

Laser cavity solitons and turing patterns in microresonator filtered lasers: properties and perspectives

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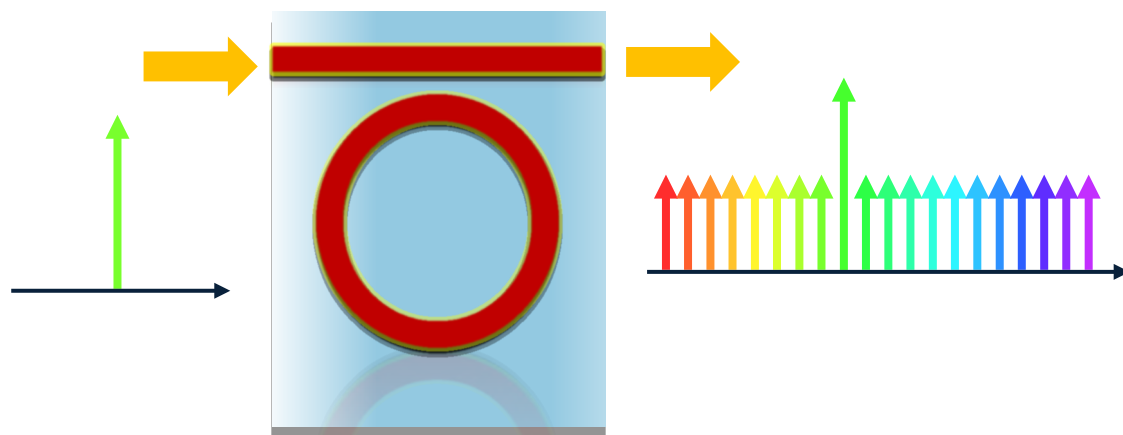
⁵*INRS-EMT, 1650 Boulevard Lionel-Boulet, Varennes, Québec, Canada J3X 1S2*

⁶*Centre for Microphotonics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia*

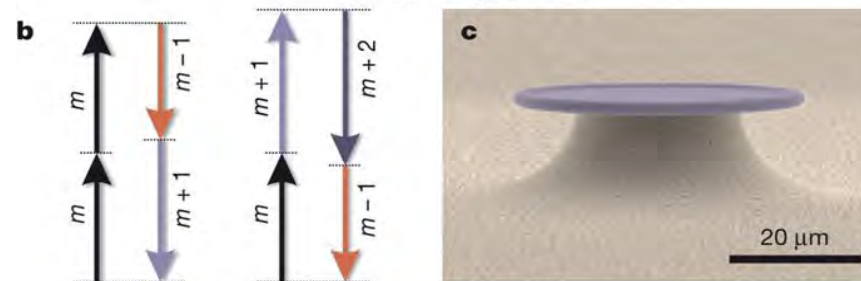
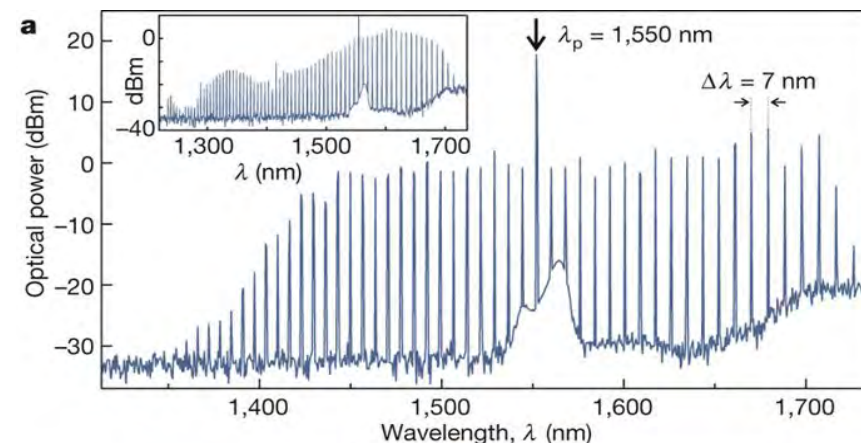
EPic | US
EMERGENT | UNIVERSITY
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- Brief overview of laser cavity solitons
- A hybrid micro-comb laser – model and experiment
- Solitons vs Turing Patterns
- Efficiency, start-up and control: challenges and perspectives

Micro-Combs and Cavity- Solitons



Lugiato-Lefever Equation



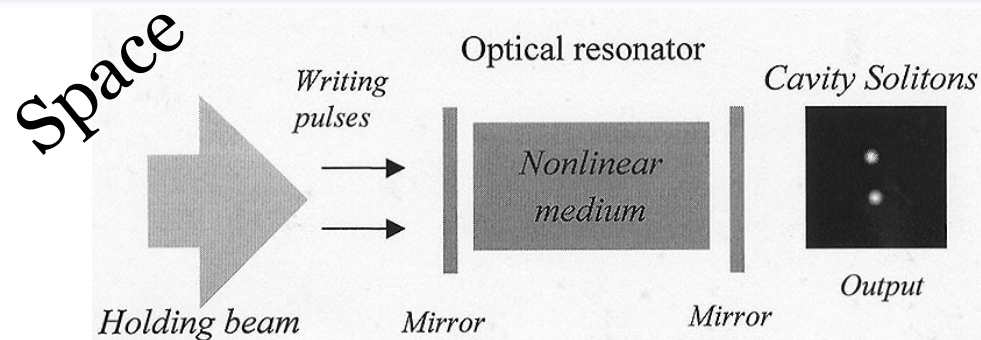
Del'Haye et al. Nature **450** 1214 (2007)

Cavity-Solitons and Transverse Patterns

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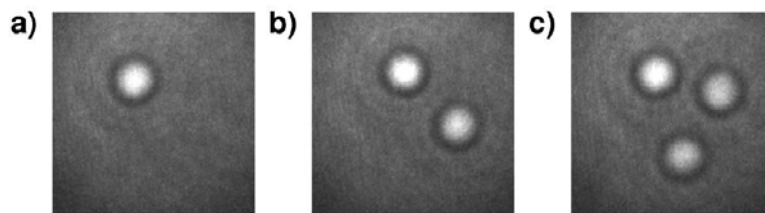
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Lugiato, Prati and Brambilla, Nonlinear Optical Systems. Cambridge University Press. (2015)

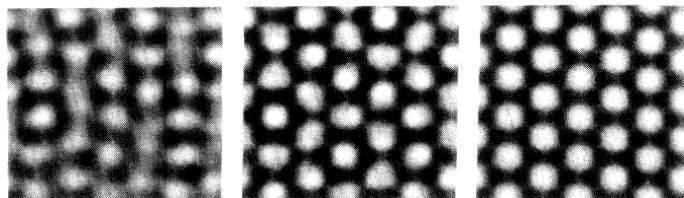


Lugiato and Lefever, Phys. Rev. Lett. **58** 2209 (1987)

Localised

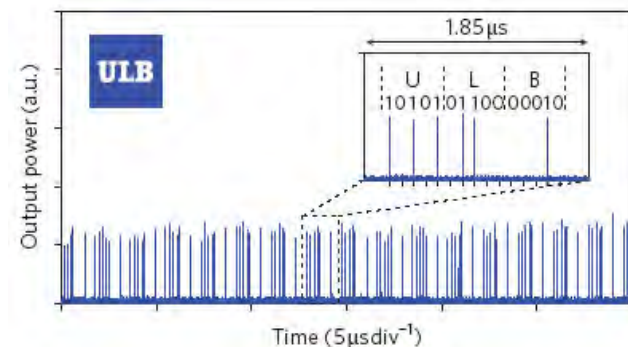


Schäpers, Feldmann, Ackemann and Lange Phys. Rev. Lett. **85**, 748 (2000)



Periodical

D'Alessandro and Firth Phys. Rev. Lett. **66** 2597 (1992)

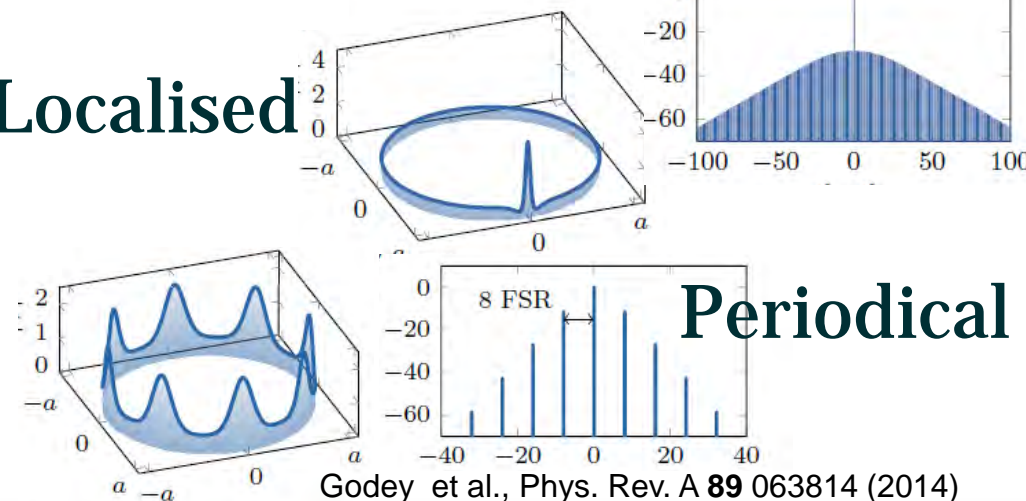


Leo et al., Nat. Photon. **4** 471 (2010)

Time

Haelterman, Trillo and Wabnitz, Opt. Comm. **91** 401 (1992)

Localised



Godey et al., Phys. Rev. A **89** 063814 (2014)

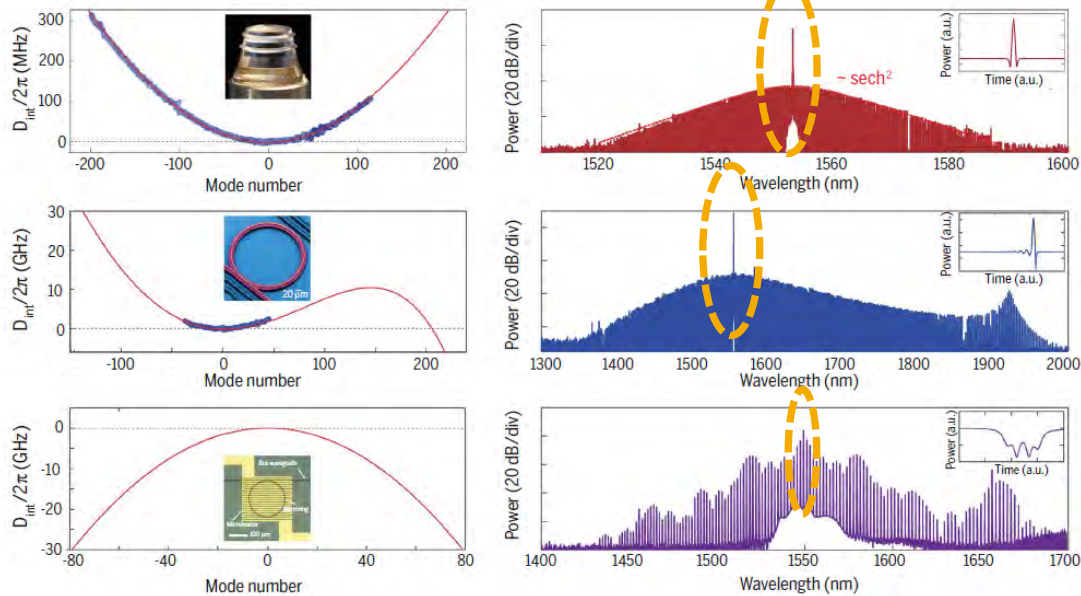
Periodical

A quest for efficiency

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Cavity-Solitons



< 5%

< 50%

Mode Efficiency
ENERGY COMB- ENERGY PUMP
ENERGY PUMP

X. Xue et al. Laser Photonics Rev. **11** 1600276 (2017)

Herr et al. Nat. Photon. **8** 145 (2014)

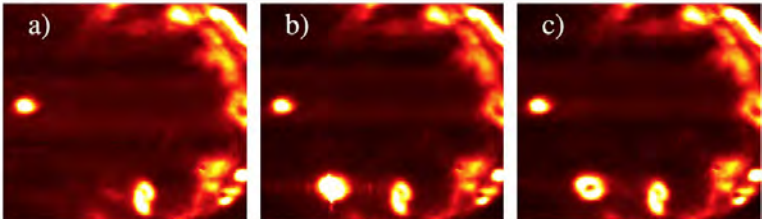
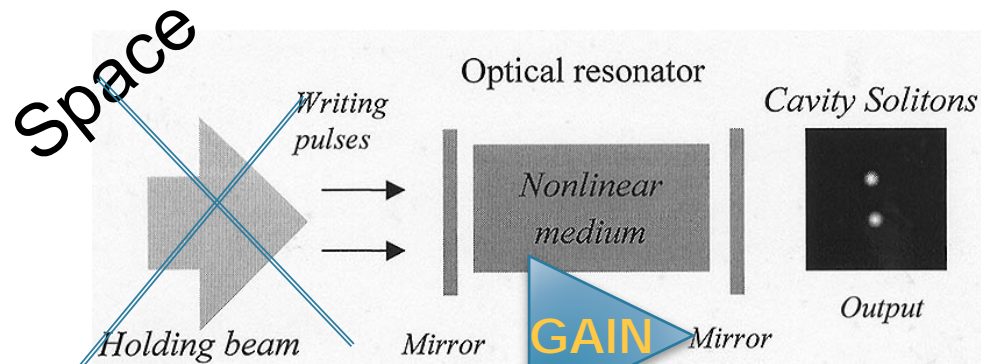
Xue et al. Nat. Photon. **9** 594 (2015)

Brasch et al. Science **351** 357 (2016)

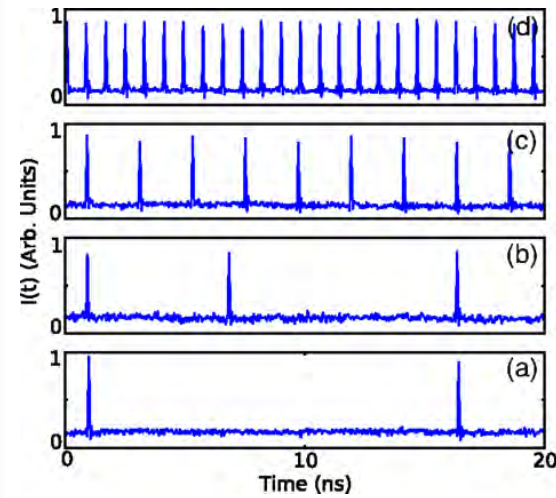
Li et al. Optica **4** 193 (2017)

Kippenberg et al. Science **361** eaan8083 (2018)

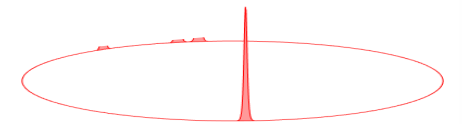
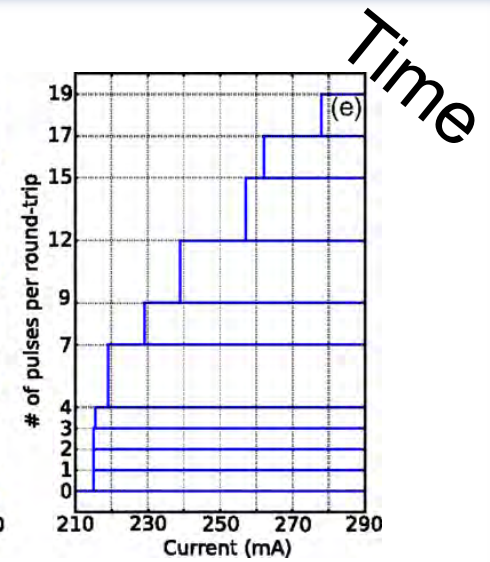
Laser Cavity-Solitons



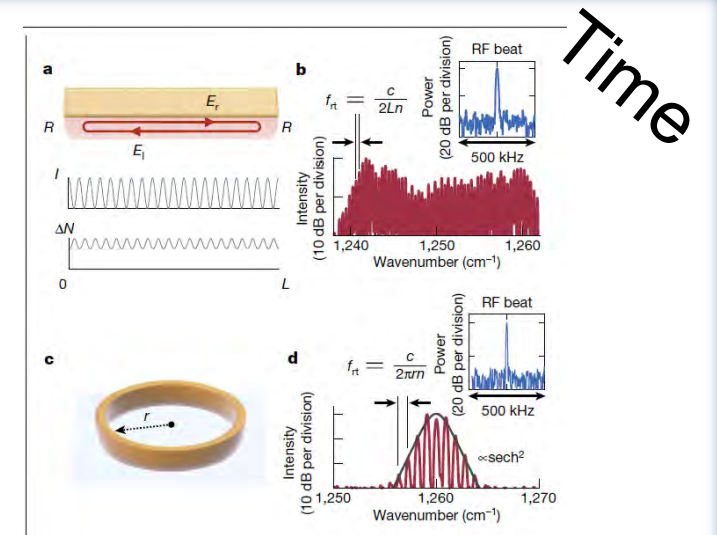
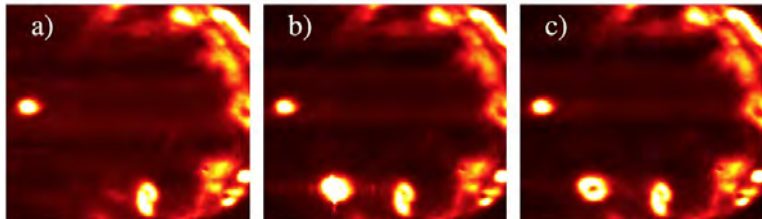
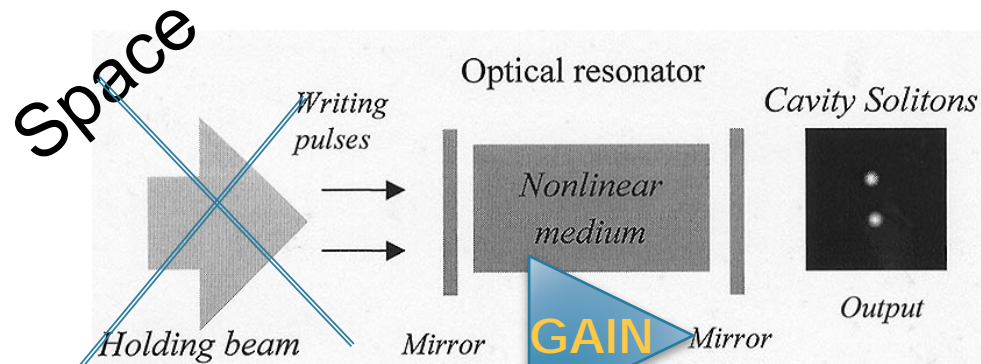
Genevet et al., *Phys. Rev. Lett.* **101**, 123905 (2008)



Marconi et al., *Phys. Rev. Lett.* **112** 223901 (2014).



Laser Cavity-Solitons



Piccardo et al., *Nature* **582**, 360–364 (2020).

L. Columbo et al, "Unifying frequency combs in active and passive cavities: CW driving of temporal solitons in ring lasers," ArXiv:2007.07533

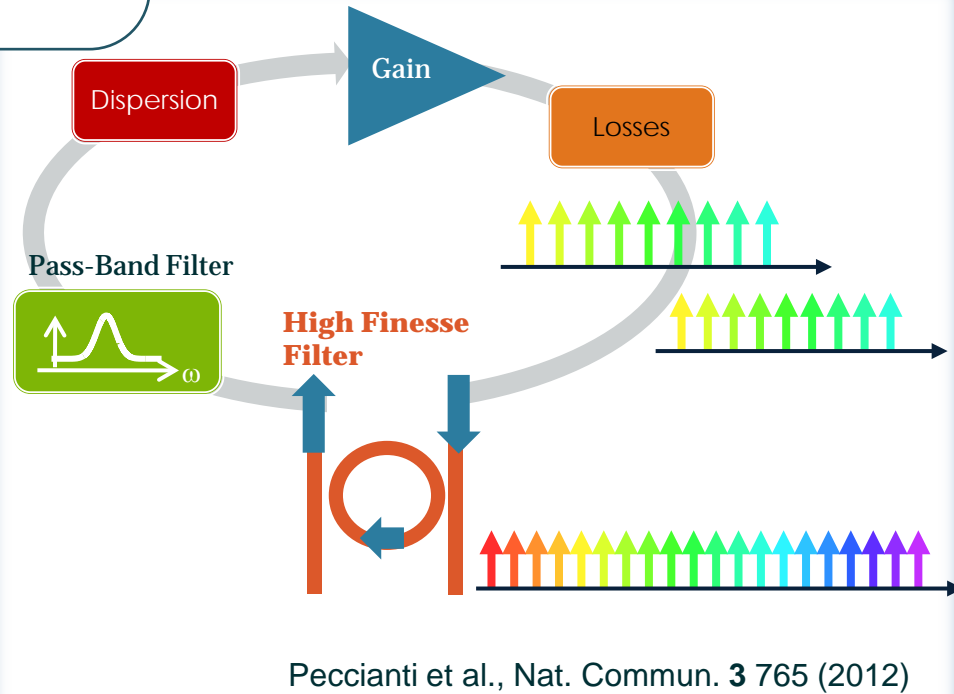
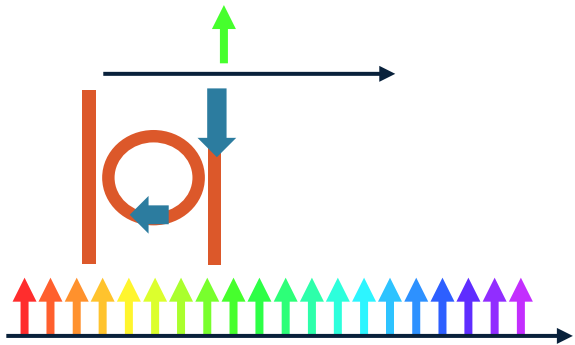
A Hybrid Micro-Comb Laser

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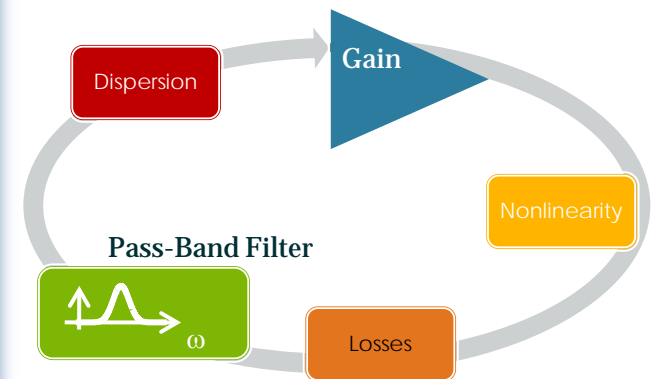
Lugiato-Lefever

-Bandwidth
Virtually Unlimited

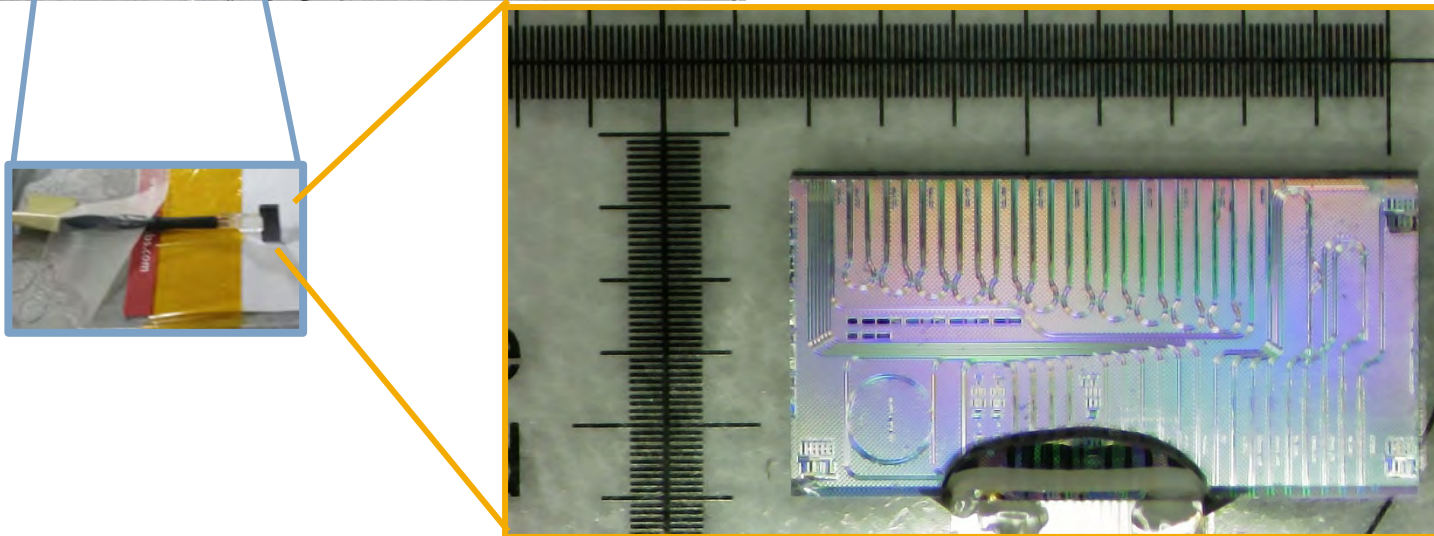
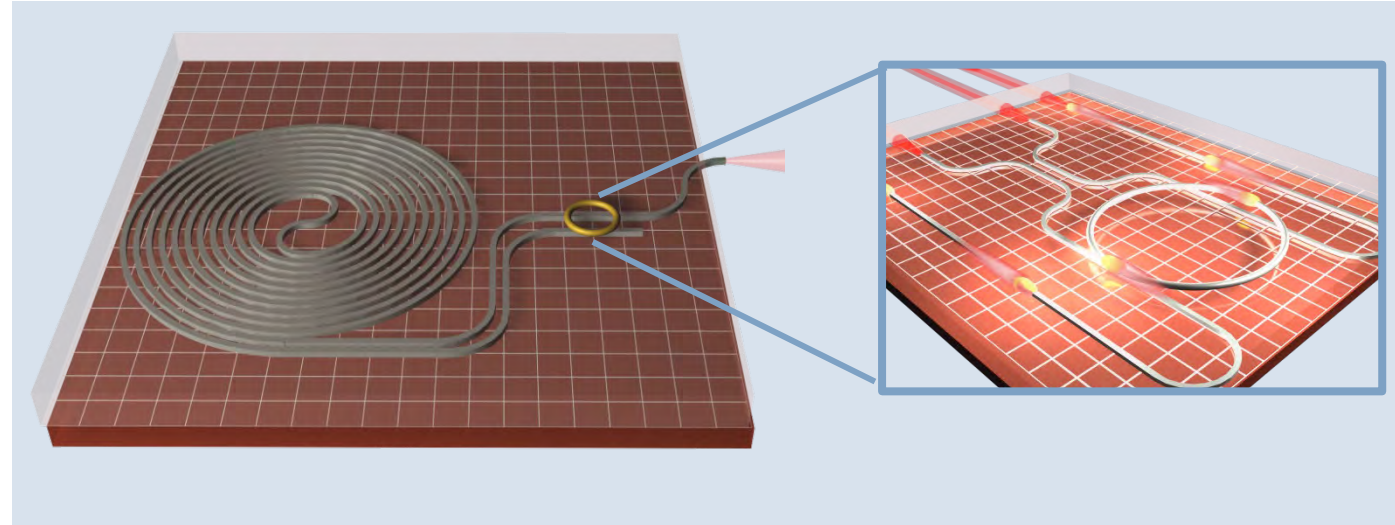
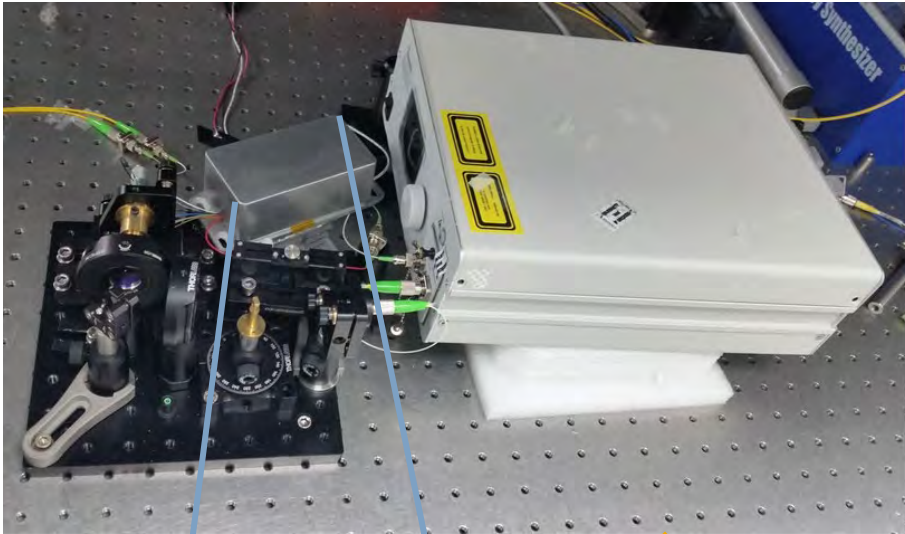


Ginzburg-Landau

-Robust
-Self-Starting

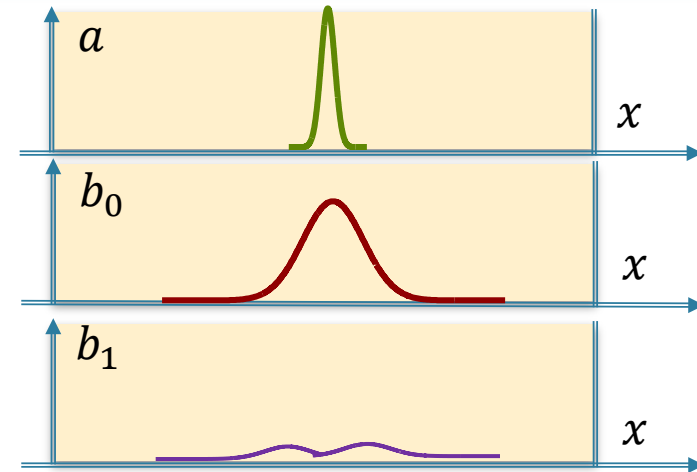
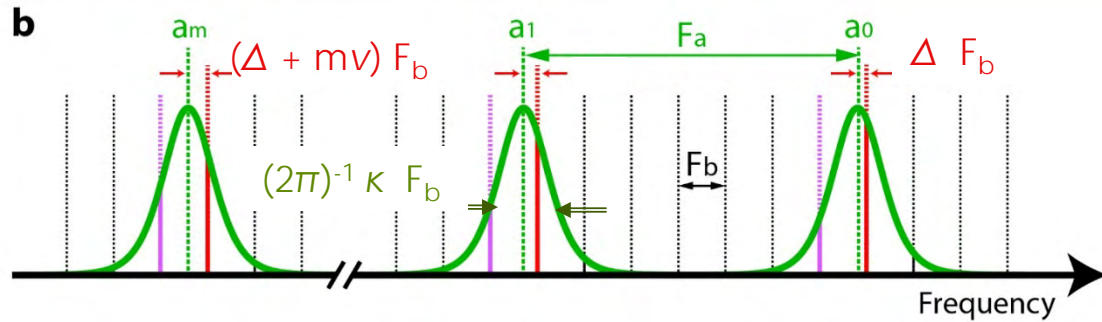
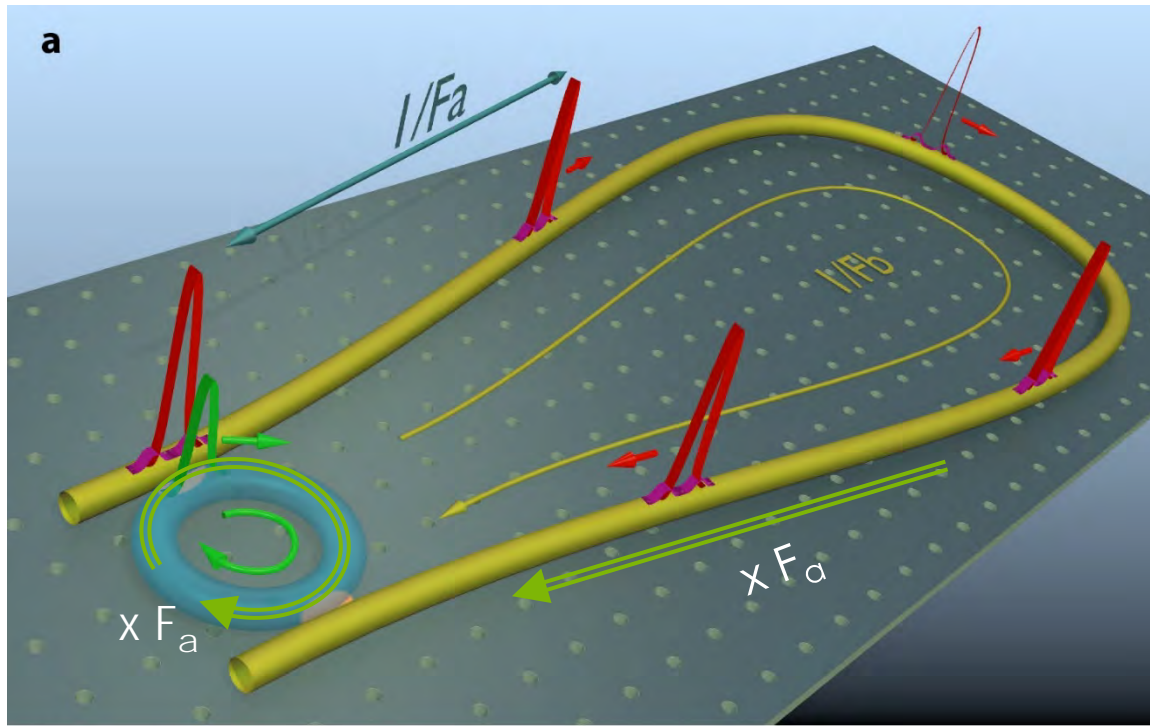


A Hybrid Microcomb Laser



50 GHz high
doped silica
resonator

Model



Dispersions: $\zeta_a; \zeta_b; \sigma$

Microcavity Linewidth : κ

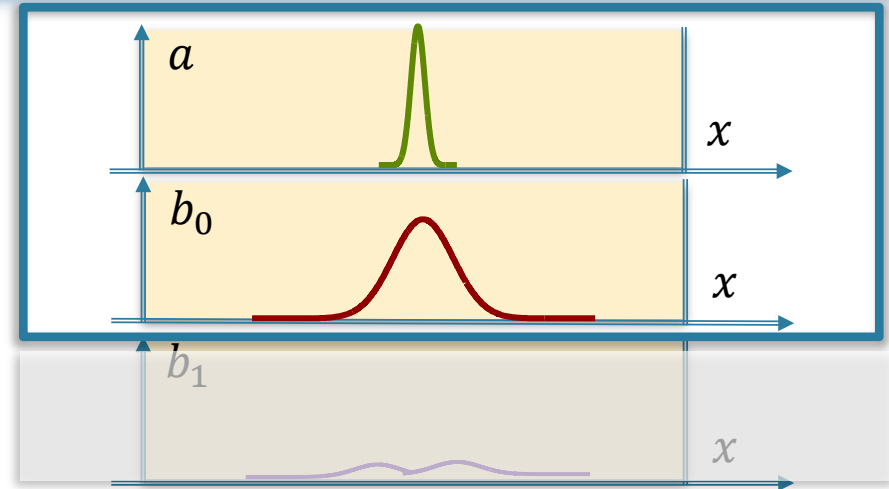
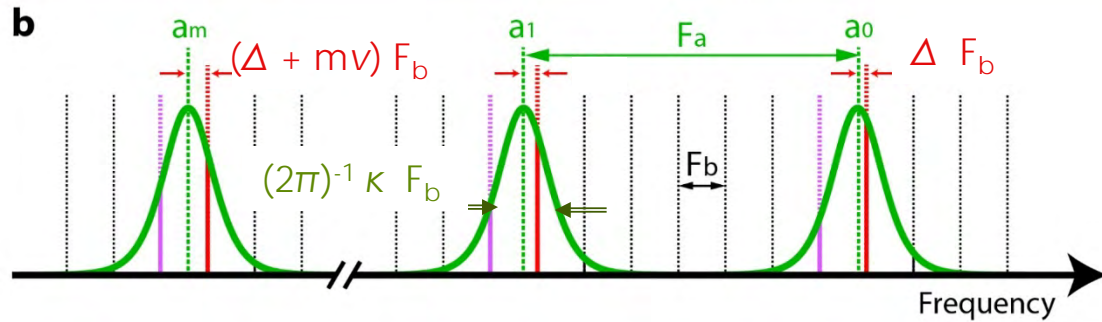
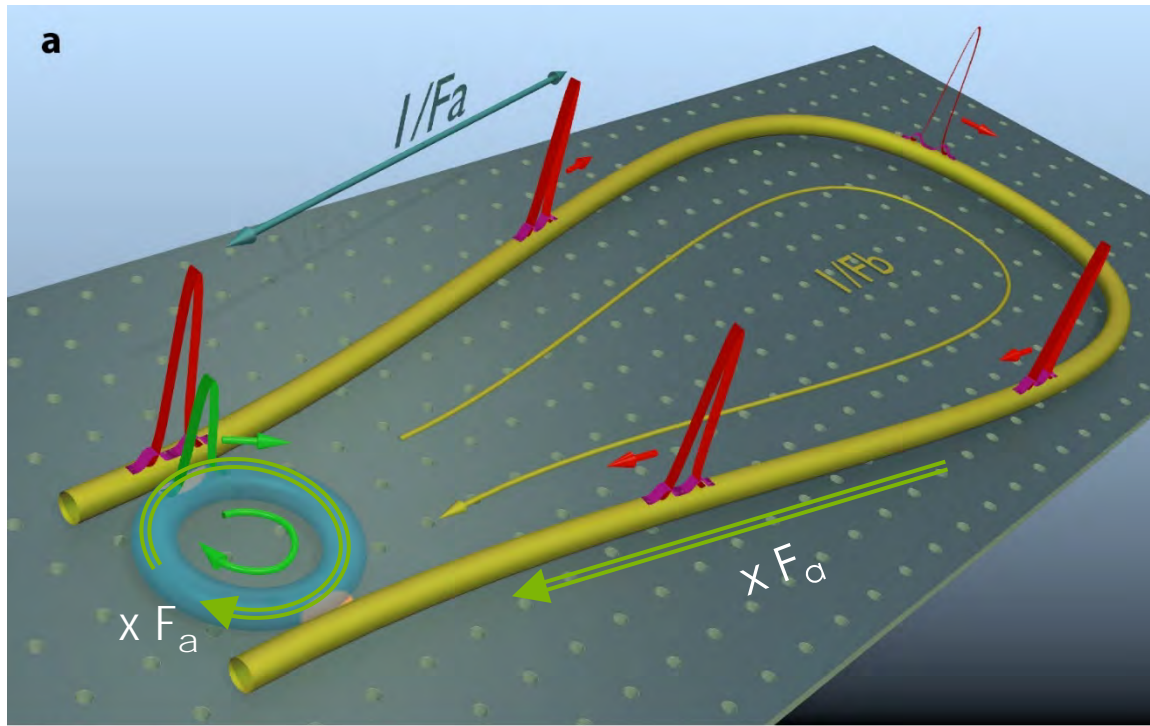
Gain: g ; Detuning: Δ

Cavities Length Mismatch : v

$$\partial_t a = \frac{i\zeta_a}{2} \partial_{xx} a + i |a|^2 a - \kappa a + \sqrt{\kappa} \sum_{q=-N}^N b_q$$

$$\partial_t b_q = \frac{i\zeta_b}{2} \partial_{xx} b_q - v \partial_x b_q - 2\pi i (\Delta - q) b_q + \sigma \partial_{xx} b_q + g b_q - \sum_{p=-N}^N b_p + \sqrt{\kappa} a$$

Model



Dispersions: $\zeta_a; \zeta_b; \sigma$

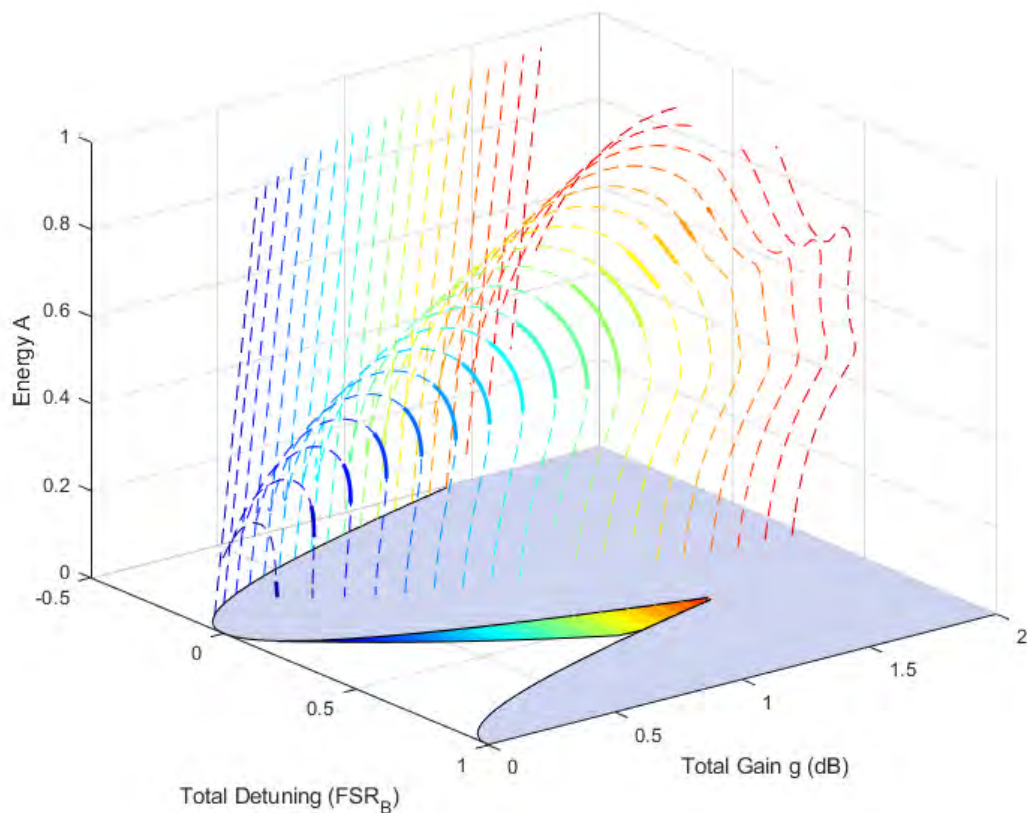
Microcavity Linewidth : κ

Gain: g ; Detuning: Δ

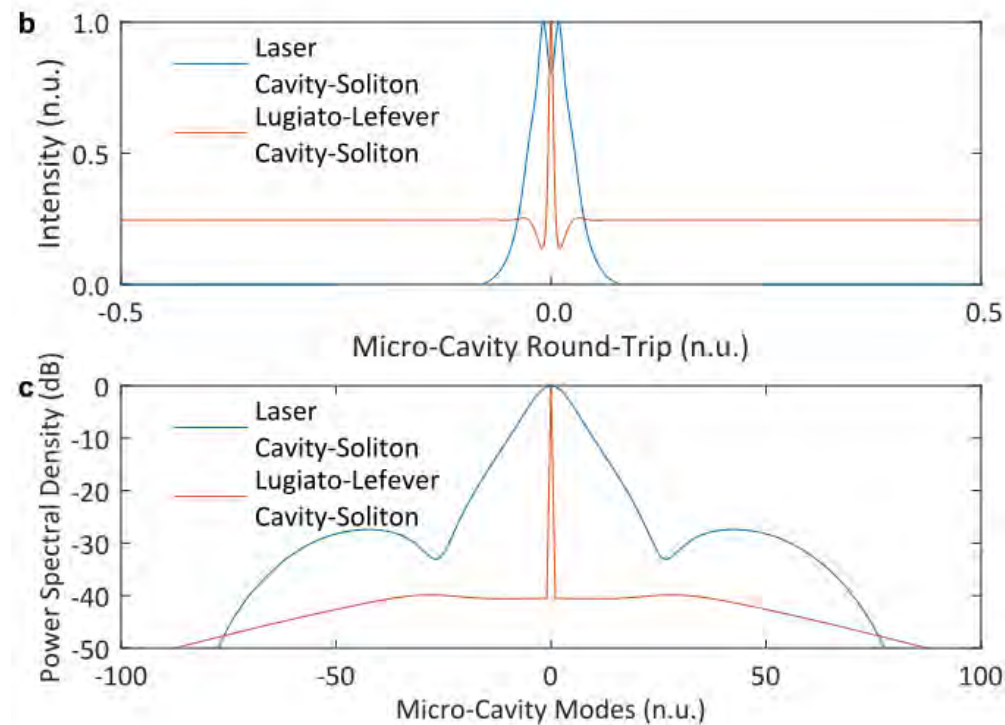
Cavities Length Mismatch : v

$$\partial_t a = \frac{i\zeta_a}{2} \partial_{xx} a + i |a|^2 a - \kappa a + \sqrt{\kappa} b_0$$

$$\partial_t b_0 = \frac{i\zeta_b}{2} \partial_{xx} b_0 - v \partial_x b_0 - 2\pi i \Delta b_0 + \sigma \partial_{xx} b_0 + g b_0 - b_0 + \sqrt{\kappa} a$$



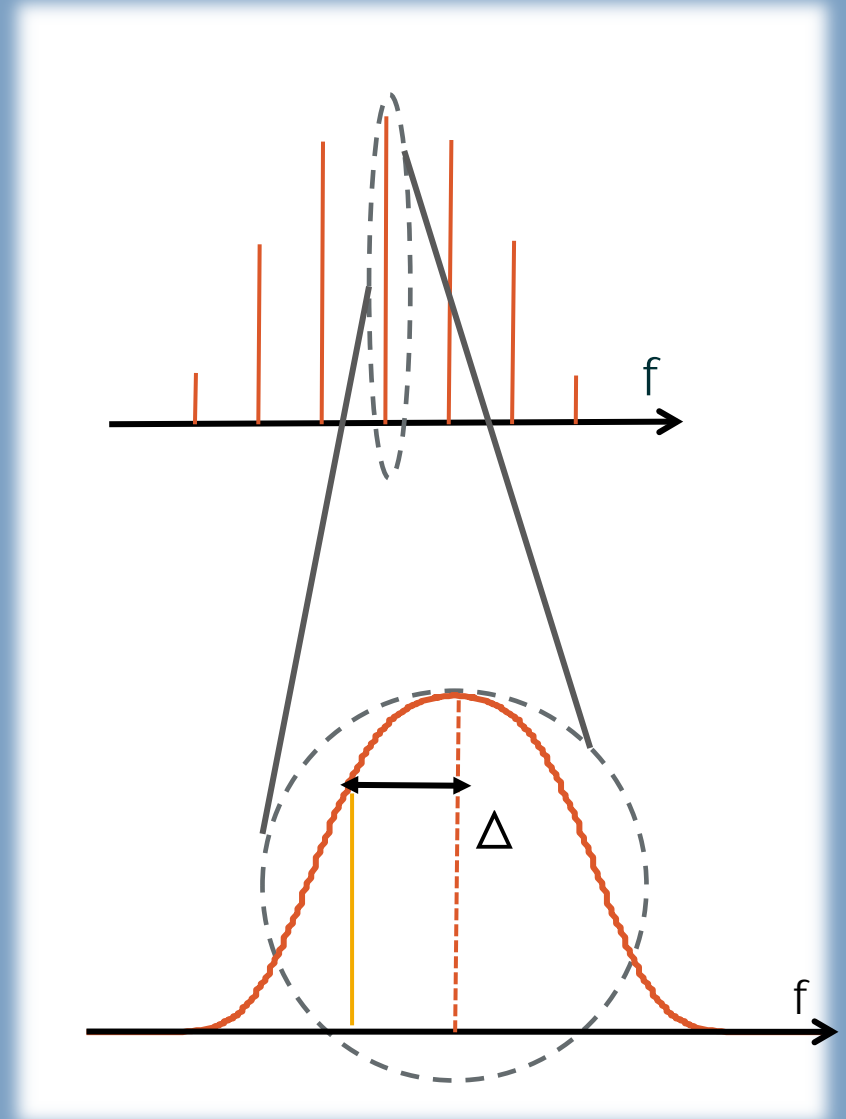
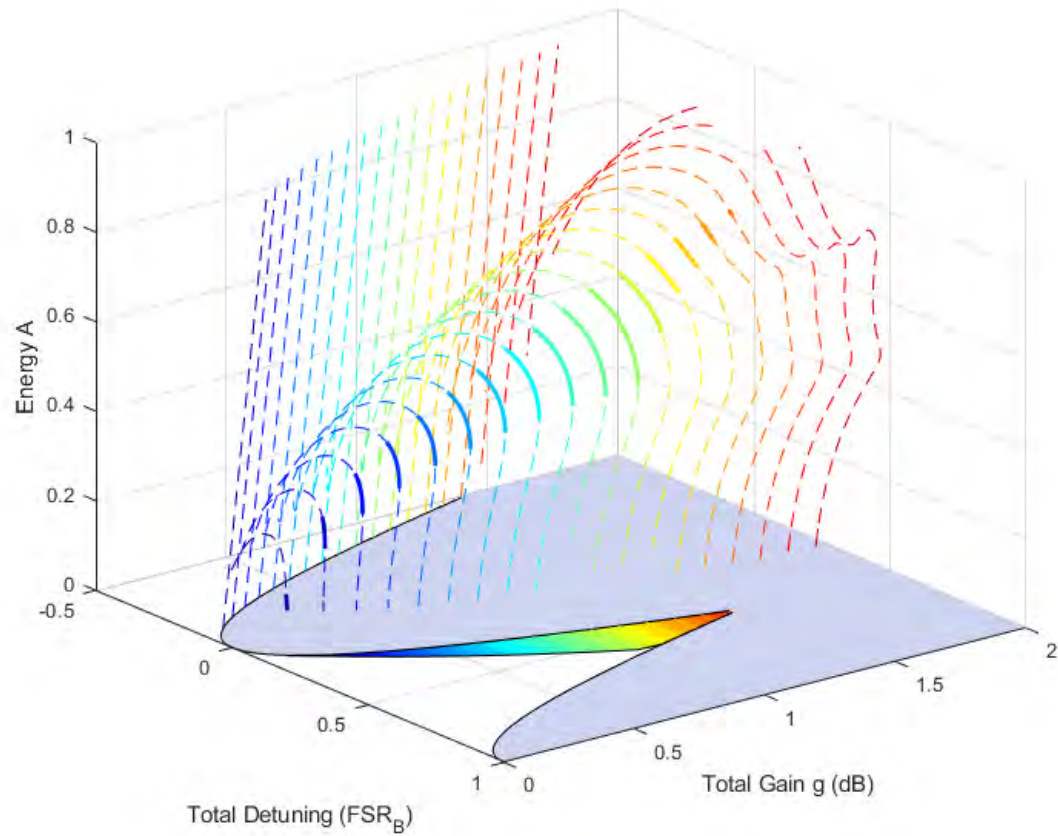
Background free
Low threshold
High efficiency!



$$\partial_t a = \frac{i\zeta_a}{2} \partial_{xx} a + i |a|^2 a - \kappa a + \sqrt{\kappa} \sum_{q=-N}^N b_q$$

$$\partial_t b_q = \frac{i\zeta_b}{2} \partial_{xx} b_q - v \partial_x b_q - 2\pi i (\Delta - q) b_q + \sigma \partial_{xx} b_q + g b_q - \sum_{p=-N}^N b_p + \sqrt{\kappa} a$$

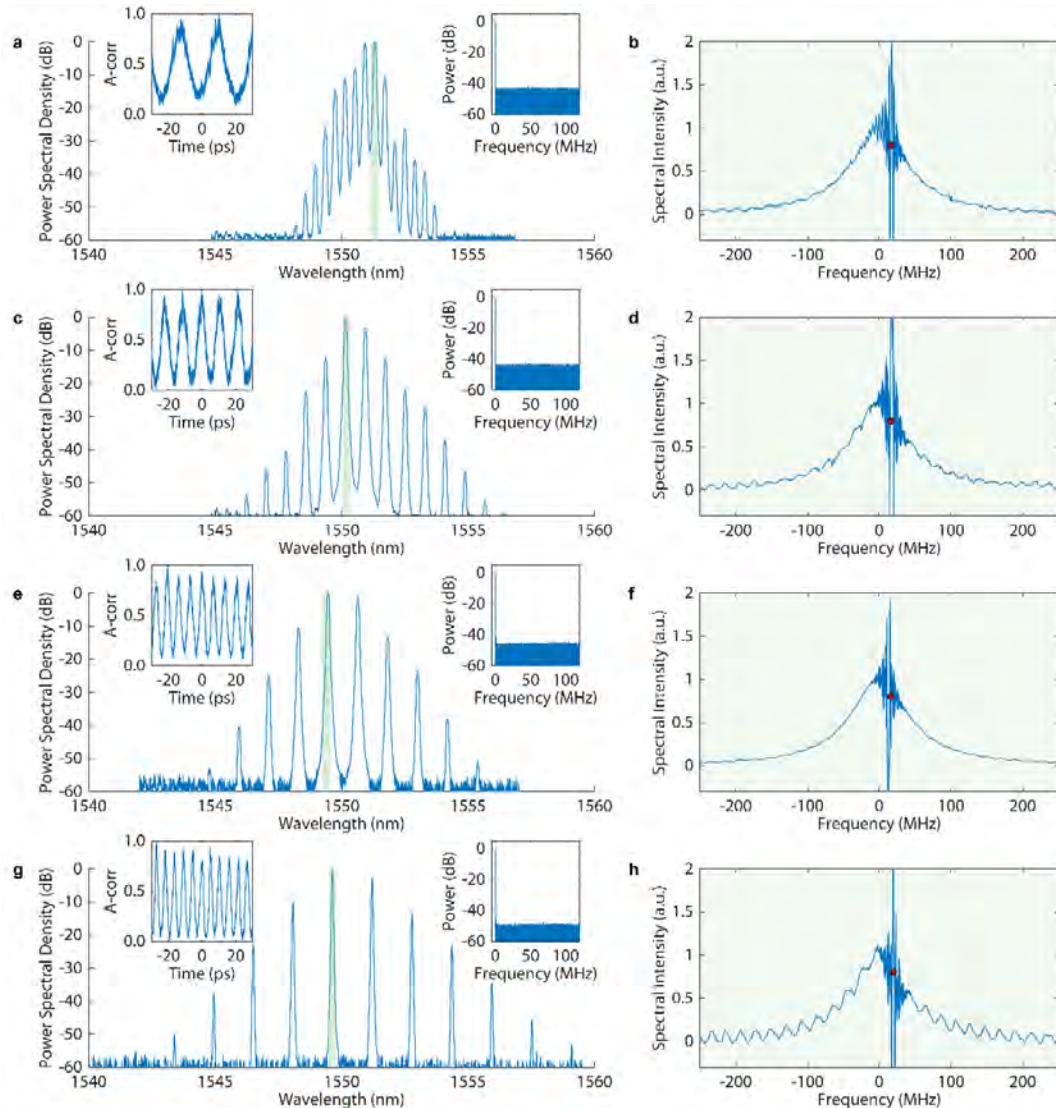
How do we distinguish the states?



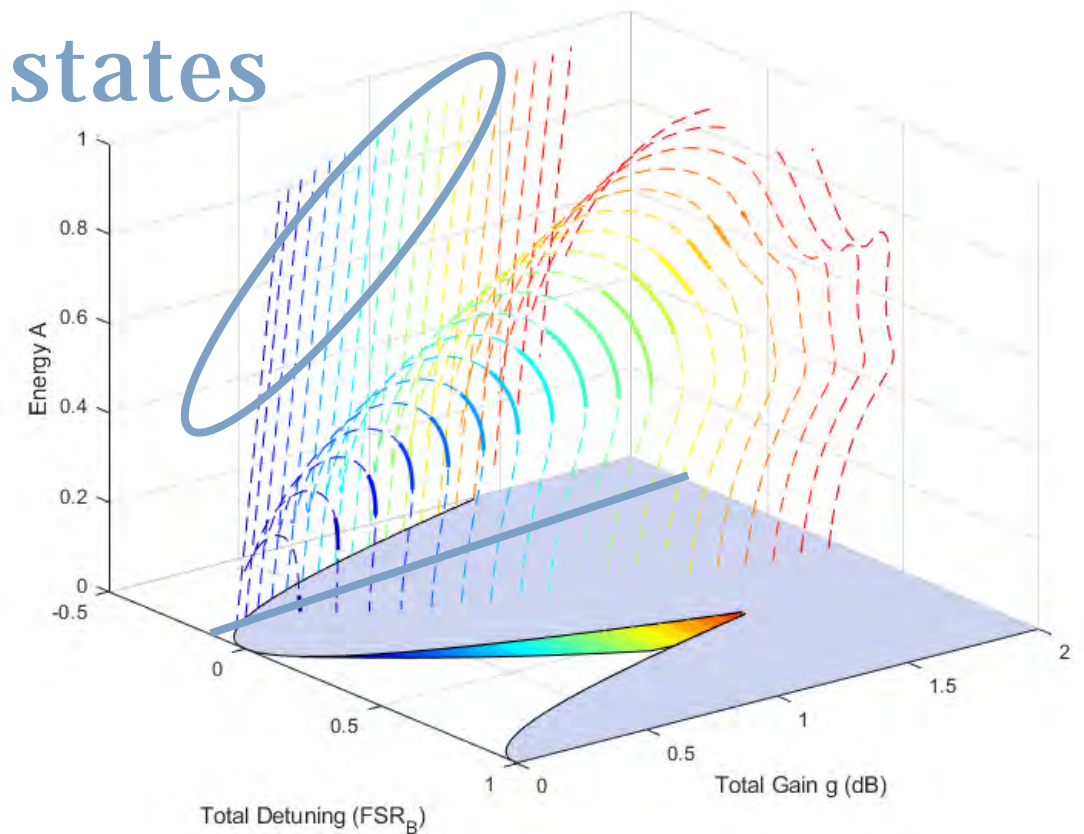
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How do we distinguish the states? Turing Patterns



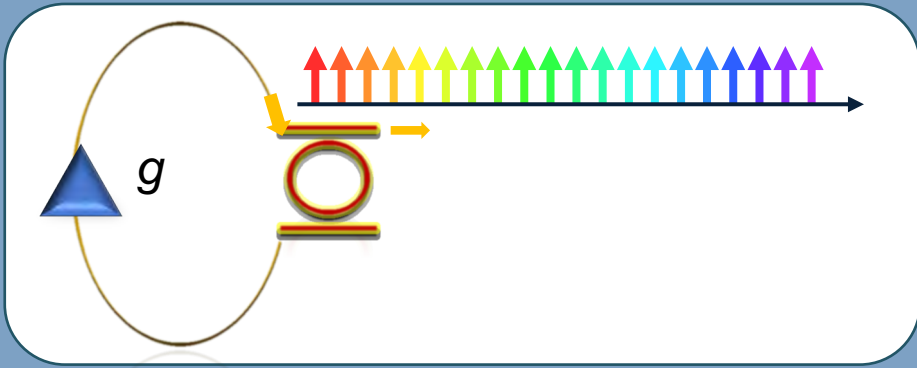
Blue detuned states



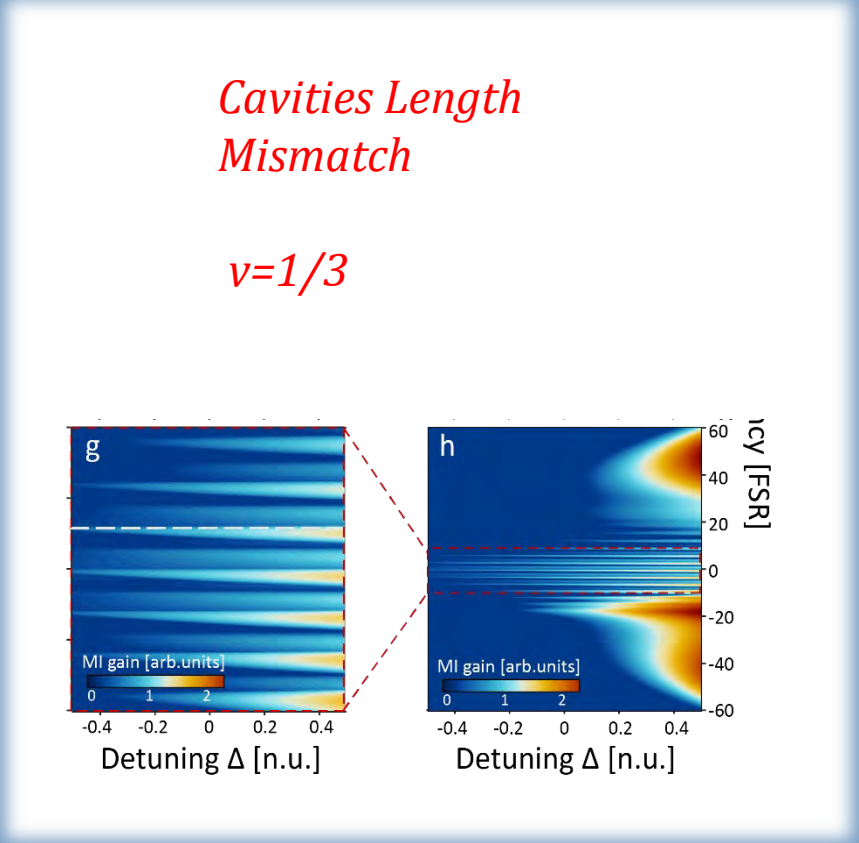
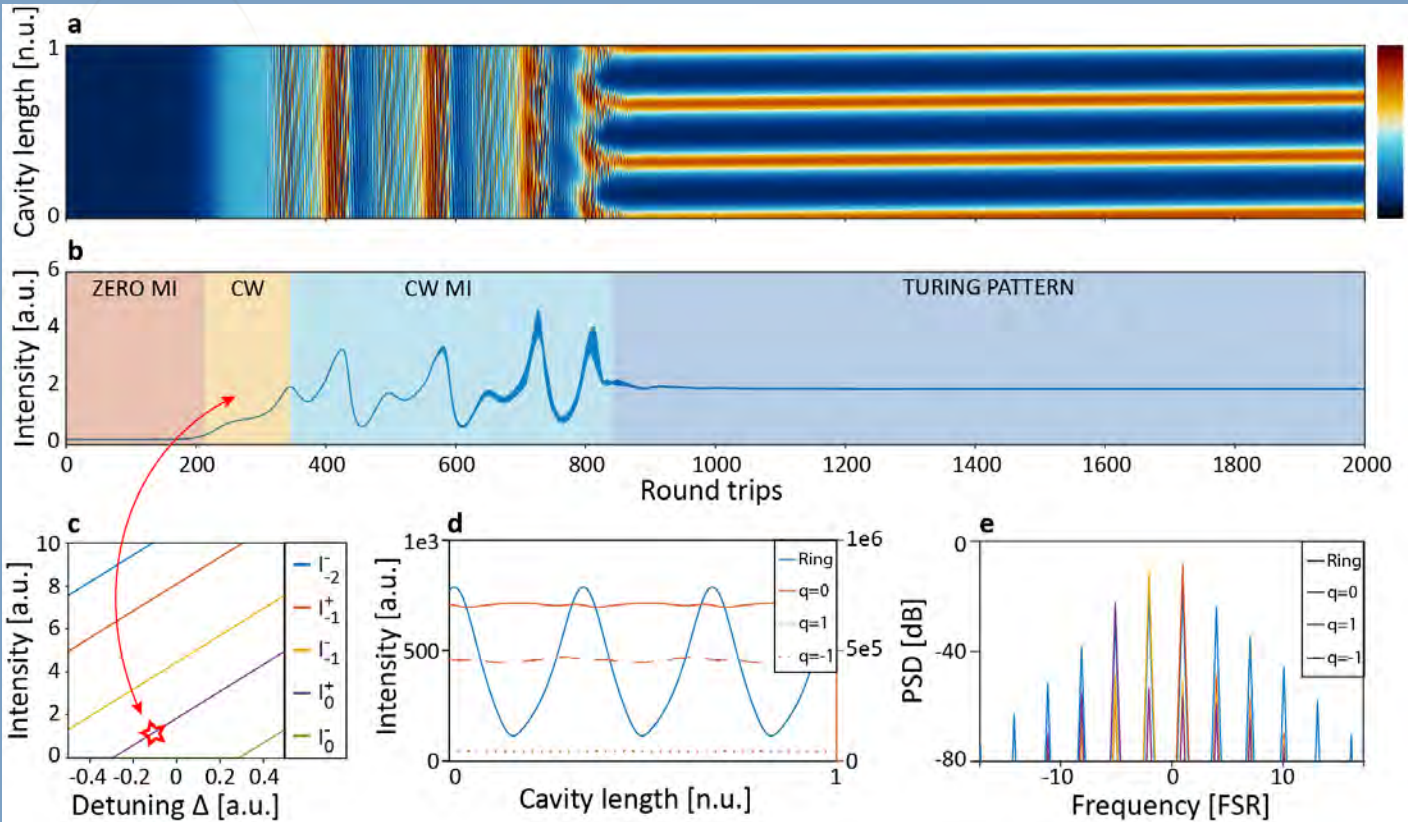
Pic
ENT
NICS

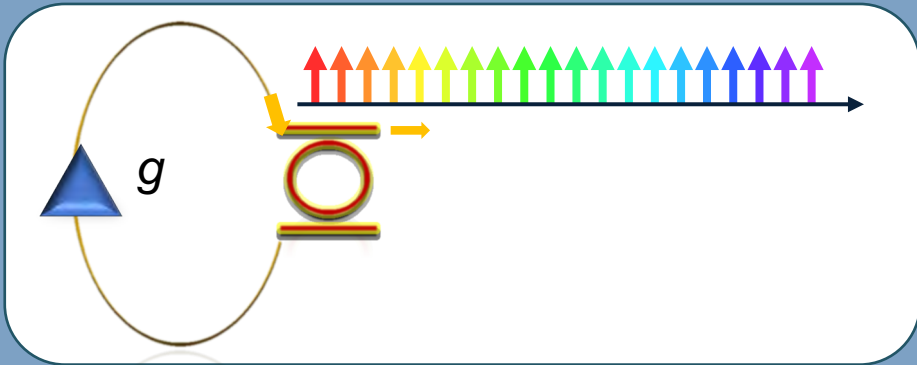
Bao et al. Phot. Res. 6, B67 (2018)

Bao et al., Phys. Rev. Research 2, 023395 (2020)



Turing Patterns





Turing Patterns

Peccianti et al., Nat. Commun. **3** 765 (2012)
 Wang et al. ACS Photon. **4** 1677 (2017)
 Bao et al. Phot. Res. **6** B67 (2018)
 Bao et al., Nat. Photon. **13** 384 (2019)
 Bao et al., Phys. Rev. Research **2**, 023395 (2020)

Cavities Length Mismatch

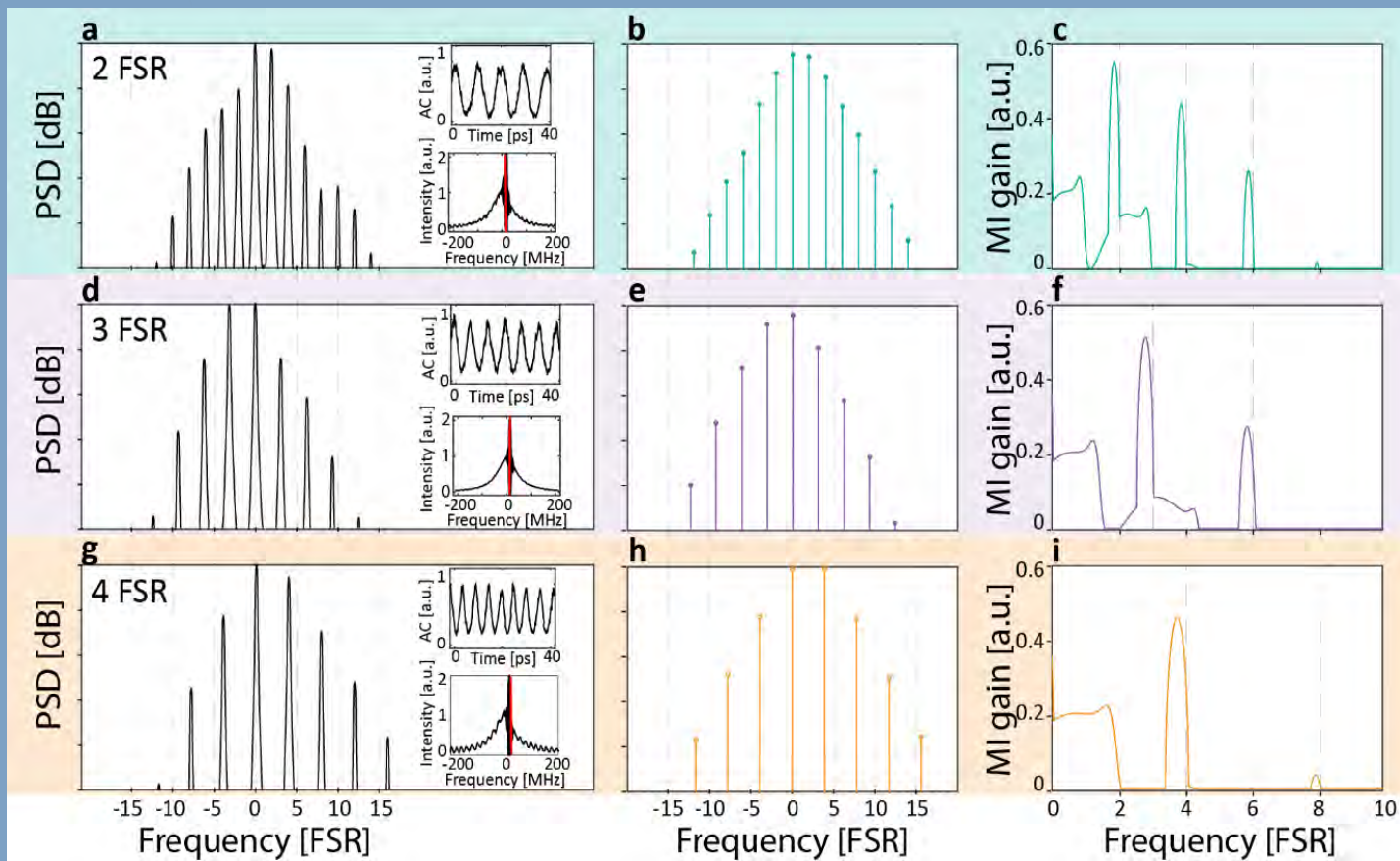
$$\nu=1/2$$

Cavities Length Mismatch

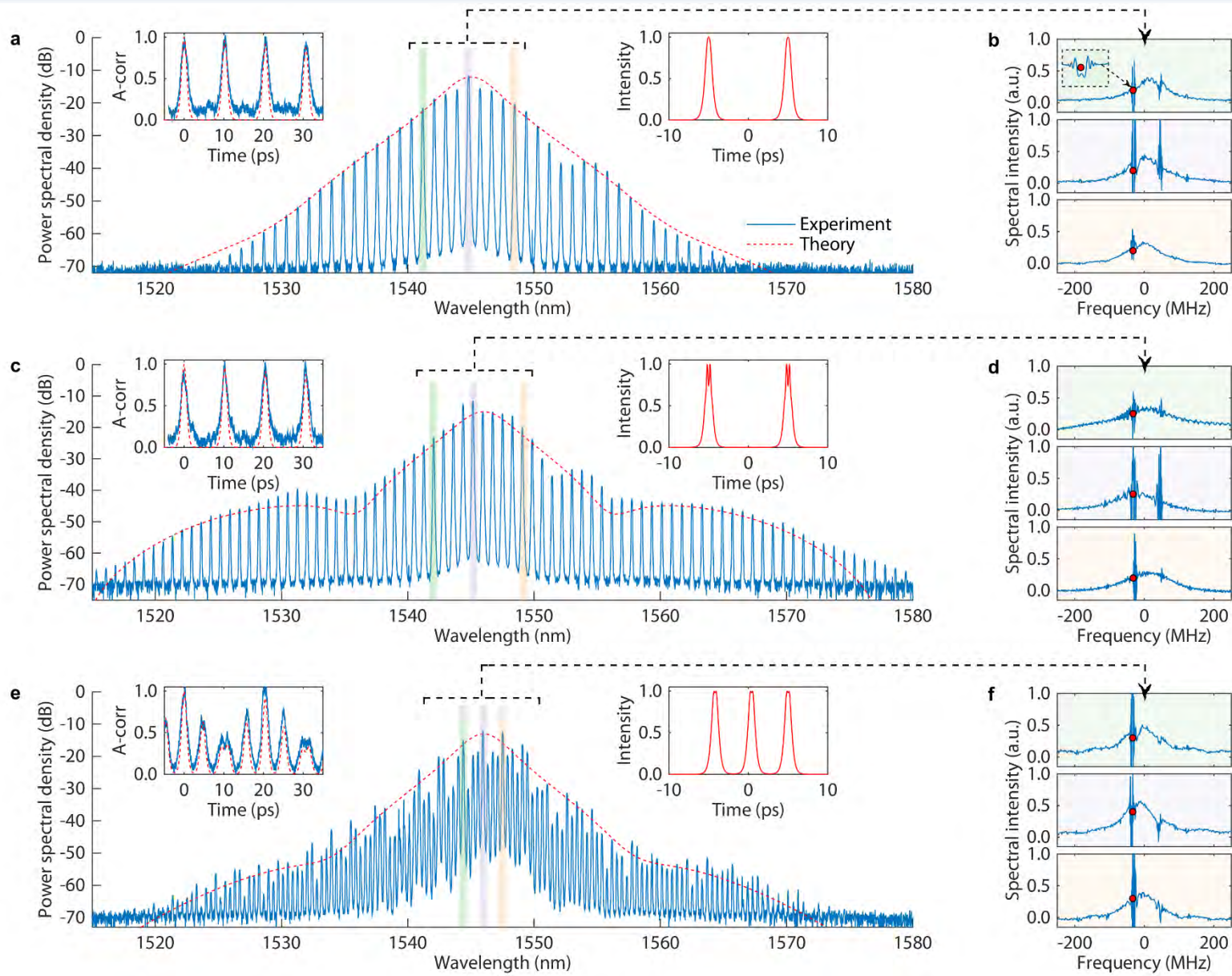
$$\nu=1/3$$

Cavities Length Mismatch

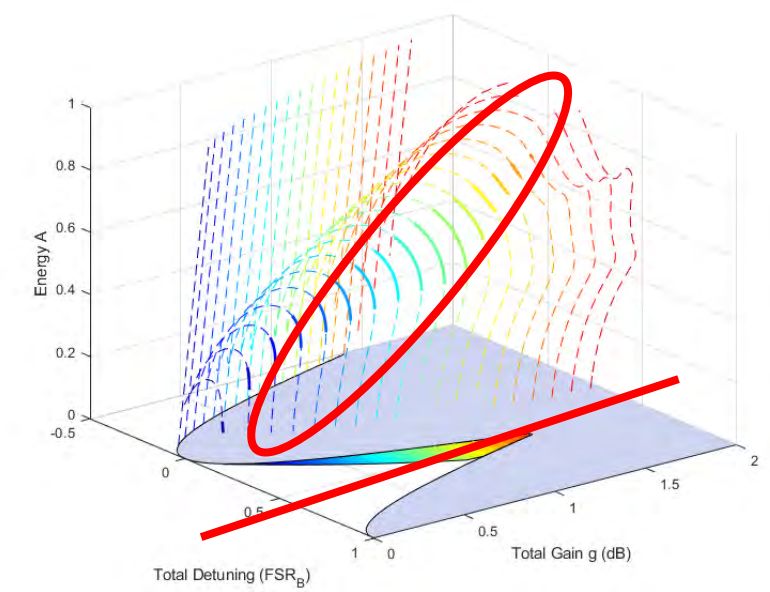
$$\nu=1/4$$



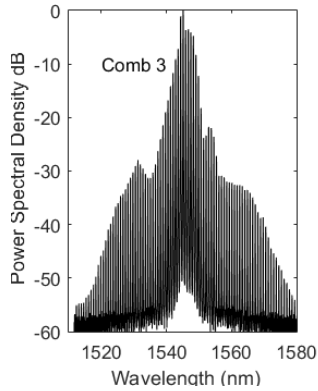
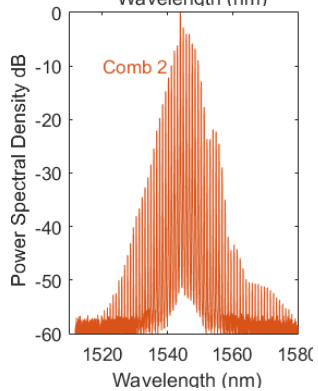
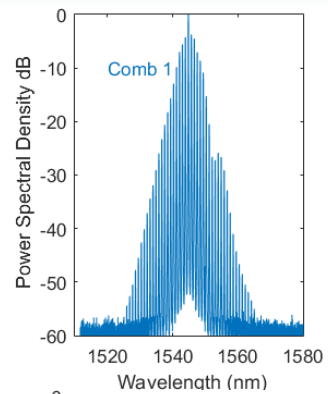
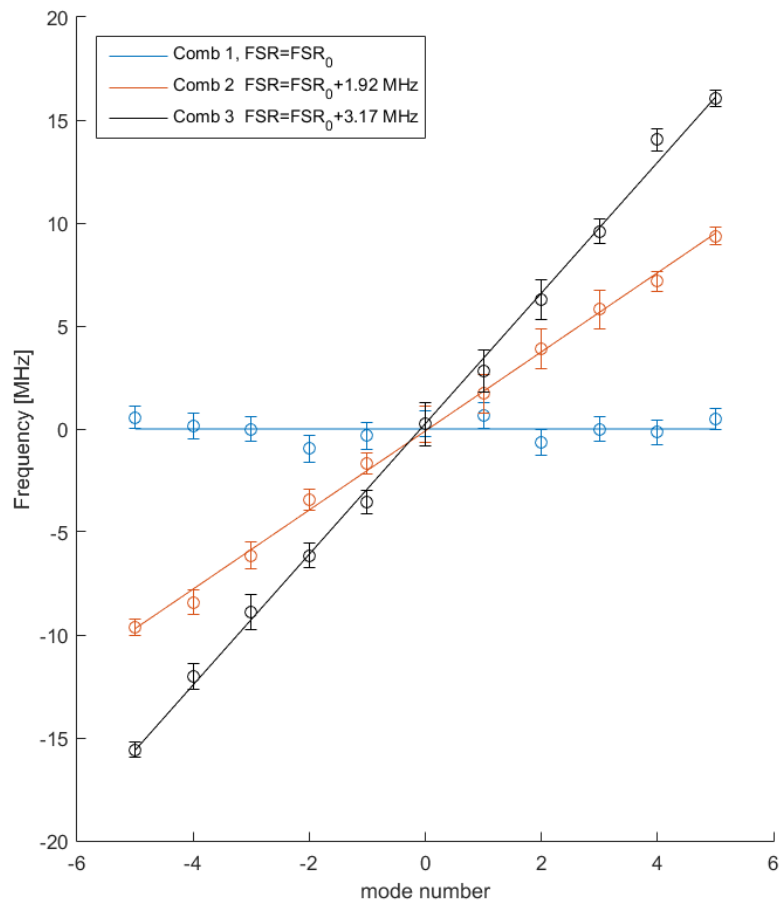
How do we distinguish the states? - Solitons



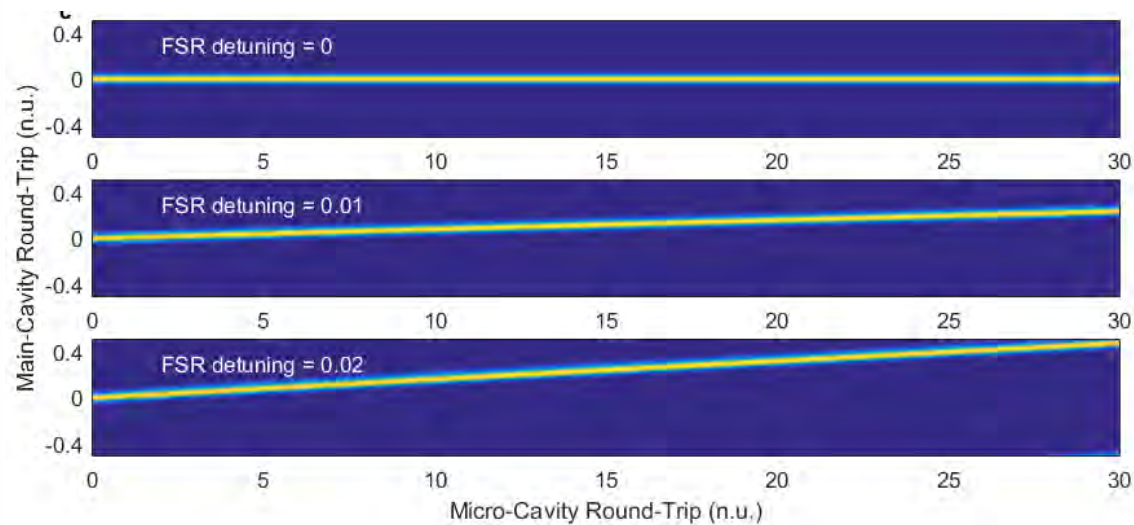
**Red
detuned
states**



Control

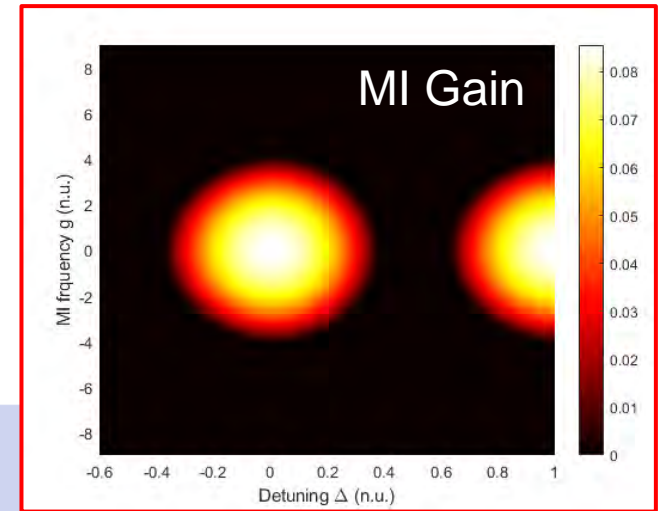
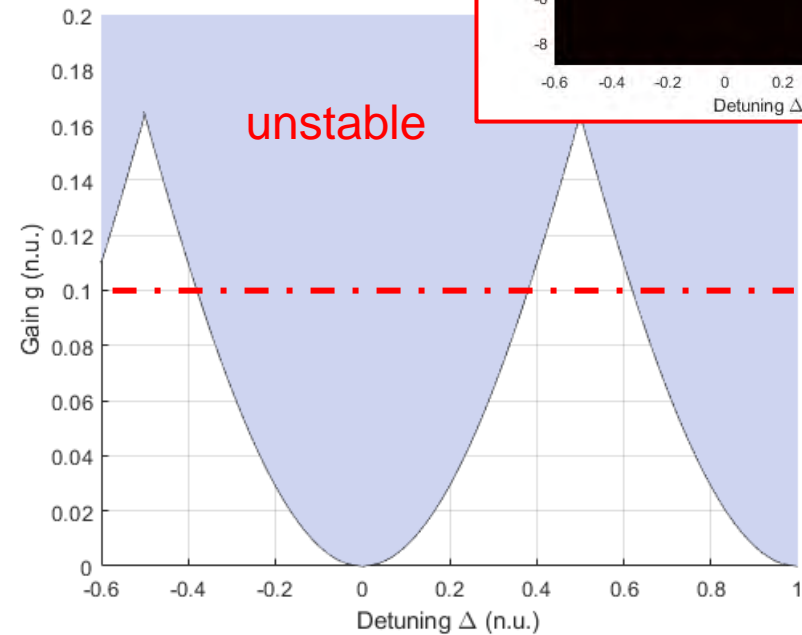
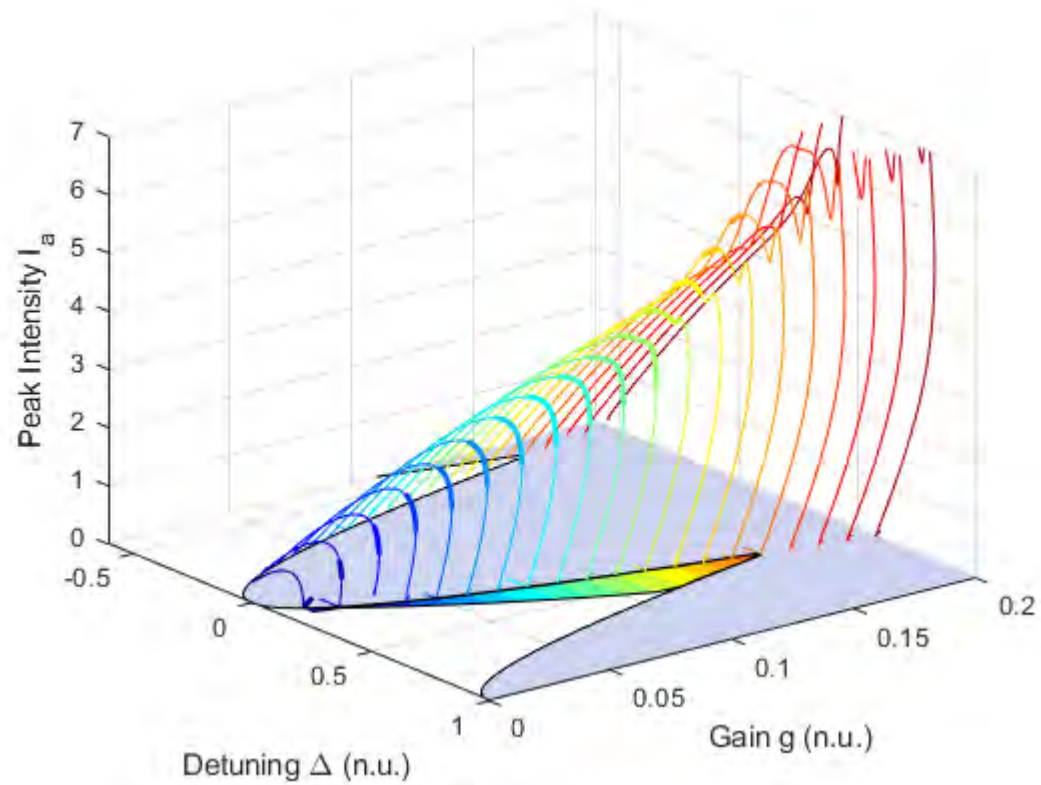
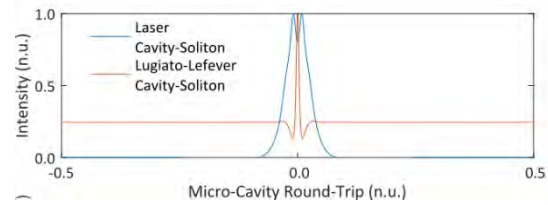


Model



Cavities Length Mismatch : v

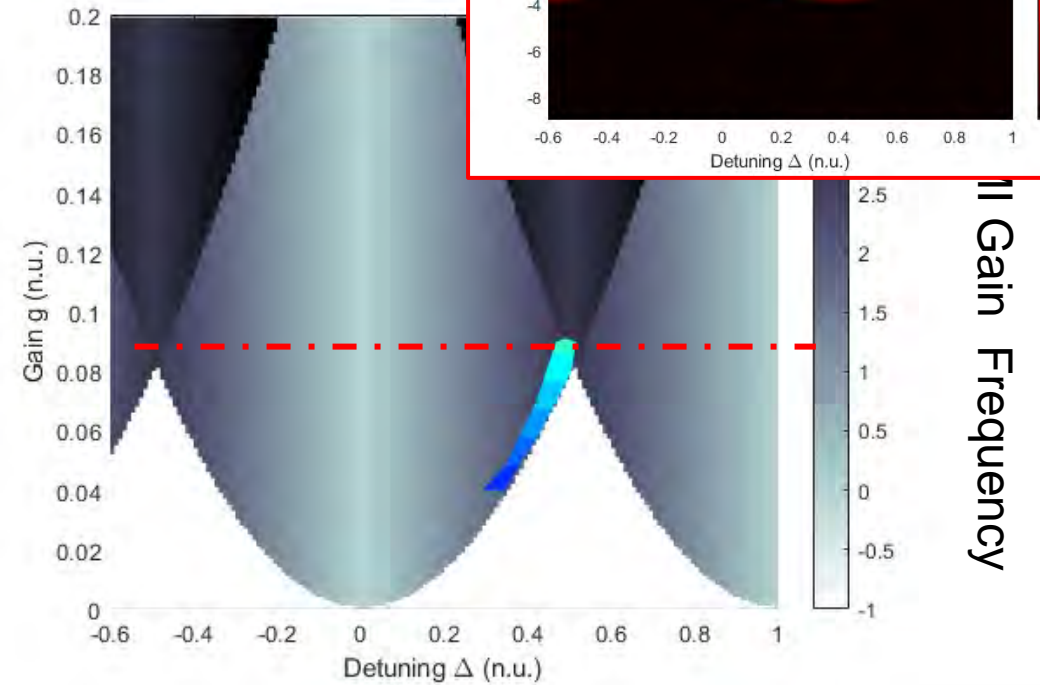
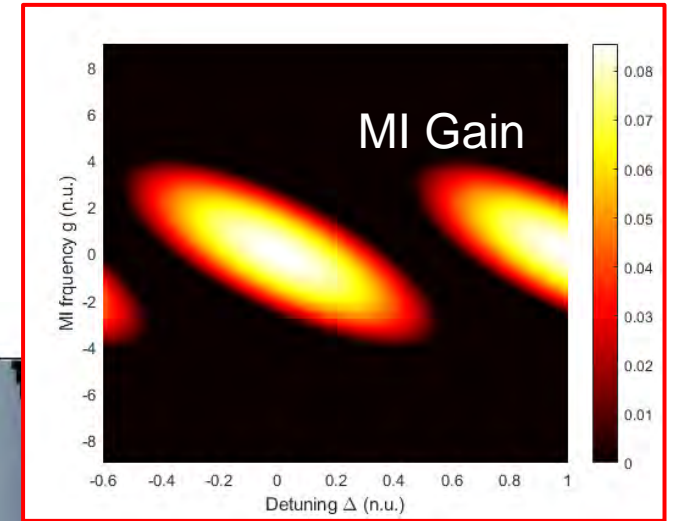
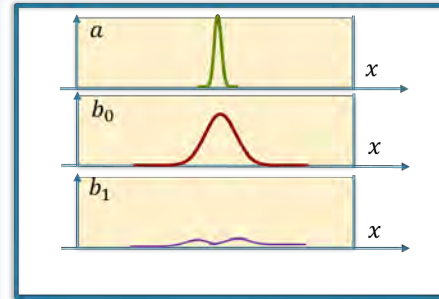
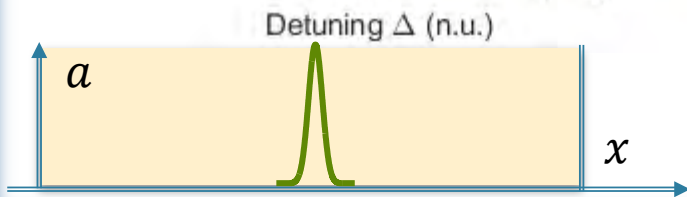
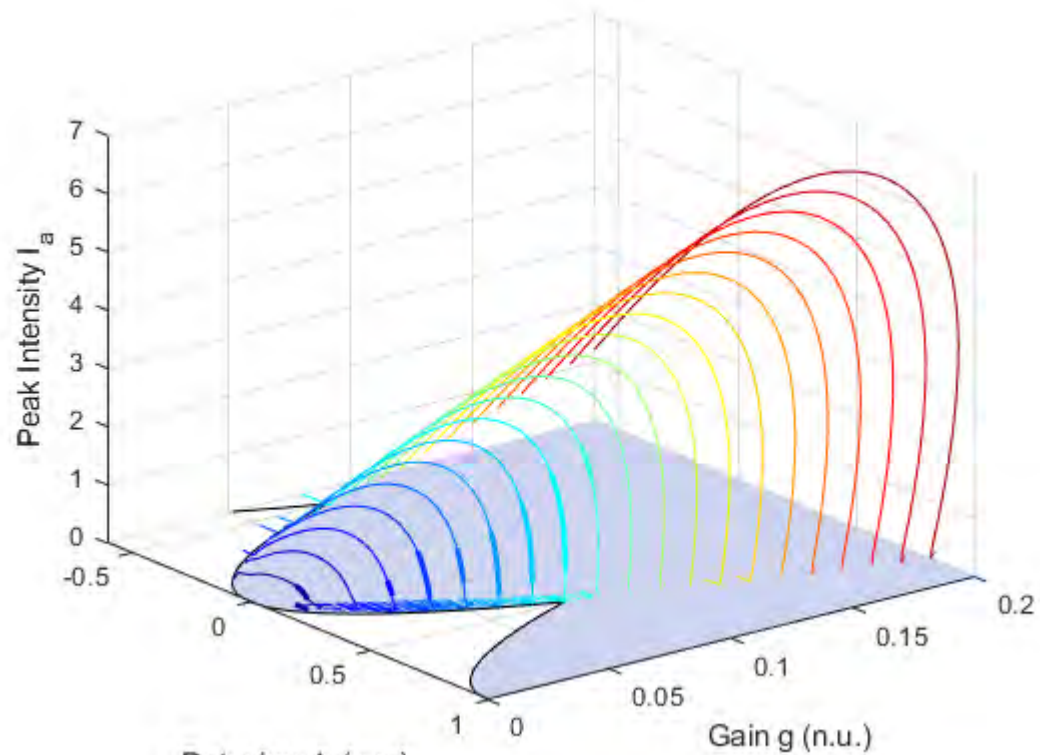
Trivial State



Solitons

One Soliton

$v=0.1$

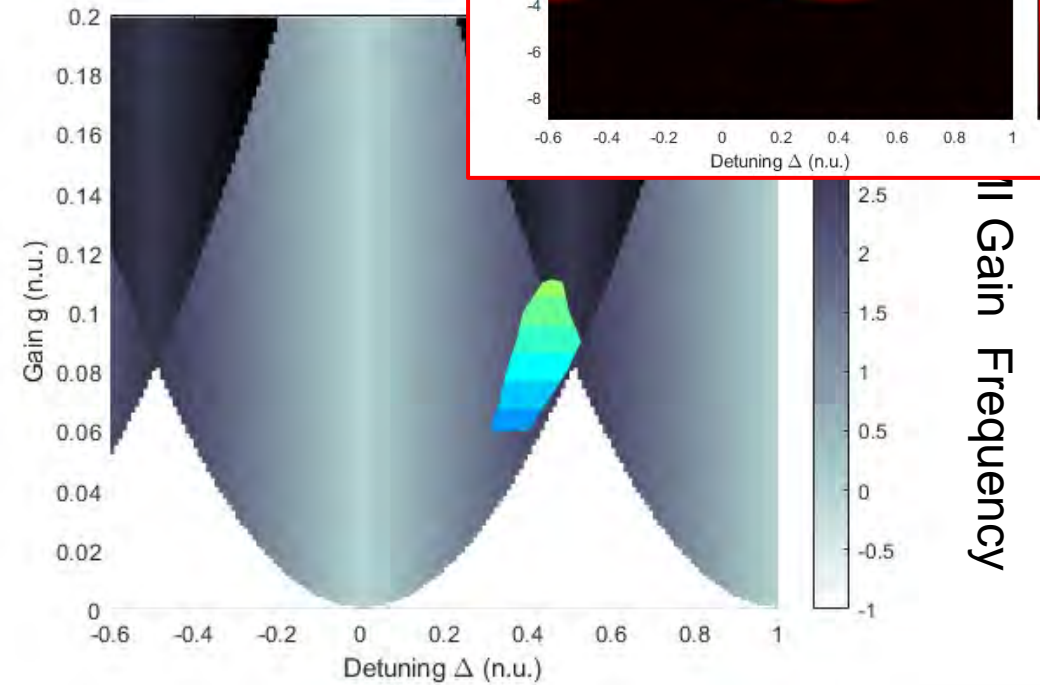
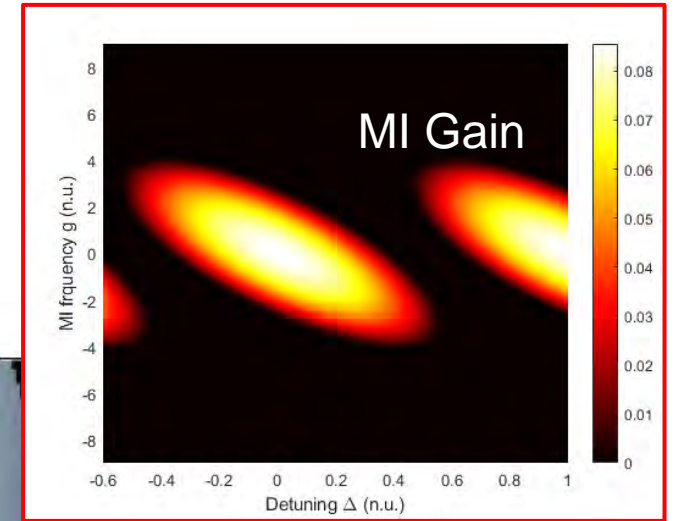
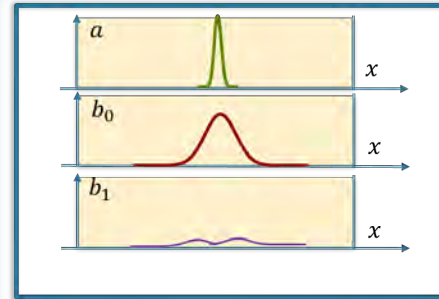
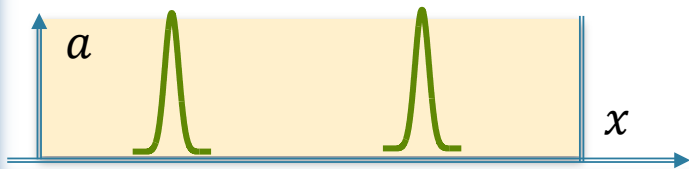
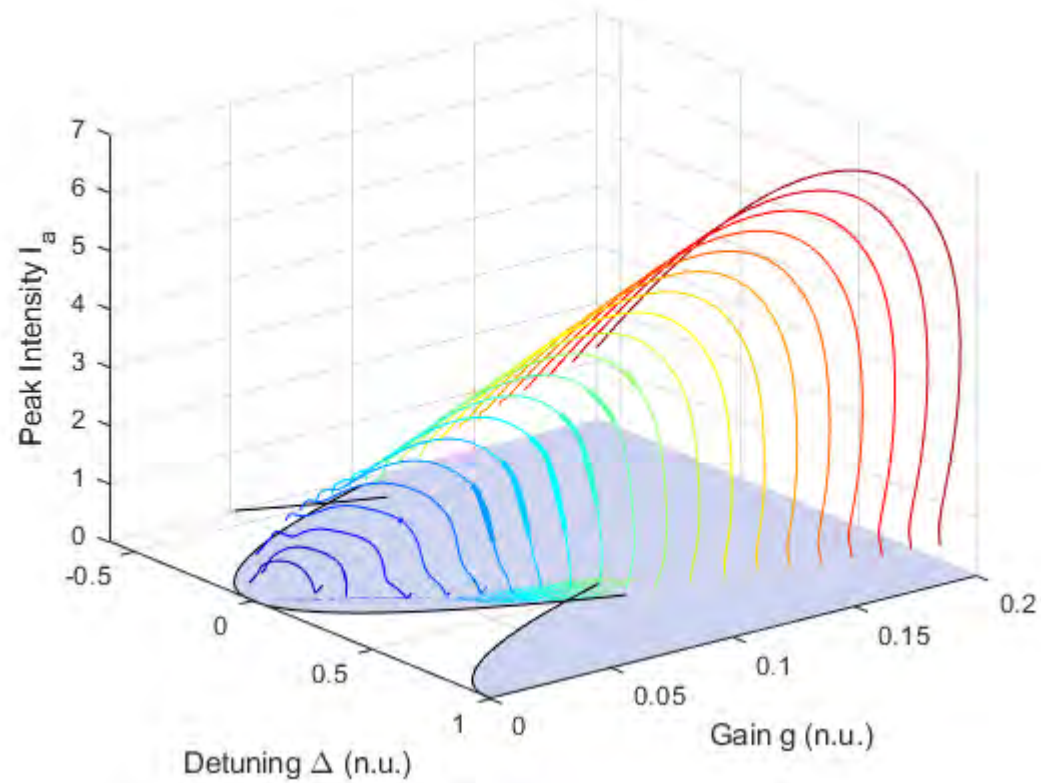


MI Gain Frequency

Solitons

Two Solitons

$v=0.1$

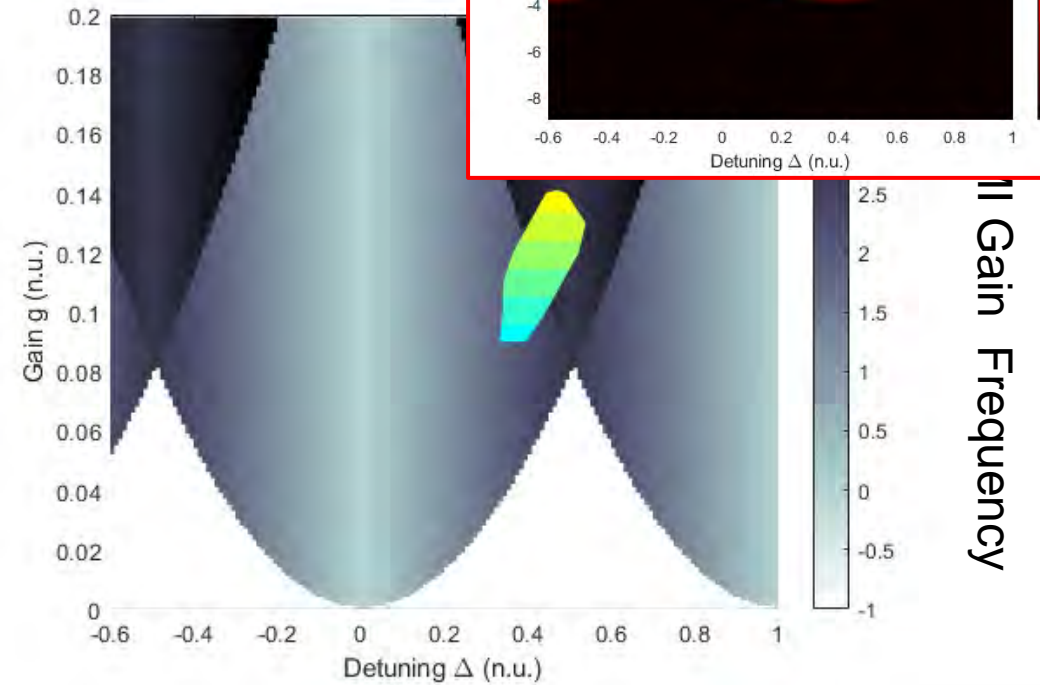
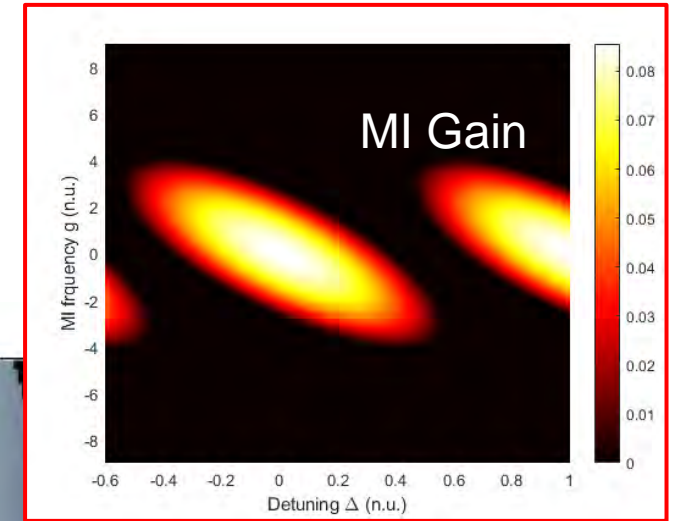
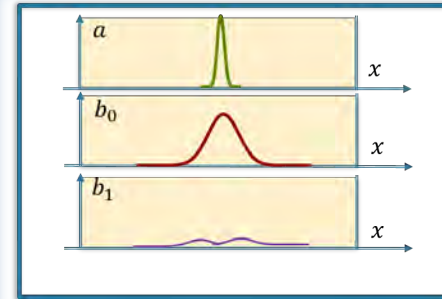
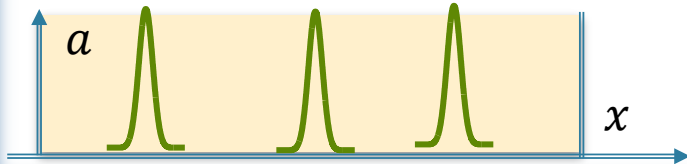
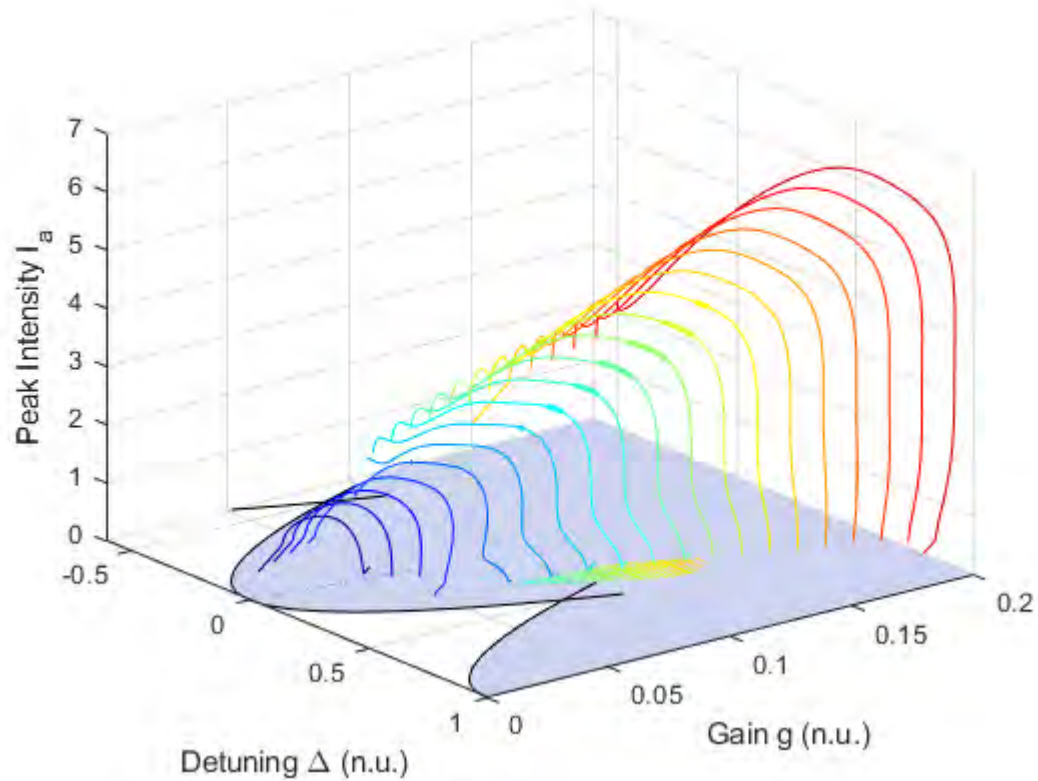


MI Gain Frequency

Solitons

Three Solitons

$v=0.1$

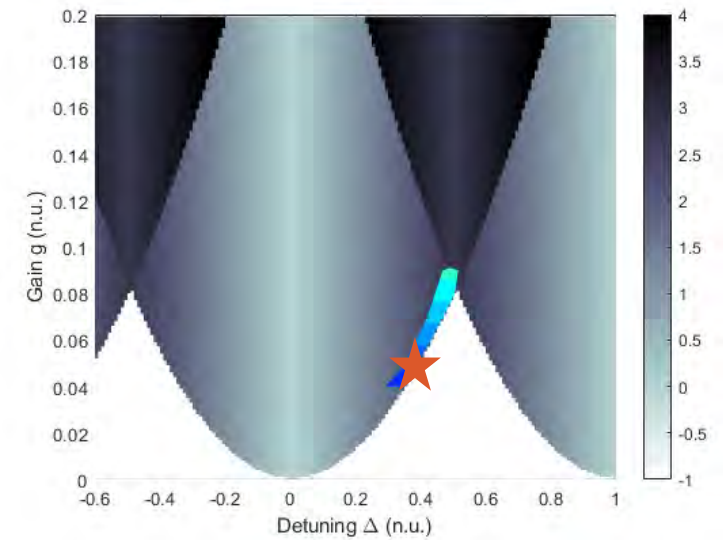
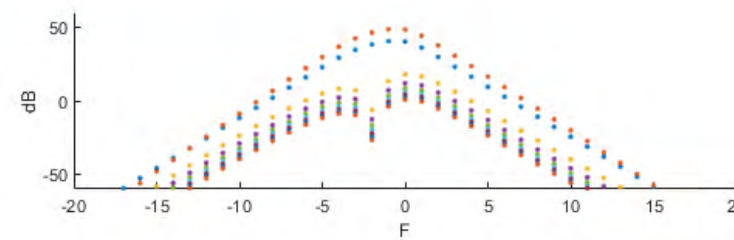
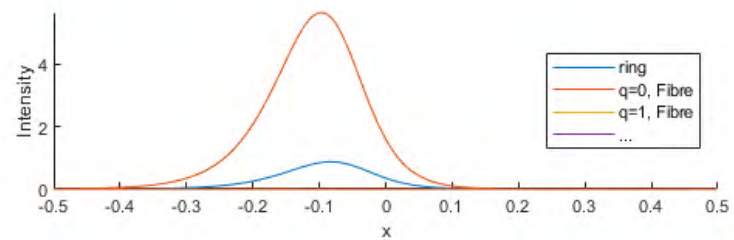
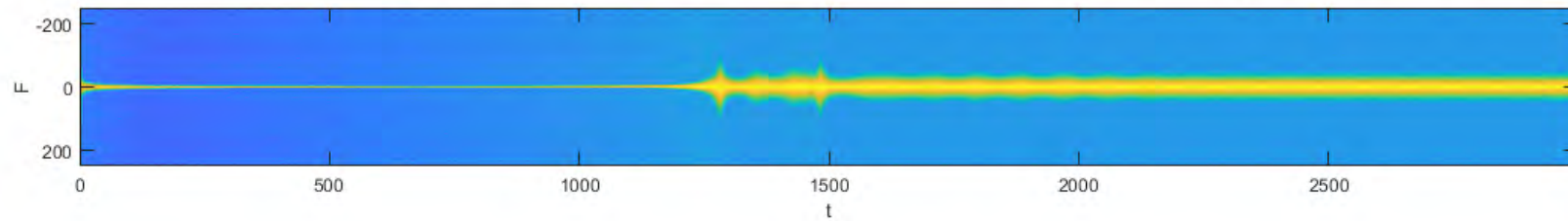
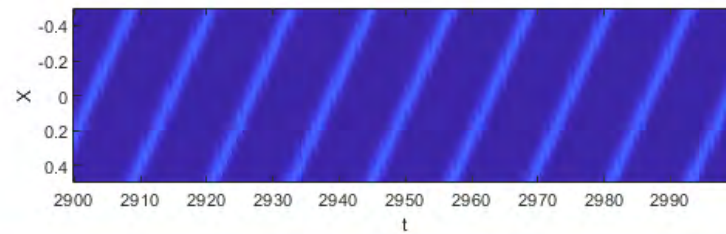
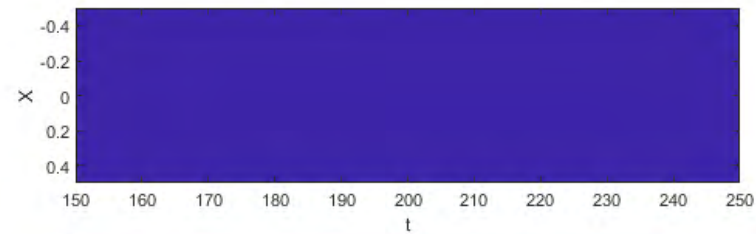
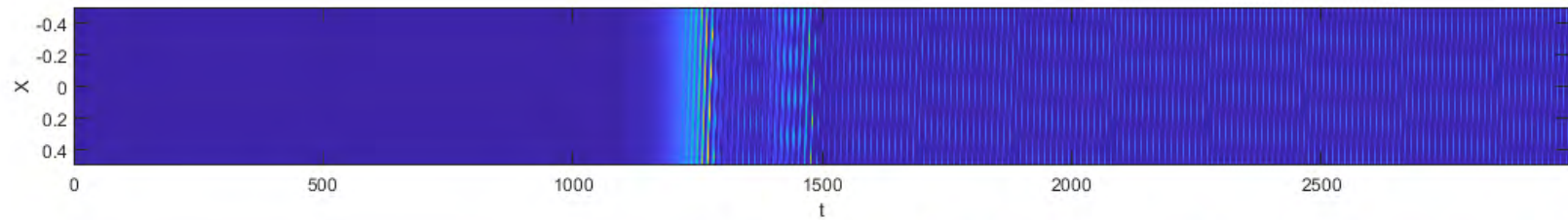


MI Gain Frequency

Solitons Start-up

One Soliton

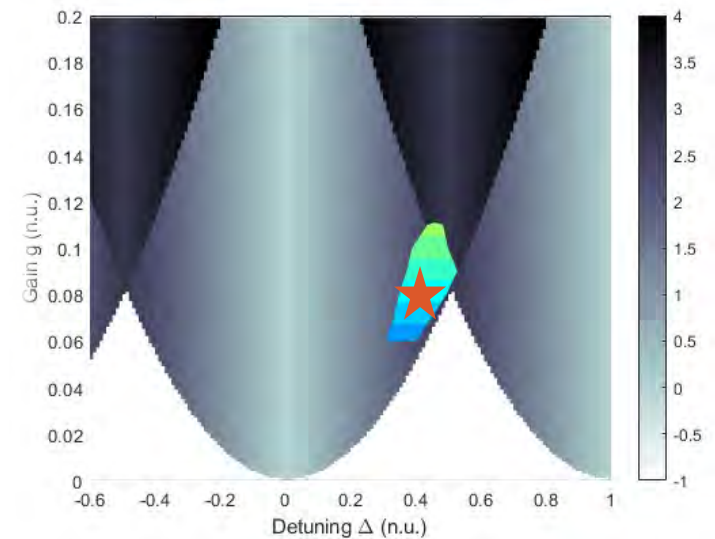
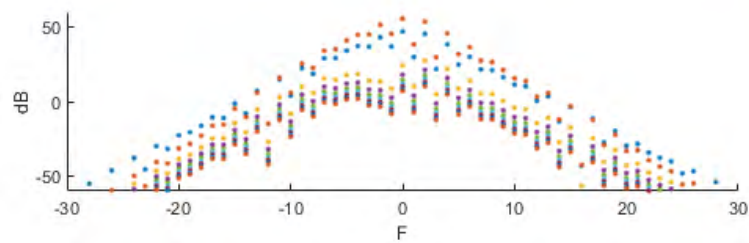
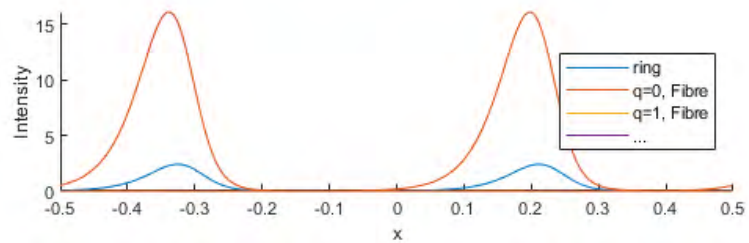
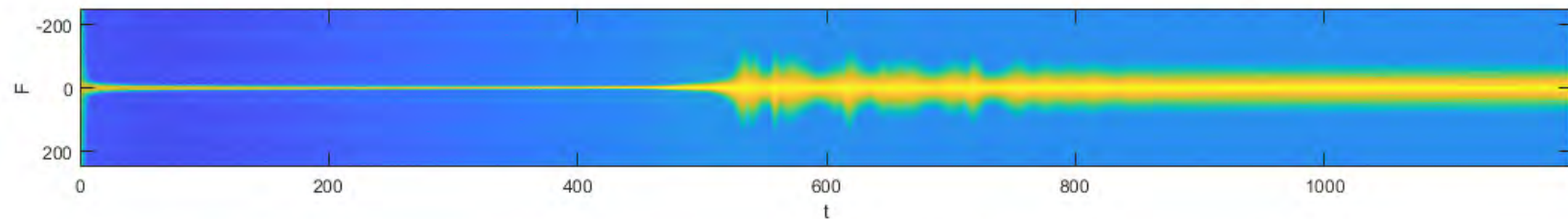
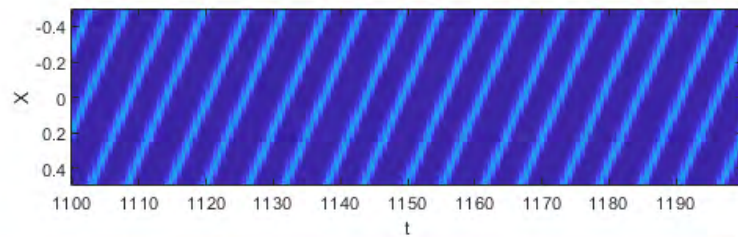
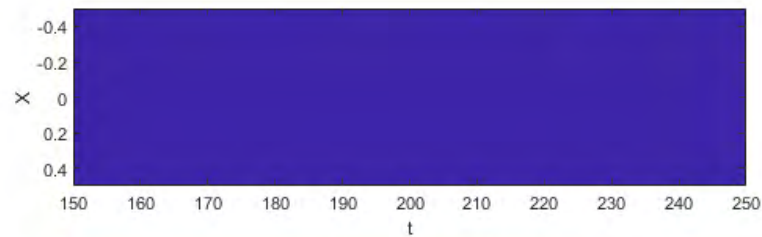
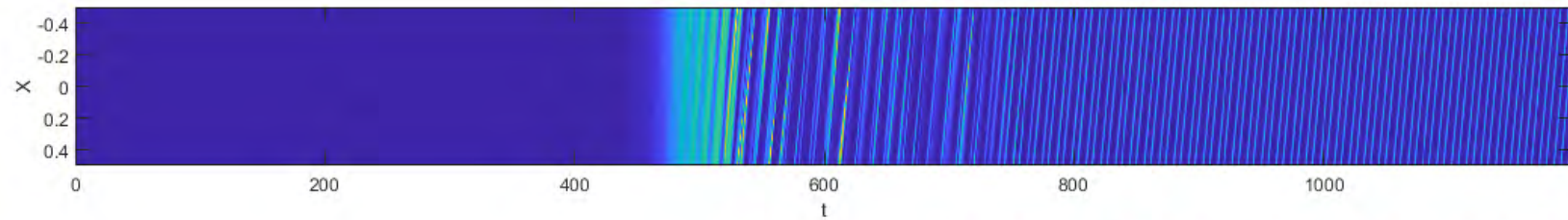
$v=0.1$



Solitons Start-up

Two Solitons

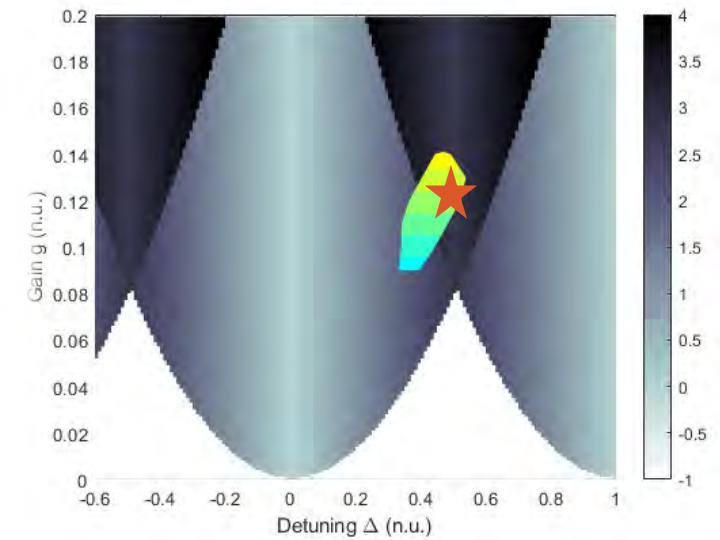
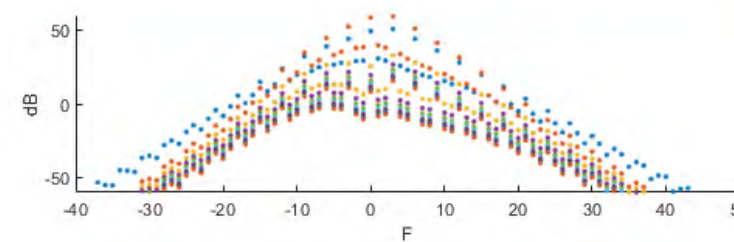
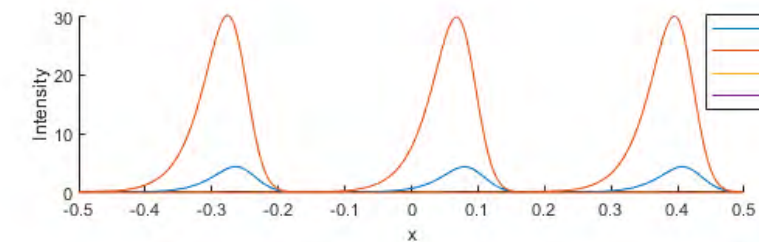
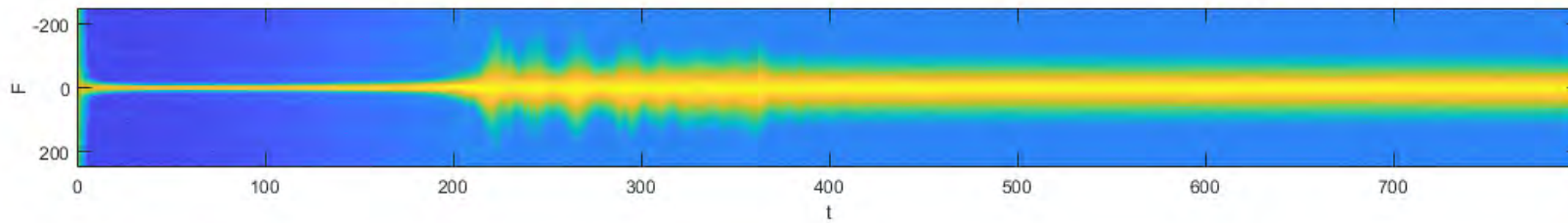
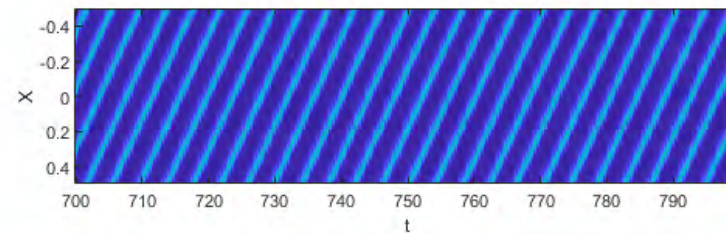
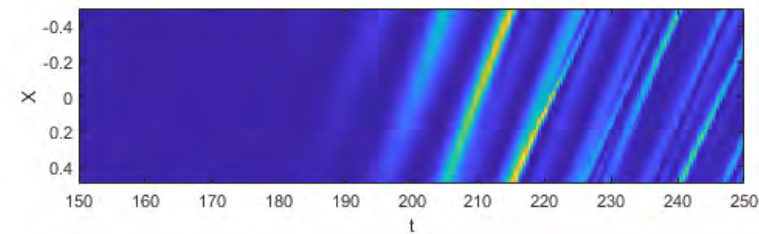
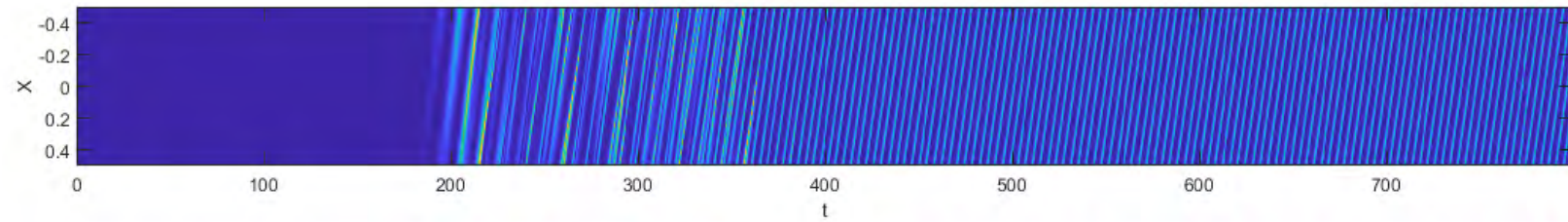
$v=0.1$



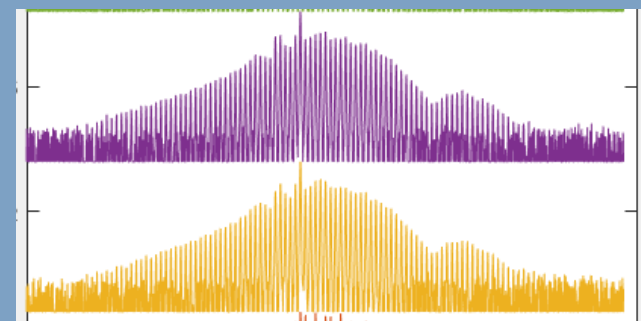
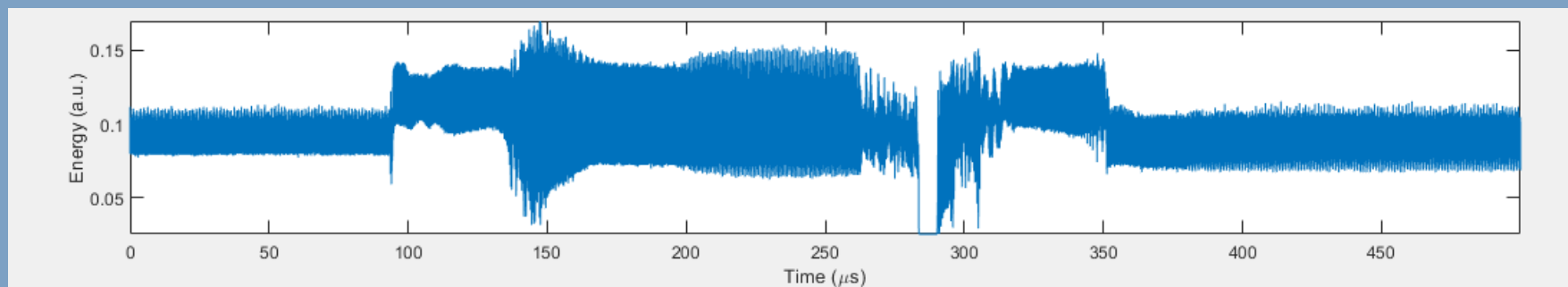
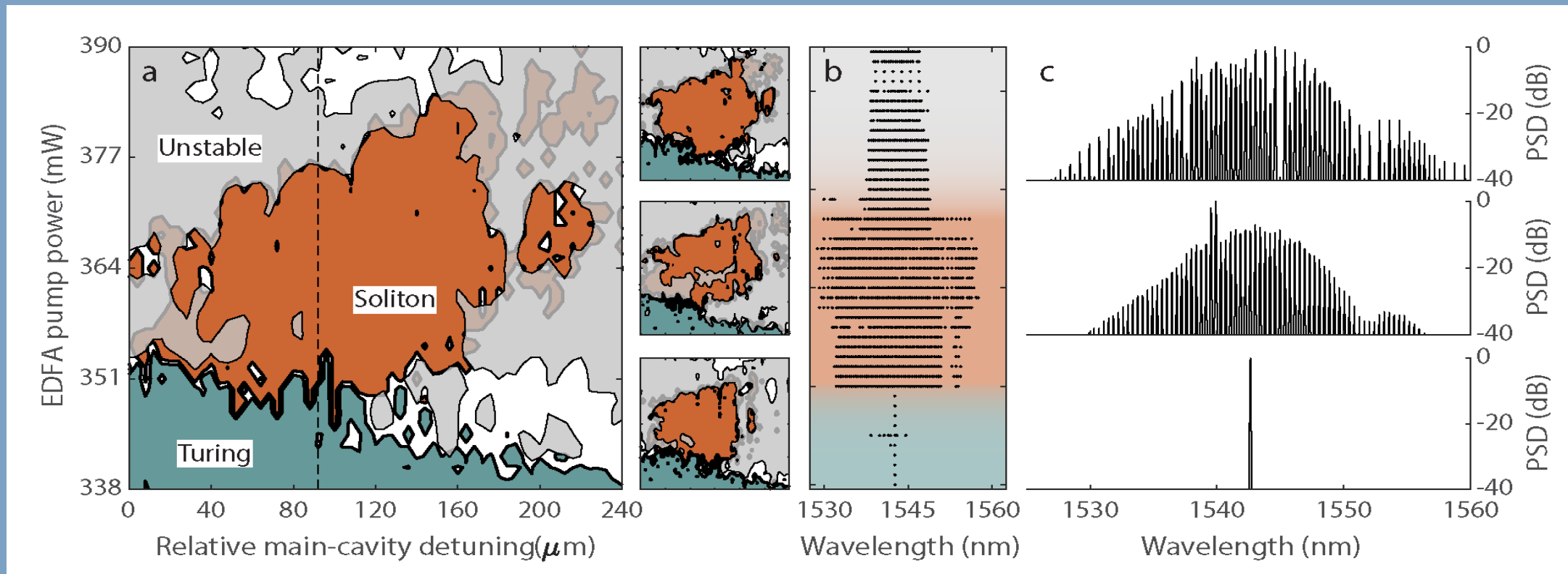
Solitons Start-up

Three Solitons

$v=0.1$



Recovery from Noise and Start-up



Efficiency- Which one?

Internal Micro Resonator Efficiency
$$\frac{\text{ENERGY THROUGH (Micro)}}{\text{ENERGY INPUT (Micro)}}$$

X. Xue et al. Laser Photonics Rev. **11** 1600276 (2017)

~40%

Mode Efficiency
$$\frac{\text{ENERGY COMB- ENERGY MAX MODE}}{\text{ENERGY MAX MODE}}$$

X. Xue et al. Laser Photonics Rev. **11** 1600276 (2017)

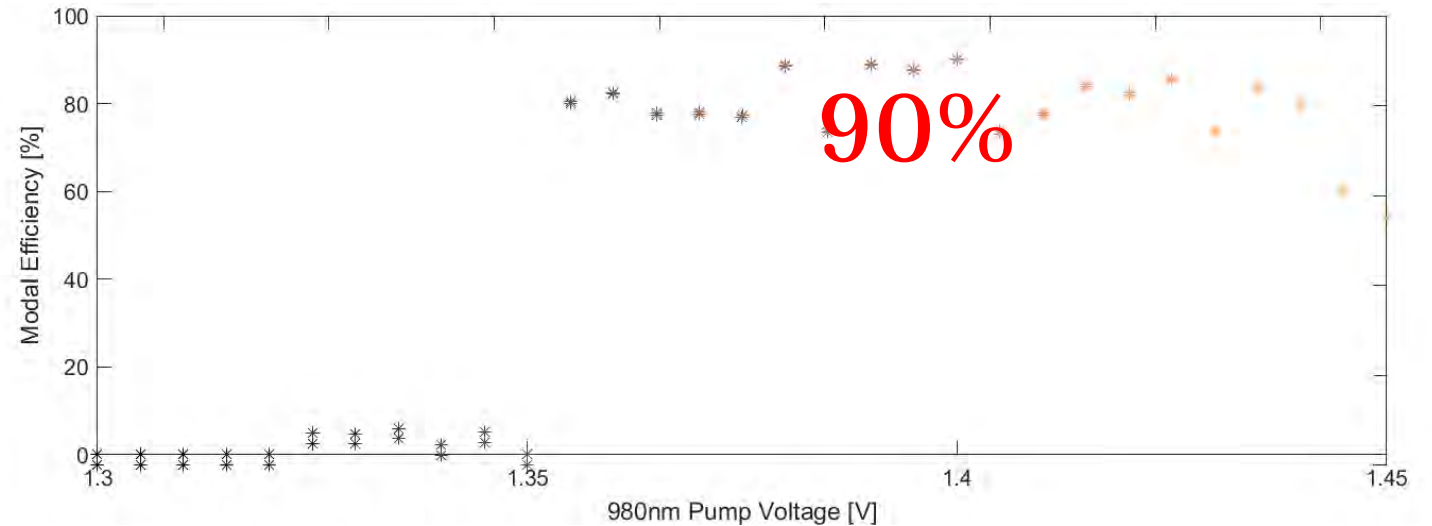
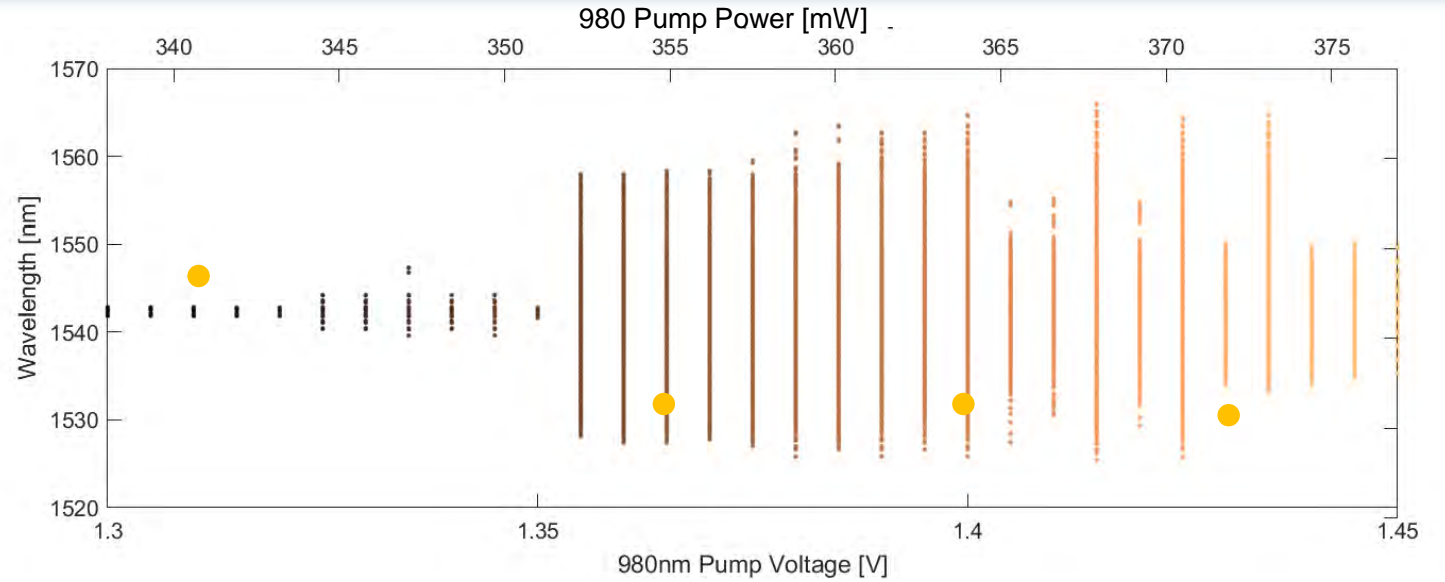
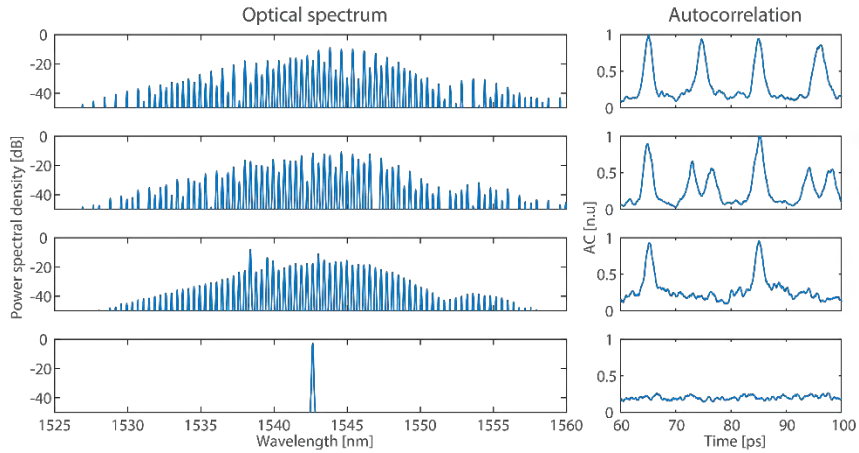
~50%

Laser Conversion Efficiency
$$\frac{\text{OUTPUT ENERGY}}{\text{GAIN ENERGY}}$$

~3-4%

Stern et al. Nature **562** 401 (2018)

Efficiency

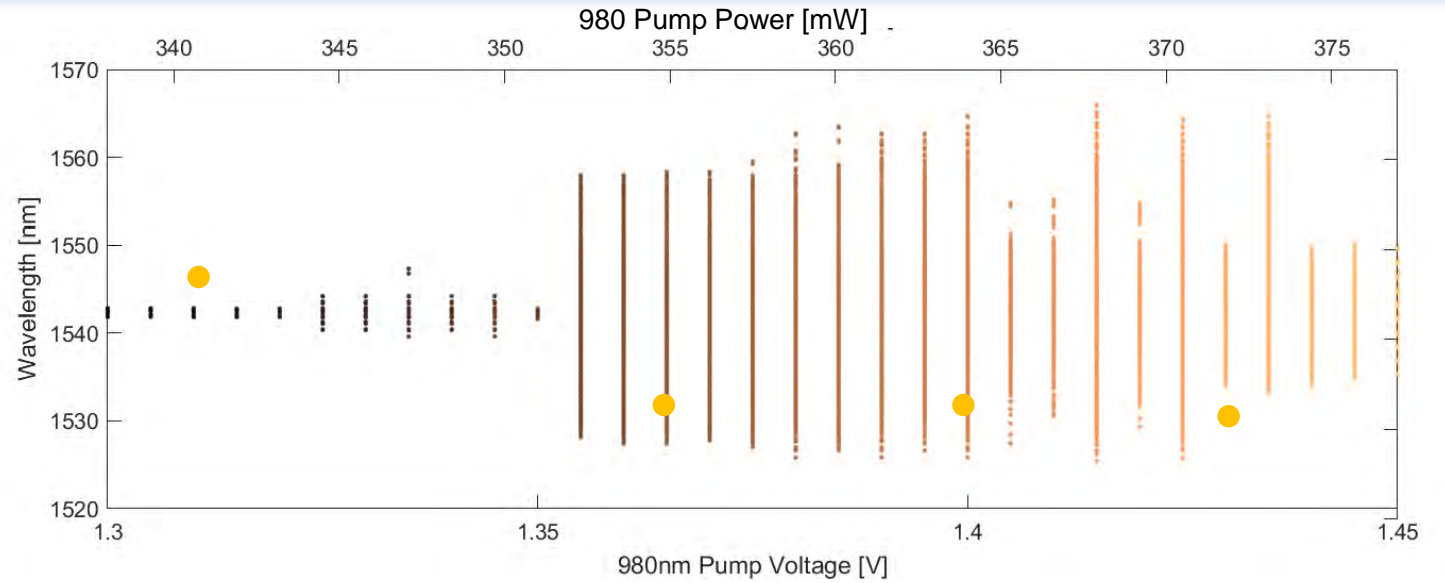
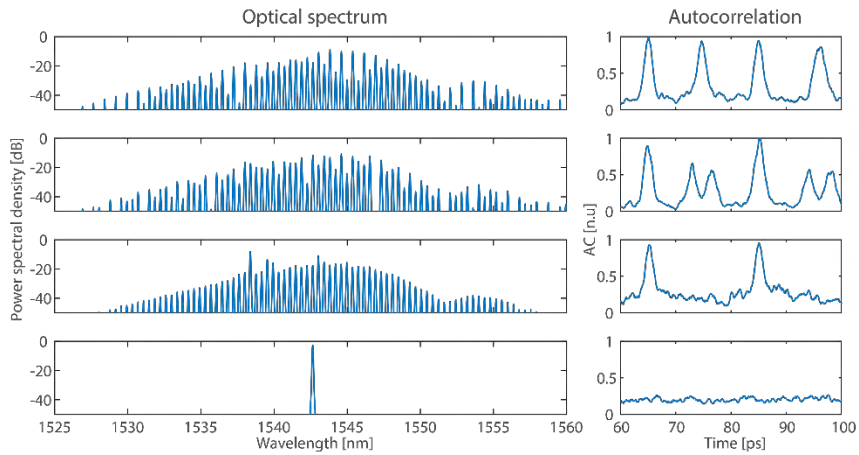


Mode Efficiency
 $\frac{\text{ENERGY COMB- ENERGY MAX MODE}}{\text{ENERGY MAX MODE}}$

X. Xue et al. Laser Photonics Rev. **11** 1600276 (2017)

~50%

Efficiency

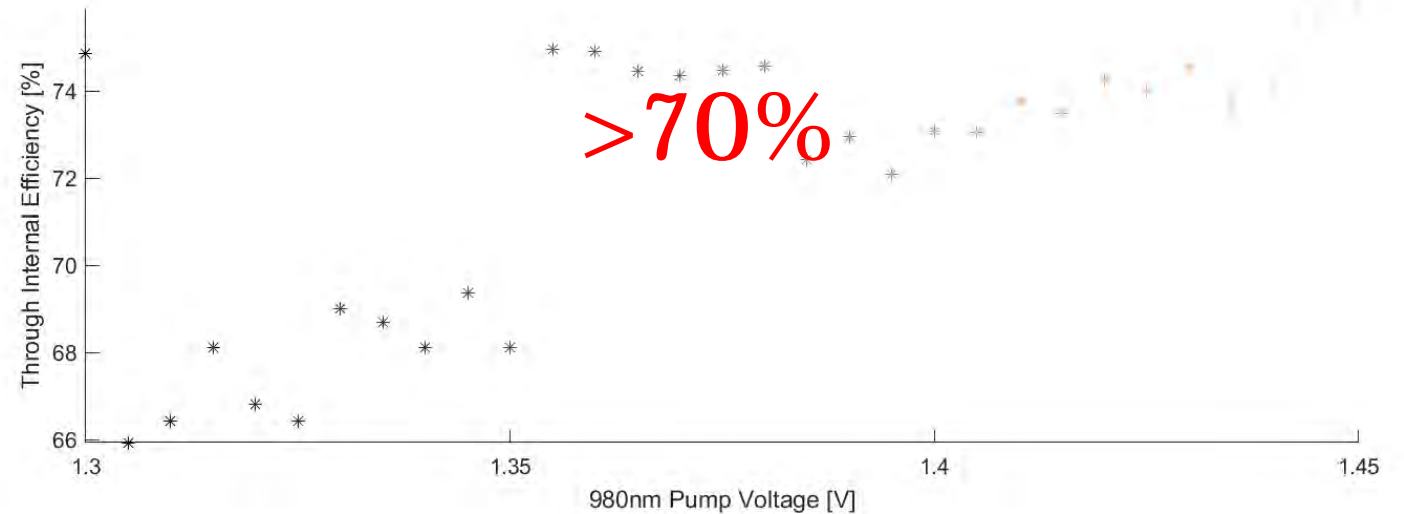


Internal Micro Resonator Efficiency

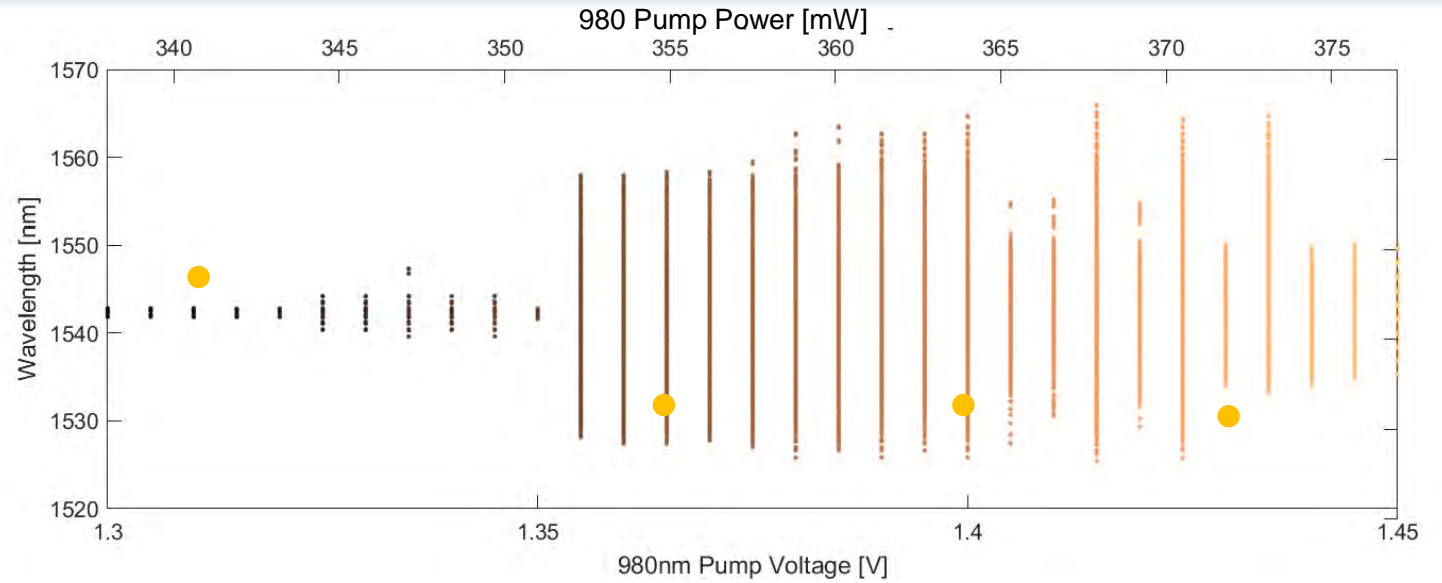
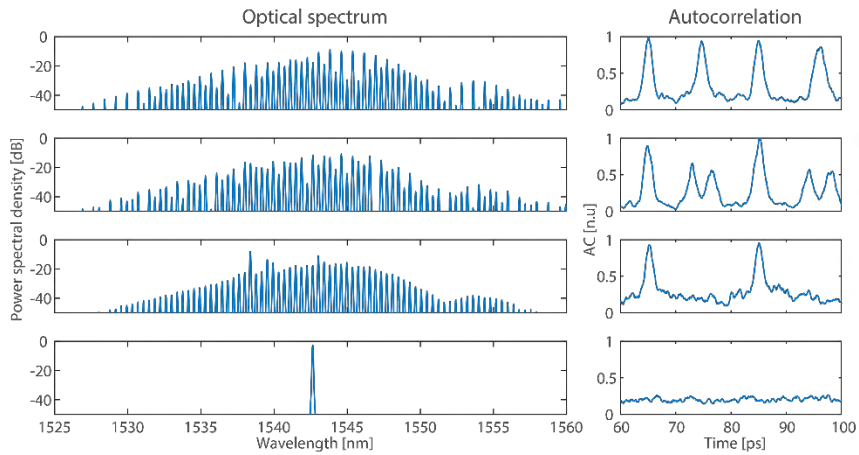
ENERGY THROUGH (Micro)

ENERGY INPUT (Micro)

~40%



Efficiency



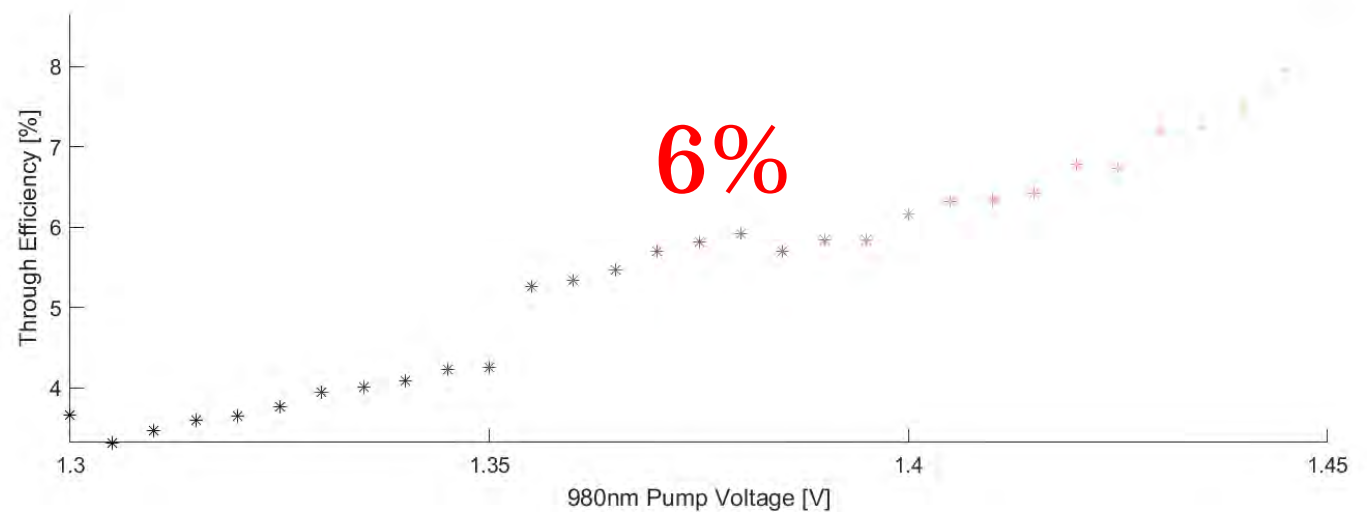
Laser Conversion Efficiency

OUTPUT ENERGY

GAIN ENERGY

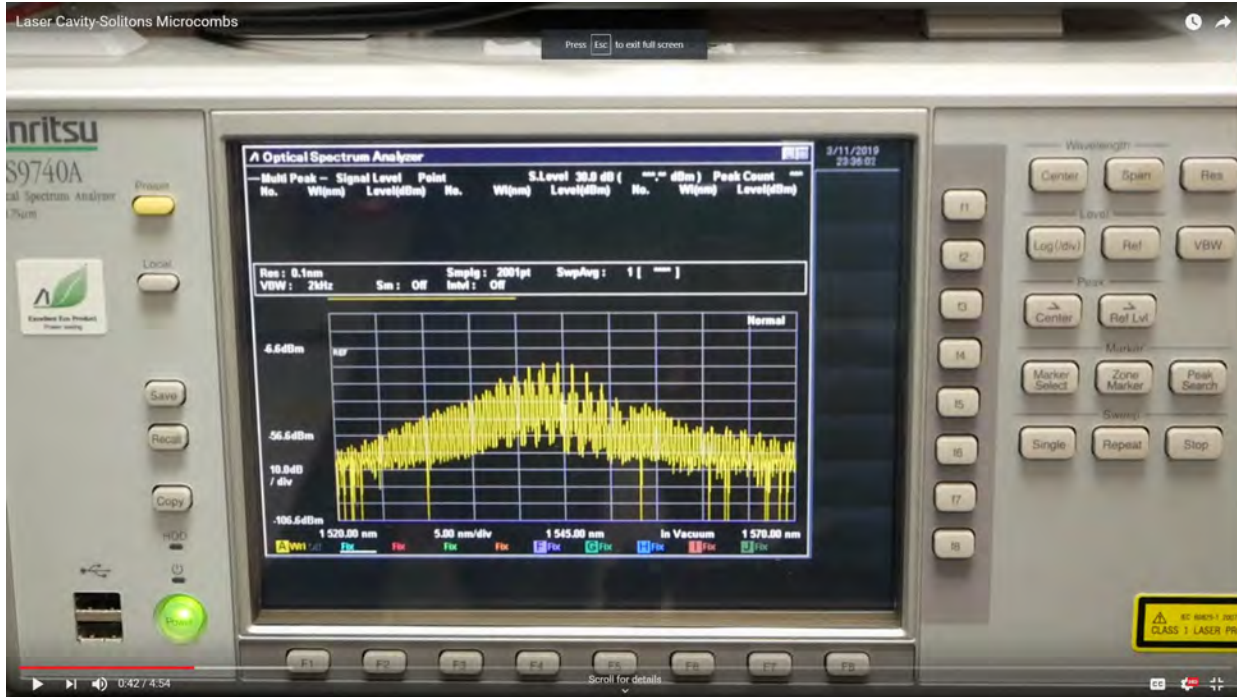
~3-4%

Stern et al. Nature **562** 401 (2018)





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Conclusions

- A Nested Cavities Laser :Modelling and parameters
- Different Regimes: Laser Cavity-Solitons and Patters
- Efficiency and self-starting

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THANKS for your attention!



Laser Cavity-Solitons Microcombs
217 views



PHOTONICS



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UK National Quantum Technology Hub in Sensors and Metrology