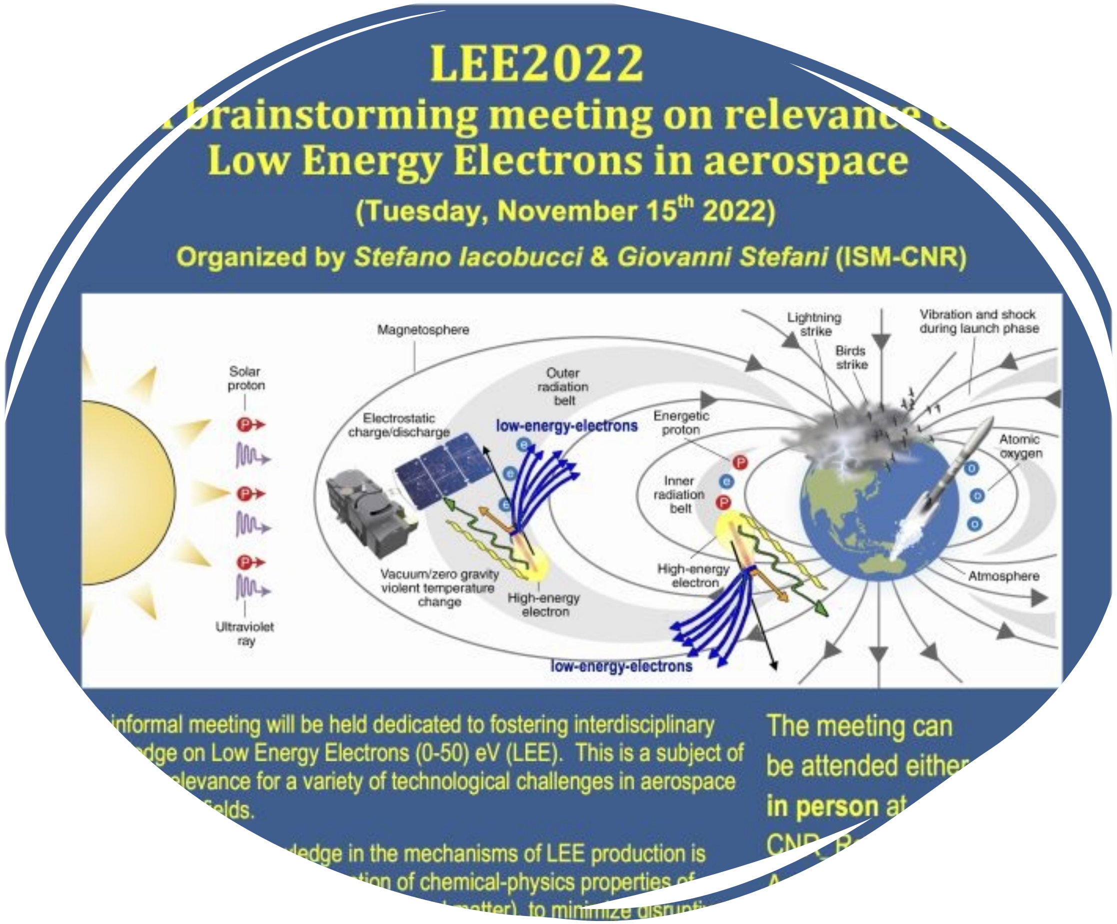



# Low Energy Electrons significance in gravitational wave detector technology

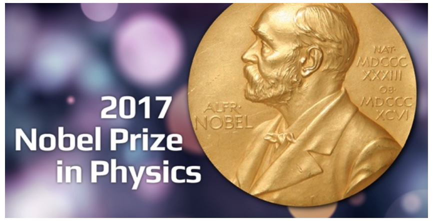

L. Spallino, M. Angelucci and R. Cimino

LNF-INFN, Frascati


November 15$^{th}$ 2022

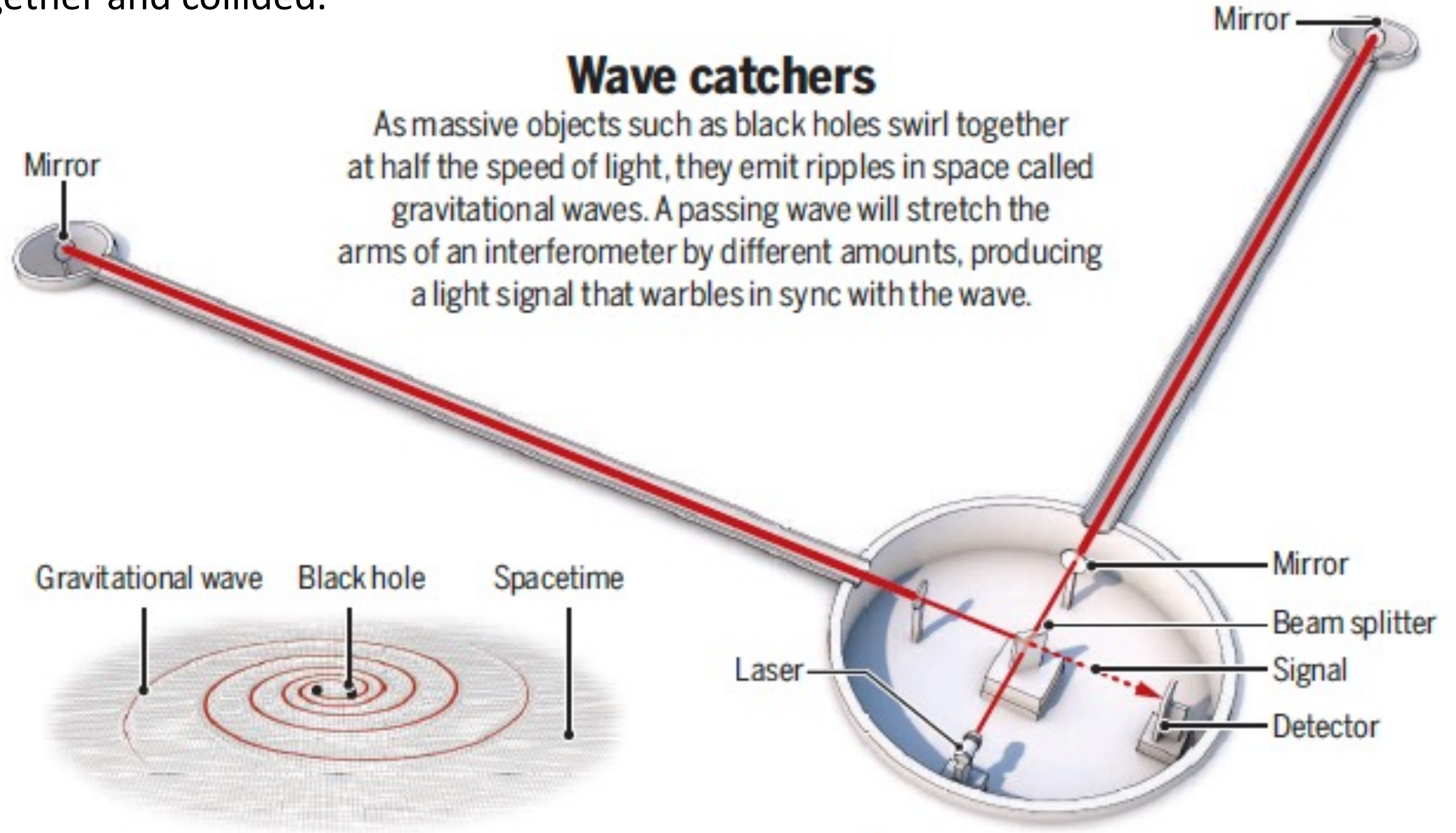
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

# Gravitational wave detectors




On September 14, 2015, LIGO made the first-ever direct observation of a feeble signal of gravitational waves generated 1.3 billion years ago when two black holes spiraled together and collided.

A. Cho, Science 371, 1089 (2021)

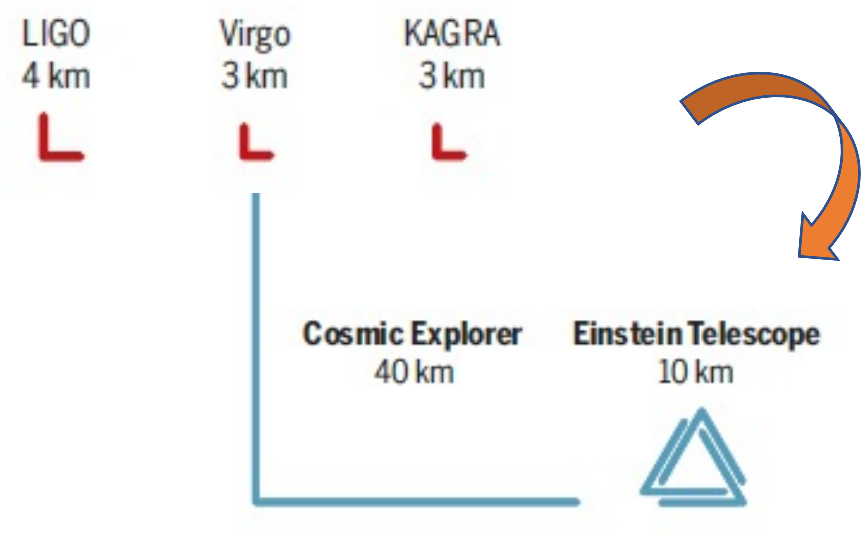




In spite of the detectors' sizes, a gravitational wave **changes** the relative **lengths** of their **arms** by less than the width of a proton

**~ $10^{-15}$ m**

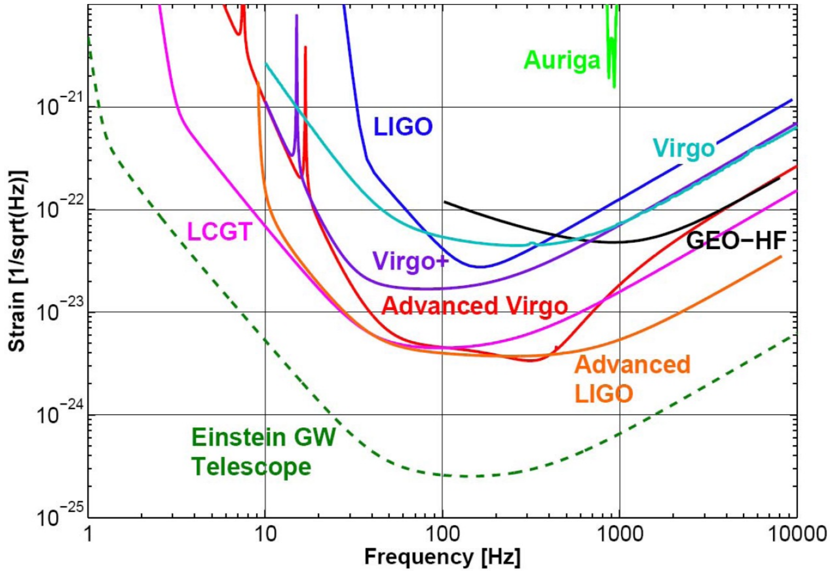
# Gravitational wave detectors

The forthcoming 3rd generation of GW detectors aims to extend and increase the detection sensitivity




**Bigger and more complex!**

ET Steering Committee Editorial Team, Design Report Update (2020)




**Dominant at low frequency (<10 Hz)**

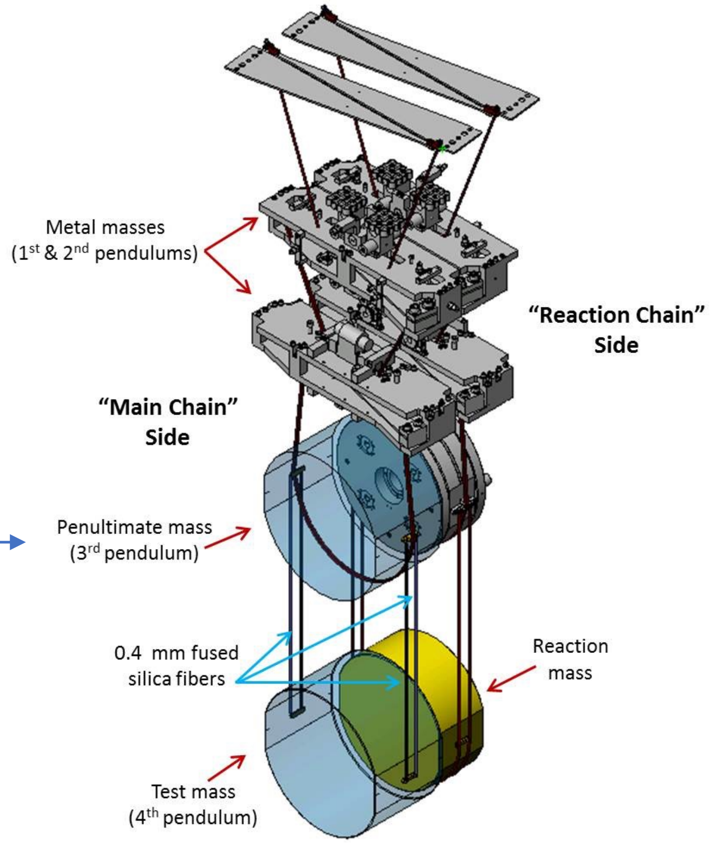
- underground infrastructure
- seismic noise
- cryogenic optics (~10 K)
- thermal noise

# Electrostatic charging on test masses of GW detector

- Unclear in origin, quantity and even sign
- Effects of charging:

  - Interferers with optical position control
  - Accumulation and motion of charges can generate fluctuating electric fields that could move the test mass at frequencies in the interferometer's sensitive band
  - Attracts dust, reducing reflectance, increasing scattering and absorption

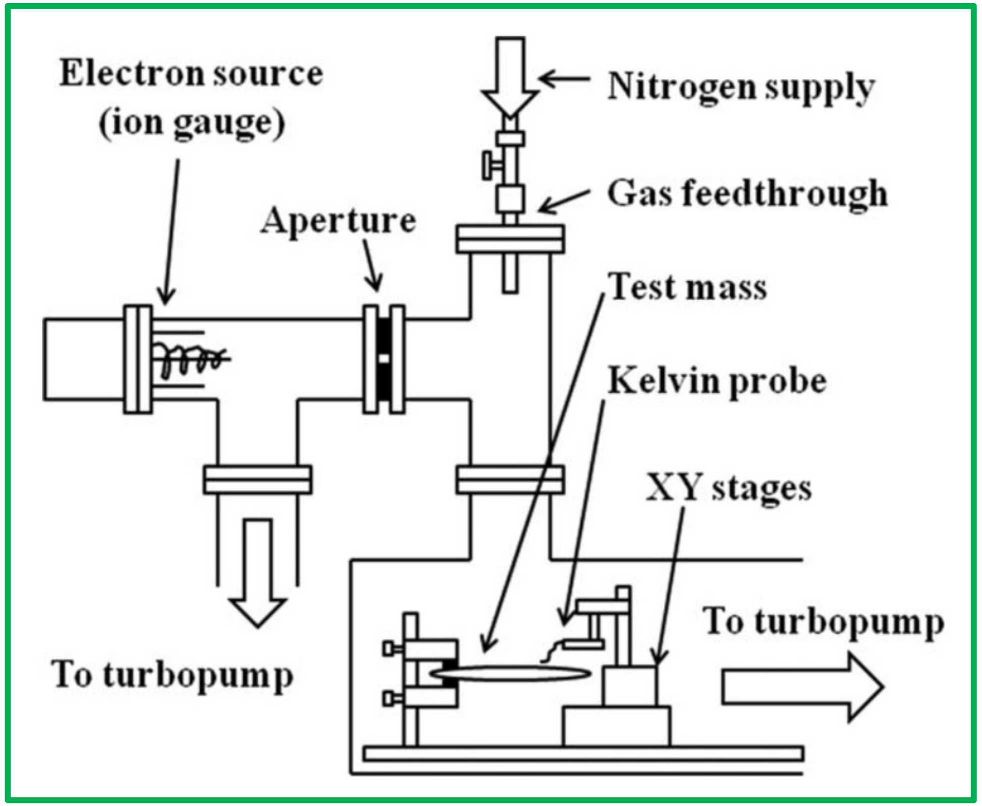
Electric field noise coupling to test mass motion




**Potentially limiting noise source**

# Charging mitigation at a-LIGO (Room Temperature)

Mirror exposure to some tenth of mbar of a $N_2$ plasma for a long time (~1 h)




D. Ugolini et al., Rev. Sci. Instrum., 82, 046108 (2011)

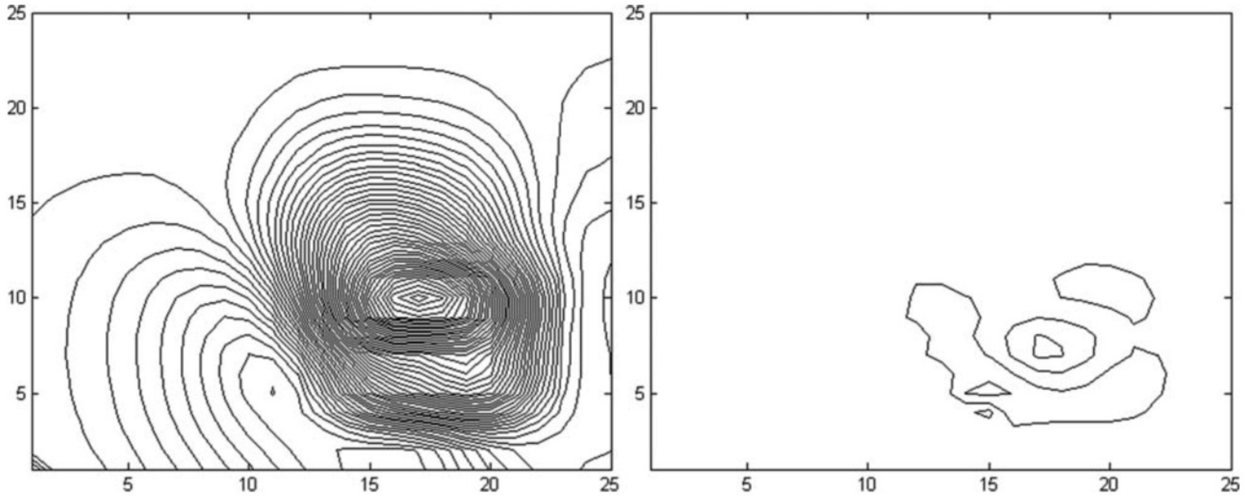
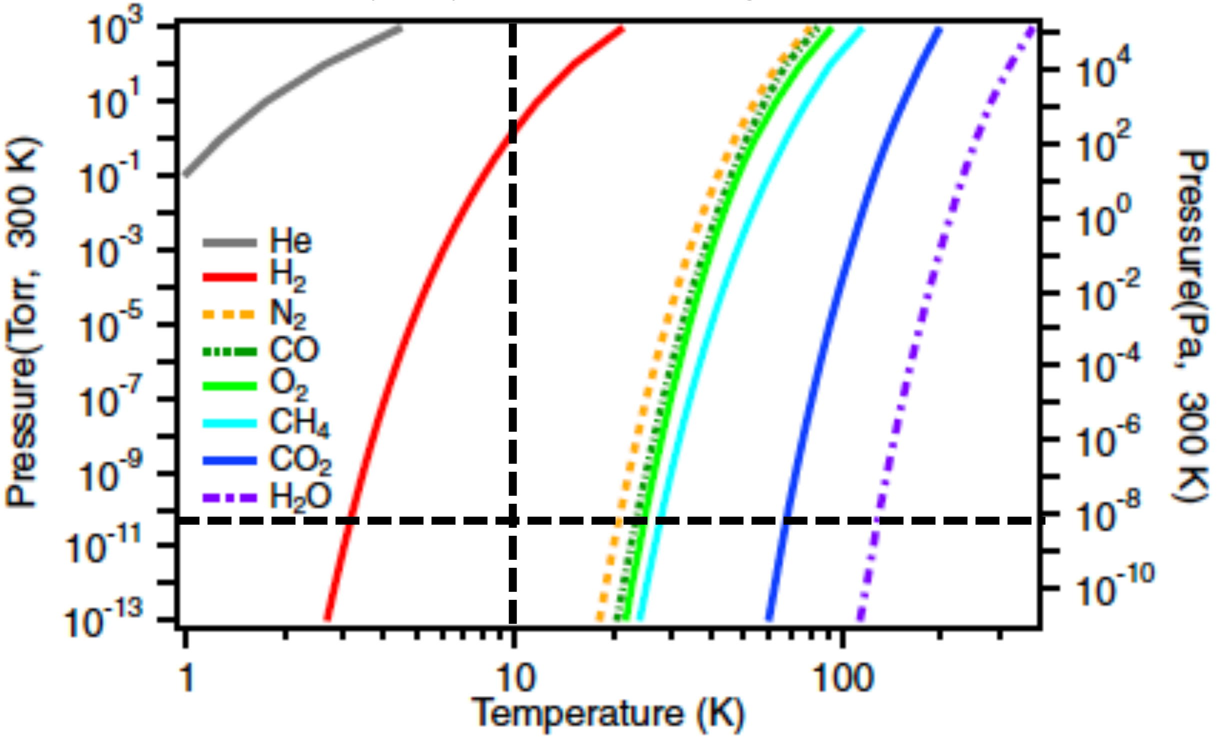


FIG. 4. Contour plots of charge density before (left) and after (right) discharging. Each contour corresponds to $2 \times 10^{-13}$ C/cm$^2$.

**Can this method be applied at Cryogenic Temperature?**

# Residual gas adsorption on cold surfaces

Saturated vapour pressure from Honig and Hook (1960)




For T~10 K and p<$10^{-10}$ mbar, the most common residual gas species in a UHV chamber (except $H_2$ and He) will be adsorbed, forming a molecular ice ("frost") on the surface

Cryosorption depends on:

- surface temperature
- gas partial pressure

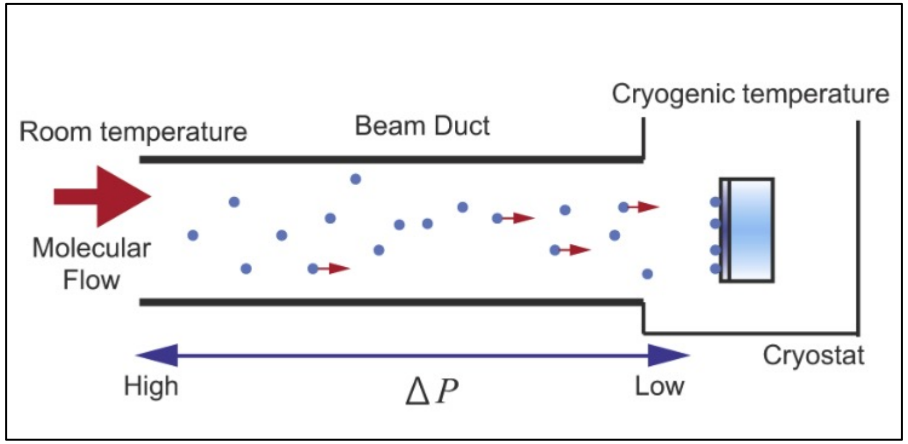
If the LIGO neutralization method will be applied at cryogenic temperature, a significant layer (~mm) of the injected **$N_2$ will be cryosorbed on the mirror surface**

**Dramatic effects on optical properties and thermal noise**

# Residual gas adsorption on cold surfaces

From KAGRA experience (Cryogenic Temperature)

Reflectivity gets affected, already after 100 nm of $H_2O$ ice




S. Tanioka et al., Phys Rev. D, 102, 022009 (2020)

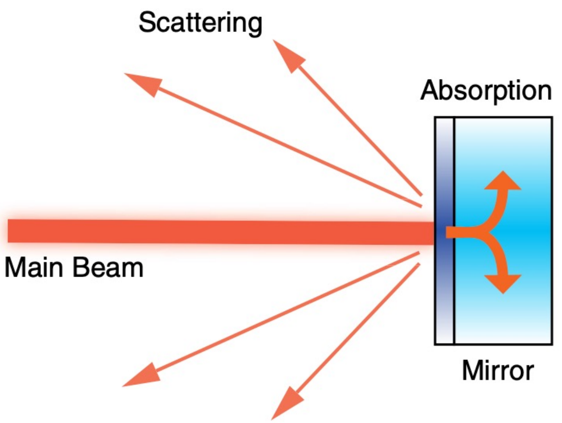
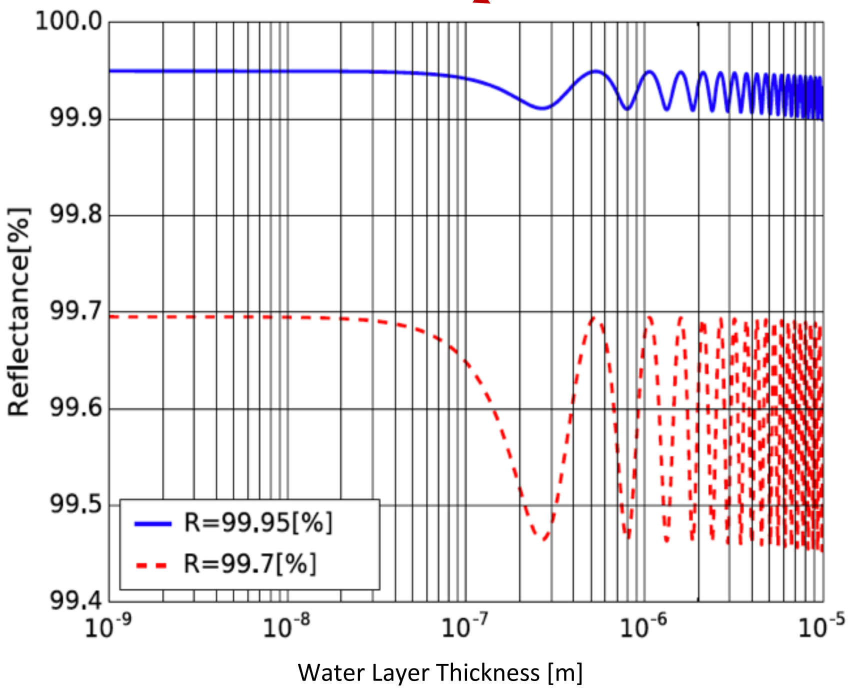


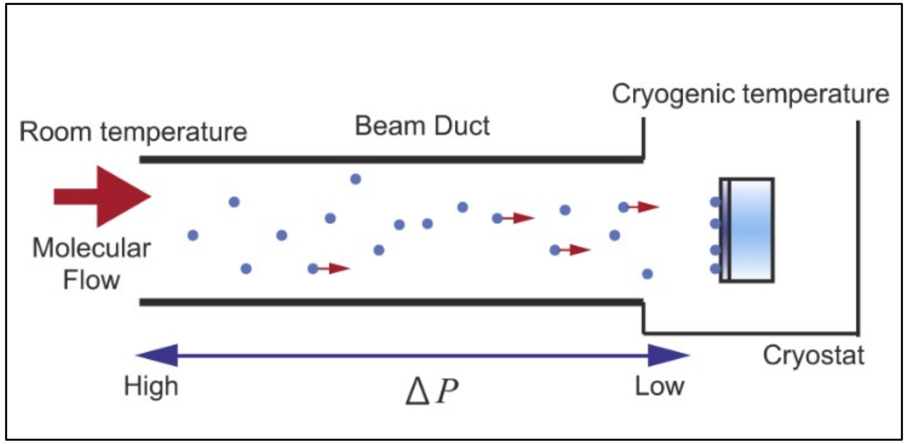

FIG. 1. Schematic drawing of the optical loss in the test mass mirror. The scattering and absorption lead to less arm cavity power, which decreases the sensitivity of GWDs. Furthermore, the optical absorption introduces an additional heat load to a cryogenic mirror.



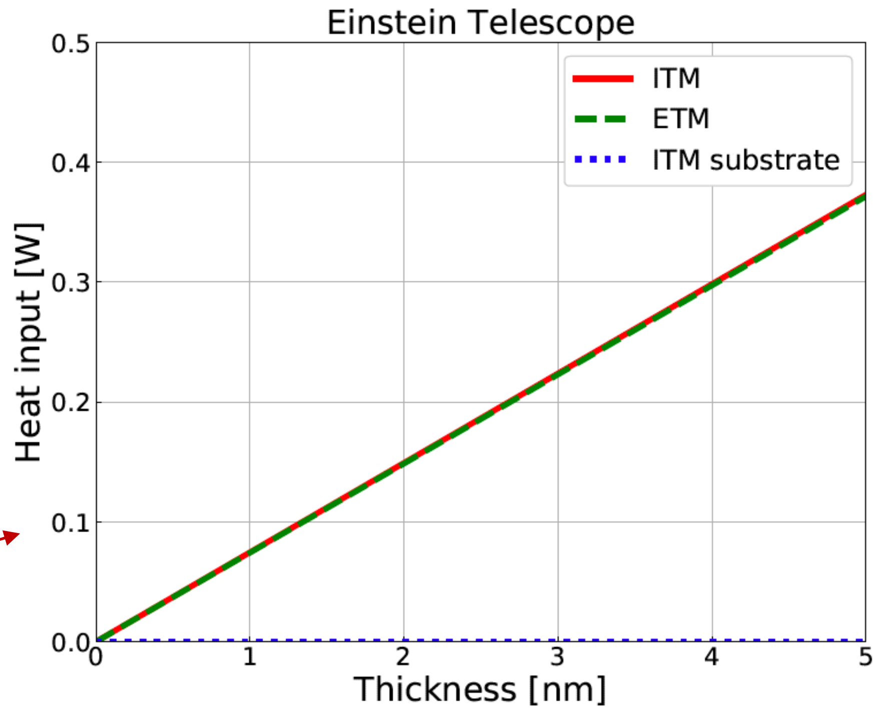

K. Hasegawa et al., Phys Rev. D, 99, 022003 (2019)

# Residual gas adsorption on cold surfaces

From KAGRA experience (Cryogenic Temperature)




ET maximum thermal budget **(~100 mW/ 1 W**) is expected to be exceeded already after ~**1-10 nm** of $H_2O$ ice!!!



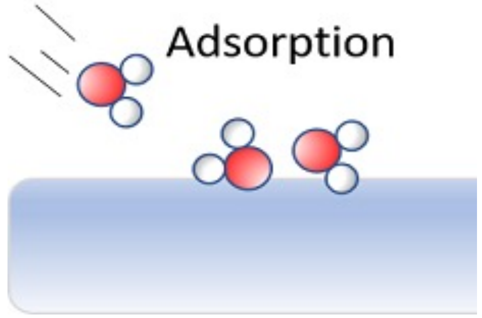

S. Tanioka et al., Phys Rev. D, 102, 022009 (2020)

# Residual gas adsorption on cold surfaces

Langmuir (L) unit:

**1 L = 1.33 x $10^{-6}$ mbar x 1s**

gas exposure of a surface (or dosage)




For sticking coefficient $S_c$= 1:
**1 L ~ 1 Monolayer (ML) cryosorbed**
for $H_2O$, 1 ML ~ 0.3 nm

**→ If $P_{H2O}$ ~ 1x $10^{-10}$ mbar, it takes 10.000 s (~3h) to build up a ML**

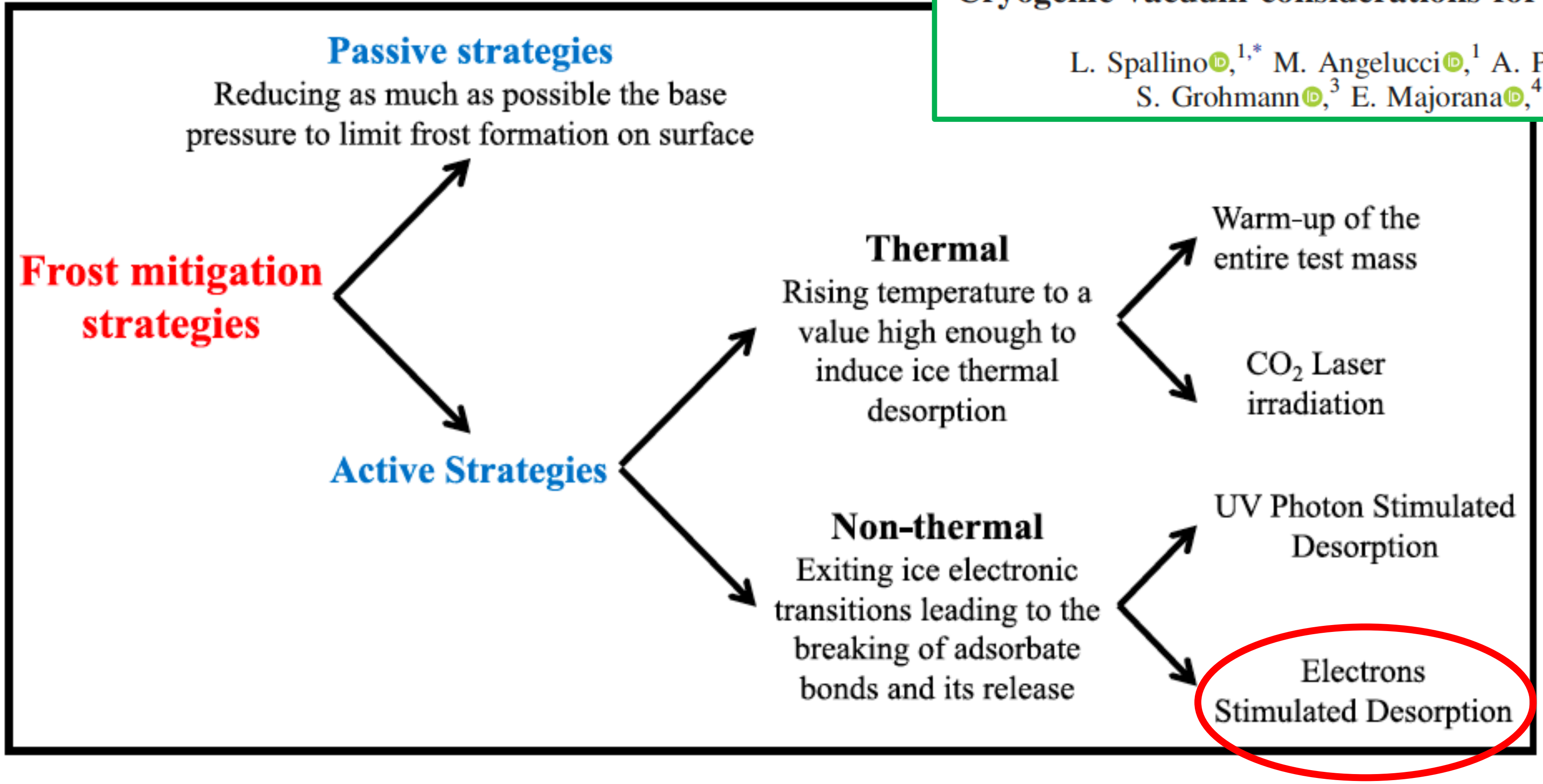
**→ If $P_{H_2O}$ ~ 1x $10^{-12}$ mbar, it takes 1.000.000 s (~300 h) to build up a ML**

**→ Timescale compatible with continuous data taking!**

PHYSICAL REVIEW D **104**, 062001 (2021)

**Cryogenic vacuum considerations for future gravitational wave detectors**

L. Spallino,[1,*] M. Angelucci,[1] A. Pasqualetti,[2] K. Battes,[3] C. Day,[3]
S. Grohmann,[3] E. Majorana,[4] F. Ricci,[4] and R. Cimino[1,†]

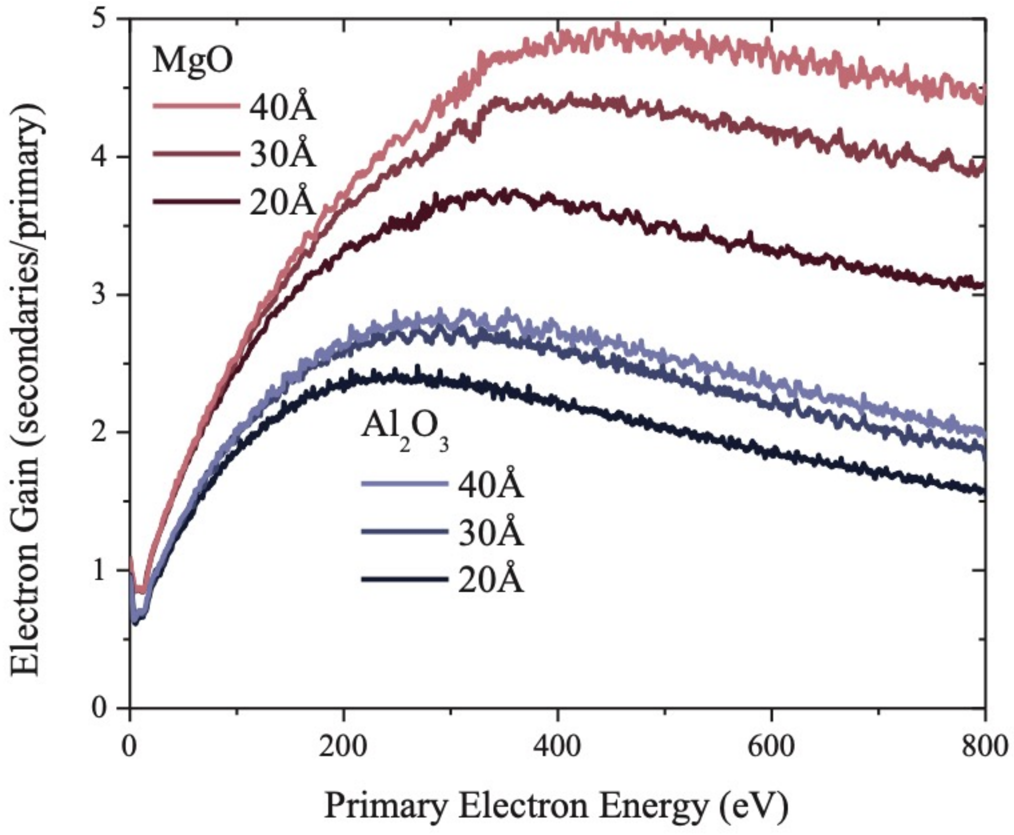



**Possible if a charging mitigation method compliant with cryogenics is proved!**

# Low energy electrons to both mitigate charging issues and to remove frost from mirrors’ surface of future GW detectors

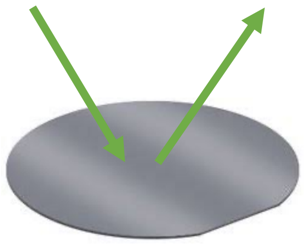
# Charging mitigation and SEY

**On a dielectric, the charge left on the surface depends on the energy of the impinging electrons**




Jokela et al. Phys. Procedia (2011)

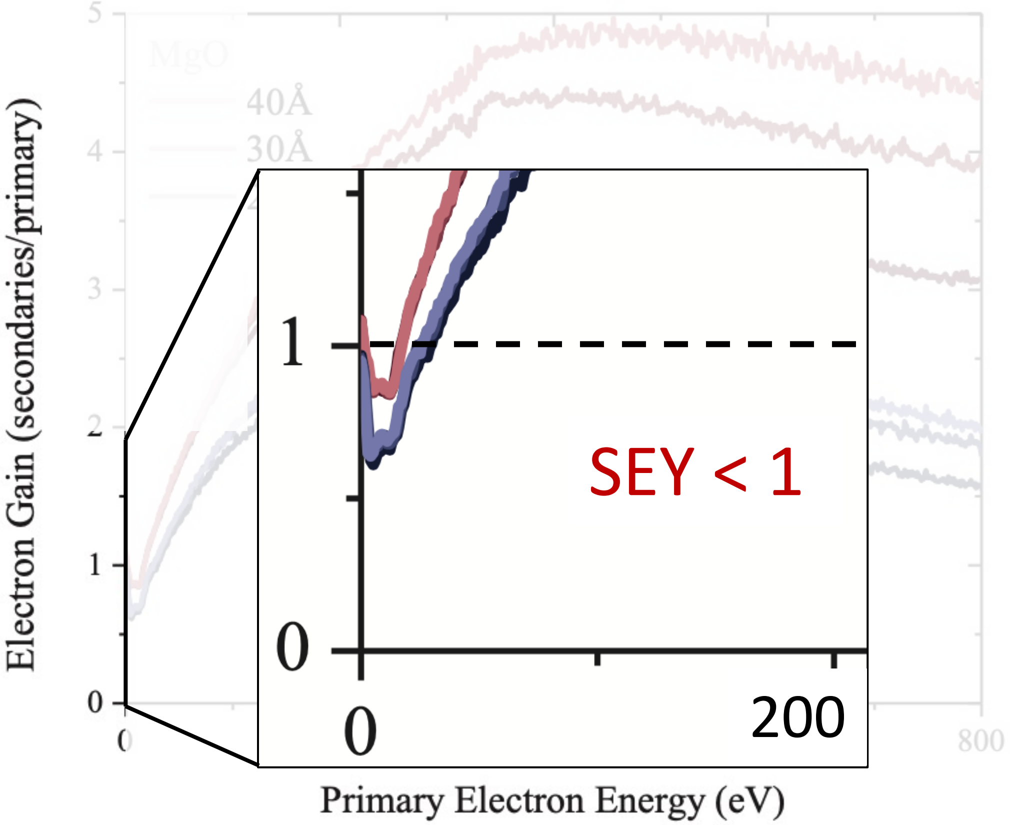
Incident electrons current ($I_p$) Emitted electrons current ($I_{out}$)



$$SEY = \delta = \frac{I_{out}}{I_{in}} = \frac{I_p - Is}{I_p} = 1 - \frac{I_s}{I_p}$$

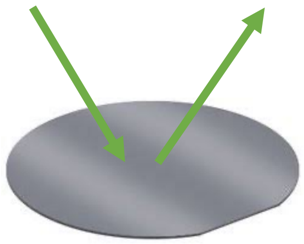
# Charging mitigation and SEY

**On a dielectric, the charge left on the surface depends on the energy of the impinging electrons**




Jokela et al. Phys. Procedia (2011)

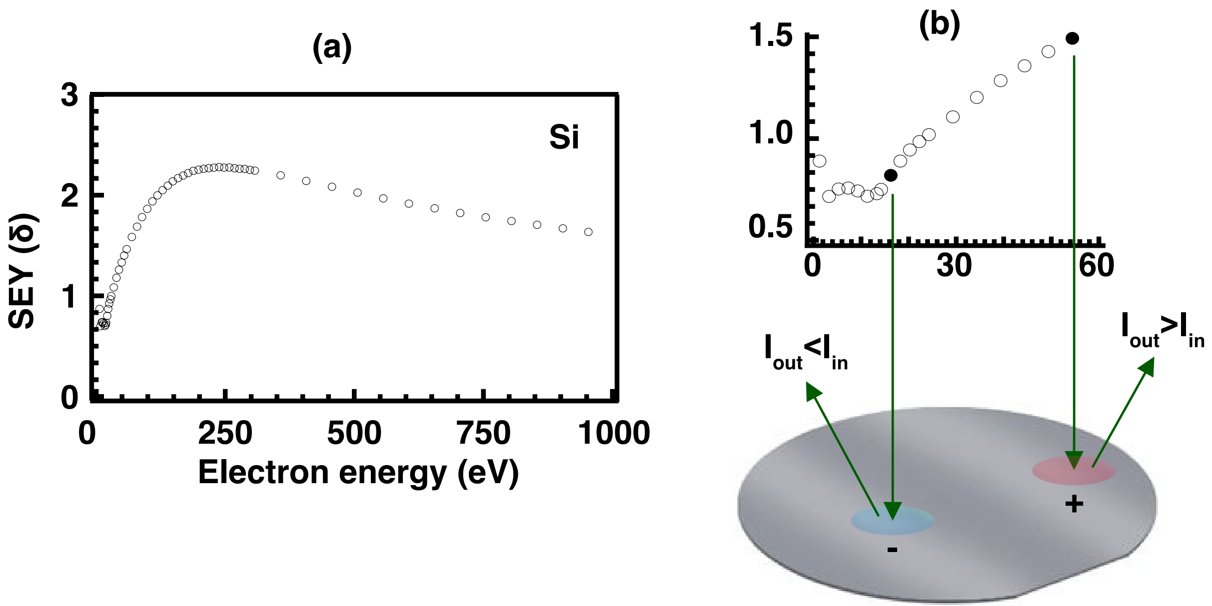
Incident electrons current ($I_p$) Emitted electrons current ($I_{out}$)



$$SEY = \delta = \frac{I_{out}}{I_{in}} = \frac{I_p - Is}{I_p} = 1 - \frac{I_s}{I_p}$$

**This can very well explain the mirrors electrostatic charge, its inhomogeneity and sign uncertainty**

# Charging mitigation and SEY




**SEY not only can explain the charging phenomenon but suggests how to cure it!**

PHYSICAL REVIEW D **105**, 042003 (2022)

**Can electrons neutralize the electrostatic charge on test mass mirrors in gravitational wave detectors?**

L. Spallino,[1,*] M. Angelucci,[1] G. Mazzitelli,[1] R. Musenich,[2] S. Farinon,[2] A. Chincarini,[2] F. Sorrentino,[2] A. Pasqualetti,[3] G. Gemme,[2] and R. Cimino[1,†]
[1]*LNF-INFN, Via E. Fermi 54, 00044 Frascati (Rome) Italy*
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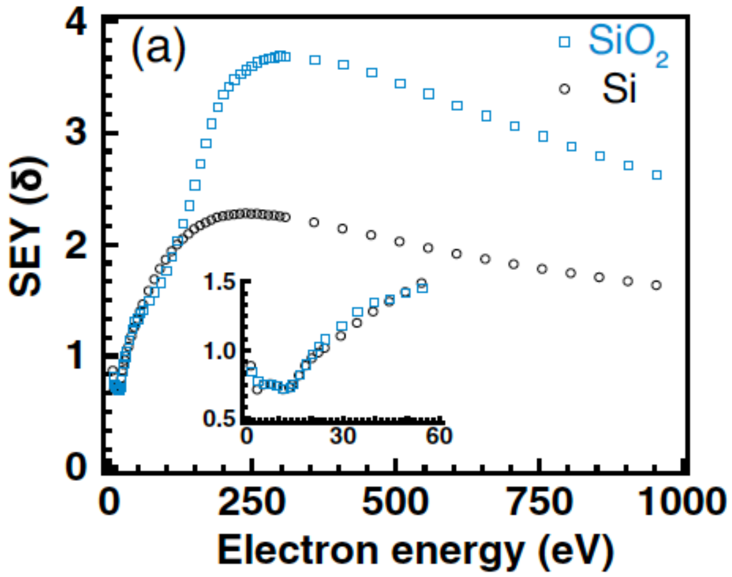
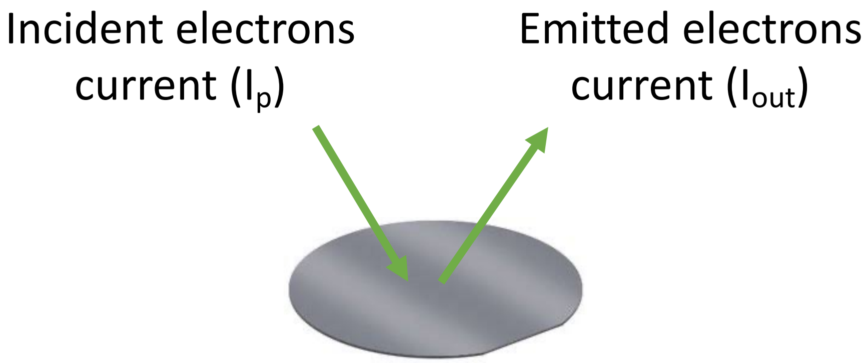
[3]*European Gravitational Observatory (EGO), 56021 Cascina (Pisa), Italy*

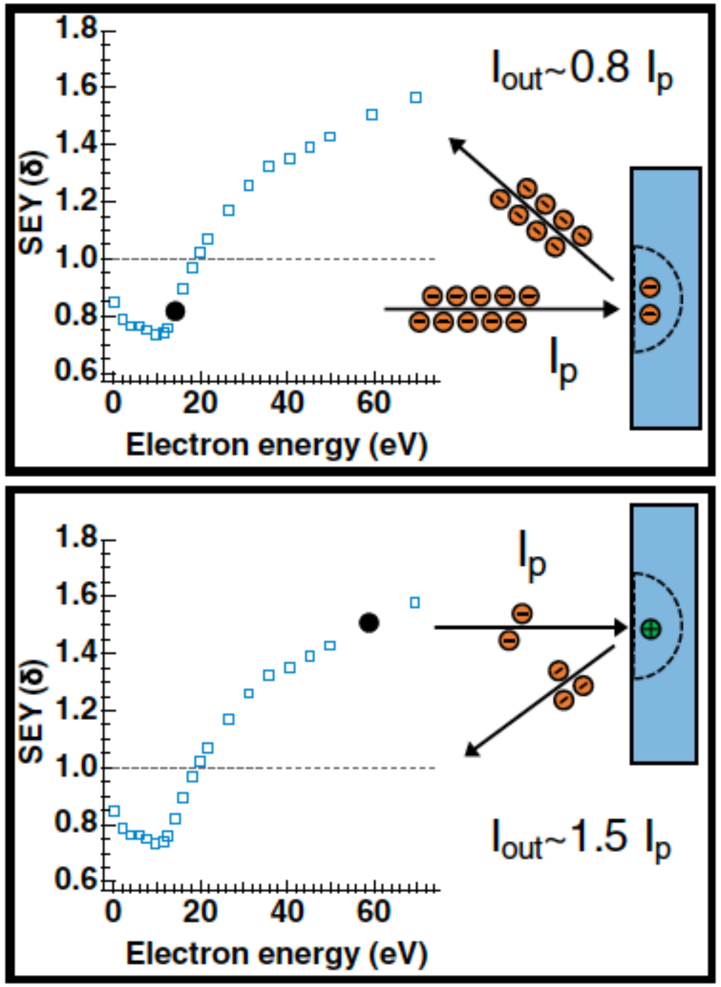
(Received 12 January 2021; accepted 20 January 2022; published 17 February 2022)

We suggested to use **electrons** of variable but **low energy** (between 10 to 100 eV) to **neutralize** unwanted **electrostatic charge on test mass mirrors**. Low energy selected electrons can indeed compensate charges of both polarity on mirror optics.

# Low energy electrons to neutralize electrostatic charging



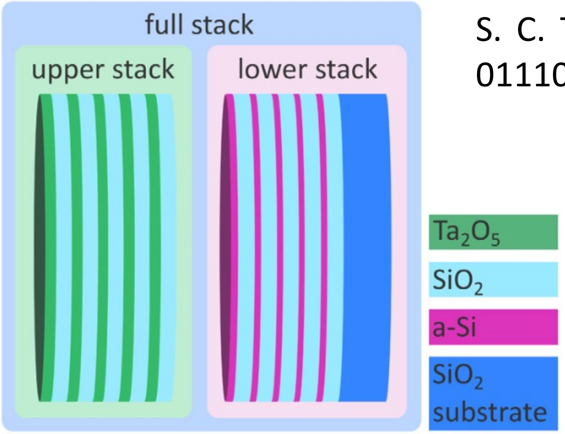




The energy of the incident electrons can be opportunely tuned to neutralize positive and negative charges on the mirror's dielectric surface

# Low energy electrons to neutralize electrostatic charging

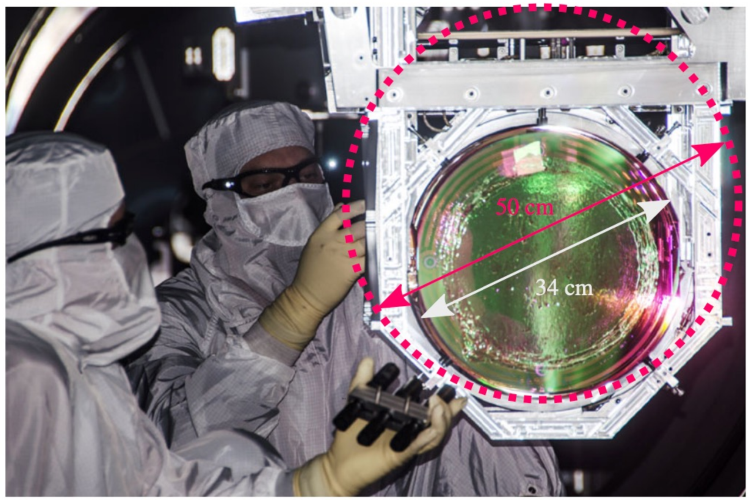
Fundamental detailed SEY investigation of specific materials (as the ones composing optics in GW detectors) →




S. C. Tait et al. Phys. Rev. Lett. 125, 011102 (2020)

Each layer has a thickness of the order of hundreds of nm

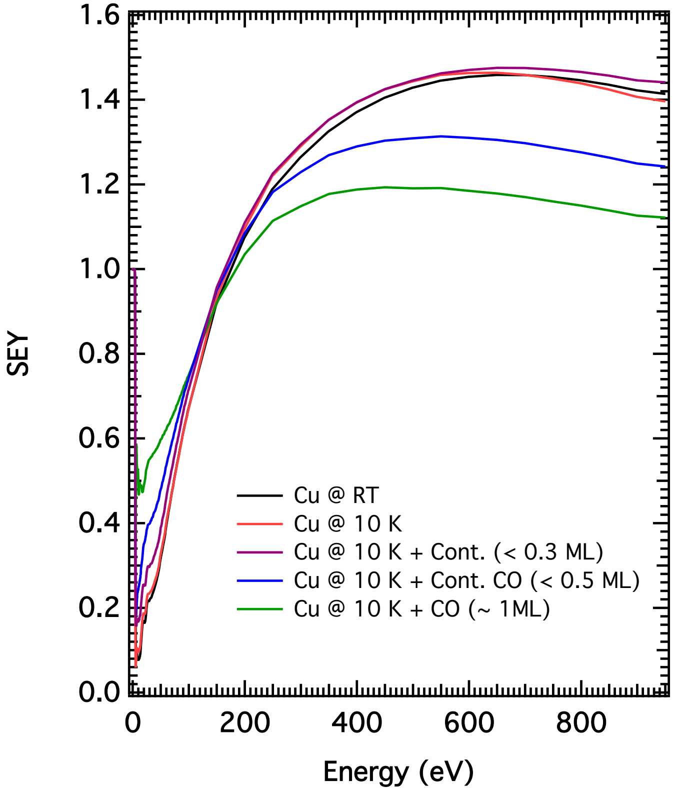
- SEY measurements on insulators (critical from the measuring point of view) → useful comparison with simulations
- Understanding of charging mechanisms and charge distribution in such kind of materials
- Taking into account environmental conditions and external interactions

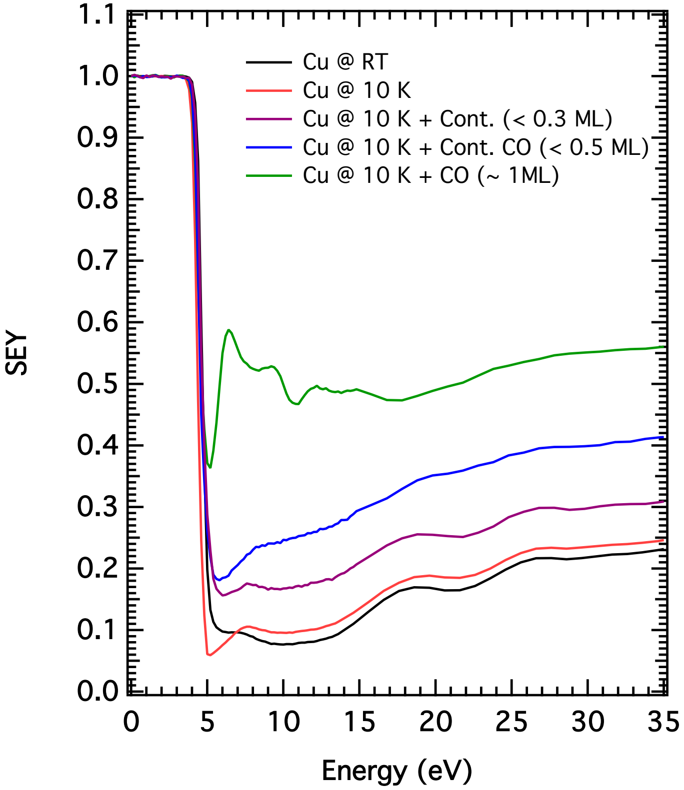


# SEY at cryogenic temperatures

See talk of M. Angelucci

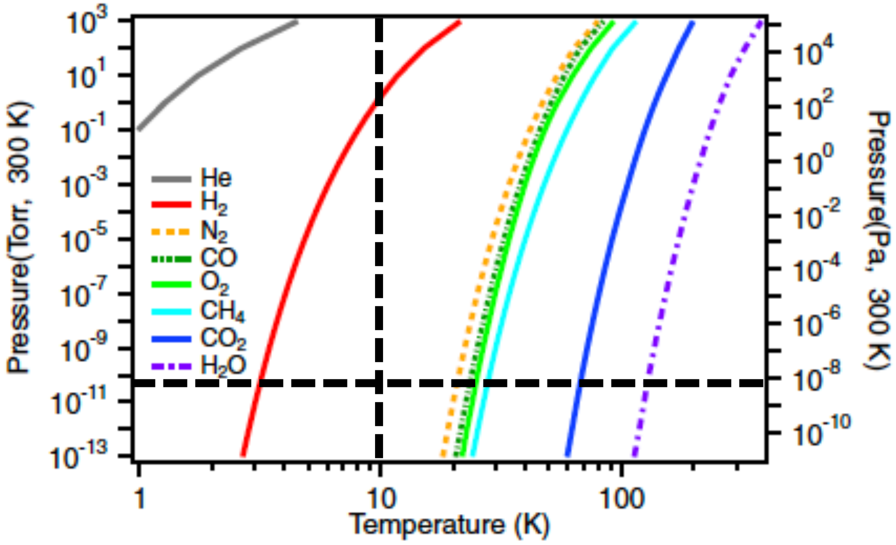
L. A. Gonzalez et al., AIP Adv. (2017)



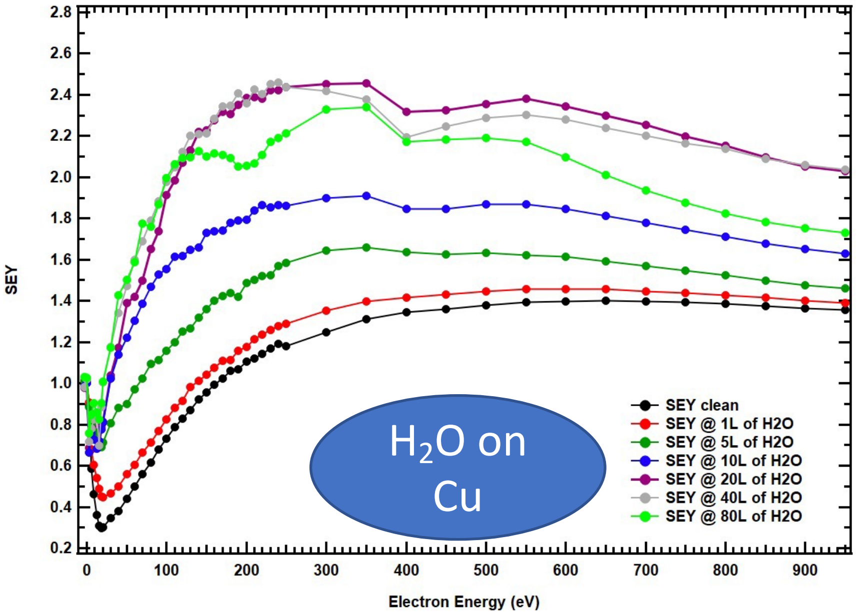

## Residual gas in a vacuum at cryogenic temperature

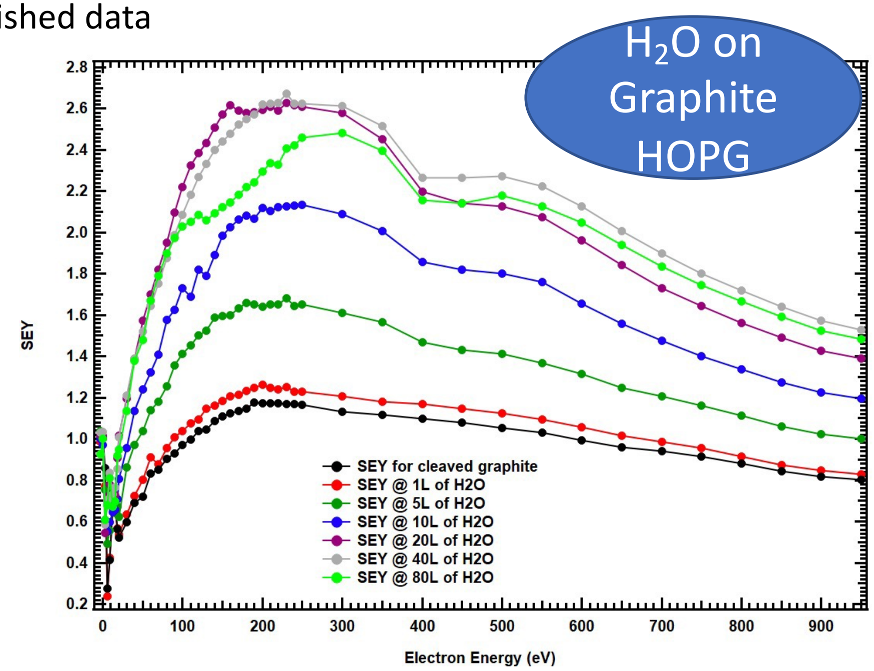
SEY of cold surfaces influenced by gas <u>physisorption</u>



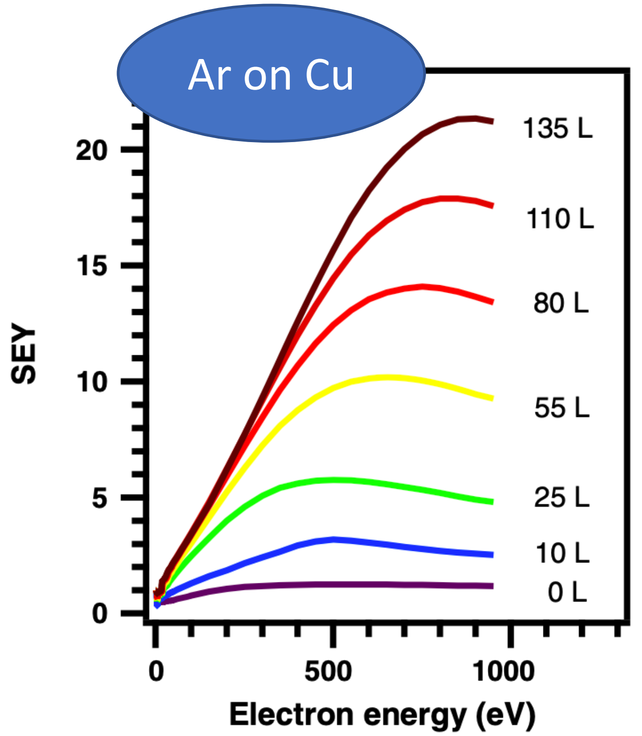
# SEY at cryogenic temperatures

Not published data



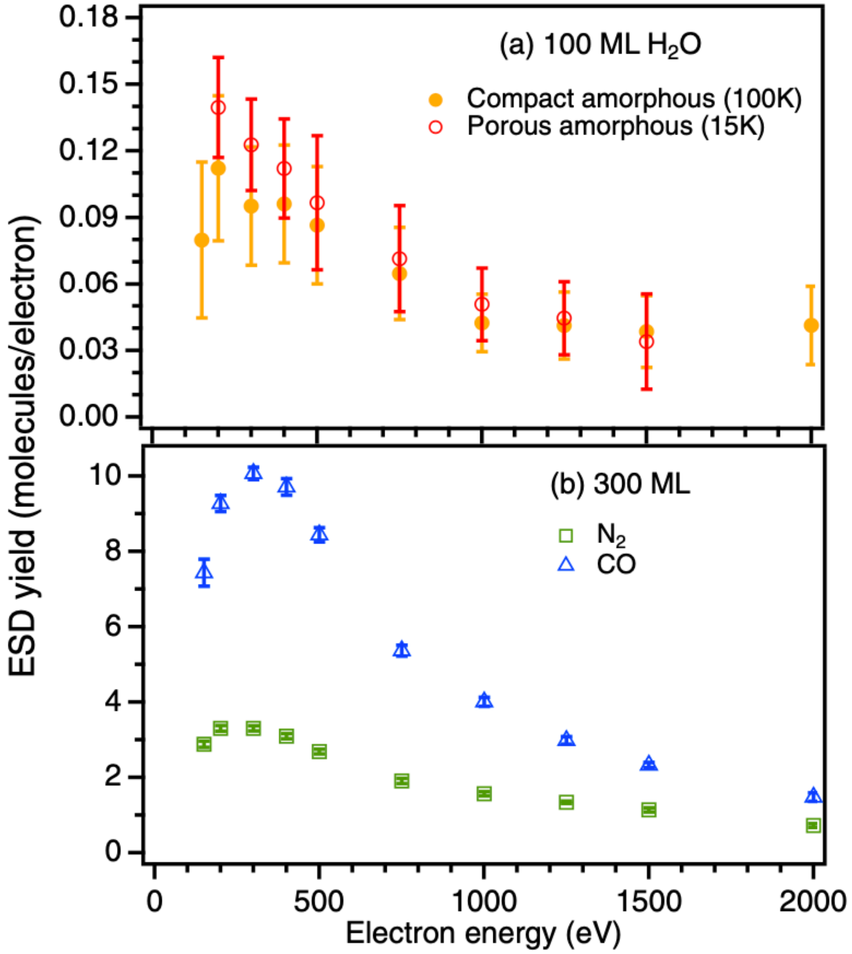

L. Spallino et al., Phys. Rev. Accel. Beams (2020)



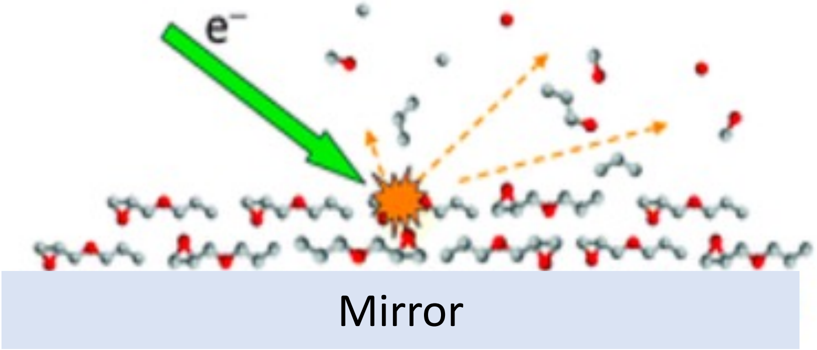

**Fundamental SEY investigation of gas condensed on a cryogenic surface**

# Low energy electrons to mitigate frost by electron Stimulated Desorption (ESD)

R. Dupuy et al. J. Appl. Phys. 128, 175304 (2020)
L. Spallino et al., Phys. Rev. D, 062001, 104 (2021)

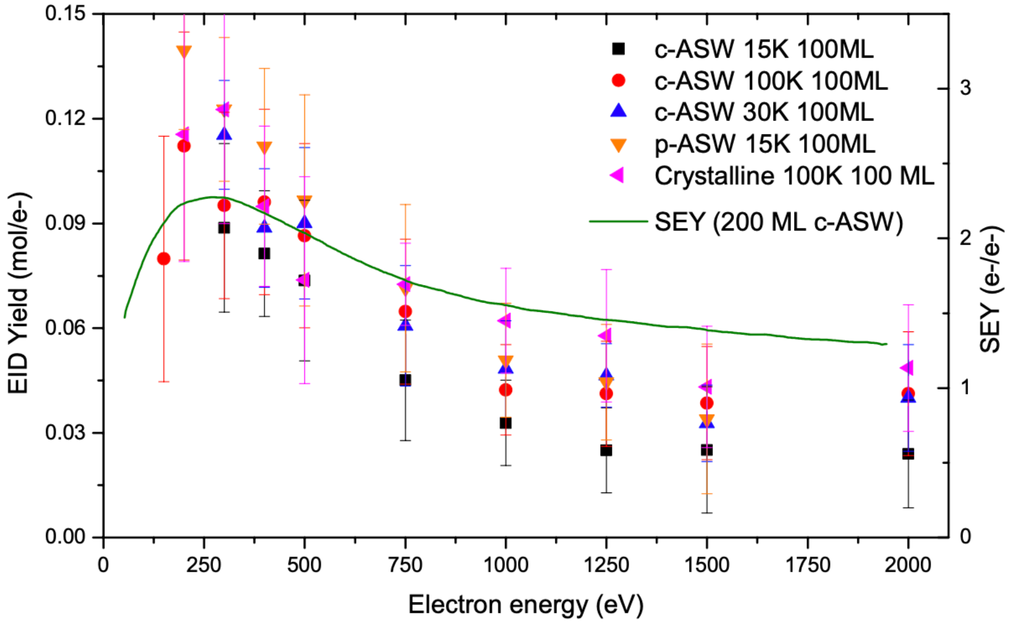



**Electrons efficiently induce molecular ice nonthermal desorption!**

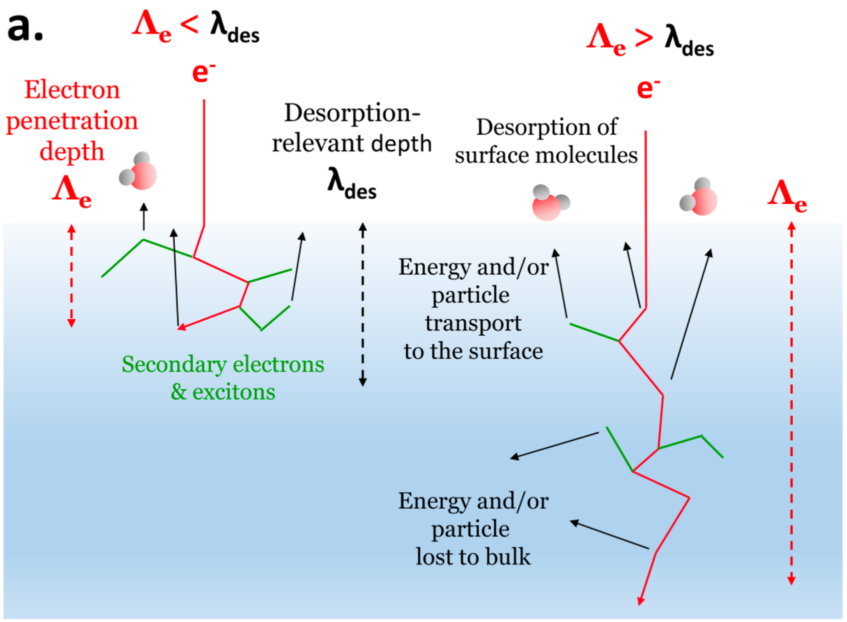



# Low energy electrons to mitigate frost by electron Stimulated Desorption (ESD)

In the limit of low-energy electrons, the desorption yield is almost proportional to the total energy of the electron, since all of the energy is deposited near the surface




R. Dupuy et al. J. Appl. Phys. 128, 175304 (2020)

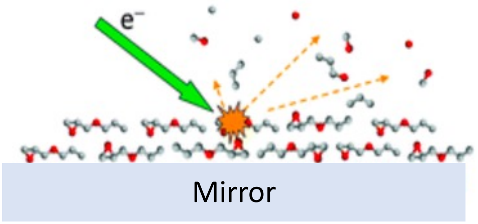



- ESD measurements critical from the measuring point of view (fine RGA) → useful comparison with simulations
- ESD is a complex matter → the study of the process and its interpretation is of fundamental importance

# Low energy electrons to mitigate frost by electron Stimulated Desorption (ESD)

If $P_{eff} \sim 1x10^{-10}$ ($H_2O$,CO,$CO_2$, etc) mbar; sticking coefficient = 1

➔ 1 monolayer ($\sim 10^{15}$ mol/cm$^2$ $\sim$ 0.3 nm) will be cryosorbed in 10.000 s.
($\sim$ 2.5nm/day $\sim 10$ times less than in KAGRA)



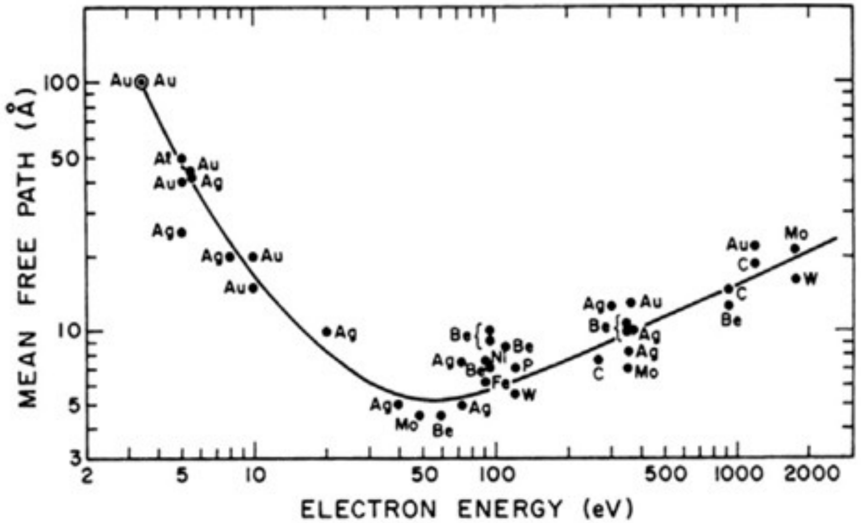

If we assume a mean **ESD η= 0.1 mol./electron (as for $H_2O$) @ 100eV**.
(R. Dupuy et al. J. Appl. Phys. 128, 175304, 2020)

To remove **1 ML** we need an el. current of: **~ 1 mAmps/cm$^2$ in one second**

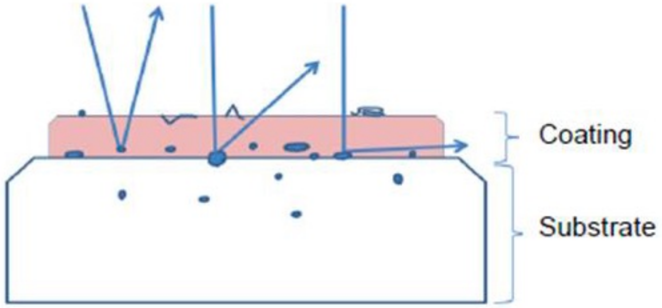
… depositing less than 100 mW/ML/cm$^2$ (not all el. energy goes in thermal heat!)

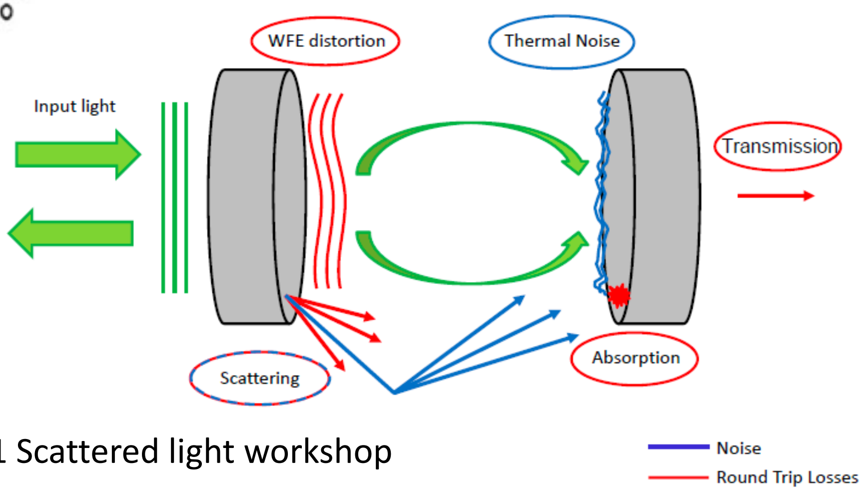
All in UHV, with marginal heating up of the mirrors and (possibly) reduced downtime.
Deserves further investigation!

# Low energy electrons and defects formation




Low energy electrons do not significantly penetrate into the mirror surface due to their low mean free path, so that **minimal effects on mirror quality are expected**.




S.Sayah et al., GWADW2021 Scattered light workshop

Any defects formation could spoil the mirrors' sensitivity.

→ The accurate investigation of the effects induced by electrons irradiation is mandatory

# Summary and conclusion

- Low energy electrons may have great significance in gravitational wave detector technology since they can contribute to solve charging and frost issues at cryogenic temperature

- A huge effort is mandatory from the fundamental point of view to go deep into the basic aspects of the electron-matter interaction

# Thank you for your attention