Progress on the study of QCD axions

Satoshi Shirai (Kavli IPMU)

Axions

- A Nambu-Goldston boson to solve the strong CP problem.
- Light CP odd particle which couples to gauge bosons.
- Associsated with spontaneous break of global PQ symmetry.
- More generally, string theory or quantum gravity predicts lots of axion candidates.

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- More generally, string theory or quantum gravity predicts lots of axion candidates.

Most important new physics particle!

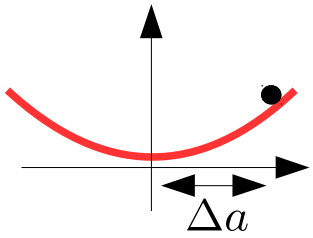
So far, 17 / 36 talks are axion-related in this workshop.

Challenge for Axions

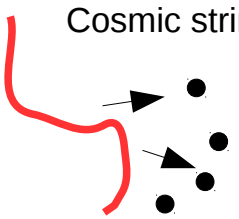
- Quantum gravity generally does not allow exact gobal symmetry.
  - Accidentally symmetric? “accion”
  - “gauged” PQ symmetry?
  - …
- Detection of axions.
  - Ground-base expetimens: collider, beam dump.
  - Asrtorophysical search: haloscope, evolution of stars.
  - Cosmology.
  - …
- Various forms of axion DM and various detection accordingly.

Axion Dark Matter

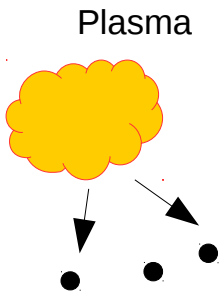
Various Production:



Misalignment



Phase transition



Thermal production

and ...

Axion Dark Matter

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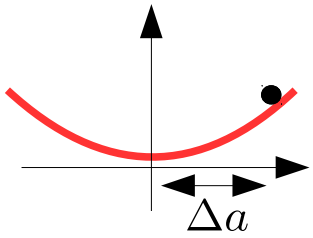

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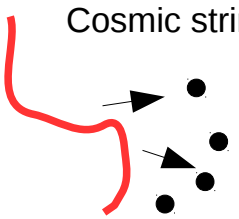

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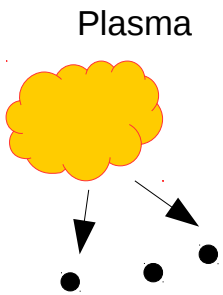
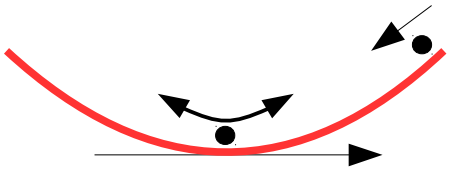


Thermal production

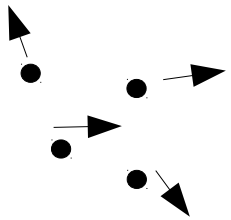
and ...

Form of Cosmic Axion

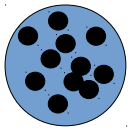


Oscillating or rolling down?

Field-like?



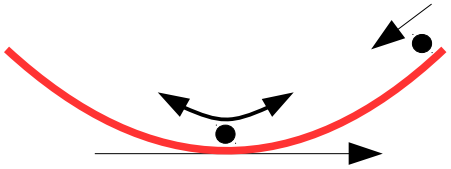
Particle-like?

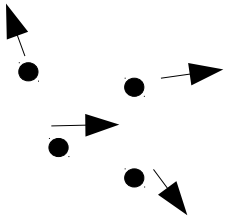


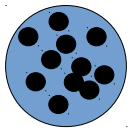
Star-formation?

and ...

Axion Dark Matter







and ...

Oscillating or rolling down?

Field-like? Particle-like? Star-formation?

Effect on CMB

MACHO Search

Interferometer

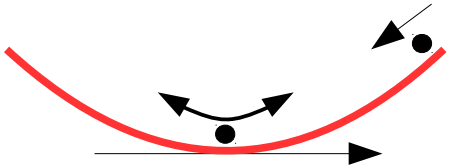
Structure formation

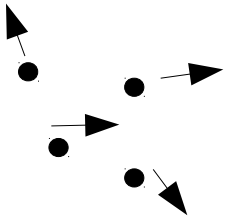
X-ray Search

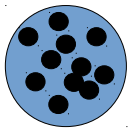
Accelerator-based approach: Collider and beam dump.
Solar axion search, and so on..

Any other?

Axion Dark Matter







Oscillating or rolling down?

Field-like?

Particle-like?

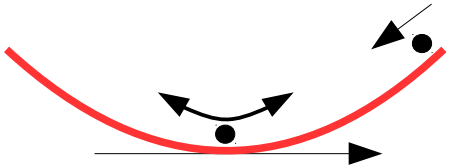
Star-formation?

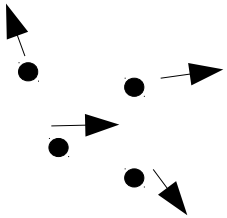
Detection of bosenova?

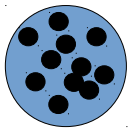
[Eby,SS,Stadnik&Takhistov,2106.14893]

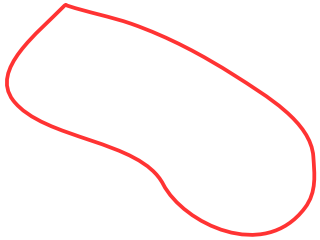
Axion Dark Matter

new form of DM?









Oscillating or rolling down?

Field-like?

Particle-like?

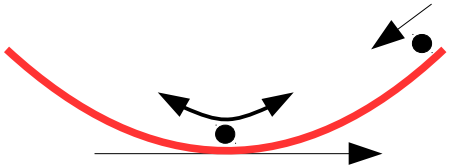
Star-formation?

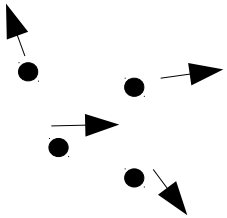
Closed Axion string?

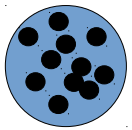
[Fukuda,Manohar,Murayam&Telem, 2010.02763]

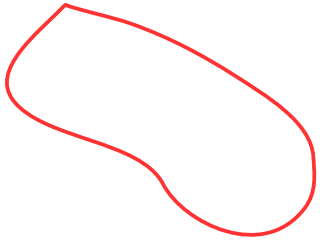
Axion Dark Matter

new form of DM?









Oscillating or rolling down?

Field-like? Particle-like? Star-formation? Closed Axion string?

[Fukuda,Manohar,Murayam&Telem, 2010.02763]

- Axion string loop DM?

  [Ibe,Kobayashi,Nakayama&SS,2102.05412]

- Axion search with ILC photon beam facility.

  [Fukuda,Otono&SS, 2203.06137]

- Axion DM detection by use of elastic scattering.

  [Fukuda&SS, 2112.13536]

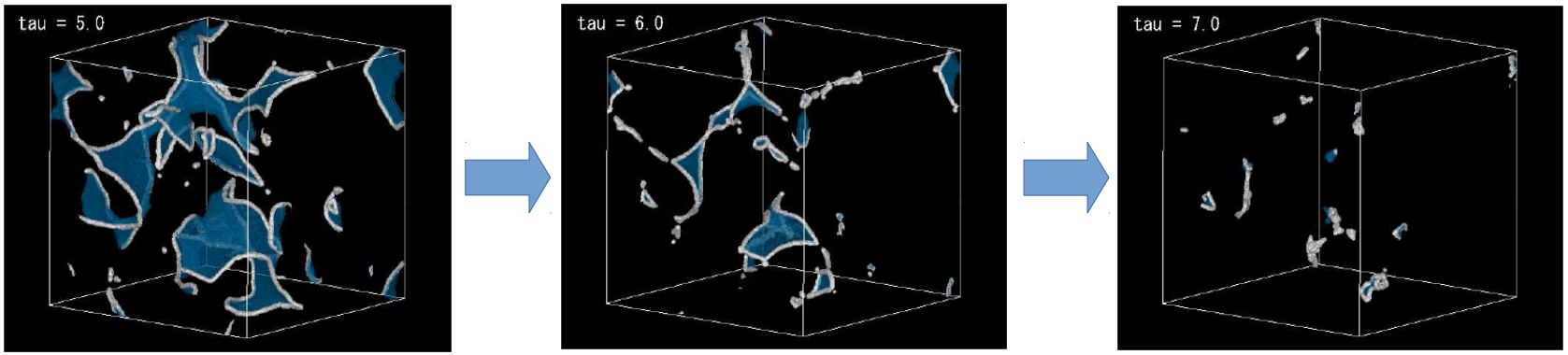
Stability of Axion String?

[Ibe,Kobayashi,Nakayama&SS,2102.05412]

Axion String

Due to PQ symmetry breaking, there appear topological objects.

[Hiramatsu,Kawasaki,Saikawa&Sekiguchi, 1202.5851]



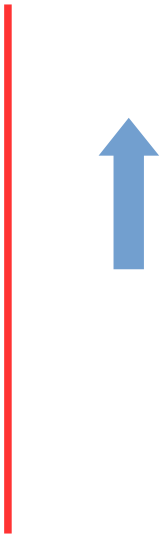
Usually, domain walls and strings are collapsed, emitting axion DM.

Axion String and Current

Axion String and Current

However, string may carry permanent current.

[Witten, NPB 249 (1985) 557]



Current of zero-mode fermions along the string

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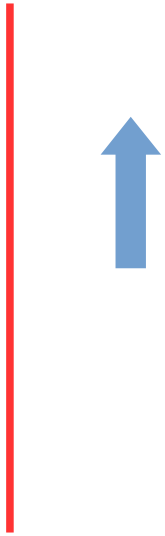
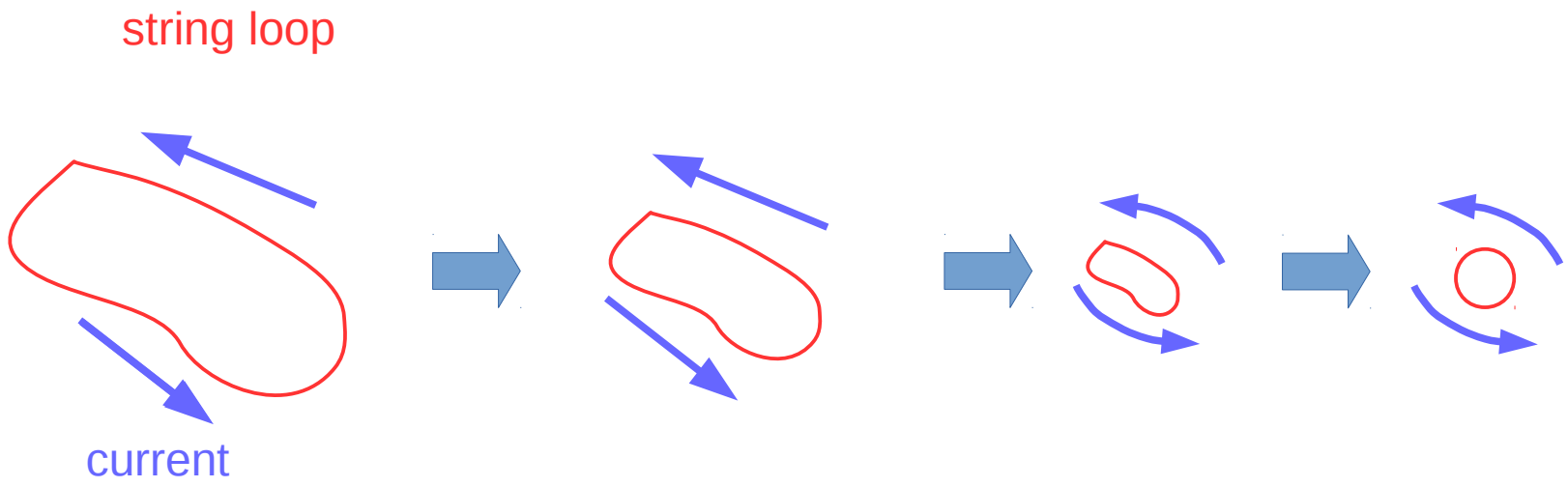


Current of zero-mode fermions along the string

Intuitively, at the center of string, symmetry is recovered.

Massless fermion at the string core.

String Loop with Current



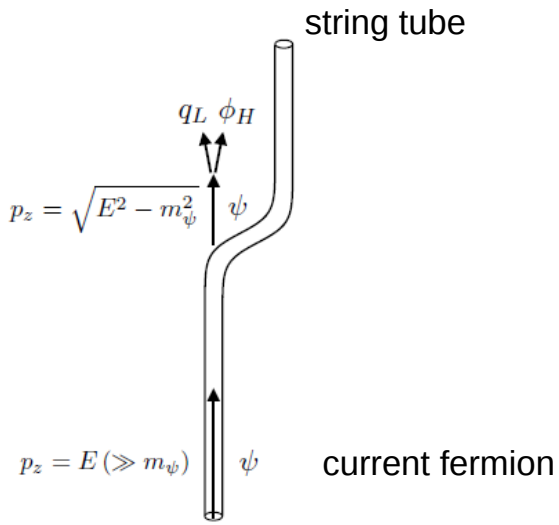
Force from current can balance with string tension?

Stabilize string loop? “Vorton” DM?

Current is Stable?

[Ibe,Kobayashi,Nakayama&SS,2102.05412]

- In reality, cosmic string is not string but has finite width.
- Cosmic string has non-zero curvature.
- Current particles are energetic.

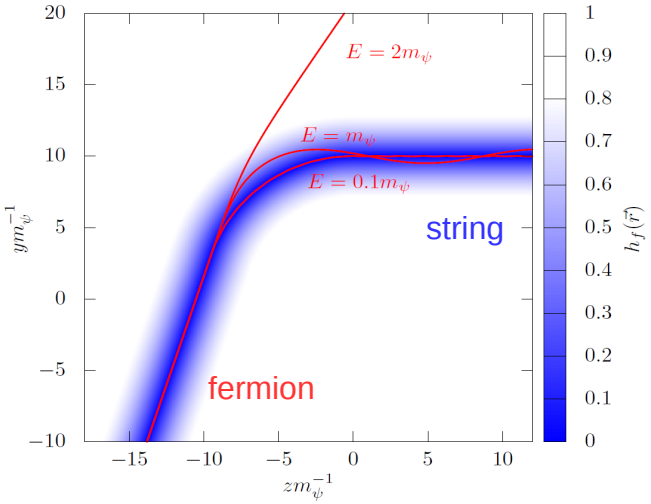


going off course?

Current is Stable?

[Ibe,Kobayashi,Nakayama&SS,2102.05412]

Classical calculation



High energy fermion highly goes off and decays.

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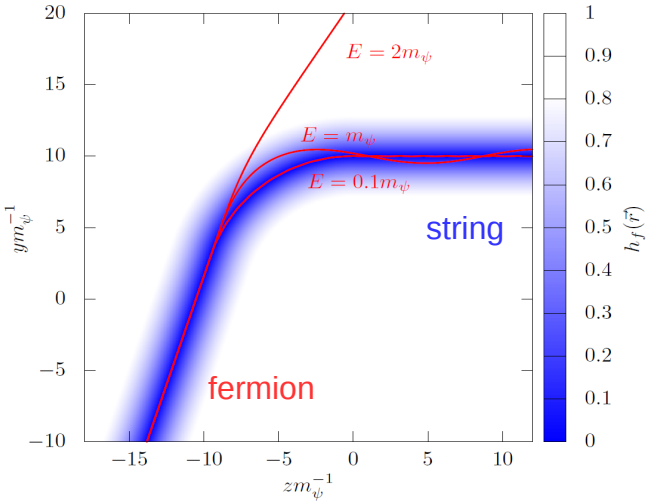

High energy fermion highly goes off and decays.

Quantum perturbative calculation

$$\Gamma \sim \frac{E}{Rm_\phi}$$

E: current energy.
R: Curvature.
m_φ: PQ Higgs mass ~ string tension

Too quick decay to be DM.

Direct Detection of Axion DM?

[Fukuda&SS, 2112.13536]

Axion DM Detection

- Conventionally, absorption/conversion or coherent nature is utilized for DM axion searches.
- WIMP search focus on elastic scattering.
- How about elastic scattering of axion DM?

Elastic Scatter of Axion DM

[Fukuda&SS, 2112.13536]

$$\mathcal{L} \sim \frac{m_N}{1000 f_a^2} a a \bar{N} N$$

fa: decay constant
N: nucleon field

- The interaction is doubly suppressed by the decay constant.
- But quantum mechanical effect is helpful?
- As the DM density is 0.3 GeV/cm^3 and velocity ~ 100 km/s

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Macroscopic Compton length

$$(m_a v_{\rm DM})^{-1} \sim \frac{0.1\,{\rm eV}}{m_a}\,{\rm cm}$$

Coherent enhancement?

$$N_{\rm target} = O(10^{23})$$

Large phase number density

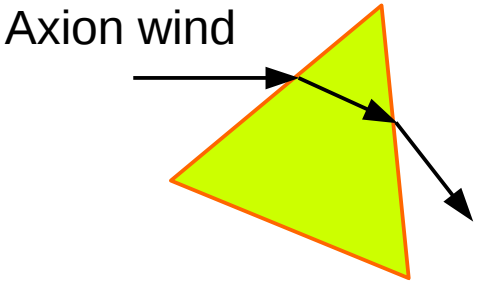
$$f_{\rm DM} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}\left(m_{\rm DM} v_{\rm DM}\right)^3} \sim 10^7 \left(\frac{m_{\rm DM}}{0.1\ {\rm eV}}\right)^{-4}$$

Stimulation effect?

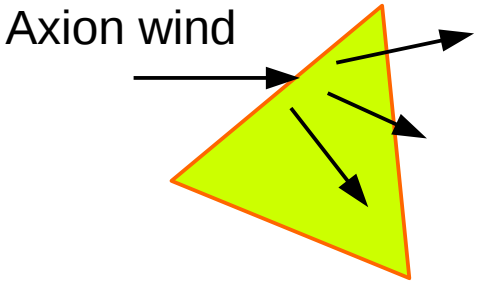
$$\sigma(aN \to aN) \to \sigma(aN \to aN) \times (1 + f_{\rm DM})$$

Detection of Axion DM

Such axion can lead additional acceleration to detector, e.g., torsion balance



Refraction: $O(f_a^{-2})$ effect.



Scattering: $O(f_a^{-4})$ effect
+ coherent + stimulate effect?

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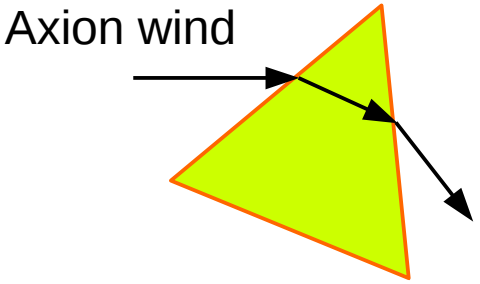
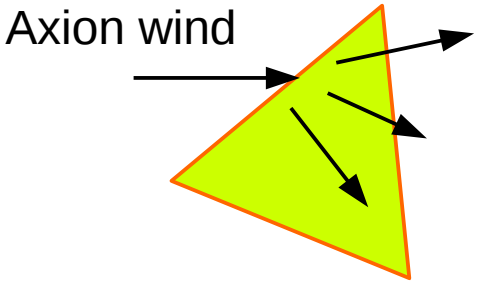


Refraction: $O(f_a^{-2})$ effect.

No net effect for uniform DM density.



Scattering: $O(f_a^{-4})$ effect
+ coherent + stimulate effect?

Stimulation effect is canceled.

c.f., relic neutrino case:
[Cabibboa&Maiani, PLB 114 (1982) 115]

After all...

- Direct detection of elastic scatter of axion DM is hard, even with help of quantum mechanical enhancement.

$$\Delta a_{\text{axion}} \sim 10^{-31}\ \text{cm/s}^2 \left(\frac{m_a}{1\ \text{meV}}\right)$$

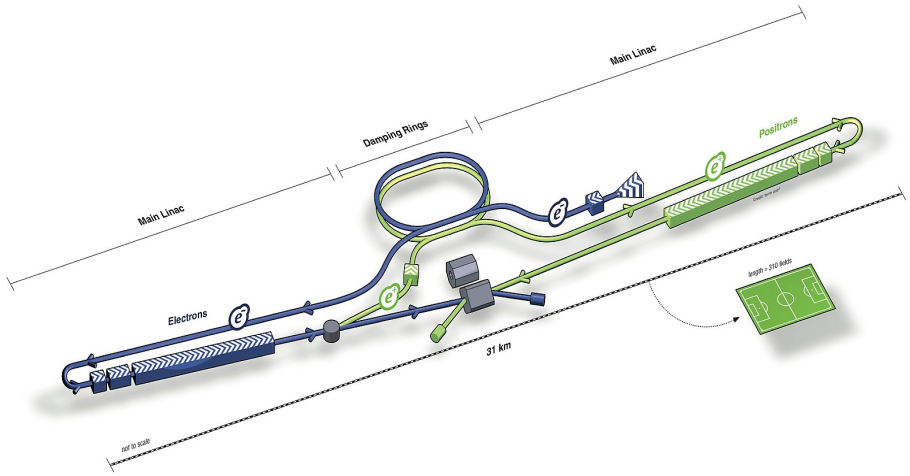
- Not enough static force. Ultimate experimental reach ~ 10^{-23} cm/s^2
- With non-uniform DM density, time-varying force is possible.
- Axion can scatter off the Sun with large probability. Any chance?

Axion Search at ILC?

[Fukuda,Otono&SS, 2203.06137]

Axion Search at ILC

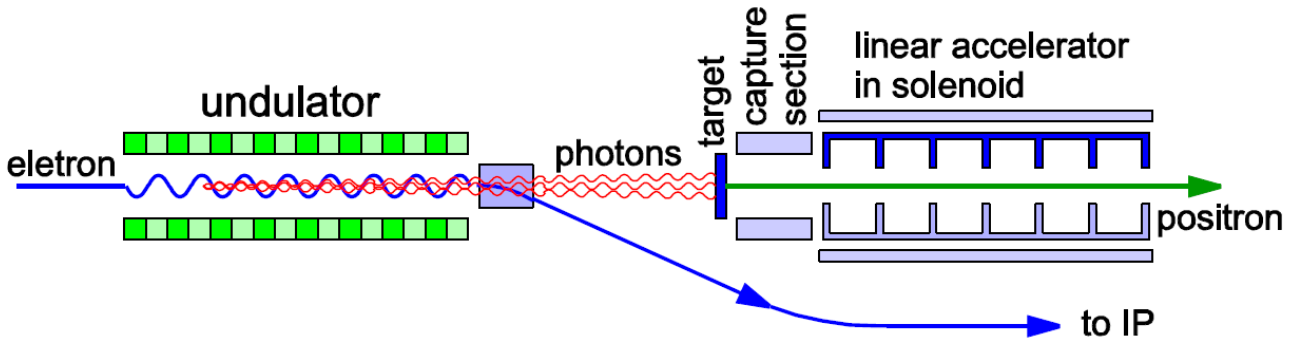
International Linear Collider is e^+e^- Collider.



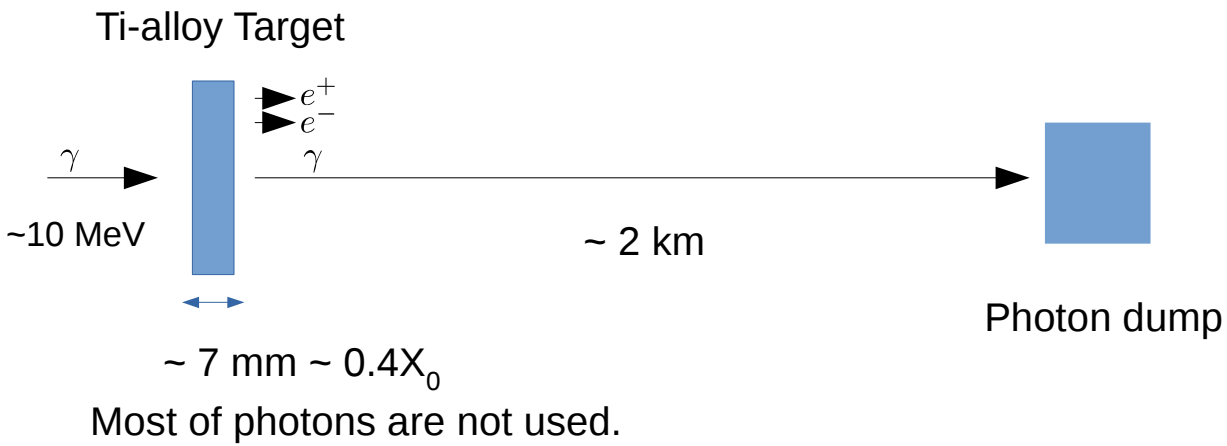
Axion search at the ILC is possible?

Positron Source

Baseline plan for positron source is based on undulator photon



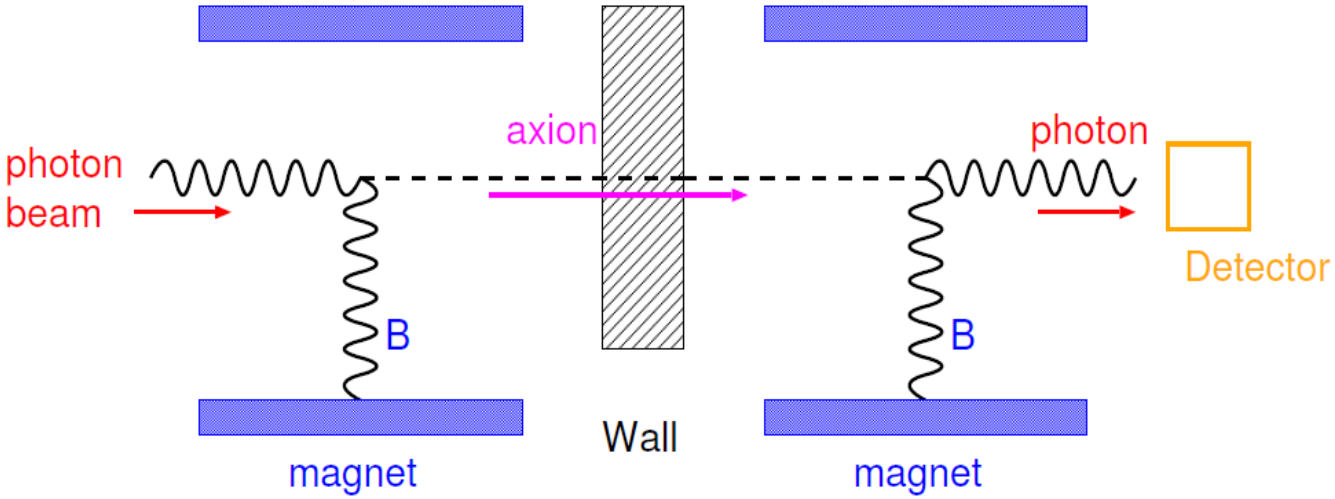
Undulator photon



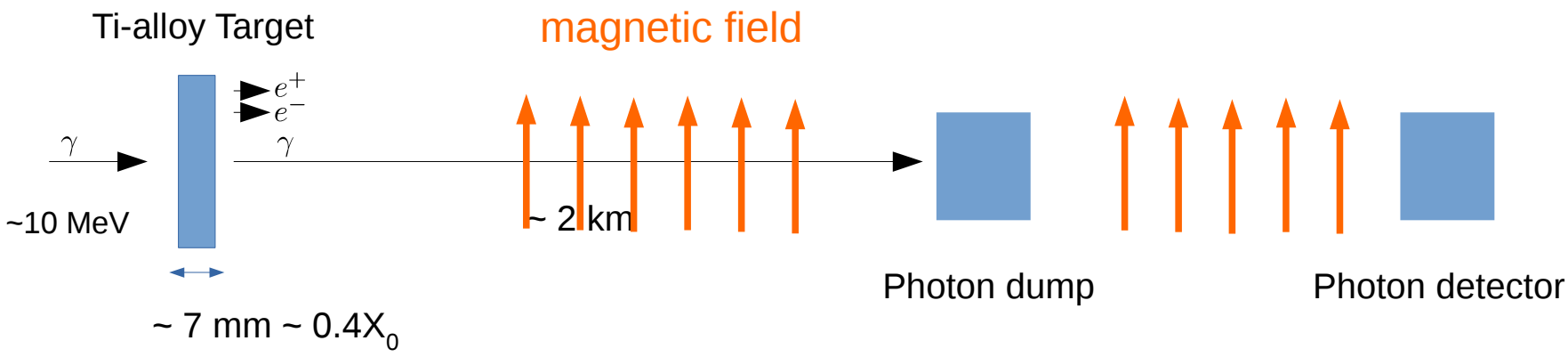
Well-collimated 10^{24} photons/year, are simply abandoned.

LSW Experiments for Axion

Light Shining through a Wall

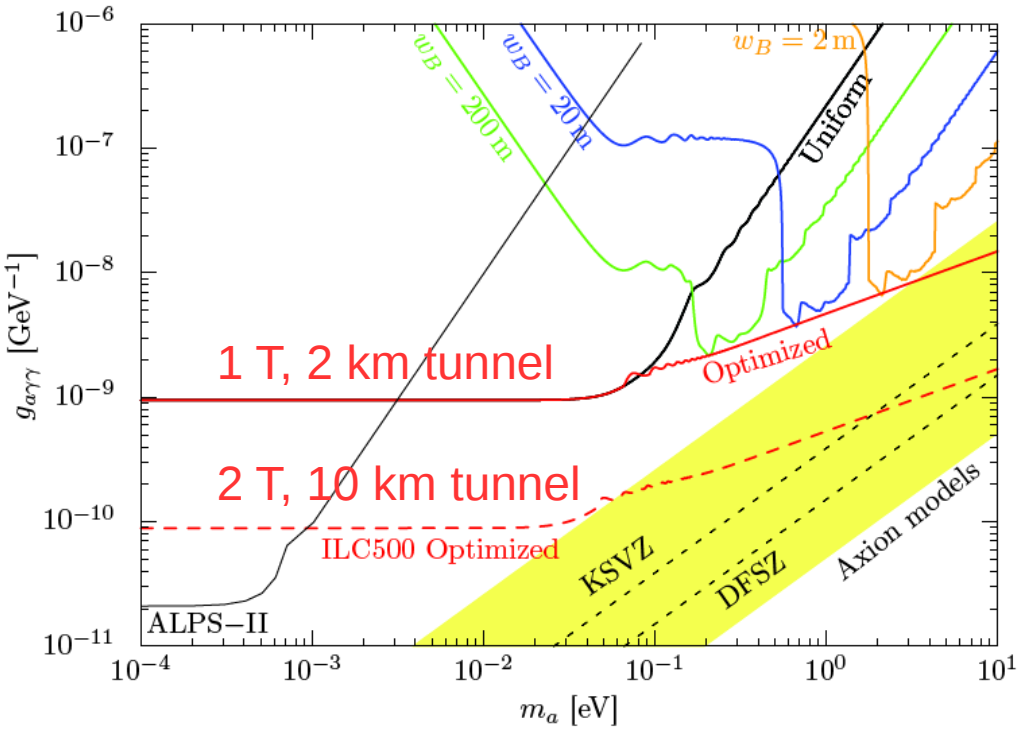


LSW Experiments at ILC



With high-energy photons, high mass axion can be probed.

Expected Sensitivity



Summary

- The axion is an important target with various theoretical and experimental challenges.
- We need more and more idea to chase this particle.
- I hope to we can pursue this interesting physics with collective efforts of all the groups.