Vortices in U(1) Dark photon

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Dark photon

- Dark photon

Okun 1982, Holdom 1985

$$\mathcal{S} = \int \mathrm{d}^4x \left(-\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \epsilon F^{\mu\nu} F'_{\mu\nu} \right)$$

- Dark photon dark matter

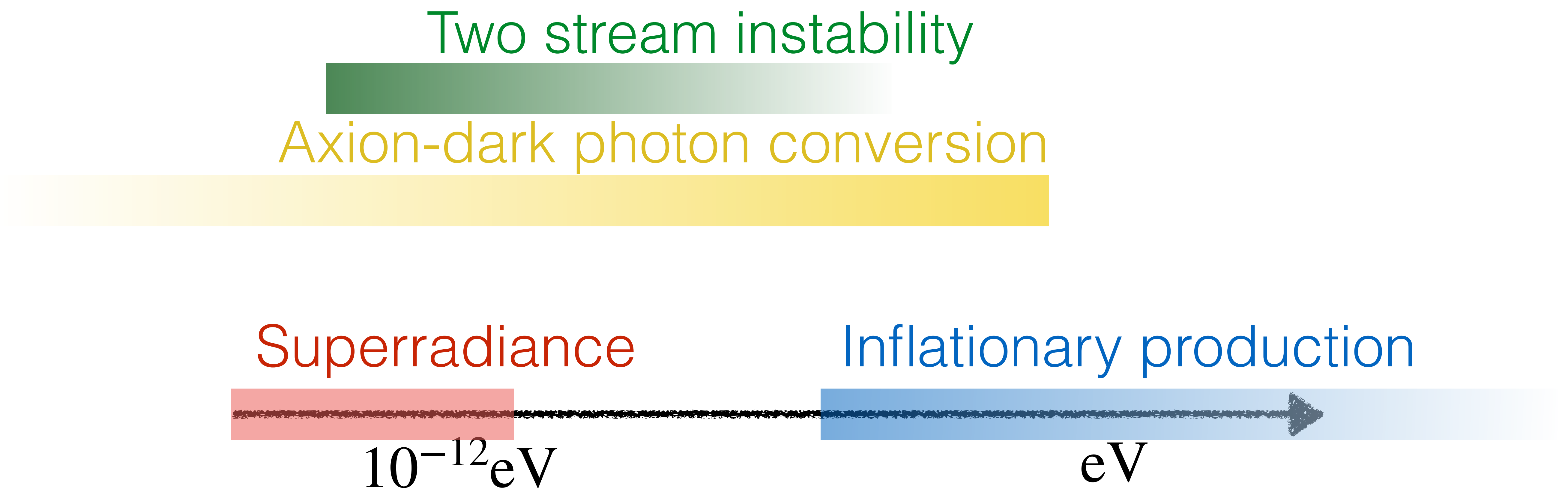
Ann Nelson and Jakub Scholtz, 2011

Suggest: Dark photon in the Stueckelberg limit can be non-thermal dark matter

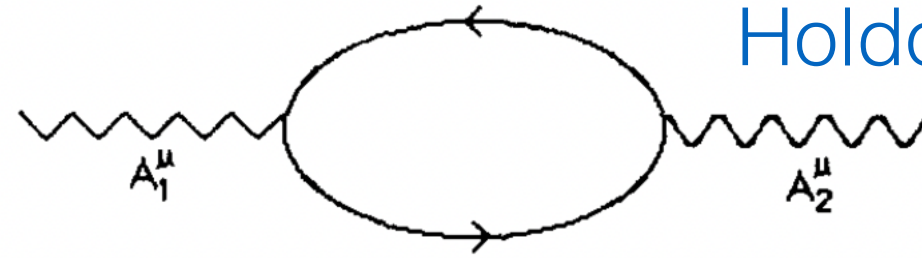
Dark photon dark matter

- Dark photon
- Dark photon dark matter
- Production mechanisms for dark photon field
  - Inflationary production
    Graham, Mardon, Rajendran, 2015
  - Axion-dark photon conversion
    Agrawal & Dror & Co & Bastero-Gil et al, 2018
  - Blackhole superradiance
    Baryakhtar, Lasenby, Teo, 2017
  - Two stream instability…
    Mardon (Talk) & Lasenby 2020

Mass range

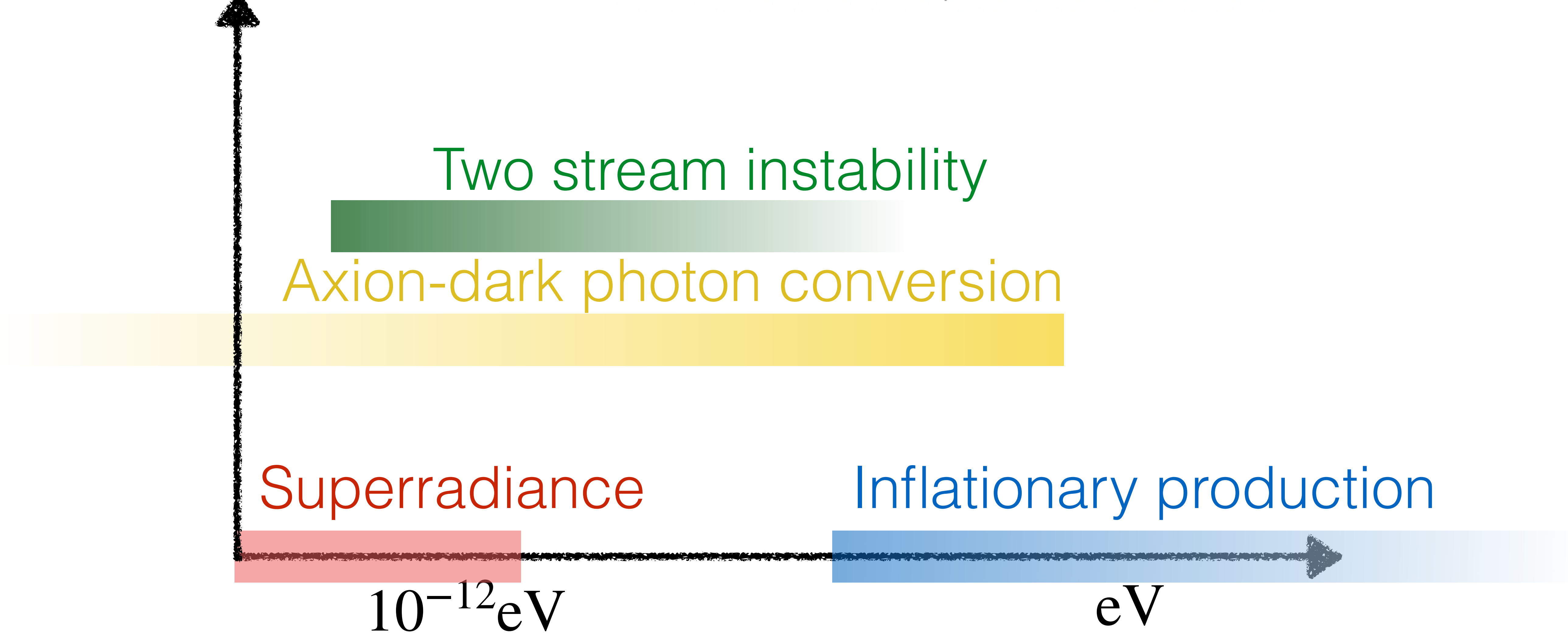

Two stream instability
Axion-dark photon conversion
Superradiance
Inflationary production
10^{-12}eV
eV

Interactions



Holdom 1985

$g_D, \epsilon \sim e g_D/16\pi^2$



Interaction & Mass

- Abelian Higgs model:

$$\mathcal{S} = \int \mathrm{d}^4x \left[\frac{1}{2}\left|D'_\mu\Phi\right|^2 - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2\right],$$

- Stuckelberg limit:

$m^2_\Phi / m^2_{A'} = \lambda / g^2_D \to \infty$ Heavy higgs, light dark photon

- Break down field strength?

Schwinger-ish: $E_c \sim B_c \sim m^2_\Phi / g_D = \lambda^{1/2} v^2 \times (\lambda / g^2_D)^{1/2}$

Summary:
This picture is incomplete

The String Photiverse has strings too

- Abelian Higgs model:

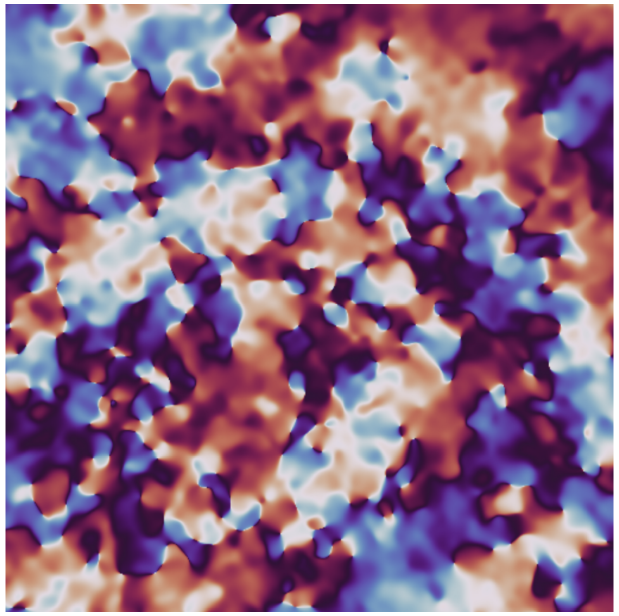
$$\mathcal{S} = \int \mathrm{d}^4x \left[\frac{1}{2} \left| D'_\mu \Phi \right|^2 - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 \right],$$

- Vortices/strings

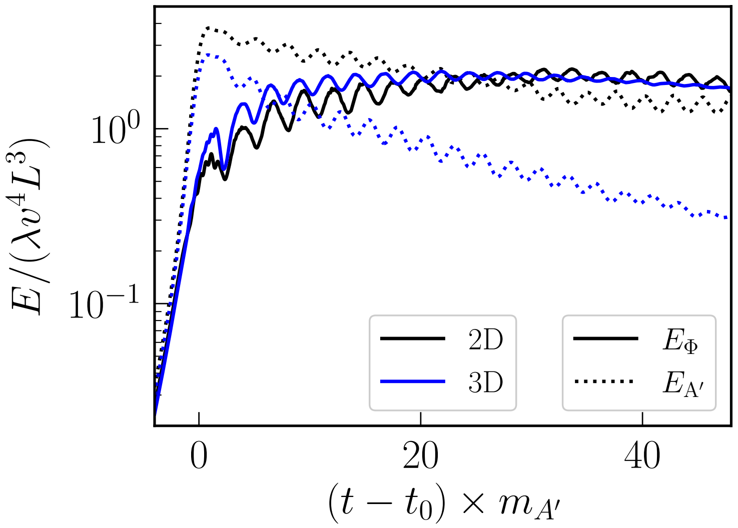
$$\mathcal{S} = -\mu \int \mathrm{d}t\mathrm{d}l \sqrt{\gamma} + \text{interactions}\ldots$$

I will demonstrate that these long/heavy defects are more likely to be produced in U(1) dark photon

Vortex dynamics



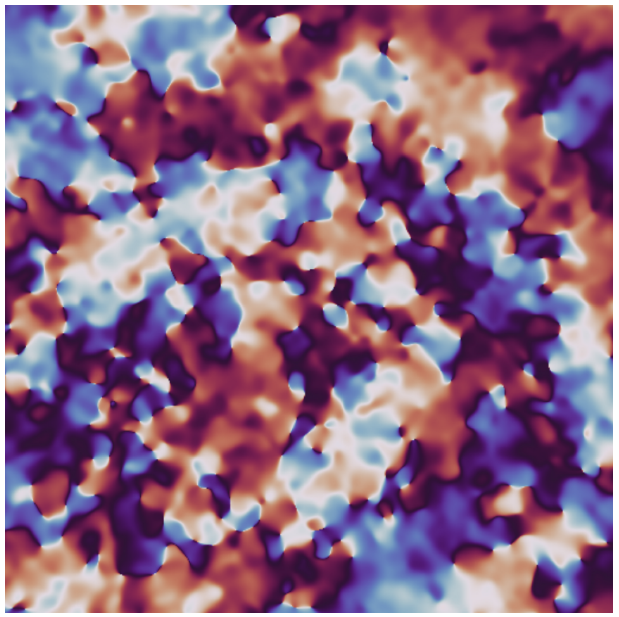
Vortex Formation



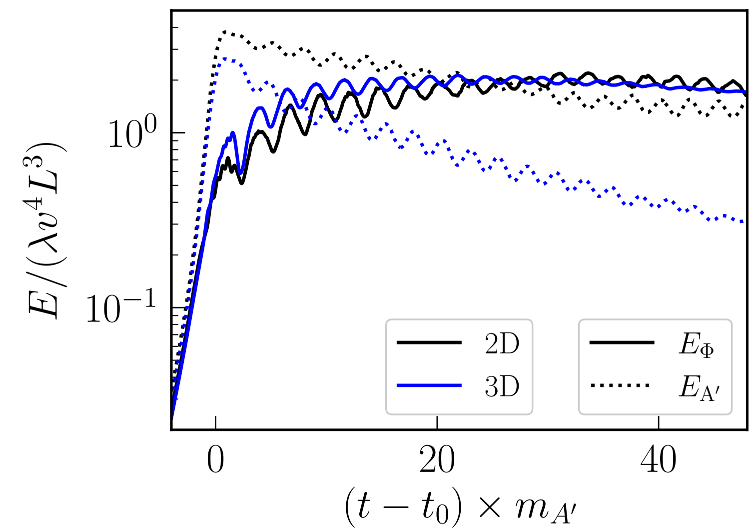
Depleting Dark Photon

Vortices depletes U(1) dark photon dark matter

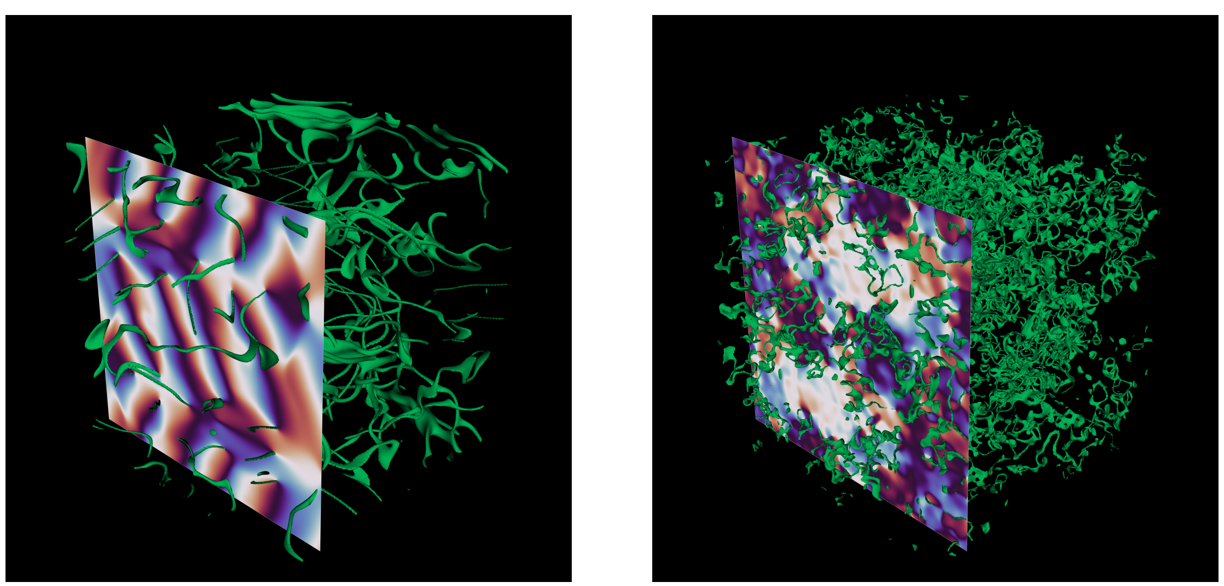
Vortex phenomenology



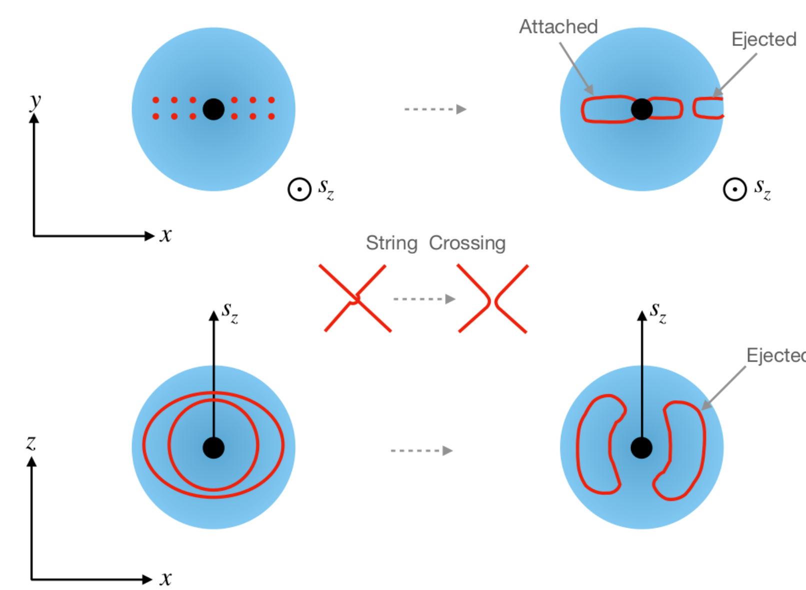
Vortex Formation



Depleting Dark Photon



Vortex melting (DM)



Vortex ejection (SR)

Vortex formation in Dark photon

Inflationary production

- Nambu-Goto

$$\mathcal{S} = -\mu \int \mathrm{d}t\mathrm{d}l\sqrt{\gamma} + \ldots \quad \text{with } \mu = \pi v^2 \log[\lambda/g_D^2]$$

- String production rate

Basu, Guth, Vilenkin 1991

$$\Gamma \sim \exp[-\mu/H_I^2]$$

- String production when

$$g_D = \frac{m_{A'}}{v} \geq \frac{m_{A'}}{H_I} = 2 \times 10^{-22} \left(\frac{m_{A'}}{\mathrm{eV}}\right)^{5/4}$$

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

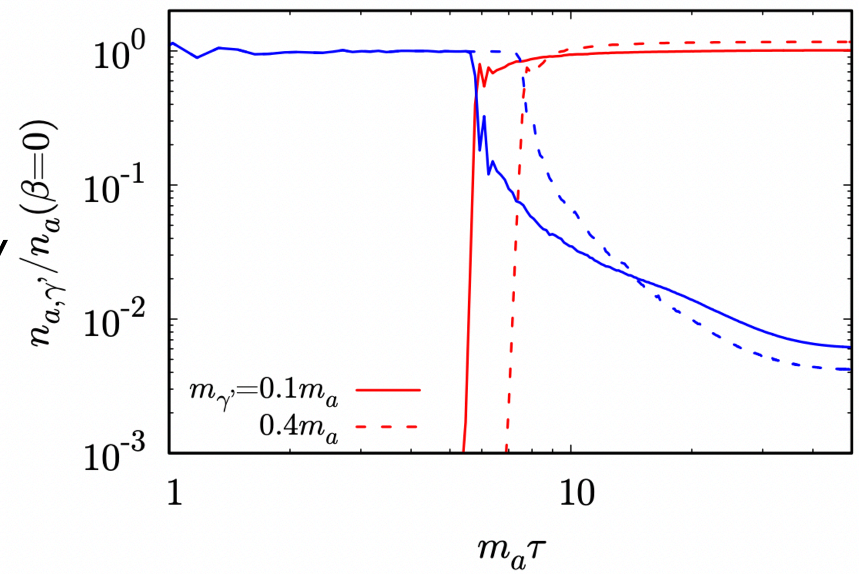
Graham, Mardon, Rajendran, 2015

Transverse mode

- Axion dark photon conversion

Agrawal et al, 2018

Produces $B' \gtrsim E'$ initially



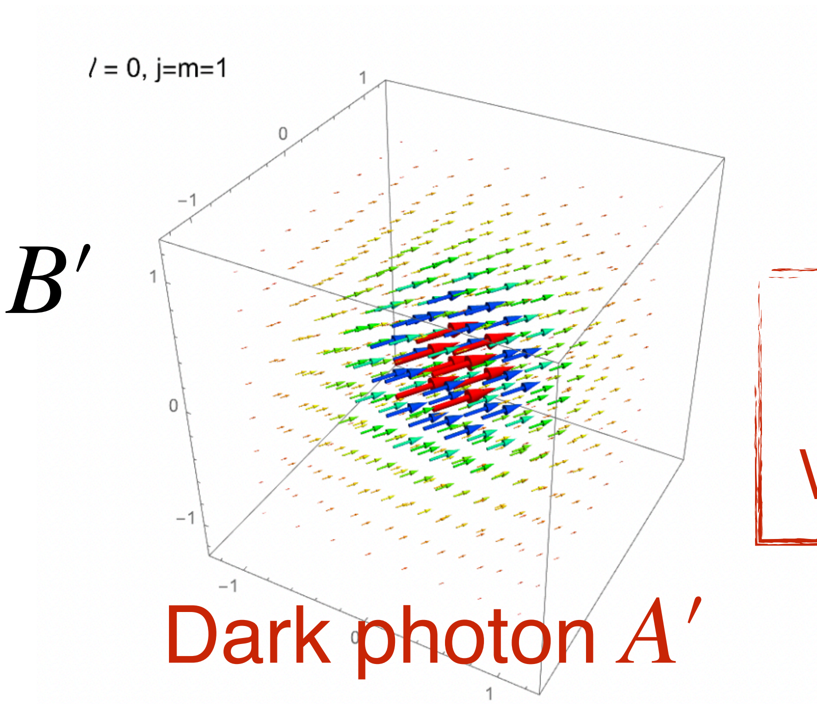
Dark photon

Axion

- Vector superradiance

Baryakhtar, Lasenby, Teo

Produces $E' \gtrsim B'$



Dark photon A'

In the transverse field,
when does vortices form?

Detour (Superconductors)

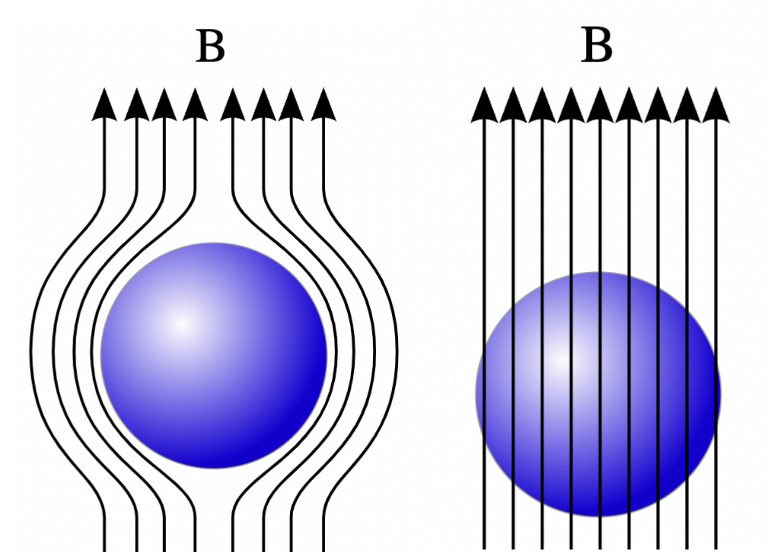
Landau Ginzburg model

- Superconductors $\Phi = ee$

$$F = \int \mathrm{d}^3x \left[\frac{1}{2} \left| D_i \Phi \right|^2 - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 - B^2 \right],$$

- Type I $(\lambda < e^2)$

Meissner Effect:



$B < B_c$ $\quad$ $B > B_c$

B

$B_c \sim \lambda v^2 / e$

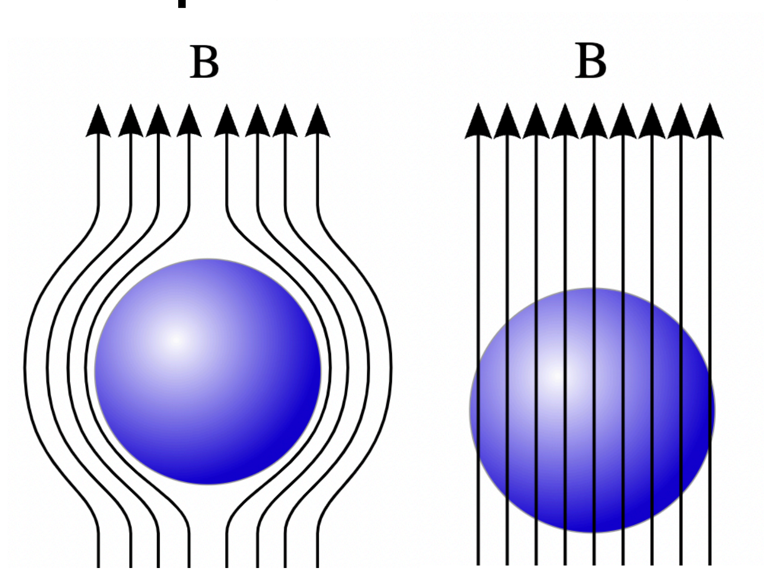
Landau Ginzburg model

- Superconductors $\quad \Phi = ee$

$$F = \int \mathrm{d}^3x \left[\frac{1}{2} \left| D_i \Phi \right|^2 - \frac{\lambda}{4} \left(|\Phi|^2 - v^2 \right)^2 - B^2 \right],$$

- Type I ($\lambda < e^2$)

Meissner Effect:



$B < B_c$ $\quad$ $B > B_c$

- Type II ($\lambda > e^2$)

$B < B_{c1}$ $\quad$ $B > B_{c2}$

B

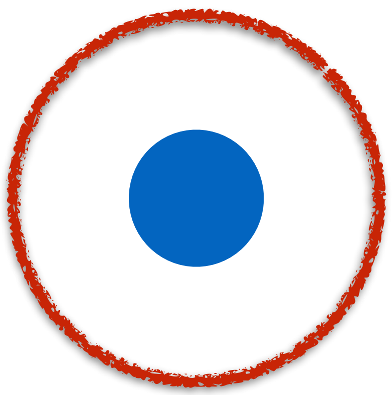
B_c $\quad B_{c2} \sim \lambda v^2 / e$

$B_{c1} \sim e v^2$

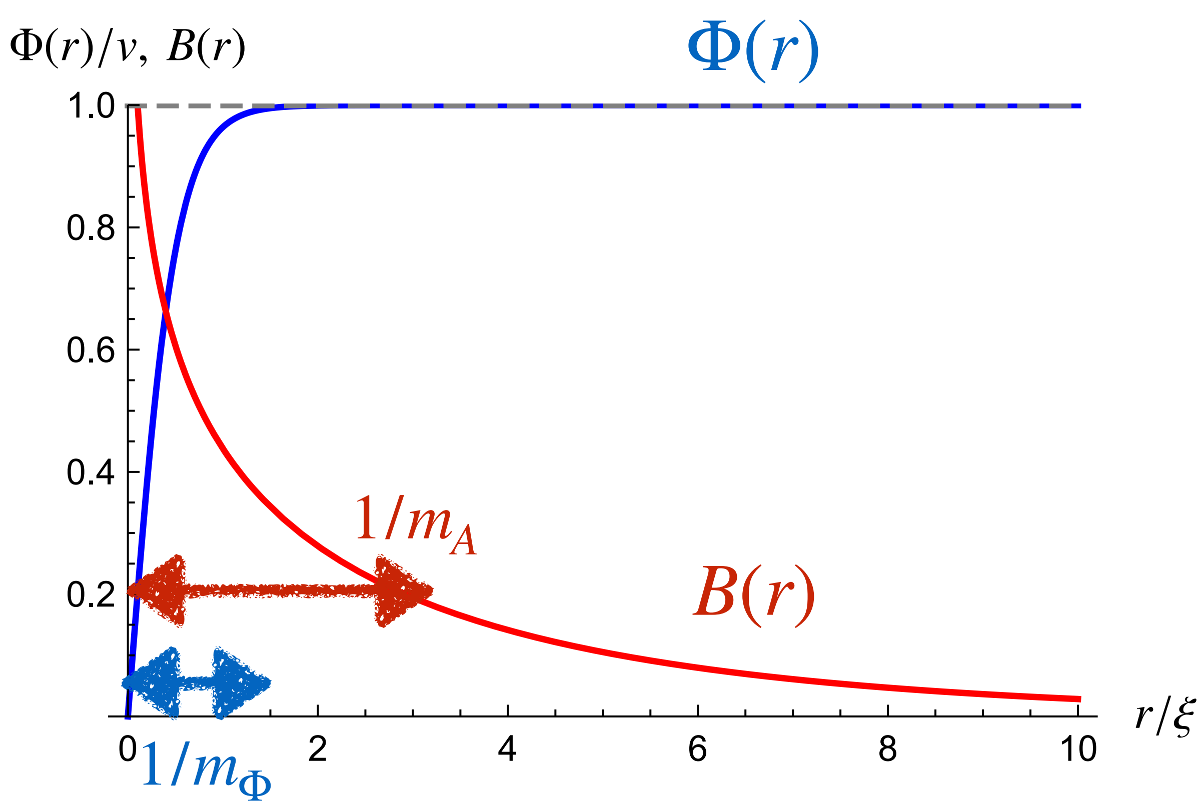
Abrikosov vortex (lattice)

$B_{c1} < B < B_{c2}$

Abrikosov 1957



$$\int A_\mu dx^\mu = \Phi_0 = \frac{2\pi}{2e}$$

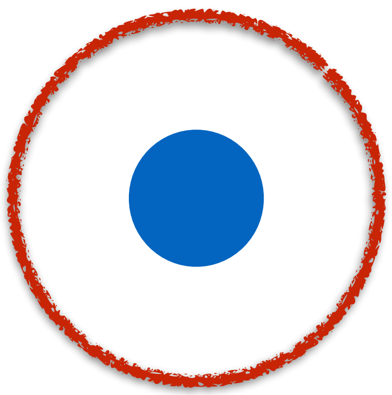


A single vortex

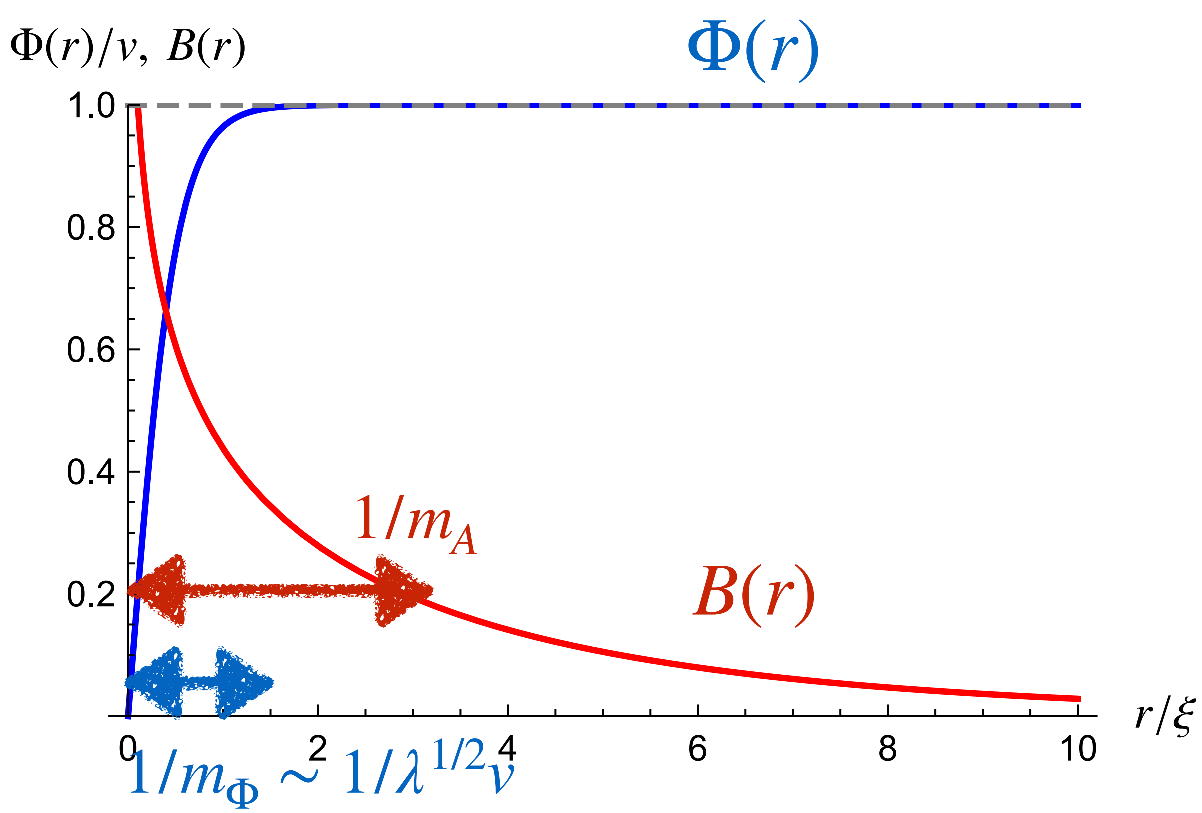
Abrikosov vortex (lattice)

$B_{c1} < B < B_{c2}$

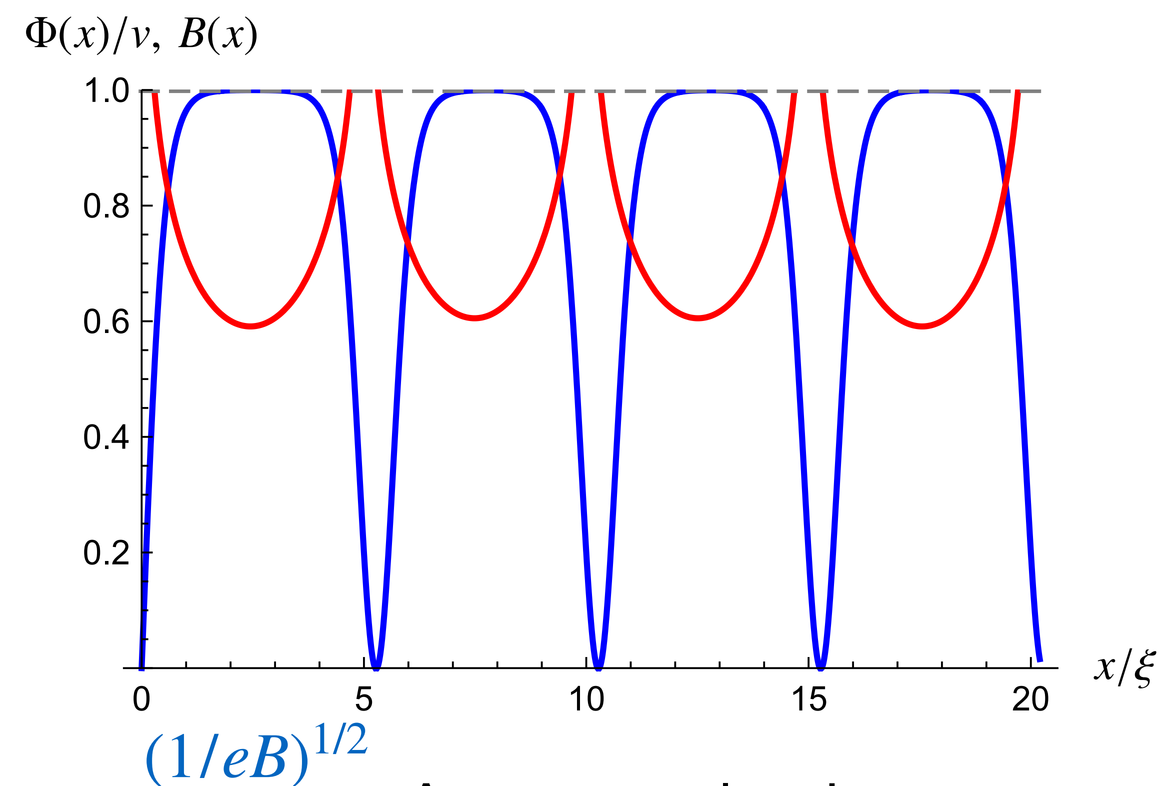
Abrikosov 1957



$$\int A_\mu dx^\mu = \Phi_0 = \frac{2\pi}{2e}$$



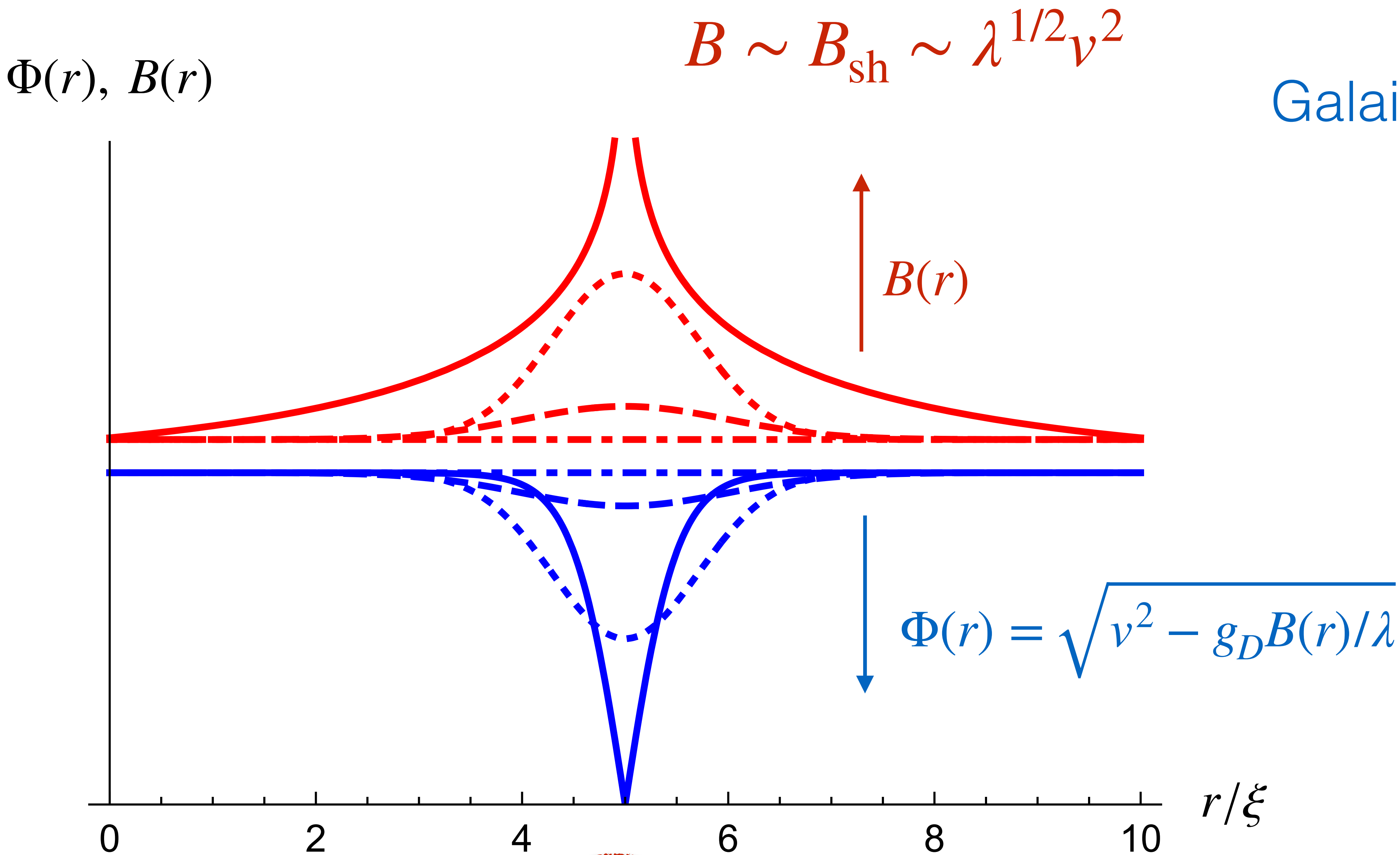
A single vortex



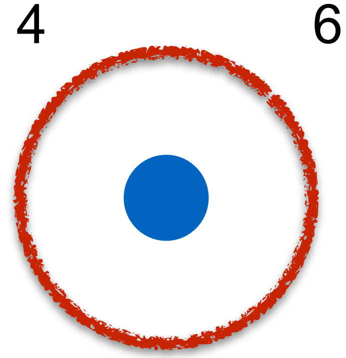
A vortex lattice

Abrikosov lattice is the ground state above B_{c1}

Superheating



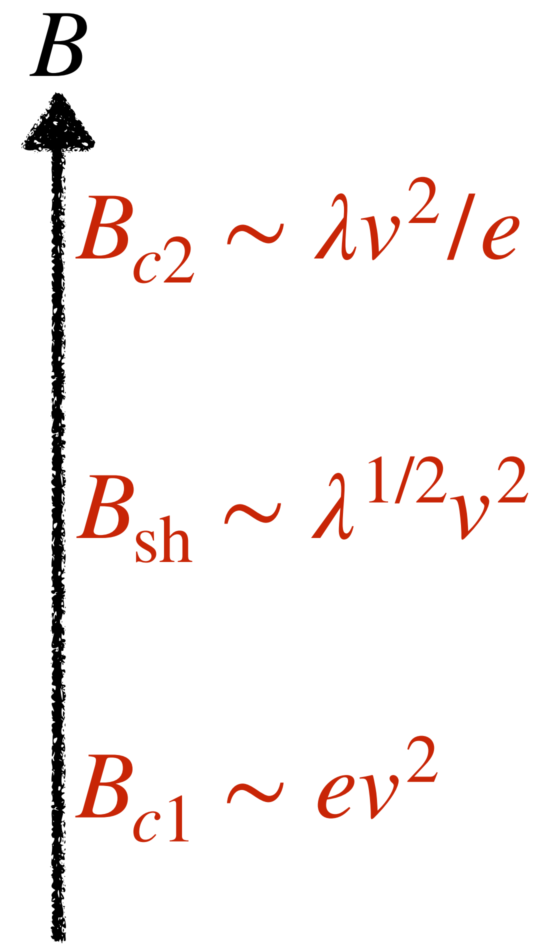
Galaiko 1966



Above the superheating field, the phase transition is second order

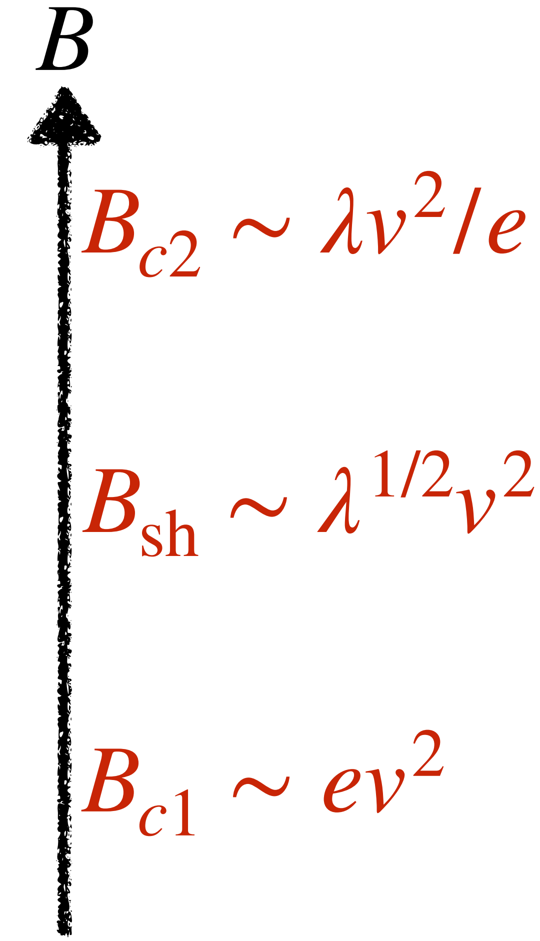
Summary

- Critical fields (Type II)
  - B_{c1}: Governs vortex evolution
  - B_{sh}: Governs vortex formation
  - B_{c2}: *Single particle production*



Summary

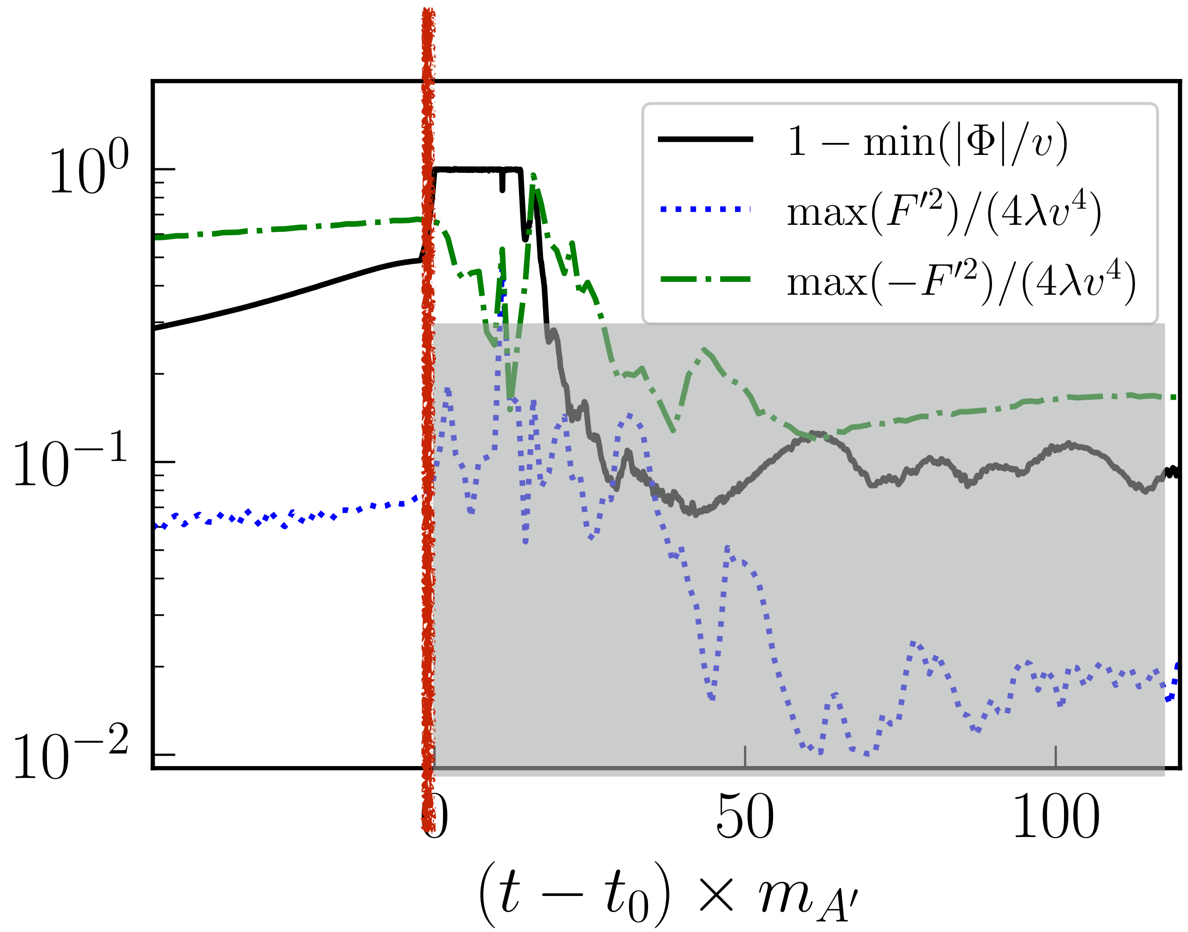
- Critical fields (Type II)
  - B_{c1}: Governs vortex evolution
  - B_{sh}: Governs vortex formation
  - B_{c2}: *Single particle production*
- The need for simulation
  - Coherent background Vs Meissner
  - Strings ending on superconductor edge
  - Time dependence
  - Electric field
  - Gravity…



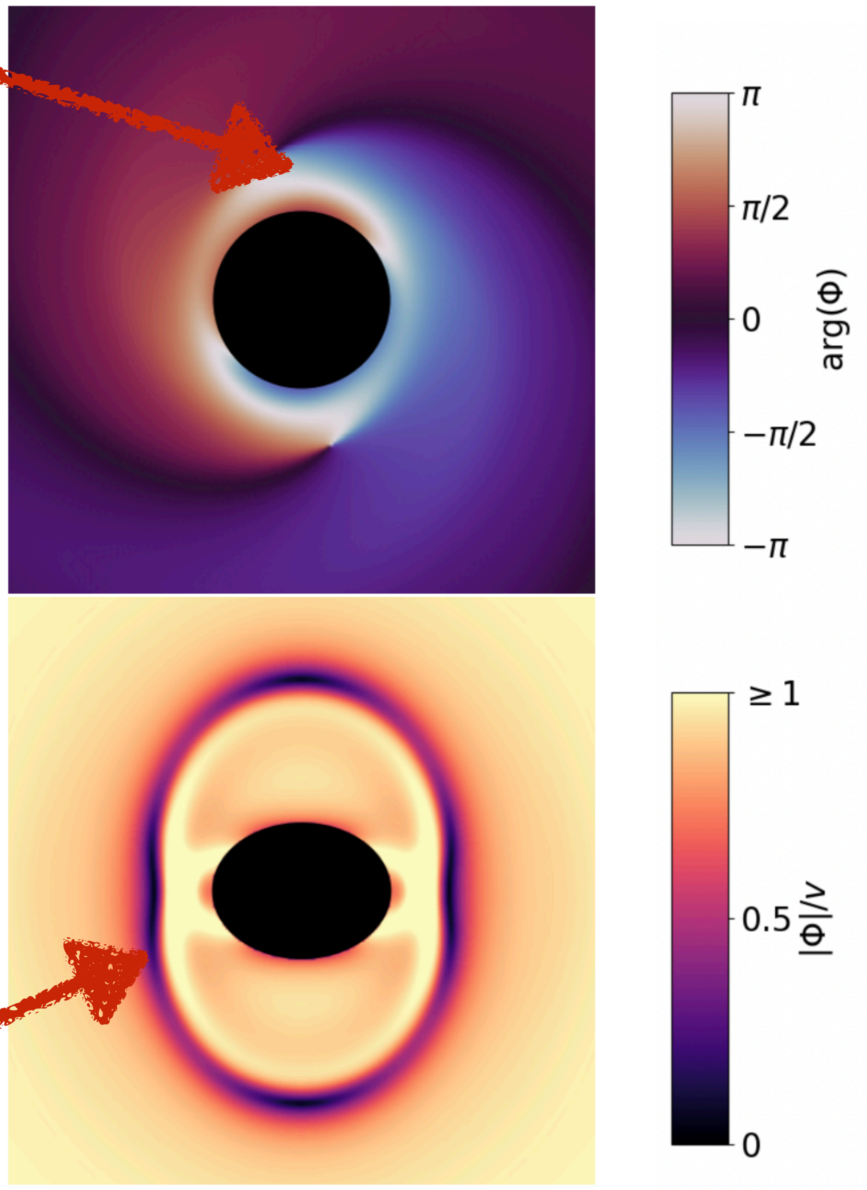
Vortex formation
(simulation)

Vortex formation (SR)

Vortex Formation



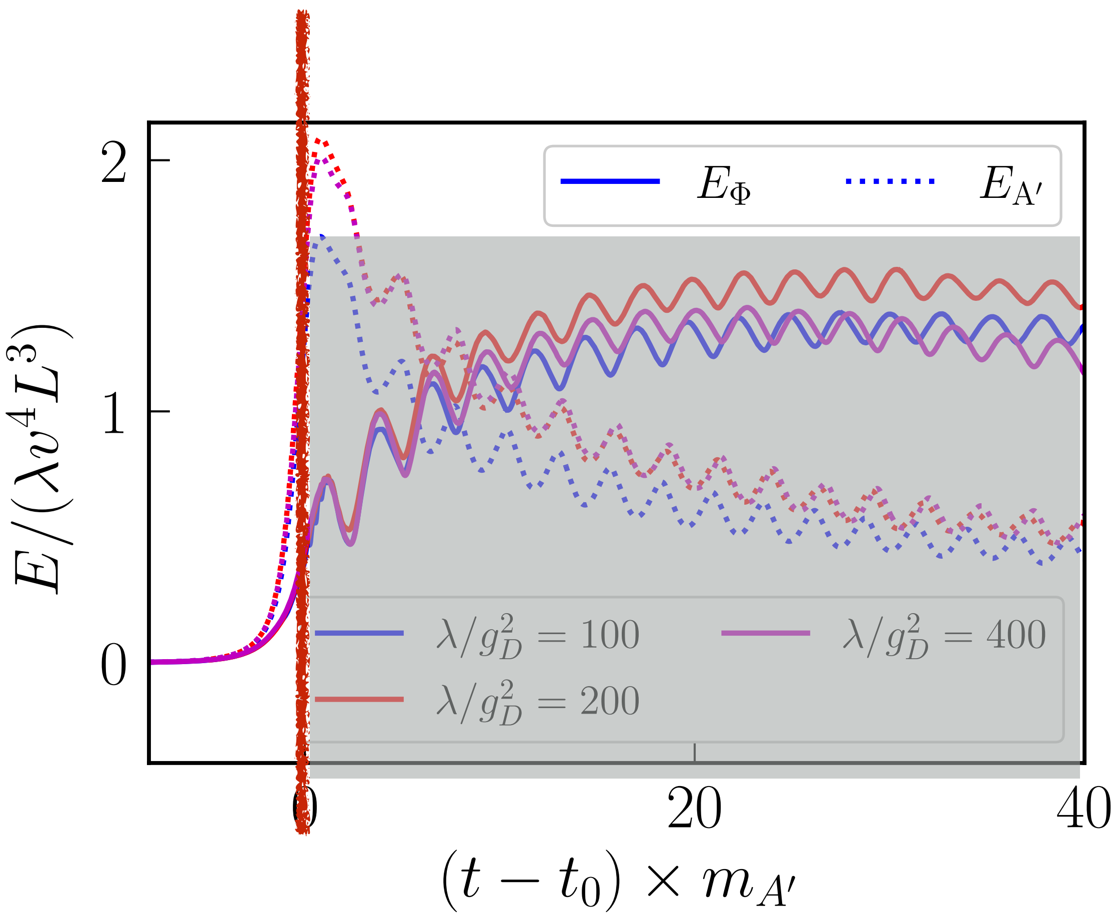
Vortex

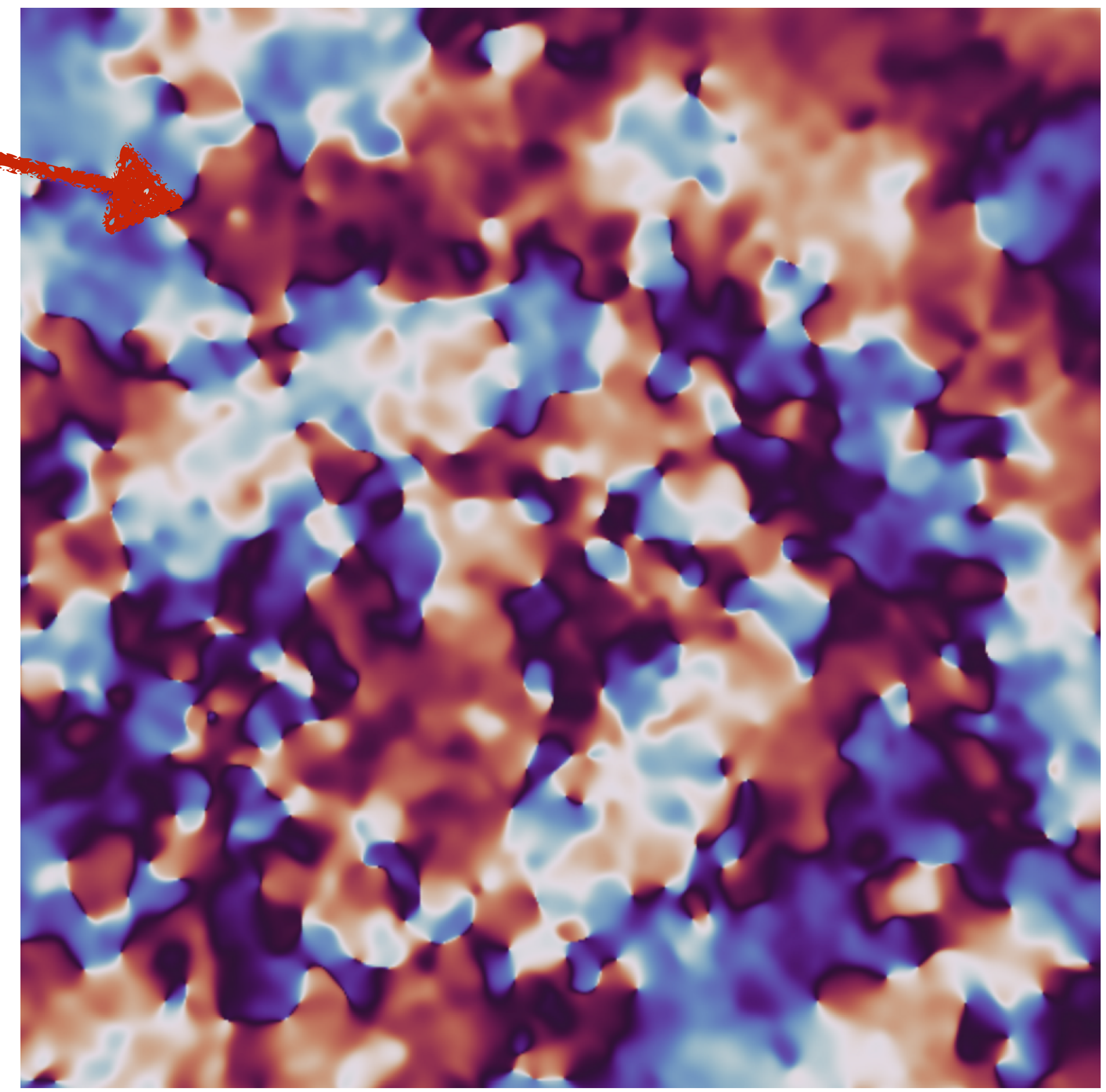


Vortex

Vortex formation (2D)

Vortex
Formation

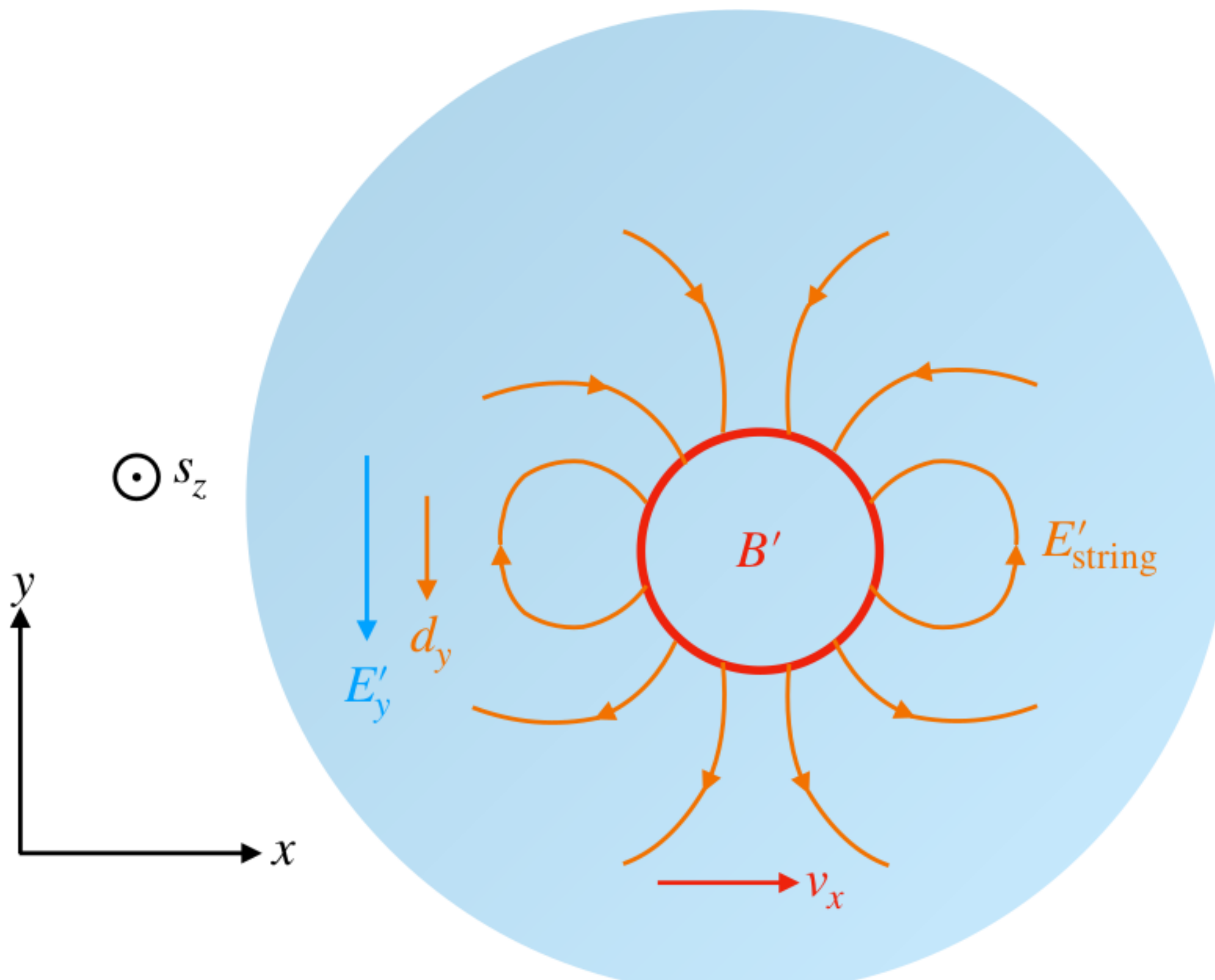




$\sim 1/m_A$

Depleting dark photon dark matter

String interacting with E/B fields



Vortex: $\vec{A} = \dfrac{\hat{\theta}}{g_D r}$

$$\vec{E} = \frac{d\vec{A}}{dt} = \vec{v} \cdot \nabla \vec{A}$$

$$\frac{d\,\vec{d}}{dl} = \frac{\vec{v}}{g_D}$$

In a background electric field, the strings wants to accelerate in directions *perpendicular* to the direction of the external electric field

The significance of B_{c1}

Background field:

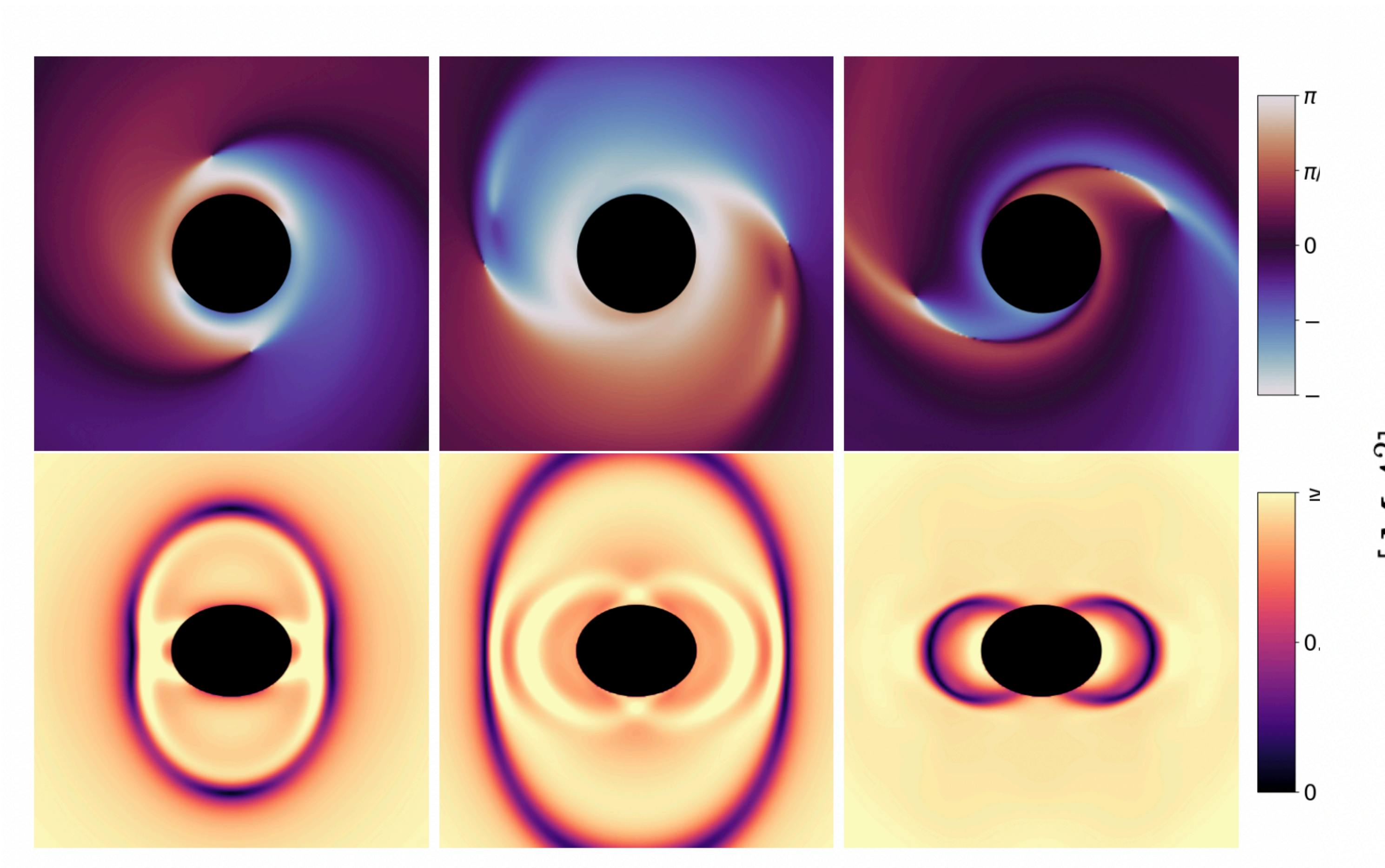
$$\frac{d\overrightarrow{d}}{dl} \cdot \overrightarrow{E} \sim v^2 \log(\lambda/g_D^2)$$

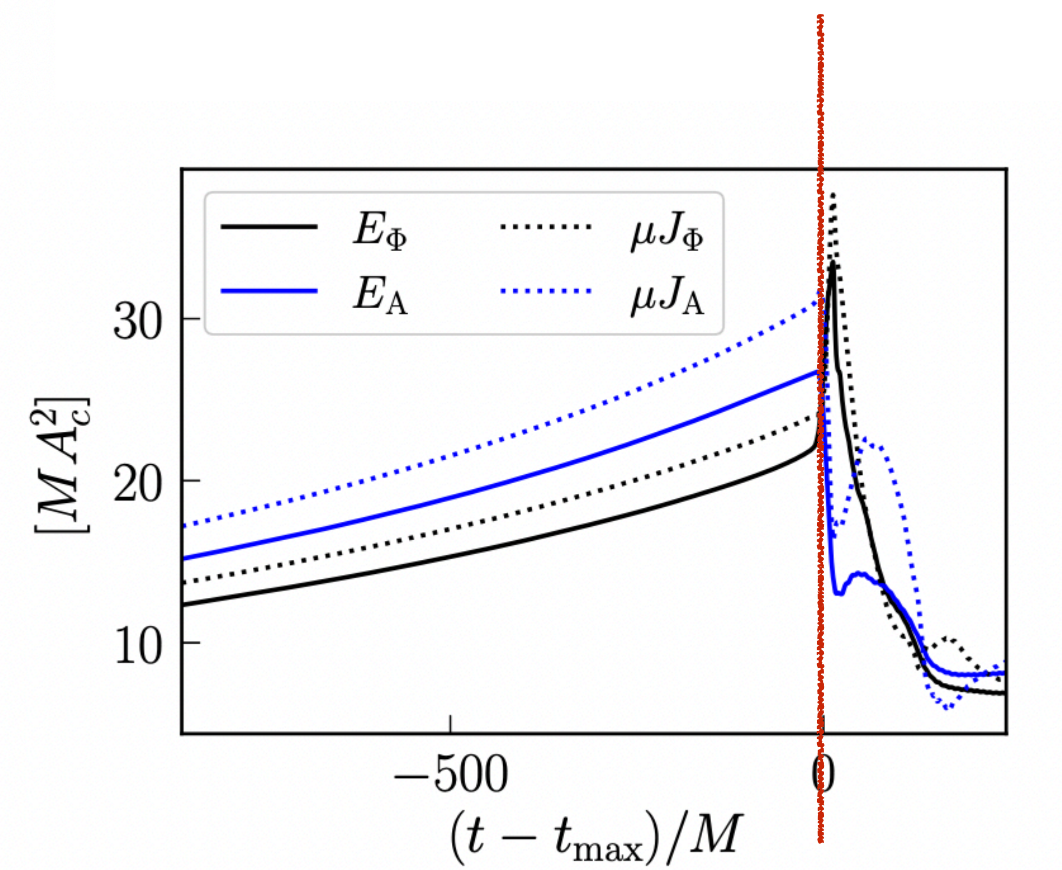
$$E_{c1} = g_D v^2 \log(\lambda/g_D^2)$$

When $E, B \gg E_{c1}, B_{c1}$, the gauge field fully determines the evolution of the vortex lines

Vortex evolution (SR)

Vortex Formation

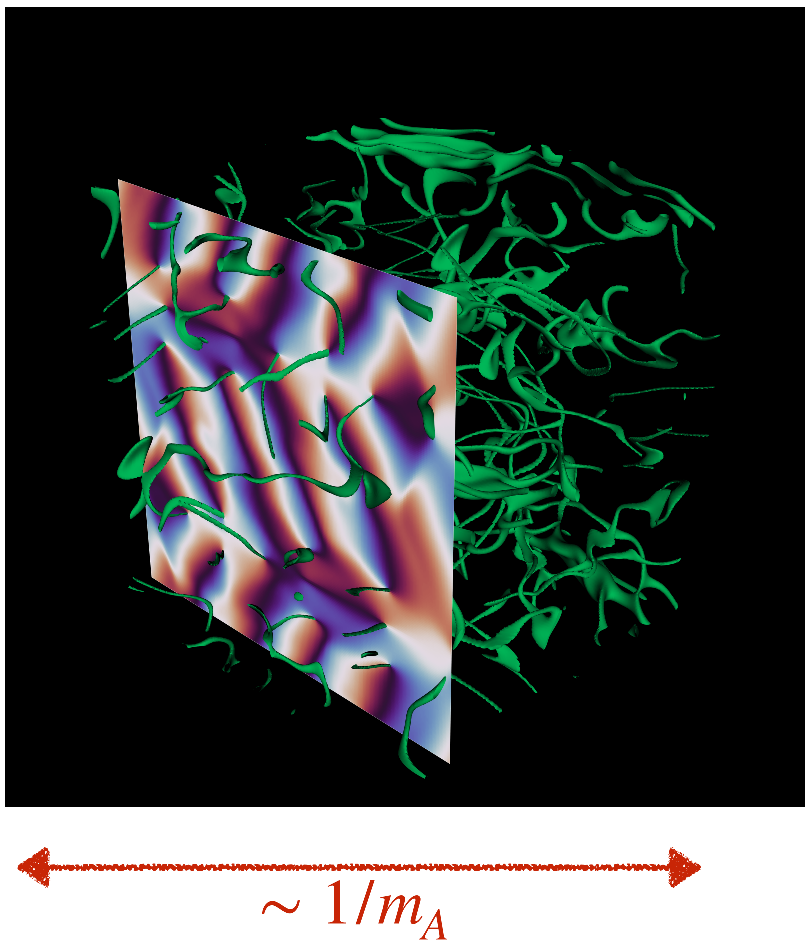




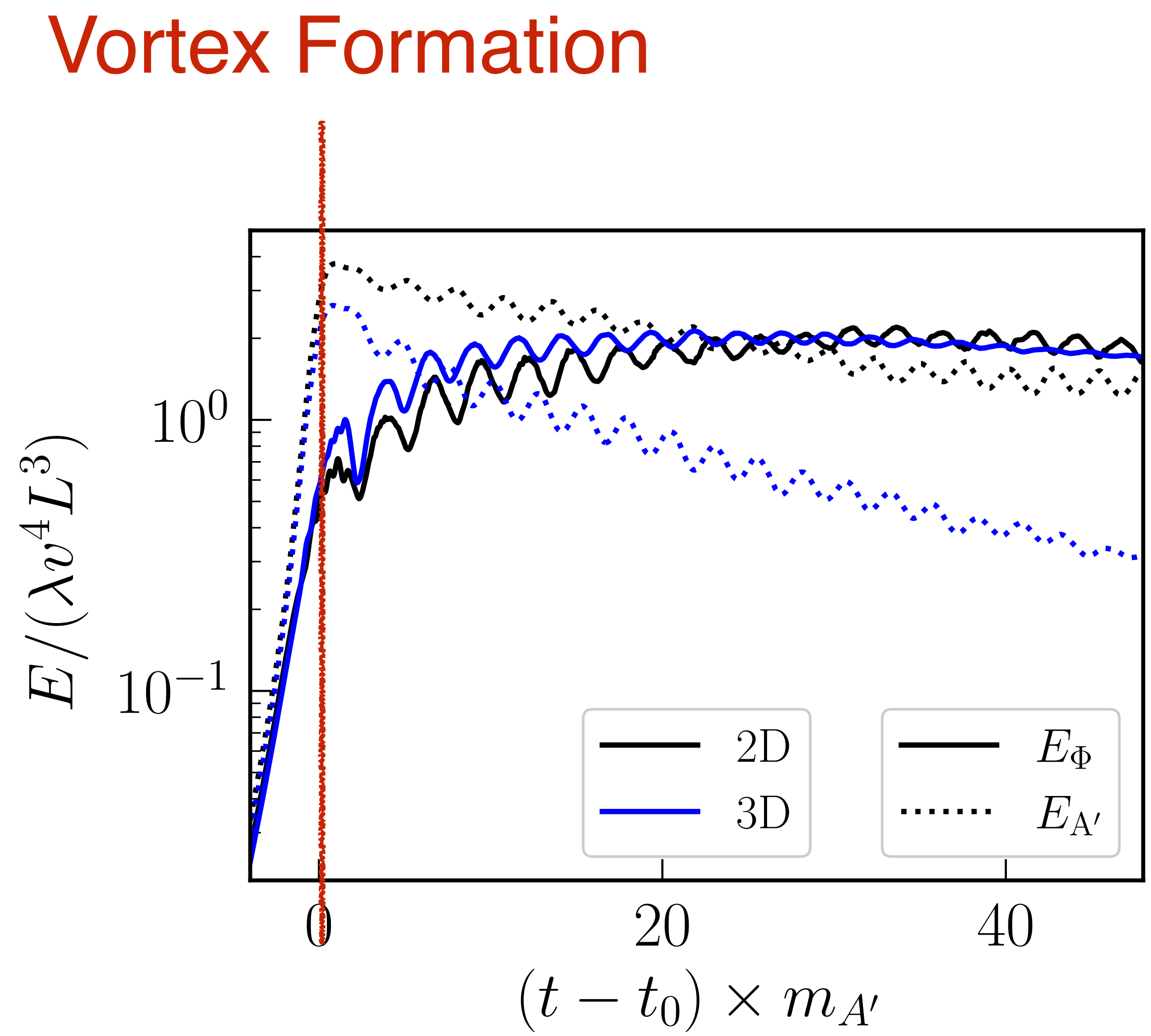
A single vortex line *expands (accelerates)* and shrinks onto the Blackhole

The energy density in the background field gets depleted

Vortex evolution (DPDM)



Vortex forms once the critical field is reached



The energy density in the dark photon *depletes*

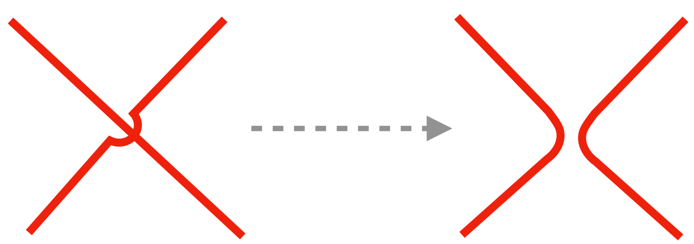
Summary

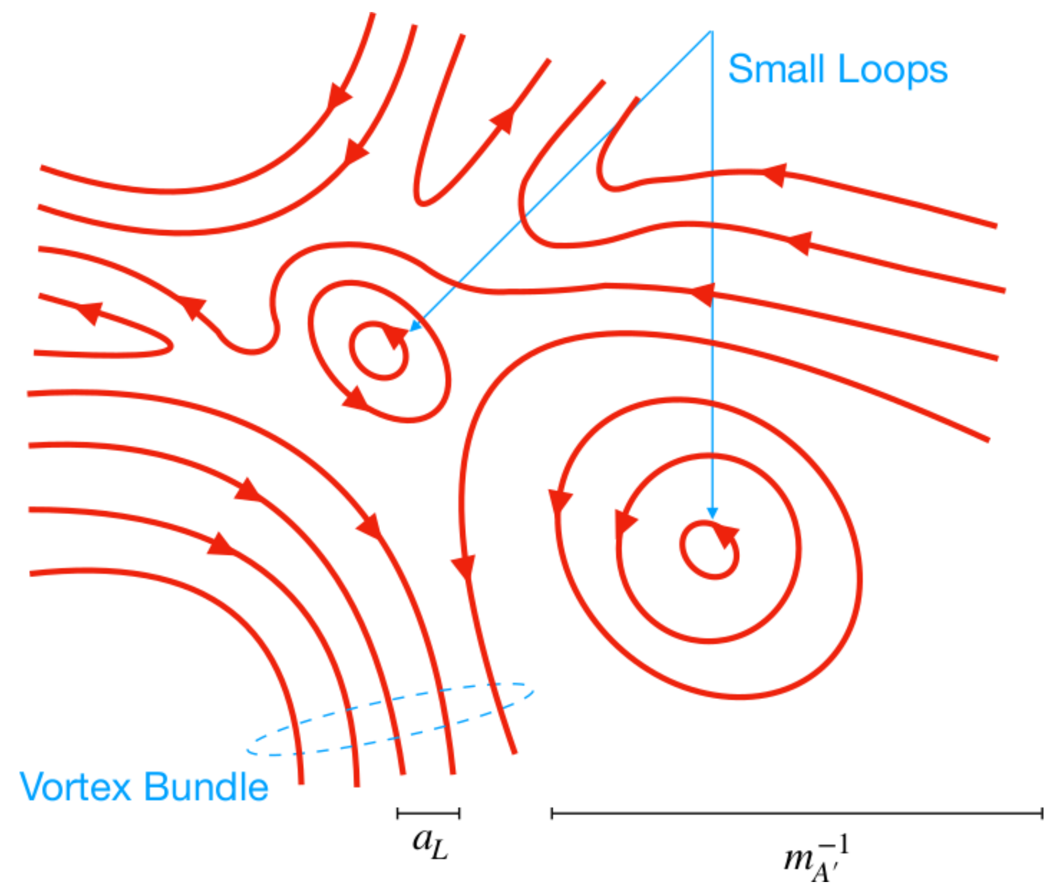
Dark photon E-field makes strings faster, B-field makes strings longer, and they are both *gone*.

The melting phase transition and phenomenology

Vortex-vortex interactions

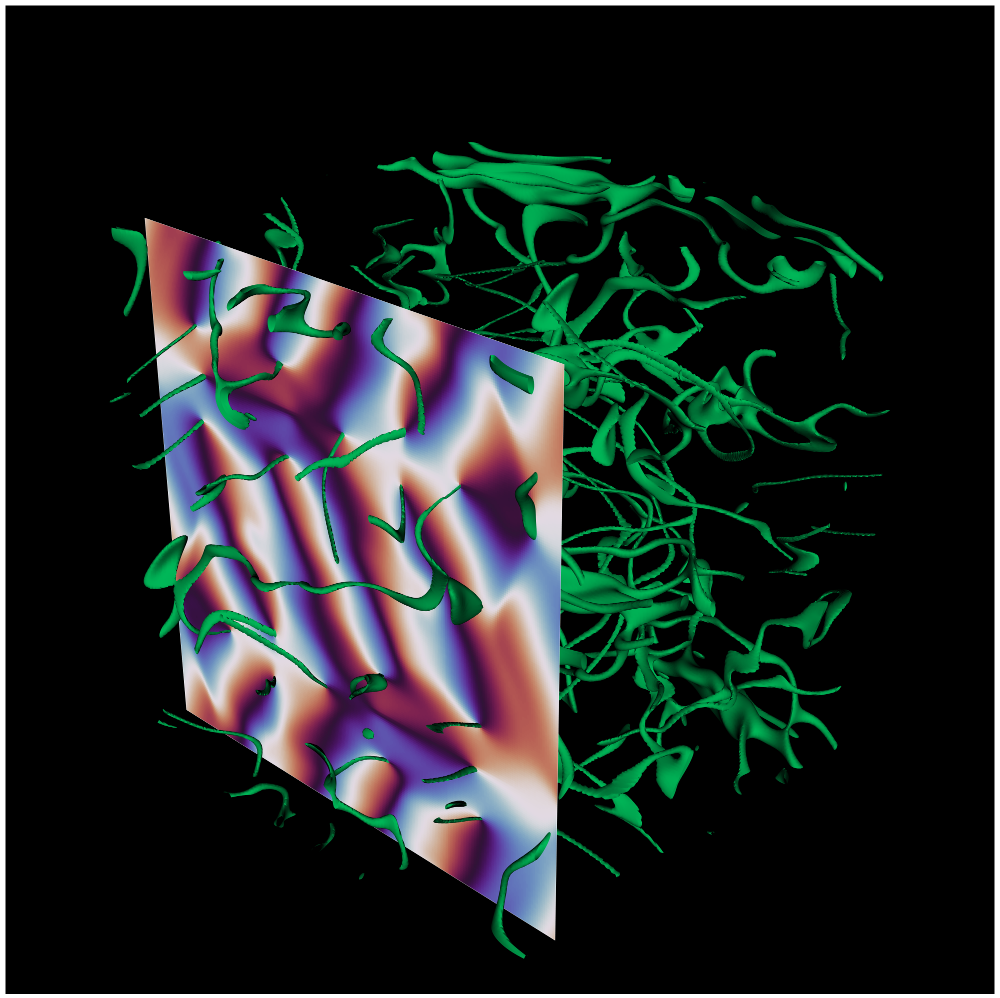
Vortex Lattice + Superheating => $O(\lambda/g_D^2)$ strings per patch

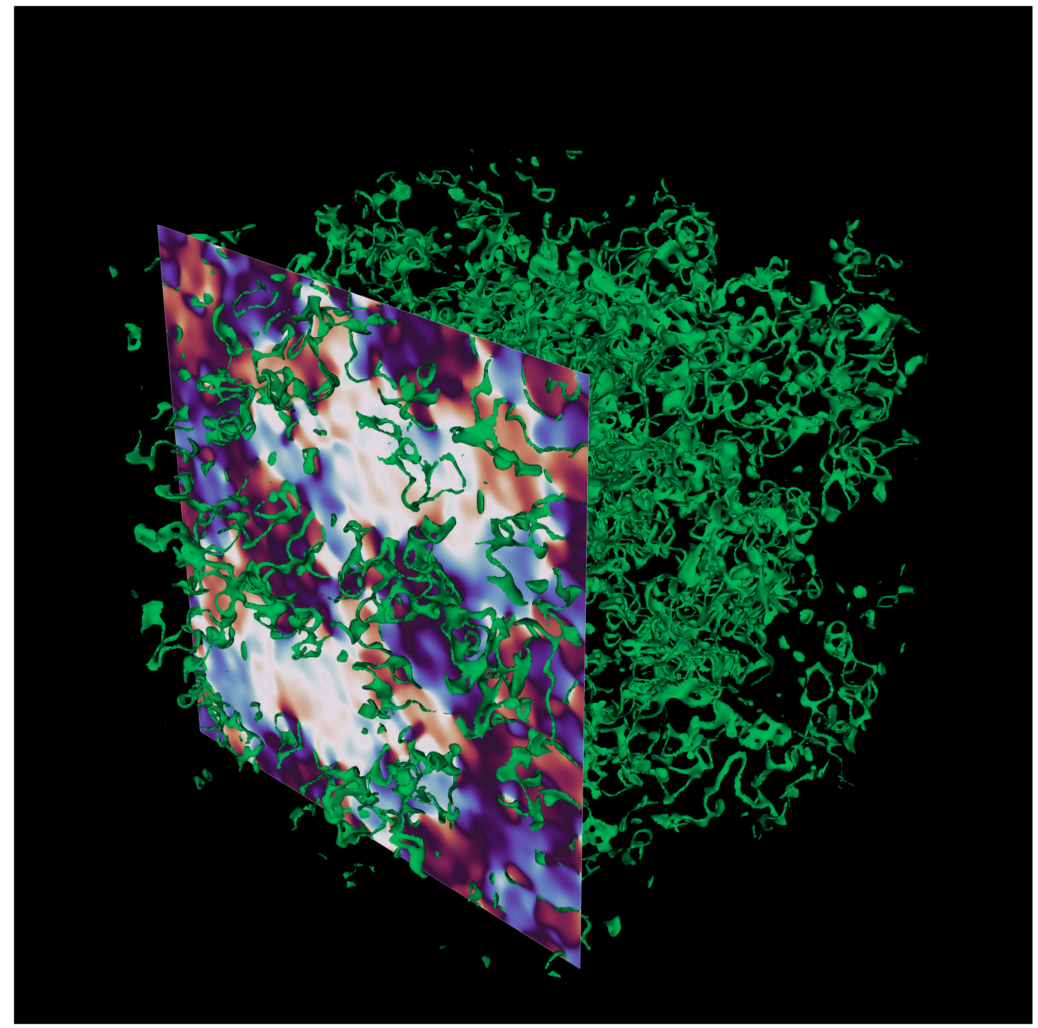




Melting: Decreasing long range order

Melting (3D)

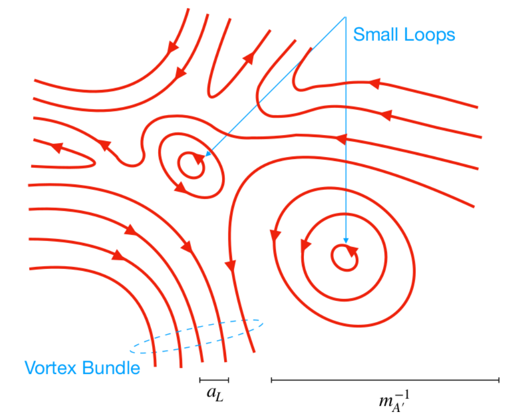


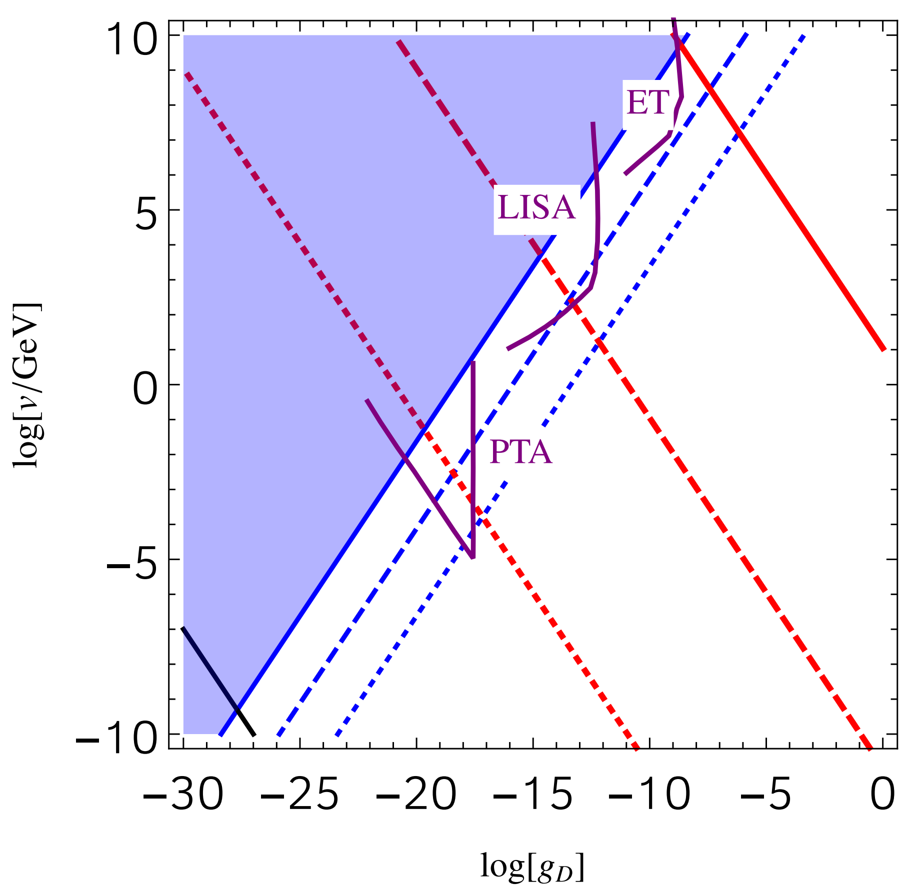


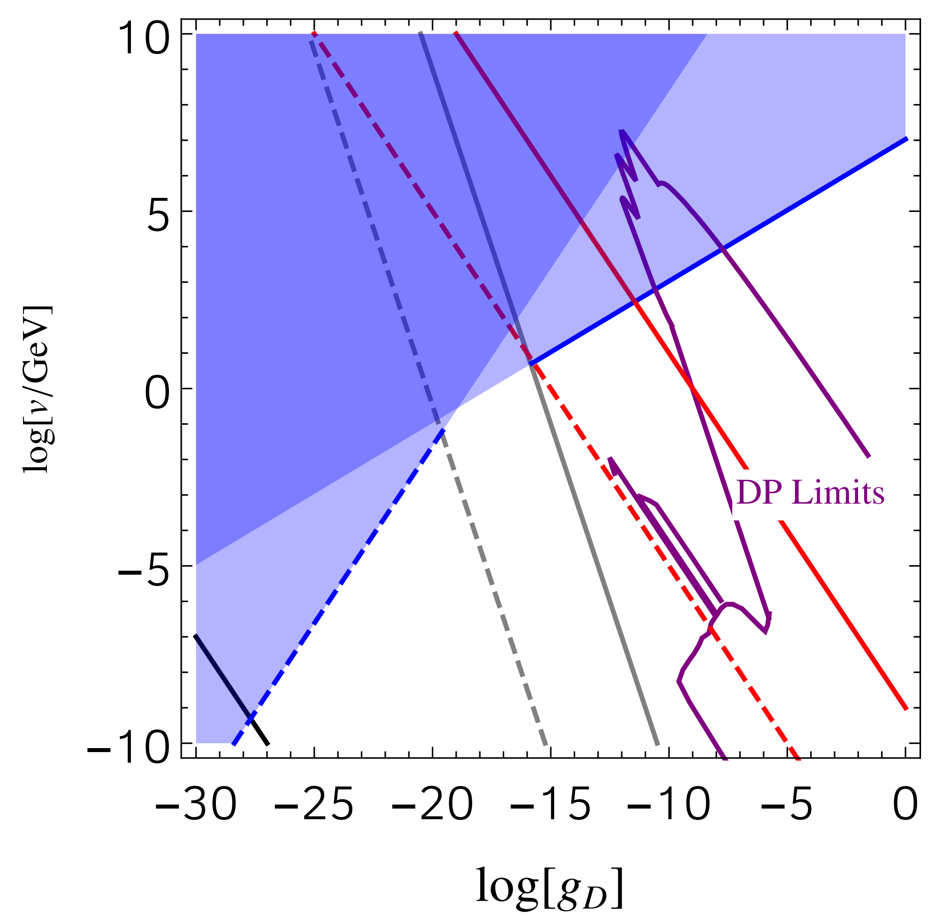
Smaller loops are produced, string lengths increases and energy dissipated into GW and dark photon radiation

Dark photon dark matter

Vortices: The fate of vortices



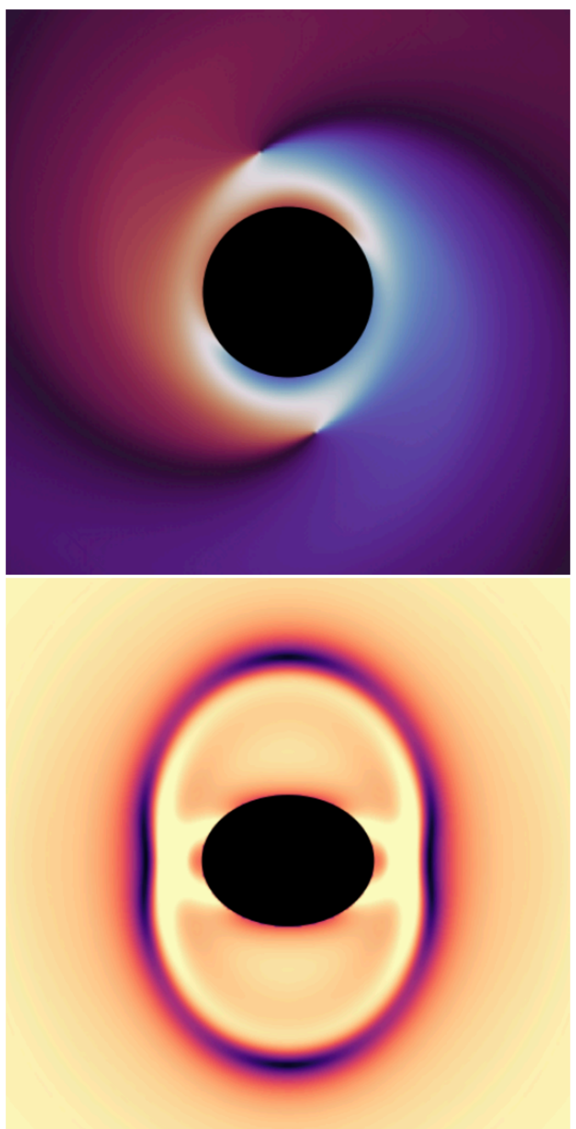


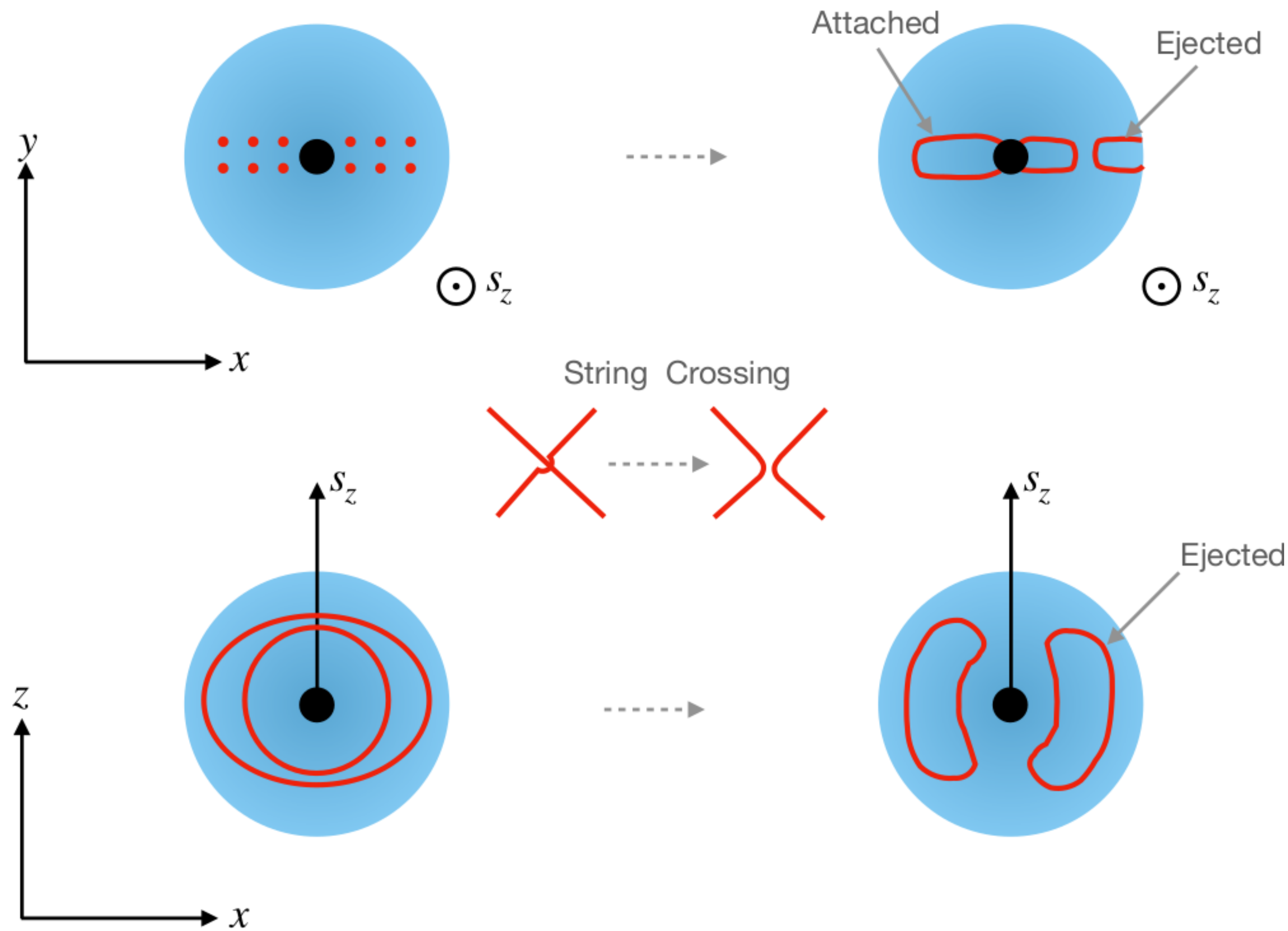


Vortex Bundle -> GW

Small loops -> Dark radiation

Vortex ejection (SR)



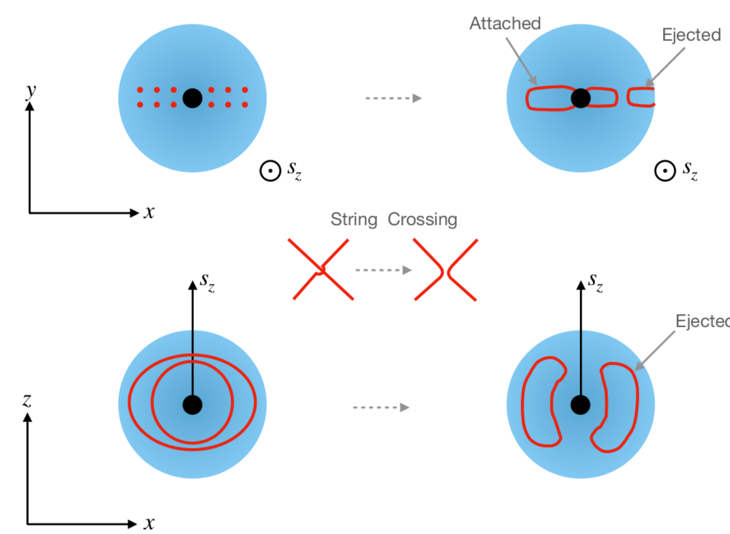


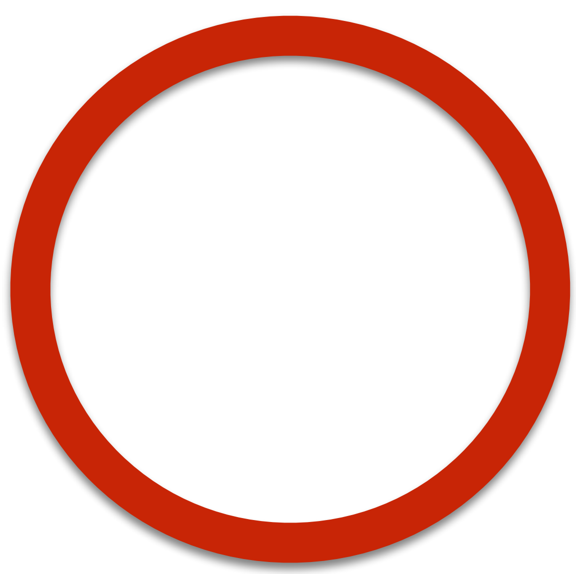
Vortices cross and get **ejected**

Boss Nova

Vortices are ejected from a solar mass BH SR cloud

$$10^3 \lesssim \lambda/g_D^2 < 10^{38}$$





Length: $L_{\text{string}} \sim 10^3\,\text{km}$

Radius: $R_{\text{string}} \sim 10^2\,\text{km}$

Tension: $G\mu_{\text{string}} \sim 10^{-5}\left(\dfrac{10^3}{\lambda/g_D^2}\right)$

Number: $N_{\max} \approx \dfrac{1}{\pi v^2 L_{\text{string}}}\displaystyle\int |E'|^2\, dV \simeq \dfrac{1}{\alpha^2}\dfrac{\lambda}{g_D^2}$

Gravitational waves

$10^3 \lesssim \lambda/g_D^2 < 10^{38}$

Tension: $G\mu_{\rm string} \sim 10^{-5}\left(\frac{10^3}{\lambda/g_D^2}\right)$

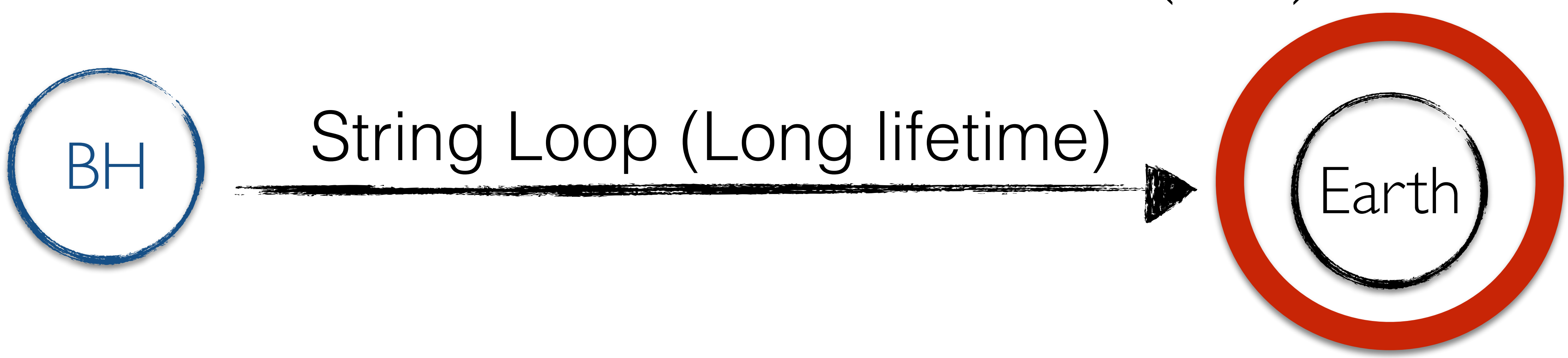
String Loop-> GW, DP radiation…

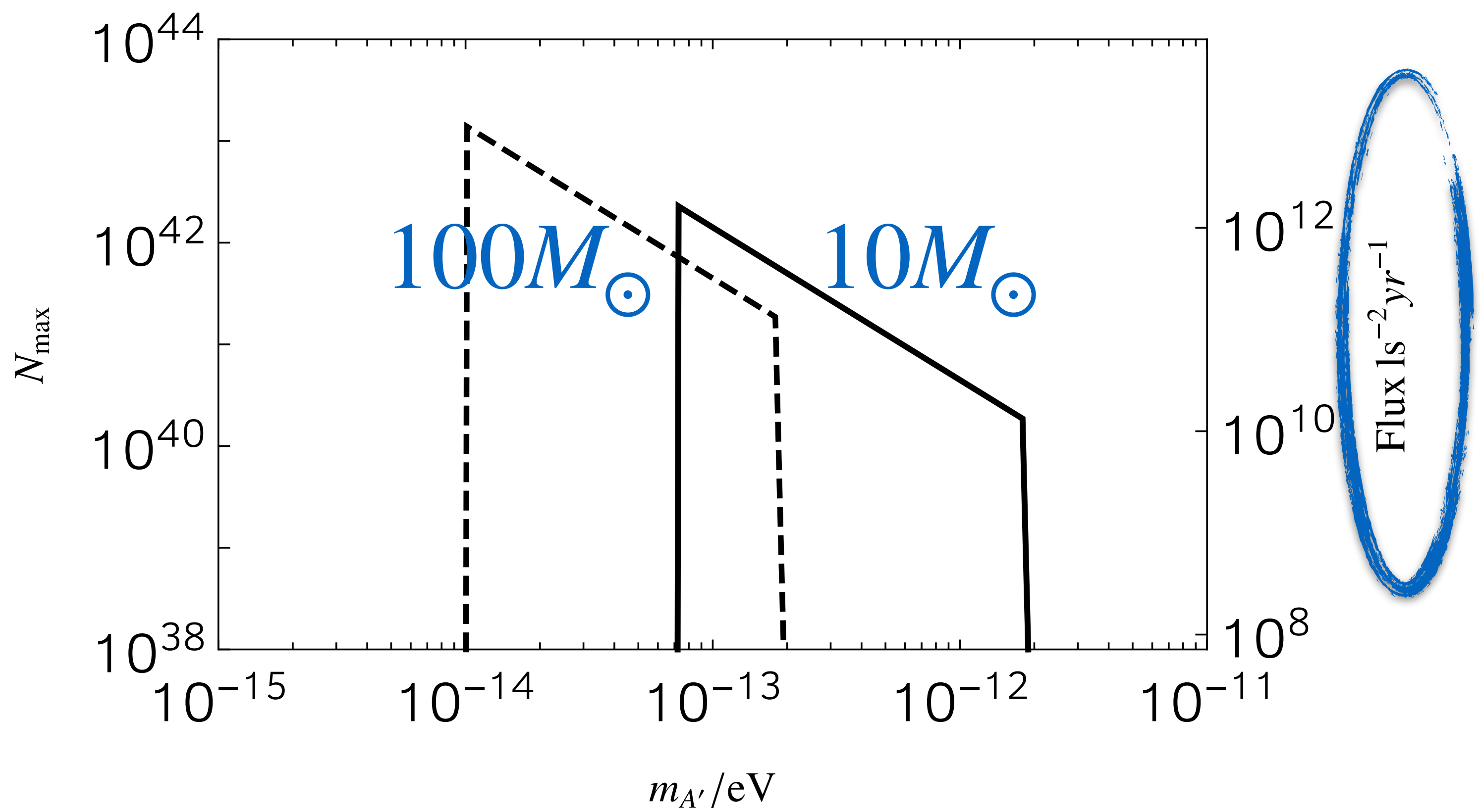
$$h \simeq 4\times 10^{-18}\left(\frac{\alpha}{0.3}\right)^3\left(\frac{1000}{\lambda/g_D^2}\right)^{1/2}\left(\frac{10^{-12}\,\mathrm{eV}}{m_{A'}}\right)\left(\frac{10\,\mathrm{kpc}}{d}\right)$$

We can see strings from BHs in our galaxy with GW in LIGO band

Boss Nova

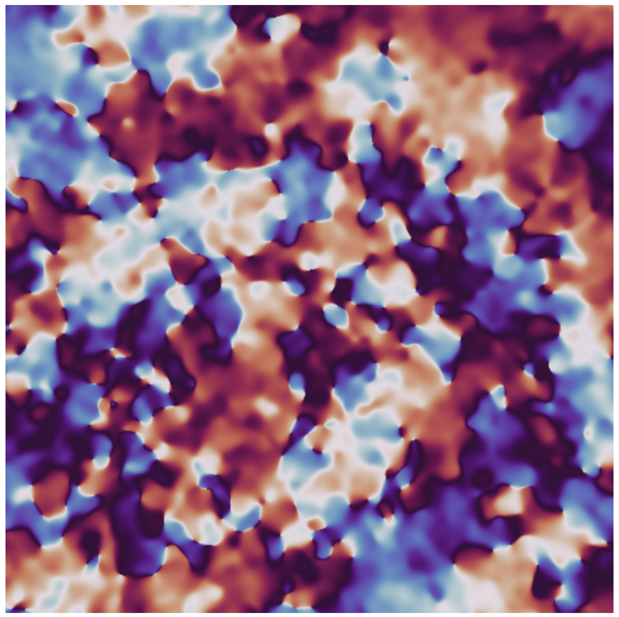
$10^3 \lesssim \lambda/g_D^2 < 10^{38}$ Tension: $G\mu_{\rm string} \sim 10^{-40}\left(\frac{10^{38}}{\lambda/g_D^2}\right)$



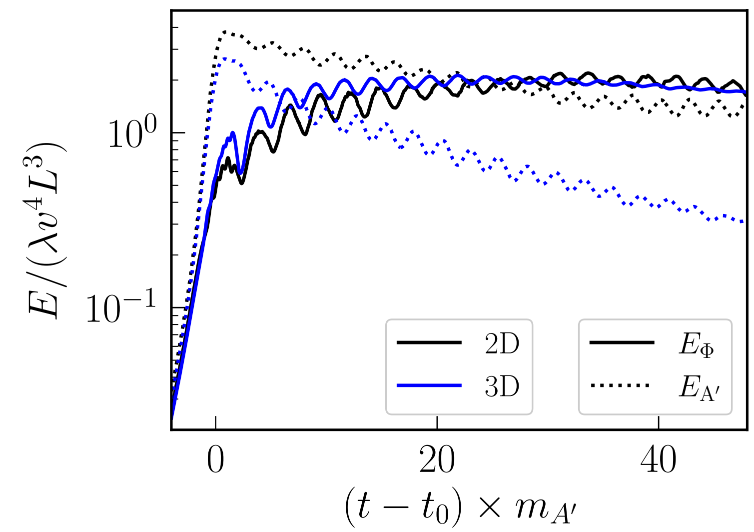


Rate on earth from a Boss Nova in the galaxy (10 kpc)

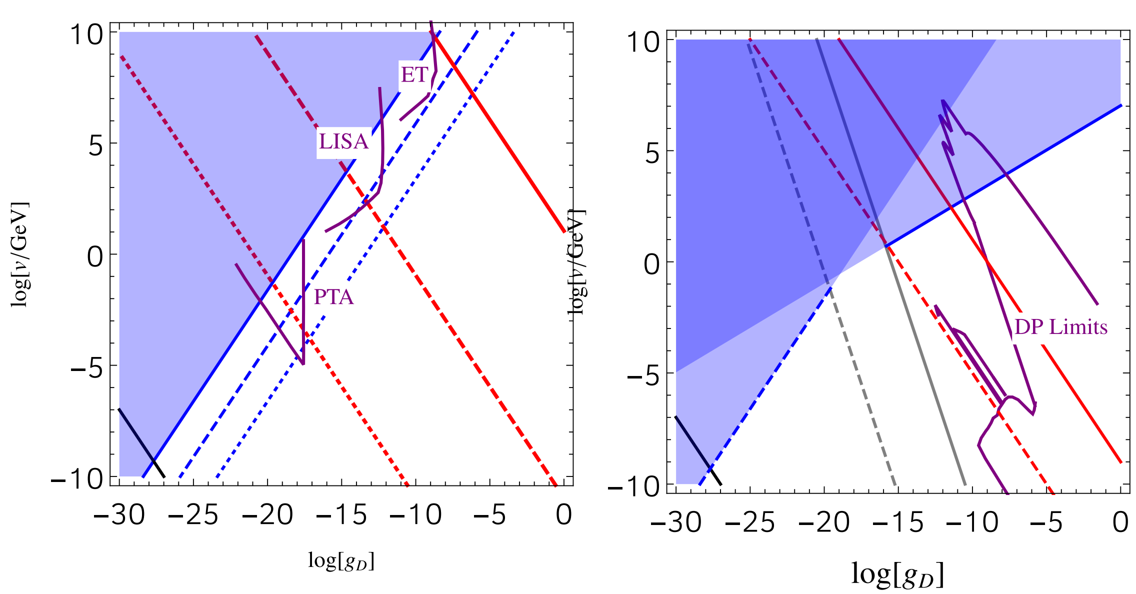
Conclusion



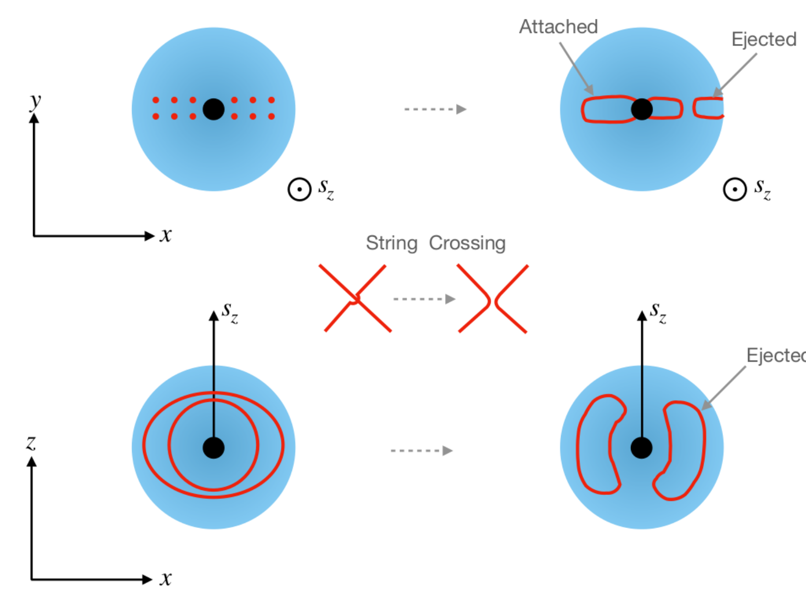
Vortex Forms



Depletes Dark Photon Dark Matter



GW, Dark radiation (DPDM)

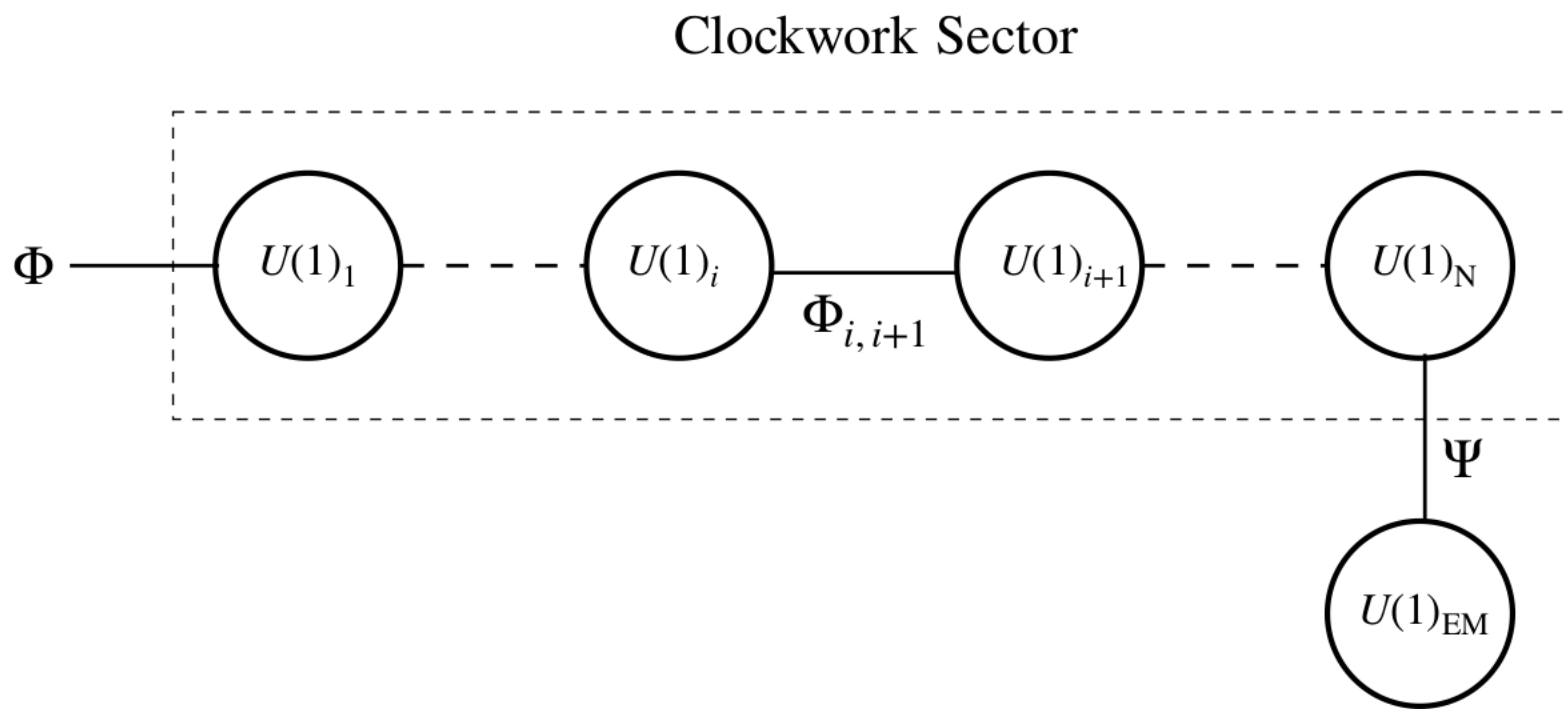


Boss Nova-> GW, String Loops (SR)

Thank you!

Back up

Clockwork



- The clockwork sector leads to a single U(1)' that couples more to Ψ than Φ in a technically natural model.
- It also couples to all the $\Phi_{i,i+1}$ more than to Φ.
- So the production of $\Phi_{N-1,N}$ vortex is not helped by having the whole clockwork sector.
- One needs a particular hierarchy of the vevs of the $\Phi_{N-1,N}$ fields to avoid string production of all the scalars and hence a hierarchy problem.