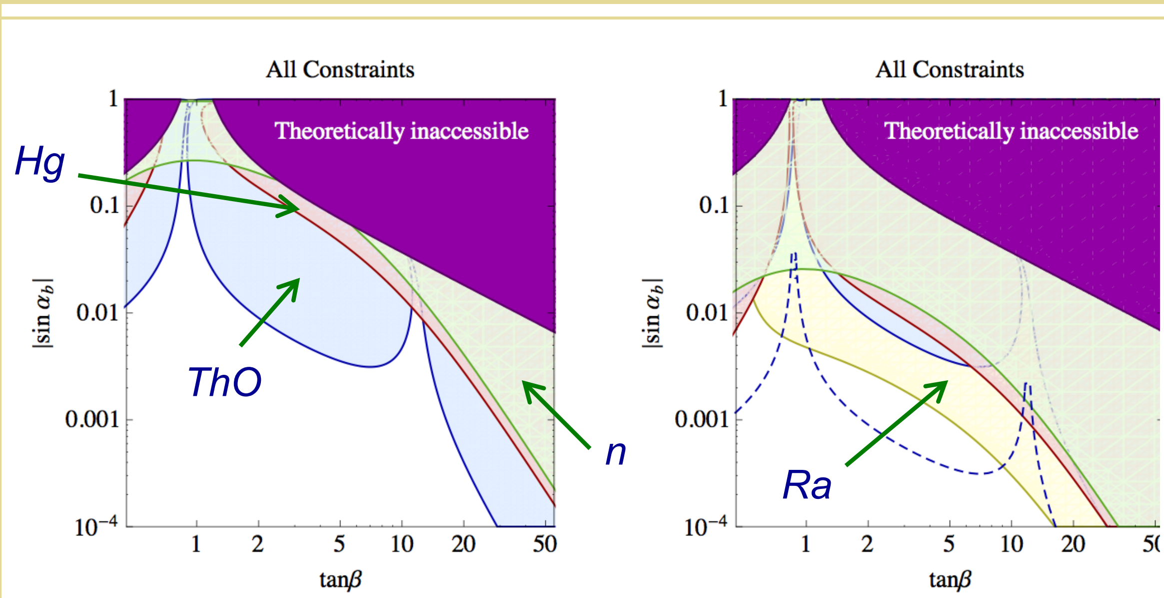

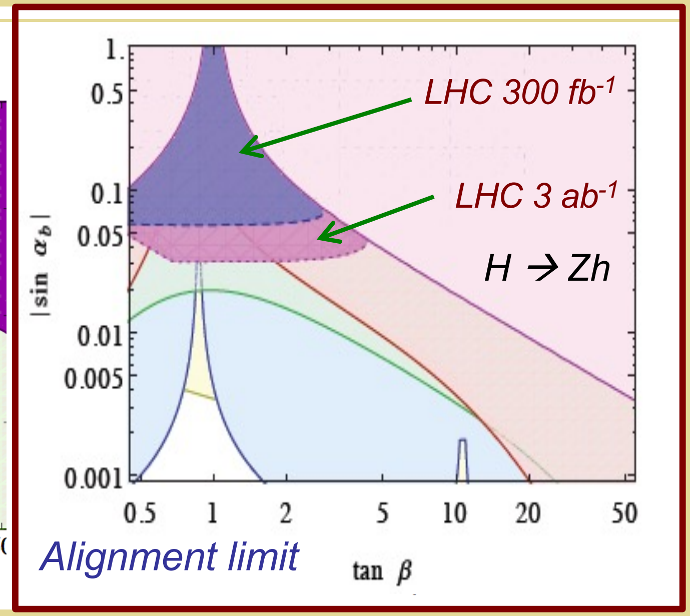

Chen, Li, R-M: 1708.00435

Present → *New HfF+*

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sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

2HDM CPV : Had & Nuc Structure

CPV & 2HDM: Type II illustration

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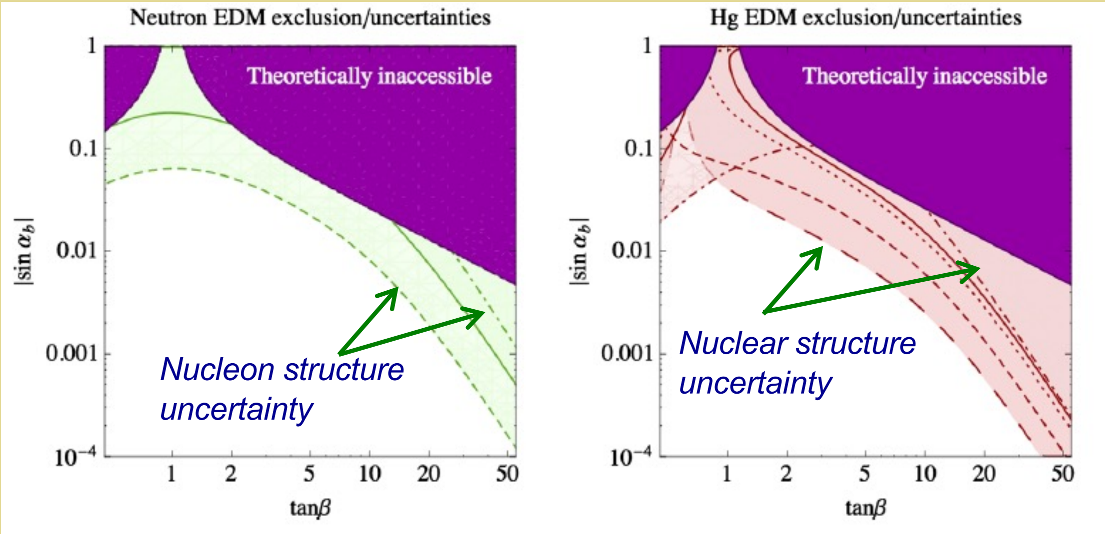

2014

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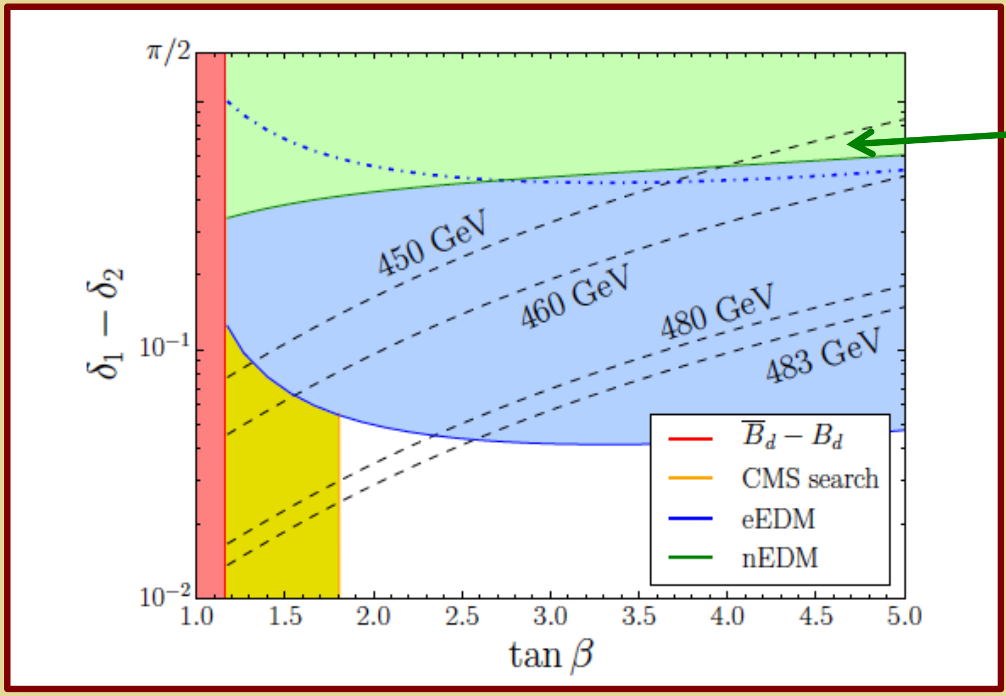
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

2HDM CPV & EWBG

2HDM CPV: Source for EWBG?

Dorsch et al, 1611.05874



EWBG viable

$\alpha_b \propto \delta_1 - \delta_2$

2HDM CPV & EWBG

2HDM CPV: Source for EWBG?

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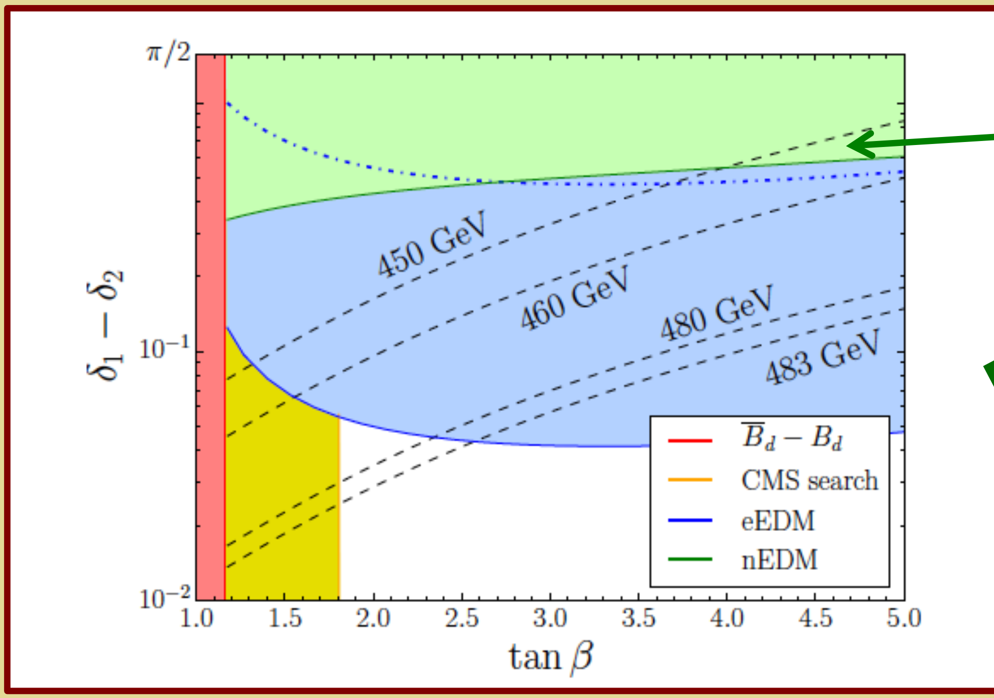
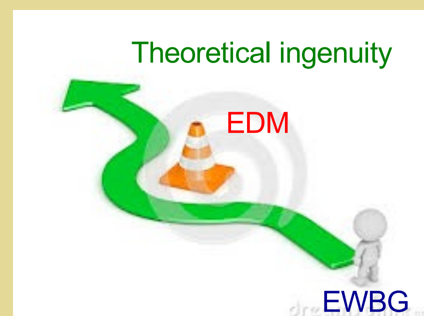


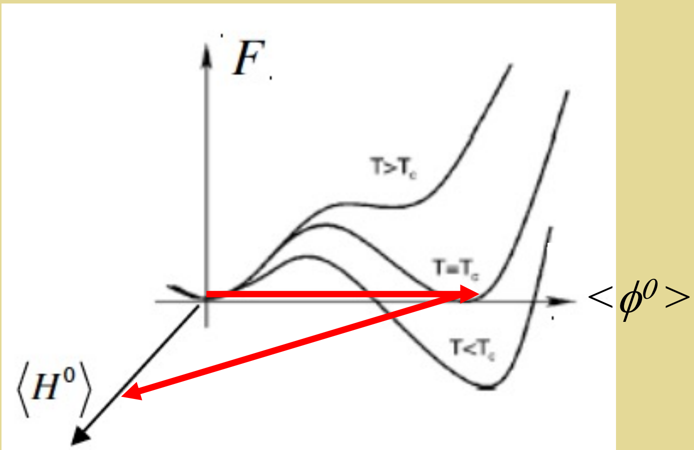
EWBG viable

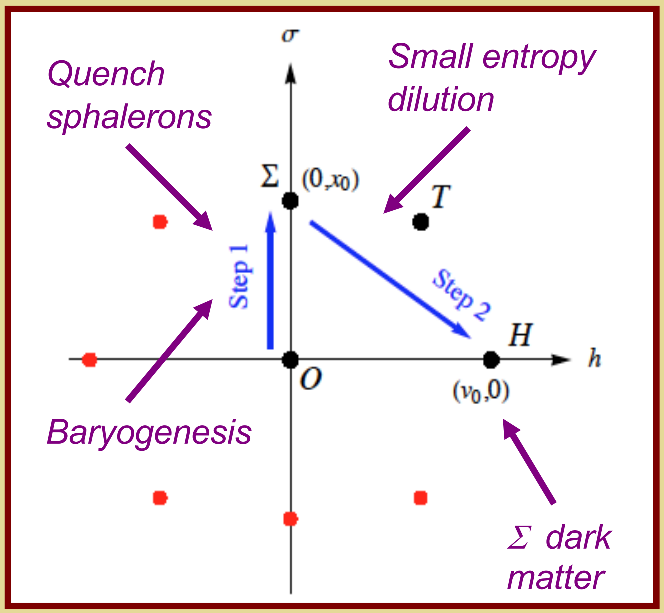
But new transport theory → see ahead



$\alpha_b \propto \delta_1 - \delta_2$

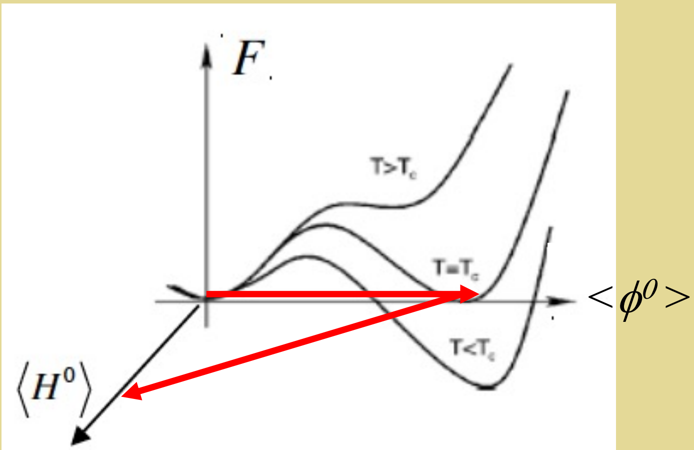
CPV for EWBG: Transport Theory & EDMs

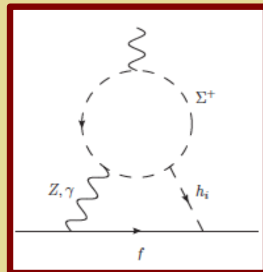




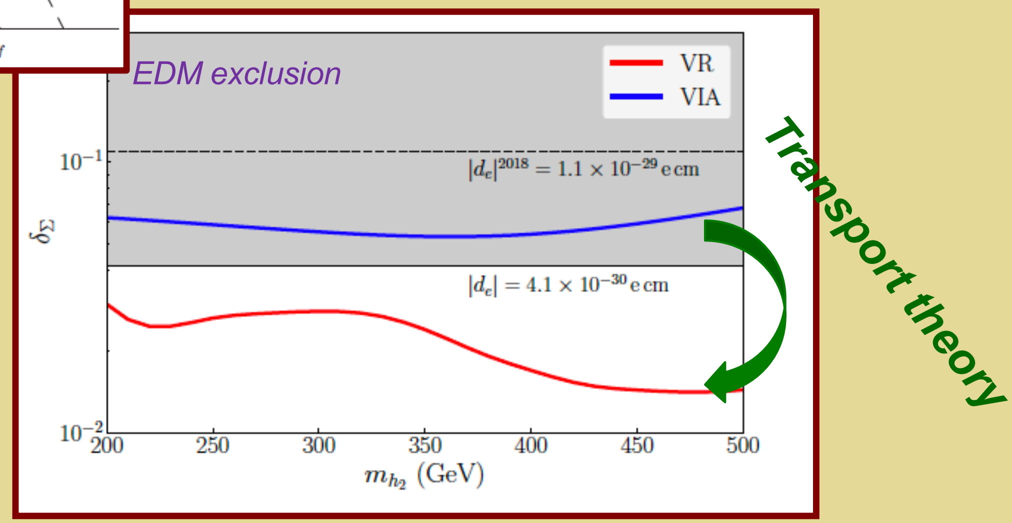
Inoue, Ovanesyan, R-M: 1508.05404

CPV for EWBG: Transport Theory & EDMs

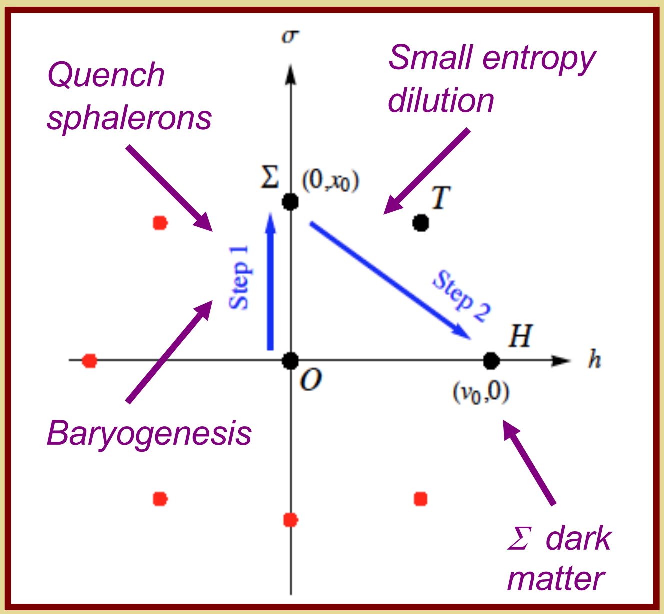




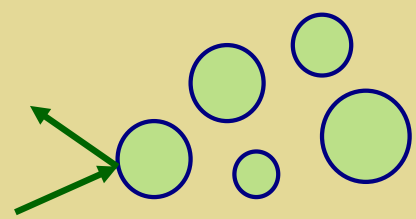
$a_2 \, H_1^* H_2 \, \Sigma^2$ + c.c.



Yuan-Zhen Li, MJRM, Jiang-Hao Yu 2404.19197

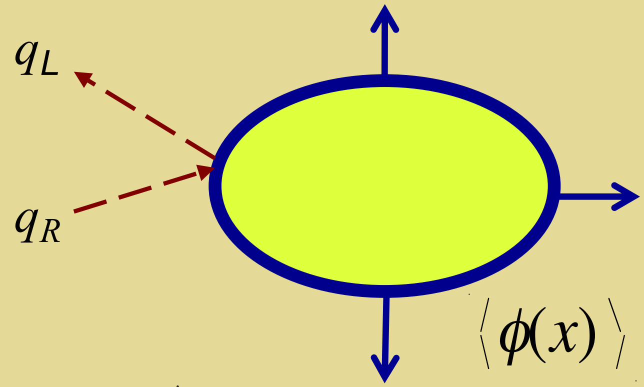


Inoue, Ovanesyan, R-M: 1508.05404

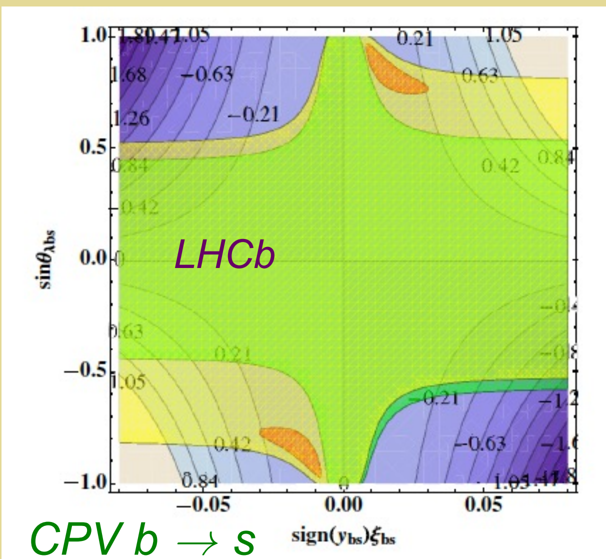


Y_B : CPV, diffusion & EW sphalerons

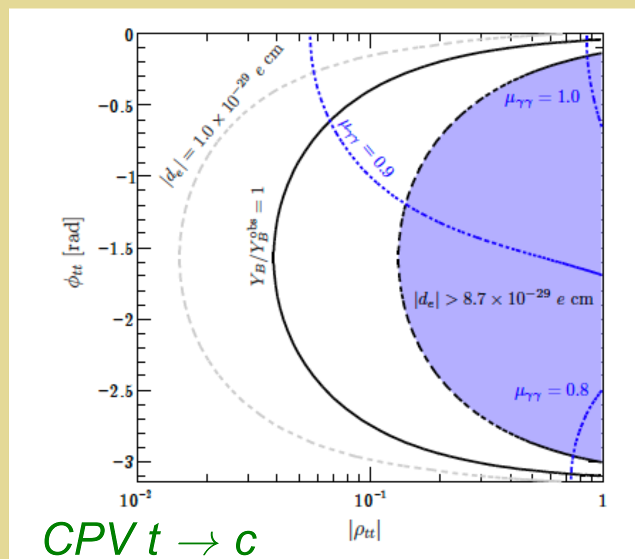
Flavored EW Baryogenesis



$$\mathcal{L} = \lambda^u_{ij}\bar{Q}^i(\epsilon H^\dagger_d)u^j_R - \lambda^d_{ij}\bar{Q}^i H_d d^j_R - y^u_{ij}\bar{Q}^i H_u u^j_R + y^d_{ij}\bar{Q}^i(\epsilon H^\dagger_u)d^j_R + \text{H.c.}$$

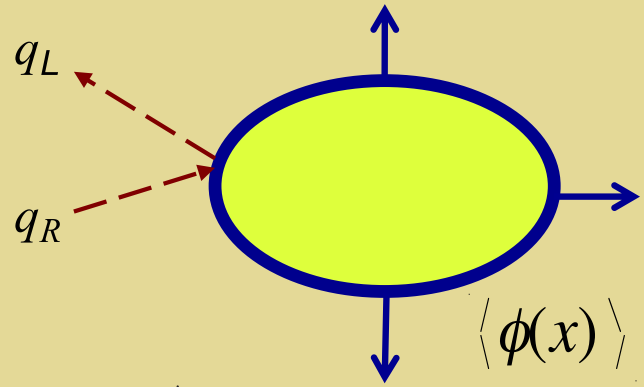


Liu, RM, Shu '12

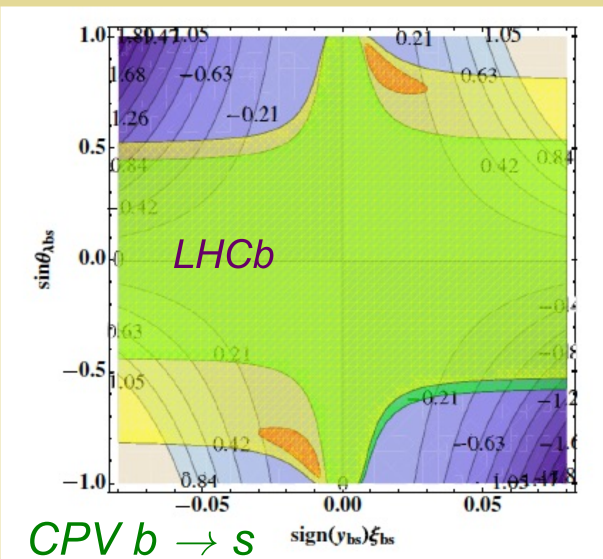


Fuyuto, Hou, Senaha '17

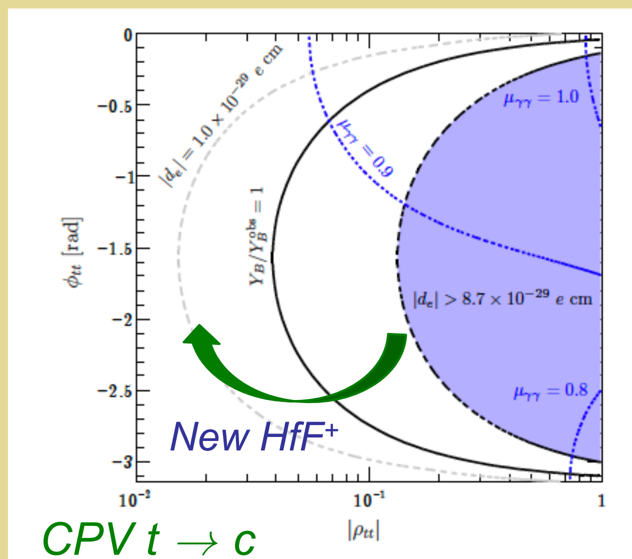
Flavored EW Baryogenesis



$$\mathcal{L} = \lambda^u_{ij}\bar{Q}^i(\epsilon H_d^\dagger)u_R^j - \lambda^d_{ij}\bar{Q}^i H_d d_R^j - y^u_{ij}\bar{Q}^i H_u u_R^j + y^d_{ij}\bar{Q}^i(\epsilon H_u^\dagger)d_R^j + \text{H.c.}$$

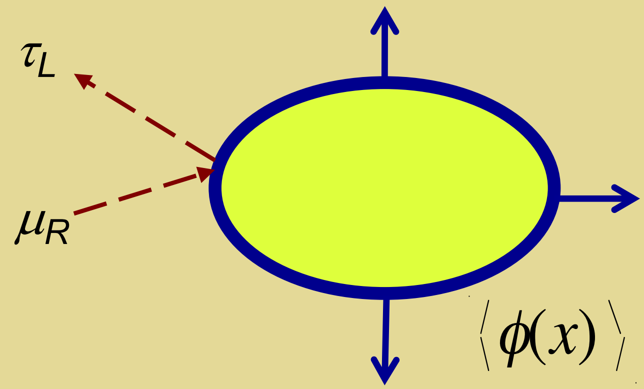


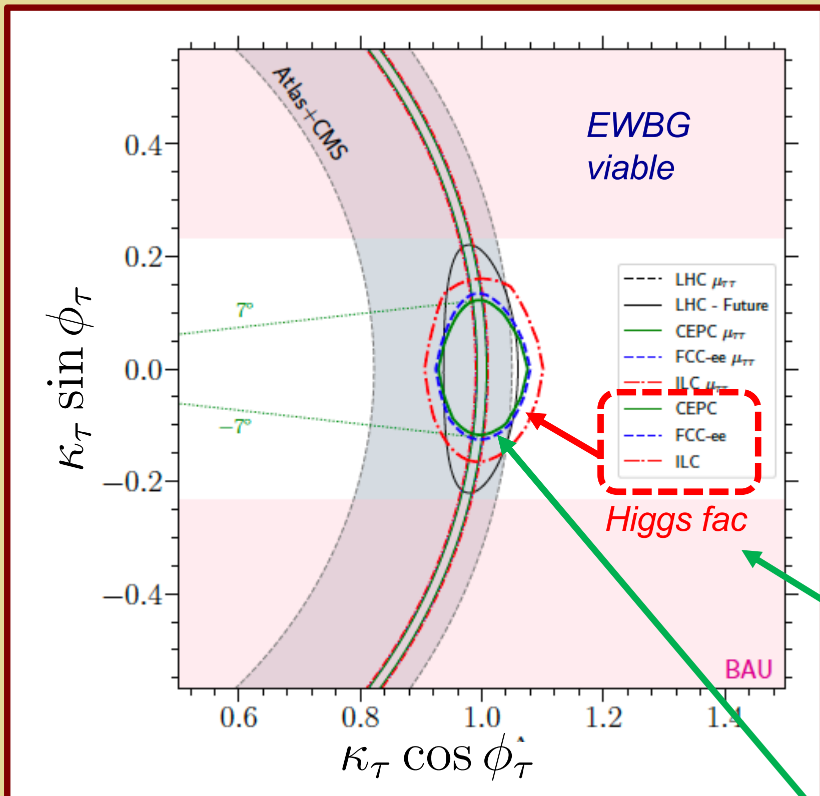
Liu, RM, Shu '12



Fuyuto, Hou, Senaha '17

Flavored EW Baryogenesis





Flavor basis (high T)

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

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

Ge, Li, Pasquini, R-M, Shu 2021.13922

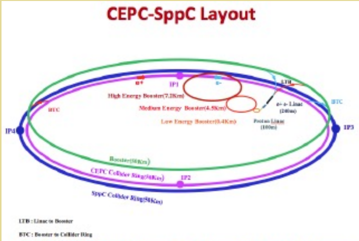
Two Themes

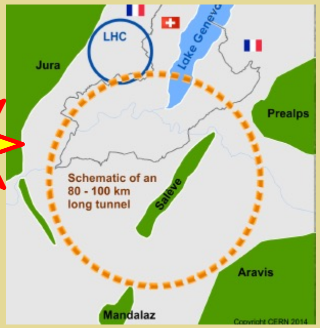
- ***Progress will come from focusing on well-posed scientific questions → potential for insights and/or discoveries***

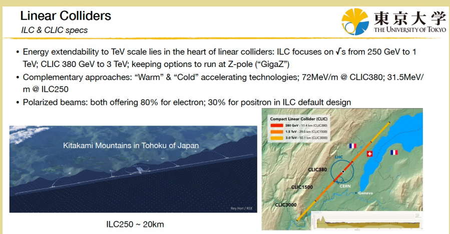
Was the matter-antimatter asymmetry generated in conjunction with electroweak symmetry-breaking ?

- ***It's important to think beyond boundaries of funding agency priorities and conventional sub-field categories → rich opportunities from inter-frontier connections***

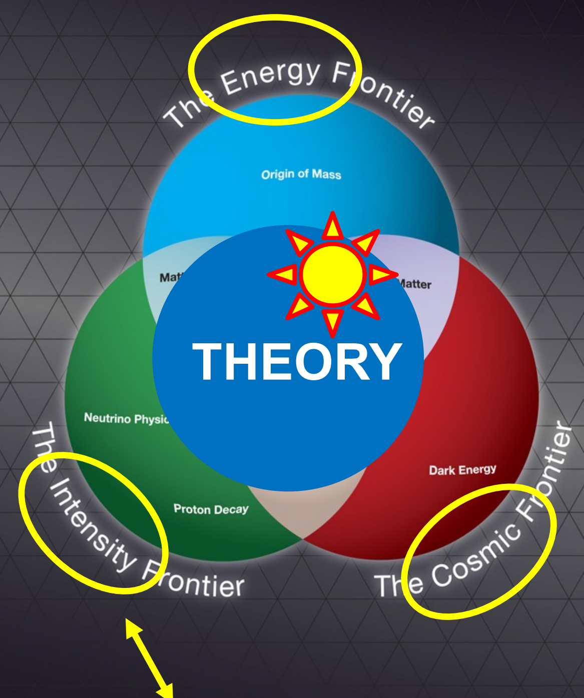
Frontiers







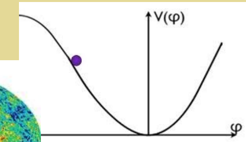
HEP : New (heavy) particles

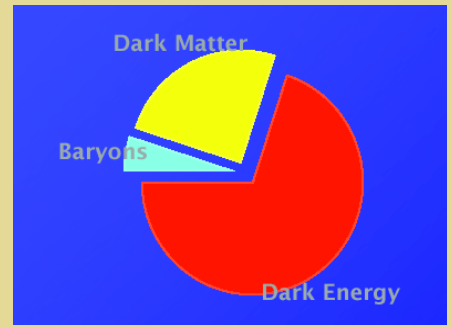


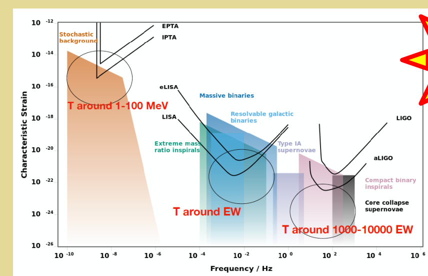
HEP + Nuc

Lifetime Frontier

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







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

Historical artifact: US HEP vision → still useful mnemonic

III. Outlook

Fundamental Physics: Past & Future