SUNny gluonia as DM

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HET-BNL; 10/03/2018

Dark Interactions @ BNL

[Caution: this talk is on an **unorthodox interpretation of DM**; most of you are unlikely to like it]

In collaboration with Yue Zhang (Northwestern U):

arXiv:1602.0071; arXiv:1610.06931; arXiv:1704.02347
**[the last one also involves
Huangyu Xiao now @ UW-Seattle]**

outline

- **Intro …**
- **Key important characteristics**
- **A notable aspect of the *VISIBLE MATTER* that may be relevant**
- **Basic philos…..seek as simple a solution as possible which *naturally* accounts for the key features of DM**
- **Viable candidate?**
- **Possible repercussions:**
- **Gigantic DSS, GWs, Cosmic selection rule for relic density**
- **Future directions…..1. gravitational lensing; 2. possible non-perturbative (lattice) studies**
- **Summary + Outlook**

Introduction + motivation

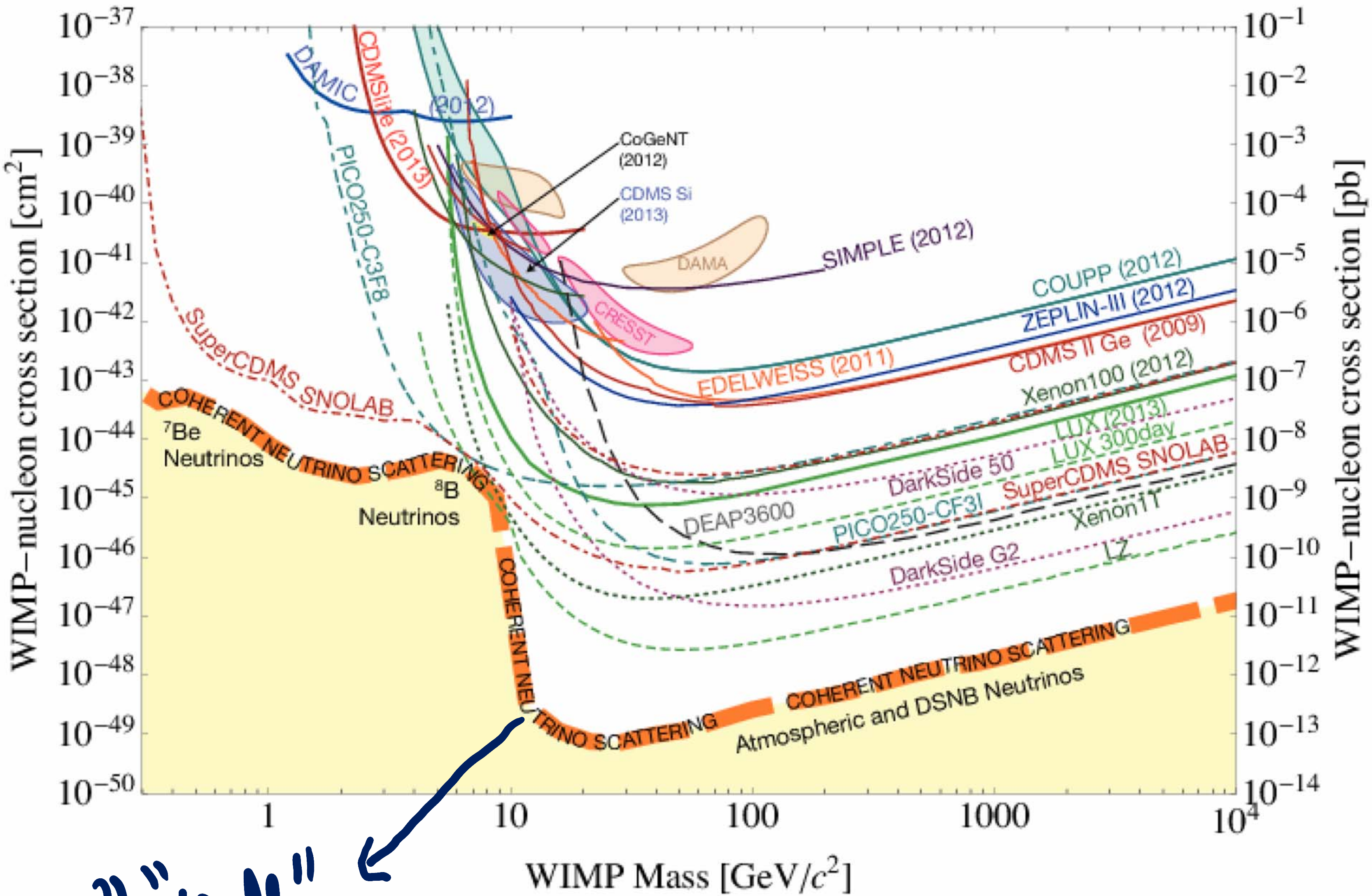
- Preponderance of DM over matter is sometimes (often) used as a rationale to suggest that the underlying explanation for DM may well require considerable complexity i.e. much more complicated than theories of visible matter[VM].

- Here will pursue different philosophy.

- Explore as simple a solution as possible and introduce complexity iff forced by experiments and observations

Two Key characteristics

- Proven to be exceedingly difficult for direct detection ……………….=> fig
- [Shocking as it may seem, it is highly likely that nature does not care a bit whether or not DM interacts with our detector!]
- Remarkably, the only compelling evidence of DM that so far we have is gravitational!
- Seek simple explanation for these key features



ν "wall"
[irreducible ν background]

CAN WE LEARN SOMETHING USEFUL FOR DM FROM VISIBLE MATTER?

DOI: 10.2478/s11534-012-0121-0

Central European Journal of Physics

Origins of mass

Review Article

Frank Wilczek[1*]

more basic concepts. Most of the mass of standard matter, by far, arises dynamically, from back-reaction of the color gluon fields of quantum chromodynamics (QCD). Additional quantitatively small, though phys-

$$\overline{m} = (m_u + m_d)/2 = 3.5^{+0.7}_{-0.2}\ \text{MeV}$$

⇐ endowed by the "Higgs mechanism"

$$\text{Mass } m = 938.272046 \pm 0.000021\ \text{MeV}$$

Huge fraction of the visible mass originates *dynamically* from the underlying non-Abelian
quanta [gluons] of SU(N=3) gauge theory! This we learned relatively recently only.

SINCE THE ONLY KNOWN MECHANISM FOR GENERATING DYNAMICAL MASS SO FAR [I.E. A NON-ABELIAN GAUGE THEORY] IS SO CRITICAL FOR VISIBLE MATTER, IT IS PLAUSIBLE THAT AN SU(N) GAUGE THEORY PLAYS A CRUCIAL ROLE IN DM ALSO.

SIMPLICITY IS OUR PRIORITY!

SU(N)…simplest theory with non-trivial, dynamical mass scale

$$\mathcal{L} = -\frac{1}{4} H^a_{\mu\nu} H^{a\,\mu\nu}$$

Pure gauge theory, no fermions

Parameters: N and thru dim. transmutation Λ

Implicit: θ   [later]

Immediate qualitative features

- **In fact this theory is so simple and so elegant, it seems difficult to believe that nature does not make use of it!**
- **But of course it makes use of it and makes use of it plenty, in fact our modern understanding [as e.g. emphasized by Wilczek] is that by far most of VM is gluonic.**
- **Bearing ATIM, one is motivated to ask wrt DM, how far a pure SU(N) gauge construct [i.e. w/o fermions] take you.**

- **"Everything should be made as simple as possible, but not simpler."…quoting someone**

Recapitulate: Basics of an SU(N) gauge theory

- Gauge quantas are confined
- Dimensional Transmutation endows a dynamical mass
- Confined quantas make bound states, gluonia or glueballs which are color [SUN]-singlets and are unconfined, asymptotic states

EXPECTED LOW LYING SPECTRUM

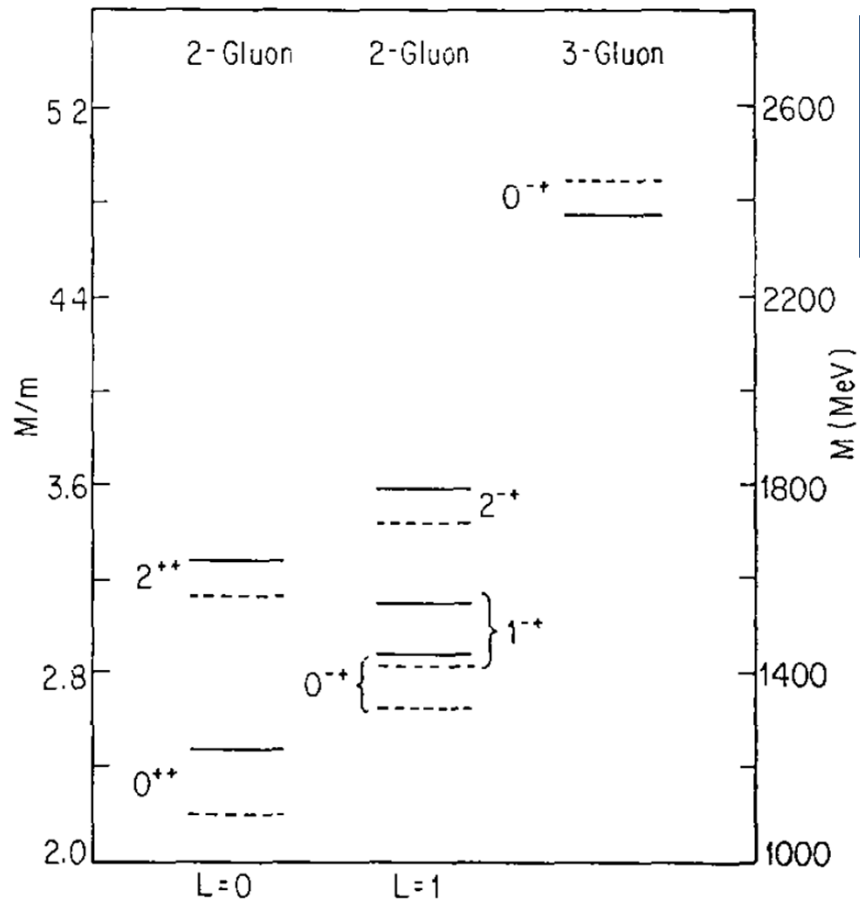
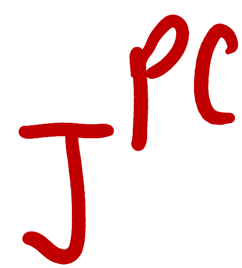


Fig. 3. Results of the numerical calculations. The scale on the left is in units of the gluon mass m; that on the right is in MeV, assuming m = 500 MeV. The solid lines refer to $s = 4m^2$ in the potential (6), and the dashed lines refer to a self-consistent determination of s.

Cornwall + AS PLB'83 [QCD]



AS IS WELL KNOWN SUCH THEORIES ARE HIGHLY NON-PERTURBATIVE AND THERE IS ONLY ONE KNOWN METHOD FOR BRINGING OUT THE FULL CONTENT OF SUCH A THEORY I.E. LGT

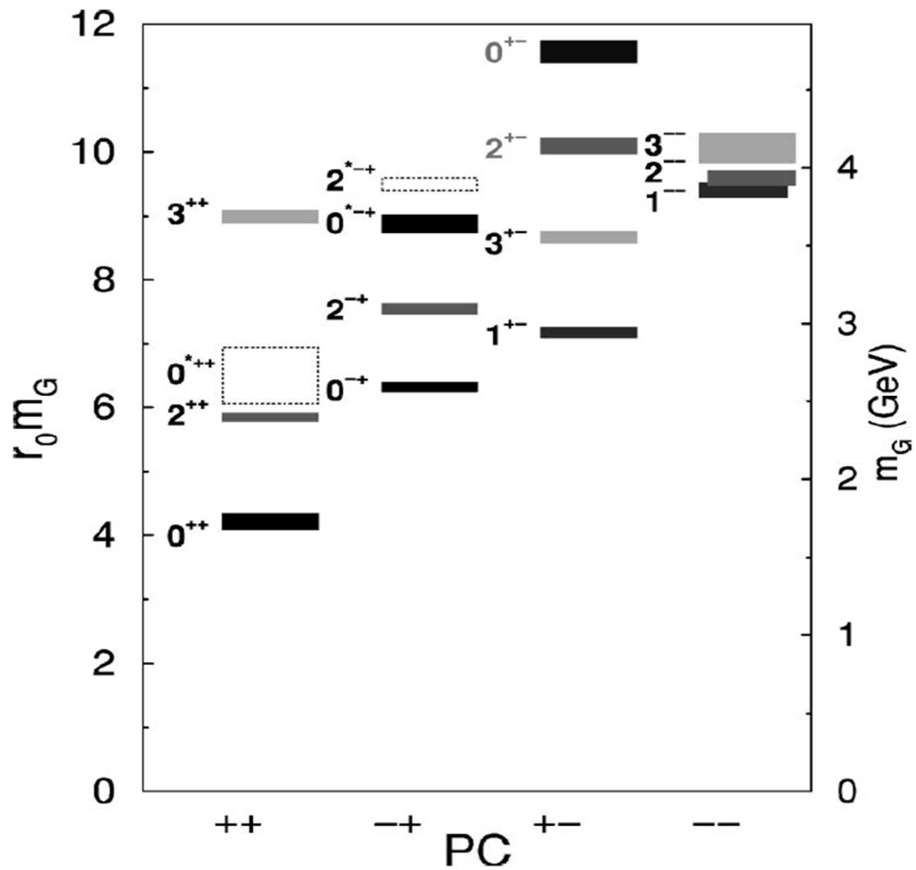


FIG. 8. The mass spectrum of glueballs in the pure SU(3) gauge theory. The masses are given in terms of the hadronic scale r_0 along the left vertical axis and in terms of GeV along the right vertical axis (assuming $r_0^{-1} = 410$ MeV). The mass uncertainties indicated by the vertical extents of the boxes do *not* include the uncertainty in setting r_0. The locations of states whose interpretation requires further study are indicated by the dashed open boxes.

MORNINGSTAR + PEARDON PRD'99 Gluona Spectrum SU(3) Pure gauge

Matured lattice simulations

Low lying spectrum

- For QCD phenomenological models, [Cornwall+AS'80]

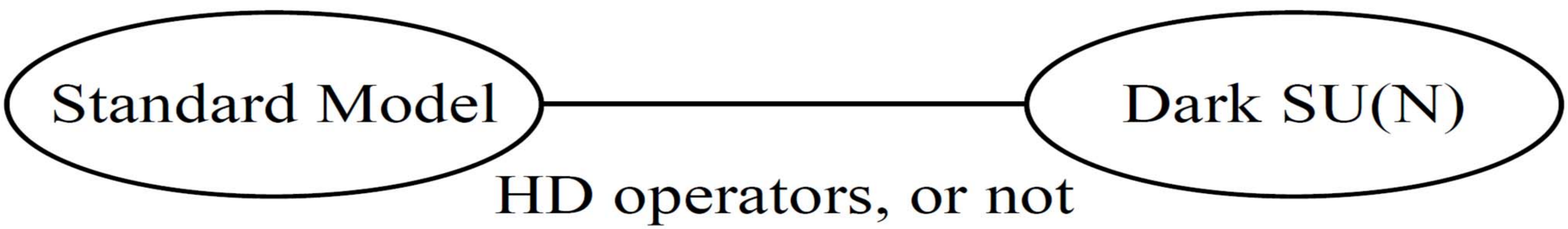
  as well as lattice calculations [Morningstar + Peardon'99] 0++ and 0-+ as lightest states with masses ~ few X Λ_{QCD}
- For N>> 1, lightest gluonia masses go as

$$(\alpha + \beta/N^2)\Lambda$$

See : Lucini + Teper '01; Lucini, Rago + Rinaldi, '10

Interactions

- Gravitational for sure…….decays to gravitons
- With SM ….unavoidable via higher dimensional operators…likely highly suppressed..c later



- No compelling reason to think nature cares whether DM interacts with our detectors or not

Decays to gravitons

m = mass of lightest (i.e. 0++ onium)

$$\Gamma_\phi \sim m^5/M_{pl}^4 \sim \tau_U^{-1}(m/10^7\,\mathrm{GeV})^5$$

where $\tau_U = 10^{17}$ sec is the age of the universe

[Dim. Analysis]

cosmologically stable

C also B. Nelson et al, arXiv:1609……

immediate consequences

- **The mentioned interactions *naturally* accounts for:**

- **Why it has been so difficult to detect DM in "direct detection experiments"**

- **SUN-onia will of course have gravitational Interactions [more later]**

Decades of effort at direct detections has so far given no clear evidence

- **SUN-ny gluonia DM readily accounts for why that may have been the case**
- **Another related line of thought is (lepton) flavored DM; see e.g. Kile + A.S. 1104.5239; Agrawal,Banchet, Chacko, 1109.3516; Kile, Kobach, A.S.1411.1407……..In such scenarios DM interactions are loop suppressed and their direct detections naturally become rather difficult**
- **SUN-ny gluonia is an *extreme* example: matter interactions are too miniscule to be detected=>positive evidence for direct detection, if ever found, would mean SUN-DM is NOT the only source of DM**

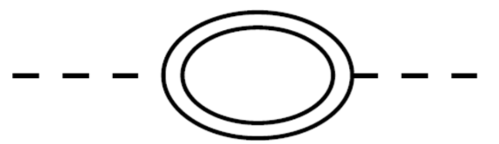
OUR FOCUS WILL BE ON THE LIGHTEST 0++ [0-+] ONIA; MORE RECENTLY FORESTELL ET AL IN 1605.08048 HAVE EXTENDED CONSIDERATIONS TO OTHER ONIA

Interactions of dark [SUN] gluonia

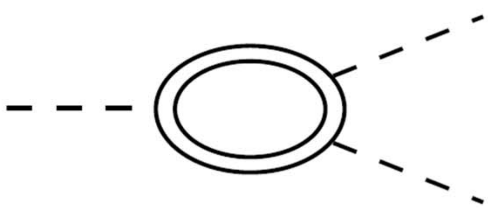
- Scalar potential:

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{1}{3!}\lambda_3\phi^3 + \frac{1}{4!}\lambda_4\phi^4 + \frac{1}{5!}\lambda_5\phi^5 + \cdots$$

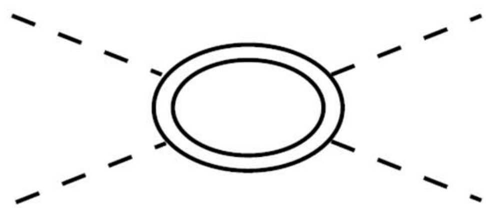
Power counting in the large N limit



$$\phi \sim \sqrt{N}$$



$$\lambda_3 \sim \frac{m}{N}$$



$$\lambda_4 \sim \frac{1}{N^2}$$

Constraints due structure formation I

- **2 to 2 elastic scattering of gluonia:**

  $\sigma \sim 1/m^2N^2$

- **For this DM to address the ``core/cusp problem''* of dwarf galaxies:**

$$0.1\,\mathrm{cm}^2/\mathrm{gram} < \sigma_{2\to 2}/m < 10\,\mathrm{cm}^2/\mathrm{gram}$$

$$m \sim 0.1\,\mathrm{GeV} \cdot N^{-4/3}$$

*See e.g. W. Blok 0910.3538

This paper gives an overview of the attempts to determine the distribution of dark matter in low surface brightness disk and gas-rich dwarf galaxies, both through observations and computer simulations. Observations seem to indicate an approximately constant dark matter density in the inner parts of galaxies, while cosmological computer simulations indicate a steep power-law-like behaviour. This difference has become known as the "core/cusp problem", and remains one of the unsolved problems in small-scale cosmology.

See e.g WJG De Blok

arXiv:0910-3538

II

- **Interactions also allow 3=>2 inelastic annihilation 3=>2 reaction rate, Γ (3=>2) ~ $(n_\phi)^2$ σ (3=>2) with σ (3=>2) ~$1/m^5N^2$**

- **The 3=>2 process tends to make ϕ relativistic & warmer until there gets to be a balance with the reverse 2=>3 rate**
- **So far in this set up, the DM relic density is given by value of n_ϕ at the decoupling of the 3=>2 annihilation; will re-visit this towards the end**

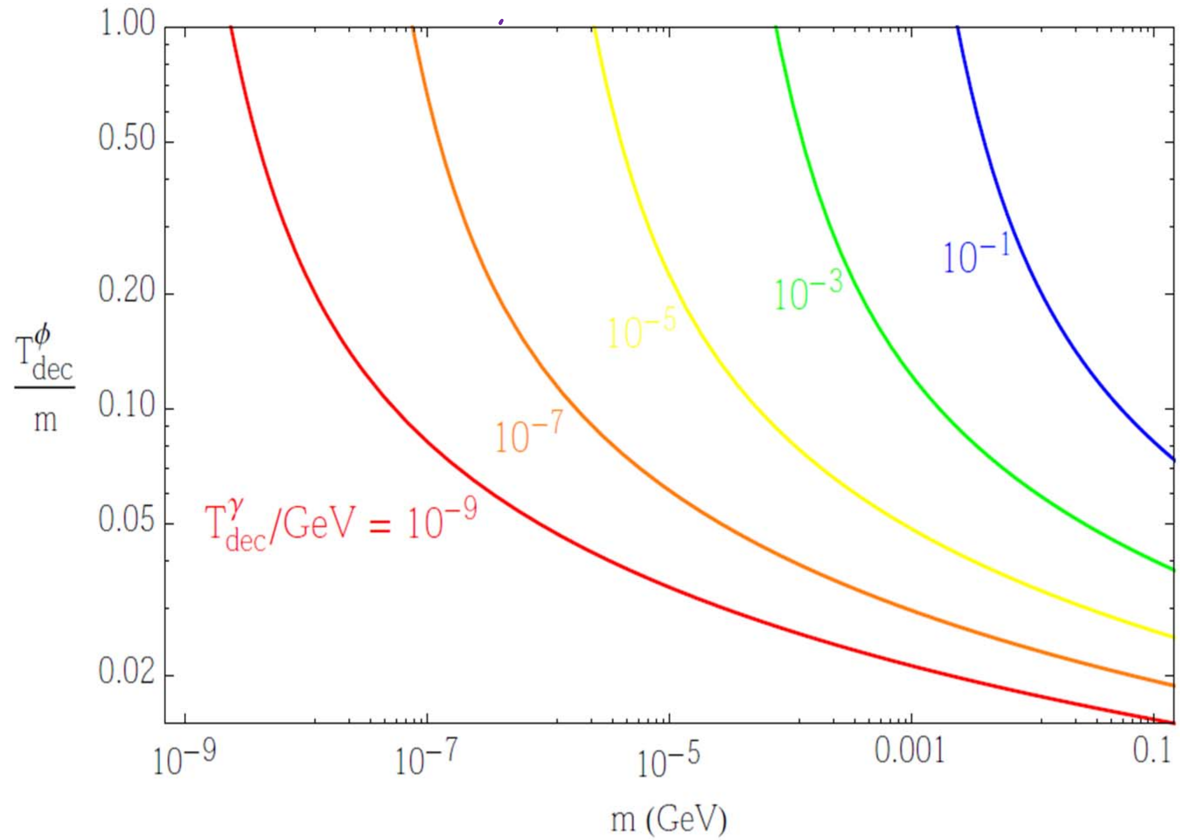


FIG. 2. Ratio of temperature T_ϕ to the mass m of ϕ particles at the decoupling of $3 \to 2$ annihilation that could give the correct dark matter relic density. The curves correspond to different photon temperatures (T^{γ}_{dec}) at this epoch. Roughly, T_ϕ is only one order of magnitude below the mass, and the ϕ particles remain heated before the decoupling.

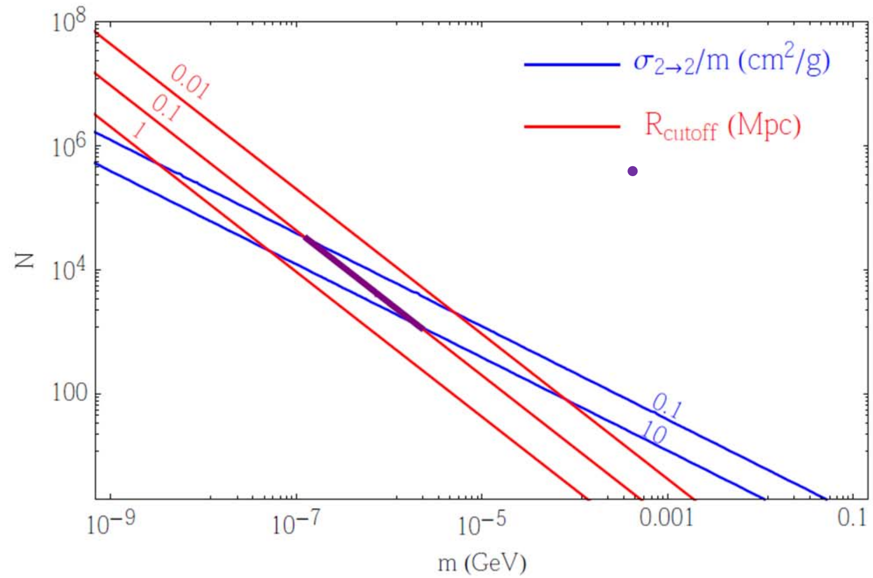


FIG. 1. The parameter space of m versus N where the lightest hidden glueball could be a self-interacting and/or warm DMC. The two blue curves correspond to constant values of DM self interaction cross section, $\sigma_{2\to2}/m = 0.1, 10\,\text{cm}^2/\text{gram}$, respectively. Self-interacting DM lives between the blue curves. The red curves correspond to constant values of damping scale in the power spectrum, $R_{\text{cutoff}} = 0.01, 0.1, 1\,\text{Mpc}$, respectively. Warm DM lives along the middle red curve. The glueball dark matter can be both self-interacting and warm at the intersection of the two regions (thick purple curve).

For SI + WARM

$10^{-4} \leq m \leq 10^{-2}$ Mev

0.1 Kev   10 Kev

$10^{5} \leq N^{-1} \leq 10^{3}$

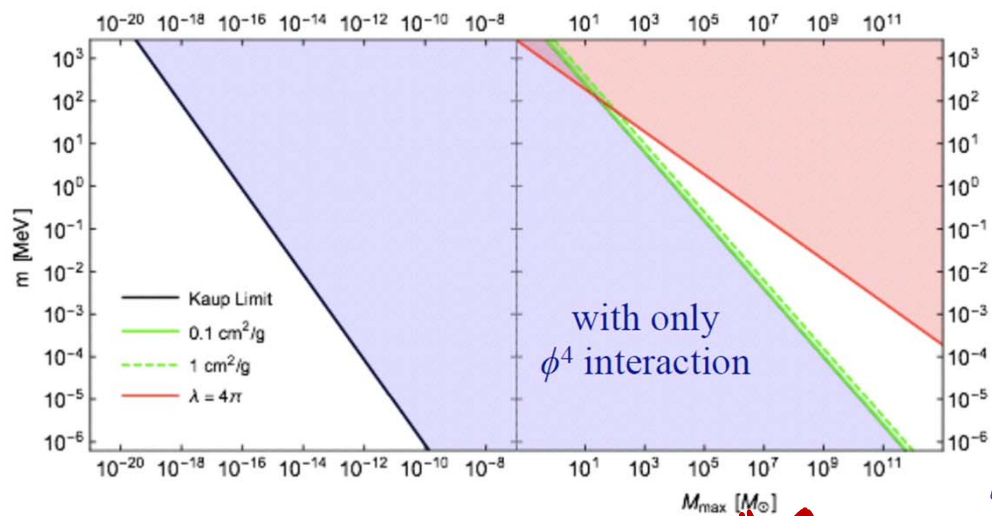
$N \gg 1$

Discuss

More Gravitational Effects

Gravitation: BEC of dark glueball yields macroscopic dark stars.

Repulsive interaction ($\lambda_4 > 0$) could leads to lensing effects.



SI+W DMC ⇒ $10^6 \to 10^8 \odot$!

10 KeV

~0.1 KeV

Further work in progress to explore more general potentials.

BEC of scalars with only ϕ^4 Repulsive interaction

Eby, Kouvaris, Nielsen, Wijewardhana (1511.04474)

27

Gravitational Waves From SU(N) Glueball Dark Matter

ARXIV:1610.06931 WITH YUE ZHANG

GWs from colliding Dark SUN stars [DSS]

- As the distance bet. the colliding DSS decreases, the frequency of emitted GWs increases.
- For binary dark stars with equal mass M and radius R, the highest frequency of the radiated GWs,
- $$f_{\max} = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \ .$$
- LIGO sensitivity is only 50 – 1000Hz

Expected freq from DSS binary collisions

- For SUNny GDM to be warm and SI,
- m ~KeV and N ~ 1000 => f ~ 10^-3 Hz << 50 Hz

- Thus that range wont be accessible by LIGO but would need eLISA

- However, somewhat cooler DM that is SI

[i.e. m ~ 100 MeV and N~ few, LIGO may be adequate] → DSS $\sim 100\ M_\odot$

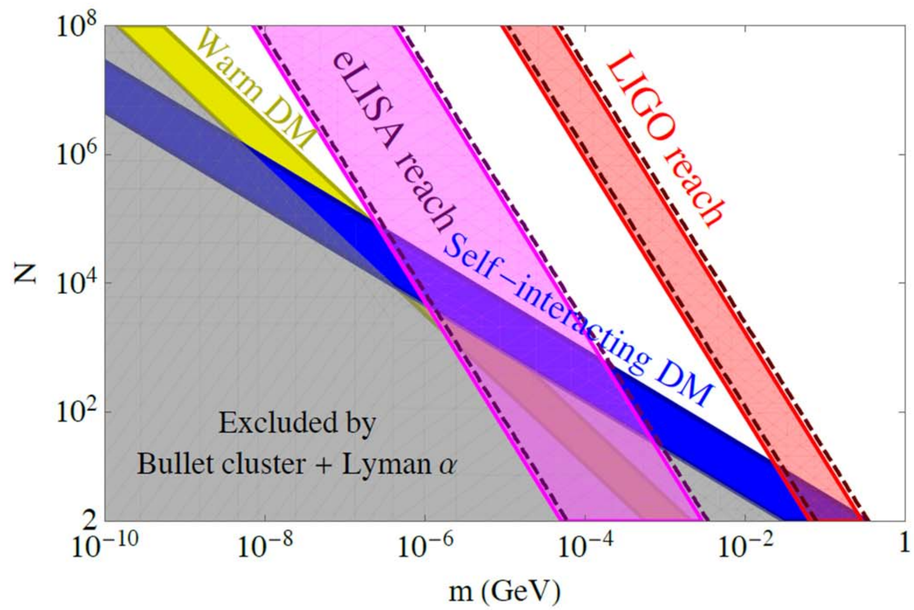


FIG. 3: The LIGO experiment could probe the SU(N) glueball dark matter parameter space, assuming binary DDS exist. In the red region, the highest frequency of gravitational wave radiation calculated based on the large N glueball potential in section B, lies between 50–1000 Hz, thus this region can potentially be within the LIGO sensitivity. In the magenta region, the highest gravitational wave frequency from binary DSS is between 0.03 mHz and 0.1 Hz and could be probed by the future LISA/eLISA project. The regions between the dashed lines corresponds the case of ϕ^4 potential (discussed in section A). For the same SU(N) model, in the the yellow band the $3 \to 2$ annihilation enables the lightest scalar glueball to have the proper free-streaming length to be a warm dark matter candidate, while in the blue band, the $2 \to 2$ elastic scattering of the glueball dark matter is large enough for it to be a self-interacting dark matter candidate [7]. In the lower left corner, the gray region is already ruled out because of the bullet cluster and Lyman alpha observations.

Cosmic selection rule(for relic density) and possible repercussions

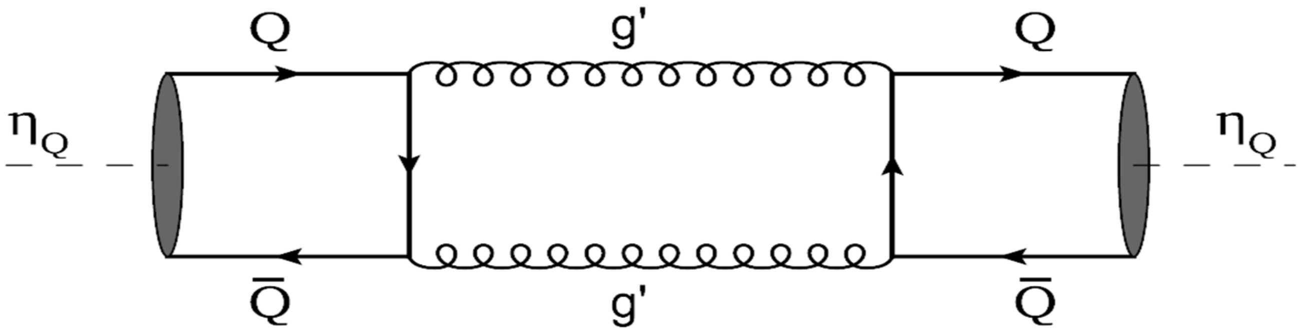
- See arXiv:1704.02347 **with Huangyu Xiao and Yue Zhang**
- **To establish a connection between the gluonia DM and the SM particles**
- **Introduce vector-like quarks ["jokers"] that act as bridge particles transforming under**

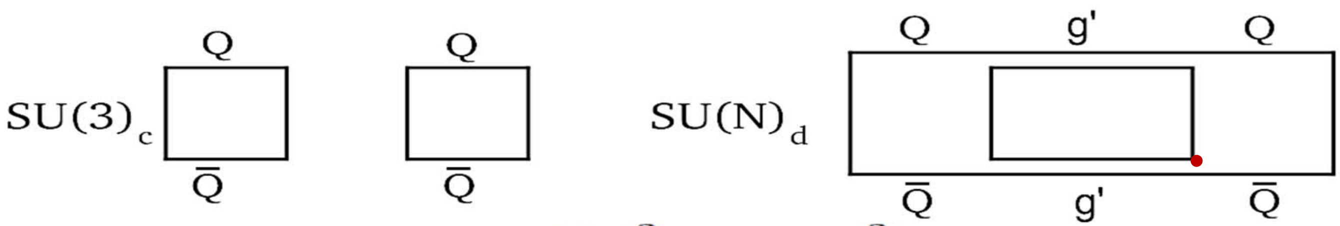
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(N)_d$$

$$Q \in (3, 2, 1/6, N_d), \quad \bar{Q} \in (\bar{3}, \bar{2}, -1/6, \bar{N}_d) .$$

This allows to build a thermal contact between the two sectors in the
early universe, when the temperature is high enough

Large N selection rules and decays of Q-onia





$$\Gamma_{\eta_Q \to gg} = \frac{N_d(N_c^2 - 1)\alpha_S^2}{4N_c m_Q^2}|R(0)|^2$$

$$\Gamma_{\eta_Q \to g'g'} = \frac{N_c(N_d^2 - 1)\alpha_d^2}{4N_d m_Q^2}|R(0)|^2$$

$$r \equiv \Gamma_{\eta \to gg}/\Gamma_{\eta \to g'g'} \simeq \alpha_S^2/\alpha_d^2$$

$r \sim N_d^2$
$[\because \alpha_d \propto 1/N_d]$

ENSURES dark gluonia density stays well below neutrinos

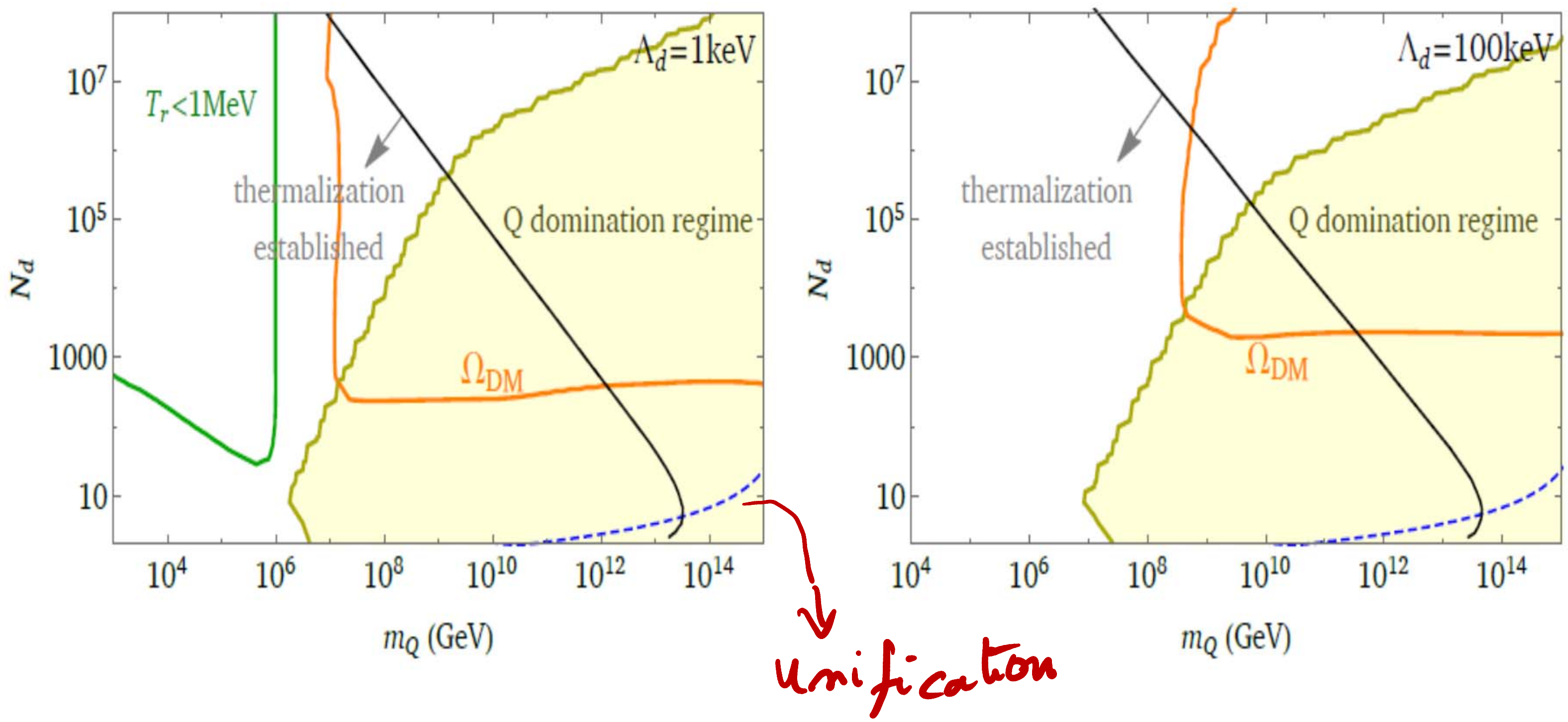


FIG. 2. In the parameter space of N_d versus m_Q, the orange curve in the two plots above corresponds to the correct relic abundance (see Eq. (17)) for the $SU(N)_d$ glueball DM, which becomes independent of the vectorlike quark mass m_Q when they are heavy enough (the horizontal part of the curve). Such UV insensitiveness occurs as long as there is a stage in the early universe when the energy density of the vectorlike quarks becomes dominant, as shown by the yellow shaded regions. The black curve is a boundary below which the vectorlike quarks and the DM and dark sector can reach thermal equilibrium at temperature around m_Q. Above the black curve we make the assumption that the vectorlike quarks are abundant enough so that their domination in the universe is guaranteed to happen. We have fixed the value of the dark sector intrinsic scale $\Lambda_d = 1\,(100)$ keV in the left (right) plot. In the left plot, the region surrounded by the green curve has too low reheating temperature after the annihilation decay of the vectorlike quarks. In both plots, along the blue curve, one may realize unification of SM gauge couplings in the presence of the vectorlike quarks.

$m_Q \gtrsim 10^7$ GeV to ensure correct relic abundance

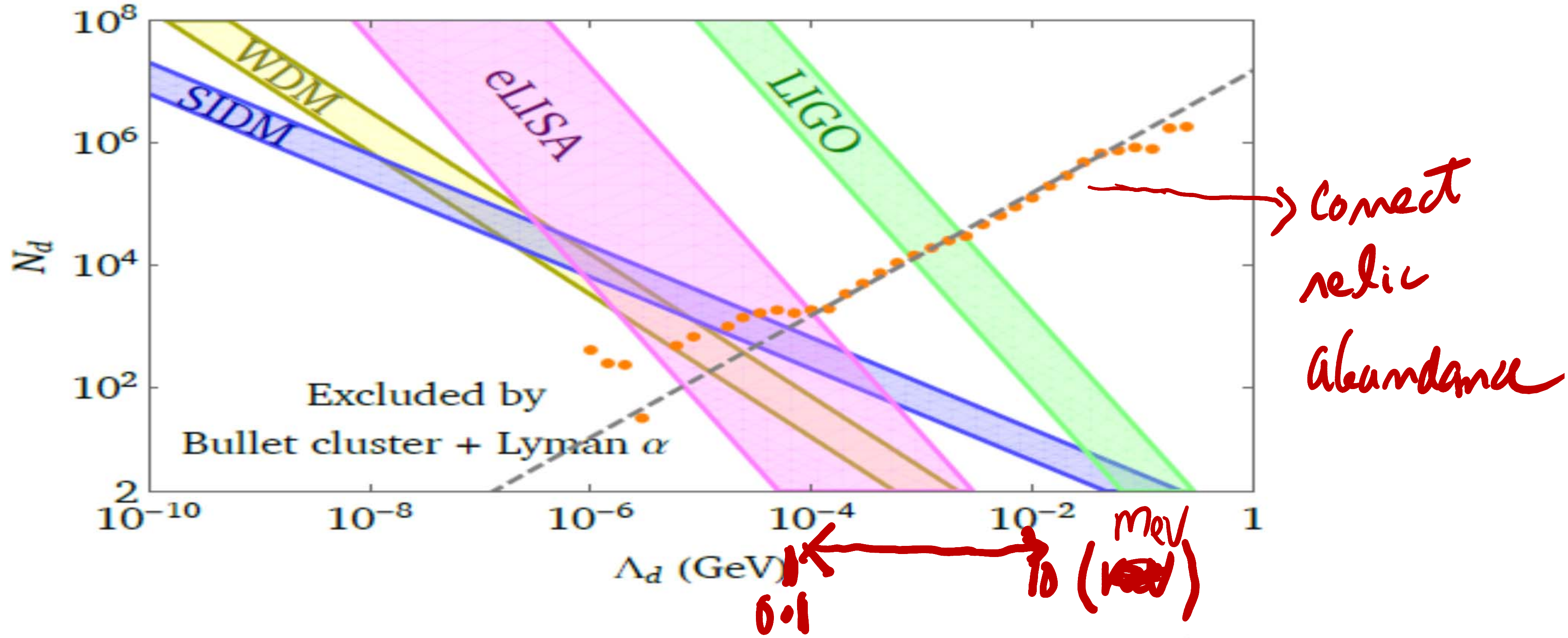


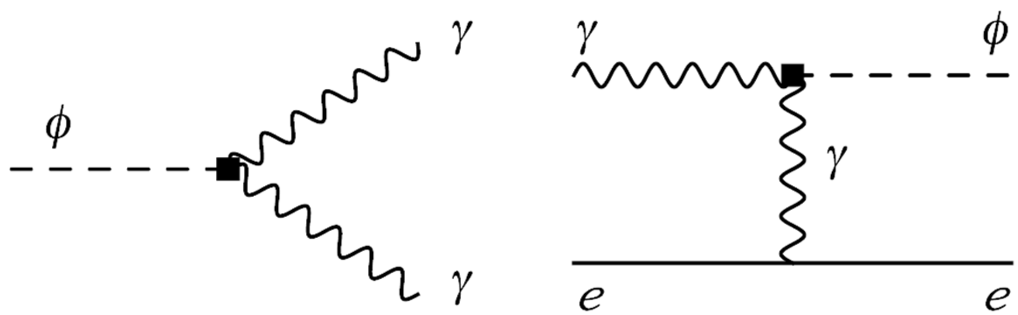
FIG. 3. The low energy parameter space of N_d versus Λ_d. The correct relic abundance to the glueball DM can be accommodated on the orange dots, where we assumed the vectorlike quarks to be heavy and abundant enough to dominate the early universe. The black dashed line corresponds to the approximate relation derived in Eq. (20), as a fit to the orange dots. Also shown are the regions of interest to astrophysical probes, including warm DM, self-interacting DM, as well as possible gravitational wave signals from massive compact objects formed by the glueball condensate.

Interactions with the SM via HDO

$$\mathcal{L}_{int} = (1/M^n) H_{\mu\nu} H^{\mu\nu} \mathcal{O}_{SM}$$

interactions with photons as an example

$$\mathcal{L}_{int} = \frac{1}{M^4} H_{\mu\nu} H^{\mu\nu} (F_{\alpha\beta} F^{\alpha\beta}) \rightarrow \frac{N m^3}{M^4} \phi F_{\alpha\beta} F^{\alpha\beta}$$



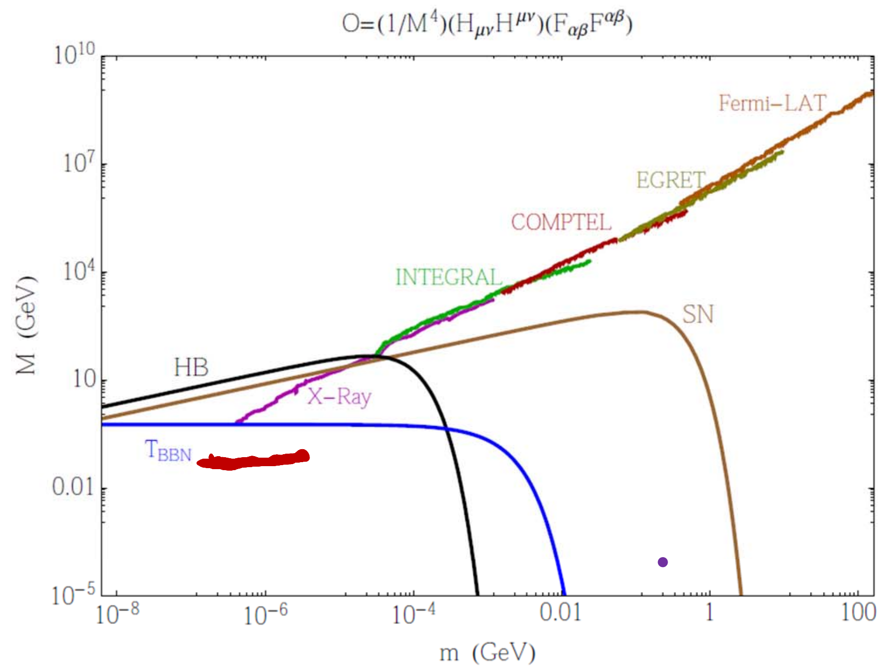


FIG. 3. Lower bounds on the cutoff scale M. Cosmic ray photon observations constrains glueball dark matter decay into photons, and from right to left, the curves correspond to constraints from Fermi-LAT, EGRET, COMPTEL, INTEGRAL, X-ray. The black (brown) solid curve is the lower bound on M from the energy loss argument of HB (SN). The blue curve represents the requirement that the hidden sector is not thermalized with the SM sector below the BBN temperature.

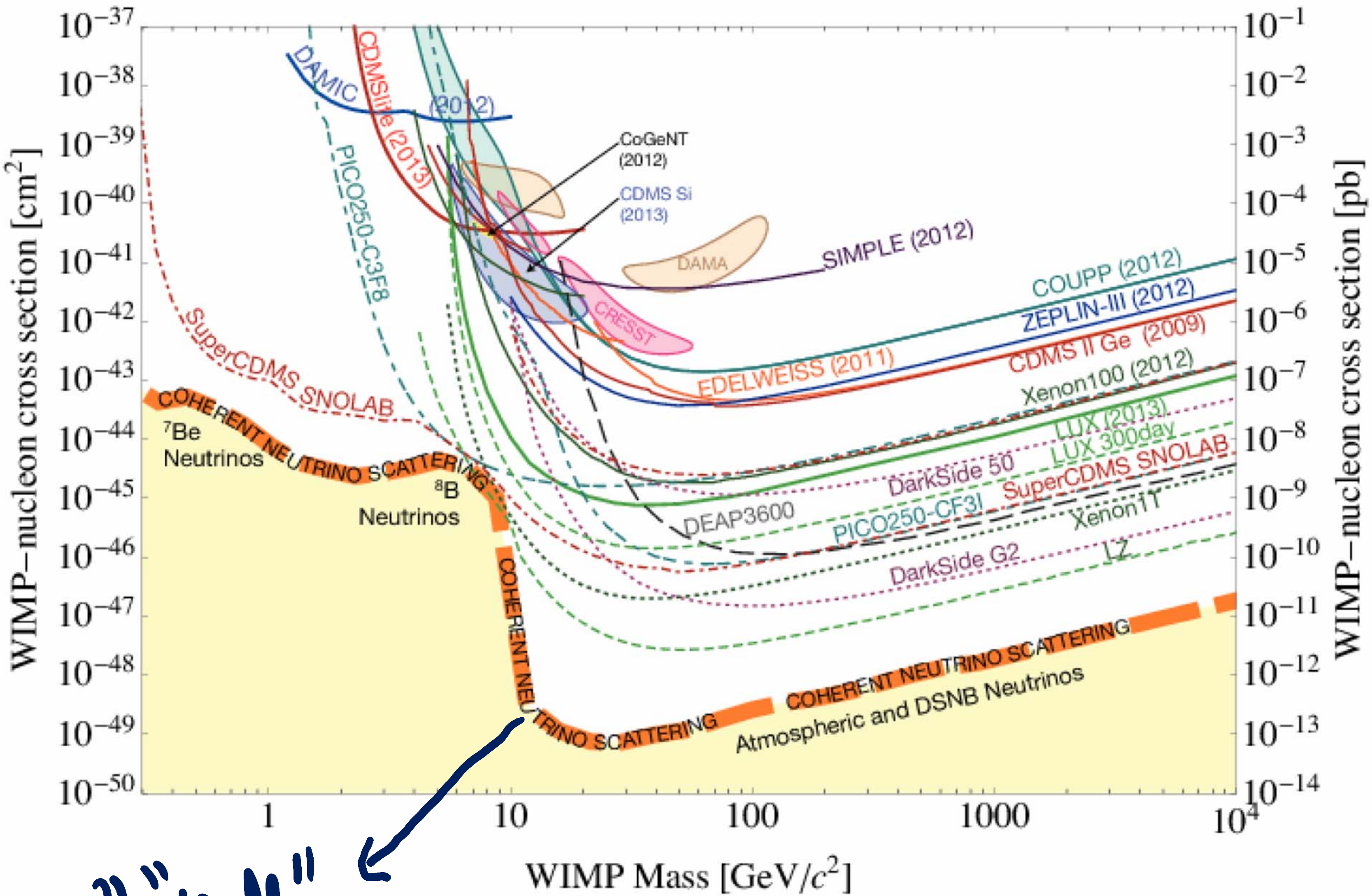
~ EW

~ KeV < m_ϕ < MeV , M ~ EW Scale ~ 100 GeV

Estimates of direct detection Xs[DDXS] of SUN DM

- **Cut-off of HDO needs to be >100 GeV**
- **That implies the DDXS < 10^{-50}/cm^{2} !!** [Very Crude]
- **This is 10^{-10} of current LUX upper bound for DMXS, see D S Akrib et al[LUX]PRL 2016**

- **This is many orders below the "neutrino wall"**



ν "wall"

[irreducible ν background]

Implications of $\theta H\widetilde{H}$

- This can generate an effective interaction with the SM

$$\theta\,(1/M^4)(H\widetilde{H})(G\widetilde{G})$$

=> $$\theta_{\rm QCD}G\widetilde{G}$$

$$\theta_{\rm QCD}\sim(m/M)^4\theta$$

< 10^{-3} automatically satisfied

Using nedm bound of 10 -26 em => $\theta_{\rm QCD}\lesssim 10^{-13}$.

Theta SUN ~ O(1) cannot be ruled out !
Possibly interesting implications

Key issues for non-perturbative studies

- Potential for s s scattering, attractive or repulsive?
- pp…..?

- Key to BEC into Dark SUN-onia stars[DSS] Repulsion
- DSS give rise to different pattern of gravitational waves as in arXiv:1610.06931 of SZ
- DSS could lead to gravitational lensing [needs to be studied]

FOR QCD SOME STUDIES

Glueball-glueball scattering in a constituent gluon model

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Abstract. In this work we use a mapping technique to derive in the context of a constituent gluon model an effective Hamiltonian that involves explicit gluon degrees of freedom. We study glueballs with two gluons using the Fock-Tani formalism. In the present work we consider two possibilities for 0^{++}: (*i*) as a pure $s\bar{s}$ and calculate, in the context of a quark interchange picture, the cross-section; (*ii*) as a glueball where a new calculation for this cross-section is made, in the context of the constituent gluon model, with gluon interchange.

arXiv 0407114

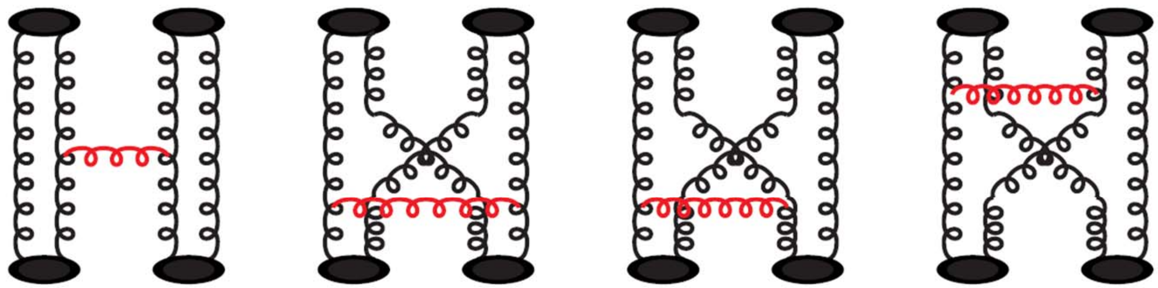
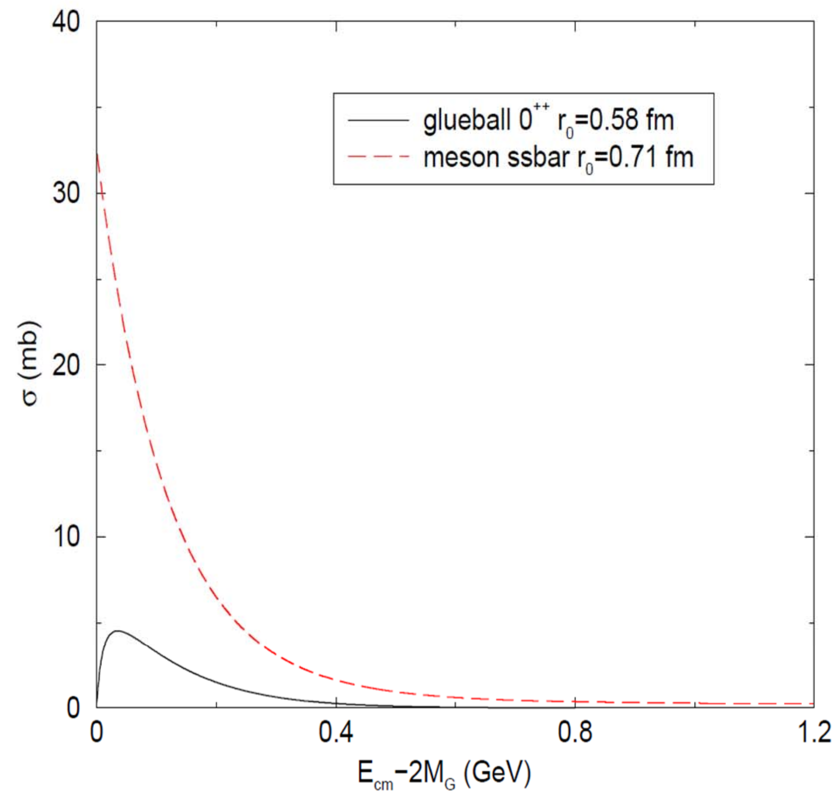


FIGURE 1. Diagrams representing the scattering amplitude h_{fi} for glueball-glueball interaction wi constituent gluon interchange.

1 gluon exch pot. model... rather naive?



0++ possibly repulsive?

FIGURE 2. Cross-section comparison for 0^{++} with the following parameters $\beta = 0.1$, $\lambda = 1.8$, $k = 0.21$, gluon mass $m = 0.6$ GeV. The $s\bar{s}$ quark model parameters: $m_q = 0.55$ GeV, $\alpha_s = 0.6$.

A well known study in QCD is ππ scattering

- In fact this is part of the RBC-UKQCD major project, K=> ππ and Ɛ' and in particular for Ɛ'

scattering phases of ππ are an important test of our framework. See [CU] thesis of Qi Liu [2012] and Daiqiang Zhang [2015] and Tianle Wang [2017-on] in progress

- See also E. Shabalin, arXiv:1511.00498 who uses ChiPT.
- Scattering length for I=2 is + → repulsive
- And for I=0 is - → attractive

Summary & Outlook

- **Dynamically generated mass may play a *central* role in DM as it does in the visible sector.**
- **SUN pure gauge theory provides a strikingly simple and viable DMC…[in fact it'd be a bit surprising if nature does not make use of the simplicity of this theory]**
- **It readily accounts for why direct detections so far have given null results. It may well also provide a *natural* explanation for the only compelling evidence, i.e. gravitational, that we have so far.**
- **Exciting possibility exists of BEC and gigantic Dark SUN "stars" possibly up to 10^8 solar masses leading to enhanced grav. lensing effects!**
- **In this context, it was gratifying and encouraging to hear Neal Weiner's talk yes'dy.**
- **DSS collisions can lead to GWs possibly accessible to LIGO and perhaps even more so to eLISA**
- **Vector-like (bridge) doublet of mass over 10^7 GeV allows suitable relic density with selection rule, N_d => Λ_d /0.1 KeV**
- **Non-perturbative studies of this simple but rich theory are called for, esp $\phi\phi \Rightarrow \phi\phi$ ….is it attractive or repulsive for low lying gluonia? [for low-lying gluonia, ϕ = o++, O-+]**

XTRAS

Black hole vs DSS

- We find the ratio of our glueball dark matter radius to its mass is $(R/M)_{\text{DSS}} = x_R/(M_{pl}^2 \mathcal{M}_*(x_R))$. In contrast, the ratio for a Schwarzschild black hole is simply $(R/M)_{\text{BH}} = 2/M_{pl}^2$. From our numerical calculation, we find that $x_R/\mathcal{M}_*(x_R) > 2$ is always the case, thus the radius of the DSS is larger than the Schwarzschild radius of a black hole with equal mass. Therefore, a DSS will not collapse into a black hole.