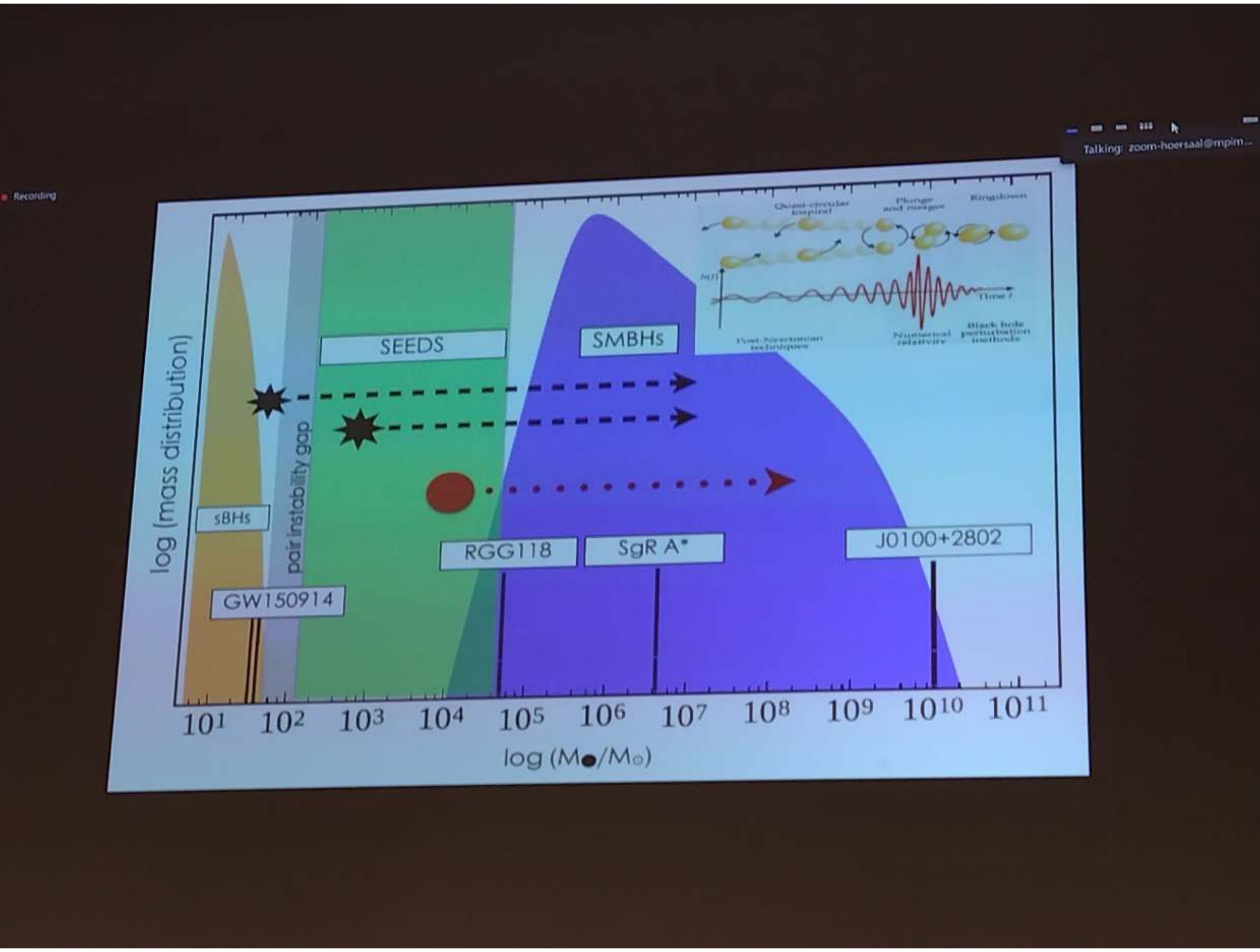
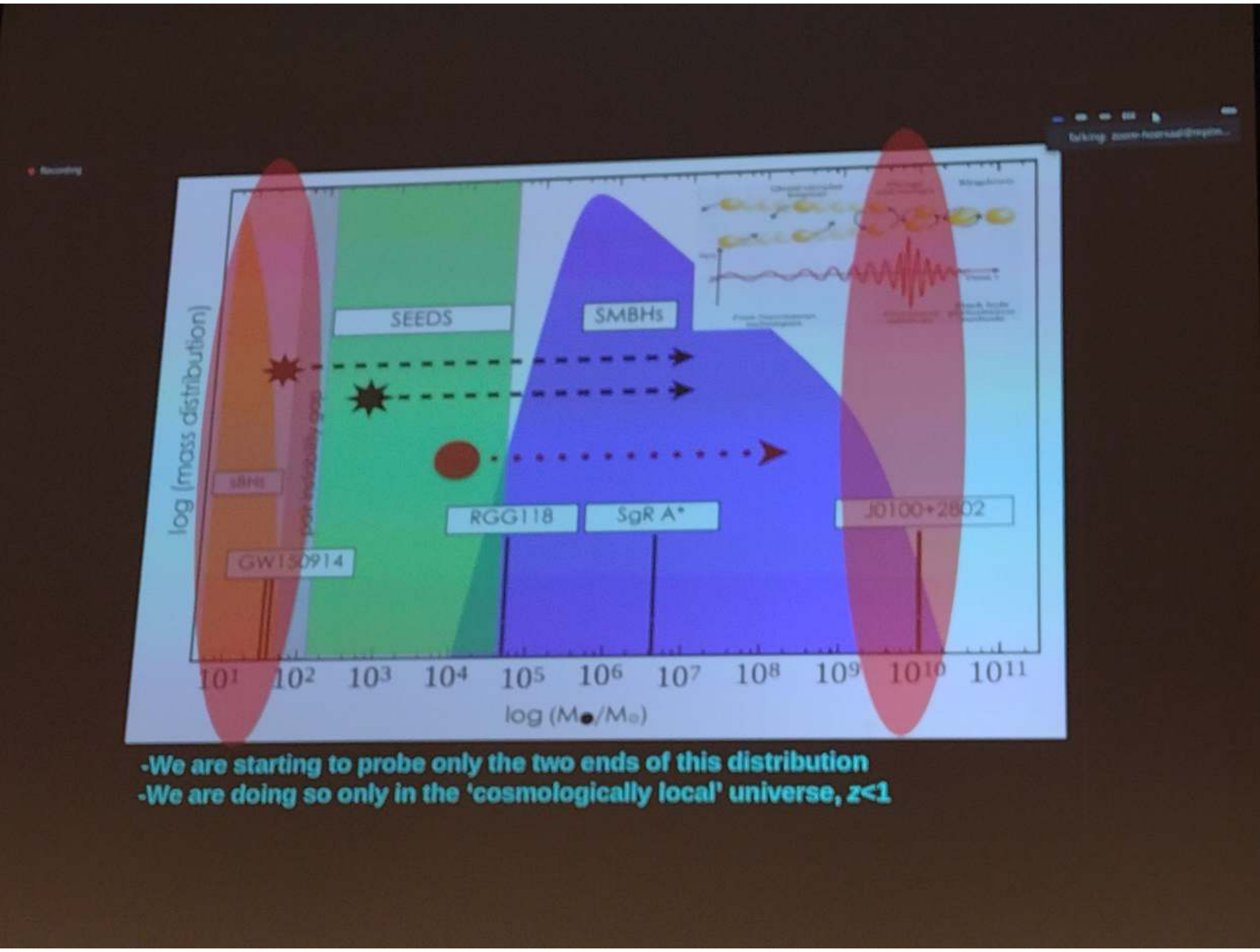

Recording
Talking: zoom-hoersaal@mpim...
SEEDS
SMBHs
log (mass distribution)
pair instability gap
sBHs
GW150914
RGG118
SgR A*
J0100+2802
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹
log (M●/M☉)


Recording
log (mass distribution)
SEEDS
SMBHs
sBHs
RGG118
SgR A*
J0100+2802
GW150914
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11
log (M●/M☉)
-We are starting to probe only the two ends of this distribution
-We are doing so only in the 'cosmologically local' universe, z<1

Heuristic scalings

We want compact accelerating systems
Consider a BH binary of mass M, and semimajor axis a

$$h \sim \frac{R_S}{a}\frac{R_S}{r} \sim \frac{(GM)^{5/3}(\pi f)^{2/3}}{c^4 r}$$

In astrophysical scales

$$h \sim 10^{-20}\,\frac{M}{M_\odot}\,\frac{\mathrm{Mpc}}{D}$$

$$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\,\frac{M_\odot}{M}$$

10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^3$
10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$
10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f < 10^{-5}$

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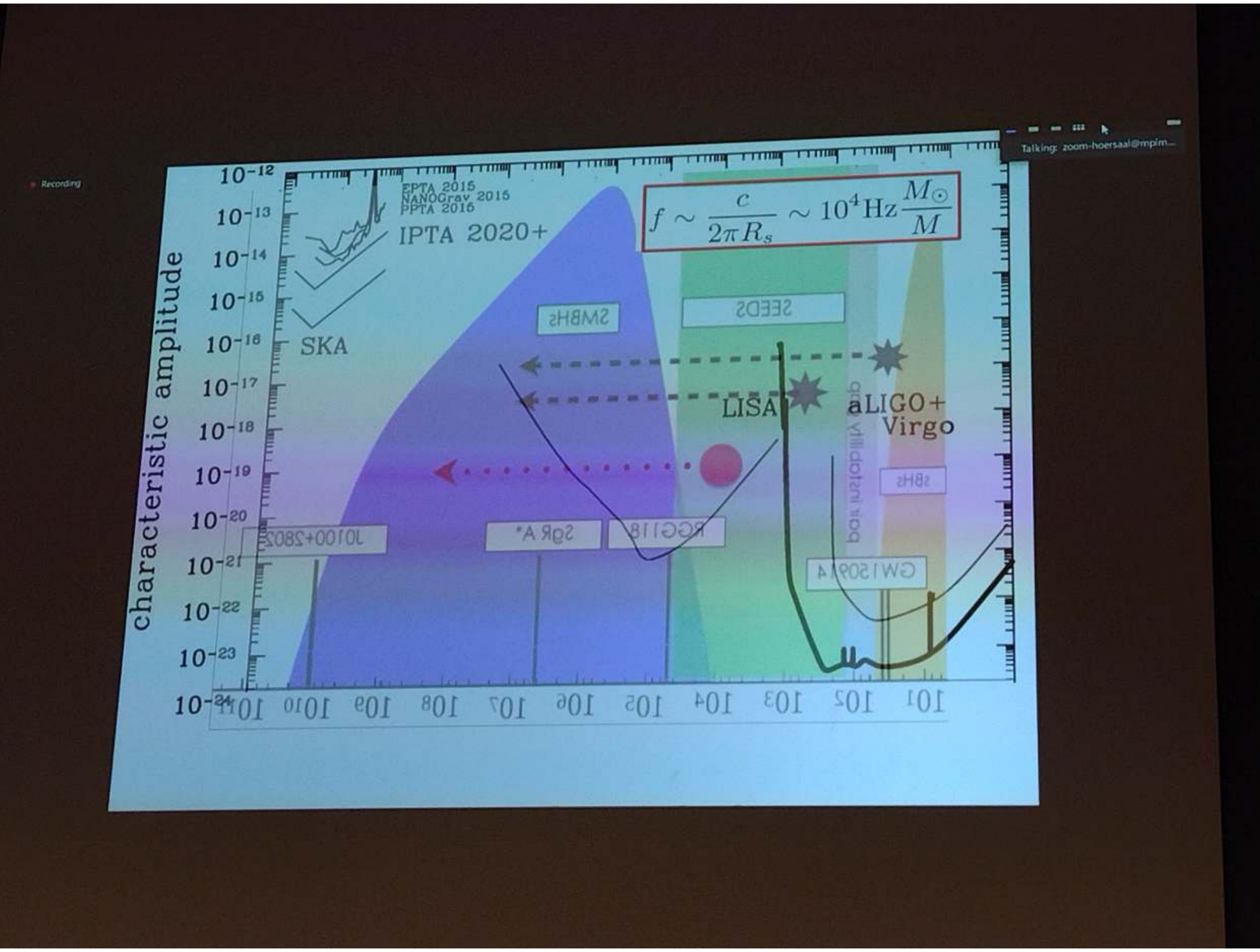
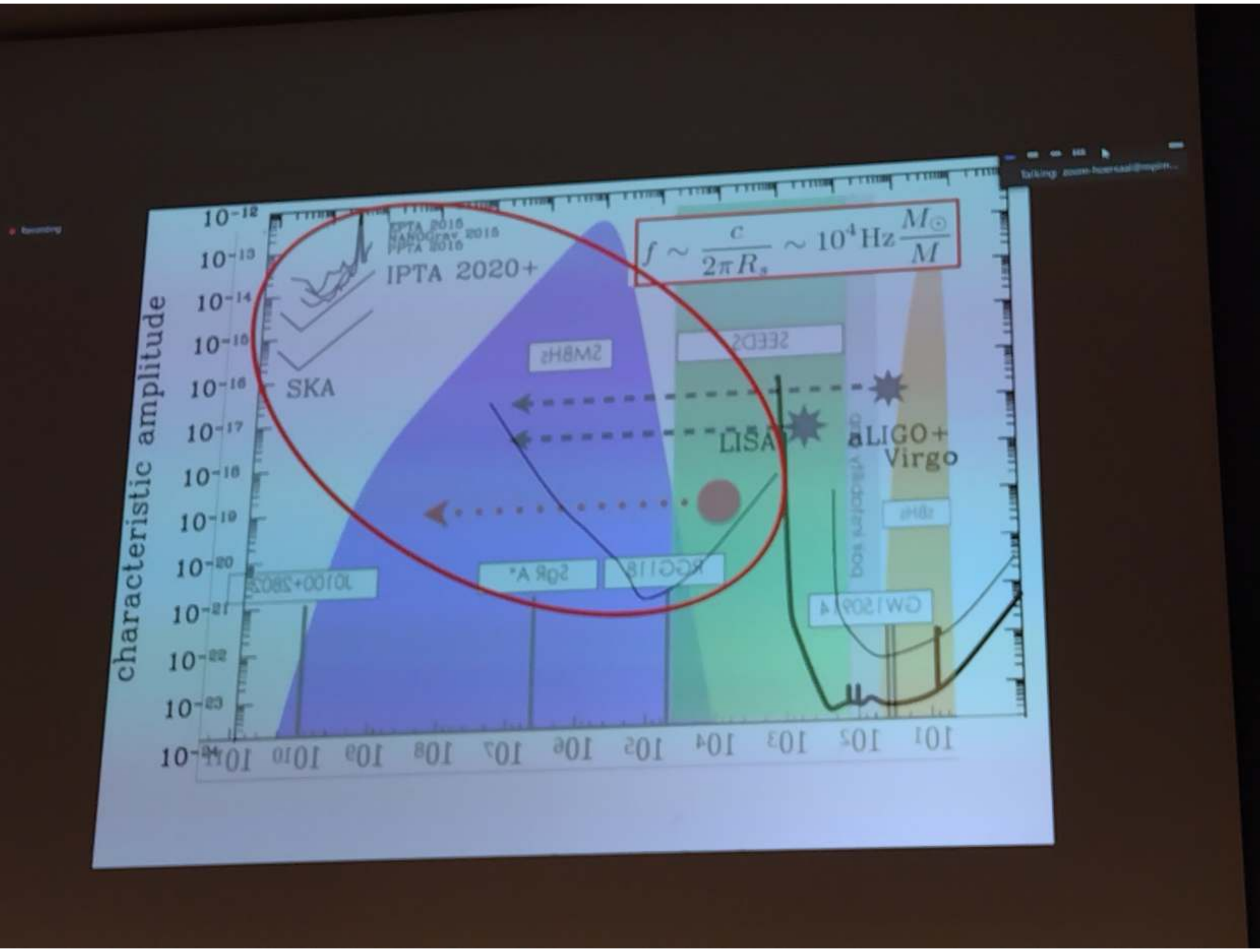

Recording
Talking: zoom-hoersaal@mpim...
characteristic amplitude
EPTA 2015
NANOGrav 2015
PPTA 2016
IPTA 2020+
SKA
$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\,\frac{M_\odot}{M}$
LISA
aLIGO+
Virgo



characteristic amplitude
EPTA 2015
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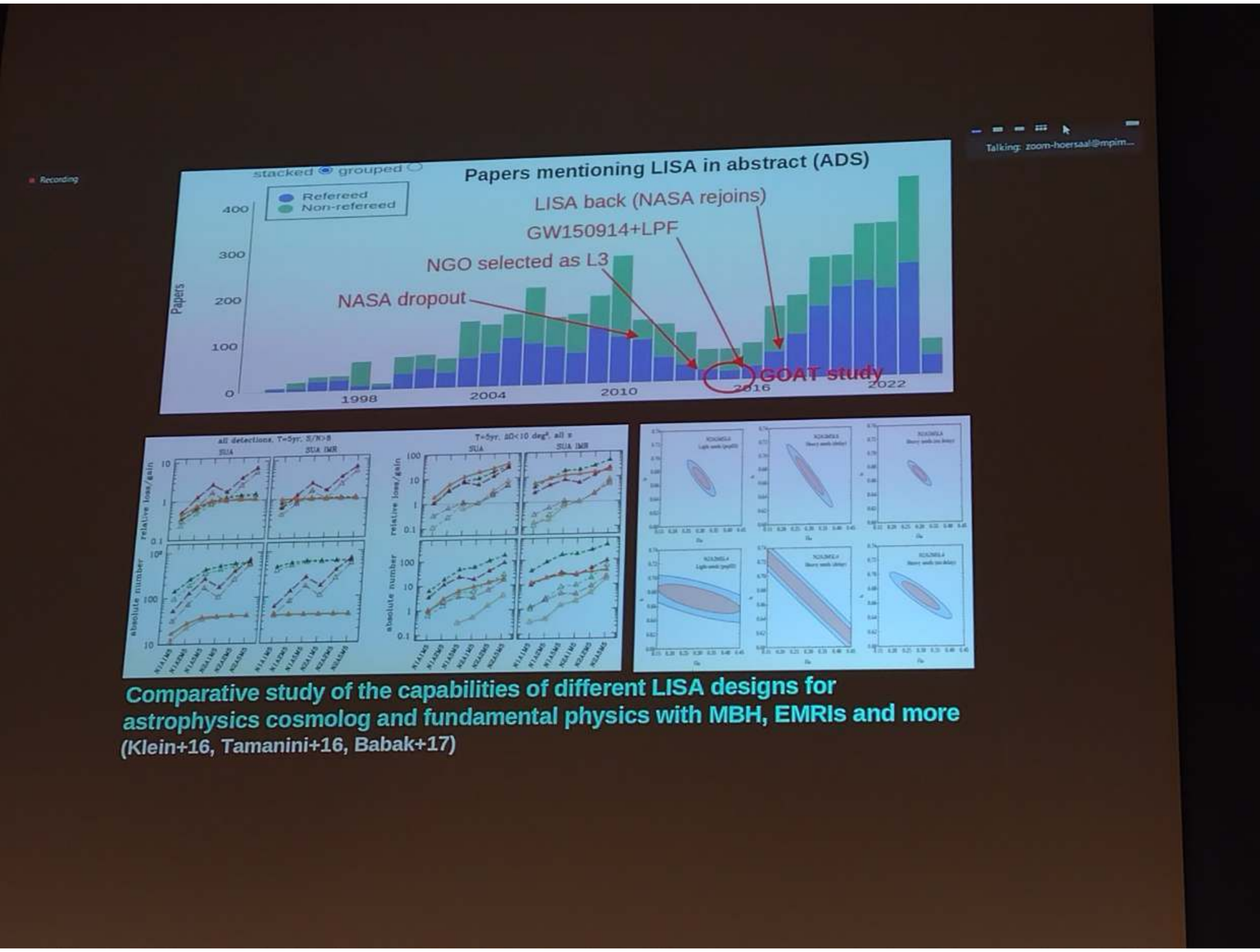
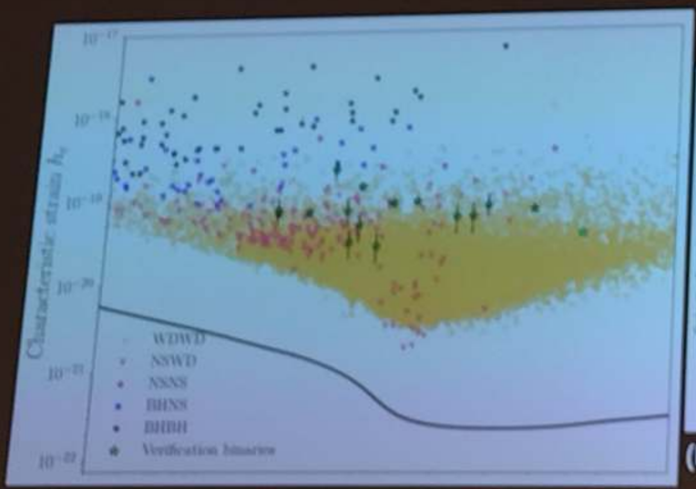
SKA
LISA
aLIGO+
Virgo
$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\,\frac{M_\odot}{M}$
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}

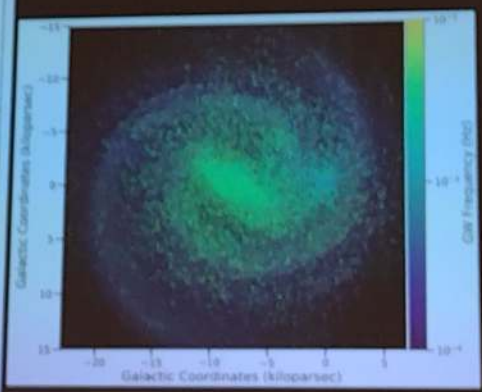

The Laser Interferometer Space Antenna
Sensitive in the mHz frequency range where massive black hole (MBH) binary (MBHB) evolution is fast (chirp)
Observes the full inspiral/merger/ringdown
(LISA Red Book: arXiv:2402.07571)
3 satellites trailing the Earth connected through laser links
Proposed baseline:
2.5M km armlength
6 laser links
4.5 yr lifetime
(10 yr goal)
Galactic Binaries
Verification Binaries
Massive BH Binaries
Stellar Mass BH Binaries
Multiband Sources
EMRIs
Observatory Characteristic Strain
Total
Characteristic Strain
Frequency (Hz)


Recording
Talking: zoom-hoersaal@mpim...
stacked grouped
Papers mentioning LISA in abstract (ADS)
Refereed
Non-refereed
Papers
400
300
200
100
0
1998
2004
2010
2016
2022
LISA back (NASA rejoins)
GW150914+LPF
NGO selected as L3
NASA dropout
GOAT study
all detections, T=5yr, S/N>8
SUA
SUA IMR
relative loss/gain
absolute number
T=5yr, ΔΩ<10 deg², all z
Comparative study of the capabilities of different LISA designs for
astrophysics cosmolog and fundamental physics with MBH, EMRIs and more
(Klein+16, Tamanini+16, Babak+17)

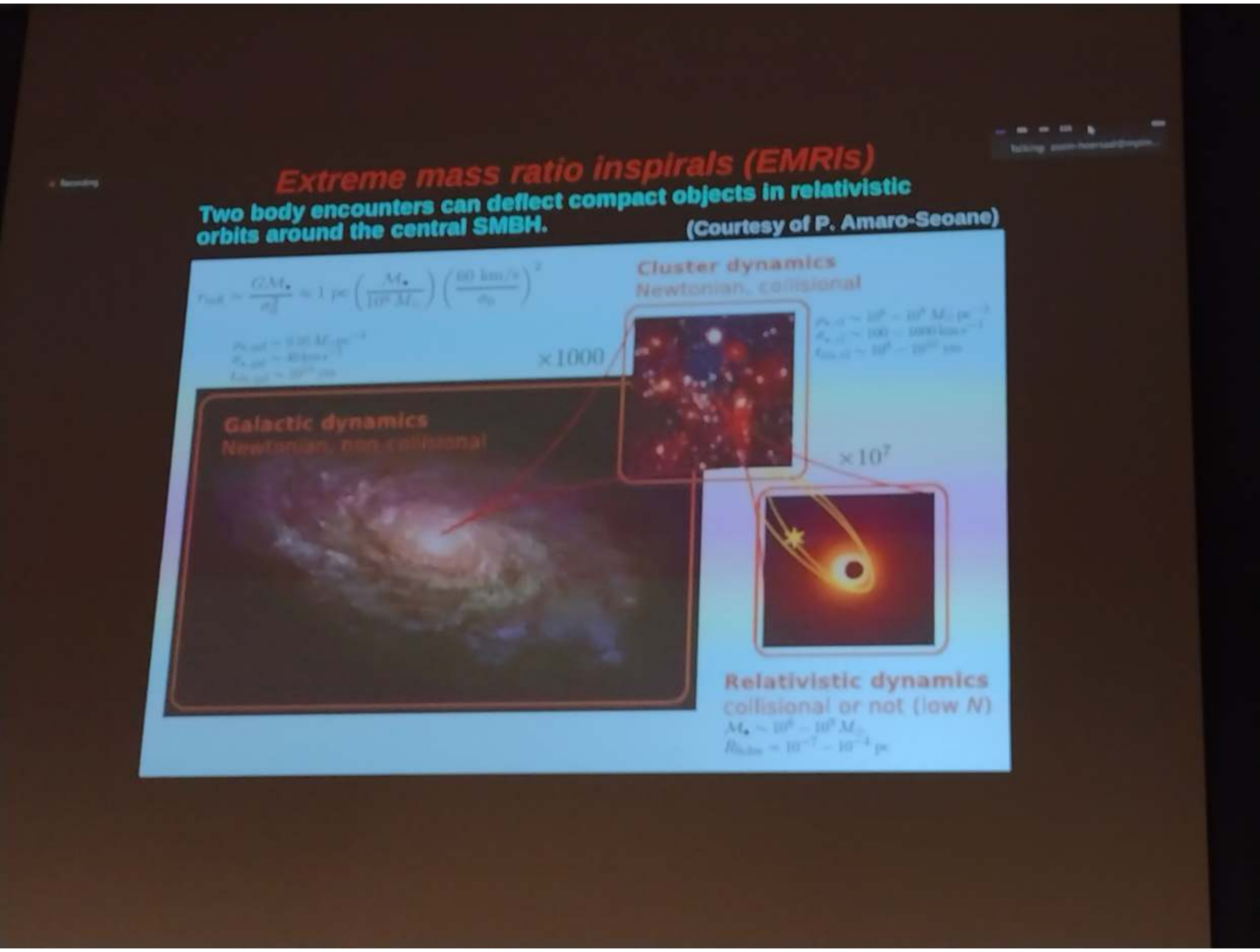
Galactic Binaries

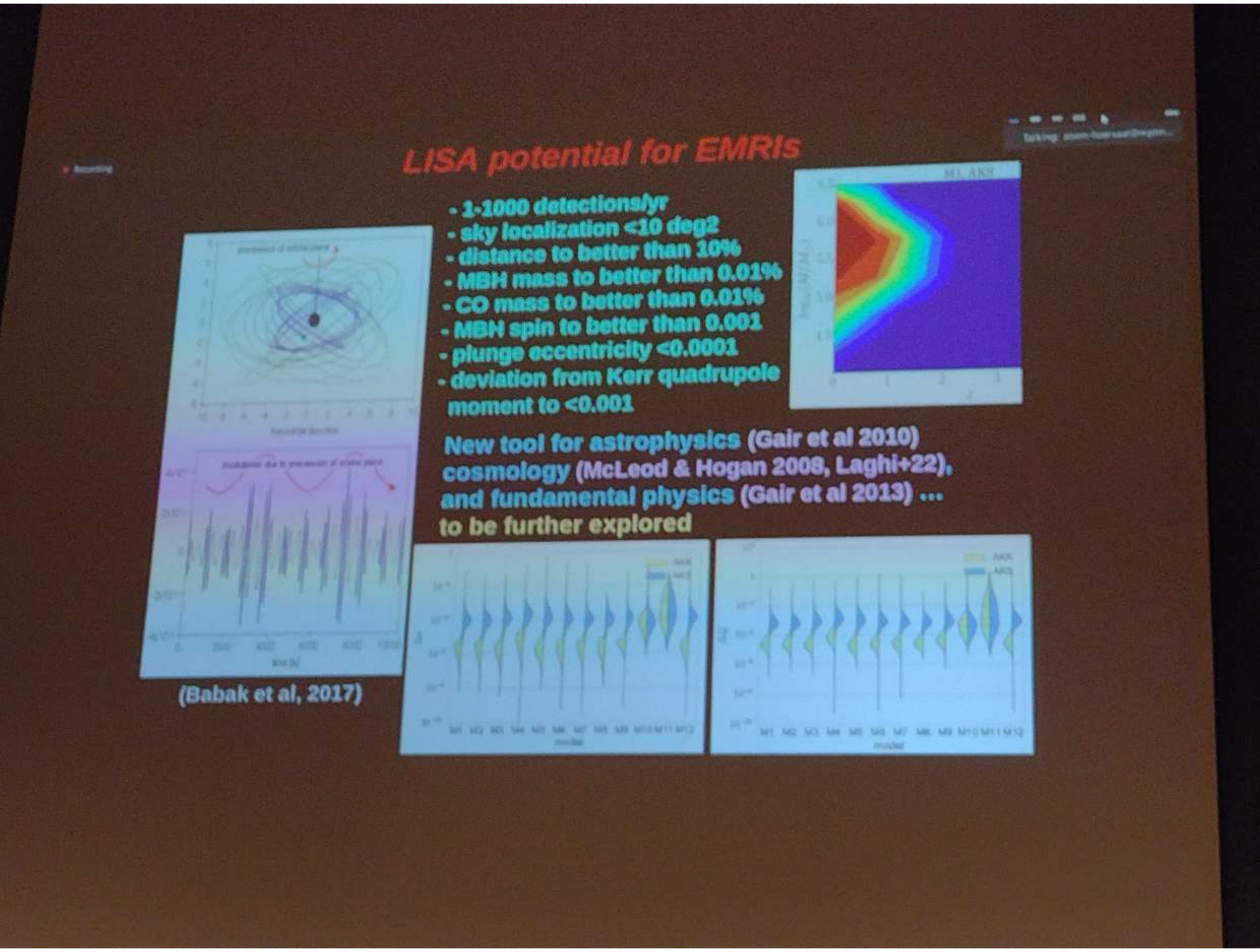
- 100M WD binaries in the Galaxy
- 20k+ individual detection + stochastic GWB
- characterization of the structure of the galaxy
- rate of WD binary mergers in our galaxy (SN1a connection?)
- binary astrophysics
- multimessenger astrophysics
- NS/BH binaries





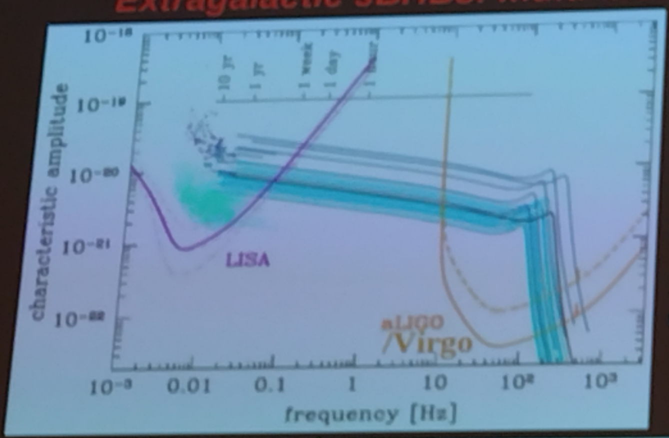
(LISA Red Book)


Extreme mass ratio inspirals (EMRIs)
Two body encounters can deflect compact objects in relativistic orbits around the central SMBH.
(Courtesy of P. Amaro-Seoane)
Cluster dynamics
Newtonian, collisional
×1000
Galactic dynamics
Newtonian, non-collisional
×10⁷
Relativistic dynamics
collisional or not (low N)



LISA potential for EMRIs
- 1-1000 detections/yr
- sky localization <10 deg2
- distance to better than 10%
- MBH mass to better than 0.01%
- CO mass to better than 0.01%
- MBH spin to better than 0.001
- plunge eccentricity <0.0001
- deviation from Kerr quadrupole moment to <0.001
New tool for astrophysics (Gair et al 2010)
cosmology (McLeod & Hogan 2008, Laghi+22),
and fundamental physics (Gair et al 2013) ...
to be further explored
(Babak et al, 2017)
M1, AKS
AKK
AKS
M1 M2 M3 M4 M5 M6 M7 M8 M9 M10 M11 M12
model

Extragalactic sBHBs: multi-band GW astronomy?



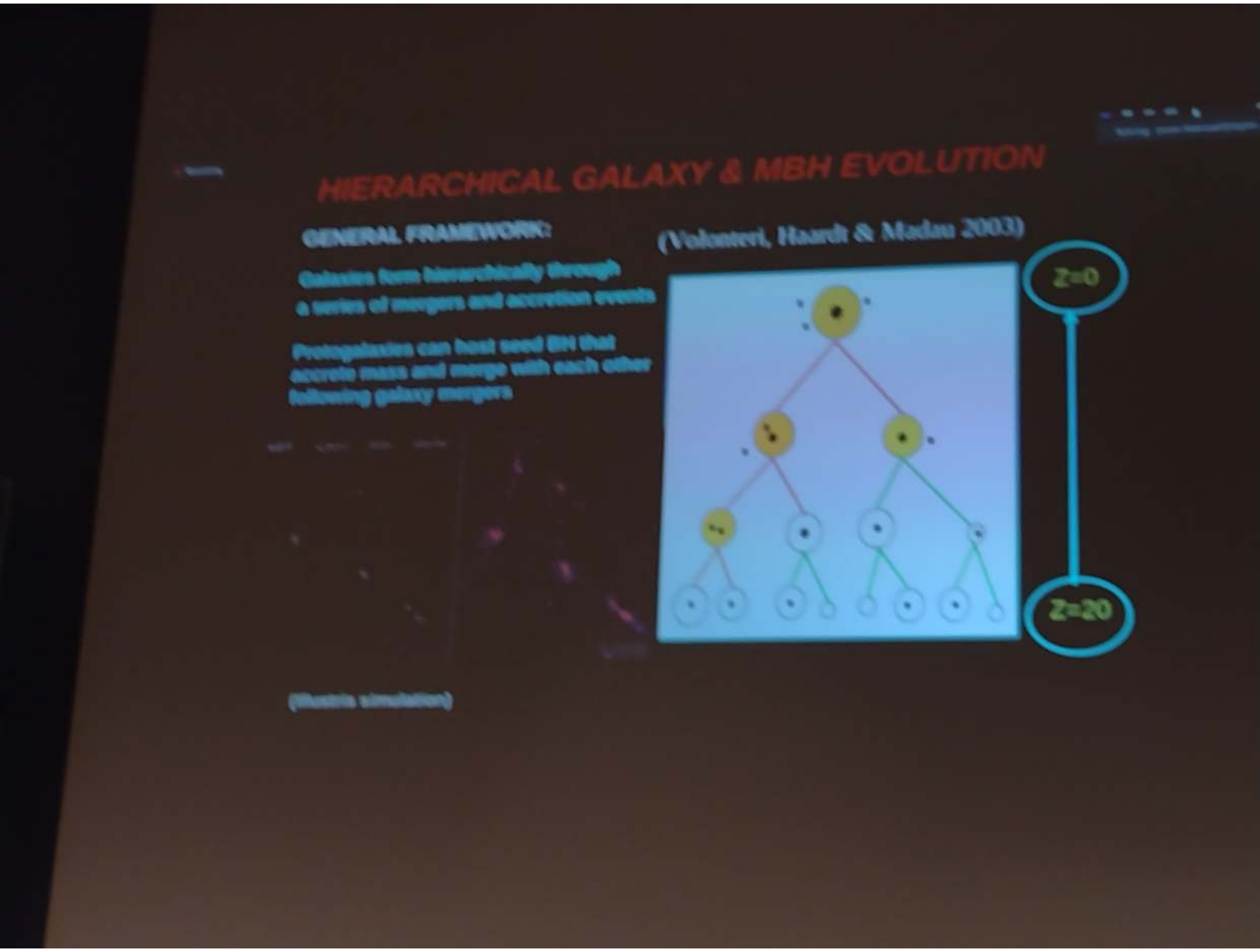
(AS 2016, PRL 116, 1102)

sBHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 4.5 year operation of LISA.

Expected rates do not seem great.

(LISA Red Book)

	sBHB type	definition	$\langle N \rangle$	90 % confidence	no sBHB (%)
SI 4.1	detected	SNR > 8	4.9	0.4 – 9.8	2.2
	archival	5 < SNR < 8 & t_c < 15 yr	5.6	0.8 – 10.0	1.4
SI 4.2	massive	SNR > 8 & $m_1 > 50\,M_\odot$	1.3	0 – 3.6	34.1
SI 4.3	multiband	SNR > 8 & t_c < 15 yr	1.5	0 – 3.8	26.7
		SNR > 8 & t_c < 4.5 yr	0.4	0 – 1.4	67.7


HIERARCHICAL GALAXY & MBH EVOLUTION
GENERAL FRAMEWORK:
(Volonteri, Haardt & Madau 2003)
Galaxies form hierarchically through a series of mergers and accretion events
Protogalaxies can host seed BH that accrete mass and merge with each other following galaxy mergers
Z=0
Z=20
(Illustris simulation)

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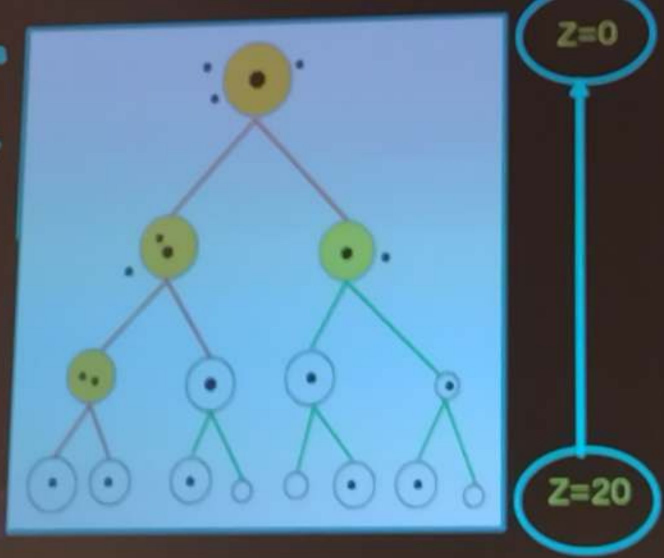
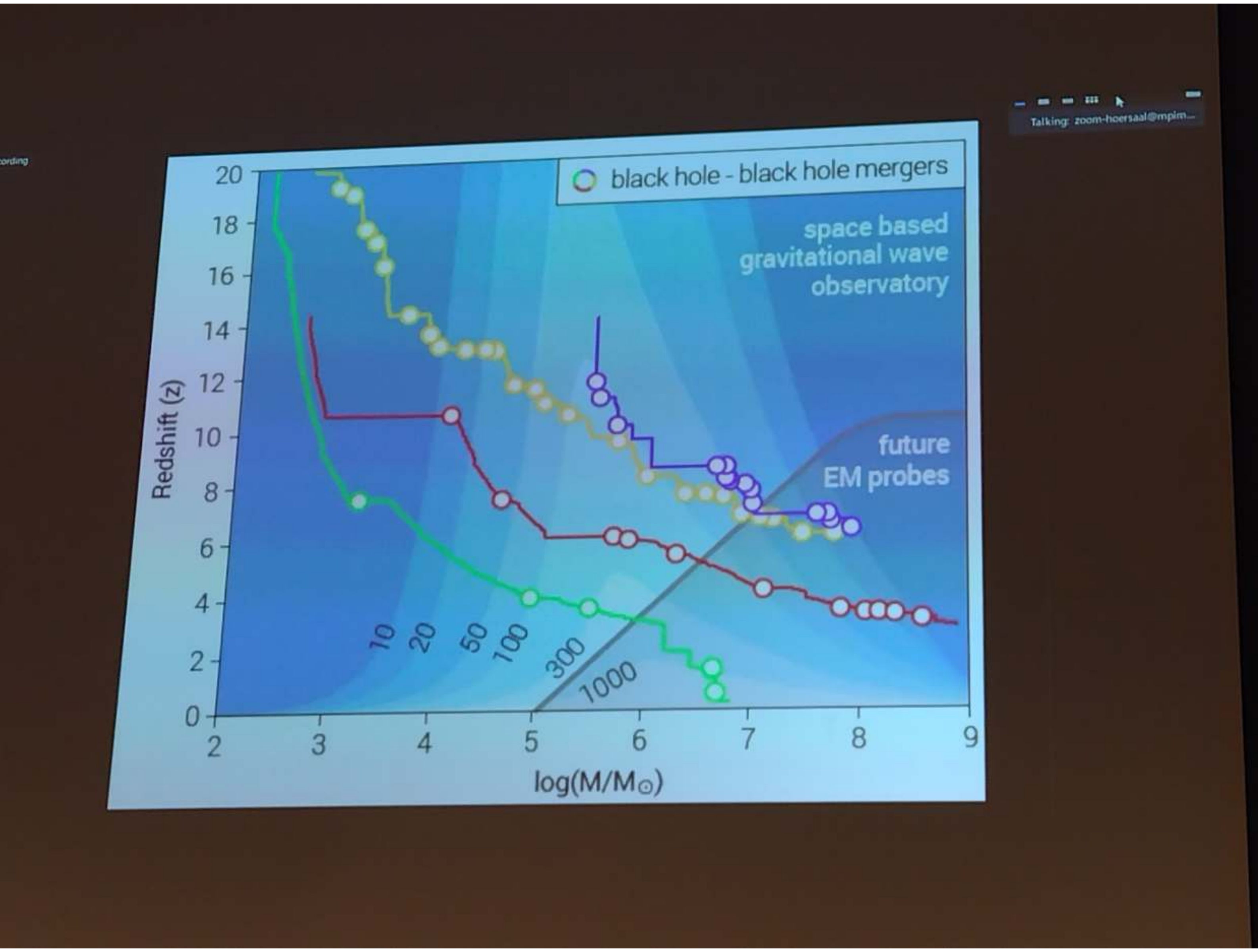
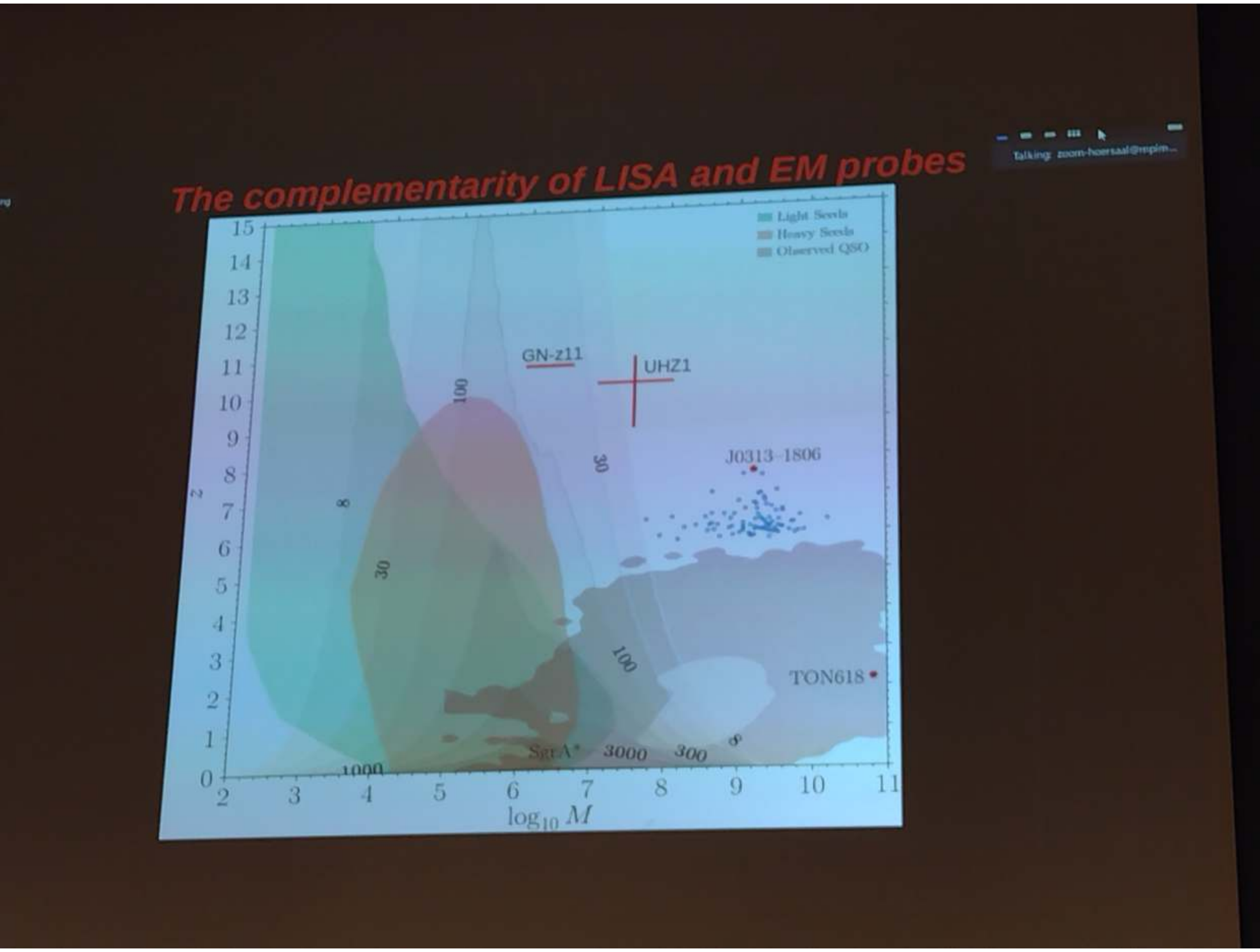


(Illustris simulation)



black hole - black hole mergers
space based gravitational wave observatory
future EM probes
Redshift (z)
log(M/M⊙)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9
10
20
50
100
300
1000

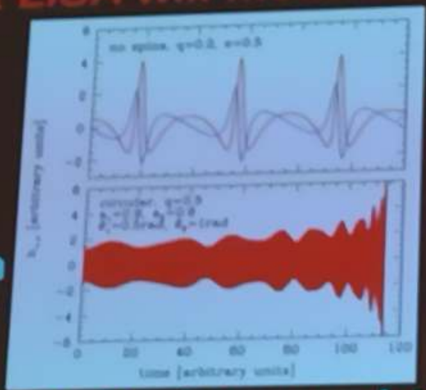

The complementarity of LISA and EM probes
Talking: zoom-hoersaal@mpim...
Light Seeds
Heavy Seeds
Observed QSO
GN-z11
UHZ1
J0313–1806
TON618
Sgr A*
z
log10 M
100
30
8
1000
3000
300

What LISA will measure

Assuming 4 years of operation:

~100+ detections

~100+ systems with sky localization to 10 deg2



~100+ systems with individual masses determined to 1%

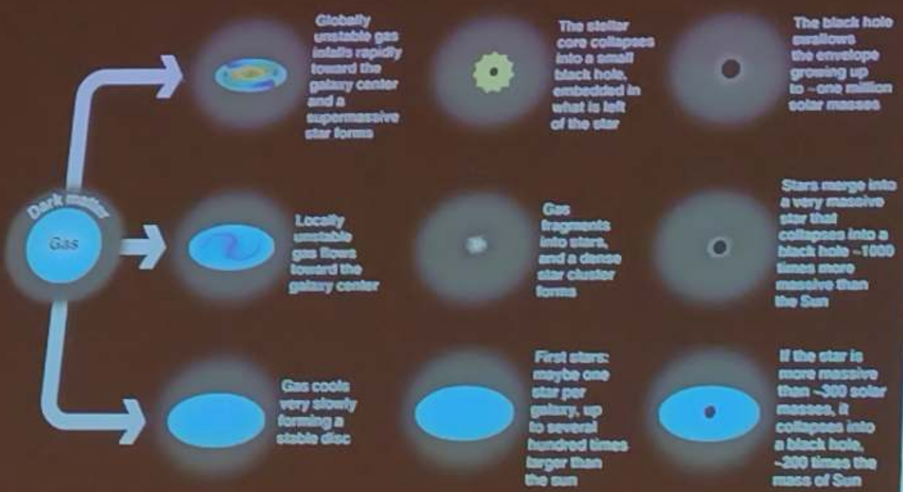
~50 systems with primary spin determined to 0.01

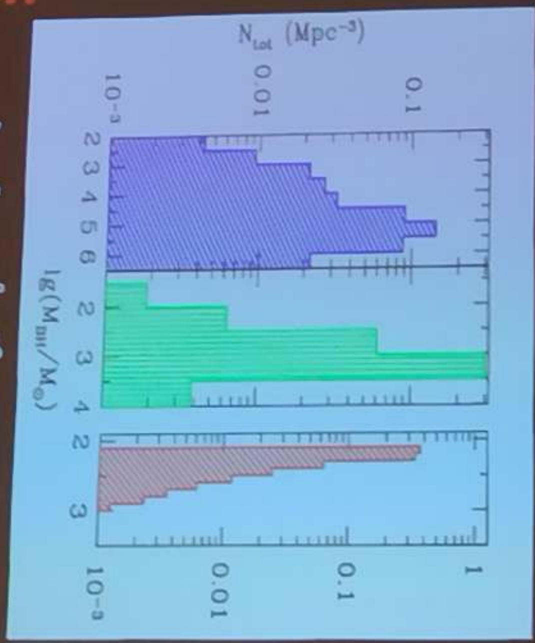
~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

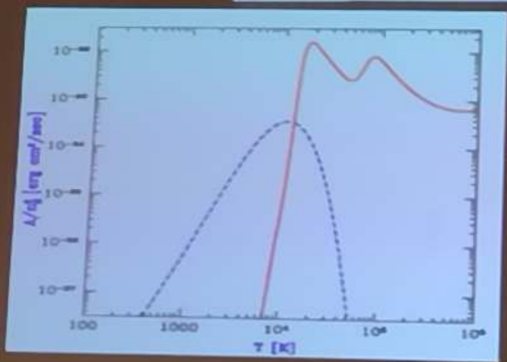
Seed BH formation

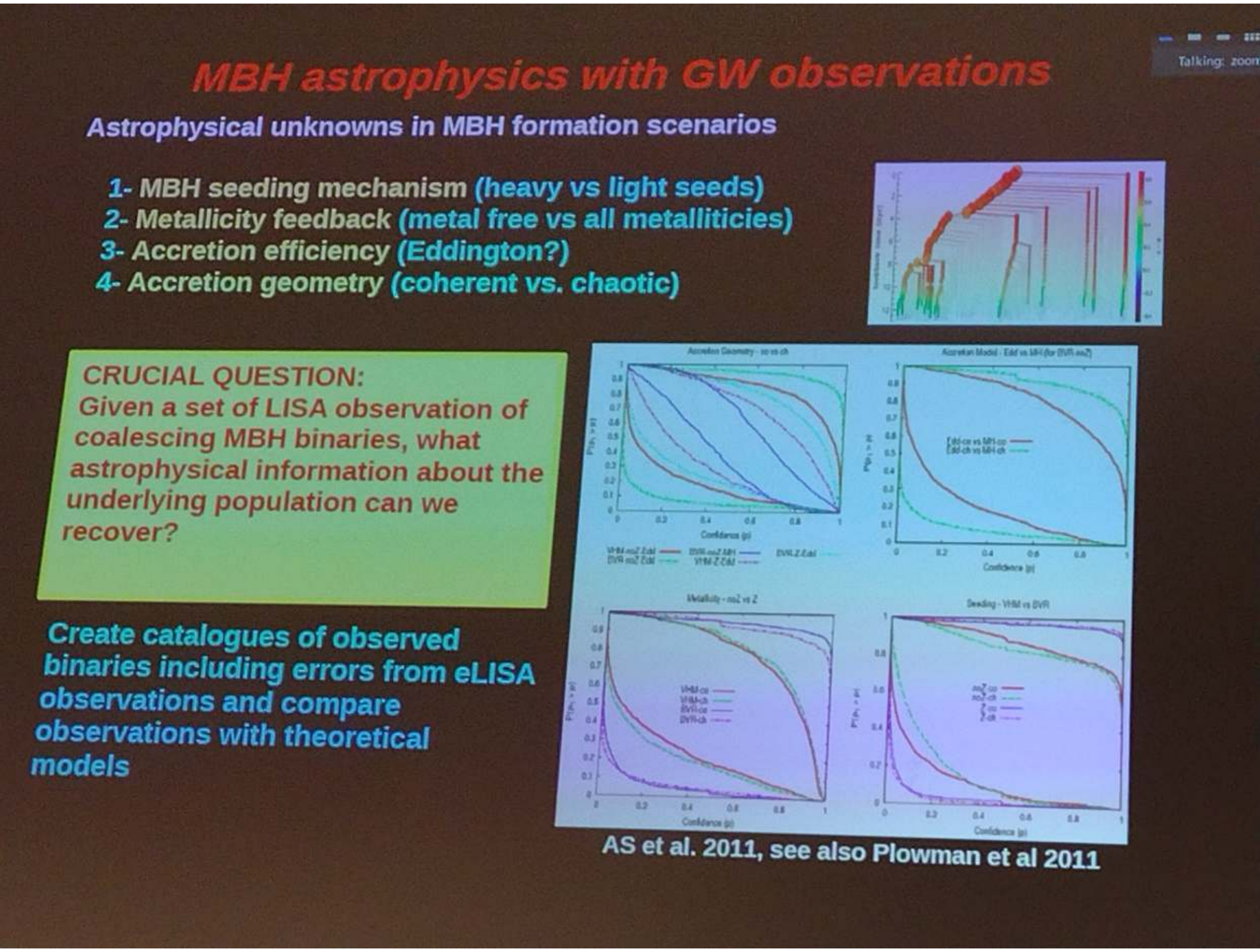


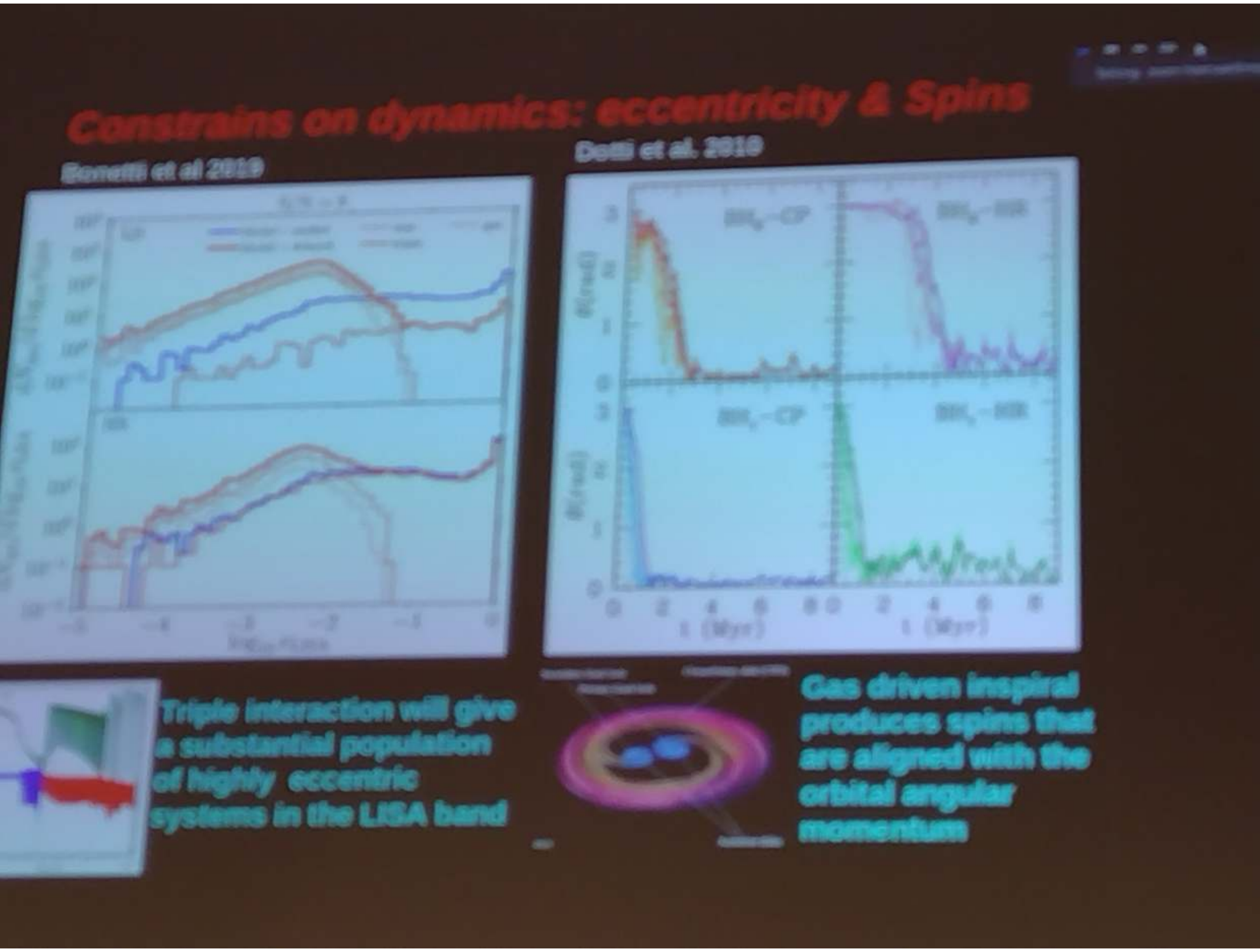


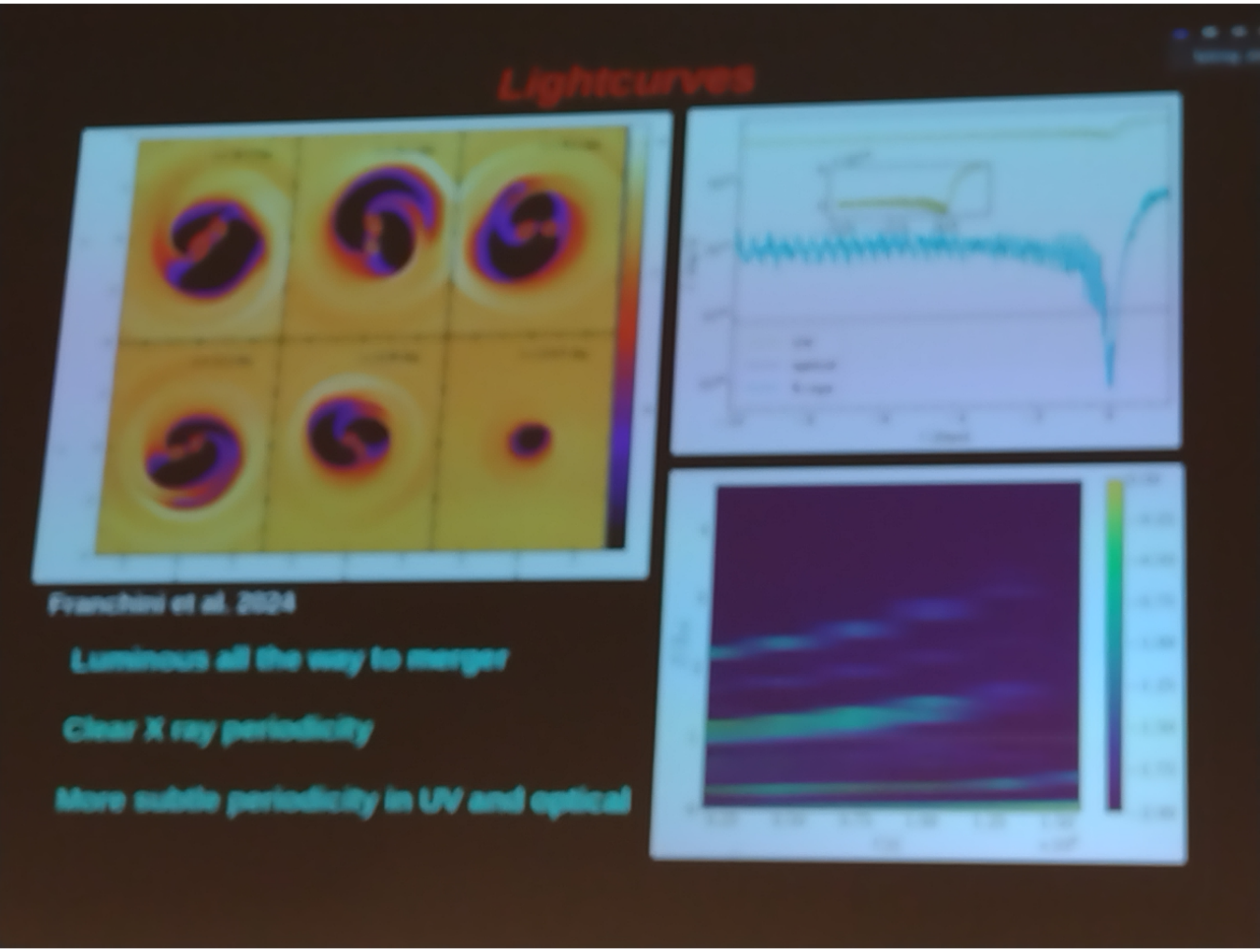
Critically depends on:

- -content of H2
- -vicinity of an ionizing source
- -fragmentation
- -metallicity



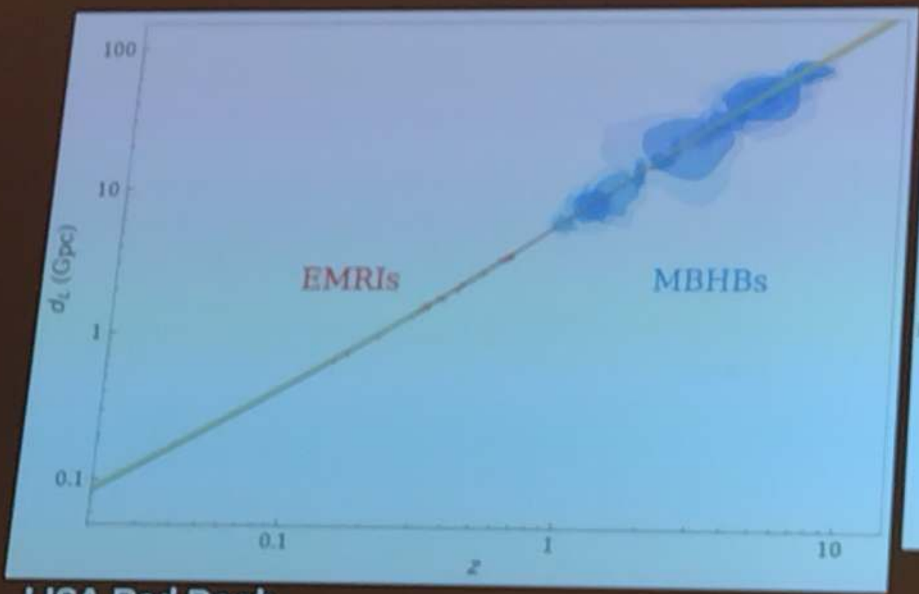

MBH astrophysics with GW observations
Astrophysical unknowns in MBH formation scenarios
1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metalliticies)
3- Accretion efficiency (Eddington?)
4- Accretion geometry (coherent vs. chaotic)
CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models
Confidence (p)
AS et al. 2011, see also Plowman et al 2011
Talking: zoom


Constrains on dynamics: eccentricity & Spins
Bonetti et al 2019
Dotti et al. 2010
Triple interaction will give a substantial population of highly eccentric systems in the LISA band
Gas driven inspiral produces spins that are aligned with the orbital angular momentum

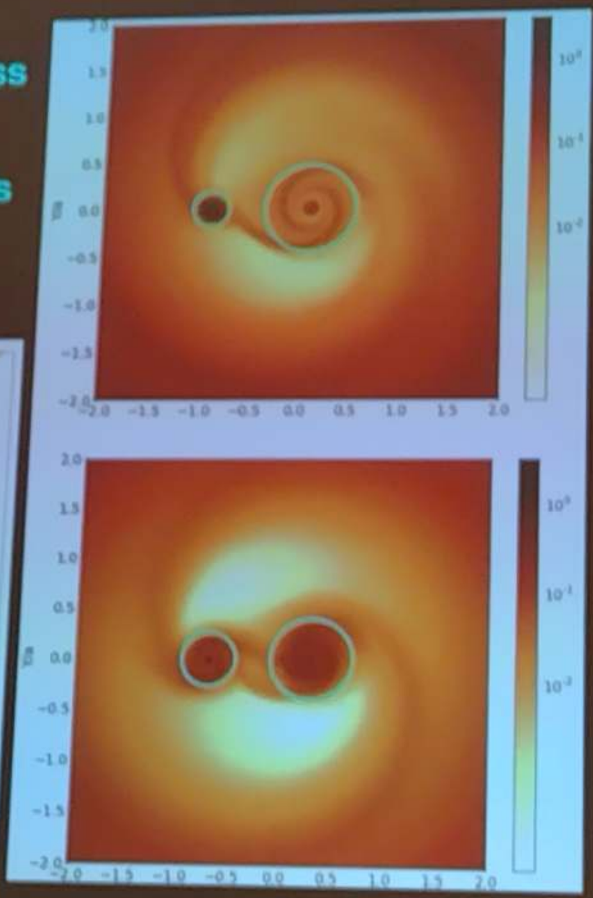

Lightcurves
Franchini et al. 2024
Luminous all the way to merger
Clear X ray periodicity
More subtle periodicity in UV and optical

Why multimessenger?

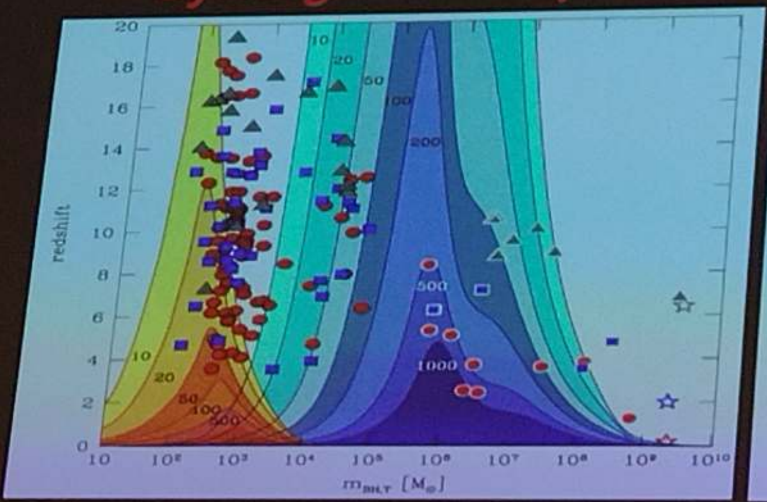
- Cosmology and cosmography at high z
- Study of accretion on MBHs with known mass and spins
- Test MBH-galaxy co-evolution
- Study of the interplay between MBHs and gas (torques, disk structure, disk models)
- Host galaxy, Jet launches, Quasar birth ...

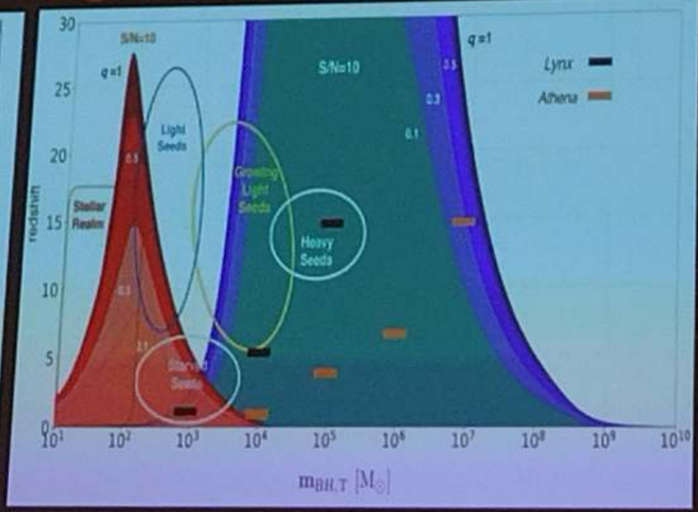


LISA Red Book

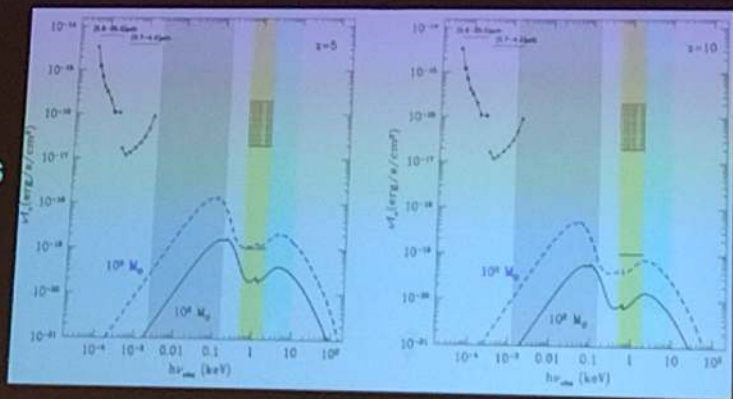


Synergies: complementing LISA with ET/CO

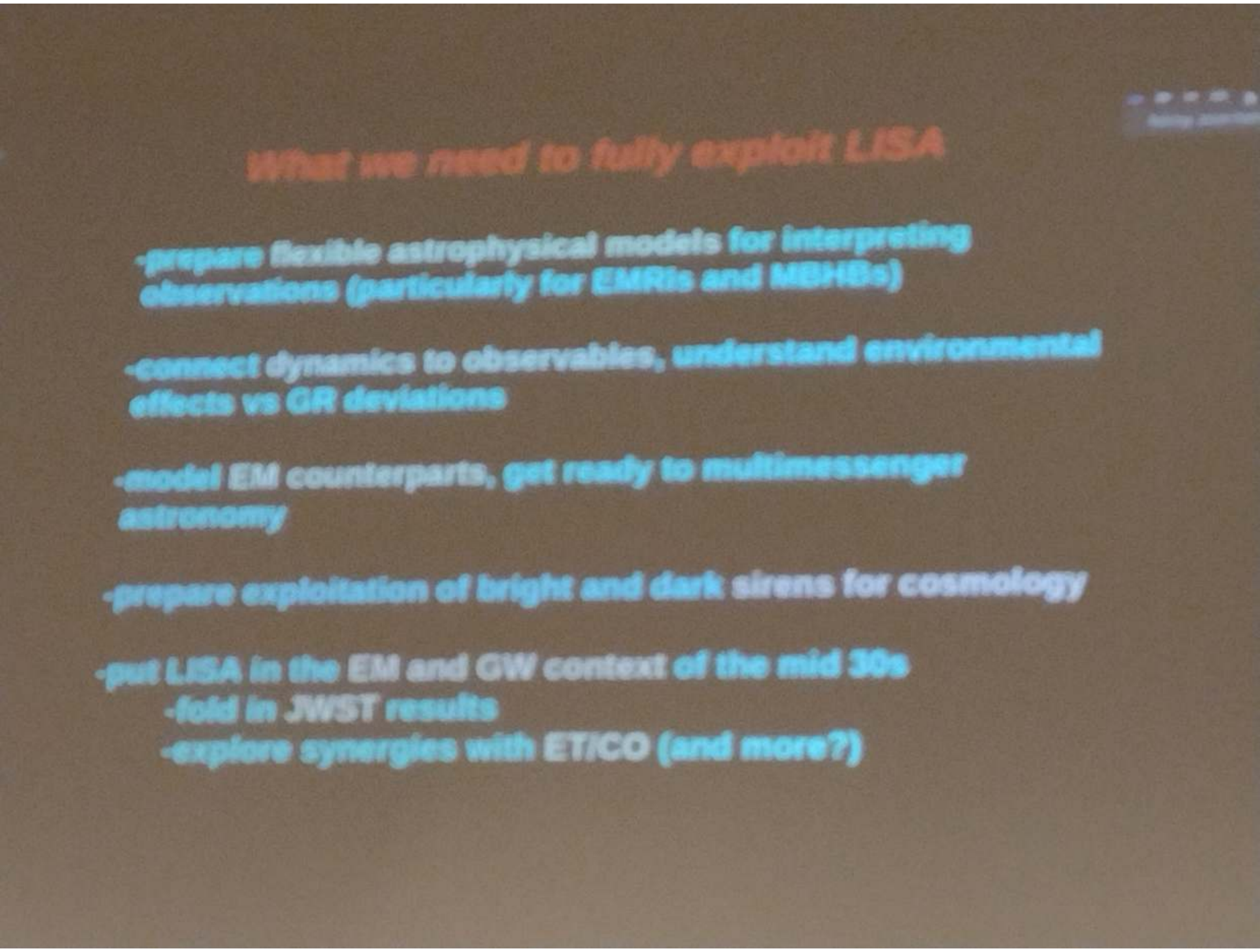


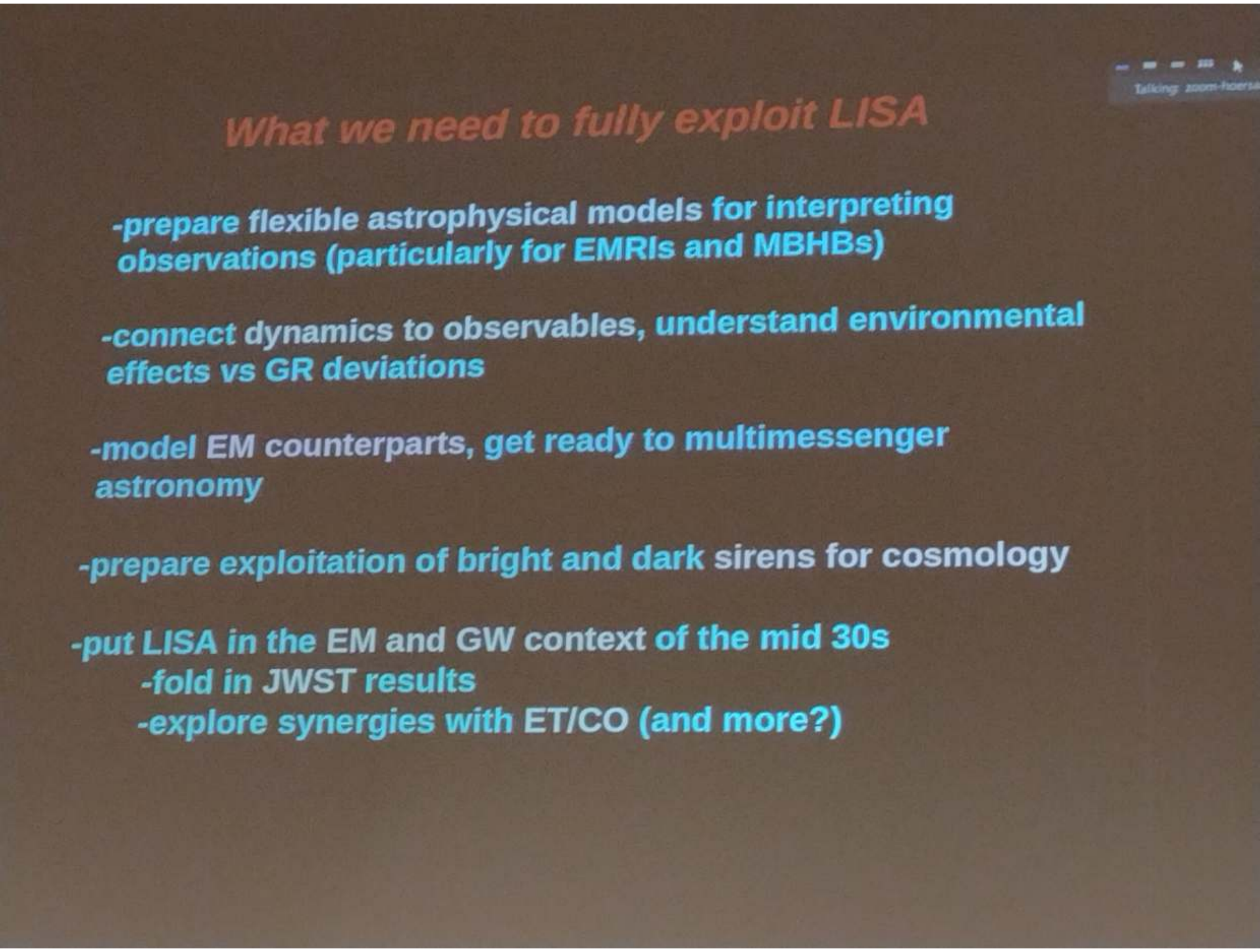


-ET is almost perfectly complementary to LISA
-can see the first mergers of popIII seeds up to high z
-it reaches deeper than EM probes



(Valiante+ 20)


What we need to fully exploit LISA
-prepare flexible astrophysical models for interpreting observations (particularly for EMRIs and MBHBs)
-connect dynamics to observables, understand environmental effects vs GR deviations
-model EM counterparts, get ready to multimessenger astronomy
-prepare exploitation of bright and dark sirens for cosmology
-put LISA in the EM and GW context of the mid 30s
-fold in JWST results
-explore synergies with ET/CO (and more?)


Talking: zoom-hoersa
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Pulsar timing

Pulsars are neutron seen through their regular radio pulses

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system

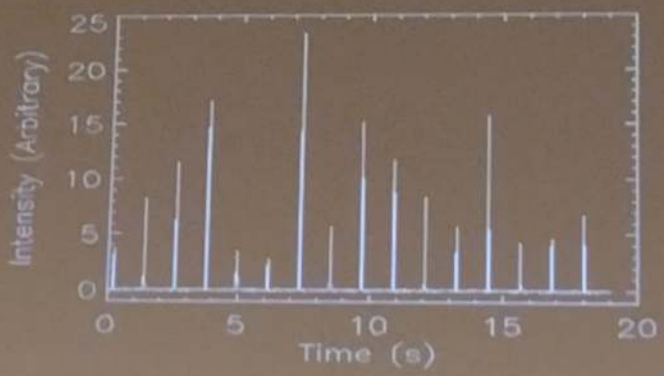
1-Observe a pulsar and measure the ToAs

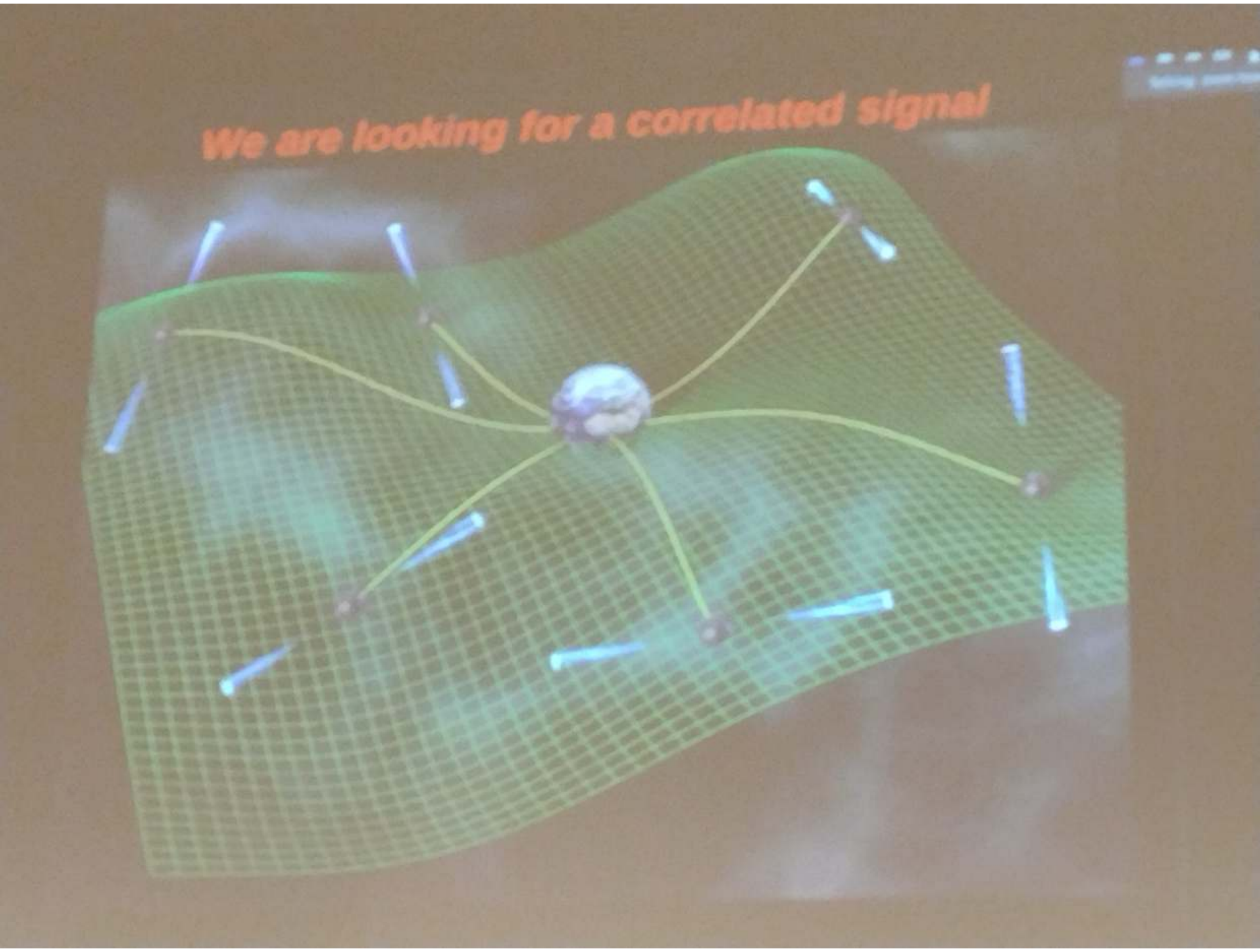
2-Find the model which best fits the ToAs

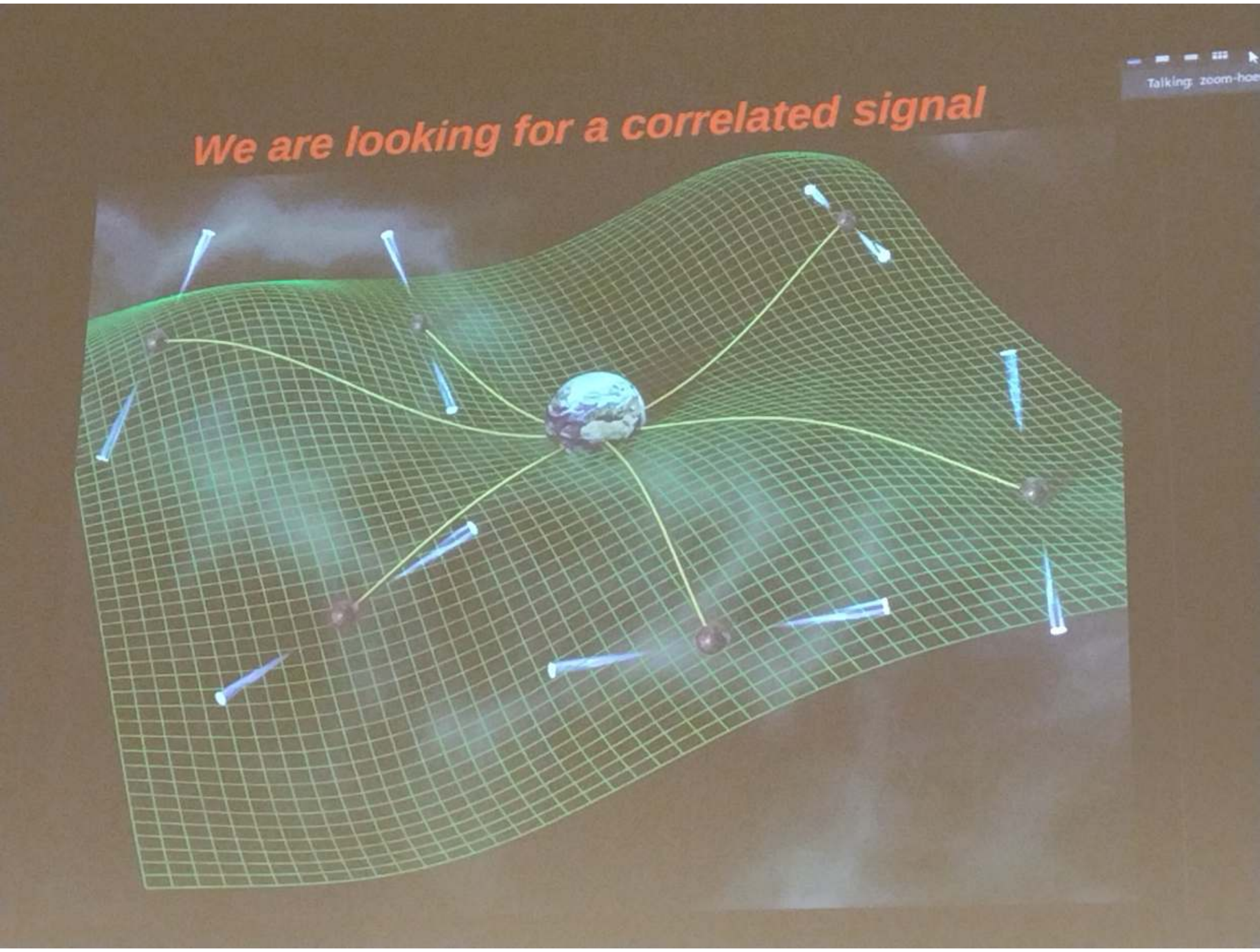
3-Compute the timing residual R

$$R = ToA - ToA_m$$

If the timing solution is perfect (and observations noiseless), then R=0. R contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) gravitational waves




We are looking for a correlated signal


We are looking for a correlated signal

"Looking at the arxiv, can't help wondering: is there any early-Universe cosmological process that DOES NOT produce the stochastic gravitational-wave background observed by Pulsar-Timing Arrays?"

Yuri Levin

-It's Inflation!

-It's phase transitions!

-It's scalar perturbations!

-It's topological defects!

-It's domain walls!

-It's turbulence induced perturbations!

Talking: zoom-hoersaal@mpim...

's Inflation!

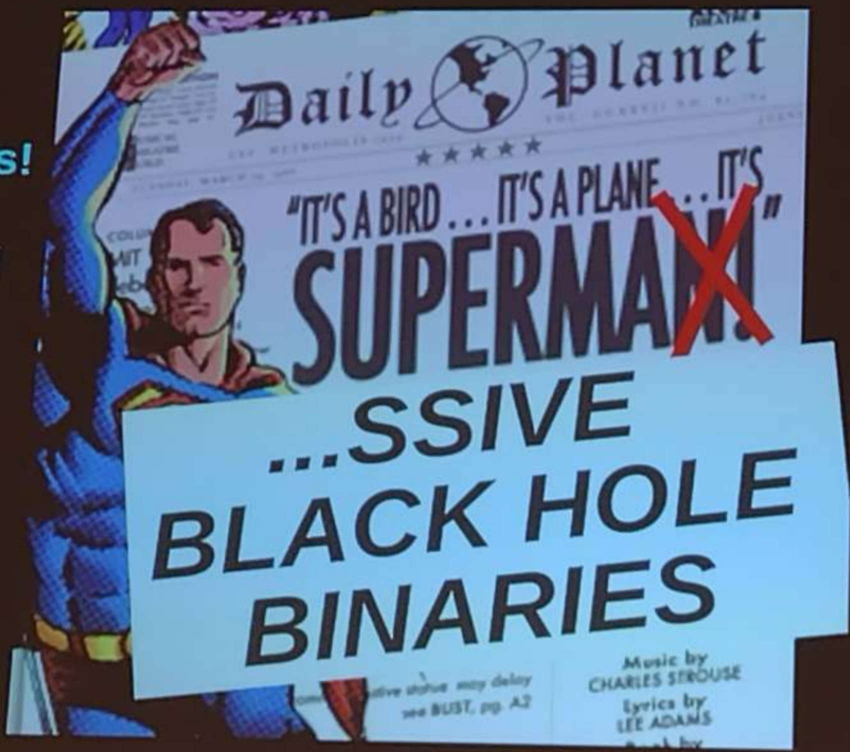
s phase transitions!

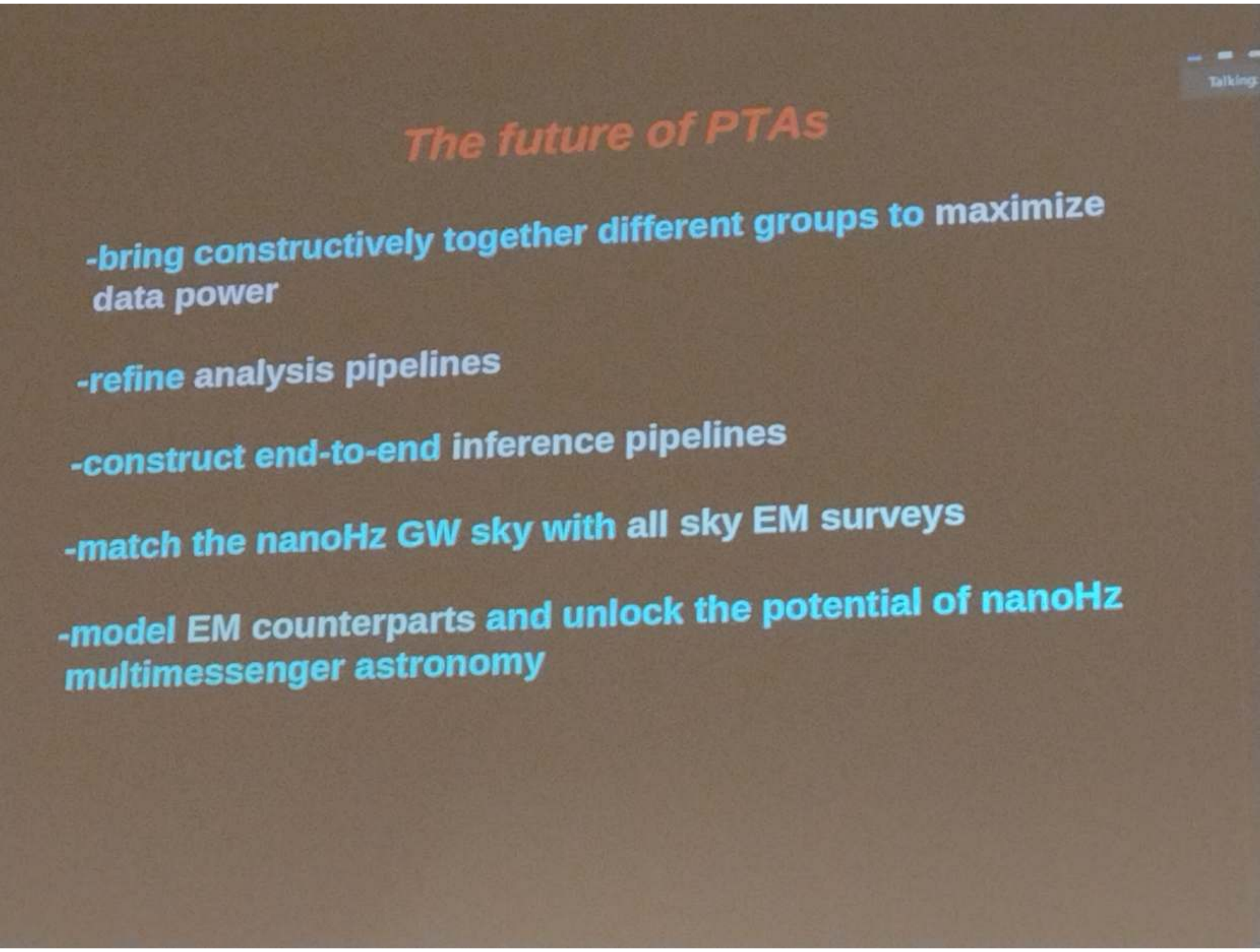
s scalar perturbations!

topological defects!

domain walls!

urbulence induced
rbations!




The future of PTAs
-bring constructively together different groups to maximize data power
-refine analysis pipelines
-construct end-to-end inference pipelines
-match the nanoHz GW sky with all sky EM surveys
-model EM counterparts and unlock the potential of nanoHz multimessenger astronomy