Glueball dark matter in SU(N) lattice gauge theory

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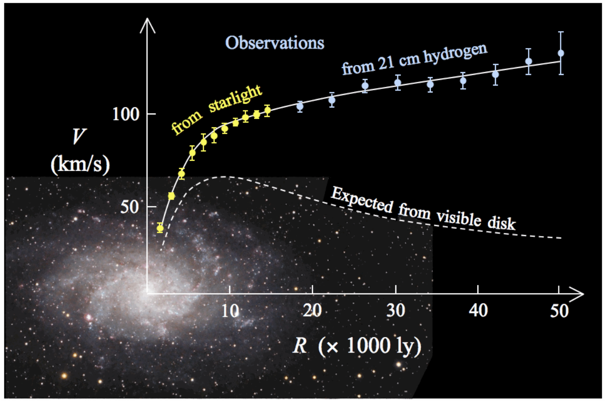
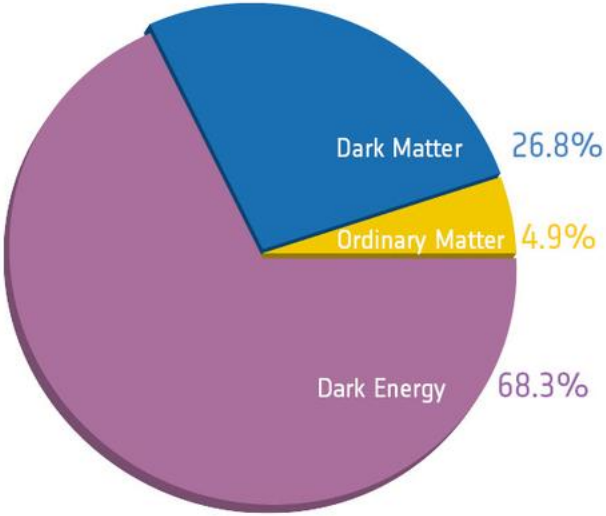
Based on
N. Yamanaka et al., arXiv:1910.01440 [hep-ph]
N. Yamanaka et al., arXiv:1910.07756 [hep-lat]
N. Yamanaka et al., arXiv:1911.03048 [hep-lat]

2020/06/02
地下宇宙

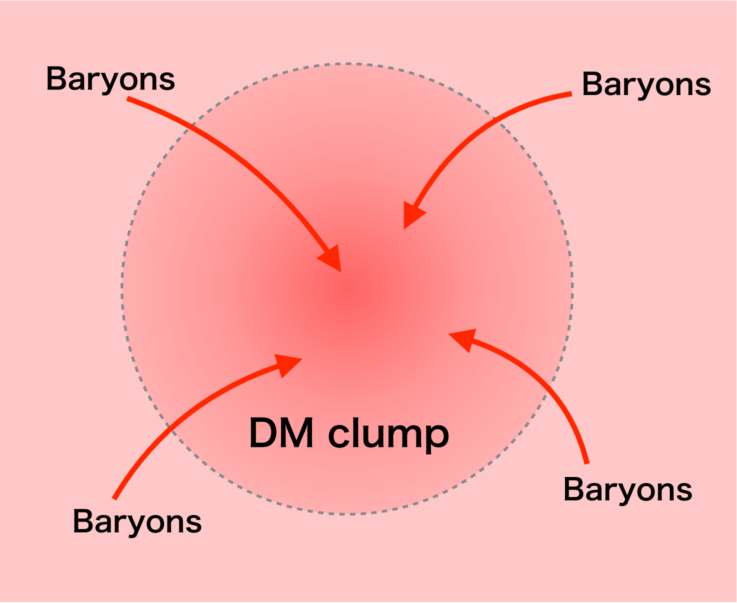
Many evidences of Dark matter



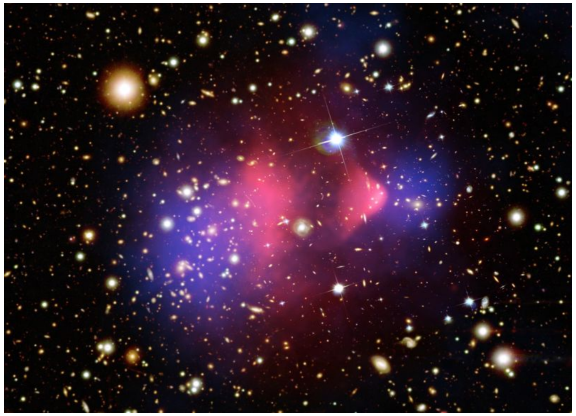
Galactic rotation curve



DM density extracted from CMB



N-body simulation : large-scale structure



Bullet cluster : collision of galaxies

SU(N) pure Yang-Mills theory

$$\mathcal{L}_{\rm YM} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu,a}$$

($a = 1,\ldots,N_c^2-1$)

⇒ The simplest interacting theory

Important properties:

$\mathscr{L}_{\rm YM}$ does not have apparent scale, but scale is dynamically generated (dimensional transmutation)

Renormalizable theory, running coupling has logarithmic scale variation,

difference of N_c can generate $\Lambda_{\rm YM}$'s which differ by orders of magnitude

No scalars and massive fermions ⇒ Free from quadratic divergences

⇒ No important fine-tuning problem in the choice of $\Lambda_{\rm YM}$!

(Suppose a GUT which generates SM and DM, the difference of mass scales between SM and DM is not serious)

⇒ **Theory with very high naturalness**

Dark matter in hidden YM theory:

Lightest particles are glueballs ! ⇒ SU(N) glueballs are candidate of DM

(summarized in the report of USQCD Collaboration : arXiv:1904.09964 [hep-lat])

Self-interacting dark matter

The DM distribution can be predicted in N-body simulation with gravity only

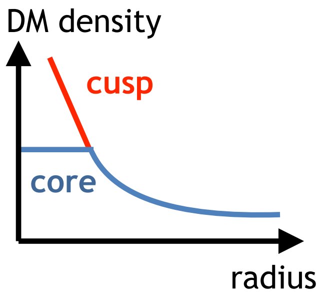
⇒ Successful in describing the large scale structure (scale > Mpc)

Introducing DM self-interaction changes the structure smaller than Mpc
(= DM-DM scattering)

There are (were?) several problems in the galactic DM distribution:

- **Core vs Cusp problem:**

  N-body simulation predicts cuspy DM distribution near the galactic center, whereas observations suggest flat ones.



- **Too-big-to-fail problem:**

  Satellite galaxies are less dense than those predicted by the N-body simulation.

- **Missing satellite problem:**

  More satellite galaxies than those predicted by the N-body simulation are observed.

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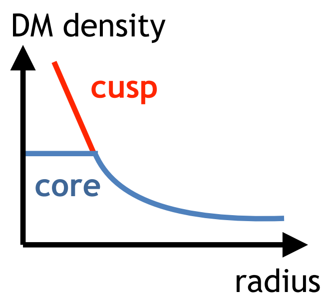

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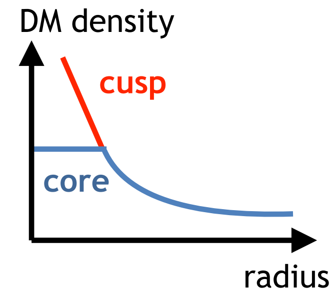

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➡ Still under debate, but this shows the importance of the investigation of DM-DM scattering

Object of study

Glueballs of SU(N) Yang-Mills theory are good candidates of dark matter

In this work, we study the interglueball scattering on lattice which is the only way to quantify nonperturbative physics of nonabelian gauge theory.

The Yang-Mills theory depends only on the scale parameter Λ (given N_c): can we determine Λ from observation?

Object:

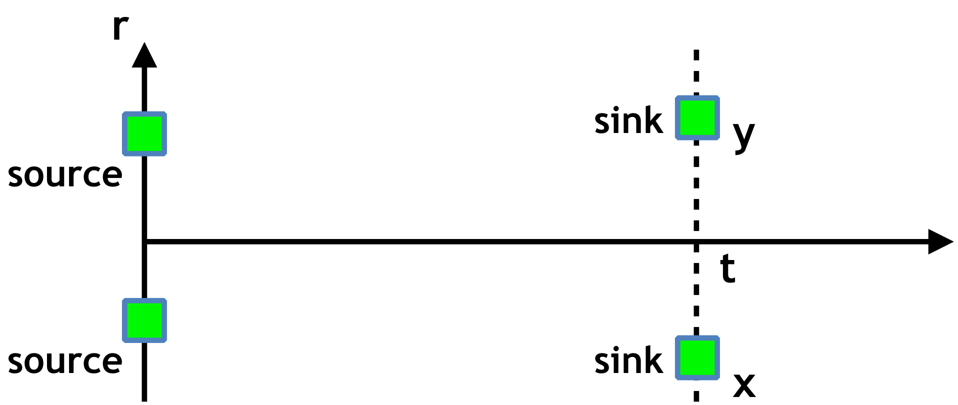
In this work, we study the interglueball scattering of SU(2) Yang-Mills theory on lattice, and set constraint on its scale parameter Λ.

Nambu-Bethe-Salpeter amplitude

The information of the scattering is included in the following n-point correlator (Nambu-Bethe-Salpeter amplitude):

$$C_{\phi\phi}(t, \mathbf{x}-\mathbf{y}) \equiv \frac{1}{V}\sum_{\mathbf{r}} \langle 0 | T[\phi(\mathbf{x}+\mathbf{r}, t)\phi(\mathbf{y}+\mathbf{r}, t) \cdot \mathcal{J}(0)] | 0 \rangle$$

$\mathcal{J}(0)$ **: source op.**



- **2-glueball (0^{++}) state mixes with all other multi-glueball states:**

  ⇒ The source may be chosen as 1-body, 2-body, etc, on convenience

- **The NBS amplitude obeys the Schroedinger equation below inelastic threshold**

HALQCD method

Extract the interglueball potential from the NBS amplitude by inversely solving Schroedinger equation

$$\left[\frac{1}{4m_\phi}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{1}{m_\phi}\nabla^2 + \frac{(\mathbf{r}\times\nabla)^2}{2m_\phi r^2}\right]R(t,\mathbf{r}) = \int d^3\mathbf{r}' U(\mathbf{r},\mathbf{r}')R(t,\mathbf{r}')$$

$$R(t,\mathbf{r}) \equiv \frac{C_{\phi\phi}(t,\mathbf{r})}{e^{-2m_\phi t}}$$

N. Ishii et al., PLB **712** (2012) 437.

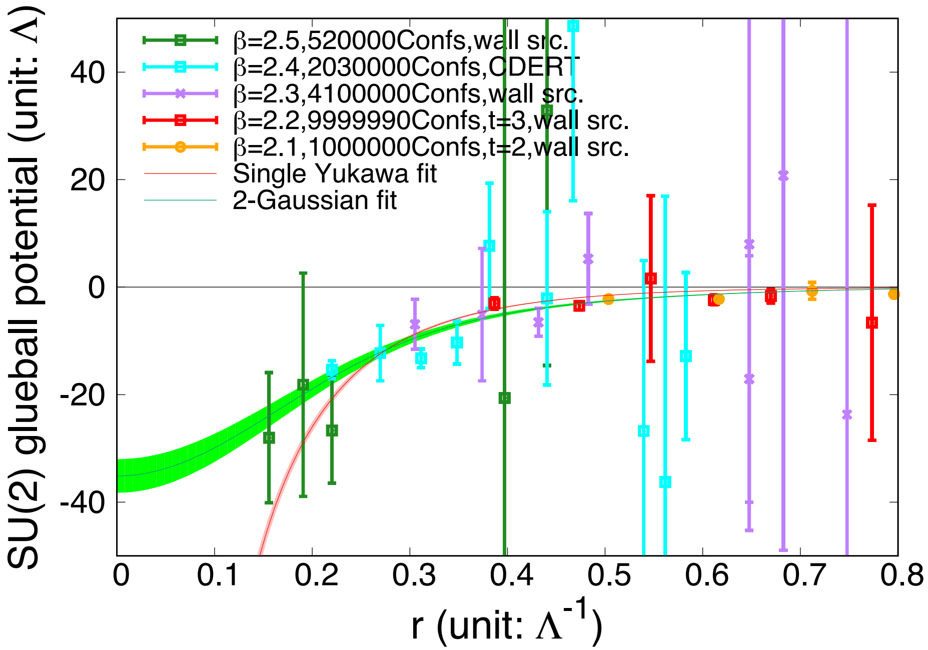
- Crucial advantage : do not need ground state saturation

➡ **Almost mandatory to use time-dependent HAL method for the glueball analysis, since the glueball correlator becomes very noisy before ground state saturation**

- Inelastic threshold for glueball = $3m_\varphi$: high enough to use low t

- Subtract centrifugal force for removing higher angular momenta

Result



We test two fitting forms:

- **Yukawa fit:**

$$V_Y(r) = V_1 \frac{e^{-m_\phi r}}{4\pi r}$$

V_1 = -231 ± 8 **x^2 d.o.f. = 1.3**

- **2-Gaussian fit:**

$$V(r) = V_1 e^{-\frac{(m_\phi r)^2}{8}} + V_2 e^{-\frac{(m_\phi r)^2}{2}}$$

V_1 = (-8.5 ± 0.5)Λ
V_2 = (-26.6 ± 2.6)Λ **x^2 d.o.f. = 0.9**

DM cross section is derived from phase shift calculated with the potentials

$$\sigma_{\rm tot} = \frac{4\pi}{k^2} \sin^2[\delta(k \to 0)]$$

Yukawa: **σ_{tot} = (2.5 - 4.7)Λ^{-2} (stat.)**

2-Gaussian: **σ_{tot} = (14 - 51)Λ^{-2} (stat.)**

σ_{tot} = (2 - 51) Λ^{-2} (stat.and sys.)

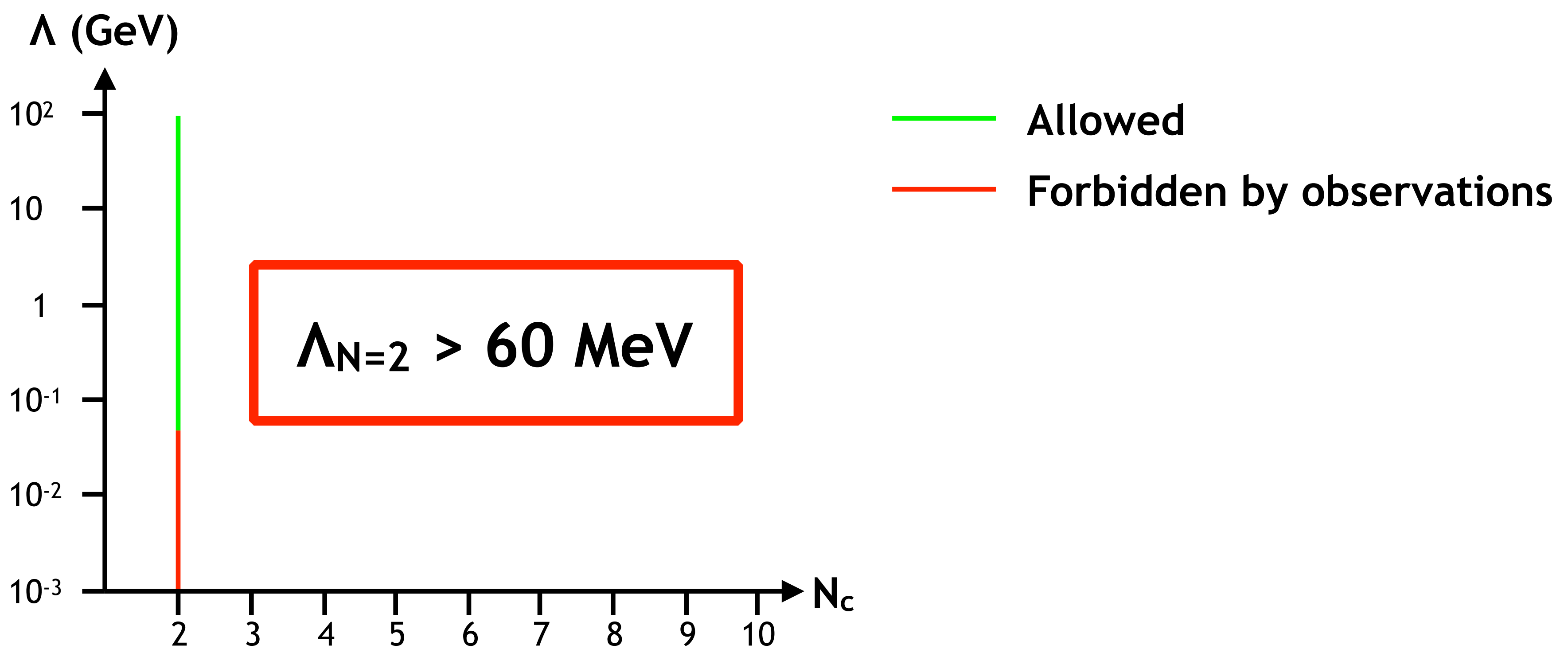
(sys. due to fitting forms)

Constraint on SU(N) YM scale parameter from DM X section

Observational constraints: $\frac{\sigma_{tot}}{m_\Phi} < 1.0\ \mathrm{cm^2/g}$

Robust constraint from galactic cluster shape, collisions (upper limit)

A. H. Peter et al., MNRAS **430**, 81 (2013), **430**, 105 (2013); S. W. Randall et al., APJ **679**, 1173 (2008).



N_c vs. scale parameter (Λ) diagram

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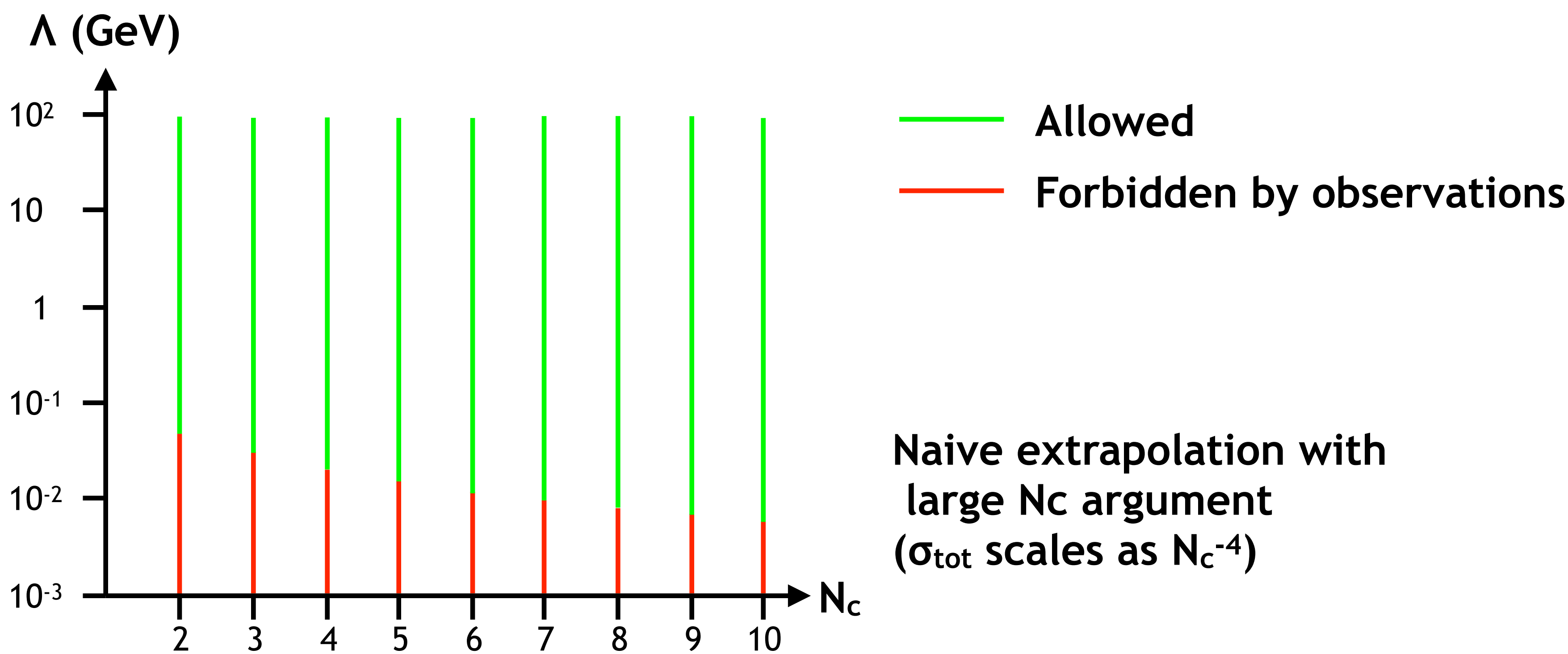

Naive extrapolation with large Nc argument (σ_{tot} scales as N_c^{-4})

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Constraint on SU(N) YM scale parameter from DM X section

Observational constraints: $0.45\ \mathrm{cm^2/g} < \frac{\sigma_{tot}}{m_\Phi} < 1.0\ \mathrm{cm^2/g}$

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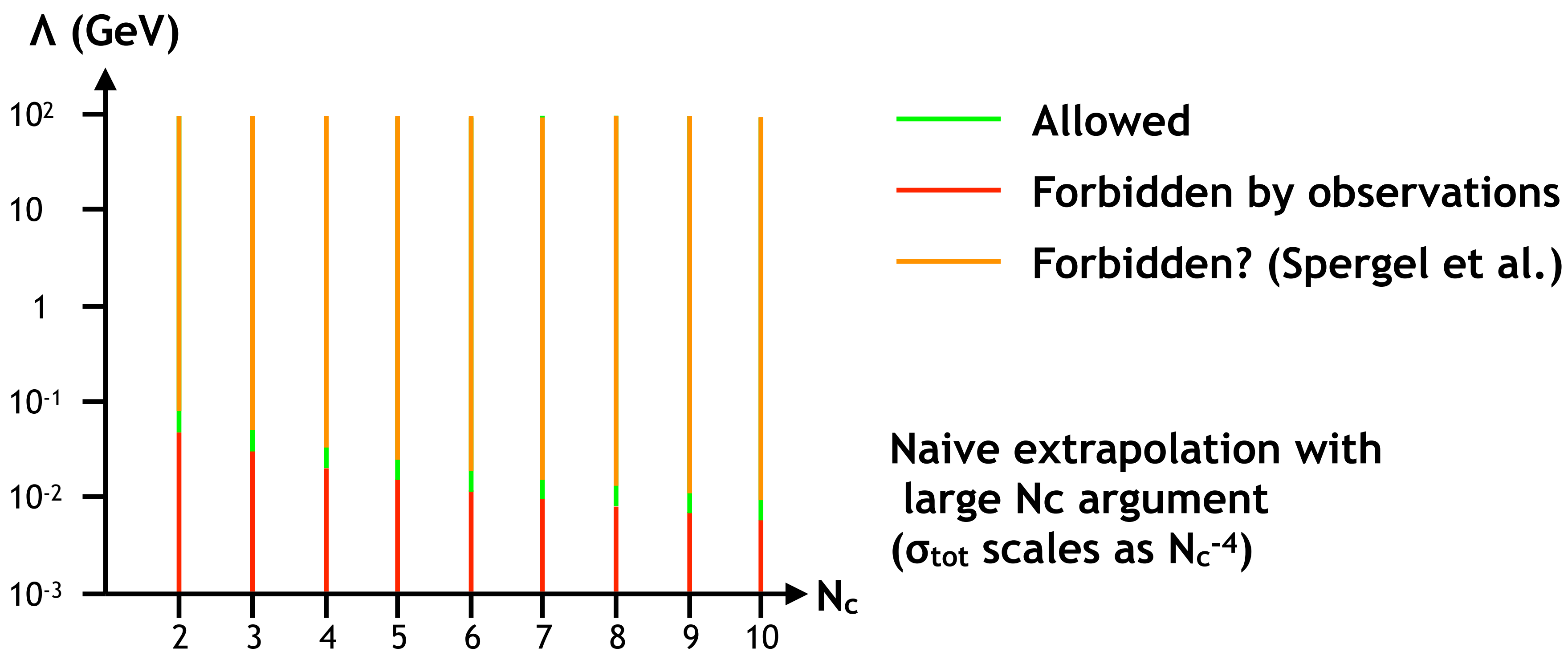
A. H. Peter et al., MNRAS **430**, 81 (2013), **430**, 105 (2013); S. W. Randall et al., APJ **679**, 1173 (2008).

Constraint from Spergel et al. (lower limit), under discussion?

D. N. Spergel et al., PRL **84**, 3760 (2000).



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Summary

- Glueballs of the SU(N) Yang-Mills theory are good candidates of dark matter : study of self-interaction is important.
- We studied the glueball cross section in the SU(2) Yang-Mills theory on lattice. HALQCD method is used to extract the interglueball potential.
- We could constrain the scale parameter of SU(2) YMT for the 1st time from observational data : $\Lambda > 60$ MeV.

Homeworks:

- Extract glueball effective lagrangian and predict other cosmologically important observables.
- Calculations for $N_c > 2$: extrapolate to large N_c.