Title: Theory Talk

Date: Aug 21, 2017  09:35 AM

URL: http://pirsa.org/17080018

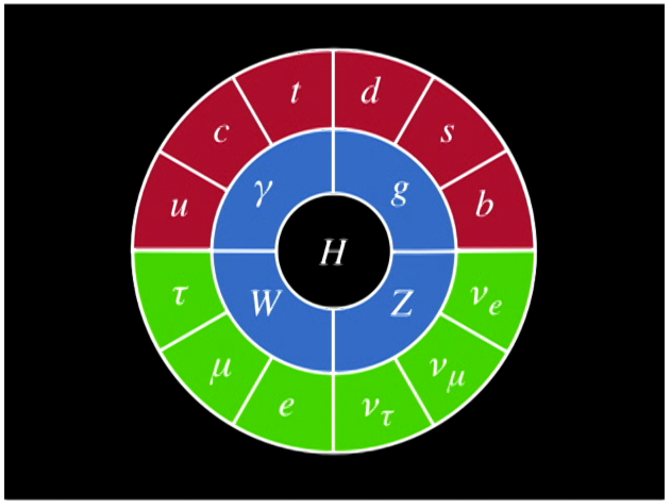
Abstract:

Welcome!


CAUTION

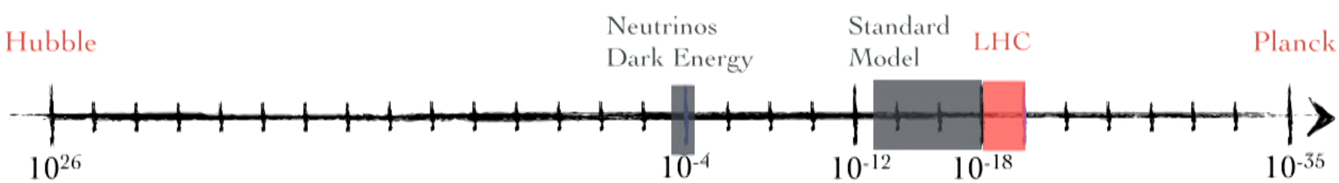
# The Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i\bar{\psi} \not{D} \bar{\psi}$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi$$
$$+ |D_\mu \phi|^2 - V(\phi)$$
$$+ M_{pl}^2 R \quad - \rho_{vacuum}$$



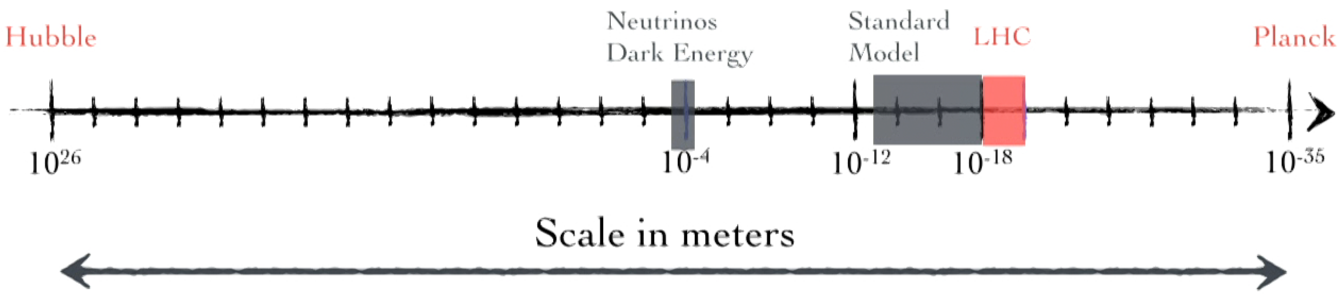

Contains ~20 particles and ~20 parameters

# The Scales in our Universe



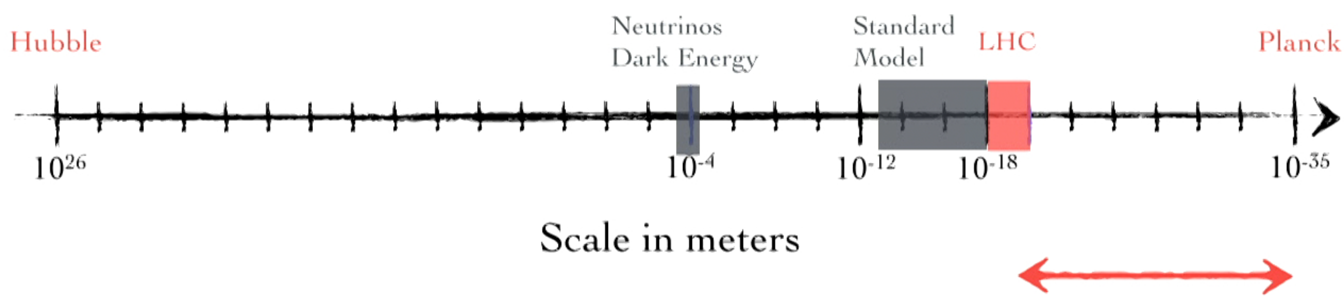

Scale in meters

# The Scales in our Universe




The Cosmological Constant Problem
Why is the Universe so large?

# The Scales in our Universe

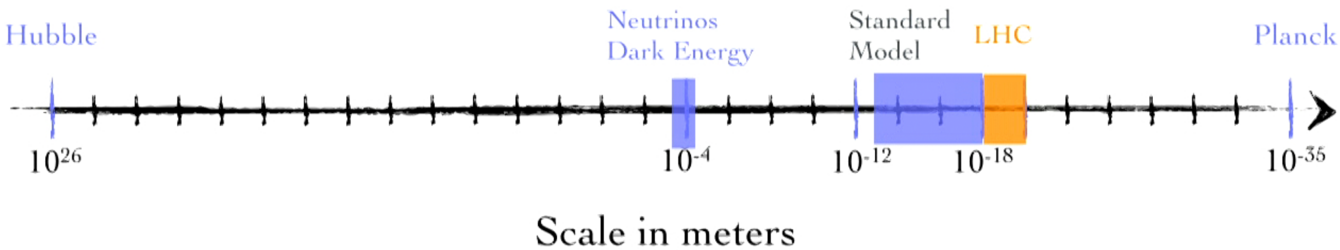



Scale in meters

The Hierarchy Problem
Why is Gravity so weak?

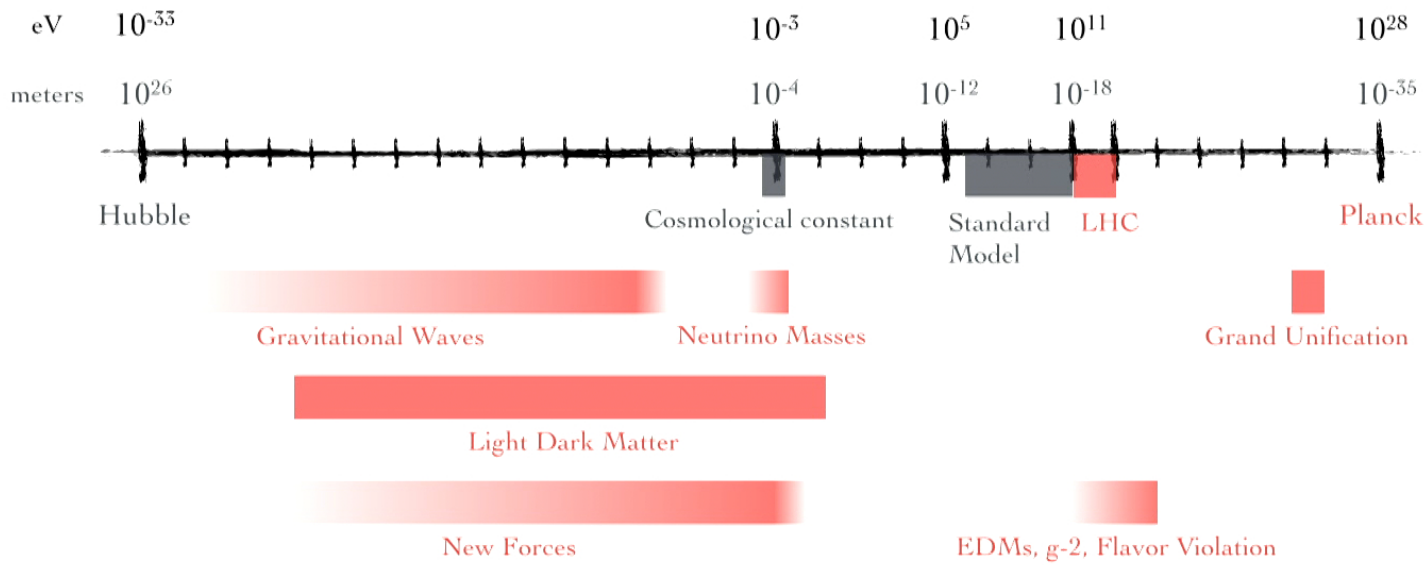
# The High Energy Frontier

# Particle Physics — Precision vs Energy Frontier

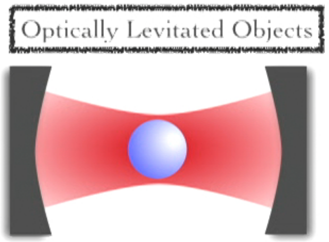


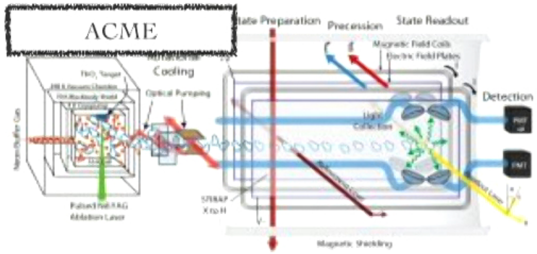

*80% of scales unexplored*

# The Scales in Our Universe

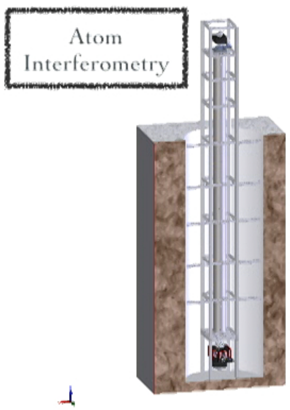


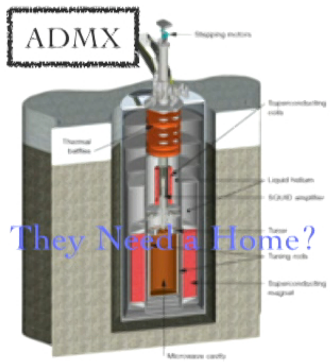
# Opportunities at the Precision Frontier

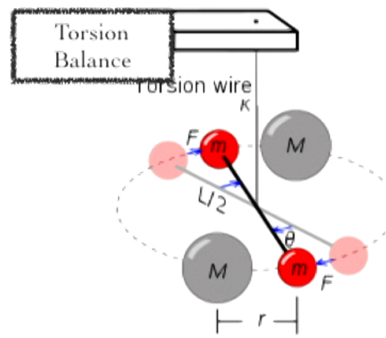




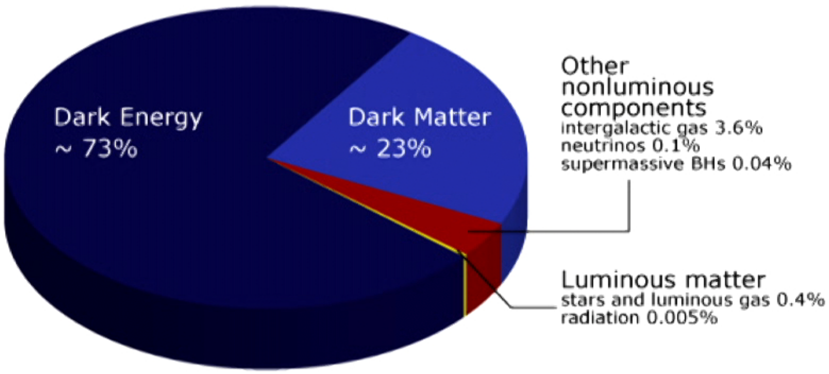




Do They Need a Home?

# The Mystery of Dark Matter



# Models of Dark Matter

- What is it made out of?

  Anything from $10^{-22}$ eV to $10^{70}$ eV in mass

- How is it produced?

- Does it have interactions other than gravitational?

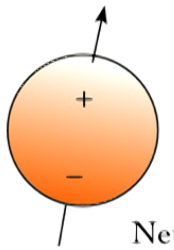
# Outline

Light Bosonic Dark Matter

- Axions
- Dark Photons
- Moduli

# Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion




Neutron
EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm $\theta_s$

Experimental bound: $\theta_s < 10^{-10}$

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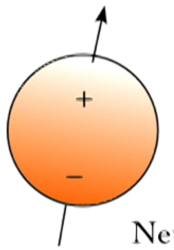


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Experimental bound: $\theta_s < 10^{-10}$

Solution:
$\theta_s$ ~a(x,t) is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11} \text{ eV } \frac{10^{17} \text{ GeV}}{f_a} \sim (3 \text{ km})^{-1} \frac{10^{17} \text{ GeV}}{\mathrm{f_a}}$$

$f_a$ : axion decay constant

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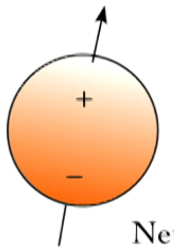


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$f_a$ : axion decay constant

Mediates new forces and can be the dark matter

# Elements of String Theory

- Extra dimensions

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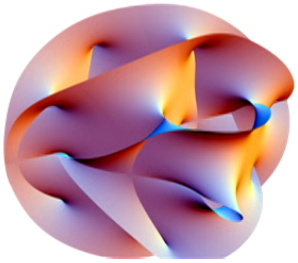
- Extra dimensions
- Gauge fields
- Topology



# Elements of String Theory

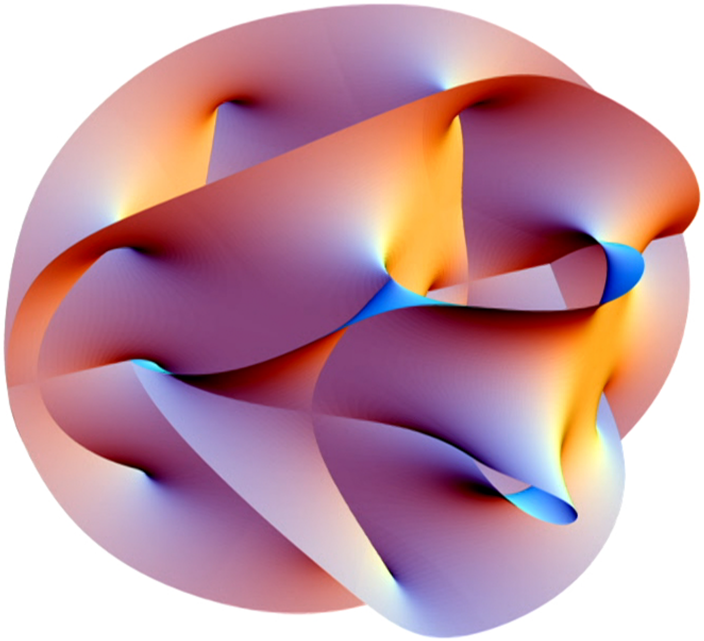
- Extra dimensions
- Gauge fields
- Topology

Give rise to a plenitude of Universes

# A Plenitude of Massless Particles

Compactification naturally gives rise to massless particles

In the presence of non-trivial topology,
non-trivial gauge field configurations can carry no energy,
resulting in 4D massless particles



# Non-trivial gauge configurations

## The Aharonov-Bohm Effect


Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

# Non-trivial gauge configurations

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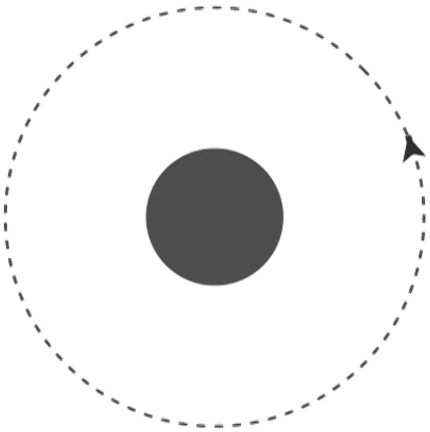

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# Non-trivial gauge configurations

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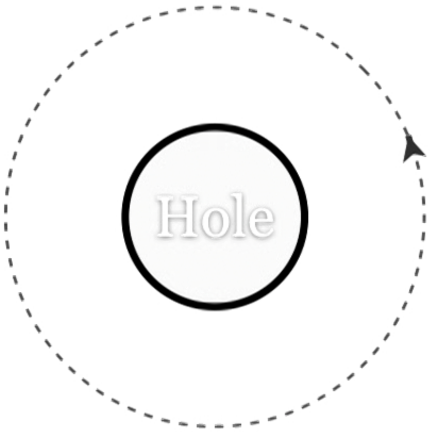


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Non-trivial topology:
"Blocking out" the core still leaves a non-trivial gauge, but no mass

# A Plenitude of Massless Particles

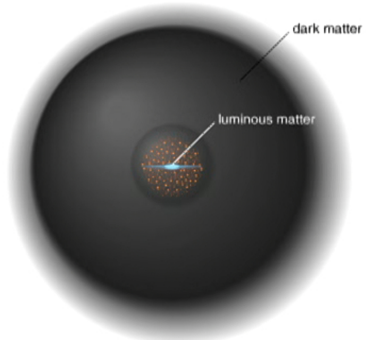
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

# Properties of Plenitude of Particles from String Theory

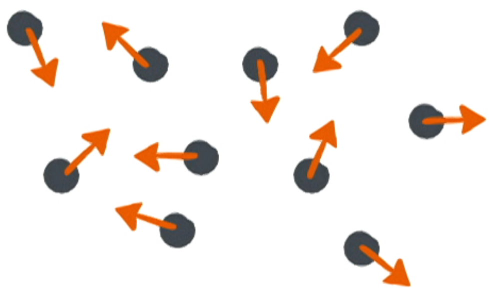
- They couple very weakly to the Standard Model
- They can be extremely light
- Constrained if the coupling is large enough by astrophysics, BBN, CMB…

# What If DM Is a Boson and Very Light?

## Dark Matter Particles in the Galaxy




Usually we think of ...



like a WIMP

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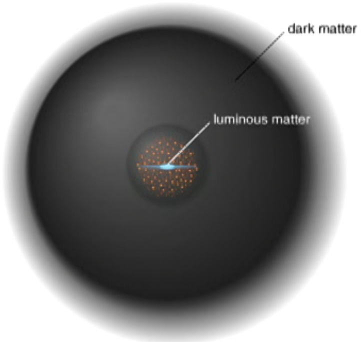


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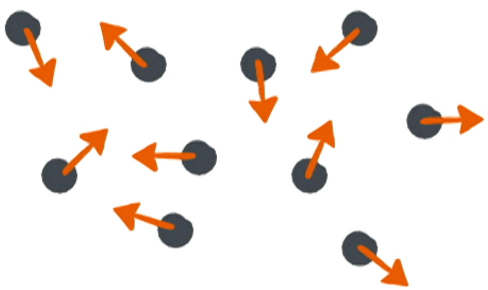
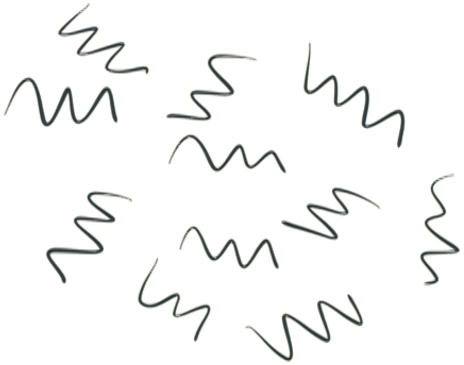


like a WIMP

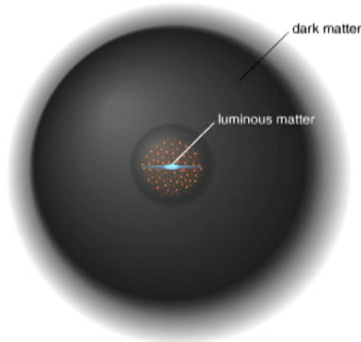
instead of…

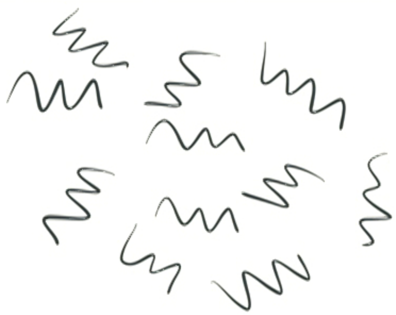


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

# What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Decreasing DM Mass

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

Equivalent to a Scalar wave

# Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1$ eV/c$^2$

we can talk about DM $\phi$(x,t) and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

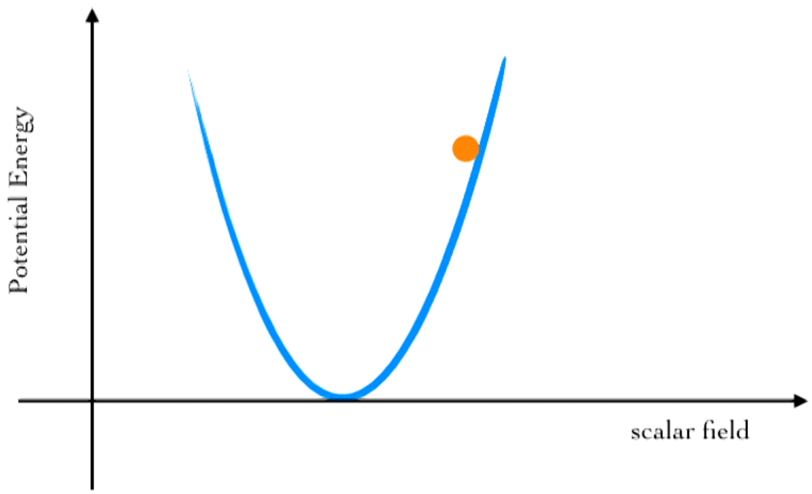
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

# Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

$$\ddot{x} + \gamma\ \dot{x} + \omega^2 x = 0$$




Frozen when:
Hubble > $m_\phi$

Initial conditions set by inflation

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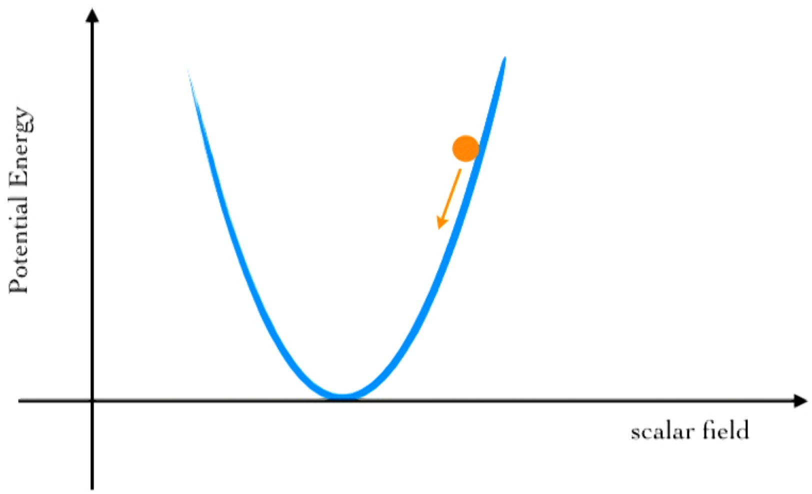



Frozen when:
Hubble > $m_\phi$

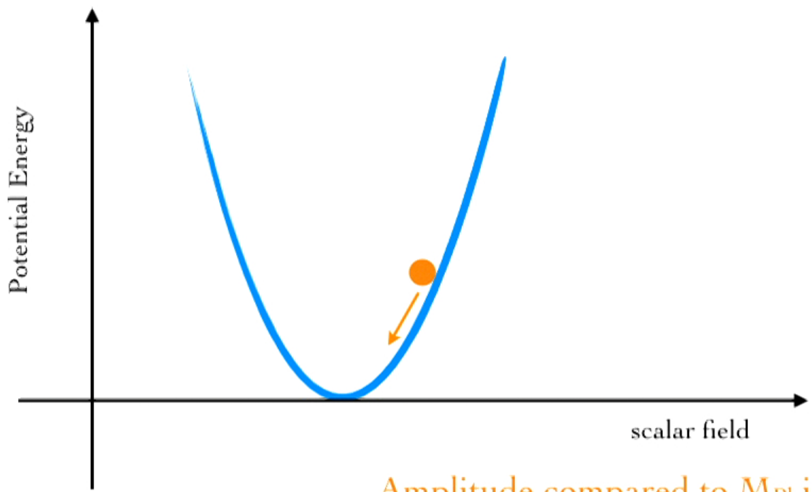
Oscillates when:
Hubble < $m_\phi$

$\rho_\phi$ scales as $a^{-3}$
just like Dark Matter

Initial conditions set by inflation

# Light Scalar Dark Matter Today

- If $m_\phi$ < 1 eV, can still be thought of as a scalar field today




$m_\phi^{\,2}\, \phi_o^{\,2}\, \cos^2 (m_\phi\, t) \sim \rho_\phi$

Coherent for $\upsilon_{vir}^{-2} \sim 10^6$ periods

Amplitude compared to $M_{Pl}$ in the galaxy:

$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4 \cdot 10^{-13} \left(\frac{10^{-18}\,{\rm eV}}{m_\phi}\right)$$

# Scalar Dark Matter and Isocurvature Fluctuations

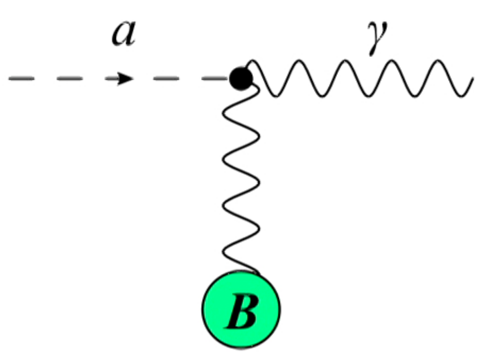
During Inflation

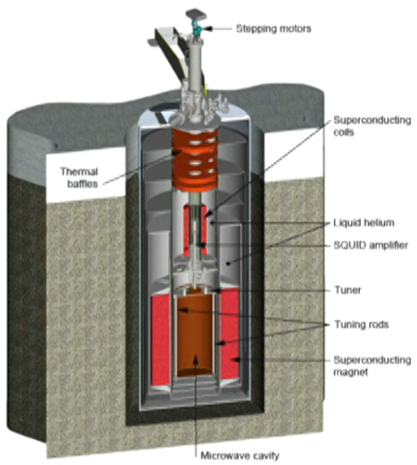
- $\delta\phi_{quantum}$ ~ Hubble
- Scalar Dark Matter carries its own fluctuation spectrum
- A discovery of tensor modes excludes large part of the parameter space

# Axion Dark Matter

Some examples

- Axion-to-photon conversion (ex. ADMX)




Cavity size = Axion size

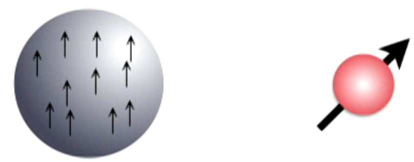
# Axion Dark Matter

Some examples

Monopole-Dipole Interaction

Mass with N nucleons    Spin

Dipole-Dipole Interaction



N spins    Spin

- Axion Force experiments and DM experiments

# Dark Photon Dark Matter

Some examples

- Detected if kinetically mixed with the photon

$$\mathcal{L} \supset \epsilon F_{EM} F_{DM}$$

- Detected like a photon (ADMX)

DM electric field $\sim \sqrt{\rho_{DM}}$ ~ 50 V/cm

# Moduli Dark Matter

- Couple non-derivatively to the Standard Model (as well axions with CP violation)

- Examples of couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, \ldots$$

Fundamental constants are not really constants

# Oscillating Fundamental Constants

AA, J. Juang, K. Van Tilburg (2014)

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e} \sqrt{\hbar c} \frac{\phi}{M_{Pl}} m_e c^2 e\bar{e}$$

$M_{pl} = 10^{18}$ GeV
reduced Planck scale in energy

$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e} \phi_0}{M_{Pl}} \cos(\omega_{DM} t)$$

$$= 6.4 \times 10^{-13} \cos(\omega_{DM} t) \left( \frac{10^{-18} \text{ eV}}{m_{DM} c^2} \right) \left( \frac{d_{m_e}}{1} \right)$$

$d_{me}$ : coupling strength relative to gravity

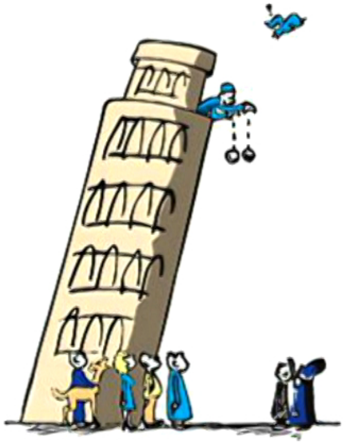
Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…

# Ultra-light Scalar Dark Matter

- Mediates new interactions in matter
    - Generates a fifth force in matter

    - Generates Equivalence Principle violation



# Oscillating Atomic and Nuclear Energy Splittings due to Dark Matter

- Optical Splittings

$$\Delta E_{\text{optical}} \propto \alpha_{EM}^2 m_e \ \sim \text{eV}$$

- Hyperfine Splittings

$$\Delta E_{\text{hyperfine}} \propto \Delta E_{\text{optical}} \alpha_{EM}^2 \left( \frac{m_e}{m_p} \right) \sim 10^{-6}\ \text{eV}$$

- Nuclear Splittings

$$\Delta E\ (m_p,\ \alpha_s,\ \alpha_{EM}) \sim 1\ \text{MeV}$$

DM appears as a signature in atomic (or nuclear) clocks

# Oscillating interatomic distances

- The Bohr radius changes with DM

  - $r_B \sim (\alpha\, m_e)^{-1}$

$$\frac{\delta r_B}{r_B} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

- The size of solids changes with DM

  - $L \sim N\, (\alpha\, m_e)^{-1}$

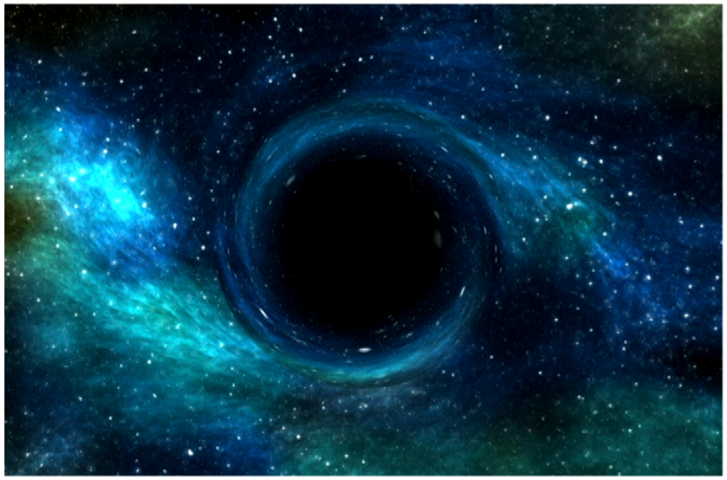
$$\frac{\delta L}{L} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

For a single atom $\delta r_B \sim 10^{-30}$ m

Need macroscopic objects to get a detectable signal

How do we look for Dark Matter if it only couples through gravity?

# Black Holes as Nature's Detectors

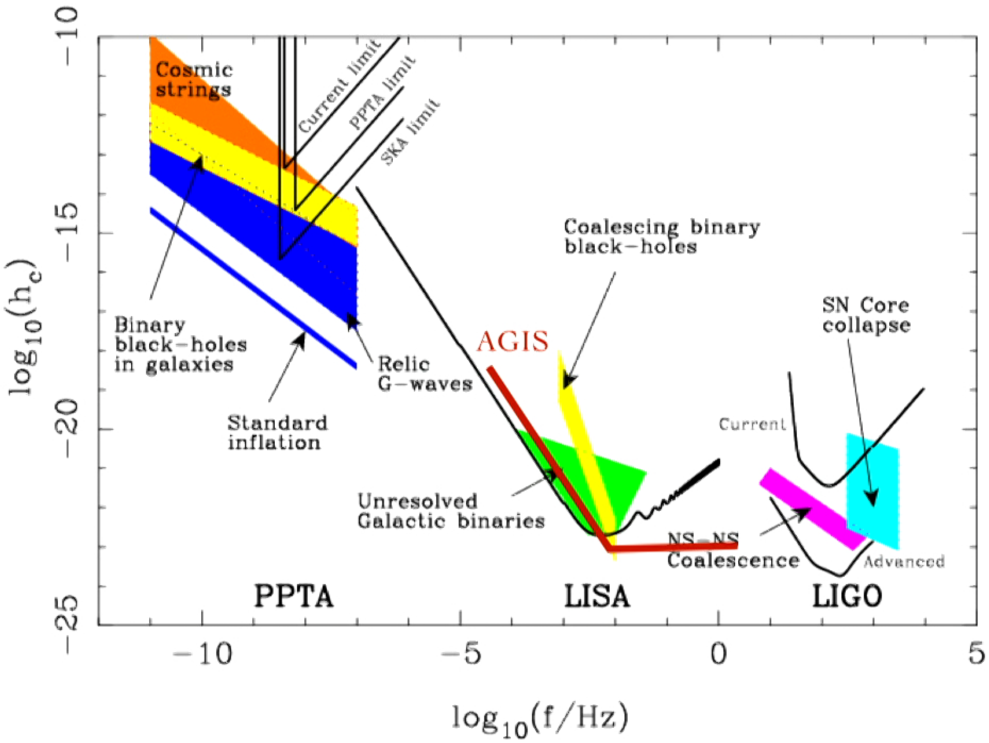


1 km -10 billion km

They can detect bosons of similar in size

# What will the Universe look like?

LIGO and PTA look at different frequencies:
Gravitational Wave Astronomy

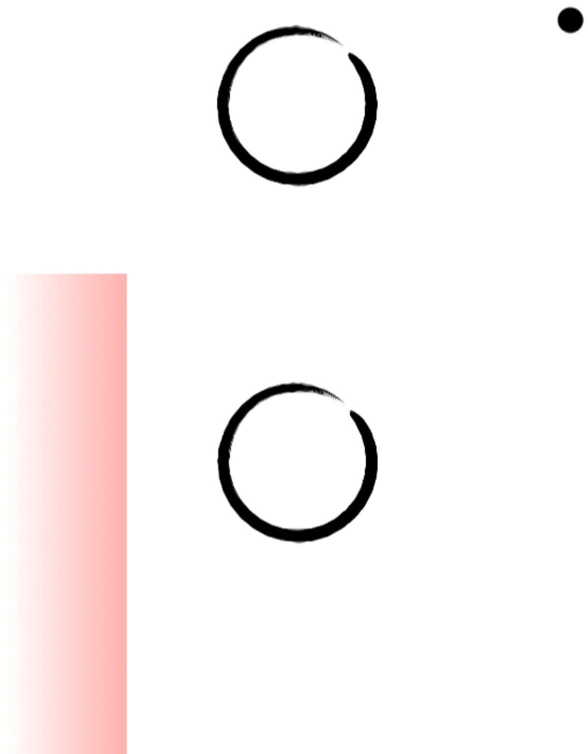



Our new "eyes" for our Cosmos

# Super-Radiance Cartoon

Super-radiant scattering of a massive object

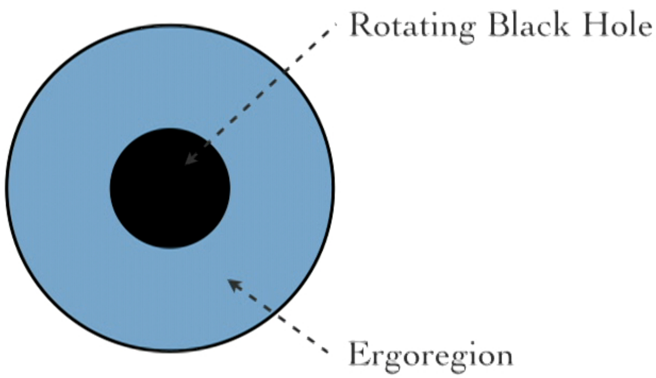
# Super-Radiance Cartoon



Super-radiant scattering of a wave

# Black Hole Superradiance

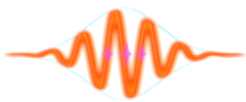
## Penrose Process

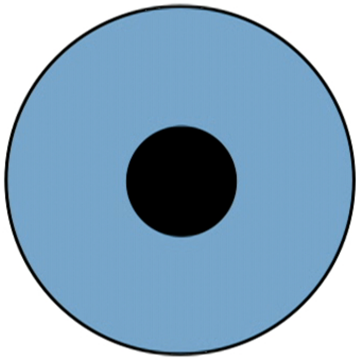



Ergoregion: Region where even light has to be rotating

# Black Hole Bomb

Press & Teukolsky 1972

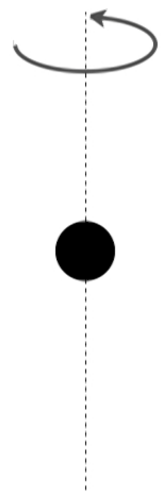




Photons reflected back and forth from the black hole
and through the ergoregion

# Superradiance for a massive boson

Damour et al; Zouros & Eardley;
Detweiler; Gaina (1970s)



Particle Compton Wavelength comparable to the size of the Black Hole

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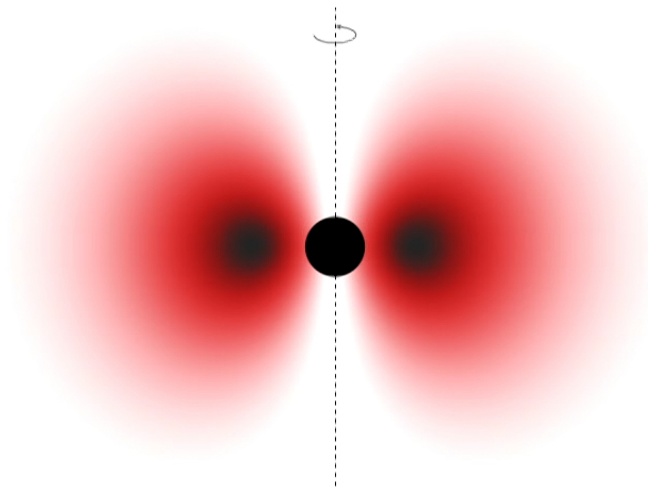

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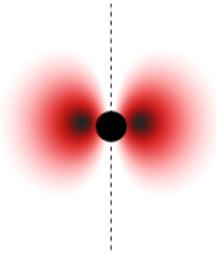
# Gravitational Atom in the Sky

## The gravitational Hydrogen Atom



Fine-structure constant: $\alpha = G_N M_{BH} \mu_a = R_g \mu_a$

Principal (n), orbital (l), and magnetic (m) quantum number for each level $E_{\text{binding}} = -\frac{\alpha^2 \mu_a}{2n^2}$

Main differences from hydrogen atom:

Levels occupied by bosons - occupation number >$10^{77}$

In-going Boundary Condition at Horizon

# Key Points About Superradiance

- For light axions(weak coupling) equation identical to Hydrogen atom

- Boundary conditions different:
  - Regular at the origin ⟶ Ingoing (BH is absorber)
  - Hermitian ⟶ Non-hermitian

# Superradiance Parametrics

## Superradiance Condition

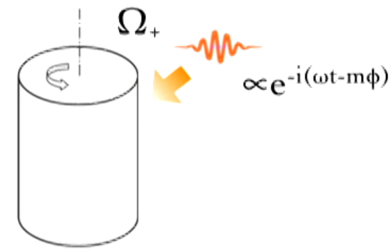
$$\omega_{\text{axion}} < m\ \Omega_+$$

$m$ : magnetic quantum number

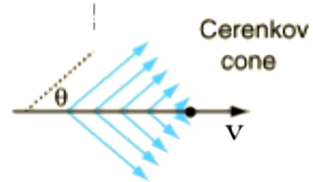
$\Omega_+$ : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder




Superluminal linear motion - Cherenkov radiation $1/n(\omega) < v$




Condition can be extracted from requiring that $dA_{BH} > 0$

# Superradiance Parametrics

## Superradiance Rate

$\tau_{sr} \sim 0.6 \times 10^7\ R_g$ for $R_g\ \mu_a \sim 0.4$

As short as 100 sec vs $\tau_{accretion} \sim 10^8$ years

When $R_g\ \mu_a >> 1$,

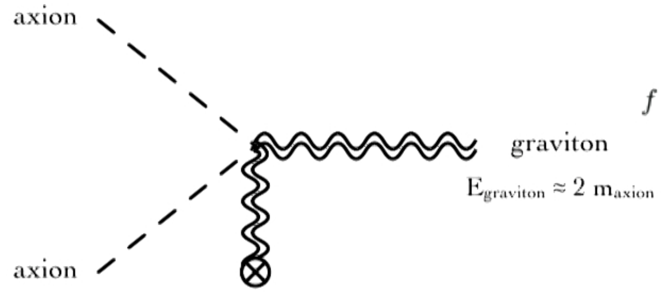
$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g\ \mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

# Super-Radiance Signatures

## GW annihilations




$$f = 10\,\mathrm{kHz} \times (\mu_a/10^{-11}\,\mathrm{eV})$$

High frequency GWs

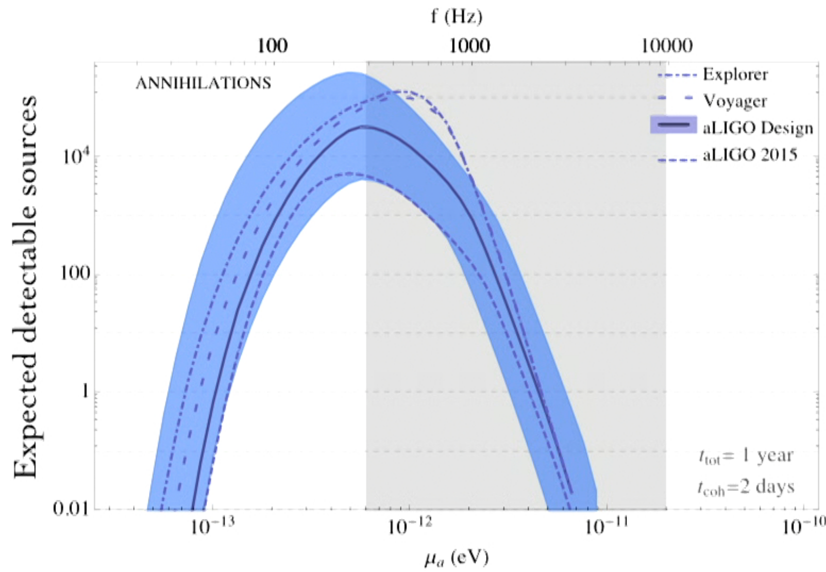
- Signal enhanced by the square of the occupation number of the state

$$h_{\mathrm{peak}} \simeq 10^{-22} \left(\frac{1\,\mathrm{kpc}}{r}\right) \left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}} \frac{\alpha^{-\frac{1}{2}}}{\ell} \left(\frac{M}{10 M_\odot}\right)$$

- Signal duration determined by the annihilation rate (can last thousands of years)

# Expected Events from Annihilations

- Large uncertainties coming from tails of BH mass distribution




Pessimistic: flat spin distribution and 0.1 BH/century

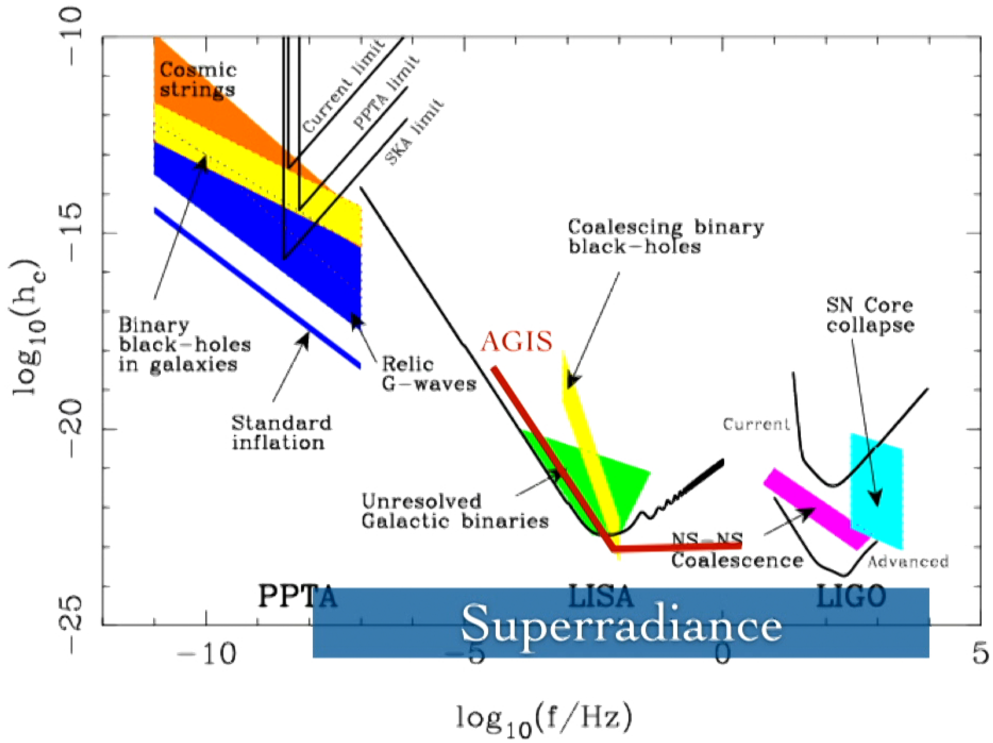
Realistic: 30% above spin of 0.8 and 0.4 BH/century

Optimistic: 90% above spin of 0.9 and 0.9 BH/century

# What will the Universe look like?

LIGO and PTA look at different frequencies:

Gravitational Wave Astronomy




Our new "eyes" for our Cosmos

# The Scales in Our Universe