Theory Group

Masahiro Kawasaki

Current members of theory group

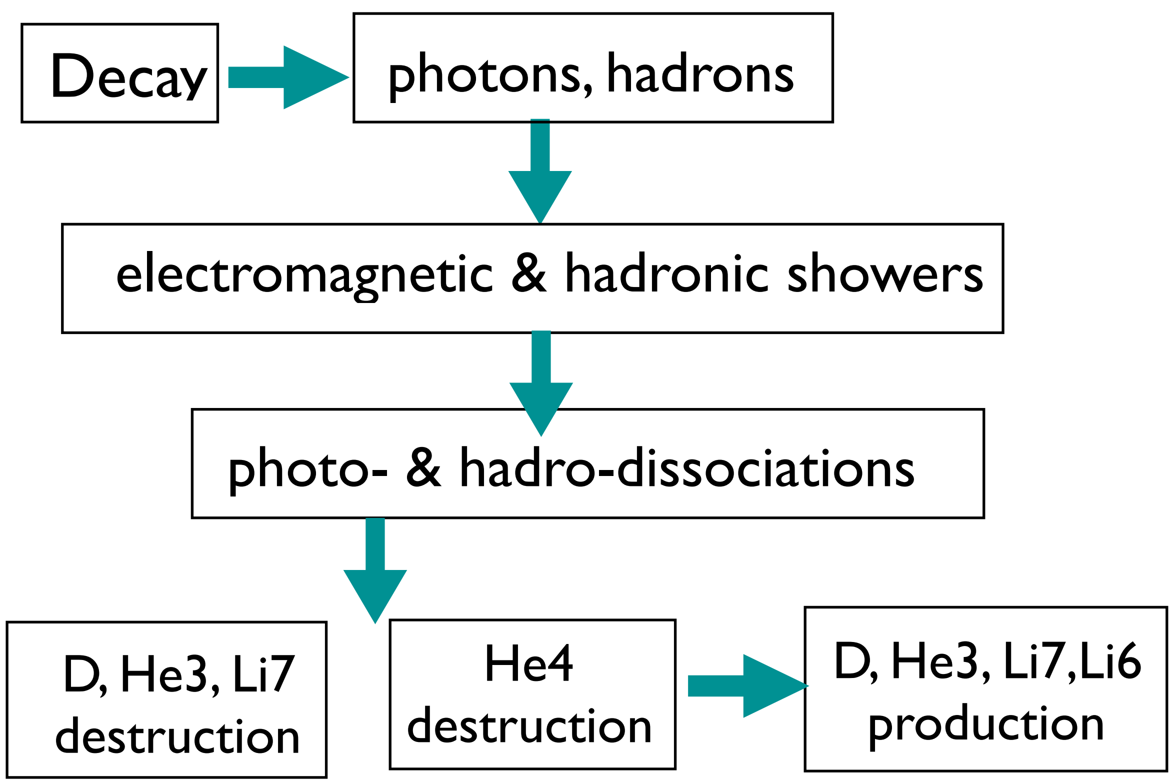
- Staffs
  - Masahiro Kawasaki (2004~) cosmology
  - Masahiro Ibe (2011~) particle physics
- Postdoctoral Fellows
  - Ippei Obata
  - Kohei Hayashi
  - Ryo Nagai
  - Takashi Hiramatsu
  - Motoo Suzuki
- Graduate students
  - 7 students in PhD course
  - 4 students in master course

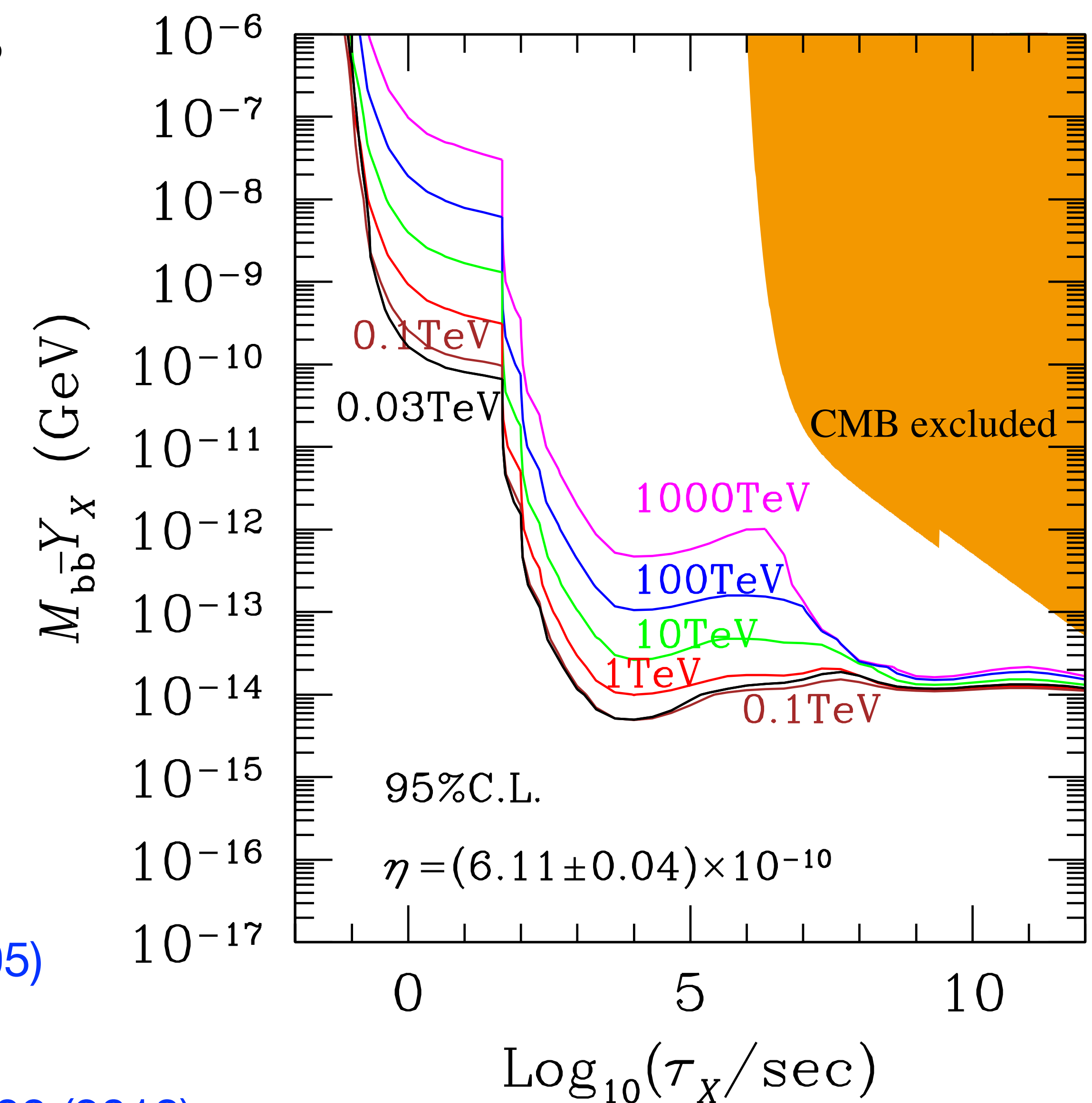
Research Activities

- Theory group is making theoretical studies on phenomenology-oriented particle physics and cosmology including
    - Higgs physics
    - Collider phenomenology
    - Dark matter
    - Axion cosmology
    - Inflation models
    - Baryogenesis
    - Big-bang nucleosynthesis
    - PBH formation
    - ....
- We published 199 papers in refereed journals during 2012-2018

Big-bang nucleosynthesis and long-lived decaying particles

- Long-lived particles with lifetime 10^{-1}-10^{12} sec
  - appear in physics beyond the standard model (SUSY, string..)
  - affect abundances of light elements (D, He4, He3…)
- BBN can give significant constraints





- First reliable constraints
  Kawasaki, Kohri, Moroi PRD D71 083502 (2005)
- Improved analysis
  Kawasaki, Kohri, Moroi, Takes PRD D97 023502 (2018)
  - effects of anti-nucleons, new observational constraints …
  - updated constraints on abundance of decaying particles

Axion emission from topological defects

- Axion is predicted in Peccei-Quinn mechanism which solves strong CP problem in QCD
- Axion models have $U(1)_{PQ}$ which is spontaneously broken at $T \sim \eta$
  - Axion strings are formed
- At QCD scale axion acquires mass $T \sim 1\text{GeV}$

$$m_a \simeq 6\,\mu\text{eV}\left(\frac{F_a}{10^{12}\text{GeV}}\right)^{-1}$$

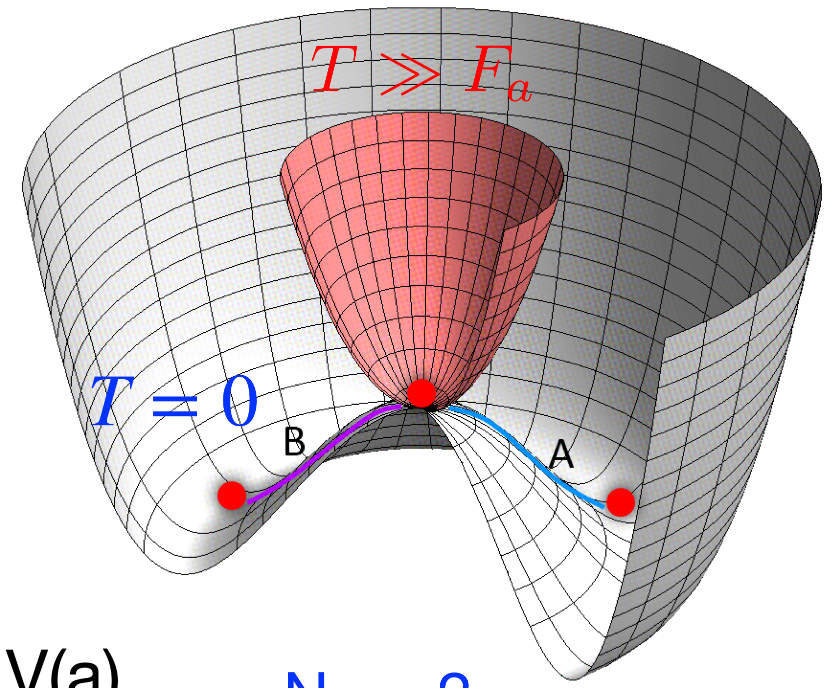
$$F_a = \eta / N_{\text{DW}}$$

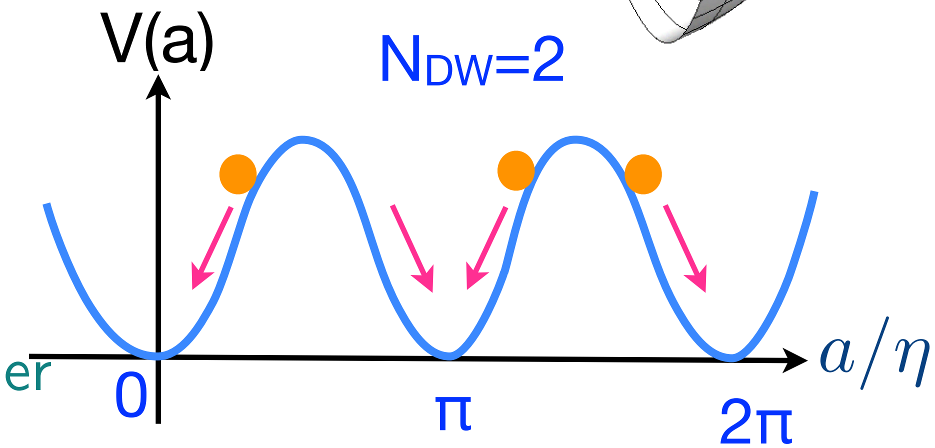
N_{DW} : domain wall number

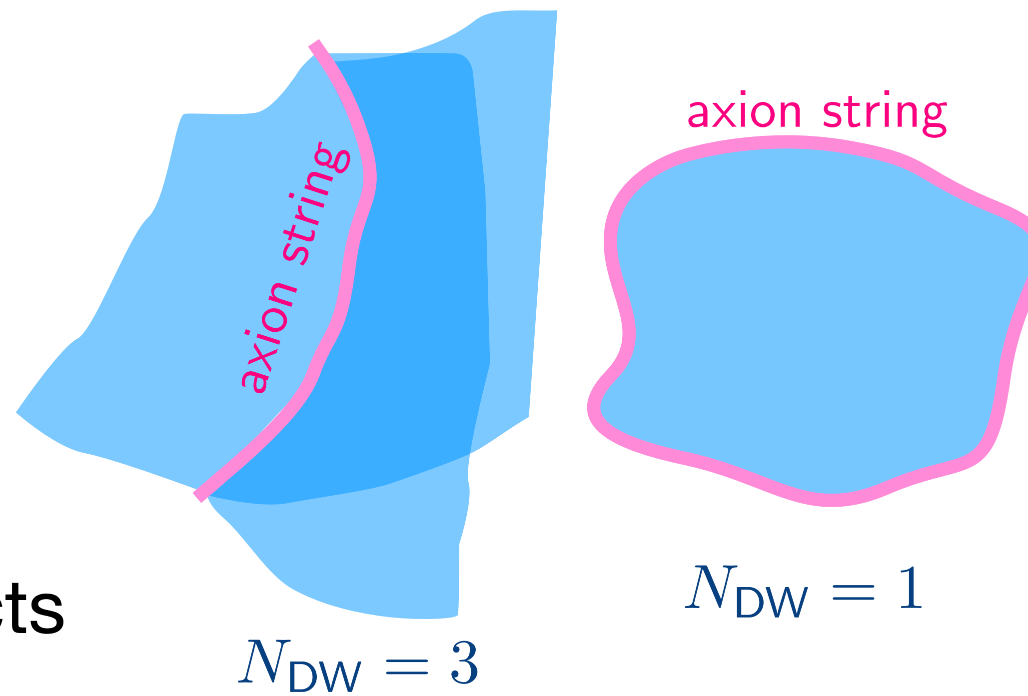
  - Domain walls are formed
  - (Coherent oscillation starts)
- Strings and domain walls emit axions

➡ significant contribution to the present axion density

- We investigated axion emission from defects





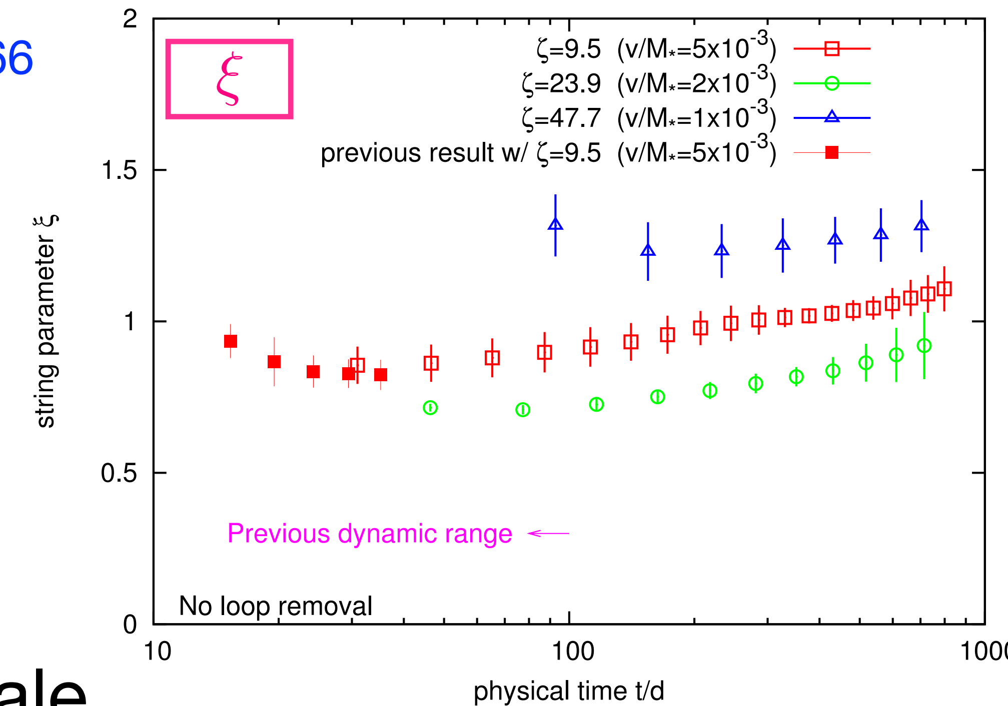


Axion emission from topological defects

- Lattice simulations with N(grid)=$(512)^3$ and $(4096)^3$
  - Kawasaki, Saikawa, Sekiguchi arXiv:1412.0789
  - Kawasaki, Sekiguchi, Yamaguchi, Yokoyama arXiv:1806.05566
- Evolution of strings
  - String density obeys scaling solution

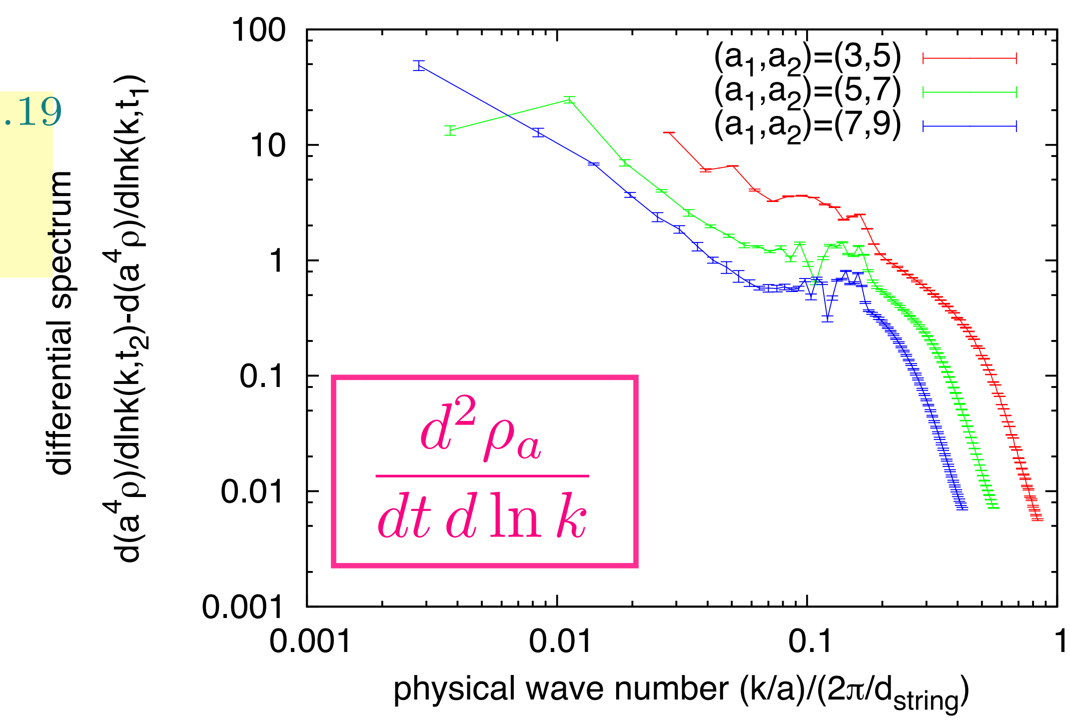
$$\rho_{\text{string}} = \xi \frac{\mu}{t^2} \qquad (\mu \sim \eta^2 \; : \; \text{string tension})$$

$$\xi = 1.0 \pm 0.5$$



  - Axion spectrum has a peak at horizon scale
  - Axion density

$$\Omega_{a,\text{string}} h^2 = (7.3 \pm 3.9) \times 10^{-3} N_{\text{DW}}^2 \left(\frac{F_a}{10^{10}\text{GeV}} \right)^{1.19}$$



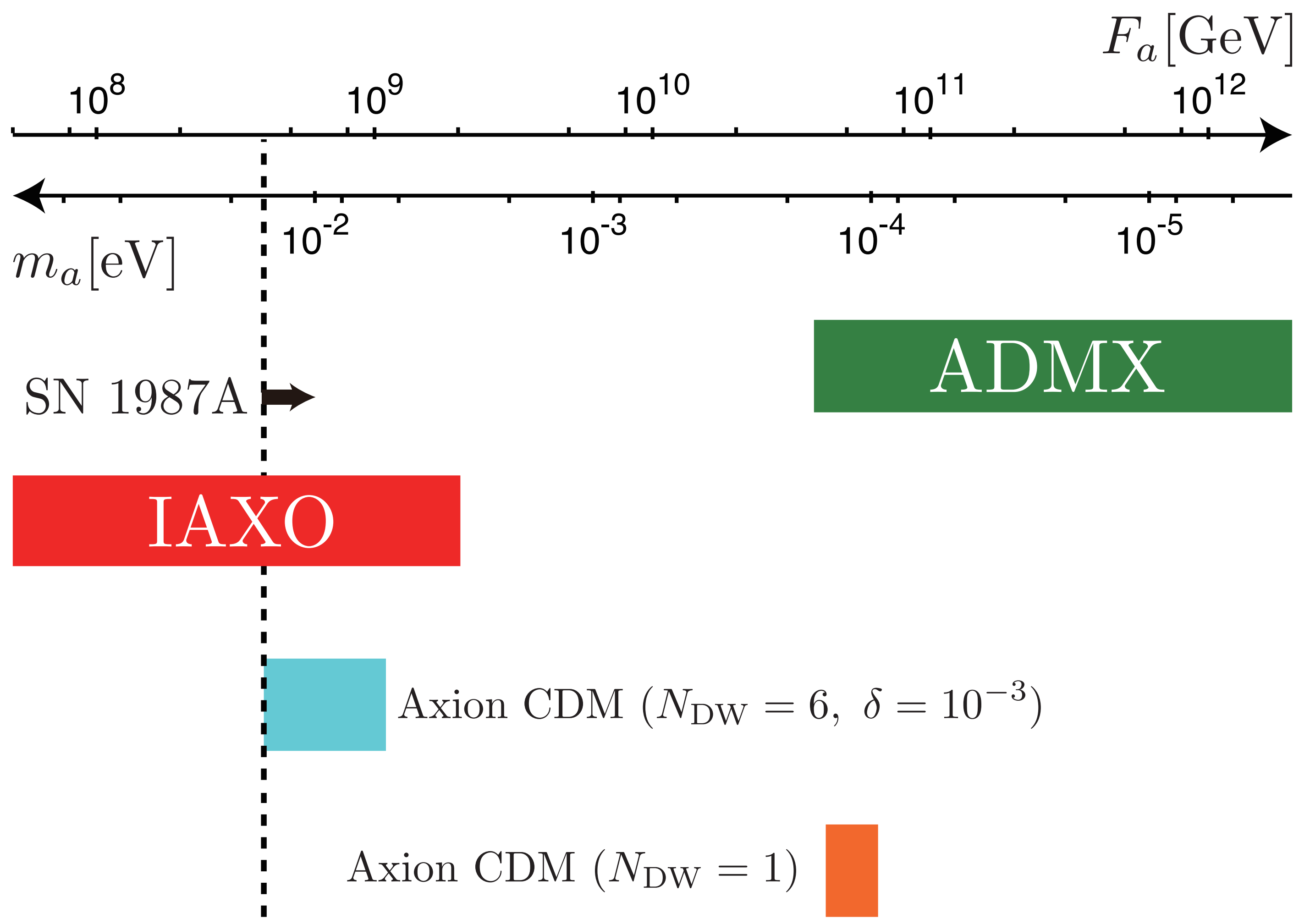
- Evolution of string-wall network
  - N_{DW}=1

$$\Omega_{a,\text{wall}} h^2 = (5.4 \pm 2.1) \times 10^{-3} \left(\frac{F_a}{10^{10}\text{GeV}} \right)^{1.19}$$

  - N_{DW} >1 string-wall systems are long-lived
    more axion emission

Axion emission from topological defects

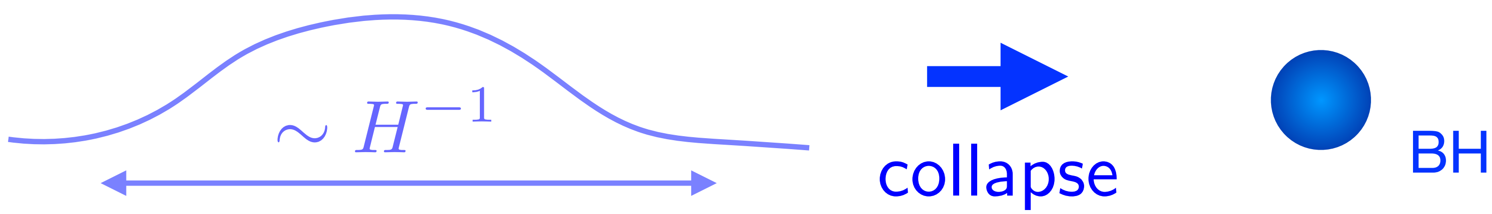
- Axions from defects can account for dark matter



- Now it is the standard to include the contribution from topological defects in considering the present axion density

Formation of primordial black holes (PBHs)

- PBHs are formed by gravitational collapse of over-density region with Hubble radius in the early universe



  - A candidate for dark matter
  - PBHs can account for GW events detected by LIGO-Virgo recently

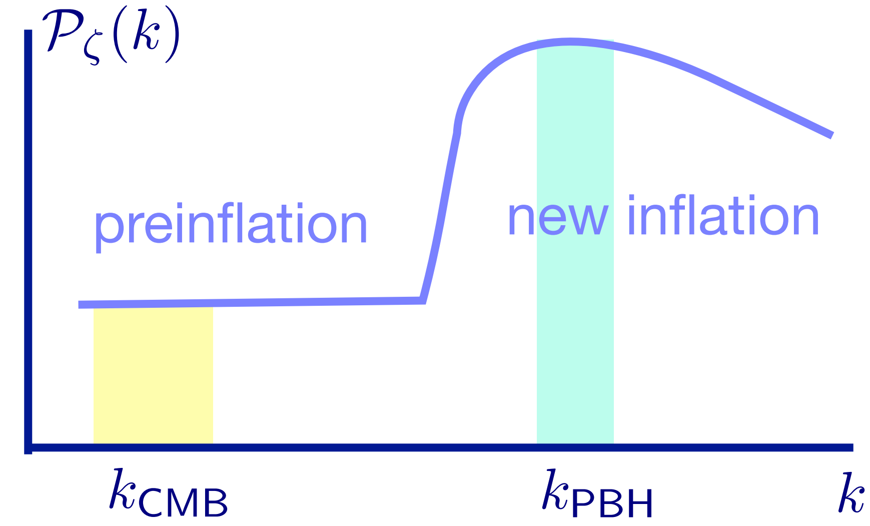
- Large density fluctuations δ with O(0.1) are required for PBH formation but δ ~ O(10^{-5}) on CMB scales

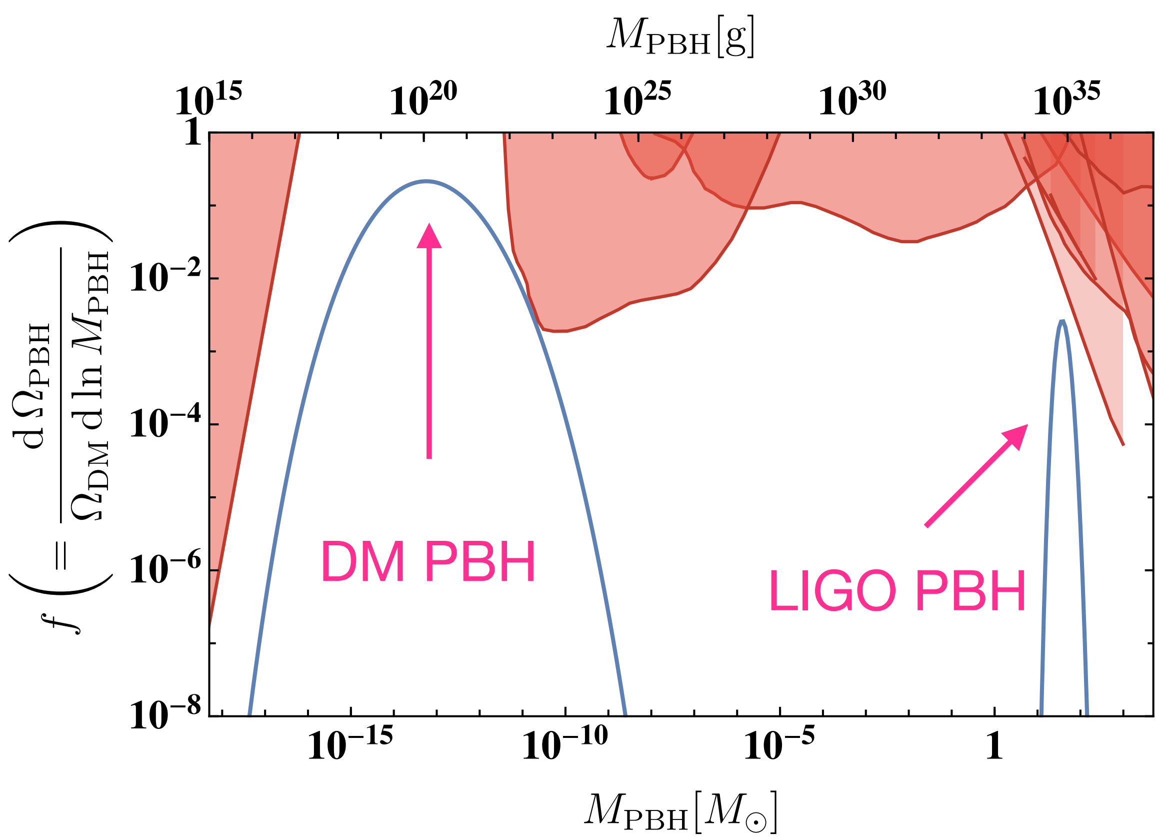
  ➡ This is difficult to realize in a simple inflation model

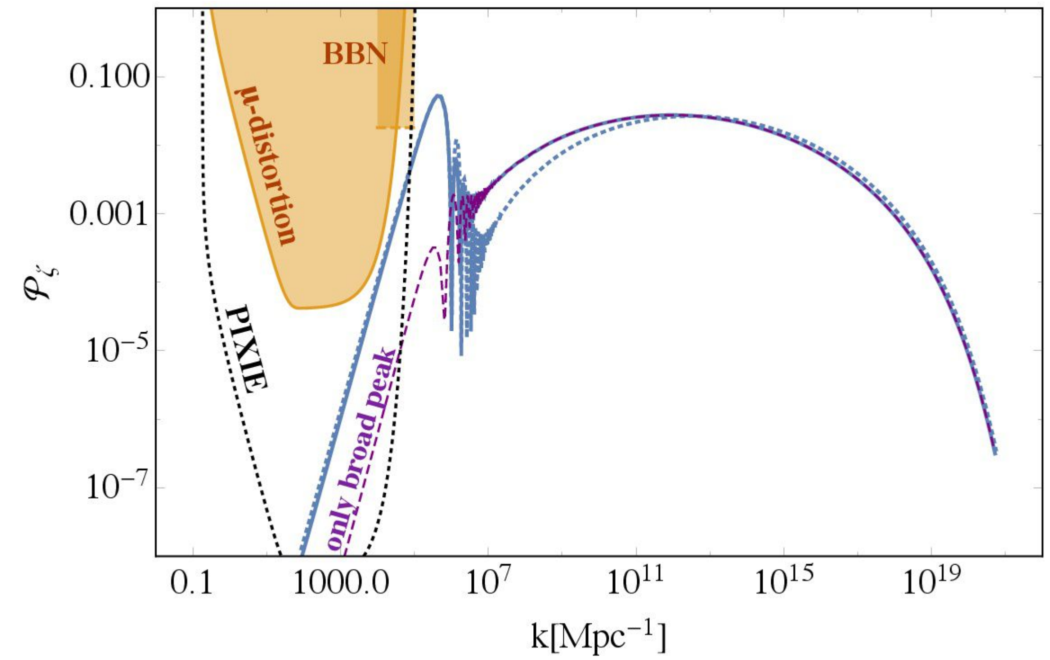
- We built sophisticated models for generating large density fluctuations
  - Double inflation model — Kawasaki Kusenko Tada Yanagida arXiv:1606.07631; Inomata Kawasaki Mukaida Tada Yanagida arXiv:1611.06130, 1701.02544, 1711.06129
  - Axion curvaton model — Ando Inomata Kawasaki et al arXiv:1711.08966; Ando Kawasaki Nakatsuka arXiv:1805.07757
  - PBH formation by Affleck-Dine mechanism — Hasegawa Kawasaki arXiv:1711.00990, 1807.00463

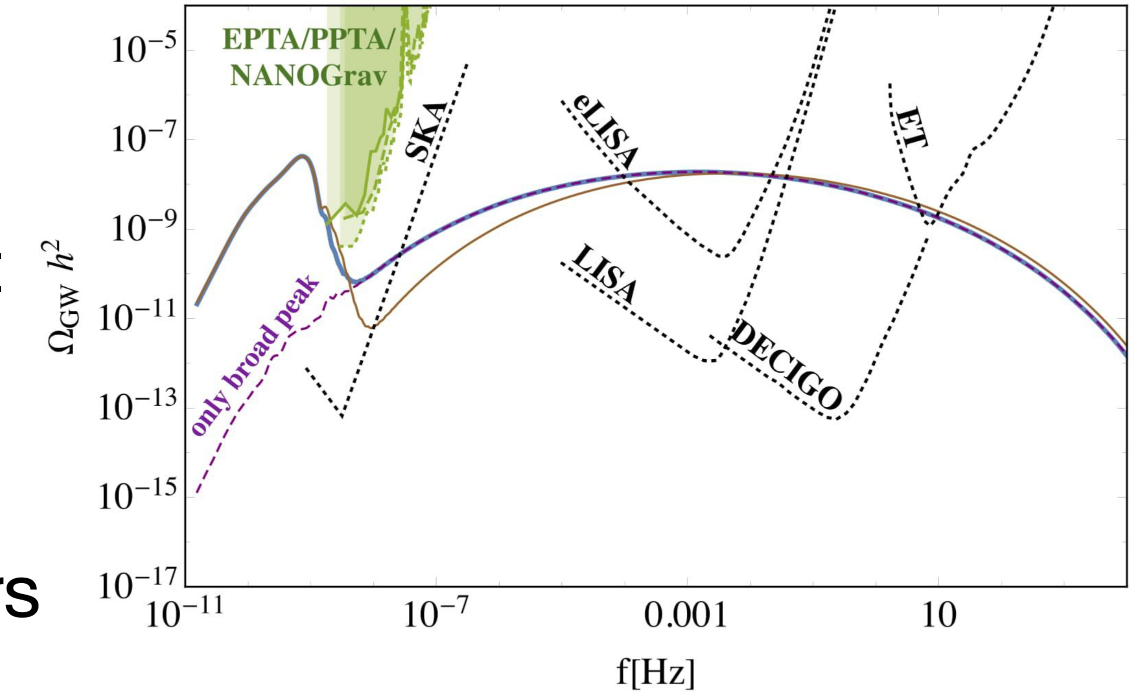
PBH formation in double inflation

- Double inflation (preinflation+new inflation)
  - Preinflation accounts for perturbations on CMB scales
  - New inflation with e-fold $N_{new} < 50$ produces large curvature perturbations on small scales







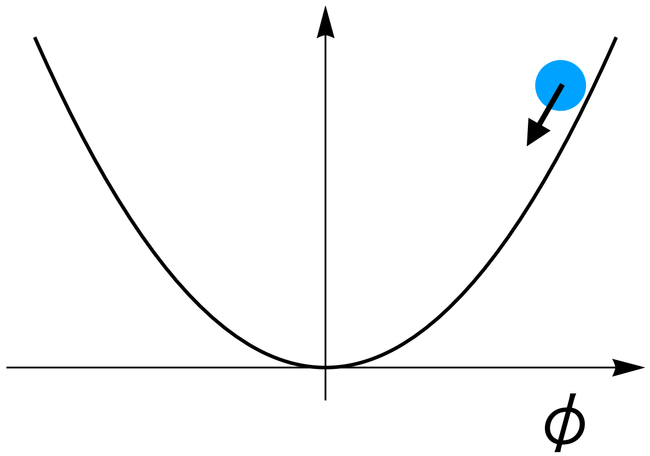


- Model can produce PBHs which account for DM and LIGO events
- Large density fluctuations produce GWs

➡ can be detected by future GW detectors

Inflation model building

The minimal model of chaotic inflation (Linde 1983)



$$V = \frac{1}{2} m^2 \phi^2$$

The slow roll conditions are satisfied for $\phi \gg M_{PL}$.

Planck 2018 (arXiv:1807.06211)

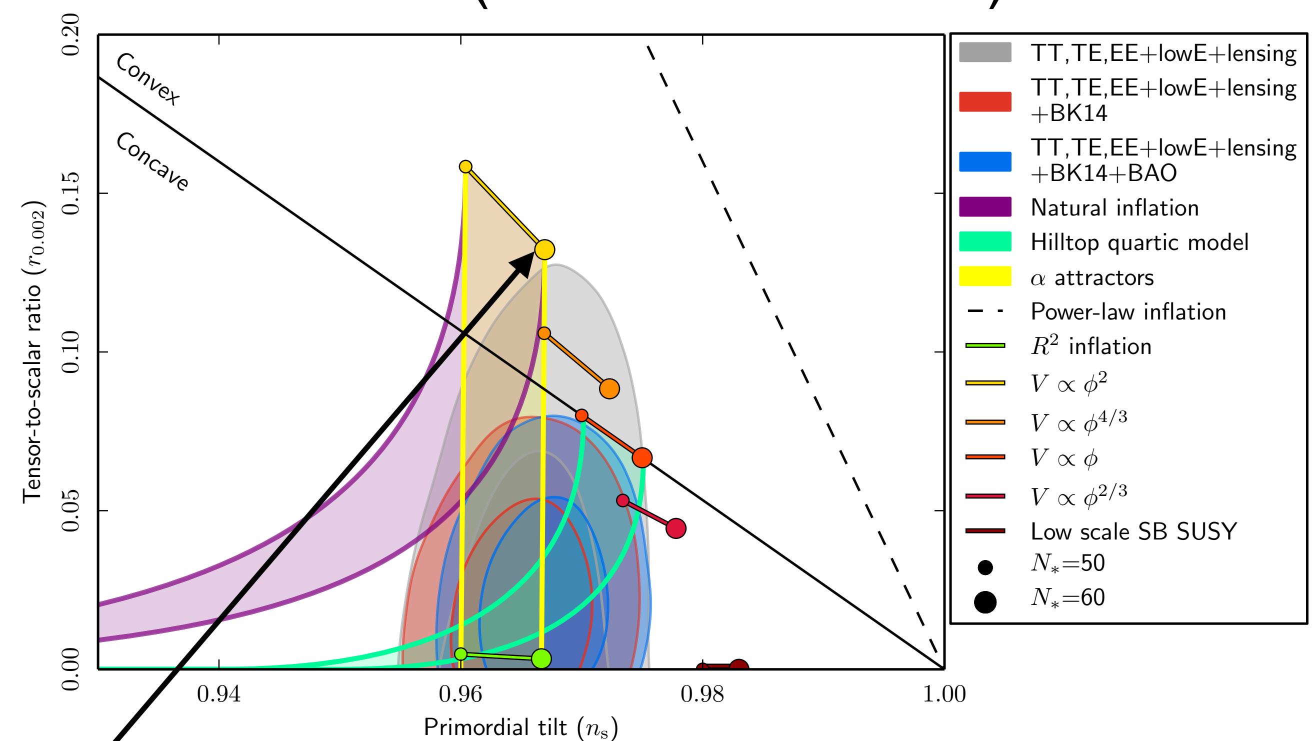


Fig. 8. Marginalized joint 68 % and 95 % CL regions for n_s and r at $k = 0.002\,\mathrm{Mpc}^{-1}$ from *Planck* alone and in combination with BK14 or BK14 plus BAO data, compared to the theoretical predictions of selected inflationary models. Note that the marginalized joint 68 % and 95 % CL regions assume $dn_s/d\ln k = 0$.

The spectral index and the tensor-to-scalar ratio are predicted:

$$n_s = 1 - \frac{2}{N_e} \simeq 0.967 \quad (N_e = 60)\ ,$$

$$r = \frac{8}{N_e} \simeq 0.133 \quad (N_e = 60)\ .$$

CMB observations disfavor the minimal model…

CMB observations rather favors a fractional power-law potential

$V \sim \phi^p \quad (0<p<1)$

How can we achieve such a potential ?

Dynamical fractional chaotic inflation

Harigaya, Ibe, Schmitz, Yanagida (1211.6241, 1403.4536, 1407.3084)

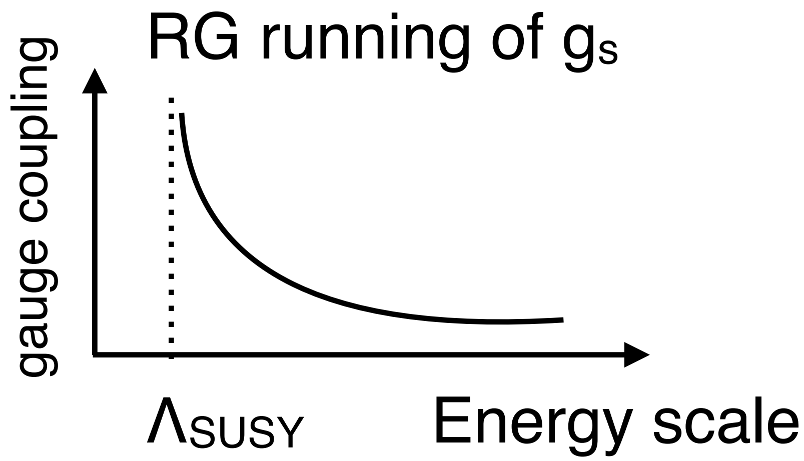
✓ Potential Energy of Inflaton = Vacuum energy

✓ In supersymmetric (SUSY) theory

Vacuum energy = Order parameters of supersymmetry

(Supersymmetric vacuum : vacuum energy = 0)

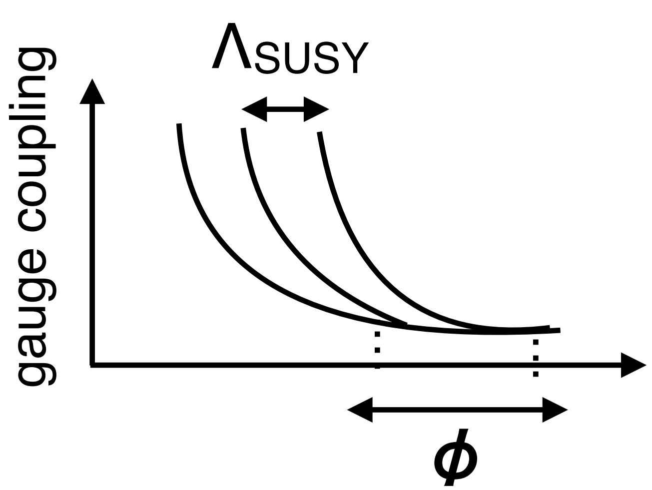
✓ Spontaneous SUSY breaking model by strong gauge dynamics



$V_{SUSY} \sim \Lambda_{SUSY}{}^4$

Λ_{SUSY} : dynamical scale (e.g. QCD scale)

✓ By modulating the dynamical scale by the field value of the Inflaton, fractional power potential can be achieved.



$\Lambda_{SUSY}(\phi) \sim \phi^q$ (q: rational number)

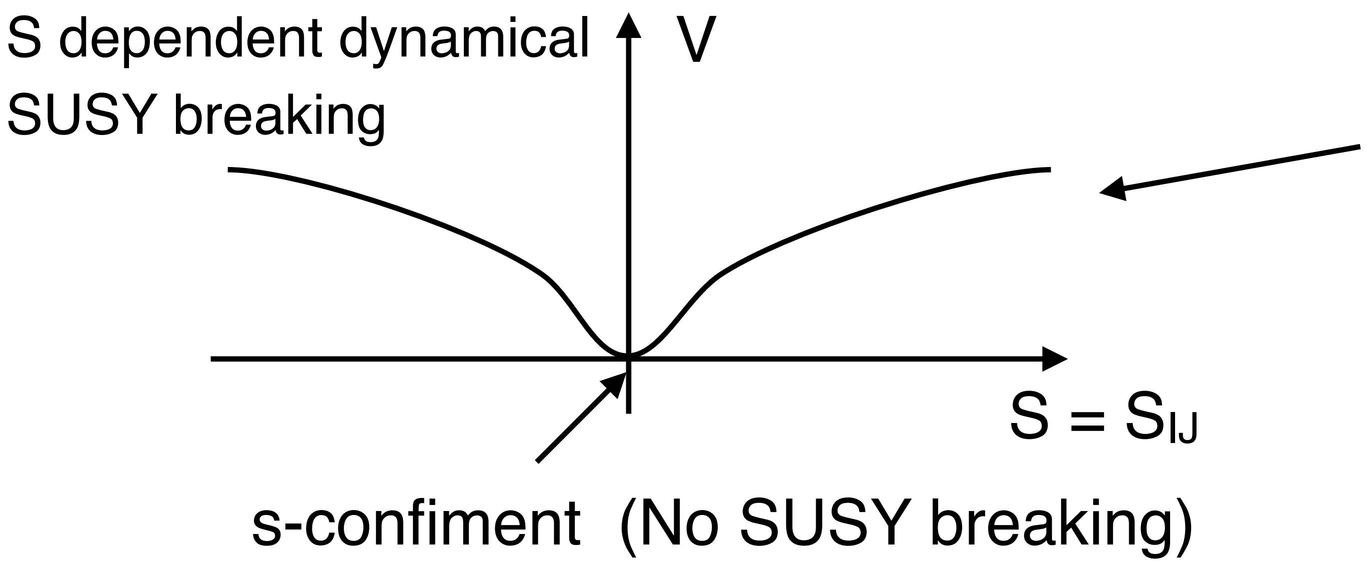
$V_{SUSY} \sim \Lambda_{SUSY}(\phi)^4 \sim \phi^{4q}$

Dynamical fractional chaotic inflation

Harigaya, Ibe, Schmitz, Yanagida (1211.6241, 1403.4536, 1407.3084)

✔ Example

SP(N_c) Supersymmetric Gauge Theory



At a large field value :

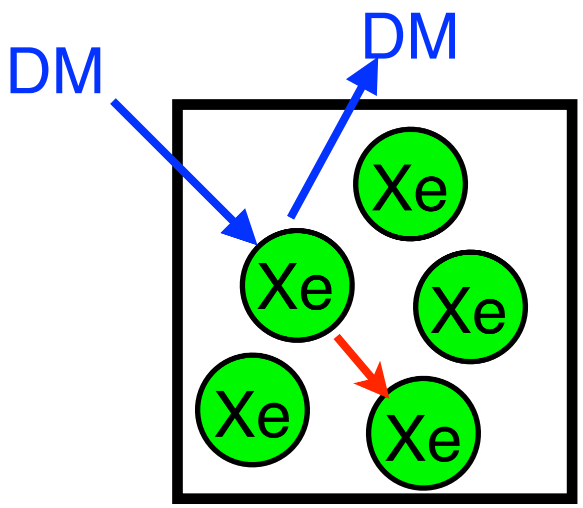
$V \sim |S|^p \quad p = 2/(N_c+1)$

e.g. SP(2) Model, p = 2/3

Can be tested by future CMB measurements !

Migdal Effect in Dark Matter Direct Detection Experiments

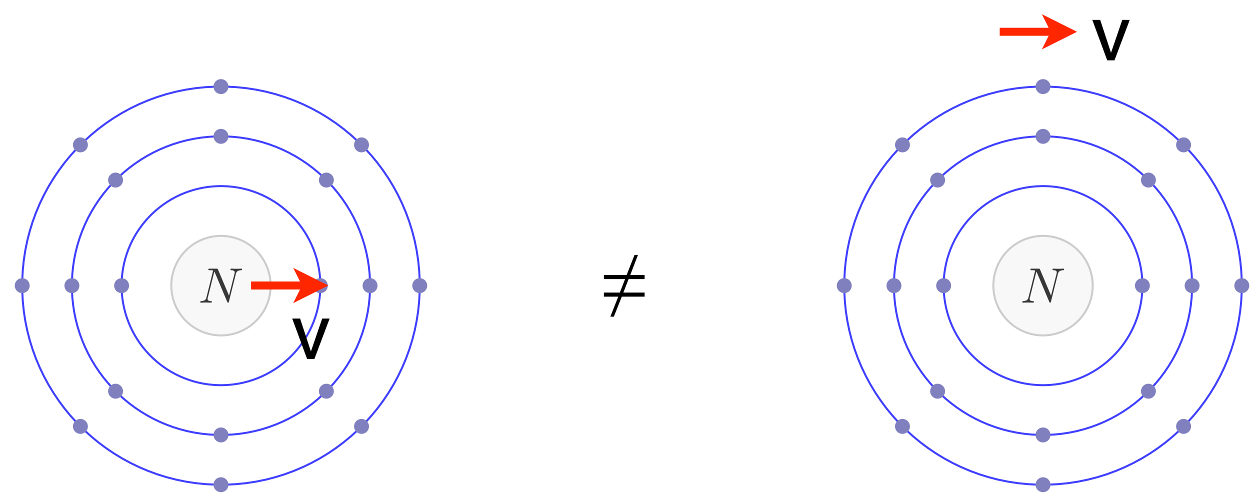
Ibe, Nakano, Shoji, Suzuki (1707.07258)



[detector]

In conventional analysis of the dark matter direct detection experiments, the recoiled nucleus scattered by dark matter is treated as a recoiled neutral atom.

✔ In reality, it takes some time for the electrons to catch up…

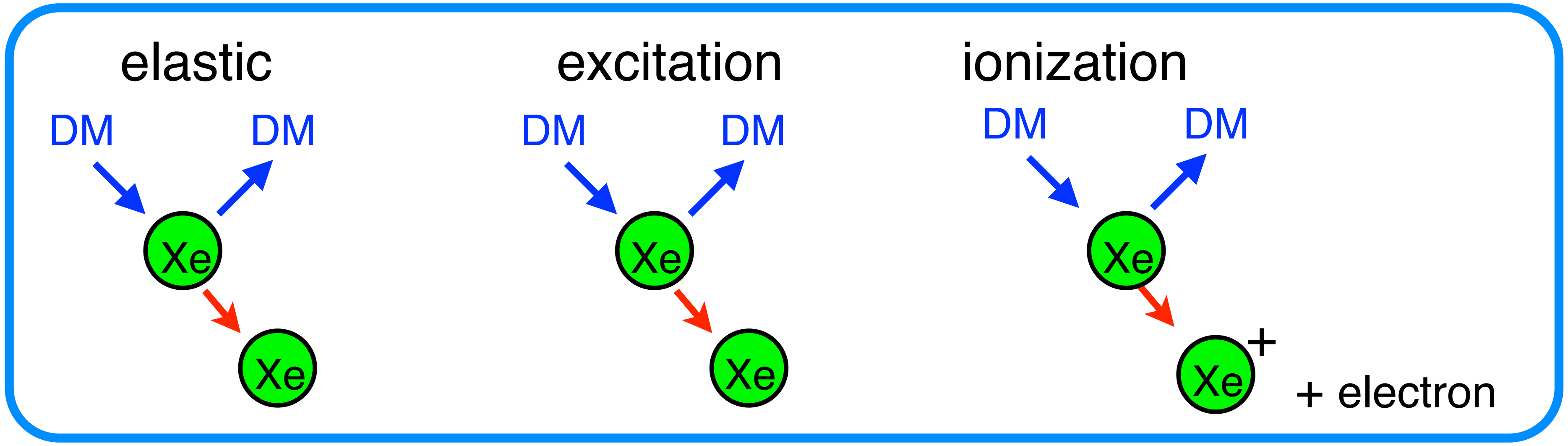


✔ The process to catch up causes electron excitations/ionizations!

→ Migdal Effect [1939, Migdal]

[’05 Vergados&Ejiri, ’07 Bernabei et al. Application to DM detection]

Migdal Effect in Dark Matter Direct Detection Experiments



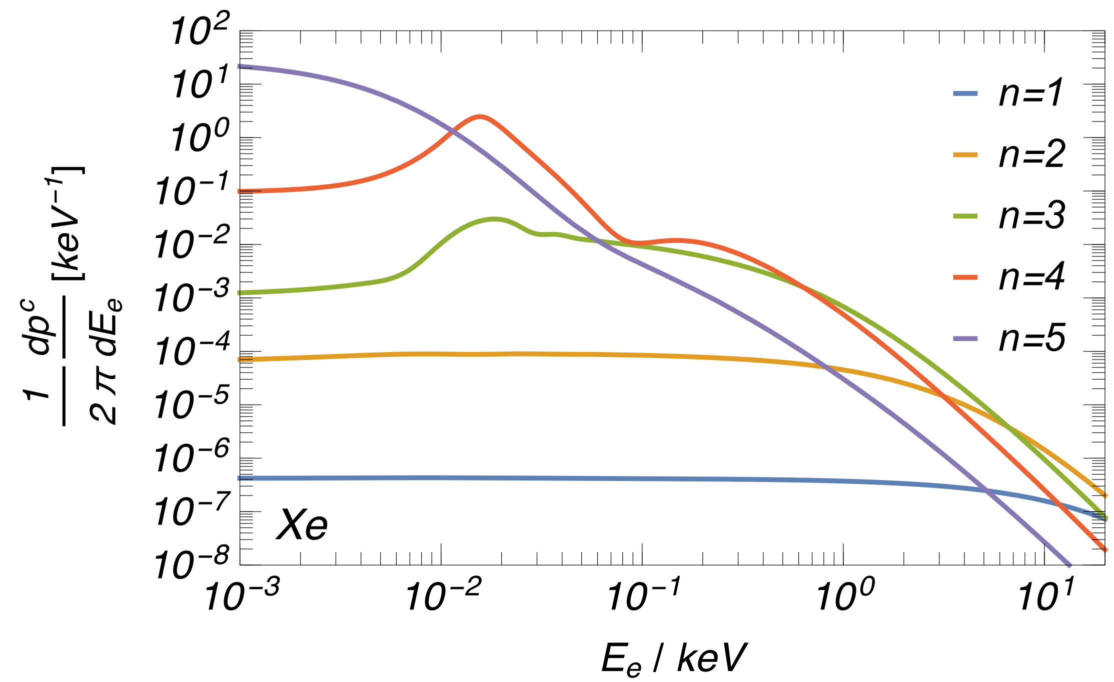
Xe ($q_e = m_e \times 10^{-3}$)

(n,ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^4	4.6×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^3	2.9×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^3	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^3	8.7×10^{-5}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^2	5.2×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^2	3.5×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^2	3.4×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^2	1.4×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.4×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.1×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	1.0×10^{-1}

(n,ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

initial state

ionization spectrum



(transition is possible only for | $\Delta \ell$ | = 1)

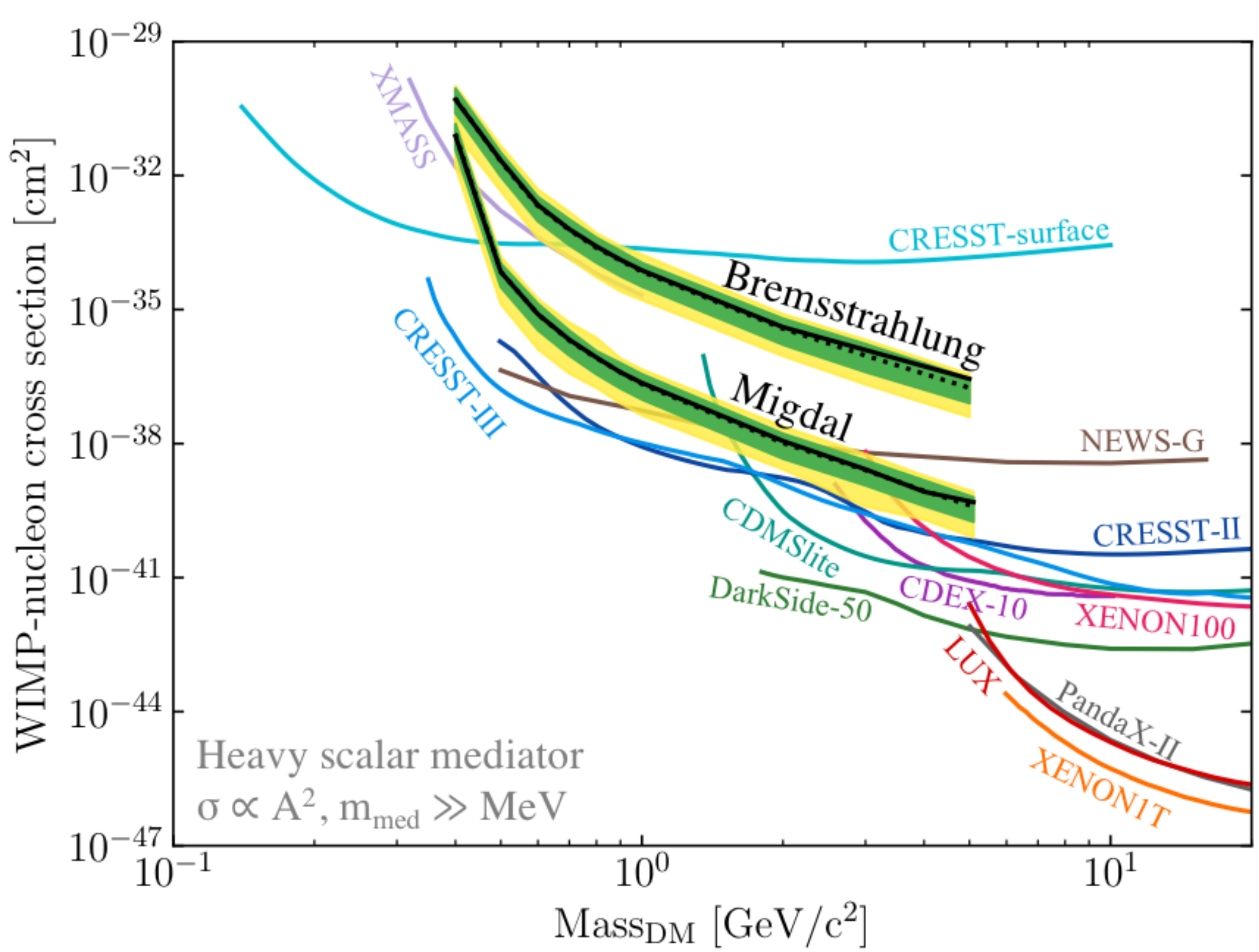
✔ The ionization rate from n = 3 state can be of O($10^{-(3-2)}$).
→ leading to O(1)keV electronic energy deposition !

Migdal Effect in Dark Matter Direct Detection Experiments

LUX result (1811.11241 LUX collaboration)

Double Phase Experiment (detect scintillation photon and ionized electrons)

✔ LUX collaboration analyzed data by taking into account of the Migdal effects.



✔ The result shows that the LXe can test the low mass dark matter region !

(Xenon1T collaboration is also working on the Migdal effects.
They unofficially said that the constraints can be more stringent.)

Education

- We accept 2-3 graduate students every year
- 12 students were awarded doctor degrees (2012-2018)
- 16 students got master degrees (2012-2018)

	2012	2013	2014	2015	2016	2017	2018
Master degree	2	2	3	1	2	4	2
Doctor degree	2	2	1	2	1	2	2

- About half of students who got a PhD continue research

Kenichi Saikawa (2013)	[DESY —> Max Planck]
Naoya Kitajima (2014)	[ACTP —> Nagoya Univ.]
Masaki Yamada (2016)	[Tufts Univ. —> MIT]
Jeong-Pyong Hong (2018)	[Seoul Univ.]

Summary

- We believe that Theory Group has been highly active and giving significant contributions to particle physics and cosmology