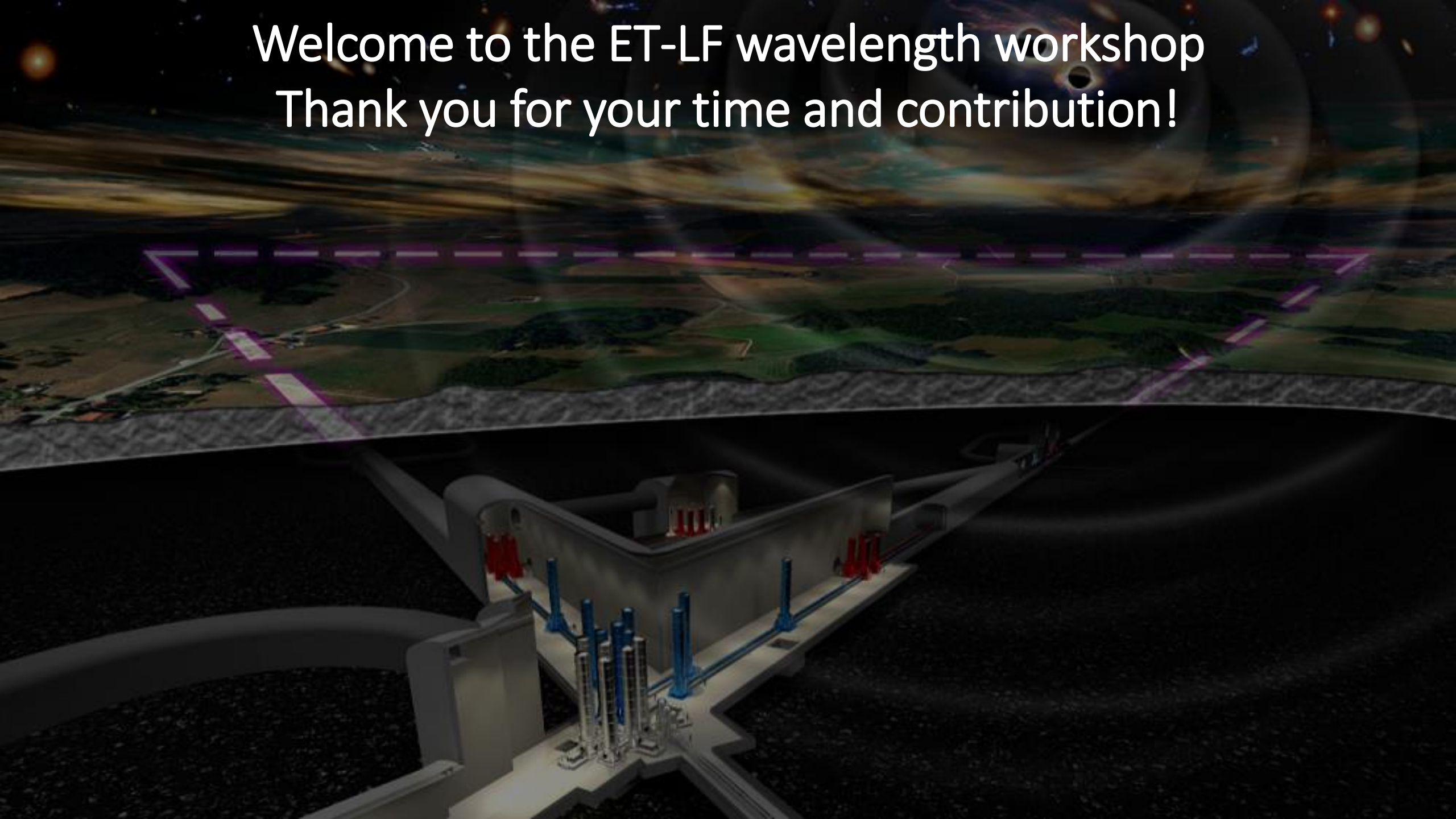
Welcome to the ET-LF wavelength workshop
Thank you for your time and contribution!

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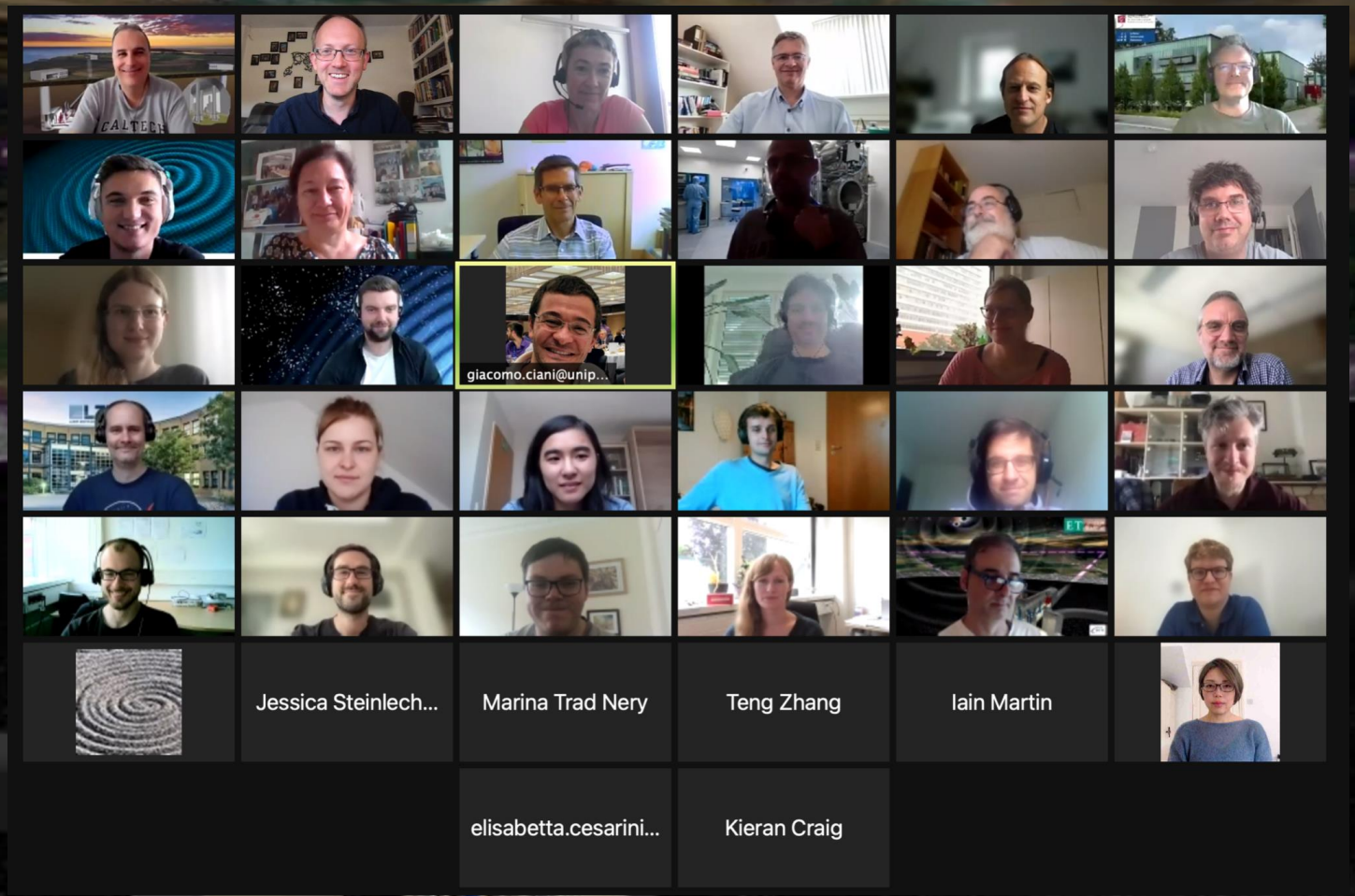
Preparatory workshop 9th July 2021



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Welcome to the ET-LF wavelength workshop

ET-LF wavelength workshop (Day 1)

Friday 3 Sep 2021, 09:00 → 12:00 Europe/Paris

Zoom

Edwige Tournefier (CNRS), Stuart Reid

Description

The aim of this workshop is to collect and discuss all the available information for the possible wavelengths which could be used for ET-LF (state of the art of the technologies, impact on the design for all Divisions, impact on the sensitivity, needed R&D and associated timelines for R&D, impact on the cost,...) and draw the path towards a decision.

The workshop will be held on Zoom. Instructions for connecting can be found on the workshop Wiki page.

The agenda of the second half day of the workshop (on September 16th) can be found on https://indico.in2p3.fr/event/24932/

09:00 → 09:10	**Introduction** Speaker: Stuart Reid	10m
09:10 → 09:25	**KAGRA's experience with sapphire mirrors** Speaker: Matteo Leonardi	15m
09:35 → 09:50	**KAGRA's experience: icing issues and cryogenic suspensions** Speaker: Takafumi Ushiba	15m
10:00 → 10:20	**ET-LF Core optics: overview on wavelength considerations** Speaker: Jessica Steinlechner, Iian Martin, Alex Amato, Benoit Sassolas	20m
10:30 → 11:00	**Wavelength considerations for ET Optics workpackages** Speaker: Margherita Turconi, Benno Willke, Keiko Kokeyama, Michal Was,Thomas Bretz, Mario Martinez, Giacomo Ciani, Henning Valbruch,Alessio Rocchi, Martin van Beuzekom	30m
11:00 → 11:10	**Overview of optical layout, pros and cons for each wavelength** Speaker: Jérôme Degallaix	10m
11:10 → 11:25	**Noise budget vs wavelength** Speaker: Teng Zhang	15m
11:35 → 11:40	**Overview of large diameter silicon** Speaker: Margot Hennig	5m
11:40 → 12:00	**Discussion**	20m

ET-LF wavelength workshop (Day 2)

Thursday 16 Sep 2021, 14:00 → 16:00 Europe/Paris

Zoom

Edwige Tournefier (CNRS), Stuart Reid

Description

The aim of this workshop is to collect and discuss all the available information for the possible wavelengths which could be used for ET-LF (state of the art of the technologies, impact on the design for all Divisions, impact on the sensitivity, needed R&D and associated timelines for R&D, impact on the cost,...) draw the path towards a decision.

The workshop will be held on Zoom. Instructions for connecting can be found on the workshop Wiki page.

14:00 → 14:20	**LIGO-Voyager viewpoint: status of 1.9/2.0/2.1 wavelength choice, availability of silicon test masses** Speaker: Aidan Brooks, Rana Adhikari	20m
14:30 → 14:45	**Suspension thermal noise: how heat load defines suspension geometry** Speaker: Giles Hammond	15m
14:55 → 15:15	**Noise budget vs wavelength** Speaker: TBD	20m
15:20 → 16:00	**Discussion**	40m

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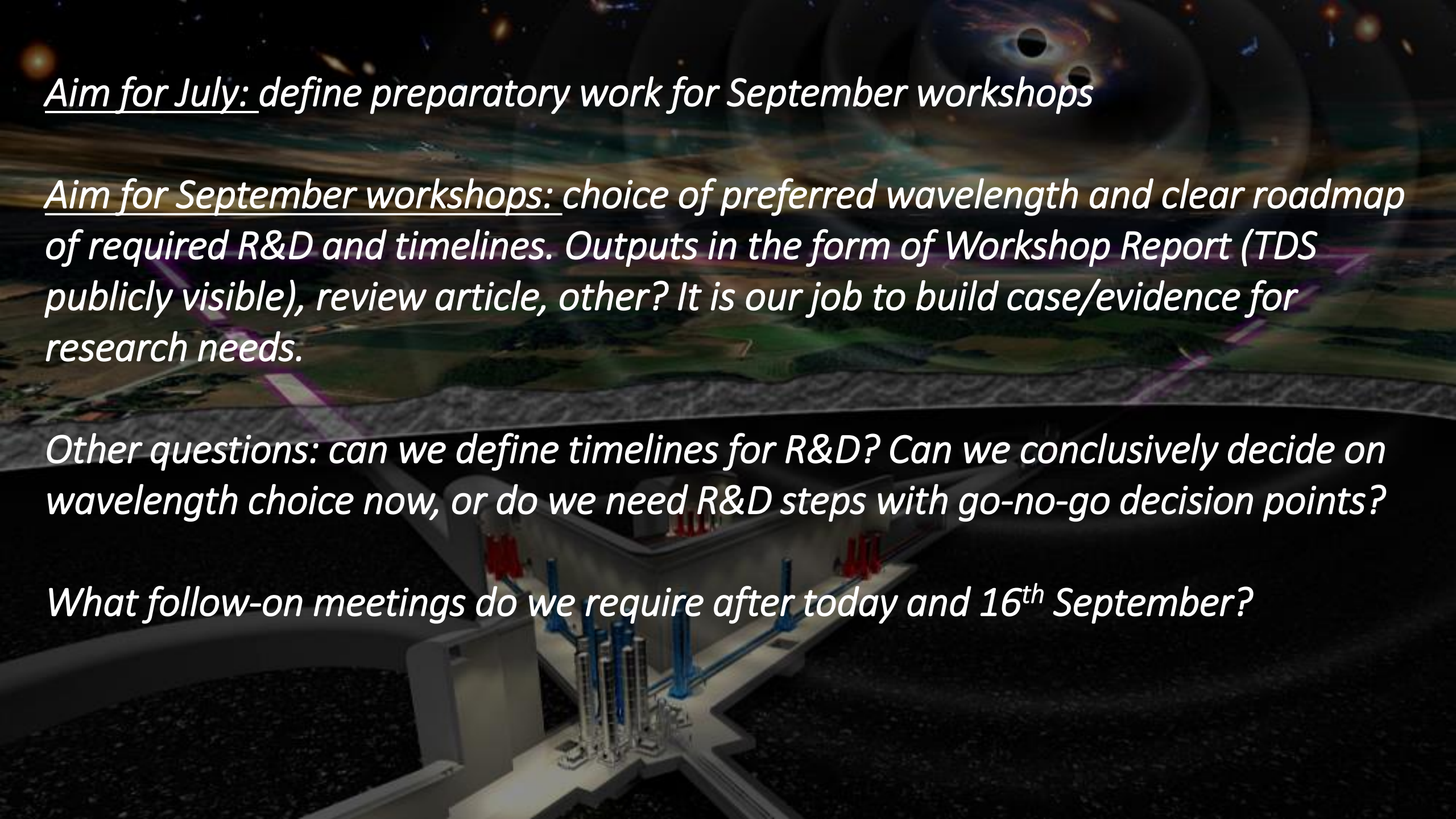


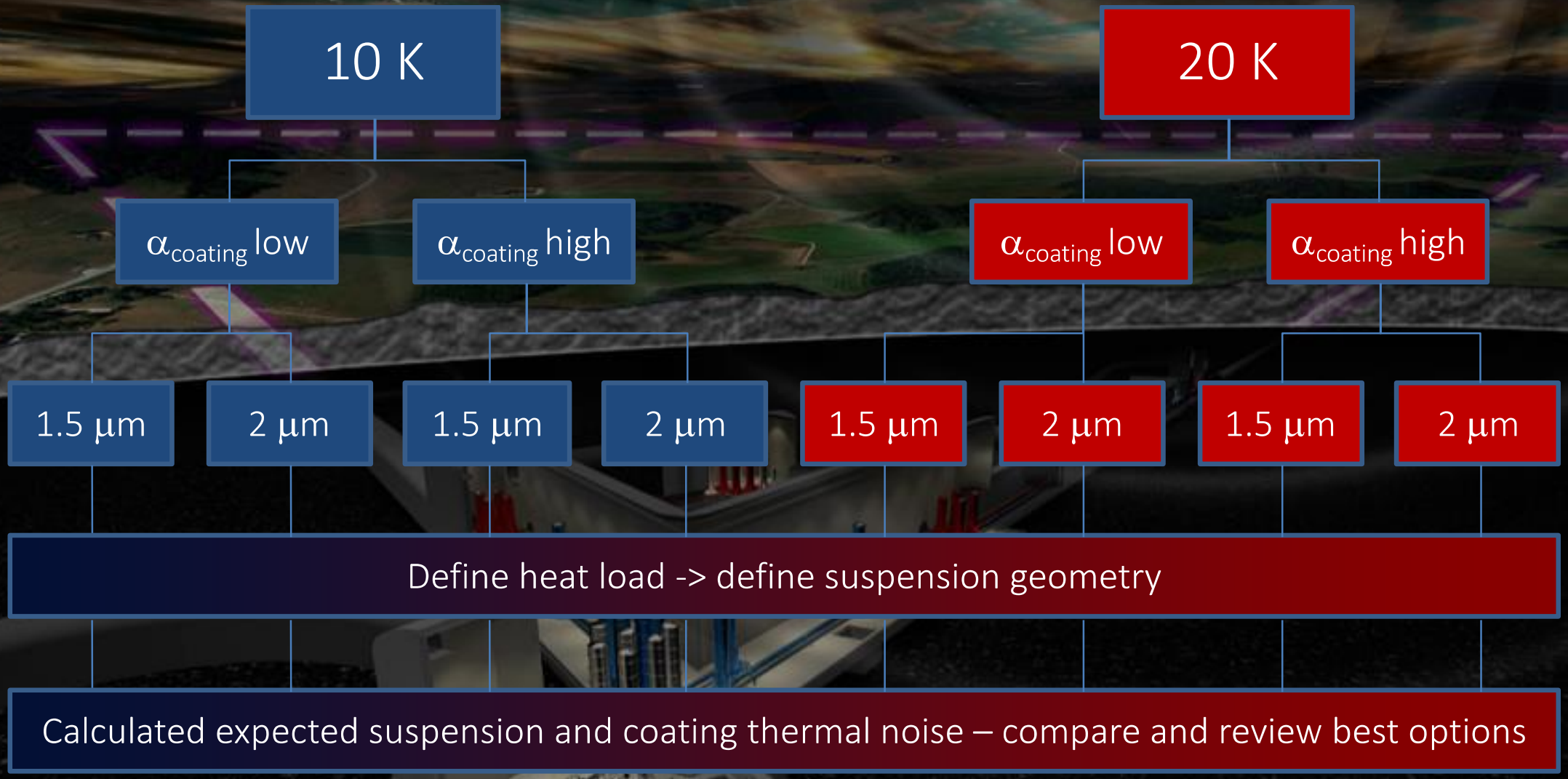
Aim for July: define preparatory work for September workshops

Aim for September workshops: choice of preferred wavelength and clear roadmap of required R&D and timelines. Outputs in the form of Workshop Report (TDS publicly visible), review article, other? It is our job to build case/evidence for research needs.

Other questions: can we define timelines for R&D? Can we conclusively decide on wavelength choice now, or do we need R&D steps with go-no-go decision points?

What follow-on meetings do we require after today and 16th September?

From mirror temperature workshop and ET Optics Division 16 April 2021



From 9th July 2021 preparatory workshop

https://docs.google.com/presentation/d/1s6DncsLAdm-gpqWodmizaMA4iEgA_WmnZXMP-gFkM44/edit?usp=sharing

Core optics (Amato/Martin/Steinlechner/Sassolas) ET-0391A-21

Assume 18kW cavity power, 32W transmitted

- 18mW heat extraction challenging for heat extraction?
- For 210kg, with 45cm dia, then Si has 57 cm thickness and Al2O3 is 33cm. If sapphire available in larger dimensions, should we consider different optimal dimensions?
- Should we consider higher power to extend detection freq above 30Hz? Use more power to broaden bandwidth or lower noise floor?
- Need to consider impact of absorption on various potential mirror coating materials: a-Si, SiNx, AlGaAs, AlGaP, GaN,
- Need to share the table with material properties with the Payload WP.
- If we are considering sapphire substrates, then 1064nm wavelength needs to be considered. (1064nm restricts low temp. coating options)
- AlGaAs transfer to sapphire or silicon: is thermal expansion a problem for delamination? Thermal cycling? Can technology be scaled up? What diameter is required?
- See "optical performance of large area crystaline coatings": https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-26-5-6114&id=382238
- Need to worry about stress in coatings? Is 2um worse than 1.5um? Needs to be considered?
- What is TCS limit on absorption? Or just heat extraction? Often the 1ppm absorption limit is cited, but not clear if this is high-power cavity requirement only?
- Paola mentioned that the absorption limit (1ppm) is more given from heat extraction: 100mW heat extraction is usually used as a maximum value: higher power means larger wire diameter which means larger suspension thermal noise. Can we define this more precisely (noise budget curves for given assumptions – it also depends on the ET-LT temperature)?

  => Input from Paola and ITF noise budget WP?

We also need to take into account thermal radiation heating (+absorption due to ice formation?)

- Suggestion to consider total heat extraction instead of absorption (ppm)
- What is the thermal conductivity for Si and Saphire? Numbers seems comparable and peaks at ~20-30K – to be checked/measured (depends a lot on exact material composition). See "heat extraction through Sapphire fibers for KAGRA" https://arxiv.org/pdf/1401.2346.pdf
- What optical losses are allowed to achieve the required finesse?
- Silicon suspensions for 1ppm: https://iopscience.iop.org/article/10.1088/0264-9381/31/2/025017/meta
- If BS is silica, then is there a grade that works for 1550/2um. What is effect of absorption from ice layer on mirrors: https://apps.et-gw.eu/tds/?content=3&r=17587
- BS absorption 100ppm/cm at 2um (for Voyager). Can we check if we expect any issues here with lower power? https://www.heraeus.com/en/hca/fused_silica_quartz_knowledge_base_1/t_calc_1/transmission_calc_opt/transmission_calculator_opt.html?chartIndex=2&selection=suprasil_311_312%2Csuprasil_3001_3002_300%2Csuprasil_1_2a%2Csuprasil_313%2Csuprasil_3301_3302%2Csuprasil_2b&thickness=10&rangeX=120%2C4500 and https://www.sciencedirect.com/science/article/abs/pii/S0030401800011524?via%3Dihub

Lasers (Wilke/Turconi) ET-0373A-21

- Lasers WP have had presentations from groups working on 1550 (e.g. AEI) and 2um (e.g. OzGrav/Adelaide/ANU)
- 1550nm lasers tested at AEI - main problem is the increase of Power noise after PMC (due to frequency noise). Amplifiers OK.
- 2um: development ongoing (wavelength from 1980 to 2090 nm). A lot of reliability studies to be done + PSL components to be developped
- 2128nm OPO conversion (Hamburg) an option?
- Need to operate these lasers in PSL to ensure free running noise is compatible with actuator range / bandwidth..
- Who will set up PSL prototypes and demonstrate robust stabilization loops? 2 years R&D?
- Availability of high-efficiency, low noise photodiodes at 2um is an issue. Need to liaise with LIGO Voyager about III-V and II-VI materials - must ensure relevant people are available for September.
- Glasgow also setting up a frequency and intensity stabilised 2um (and 1550nm) laser system. - timelines for these?
- 2090nm laser work at ILT Aachen in the scope of the ETEST (ETpathfinder) project.
- R&D needed:
  - Reliability studies at 2um + PSL components
  - 1.5 & 2um: prototypes + stabilization loops + LF preformances

IOO (Kokeyama/Was) ET-0363A-21, ET-0367A-21

- EOMs: absorption seems OK at both wavelentghs but need to study scattering
- Faraday isolators for high/low power. Less isolation at 2um (30dB vs 40 dB) and more losses -> R&D needed
- Photodiodes: InGaAs ok at 1550nm but 80-85% QE at 2um. HgCdTe photodiodes have ~92% efficiency for 2um. [http://www.teledynejudson.com/news/Documents/2.5%20um%20SWIR%20PV%20MCT%20product%20chart.pdf] Lots of R&D needed at 2um for: QE, noise, linearity, high power
- Sebastian stated: There's some discussion between Voyager-people and some ET folk with UWA group of Lorenzo Faraone on HgCdTe PDs. Looked like this material could be optimised for us, but not sure what current status of the discussions is (Bram/Aidan/Joris leading those discussions).
- Absorption at 2um associated with water needs taken care of? Also CO2. Would need to put all optics under vacuum if wavelength between 1.9 and 2.0 um (Ok above)? => would prefer longer wavelength e.g. opo to 2.1um?
- II-VI in OzGrav.
- Aidan speak to NPL to discuss III-V
- Beam dumps - choice of material - do we have good options for both 1.5um and 2um?
- Standard optics: increasing absorption of Fused Silica at 2um) -> move to Silicon or MgF2?
- R&Ds:
  - Photodiodes at 2um: reduce losses by a factor 20
  - Faraday isolator: reduce losses by a factor 10
  - Check scattering of all elements for both wavelength
  - Air absorption problem at 1.9-2.0um

Voyager paper: https://iopscience.iop.org/article/10.1088/1361-6382/ab9143/pdf

From 9th July 2021 preparatory workshop

https://docs.google.com/presentation/d/1s6DncsLAdm-gpqWodmizaMA4iEgA_WmnZXMP-gFkM44/edit?usp=sharing

Scattered light (Bretz/Martinez) ET-0396A-21

- Work quite independent of wavelength: properties of materials (reflectance and absorption) are similar
- 2um: less random back scatter (dust) - motivation for Voyager
- Scattered light noise scales with 1/wavelength ⇒ lower noise with 2um
- Tube diameter scales with wavelength -does this have any critical effect on budget or infrastructure? Perhaps not critical (need to check?) but has to be taken into account for all design/infrastructure considerations.
  - We need to come up with some figure of merit - are there strong science argument to push to 2um and increase infrastructure cost (vacuum is second-highest cost after tunnels). Not a 'small' issue.
- Conor stated that longer wavelength choice for Voyager is partly driven by scattered light? Check.
- Clipping noise: Mario and Thomas looking at calculating this and scaling with wavelength.
- Radius of curvature for mirror? Current models are using LIGO/Virgo RoC - need to evaluate for different RoC.
- Spiral baffles and other non-standard shapes - are these feasible and beneficial?? How much advantage?
- Can baffles be compatible for both 1.5um and 2um to allow initial ET-LF to be 1.5um and changed to 2um in the future?
- There needs to be an R&D campaign at both wavelength, to characterise optically and for robustness. Who will do this?

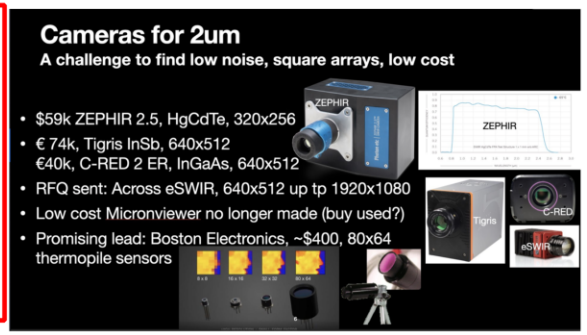
Squeezed light (Vahlbruch/Ciani) ET-0365A-21

- Most performances are limited by optical losses
- 1550nm limit: 13dB at MHz, 10dB at kHz - Demonstrator needed (especially for LF performance) but no showstopper
- 2um limit: 7dB at MHz, 4dB at kHz - mainly limited by photodiodes losses
- 15dB squeezing in audio band and down to 1Hz is not demonstrated. Who will develop and test this?
- 1550nm squeezing at low freq planned in AEI.
- Is anyone working on 2um? ANU has growing interest to do this. Adelaid working at 1985nm. Hamburg?
- R&D:
  - Demonstrator at 1.5 & 2um
  - LF performances: squeezing down to 1Hz to be demonstrated in both cases

Non-linear materials (OPA/SHG)	🙂	🙂
Low loss Faraday Isolators	🙂	?
High QE PDs (>99%)	🙂	☹
Low noise laser systems	😐	?
Metrology (low dark noise sensors & cameras)	😐	☹
15dB squeezing at audio frequencies	?	?
Squeezing down to 1Hz	?	?

WSC (Rocchi/van Beuzekom) ET-0366A-21

- QPD and phase cameras - status at 1.5 and 2um?
- 1.5um PDs is established technology, 2um requires significant R&D
- See development done for LISA: low capacity InGaAs QPDs for <1600nm
- 2um CCD technology is limited and very expensive - can we define state-of-the-art and if we can find dark noise and linearity?
- Quantum dot cameras
- Slide by Josh Smith:



Suspensions-Cryogenics/ ITF /Other (all)

Items that are not in a WP, in a different WP, or common to all WPs.

- Alex Amato / Flavio propose wiki page with material database [Action: Alex/Flavio]
- Include thermal conductivity of Al2O3 and Si suspensions.
- KAGRA study on Al2O3 thermal conductivity: https://arxiv.org/pdf/1401.2346.pdf
- Heat load table on Wiki proposed by Steffen Grohmann [Action: Steffen].
- Water layers on cold mirrors changes the absorption
- See summary on mirror temperature for ET-LF: ET-0317A-21
- Can we have a rough optical layout at 1.5 & 2um in order to assess the compatibility of vacuum tubes / baffles design,... with both options [Action: ITF - optical design WP]
- What optical losses are allowed to achieve the required finesse?[Action: ITF - optical design WP]
- Can we have a noise budget for both options - what is missing? [Action: ITF - noise budget WP with inputs from Suspensions, Cryo & Optics] - see also ET-0317A-21

Key homework points: Action+Responsible person (all)

- Targeted workshop with suspensions to look at heat extraction/strength/thermal noise modelling?
- If we minimise the thermal load on mirror, we can reduce dimensions on suspensions (great!) but that also increases the cooldown time if relying on conduction through fibres. Do we need Mariela Masso Reid in Glasgow to show simulations for this in Sept?
- Sebastian: Maybe just as an aside, there are some thoughts on converting the 2um back to 1064nm for detection; or using entangled light to shift the squeezing to MHz frequencies. However, this all inherently adds loss and complications — looks fine on paper, but definitely would need to be demonstrated that it is not doing more harm than good.
- ET will be an infrastructure for 50 years - are we sure that all decisions are not limiting the future use/upgrades to the facilities. Can we start ET-LF at 1.5um and move to 2um later?
- Andreas & Gianluca: we need all the information to make a smart decision + need a baseline design for the light TDR (including cost estimate)
- Keiko: 2um better for low absorption in coatings and low scattering: is it an advantage for ET-LF?

Aim of this workshop

https://docs.google.com/presentation/d/1s6DncsLAdm-gpqWodmizaMA4iEgA_WmnZXMP-gFkM44/edit?usp=sharing

List of possible wavelengths: technologies, properties/known issues "decision matrix"

Wavelength	1064	1550	1950	1980/5	2050	2090	2128
Substrate (material and properties)	Sapphire abs= thickness= issues= biref, polishing, cost	Silicon abs=5-10ppm (T>50K) thickness=57cm Issues = large size?	Silicon abs=5-10ppm (T>50K) thickness=57cm Issues = large size? Low abs only in smaller segments -> composite mirrors?				
Coating (type, expected/known properties: absorption, loss,..)	??Amorphous: possible that mixed material will meet noise requirements? Check. Crystalline: AlGaAs very promising but scaling issues.	Amorphous: mixed material designs (*e.g.* Craig *et al.*, Phys. Rev. Lett. 122, 231102, 2019) Crystalline: AlGaAs very promising but scaling issues.	a-Si likely good choice here - possibly any shift to longer wavelength helpful?				
Laser (technology, performances, issues...)	Power:OK Stabilisation: LF noise to be improved	Power:OK Stabilisation: LF noise to be improved	Power : development ongoing, lot of reliability studies to be done. Stabilisation: PSL components to be developed, low noise performances to be demonstrated				(OPO conversion of 1064.) For Power and stabilisation see left cell. Maybe some advantages coming from 1064nm pump.
Photodet. (technology and performances)	InGaAs QE>99%	InGaAs QE>99%	InGaAs, QE~80-85%, large 1/f noise HgCdTe QE~92% InAsSb QE~80%				
Known issues			Water vapor absorption: is it an issue for the laser components? What would need to go under vacuum? And for IOO?				
Others						Is fused silica absorption an issue (120ppm/cm at 2128) for BS?	

Possibly two versions of the above. One with simple traffic light system (green-amber-red) and one with breakdown of R&D requirements/timelines/risks etc.