Gravitational-wave Detection with Cavity-assisted Atom Interferometry

Miguel Dovale Álvarez

GRASS in Padova, 1-2 March 2018

Birmingham Institute of Gravitational Wave Astronomy

sr.bham.ac.uk/gwgroup/

UNIVERSITY OF BIRMINGAM - birmingham.ac.uk

@UoBIGWaves

Cold Atoms group:

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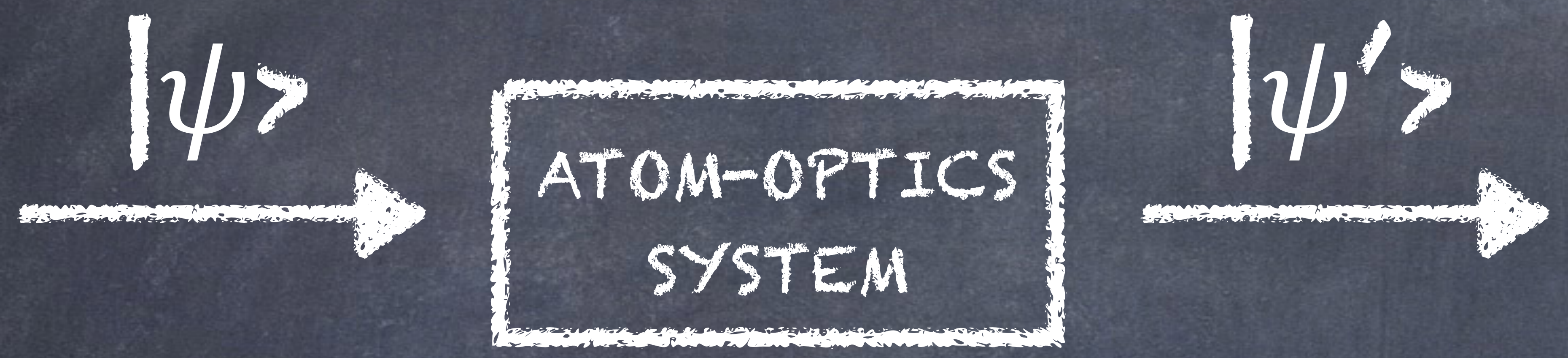
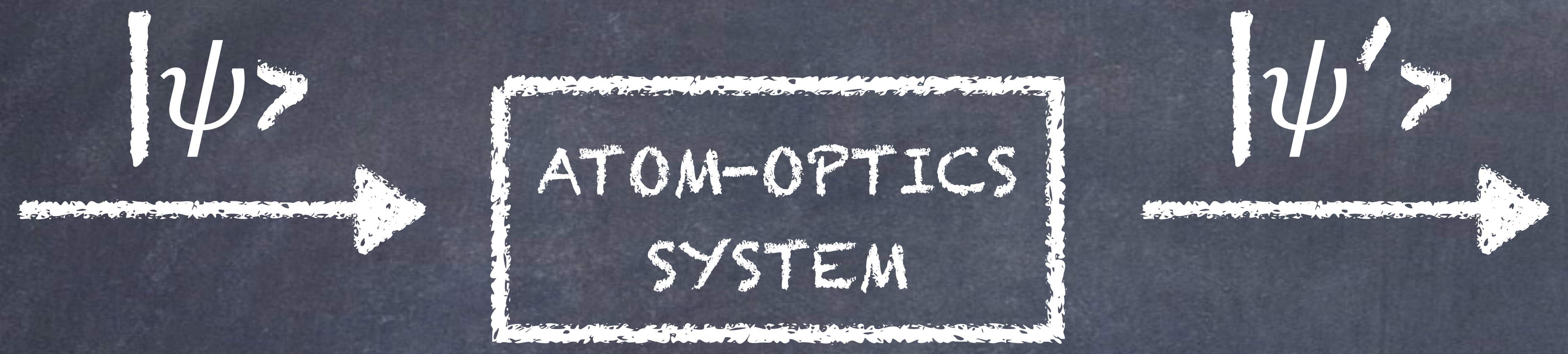
Daniel D Brown
Aaron W Jones
Conor M Mow-Lowry
Haixing Miao
Andreas Freise

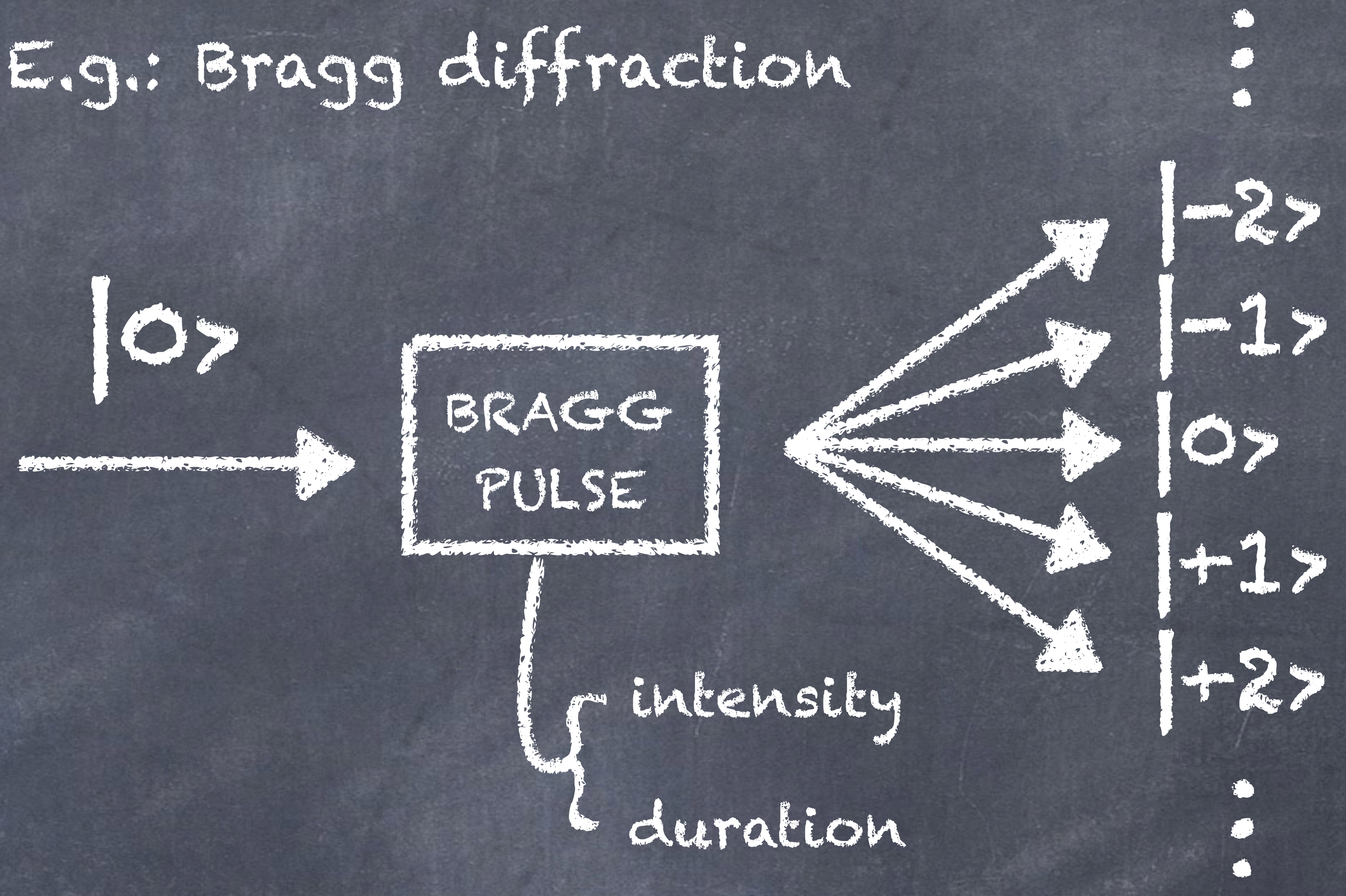
- Atom optics



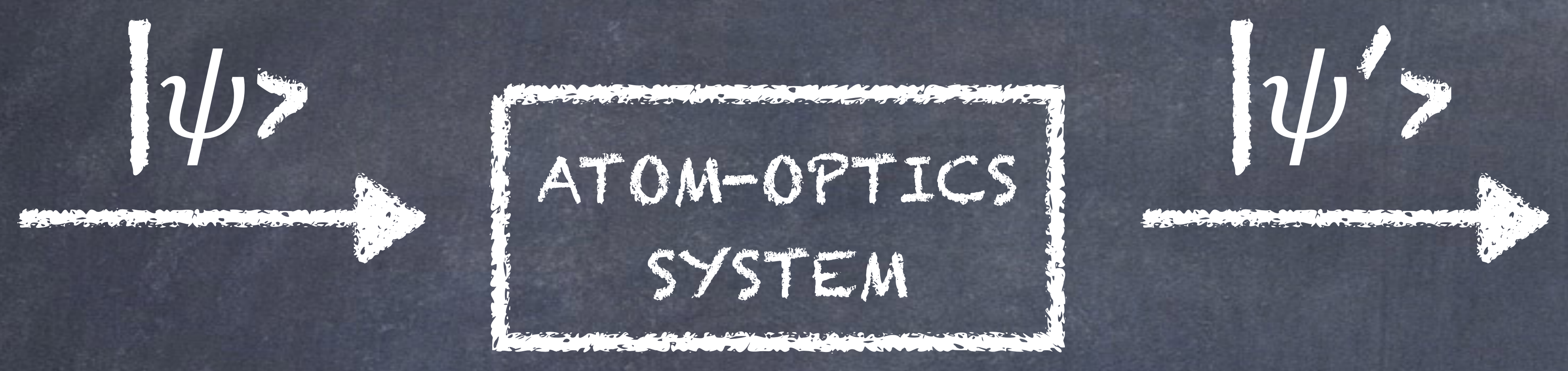
- Atom optics



E.g.: Bragg diffraction



- Atom optics



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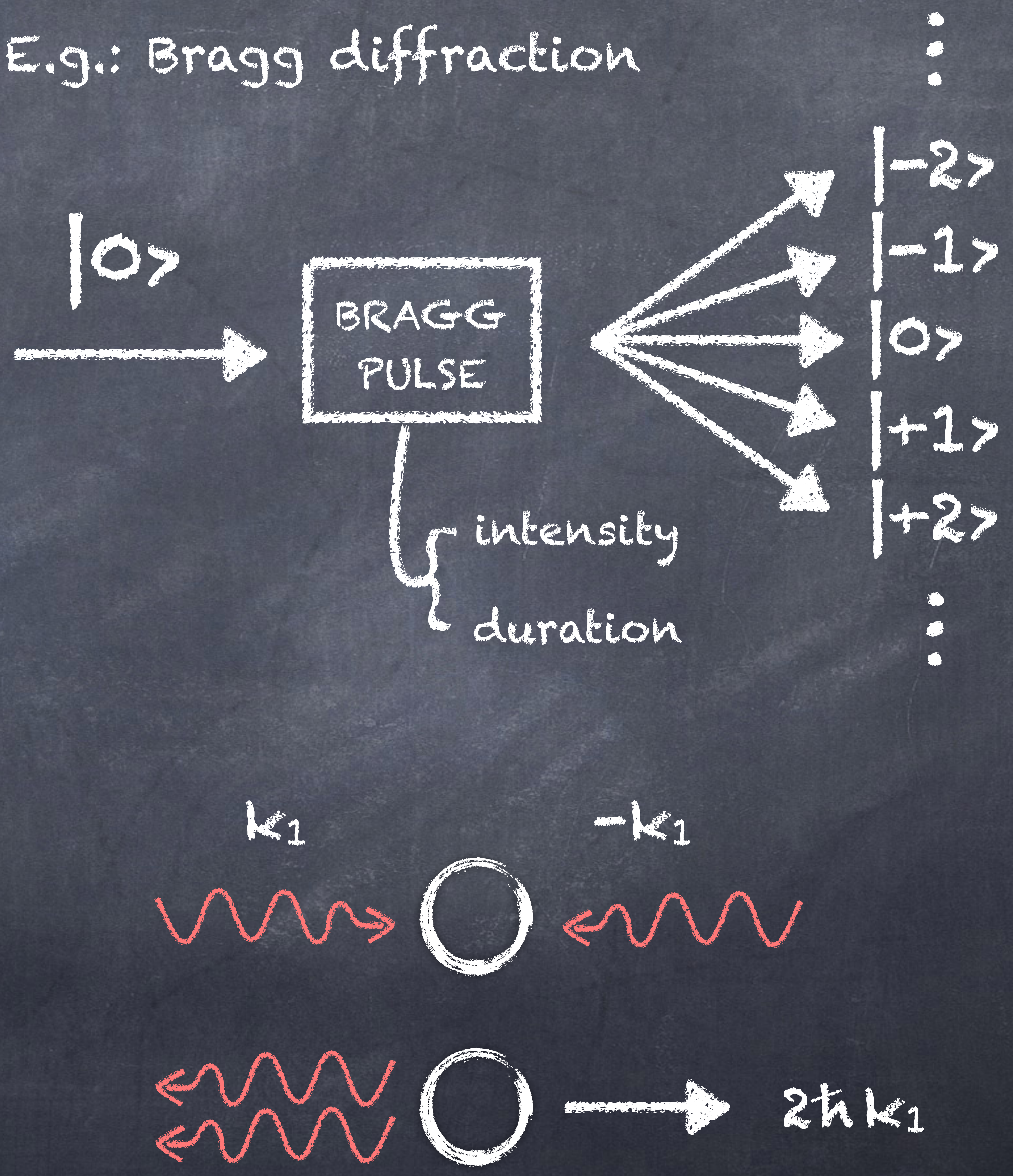

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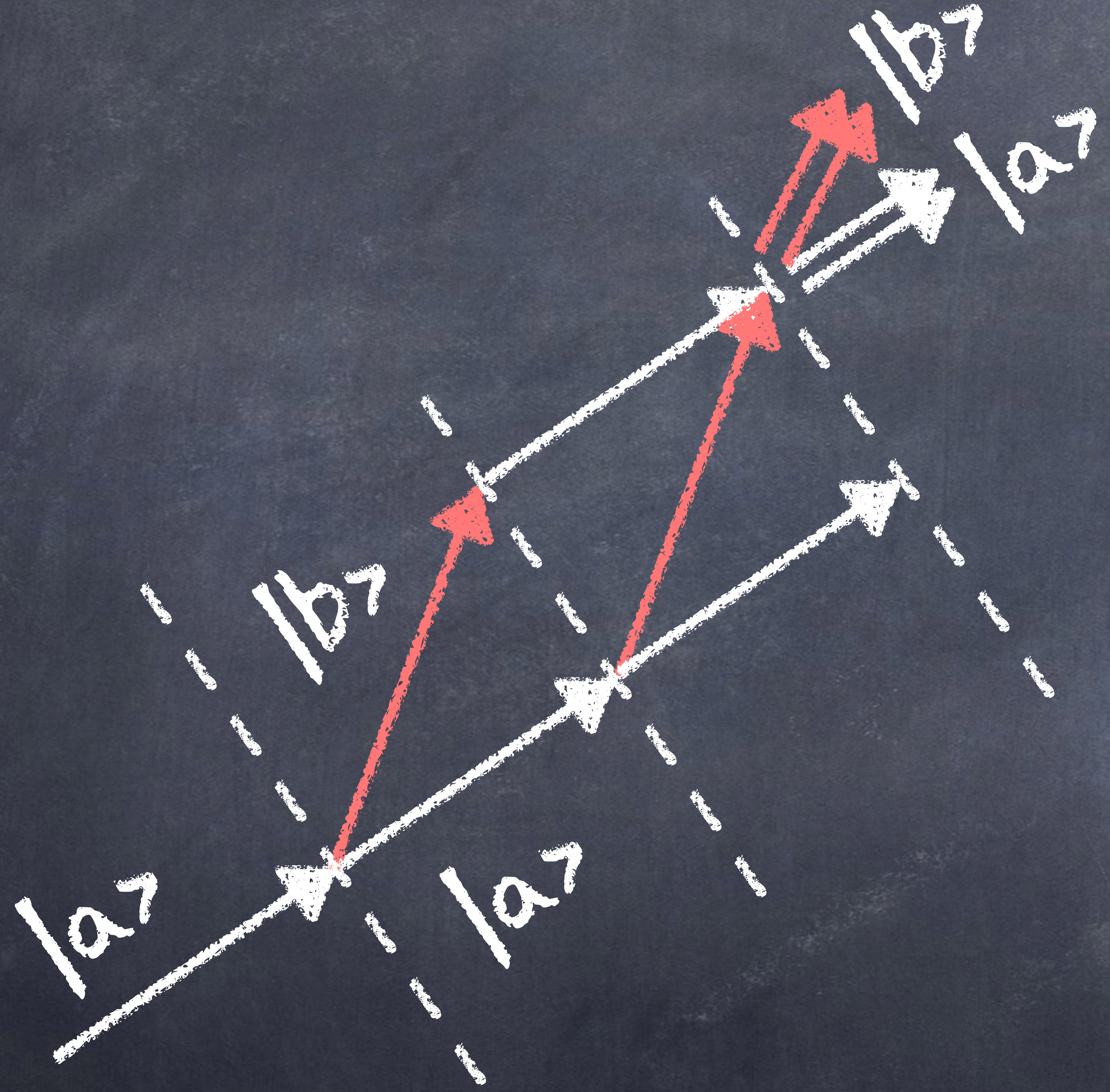

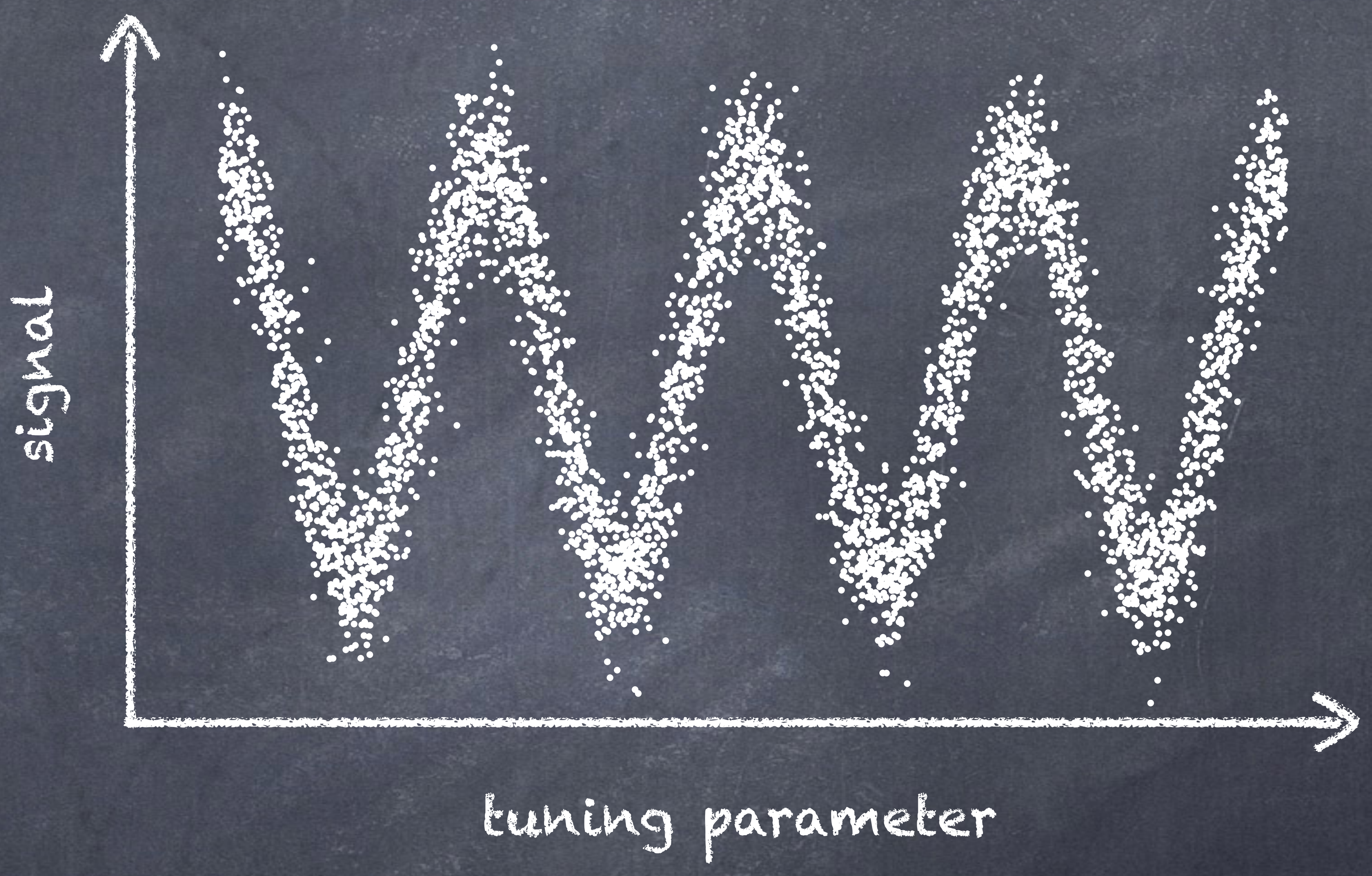

- Optical cavities

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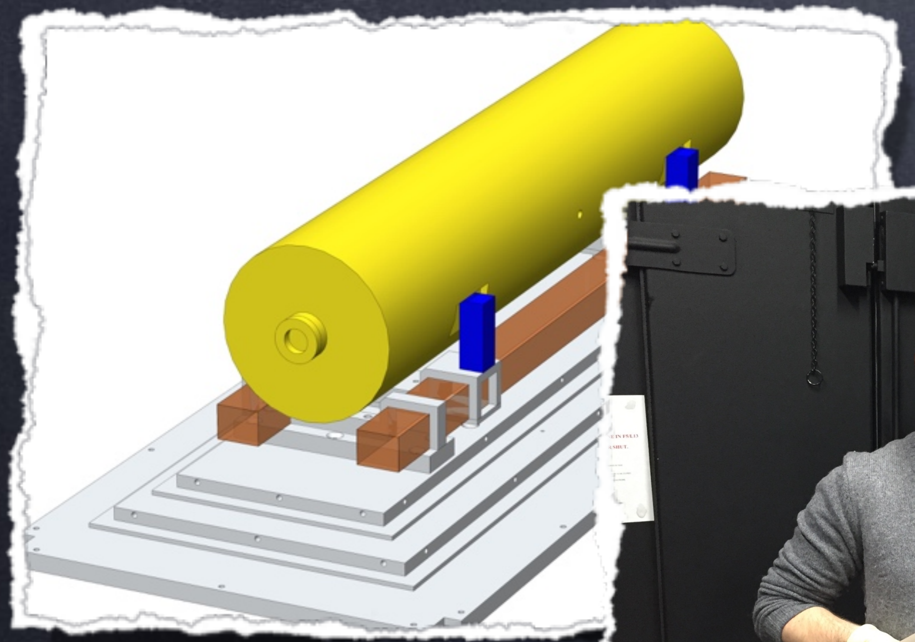
NPL



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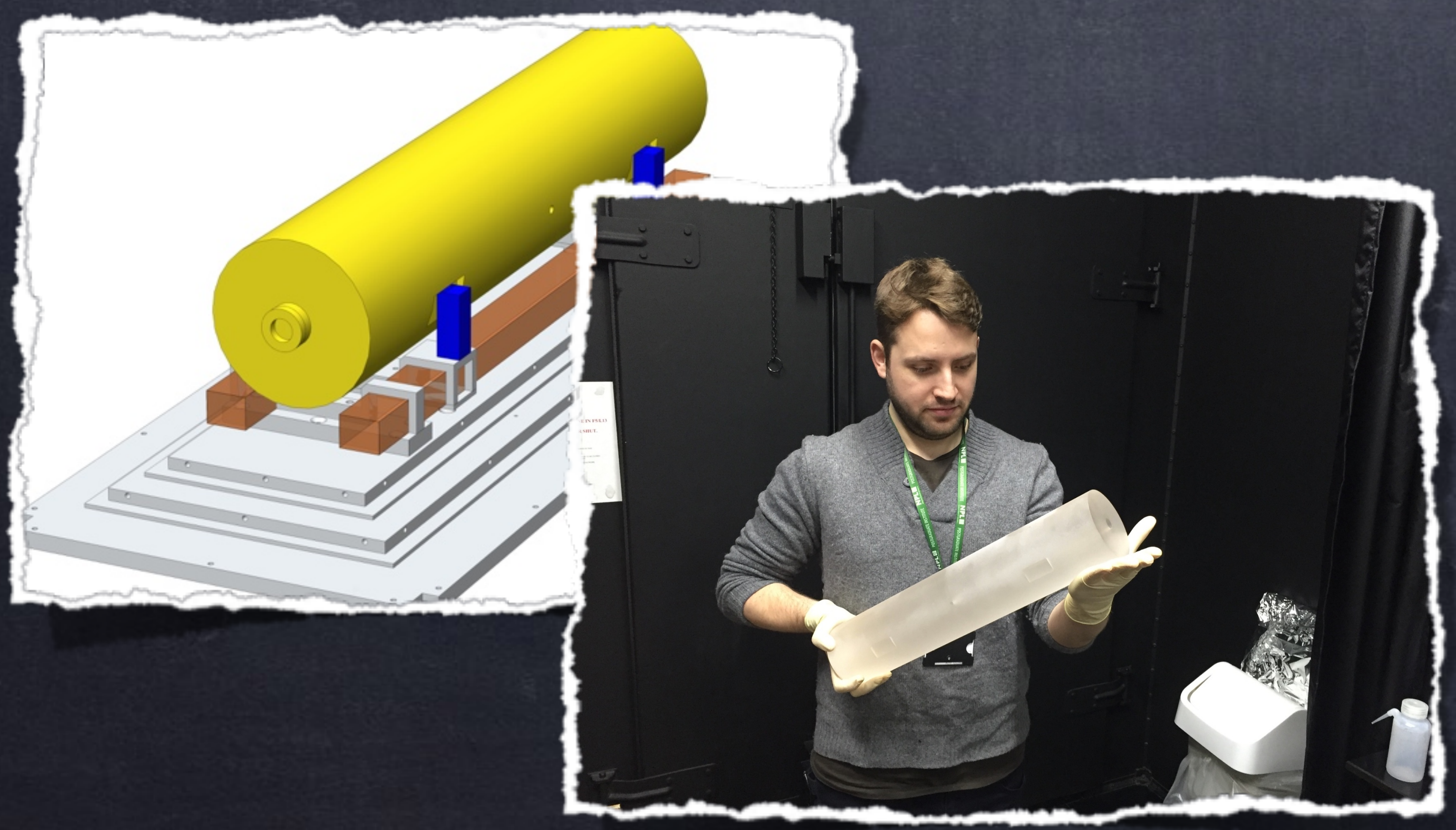
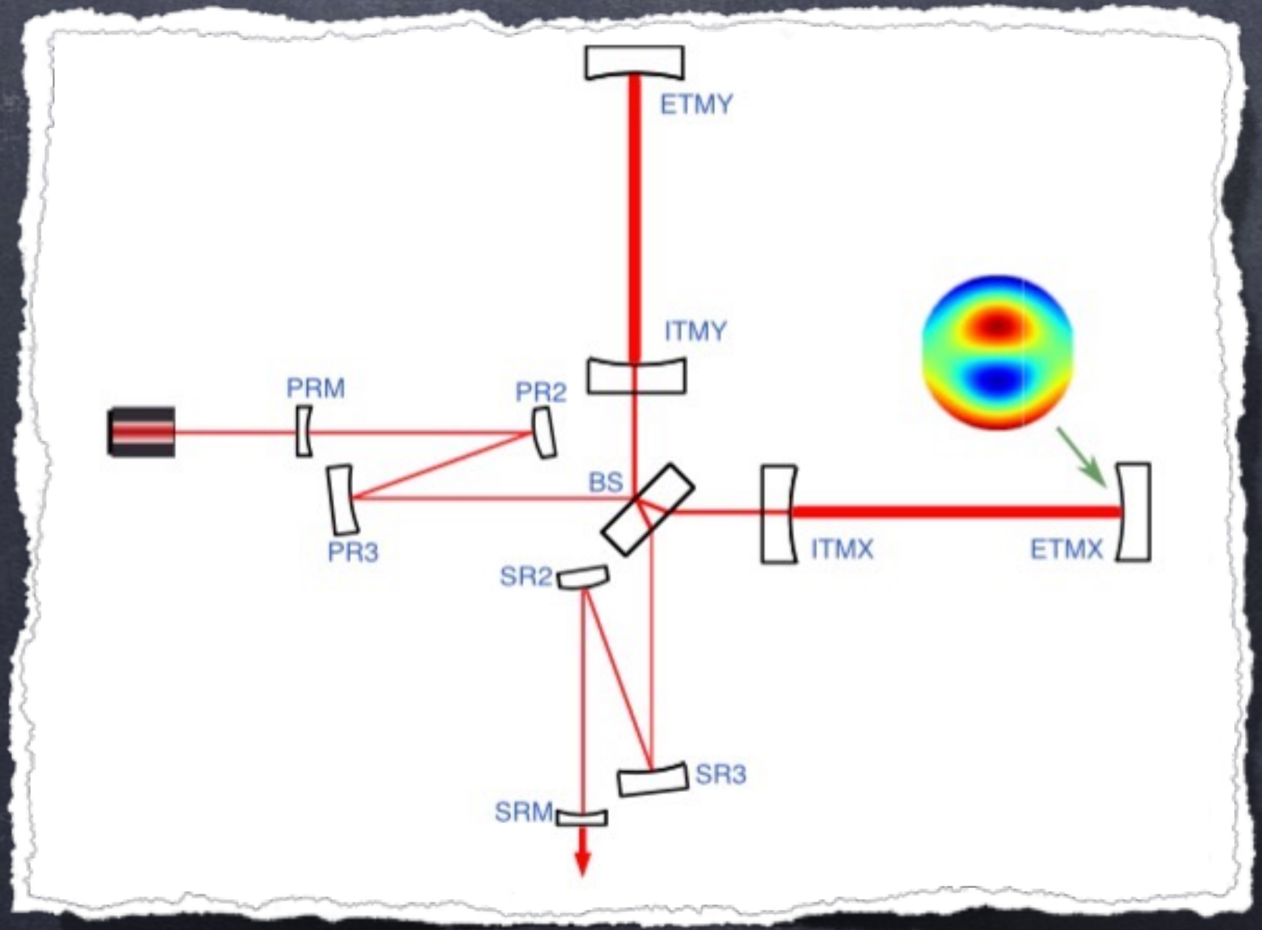
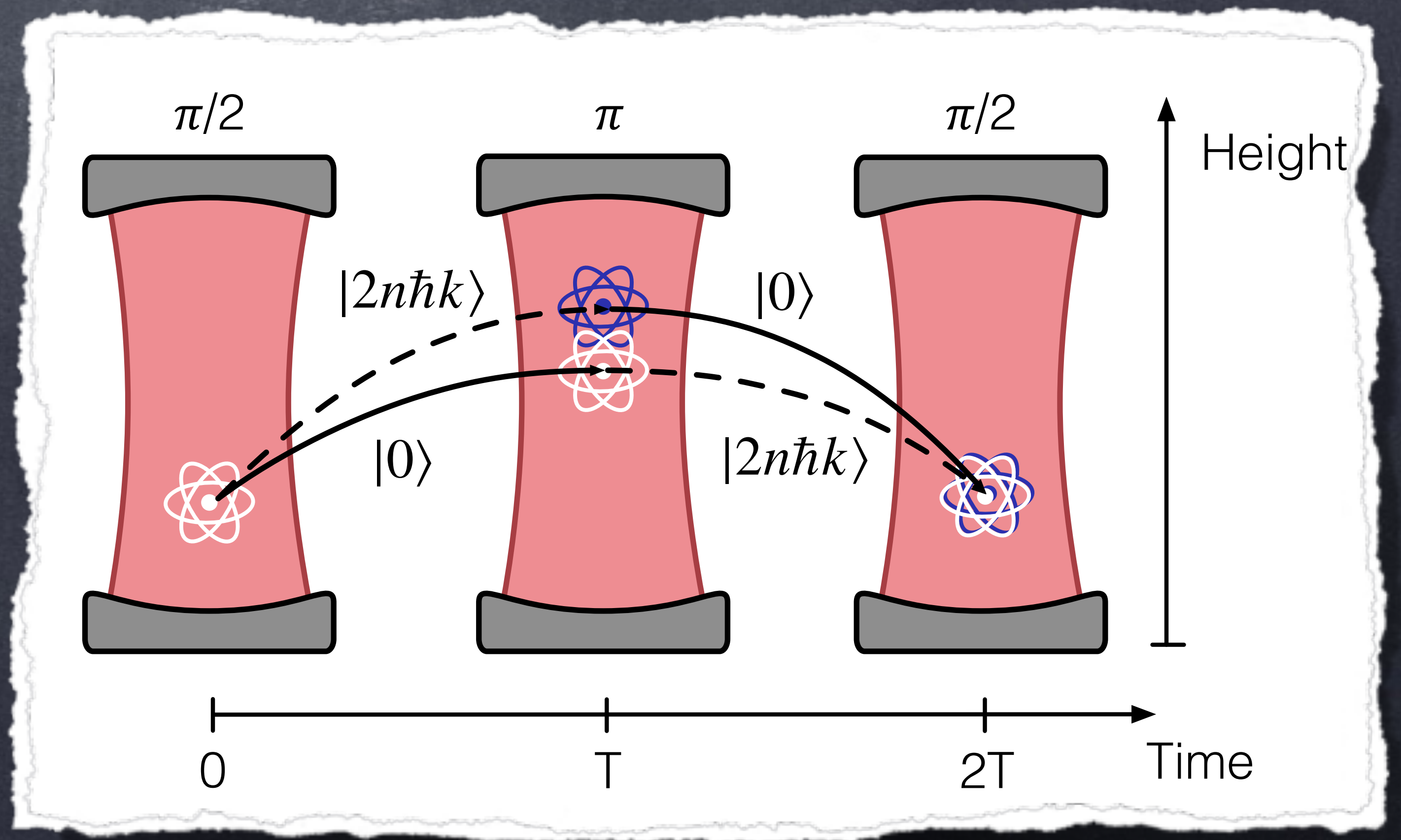


LIGO



Cold Atoms



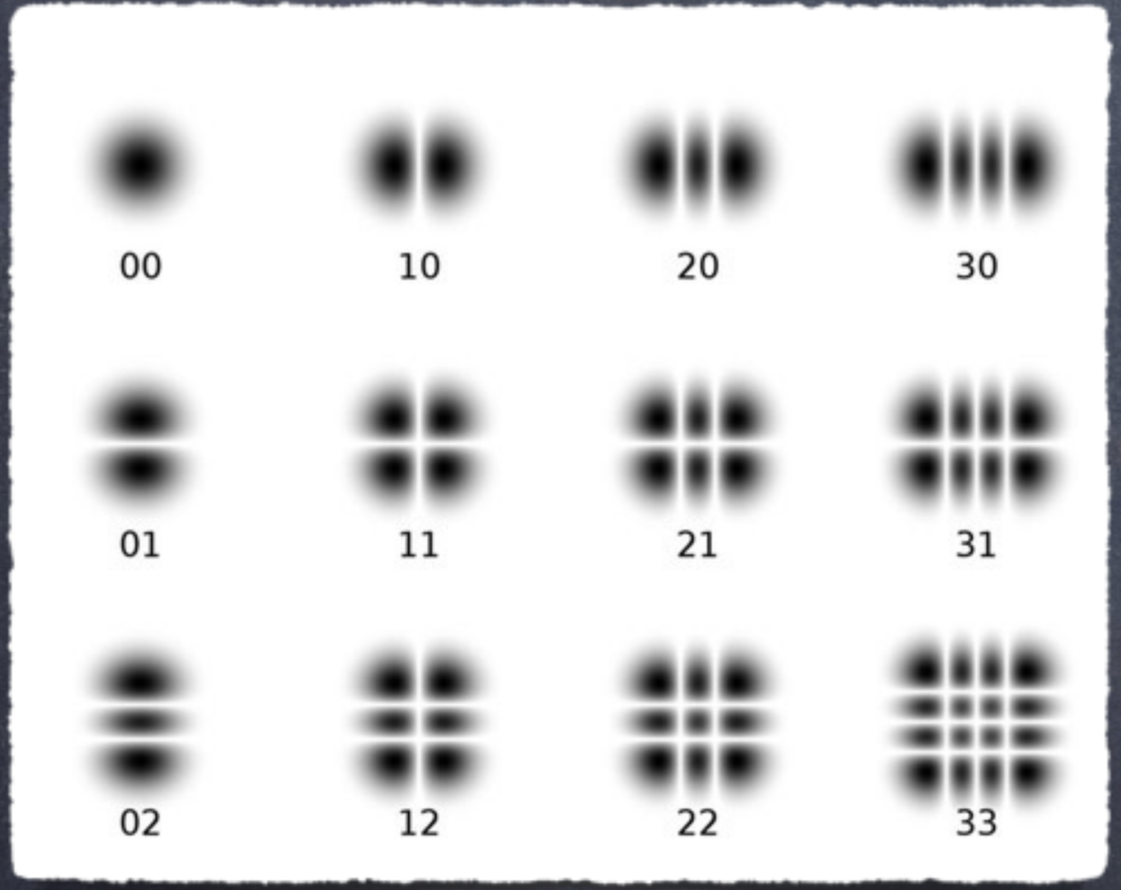
- Optical cavities

$$\text{field} = \sum_{nm} c_{nm} HG_{nm}$$

"Hermite-Gauss" modes

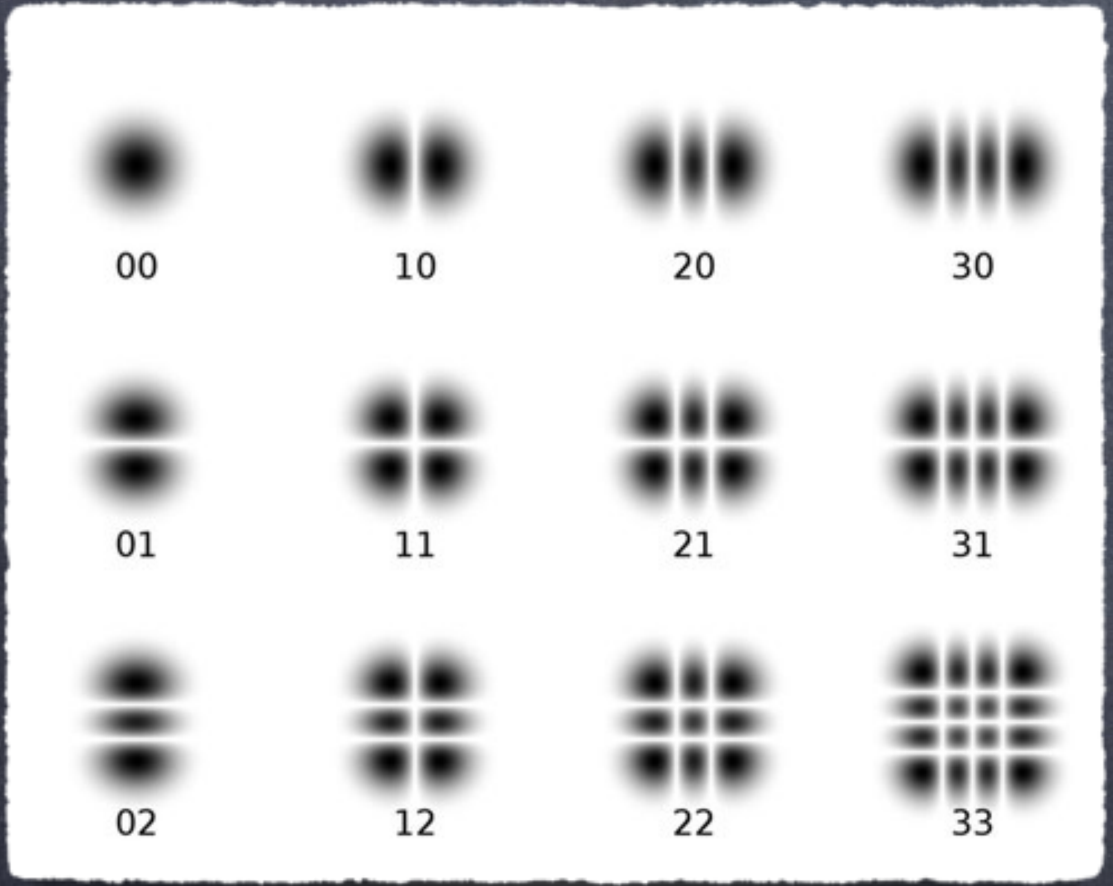
- Optical cavities

$$\text{field} = \sum_{nm} c_{nm} HG_{nm}$$

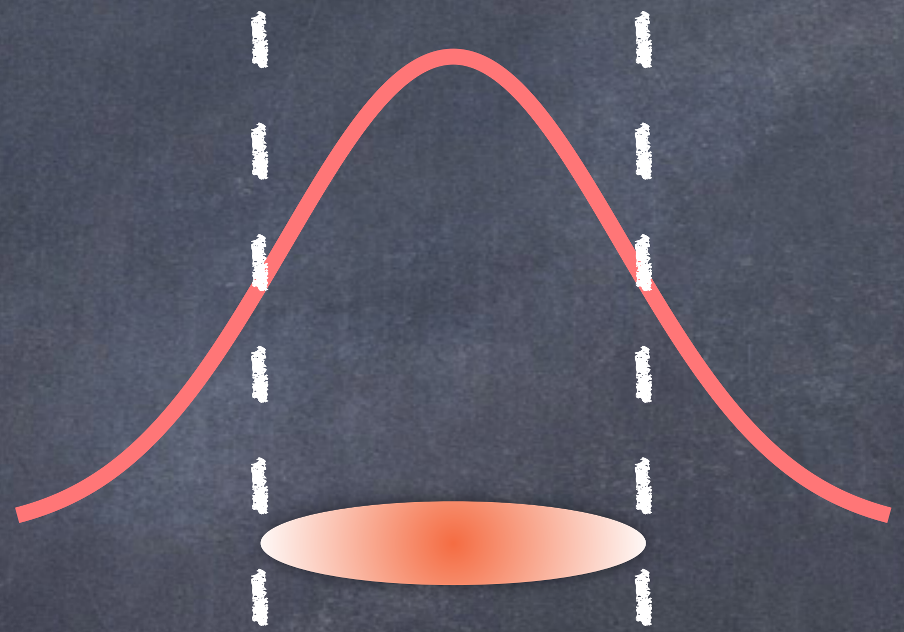


• Optical cavities

field $= \sum_{nm} c_{nm} HG_{nm}$

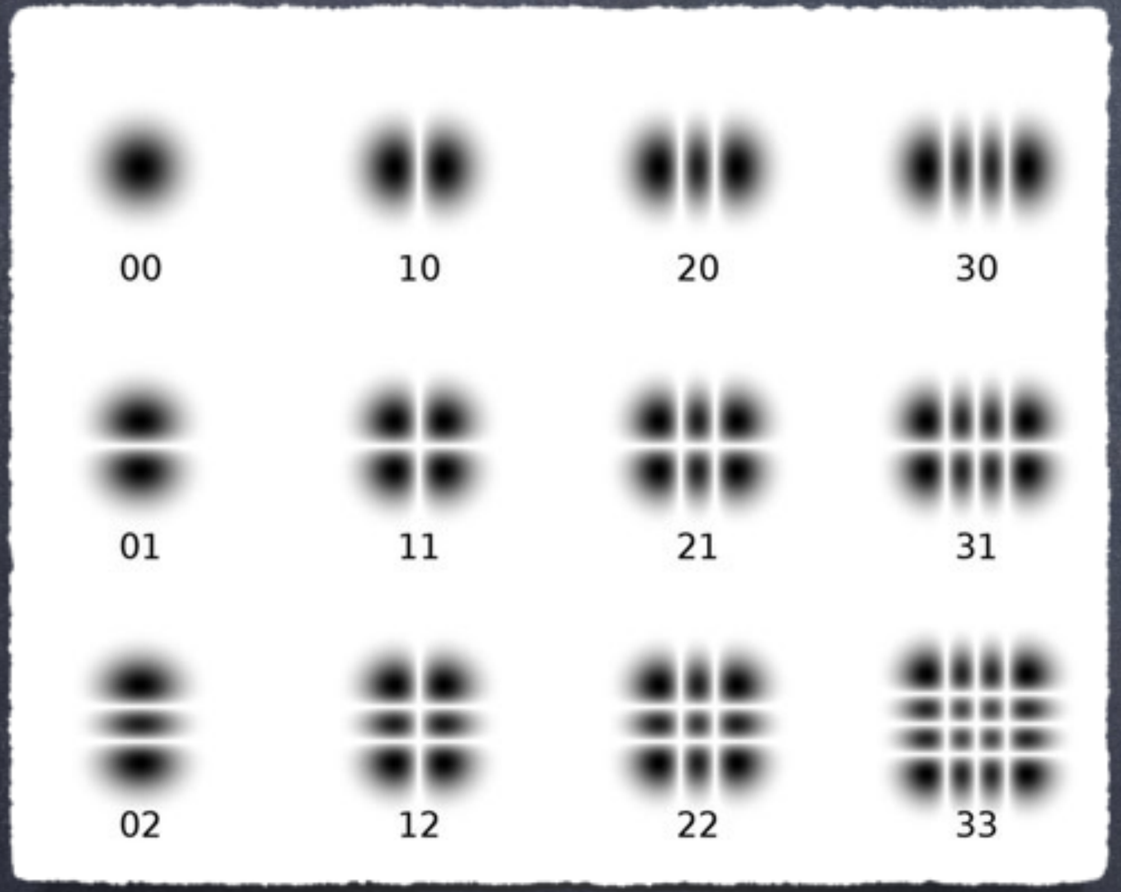


Ideal field $= HG_{00}$



Optical cavities

$\text{field} = \sum_{nm} c_{nm} HG_{nm}$



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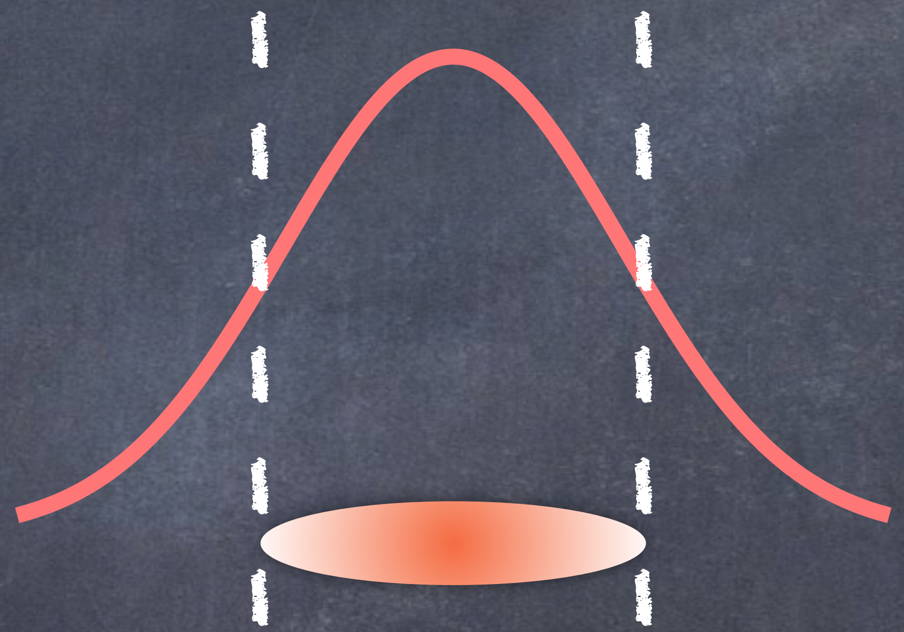
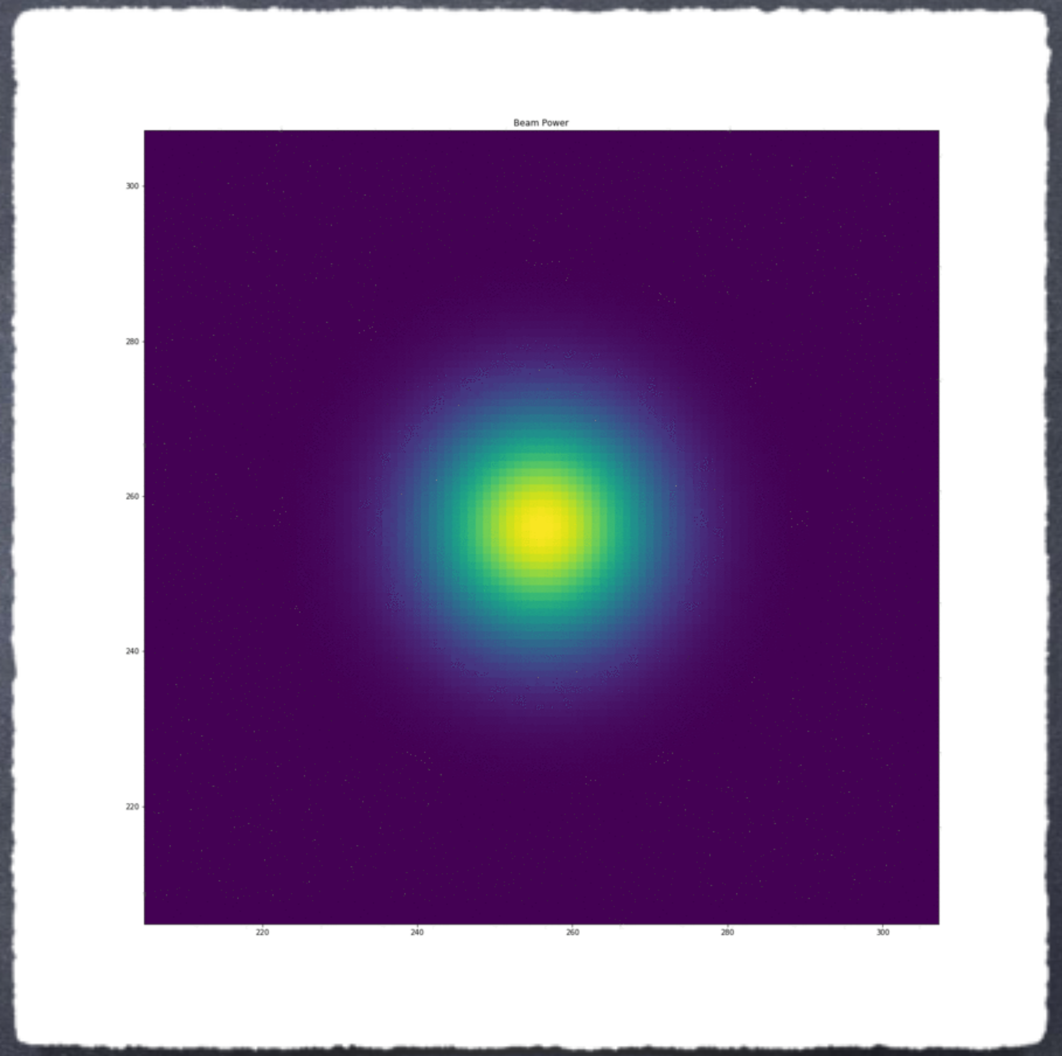


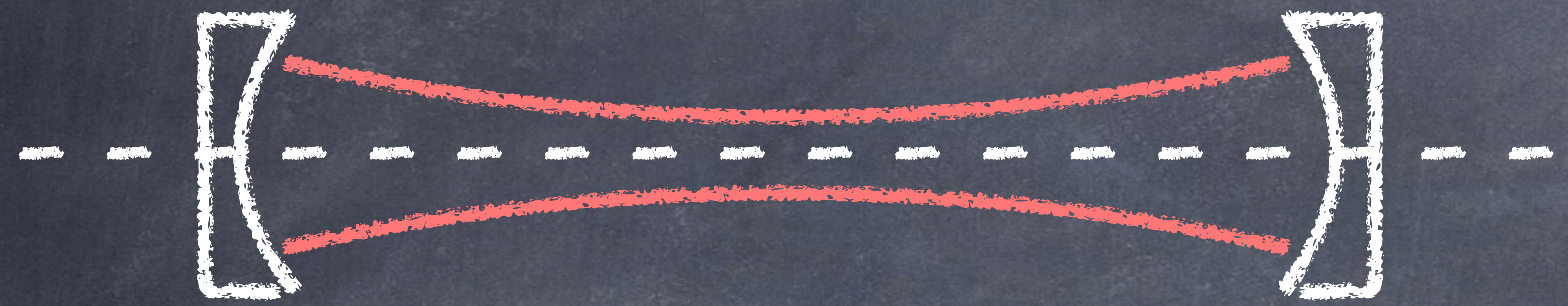
$HG_{00} + HG_{01}$



Generated with PyKat

gwoptics.org/pykat/

- Optical cavities



ROC
Length

} Gouy phase shift

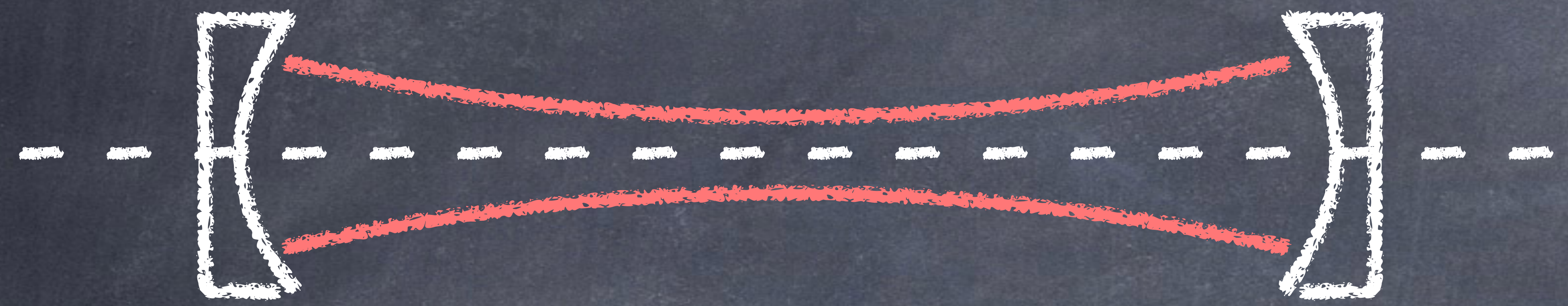
$\Delta f = 2 \arccos(\pm\sqrt{g_1 g_2})$

↓

$\Delta\phi_{nm} = (n+m)\,\Delta f$

• Optical cavities

$g_i = 1 - R_i/L$



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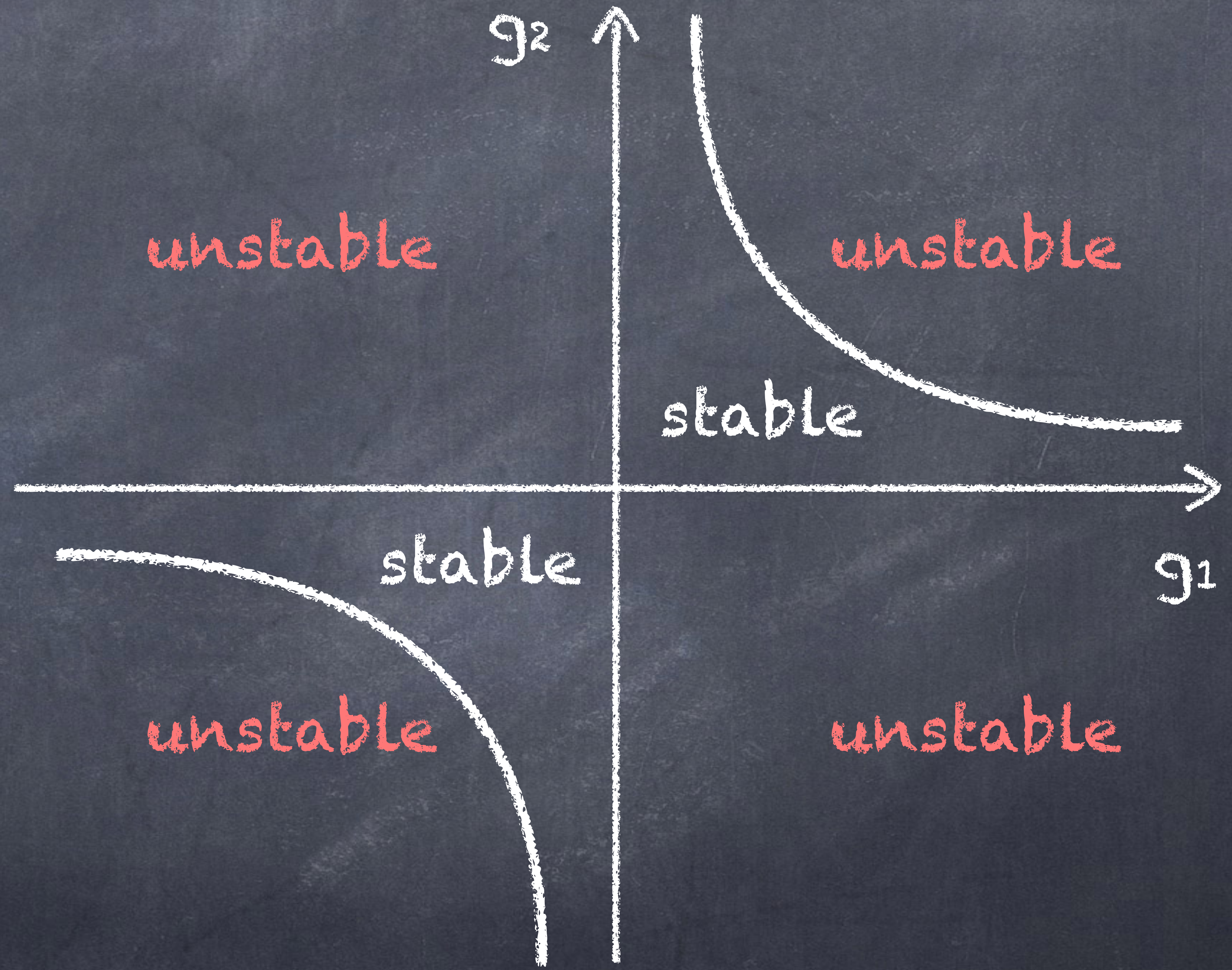
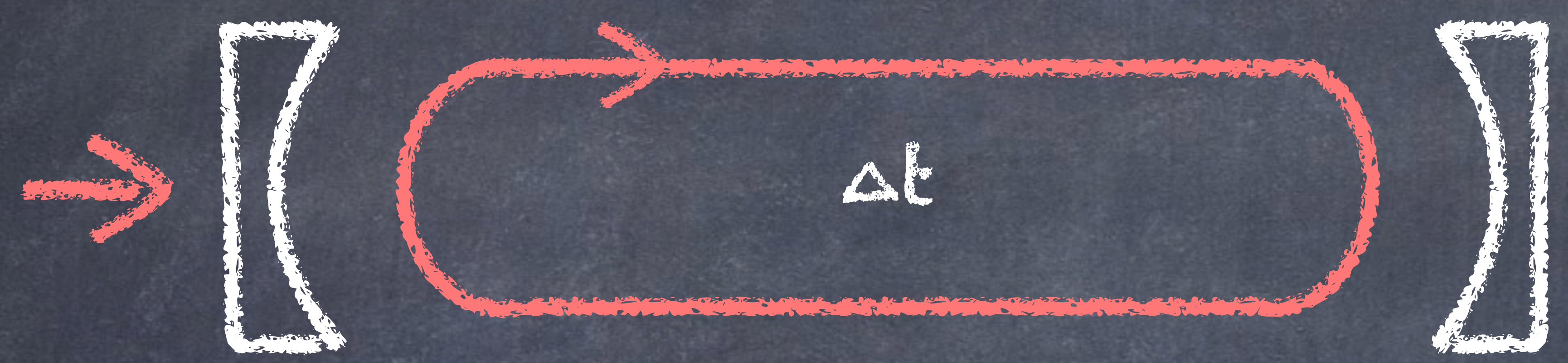


- Optical cavities

Finesse, Length	Bandwidth, $\Delta\nu = c/(2LF)$
	Photon lifetime, $\Delta t = \pi c/(LF)$

- Optical cavities



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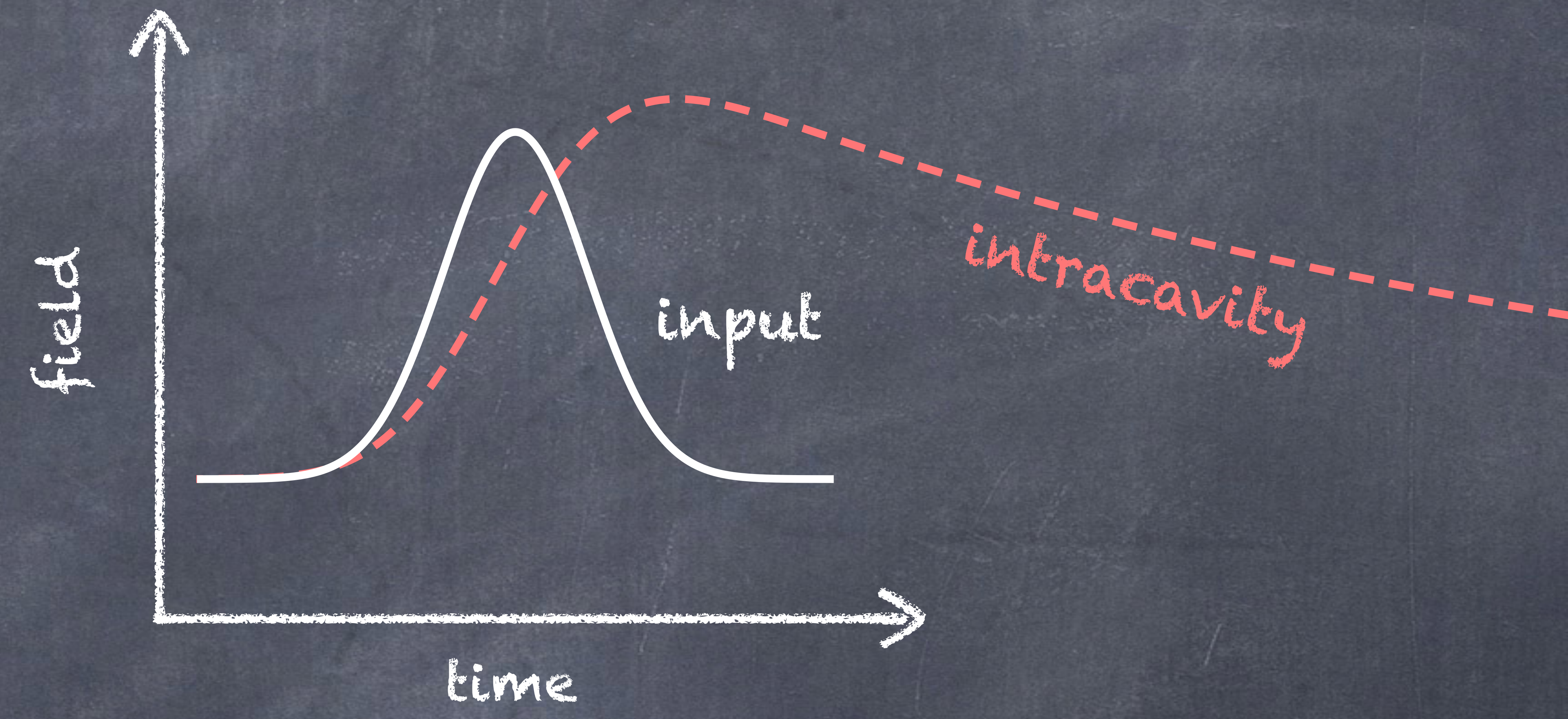
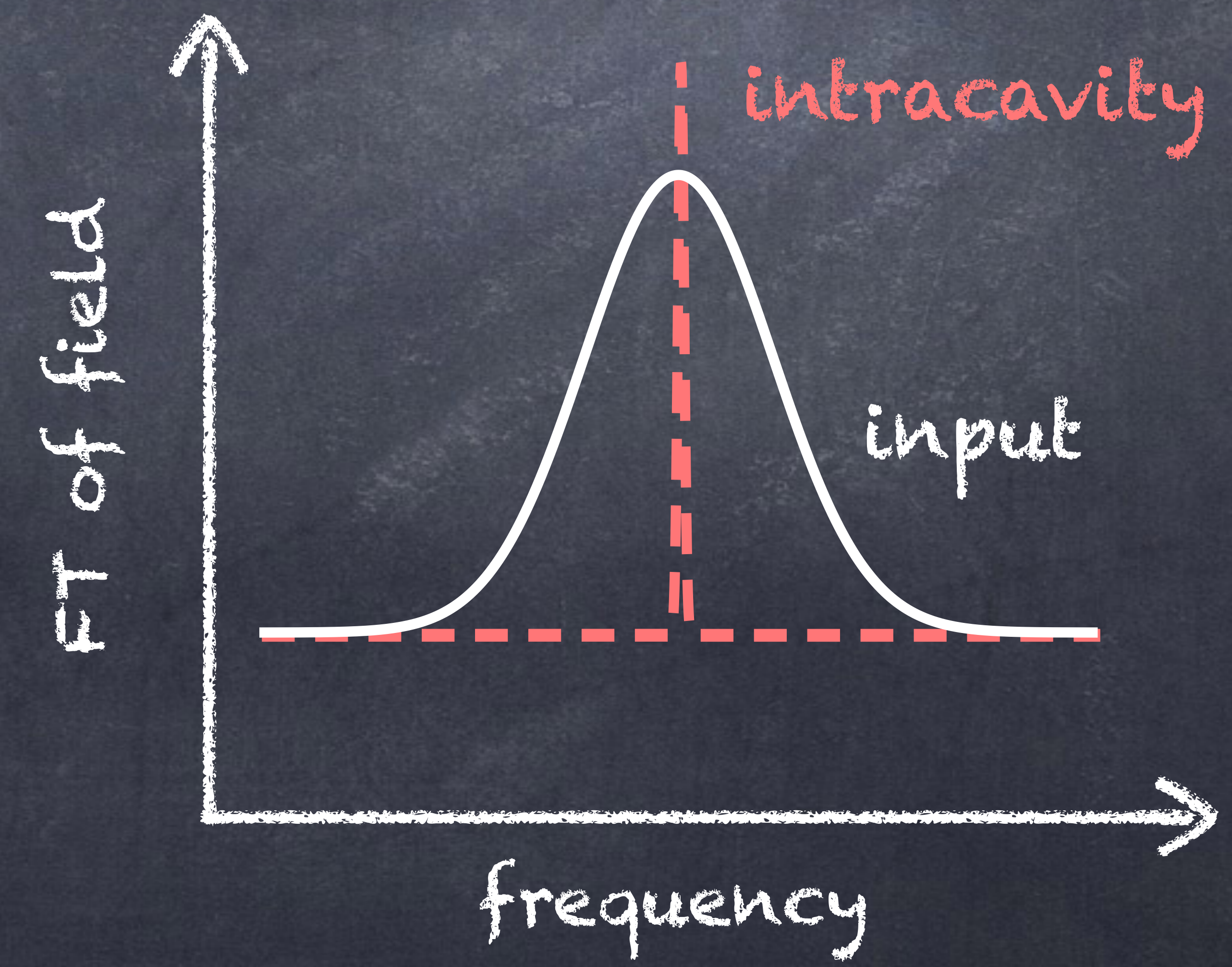
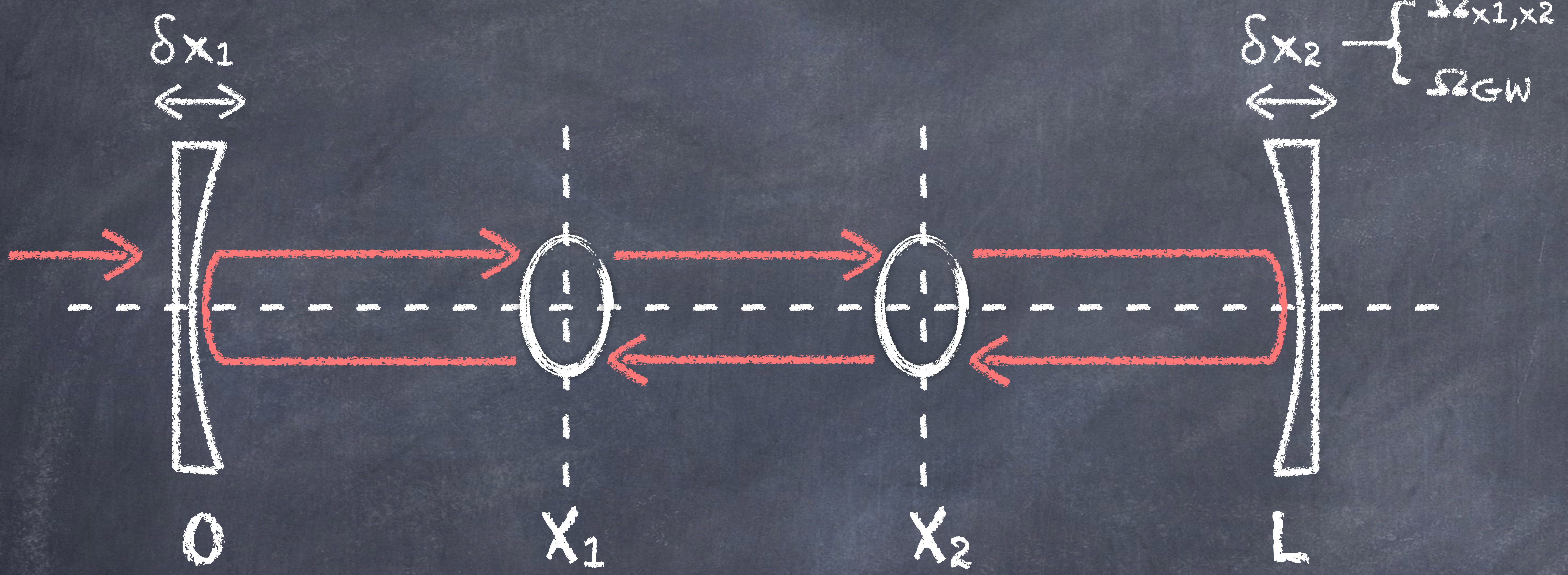




- GW detection with AI in an OC



Differential signal: $\Delta\phi_1 - \Delta\phi_2$

↓

$\Delta\phi_1 = \Delta\phi_{field} + \Delta\phi_{inertial} + \Delta\phi_{noise}$

↓

$\Delta\phi_{field} \propto n\, \Delta t_{RT}\, v(t)$

{ Mirror vibration
GW strain

- Effect of the cavity on the atomic transitions
    - How do the cavity parameters affect the transitions?
    - Are there optimal values?
    - How does the order of the process come into play?
    - Can we set interferometer constraints based on the performance of the cavity?

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arxiv.org/abs/1710.02448

PHYSICAL REVIEW A **96**, 053820 (2017)

Fundamental limitations of cavity-assisted atom interferometry

M. Dovale-Álvarez,* D. D. Brown, A. W. Jones, C. M. Mow-Lowry, H. Miao, and A. Freise
School of Physics and Astronomy and Institute of Gravitational Wave Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

(Received 25 September 2017; published 8 November 2017)

- Effect of the cavity on the atomic transitions

BRAGG PULSE

- intensity
- duration

- Effect of the cavity on the atomic transitions

BRAGG PULSE

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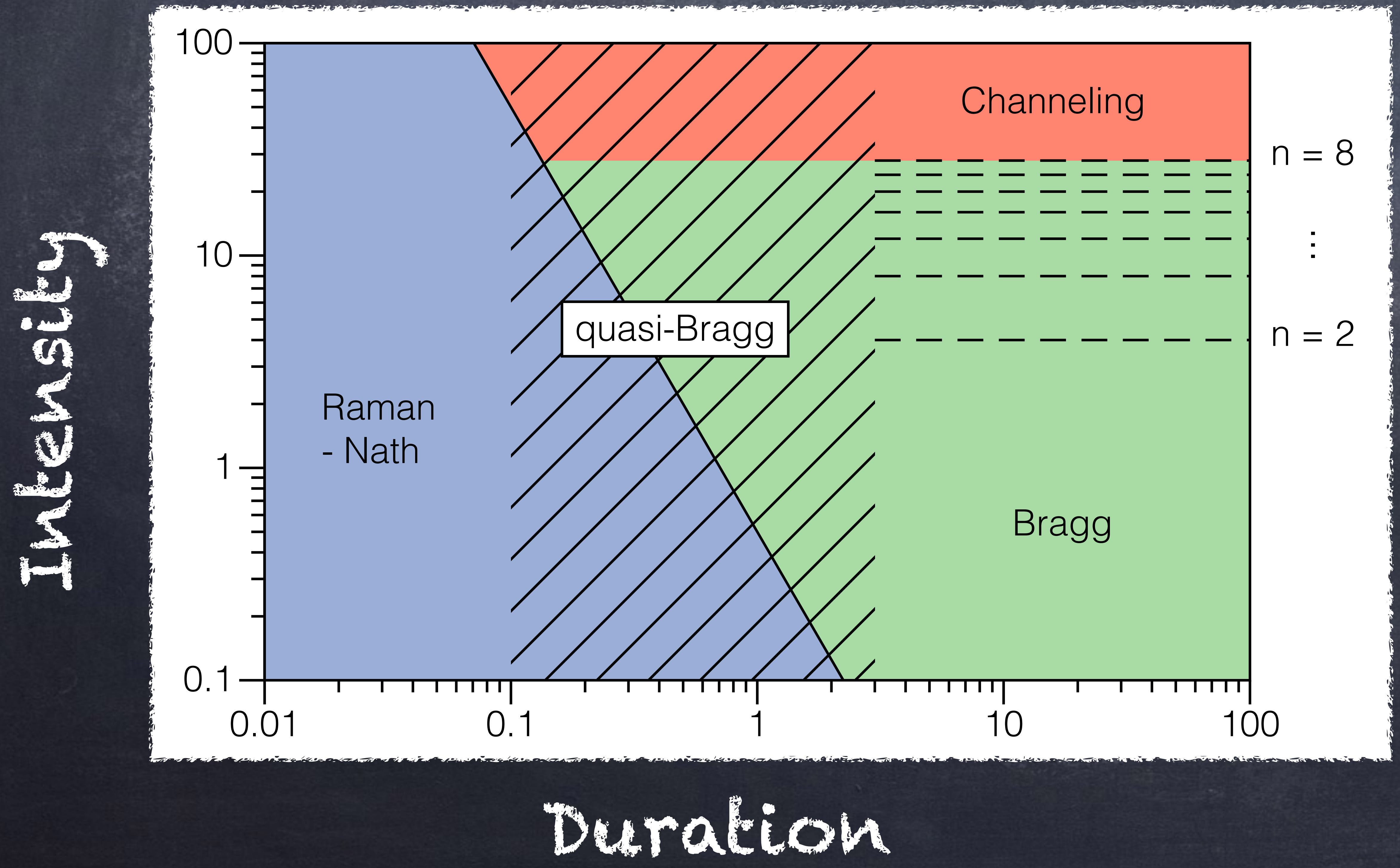

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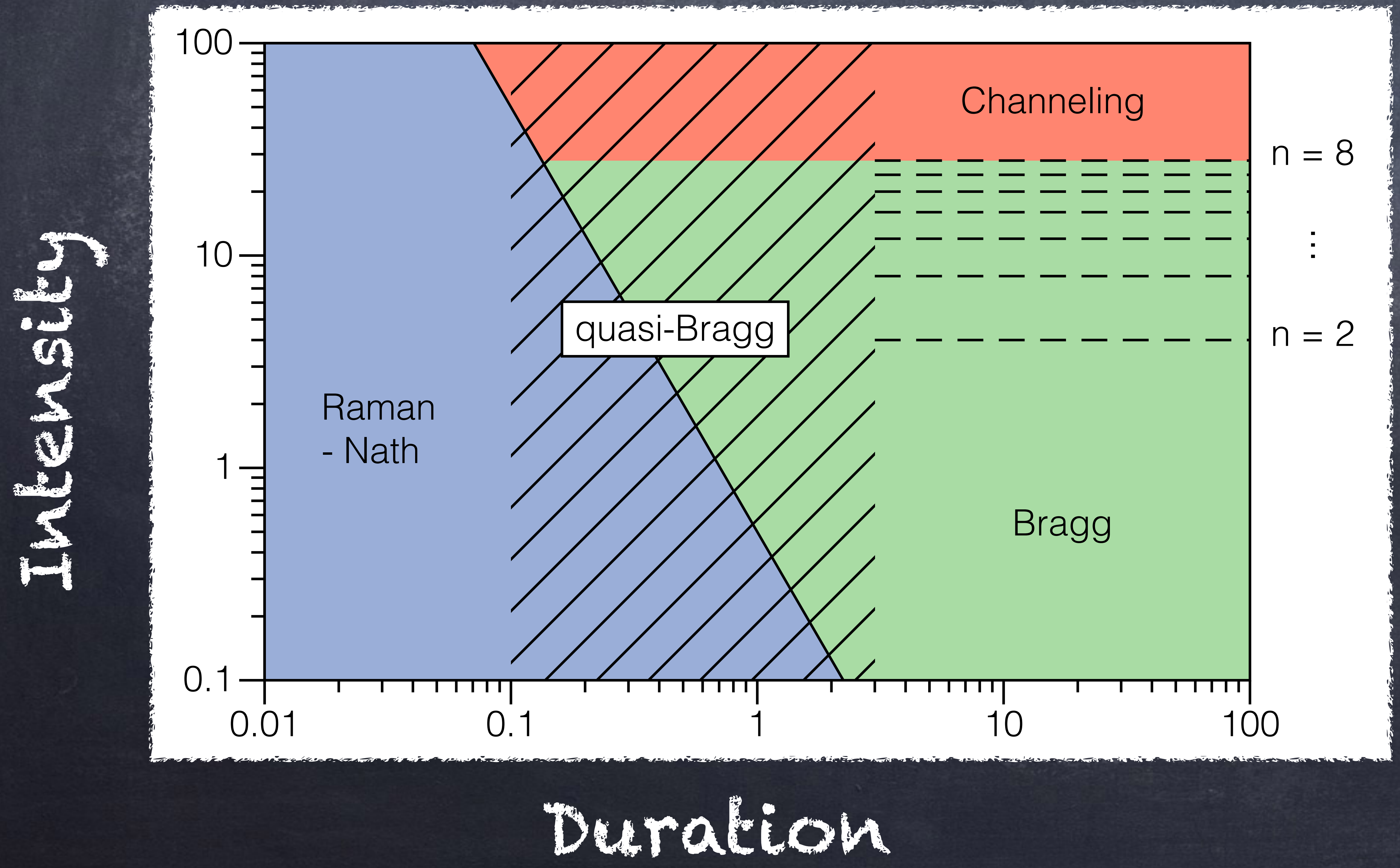

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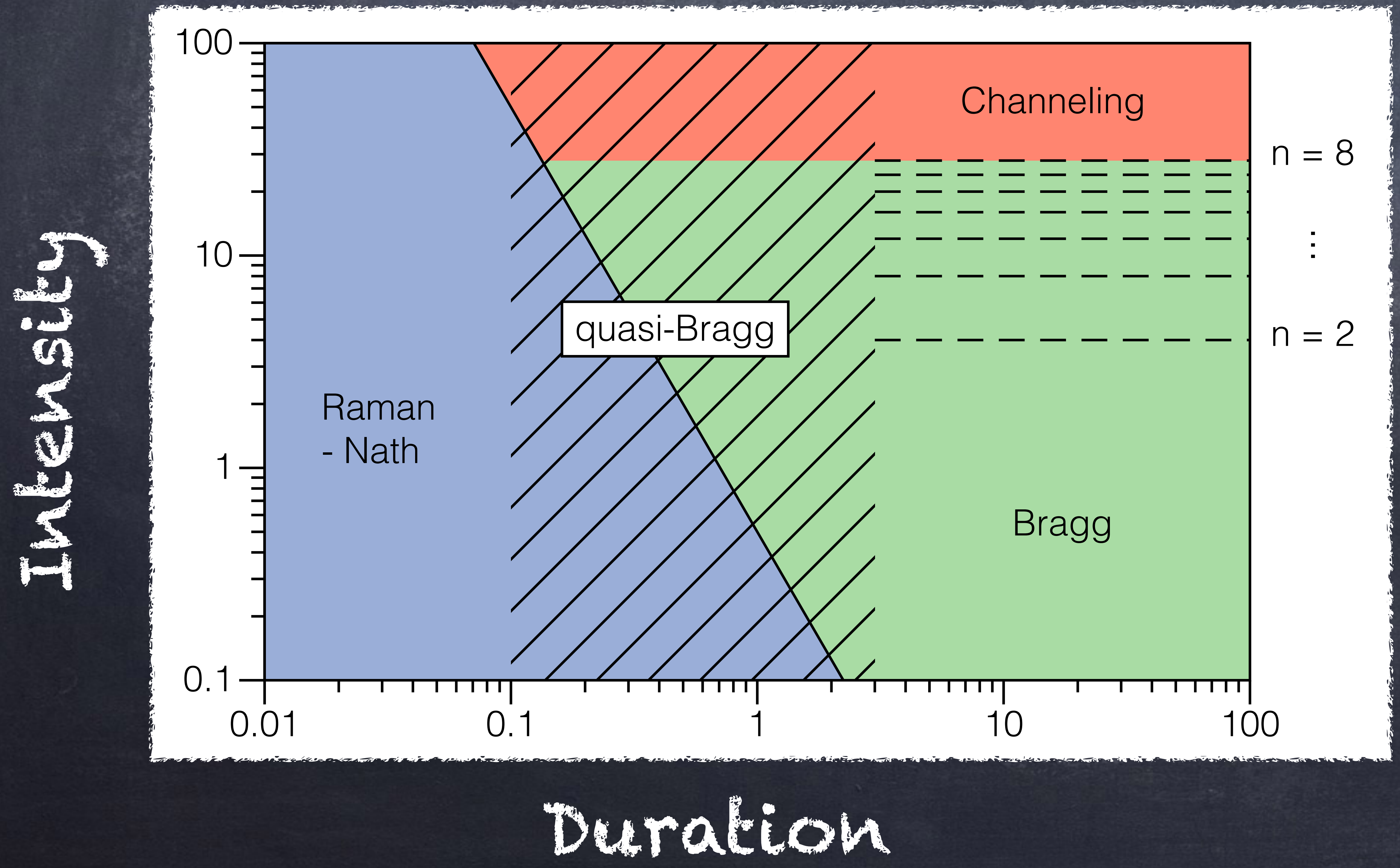
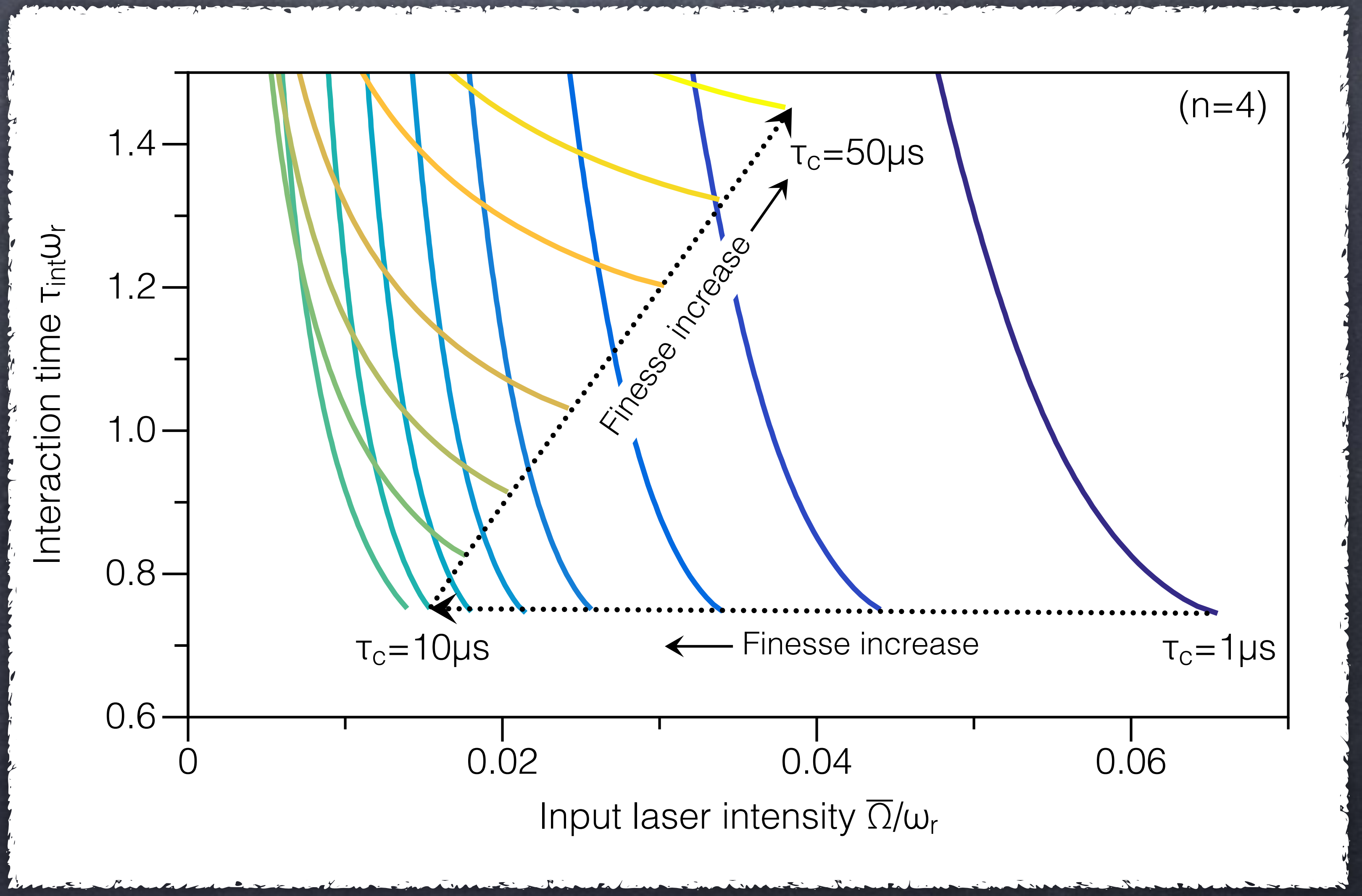
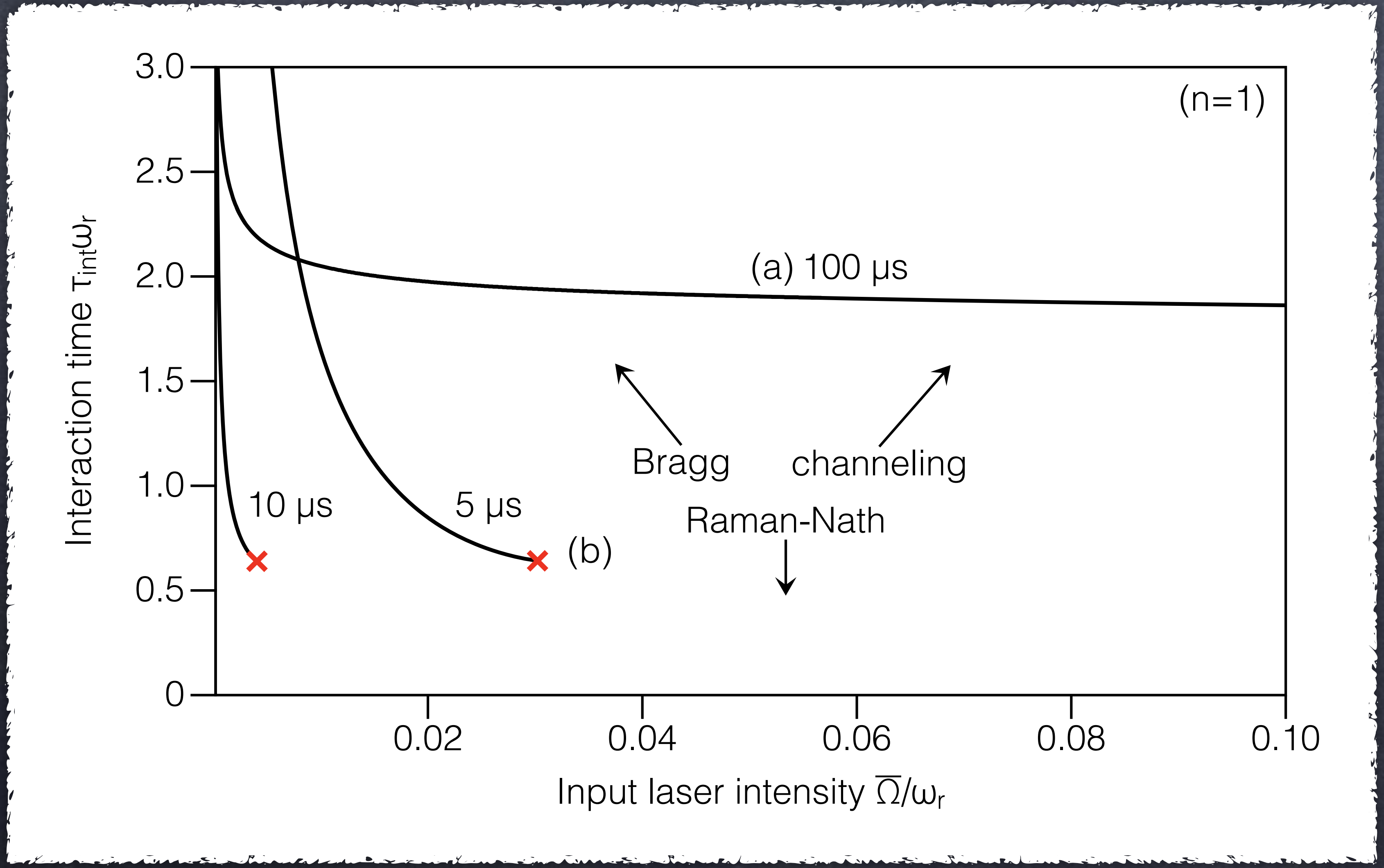


• Cavity length/finesse changes will transform the landscape in the parameter space of the interaction.



• Effect of the cavity on the atomic transitions

- Cavity "pushes" the interactions to the Bragg and channeling regimes, and away from the Raman-Nath and quasi-Bragg zone.



- There is an optimal photon lifetime, above which the minimum interaction time increases linearly.
=> the transitions become adiabatic.

- The order of the process makes the intensity/duration variation over the optimal photon lifetime more steep.

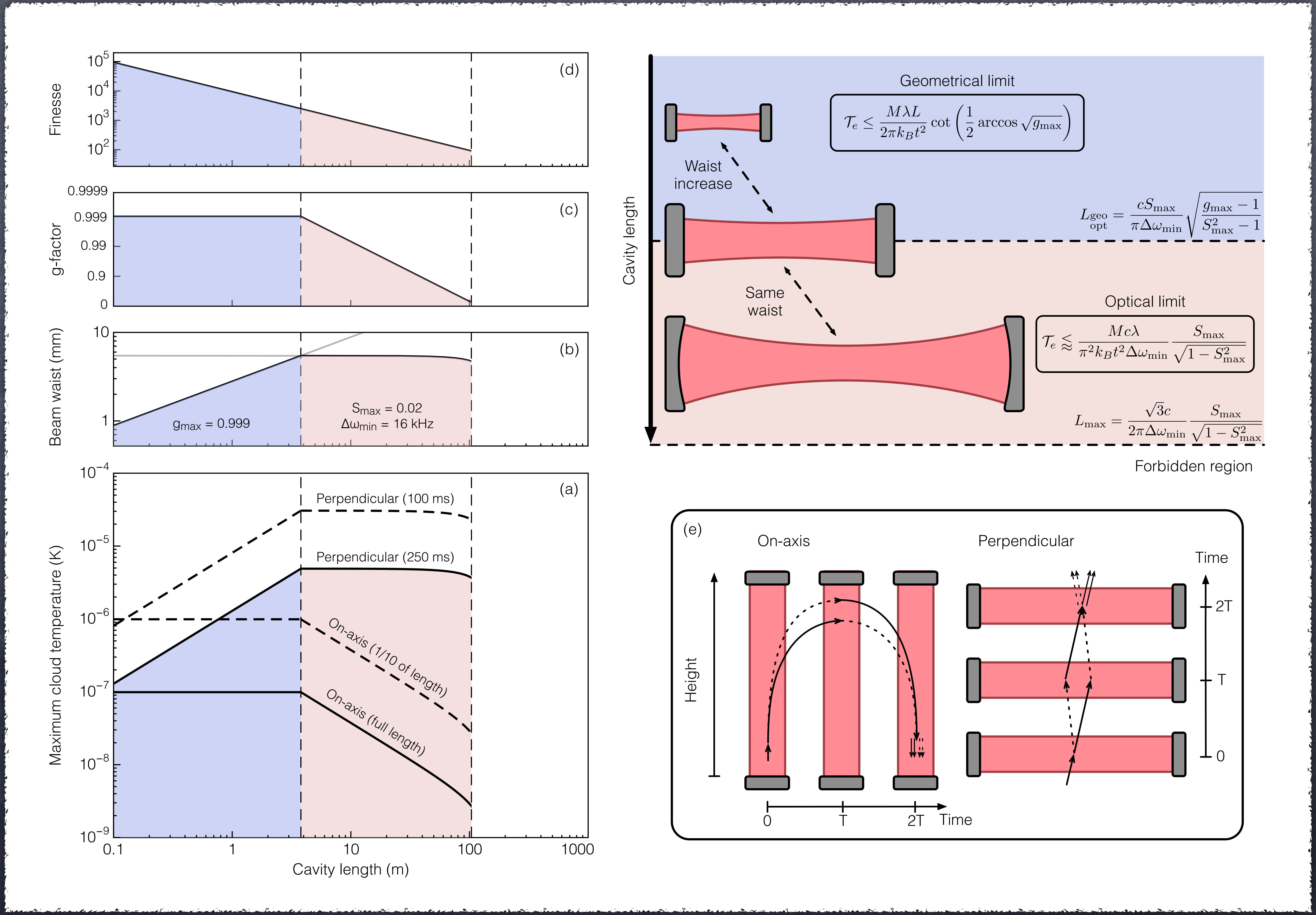
• Effect of the cavity on the atomic transitions

Geometrical limit:

$g \leq g_{max}$

Optical limit:

$S_{01}, S_{02} \leq S_{max}$
$\Delta\omega \geq \Delta\omega_{min}$



- Cavities have an optimal photon lifetime or bandwidth for Bragg diffraction.
- It depends on the order of diffraction, higher orders have more acute intensity/duration changes around the turning point.
- Taking that as a design limit, we can derive temperature limits based on:
  - Having a geometrically stable configuration.
  - Achieving a certain level of spatial filtering.
- Cavities are great for atom interferometry and GW detection.

Future work

- Previous work only 1D (constrain on beam quality introduced by optical suppression of HOMs)
- Future modelling work to include full-3D wavefront model (constrain on beam quality introduced by target interferometric contrast)
- Currently developing a four-mirror large-waist cavity with a total Gouy phase shift close to 180 degrees.

Thank you!

My papers:

Feasibility of near-unstable cavities for future gravitational-wave detectors
PRD **97**, 022001 (2018)

Fundamental limitations of cavity-assisted atom interferometry
PRA **96**, 053820 (2017)

The influence of dual-recycling on parametric instabilities at Advanced LIGO
CQG **34**, 205004 (2017)

Thermal modelling of Advanced LIGO test masses
CQG **34**, 115001 (2016)

Development of a four-mirror large-waist optical cavity for atom optics
In preparation (2018)

Ultra-stable low-drift laser towards 10^{-17}
In preparation (2018)

Currently job-seeking

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