Prospects for the Development of Fast-Light Inertial Sensors

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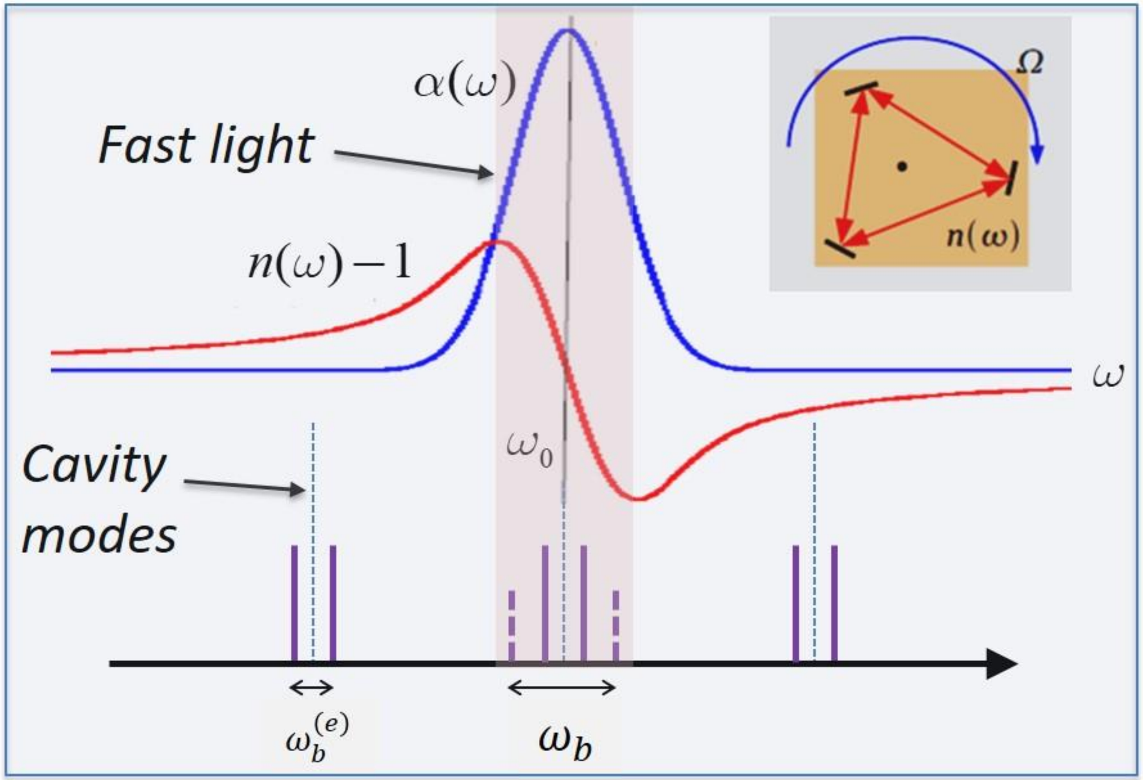
Relevance

- Critical Need: ***"NASA's future missions show a diverse set of navigational challenges that cannot be supported with current methods. Onboard autonomous navigation and maneuvering (OANM) techniques are critical."*** Addresses TA-05 for minimization of mass, power and volume while increasing performance, avoiding navigation from becoming a constraint, and eliminating Earth from the real-time decision loop.
- Problem: Current inertial sensors limited in precision and require periodic attitude or position updates (e.g. using GPS or Star-trackers).
- Conventional means of increasing precision:
    1) Increase gyro size → problematic in spaceflight
    2) Increase measurement integration time → upper limit due to higher-order noise. Not useful for rapid accelerations.
- Technologies relying on external signals (GPS, DSN, Star-trackers, XNAV, etc.) limited by large lag times (measurements in the past) and/or low flux (long integration times). They can be spoofed, incorrectly identified, occluded, obscured, delayed, attenuated, or insufficiently available.
- **Fundamental improvements needed in precision of inertial sensors!**

The Problem – The Solution

Problem: Best gyros limited in precision, resulting in errors that require periodic correction. ***Fundamental improvements needed in gyro technologies!***

Solution: Develop ultrasensitive superluminal (or fast-light) gyros ⇒ more rapid and precise measurements with smaller gyros.



Scale Factors:

$$s^{(e)} = \frac{d\omega_b^{(e)}}{d\Omega} \propto Area$$

$$s = \frac{d\omega_b}{d\Omega}$$

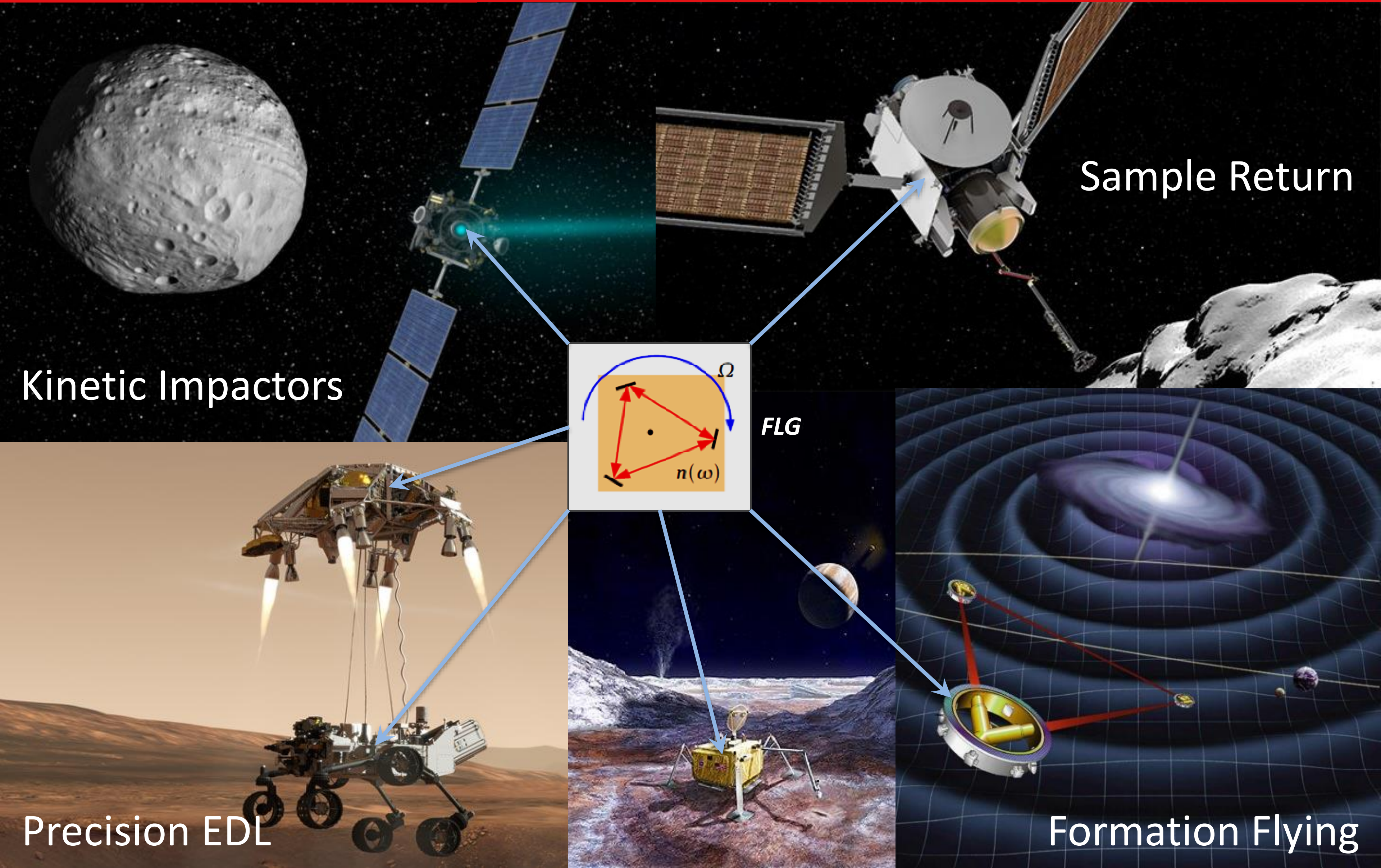
Scale Factor Enhancement (w/o increasing Area):

$$\boxed{S = \frac{s}{s^{(e)}} = \frac{d\omega_b}{d\omega_b^{(e)}} > 1}$$

Increase in Error: $\varepsilon = \frac{\sigma}{\sigma^{(e)}}$

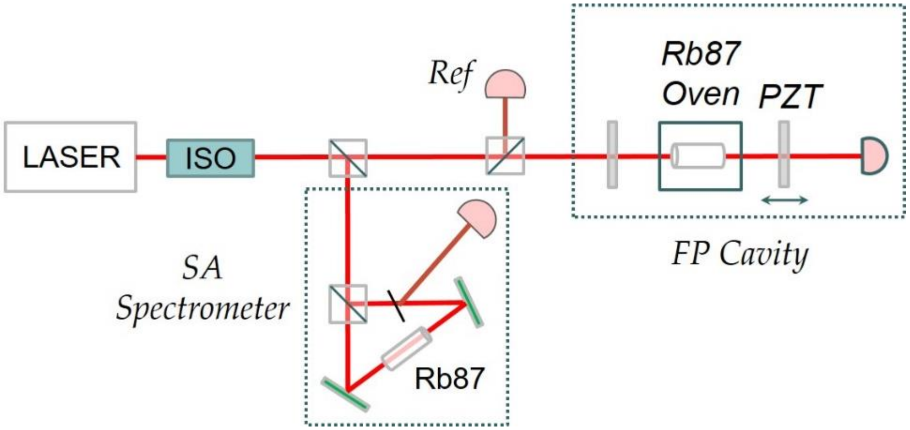
⇒ *Enhancement in Precision when:* $\boxed{\zeta = \frac{S}{\varepsilon} > 1}$

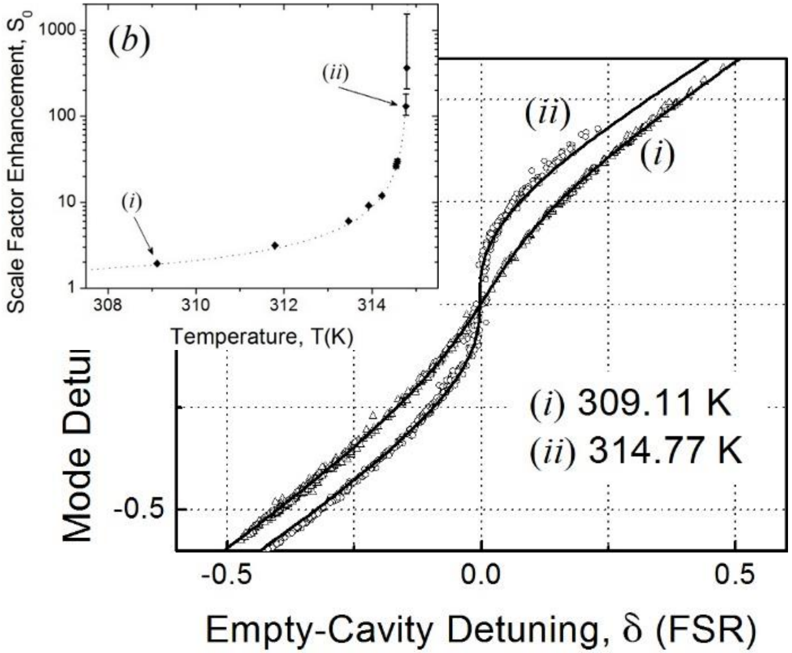
Potential Applications

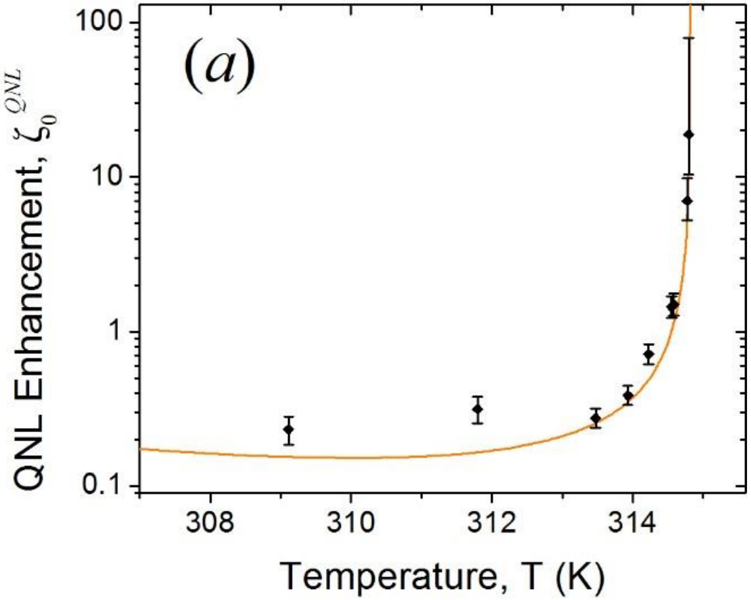


Passive FL Cavity

- First achievement of enhanced scale factor sensitivity (*S*) to OPL changes (*S* = 363).
- Tuning of *S* by temperature and by optical pumping







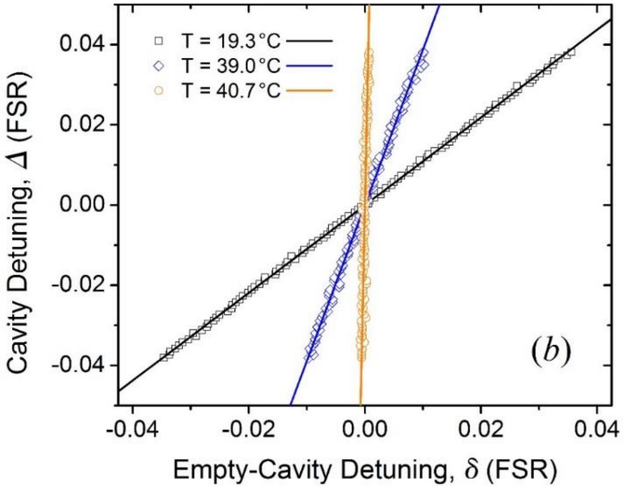
D. D. Smith et al., *Phys. Rev. A* 94, 023828, (2016).

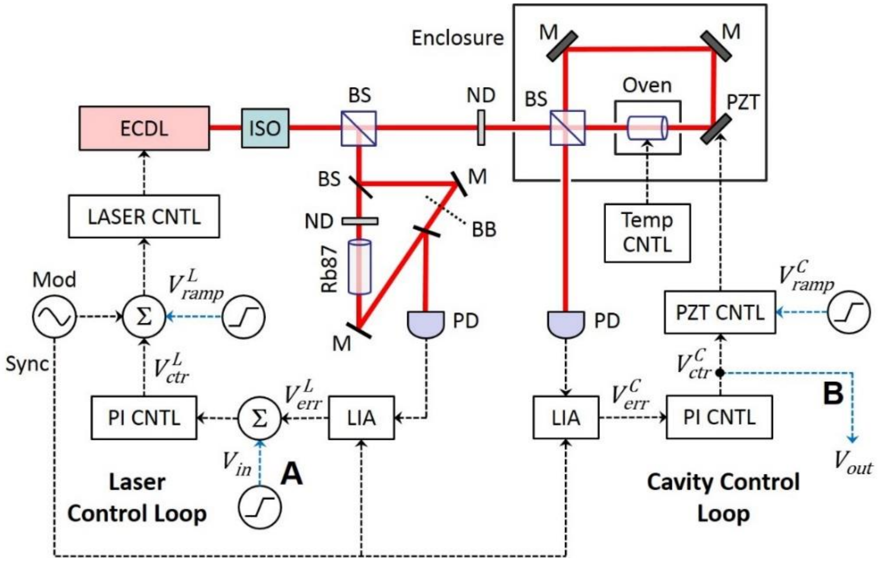
Limitations of Prior Experiments

- Cavity detunings Δ and δ not measured directly in real time in an operating device. Instead S and ε are deduced, after the fact, from the spectra
  - → Slow (5 mins vs. <1 sec. for closed-loop). Large amount of unnecessary data recorded.
  - → No real experimental evidence of enhancement. ζ inferred for ideal (QNL & high-SNR) conditions only.
- Instability due to mode pushing → data scarce near resonance. Large uncertainty in S. Stabilization needed.

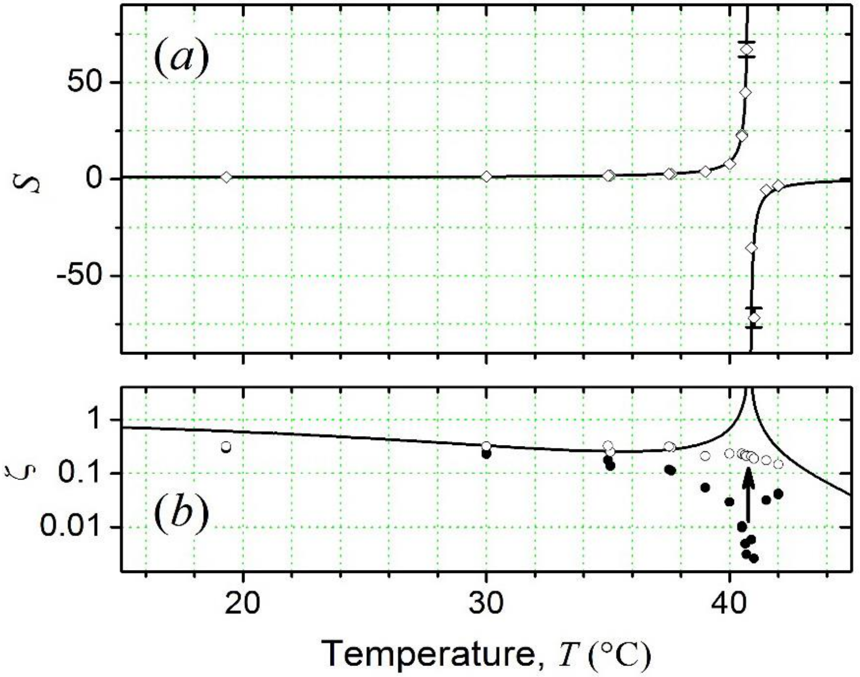
Closed-Loop Passive FL Cavity

- First direct measurement of boost in scale-factor sensitivity (*S*) in a ***closed-loop device*** using FL. ⇒ Paves way for passive FL gyro.
- Cavity remained locked through critical temperature. Both positive and negative values of *S* observed.
- Increase in ζ not yet observed due to classical noise. ⇒ Gyro geometry needed.





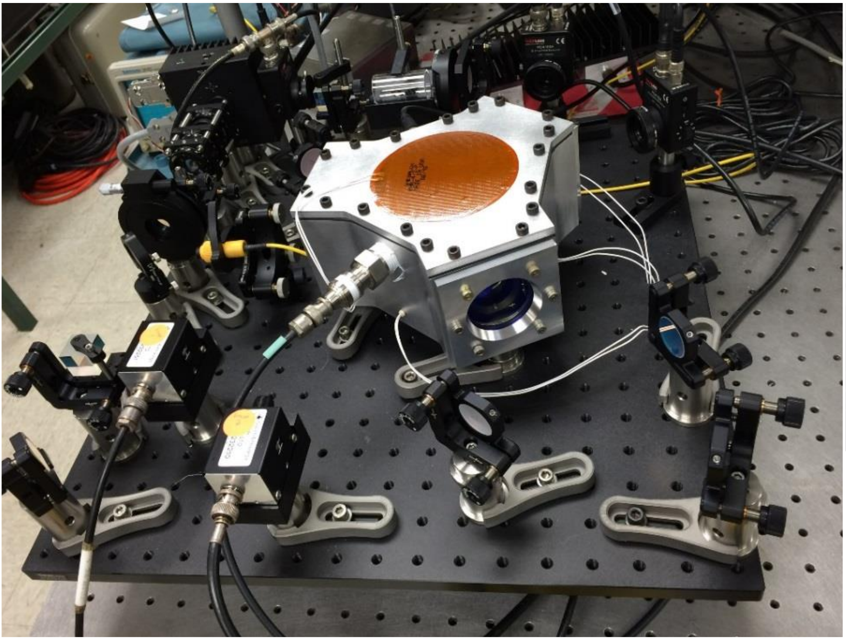
D. D. Smith et al., *Opt. Expr.* 26, 14905, (2018).



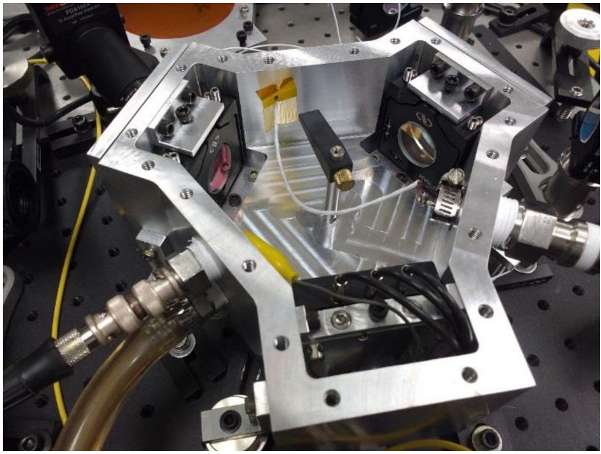
Passive FL Gyro

- Objective: Scale-factor enhancement for rotation has never been demonstrated in any experiment.

Table Shaker



Laser and Cavity on Rotation Stage



Passive Cavity

- Monolithic, vacuum-enclosed, magnetically-shielded, and temperature-stabilized to reduce noise.

Advantages / Limitations of Passive FLGs

Advantages

- Simpler and less costly to obtain preliminary data
- Avoids nonlinear dynamics from gain medium
- Only system so far to have shown boost in *S* to OPL changes.

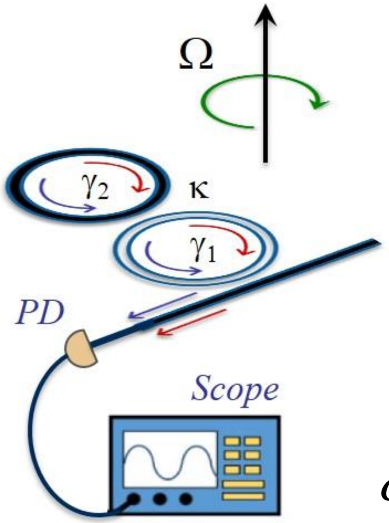
Challenges / Limitations

- Sensitive to relative motion of components external to cavity
- Cavity modes attenuated by absorption. Reduced signal to noise.
- Saturation alters lineshape, couples counterpropagating beams, and limits achievable signal to noise.
- Require complicated closed-loop locking schemes
- Cavity linewidth also broadens. Not necessarily true for active cavities. **Active FL gyros may have higher enhancement in precision!**

Challenges for Active FL Gyros

- Dynamics of gain medium may cancel enhancement to some degree.
- No known composition of gases that eliminate gain competition for the two directions ⇒ unidirectional lasing
- Current approaches significantly more complex requiring multiple lasers. Rely on NLO processes generated by added pump beams
  - → **Difficult to miniaturize**
  - → Careful control of cavity and pump parameters
  - → Sophisticated control schemes required
  - → Added sensitivity to environmental effects
- Enhancement in *S* still not demonstrated directly, only inferred.
- Reliance on discrete material transitions (applies for passive as well)
  - → Transitions are inherently temperature dependent, requiring SOA stabilization techniques to minimize the resultant noise.
  - → **Limited operation wavelength inhibits wide adoption. RLG manufacturers want to stick with He-Ne wavelengths.**

Coupled Resonator (CR) Gyros



$$\gamma = \gamma_1 - \gamma_2 \neq 0$$

$\rightarrow$ **Non-Hermitian**

$$\gamma_2 = -\gamma_1$$

$\rightarrow$ **PT-Symmetric**

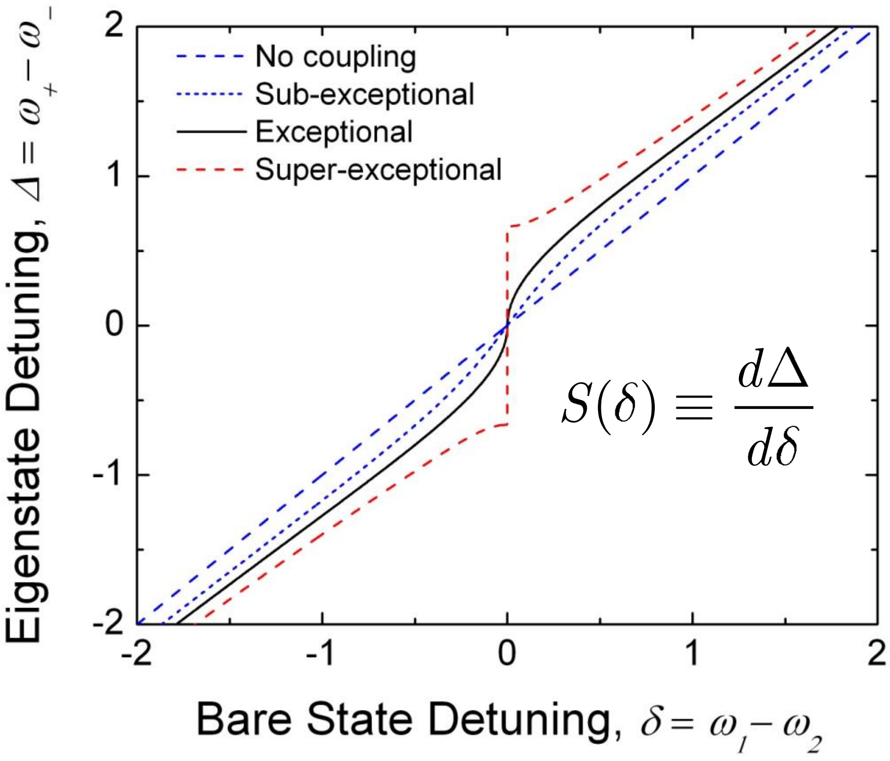
$$\tilde{\delta} = \delta - i\frac{\gamma}{2}$$ *Complex detuning*

Complex Eigenvalues:

$$\tilde{\omega}_\pm = \tilde{\omega}_{\text{avg}} \pm \frac{\tilde{\Omega}}{2} \qquad \tilde{\Omega} = \left[\tilde{\delta}^2 + \kappa^2\right]^{1/2}$$

$$\boxed{\kappa = |\gamma/2|}$$

Exceptional point!
Degenerate Eigenvalues.



$$S(\delta) \equiv \frac{d\Delta}{d\delta}$$

$$S(0) = \left[1 - (2\kappa/\gamma)^2\right]^{-1/2} \rightarrow \infty$$

Exceptional Point (EP) Coupling = Critical Anomalous Dispersion!

Advantages / Limitations of CR Gyros

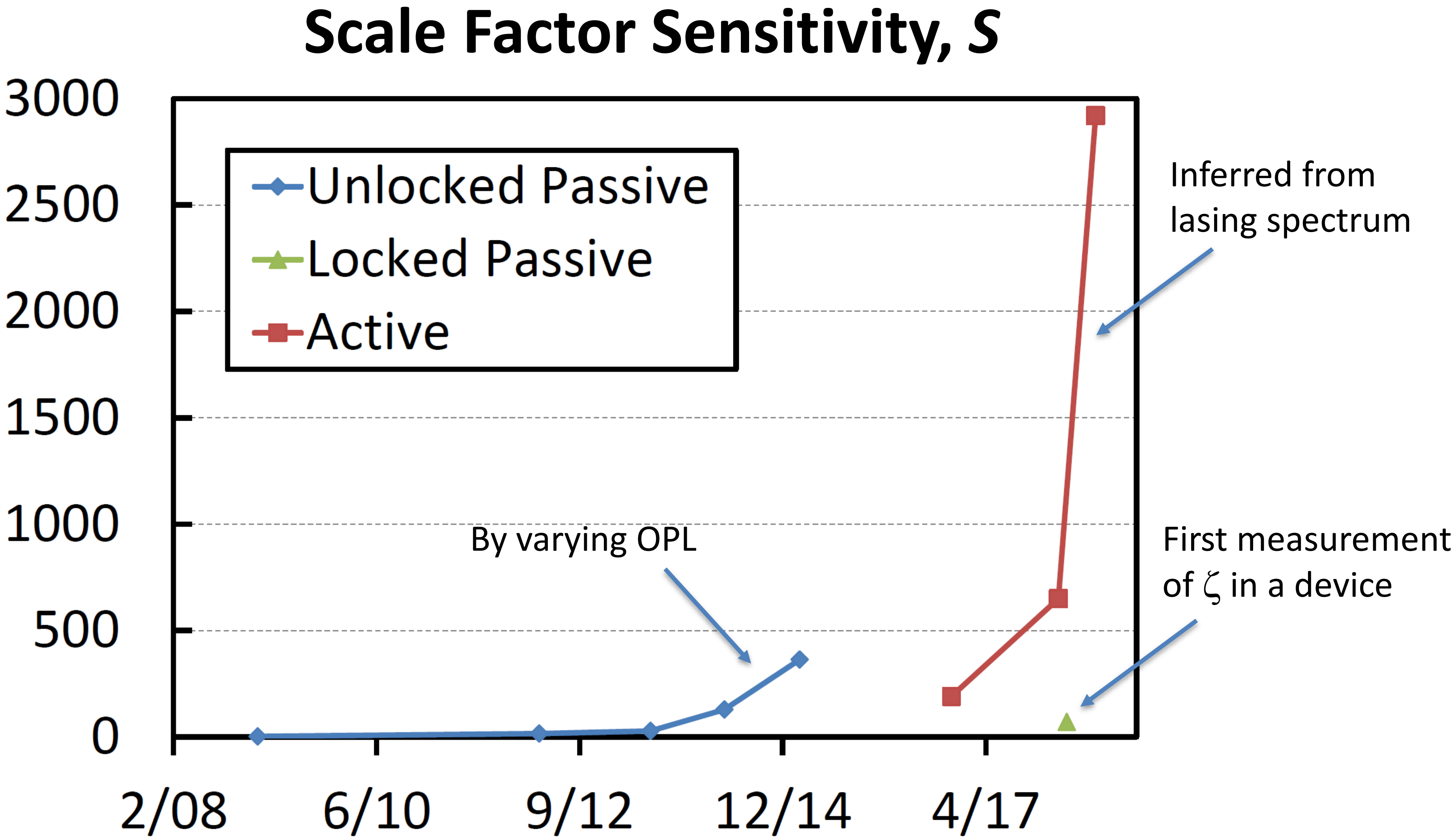
Advantages

- Easy to miniaturize via microfabrication
- Entirely linear effect, no saturation ⇒ higher signal-to-noise
- Eliminates temperature dependence of atomic absorption ⇒ potential for better scale-factor stability.
- Not limited to operation at atomic resonance frequencies. **Any wavelength possible, including He-Ne.**

Challenges / Limitations

- **PT-symmetric gyros not common path.** Resonators suffer from independent amounts of noise and drift. ⇒ Reduced common-mode noise rejection.
- **PT-symmetric gyros haven't shown any definitive boost in sensitivity**, b/c at small rotation rates the two modes (at each gyro output direction) are not distinguishable.

Increase in SOA over Time



By varying OPL

Inferred from lasing spectrum

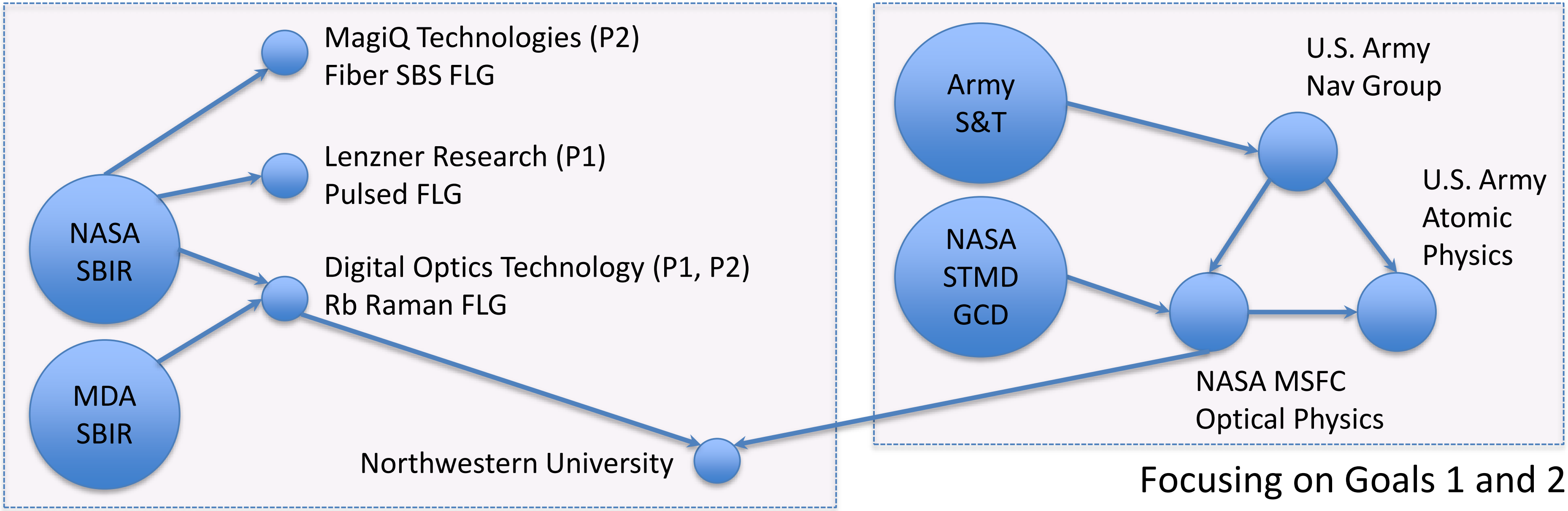
First measurement of ζ in a device

What is still needed

1) Demonstrate scale-factor enhancement, *S*, to rotation.
2) Demonstrate enhancement in precision, ζ.
3) FL gyros that:
   - → Are common path
   - → Are not limited in signal to noise
   - → Do not require frequency locking
   - → Permit operation at any wavelength
   - → Can be easily miniaturized
   - → Are relatively insensitive to environmental (e.g. temperature) variations
   - → Can operate in varying G-conditions

Development Plan

Active FLGs ***Passive FLG*** ***In-house Program***



Focusing on Goal 3

Focusing on Goals 1 and 2

Other Past & Present: Torch Technologies, Triad Technology, Aegis Technology, Honeywell, Los Gatos Research, Photodigm, Vescent Technologies, Freedom Photonics, Rochester Scientific, College of William and Mary.

International Efforts: Tel Aviv Univ. (Israel), National Univ. of Defense Technology (China), Harbin Institute of Technology (China), Thales Aerospace (France).

Valley of Death: To accomplish goal 2 may require development of a high-quality gyro. Sufficient funding for such development less likely until goal 2 met.

Future State: IMUs incorporating FL gyros/accelerometers with orders-of-magnitude (10^6 upper limit) reduced ARW.