ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Illuminating the Dark Side in Adelaide

Dipan Sengupta

THE UNIVERSITY of ADELAIDE

Australian Government
Australian Research Council

THE UNIVERSITY of ADELAIDE

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

1. Cosmological constraints on SuperWimps.

Meera Deshpande

+ Hamman, DS, White, Williams, Wong

2. Consequences of neutron decays into dark sector in neutron stars.

Wasif Husain

+ DS, Thomas

+

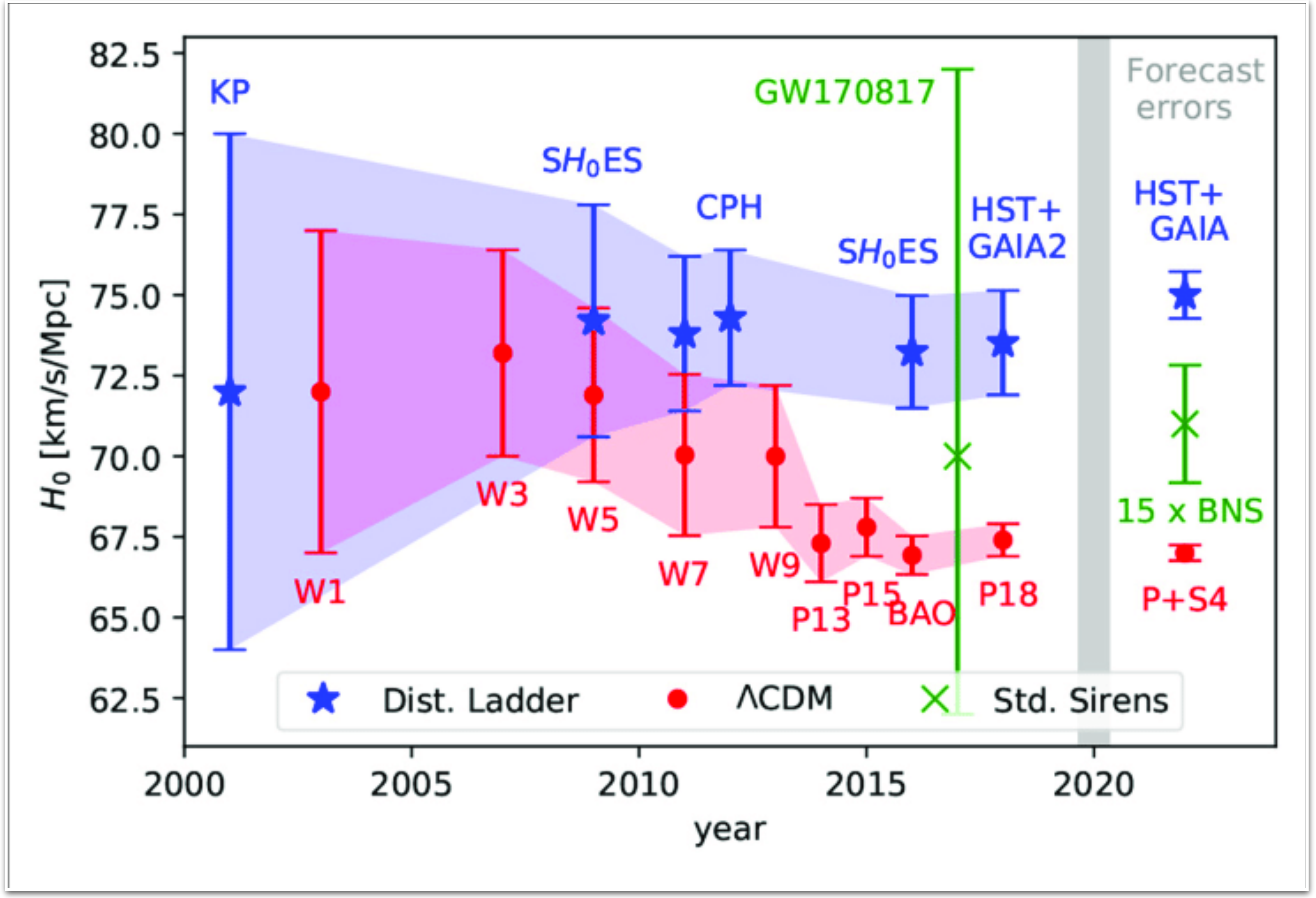
3. Estimating the relic of KK graviton dark matter accurately.

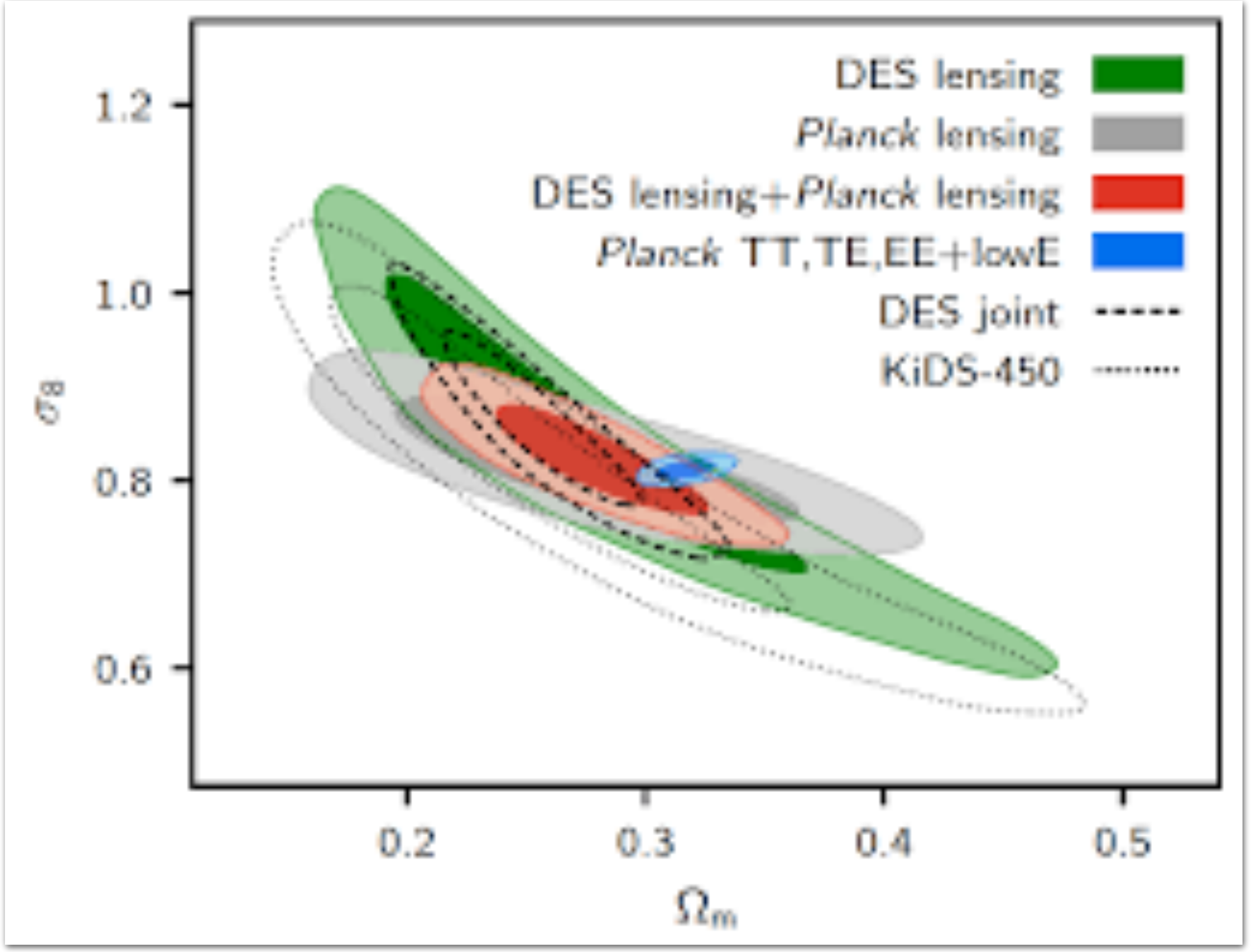
Josh Gill

+ Cacciapaglia(CNRS),
+ Lee(KIAS), DS, Williams

Cosmological constraints on SuperWimps.

Two anomalies in cosmology





$$H_0 = 67.27 \pm 0.60 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$H_0 = 74.3 \pm 2.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

$$S_8 = 0.834 \pm 0.016 \quad \text{Planck}$$

$$S_8 = 0.766^{+0.020}_{-0.014} \quad \text{KiDS-1000}$$

Cosmological constraints on SuperWimps.

Modifications to ΛCDM model

S_8 and the H_0 tensions are correlated

Models of Decaying Dark Matter (DDM) to solve S_8

CDM $\longrightarrow$ WDM + DR

$\varepsilon = (1/2)[1 - m^2_{\rm wdm}/m^2_{\rm dcdm}]$ $\Gamma^{-1} \simeq 55$ Gyrs $\varepsilon \simeq 0.7\ \%$ Poulin-Abellan-Lavalle-Murgia : 2020

Suppression of Linear Matter power spectrum at intermediate and small scales with a cut-off scale determined by the free streaming length

Difference between ΛCDM and ΛDDM : Very small at low redshifts , and therefore Planck cannot distinguish them

Cosmological constraints on SuperWimps.

What kind of models can we construct ? Look no further than SUSY

Yanagagida et al. 2020

Consider a gravitino CDM populated thermally in the early universe through scatterings

$$\Omega_{3/2}h^2 = 0.217 \left(\frac{T_{\rm RH}}{10^7 {\rm GeV}}\right) \left(\frac{100{\rm GeV}}{m_{3/2}}\right) \left(\frac{m_{\tilde{g}}(\mu)}{10{\rm TeV}}\right)^2$$

$$m_{3/2} = \frac{|F|}{\sqrt{3}M_P}$$

$$\tilde{G}_\mu \to \tilde{N}_1 + N_1$$

$$\Gamma(\tilde{G}_\mu \to \tilde{N}_1 + N_1) = \frac{m_{3/2}^3}{192\pi M_P^2} \times \left[1 - \left(\frac{m_1}{m_{3/2}}\right)\right]^2 \left[1 - \left(\frac{m_1}{m_{3/2}}\right)^2\right]^3$$

Solves the Sigma_8 tension

Cosmological constraints on SuperWimps.

What if the reheating temperature is low ? Thermal processes are suppressed

Gravitino abundance is populated non thermally through decays

$$\Gamma(\chi_1^0 \to \tilde{G}\gamma) \equiv \frac{\cos^2\theta_W m_{\chi_1^0}^5}{48 M_P^2 m_{\tilde{G}}^2}\left[1 - \frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right]^3 \left(1 + 3\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right)$$

$$\tau \equiv 2.3 \times 10^7 \left(\frac{100\ \mathrm{GeV}}{\Delta m}\right)^3 \mathrm{s}$$

Energy released in Photons

$$E_\gamma = \frac{m_{\chi_1^0}^2 - m_{\tilde{G}}^2}{2 m_{\chi_1^0}}$$

Fractional energy

$$E_{\mathrm{SM}} = E_\gamma / m_{\chi_1^0}$$

Energy deposited in the thermal plasma causes spectral distortions

Cosmological constraints on SuperWimps.

Energy Injection Constraints

Spectral Distortions

Distortions of the Blackbody spectrum of the primordial photon bath

Energy injection and deposition into the Intergalactic Medium (IGM)

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{dep,c}} = \left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{inj}} f_{\mathrm{c}} = \left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{inj}} f_{\mathrm{eff}}\ \chi_c \equiv \dot{Q}\,\chi_c$$

injection efficiency function $f_{\mathrm{eff}}(z)$

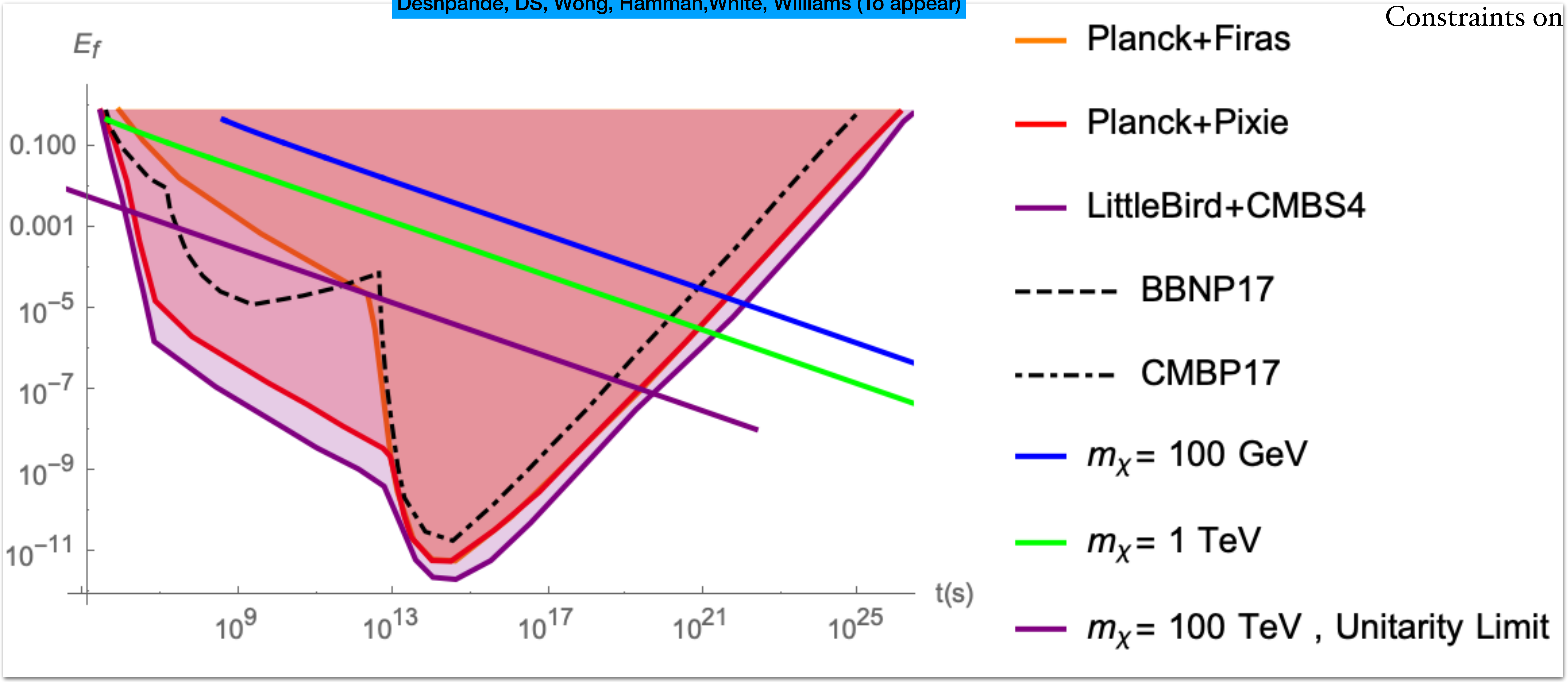
deposition *fraction* $\chi_c(z)$

Thermalisation via Compton, Double Compton and Brehmstrahlung scatterings ⟶ Photon Phase Space Distribution

Distortions manifested in terms of temperature shifts ***g***, chemical potential distortions ***mu***, and Compton distortions ***y***

Cosmological constraints on SuperWimps.

Deshpande, DS, Wong, Hamman,White, Williams (To appear)



Constraints on Gravitino SuperWIMP

Similar considerations for axino SuperWimps : Additional freedom in decay width due to axion decay constant

In consideration : Complementarity between collider, Warm DM bounds

Future : Axino/Gravitino decays for solving Hubble/S_8 tensions consistent with constraints

Release Code to do understand general multistep process in Class/Exoclass

Other DDM scenarios

1. Cosmological constraints on SuperWimps.

Meera Deshpande

+ Hamman, DS, White, Williams, Wong

2. Consequences of neutron decays into dark sector in neutron stars.

Wasif Husain

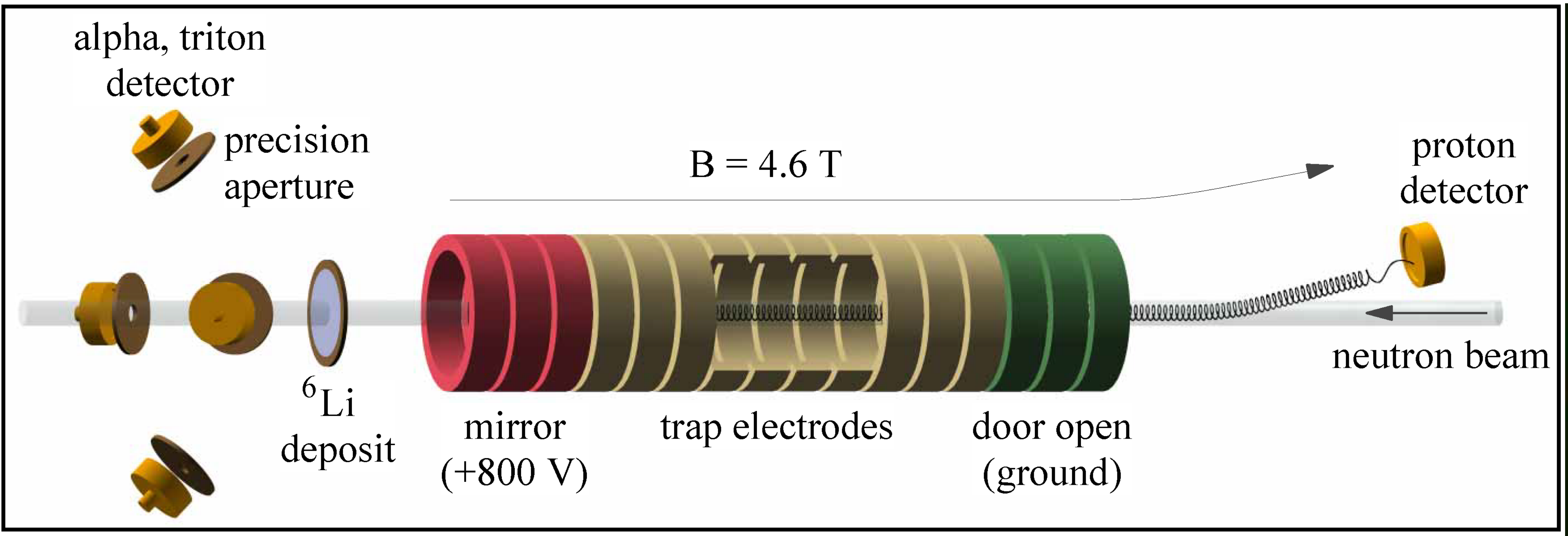
+ DS, Thomas

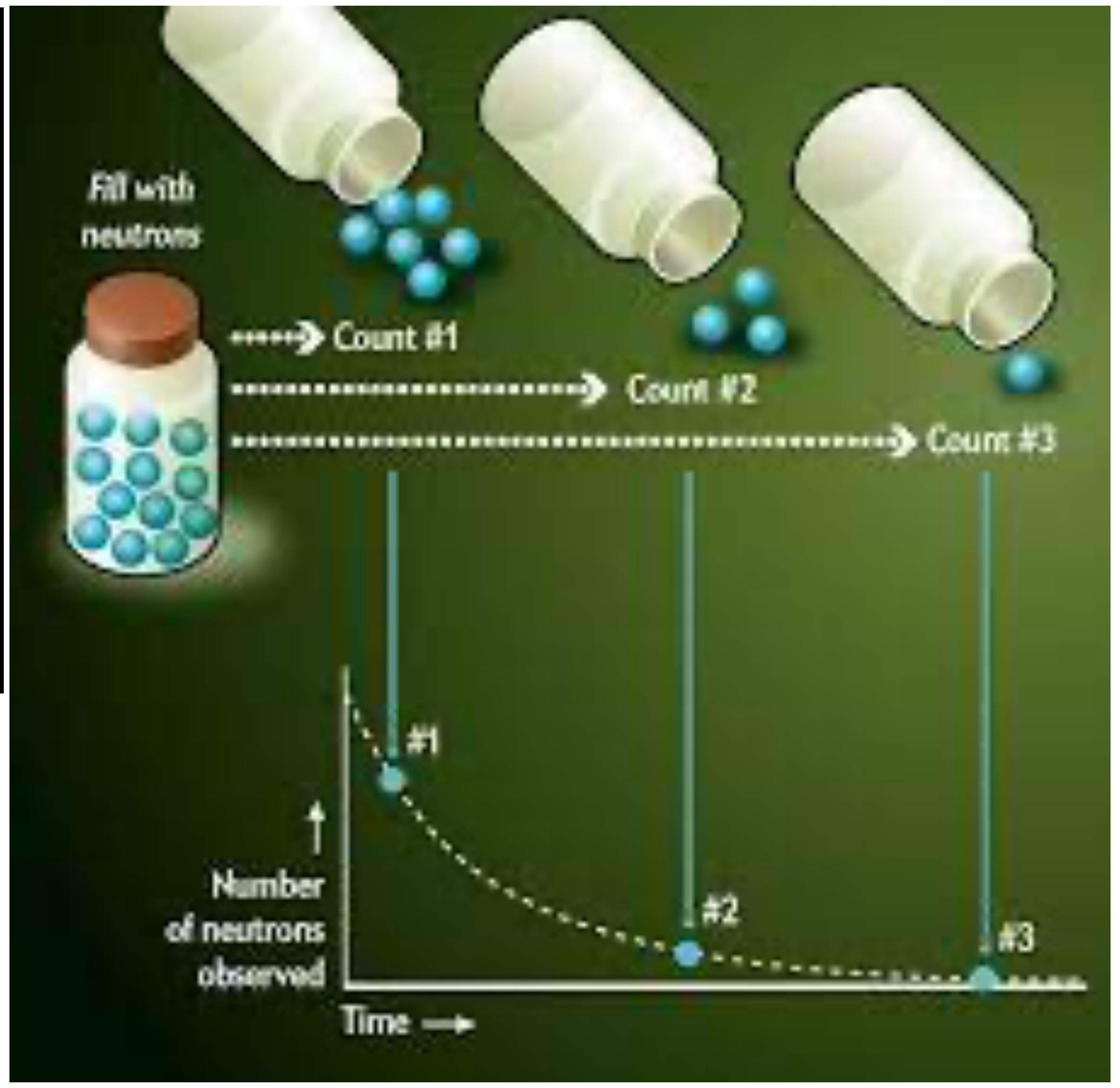
3. Estimating the relic of KK graviton dark matter accurately.

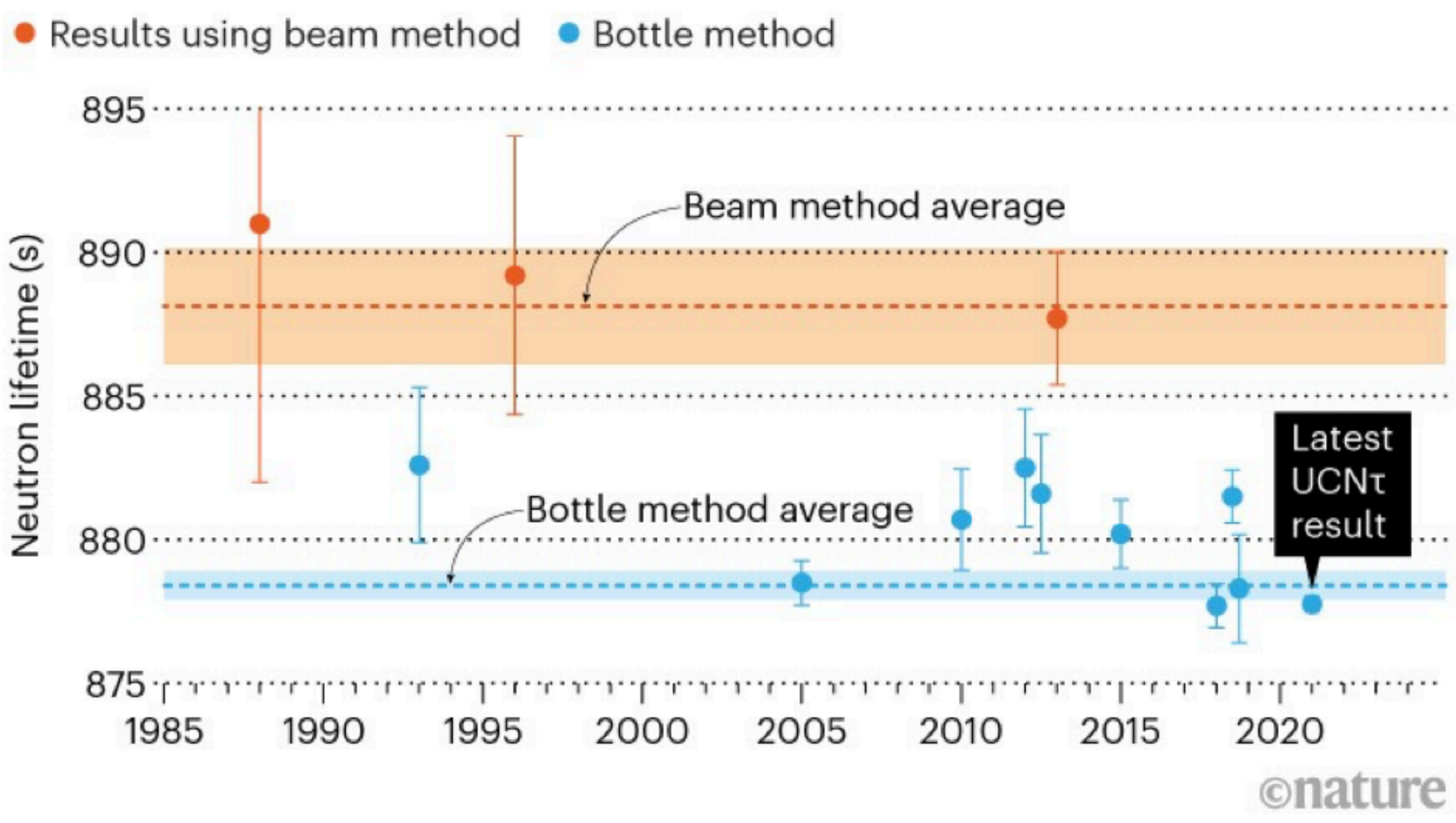
Josh Gill

+ Cacciapaglia, Lee, DS

Bottle vs Beam experiments







$$n \to p + e^- + \bar{\nu}_e \qquad \mathcal{M} = \frac{1}{\sqrt{2}} G_F V_{ud}\, g_V \left[\bar{p}\,\gamma_\mu n - \lambda\,\bar{p}\,\gamma_5\gamma_\mu n\right]\left[\bar{e}\,\gamma^\mu(1-\gamma_5)\nu\right]$$

$$\tau_n = \frac{4908.7(1.9)\,\mathrm{s}}{|V_{ud}|^2(1+3\,\lambda^2)} \qquad \tau_n \text{ between } 875.3\,\mathrm{s} \text{ and } 891.2\,\mathrm{s} \text{ within } 3\,\sigma$$

$$\tau_n^{\mathrm{beam}} = 888.0 \pm 2.0\ \mathrm{s} \qquad \tau_n^{\mathrm{bottle}} = 879.6 \pm 0.6\ \mathrm{s}$$

$$\Delta\Gamma_n^{\mathrm{exp}} = \Gamma_n^{\mathrm{bottle}} - \Gamma_n^{\mathrm{beam}} \simeq 7.1 \times 10^{-30}\ \mathrm{GeV}$$

New Physics Interpretations

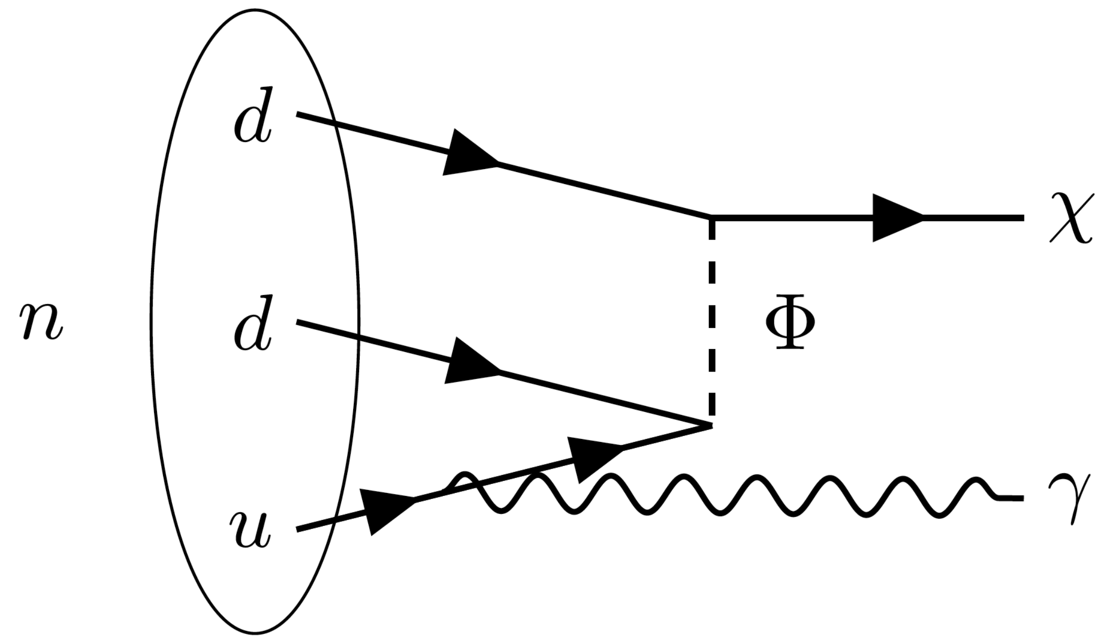
New Physics scenarios :

Set I

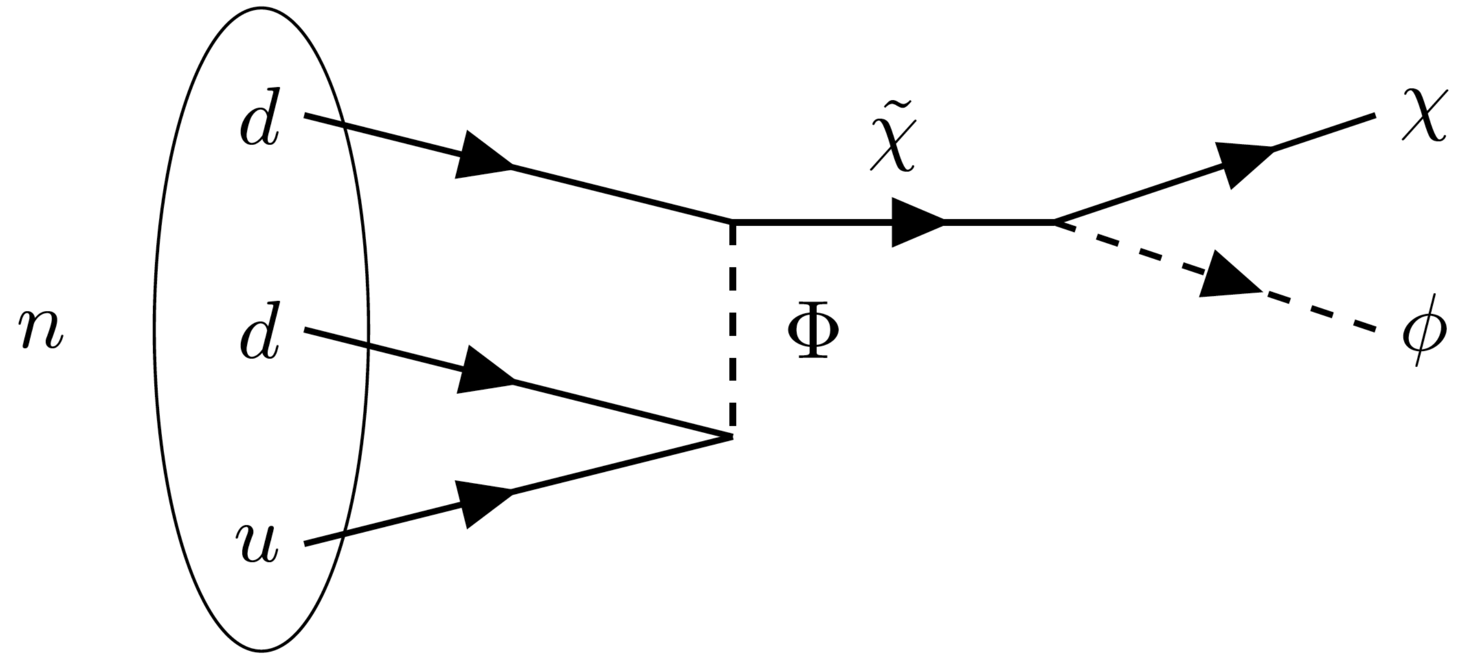
$n \to \chi\,\gamma$

$n \to \chi\,\phi$

$n \to \chi\,e^+e^-$



Fornal-Grienstein, Nelson et al …



$\Phi = (3,1)_{-1/3}$

$937.900\ \text{MeV} < m_\chi + m_\phi < 939.565\ \text{MeV}$

Set II

DM quantum numbers			DM interactions		
B	L	spin	dimension	with quarks	with hadrons
1	0	1/2	6	χudd	χn
1/3	0	1/2	9	$\chi\chi\chi udd$	$\chi\chi\chi n$
2/3	0	0	9	$\phi^3(udd)^2$	$\phi^3 n^2$
2	0	0	7	$\phi(udd)^2$	ϕnn
0	1	1/2	4, 6	$\chi LH, \chi\ell f\bar{f}$	$\chi\ell\pi, \chi\ell p\bar{n}$
0	2	0	6, 8	$\phi(LH)^2, \phi\ell\ell Xq\bar{q}$	$\phi\nu\nu, \phi\ell\ell\pi\pi$
1	1	0	7	$\phi LQQQ, \phi\ell uud$	$\phi n\nu, \phi p\ell$
1	-1	0	8	$\phi\bar{\ell}Xqqq$	$\phi n\bar{\nu}, \phi\Delta^-\bar{\ell}, \phi n\pi^-\bar{\ell}$
1	2	1/2	9	$\chi\ell\nu qqq$	$\chi n\nu\nu, \chi p\ell\nu$

Strumia's classification

$n \to \chi\chi\chi$

Neutron Star Considerations with the decay

The new decay softens the neutron star EOS at high densities ⟶ Makes it impossible to support NS above 2 solar masses

Two Solutions

1. Large repulsive self interactions between DM, stiffens the EOS by raising DM chemical potential, reduces DM to baryon fraction in equilibrium
2. Repulsive DM-Baryon interactions : energetically disfavours DM production in a pure baryonic medium

$$U = \pm \frac{g_\chi g_n}{4\pi} \frac{e^{-m_\phi r}}{r}$$

TOV equation for hydrostatic equilibrium with DM and Neutrons

Grinstein et al. 2018

ϕ **In principle can cause problems by adding to N_{eff} : Ideally should decay before start of BBN to avoid all constraints**

New Physics Interpretations

What if the boson decayed ?

$n \rightarrow \chi\,\phi$ $\qquad 937.900 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV}$

Both Stable if $\qquad |m_\chi - m_\phi| < 938.783 \text{ MeV}$

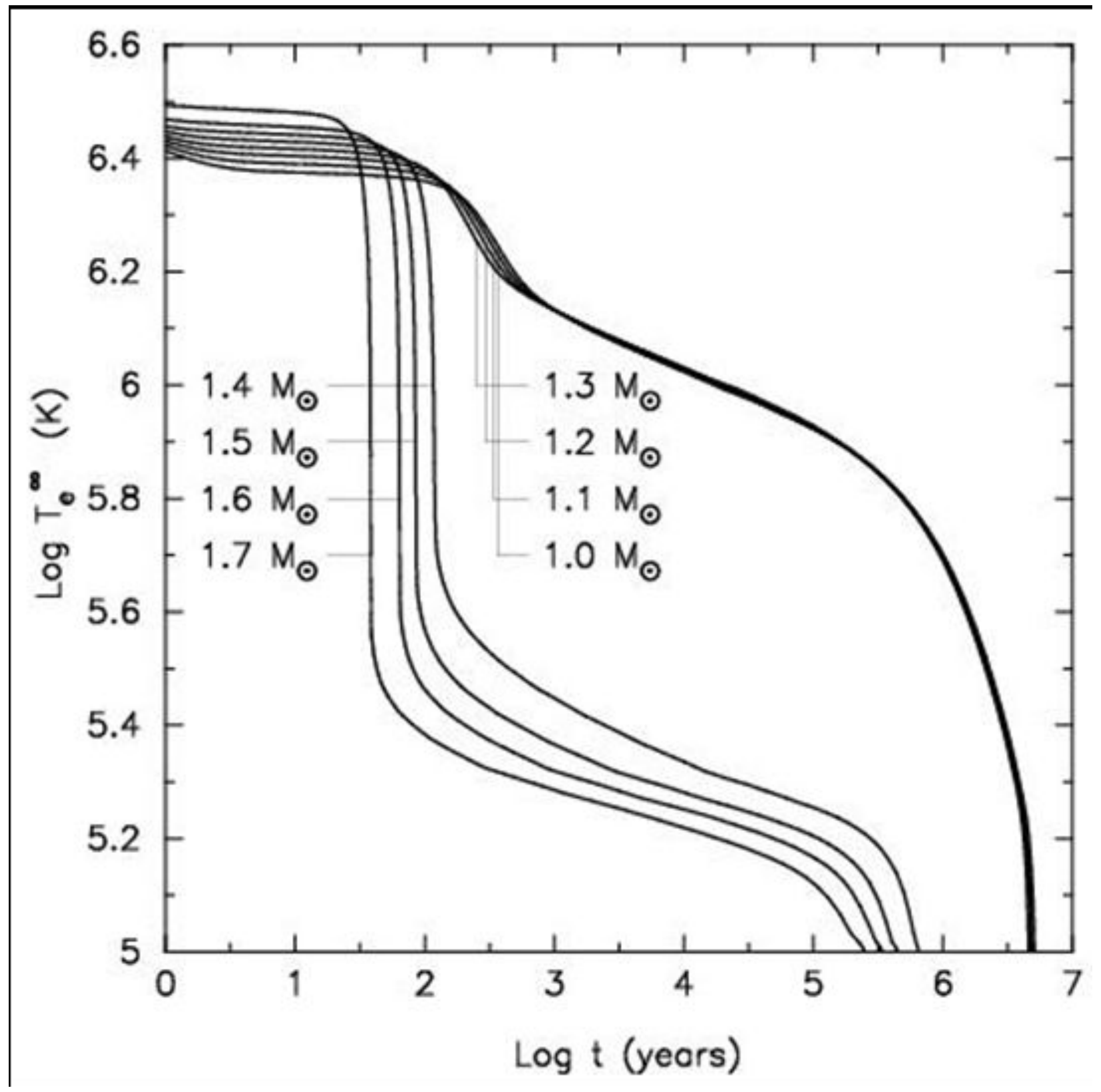
How do we estimate the mass and the lifetime of the Boson ?

Urca and inverse Urca processes cool neutron stars down

neutron stars have a luminosity $10^{31.5}$ erg/s at 1 M years

Cooling Processes

- Direct Urca: $n \rightarrow p + e + \bar{\nu}_e$
- Modified Urca: $n + n \rightarrow n + p + e + \bar{\nu}_e$
- Photons: $\rightarrow \gamma$
- Bremsstrahlung: $n + n \rightarrow n + n + \nu + \bar{\nu}$



Page and Applegate 92

Additional cooling process due to SM particles from boson decays should not cool it below $10^{31.5}$ erg/s

m_ϕ		
	300 MeV	**47 x 10^13 years**
	700 MeV	**70 x 10^13 years**

New Physics Interpretations

Scalars

$$\mathcal{L}_{int} = \frac{C_s}{f_{eff}} \phi F_{\mu\nu} F^{\mu\nu} + \frac{m_l}{f_{eff}} \phi \bar{\ell} \ell + \cdots$$

$$\mathcal{L} \in L_{kin} + \lambda_{eff} n \chi \phi$$

Pseudo-Scalars

$$\mathcal{L}_{int} = \frac{C_{s\gamma}}{f_{eff}} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{f_{eff}} (\partial_\mu \phi) \bar{\ell} \gamma^\mu \gamma^5 \ell + \cdots$$

$$\mathcal{L} \in L_{kin} + \lambda_{eff} n \chi \gamma^5 \phi$$

Spin-1

Photon is (almost) ruled out experimentally

$$\mathcal{L} = \frac{\epsilon}{2 \cos \theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{L} \in e\epsilon (n \sigma^{\mu\nu} \chi F'_{\mu\nu})$$

Spin-2

$$\mathcal{L} = \frac{1}{\Lambda} h_{\mu\nu} T^{\mu\nu}_{SM}$$

In the works : A full analysis of complementary constraints on this scenario including stellar cooling bounds, low energy and collider experiments, BBN and CMB bounds

1. Cosmological constraints on SuperWimps.

Meera Deshpande

+ Hamman, DS, White, Williams, Wong

2. Consequences of neutron decays into dark sector in neutron stars.

Wasif Husain

+ DS, Thomas

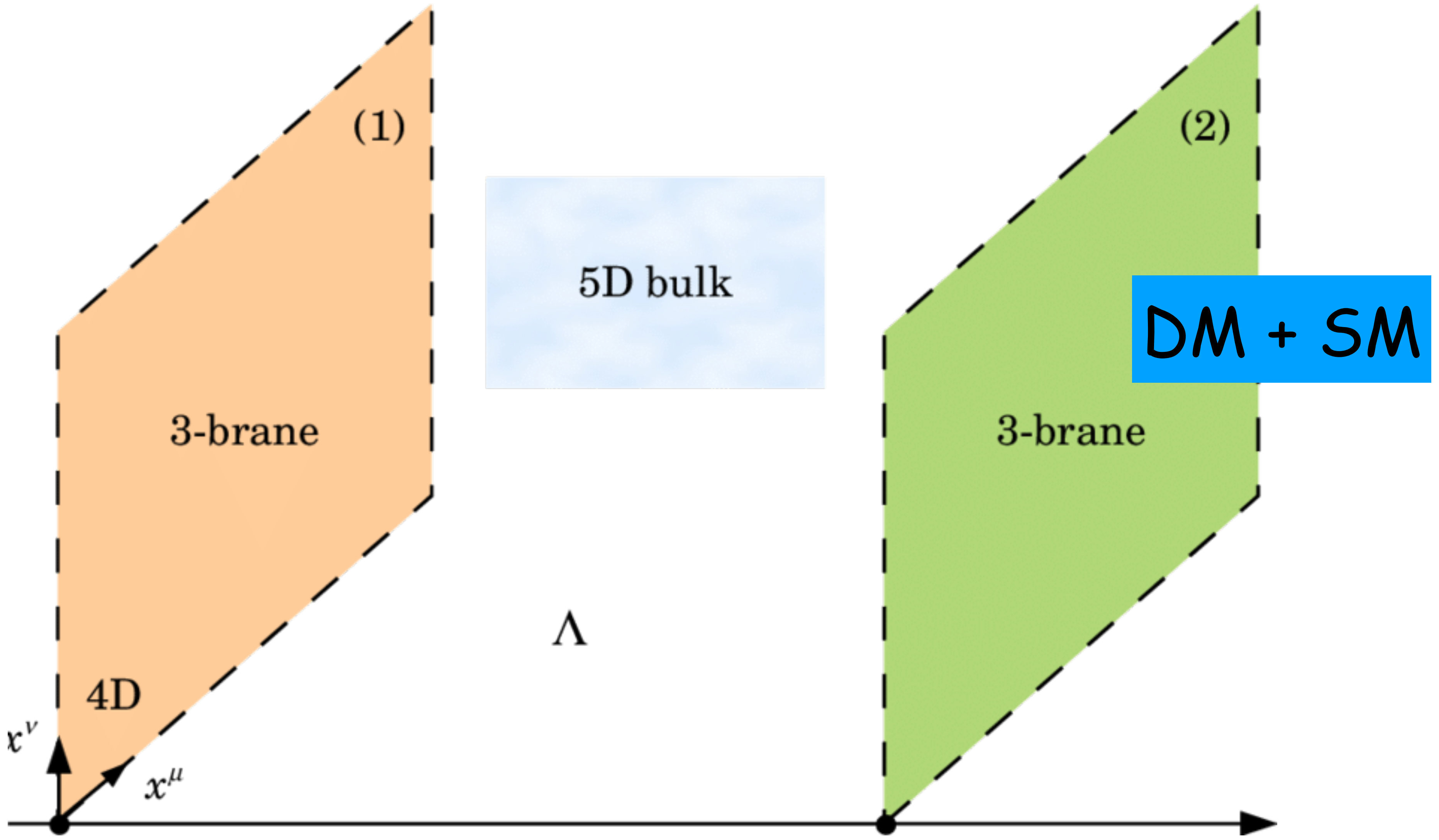
3. Estimating the relic of KK graviton dark matter accurately.

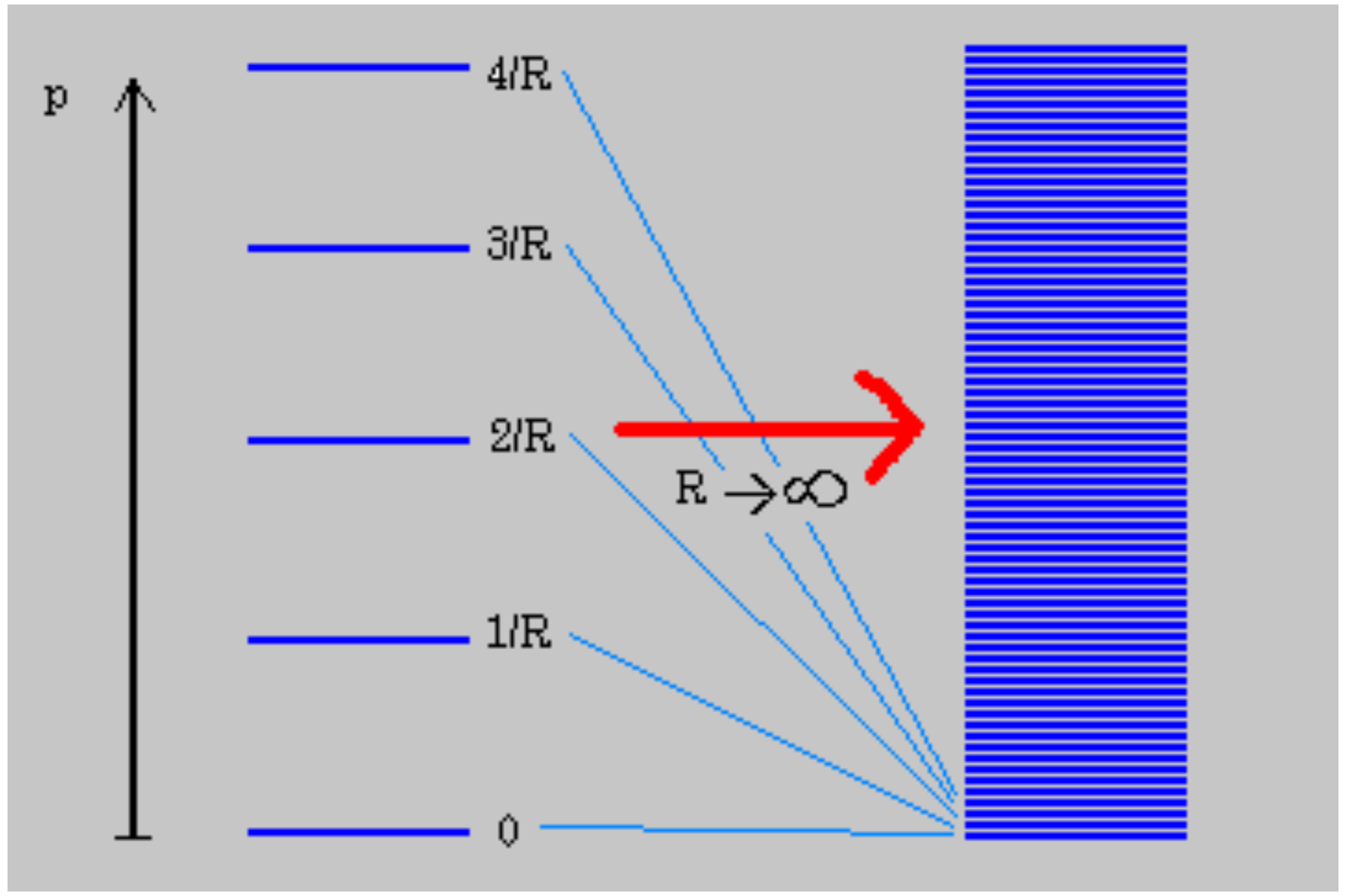
Josh Gill

+ Cacciapaglia, Lee, DS

Estimating Accurate Relic Densities for DM models with KK gravitons

Massive Spin-2 KK gravitons arise as a result of compactifying extra dimensions





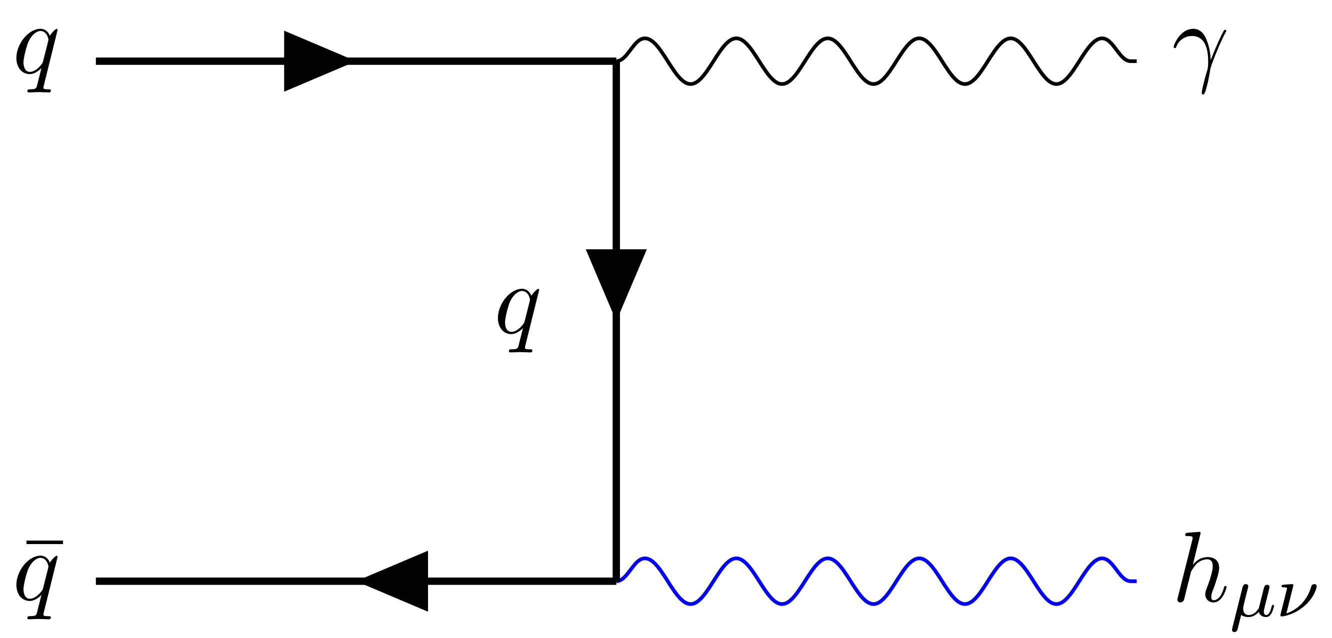
$$\mathcal{L} = \frac{1}{\Lambda} h_{\mu\nu} T^{\mu\nu}_{SM}$$

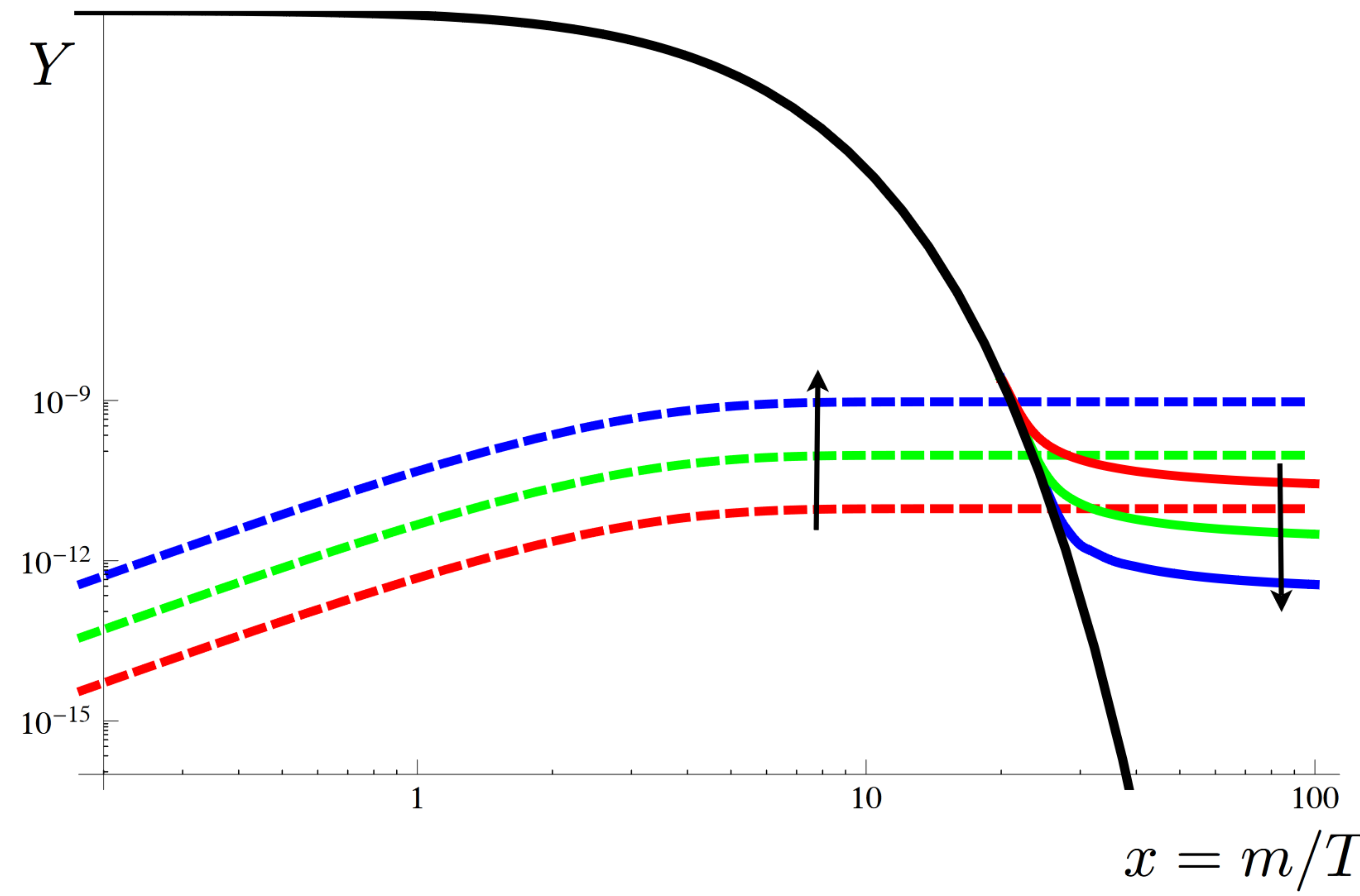
Naive Expectation of all EFT scales in the theory

Estimating Accurate Relic Densities for DM models with KK gravitons

A light KK graviton with a lifetime greater than the age of the Universe.

UV freeze-in through higher dimensional operators



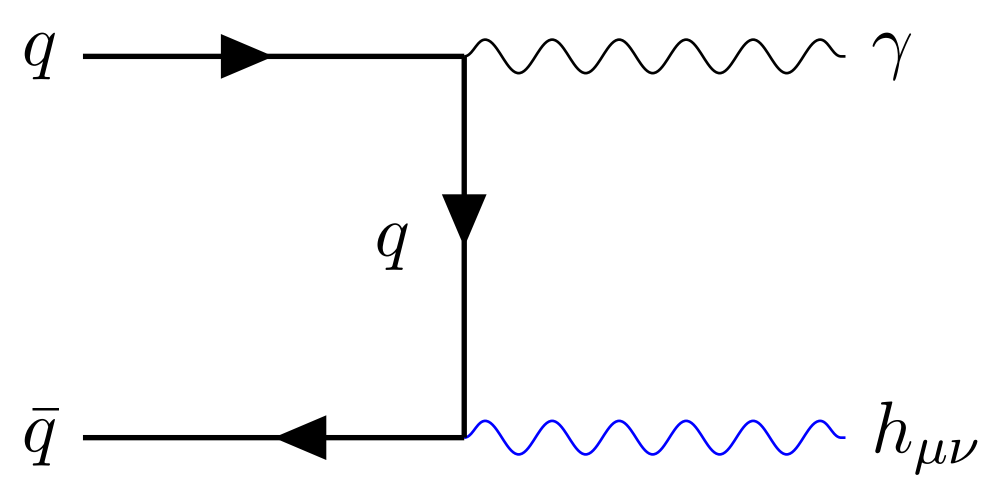


$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B}(\xi_B - \xi_A)\mathcal{N}(A \to B)$$

The matrix element contains information about the velocity averaged cross section

Unitarity limits for effective theories determine the validity of the theory

Estimating Accurate Relic Densities for DM models with KK gravitons



+t + u + contact diagrams

$$\lambda_G = \pm 2, \qquad \varepsilon^{\mu\nu}_{\pm 2} = \varepsilon^{\mu}_{\pm 1}\varepsilon^{\nu}_{\pm 1},$$

$$\lambda_G = \pm 1, \qquad \varepsilon^{\mu\nu}_{\pm 1} = \frac{1}{\sqrt{2}}\left[\varepsilon^{\mu}_{\pm 1}\varepsilon^{\nu}_{0} + \varepsilon^{\mu}_{0}\varepsilon^{\nu}_{\pm 1}\right],$$

$$\text{l: } \lambda_G = 0, \qquad \varepsilon^{\mu\nu}_{0} = \frac{1}{\sqrt{6}}\left[\varepsilon^{\mu}_{+1}\varepsilon^{\nu}_{-1} + \varepsilon^{\mu}_{-1}\varepsilon^{\nu}_{+1} + 2\varepsilon^{\mu}_{0}\varepsilon^{\nu}_{0}\right]$$

$$\varepsilon^{\mu}_{0}(k_2) = \frac{E_{k_2}}{m_G}\left(\sqrt{1 - \frac{m_G^2}{E_{k_2}^2}},\ \hat{k}\right)$$

Matrix Element naively grows like 1/ M_{KK}^{2}

Only one EFT scale, should not have any low energy divergences

Incorrect estimations in the literature , Lee et al, Sanz et al, Sloth et al, Bernal et al, Mambrini et al ….

Solution : Sum the KK tower , All low energy divergences should cancel out

Status : Messy matrix elements, 40 Helicity combinations, manipulations to get them into a tractable form. Sum the KK tower, Calculate the cross section , integrate the Boltzmann Equation

Summary

The Adelaide Theory Group has a rich DM/Cosmology theory programme working on a variety of topics

A lot of scope and directions to collaborate