aLIGO Design
Presentation at UF
October 5th, 2015
GM

Source Material:

- T0900043
- Optics Express, Vol 16(14), 10018 (2008)
- Appl. Opt. 42(7) 2003, 1244-1256
- Appl. Opt. 42(7) 2003, 1257-1268

Understanding aLIGO

Generation of signal field:
Phase modulation of cavity internal field

$$E_{Cav} = E_0 e^{i(kL-\omega t)} e^{ik\delta L sin\Omega t}$$

$$\approx E_0 e^{i(kL-\omega t)} \left[1 + \frac{k\delta L}{2}\left(e^{i\Omega t} - e^{-i\Omega t}\right)\right]$$

Understanding aLIGO

Signal (outside cavity):

- Amplitude: $$E_{Out}^{SB} = t_{Cav}(\Omega_{GW})\frac{k\delta L}{2}E_0$$

$$t_{Cav} = \frac{it_I}{1 - r_I r_E e^{i\phi_{RT}}} \qquad \phi_{RT} = \frac{\Omega}{FSR}$$

- Max-Signal (Ω_{GW} small): Impedance matched cavity

$$T_{ITM} = Losses$$

Understanding aLIGO

$$T_{ITM} = Losses$$

State of the art cavity losses:
- < 1ppm coating absorption
- ~5-10 ppm transmission
- ~50-100 ppm scatter across beam

➡ T_{ITM} ~ 100ppm

Cavity with T_{ITM} ~ 100ppm:
- Finesse = 3×10^4
- Line width (HWHM) ~ 1Hz

➡ would average out all relevant GW signals

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- T_{ITM} is compromise between signal amplitude (gain) and detector band width
- but also reduces carrier inside cavity

$$E_0 = \frac{t_I}{1 - r_I r_E} E_{in}$$

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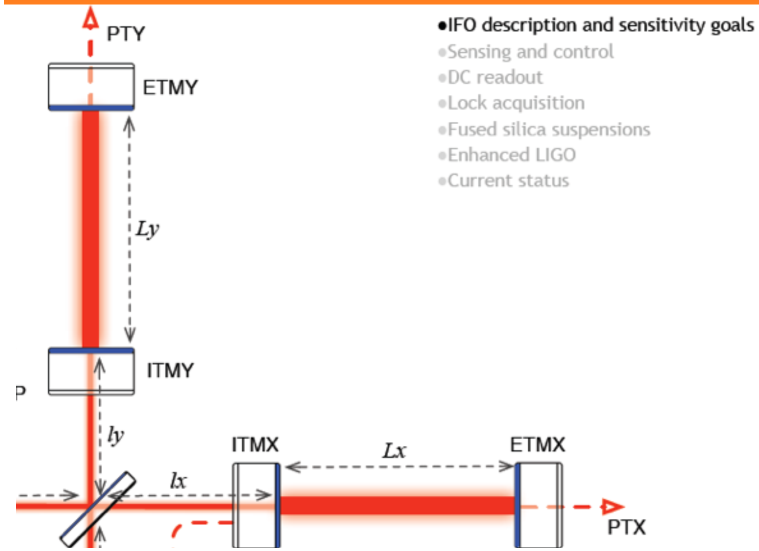
Take advantage of
- Michelson Interferometer
- Quadrupole nature of GW
  - SB generated 180deg out of phase in both arms

➡ Tune MI to dark
  - Carrier goes back to laser
    - all laser noise suppressed in dark port
  - Signal field goes to dark port
    - not affected by anything between BS and laser



$$E^0_{refl} = E_{in}\left[r^2_{BS} r_{Cav1} e^{ikl_1} + t^2_{BS} r_{Cav2} e^{ikl_2}\right]$$

$$E_{DP} = E_{signal}\left[t_{BS} e^{ikl_1} + r_{BS} e^{ikl_2}\right]$$

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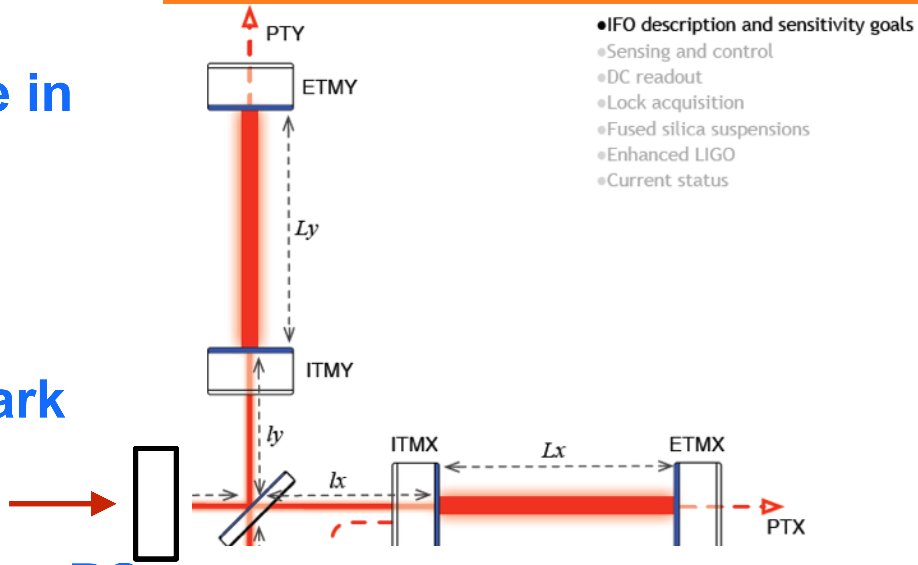

➡ Allows power recycling. Best gain: Impedance matching

$$R_{MI} \approx R_{Cav} \approx 1 - \frac{4L}{T_I}$$ + MI losses

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Lets put this together:

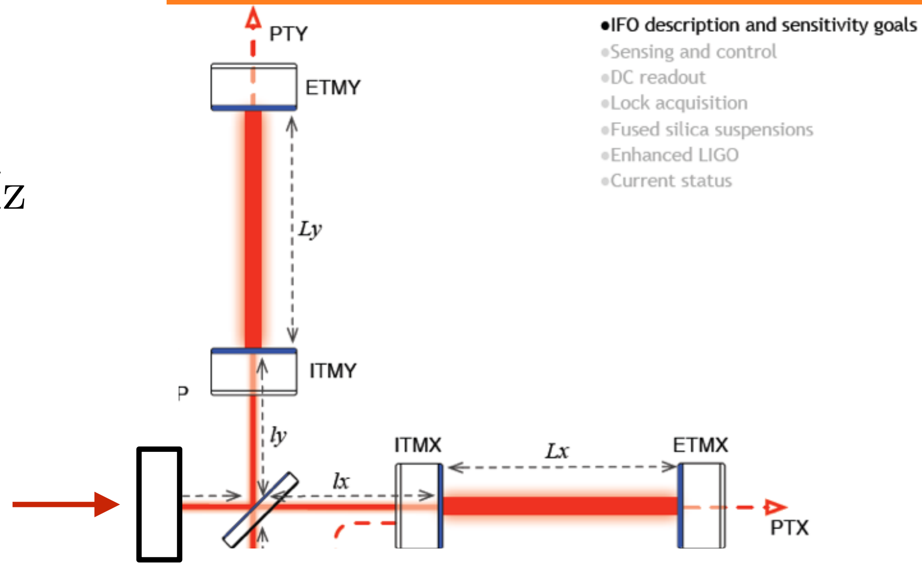
- **GW bandwidth sets T_{ITM}**

$$HWHM = \frac{FSR}{2F} = \frac{FSR}{2\pi} T_I \approx 100\text{Hz}$$

$$T_I \approx 1.5\%$$

- **Anticipated Losses determine T_{PR}**

$$T_{PR} \approx \frac{4L}{T_I} \approx \frac{450ppm}{1.5\%} = 3\%$$



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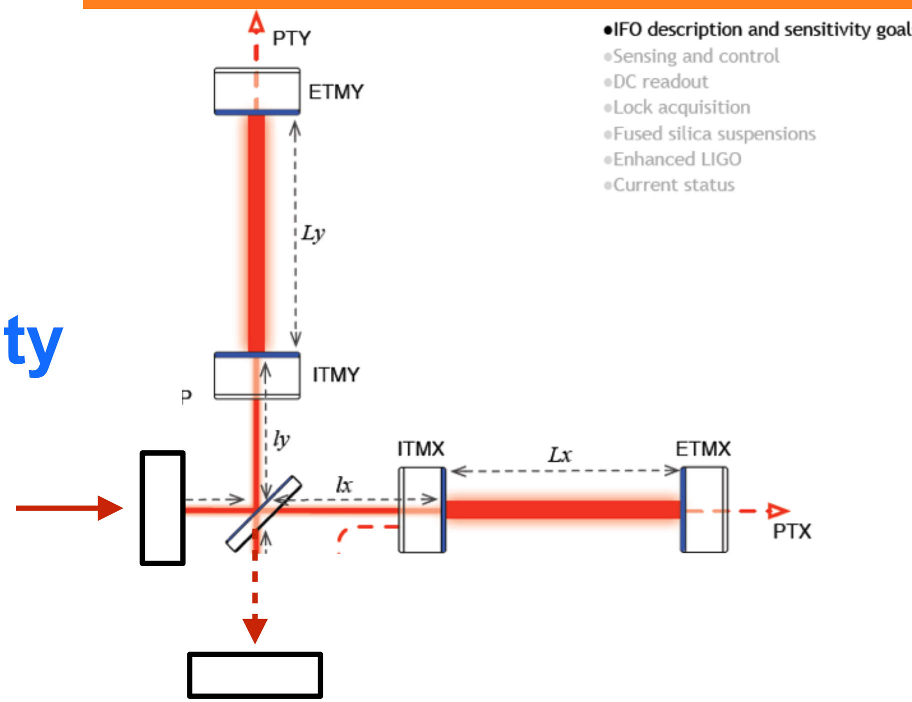
Signal Recycling:
- **Coherent amplification or**
- **Coherent extraction**

of signal field

IFO for signal ~ 3 mirror cavity



ITM/SR: Compound mirror

$$r_{CM}e^{i\phi_{CM}} = \frac{r_{ITM} - r_{SR}e^{i\phi_{SR}}}{1 - r_{ITM}r_{SR}e^{i\phi_{SR}}}$$

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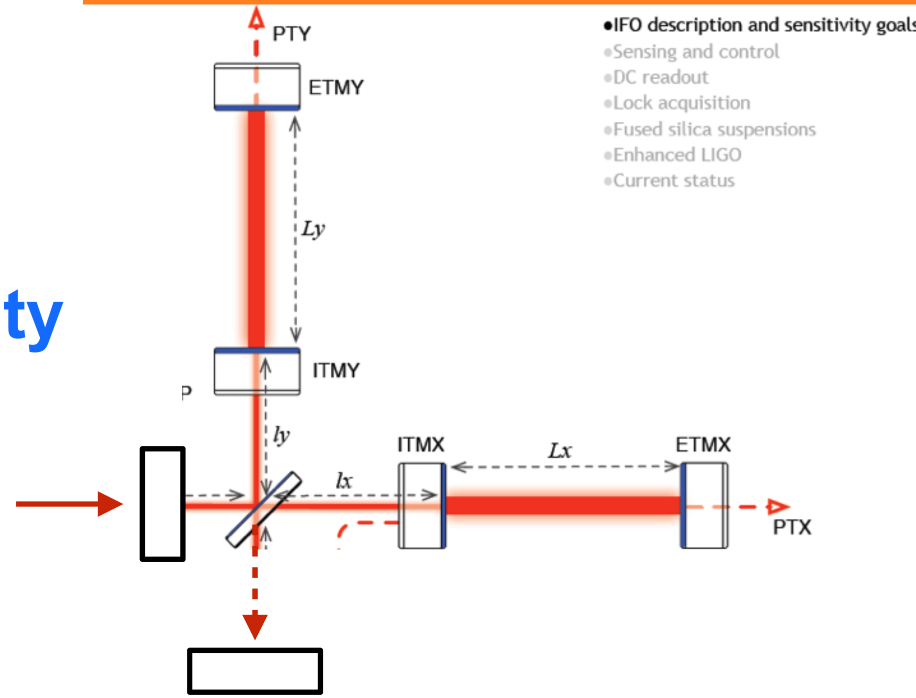

used to tailor frequency response of aLIGO

$$T_{SR} = 20\% \quad today$$

taking into account all known
- noise sources
- potential signals
- locking issues

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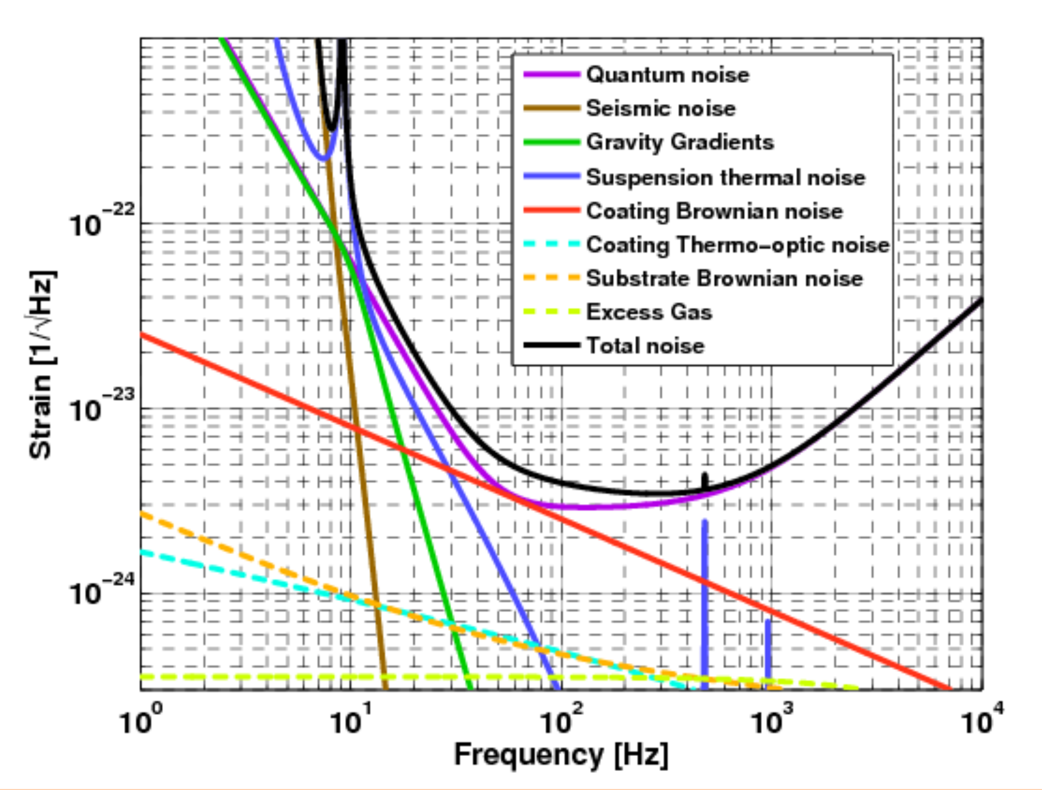
Important mirror parameters:
✓Transmissivity
- Mass = 40kg
  - as heavy as necessary
  - as light as possible
  - RPN ~ Suspension thermal
    - Limits useful mass



- Radius of curvature
  - Increase beam size
    - reduce coating TN
    - limited by
      - diffraction losses to ~6cm
      - cavity stability
      - stability against thermal deformation

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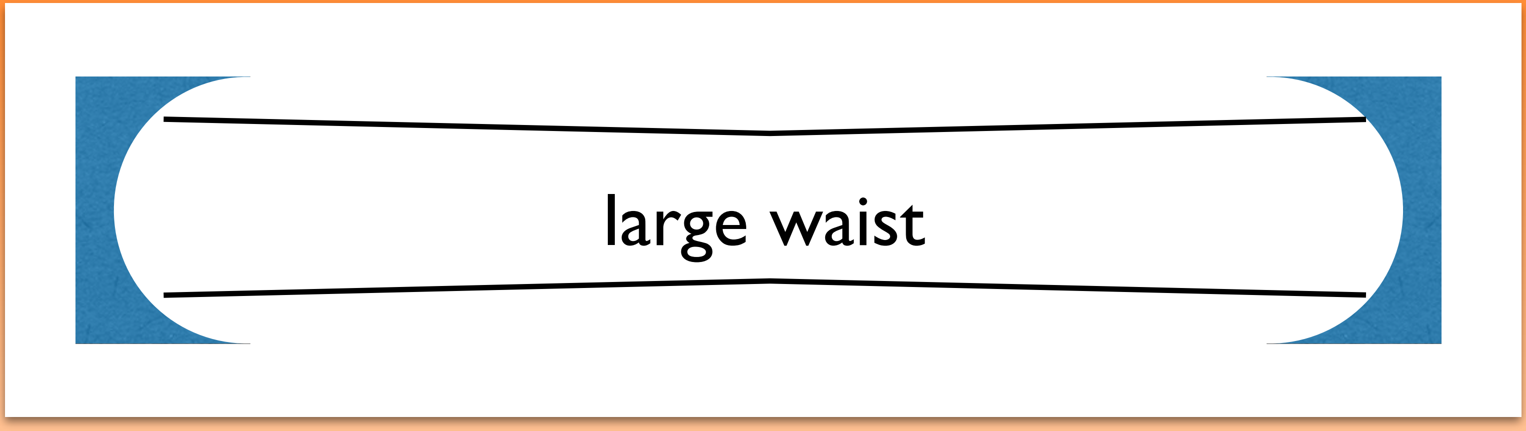
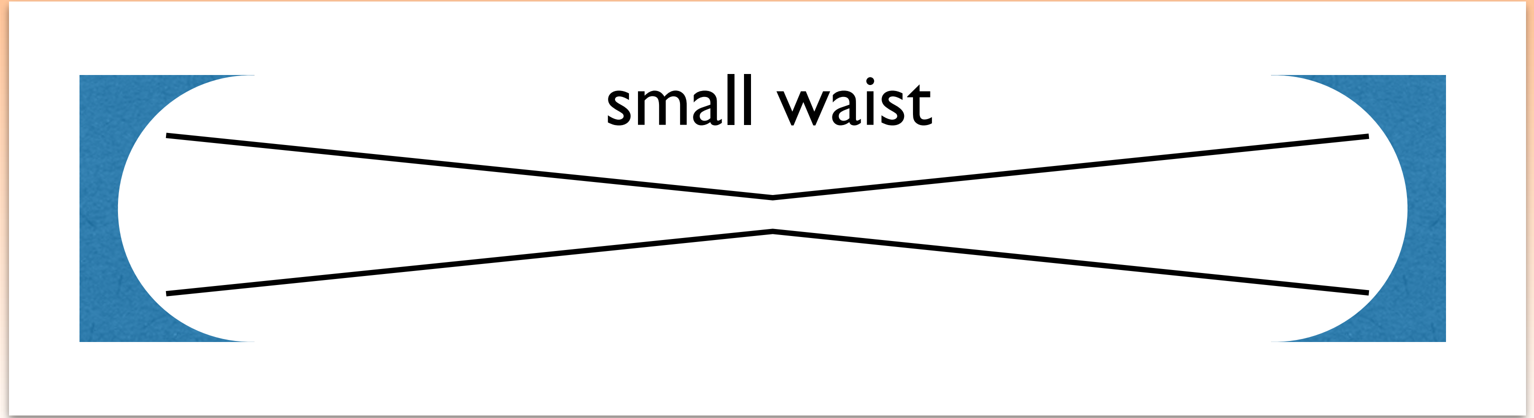
Beam size on test masses:

- Two options





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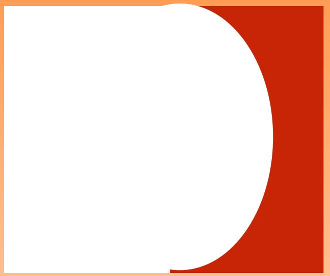
Beam size on test masses:
- Two options

- Large:
  - Smaller beam size at BS
  - ROCs difficult to measure ~ 52km $\delta s \approx 36\ nm$

- Small:
  - Stable against ROC increases due to heating
  - ROCs easier to measure ~ 2080m $\delta s \approx 1\ \mu m$



More coating layers on ETM (increases thermal noise)
Diffraction larger issue at beam splitter:
- Increase beam size at ETM to ~ 6.3cm
- Decrease beam size at ITM to ~ 5.7cm

Final design: R_{ETM} = 2245m R_{ITM} = 1934m

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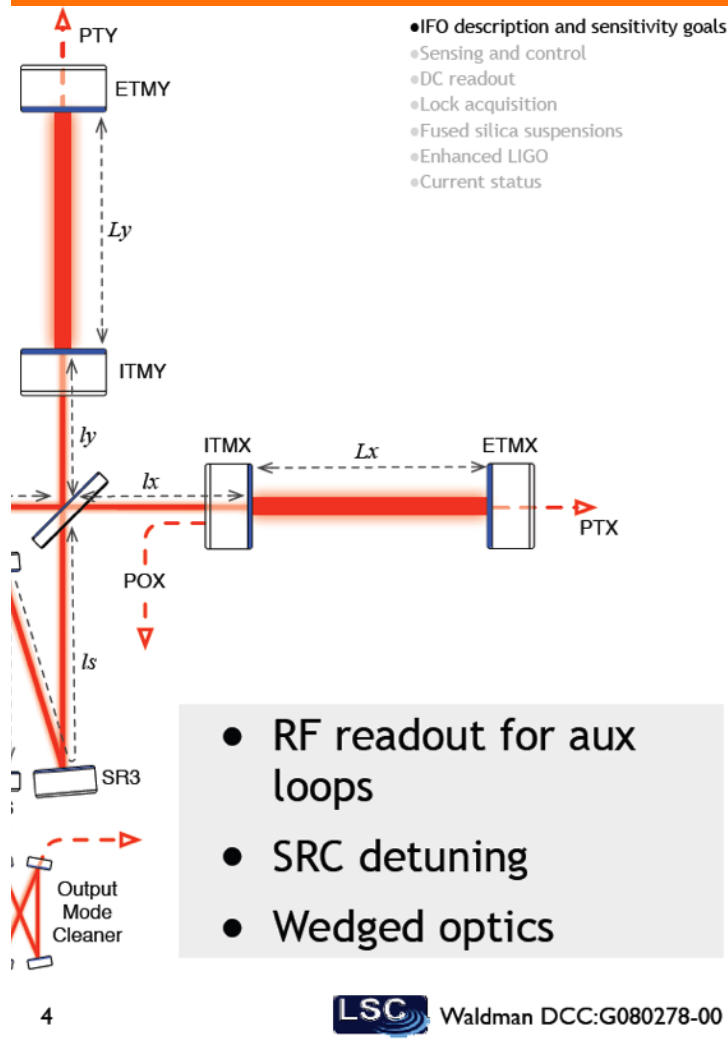
Recycling cavity design:

- Two options

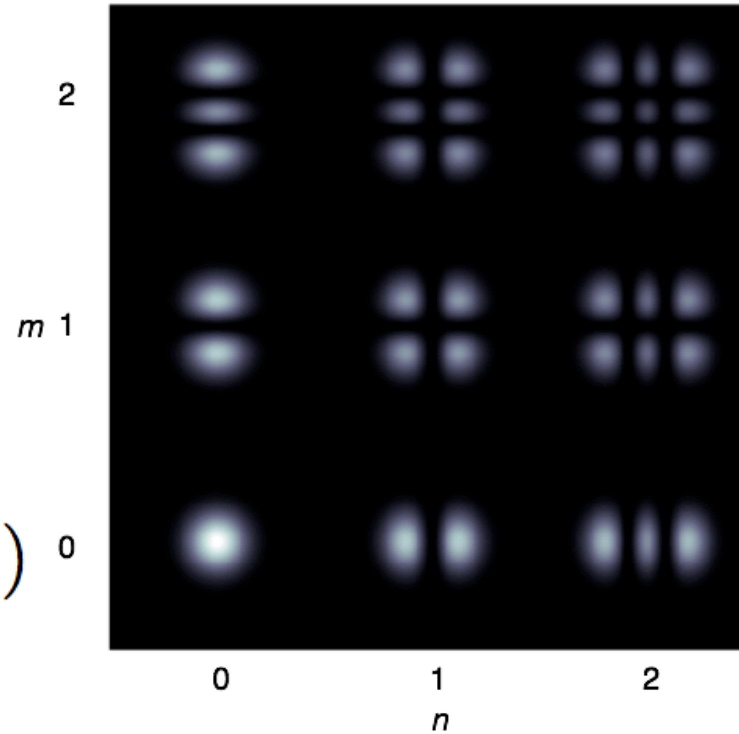
- Simple, but barely stable:
  - R ~ 1400m
  - g = 1 - 20/4000 ~ 1 (nearly unstable)
    - higher order modes near resonant
    - bad for alignment sensing
    - very power dependent eigenmodes
    - bad experience in iLIGO
- Folded recycling cavity
  - g selectable
  - HOMs non-resonant
  - nearly power independent eigenmodes



Higher-order HG modes

- Spatial field distributions which reproduce after cavity roundtrip = spatial eigenmodes
- Have different resonance frequencies (except for g~1)
- Separable in x and y = HG-modes

$$u_{\mathrm{nm}}(x,y,z) = u_{\mathrm{n}}(x,z)u_{\mathrm{m}}(y,z)$$



$$u_{\mathrm{nm}}(x,y,z) = \left(2^{n+m-1}n!m!\pi\right)^{-1/2}\frac{1}{w(z)}\;\exp\left(\mathrm{i}\,(n+m+1)\Psi(z)\right)\;\times$$
$$H_n\left(\frac{\sqrt{2}x}{w(z)}\right)H_m\left(\frac{\sqrt{2}y}{w(z)}\right)\exp\left(-\mathrm{i}\,\frac{k(x^2+y^2)}{2R_C(z)}-\frac{x^2+y^2}{w^2(z)}\right)$$

$$H_0(x) = 1 \qquad H_1(x) = 2x$$
$$H_2(x) = 4x^2 - 2 \quad H_3(x) = 8x^3 - 12x$$

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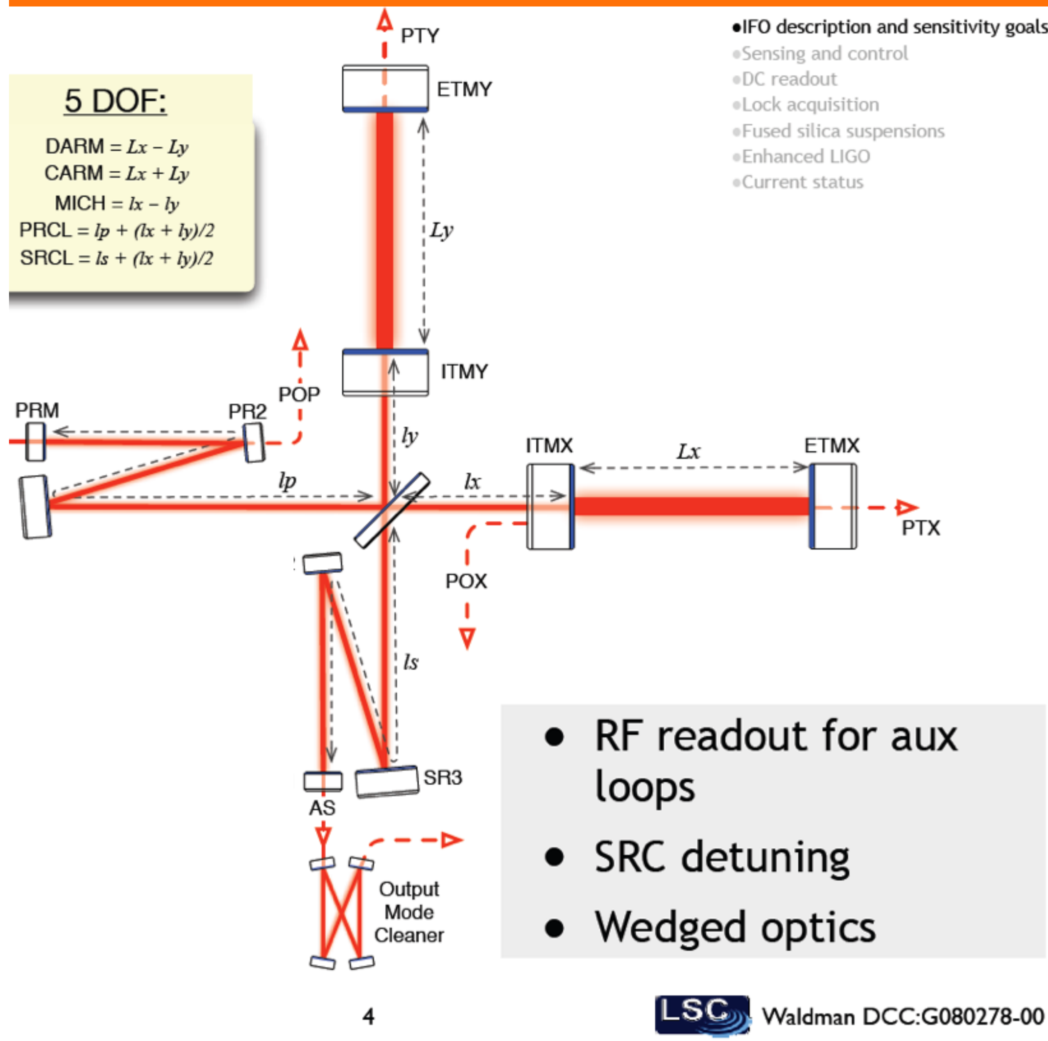
Recycling cavity design:
- Two options

- Folded recycling cavity
  - g selectable
  - HOMs non-resonant
  - nearly power independent eigenmodes

- PR3 focuses ~6cm beam
  - waist after PR2
- Stable mode between PR2 and PRM (sets Gouy phase)
- MM very sensitive to PR2/PR3 distance/ROCs
- SR-cavity similar



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Length sensing basics:

- Paul will discuss in more detail

Important for design:

Each degree of freedom has to be sensed by some field

- Requires resonant SBs inside recycling cavities
- f1 for power recycling
- f2 for signal recycling but has to pass through power recycling and MI

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Power Rec. cavity design:

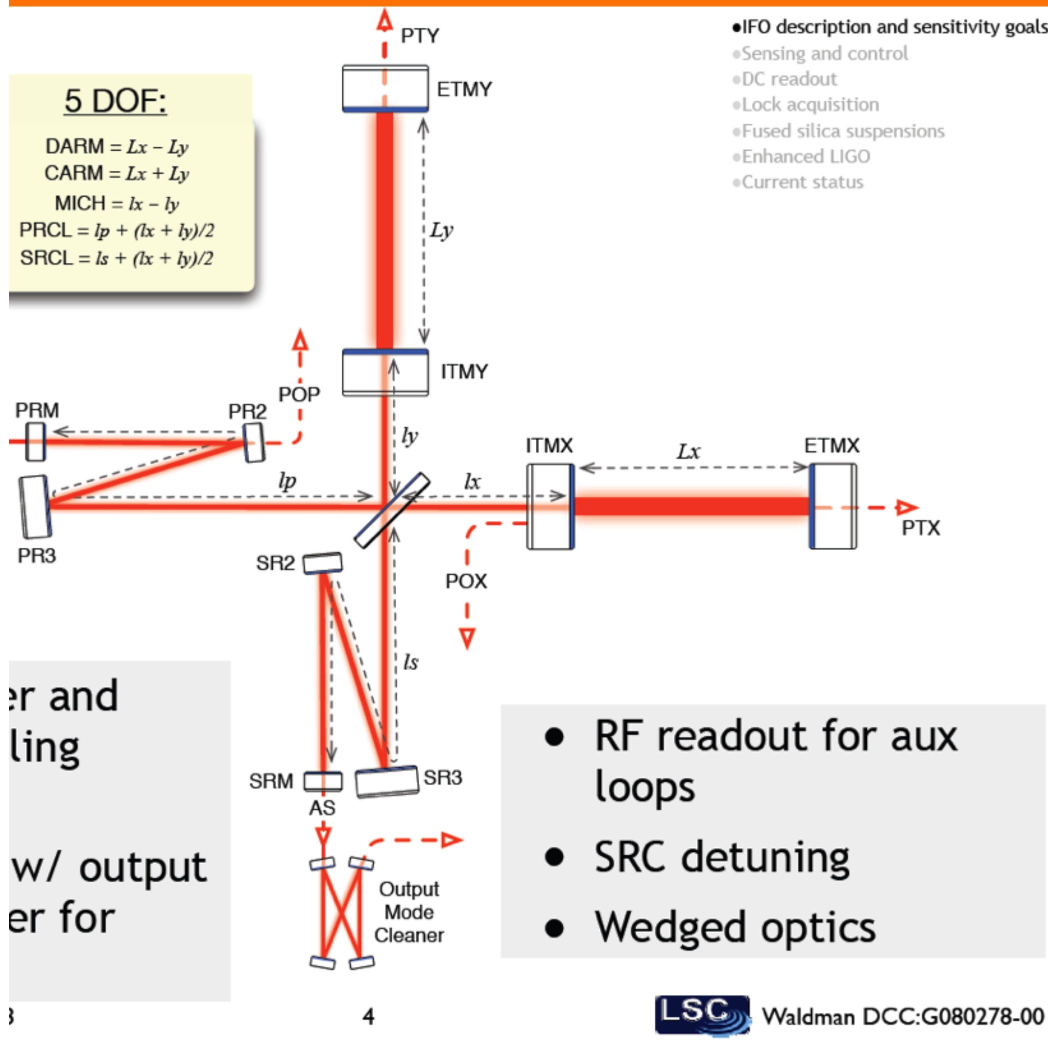
- Length~55m depends on Vacuum envelope
  - ~16m between PRM/PR2
    - HAM2/3 distance
    - times 3
  - + HAM3-ITM distance
  - incl. BS/ITM substrates

gives modulation frequencies:

$$f = (N + 0.5) \times \frac{c}{2L}$$

$$N = 3 \qquad f \approx 9.1 MHz$$

0.5: because carrier is resonant in arm cavities



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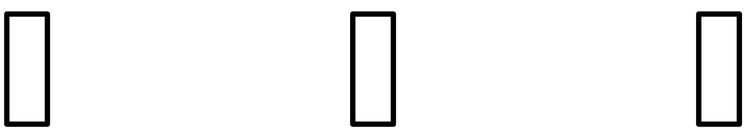
Signal Rec. cavity design:

- Length ~55m
- SB has to pass through PR

Two ways:

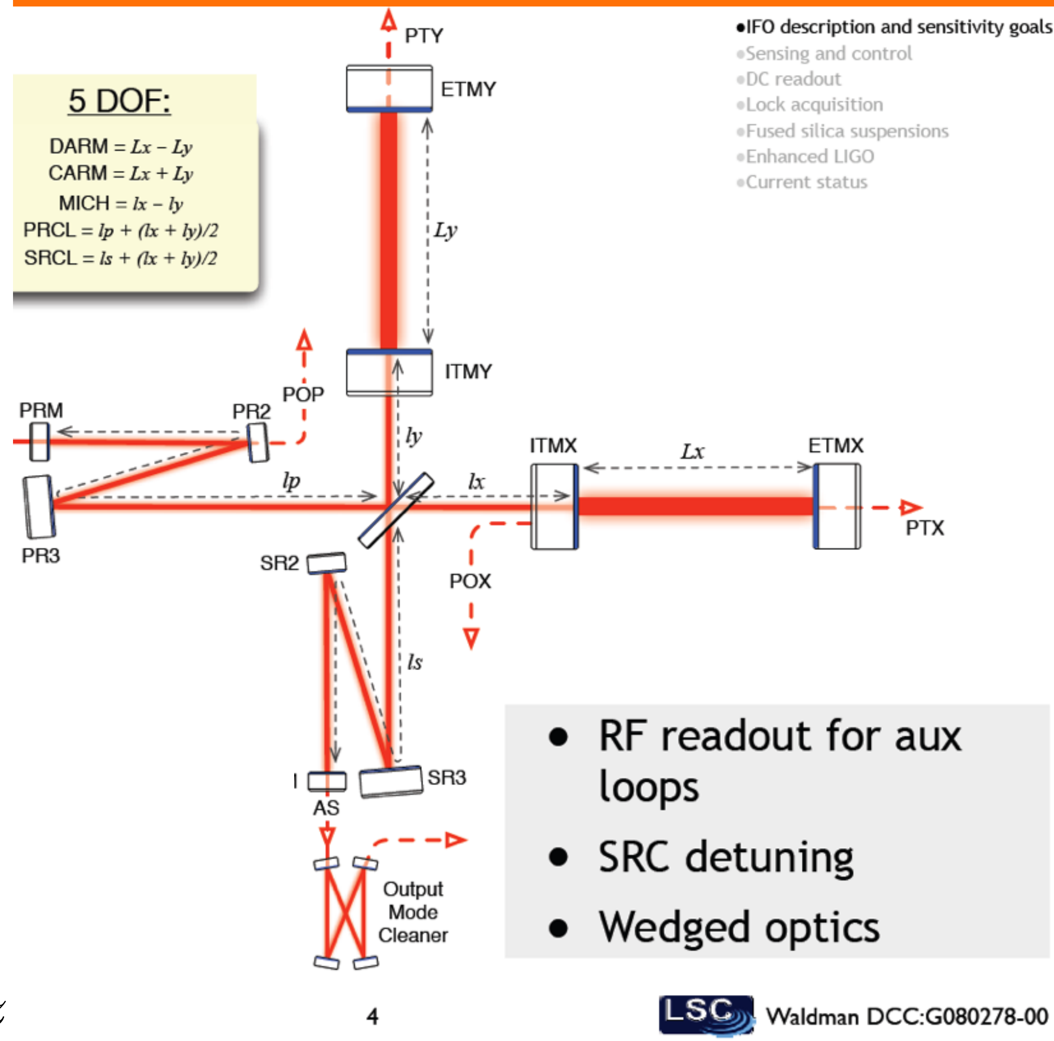
- Make MI bright for 2nd SB
- Couple both cavities



r_{PR} r_{BS} r_{SR}

$$t_{BS} = 2\pi f_{Mod} \frac{2\Delta L}{c}$$

$\Delta L \approx 4\ cm$ $\qquad f_{Mod} = 45.5\ MHz$



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Summary:

- Transmission of ITM set by detector bandwidth
- Power recycling gain set by losses in arm cavities and MI
- Signal recycling mirror forms compound mirror with ITM to
  - tailor frequency response. Choices between:
    - High gain/low BW
    - low gain/high BW
      - ampl. displacement noise, only useful where shot noise limited
- Stable recycling cavities to
    - contain spatial mode
    - reduce scatter into other spatial modes
- Length sensing:
    - Need sidebands to probe recycling cavities