Scalars 2023

An opportunity to discuss various aspects of scalar particles.

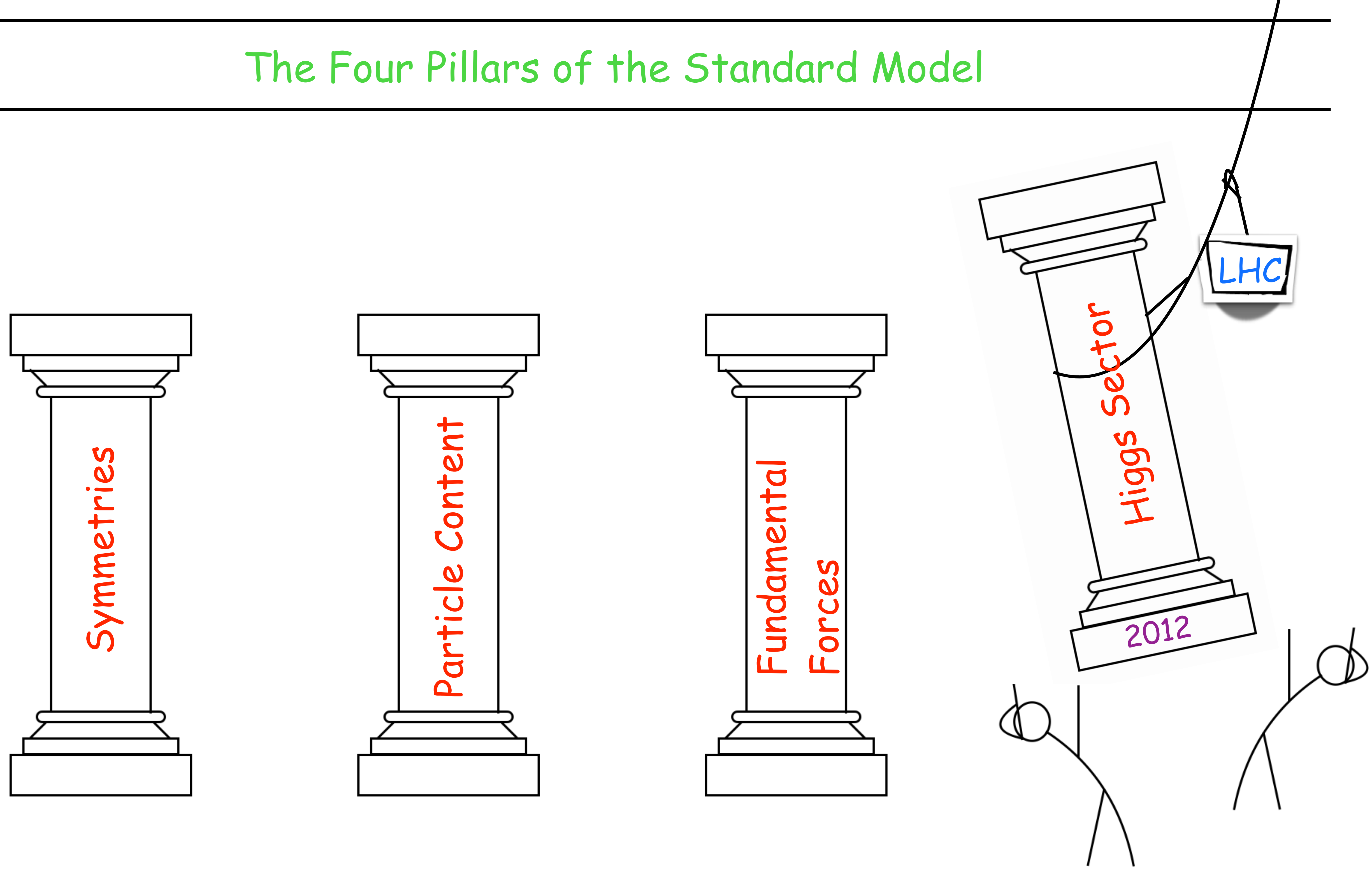
13-16 September 2023
Warsaw (Ochota Campus)

scalars2023.fuw.edu.pl

Signals of Primordial Gravitational Waves from a Strong First Order Electroweak Phase Transition

KIT Karlsruhe Institute of Technology
ITP Institute for Theoretical Physics
P H

The Four Pillars of the Standard Model



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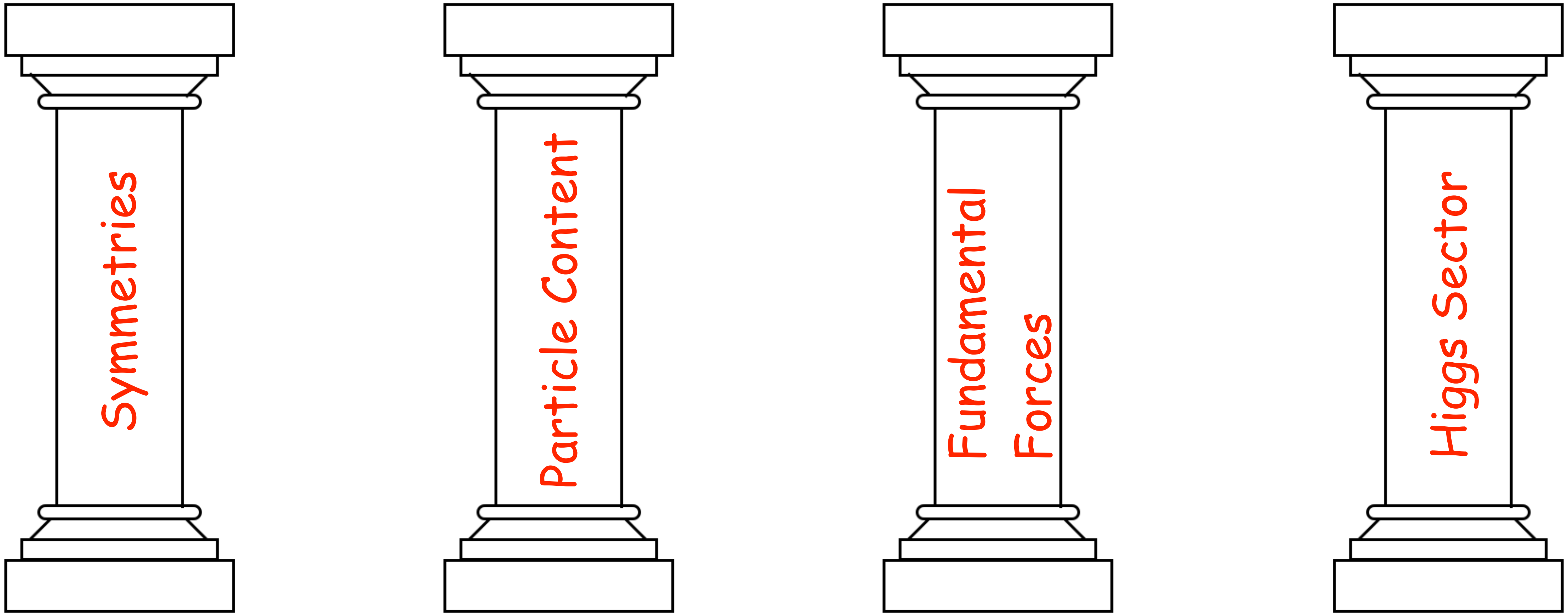
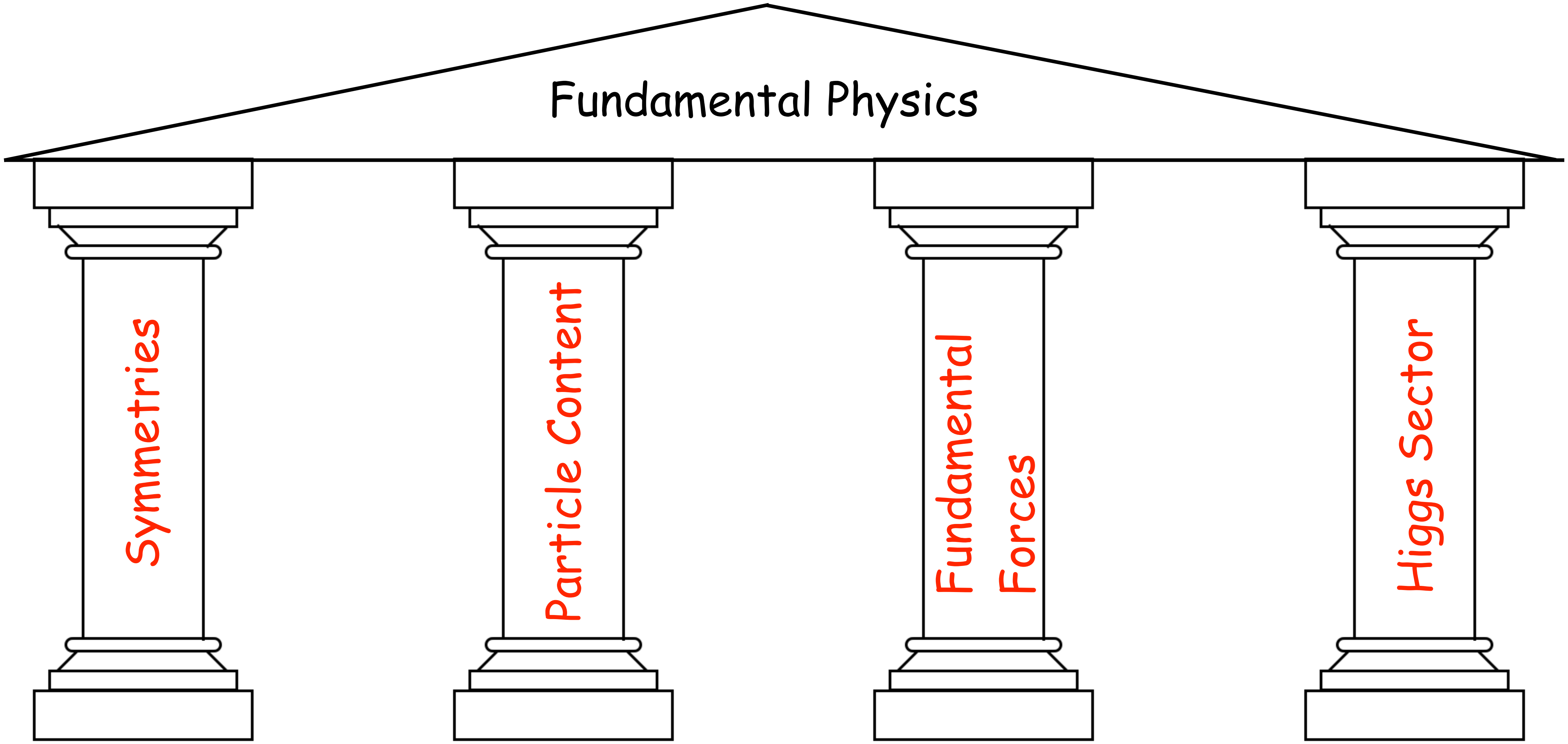
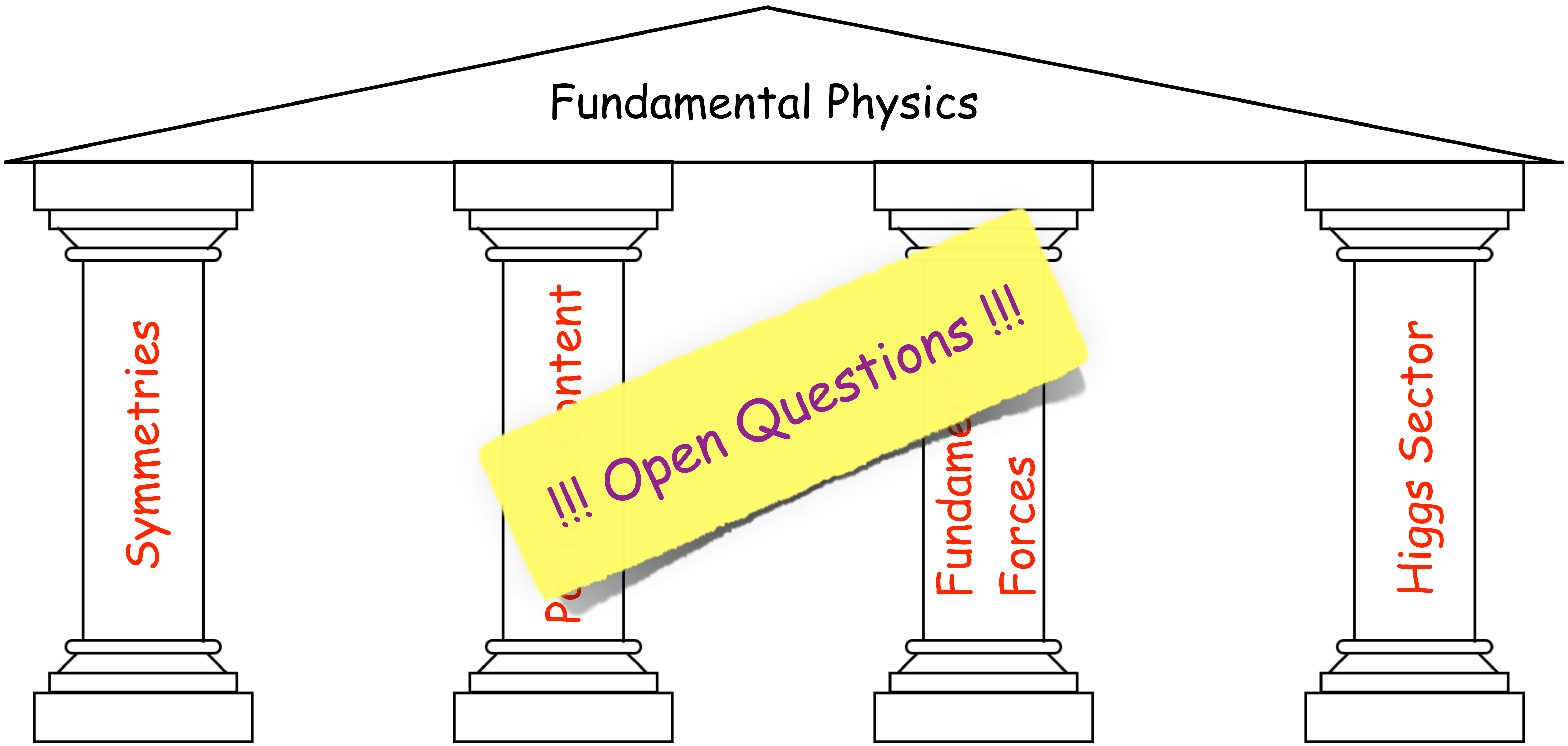
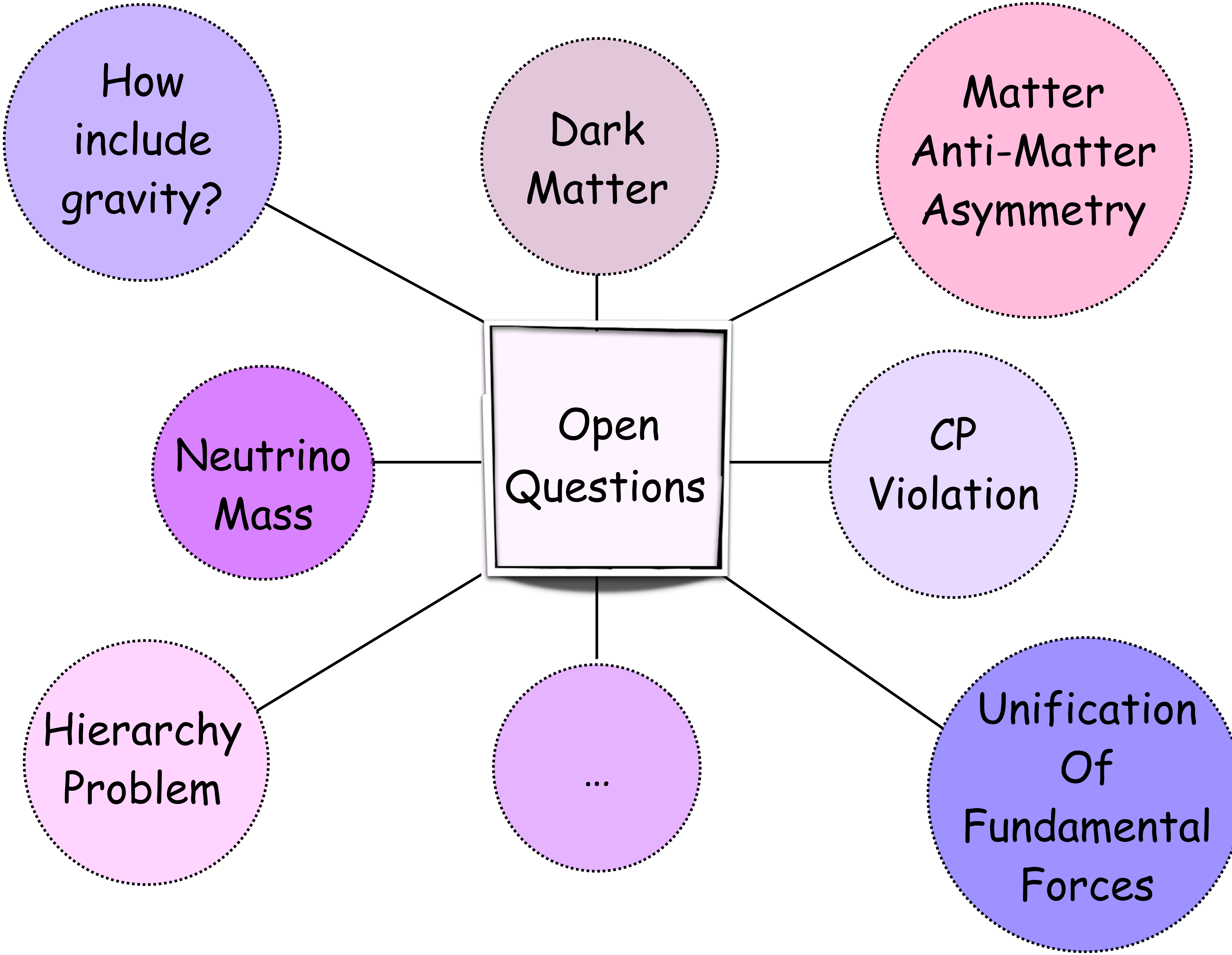


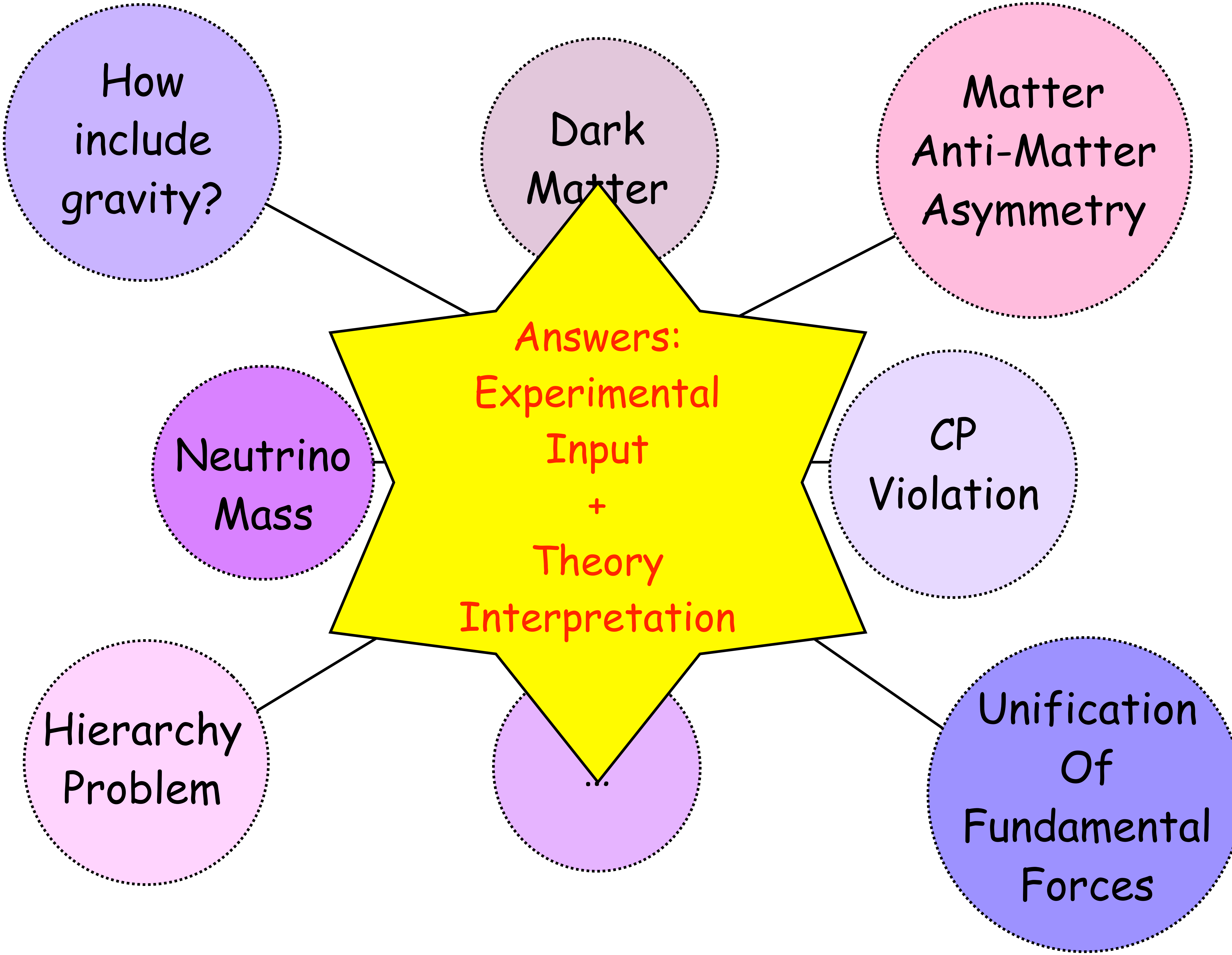
The Standard Model is Structurally Complete



The Standard Model is Structurally Complete - But




How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Questions
CP Violation
Hierarchy Problem
...
Unification Of Fundamental Forces


How include gravity?
Dark Matter
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Answers: Experimental Input + Theory Interpretation
CP Violation
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Unification Of Fundamental Forces

Strong First Order Electroweak Phase Transition (SFOEWPT) The Code BSMPT

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

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Requires beyond the SM physics: extended Higgs sectors

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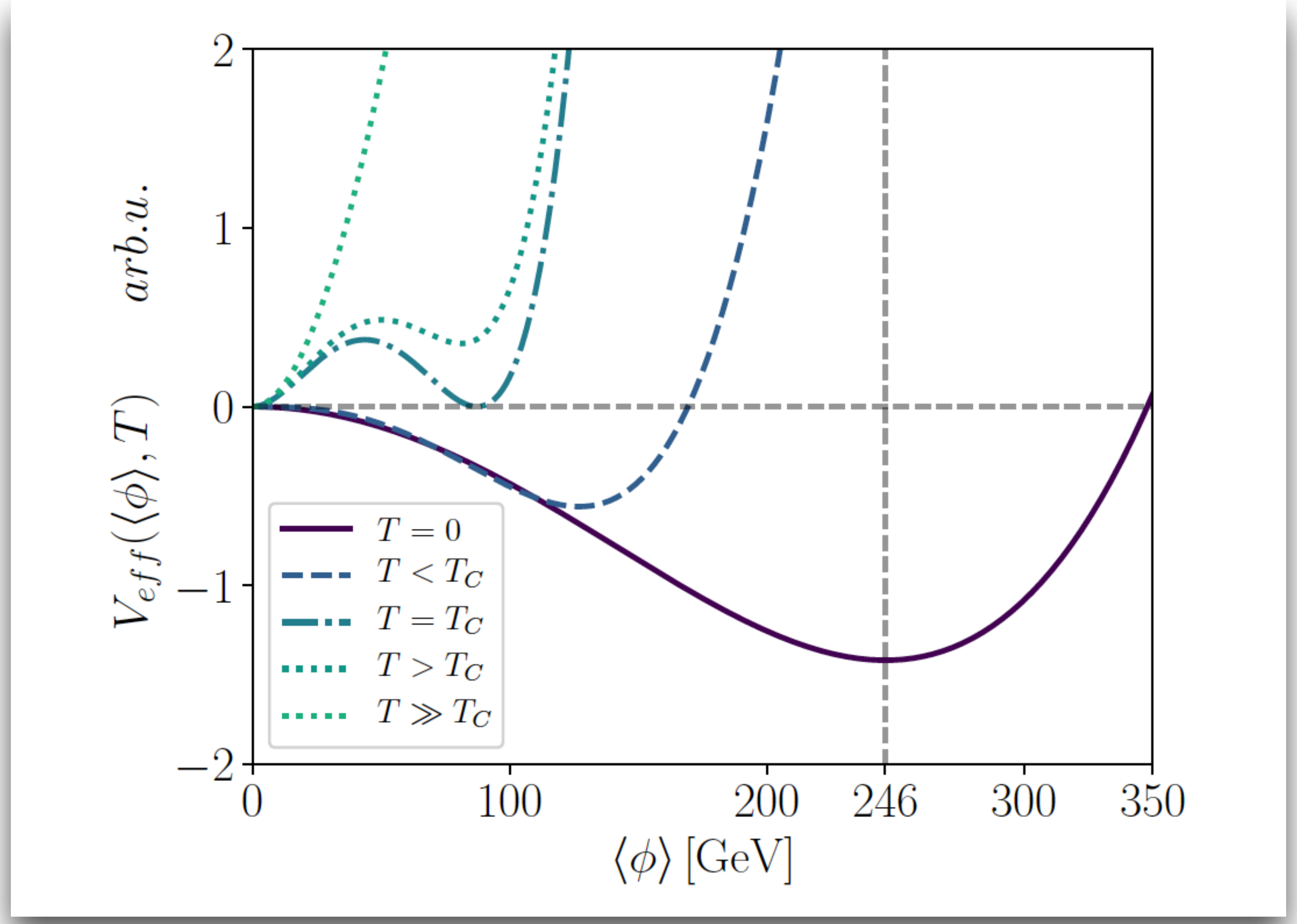
Strong First Order Electroweak Phase Transition (SFOEWPT)

[From Ph. Basler, PhD Thesis]



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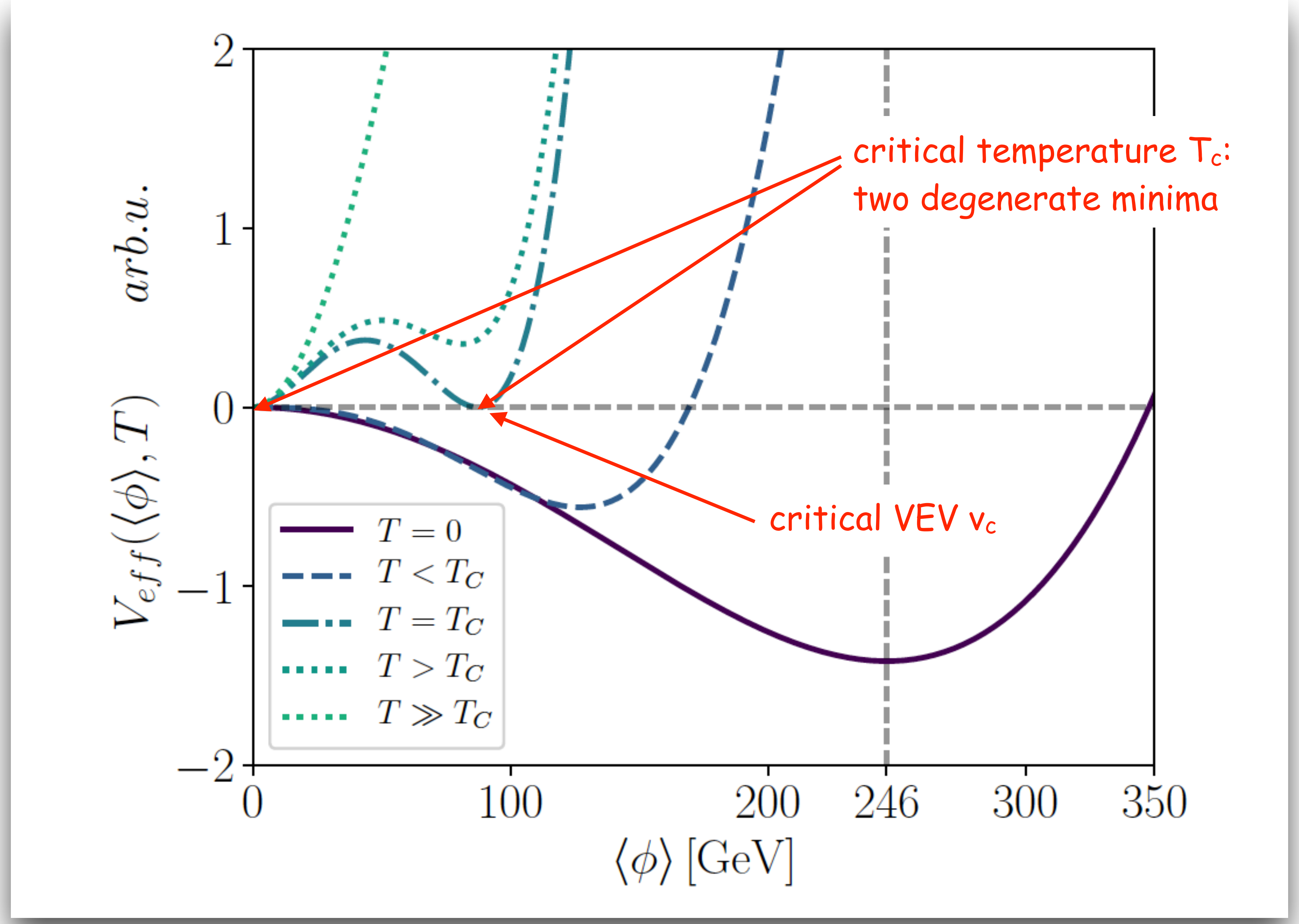
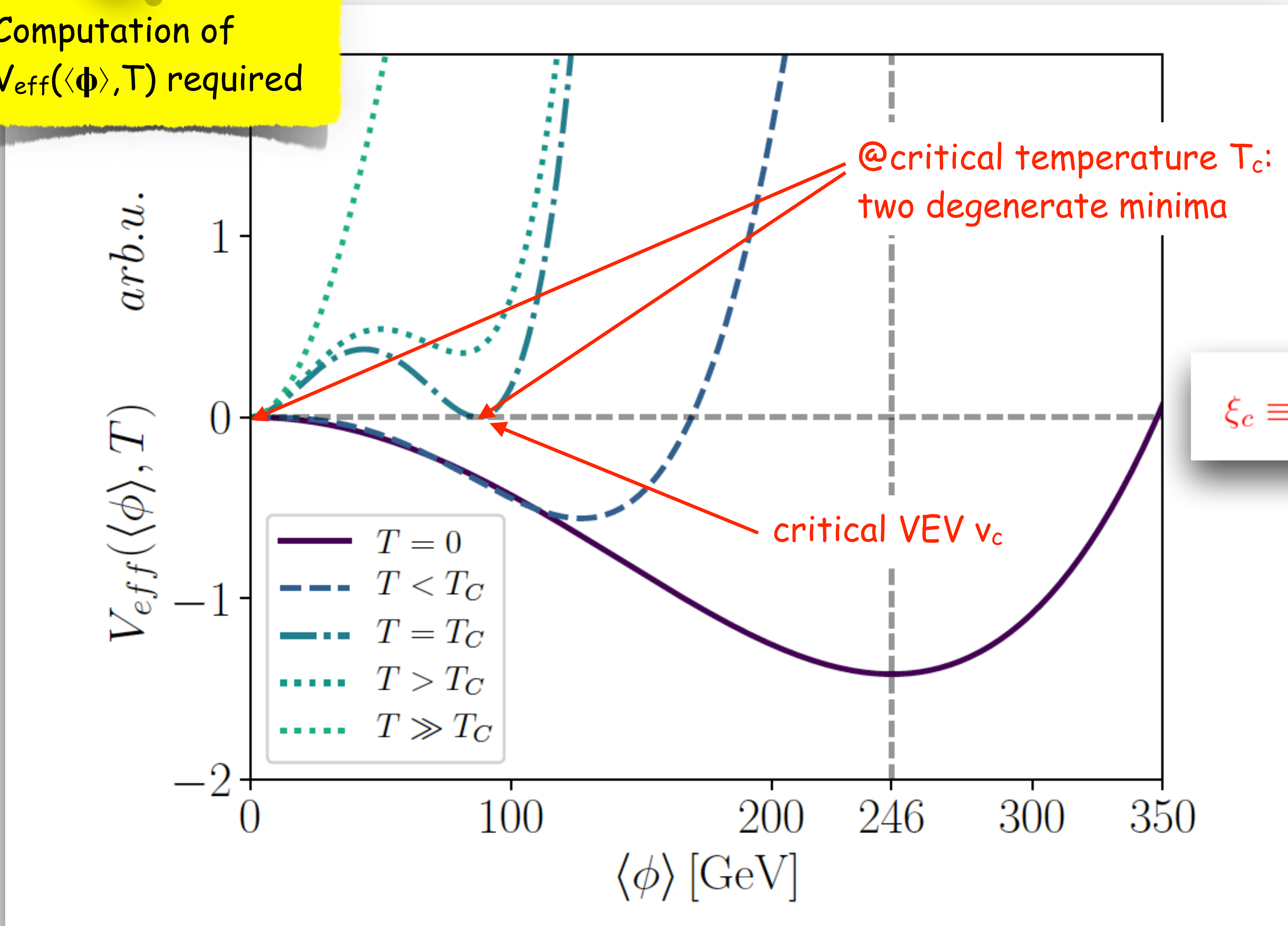


Strong First Order Electroweak Phase Transition (SFOEWPT)

[From Ph. Basler, PhD Thesis]

Computation of $V_{eff}(\langle\phi\rangle, T)$ required



$$\xi_c \equiv \frac{\langle\Phi_c\rangle}{T_c} \geq 1\,?$$

The Code BSMPT

[v1:Basler,MM,'18]

Beyond-the-Standard-Model Phase Transitions - BSMPT:
A tool for electroweak phase transitions in extended Higgs sectors

- Computation of the loop-corrected effective potential V_{eff} at finite temperature, including thermal masses
- For extended Higgs sectors
- Determination of VEV $\langle\phi\rangle(T) \rightsquigarrow \xi_c = v_c/T_c$
- In on-shell (OS) renormalization scheme: masses and mixing angles from V_{eff}^{loop} are equal to leading-order values $\rightsquigarrow$ efficient scan of parameter space of the models
- Computation of loop-corrected trilinear Higgs self-couplings in OS scheme
- Easy implementation of new models
- Programming language: C++

$$V^{(1)}(\omega,T) = V^{(0)}(\omega,T) + V^{CW}(\omega) + V^{T}(\omega,T) + V^{CT}(\omega)$$

$V^{(0)}(\omega,T)$	$V^{CW}(\omega)$	$V^{T}(\omega,T)$	$V^{CT}(\omega)$
tree-level	T-indep. Coleman-Weinberg potential MSbar renormalized	T-dep. UV fin. IR fin. after resumm. $m^2 \to m^2 + \Pi^{(1)}(0)$	finite shift of scalar masses & mixing angles
	[Coleman,Weinberg,'73]	[Carrington,'92] [Parwani,'92] [Arnold,Espinosa,'93]	[Basler eal,'17]

BSMPT: Global minimization of loop-corrected effective potential at T ϵ {0,300} GeV in all possible field directions ω at T ≠ 0 GeV.

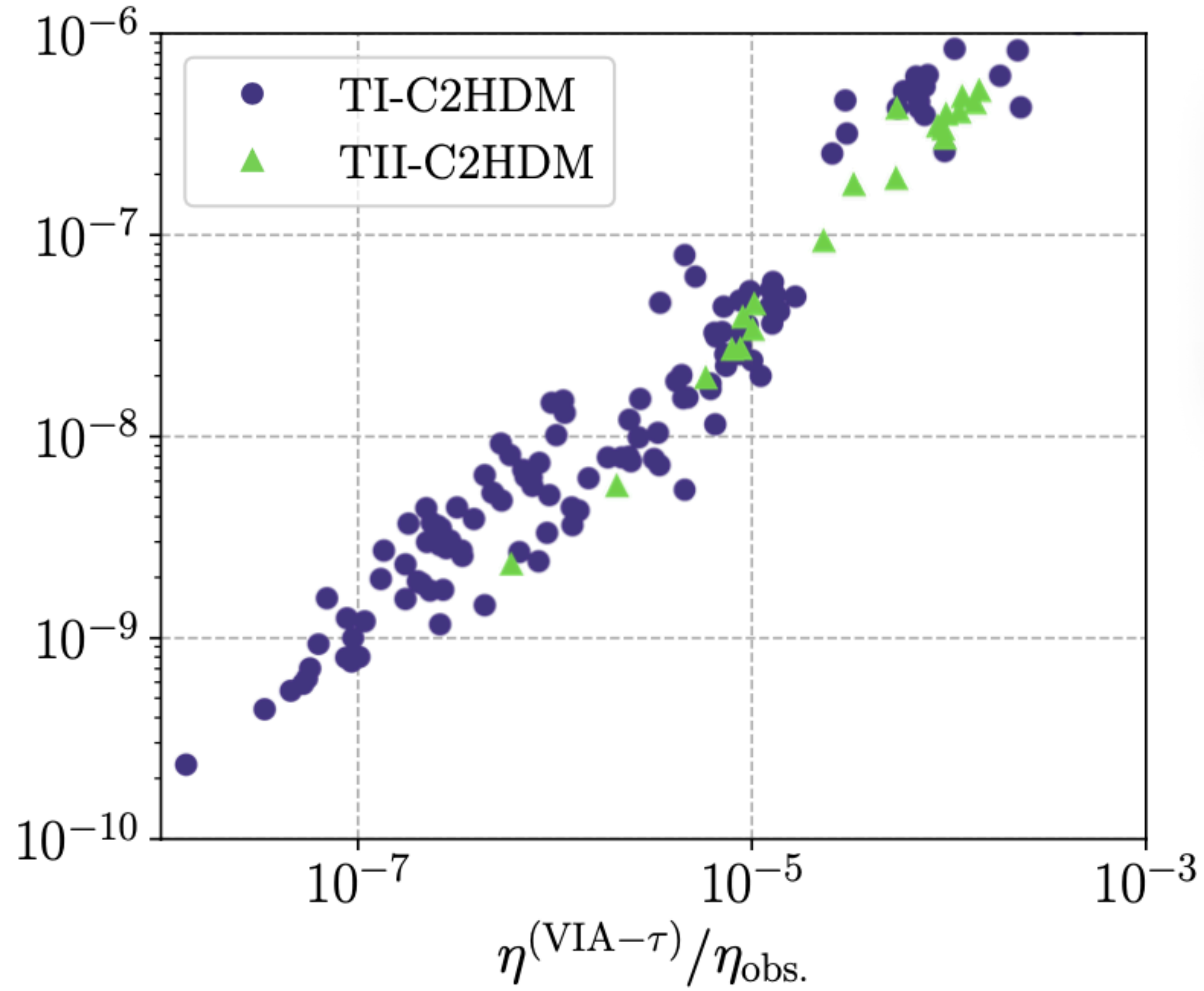
SFOEWPT: $\xi = v_c/T_c > 1$

Upgrade to BSMPTv2

- Calculation of the BAU for the CP-violating 2HDM (C2HDM), using
  * the semiclassical force approximation (FH)
  * the VEV-insertion approximation (VIA)

  (wall profile is approximated by the Kink profile)
- Implementation of a new model: CxSM - further code improvements

[Basler,MM,Müller,'20, +Biermann,'21]



Take with caution VIA:
[Postma eal,'22]:
LO source term in VIA vanishes

Code available at: https://github.com/phbasler/BSMPT

README.md

Program: BSMPT version 2.6.0

Released by: Philipp Basler and Lisa Biermann and Margarete Mühlleitner and Jonas Müller

GitHub Discussions | Ubuntu unit tests passing | Mac unit tests passing | Windows unit tests passing | codecov 81% | Documentation master | Benchmark master | Maintained? yes | license GPL-3.0 | release v2.6.0

Manual: version 2.0

BSMPT - Beyond the Standard Model Phase Transitions: The C++ program package BSMPT calculates the strength of the electroweak phase transition in extended Higgs sectors. For this the loop-corrected effective potential at finite temperature is calculated including the daisy resummation of the bosonic masses. The program computes the vacuum expectation value (VEV) \f$ v \f$ of the potential as a function of the temperature, and in particular the critical VEV \f$v_c\f$ at the temperature \f$T_c\f$ where the phase transition takes place. In addition, the loop-corrected trilinear Higgs self-couplings are provided. We apply an 'on-shell' renormalization scheme in the sense that the loop-corrected masses and mixing angles are required to be equal to their tree-level input values. This allows for efficient scans in the parameter space of the models.

The models implemented so far are

- CP-conserving 2-Higgs-Doublet Models (R2HDM)
- CP-violating 2-Higgs-Doublet Models (C2HDM)
- Next-to-Minimal 2HDM (N2HDM)
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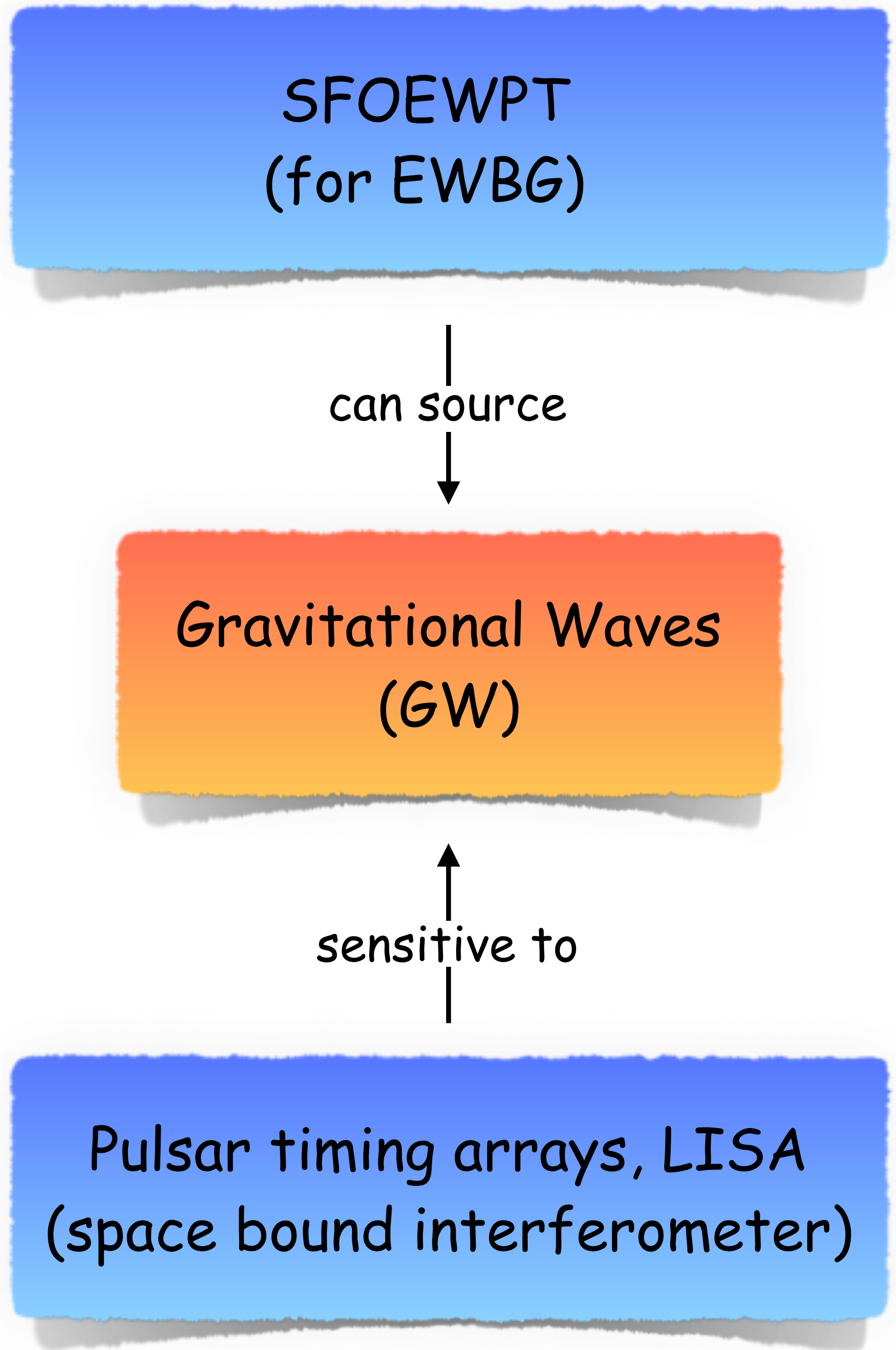
Gravitational Waves
BSMPTv3

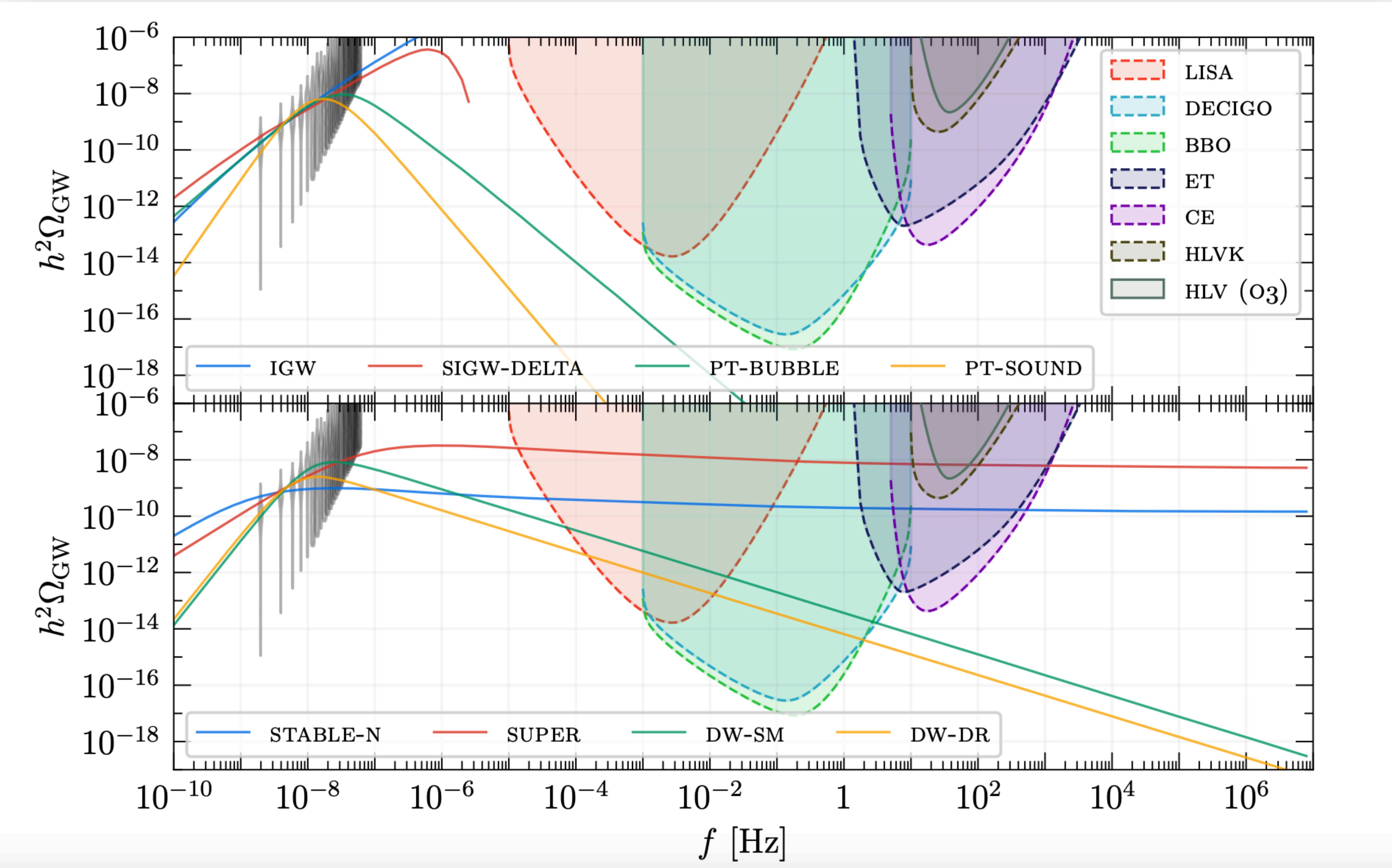
SFOEWPT and Gravitational Waves



Experiments Sensitive to GW from FOEWPT

[Azfal et al.,'23]

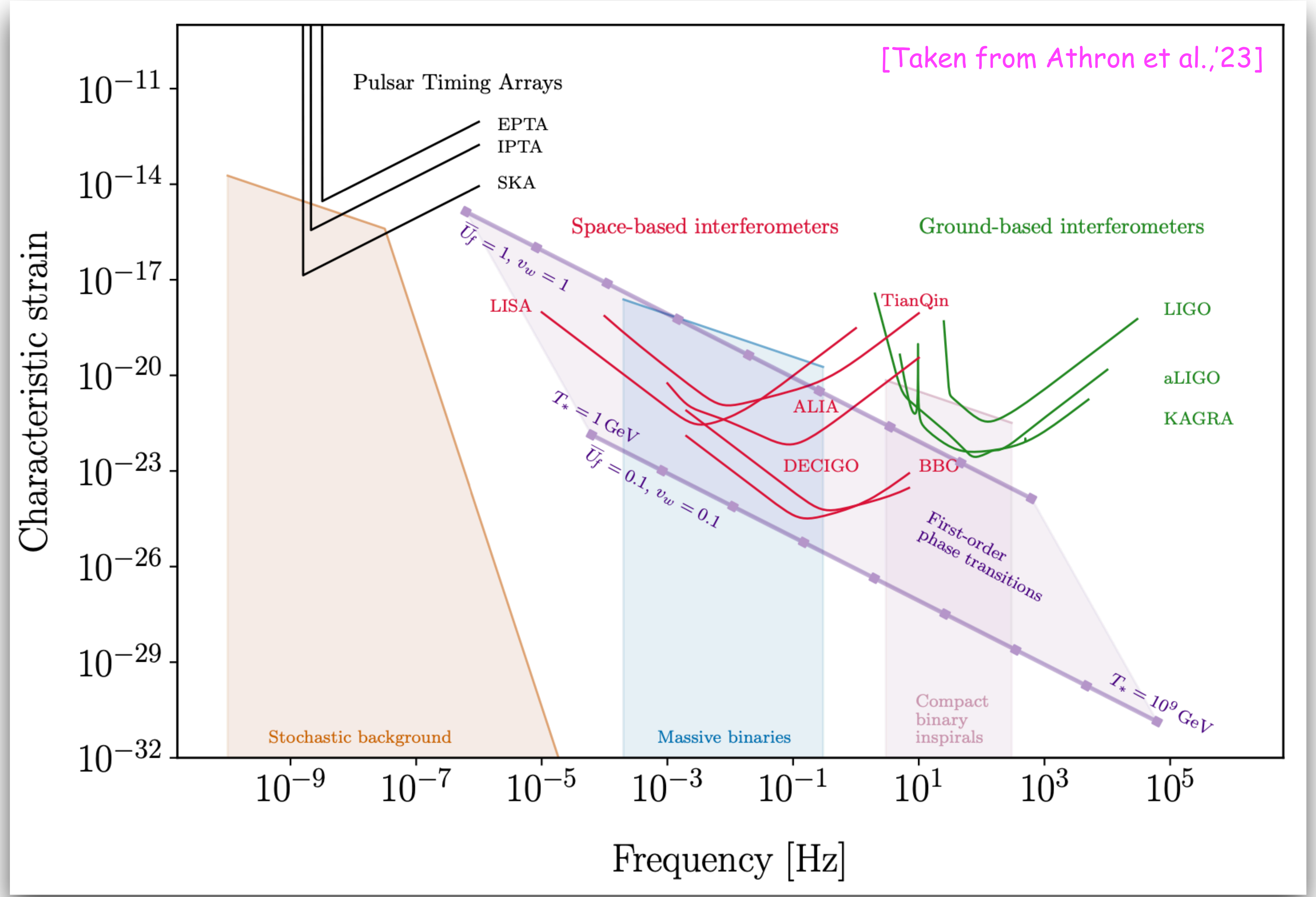
NANOGrav: 3 evidence for stochastic GW background which could come from FOEWPT



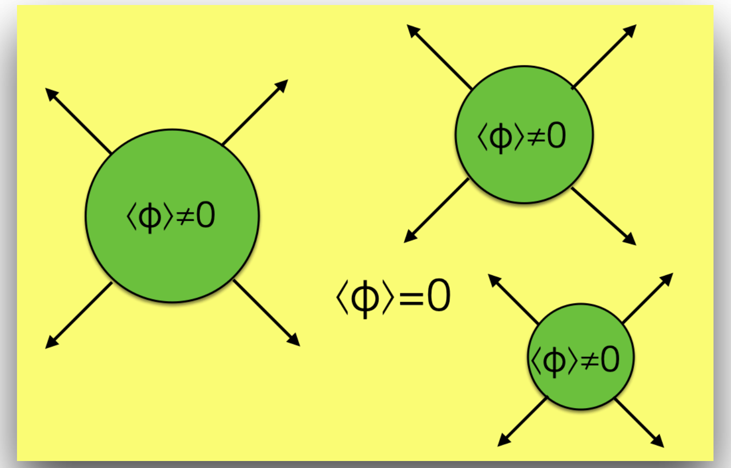
Experiments Sensitive to GW from FOEWPT

LISA: expected sensitivity in frequency range associated w/ FOEWPT

[Amaro-Seoane et al.,'17]



Gravitational Waves from an FOEWPT



- FOEWPT ⇝ bubble nucleation

- Bubble wall expands into hot plasma
  ⇒ spherical symmetry breaking ⇝ gravitational waves

- Source of gravitational waves:

  - bubble collisions and mergers [Kosowsky et al.,'92,93,94]
  - magnetohydronamic turbulence (shocks in fluid) [Caprini,Durer,'06;Kahniashvili eal,'08/10]
  - sound waves (bubble-wall accelerated plasma) [Giblin,Mertens,'13/14;Hindmarsh eal,'14/15]

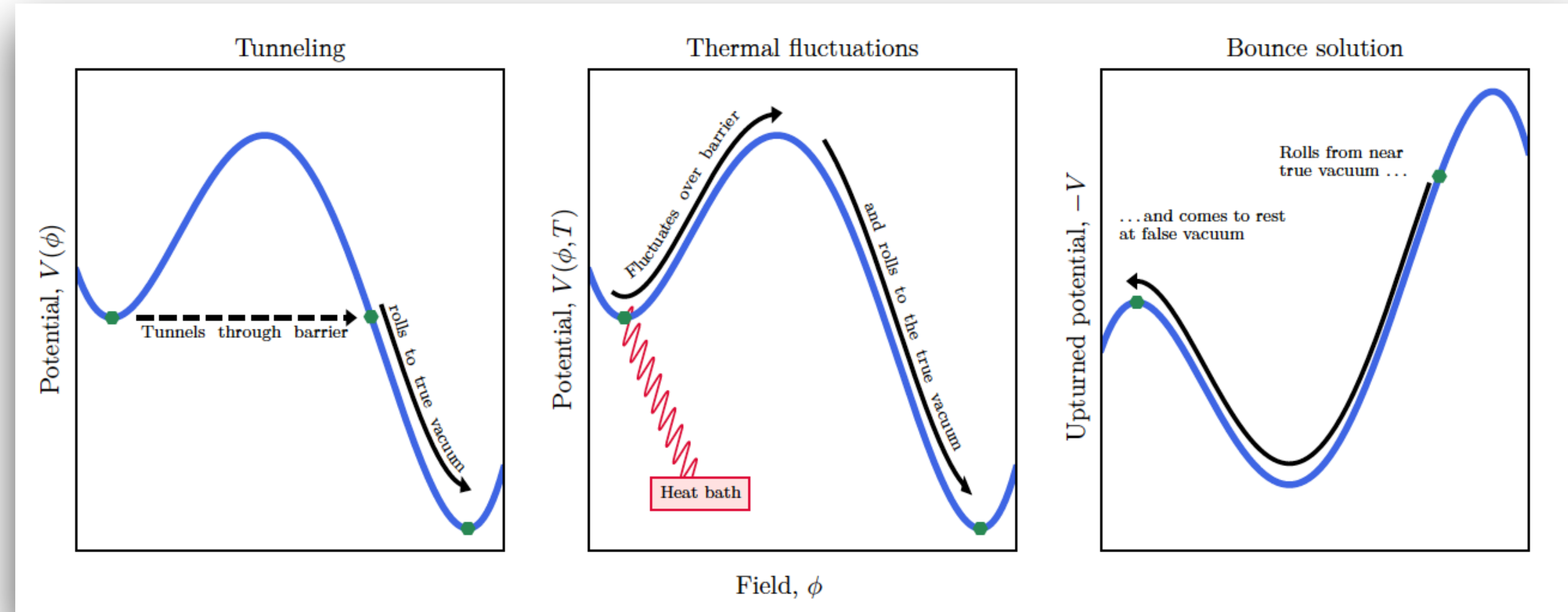
- Sound waves dominant contribution:

  if bubble walls interact w/ surrounding plasma, hence for

  - enough friction with the plasma ⇒ non-runaway bubbles, reaching a terminal velocity v_b
  - no early onset of turbulent regime, $\alpha < 1$

- Vacuum decay: transition from false to true vacuum through quantum tunneling or thermal fluctuations

[Plot from Athron eal,'23]



- Tunneling rate per unit volume:

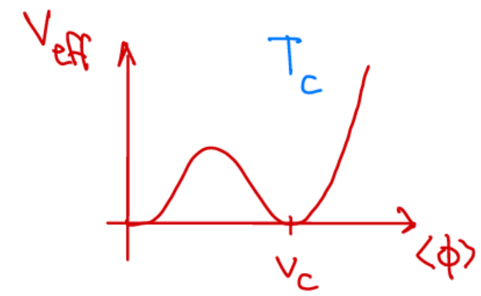
$$\Gamma(T) = A(T)\, e^{\frac{\hat{S}_3}{T}} \simeq T^4 \left(\frac{\hat{S}_3}{2\pi T} \right)^{\frac{3}{2}} e^{\frac{\hat{S}_3}{T}}$$

$\hat{S}_3$: minimized O_3-symmetric Euclidean action (action of the bounce solution)

Expanding bubbles w/ true vacuum, racing against expanding universe, interactions with plasma in front of bubble wall

Time Scales

- Critical Temperature T_c: true ($v \neq 0$) and false ($v=0$) vacuum are degenerate, PT starts via quantum tunneling



- Nucleation Temperature T_n: one bubble nucleated per cosmological horizon; resp. tunneling rate matches Hubble rate

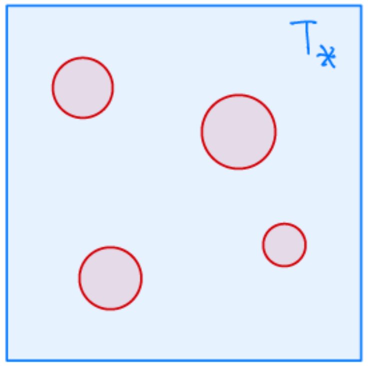
  if not matched ⇝ vacuum trapped in false vacuum

  [see e.g. Baum eal,'21; Biekötter eal,'23]

- Percolation temperature T_*: probability of finding point in false vacuum is 70%

  [Ellis eal,'19]

$$P_f(T_*) = \mathrm{e}^{-I(T_*)} \equiv 0.7 \text{ with } I(T) = \frac{4\pi v_b^3}{3} \int_T^{T_c} \frac{\Gamma(T')dT'}{T'^4 H(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})} \right)^3$$



Computation of the Gravitational Waves Spectrum

- Relevant quantities for GW spectrum:

  - PT strength, resp. released latent heat during PT

$$\alpha = \frac{1}{\rho_\gamma}\left[V(\vec{\phi}_f) - V(\vec{\phi}_t) - \frac{T}{4}\left(\frac{\partial V(\vec{\phi}_f)}{\partial T} - \frac{\partial V(\vec{\phi}_t)}{\partial T}\right)\right]_{T=T_*}$$

  - inverse time scale of the PT $\quad \frac{\beta}{H} = T_* \frac{d}{dT}\left(\frac{\hat{S}_3(T)}{T}\right)\Bigg|_{T_*}$

  - bubble wall velocity v_b

H	Hubble constant
τ_{sh}	fluid turnover time shock formation time
g_*	eff. number of rel. energy d.o.f.
c_s	sound speed
κ	efficiency factor

- Peak frequency and amplitude of acoustic GWs [Hindmarsh eal,'17;Caprini eal,'20]

$$f^{\text{peak}} = 26 \times 10^{-6}\, \frac{\beta}{H}\left(\frac{1}{(8\pi)^{\frac{1}{3}}\max(v_b,\, c_s)}\right)\left(\frac{T_*}{100\,\text{GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}} \text{Hz}$$

$$h^2\Omega_{\text{GW}}^{\text{peak}} = 4 \times 10^{-7}\left(\frac{100}{g_*}\right)^{\frac{1}{3}} \begin{cases} \frac{(8\pi)^{1/3}\max(v_b, c_s)}{\beta/H}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2 & \text{if} \quad H\tau_{\text{sh}} \simeq 1 \\ \frac{2}{\sqrt{3}}\left(\frac{(8\pi)^{1/3}\max(v_b, c_s)}{\beta/H}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^{3/2} & \text{if} \quad H\tau_{\text{sh}} < 1 \end{cases}$$

Available Codes

- Codes for the computation of the bounce action:

  - CosmoTransitions [Wainwright,'11]: via path deformation

  - AnyBubble [Masoumi,'17]: via a multiple shooting algorithm

  - BubbleProfiler [Athron eal,'19]: via semi-analytic algorithm [Akula eal,'16]

  - SimpleBounce [Sato,'19]: via gradient flow method

  - FindBounce [Guada eal,'18,'20]: via polygonal multifield method

  - OptiBounce [Bardsley,'21]: vial solving the ‚reduced' minimization problem [Coleman,'77]

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Coming soon: BSMPTv3 [Biermann,MM,Santos,Viana,'23]

Upgrade to BSMPTv3

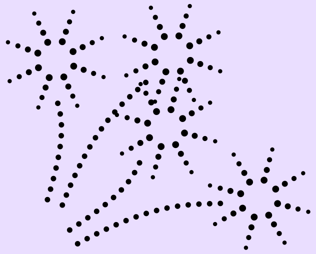
[Biermann,MM,Santos,Viana]

- Determination of tunneling path
- Computation of the bounce action, computation of the tunneling rate
- Computation of the nucleation temperature T_n, of the percolation temperature T_*
- Calculation of the latent heat release α, of the inverse time scale of the PT β/H
- Calculation of the peak frequency and the peak amplitude of the acoustic GWs

Why BSMPTv3

[Basler,MM,v1,'18] [Basler,MM,Müller,v2,'20] [Biermann,MM,Santos,Viana,v3,'23]

- Optimized minimum tracing & tracking of temperature-dependent coexisting minimum phases over any temperature interval
- Numerical derivation of the bounce solution for any number of field dimensions
- More precise calculation of the nucleation temperature (compared to CosmoTransitions)
- Calculation of the percolation temperature (not implemented in CosmoTransitions)
- Calculation of the GW parameters α, β/H
- Calculation of f^{peak} and $h^2\Omega^{peak}$ of the (acoustic) GW spectrum
- Computation of signal-to-noise-ratio at LISA
- For all implemented models (CxSM, R2HDM, C2HDM, N2HDM, CP in the Dark)
- Embedded in the framework of the existing BSMPT code
  -> consistent computation of all EWPT-related observables
  -> easy user interface for implementing a new model
  -> designed to use input from ScannerS



Gravitational Waves from SFOEWPT in ‚CP in the Dark‘

The Model „CP in the Dark"

✦ Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,Wittbrodt,'18]

$$V^{(0)} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + \text{ h.c.}\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 .$$

✦ with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$

one SM-like Higgs plus dark sector: $h_1, h_2, h_3, H^\pm$

✦ trilinear coupling A is complex: dark sector with explicit CP violation <- not constrained by electric dipole moment

Vacuum Structure of „CP in the Dark“

- General vacuum structure at T≠0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_1 + i\eta_1 \\ \zeta_1 + \omega_1 + i\Psi_1\end{pmatrix}, \ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_2 + \omega_{CB} + i\eta_2 \\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{CP})\end{pmatrix}, \ \Phi_S = \zeta_S + \omega_S$$

electroweak VEVs: ω_1, ω_2 , CP-violating VEV: ω_{CP}

charge-breaking VEV: ω_{CB} (unphysical; found to be zero for all of our scan points)

Z_2-symmetry breaking VEV: ω_S

- General vacuum structure at T=0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1\end{pmatrix}, \ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2\end{pmatrix}, \ \Phi_S = \zeta_S$$

$$\langle\Phi_1\rangle|_{T=0} = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v_1\end{pmatrix}, \ \langle\Phi_2\rangle|_{T=0} = \begin{pmatrix}0 \\ 0\end{pmatrix}, \ \langle\Phi_S\rangle|_{T=0} = 0$$

$\omega_1|_{T=0\ GeV}$ = v1 ≡ v = 246.22 GeV

Parameter Scan

✦ Scan in parameter space of the model w/ ScannerS [Coimbra eal,'13;MM eal,'20]

✦ Keep only points compatible w/

theoretical constraints: bounded-from-below, perturbative unitarity, EW vacuum ✓

experimental constraints: (EDMs automatically fulfilled)
- EW precision tests
  SM-like Higgs h compatibility w/:
- m_h=125 GeV
- Higgs Data [HiggsSignals]
(- Higgs exclusion limits [HiggsBounds])
- BR(h->inv) < 0.11 [ATLAS,'19]
- $\mu(h\rightarrow\gamma\gamma)$=1.12±0.09 [CMS,'21]

DM observables (through MicrOMEGAs):
- relic density $\Omega_{obs}h^2$=0.1200±0.0012 [Aghanim eal,'18] (require it to below)
- XENON1T exclusion limit [Aprile eal,'18]
- new LUX-ZEPLIN exclusion limit [Aalbers eal,'22]

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SM-like Higgs h has SM couplings by construction w/ exception of:
- hH^+H^- coupling modifies loop-ind. $h\gamma\gamma$ coupling
- $h\to h_i h_j$ decay ($h_{i,j}$ dark sector particles), modifies total width & hence BRs

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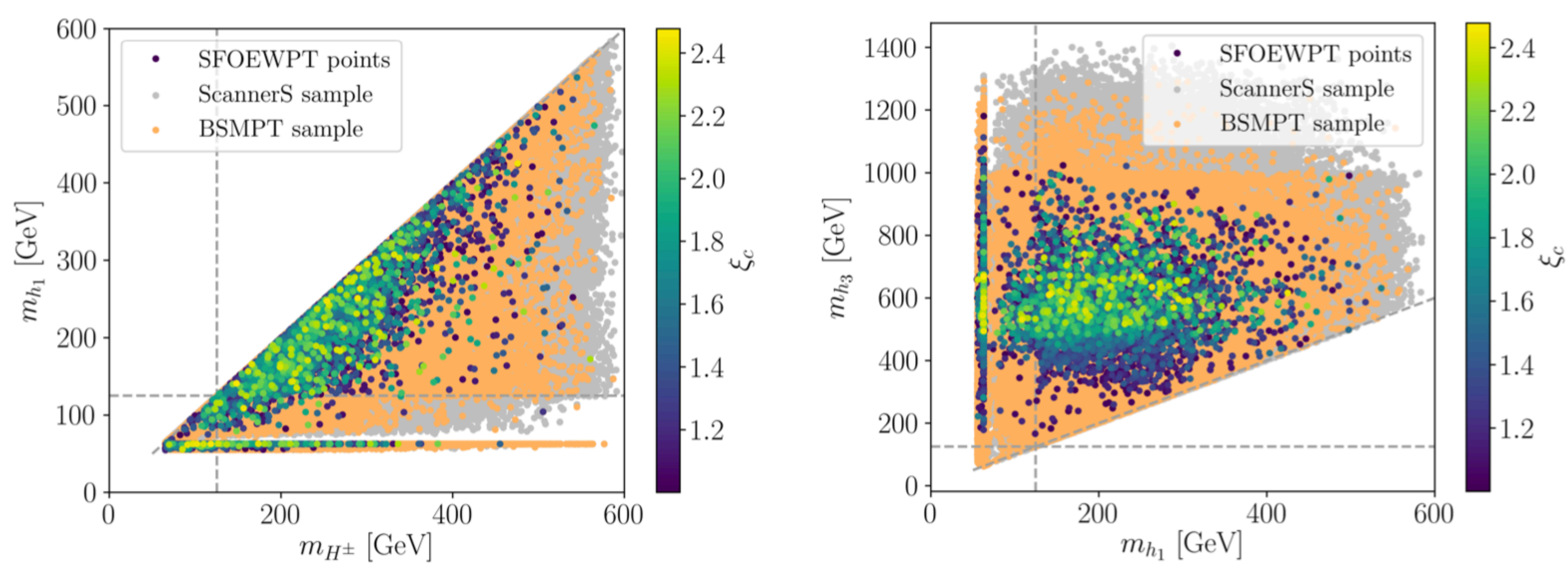
SFOEWPT
in
‚CP in the Dark‘

Mass Parameter Distribution for SFOEWPT

[Biermann,MM,Müller,'22]



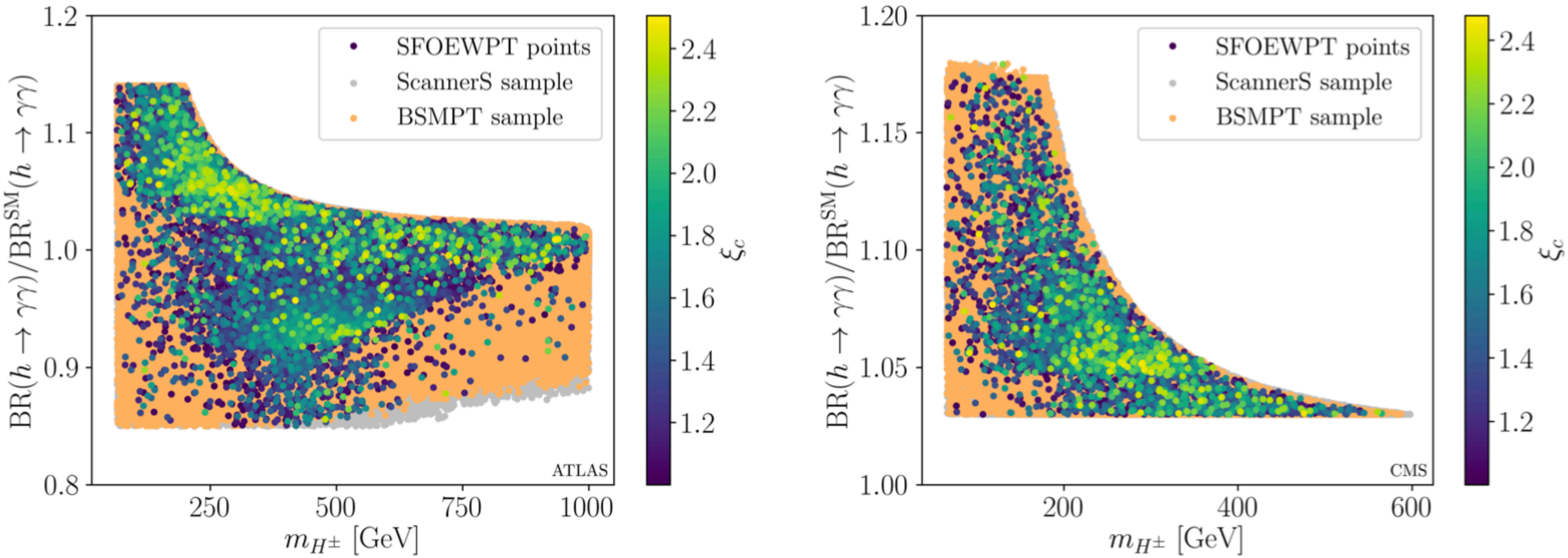
- points compatible w/ theor. & exp. constraints (ScannerS/grey), w/ NLO stable vacuum (BSMPT/orange) & w/ SFOEWPT (BSMPT/colored) scattered all over mass parameter planes $\rightsquigarrow$ no further constraint on mass parameter space
- $m_{H^\pm}$ range constrained due to $\mu_{\gamma\gamma}$ (from CMS)

Impact of Higgs-to-Photon Decay

[Biermann,MM,Müller,'22]

$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.99^{+0.15}_{-0.14}$ [Aaboud et al., '18]

$\mu_{\gamma\gamma}^{\text{CMS}} = 1.12^{\pm 0.09}$ [Sirunyan et al., '21]

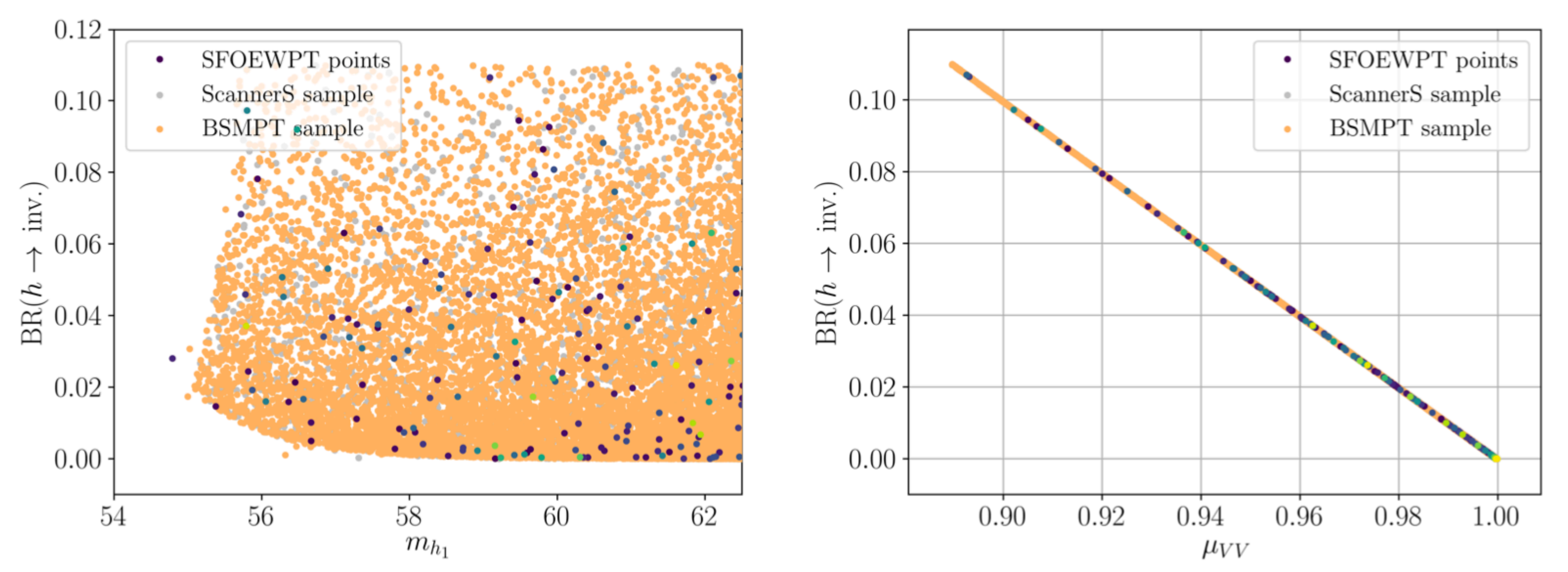


- increase for smaller $m_{H^\pm}$ (governed by λ_3)
- upper limit on $\mu_{\gamma\gamma}$: BFB and unitarity bounds ⇝ restrict max. λ_3 value

  => future increased precision in $\mu_{\gamma\gamma}$ can cut parameter space substantially

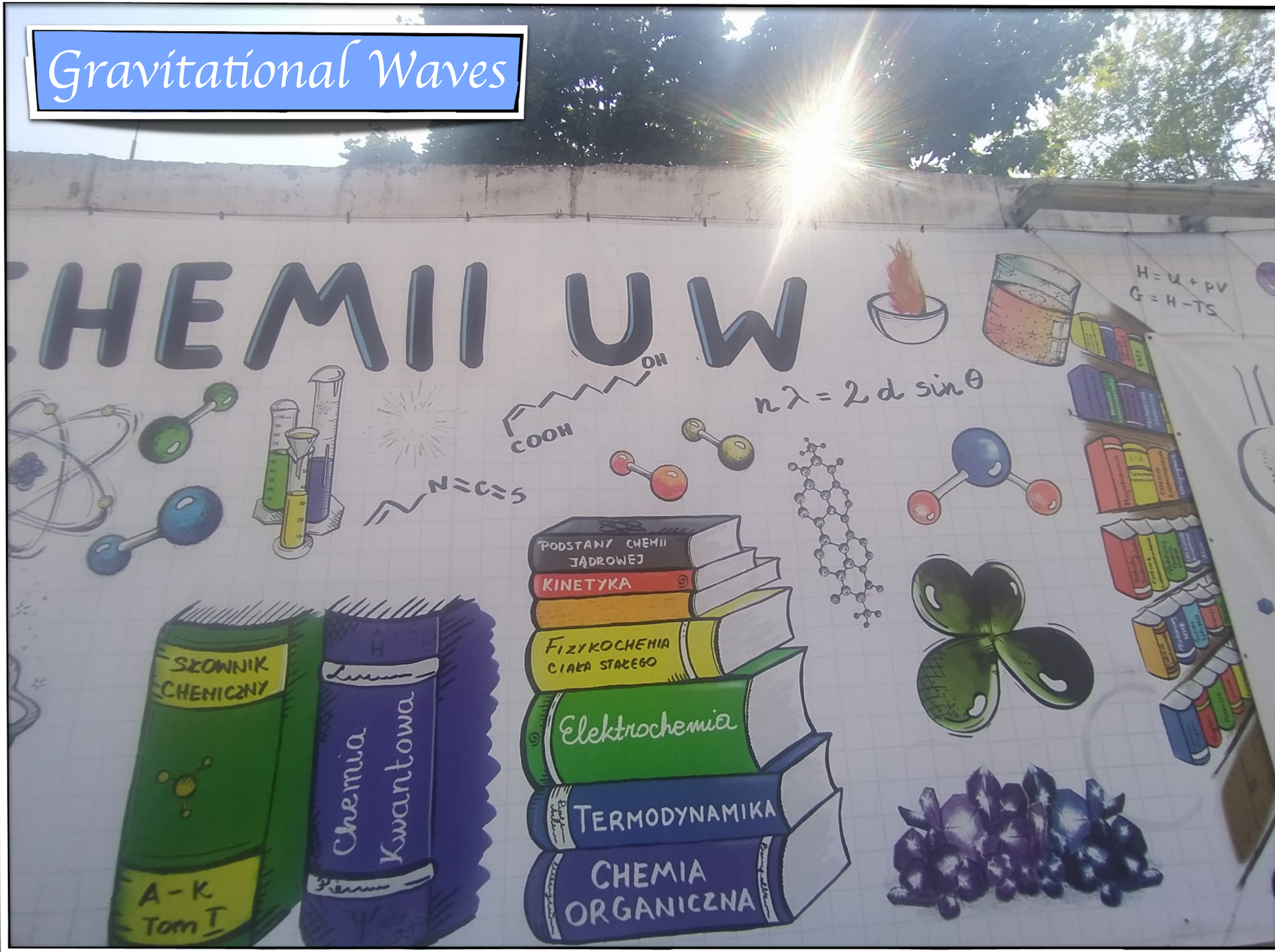
Higgs-to-Invisibles Decay

[Biermann,MM,Müller,'22]

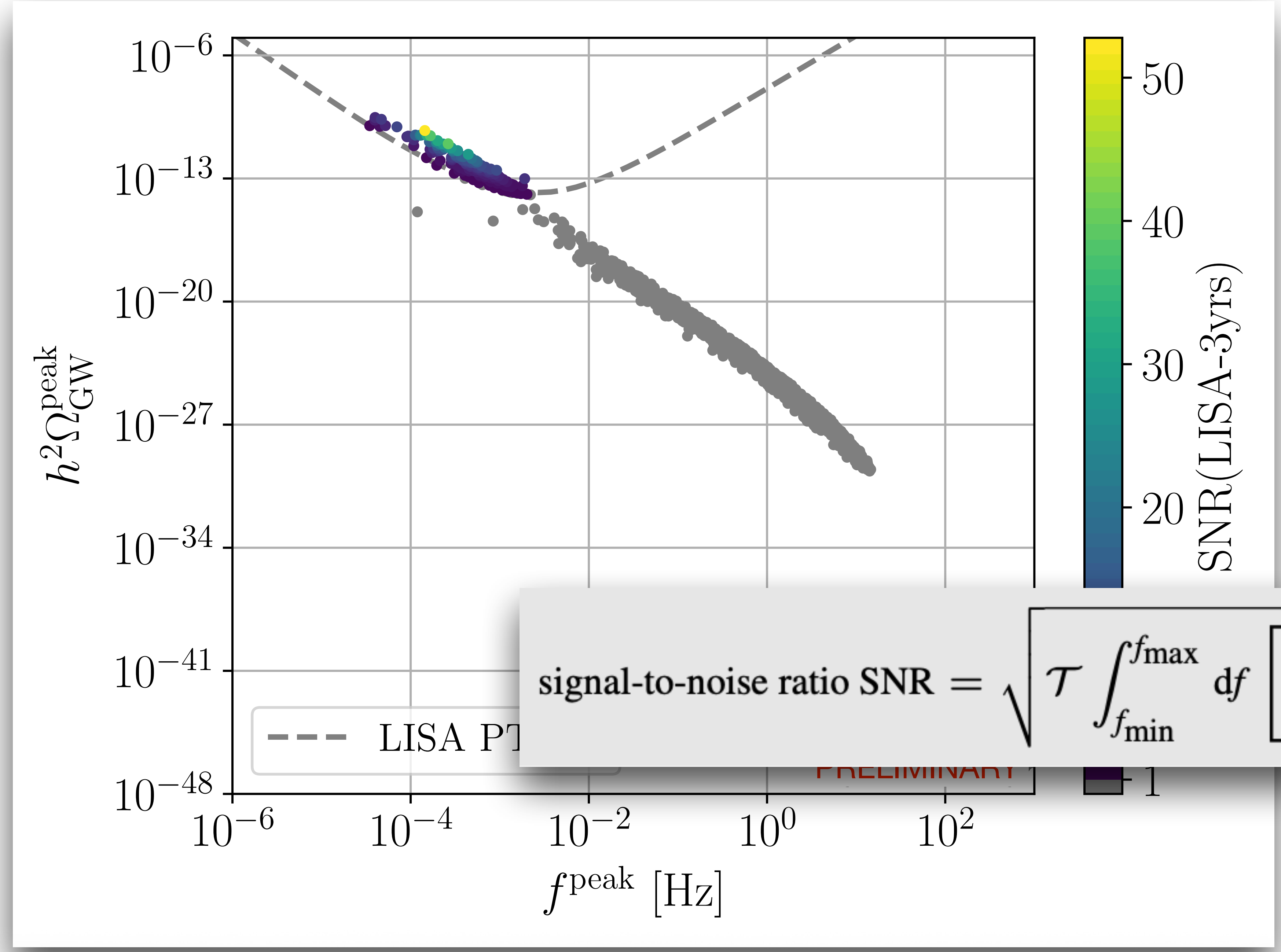


- SFOEWPT points scattered across allowed ScannerS parameter space
- BR(h->inv) strongly correlated w/ μ_{VV} ($V=W^{\pm},Z$): for μ_{VV}->1 SM-like Higgs BRs converge to SM values $\rightsquigarrow$ BR(h->inv) forbidden =>
- future increased precision in BR(h->inv) and μ_{VV} constrain parameter space, however, no further insights in strength of EWPT gained

Gravitational Waves



GW from (S)FOEWPT in ‚CP in the Dark'

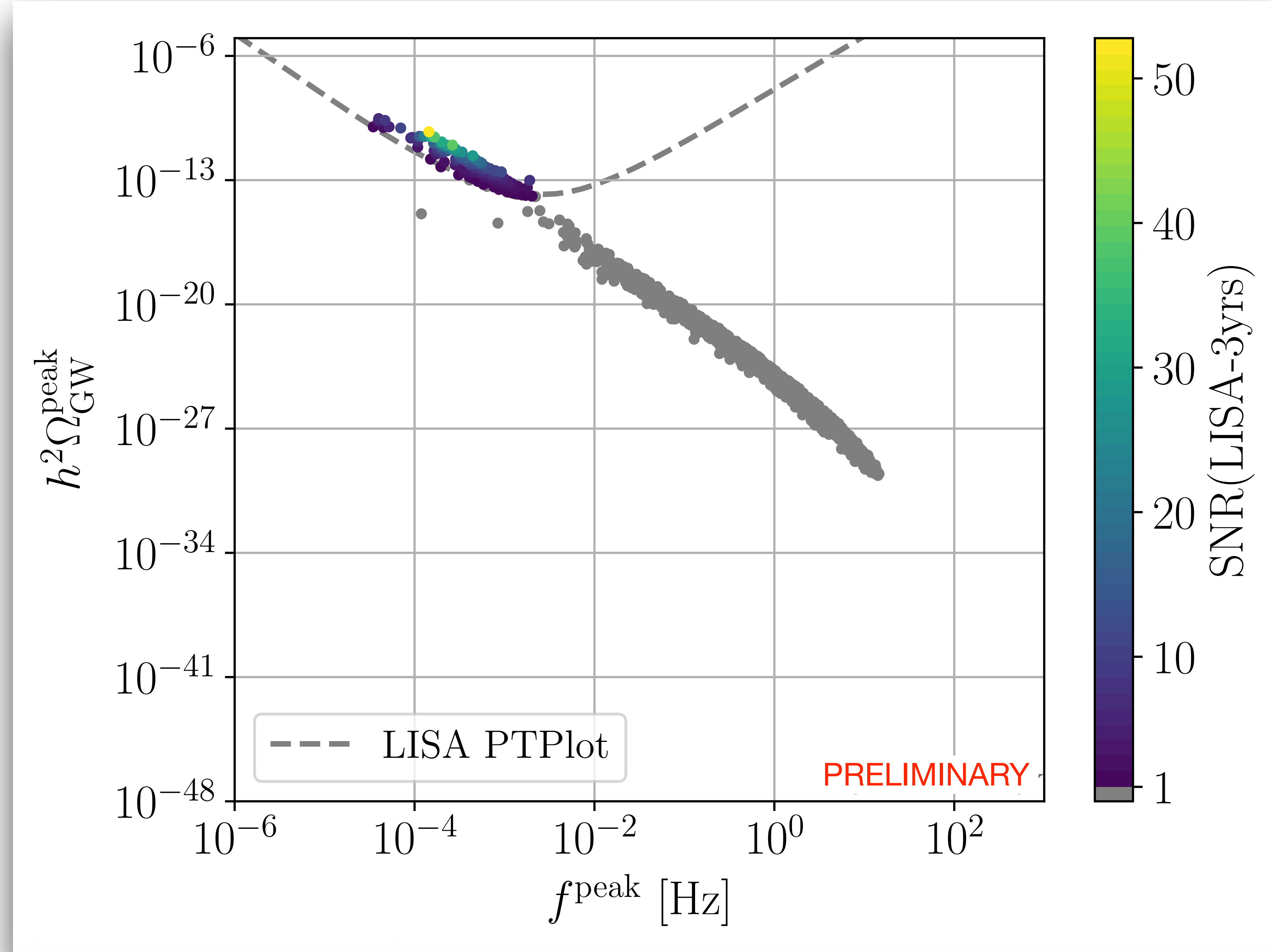


[Biermann,MM, Santos,Viana]

$$\text{signal-to-noise ratio SNR} = \sqrt{\mathcal{T}\int_{f_{\rm min}}^{f_{\rm max}} df \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm Sens}(f)}\right]^2}$$

- ∃ points w/ SNR(LISA-3yrs)>10, compatible w/ all relevant theor. and exp. constraints
- all points lead to EW minimum at T=0 (no vacuum trapping)
- all of the LISA-sensitive points (colored points) have SFOEWPT: ξ_c>1

GW from (S)FOEWPT in ,CP in the Dark'



[Biermann,MM, Santos,Viana]

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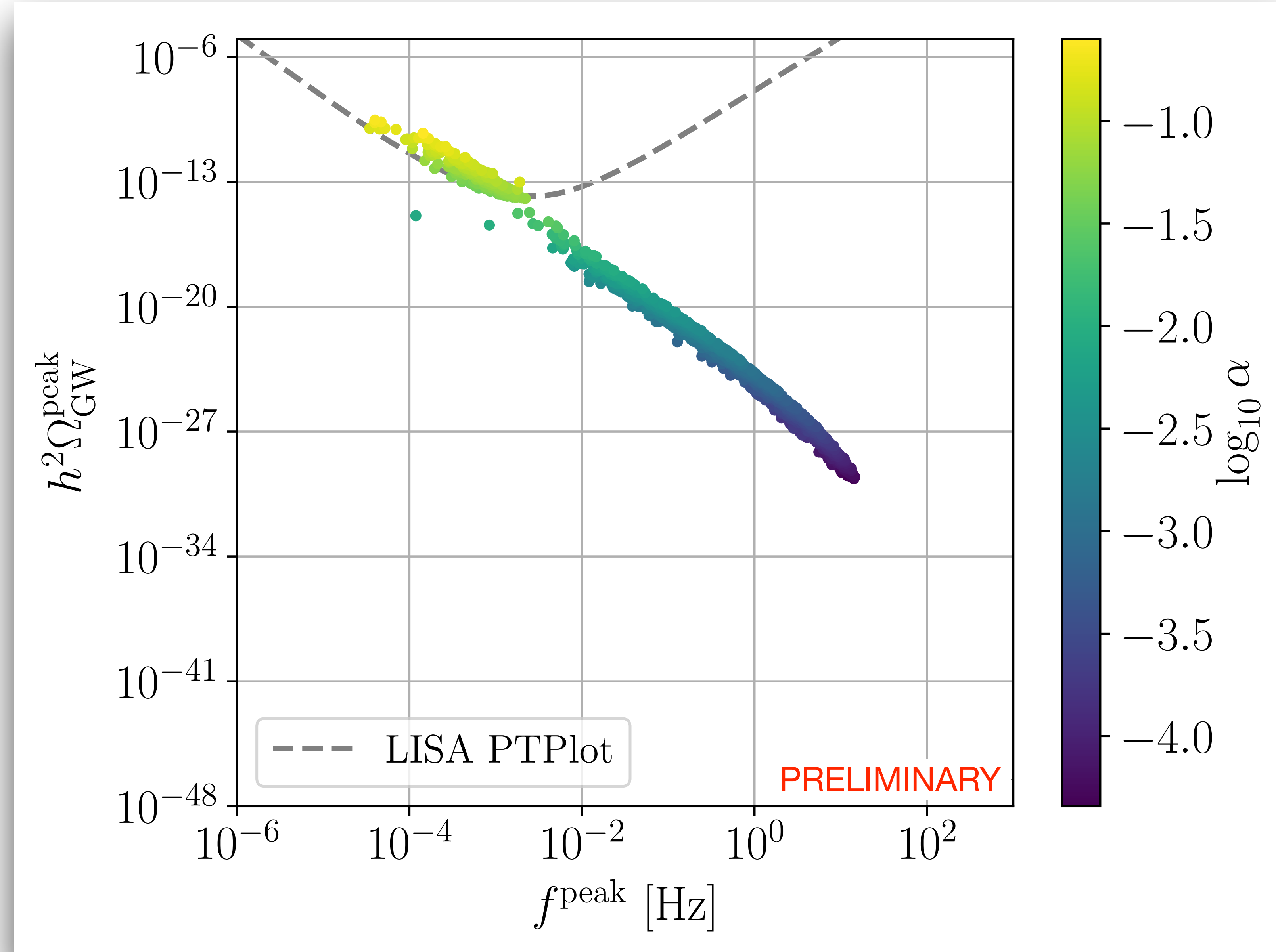
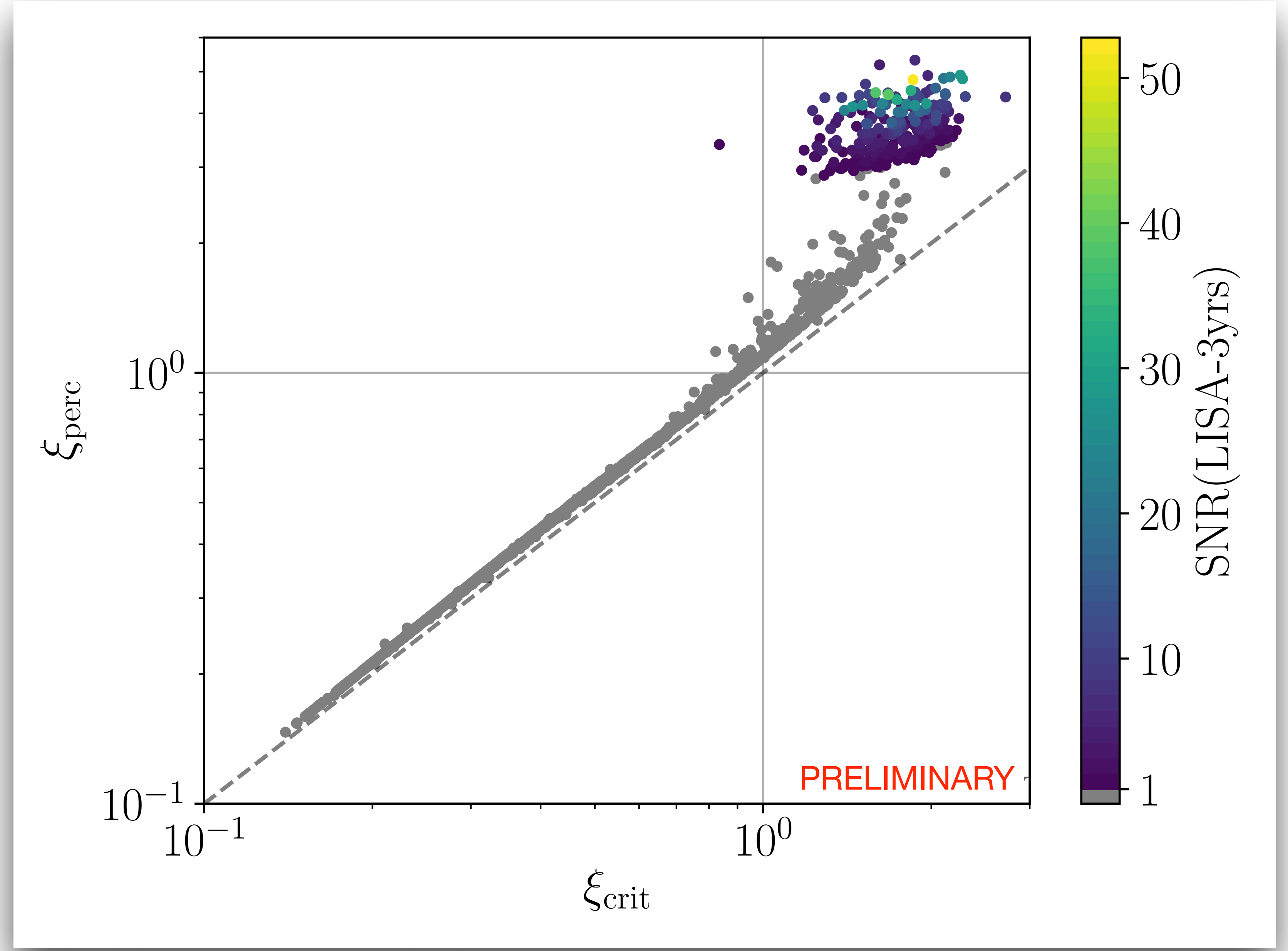
GW from (S)FOEWPT in ‚CP in the Dark'

[Biermann,MM, Santos,Viana]



Comparison with released latent heat during PT

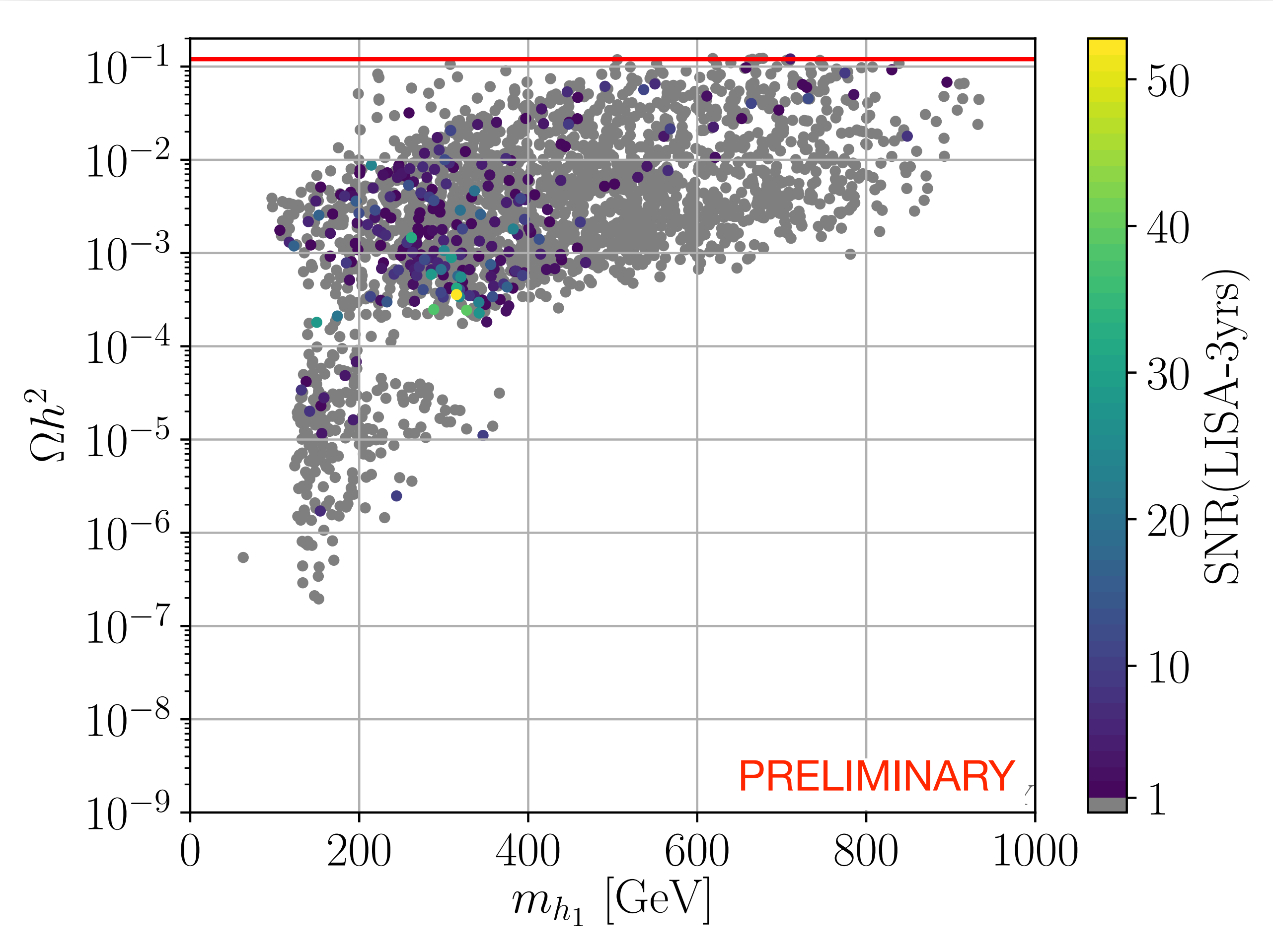
GW from (S)FOEWPT in ‚CP in the Dark'

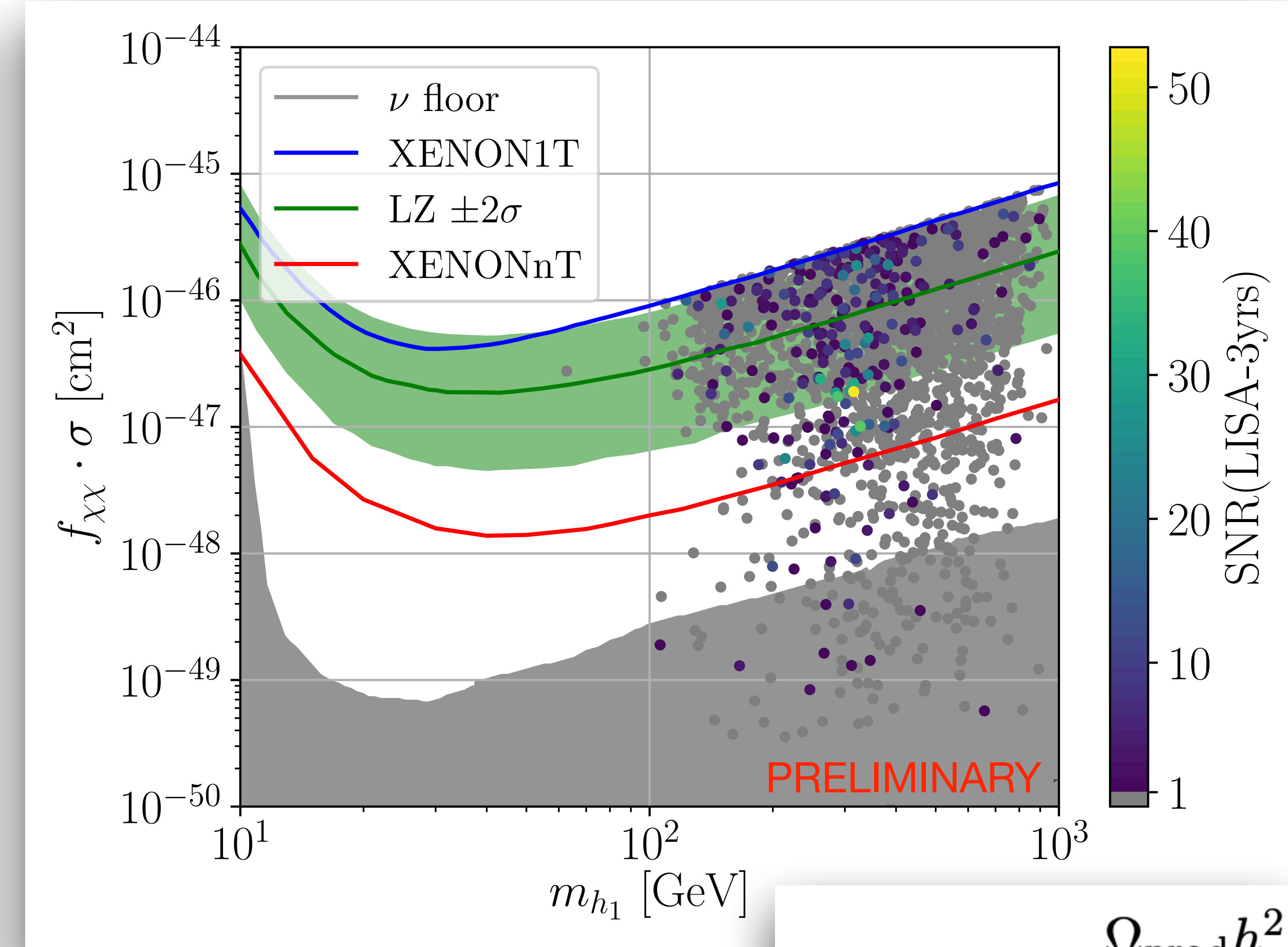


[Biermann,MM, Santos,Viana]

- comparison of $\xi_{per}=v_*/T_*$ and $\xi_c=v_c/T_c$
- colored points SNR(LISA-3yrs)>1
- (almost) all of the LISA-sensitive points have SFOEWPT: ξ_c>1

[Biermann,MM,Santos,Viana]



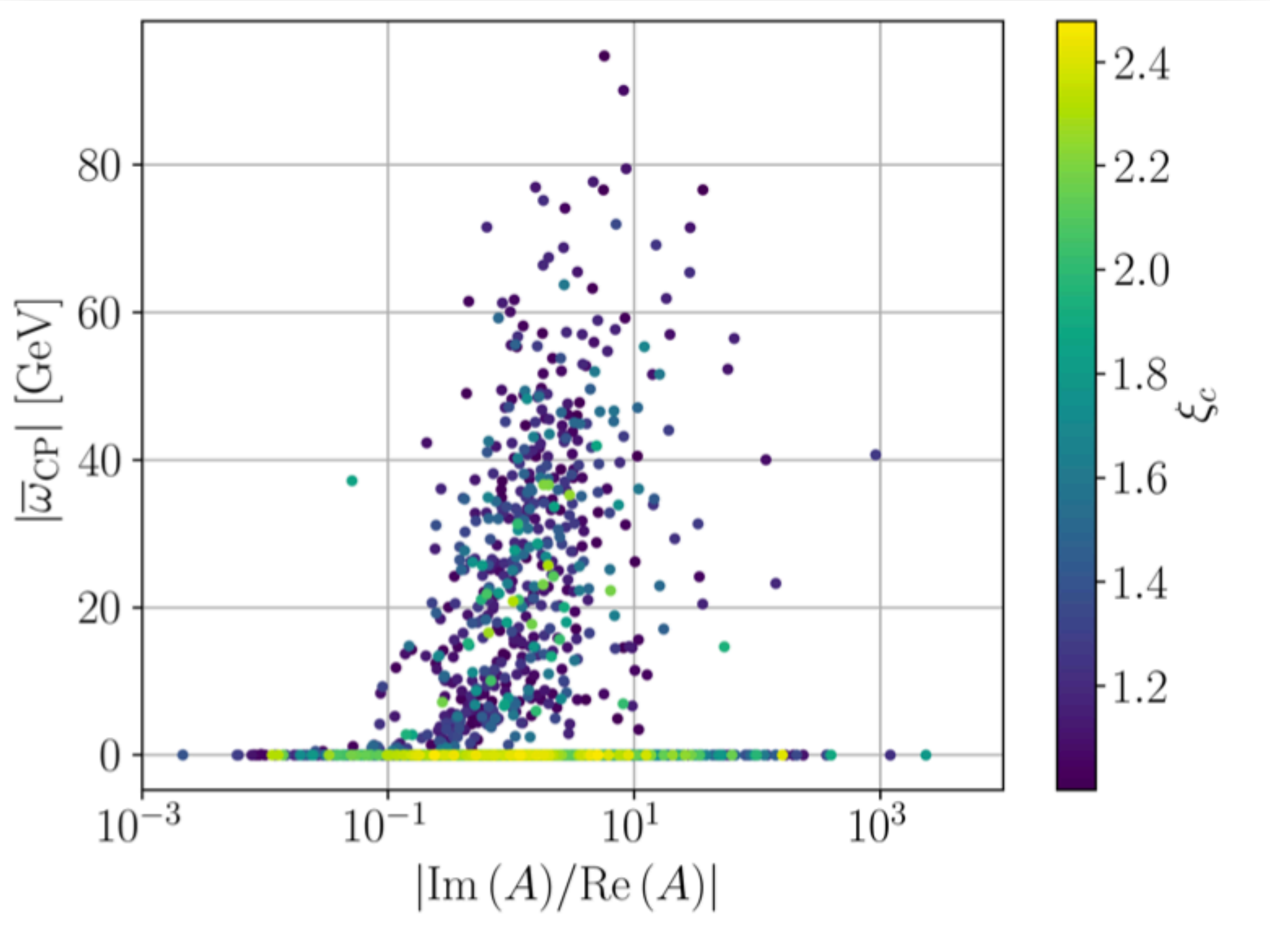


$$\sigma \cdot f_{\chi\chi} \equiv \sigma \cdot \frac{\Omega_{\rm prod} h^2}{\Omega_{\rm obs} h^2}$$

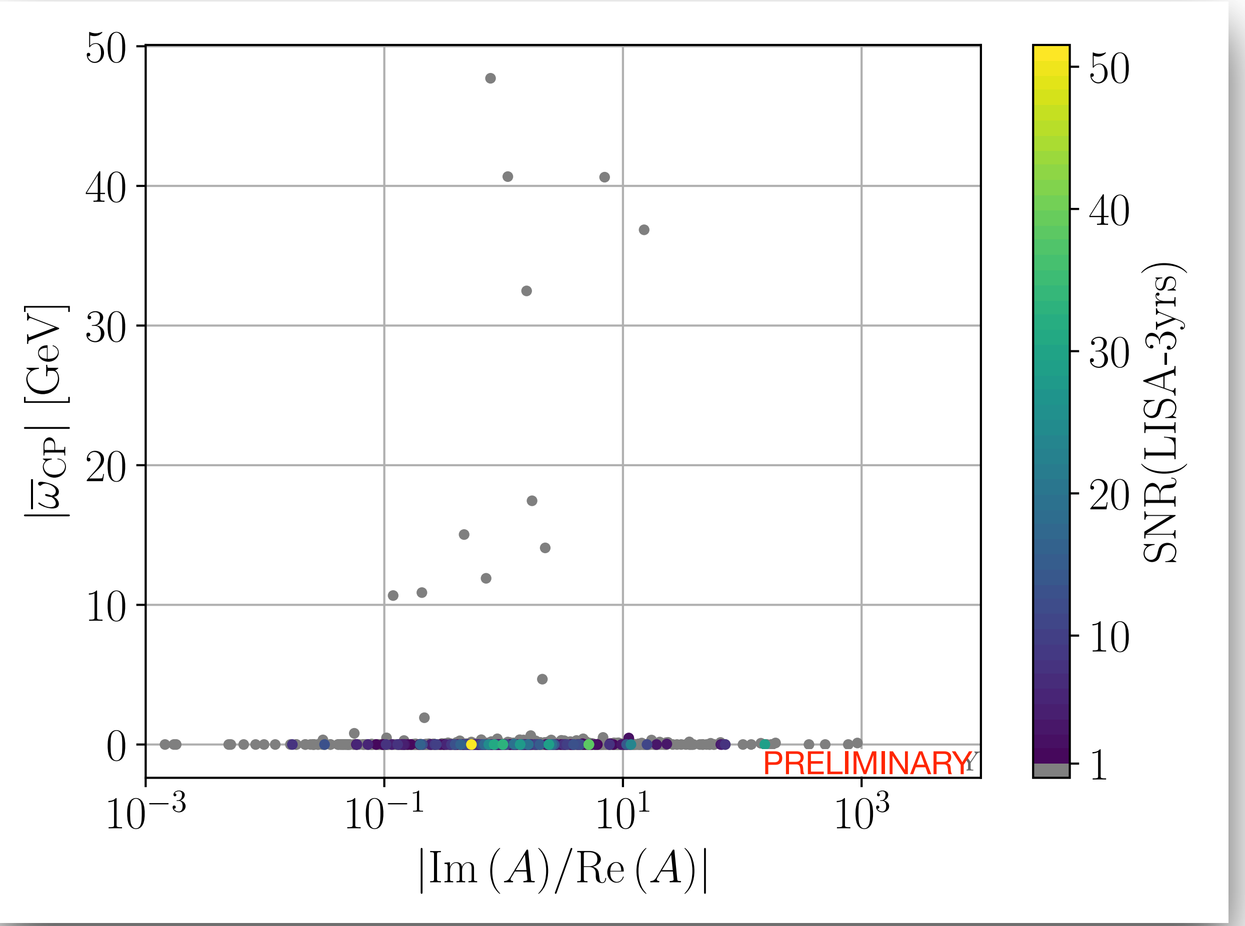
- Viable GW points (SNR(LISA-3yrs)>1 - colored points):
  compatible w/ relic density (<Ωh^2)
  above neutrino floor
  testable at future direct detection experiments

Spontaneous CP Violation

[Biermann,MM,Müller,'22]



[Biermann,MM,Santos,Viana]



- possibility of SFOEWPT & spontaneous CP violation (CPV)
- spontaneous Z_2 violation also possible => non-standard CPV transferred to visible sector
- interesting for EWBG!

- SNR(LISA-3yrs)>1 (colored) for max. $|\omega_{CP}|=O(10^{-1})$
- spontaneous Z_2 violation leads to plasma friction w/ (former) DM direction =>
- spontaneous CPV may escape run-away

Conclusions

- Generation of BAU through EWBG requires BSM physics: extended Higgs sectors
- SFOEWPT induces gravitational waves testable at LISA
- Code BSMPT: Calculation of loop-corrected effective potential incl. thermal masses
- BSMPTv3: Calculation of gravitational waves spectrum, signal-to-noise ratio at LISA
- Model ‚CP in the Dark': SM-like Higgs, extended dark sector w/ explicit CP violation
- ‚CP in the Dark': parameter points
  * compatible w/ all relevant exp. (incl. DM observables) & theor. constraints
  * strong first-order electroweak phase transition
  * spontaneous CP and Z_2 violation possible ⇝ CP violation transferred to visible sector
  * gravitational waves spectrum testable at LISA
- Code BSMPTv3 to be released soon - stay tuned.


Bijou
www.bijoudecascais.pt
Thank you for your attention!

Slide taken from Lisa Biermann

How to choose v_b?

see [Athron et al., '23] for a review and references within

- $v_b = 0.95$ for our plots; calculation of v_b is still an open question:
- basic problem: when does plasma friction match driving pressure of bubble expansion? (model-dependent out-of equilibrium calculation)
- *but* only two equations from energy-momentum tensor conservation for unknown v_b, plasma temperature and plasma velocities around bubble wall are unknown
- often-made approximation: local thermal equilibrium → + entropy conservation
- *but* solving Boltzmann equation requires knowledge of collision integral, simplified by ansatz for distribution function (model-dependent!)

- `BSMPTv3` provides:
  - v_w as input parameter or set to $v_w = 0.95$
  - estimate by [Lewicki et al., '22] (assuming steady-state ($\dot{v}_b = 0$) and local thermal equilibrium):

$$v_b \simeq \begin{cases} \sqrt{\frac{\Delta V}{\alpha \rho_\gamma}} & \text{if} \quad \sqrt{\frac{\Delta V}{\alpha \rho_r(T_*)}} < v_{\text{CJ}} \\ 1 & \text{if} \quad \sqrt{\frac{\Delta V}{\alpha \rho_r(T_*)}} > v_{\text{CJ}} \end{cases}$$

  - estimate by [Laurent et al., '23] (assuming local thermal equilibrium):

$$v_b = \left(\left| \frac{3\alpha + \Psi - 1}{2\left(2 - 3\Psi + \Psi^3\right)} \right|^{\frac{p}{2}} + \left| v_{\text{CJ}} \left(1 - a \frac{(1 - \Psi)^b}{\alpha} \right) \right|^{\frac{p}{2}} \right)^{\frac{1}{p}}$$

  with Chapman-Jouguet velocity $v_{\text{CJ}} = \frac{1}{1+\alpha}\left(c_s + \sqrt{\alpha^2 + \frac{2}{3}\alpha}\right)$ (expansion mode of chemical combustion, need not be satisfied in cosmological phase transition [Laine, '94], $v_b > v_{\text{CJ}}$ in general (otherwise stopped by plasma friction))
  - estimates of v_b in *local thermal equilibrium* serve as **upper bound** as v_b gets reduced by non-equilibrium effects!

$$\rho_r(T_*) = \frac{\pi^2}{30} g^*(T_*) T_*^4$$

rel. matter density

$$\Psi = \frac{\omega_t}{\omega_f}$$ enthalpy ratio

$a = 0.2233$ num. fit result

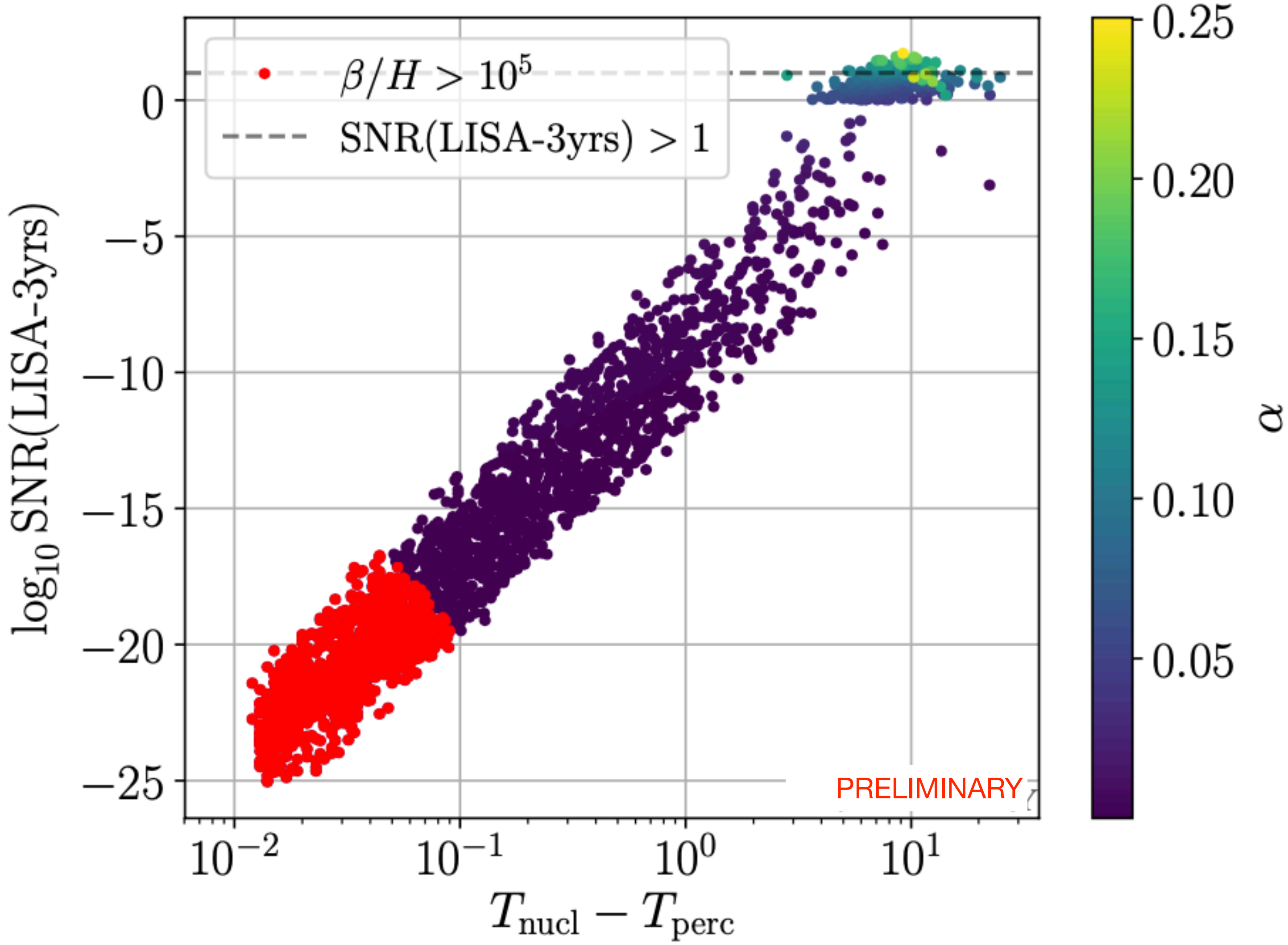
$b = 1.704$ num. fit result

$p = -3.433$ num. fit result

$$c_s = \frac{1}{\sqrt{3}}$$ sound speed

What about supercooling?

Slide taken from Lisa Biermann



$\Rightarrow$ transition duration around 10 GeV for SNR(LISA-3yrs) > 1

$\rightarrow$ [Wang et al., '20]:

- $*$ *slight supercooling* for $\alpha \leq 0.1$
- $*$ *mild supercooling* for $0.1 \leq \alpha \leq 0.5 \rightarrow$ case for our SNR(LISA-3yrs) > 1 points
- $*$ *strong supercooling* for $\alpha > 0.5$

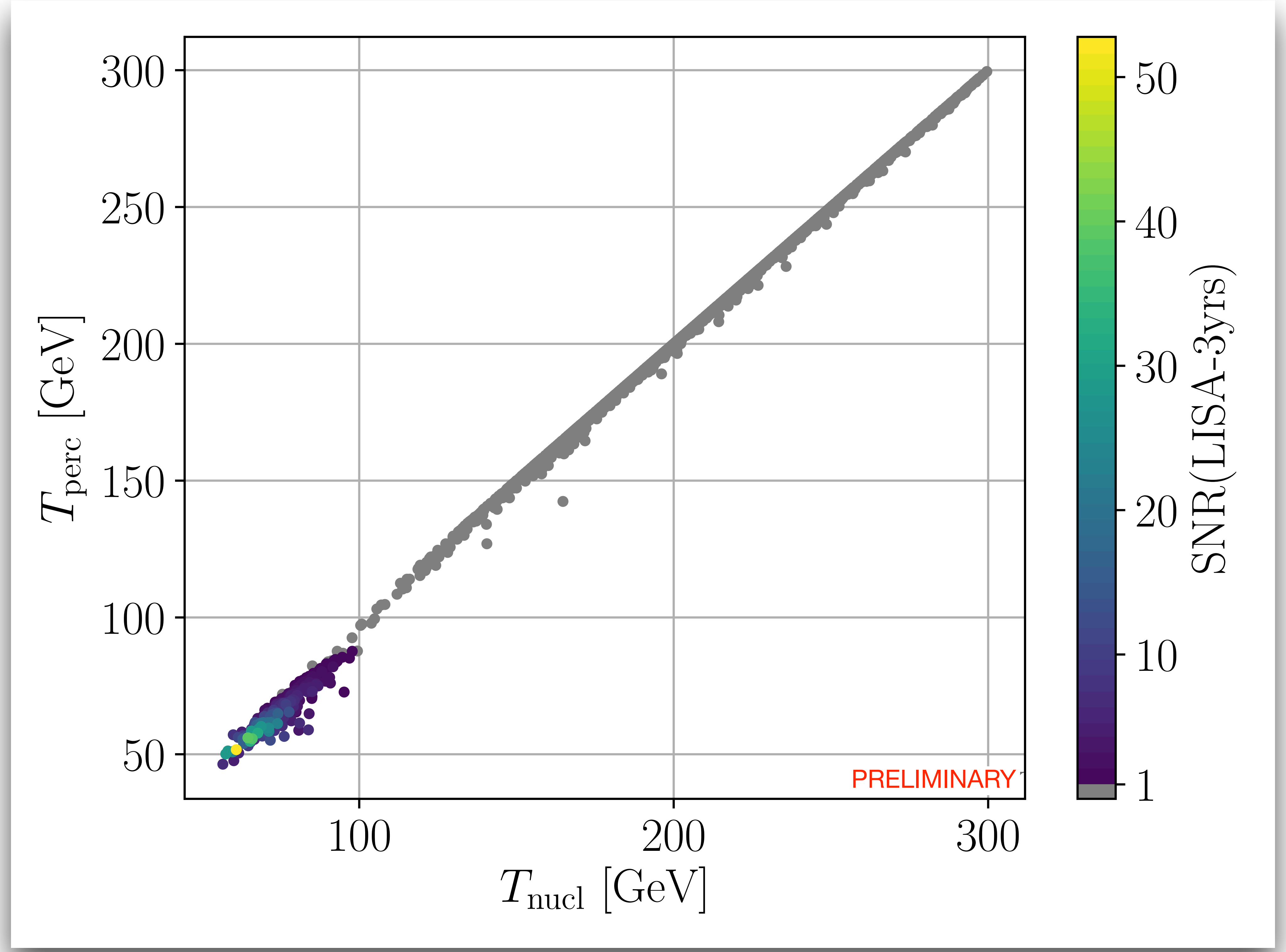
Gravitational Waves Spectrum

✦ Power Spectrum:

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm GW}^{\rm peak}\left(\frac{4}{7}\right)^{-\frac{7}{2}}\left(\frac{f}{f_{\rm peak}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{\rm peak}}\right)^2\right]^{-\frac{7}{2}}$$

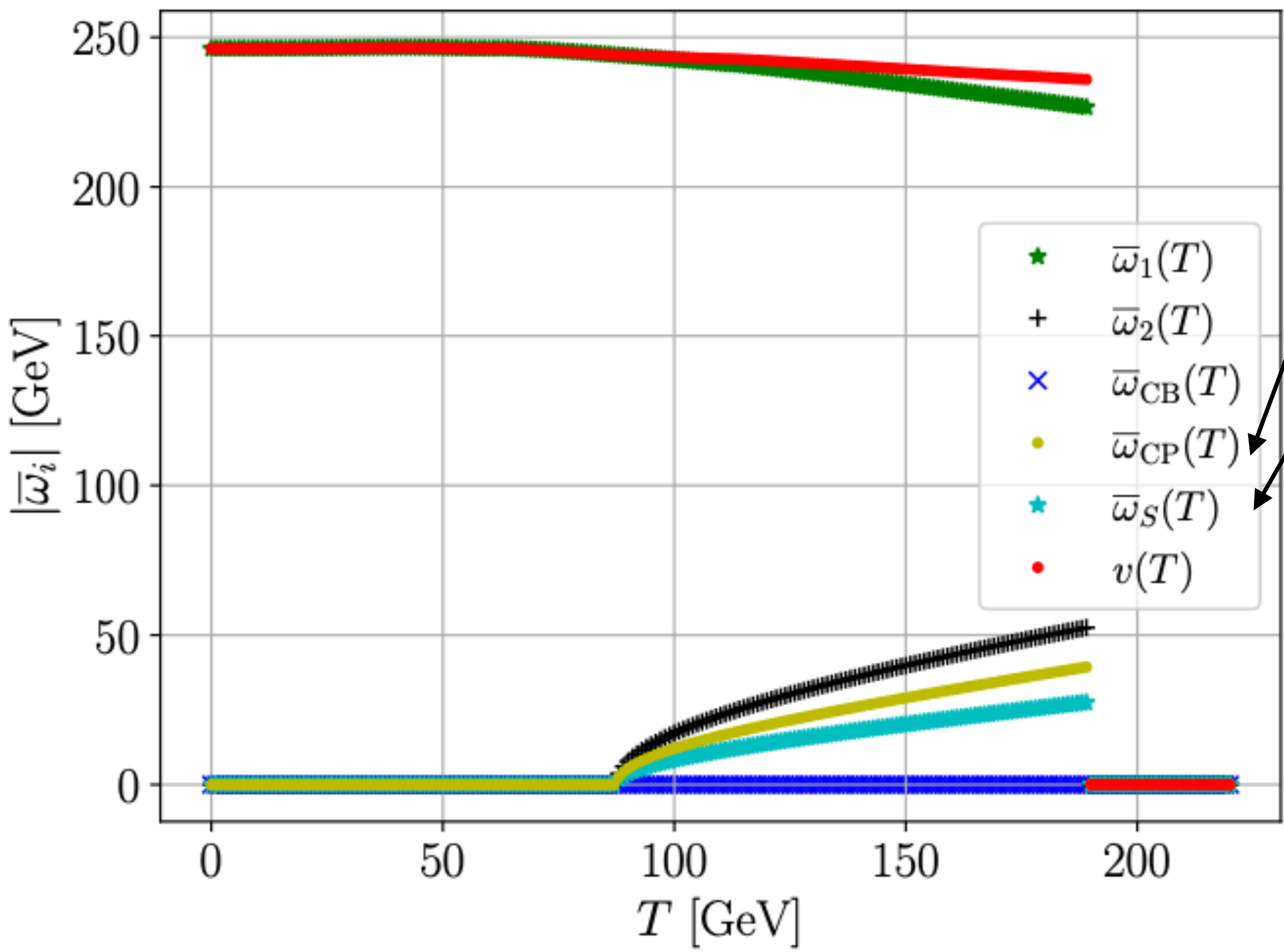
Nucleation and Percolation Temperatures

[Biermann,MM,Santos,Viana]



Spontaneous CP Violation

[Biermann,MM,Müller'22]



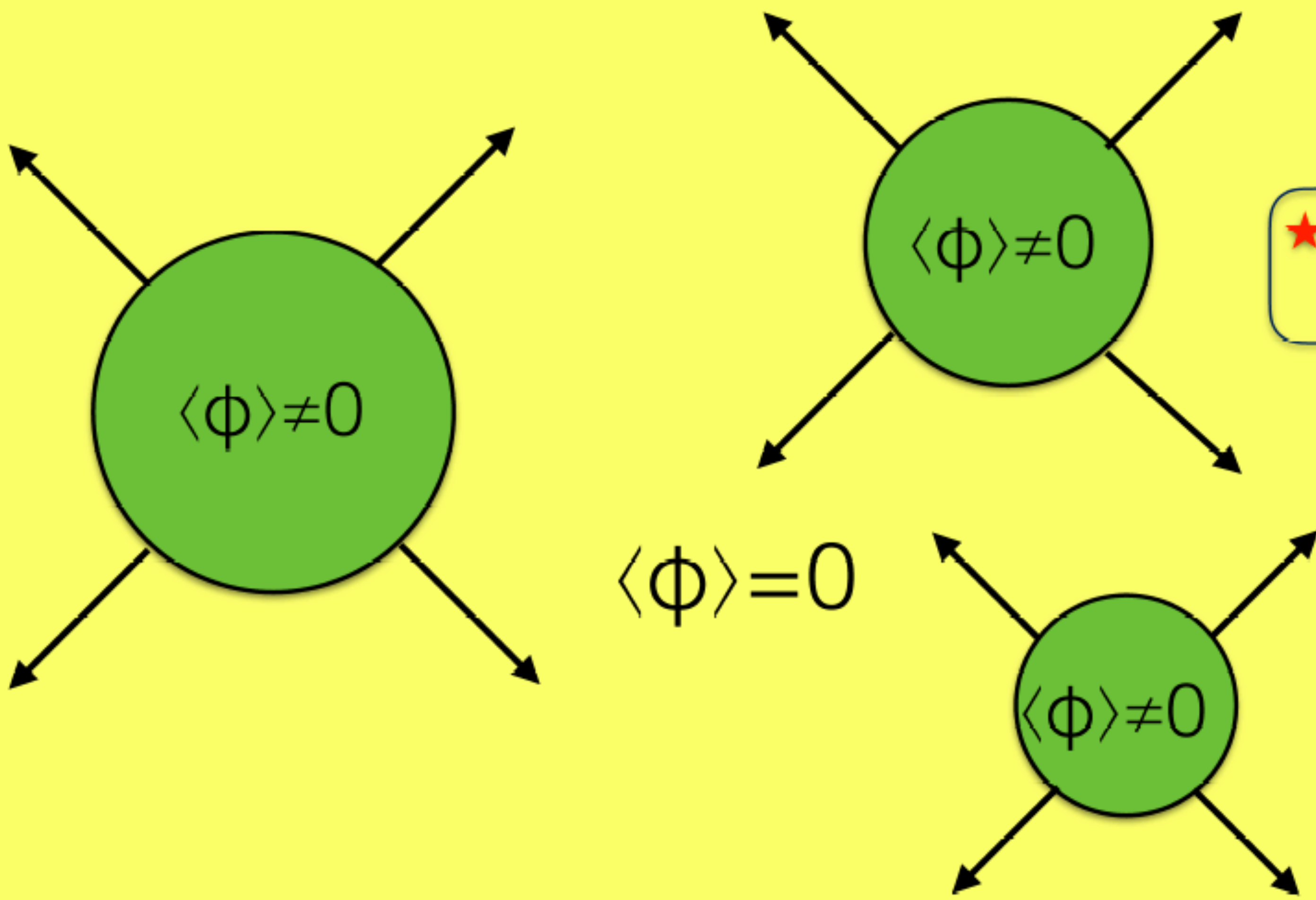
CP-violating VEV in dark sector plus singlet VEV generated spontaneously => CP violation transferred to visible sector

Strong first order electroweak phase transition

Baryogenesis in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle \phi_c(T_c) \rangle / T_c \geq 1$

ϕ_c, T_c
VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall ★