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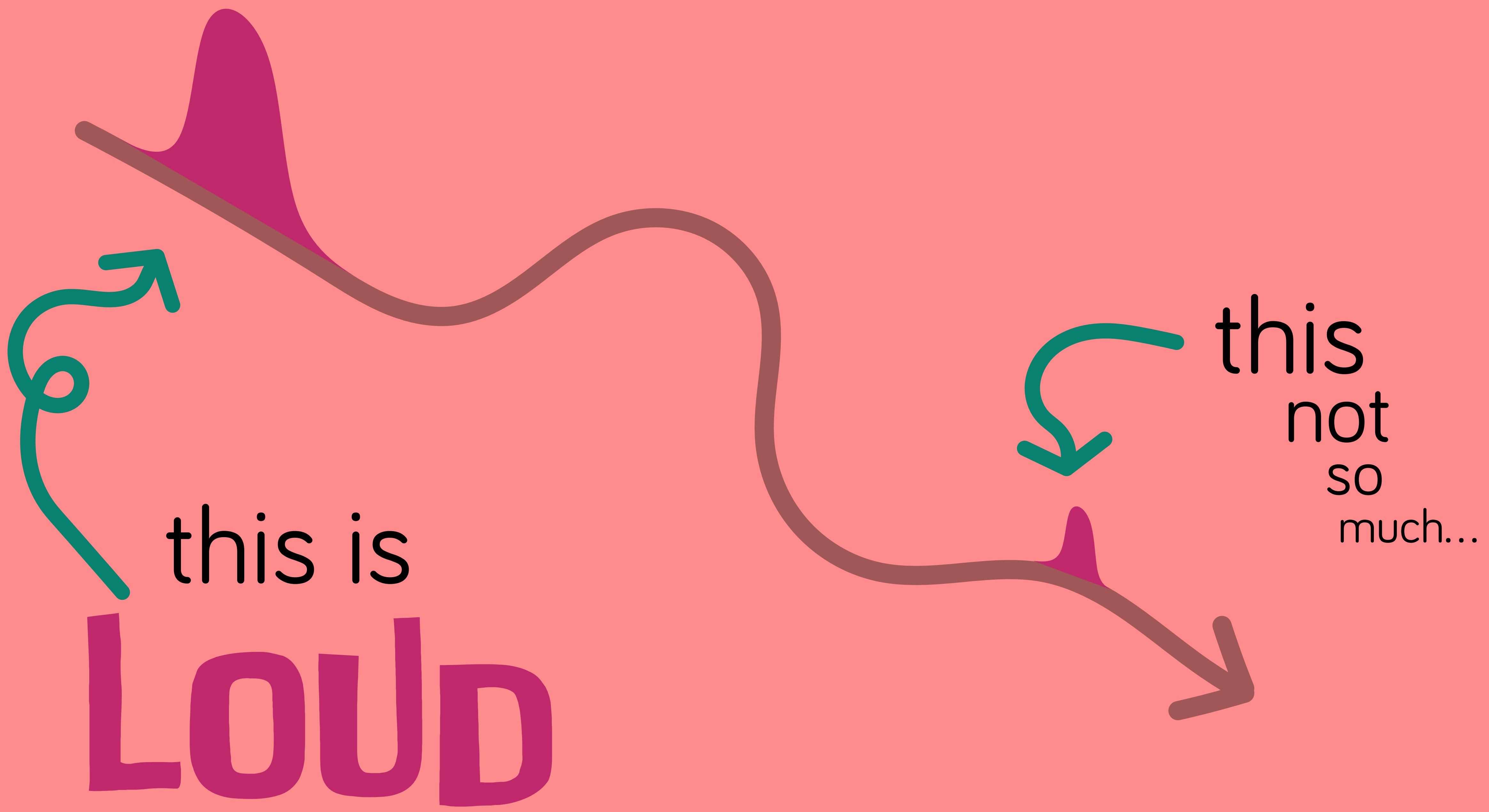
# SCREAM & (QUANTUM) SHOUT

(or how to amplify more than a single photon) people are LOUD

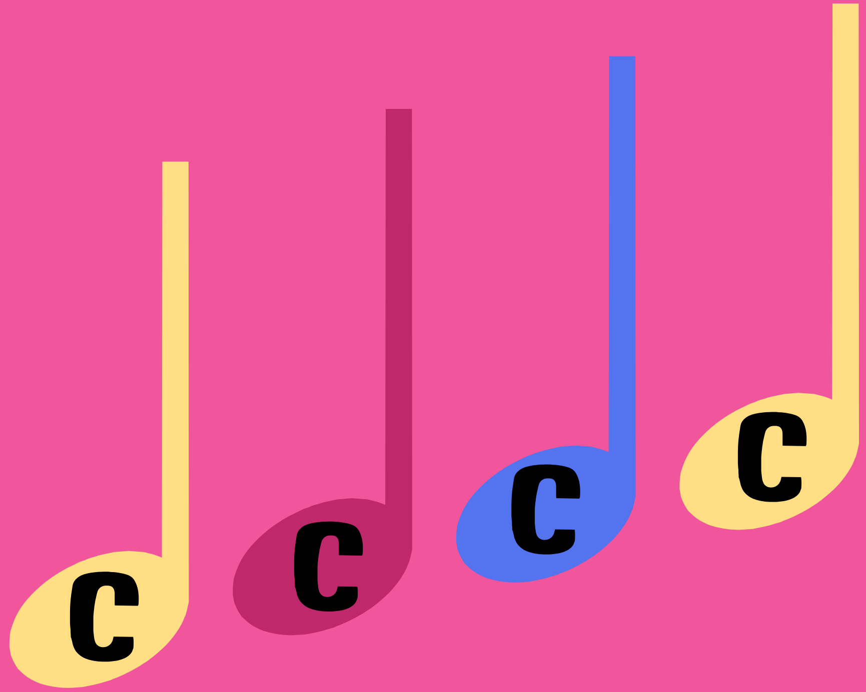
people *like* **LOUD**

people *also* like **QUANTUM**

but
being QUANTUM
LOUD is hard

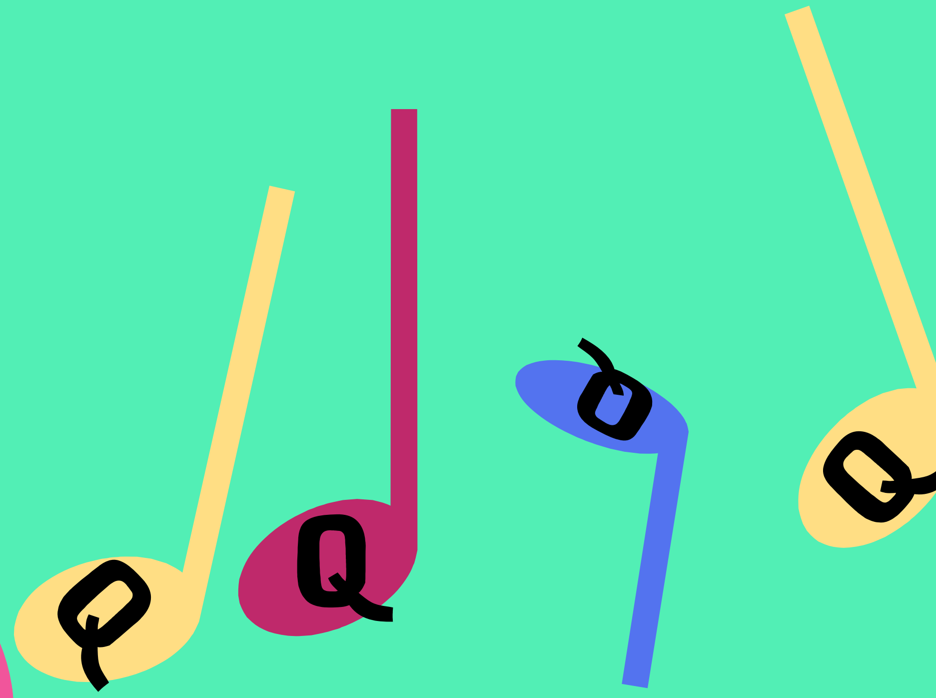

this is
LOUD
this
not
so
much...

it's easy to
be loud classically...



... but

# QUANTUMLY?

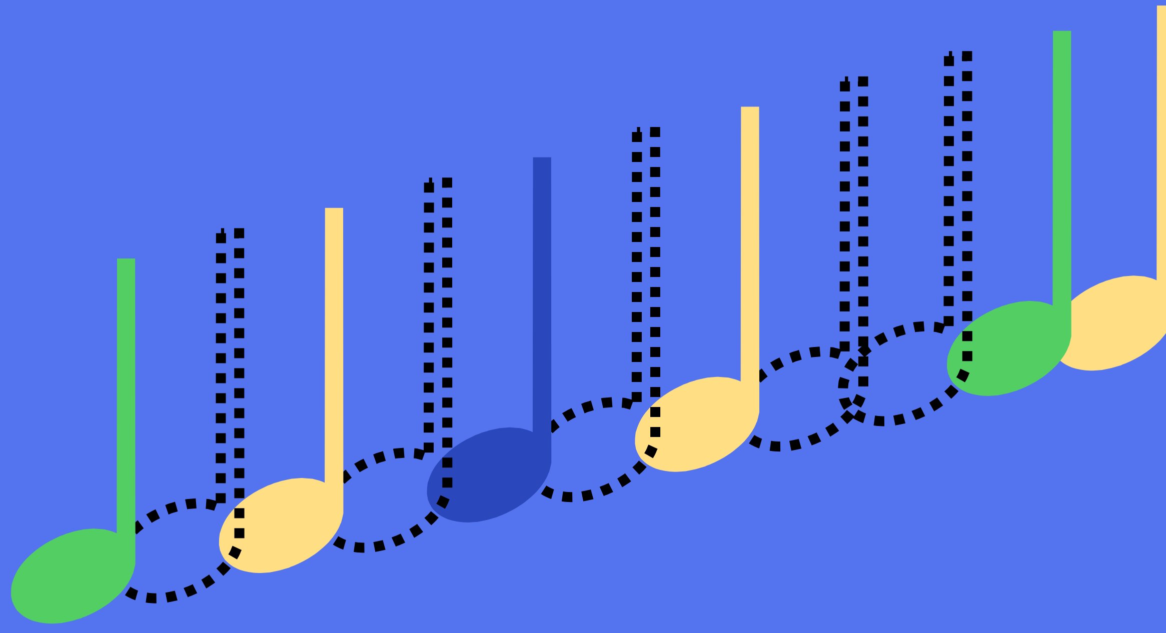


due to a little thing called "no-cloning"

but


you can do it
PERFECTLY
...sometimes

# Noiseless Linear Amplification



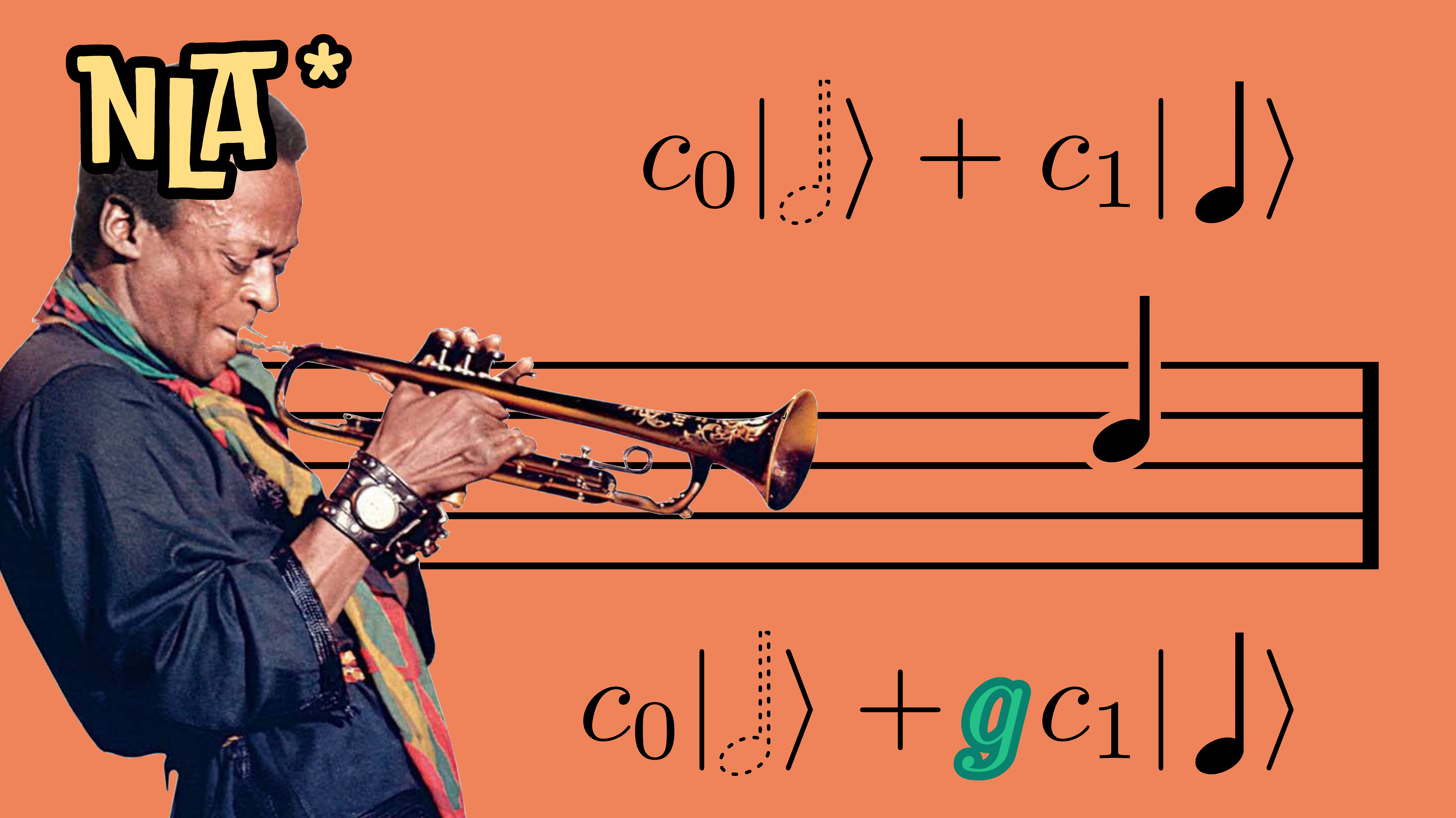

$|\psi\rangle$
NLA
$|g\psi\rangle^*$

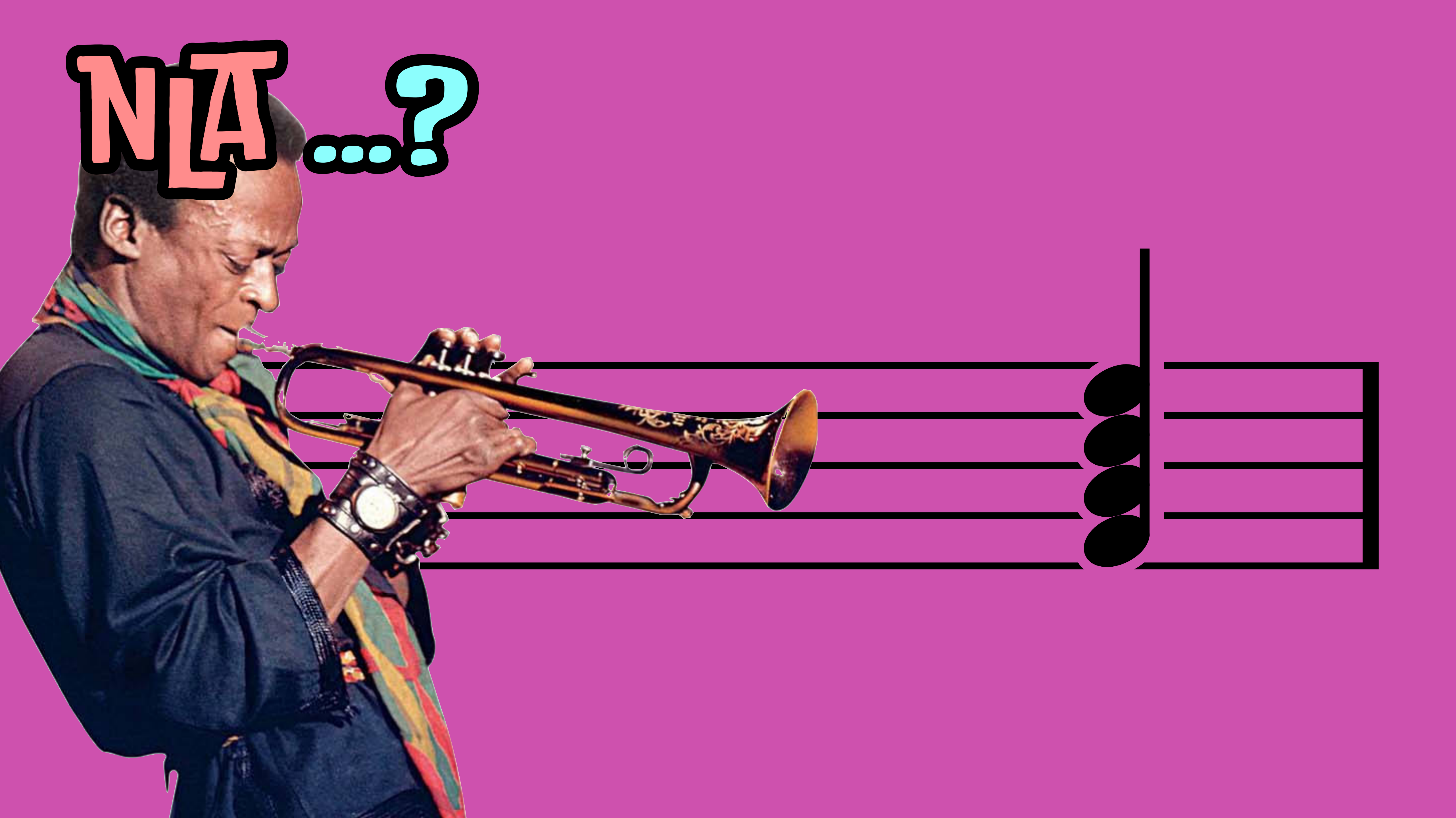

NLA
me

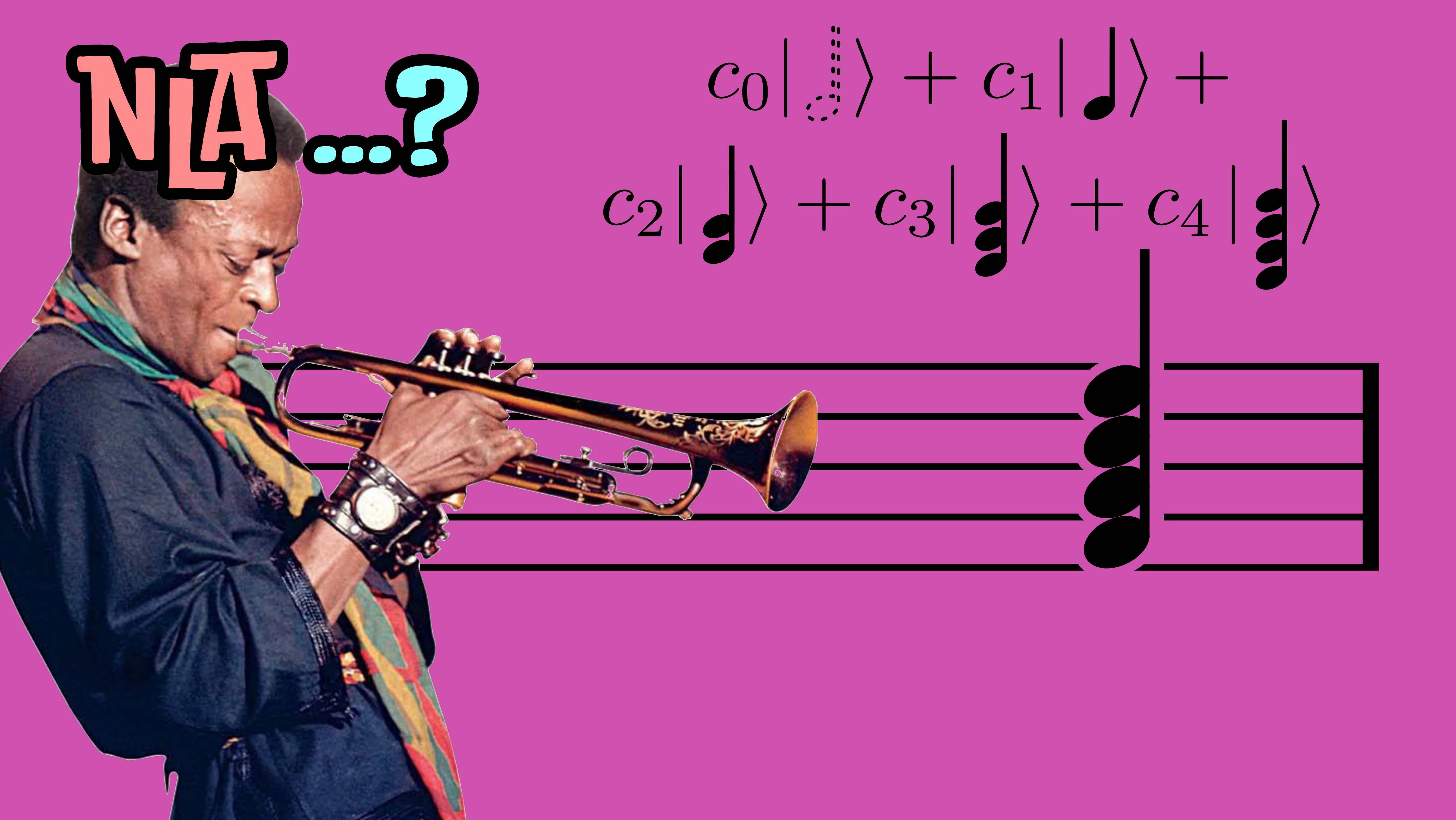

not really
me
NLA

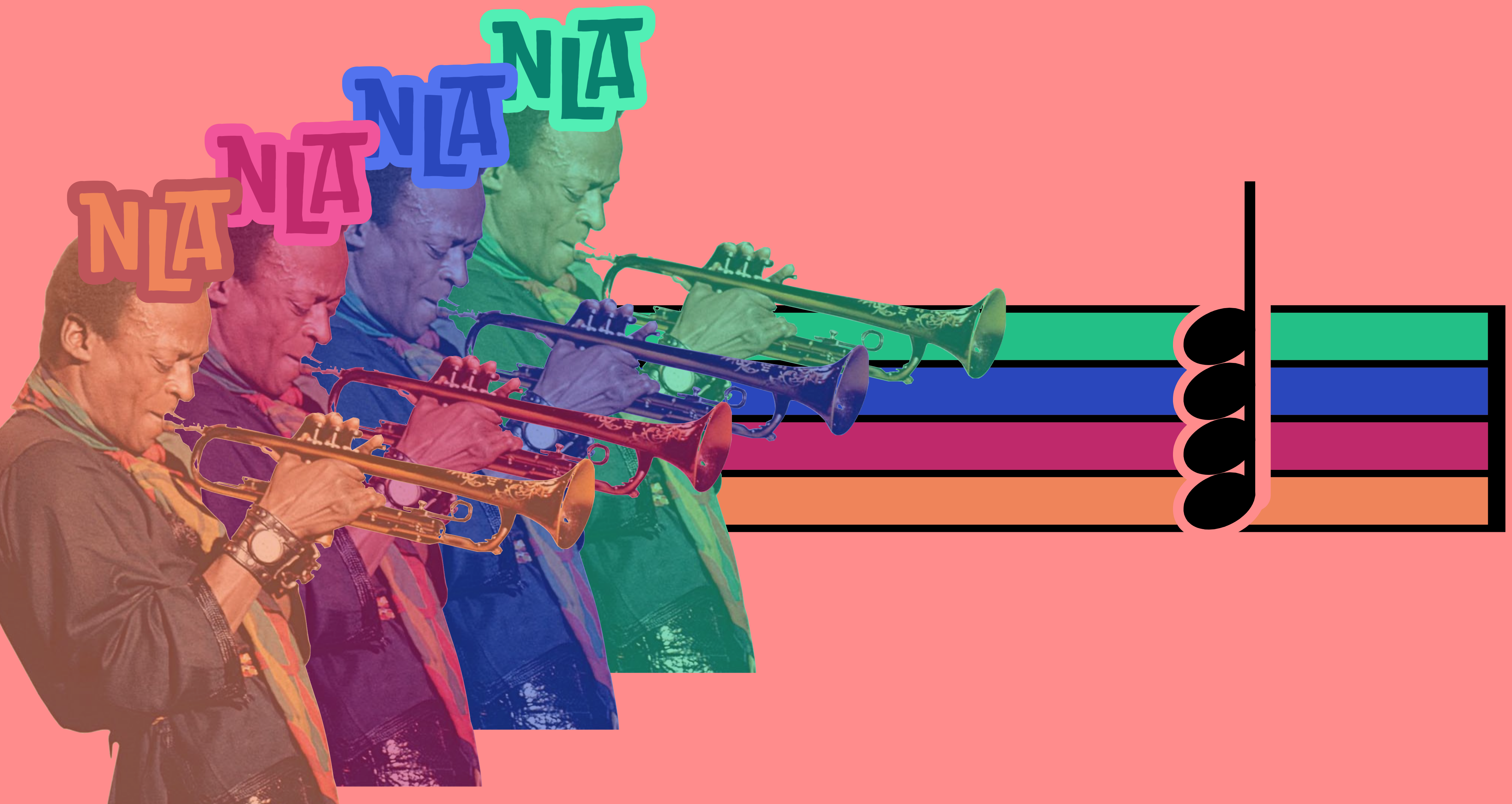
# NLA*

* only 1 note at a time

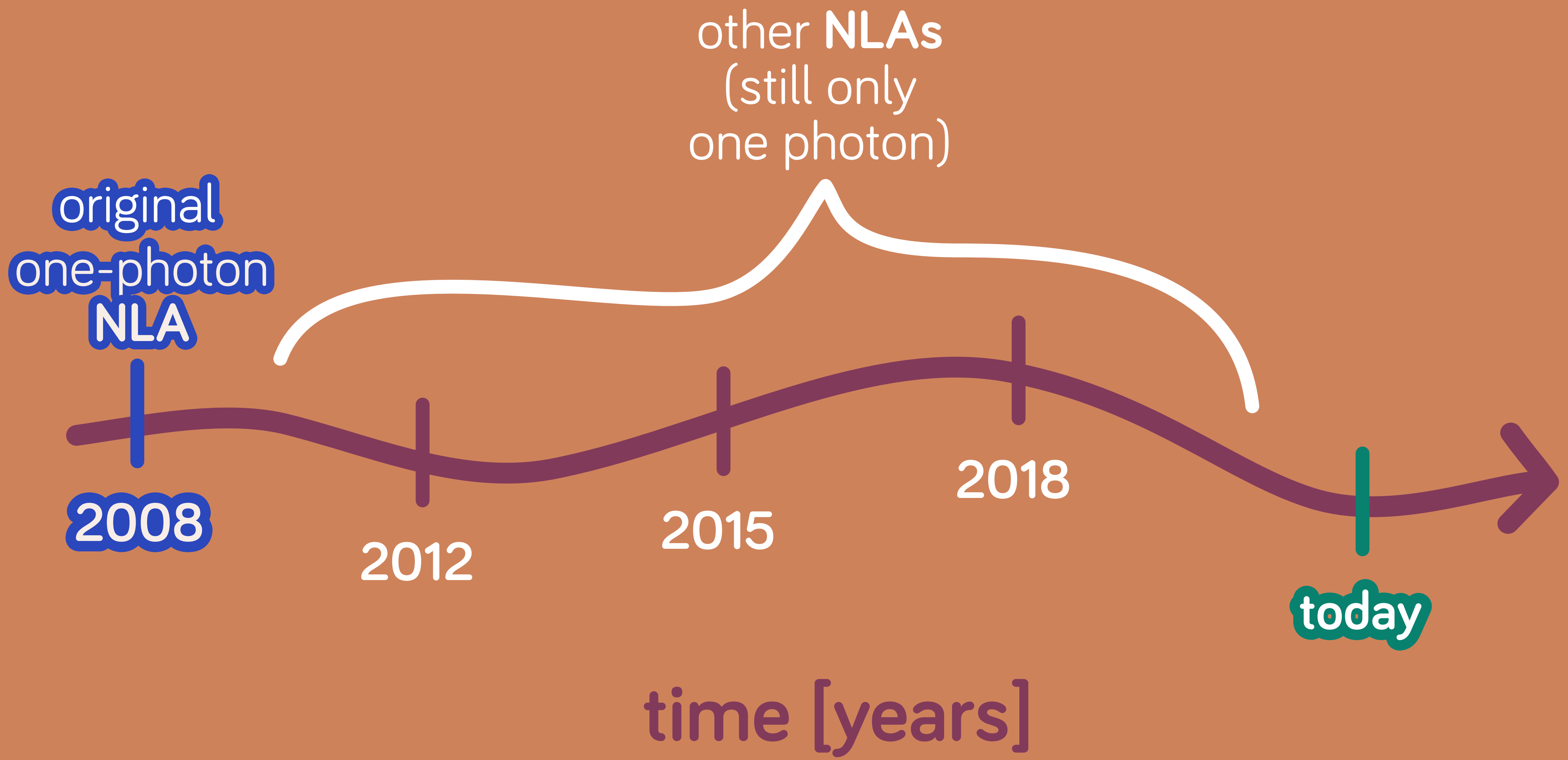

NLA*


NLA ...?


NLA ...?

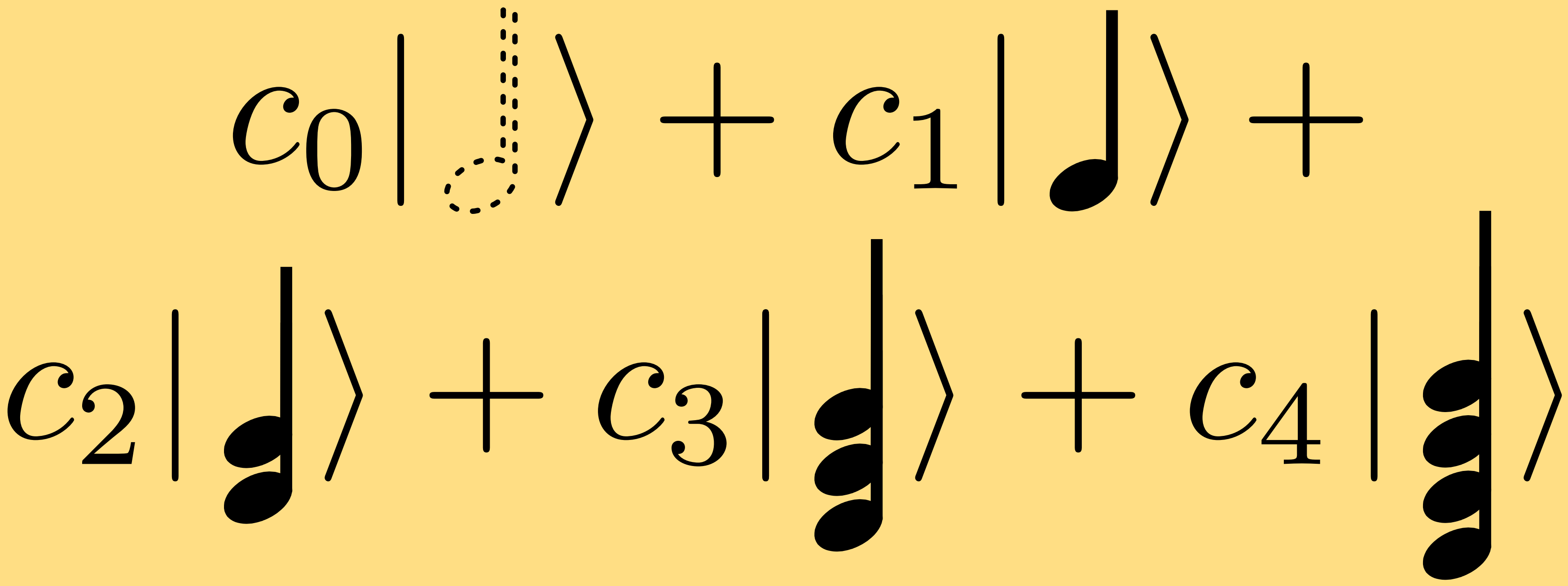

NLA
NLA
NLA
NLA

doesn't really
work all that well

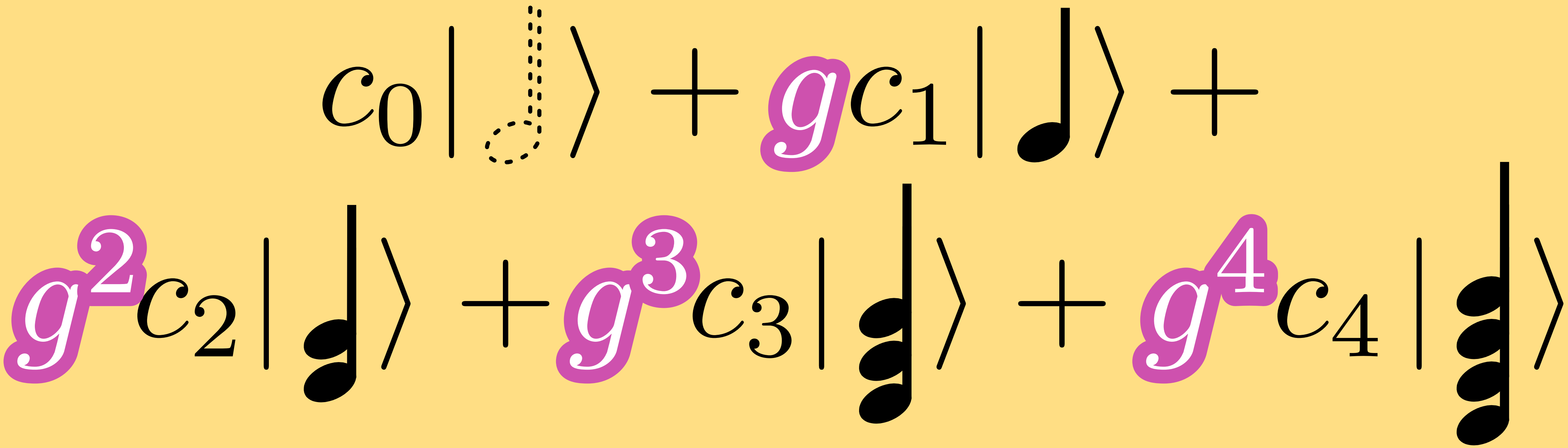

other **NLAs**
(still only
one photon)
original
one-photon
NLA
2008
2012
2015
2018
today
time [years]


TRUE
MULTI-NLA

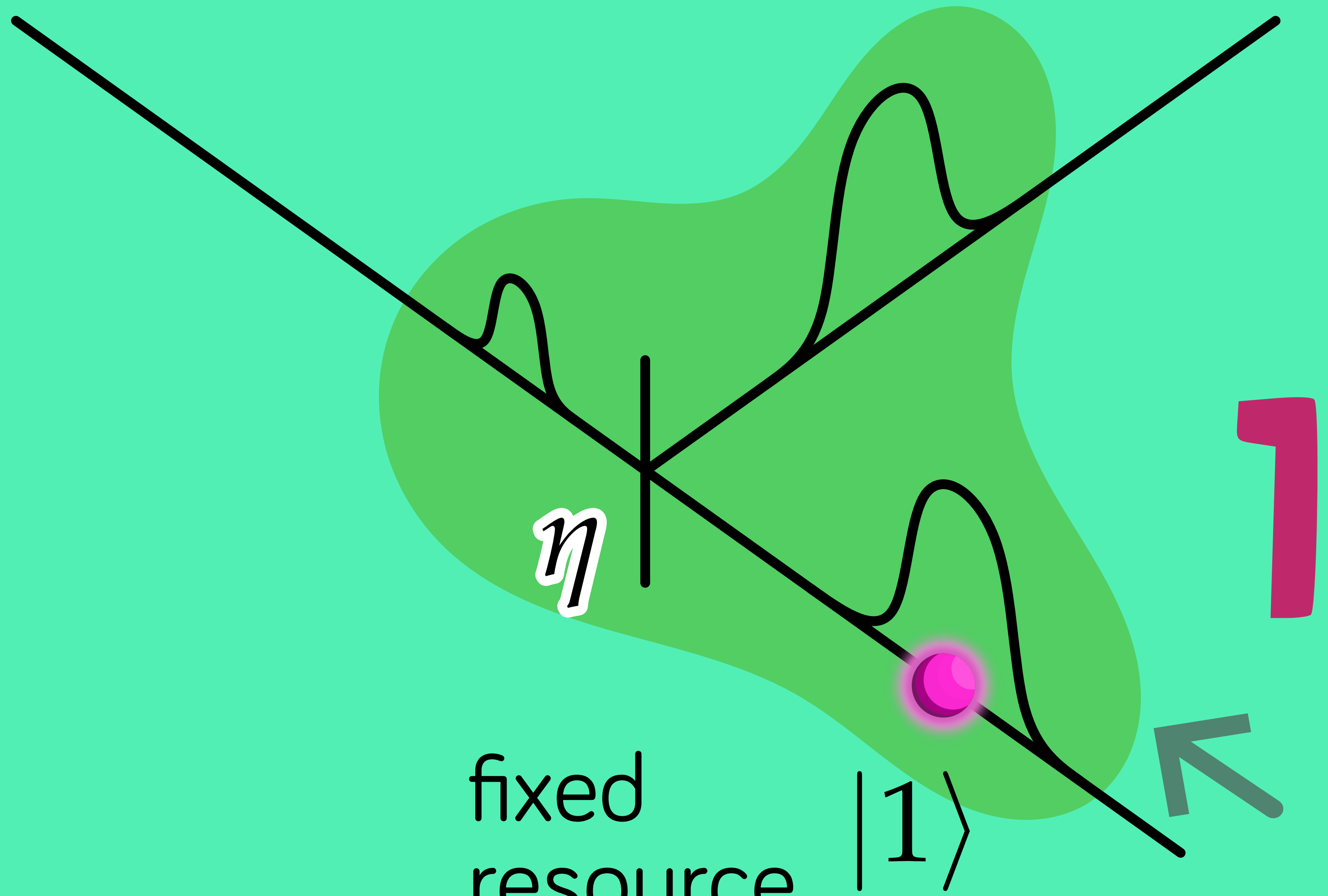
# TRUE MULTI-NLA



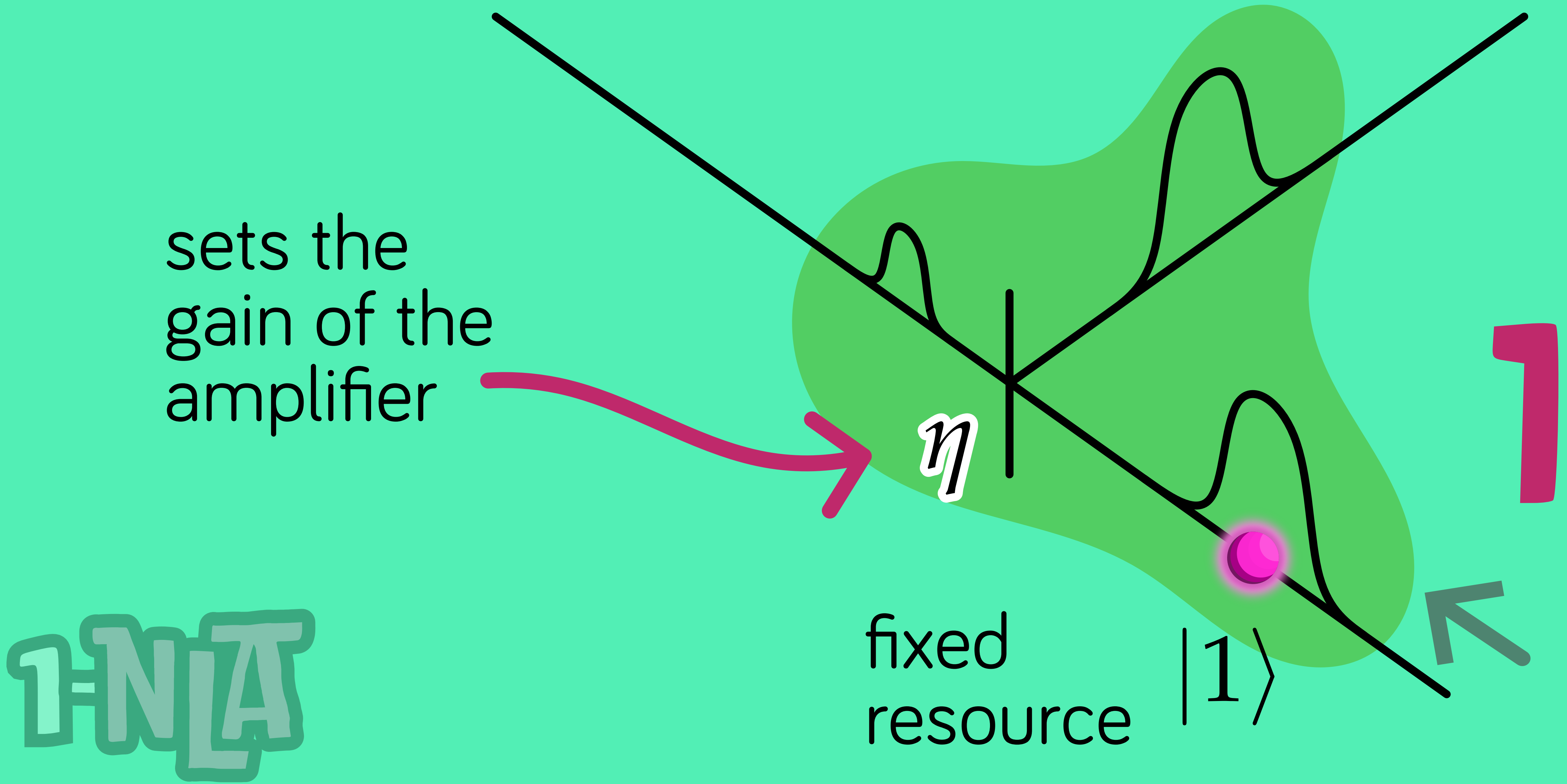
# TRUE MULTI-NLA

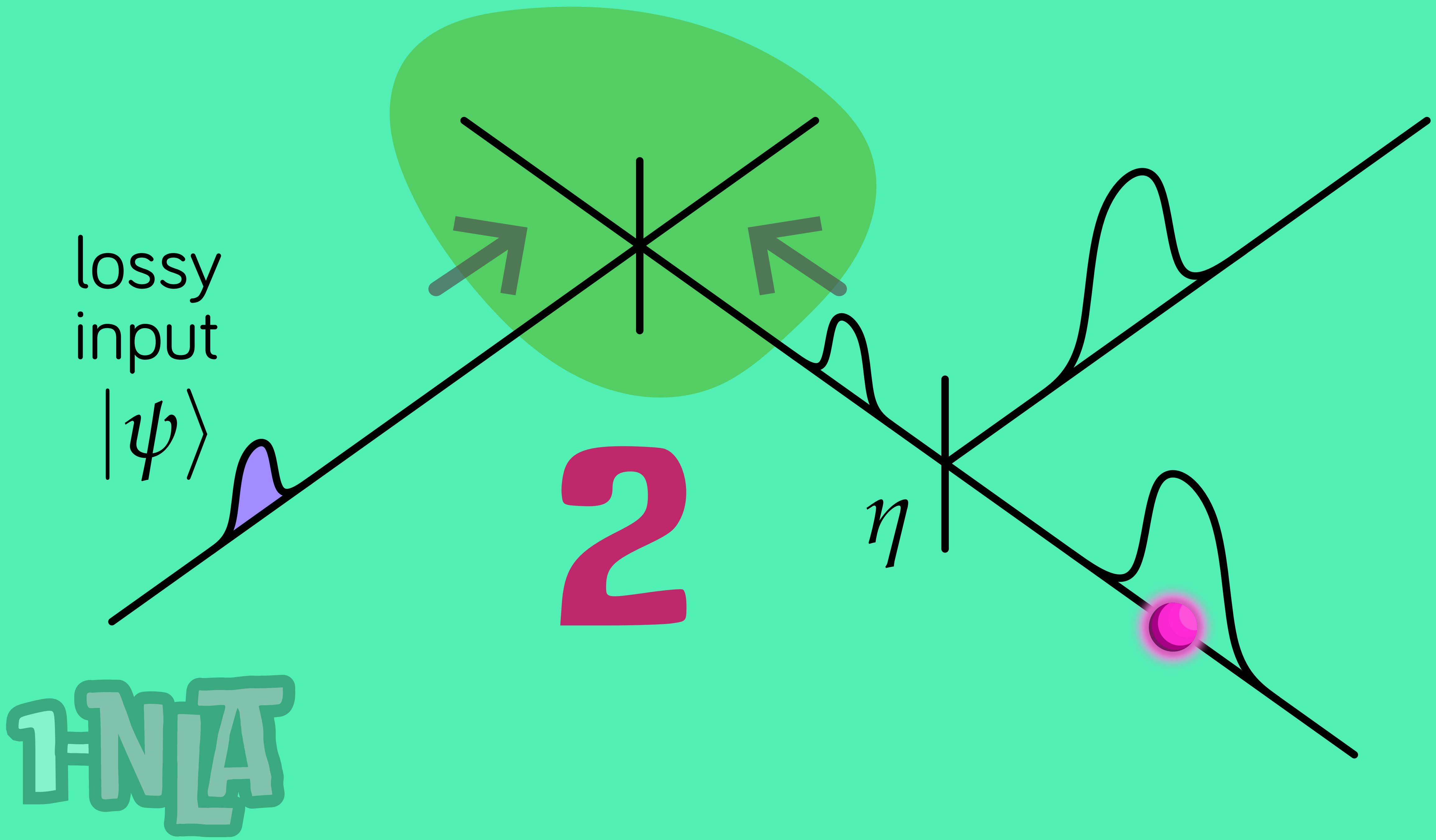


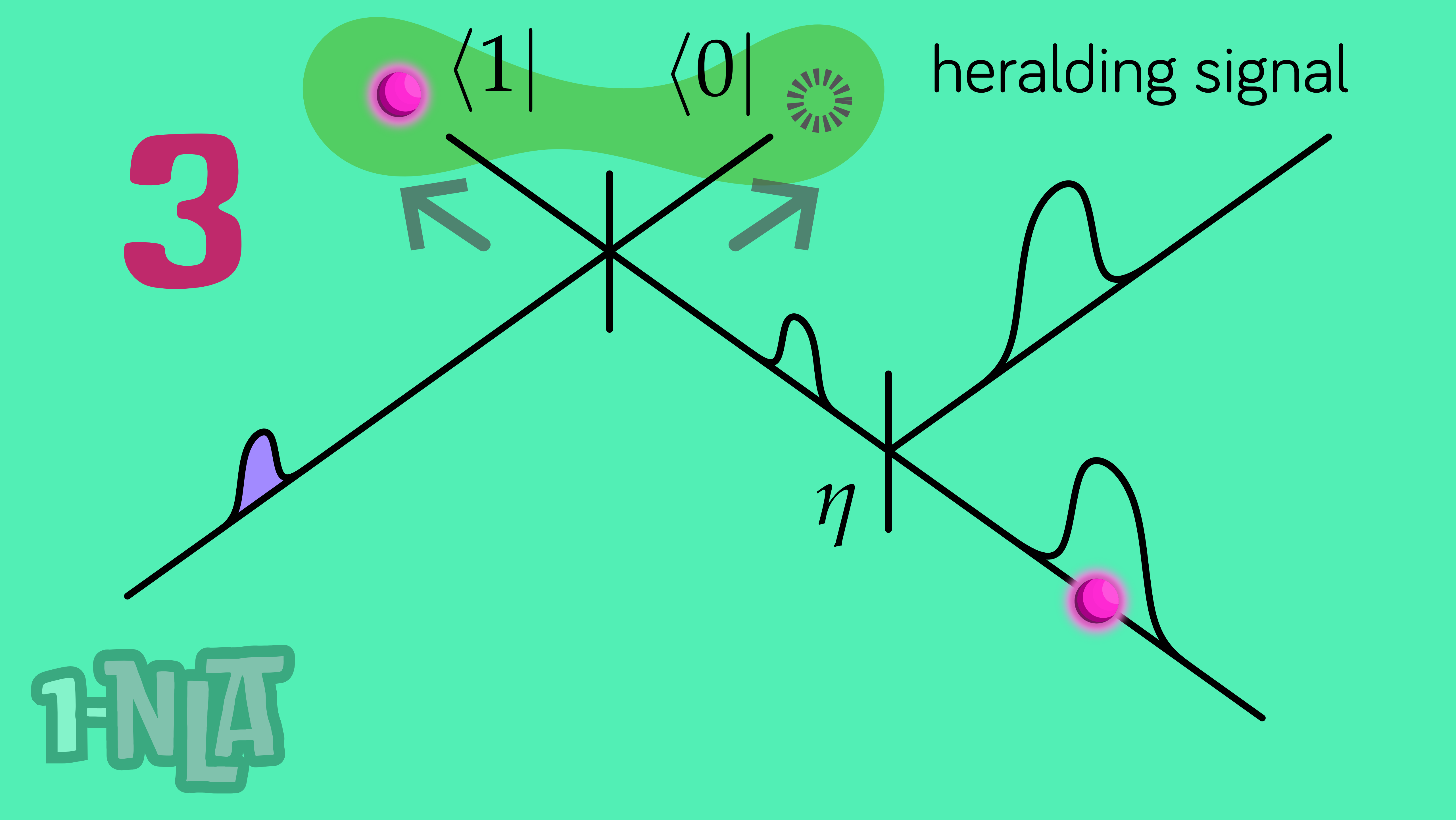
how does it ***work***?



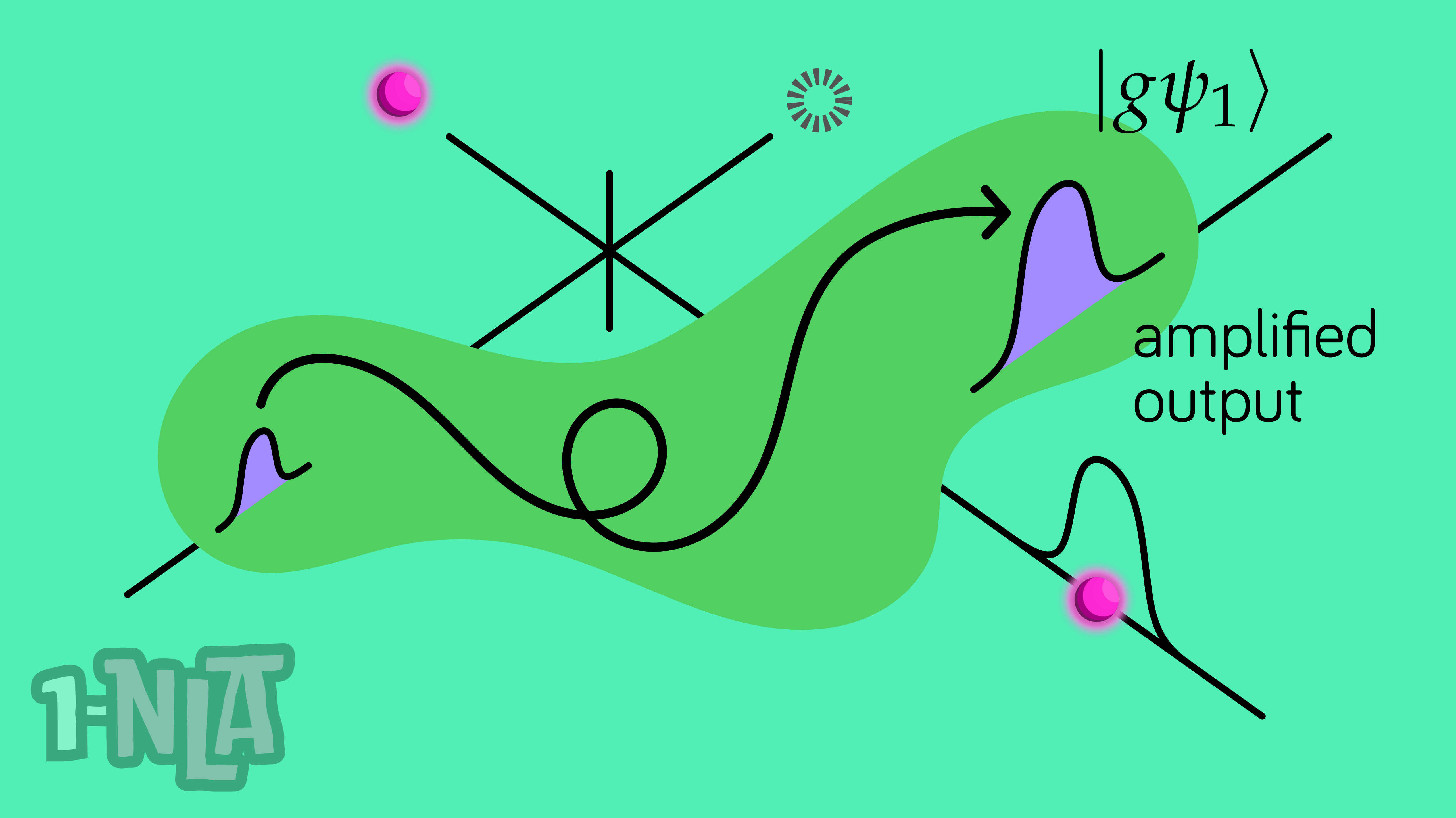
$\eta$
fixed
resource
$|1\rangle$
1


sets the
gain of the
amplifier
η
fixed
resource
|1⟩
1-NLA

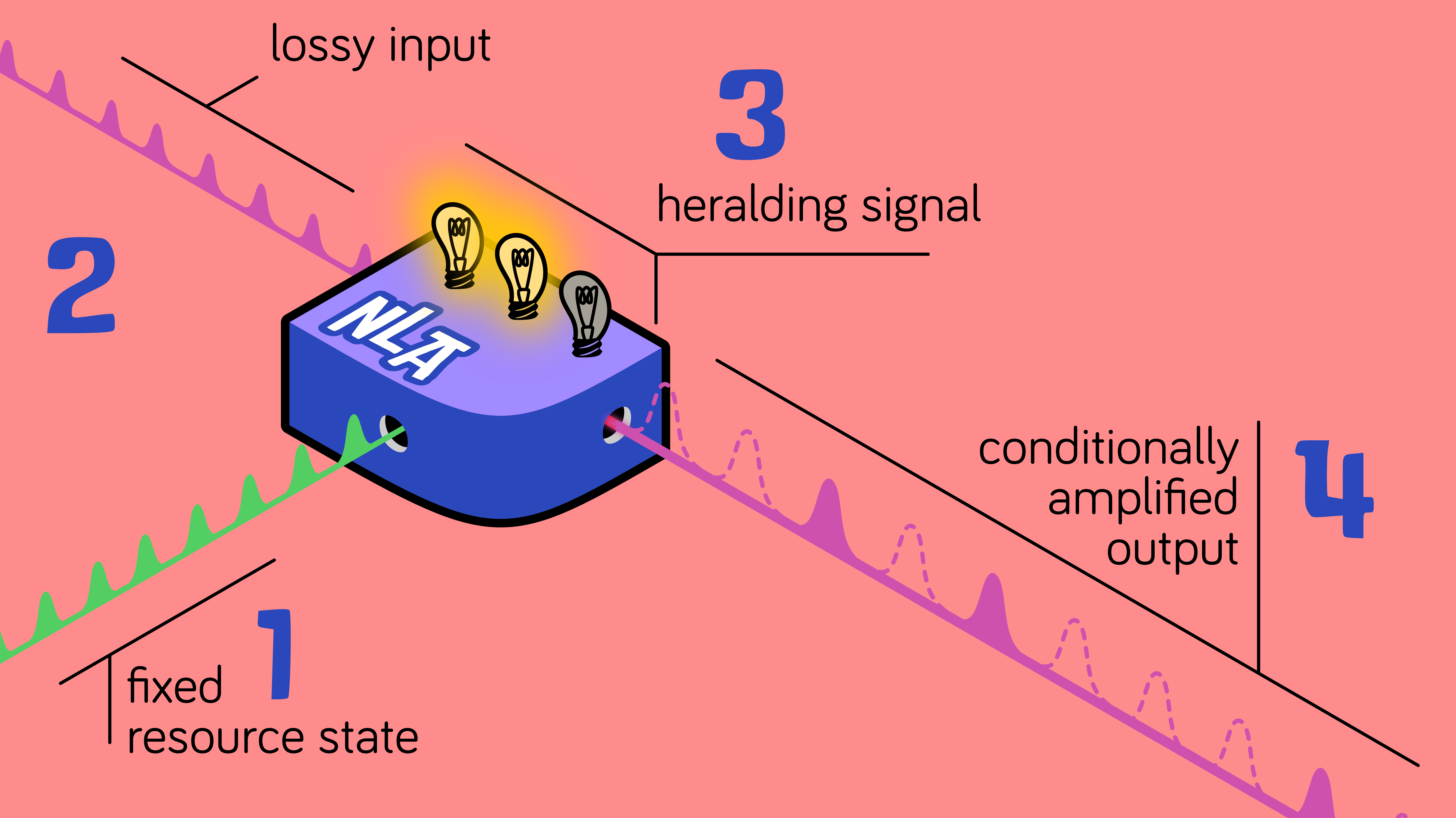

lossy
input
$|\psi\rangle$
2
$\eta$
1-NLA

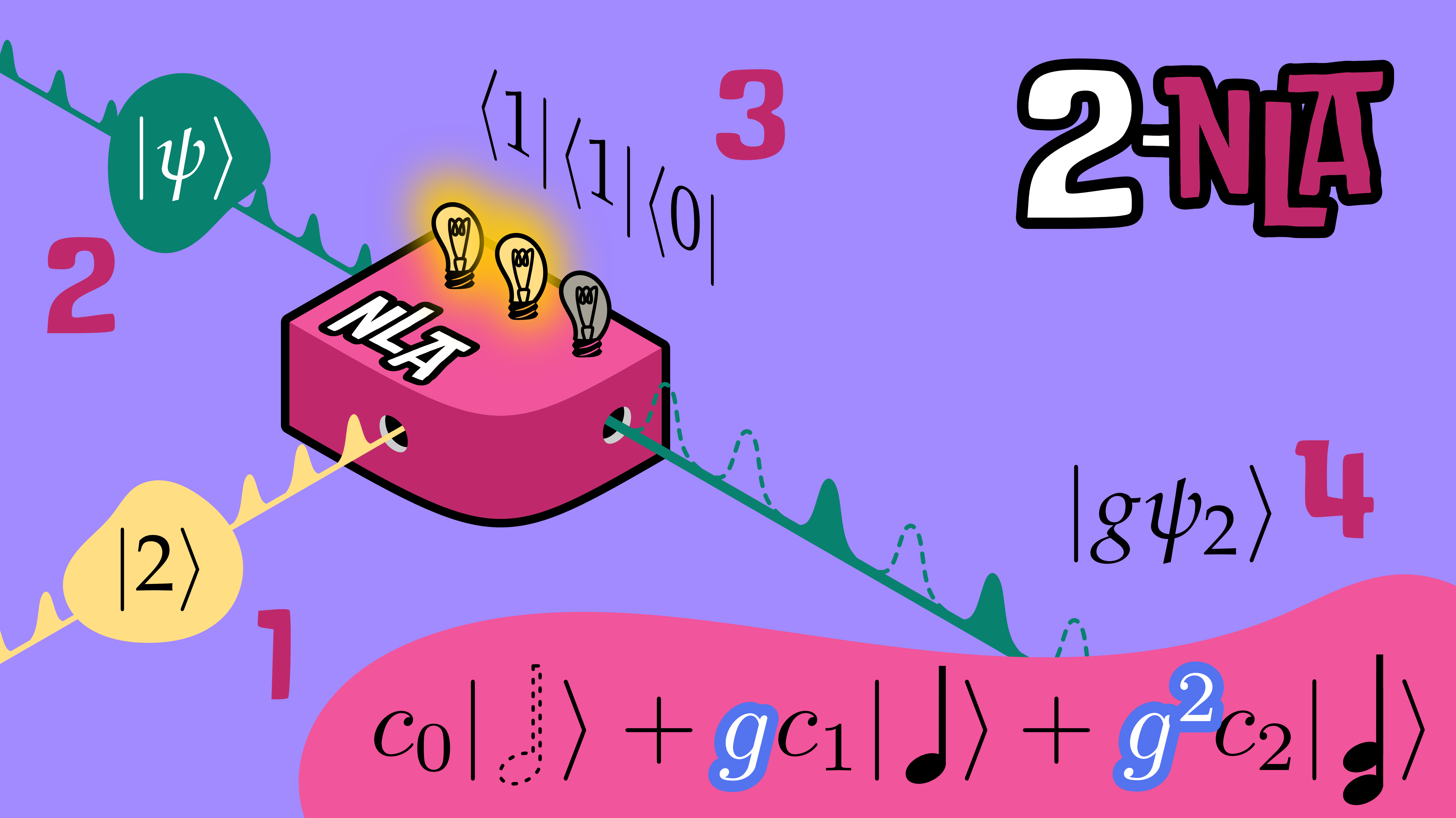


3
⟨1|
⟨0|
heralding signal
η
1-NLA



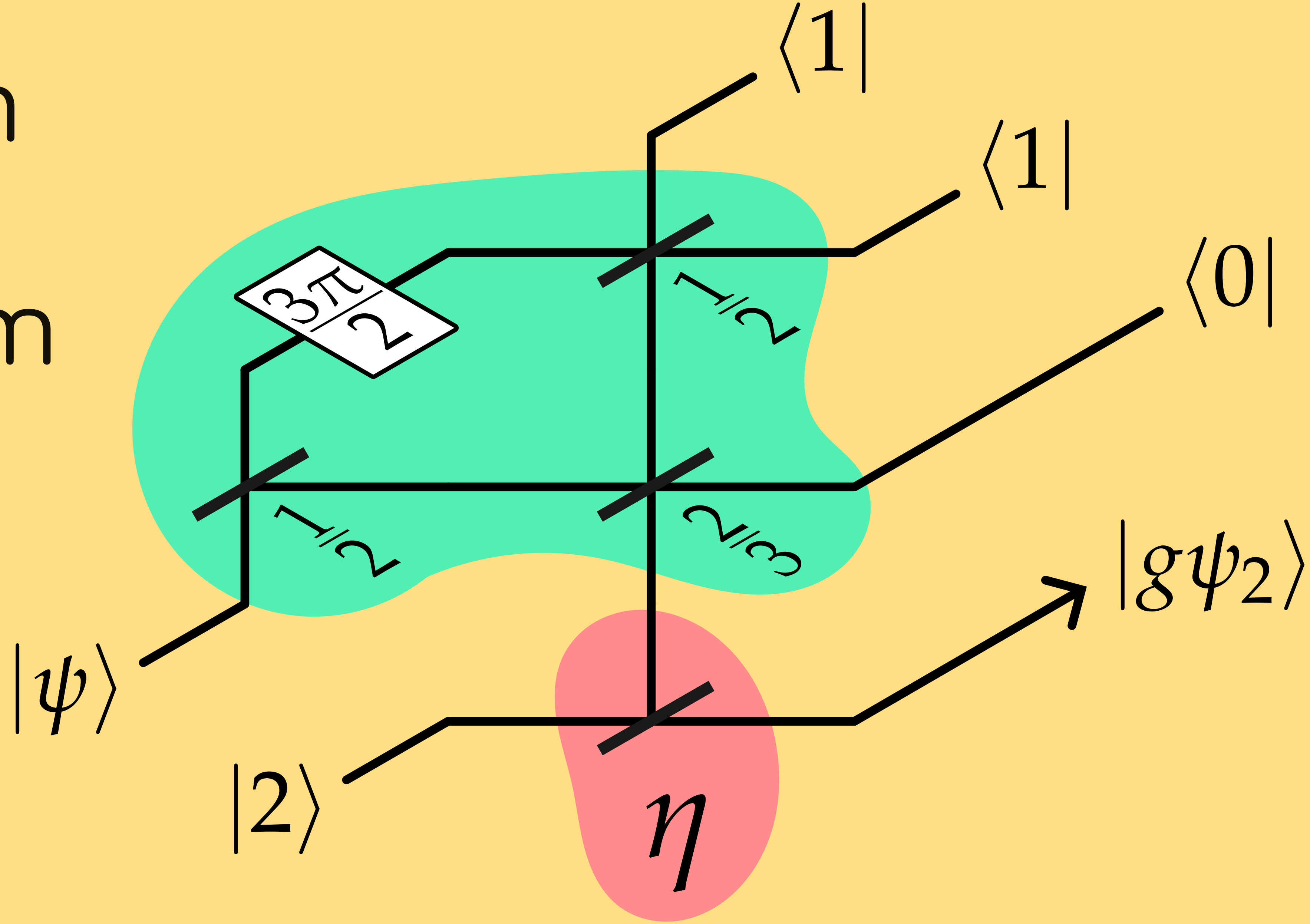
$|g\psi_1\rangle$
amplified output
1-NLA

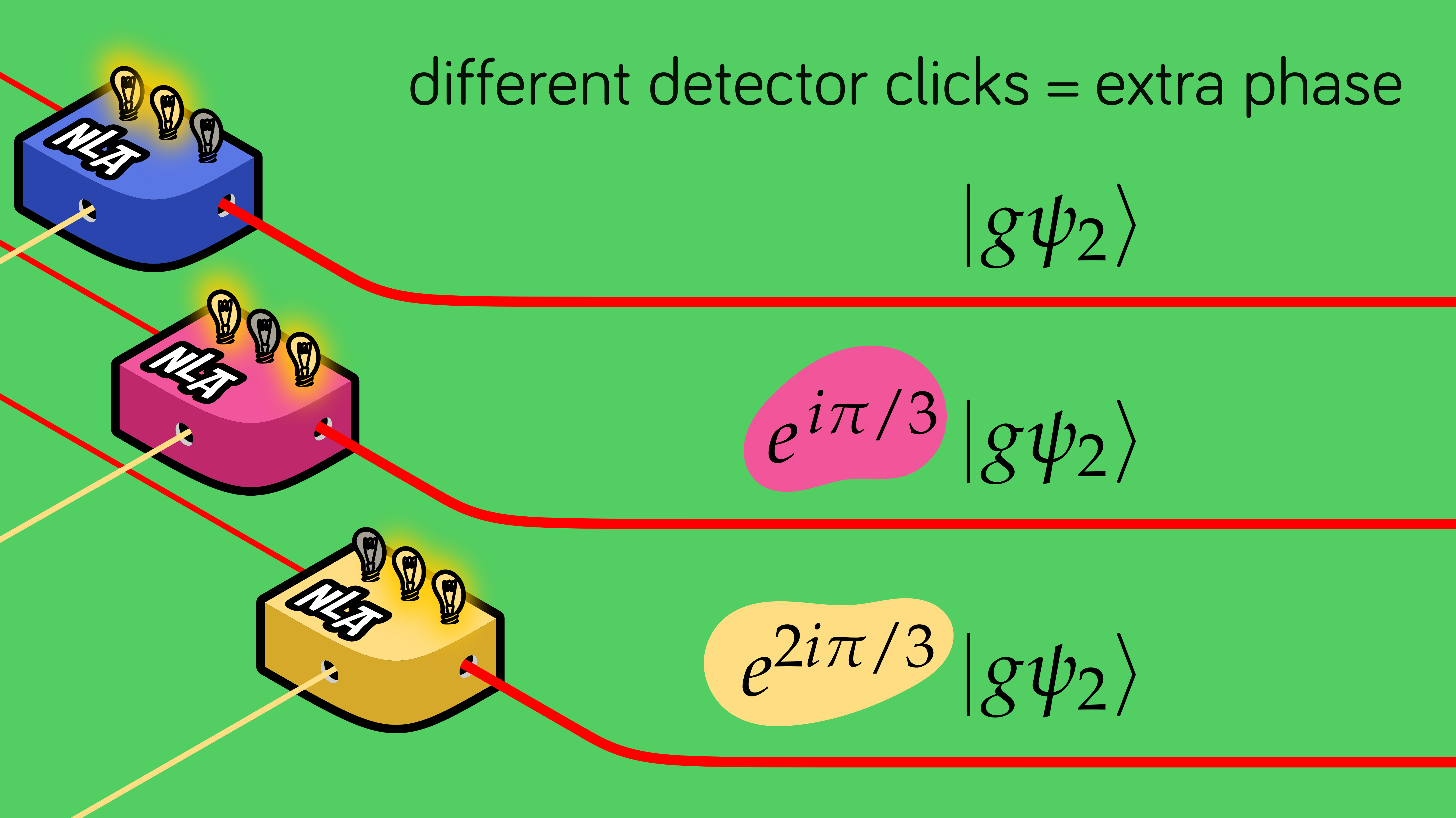

lossy input
3
heralding signal
2
NLA
conditionally amplified output
4
1
fixed resource state

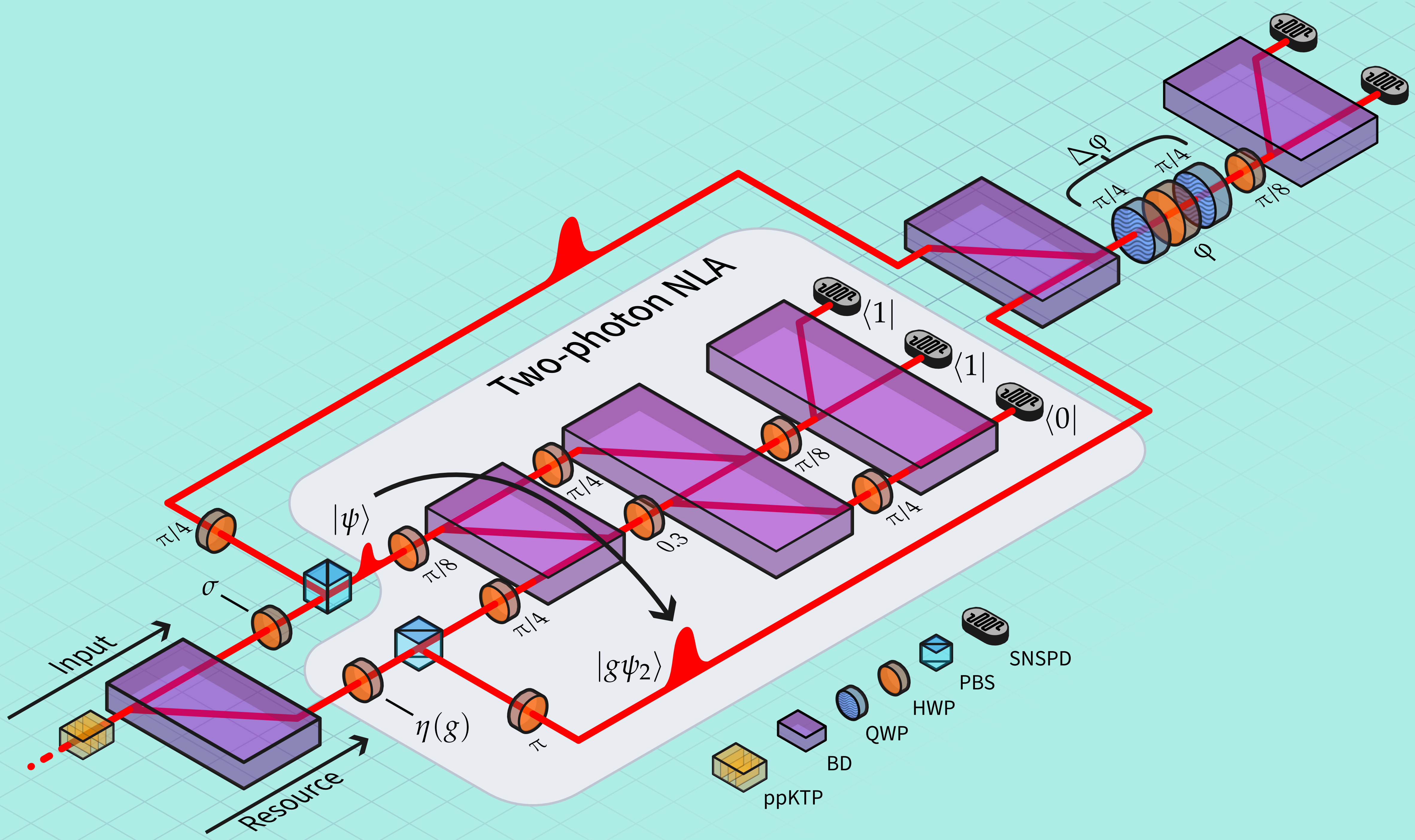


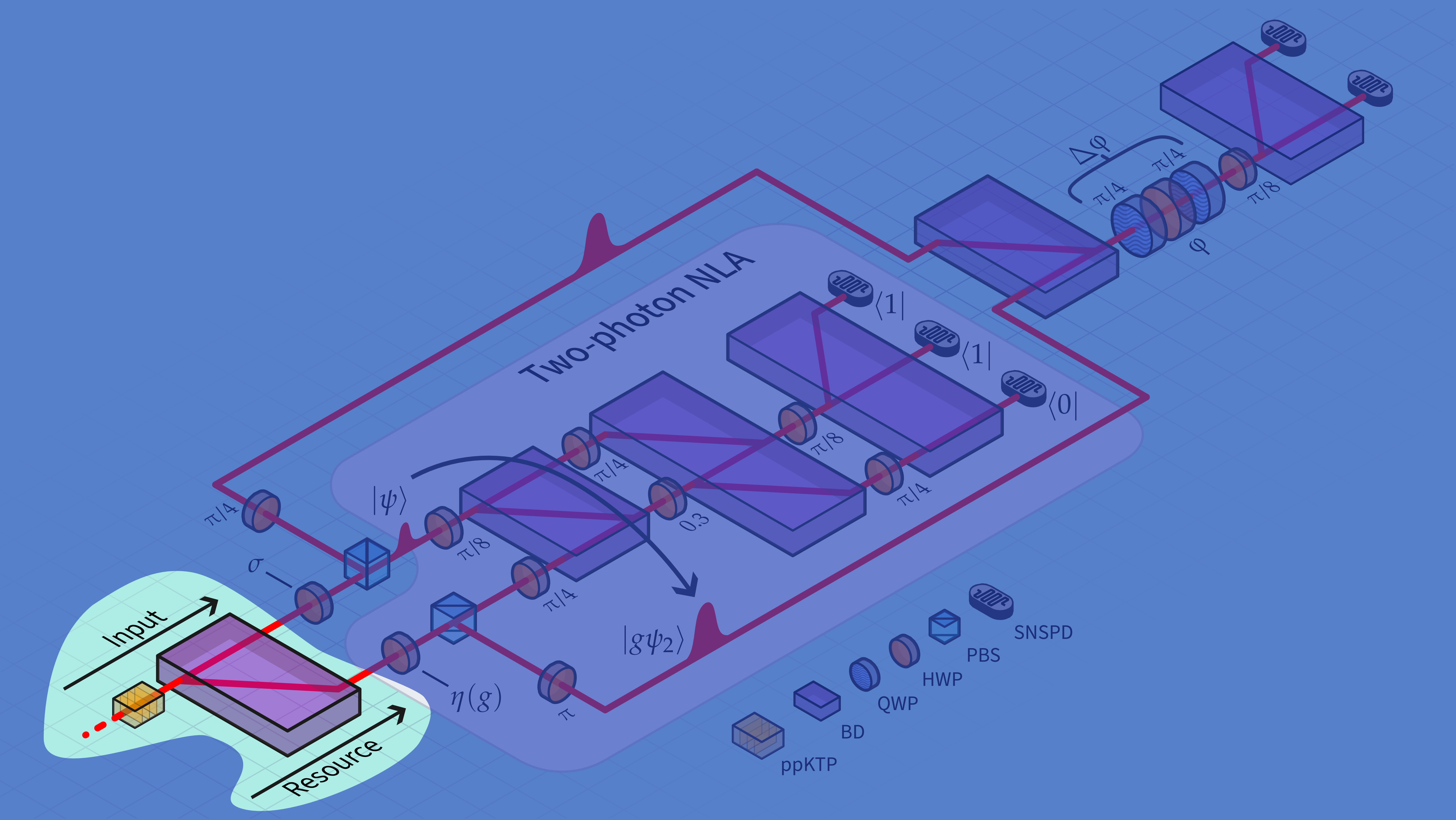
2-NLA
$\langle 1|\langle 1|\langle 0|$
3
$|\psi\rangle$
2
NLA
$|2\rangle$
1
$|g\psi_2\rangle$
4
$c_0|\;\rangle + g c_1|\;\rangle + g^2 c_2|\;\rangle$

# Quantum Fourier Transform

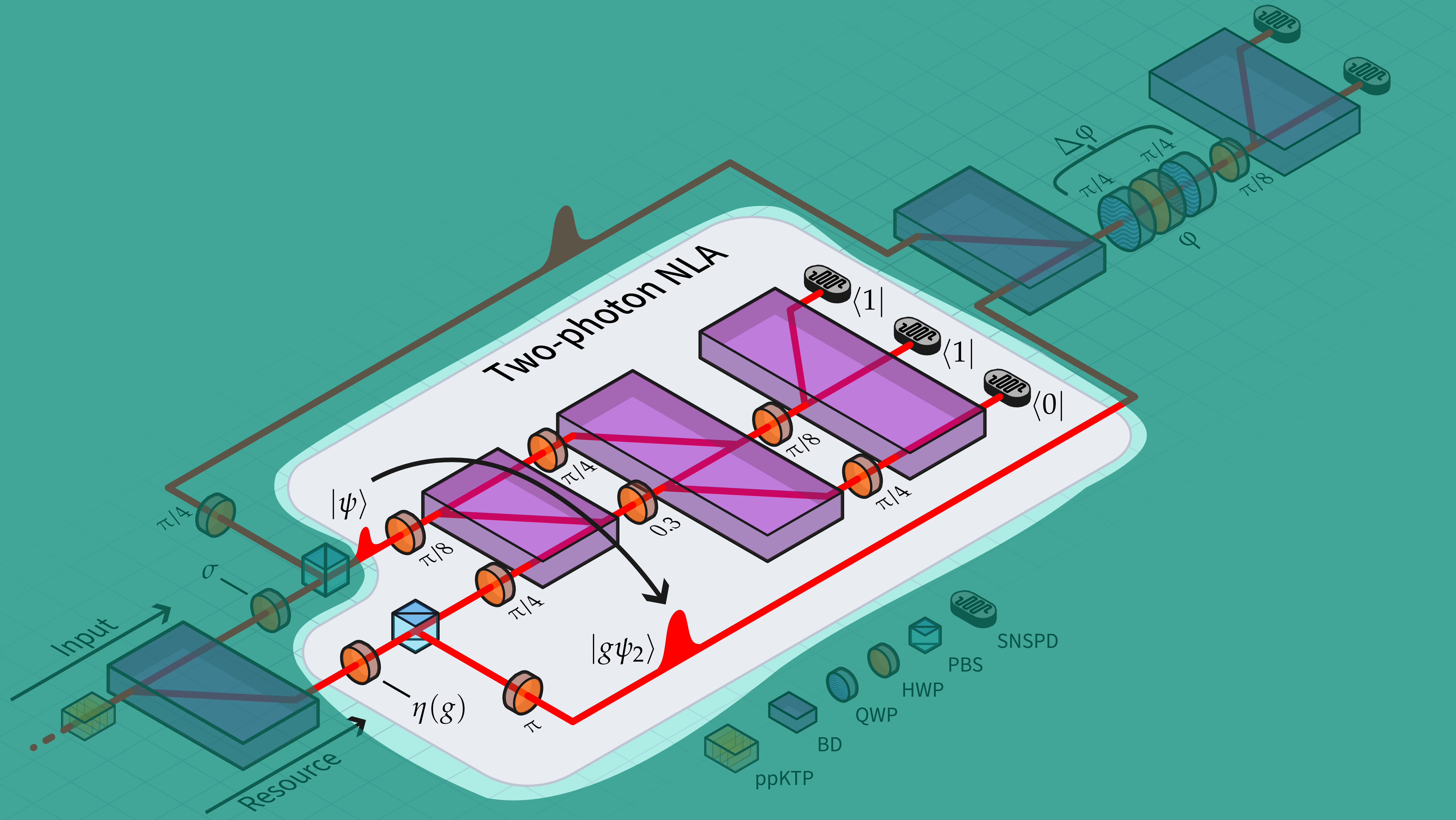



different detector clicks = extra phase
NLA
NLA
NLA
$|g\psi_2\rangle$
$e^{i\pi/3}|g\psi_2\rangle$
$e^{2i\pi/3}|g\psi_2\rangle$

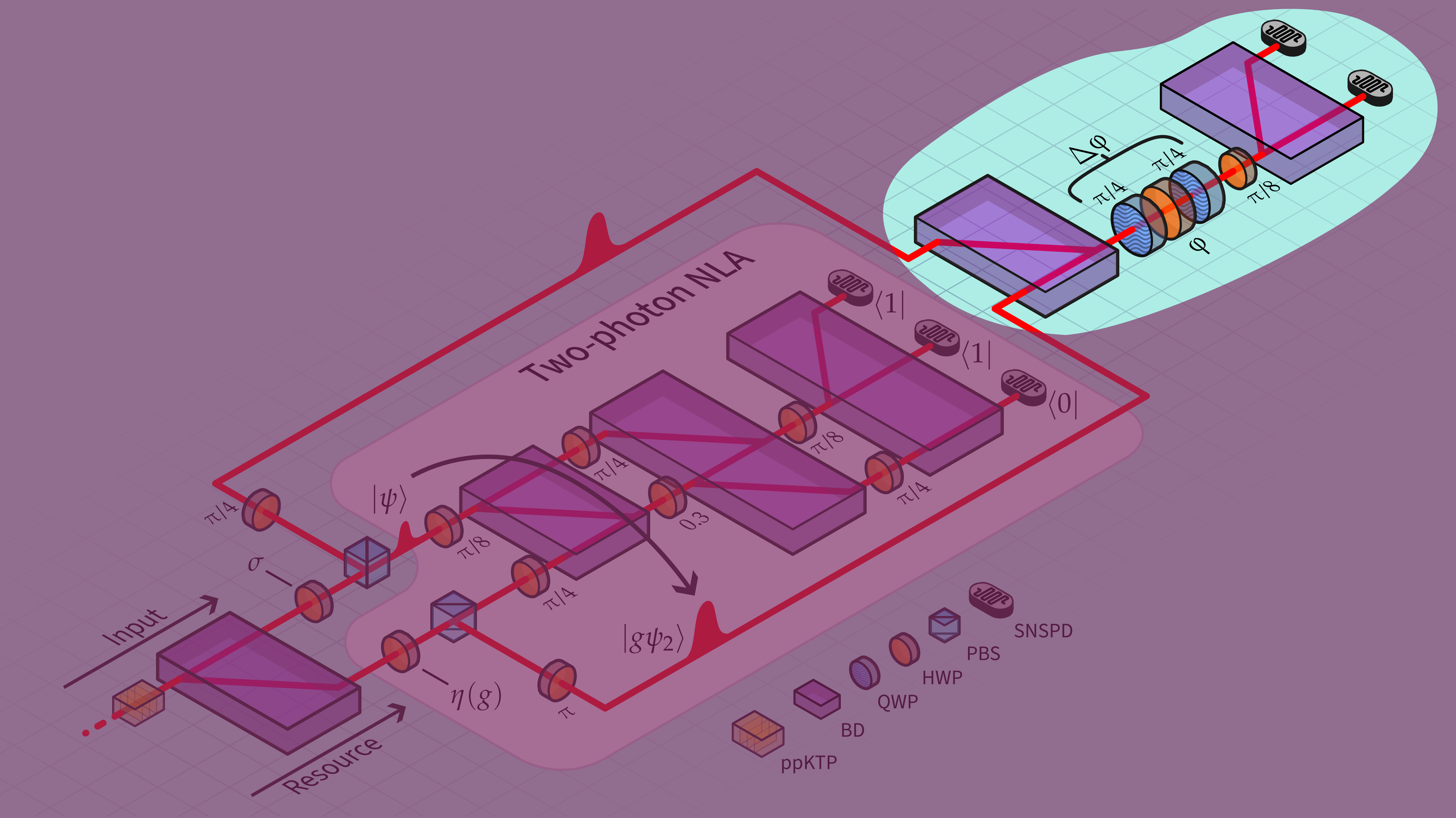

Two-photon NLA
Input
Resource
σ
π/4
|ψ⟩
π/8
π/4
π/4
0.3
π/8
π/4
⟨1|
⟨1|
⟨0|
η(g)
π
|gψ₂⟩
Δφ
π/4
π/4
π/8
φ
ppKTP
BD
QWP
HWP
PBS
SNSPD



Two-photon NLA
Input
Resource
$|\psi\rangle$
$|g\psi_2\rangle$
$\sigma$
$\eta(g)$
$\pi/4$
$\pi/8$
$0.3$
$\pi$
$\langle 1|$
$\langle 1|$
$\langle 0|$
$\Delta\varphi$
$\varphi$
ppKTP
BD
QWP
HWP
PBS
SNSPD

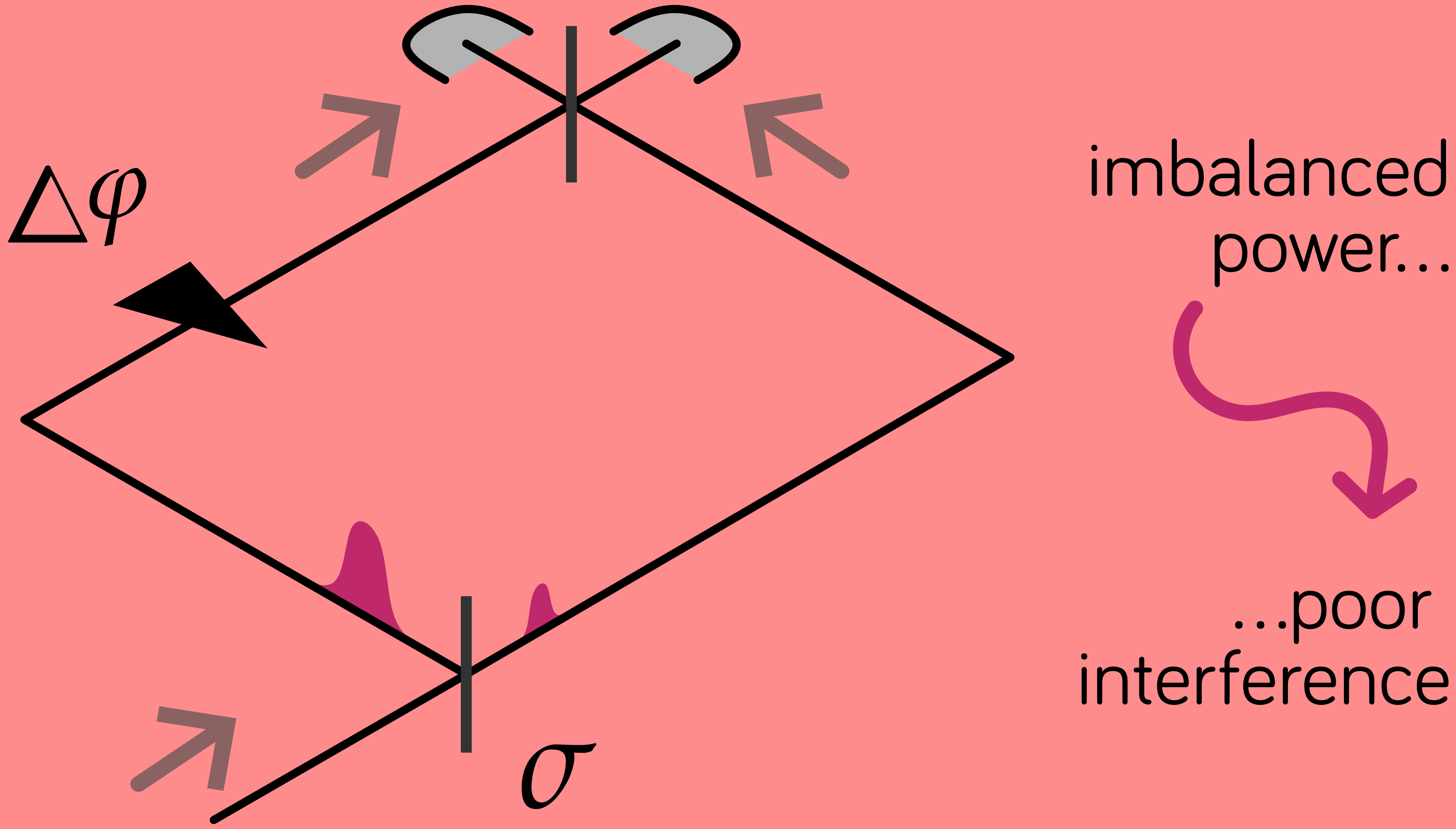


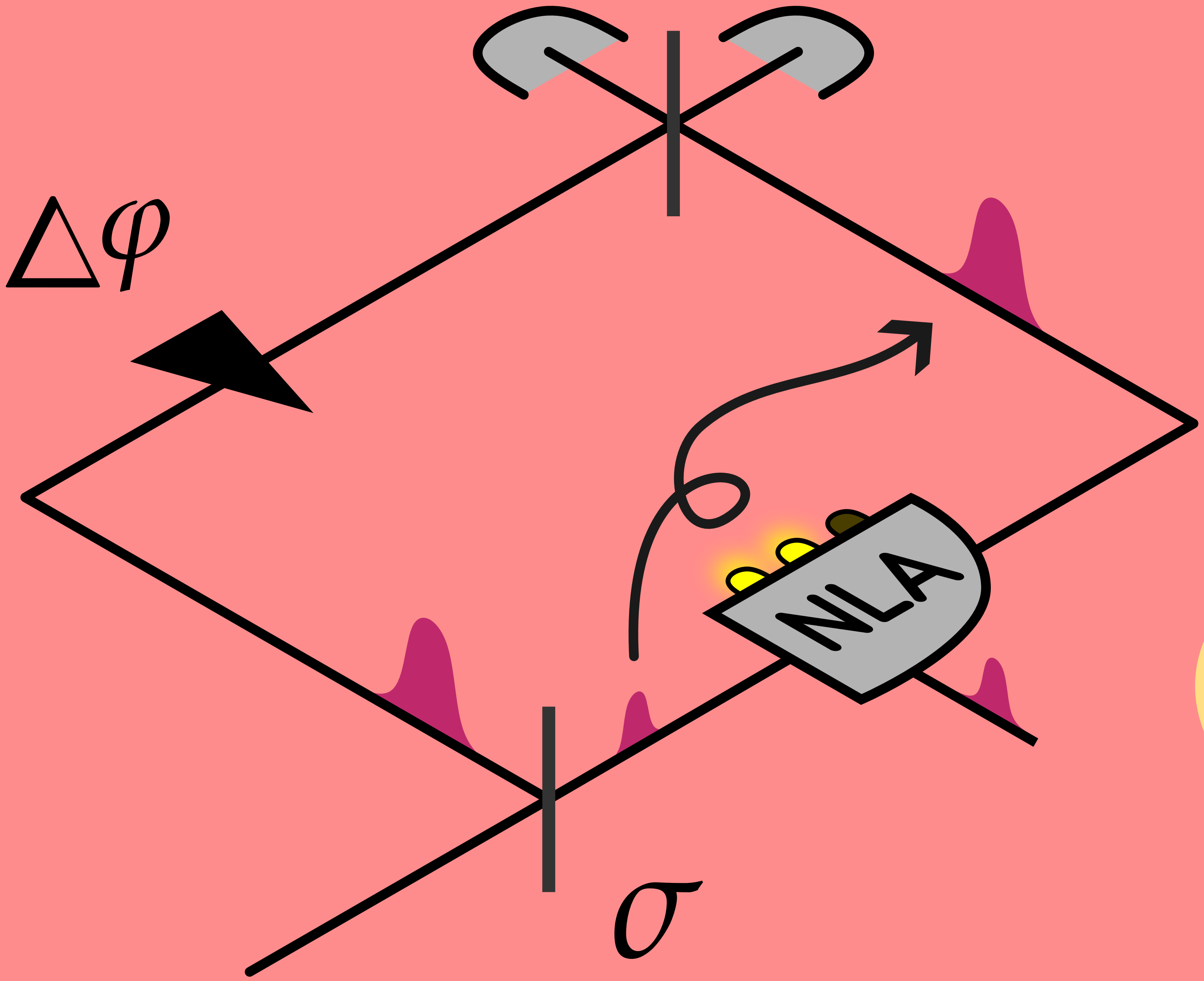
Two-photon NLA
Input
Resource
|ψ⟩
|gψ₂⟩
η(g)
σ
π/4
π/8
0.3
π
⟨1|
⟨1|
⟨0|
Δφ
φ
ppKTP
BD
QWP
HWP
PBS
SNSPD



Two-photon NLA
Input
Resource
$|\psi\rangle$
$|g\psi_2\rangle$
$\sigma$
$\eta(g)$
$\pi/4$
$\pi/8$
$0.3$
$\pi$
$\langle 1|$
$\langle 1|$
$\langle 0|$
$\Delta\varphi$
$\varphi$
ppKTP
BD
QWP
HWP
PBS
SNSPD

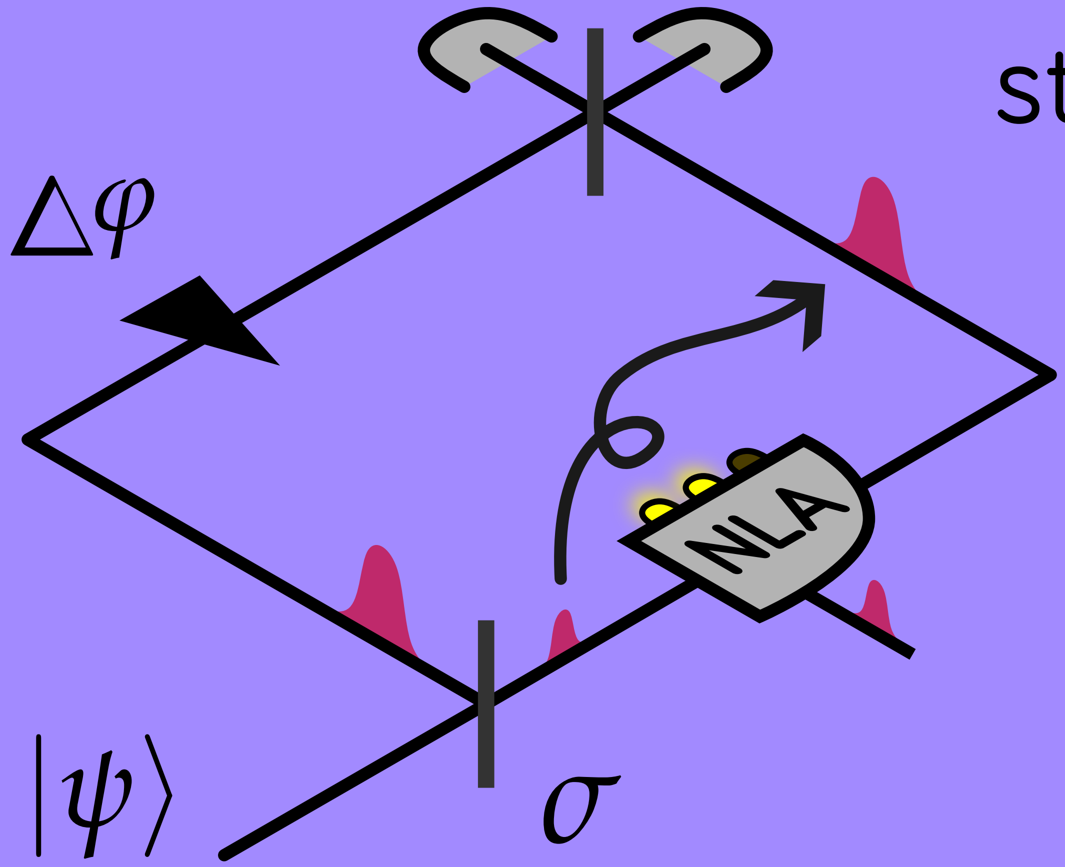
# how do we test it?


$\Delta\varphi$
$\sigma$
imbalanced power...
...poor interference




and if we set
the correct
gain...

here's some numbers:

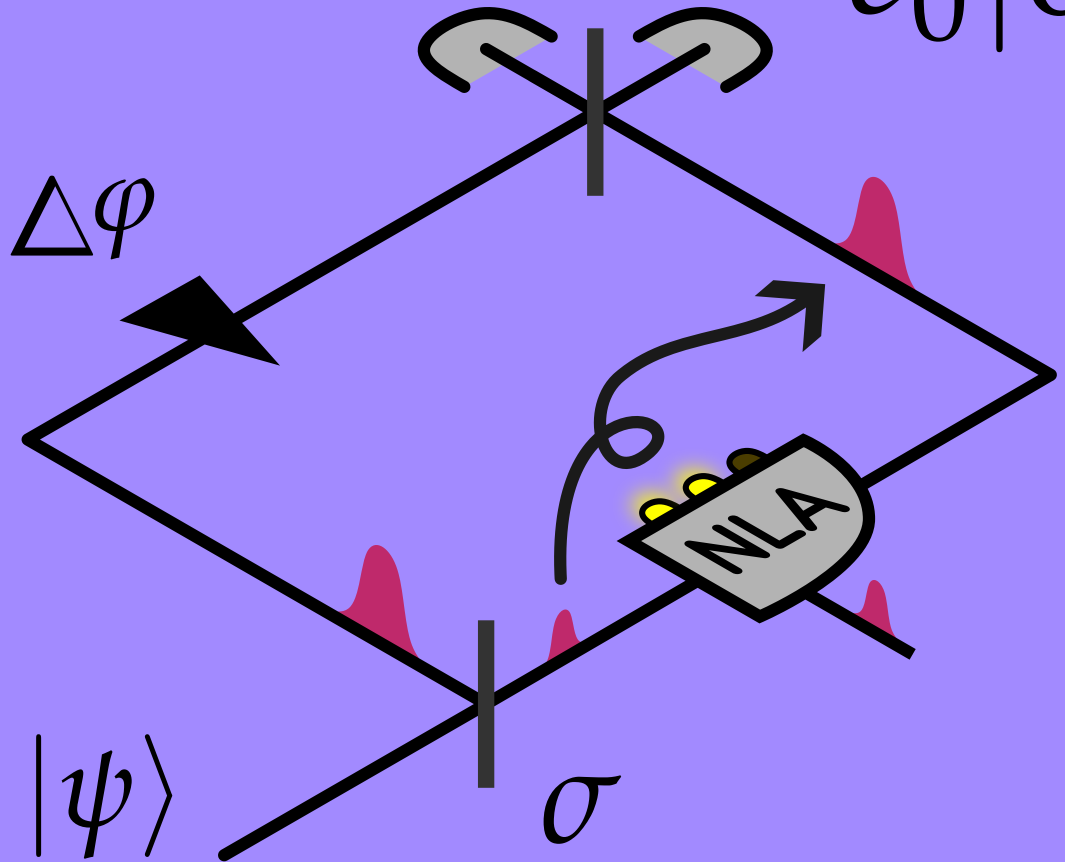



starting from $|\psi\rangle = |2\rangle$

$\sigma = 0.1$

90:10 split

$$c_0|0\rangle + gc_1|1\rangle + g^2c_2|2\rangle$$

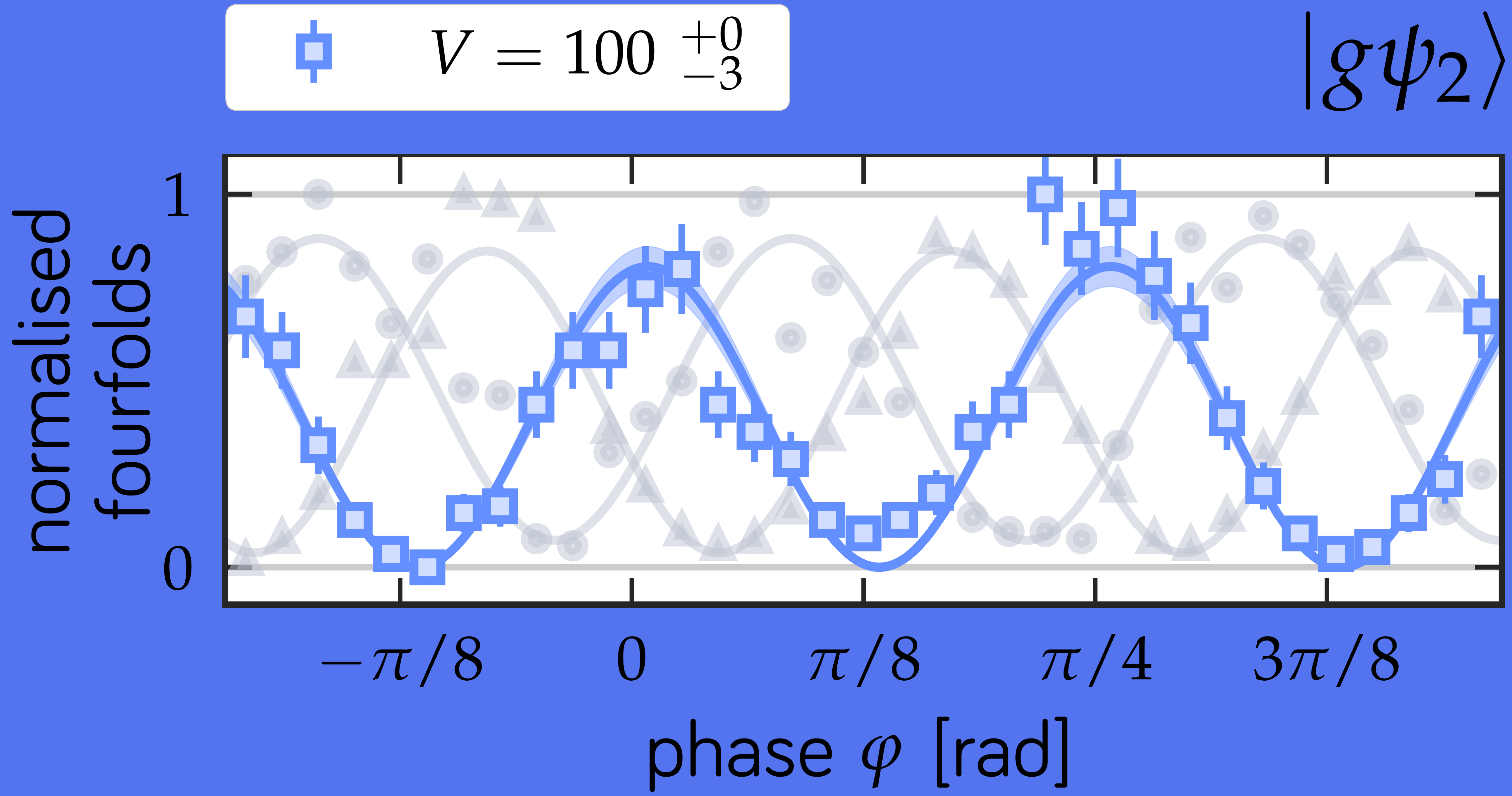



amplitude gain

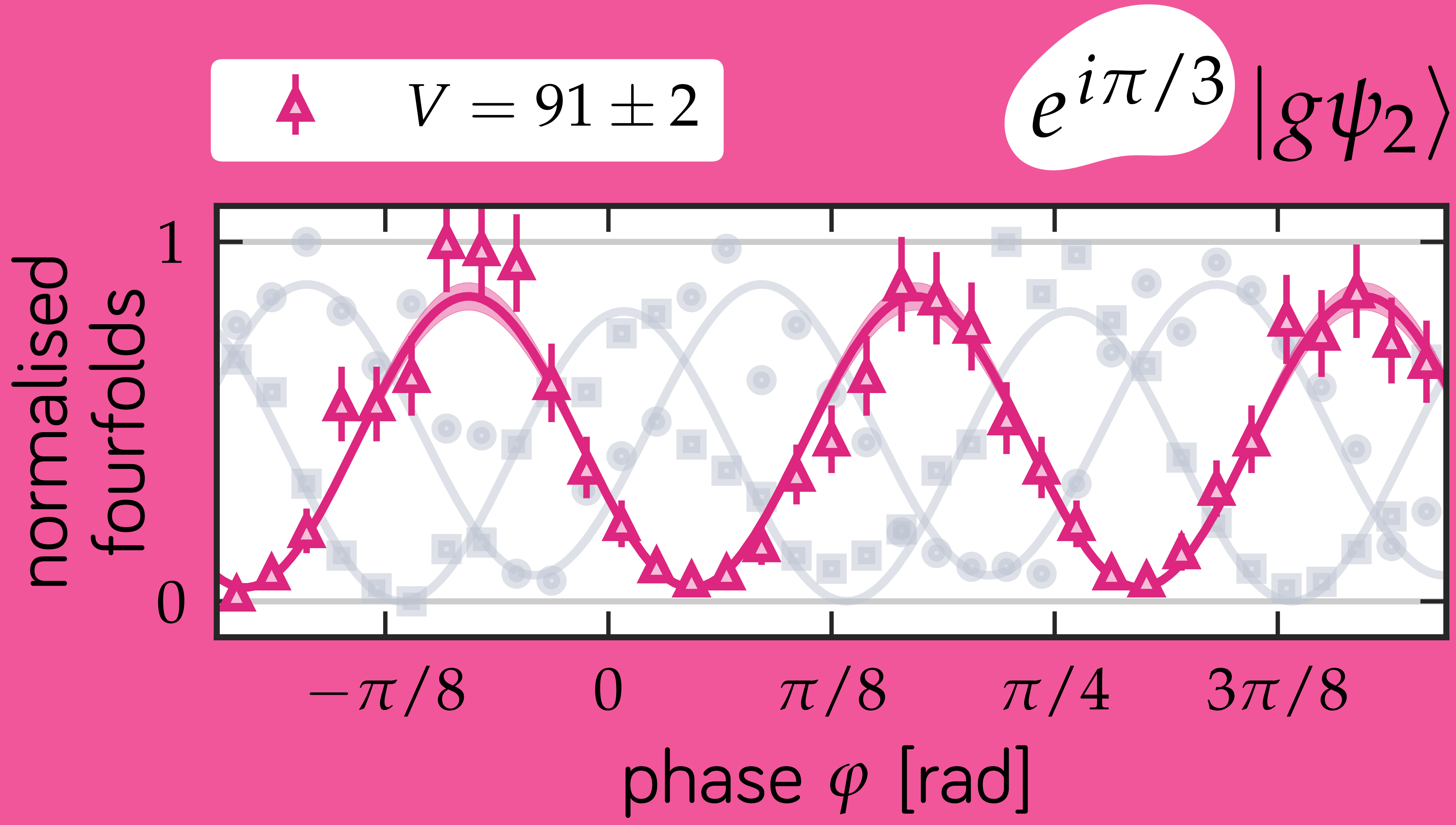
$$g = 3$$

***intensity*** gain

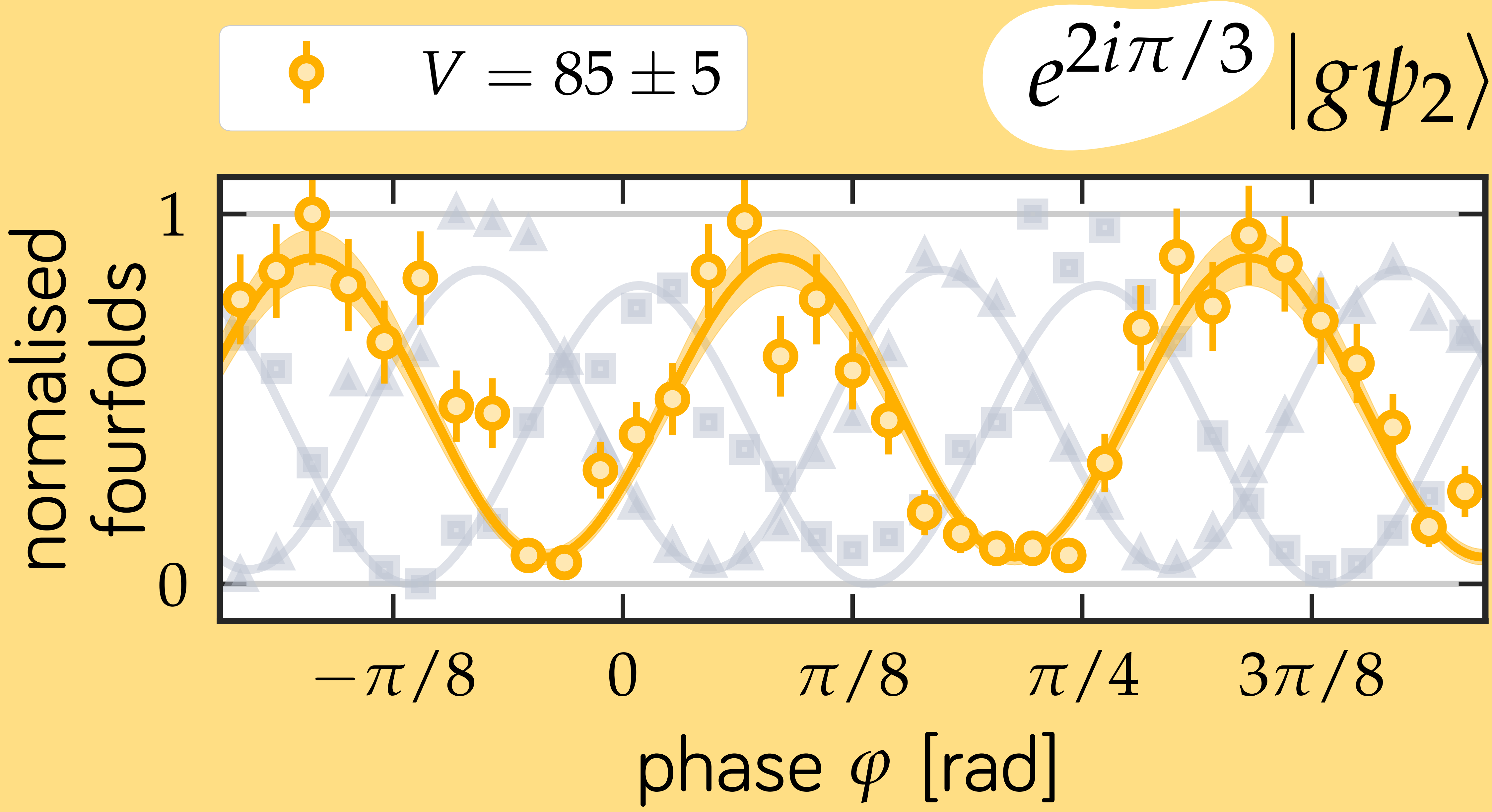
$$|g^2|^2 = g^4 = 81$$



$V = 100\,^{+0}_{-3}$
$|g\psi_2\rangle$
1
0
normalised fourfolds
$-\pi/8$
0
$\pi/8$
$\pi/4$
$3\pi/8$
phase $\varphi$ [rad]

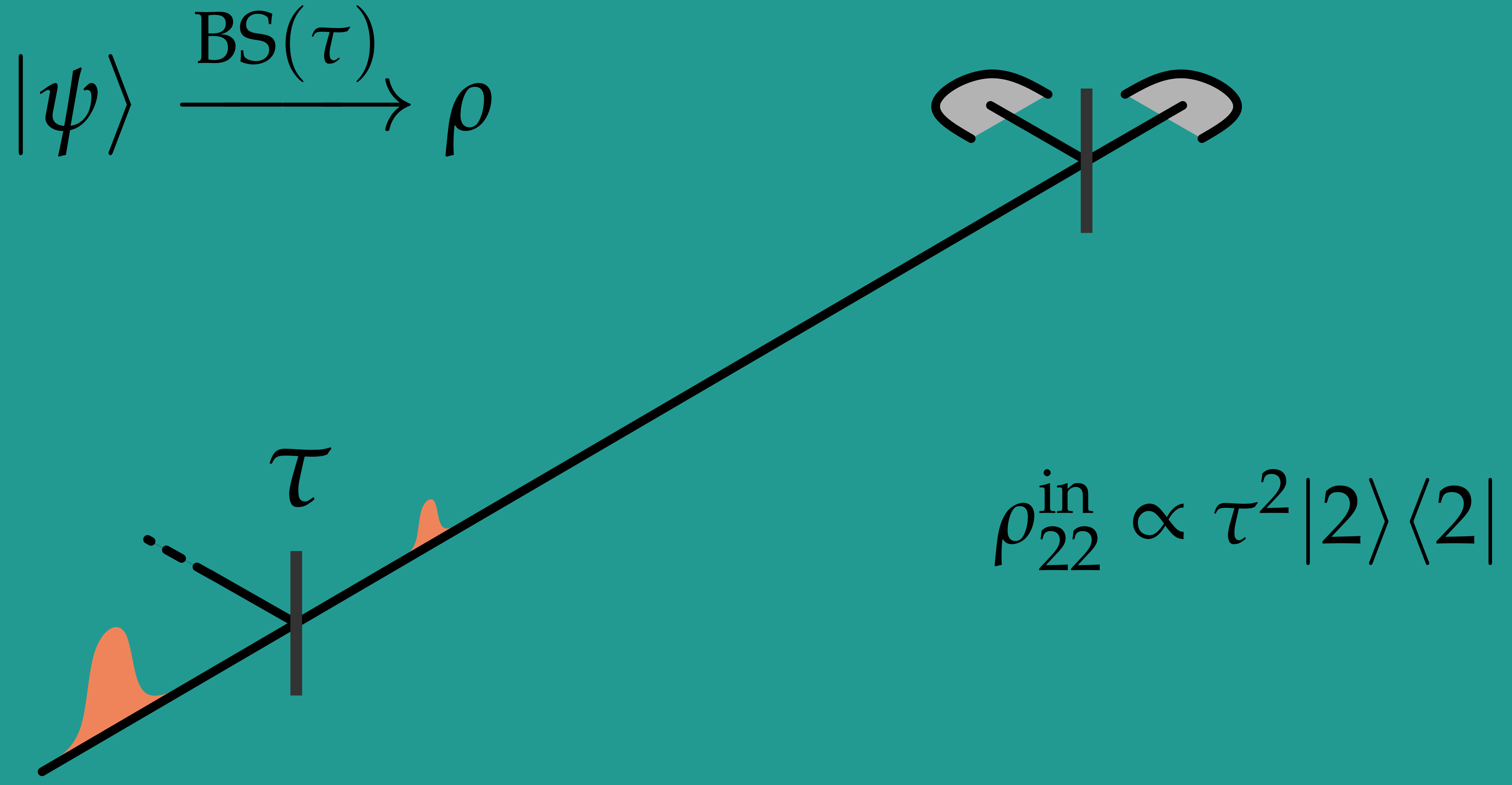


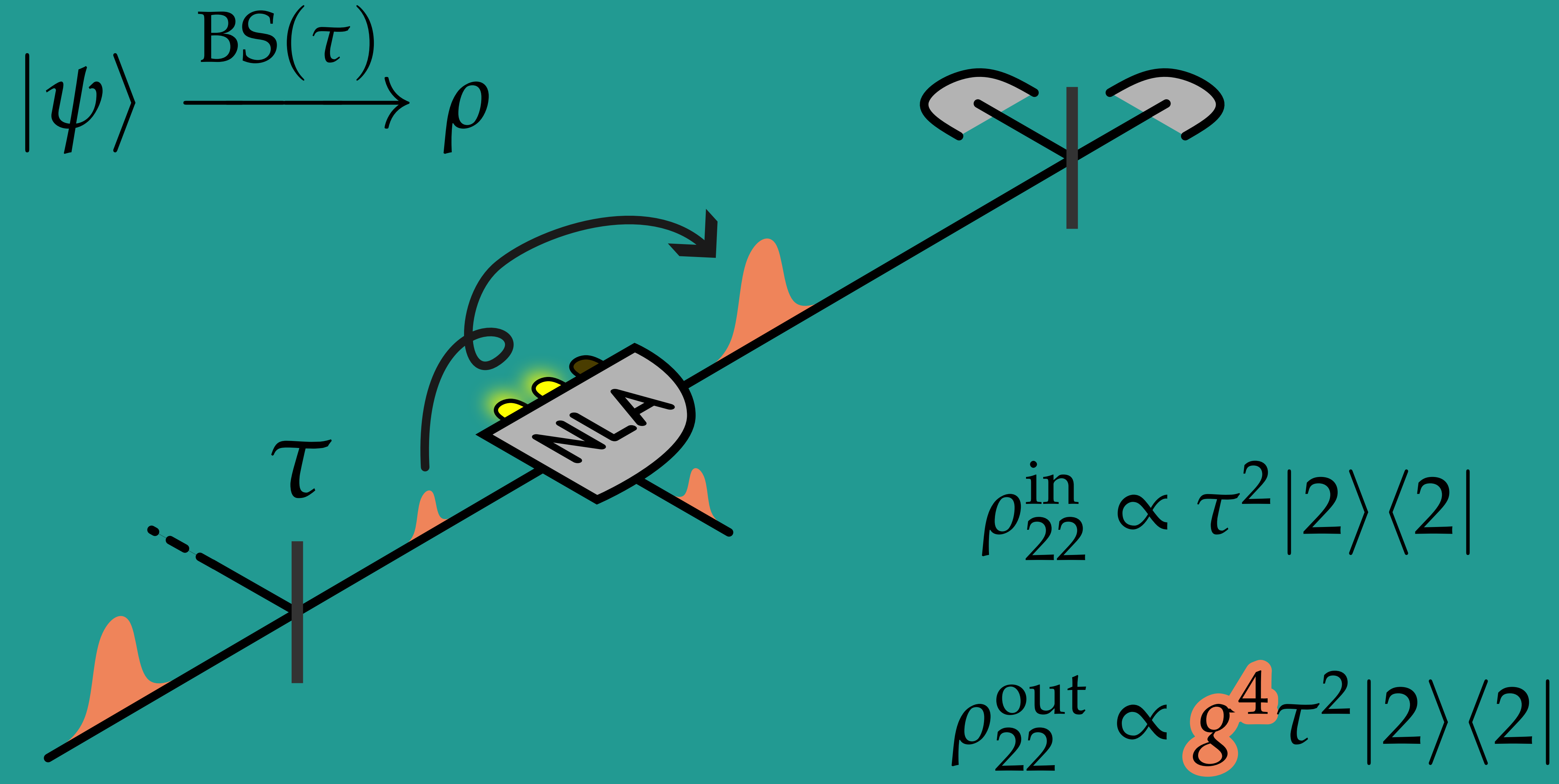
$V = 91 \pm 2$
$e^{i\pi/3} |g\psi_2\rangle$
normalised fourfolds
1
0
$-\pi/8$
0
$\pi/8$
$\pi/4$
$3\pi/8$
phase $\varphi$ [rad]



$V = 85 \pm 5$
$e^{2i\pi/3} |g\psi_2\rangle$
1
0
normalised fourfolds
$-\pi/8$
0
$\pi/8$
$\pi/4$
$3\pi/8$
phase $\varphi$ [rad]

we can also measure
the gain directly


$|\psi\rangle \xrightarrow{\mathrm{BS}(\tau)} \rho$
$\tau$
$\rho_{22}^{\mathrm{in}} \propto \tau^2 |2\rangle\langle 2|$



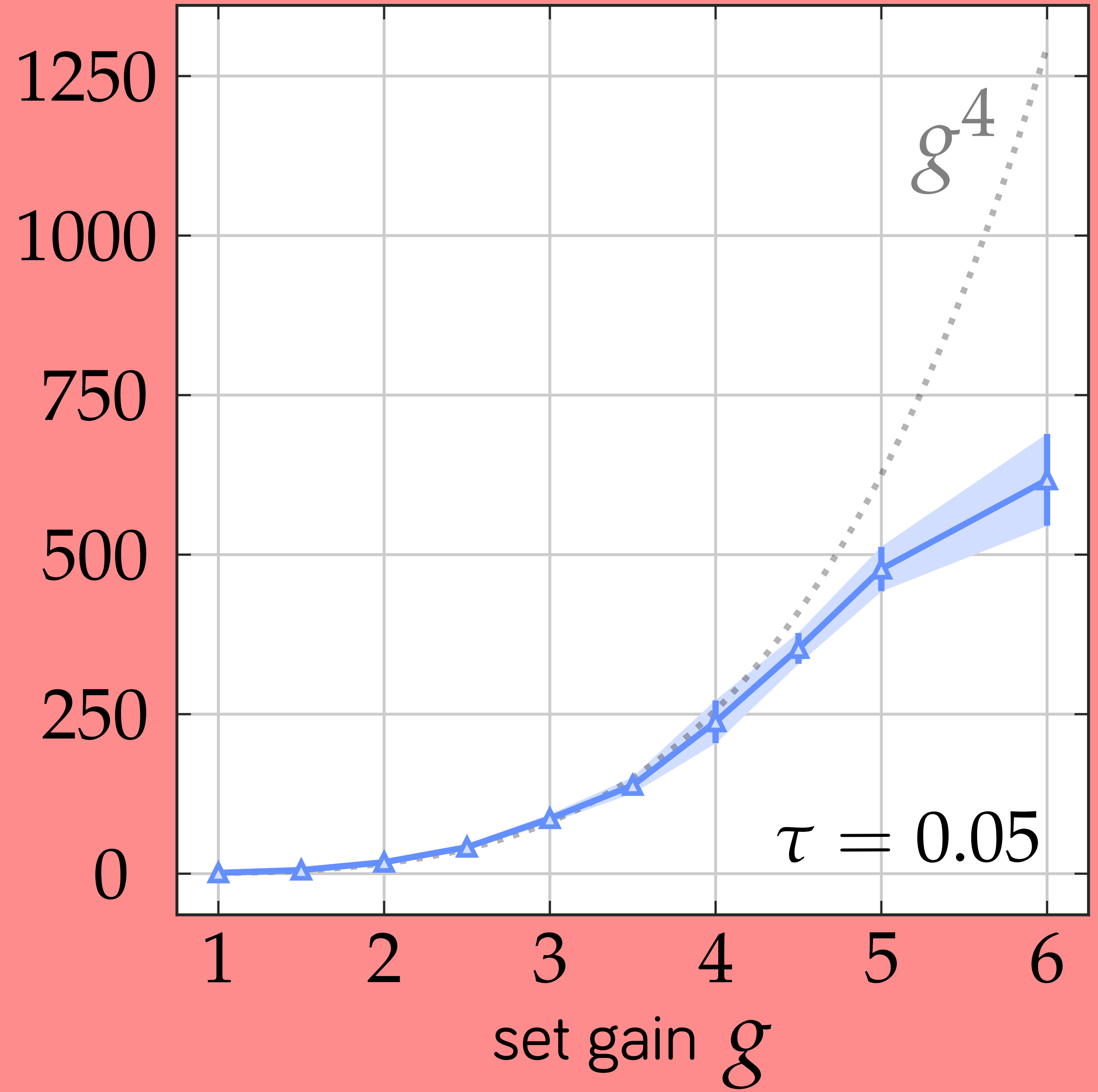
$|\psi\rangle \xrightarrow{\mathrm{BS}(\tau)} \rho$
$\tau$
NLA
$\rho_{22}^{\mathrm{in}} \propto \tau^2 |2\rangle\langle 2|$
$\rho_{22}^{\mathrm{out}} \propto g^4 \tau^2 |2\rangle\langle 2|$

$$\frac{\rho_{22}^{\mathrm{out}}}{\rho_{22}^{\mathrm{in}}} = g^4$$

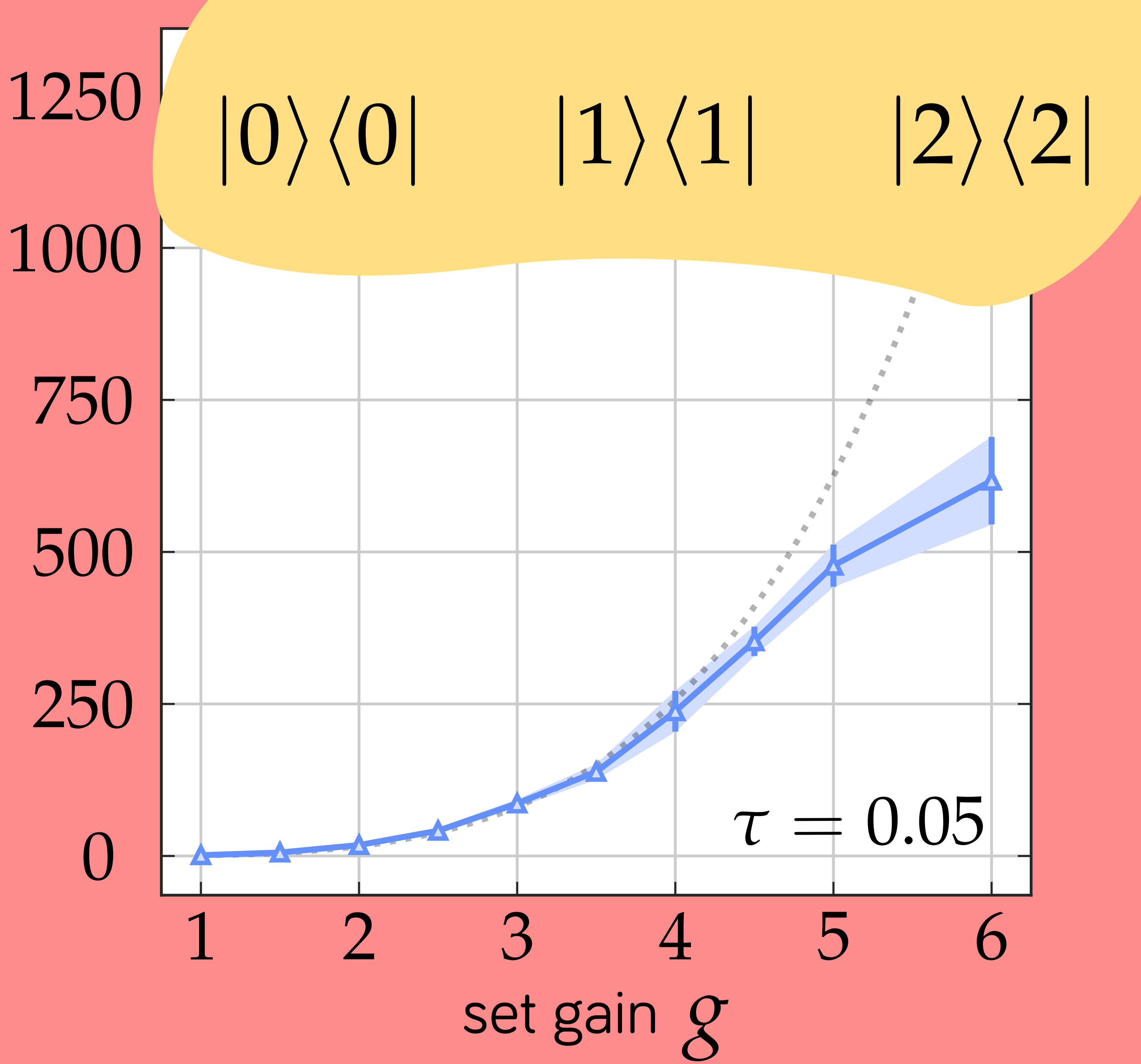
$$\frac{\rho_{22}^{\mathrm{out}}}{\rho_{22}^{\mathrm{in}}} = g^4$$

how **LOUD**
can we get?

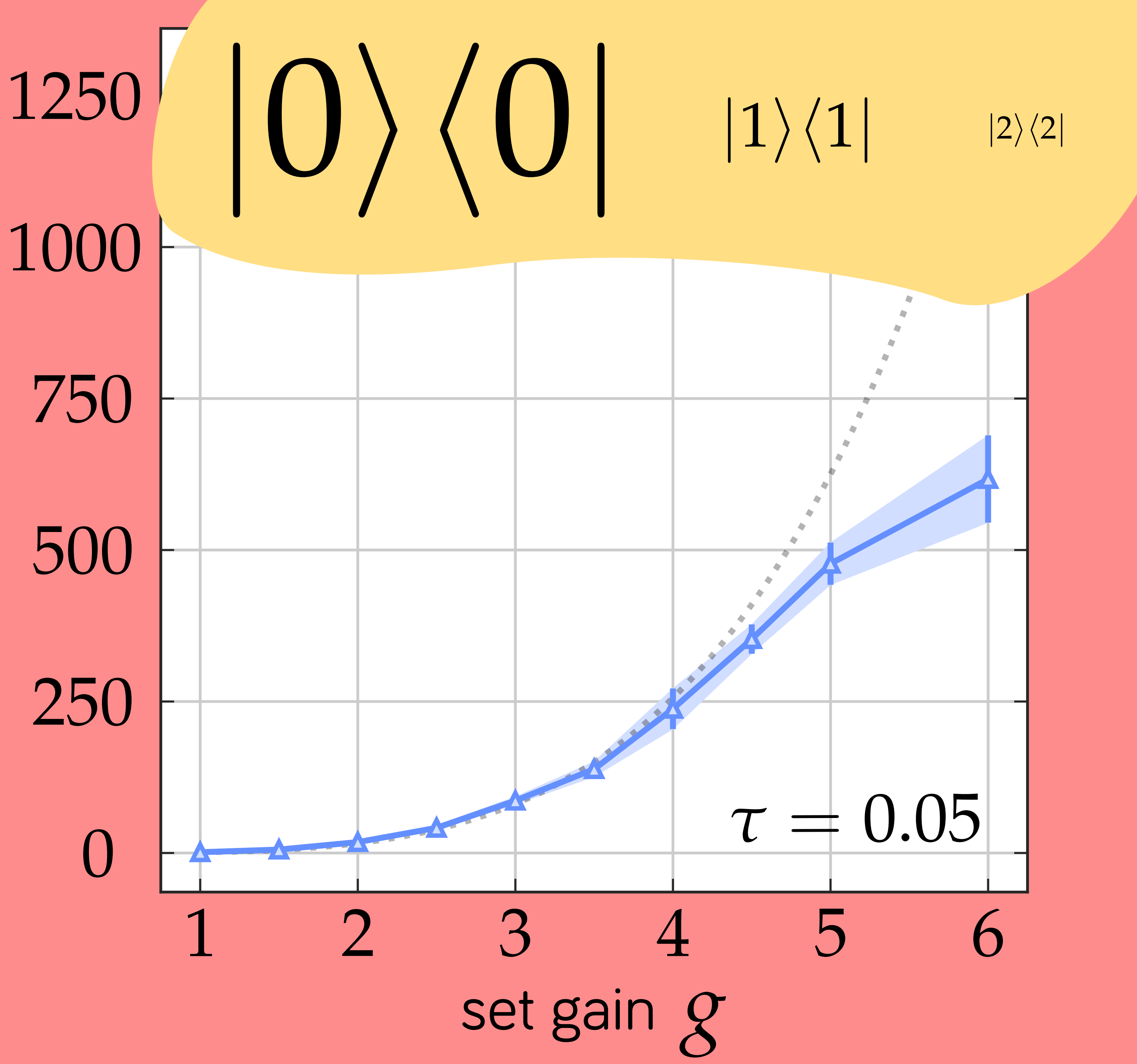
$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



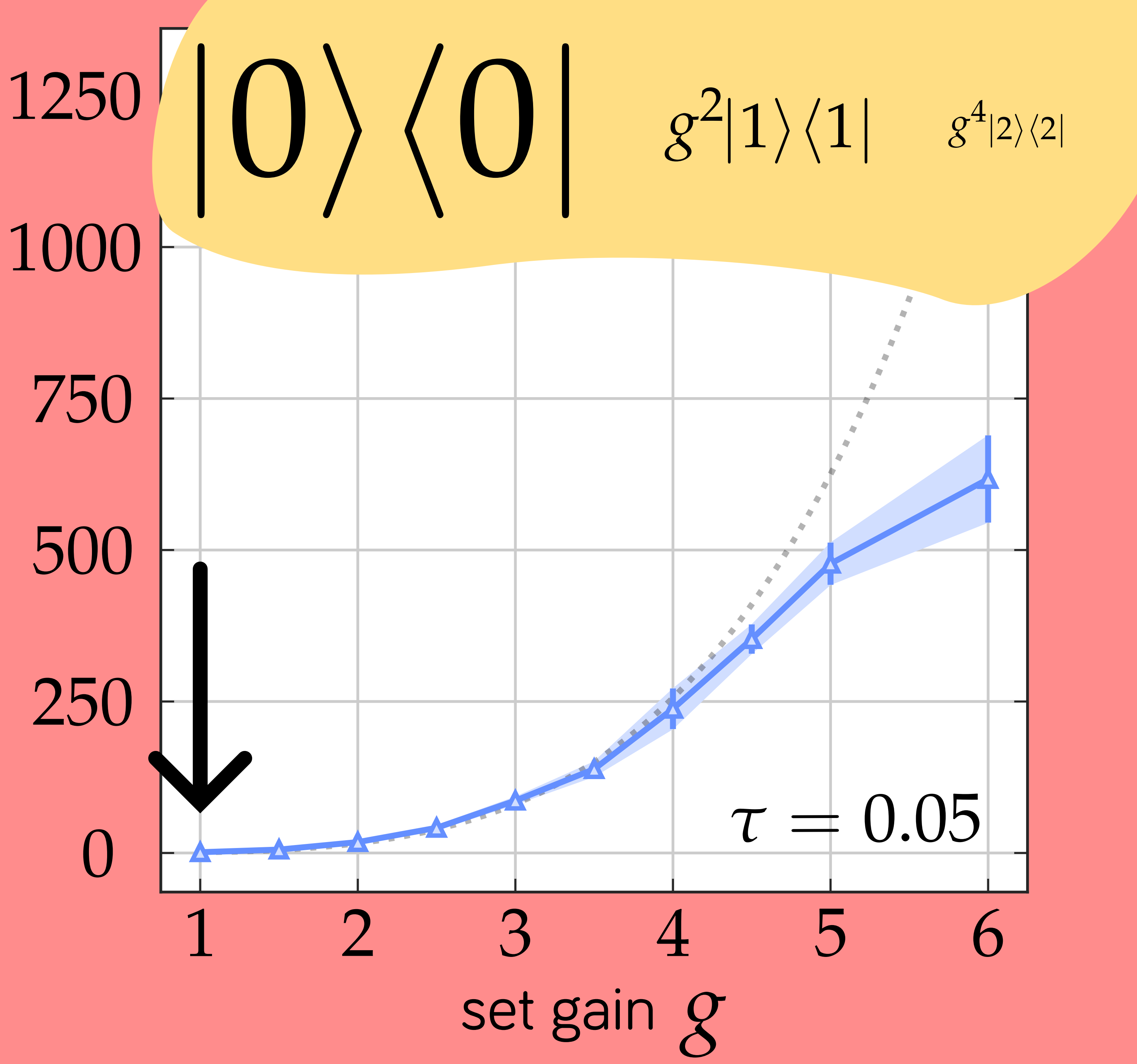
$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



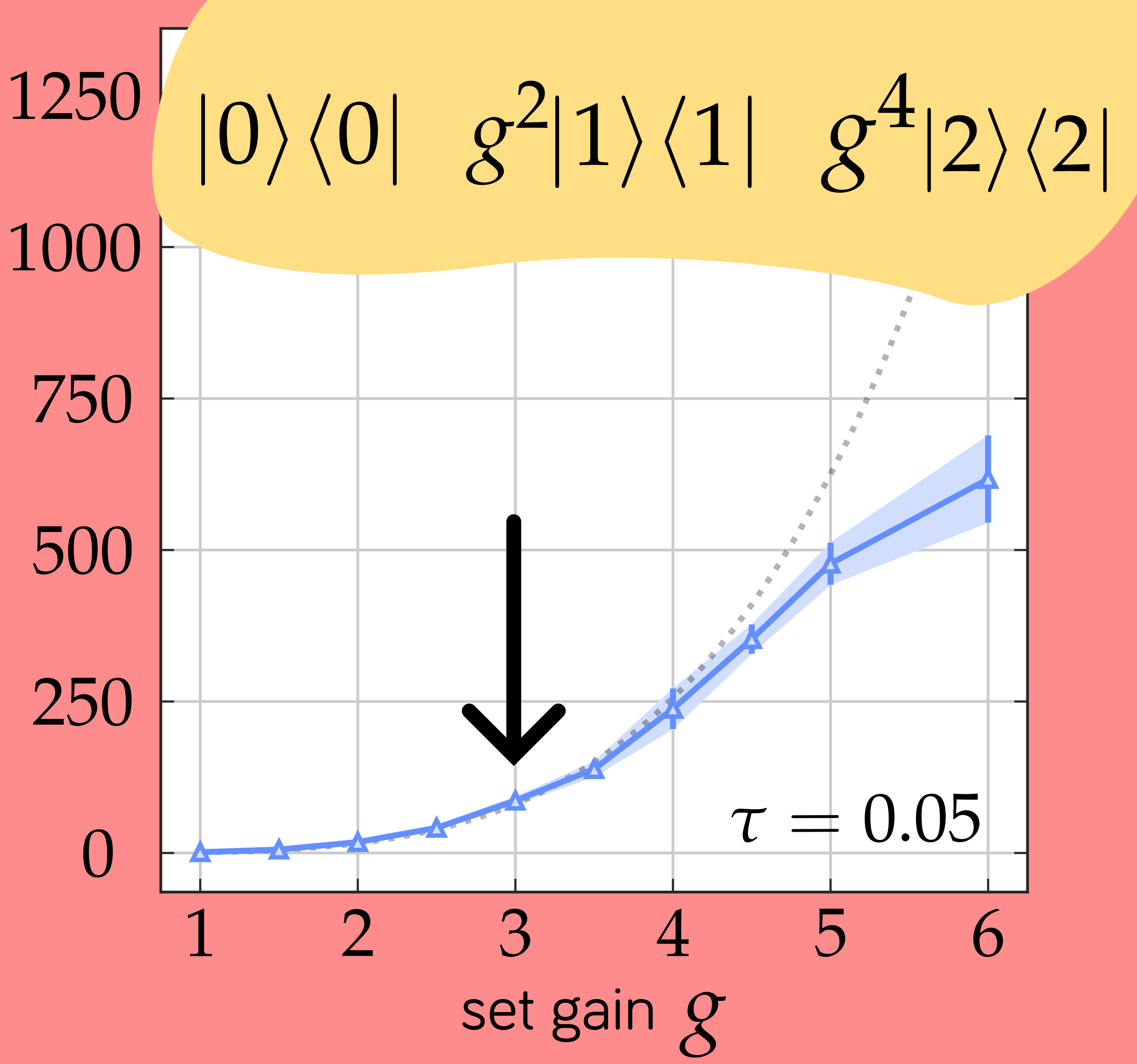
$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



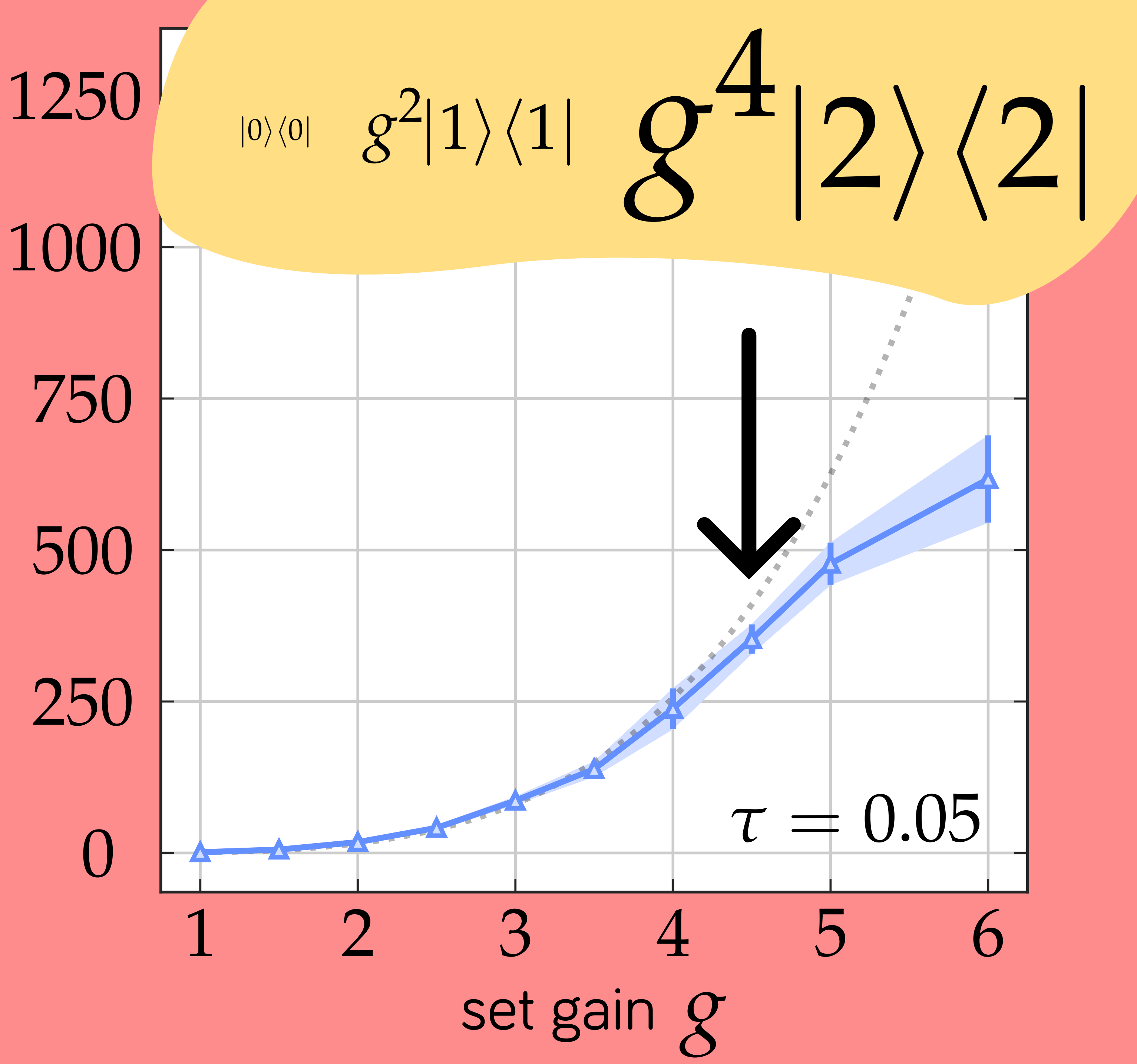
$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



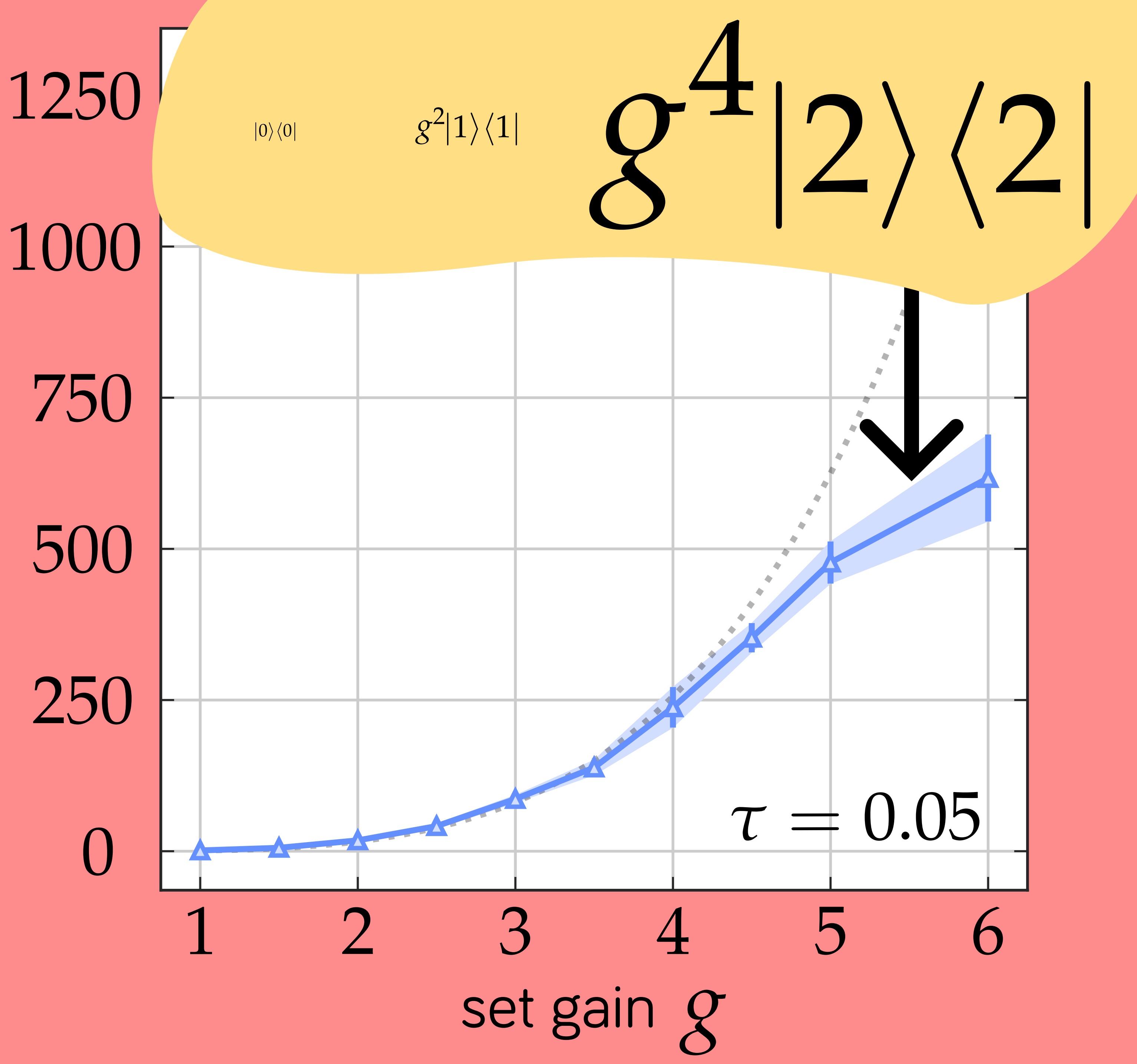
$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



$$\frac{\rho_{22}^{\text{out}}}{\rho_{22}^{\text{in}}} = g^4$$



$$\frac{\rho_{22}^{\mathrm{out}}}{\rho_{22}^{\mathrm{in}}} = g^4$$



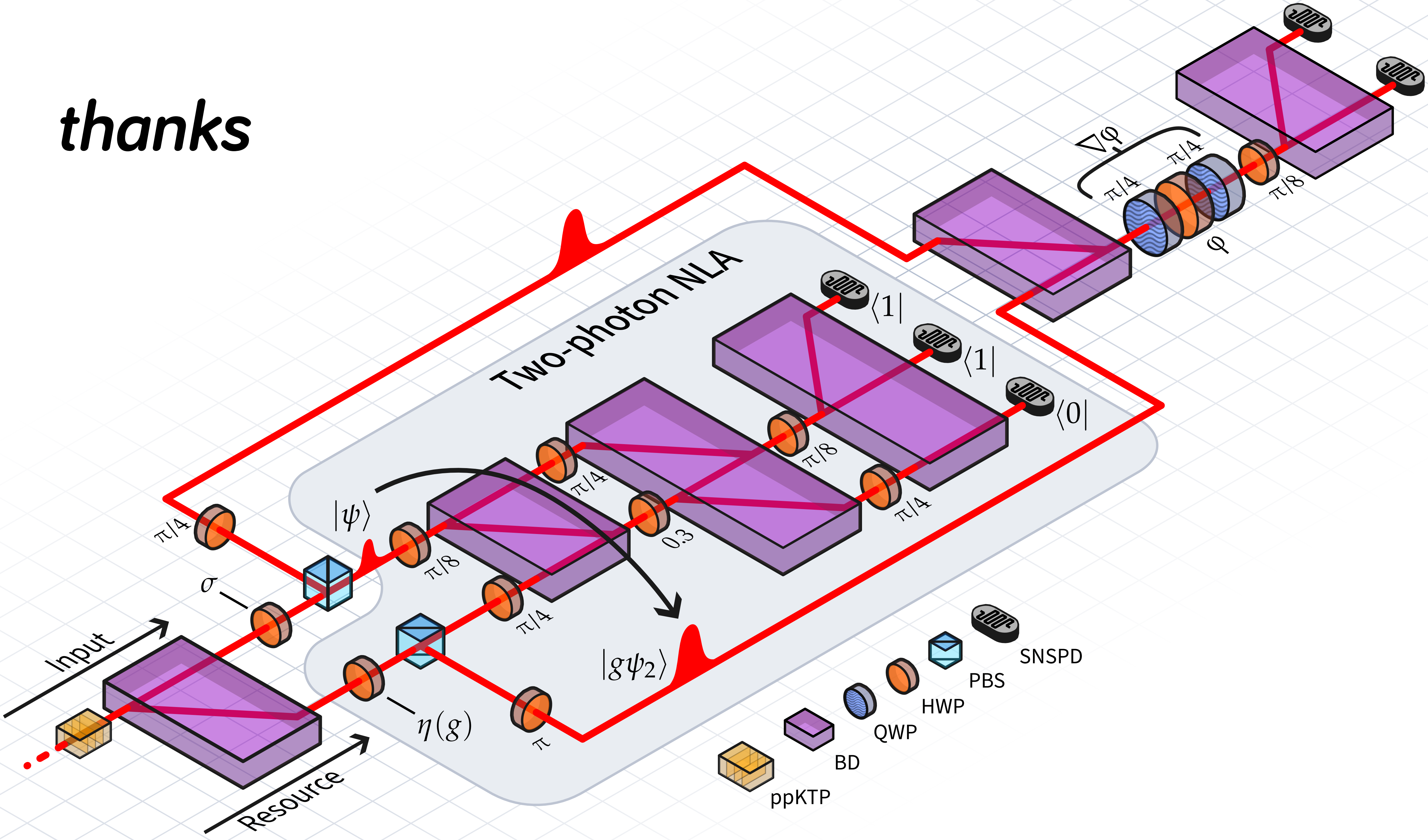
pretty LOUD

## *to conclude:*

communication ***needs*** amplification

amplifying more than one photon
has been very difficult until now

*thanks*



Two-photon NLA
Input
Resource
σ
η(g)
|ψ⟩
|gψ₂⟩
⟨1|
⟨1|
⟨0|
π/4
π/8
π/4
π/4
0.3
π/8
π/4
π
∇φ
π/4
π/4
π/8
φ
ppKTP
BD
QWP
HWP
PBS
SNSPD