TOHOKU
UNIVERSITY

Dark Matter

Feb. 18 2020
“Cosmic Acceleration”@Kavli IPMU

Fumi Takahashi
(Tohoku)

What is DM?


dark matter ?
100% COTTON
Axion
MACHINE WASH COLD
TUMBLE DRY LOW
DO NOT BLEACH
WARM IRON IF NEEDED

What is DM?

- WIMP, SIMP,…
- PBH
- Axion
- Sterile neutrino
- Hidden photon
- Hidden monopole
- Hidden neutron, hidden electron
- Hidden glueball, hidden meson,…

Dark Matter

Ultimate theory

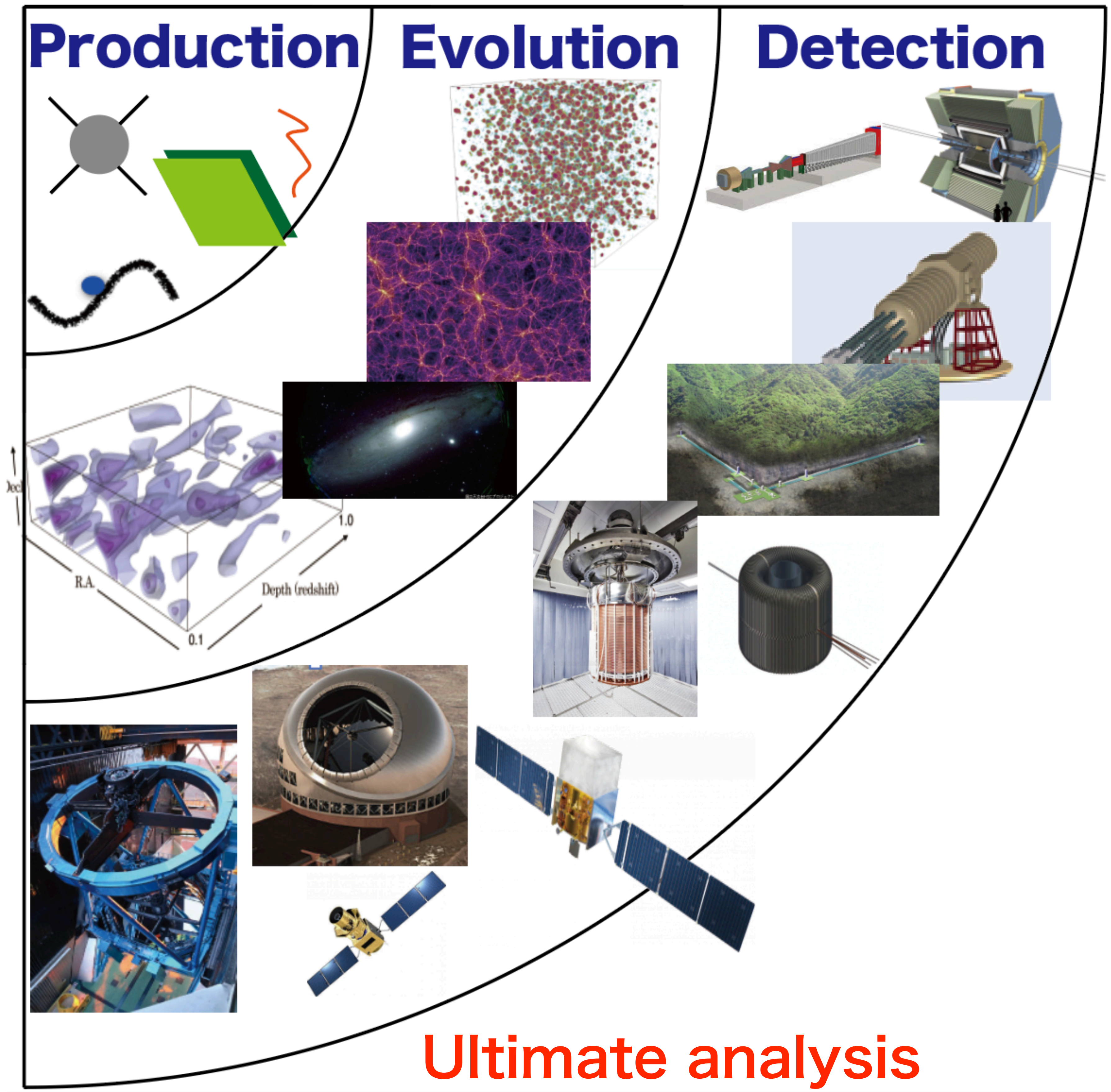
Inflation

Early Universe

Late Universe

Dark energy

Present Universe



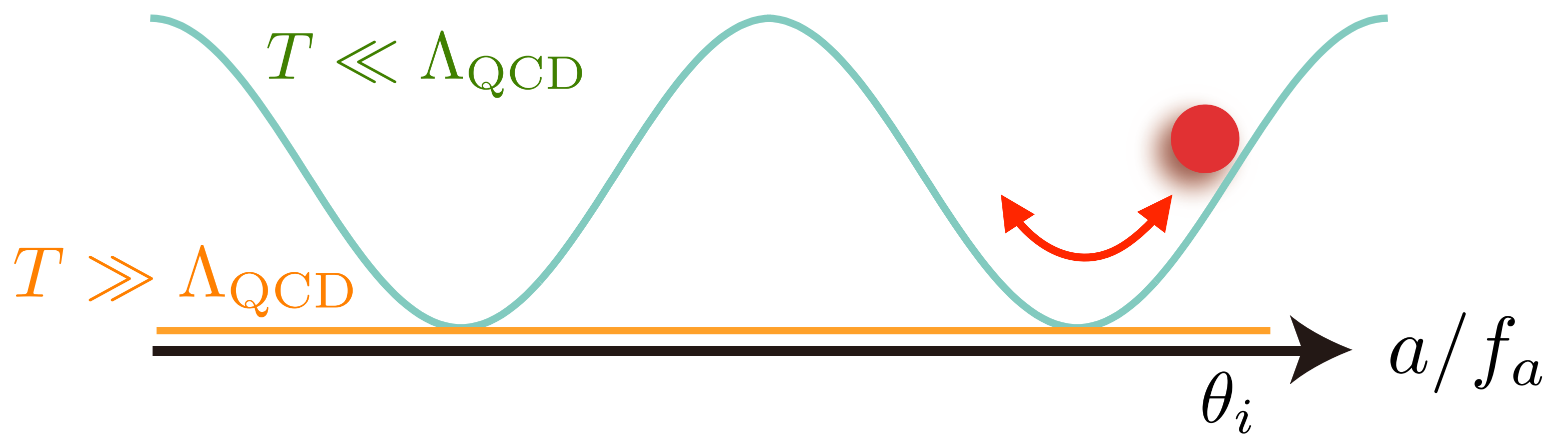
Production

Axion Dark Matter

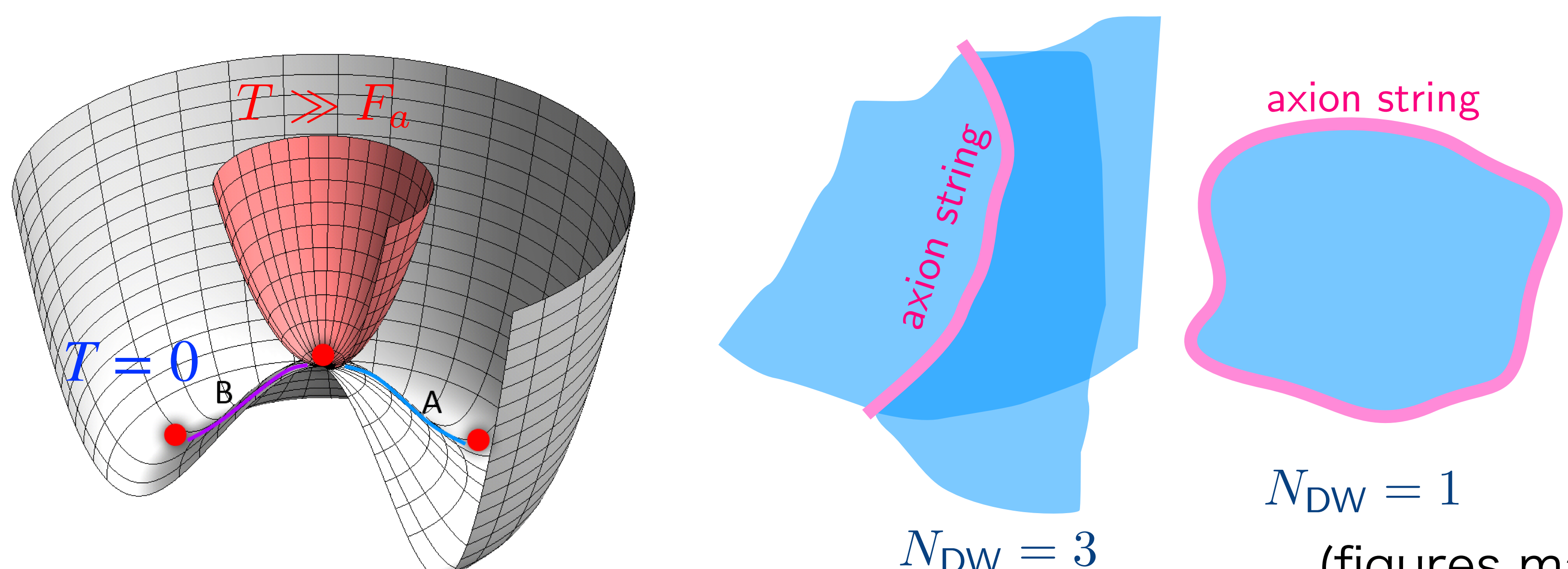
The axion DM can be produced by

(1) the misalignment mechanism

Preskill, Wise, Wilczek `83, Abbott, Sikivie, `83, Dine, Fischler, `83



(2) decay of topological defects



(figures made by Kawasaki)

Axion Dark Matter

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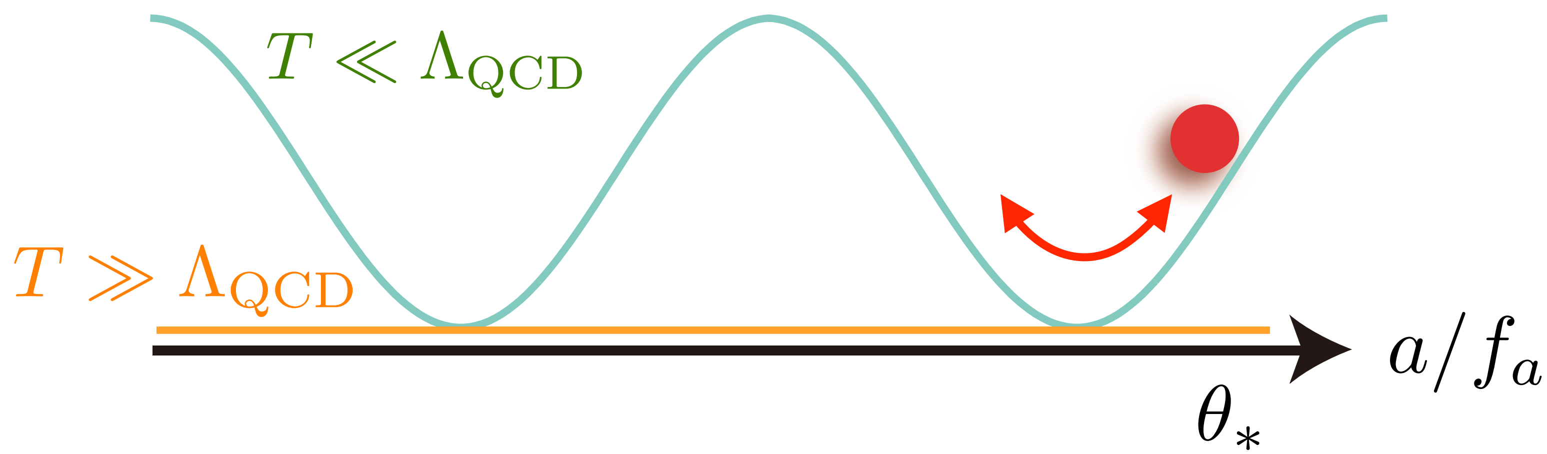
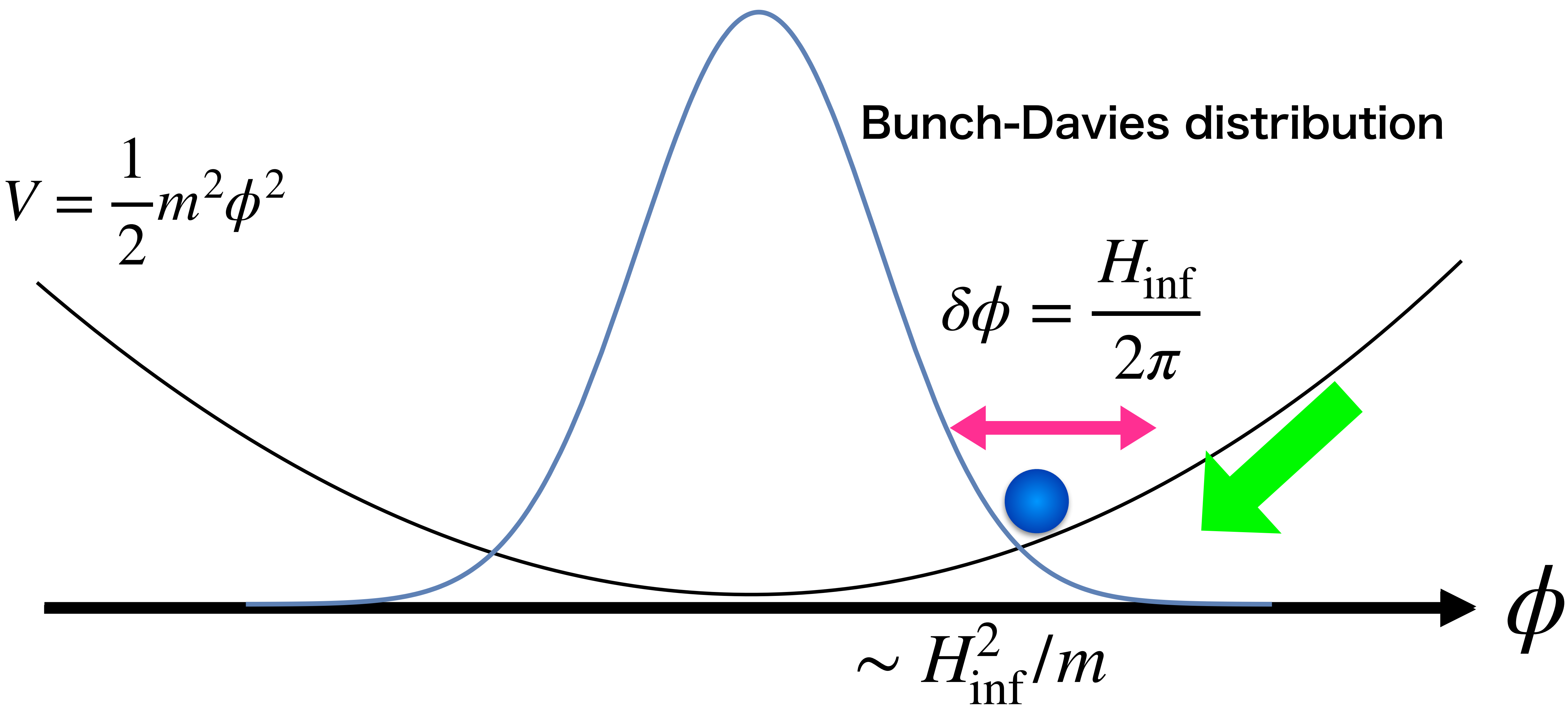


$$\Omega_a h^2 \simeq 0.14\, \theta_*^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.17}$$

"Classical axion window": $10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$

assuming $\theta_* = \mathcal{O}(1)$

In fact, the typical initial angle depends on H_{inf}.



If the inflation lasts sufficiently long, it is typically of order

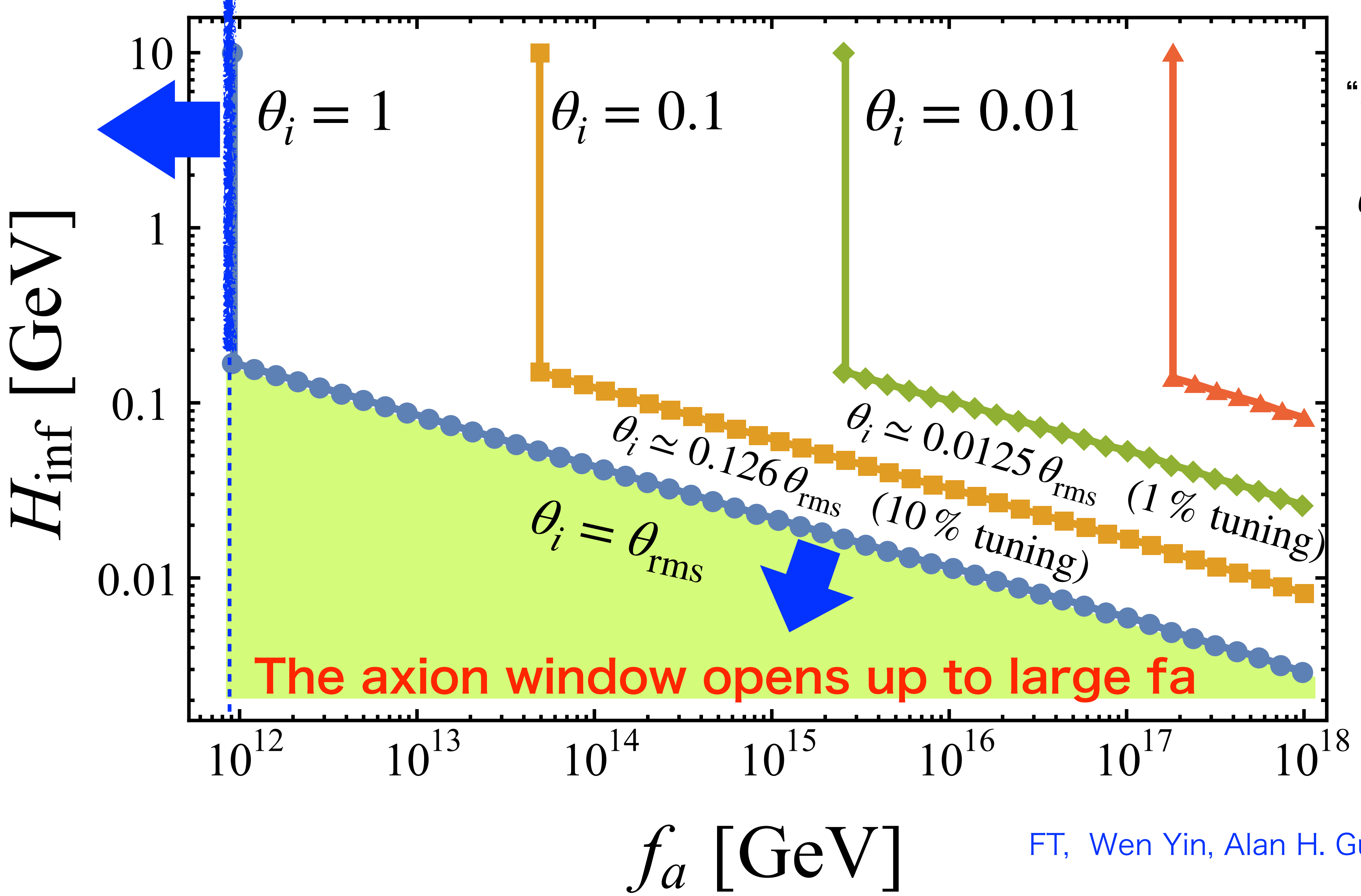
$\theta_* \sim \frac{H_{\rm inf}^2}{m_a(T_{\rm GH}) f_a}$ which can be smaller than unity.

Peter W. Graham, Adam Scherlis, 1805.07362,
FT, Wen Yin, Alan H. Guth, 1805.08763

The upper end of the QCD axion window can be relaxed in low-scale inflation with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

Conventional axion window, $f_a \lesssim 10^{12}\,\mathrm{GeV}$

Peter W. Graham, Adam Scherlis, 1805.07362,
FT, Wen Yin, Alan H. Guth, 1805.08763



"Bunch-Davis distribution"

$$\theta_{\rm rms} = \sqrt{\frac{3}{8\pi^2}\frac{H_{\rm inf}^2}{f_a m_a(T_{\rm inf})}}$$

FT, Wen Yin, Alan H. Guth, 1805.08763

Axions 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 $T \sim 1\text{GeV}$

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

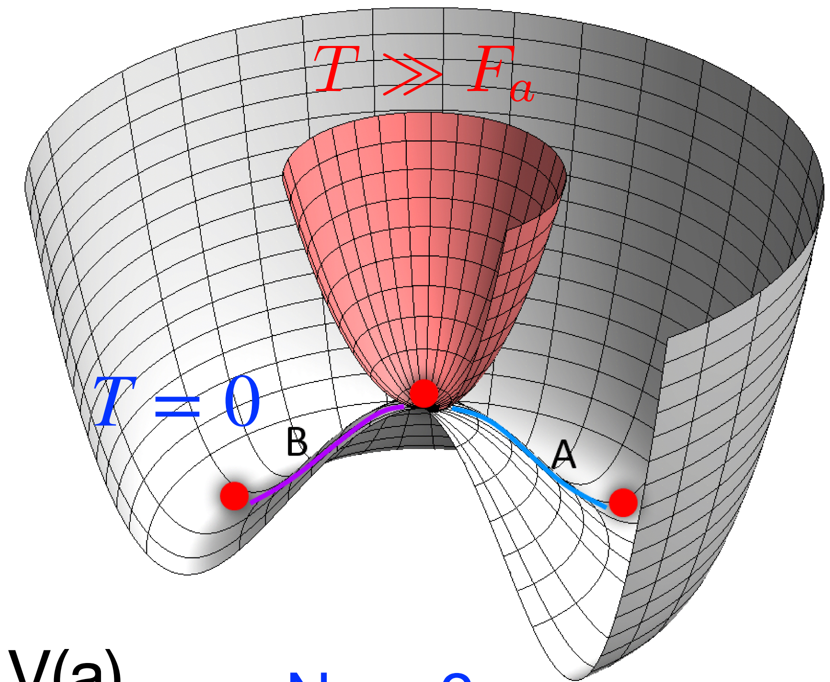
$F_a = \eta/N_{\text{DW}}$

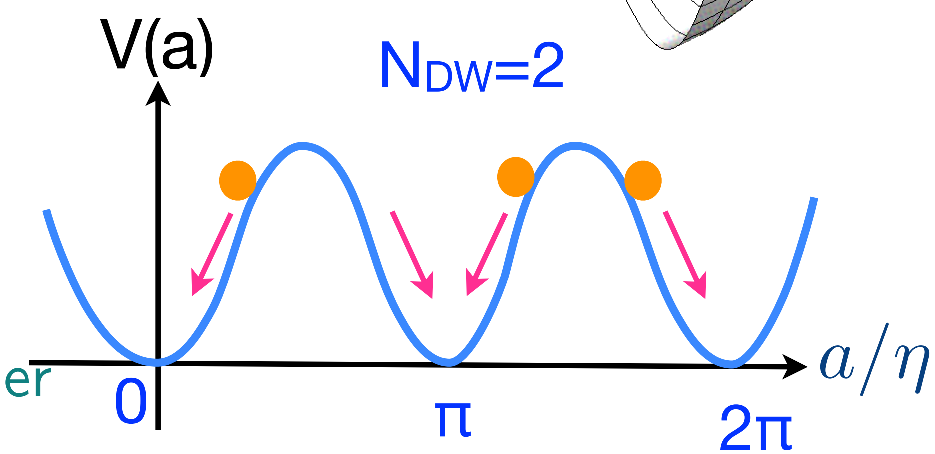
N_{DW} : domain wall number

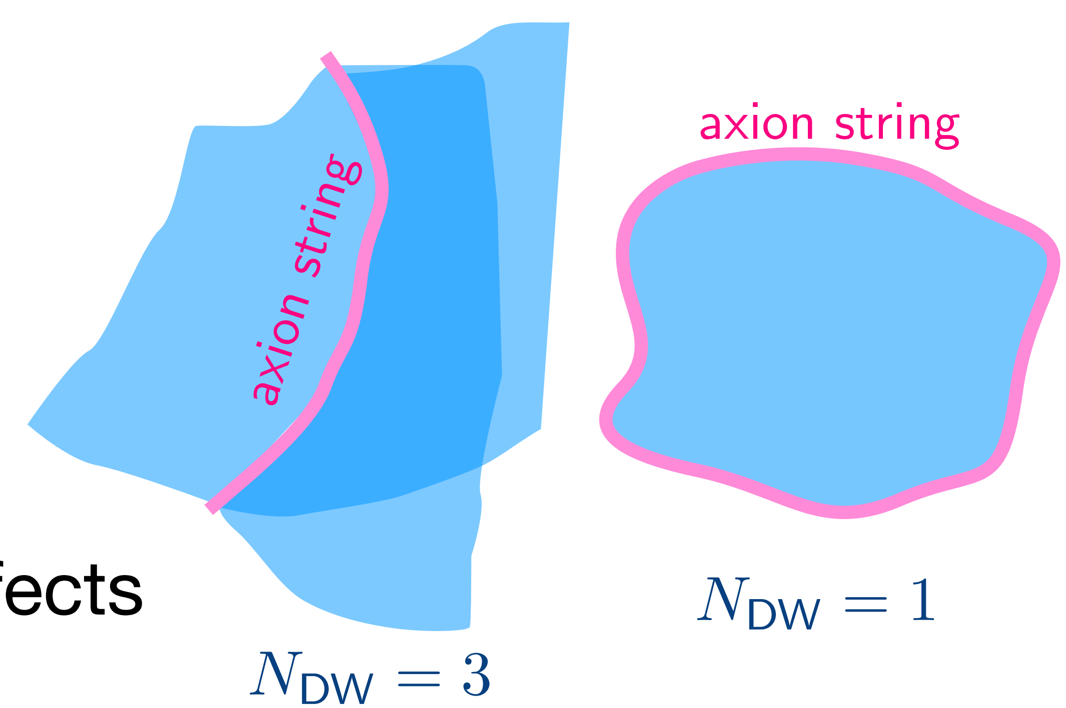
  - Domain walls are formed
  - (Coherent oscillation starts)
- Strings and domain walls emit axions

→ significant contribution to the present axion density

- We investigated axion emission from defects







(slide made by Kawasaki)

Axions from topological strings

(slide made by Kawasaki)

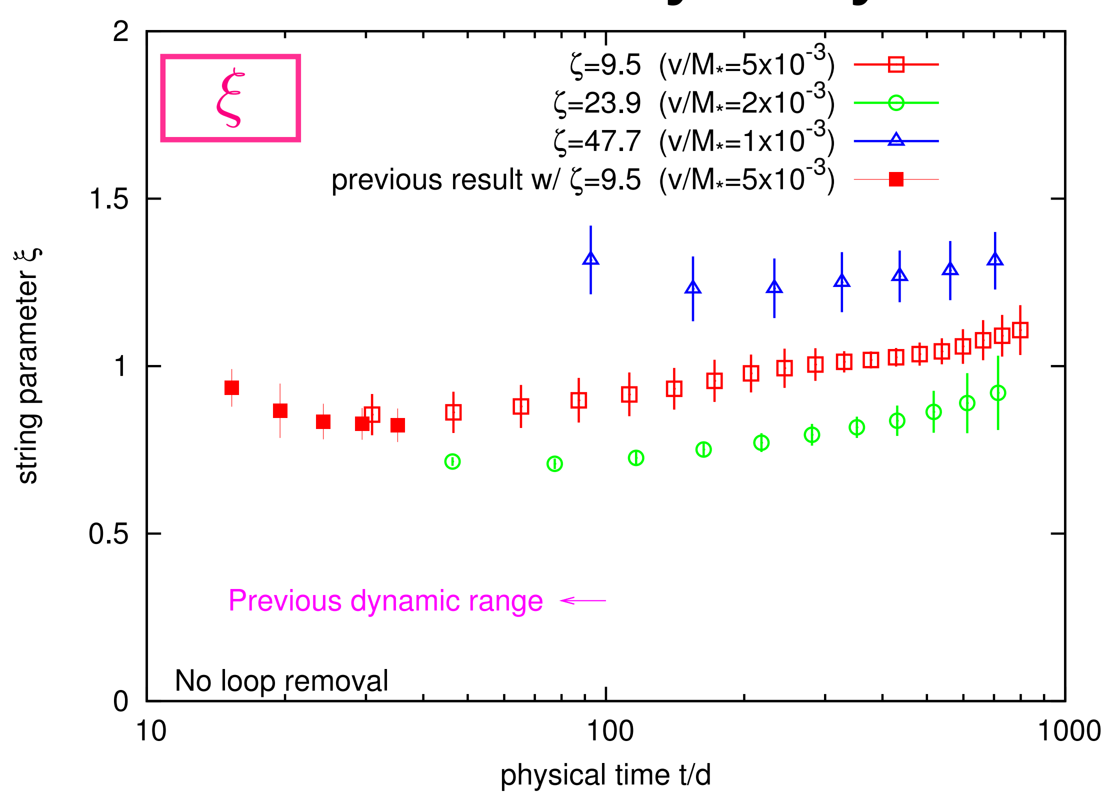
Kawasaki, Sekiguchi, Yamaguchi, Yokoyama arXiv:1806.05566

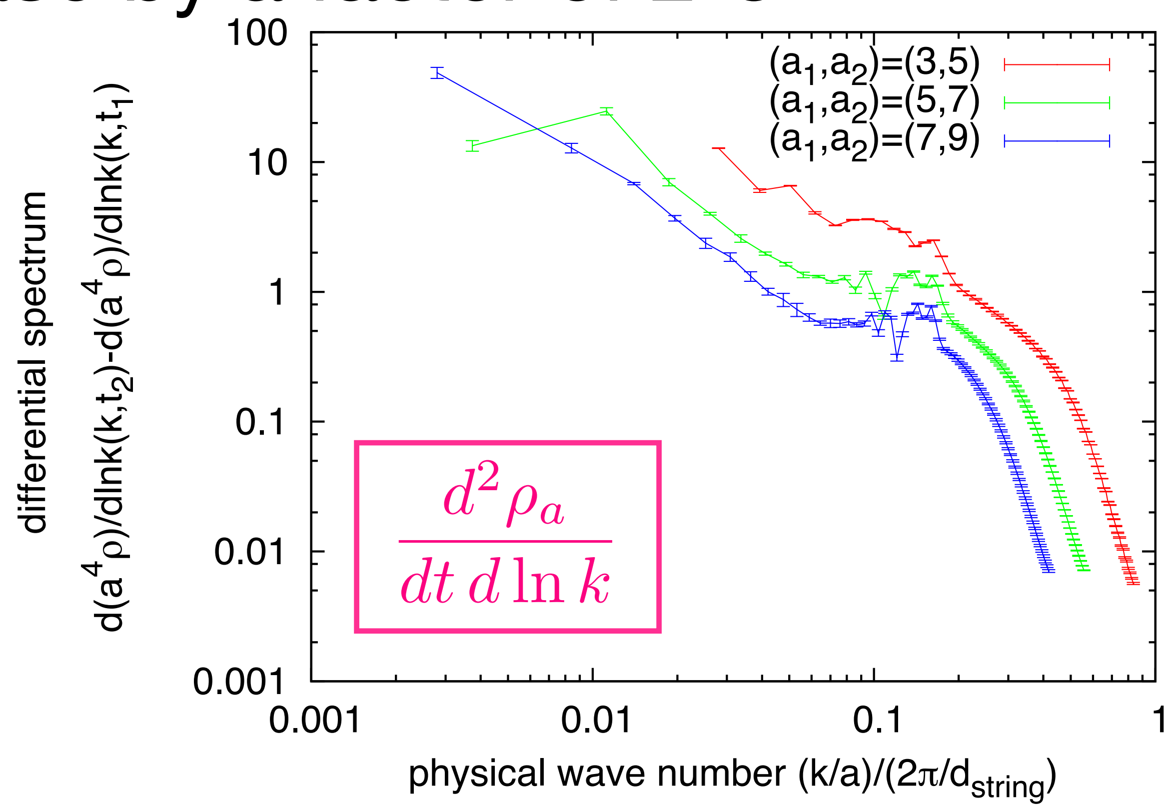
- Previous estimation using lattice simulation N(grid)=(512)³
  - DM axion density $$\Omega_{a,\mathrm{string}}h^2 = (7.3 \pm 3.9) \times 10^{-3} N_{\mathrm{DW}}^2 \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{1.19}$$
- New lattice simulation N(grid)=(4096)³
- Evolution of strings
  - String density almost obeys scaling solution
  - Axion spectrum has a peak at horizon scale

scaling parameter increases logarithmically

cf. Gorghetto, Hardy, Villadoro 1806.04677, Buschmann, Foster, Safdi 1906.00967

- DM axion density may increase by a factor of 2-3





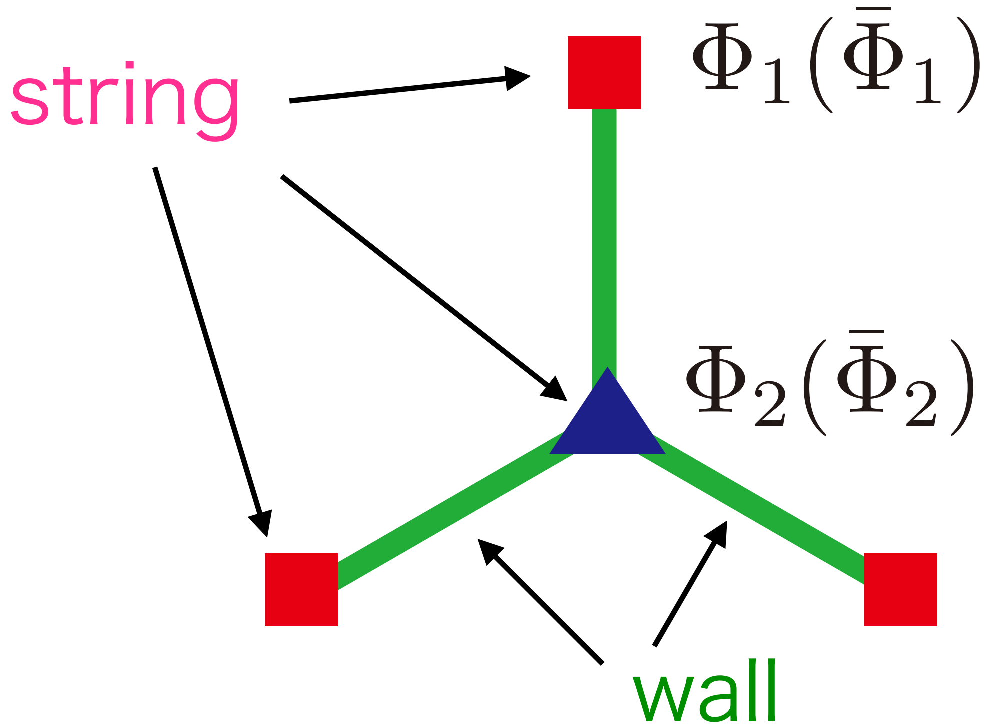
Note: string and wall evolution may depend on the UV completion:

e.g. clockwork axion model

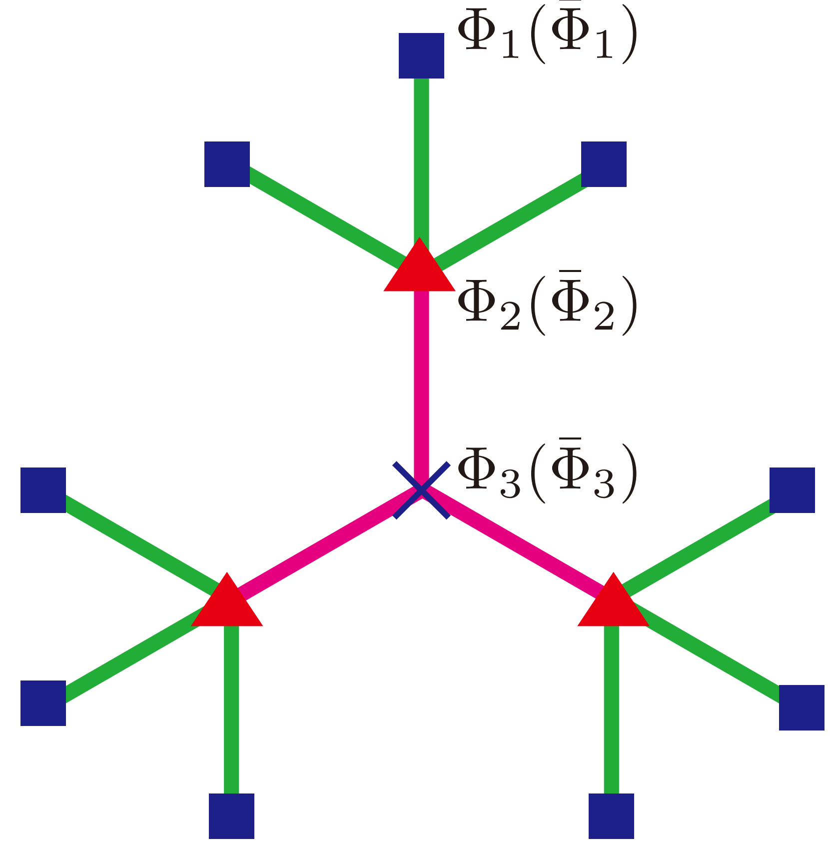
See also Sikivie `86 Kim, Nilles, Peloso, hep-ph/0409138 Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923 Harigaya and Ibe, 1407.4893, Choi and Im, 1511.00132, Kaplan and Rattzzi, 1511.01827, Giudice and McCullough 1610.07962

$$V = \sum_{i=1}^{N} \left(-m_i^2|\Phi_i|^2 + \lambda_i|\Phi_i|^4\right) + \sum_{i=1}^{N-1} \epsilon \left(\Phi_i \Phi_{i+1}^3 + \text{h.c.}\right)$$

$$\Rightarrow \quad f_a \sim 3^N f$$



$N = 2$



$N = 3$

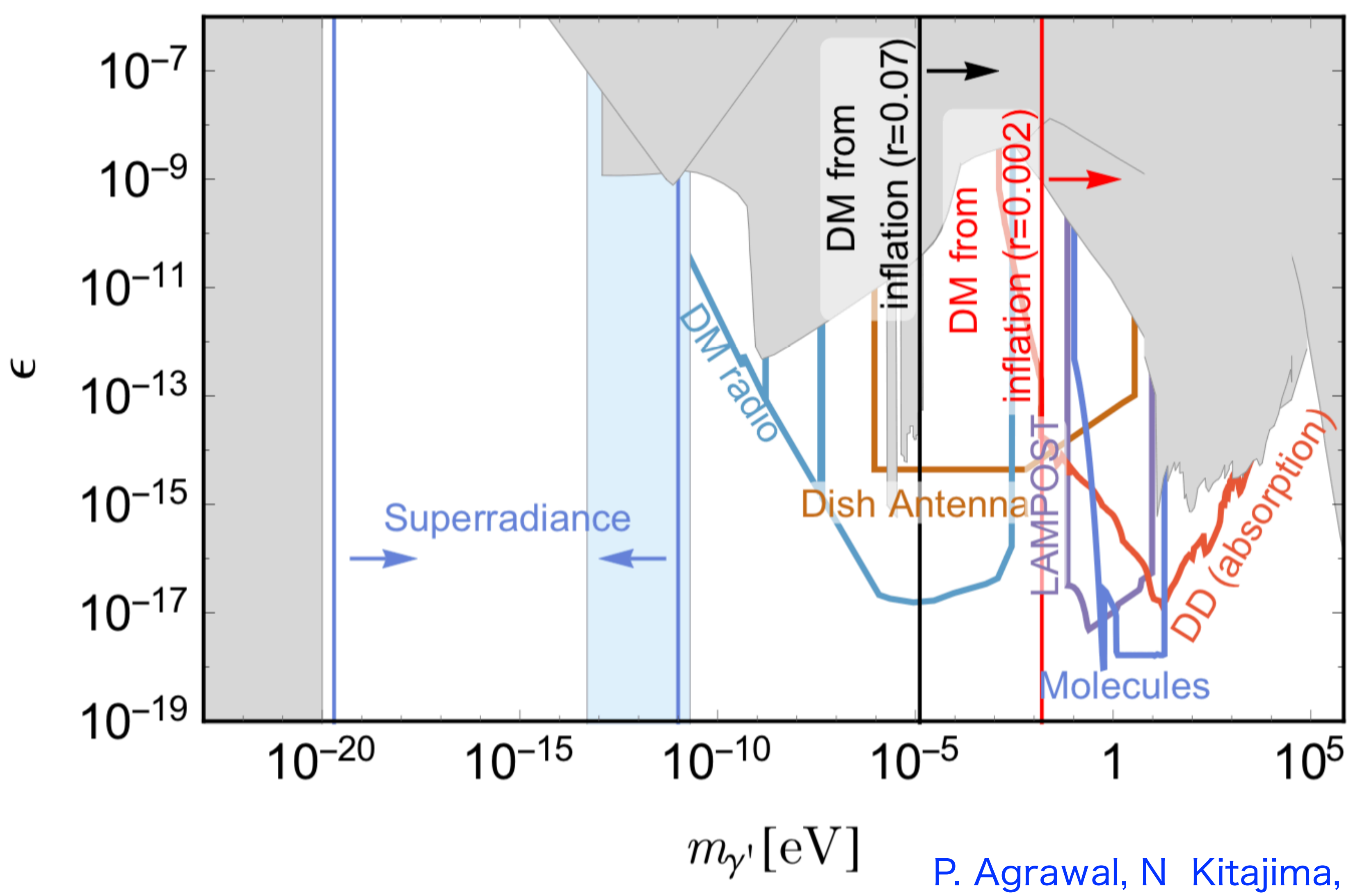
Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

Hidden photon DM

A long-standing problem for dark photon DM models is to obtain the correct relic abundance of DM. One way is to use the quantum fluctuations:

$$\Omega_{\gamma'} = \Omega_{DM} \sqrt{\frac{m_{\gamma'}}{6 \times 10^{-6}\ \mathrm{eV}}} \left(\frac{H_I}{10^{14}\ \mathrm{GeV}} \right)^2 ,$$

Graham, Mardon, and Rajendran, Phys. Rev. D93, 103520 (2016), 1504.02102.



P. Agrawal, N Kitajima, M. Reece, T. Sekiguchi and FT

Evolution

(Slide made by Taruya)

Nonlinear structure formation

Shell crossing and multi-stream flows are natural outcome of nonlinear structure formation in CDM cosmology

⟶ Test for CDM paradigm

Quantitative understanding of their properties:

- Describing shell-crossing structure, and beyond

S. Saga, A. Taruya, S. Colombi

A first detailed comparison between Lagrangian PT & Vlasov-Poisson simulation

- Characterizing multi-stream flows

T. Nishimichi, H. Sugiura, Y. Rasera, and A. Taruya

Confrontation of self-similar solution against dark halos from *N*-body simulations

(Slide made by Taruya)

Lagrangian perturbation theory *(LPT)*

Perturbative description for motion of mass element via Lagrangian picture

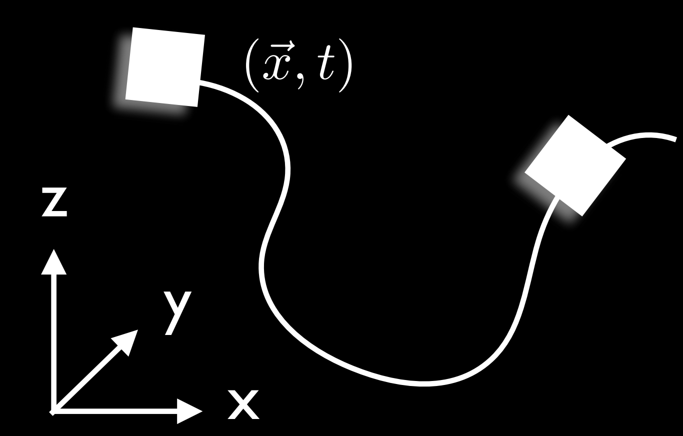
Moutarde et al. ('91); Bouchet et al. ('92); Buchert ('92); Buchert & Ehlers ('93); Bouchet et al. ('95), …, Matsubara ('15), Rampf & Frisch ('17)

Position & velocity of each mass element:

$$\boldsymbol{x}(\boldsymbol{q},t) = \boldsymbol{q} + \boldsymbol{\Psi}(\boldsymbol{q},t), \qquad \boldsymbol{v}(\boldsymbol{q},\,t) = \frac{d\boldsymbol{\Psi}(\boldsymbol{q},\,t)}{dt}$$

$\boldsymbol{q}$: Lagrangian coordinate (initial position)

$\boldsymbol{\Psi}$: displacement field $\left(\boldsymbol{\Psi} \xrightarrow{t\to 0} 0\right)$



Basic eqs.

$$\ddot{\boldsymbol{x}} + 2H\dot{\boldsymbol{x}} = -\frac{1}{a^2}\nabla_x\,\phi(\boldsymbol{x})$$

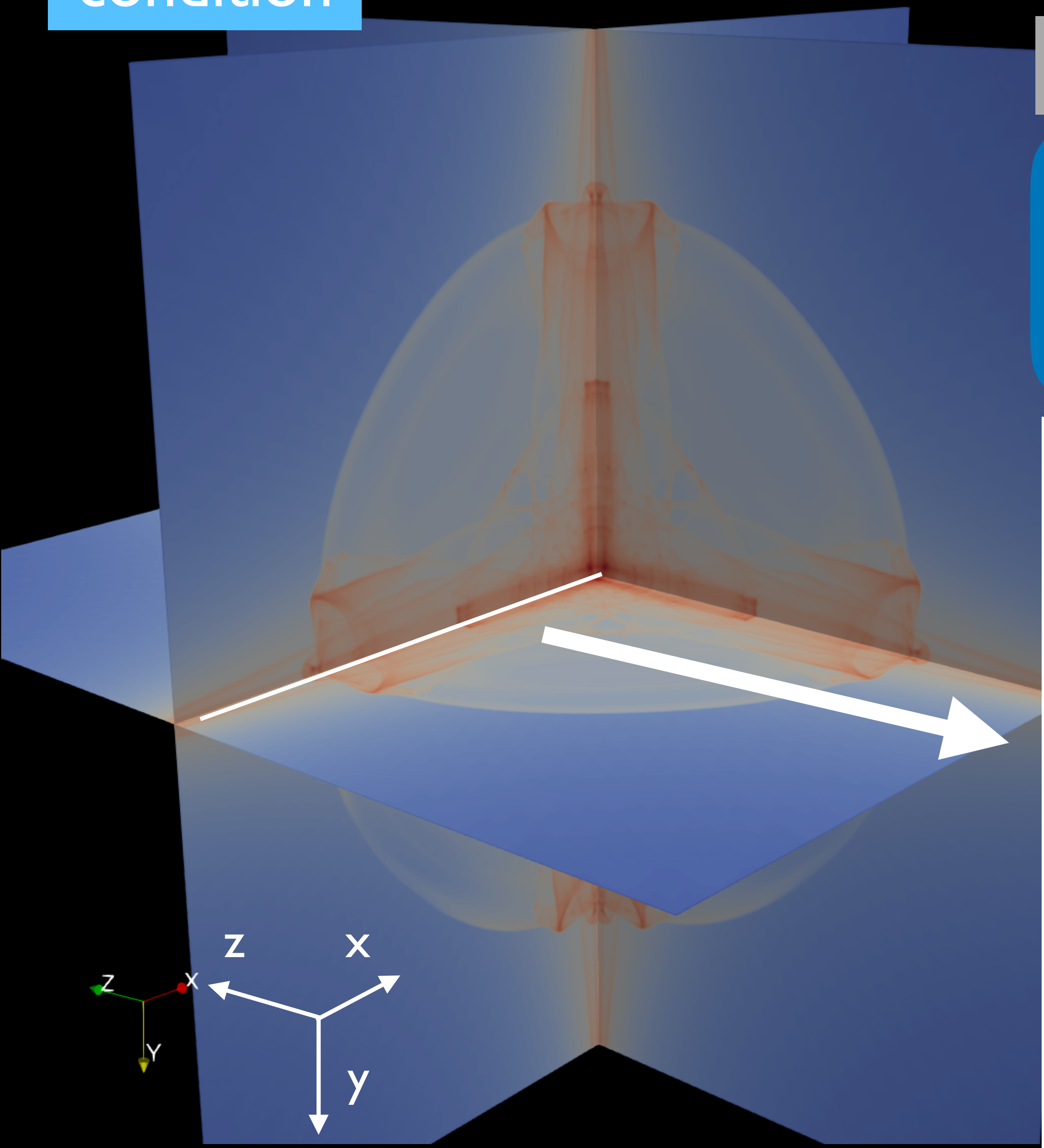
$$\nabla_x^2\,\phi(\boldsymbol{x}) = 4\pi\,Ga^2\overline{\rho}_{\rm m}\,\delta(\boldsymbol{x})$$

$$\boldsymbol{\Psi}(\boldsymbol{q},t) = \boldsymbol{\Psi}^{(1)}(\boldsymbol{q},t) + \boldsymbol{\Psi}^{(2)}(\boldsymbol{q},t) + \boldsymbol{\Psi}^{(3)}(\boldsymbol{q},t) + \cdots$$

(Slide made by Taruya)

Results

Initial condition Single density peak in a periodic boundary box

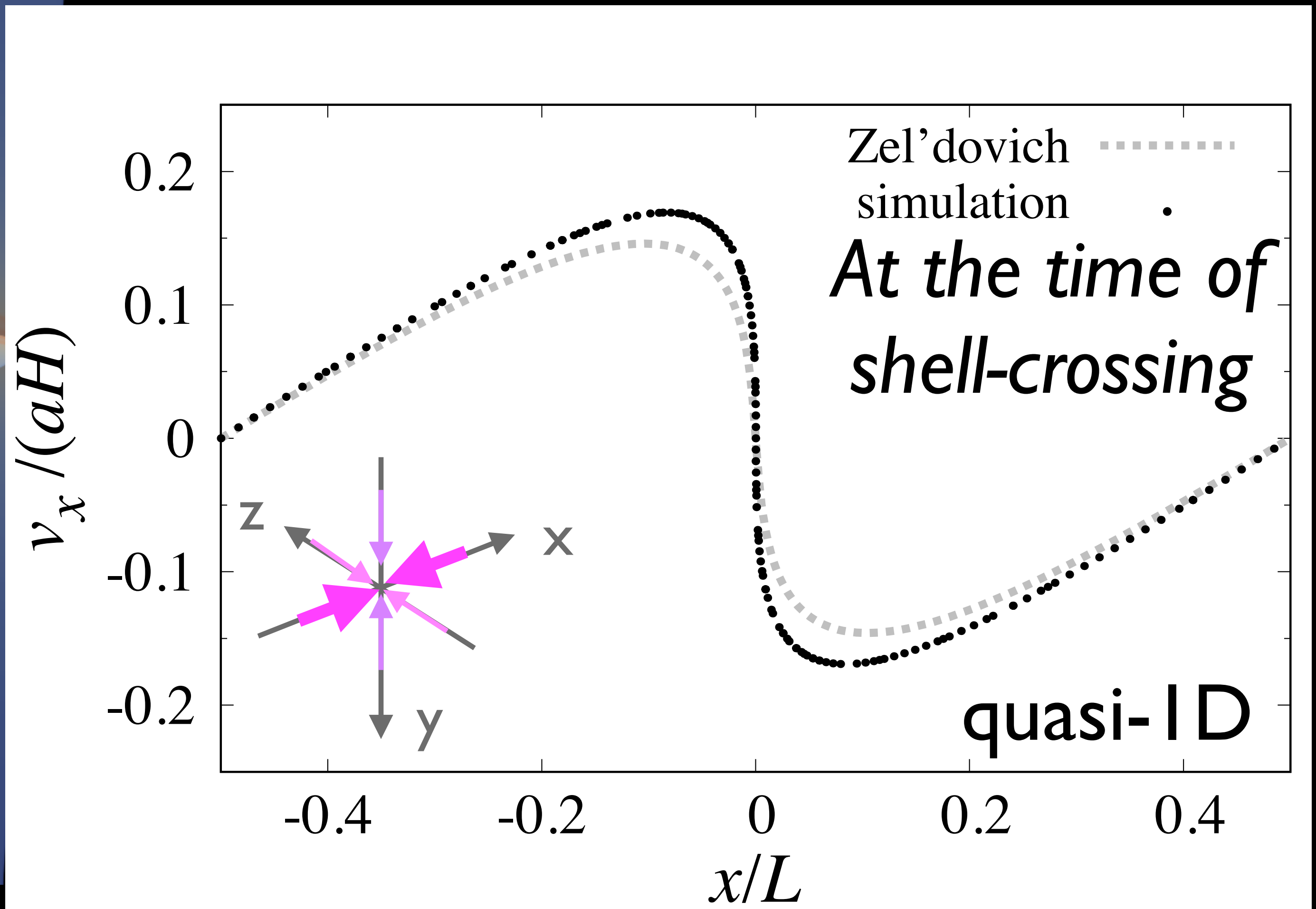


Three crossed sine waves

Displacement field

$$\mathbf{\Psi}^{(1)}(\boldsymbol{q}, t_{\rm init}) = D_+(t_{\rm init}) \begin{pmatrix} \epsilon_{\rm x} \sin q_x \\ \epsilon_{\rm y} \sin q_y \\ \epsilon_{\rm z} \sin q_z \end{pmatrix}$$

Linear growth factor

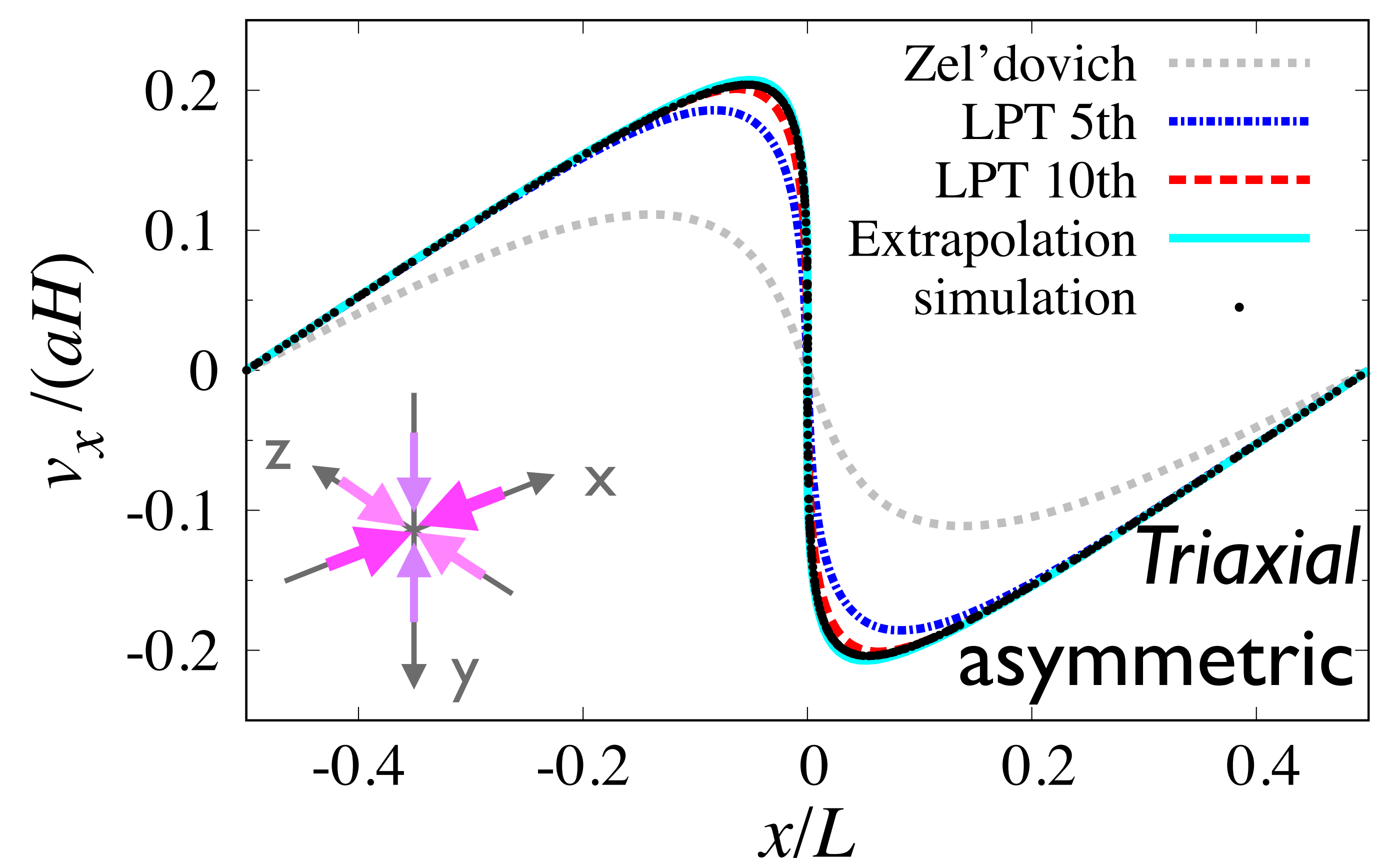


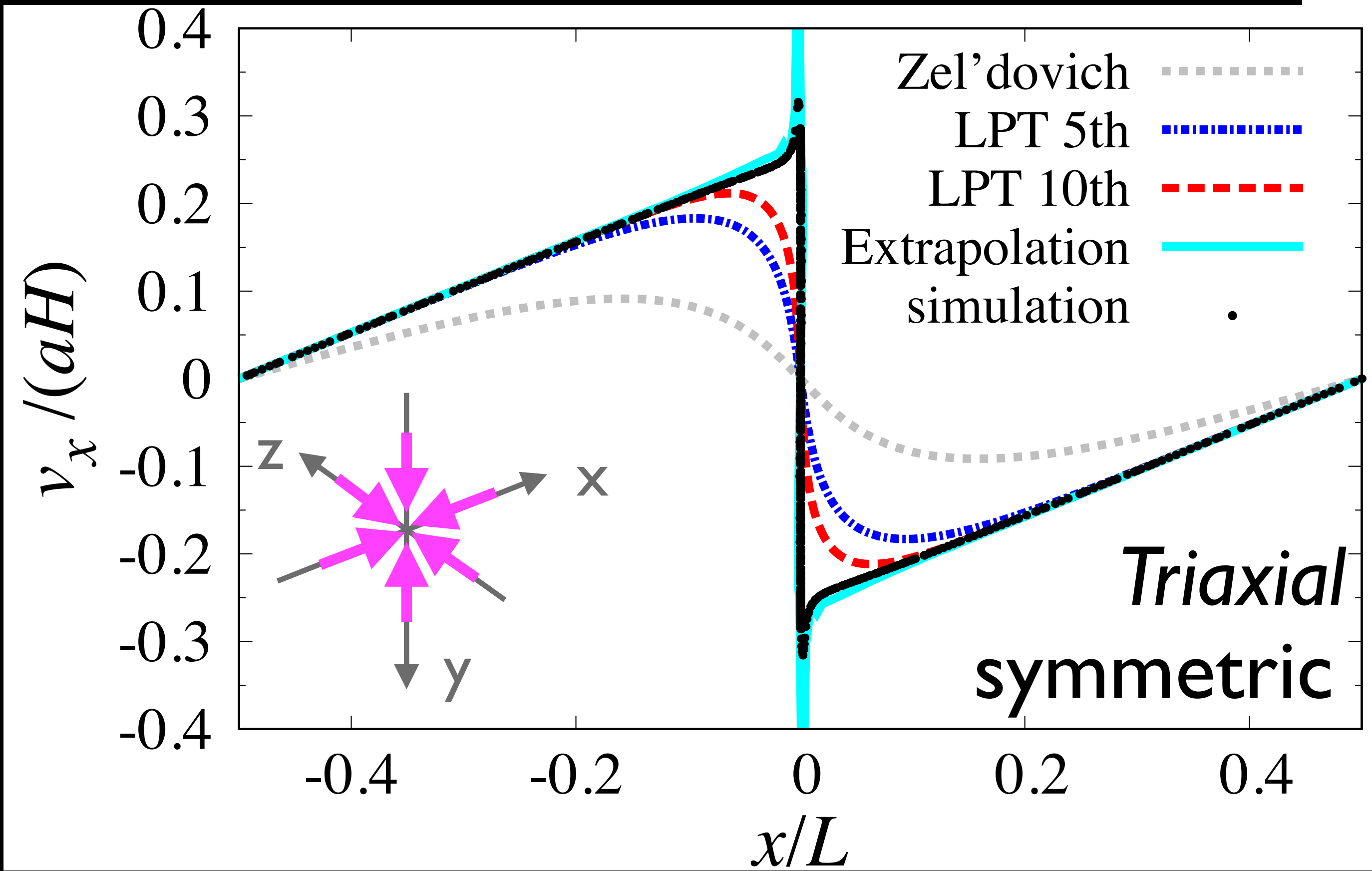
(Slide made by Taruya)

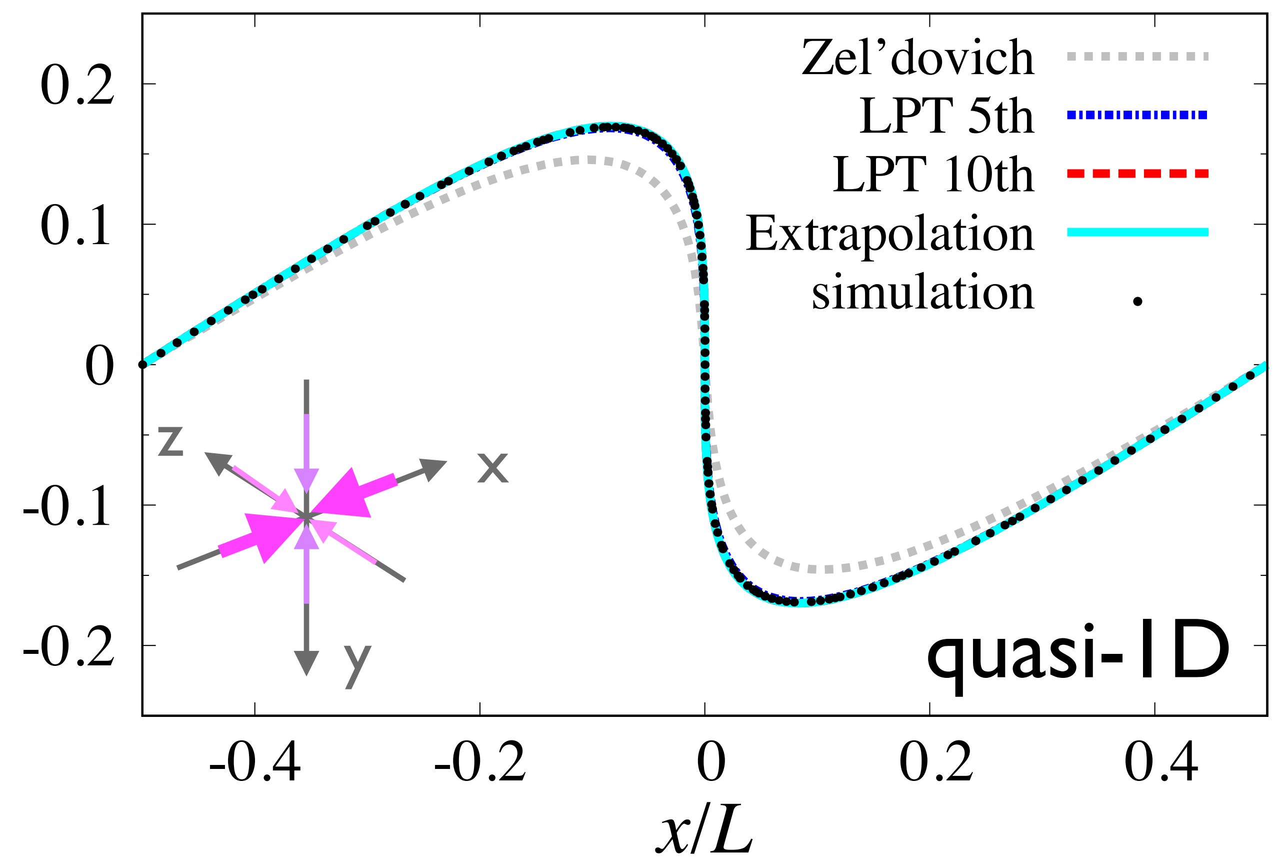
Vlasov simulation vs LPT

Saga, Taruya & Colombi ('18)

Extrapolation based on LPT up to 10th order



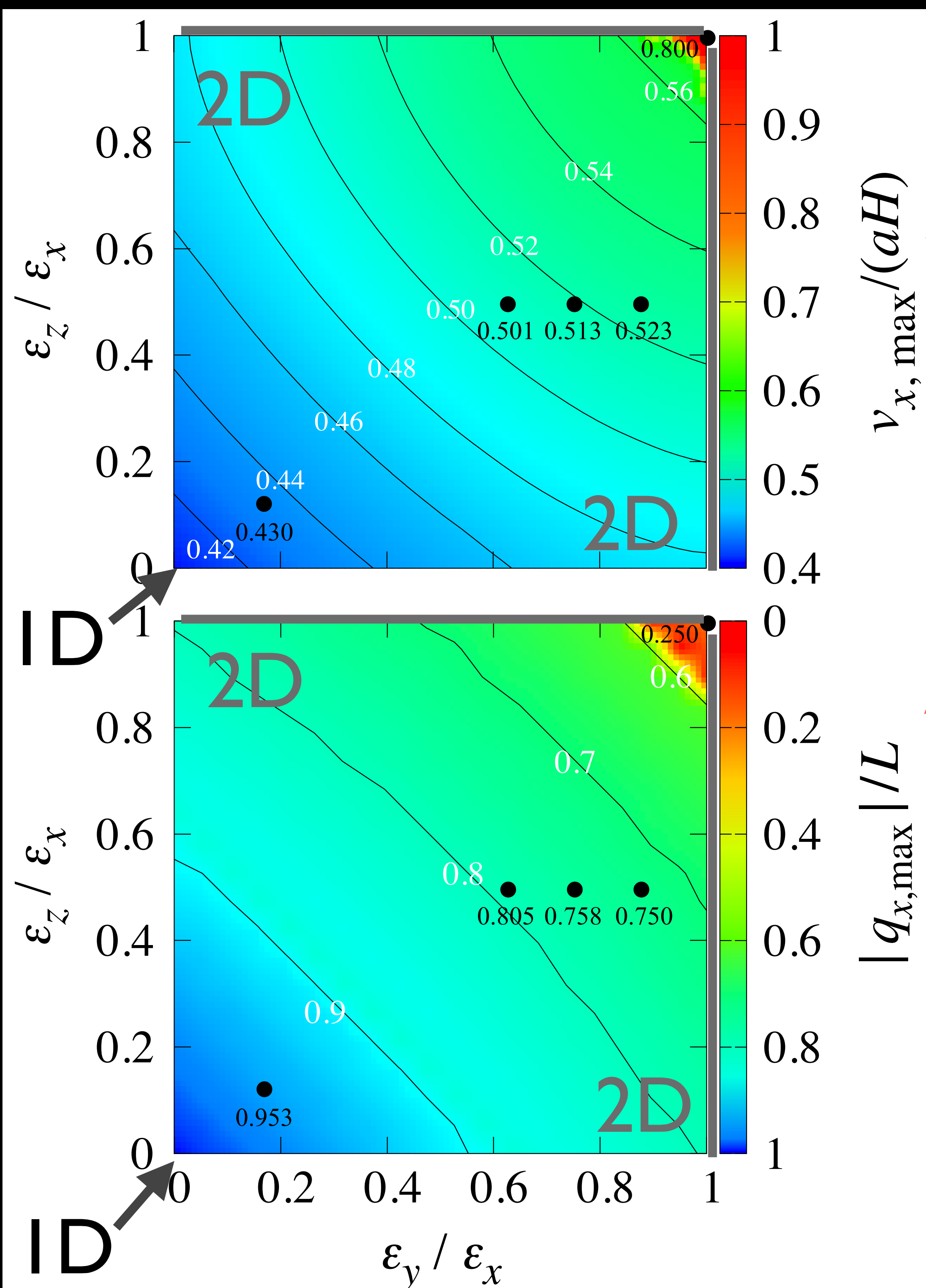


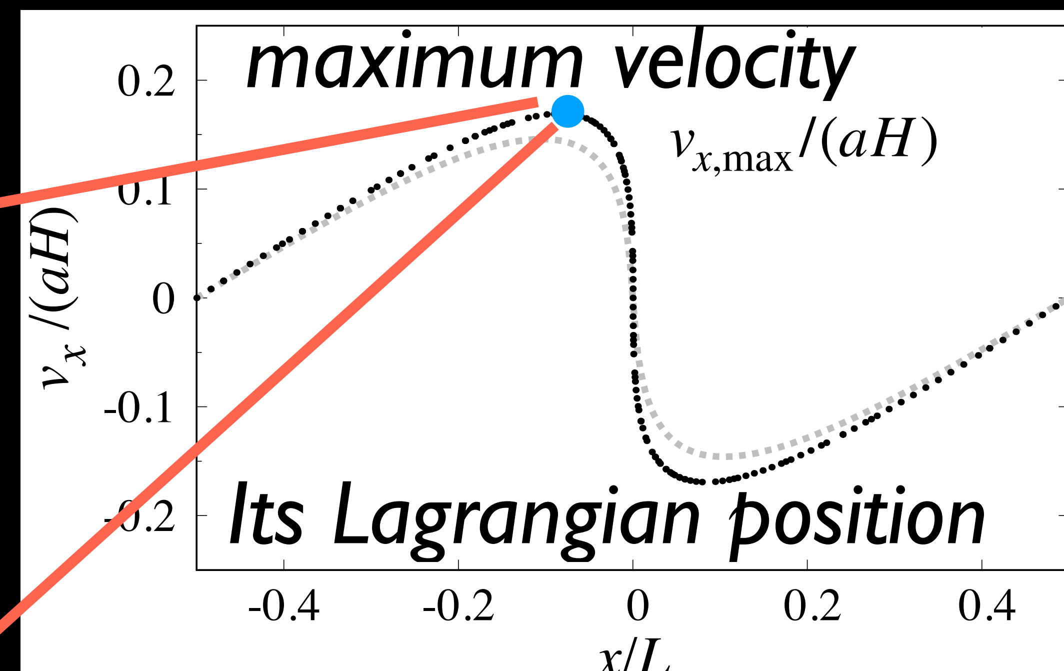


(Slide made by Taruya)

Shell crossing structure

Structure of shell crossing depends generally on parameters $\epsilon_{y,z}/\epsilon_x$





Except $\epsilon_{y,z}/\epsilon_x \simeq 1$,

phase-space of shell crossing is similar to quasi-1D case (← color changes gradually)

Dynamics near collapse looks quasi-1D ?

Oscillon/I-ball of ultra-light axion-like particle

Kawasaki, Nakano, Sonomoto arXiv:1909.10805

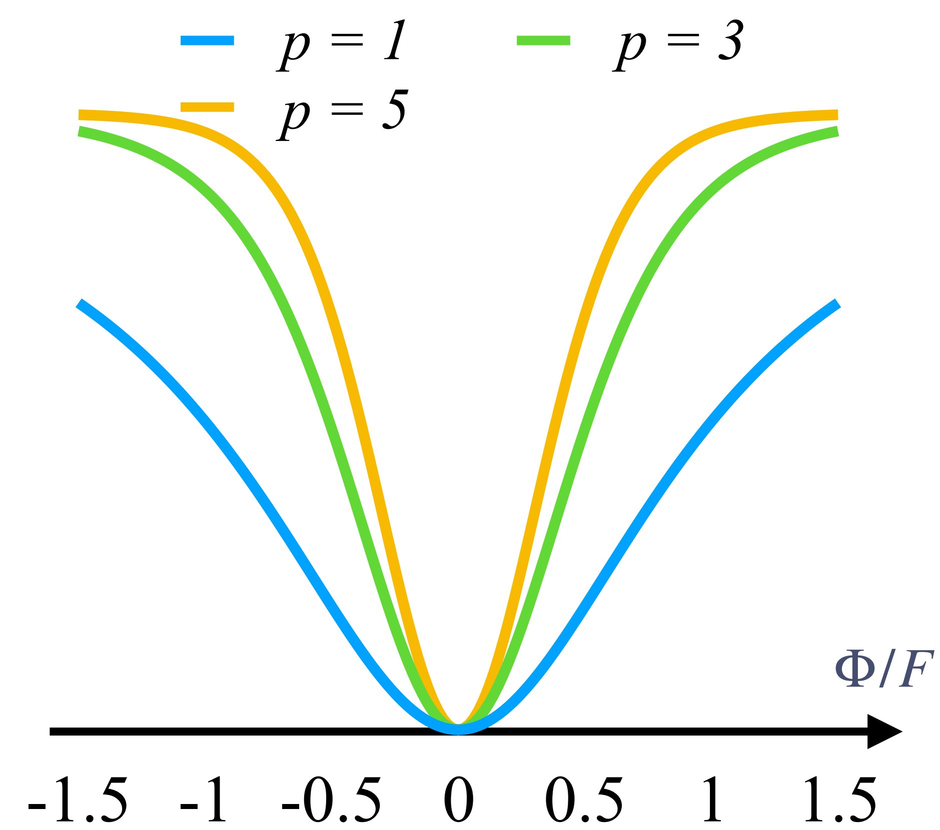
- Potential for axion-like particle

$$V(\phi) = \frac{m^2 F^2}{2p}\left[1 - \left(1 + \frac{\phi^2}{F^2}\right)^{-p}\right]$$

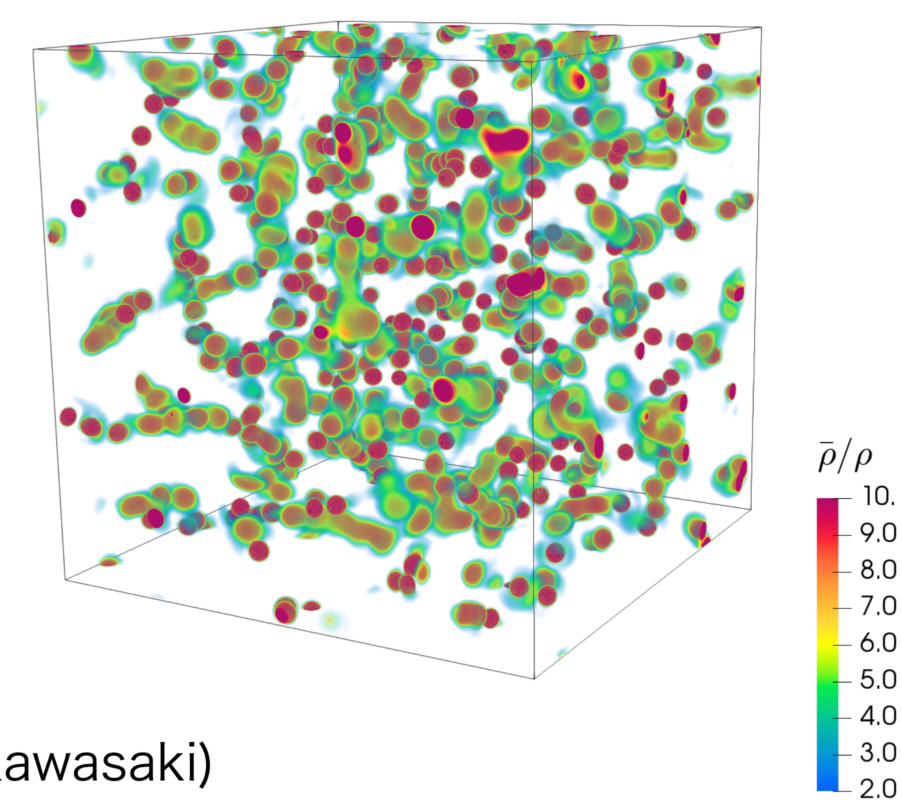
Nomura Watari Yamazaki (2017)

  - stronger instability for fluctuations than cosine potential

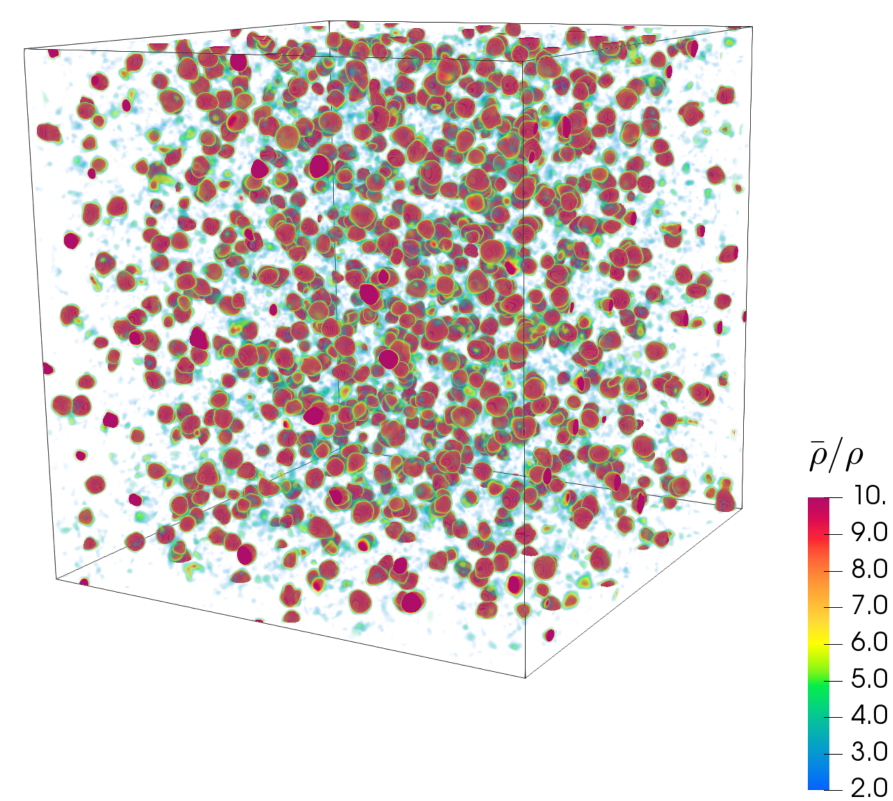
  - Oscillon/I-ball formation



$p = 2.5$



$p = 4$



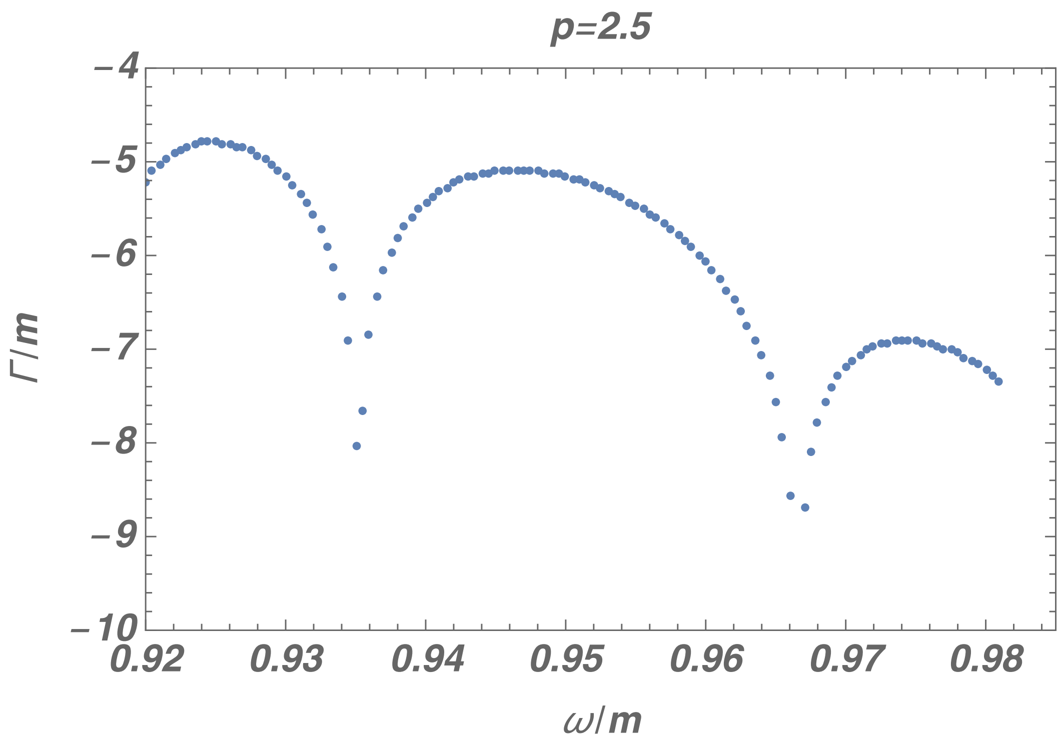
(slide made by Kawasaki)

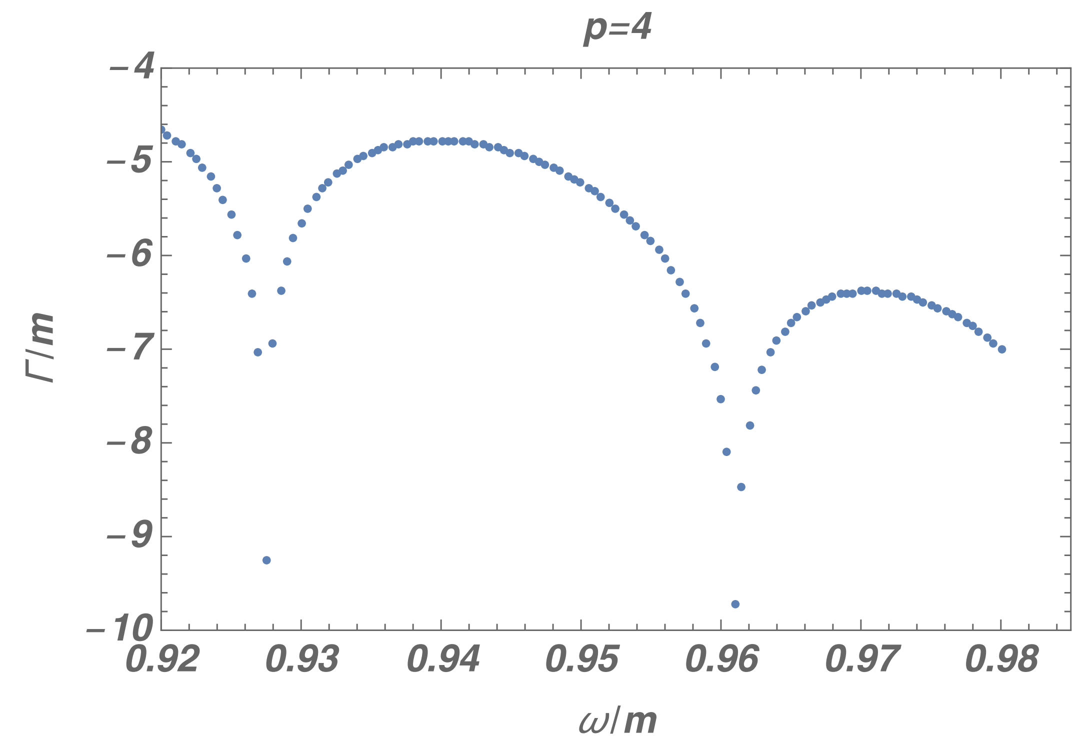
Oscillon/I-ball of ultra-light axion-like particle

- Oscillon lifetime [Γ : decay rate]

  - Classical decay rate is estimated by solving eom of fluctuations around the theoretical oscillon profile

    Ibe, Kawasaki, Nakano, Sonomoto arXiv:1901.06130





  - ULAP Oscillon is stable at least for $\mathcal{O}(10^7 m_a^{-1})$

    $\tau \sim 10^8$years for $m_a \sim 10^{-22}$eV

    de Broglie wavelength $\sim \mathcal{O}(\text{kpc})$

    Solution for core-cusp problem

  - Some ULAP oscillons have longer lifetimes and live in the present universe

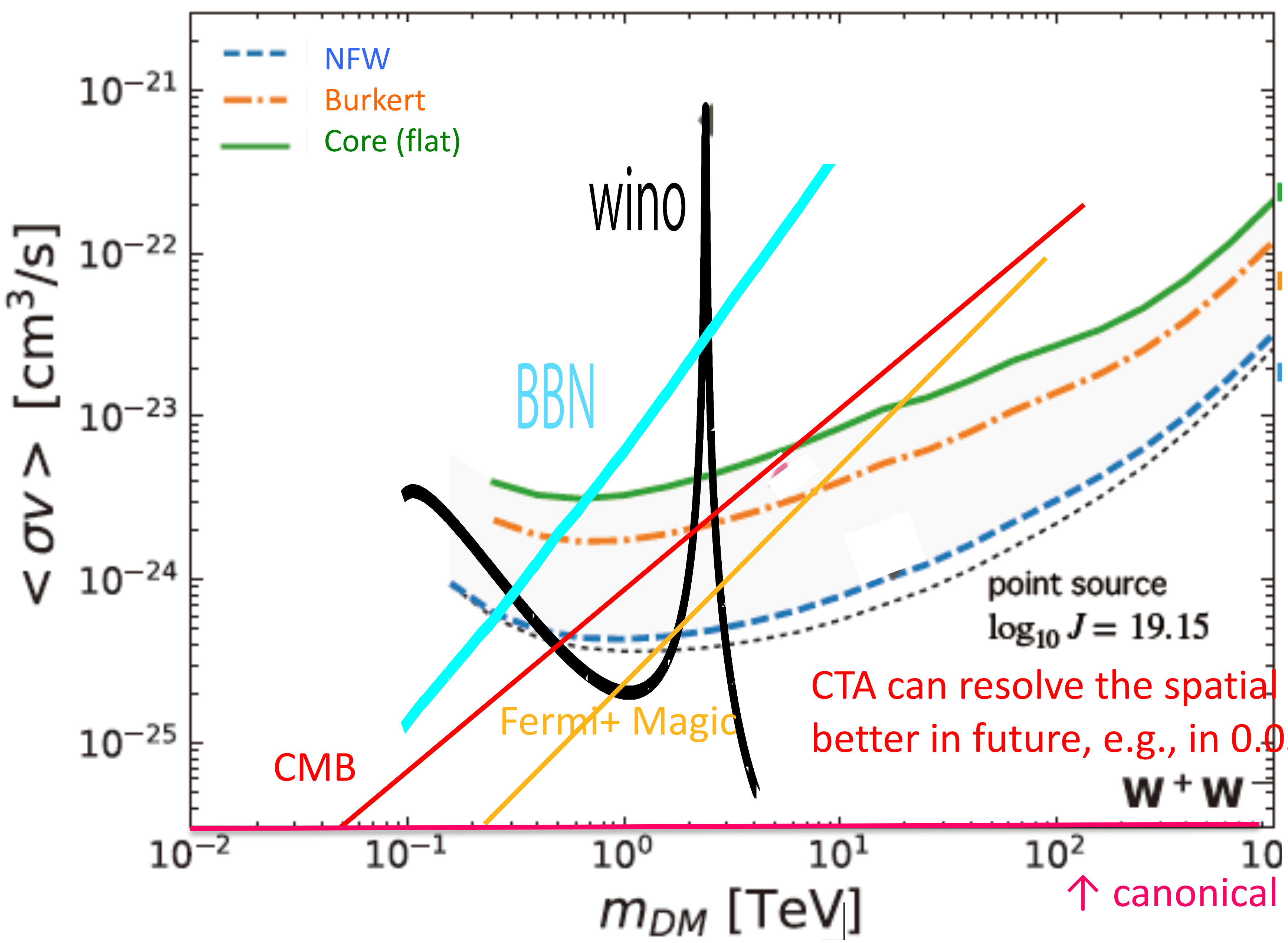
(slide made by Kawasaki)

Detection

Dwarf spheroidal galaxies are dominated by dark matter, and so, they are good targets to look for DM annihilation/decay signatures.

Forecasts of upper bounds on annihilation cross section from gamma-ray observations by CTA towards Dwarf Spheroidal Galaxies

N.Hiroshima, M.Hayashida, and KK, arXiv:1905.12940 [astro-ph.HE]



CTA can resolve the spatial structure much better in future, e.g., in 0.03° x 0.03°

↑ canonical cross section

Big uncertainties due to a variety of density profiles

DM = inflaton?

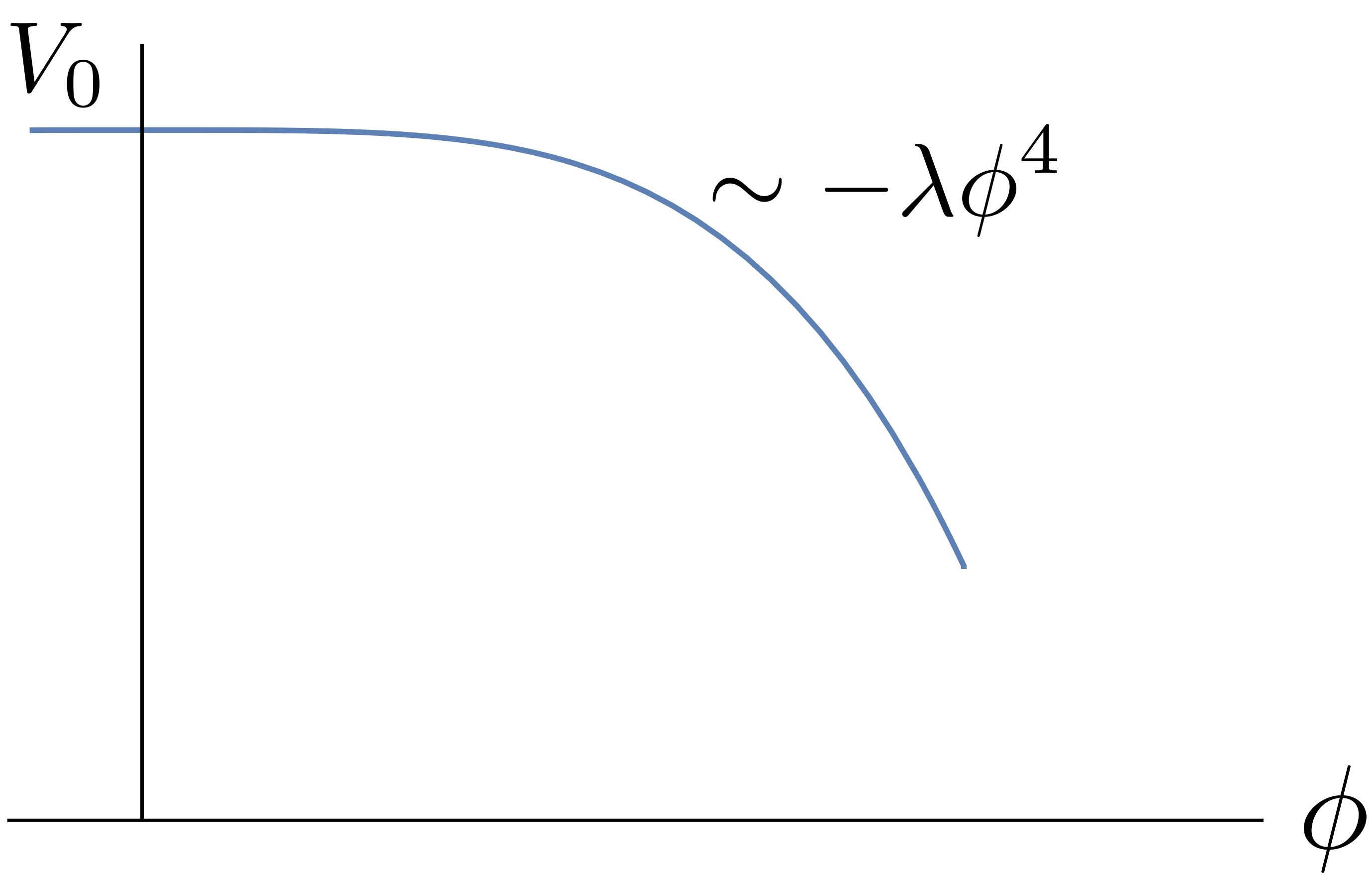
• Axion hilltop inflation

Czerny, FT 1401.5212,
Czerny, Higaki, FT 1403.0410, 1403.5883
Croon and Sanz, 1411.7809
FT, Yin, 1903.00462

Low-scale axion inflation can be realized with **at least two cosine terms**: *"Multi-natural inflation"*

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{\kappa}{n^2} \cos\left(\frac{n\phi}{f}\right)\right) + {\rm const.}$$

$$= V_0 - \lambda\phi^4 - \theta\frac{\Lambda^4}{f}\phi + (\kappa - 1)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots \qquad \lambda \sim \frac{\Lambda^4}{f^4}$$



CMB normalization:

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$

• Axion hilltop inflation

Czerny, FT 1401.5212,
Czerny, Higaki, FT 1403.0410, 1403.5883
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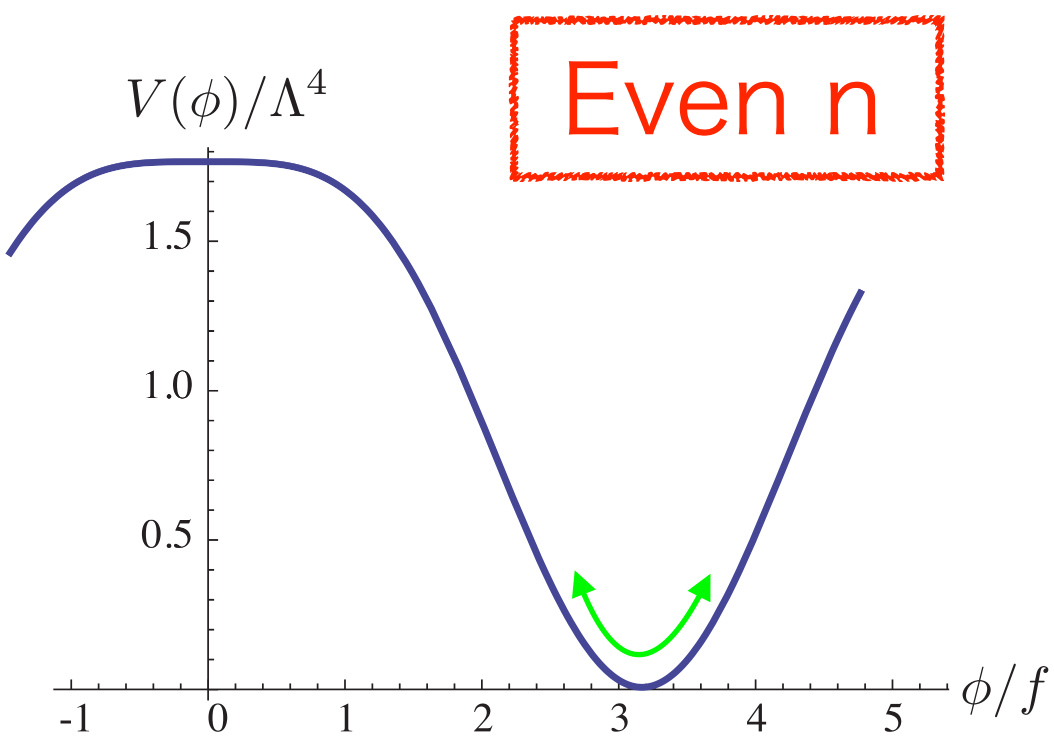
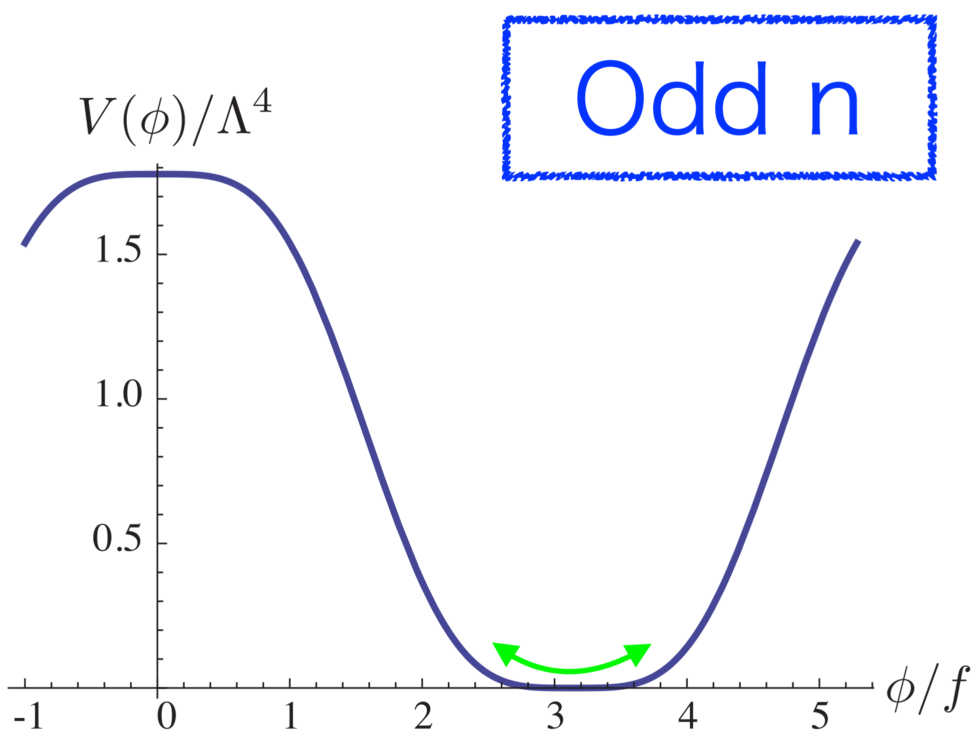
The inflaton mass at the minimum, m_ϕ, depends on *n*.



$$m_\phi \sim \Lambda^2/f$$

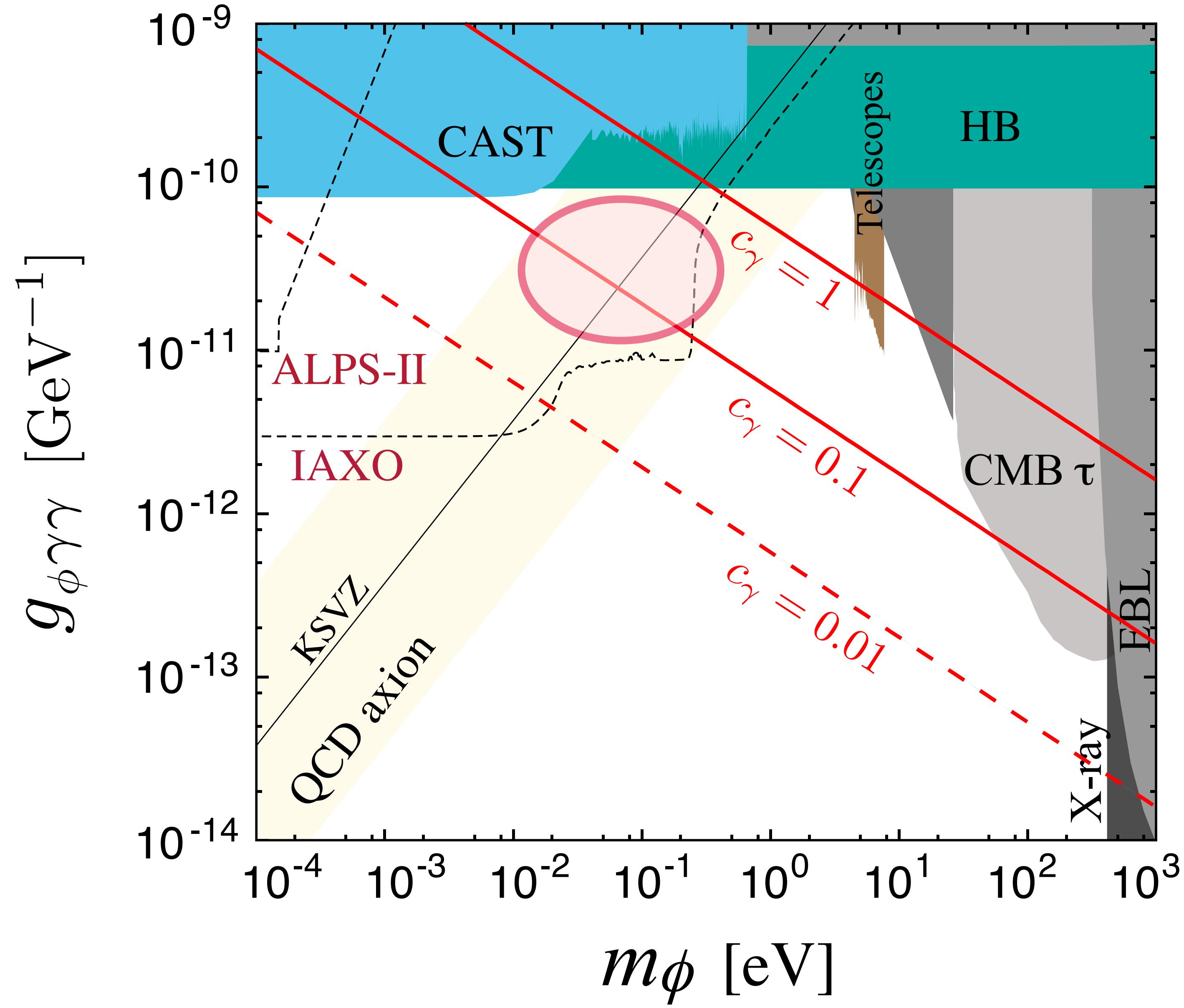


$$m_\phi \ll \Lambda^2/f$$

Inflaton = DM = ALP

$$m_\phi = \mathcal{O}(0.01 - 1)\,\mathrm{eV}$$
$$g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

within the reach of future axion helioscopes and laser experiments.

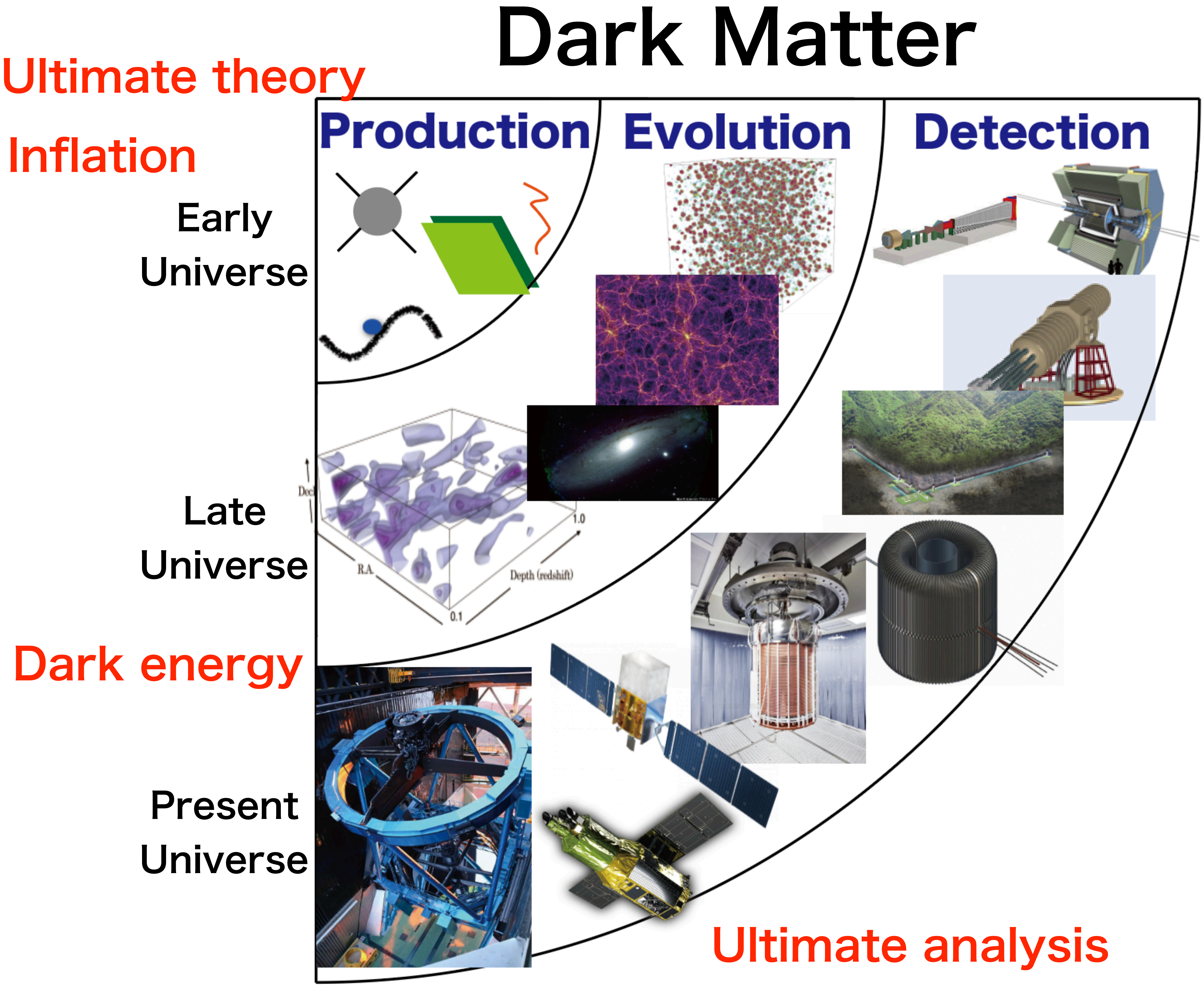


"An ALP miracle"

*Plus, there is a preference for extra cooling of HB stars

$$g_{\phi\gamma\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\mathrm{GeV}^{-1}$$

Ayala, Dominguez, Giannotti, Mirizzi and Straniero, 1406.6053, DESY- PROC-2015-02


Dark Matter
Ultimate theory
Inflation
Early
Universe
Production
Evolution
Detection
Late
Universe
Dec
R.A.
Depth (redshift)
0.1
1.0
Dark energy
Present
Universe
Ultimate analysis

Back-up slides

What is the cosmological role of ALP?

1. Dark matter

Misalignment mechanism $\theta_* = \mathcal{O}(1)?$

strings/walls?

Bunch-Davies distribution.

String and wall evolution depends on the UV completion:
e.g. clockwork axion model

See also Sikivie `86 Kim, Nilles, Peloso, hep-ph/0409138 Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923 Harigaya and Ibe, 1407.4893, Choi and Im, 1511.00132, Kaplan and Rattzzi, 1511.01827, Giudice and McCullough 1610.07962

$$V = \sum_{i=1}^{N} \left(-m_i^2 |\Phi_i|^2 + \lambda_i |\Phi_i|^4\right) + \sum_{i=1}^{N-1} \epsilon \left(\Phi_i \Phi_{i+1}^3 + \text{h.c.}\right)$$

$$f_a \sim 3^N f$$

- **Phase transition takes place at lower** $T \sim f \ll f_a$
- **Strings and walls form complicated network**