Forbidden Conformal Dark Matter at a GeV

Steven Ferrante
In collaboration with Ameen Ismail, Seung J. Lee, Yunha Lee

arXiv:2308.16219

Gravitational Wave Signals!

- June 2023 – NANOGrav observes new GW signals
- Pulsar timing array – sensitive to very low frequencies !

NANOGrav
Physics Frontiers Center

NANOGrav Collaboration, 2306.16217, 2306.16213, 2306.16219

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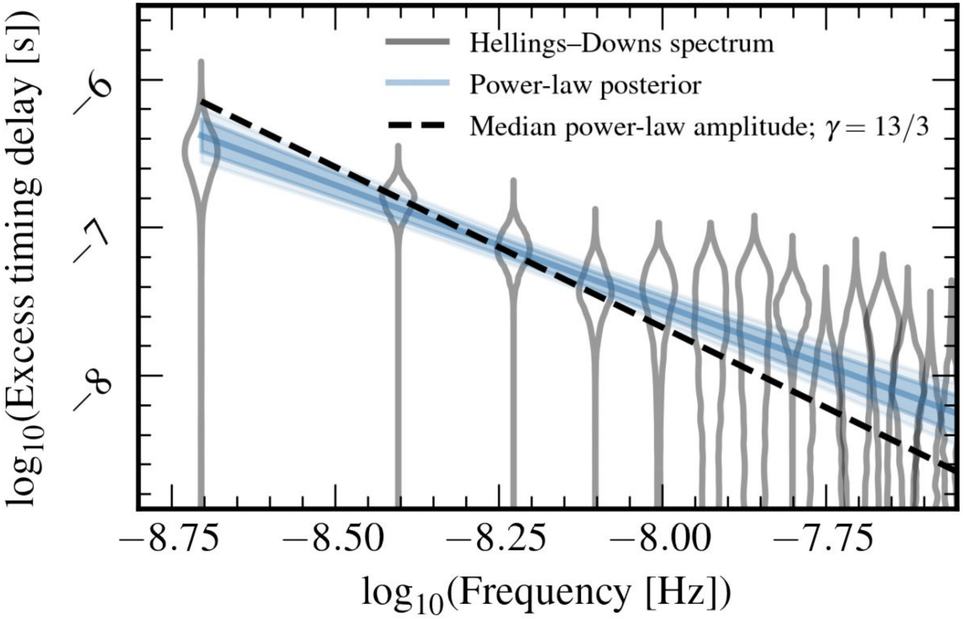

Apart from SMBHB explanation:

- Cosmic inflation
- 1st order phase transition
- Topological defects

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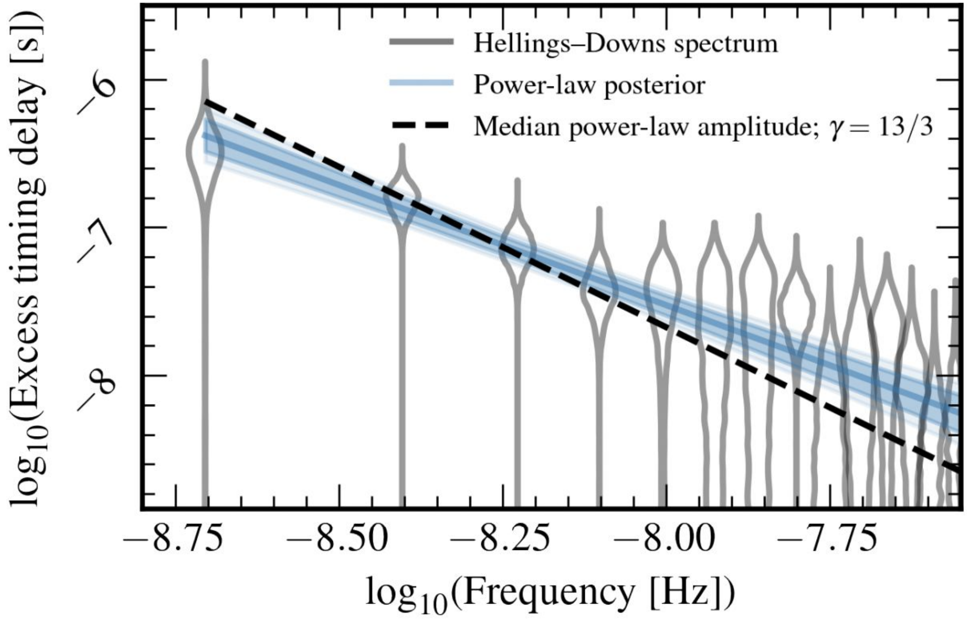

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Model Building

1. Spontaneously broken conformal symmetry f, Λ
2. GeV-scale dynamics / phase transition

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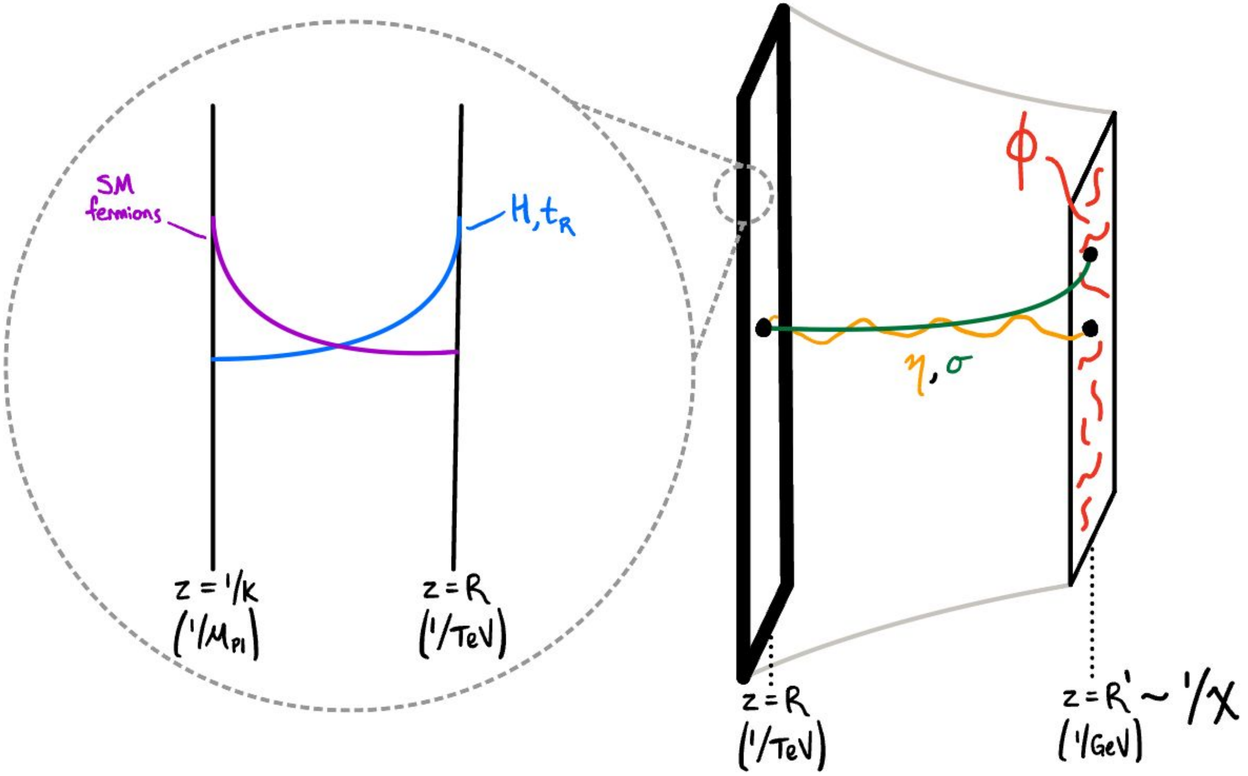
5d perspective:



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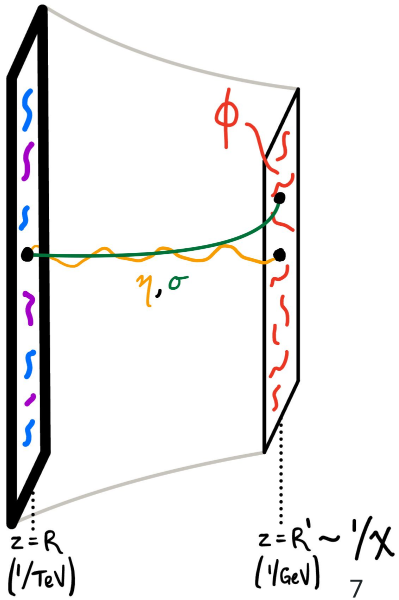
- Freeze-out via
  - $\langle \sigma v(\phi\phi \to \mathrm{SM}) \rangle \sim m_\phi^2/\Lambda^4 \ll obs.$



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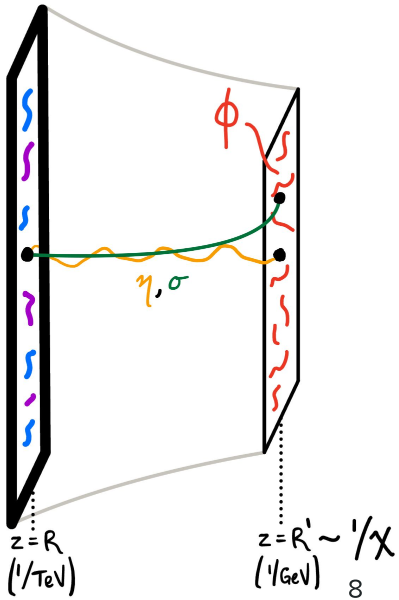
"secluded"
$(m_\phi > m_\sigma)$



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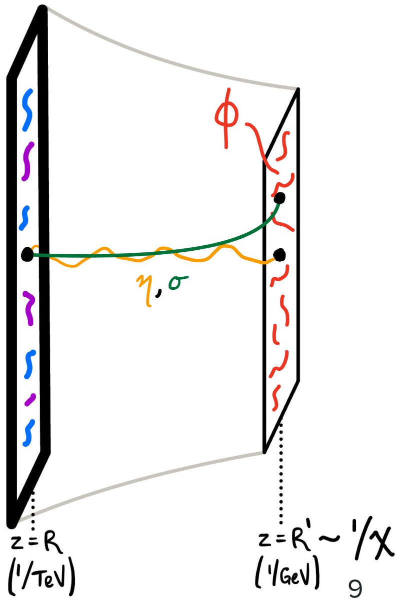

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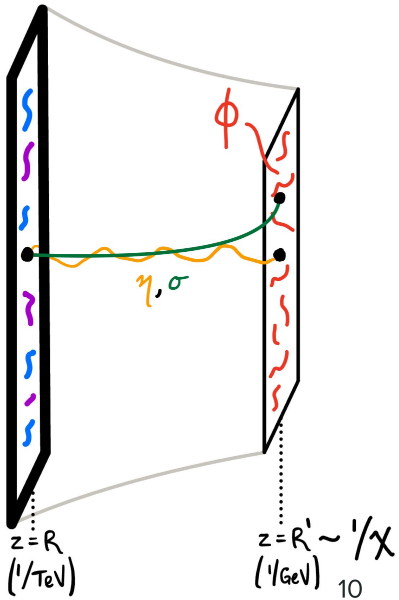

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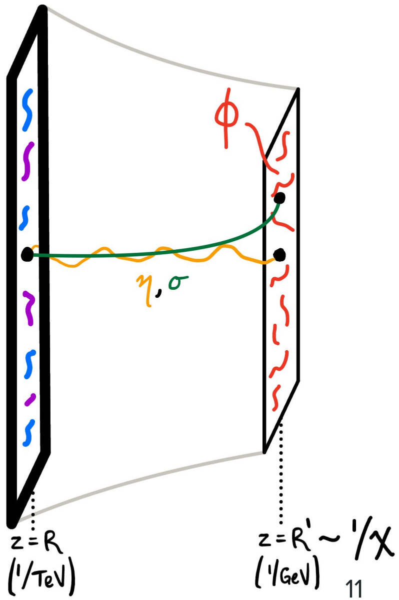
"forbidden" $(m_\phi < m_\sigma)$ $\sim obs.?$

- Provides 5d explanation for $\mathcal{O}(m_\sigma) \sim \mathcal{O}(m_\phi)$!



Ruderman et al, 1505.07107

Forbidden DM

- Dilaton interactions come from Goldberger-Wise stabilization

$$\int d^5x \;\; \mathcal{L}_\eta \;\; \rightarrow \;\; \int d^4x \; \mathcal{L}_\chi$$

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$$\int d^5x \;\; \mathcal{L}_\eta \;\; \rightarrow \;\; \int d^4x \; \mathcal{L}_\chi \sim \chi^4 - \chi^{4+\epsilon}$$

$$\int dy, \quad \chi \sim 1/R',$$

$$\epsilon \sim \sqrt{4+m_\eta^2} - 2$$

Forbidden DM

- Dilaton interactions come from Goldberger-Wise stabilization

$$\int d^5x \ \mathcal{L}_\eta \ \rightarrow \ \int d^4x \ \mathcal{L}_\chi \ \rightarrow \ \int d^4x \ \mathcal{L}_\sigma$$

$$\chi = \langle \chi \rangle + \sigma$$

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$$\int d^5x \;\; \mathcal{L}_\eta \;\rightarrow\; \int d^4x \; \mathcal{L}_\chi \;\rightarrow\; \int d^4x \; \mathcal{L}_\sigma$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{5}{6}\frac{m_\sigma^2}{f}\sigma^3 - \frac{11}{24}\frac{m_\sigma^2}{f^2}\sigma^4$$

} **GW Potential**

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GW Potential

Spurion Analysis

$$m_\phi \to m_\phi \frac{\chi}{\langle\chi\rangle}$$

Spurion Analysis

$$m \to m\frac{\chi}{\langle\chi\rangle}(R\langle\chi\rangle)^2$$

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GW Potential

$$+ \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4!}\lambda_\phi^4 - \left(\frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right)\frac{1}{2}m_\phi^2\phi^2$$

Spurion Analysis $m_\phi \rightarrow m_\phi \frac{\chi}{\langle\chi\rangle}$

$$- \frac{\sigma}{\Lambda^2/f}\left[\sum_{\rm fermions} m_\psi \overline{\psi}\psi + m_h^2 h^2 - 2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu\right]$$

Spurion Analysis $m \rightarrow m\frac{\chi}{\langle\chi\rangle}(R\langle\chi\rangle)^2$

- These interactions are used to calculate Relic Abundance!

Belanger et al, 1005.4133

Conformal Phase Transition

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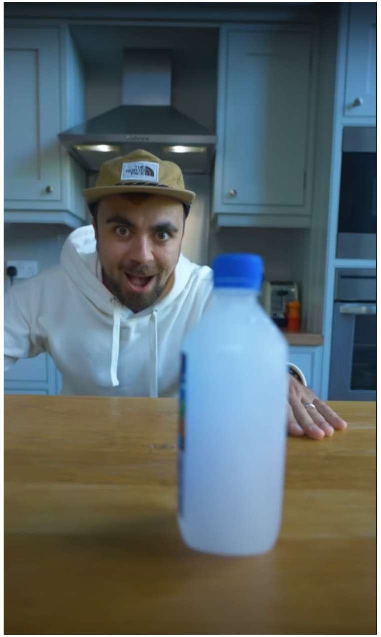

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- Gravitational Waves:
  - Frequency

$$f_{\rm GW} \sim \frac{\beta_{\rm GW}}{H} = T \frac{dS_b}{dT}\bigg|_{T_n}$$

Caprini et al, 1512.06239

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- PT Completion: $\Gamma > H^4 \Rightarrow T_n \; (< T_c)$
- Gravitational Waves:
  - Frequency
  - Amplitude

$$\alpha_{\mathrm{GW}} \sim \frac{\text{energy released during PT}}{\text{energy of radiation bath}} \sim \frac{T_c^4}{T_n^4} \gg 1$$

Caprini et al, 1512.06239

Dilaton Phenomenology

- Dilaton coupling to fermions = Higgs couplings, scaled by $\kappa = \frac{vf}{\Lambda}$
- Theoretical Bounds
  - Dilaton EFT – $m_\sigma < 4\pi f$
  - PT Completion – $\Gamma > H^4$
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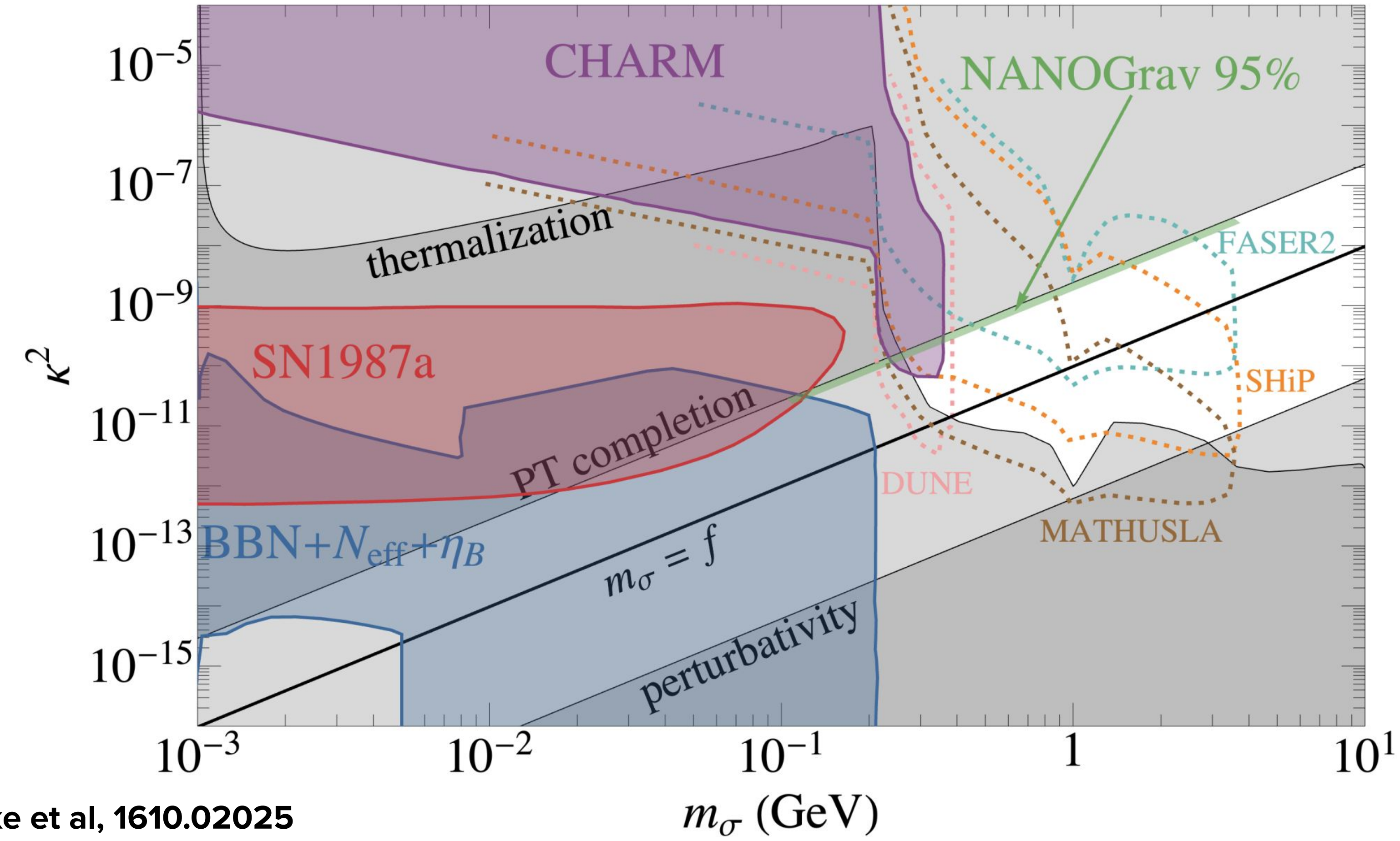
  - Thermalization – $\Gamma_\sigma > H$
- Experimental Bounds
  - Cosmological bounds on late decays
  - Supernovae cooling
  - CHARM beam dump experiment
- NANOGrav prediction
  - Frequency $\beta_{\rm GW}/H < 27$
  - Amplitude $T_R \in (0.017, 3.3)\ \text{GeV}$

Dilaton Phenomenology



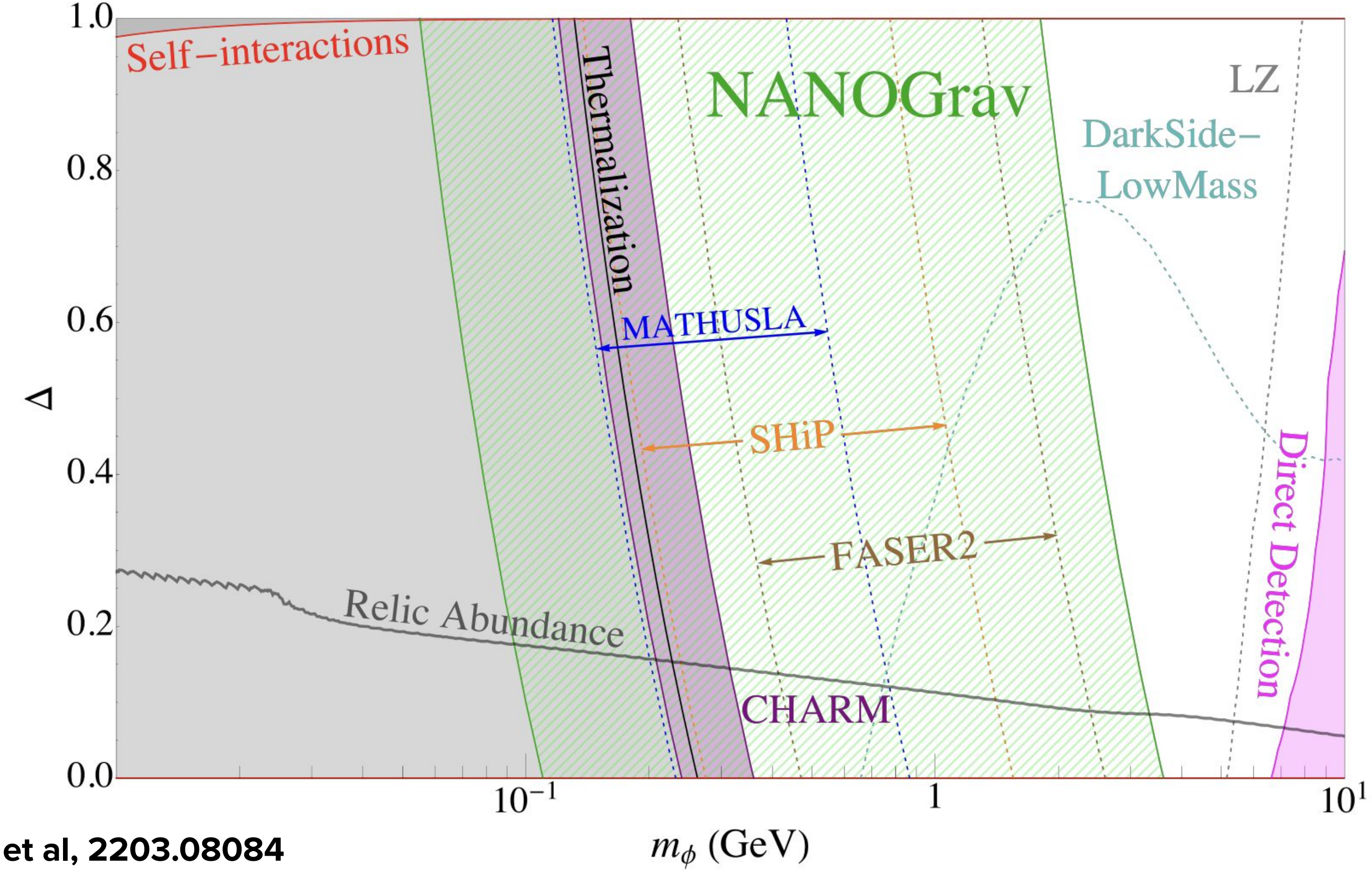
T Flacke et al, 1610.02025

DM Phenomenology

- Mass splitting defined by $\Delta = \frac{m_\sigma - m_\phi}{m_\phi}$ … "how 'forbidden' the DM is"
- Other experimental constraints:
  - Merging Galaxy Clusters (Self-Interactions σ_{SI})
  - Direct Detection Constraints (DM-Nucleon $\sigma_{\phi N}$)

DM Phenomenology

$$f = 4.5 m_\sigma$$



D.S. Akerib et al, 2203.08084

Conclusion

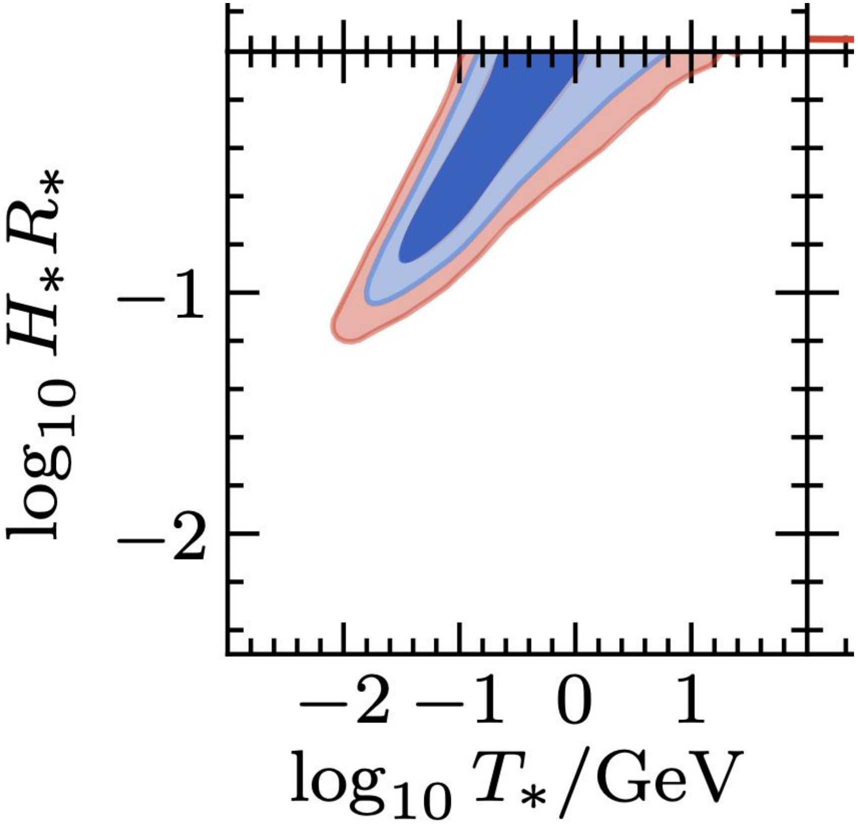
- Stochastic GWs can provide a new probe of DM models or other new physics scenarios.

- Forbidden conformal DM at a GeV is a natural hypothesis for the NANOGrav signal
  - Even outside of NANOGrav, provides a viable DM candidate

- Future:
  - Consider entire frequency spectrum and compare to data, SMBHBs
  - Consider secluded case -- (BHs can open channels for d-wave DM…)
  - Consider non-minimal scenarios
  - Wait eagerly for more data !!

BACKUP

Backup – nanograv bounds



$$T_R \sim T_*$$

$$\beta/H = (8\pi)^{1/3}/(H_* R_*)$$

Backup – dilaton couplings to trace anomaly

$$-\frac{\sigma}{\Lambda^2/f}\left[\frac{\beta_e(e)}{2e^3}F_{\mu\nu}^2+\frac{\beta_3(g_3)}{2g_3^3}\left(G_{\mu\nu}^a\right)^2+\sum_{\text{fermions}}\gamma_\psi\overline{\psi}\psi\right]$$

Backup – detailed result for Relic Abundance approx

$$\Omega_\phi h^2 \sim 0.1 g_\Delta(x_f) \frac{9\pi (f/m_\phi)^4 m_\phi^2}{(20\ \mathrm{TeV})^2} e^{2\Delta x_f},$$

$$g_\Delta(x_f) = \frac{2(1+\Delta)^4}{\sqrt{\Delta(2+\Delta)}\,(1-4\Delta-2\Delta^2)^2}\left[1 - 2\Delta x_f e^{2\Delta x_f}\int_{2\Delta x_f}^{\infty} dt \frac{e^{-t}}{t}\right]^{-1}.$$

Backup – thick wall approx

$$\frac{\sqrt{3}}{\pi}\frac{N^3\chi_r^3}{T_n\sqrt{V(\langle\chi\rangle)(T_n/T_c)^4 - V(\chi_r)}} < 4\left(\log\frac{M_{pl}}{T_c} + \log\frac{T_n}{T_c}\right)$$

Backup – model details

$$V(\chi) = \frac{3N^2}{2\pi^2}\left[-\lambda\chi^4 + \lambda_{\rm GW}\frac{\chi^{4+\alpha}}{R^{-\alpha}}\right] + V_0$$

$$\langle\chi\rangle = R^{-1}\left(\frac{\lambda}{\lambda_{\rm GW}}\right)^{1/\alpha}$$

$$\chi = \langle\chi\rangle + \sqrt{2\pi^2/3N^2}\sigma$$

$$m_\sigma^2 = 4\alpha\lambda\langle\chi\rangle^2$$

$$f = \sqrt{3N^2/2\pi^2}\langle\chi\rangle$$

Backup – additional constraints

- DM annihilation to SM through dilaton portal
  - Cross section below constraints on EM energy injection in early universe
  - Can get a Sommerfeld enhancement, ends up being too small
- Higgs ➔ invisible decays into KK modes
- Can estimate

$$\Gamma(h \to \text{invisible}) \sim \frac{m_h}{8\pi}\left(\frac{f}{\Lambda}\right)^4 < 0.11$$

Relic Abundance

- Set by $\phi\phi \to \sigma\sigma$

$$\Omega h^2 \sim \frac{(20\ \mathrm{TeV})^{-2}}{\langle \sigma v \rangle_{\phi\phi \to \sigma\sigma}}$$

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$$\Omega h^2 \sim \frac{(20\ \mathrm{TeV})^{-2}}{\langle \sigma v \rangle_{\sigma\sigma \to \phi\phi} \left(\frac{n_\sigma^{eq}}{n_\phi^{eq}}\right)^2}$$

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- Set by $\phi\phi \to \sigma\sigma$

$$\Delta = (m_\sigma - m_\phi)/m_\phi$$
$$x = m_\phi/T$$

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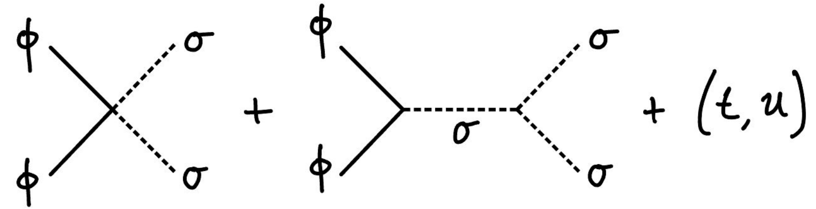

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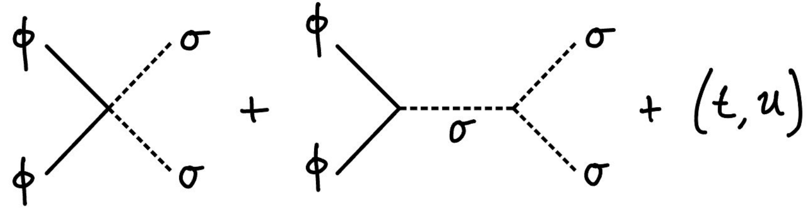


- Numerics: `micrOMEGAs`

Belanger et al, 1005.4133

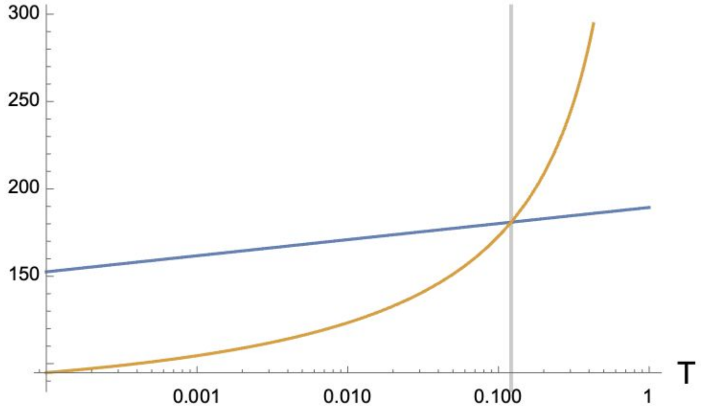
Conformal Phase Transition

- Deconfined → Confined … @ critical temperature $T_c \sim \sqrt{m_\sigma f}$
- PT Completion:

$$\Gamma > H^4$$

$$\Downarrow$$

$$S_b(T_n) < 4\log\left(\frac{M_{pl}T_n}{T_c^2}\right)$$



Harling et al, 1711.11554

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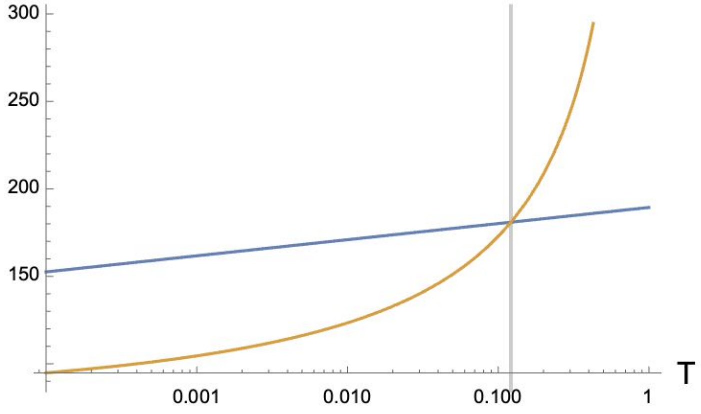

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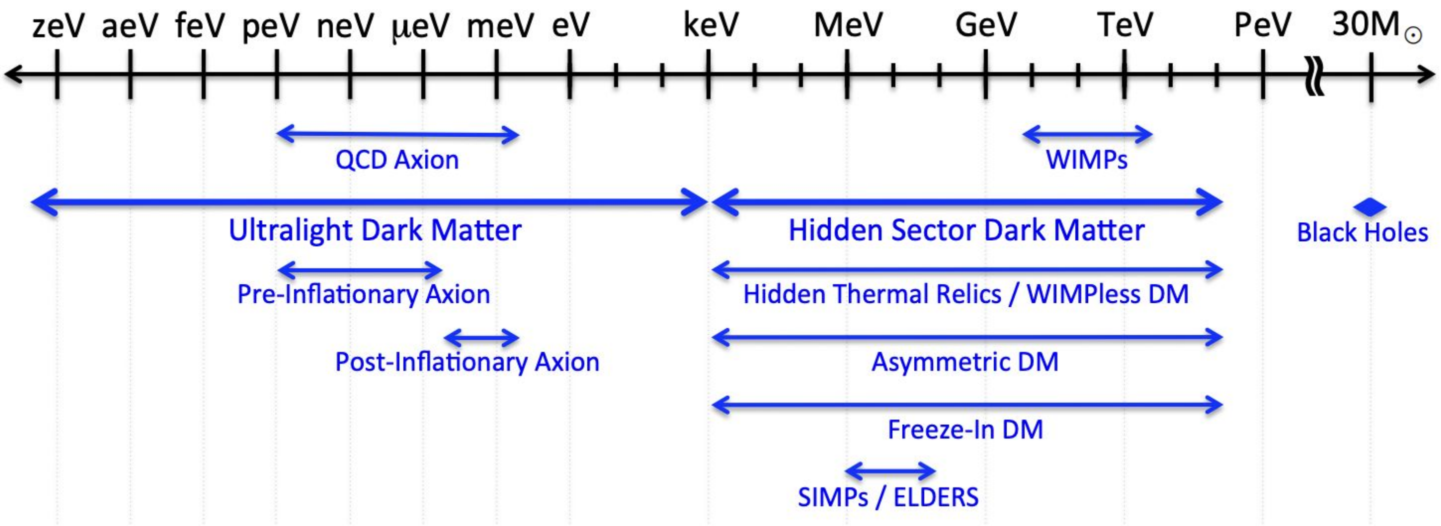
DM Candidates "What the hell is going on" – Nima 2017

- WIMPs facing increasing experimental pressure … exciting time for other scales !



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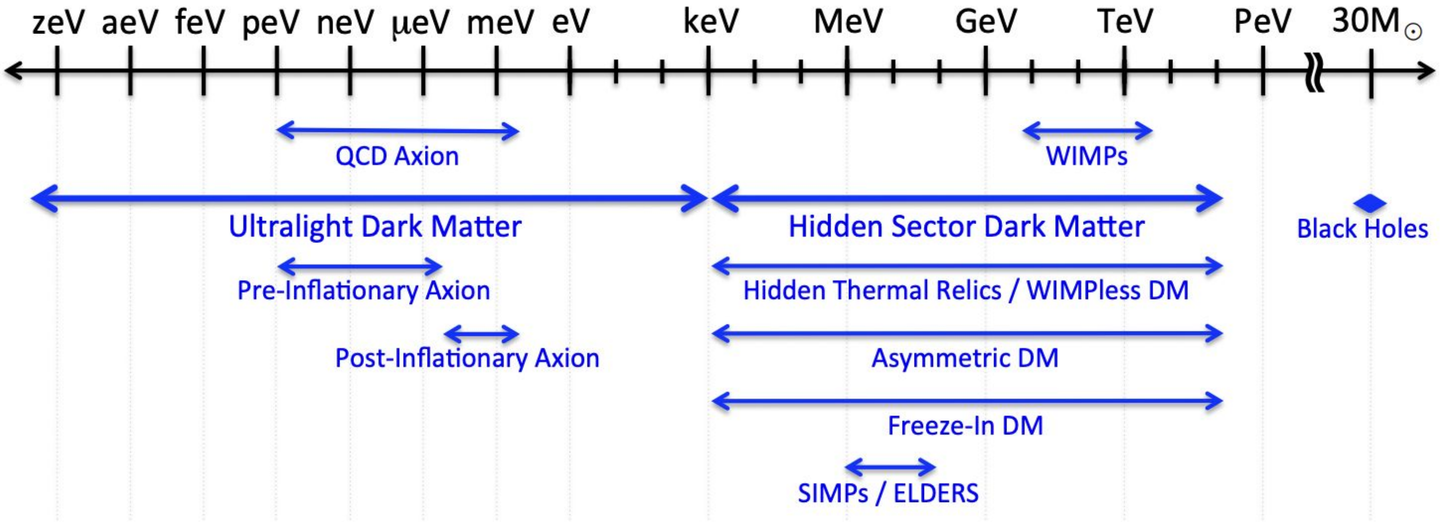
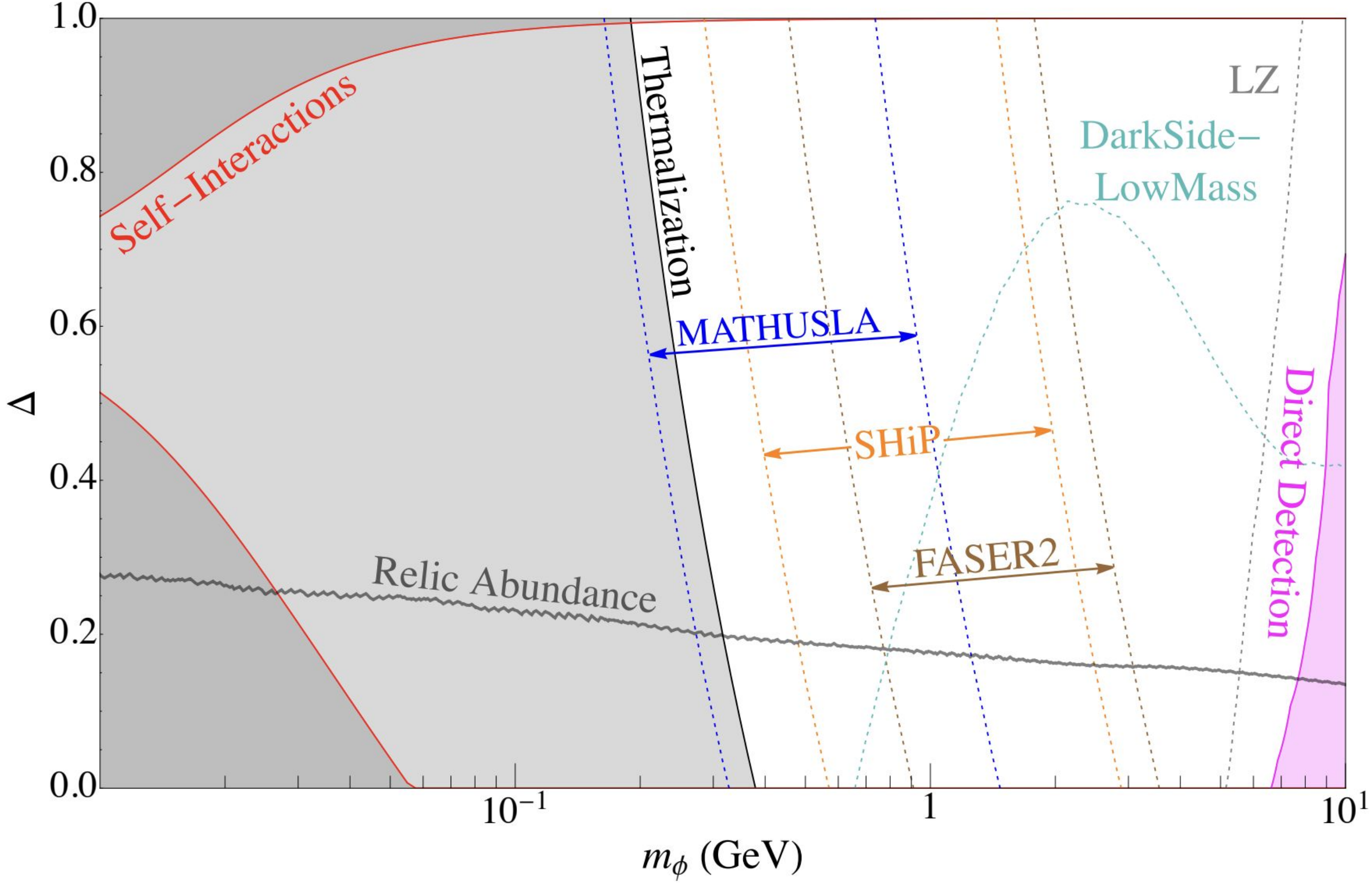


- Dark sector w/ spontaneously broken conformal symmetry
- GeV-scale phase transition

DM Phenomenology

$$f = m_\sigma$$



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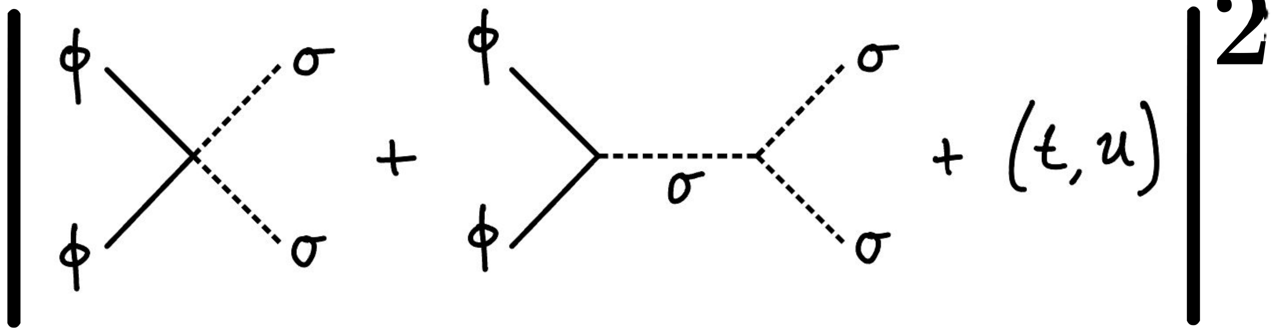

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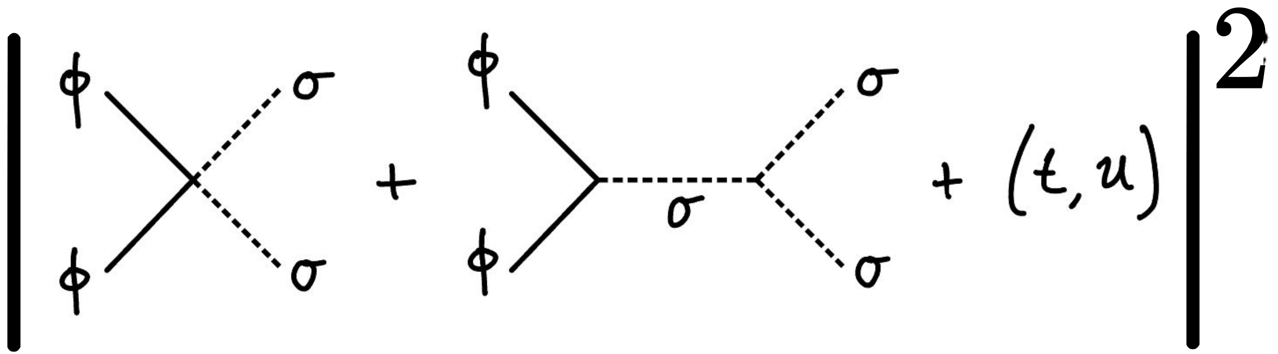

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