Quantum interferometry for new physics

Denis Martynov, University of Birmingham

QI collaboration

QTPF School, Cambridge, 2023

Overview

- Quantum Interferometry (QI) collaboration
  - Squeezed light
  - Single photon detectors
  - Quantum amplifiers
- Lecture 1: Dark matter
- Tutorial: optical cavities
- Lecture 2: Quantum measurements

Collaboration

University of Birmingham

Denis Martynov

Vincent Boyer

University of Glasgow

Robert Hadfield

University of Strathclyde

Stuart Reid

University of Warwick

Animesh Datta

Cardiff University

Hartmut Grote (PI)

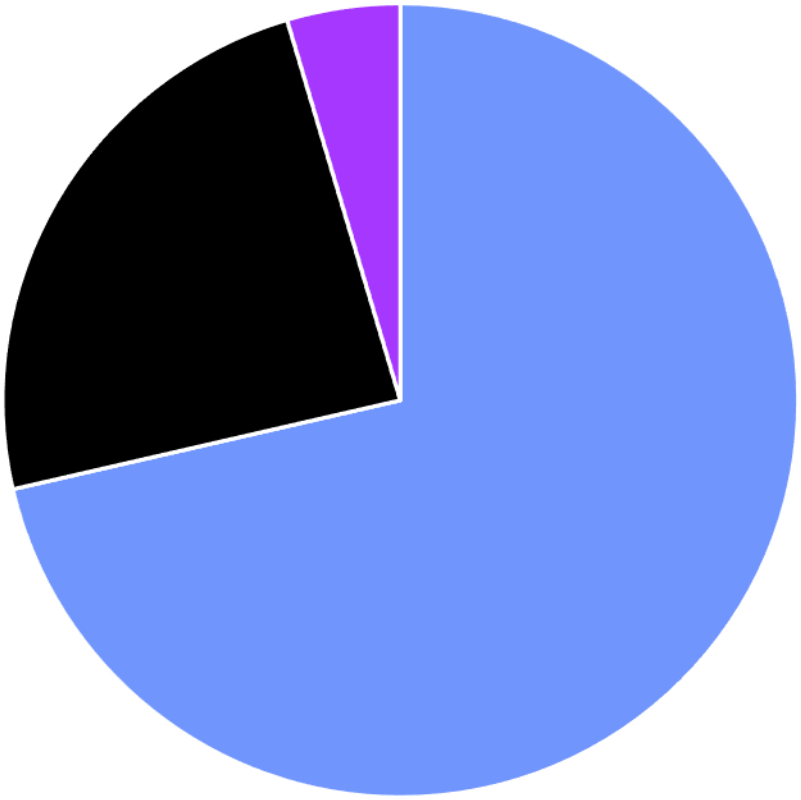
Katherine Dooley

sr.bham.ac.uk/qi/

@QIProject1

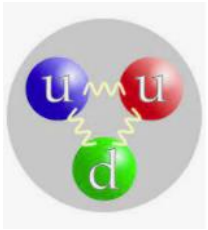
547 followers
in 47 countries!

Energy density in the universe

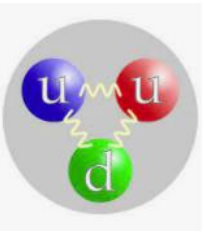


Matter – antimatter annihilation

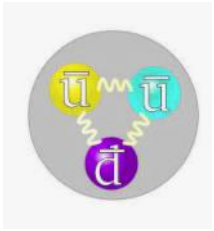
Matter



2 ppb of matter

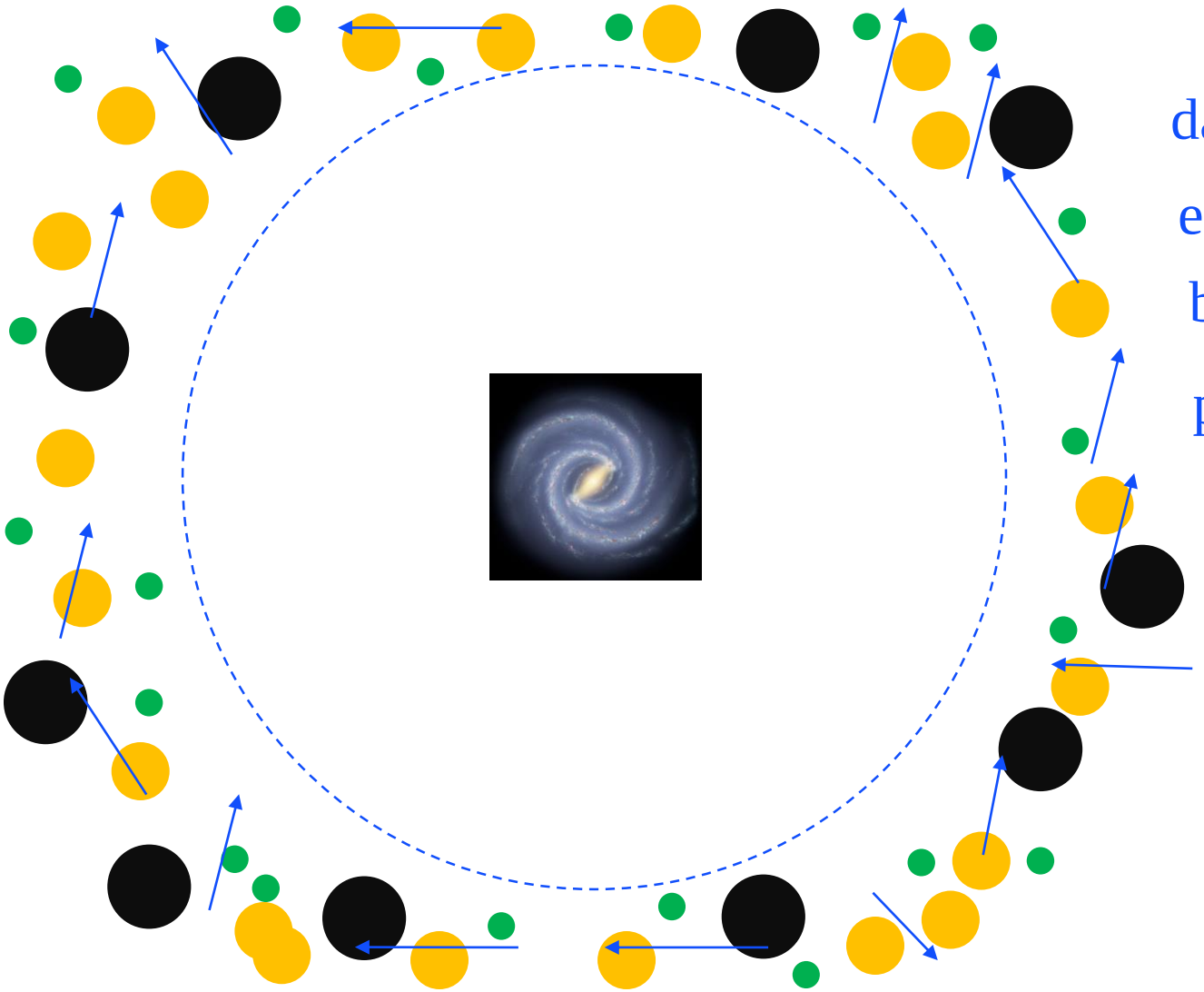


Symmetry breaking



Antimatter

Cosmic microwave background



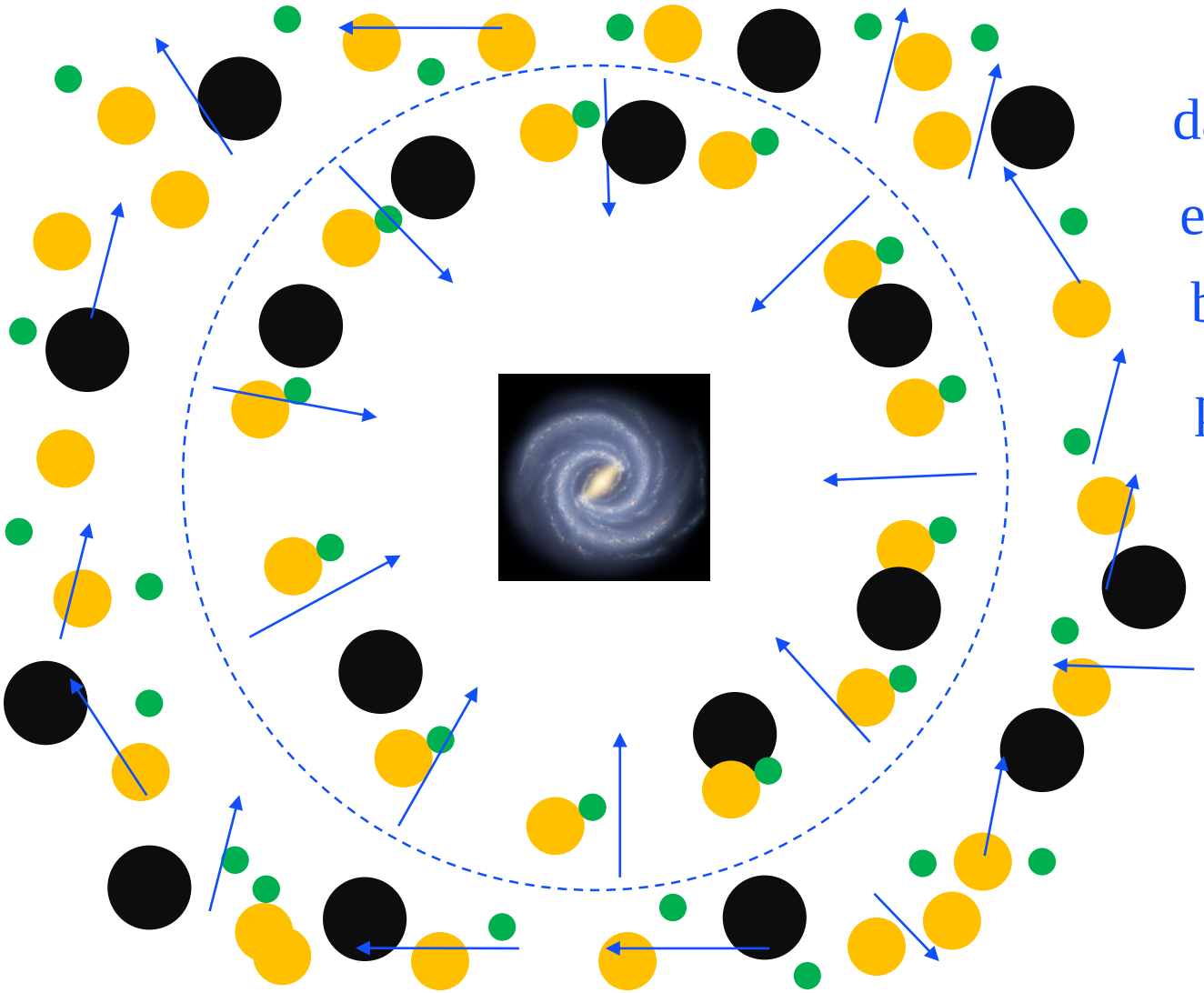
dark matter

electron

baryons

photon

Cosmic microwave background



dark matter

electron

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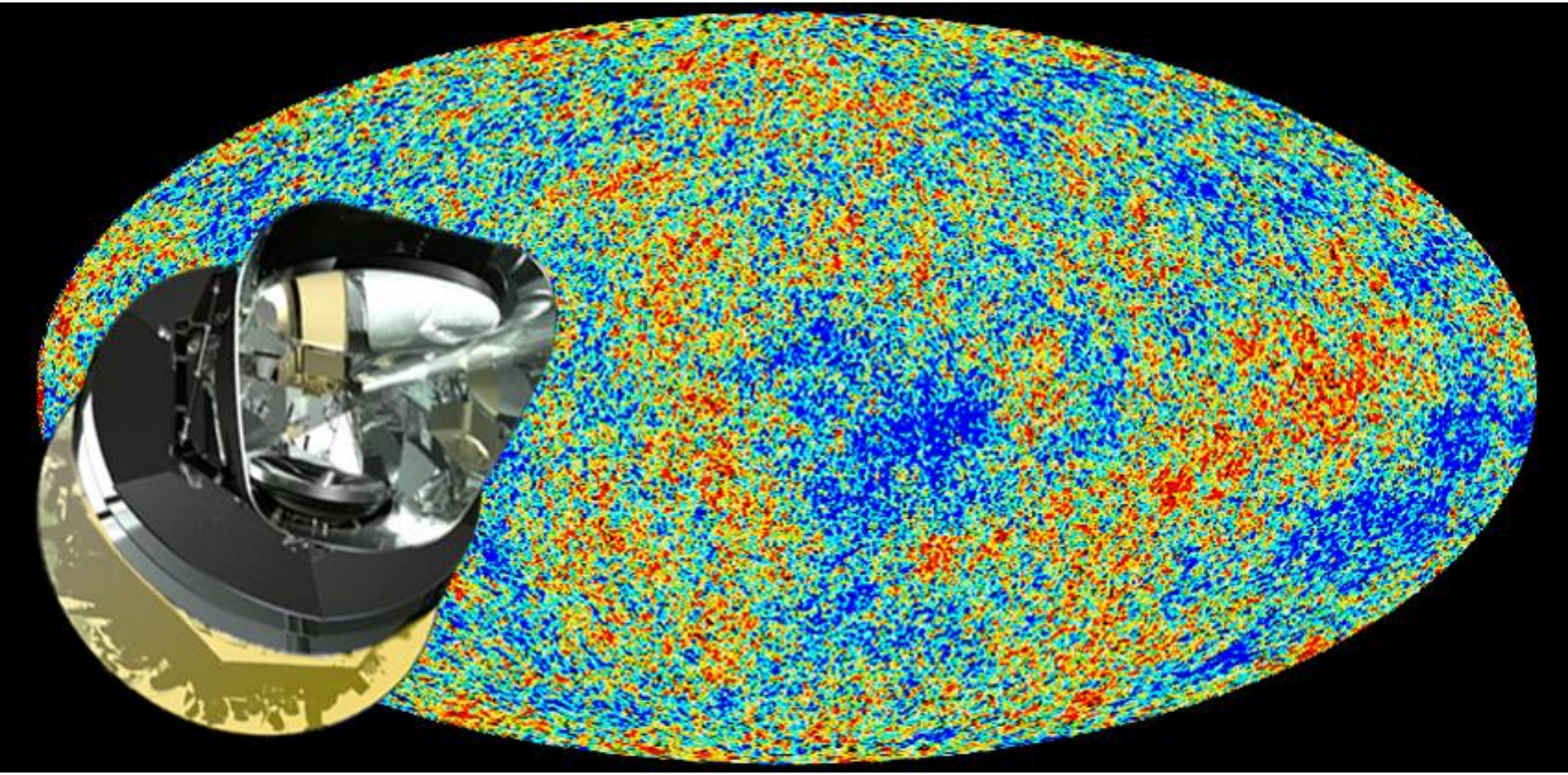
photon

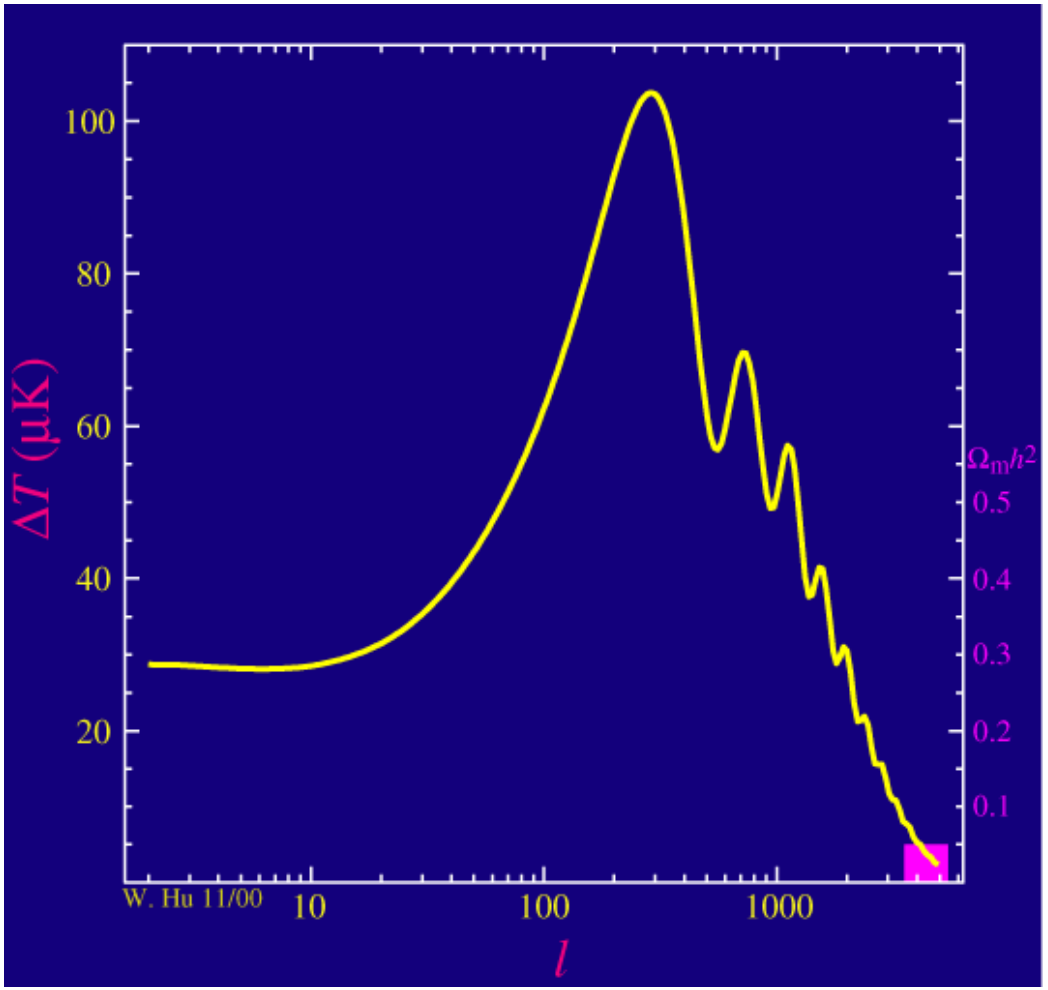
Planck measurements



Dark matter level

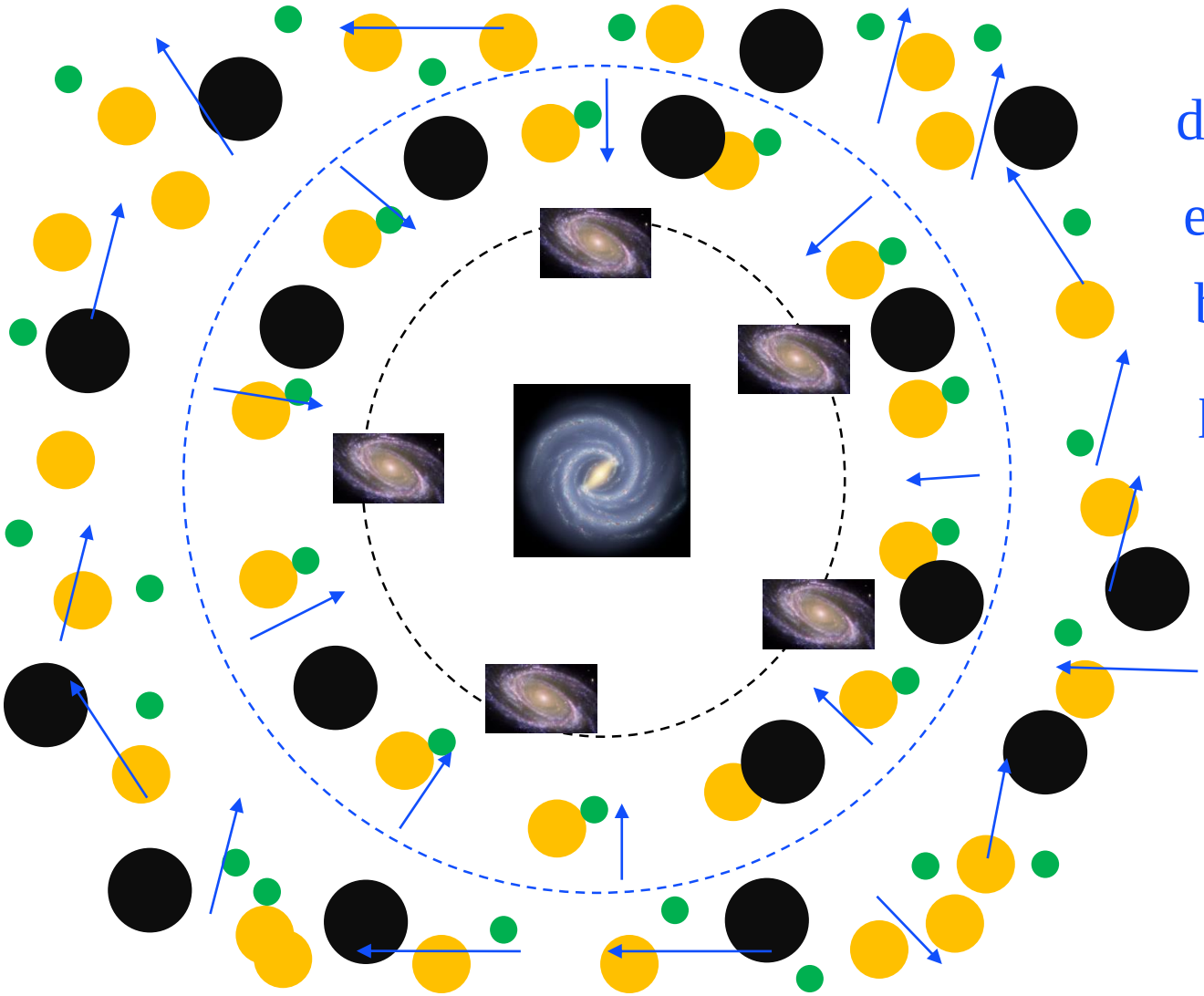
More dark matter =>

- smaller peaks
- prominent 3rd peak



http://background.uchicago.edu/~whu/intermediate/driving2.html

Dark ages



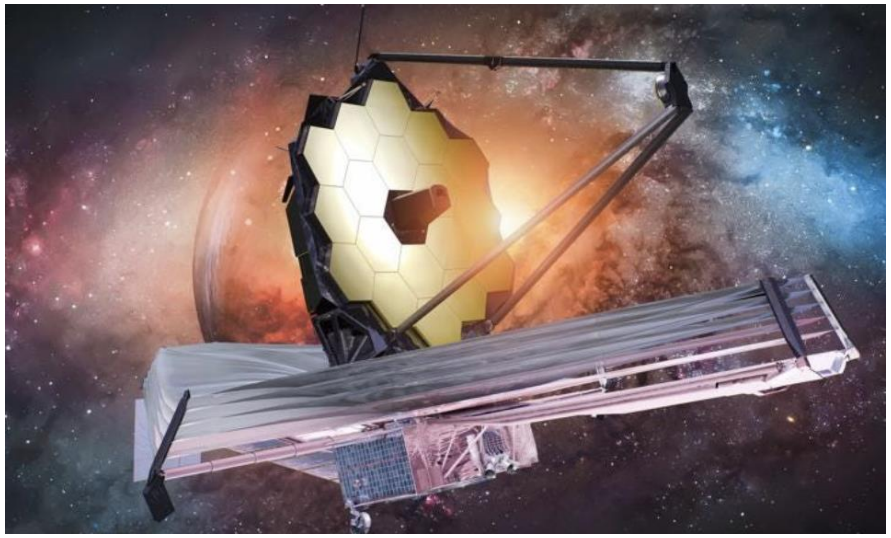
dark matter

electron

baryons

photon

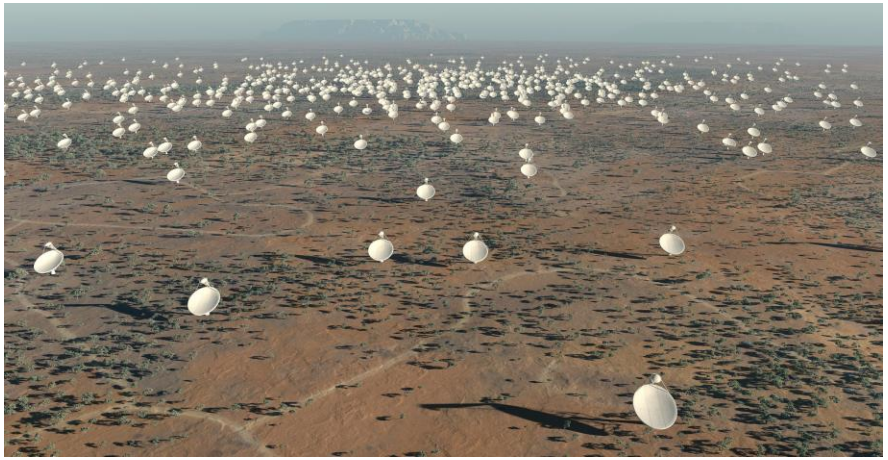
New observatories: James Webb



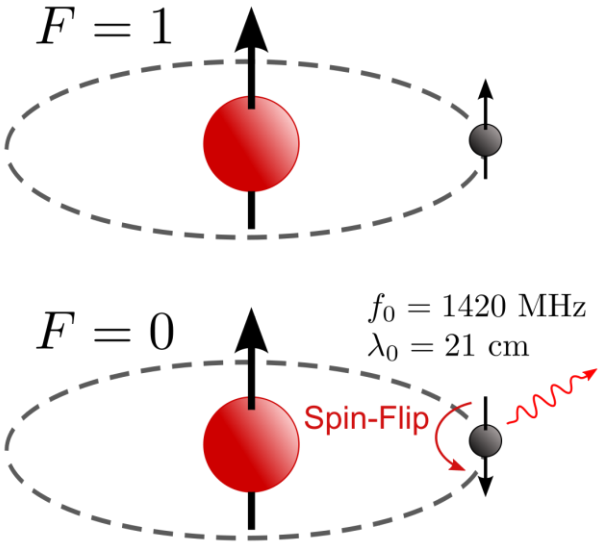
Candidates at z=12-20!

Seems like the early universe was surprisingly efficient in making stars.

New observatories: 21-cm line

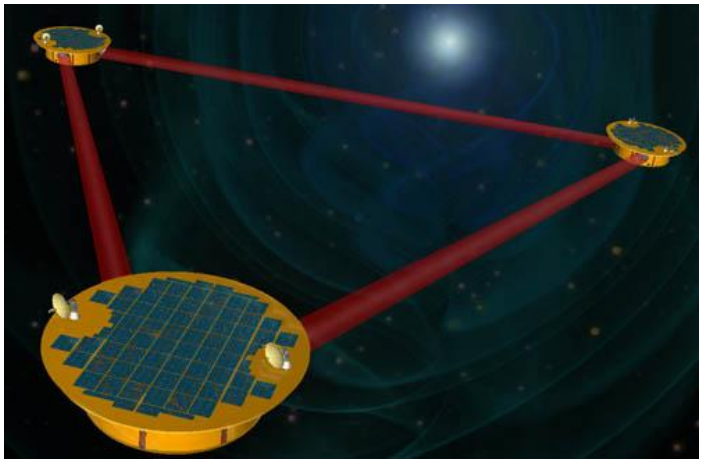


Square Kilometer Array

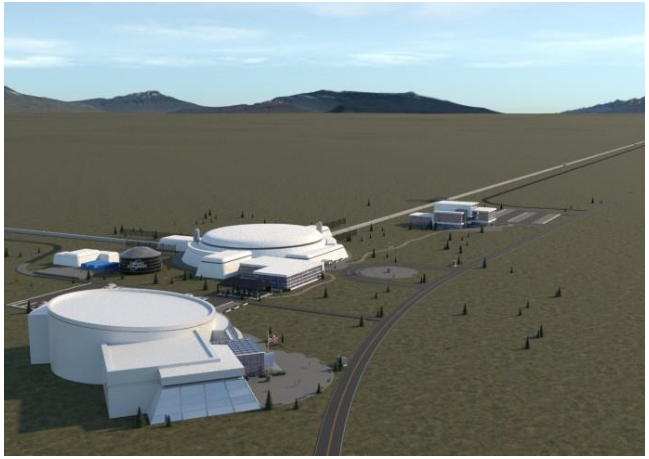


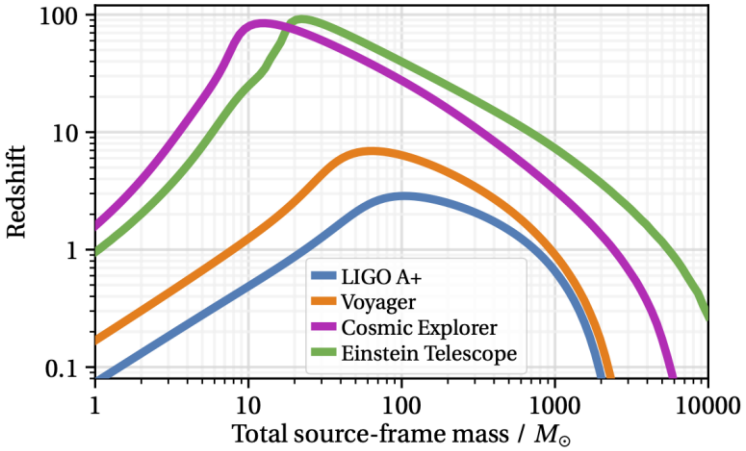
Observe evolution of the universe during the dark ages.

New gravitational-wave observatories



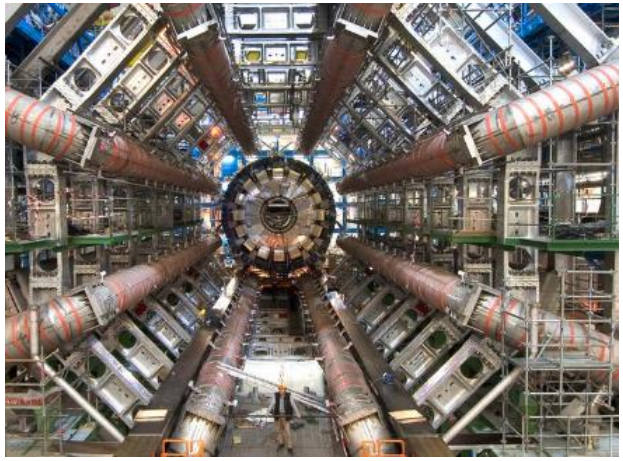
Search for black holes at cosmological distances.





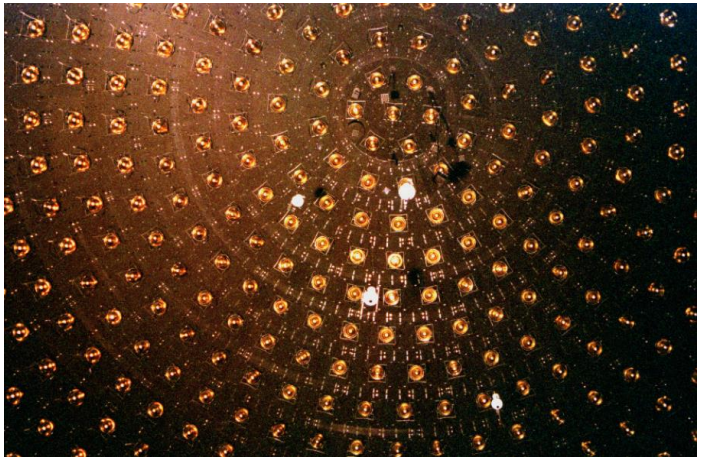
Direct searches for dark matter

- Baryonic dark matter mostly ruled out by micro-lensing
- Non-baryonic dark matter
  - » Weakly interacting massing particles
  - » New flavors of neutrinos
  - » Axions



LHC

Xenon



MiniBooNE

Axion hints

- CP-symmetry: Physics is the same if
  - » Particles < = > antiparticles
  - » Left handed < = > right handed particles
- Broken in weak interactions but not in strong ones
- Peccei-Quinn solution: introduce a new particle (axion)
- Anomalous transmission of TeV photons

Axion-photon interaction

- Maxwell's equations

$$\nabla \cdot \vec{E} = -\frac{1}{f}\nabla a \cdot \vec{B}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \frac{1}{f}(\dot{a}\,\vec{B} + \nabla a \times \vec{E})$$

- Plane-wave solution

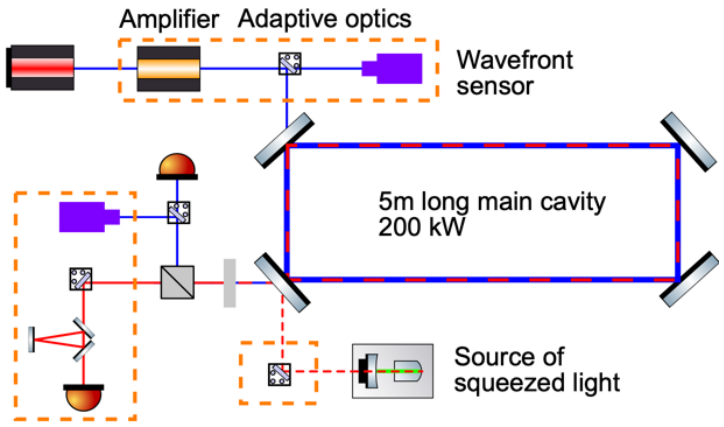
$$v_{\text{phase}} \approx 1 \pm \frac{\dot{a}}{2kf}$$

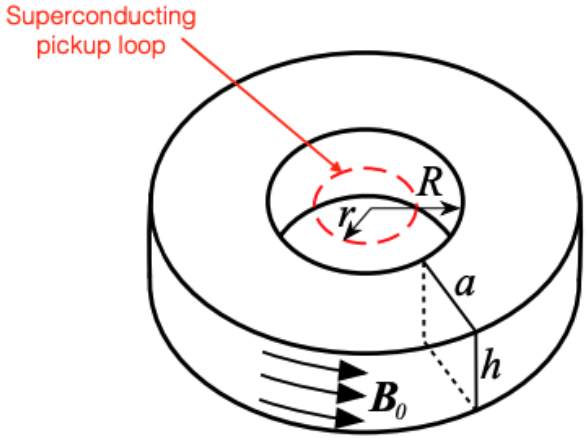
Axion-photon interaction

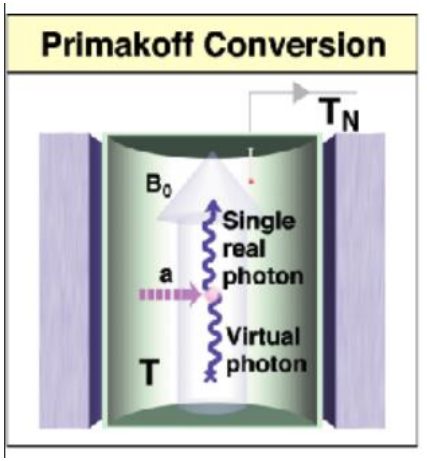
Axion field behaves classically

$$a(t) = a_0 \sin(\Omega_a t + \delta(t))$$

amplitude of the field — axion mass — phase of the field

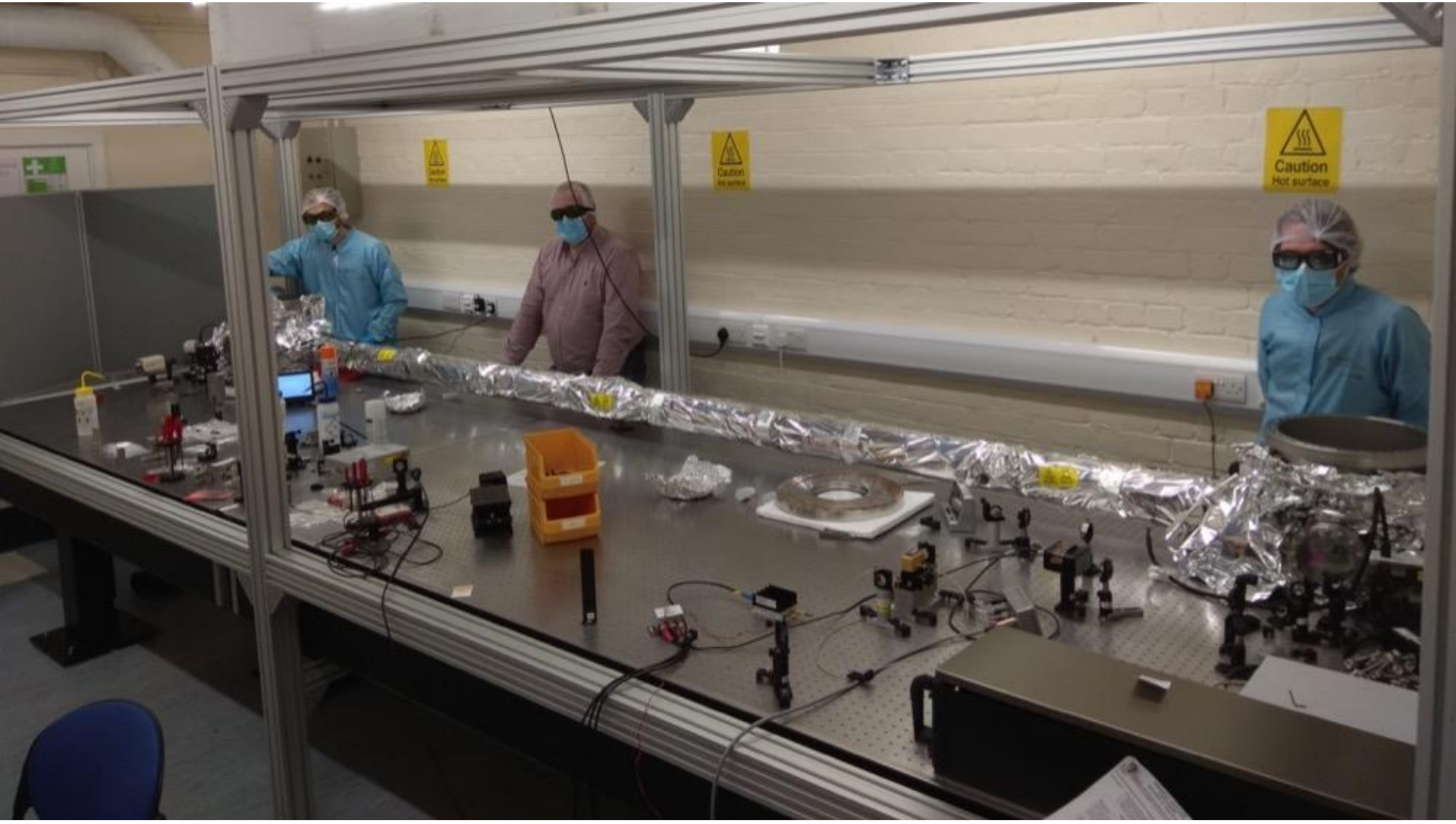




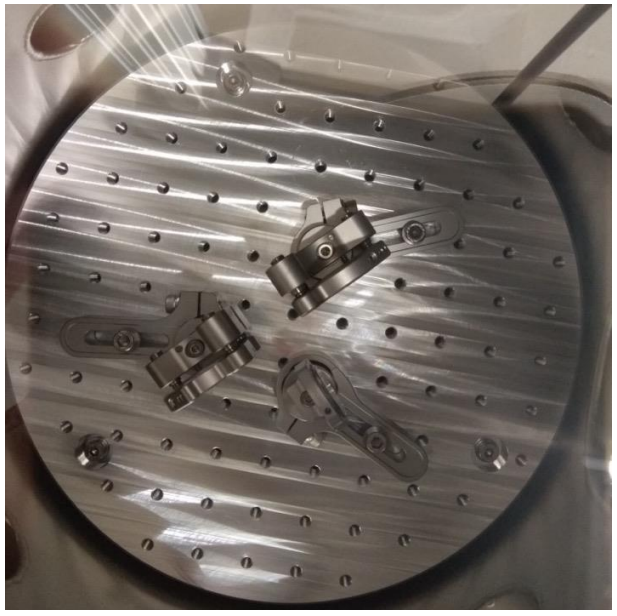


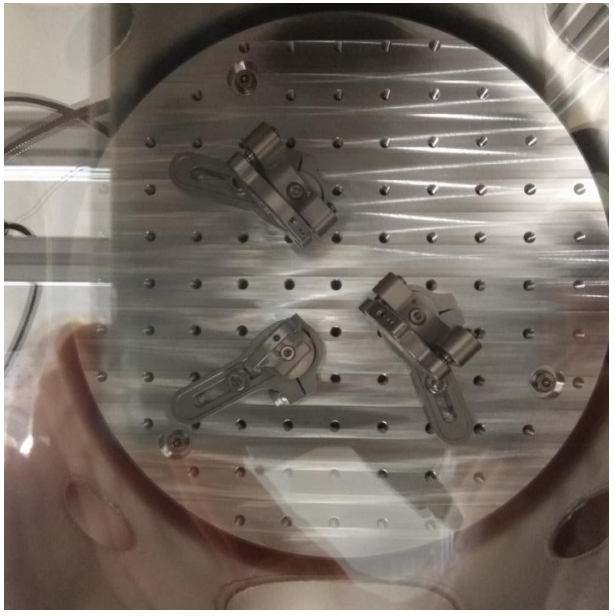
Birmingham experiment — ABRACADABRA — ADMX

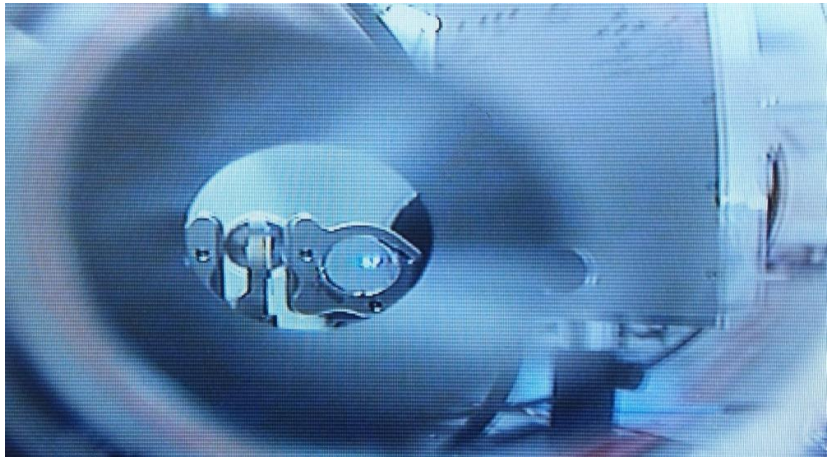
WP 1: Laser Interferometric Detector for Axions (LIDA)

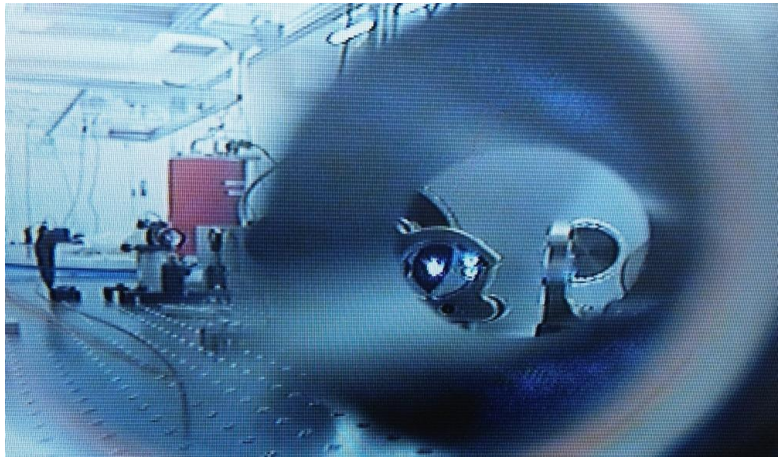


WP 1: Laser Interferometric Detector for Axions (LIDA)

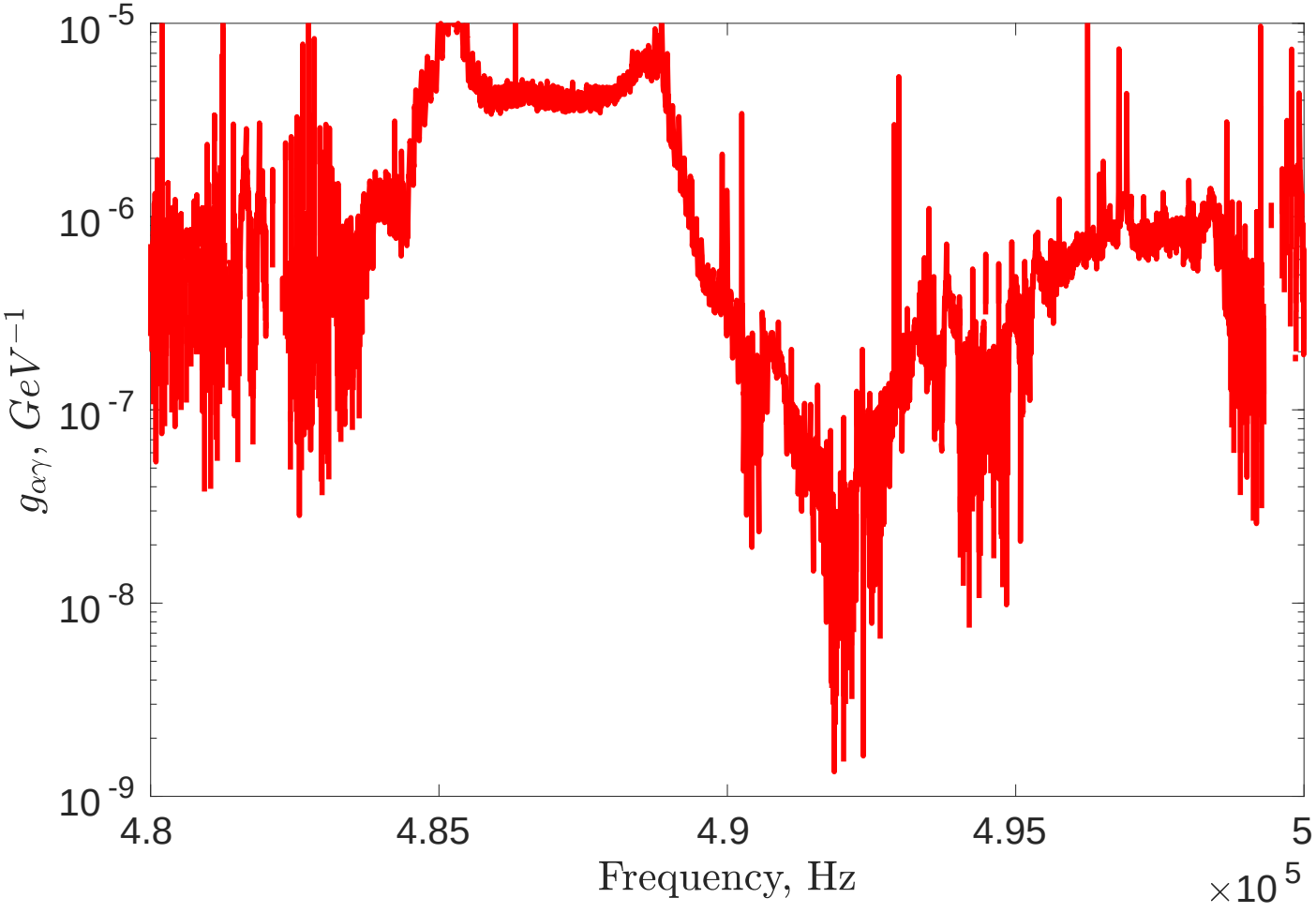




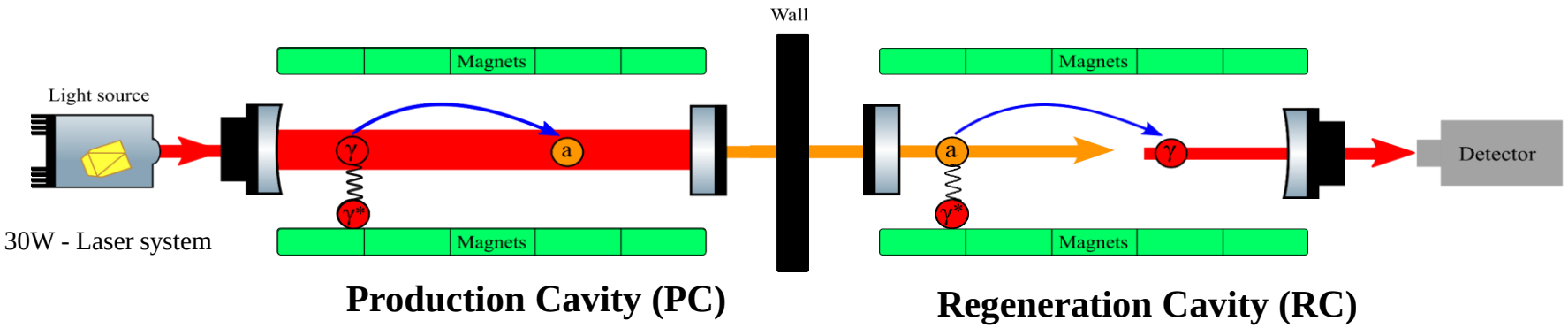


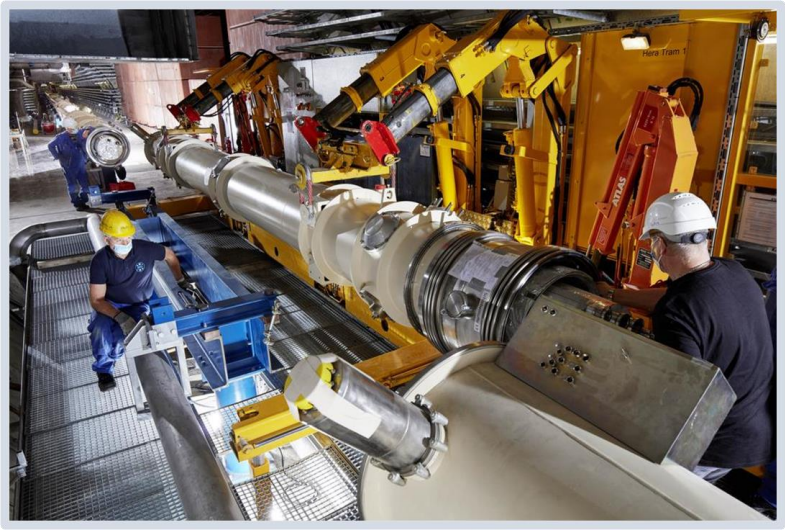


WP 1: Laser Interferometric Detector for Axions (LIDA)



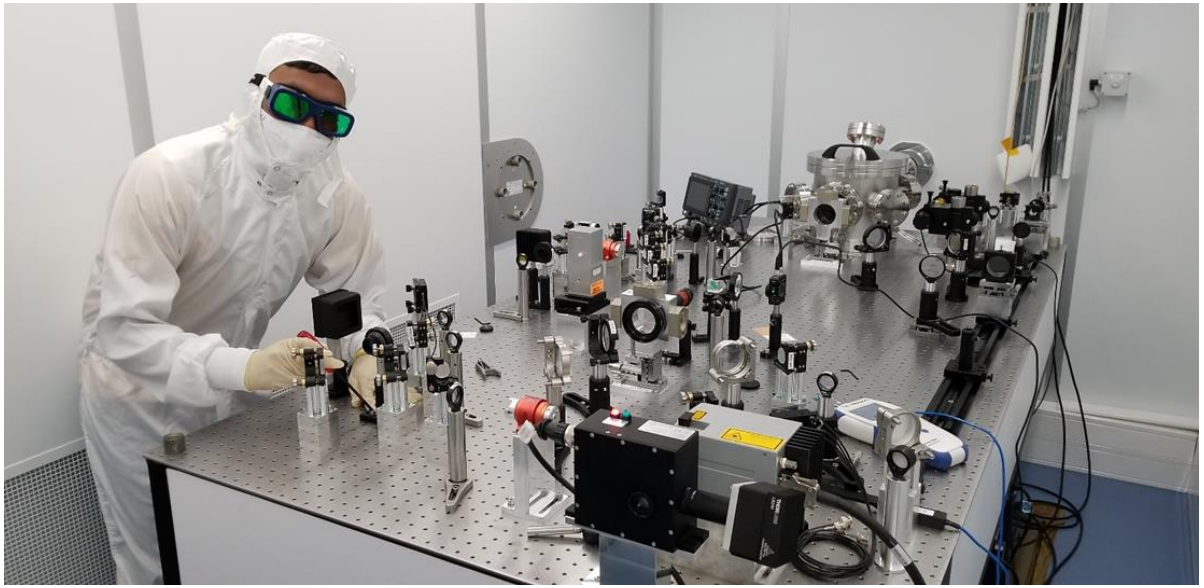
WP 2: contribution to ALPS II Light-shining-through-a-wall

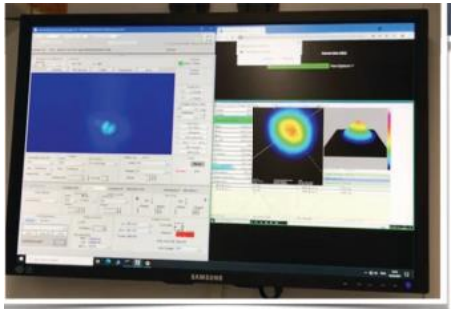




Photos: Marta Mayer DESY https//www.desy.de/news

ALPS II commissioning at DESY





- Laser frequency stabilized to a 250 m optical cavity
- Remote control
- Characterization of environmental noise and optics on going

Fabry-Perot interferometer

$$E(z=0) = E_0 \sin(\omega_0 t + \phi_0)$$

$$E(z=0) = E_0 \frac{e^{i(\omega_0 t + \phi_0)} - e^{-i(\omega_0 t + \phi_0)}}{2i}$$

$$E(z=0) = \frac{E_0}{2i} e^{i\omega_0 t} e^{i\phi_0} + c.c$$

$$E(z) = \frac{E_0}{2i} e^{i\phi_0} e^{i\omega_0 t} e^{-i\varphi} + c.c. \; ; \; \phi = kz$$

Fabry-Perot interferometer

$$E(z) = \underbrace{\frac{E_0}{2i} e^{i\phi_0}}_{E_1} e^{i\omega_0 t} e^{-i\varphi} + c.c. \; ; \; \phi = kz$$

$$E_1 \xrightarrow{\text{propagatron}} E_1 e^{-i\varphi}$$

$$E(z) = E_1 e^{-i\varphi} e^{i\omega_0 t} + c.c.$$

Fabry-Perot interferometer

$r^2 + t^2 = 1$ (no loss case)

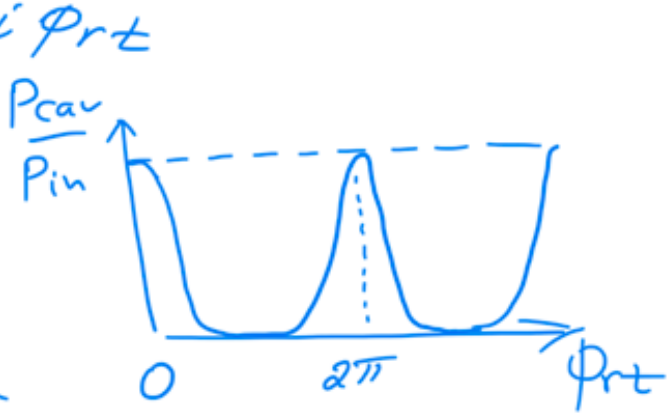
$R = r^2$ (power reflectivity)

$T = t^2$ (power transmissivity)

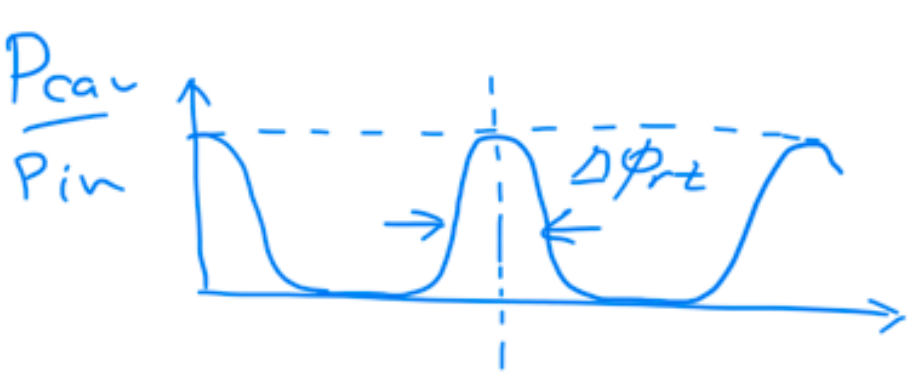
$$E_{cav} = E_{in}\, t + r^2 E_{cav} e^{-i\phi_{rt}}$$

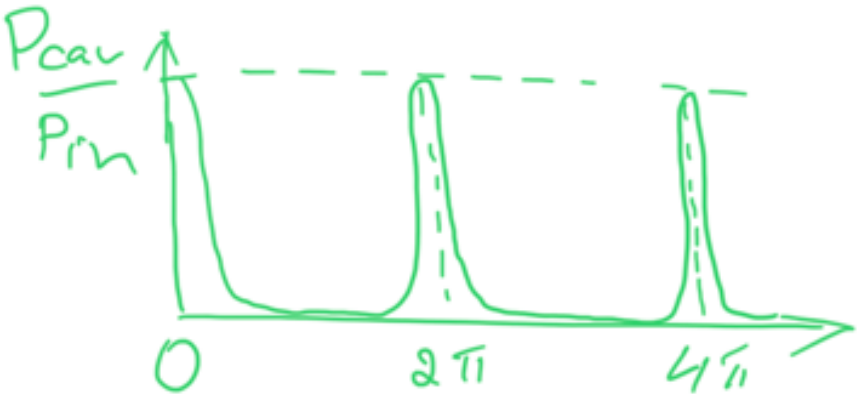
$$E_{cav} = \frac{t}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$

$$P_{cav} = \left| \frac{t}{1 - r^2 e^{-i\phi_{rt}}} \right|^2 P_{in}$$



Fabry-Perot interferometer

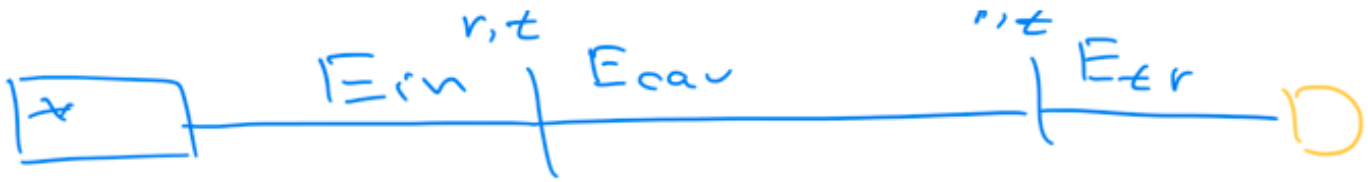




$$\mathcal{F} = \frac{2\pi}{\Delta\varphi_{rt}}$$ (resonator finesse)

full width at half maximum

Fabry-Perot interferometer

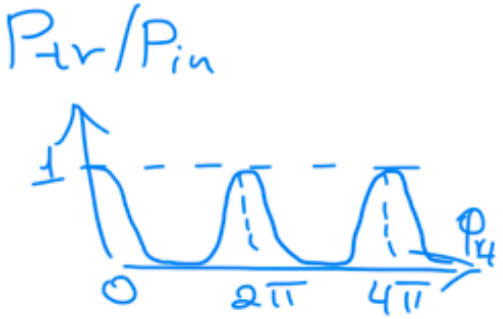


$$E_{cav} = \frac{t}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$

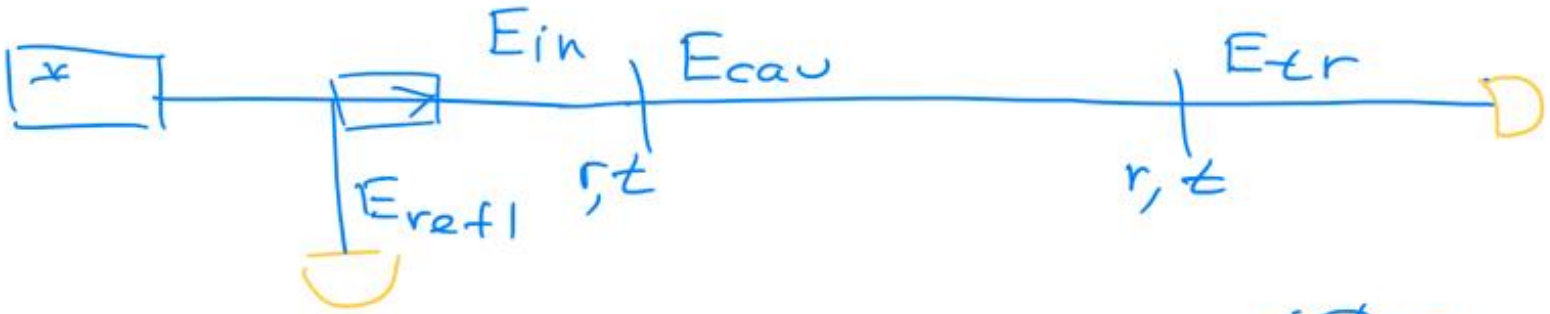
$$E_{tr} = E_{cav} e^{-i\frac{\phi_{rt}}{2}} t$$

$$E_{tr} = \frac{t^2 e^{-i\phi_{rt}/2}}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$

$$P_{tr} = \left| \frac{t^2 e^{-i\frac{\phi_{rt}}{2}}}{1 - r^2 e^{-i\phi_{rt}}} \right|^2 P_{in}$$



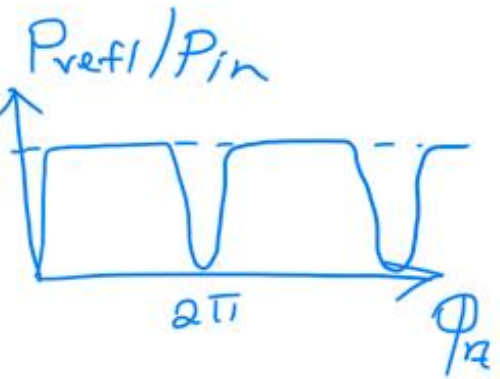
Fabry-Perot interferometer



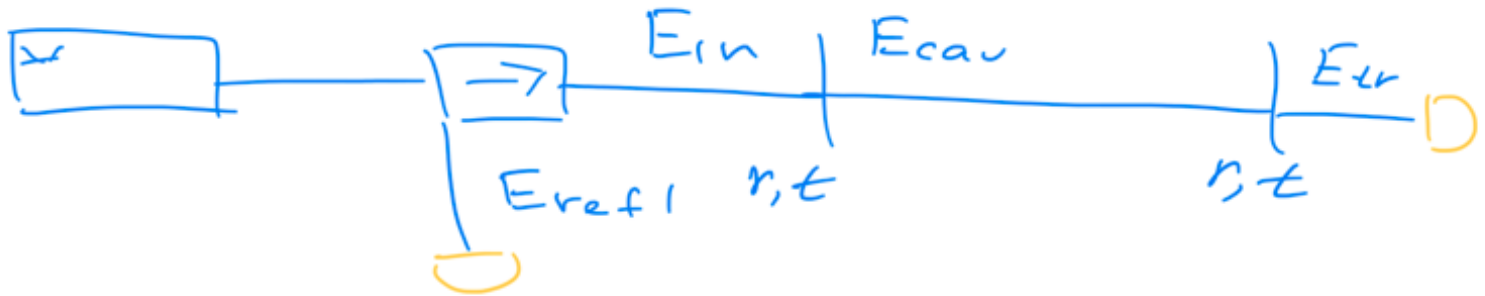
$$E_{refl} = -r E_{in} + t E_{cav}\, r e^{-i\phi_{rt}}$$

$$E_{refl} = \left(-r + \frac{t^2 r e^{-i\phi_{rt}}}{1 - r^2 e^{-i\phi_{rt}}} \right) E_{in}$$

$$E_{refl} = \frac{-r + r e^{-i\phi_{rt}}}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$



Optical gain



$$E_{refl} = r \frac{e^{-i\phi_{rt}} - 1}{1 - r^2 e^{-i\phi_{rt}}} E_{in}$$

For $\phi_{rt} - 2\pi N \ll 1$, $T \ll 1$

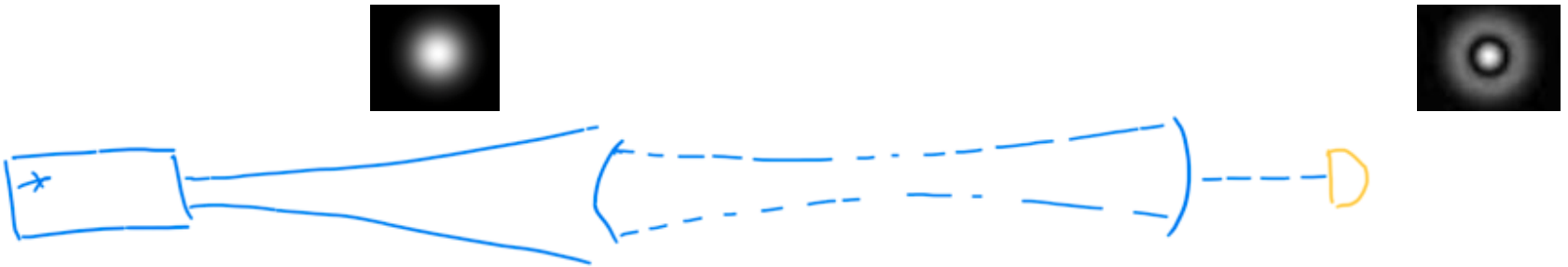
$$E_{refl} = r \frac{1 - i\phi_{rt} - 1}{1 - r^2 + r^2 i\phi_{rt}} E_{in} \simeq -\underbrace{\frac{i\phi_{rt}}{T}} E_{in}$$

$$\simeq -i\phi_{rt} B$$

Practical concerns

- Alignment

- Mode matching



Solution to the wave equation

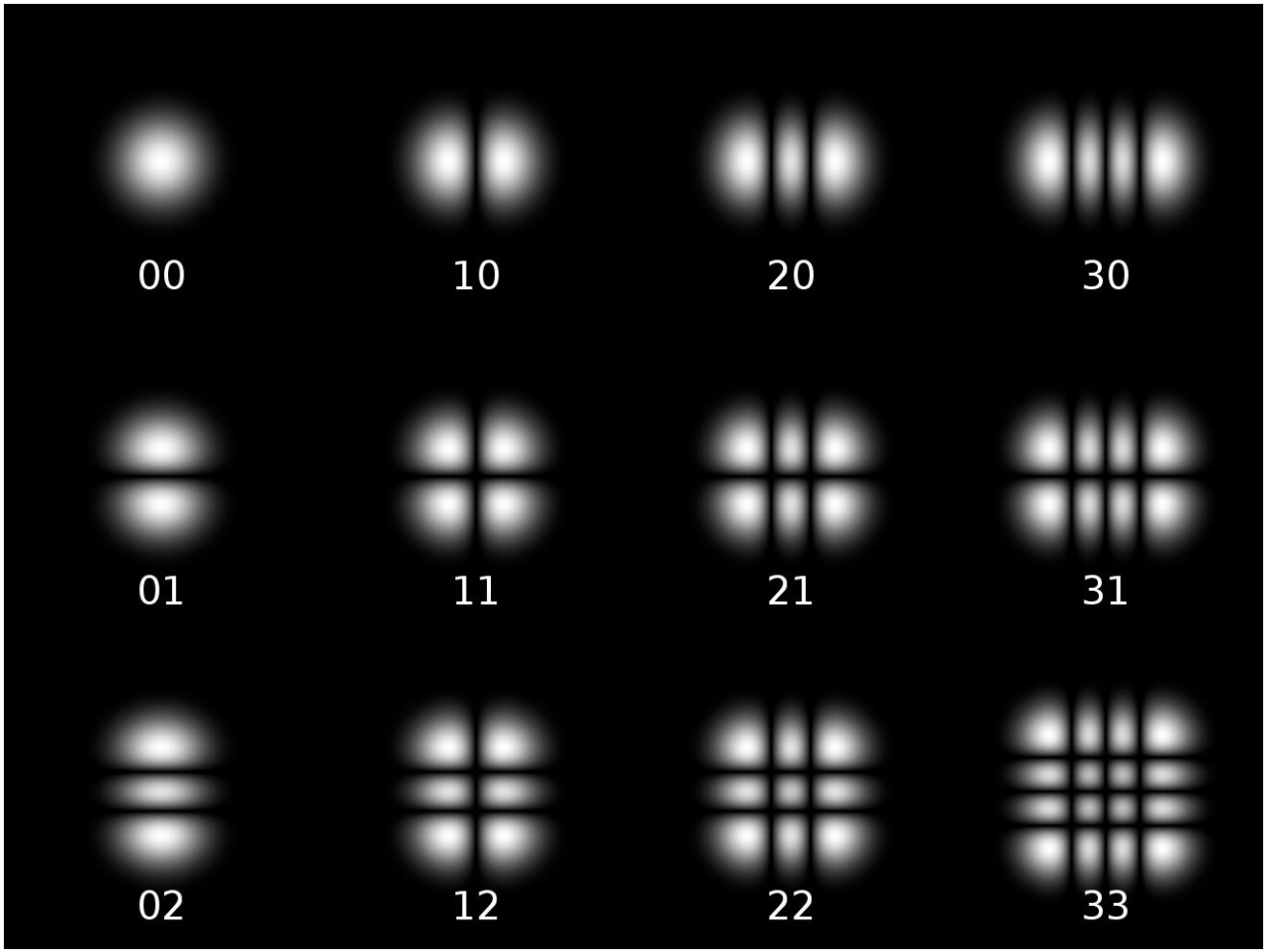
$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = 2ik\frac{\partial E}{\partial z}$$

$$E_{l,m}(x,y,z) = E_0 \frac{w_0}{w(z)} \underbrace{He\left(\frac{\sqrt{2}x}{w(z)}\right) Hm\left(\frac{\sqrt{2}y}{w(z)}\right)}_{\text{Hermite polynomials}} \times$$

$$\exp\left(-(x^2+y^2)\left(\underbrace{\frac{1}{w(z)^2}}_{\text{beam size}} + \underbrace{\frac{ik}{2R(z)}}_{\text{curvature}}\right)\right) \times$$

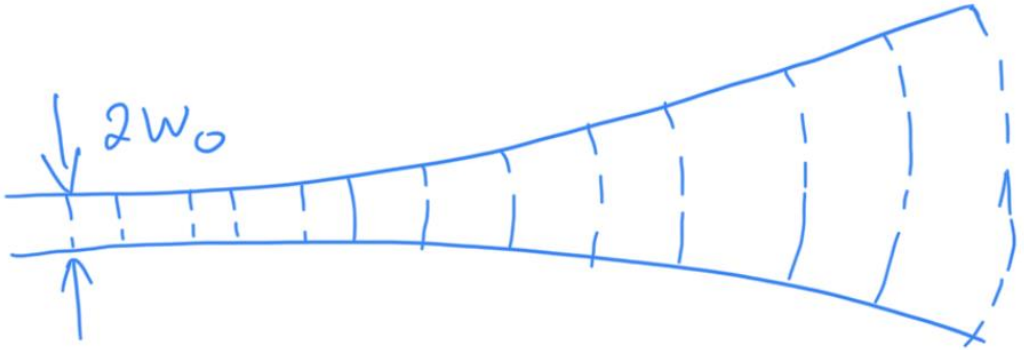
$$\exp\left(i\underbrace{\psi(z)}_{\text{Gouy phase}}\right)$$

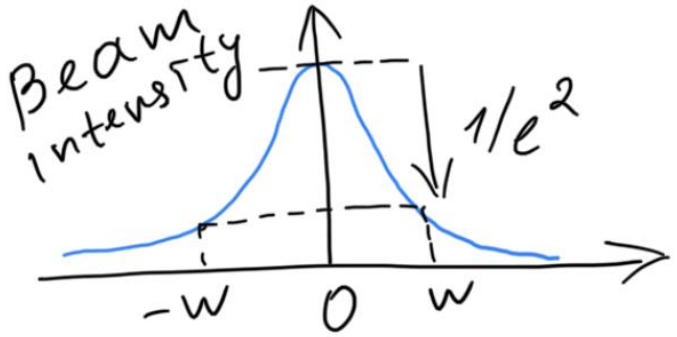
Hermite-Gaussian modes



LIGO output mode

Properties of the Gaussian beam





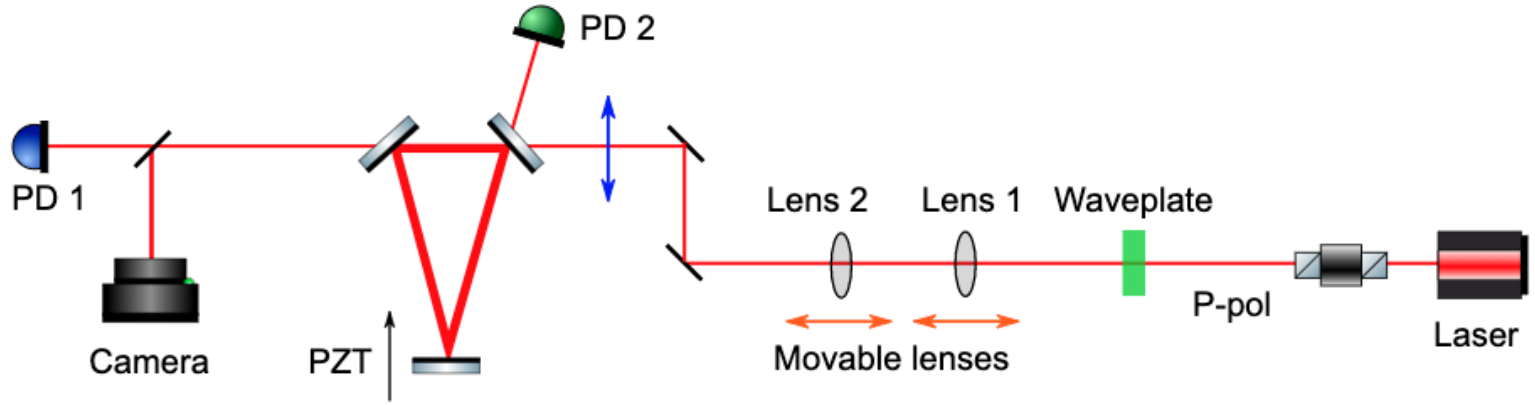
Rayleigh range:

$$z_R = \frac{\pi w_0^2}{\lambda}$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

$$R(z) = z\left(1 + \left(\frac{z_R}{z}\right)^2\right)$$

Tutorial



List of tasks:

- Rotate the waveplate to couple only S- or P-polarisation into the cavity
- Maximise mode matching to the cavity
- Align the input beam relative to the cavity axis
- Find optical finesse of the cavity for S- and P-polarisation
- Find the round trip Gouy phase of the cavity

Waveplate angle, degrees: **20**

Lens 1 offset, cm: **0**

Lens 2 offset, cm: **0**

Beam X-offset, um: **0**

Beam Y-offset, um: **0**

Save data

Click on the spectrum to see the camera image corresponding to that position