Gravitational physics @ FZU

Michael Prouza

czechLISA meeting – March 11, 2024

FZU – Institute of Physics of the Czech Academy of Sciences

CEICO: Central European Institute of Cosmology @FZU

Cosmology & Gravity

String and high energy theory

Instrumentation for cosmological surveys

GW: involvement with LISA

Research Themes

- New theories of gravity and dark sector
- Dark matter and astro-particle physics
- Early Universe physics
- Cosmological phenomenology and model testing
- Gravitational waves
- Physics of compact objects

Generation of GW: in GR or new physics

Indirect use of GW: test fundamental physics

Slides prepared by Constantinos Skordis

PRL **119,** 251301 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

Strong Constraints on Cosmological Gravity from GW170817 and GRB 170817A

T. Baker,[1] E. Bellini,[1] P. G. Ferreira,[1] M. Lagos,[2] J. Noller,[3] and I. Sawicki[4]

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(Received 16 October 2017; published 18 December 2017)

The detection of an electromagnetic counterpart (GRB 170817A) to the gravitational-wave signal (GW170817) from the merger of two neutron stars opens a completely new arena for testing theories of gravity. We show that this measurement allows us to place stringent constraints on general scalar-tensor and vector-tensor theories, while allowing us to place an independent bound on the graviton mass in bimetric theories of gravity. These constraints severely reduce the viable range of cosmological models that have been proposed as alternatives to general relativistic cosmology.

$$S_h = \frac{1}{2}\int d^3x dt M_*^2[\dot{h}_A^2 - c_T^2(\nabla h_A)^2].$$

$$|\alpha_T| \lesssim 1 \times 10^{-15}.$$

• Horndeski	Surviving: $L = G_4(\phi)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi$	
• Beyond-Horndeski	$c_T^2 = 1$	models ruled out by graviton decay
• Massive gravity	OK	
• Einstein-Aether theory	Surviving: $L = R + \mathcal{F}\left[F_{\mu\nu}F^{\mu\nu} + c_2(\nabla_\mu A^\mu)^2\right] + \lambda(A_\mu A^\mu + 1)$	
• Generalized Proca theories	Surviving: $L = R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(X) + G_3(X)\nabla_\mu A^\mu$	
• Original + generalised TeVeS	$c_T^2 \neq 1$	Ruled out

PHYSICAL REVIEW D **100,** 104013 (2019)

Gravitational alternatives to dark matter with tensor mode speed equaling the speed of light

Constantinos Skordis* and Tom Złośnik†

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(Received 25 June 2019; published 7 November 2019)

PHYSICAL REVIEW LETTERS **122,** 061301 (2019)

Dark Energy after GW170817 Revisited

Edmund J. Copeland,[1,*] Michael Kopp,[2,†] Antonio Padilla,[1,‡] Paul M. Saffin,[1,§] and Constantinos Skordis[2,∥]

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(Received 27 November 2018; revised manuscript received 21 January 2019; published 12 February 2019)

We revisit the status of scalar-tensor theories with applications to dark energy in the aftermath of the gravitational wave signal GW170817 and its optical counterpart GRB170817A. At the level of the cosmological background, we identify a class of theories, previously declared unviable in this context, whose anomalous gravitational wave speed is proportional to the scalar equation of motion. As long as the scalar field is assumed not to couple directly to matter, this raises the possibility of compatibility with the gravitational wave data, for any cosmological sources, thanks to the scalar dynamics. This newly "rescued" class of theories includes examples of generalized quintic Galileons from Horndeski theories. Despite the promise of this leading order result, we show that the loophole ultimately fails when we include the effect of large scale inhomogeneities.

Gravity on Cosmological Scales and GWs

Sawicki, Trenkler, Trombetta, Vikman

THE QUESTION

- Best way to use GW → test gravity on super-galactic scales?

THE SETUP

- Shift-symmetric scalar-tensor theories (e.g. galileons)
- Vacuum is stationary, but **not** static (non-vanishing time-like gradient of scalar) $\nabla_\mu\phi \quad \dot{\phi} \neq 0$
- End-point of evolution is de Sitter-like but with Lorentz violation

CONSEQUENCES

- The scalar hair around stars must eventually connect to cosmology → how to do it? → what are the implications?
- Scalar provides a medium for propagation of GWs – is this observable?

Gravity on Cosmological Scales and GWs

Sawicki, Trenkler, Trombetta, Vikman

- Some ST operators $\mathcal{O}_{dec}$ → very fast decay of GWs over cosmological distances (Creminelli, Vernizzi)

  Observation of GWs → $\mathcal{O}_{dec}$ irrelevant to cosmology

- Some ST operators $\mathcal{O}_{ins}$ → in presence of GW: ghosts or other instabilities →
  - Fundamental problem or is it just a frame-dependent statement?

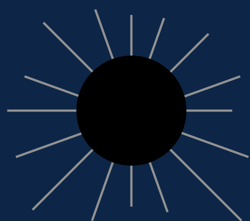
IN PROGRESS: Understand general problem of background stability in these ST theories →

Constrain remaining operators

Give predictions for new observable physics (e.g. Čerenkov emission)

Gravity on Cosmological Scales and GWs

Sawicki, Trenkler, Trombetta, Vikman



- Body sources the scalar field

Interaction terms are large → non-linear configuration: Vainshtein screening

Can this static configuration be connected smoothly to the cosmological one?

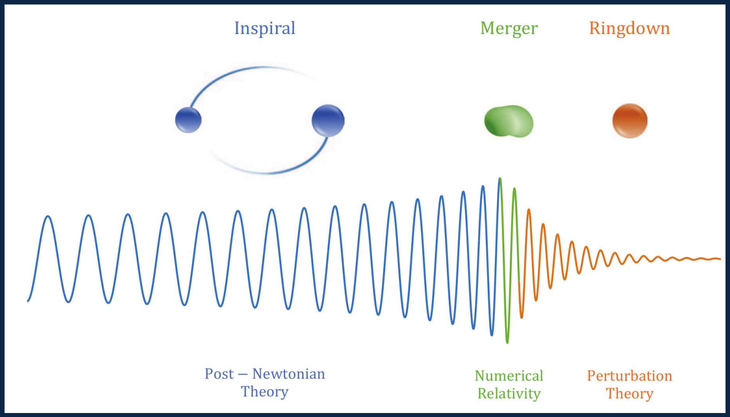
Not for every operator

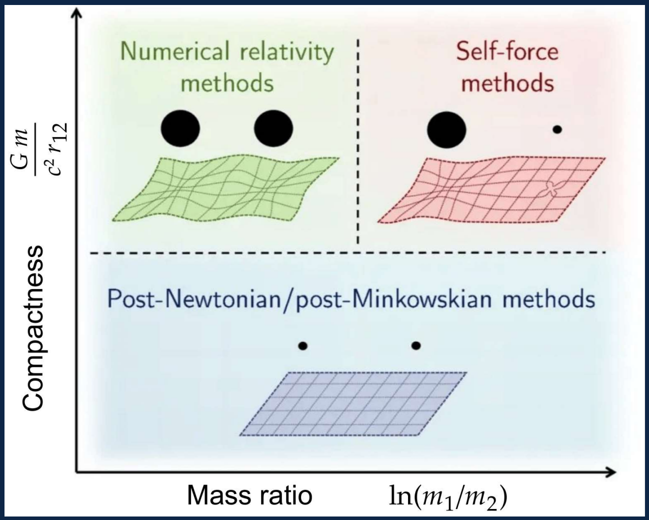
Even if yes. configuration near star/BH different than standard Vainshtein case

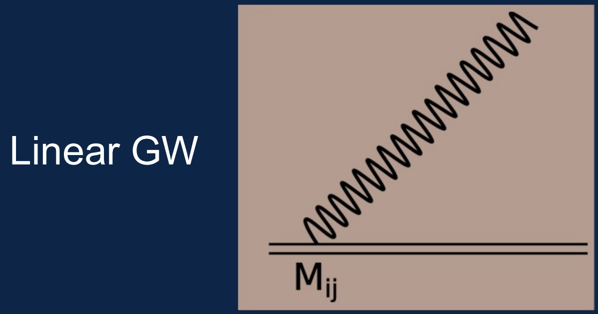
IN PROGRESS: understand impact of these new configurations →

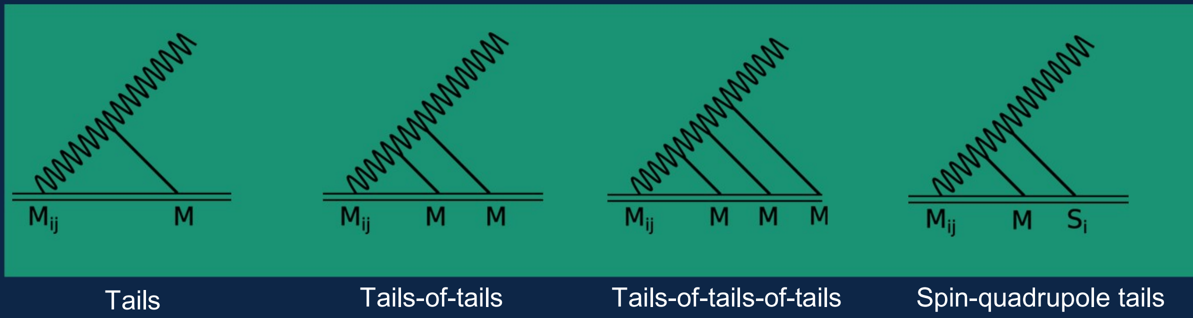
- Static or quasi-static BHs exist for all theories?
- Is screening punctured near star? → channel to emit scalar radiation?

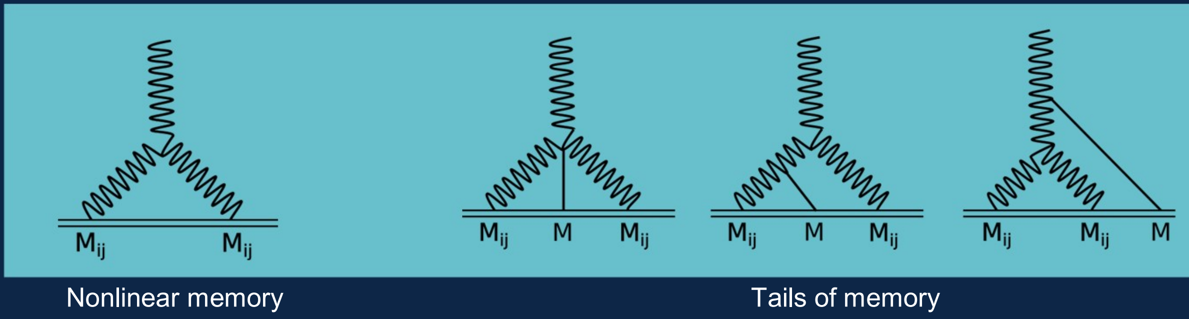
Nonlinear propagation effects in PN — **Trestini** & Blanchet 2023







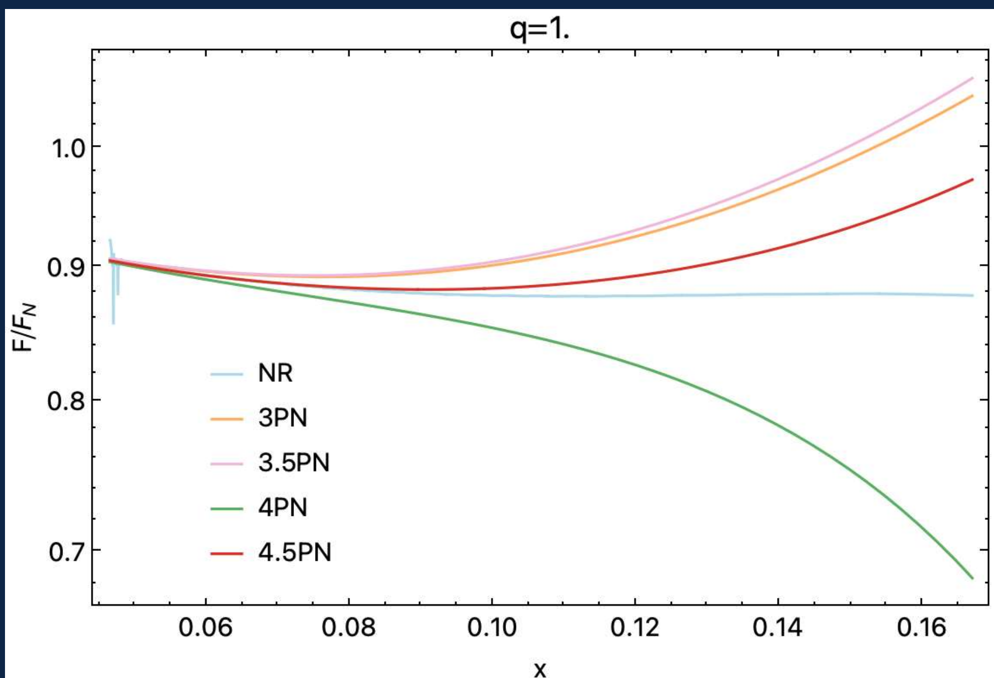




Highly-accurate analytical predictions for observables

General relativity

Blanchet, Faye, Henry, Larrouturou & **Trestini** 2023

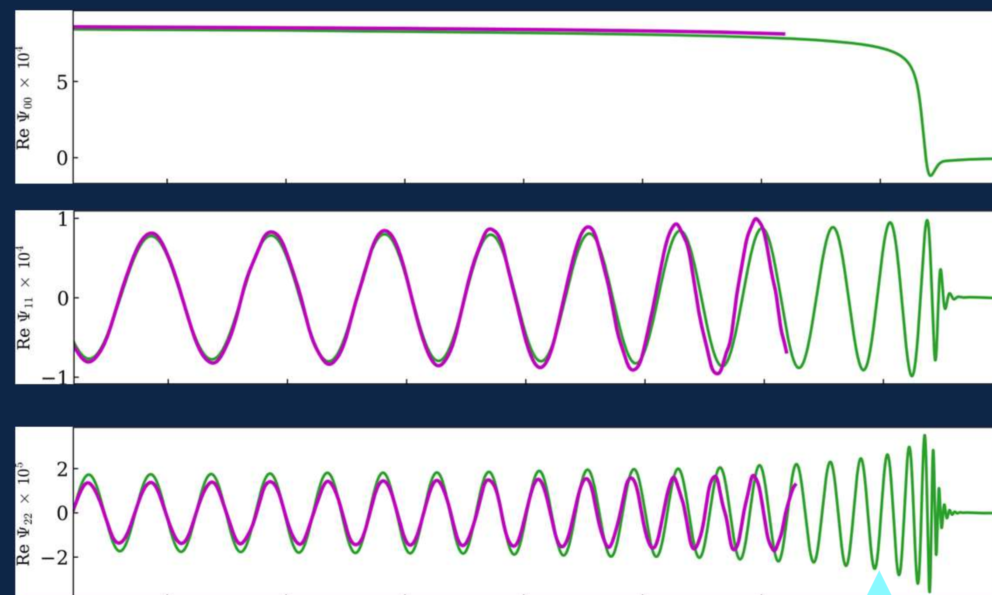


Normalized flux in NR and PN in terms of adimensional frequency

$$x = \left(\frac{GM\omega}{c^3}\right)^{2/3}$$

Scalar-tensor theories

Bernard, Blanchet & **Trestini** 2022



Waveform as a function of time for the scalar sector
Comparison between NR and PN

Ma, Varma, Stein et al. (2023)

Neutron star as novel probes for cosmological constant problem

Giulia Ventagli

Λ Observations point to it — Not theoretically understood — Fine-tuning problem

- Can the underlying value of Λ change through a phase transition and be screened?
- Core of NS → pressure high enough to trigger phase transition.

Modify EOS: introduce QCD; introduce vacuum energy phase transition in core

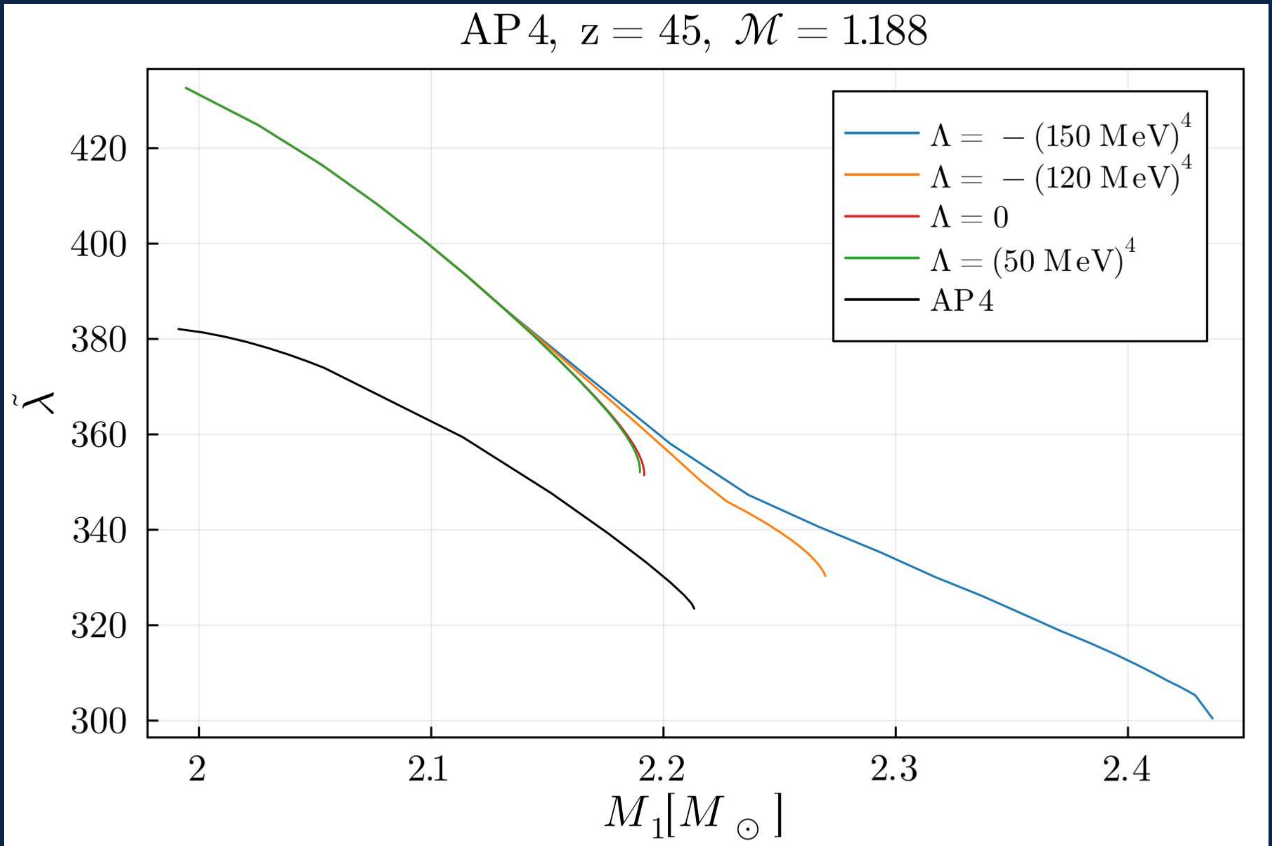
↓

Imprints on properties of the star
- M-R relations
- tidal deformability!

Neutron star as novel probes for cosmological constant problem

Giulia Ventagli

- Indirect use of GW: Use GW to measure tidal deformability
- Test the model against data — is it favoured / disfavoured?

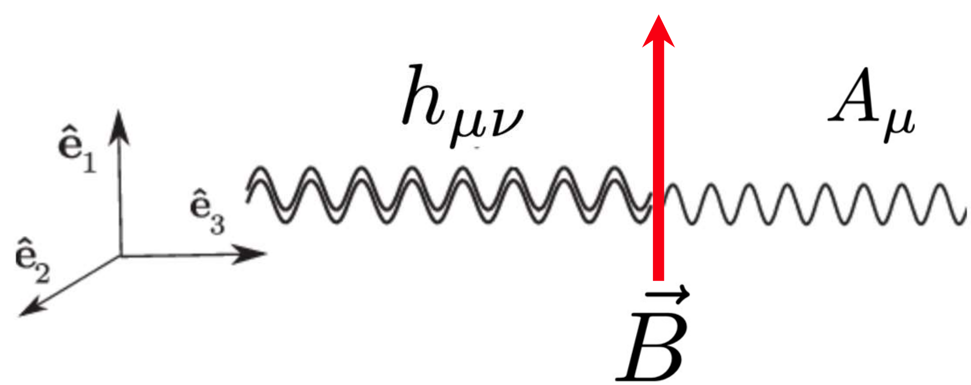


Ventagli, Fernandes, Maselli, Padilla and Sotiriou. Soon to appear on the arXiv.

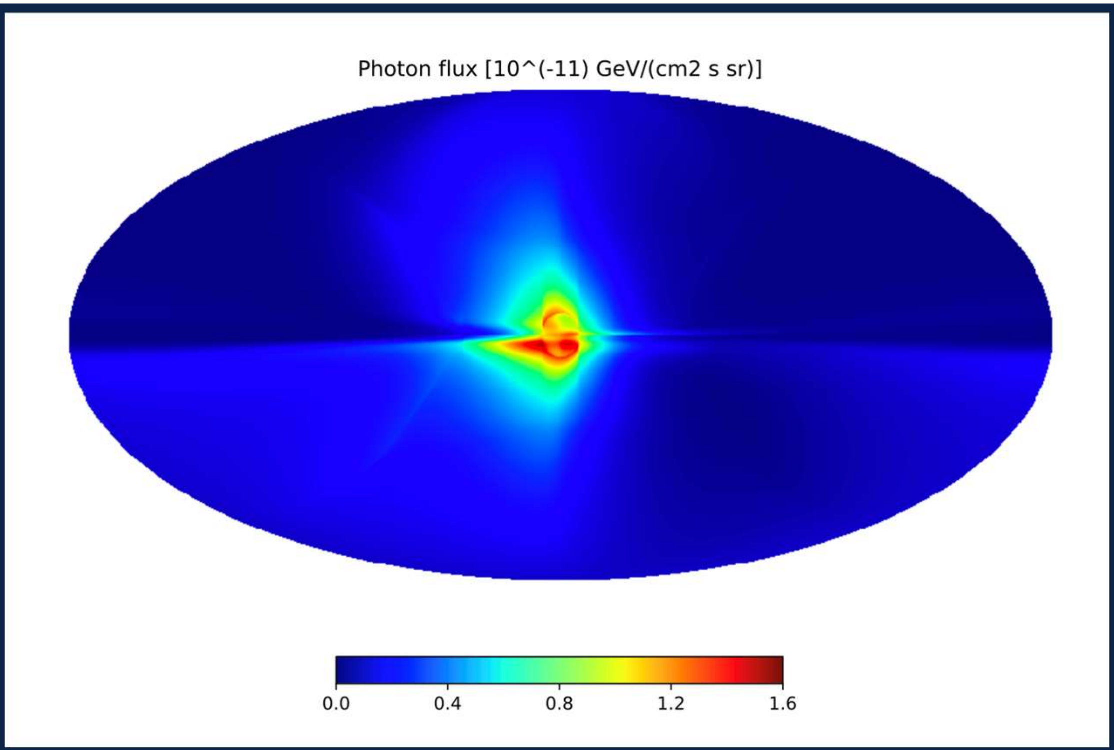
Gertsenshtein effect: graviton conversion into photons through a magnetic field

S. Ramazanov, R. Samanta, G. Trenkler & F. Urban
JCAP 06, 019 (2023)

$$\mathcal{L}_{em} = -\frac{1}{4} g^{\mu\lambda} g^{\nu\rho} F_{\mu\nu} F_{\lambda\rho} \qquad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



Can some UHE gamma rays detected be due to gravitons passing through galactic magnetic field?



S. Ramazanov, R. Samanta, G. Trenkler & F. Urban

JCAP 06, 019 (2023)

Distinct imprint of gravitons on gamma-ray sky

Good prospects for distinguishing signal from different sources

Current observations (e.g. LHAASO) → Sensitive to $\Omega_{GW} h_7^2 \sim 1$ @ sub-PeV energies

Cosmologically allowed values $\Omega_{GW} h_7^2 \sim 0.01$ → Reachable with future gamma-ray observatories

↓

e.g. superheavy DM decay into gravitons

Melting domain walls → GW signal

E. Babichev, D. Gorbunov, S. Ramazanov, R. Samanta,& A. Vikman
arXiv: 2307.04582

NANOGrav and other PTAs

Evidence of stochastic GW background $\sim nHz$

$$\Omega_{GW}(f) \propto f^{1.8\pm0.6}$$

Common explanation: GW from supermassive BH binary mergers

BUT: $\Omega_{GW}(f) \propto f^{0.667}$ → Tension!

Any other possible explanations of NANOGrav signal? → Great prospects for discovering new physics

Domain walls: topological defects

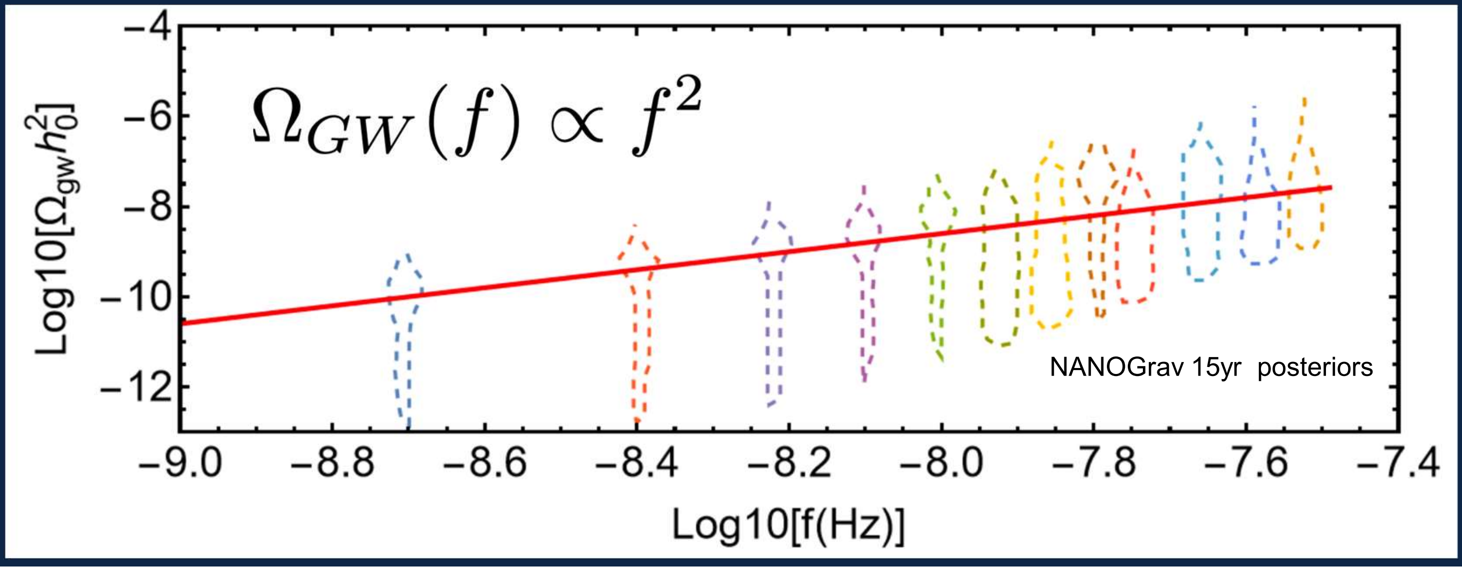
Spontaneous breaking of *discrete* symmetries

E. Babichev, D. Gorbunov, S. Ramazanov, R. Samanta,& A. Vikman

arXiv: 2307.04582

$$S=\int d^4x\sqrt{-g}\left[\frac{(\partial_\mu\chi)^2}{2}-\frac{M_\chi^2\chi^2}{2}-\frac{\lambda_\chi\chi^4}{4}+\frac{g^2\chi^2|\phi|^2}{2}\right] ,$$

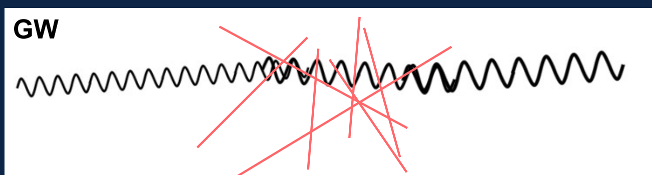
Melting domain wals — scale-invariant models



Probing neutrino physics with GW tomography

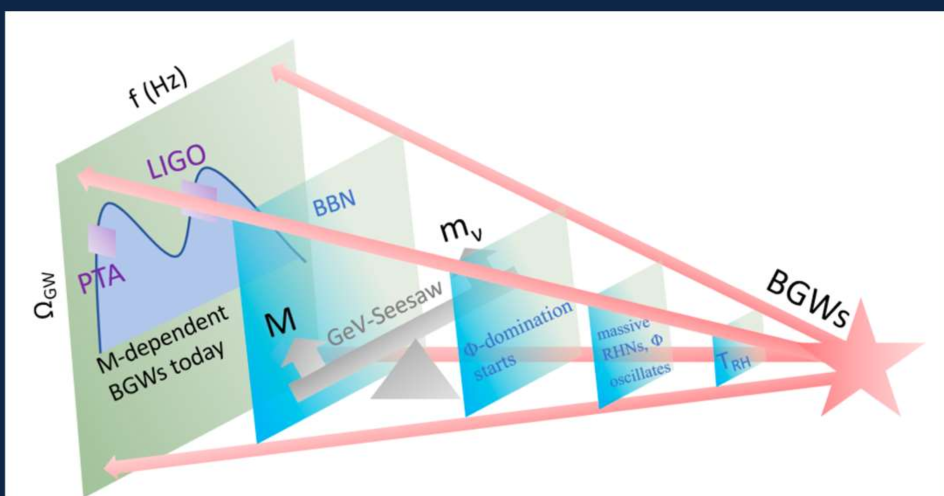
S. Datta & R. Samanta
Arxiv: 2307.00646, to appear in Phys. Rev. D Letter

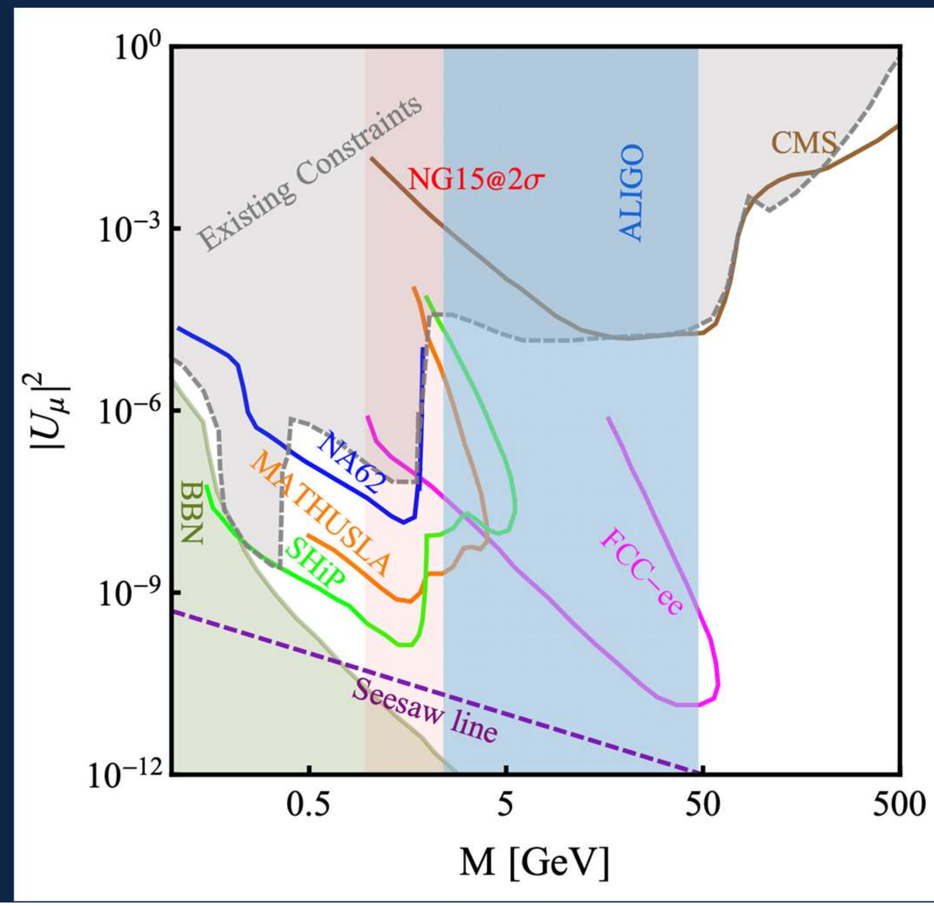
Early Universe — **BSM - GeV sterile neutrinos** — **Today: PTA, ALIGO**



Sterile neutrino mediated matter domination affecting GW propagation

final GW-spectral features → **Properties of BSM theory imprinted**





Synergies

CEICO: Central European Institute of Cosmology

- Better understanding of gravity
- New theories of gravity and dark sector
- Physics of compact objects
- Gravitational waves
- Early Universe physics
- Dark matter and astro-particle physics
- Cosmological phenomenology and model testing

The road goes on

Group of Ippocratis Saltas
(supported by Lumina Quaeruntur and Junior Star grants)

(non-negligible overlap with CEICO activities)

Slides prepared by
Ippocratis Saltas

Gravitational waveform modelling

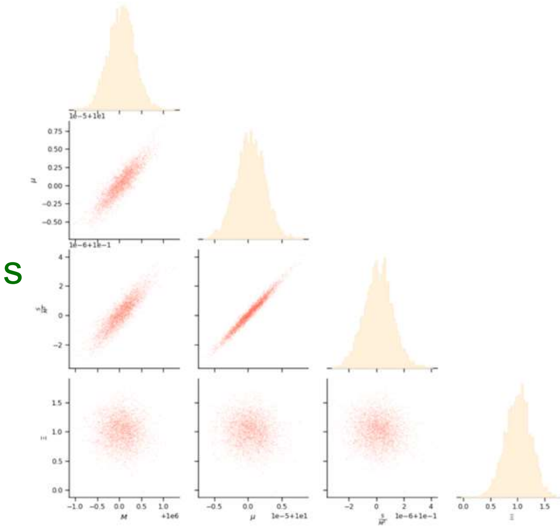
EMRI_MC: A GPU-based code for Bayesian inference of EMRI waveforms

Ippocratis D. Saltas[a§], **Roberto Oliveri**[b†]

[a] *CEICO, Institute of Physics, Czech Academy of Sciences Na Slovance 2, 182 21 Praha 8, Czech Republic*

[b] *LUTH, Laboratoire Univers et Théories, Observatoire de Paris CNRS, Université PSL, Université Paris Cité, 5 place Jules Janssen, 92190 Meudon, France*

GPU-accelerated and parallelisable, modular Python code for EMRI waveforms and LISA forecasts



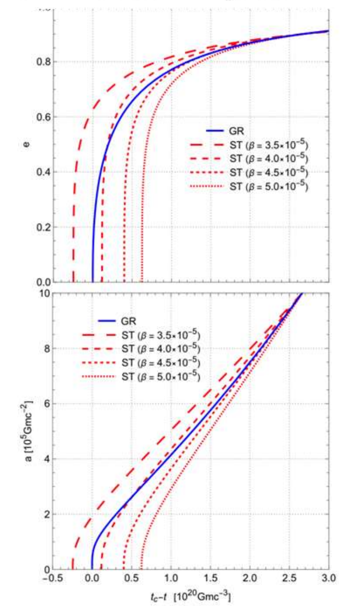
Gravitational waves and orbital evolution for eccentric compact binaries in scalar-tensor theories at second post-Newtonian order

David Trestini[1,*]

[1] *CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, 182 21 Praha 8, Czechia*

(Dated: January 23, 2024)

The first systematic & analytical study of eccentric binaries in scalar-tensor theories.



Gravitational tests of the standard model of particles & forces

Incompatibility of gravity theories with auxiliary fields with the standard model

Giulia Ventagli,[1,2,3] **Paolo Pani,**[4] and **Thomas P. Sotiriou**[1,2,5]

[1] *Nottingham Centre of Gravity, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*
[2] *School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*
[3] *CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, 182 21 Praha 8, Czechia*
[4] *Dipartimento di Fisica, "Sapienza" Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy*
[5] *School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*

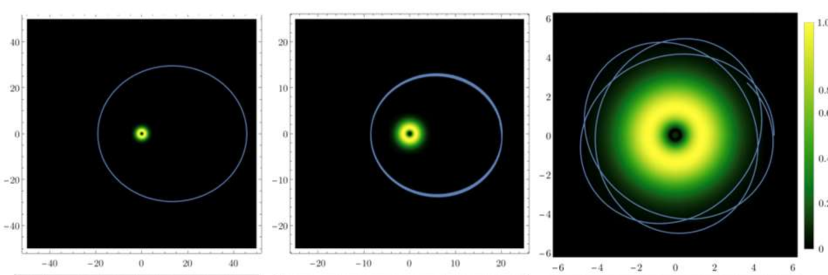
Testing the consistency of generic theories of gravity through their compatibility with the Standard Model of particles

A Sun-like star orbiting a boson star

Alexandre M. Pombo[1] and Ippocratis D. Saltas[2]

[1,2] CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, 182 21 Praha 8, Czechia

Challenging the existence of new boson fields with high-precision astrometry observations of GAIA



Further gravitational tests of the standard model of particles & forces

Testing dark matter with Extreme-Mass-Ratio-Inspirals and LISA (predictions of de-phasing and LISA forecasts) [D. Trestini, in progress]

Probes of new particles and forces beyond the Standard Model with stellar structure and asteroseismology [A. Hackett, in progress]

Inferences of the neutron star equation of state with deep learning [G. Ventagli, in progress]

Boson-star configurations and their coupling to matter [A. Pombo, in progress]

FSUA – actuator development for the LISA mission of ESA

@FZU: Asen Christov, Sergey Karpov, David Hlaváček, Niels Lund, Libor Švéda and Michael Prouza

Slides prepared by
Asen Christov

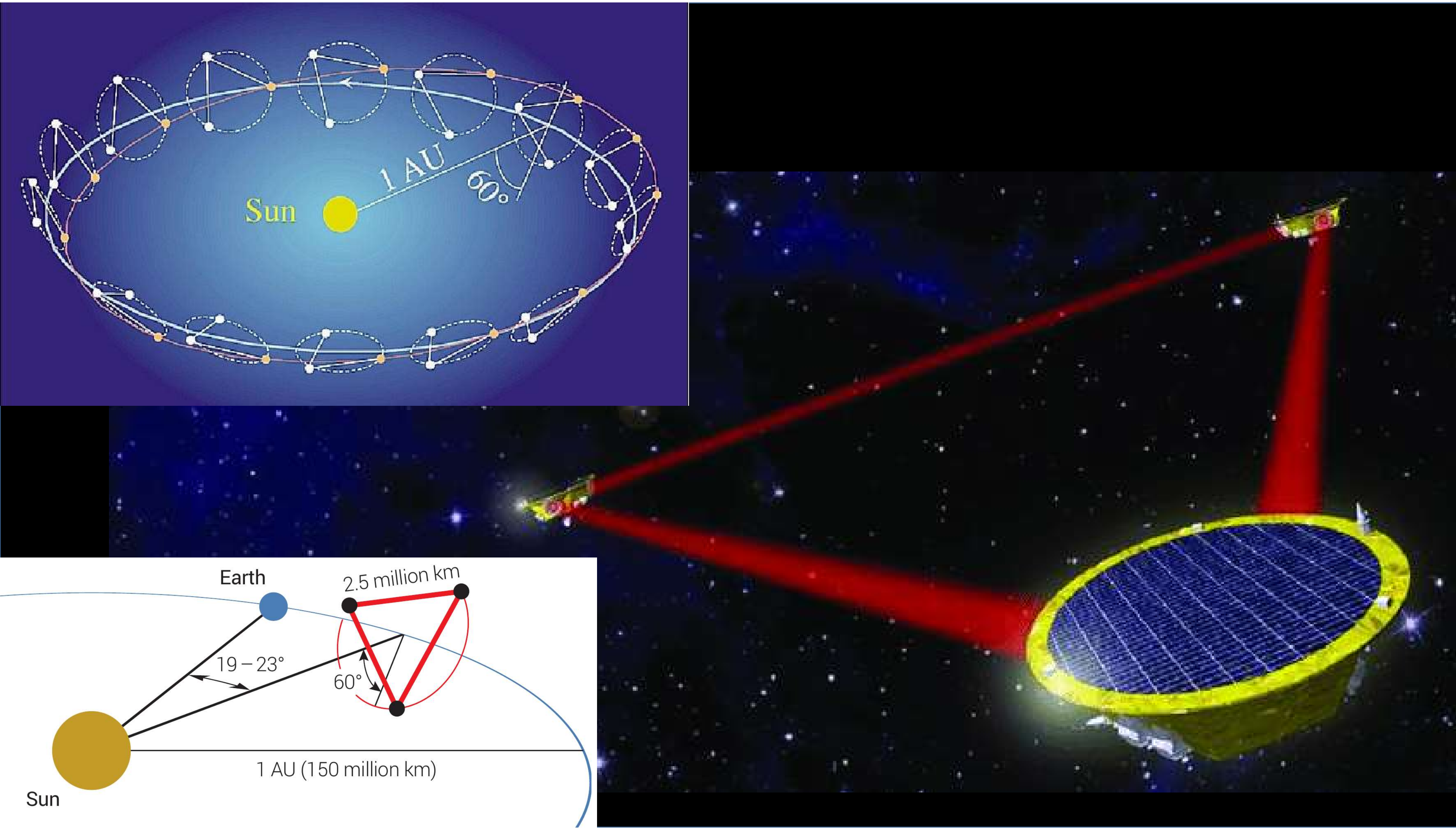
On behalf of:

FZU Institute of Physics of the Czech Academy of Sciences

INSTITUTE OF THERMOMECHANICS CZECH ACADEMY OF SCIENCES

Astronomical Institute of the Czech Academy of Sciences

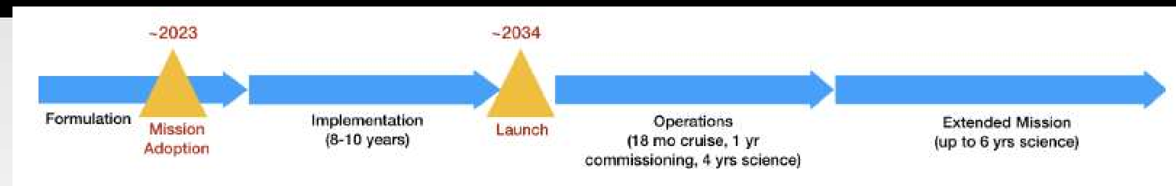
ÚSTAV FYZIKY ATMOSFÉRY AV ČR

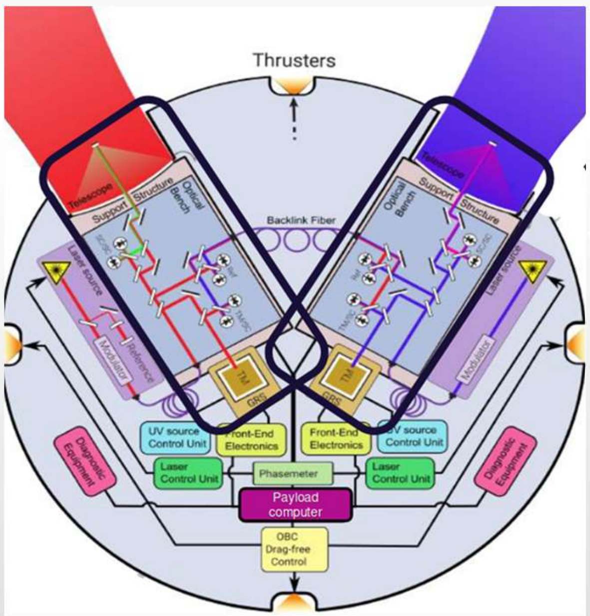


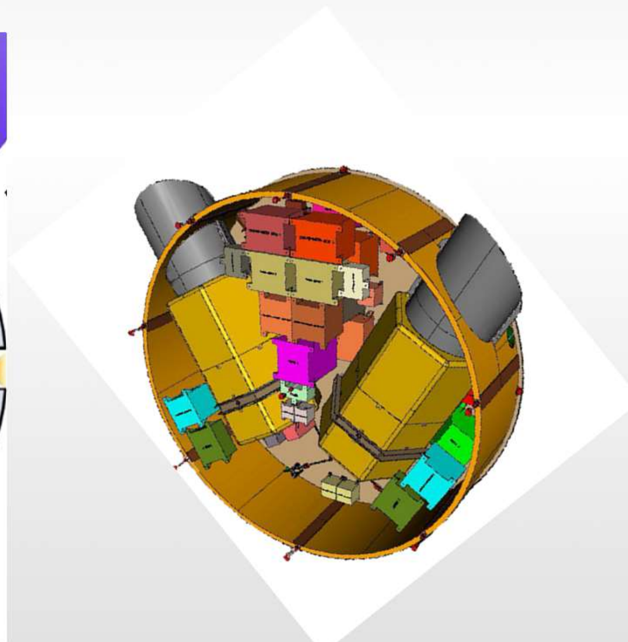
Sun
1 AU
60°
Earth
2.5 million km
19 – 23°
60°
1 AU (150 million km)
Sun

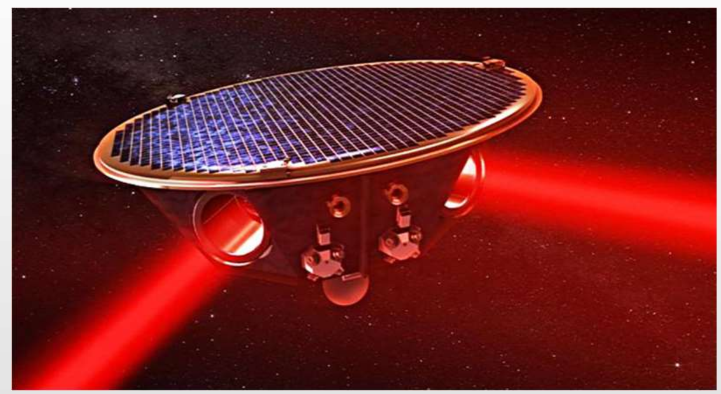
LISA Satellite Layout

- Constellation of three satellites
- 2.5M km separation
- 14 month travel to the final orbit

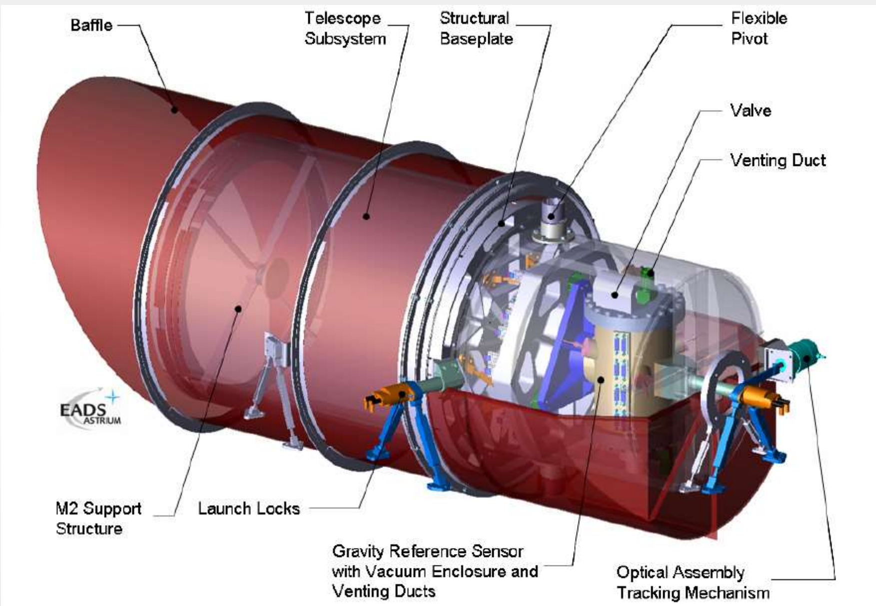


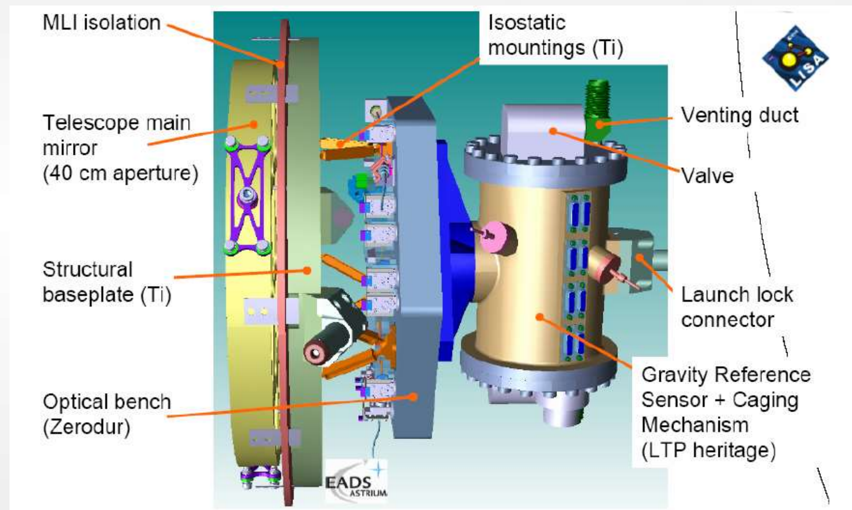






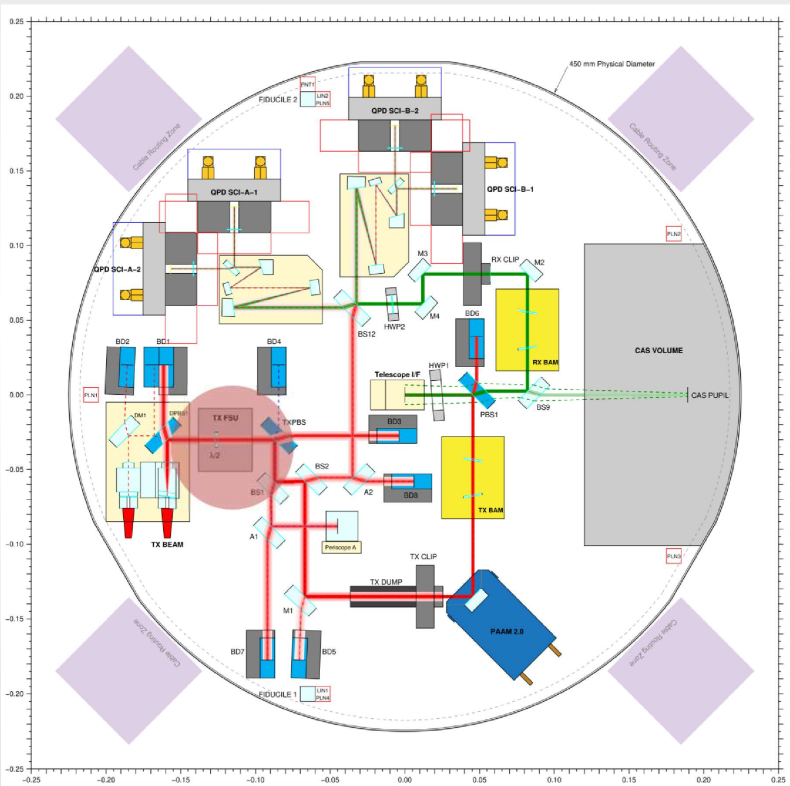
Moving Optical SubAssembly



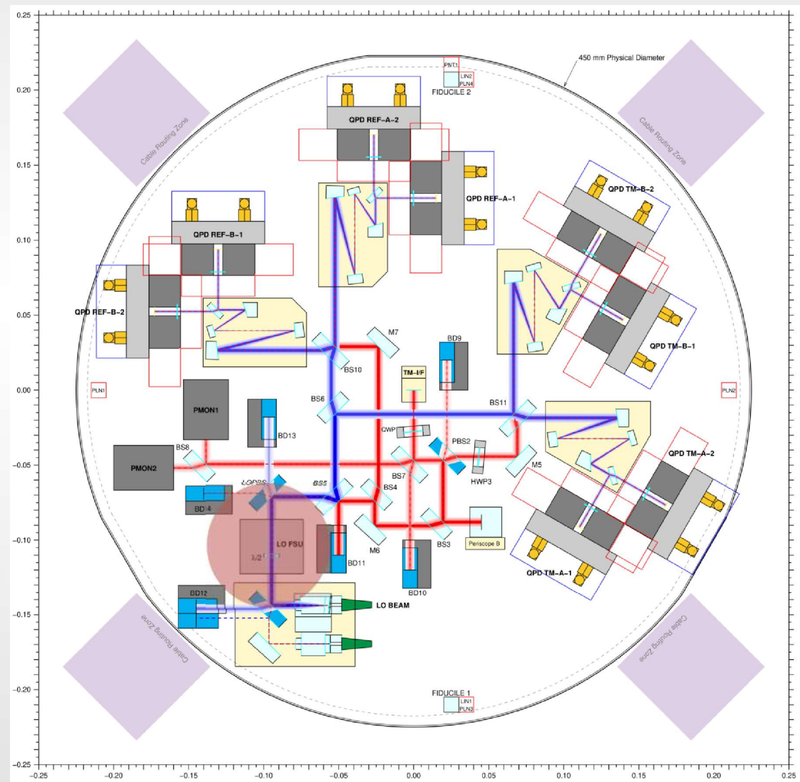


LISA optical bench

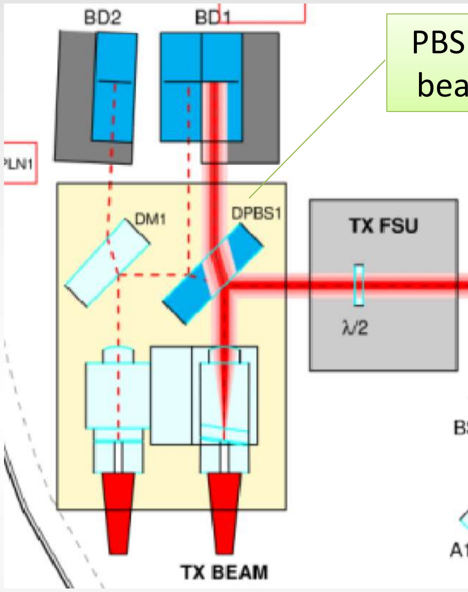
Side A (transmission)



Side A (test mass)

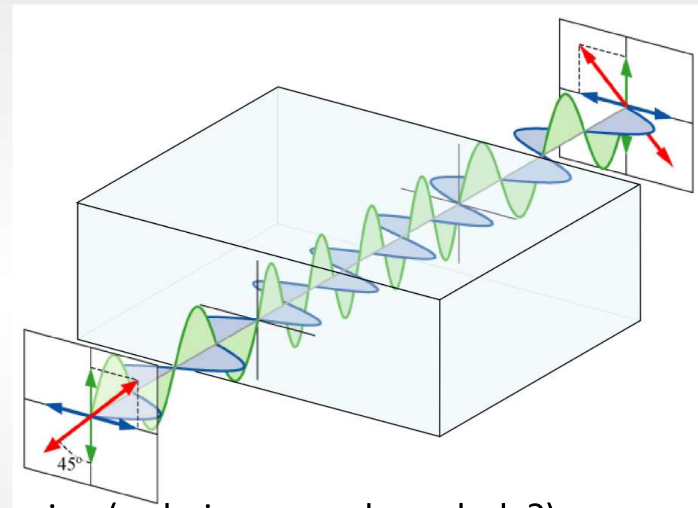


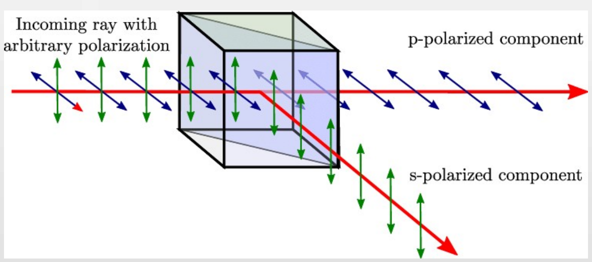
FSUA - fibre switching unit assembly



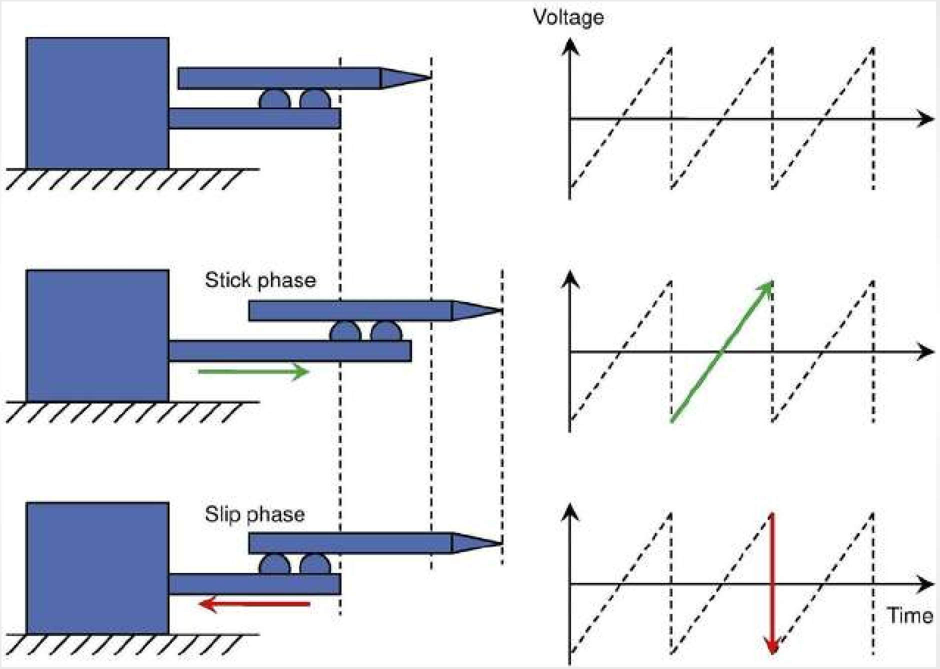
PBS (polarizing beam splitter)

- Fixing the beam polarization when switching between primary and redundant laser
- Principle of operation:
  - Rotation of $\lambda/2$ polarization plate
- Needs to be:
  - non-magnetic,
  - stable when off,
  - provide position measurement
  - survive launch,
  - function after many years of not moving (or being moved regularly?)

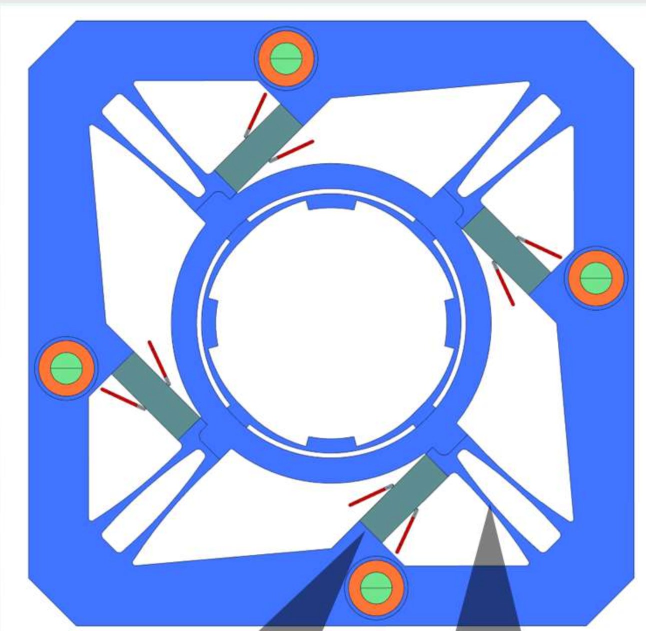




Piezo slip stick

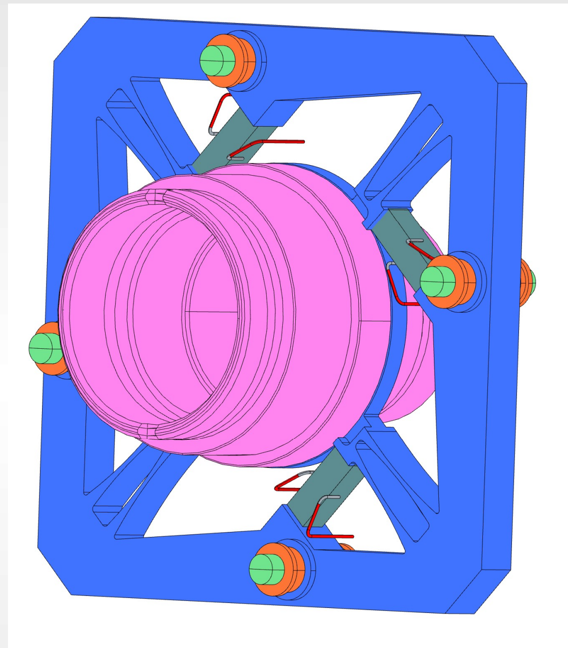


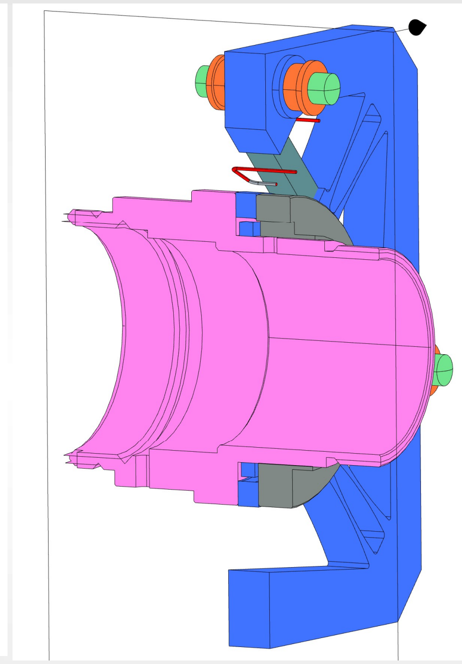
Demonstrator Model



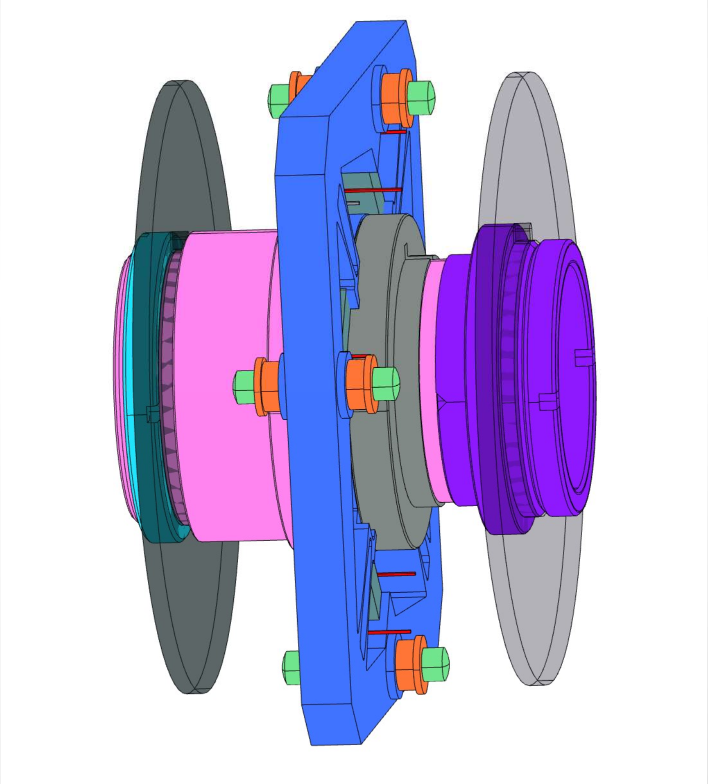
Piezos move the inner ring counter clock wise

Flexible hinges return it into position

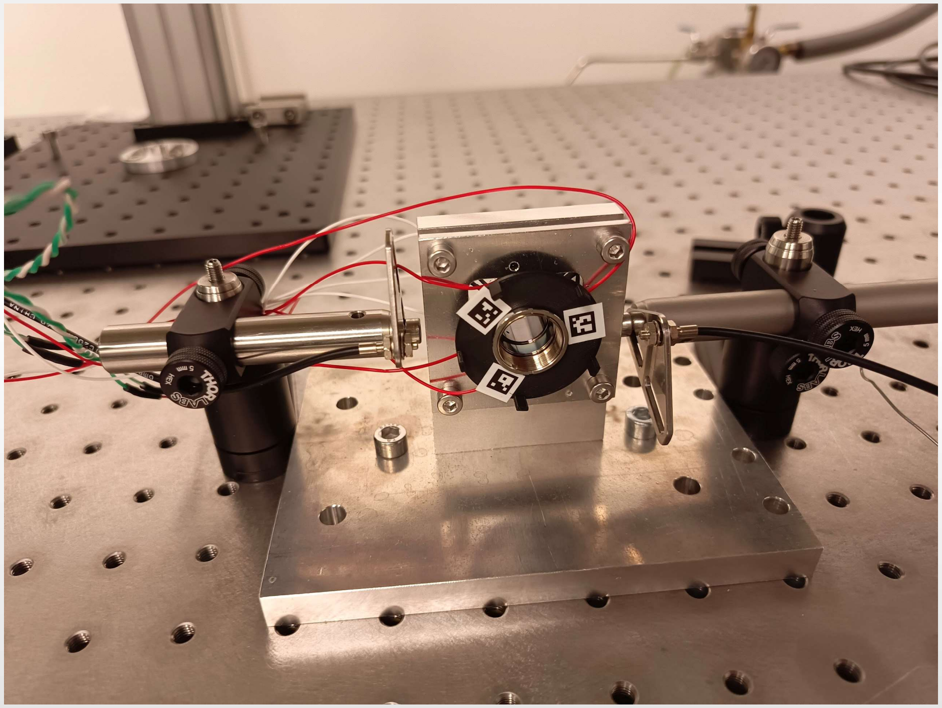




Demonstrator Model

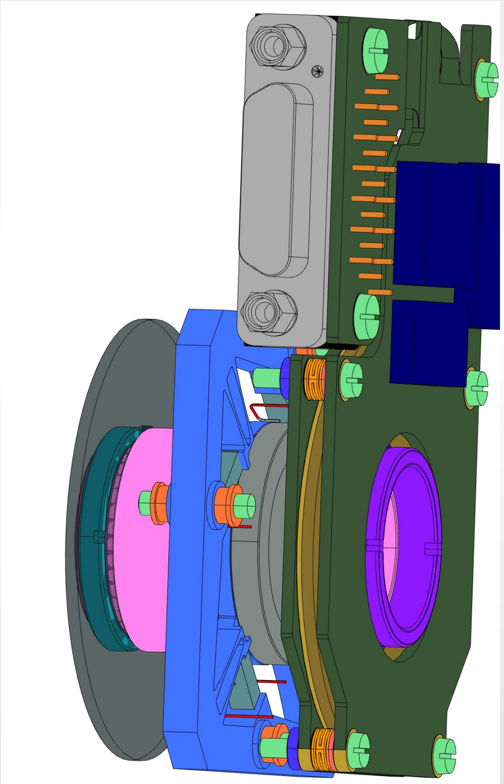


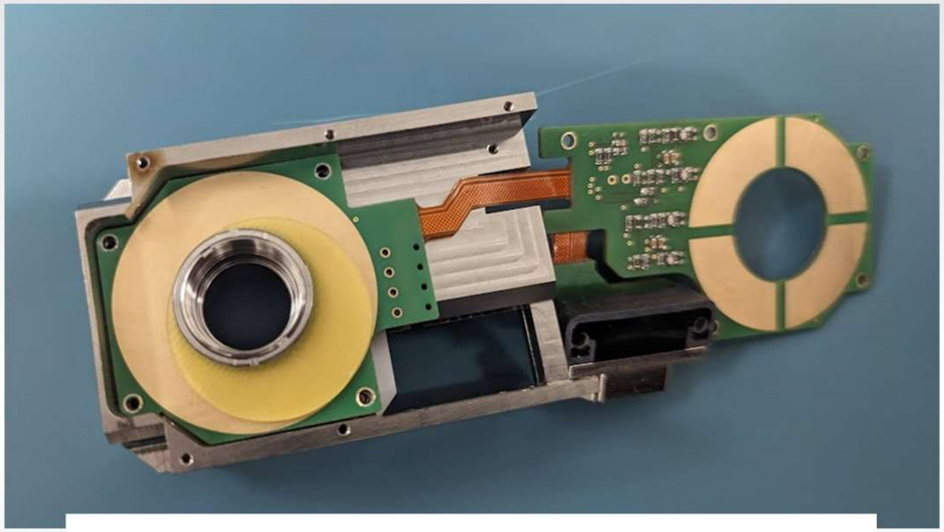
Tests in the laboratory

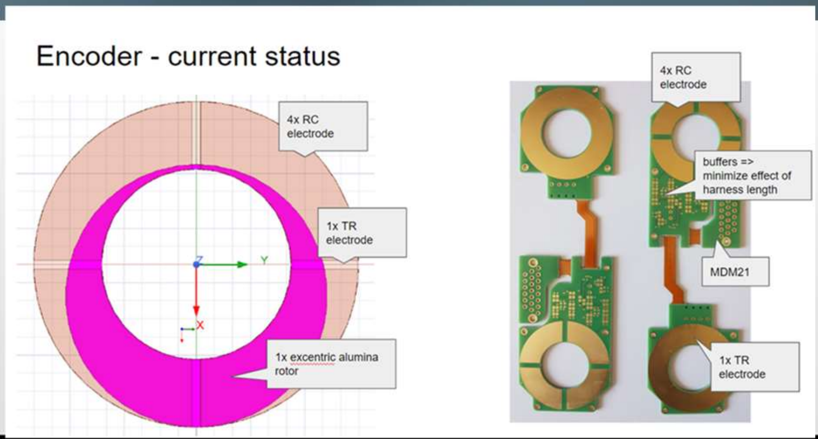


- Tests done with partial configuration.
- Easier access to the core components.
- Let’s finish assembling it, test results will follow…

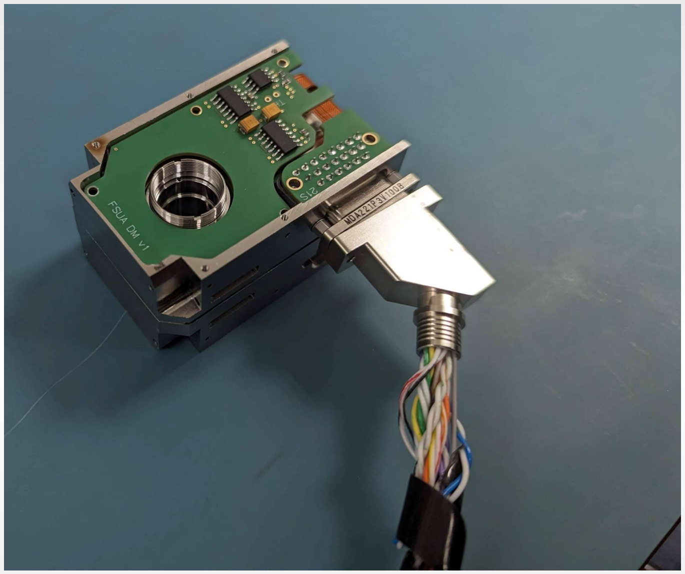
Encoders





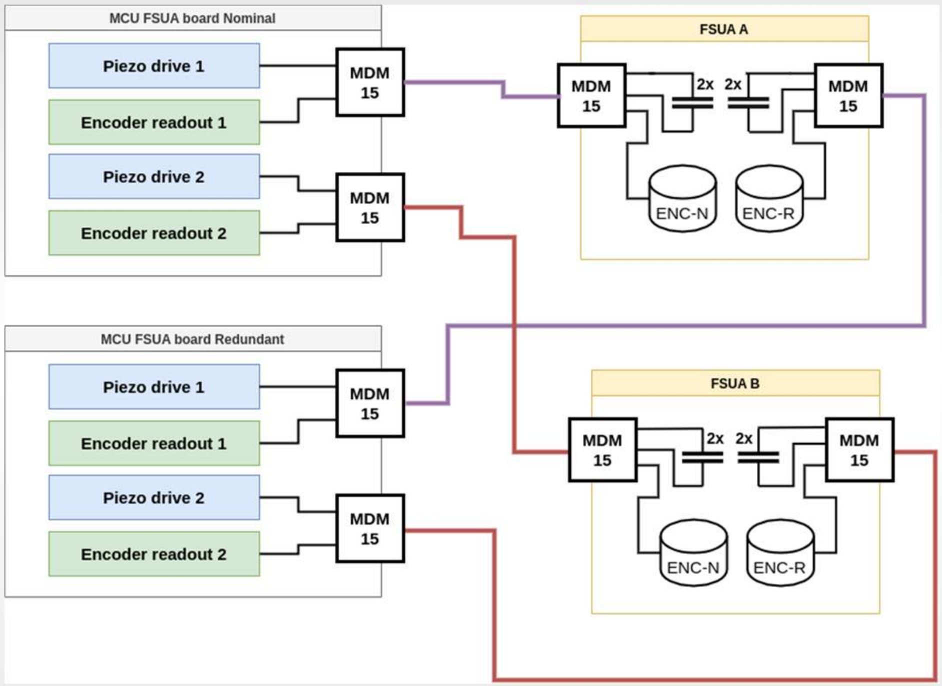

Encoder - current status
4x RC electrode
1x TR electrode
1x excentric alumina rotor
4x RC electrode
buffers => minimize effect of harness length
MDM21
1x TR electrode

Prototypes status



- Found some conflicts
- Improvements to the design identified
- Simple ones implemented now, rest for the EM
- Will assemble again and run using the mech. Electronics to drive it

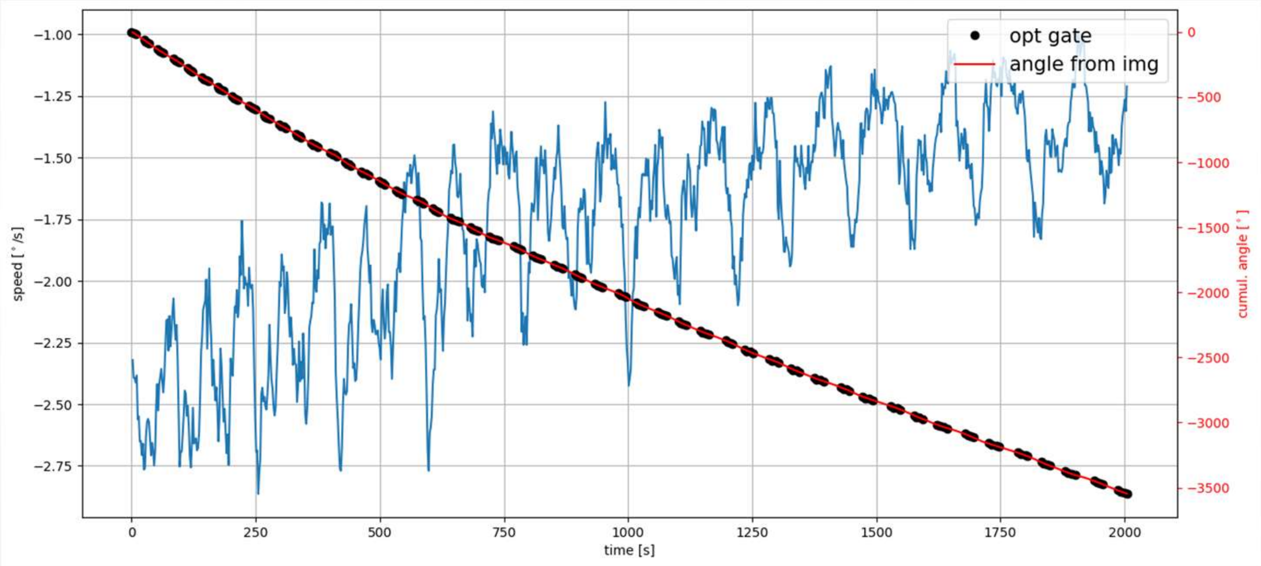
Electronics layout

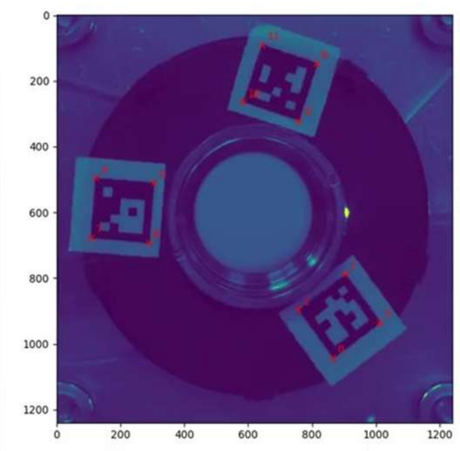


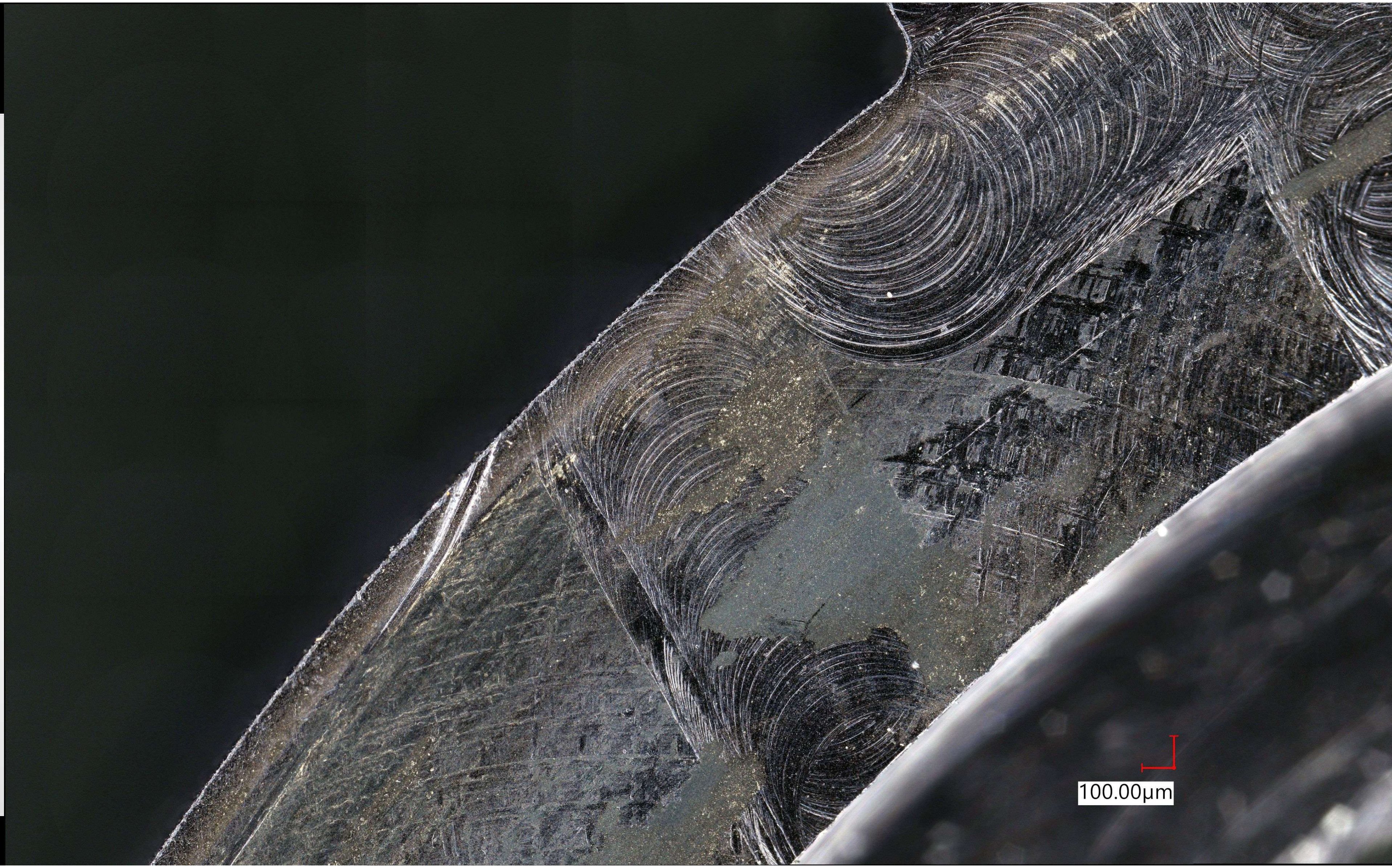
- Mechanism driven by two piezos out of four
- Full redundancy of drive and encoder

Some test results

- The “difficult” direction – piezos do the slip
- Some issues:
  - Speed variations
  - Slowdown
- Measured using external electronics and machine vision detection of the rotations





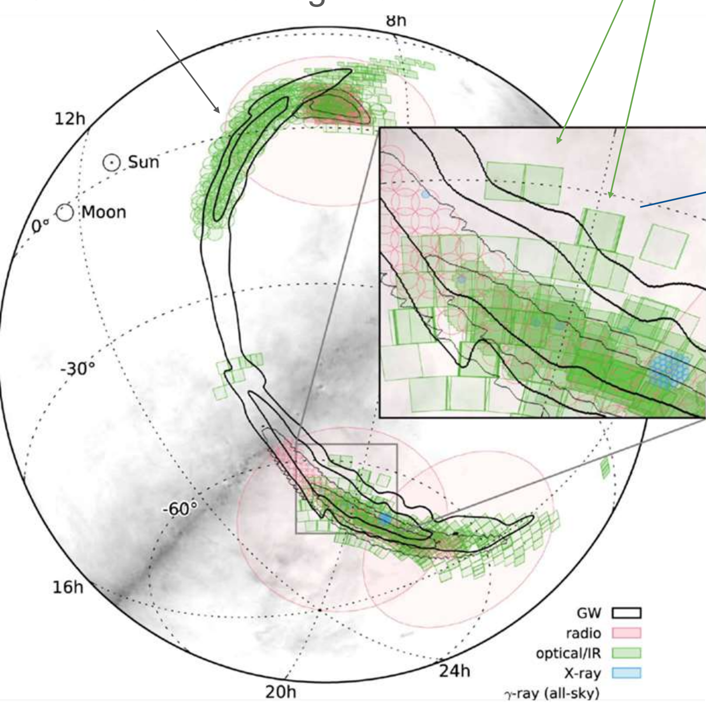

100.00μm

Optical follow-up of LIGO-Virgo gravitational wave events during O3 and O4 runs

Mergers of compact objects
- NS+NS - kilonovae
- NS+BH - ???

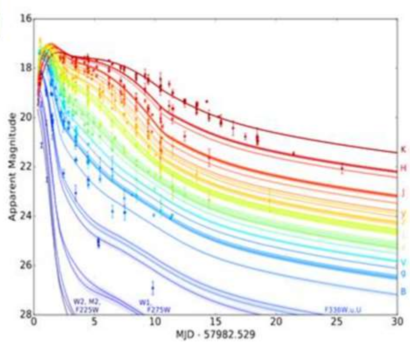
Tiling observations with wide-field optical telescopes

GW localization regions



Transient candidates

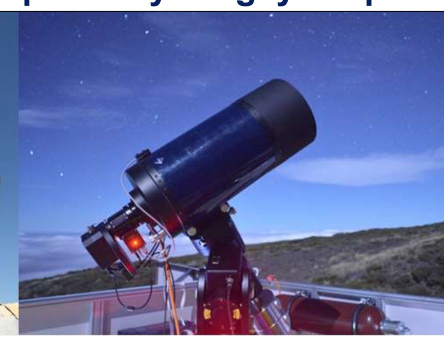
Multi-wavelength follow-up



GRANDMA collaboration: 29 groups - 18 countries - 90 scientists
FZU participation: **FRAM** telescopes + **STDPipe** photometric pipeline

~30 follow-ups during O3 (2019), O4 ongoing now (2023-2024)

Slide prepared by Sergey Karpov



Final note:

As I said during the meeting in December 2023, we are planning to submit an application for the new Research Infrastructure (on the National Roadmap of the Czech Republic), which will be devoted to gravitational wave detection.

Collaborating institutes are most welcome!

The application will have to be submitted in the second half of 2025.

Please, contact me at prouza@fzu.cz.

And – MoU signing with the German Center for Astrophysics – expected in June in Prague