Basic concepts for 3rd generation detectors

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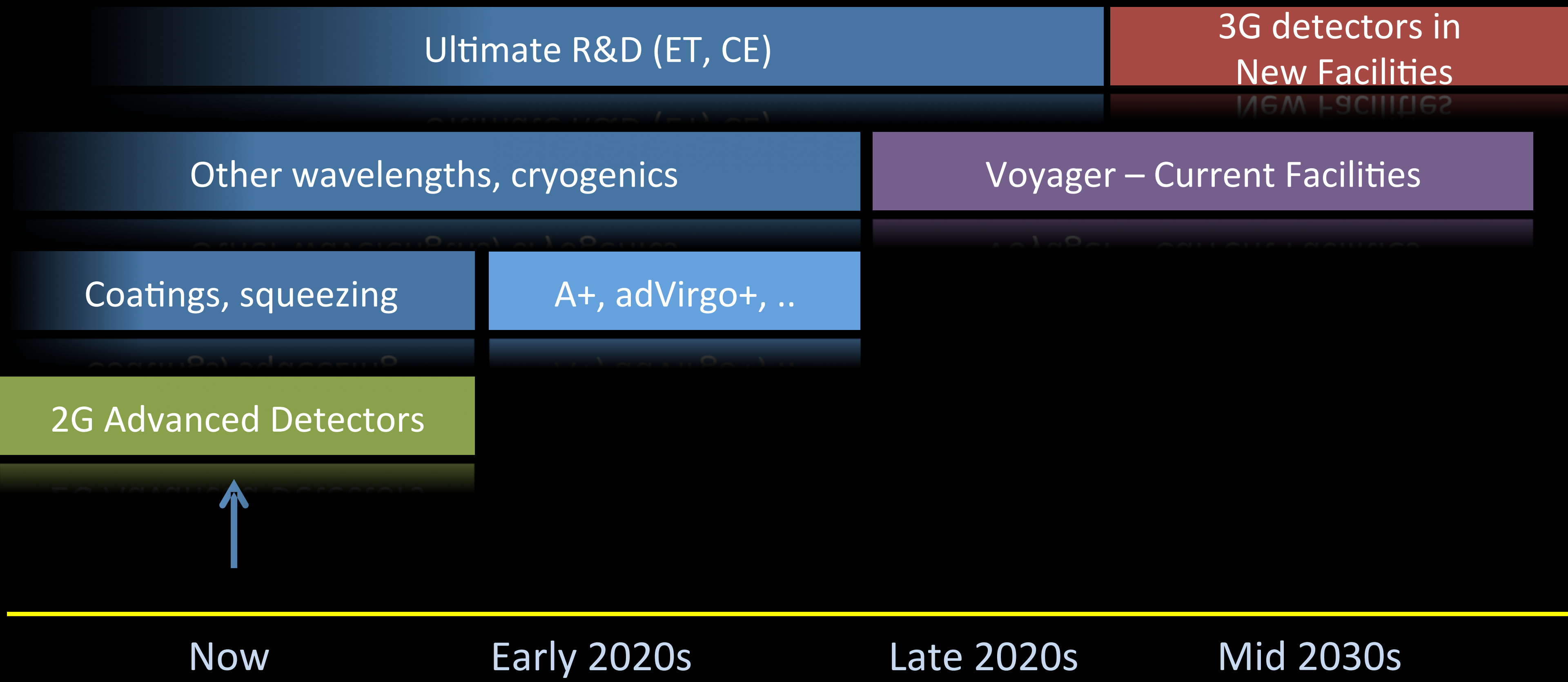
The GW world-wide network

- **The present (2G):**
  Advanced LIGO (4km), Advanced Virgo (3km), GEO HF (600m)
- **The near future:**
  - KAGRA (coming online 2019-2020): a 3km 2G detector, pioneering 3G technologies (underground, cryogenic)
  - LIGO A+, adVirgo+, .. (2024): improved detectors in current facilities: same materials, laser wavelength, better coatings, broadband squeezing
  - LIGO-INDIA (~2025): it will be a 4km LIGO A+ instrument
- **Longer term future in current facilities (like LIGO Voyager):**
  - 3G technologies in 2G facilities
  - Length and shape constrained by existing facilities
- **New detectors in new facilities (3G)**
  - Einstein Telescope project, Cosmic Explorer concept
  - Longer than 2G detectors (10-40km), more than x10 better sensitivity

Concept Roadmap



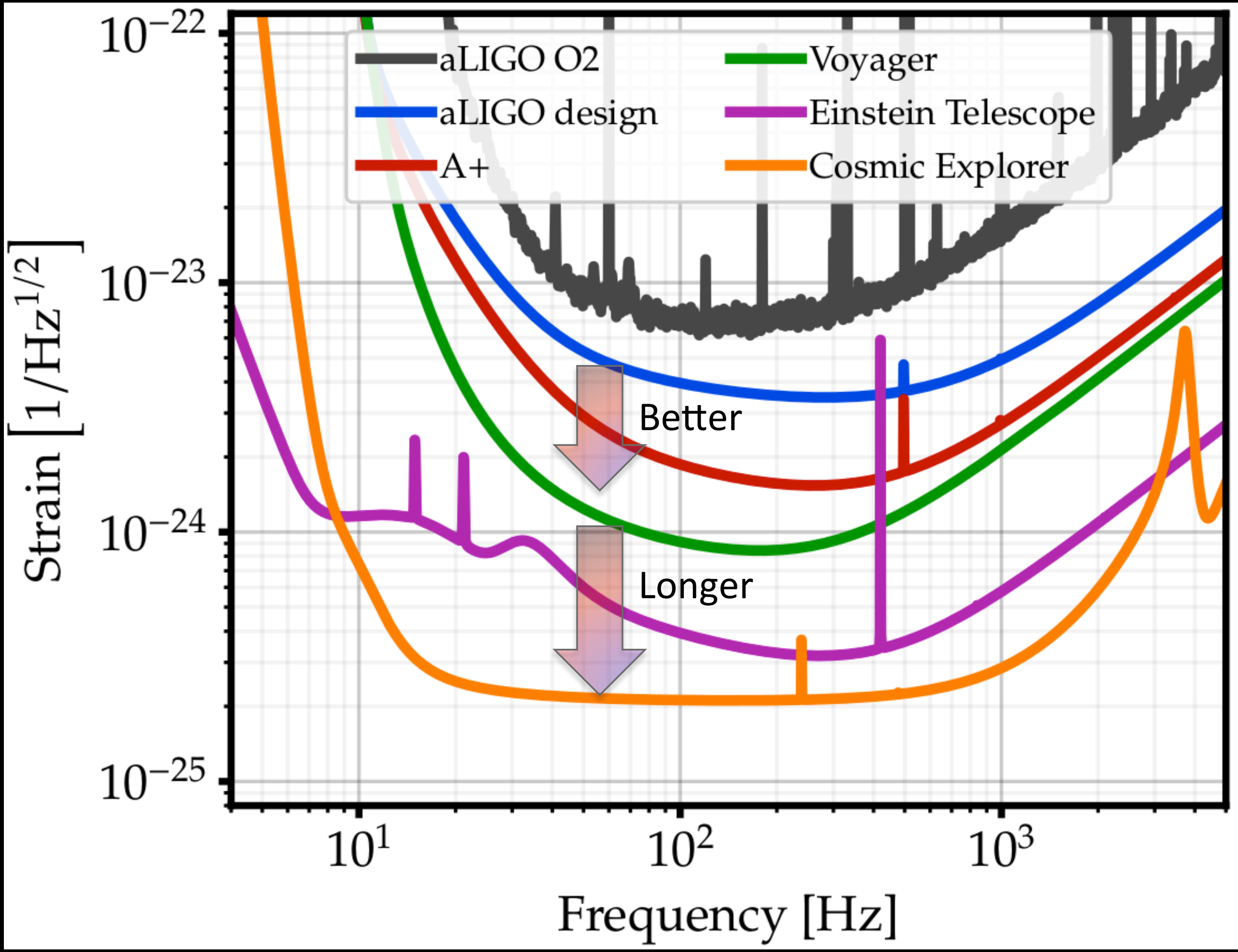
Ingredients to go beyond current 2G detectors

- **More of the same, but even better**: more power, bigger/heavier masses, lower loss mirror coatings, better suspensions, …
- **New technologies**: broadband squeezed light, alternative wavelengths + cryogenics, alternative optical configurations, ..

- **Make it longer:** take advantage of scaling of noises with arm length
- **Go Underground:** access low frequencies
- **New concepts:** triangular shape, xylophone, ..

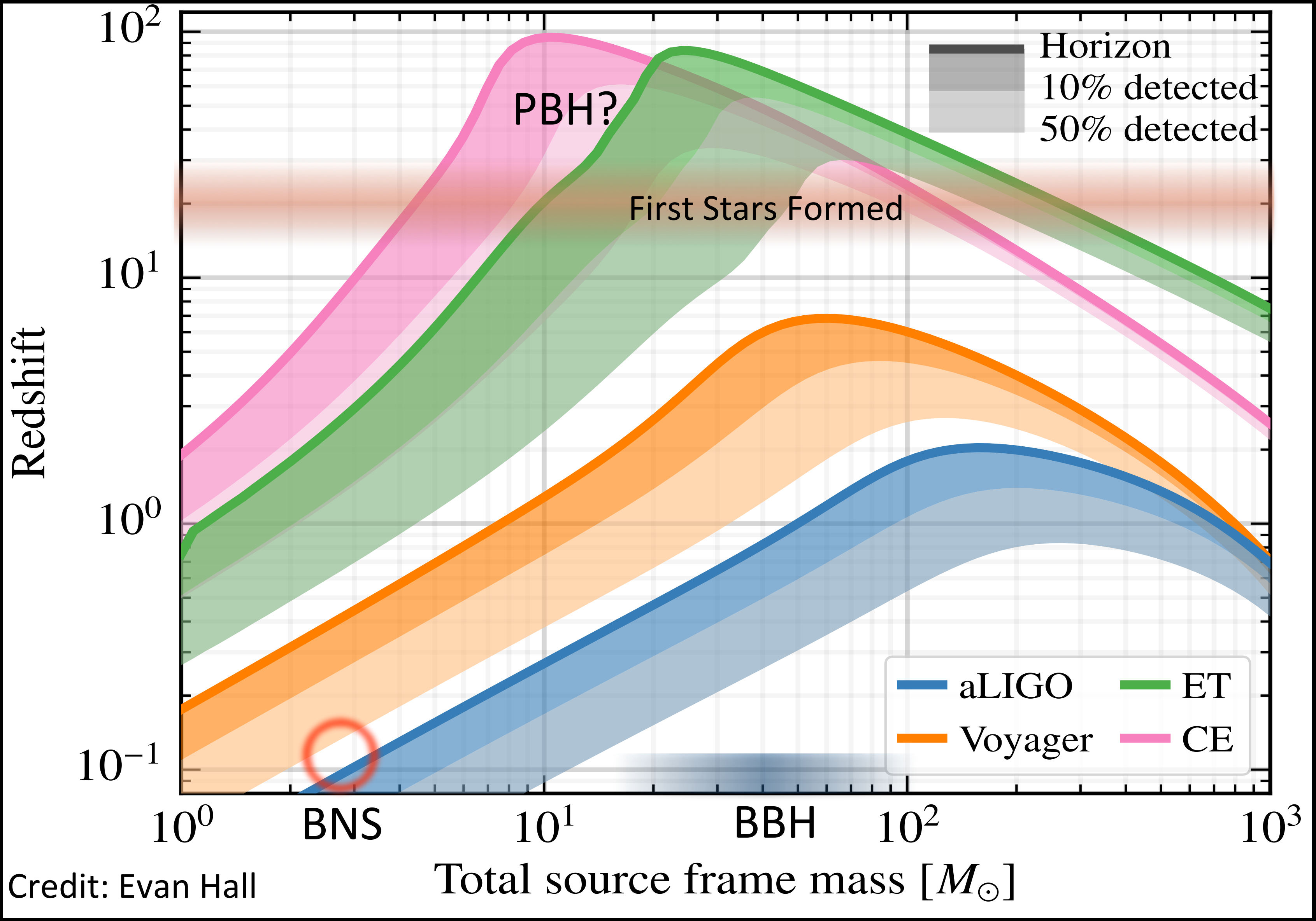
ONLY FOR NEW FACILITIES

From 2G to 3G: Example of Sensitivity Progression

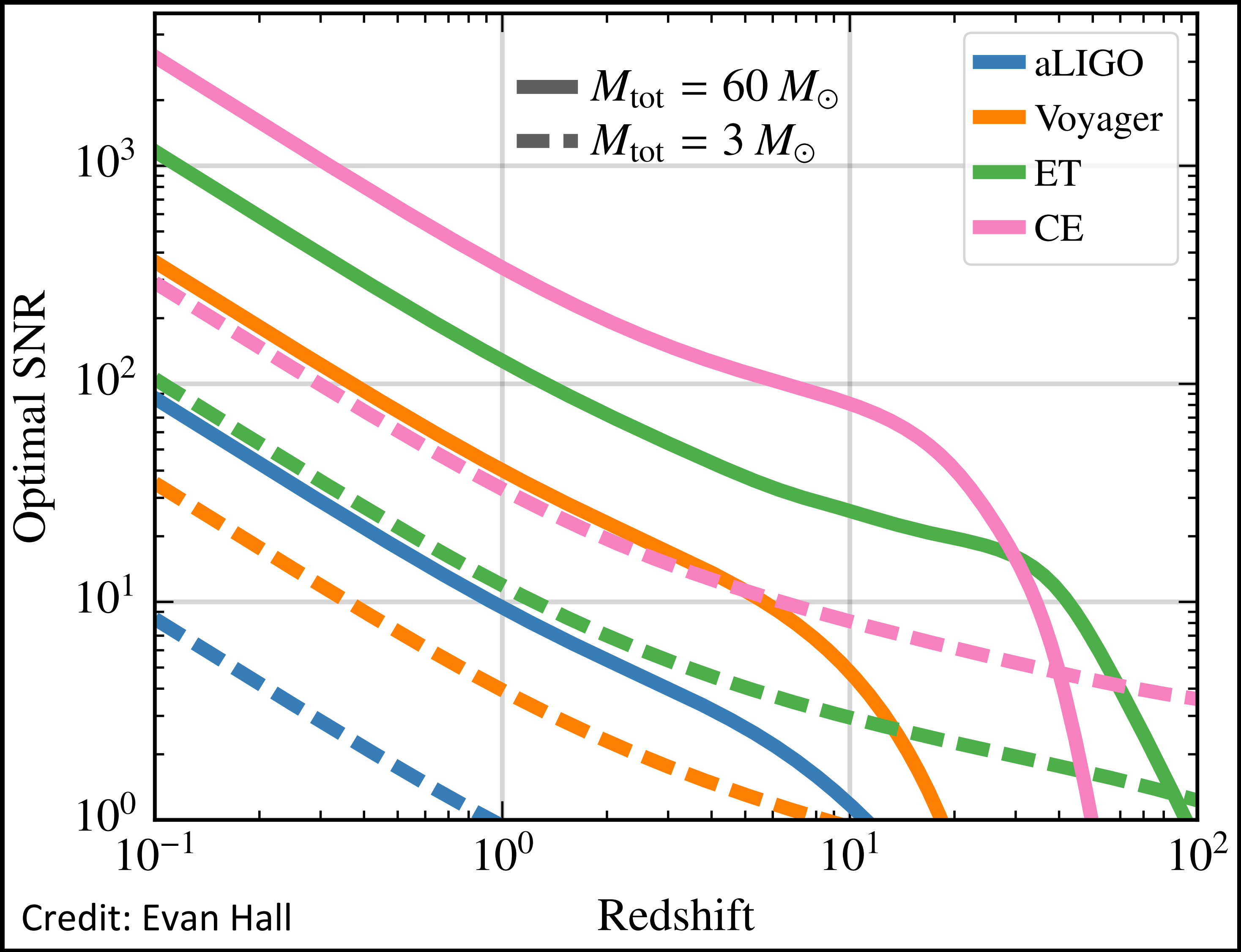


Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

BBH and BNS from the entire Universe

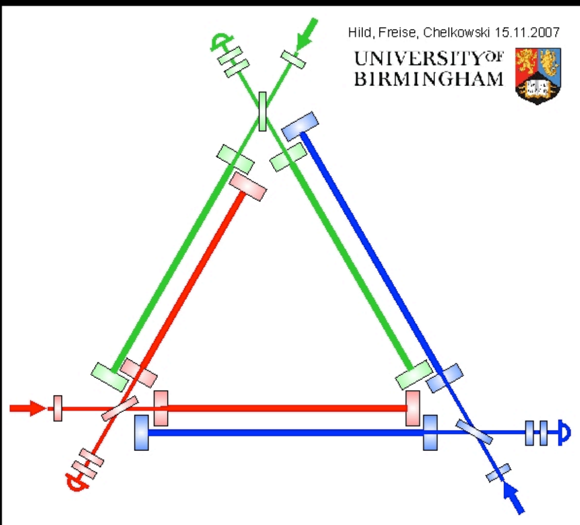


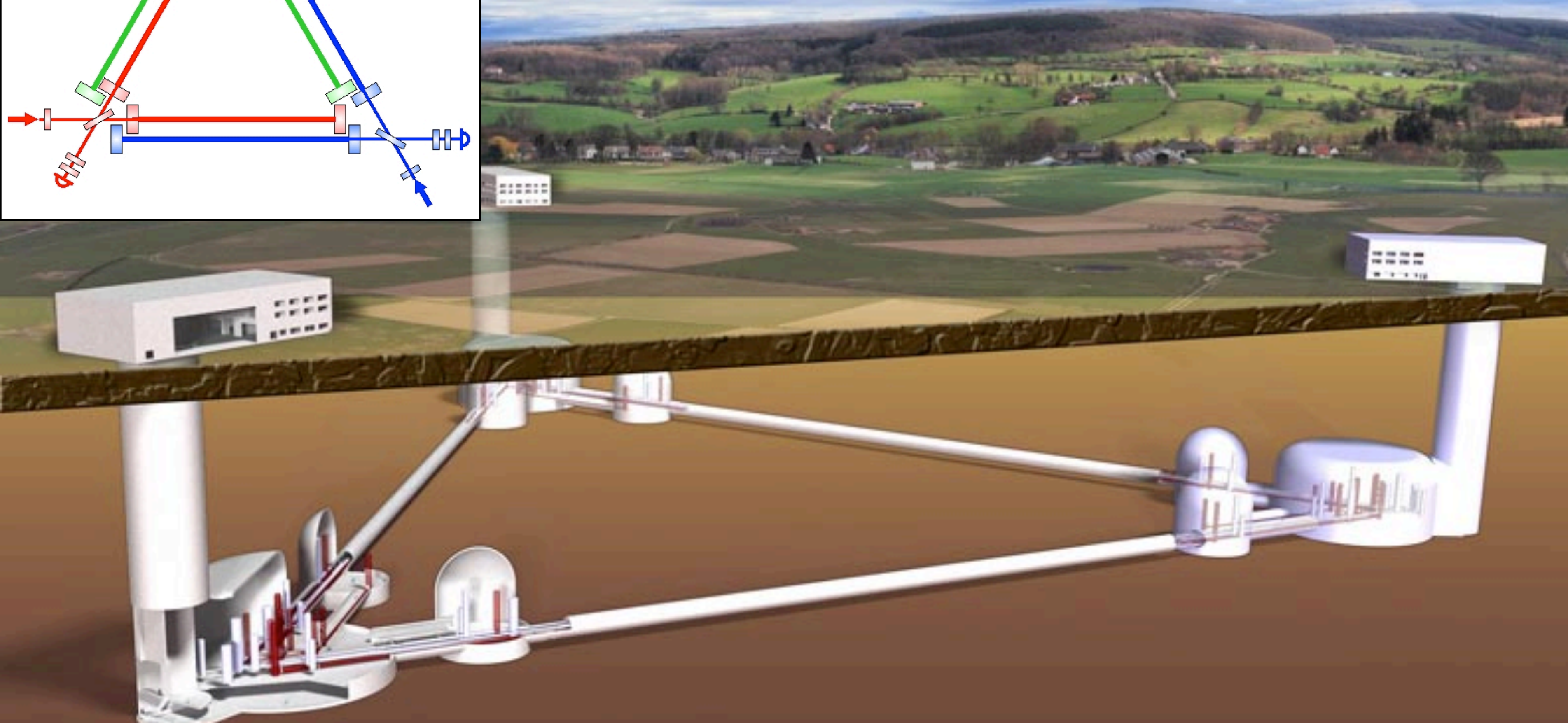
High SNR signals



ET EINSTEIN TELESCOPE

et-gw.eu





Original design: Underground, triangular, 10km on a side, 6 interferometers

ET: Why Triangular?

- Best science with a single 3G detector (polarization information)
- Concept compatible with construction in Europe: underground
- Excavation cost also favors a triangular configuration
- Facility able to support further detector improvements


cosmicexplorer.org
Cosmic Explorer
Surface, right-angle, 40km on a side, 1 interferometer

CE: Why L-shaped?

- CE concept developed assuming ET is operational:
  - CE is the optimal design scale for our astrophysical targets (BNS mergers, core collapse supernovae, ...)
  - best way to expand 3G science

CE: Why 40km?

- Fundamental noises scale with length, but not as 1/L as one might guess from h = ΔL/L
  - 40 km is a nearly optimal choice

How do fundamental noises scale?

Shot Noise
while maintaining bandwidth

$$\frac{h_{\text{shot}}}{h_{0\,\text{shot}}} = \sqrt{\frac{2\ \text{MW}}{P_{\text{arm}}}}\sqrt{\frac{\lambda}{1.5\ \mu\text{m}}}\left(\frac{3}{r_{\text{sqz}}}\right)\sqrt{\frac{40\ \text{km}}{L_{\text{arm}}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\,\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2\ \text{MW}}}\sqrt{\frac{1.5\ \mu\text{m}}{\lambda}}\left(\frac{3}{r_{\text{sqz}}}\right)\left(\frac{320\ \text{kg}}{m_{\text{TM}}}\right)\left(\frac{40\ \text{km}}{L_{\text{arm}}}\right)^{3/2}$$

Coating Thermal Noise
constant loss angle…

$$\frac{h_{\text{CTN}}}{h_{0\,\text{CTN}}} = \sqrt{\frac{T}{123\ \text{K}}}\sqrt{\frac{\phi_{\text{eff}}}{5\times 10^{-5}}}\left(\frac{14\ \text{cm}}{r_{\text{beam}}}\right)\left(\frac{40\ \text{km}}{L_{\text{arm}}}\right)$$

Residual Gas Noise
facility limit…

$$\frac{h_{\text{gas}}}{h_{0\,\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4\times 10^{-7}\ \text{Pa}}}\sqrt{\frac{14\ \text{cm}}{r_{\text{beam}}}}\sqrt{\frac{40\ \text{km}}{L_{\text{arm}}}}$$

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Shot Noise
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How do fundamental noises scale?

Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}}\sqrt{\frac{\lambda}{1.5\ \mu\rm m}}\left(\frac{3}{r_{\rm sqz}}\right)\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^3$$

Coating Thermal Noise
loss angle dependence?

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}}\sqrt{\frac{\phi_{\rm eff}(T)}{5\times 10^{-5}}}\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times 10^{-7}\ \rm Pa}}\sqrt{\frac{40\ \rm km}{L_{\rm arm}^{3/2}}}$$

CE: Why 40km?

- Fundamental noises scale with length, but not as 1/L as one might guess from h = ΔL/L
  - 40 km is a nearly optimal choice
- Free-Spectral-Range for a 40km detector is 3.75kHz, going beyond 40km would reduce the interferometer bandwidth and compromise its scientific potential (like neutron-star merger and supernovae)

Conclusions

- ET original triangular design, and CE L-shaped, 40km concept are the natural choices given constraints and historical development
- GWIC-3G science team will influence ET and CE final design choices
- A third 3G detector could draw from both ET and CE designs to complement and complete a network capable of precision pointing
- More about enabling technologies and governance in Michele's talk