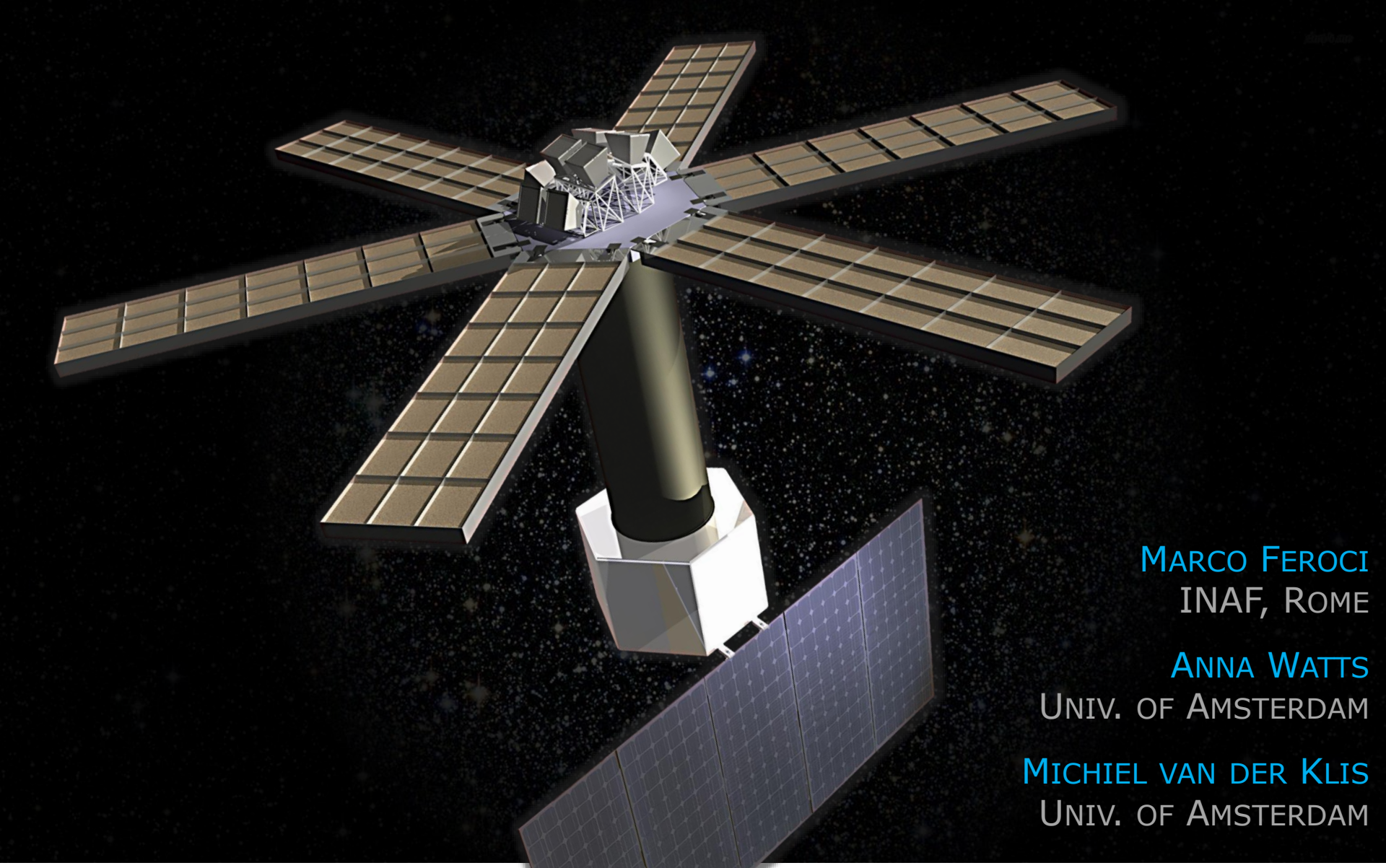


MARCO FEROCI
INAF, ROME

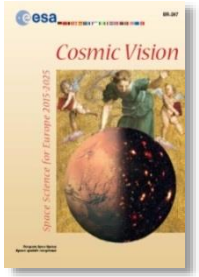
ANNA WATTS
UNIV. OF AMSTERDAM

MICHIEL VAN DER KLIS
UNIV. OF AMSTERDAM

ON BEHALF OF THE LOFT CONSORTIUM

LOFT
LARGE OBSERVATORY
FOR X-RAY TIMING

ESA COSMIC VISION M3
CANDIDATE MISSIONS PRESENTATION EVENT

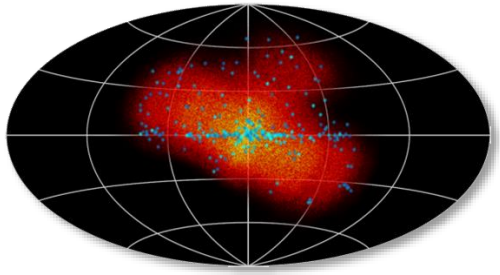


LOFT ADDRESSES THE COSMIC VISION THEME *"Matter Under Extreme Conditions"*

Probe the state of matter at supra nuclear densities in Neutron Stars ("**Dense Matter**")

Probe gravity theory in the very strong field environment of Black Holes ("**Strong Gravity**")

Probe physics of hundreds of galactic and bright extragalactic cosmic sources ("**Observatory Science**")



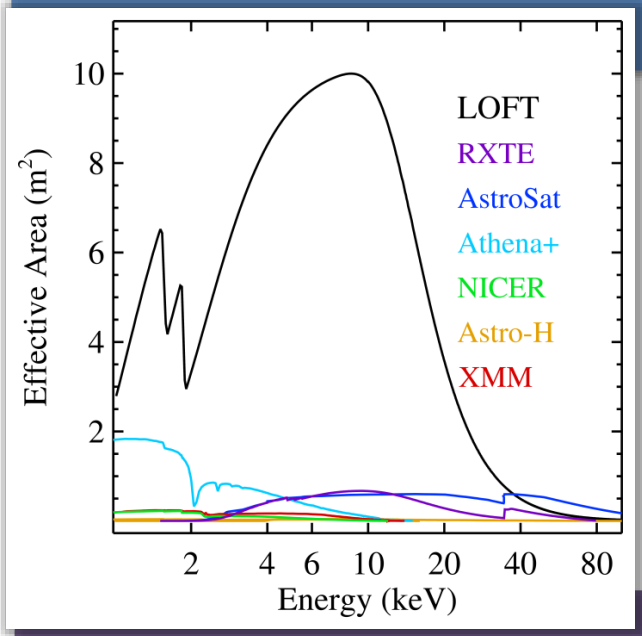
WHAT LOFT MUST HAVE

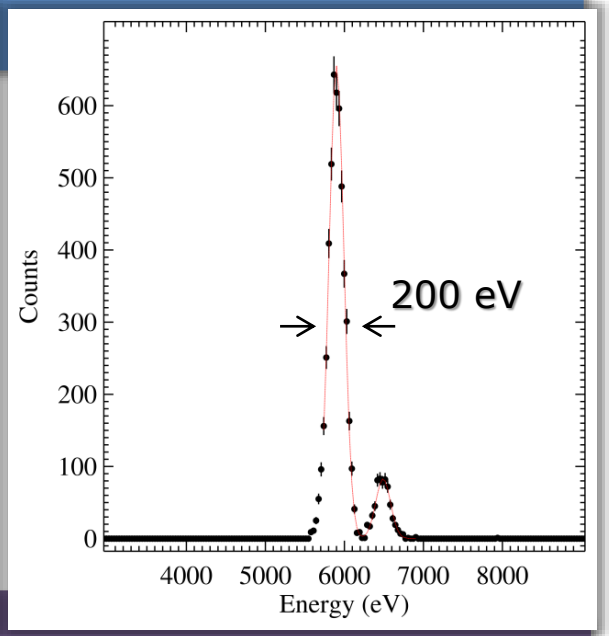
Exploit the Diagnostics of X-ray Variability on Dynamical Timescales:
Large Collecting Area

Exploit the Diagnostics of Spectral Variability on Dynamical Timescales:
Good Energy Resolution (XMM-class)

WHAT LOFT HAS!

Large Collecting Area

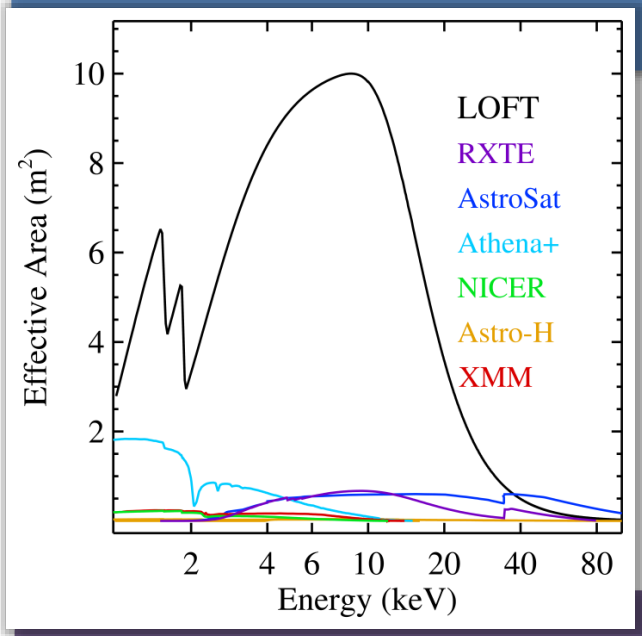


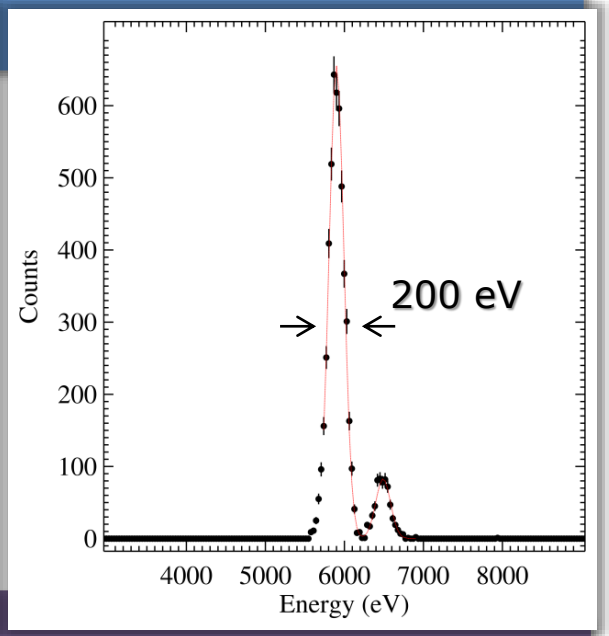


Good Energy Resolution (XMM-class)

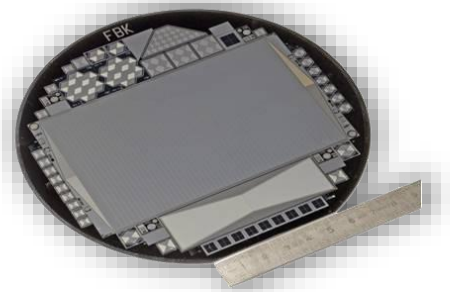
WHAT LOFT HAS!

Large Collecting Area

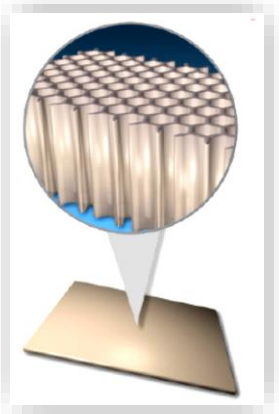




Good Energy Resolution (XMM-class)



LHC SDD Detectors Heritage



Microchannel Plate Collimators

LOFT UNITES SPECTROSCOPY & TIMING, AT ENORMOUS AREA

RXTE
1100 eV, 0.65 m²

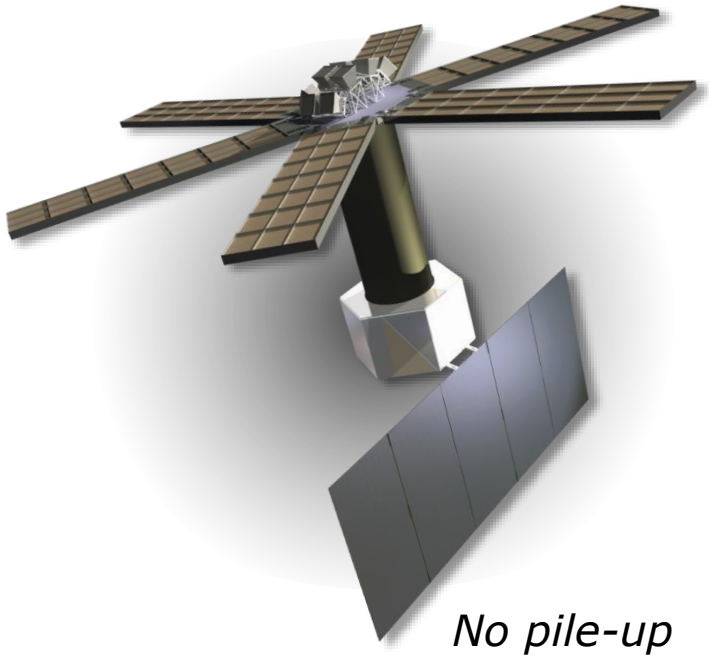
XMM
130 eV, 0.085 m²

pile-up-limited

TIMING
X 15

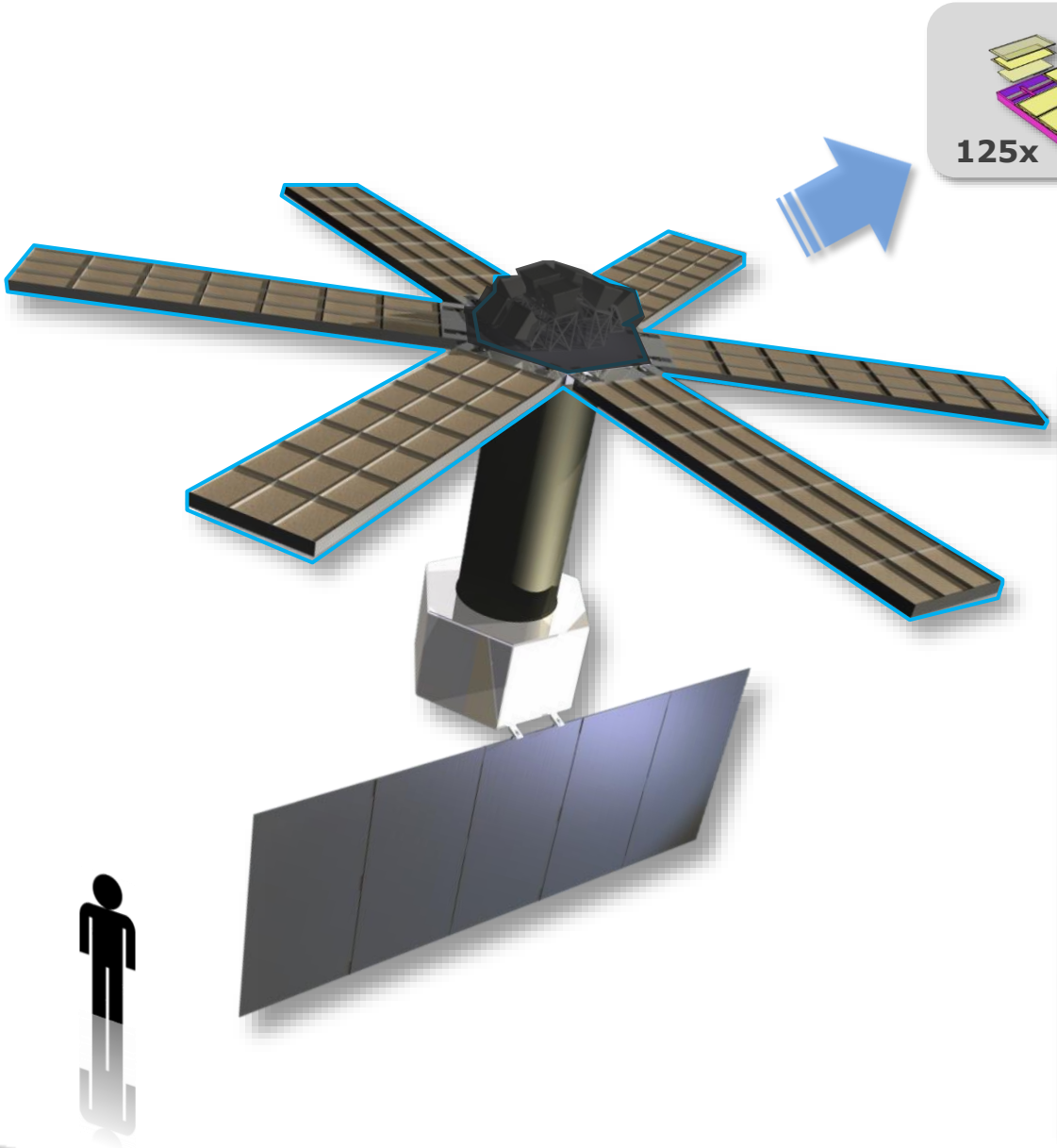
SPECTROSCOPY
X 100

LOFT
200 eV, 10 m²

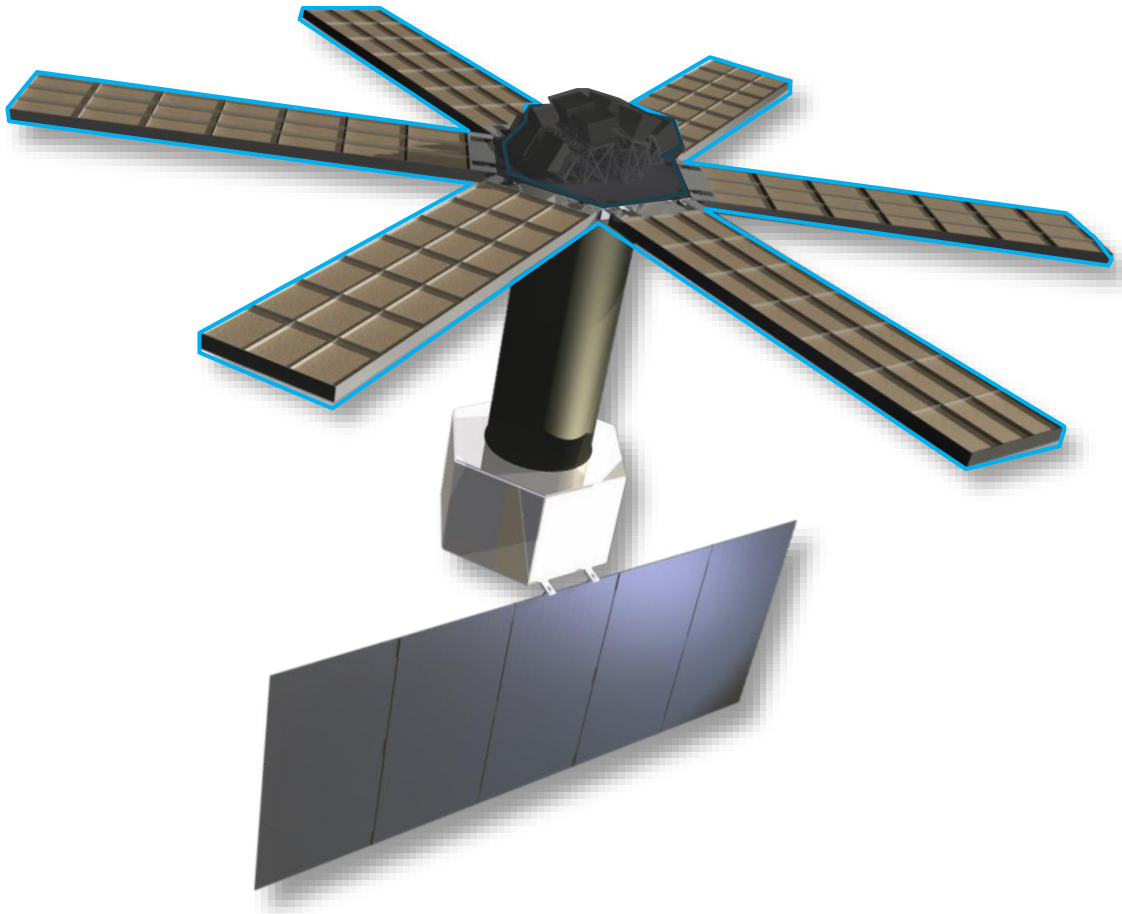


No pile-up

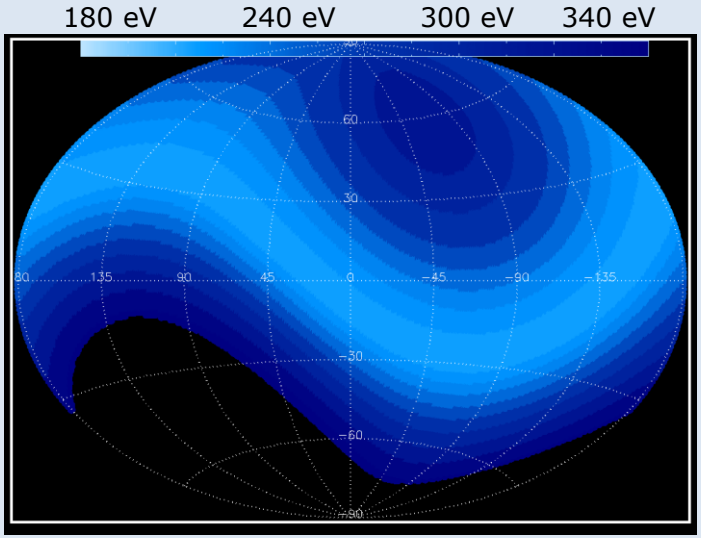
not part of any planned X-ray mission



EFFECTIVE AREA	4 m^2 @ 2 keV 10 m^2 @ 8 keV 1 m^2 @ 30 keV
ENERGY RANGE	2-30 keV (30-80 keV ext.)
ENERGY RESOLUTION FWHM	200 eV @ 6 keV
COLLIMATED FOV	1 deg FWHM
ABSOLUTE TIME ACCURACY	1 μs

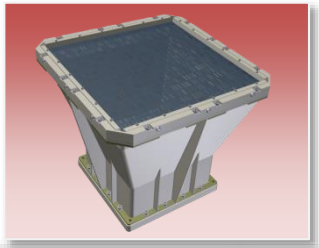


LAD
INSTANTANEOUS SKY VISIBILITY



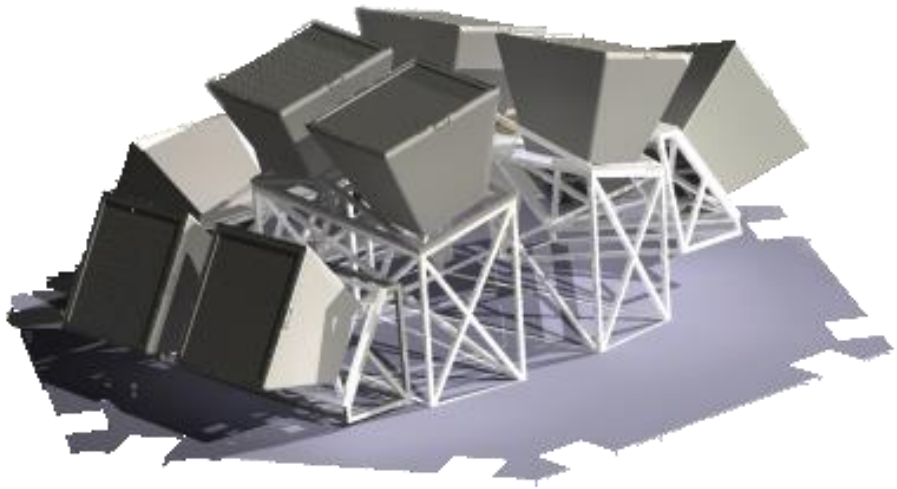
75% of the sky accessibile to LAD at any time.

Combination of Sky Visibility and Mission Duration ensures required number of transients

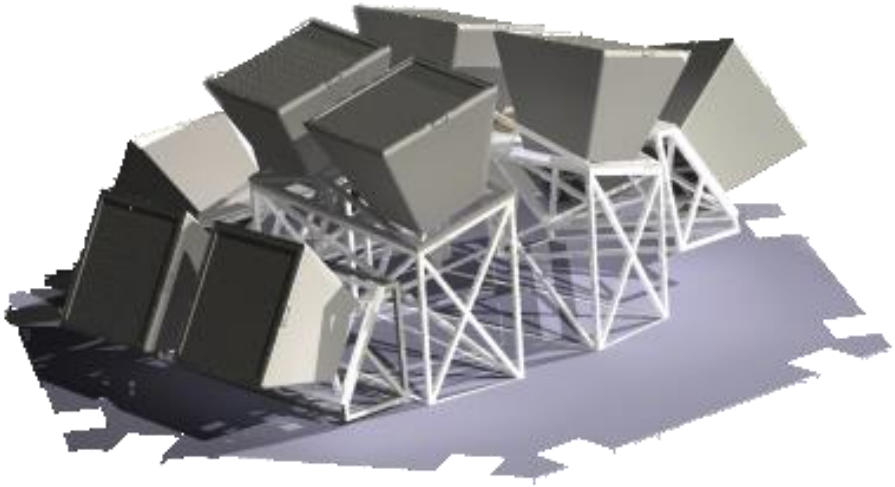


5 Units

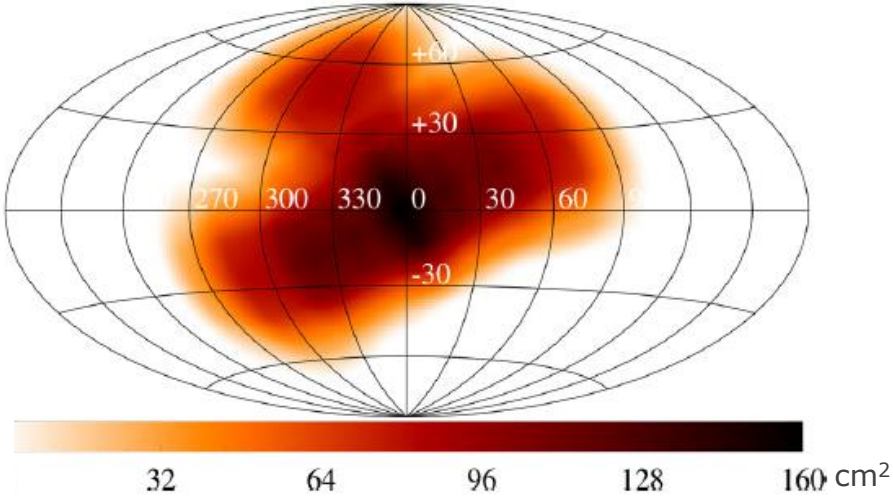
└ 10 Cameras



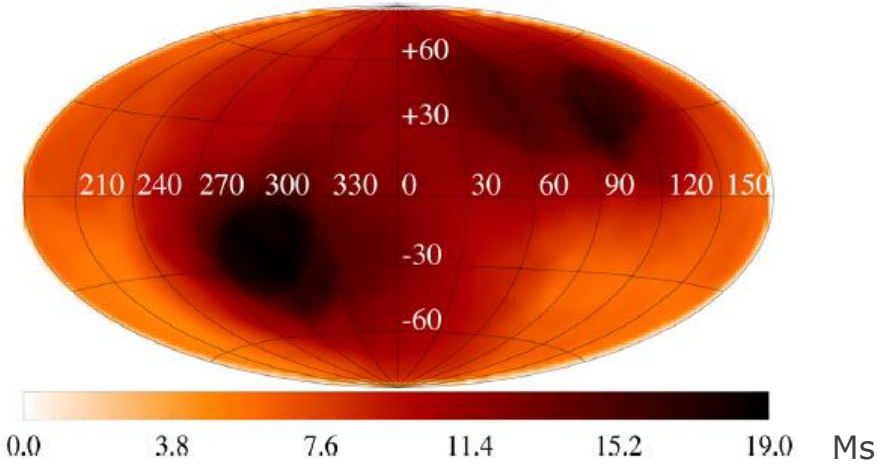
FIELD OF VIEW	5.5 steradian
POSITION ACCURACY (10σ)	1 arcmin
ENERGY RANGE	2-50 keV
ENERGY RESOLUTION	300 eV @ 6 keV
COLLECTING AREA	1820 cm^2
TIME RESOLUTION	10 μs (trigger) ~minutes (images)
SENSITIVITY (5σ, GALACTIC CENTER)	270 mCrab (3s) 2.1 mCrab (1day)
GROUND TRANSMISSION OF GRB COORDINATES	< 30s



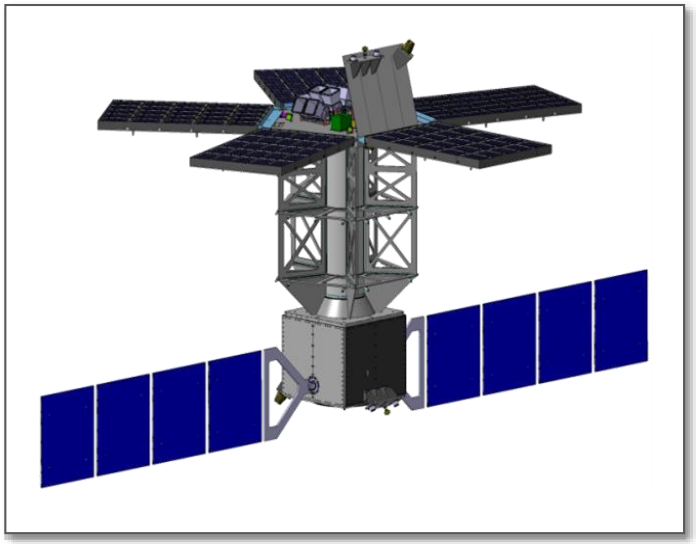
FIELD OF VIEW

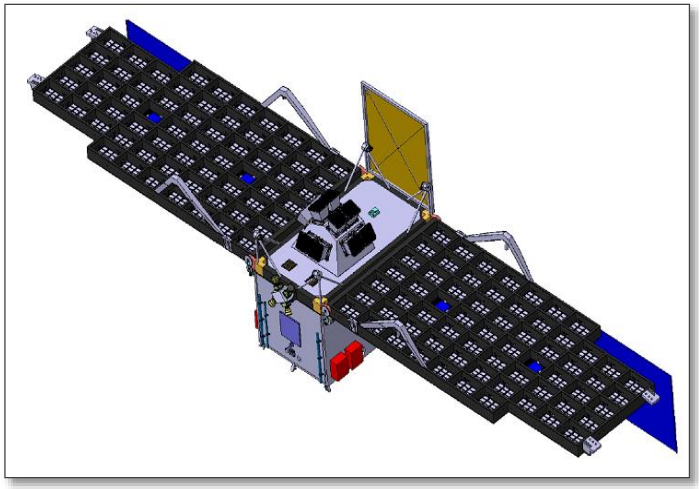


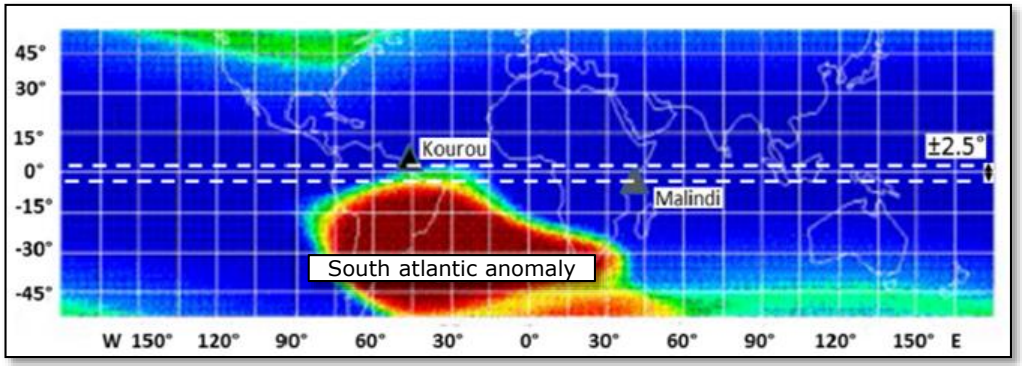
EXPOSURE MAP



FEASIBLE MISSION IN SEVERAL CONFIGURATIONS, WITH STANDARD EQUIPMENT







Item	Value
Orbit	Equatorial, 550 km
Launcher	Soyuz (6,000 kg launch capability)
Mass	4,000 kg
Power	4 kW
Telemetry	6.7 Gbit/orbit
Ground Stations	Kourou, Malindi
Pointing	3-axis stabilized
Mission Duration	3+2 years

FEASIBLE MISSION IN SEVERAL CONFIGURATIONS, WITH STANDARD EQUIPMENT

ESA Review:

"**mission feasible** and of **low technical risk** and medium schedule risk for a 2022 launch date;
a launch in 2023 is seen as realistic"

"*The overall instrument as well as the Science Ground Segment concept is considered to be mature and well documented. The level of detail with which the instrument design is described significantly exceeds general expectations at the end of a Phase A study.*"

The ESA Preferred LOFT Concept

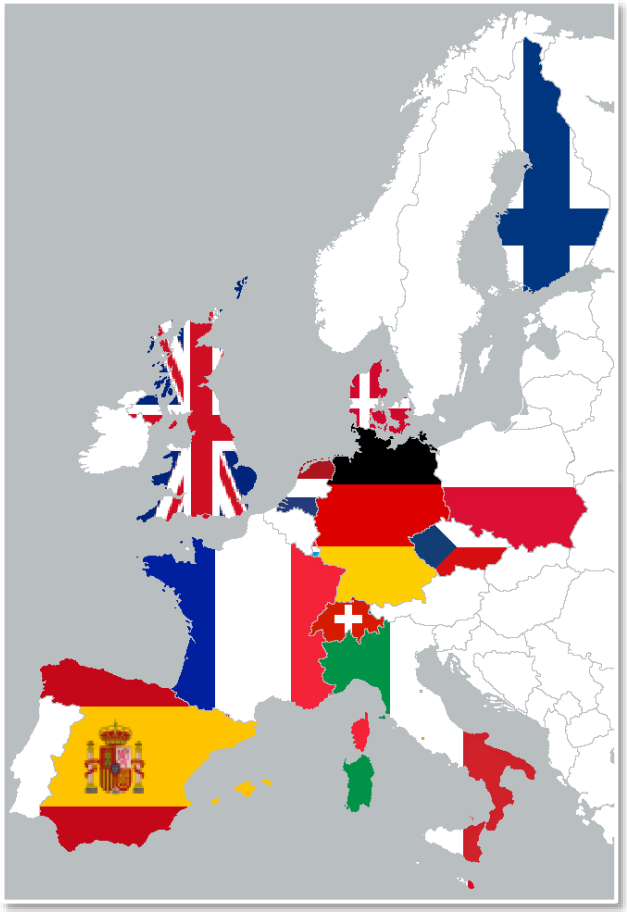
Payload and Science Data Center provided by Institutes in ESA Member States. LOFT Science Team even wider in Europe and worldwide

LOFT IS AN OPEN OBSERVATORY

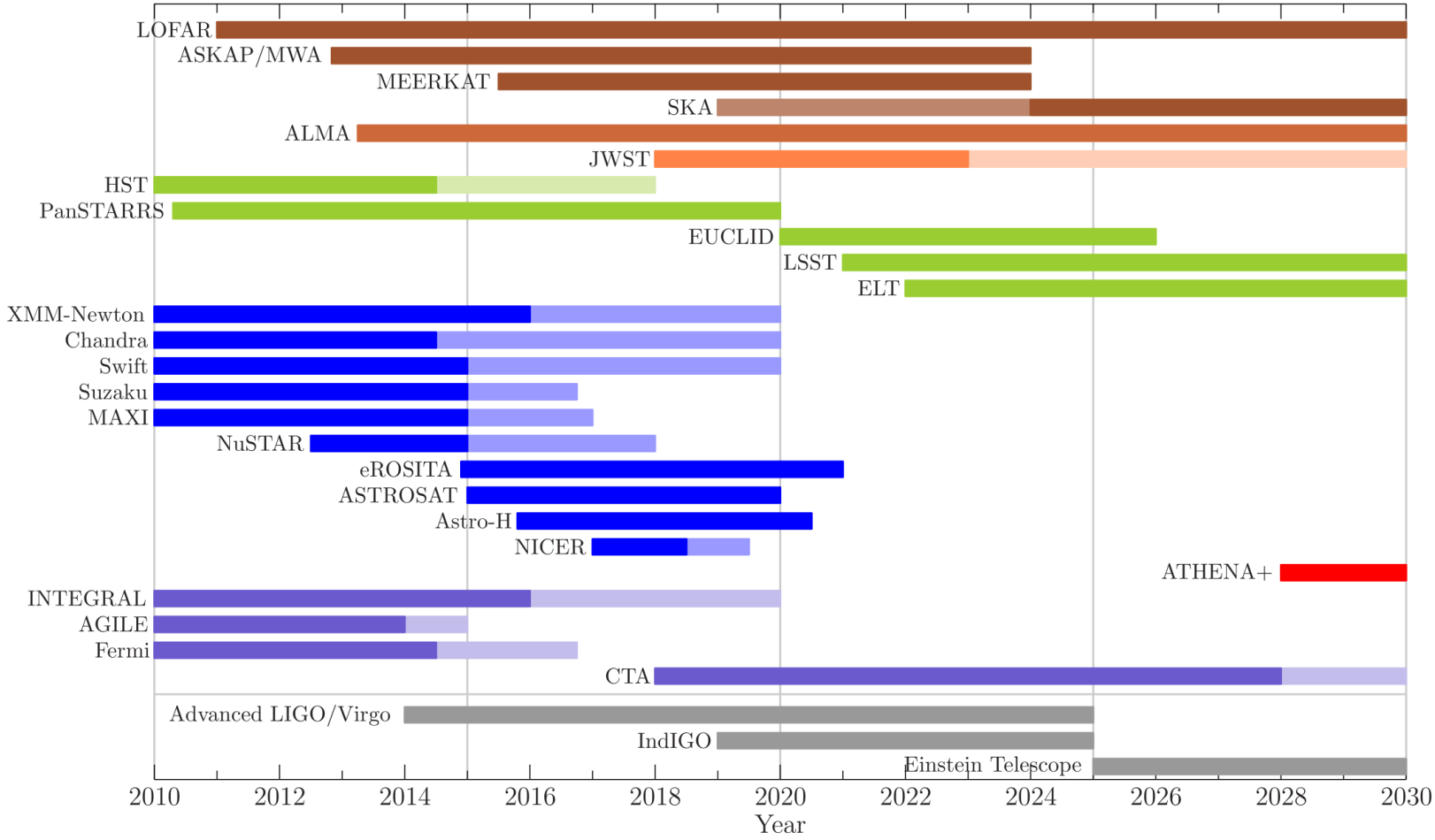
All LAD data open to the Community through peer-reviewed proposals.

All WFM data public after validation.

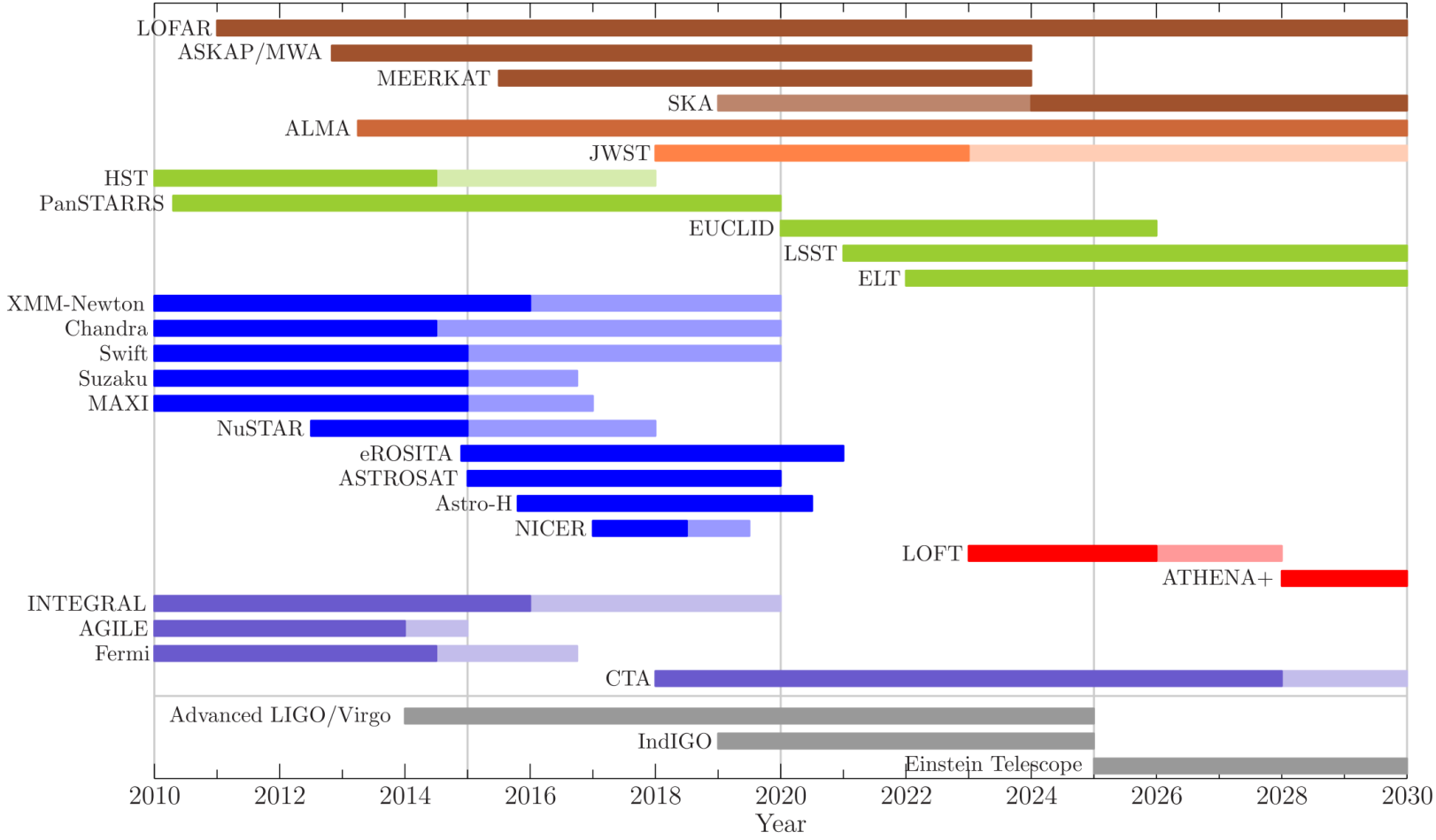
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
UCL MSSL
DTU
ISDC
CSIC
IEEC INSTITUT D'ESTUDIS ESPACIALS DE CATALUNYA
irap
EBERHARD KARLS UNIVERSITÄT TÜBINGEN
UNIVERSITÉ DE GENÈVE
SRON
INFN
University of Leicester
UNIVERSITY OF HELSINKI
CBK
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
UNIVERSITY OF AMSTERDAM



LOFT in the Multi-wavelength and Multi-messenger Context of Time Domain Astronomy



LOFT in the Multi-wavelength and Multi-messenger Context of Time Domain Astronomy



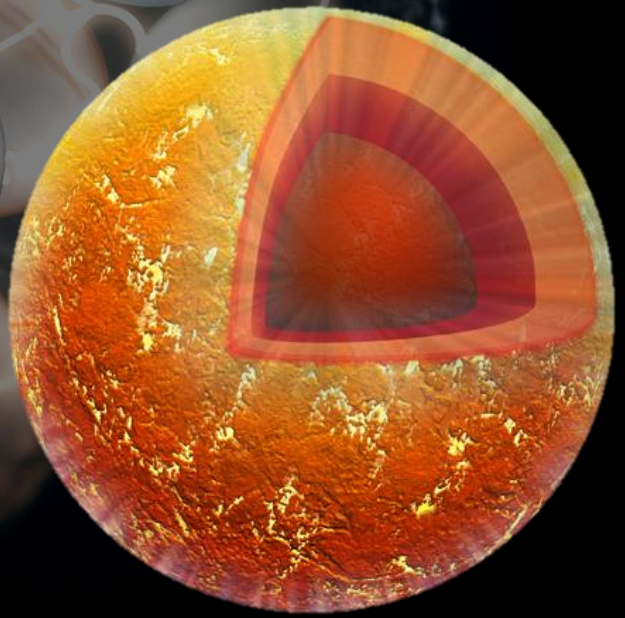
Dense matter

Strong field gravity

Observatory science

The strong force determines the state of nuclear matter - from atomic nuclei to neutron stars.

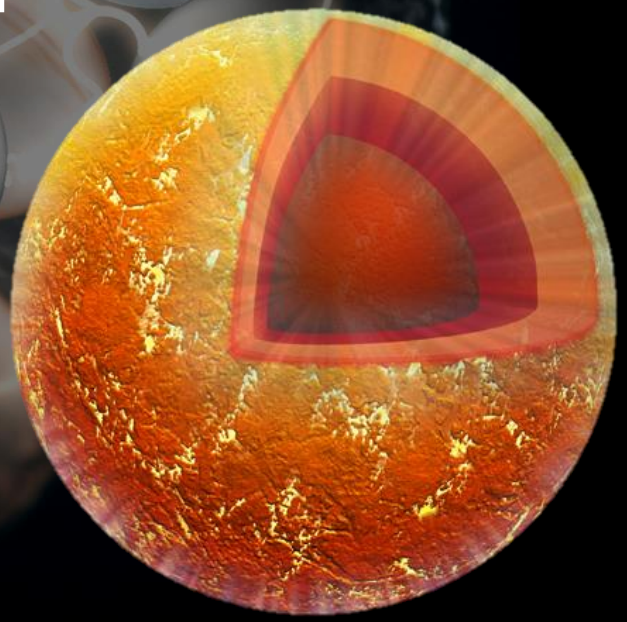
It is a major problem within modern physics.

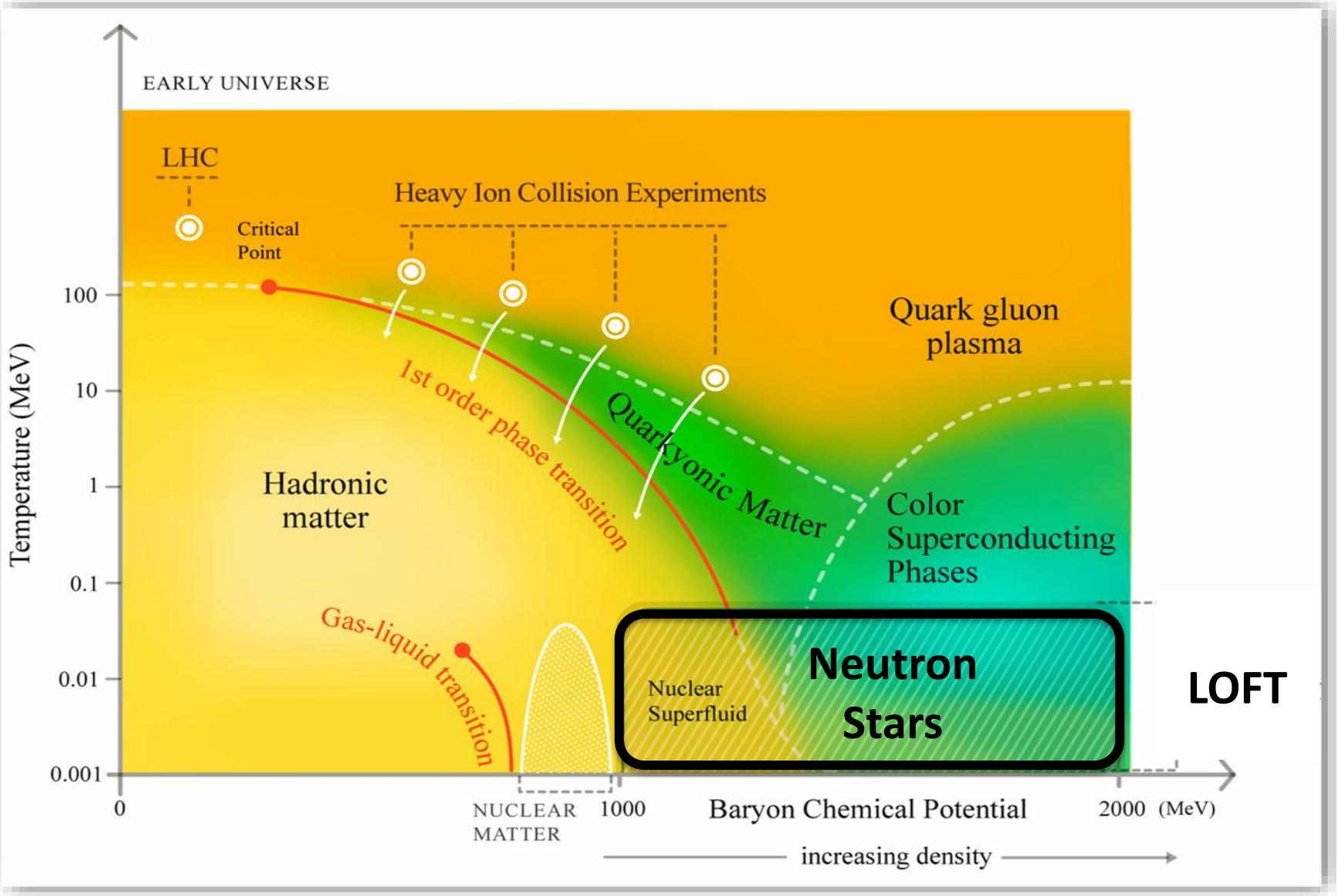


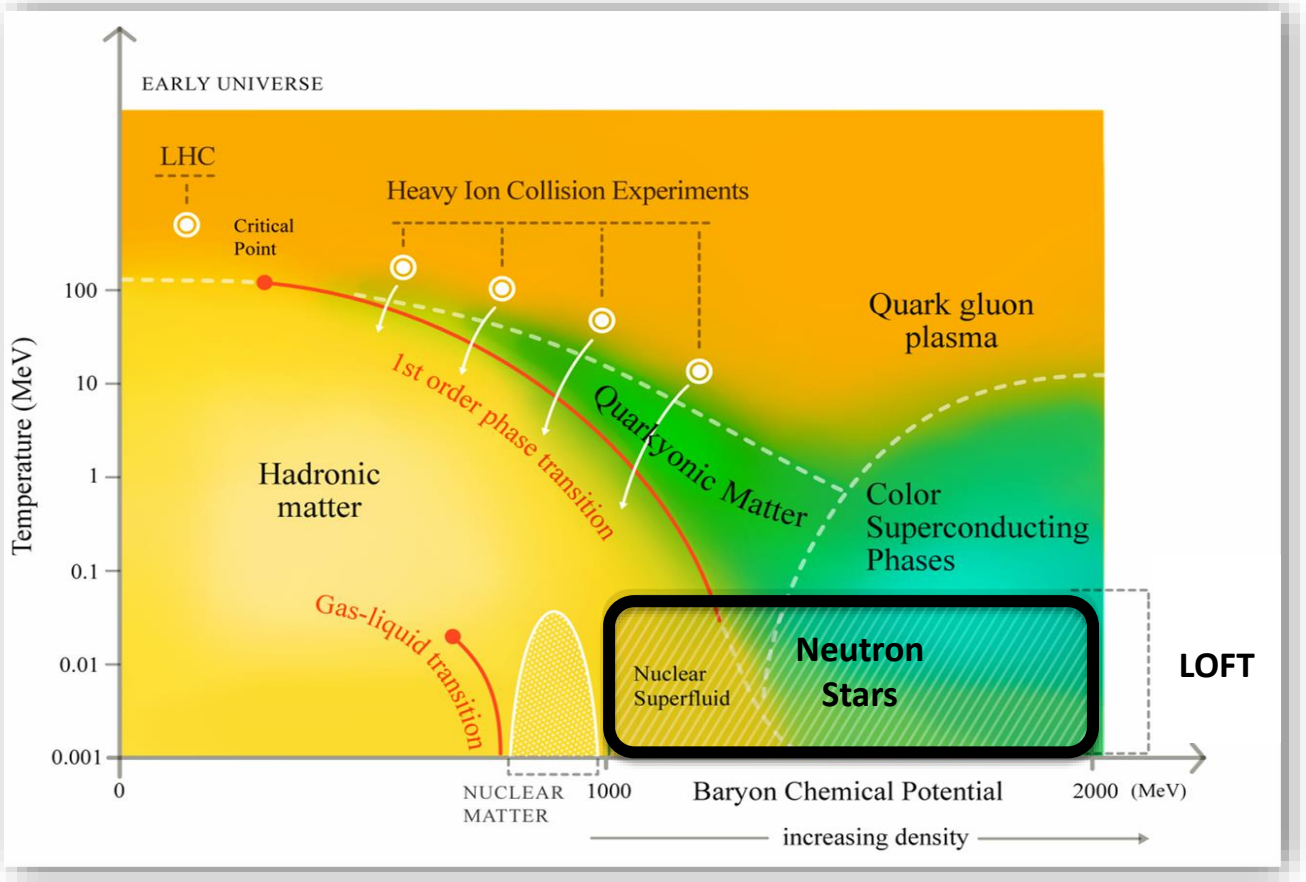
The strong force determines the state of nuclear matter - from atomic nuclei to neutron stars.

It is a major problem within modern physics.

PROGRESS IS DRIVEN BY **LABORATORY EXPERIMENT** AND **ASTROPHYSICAL OBSERVATION**.

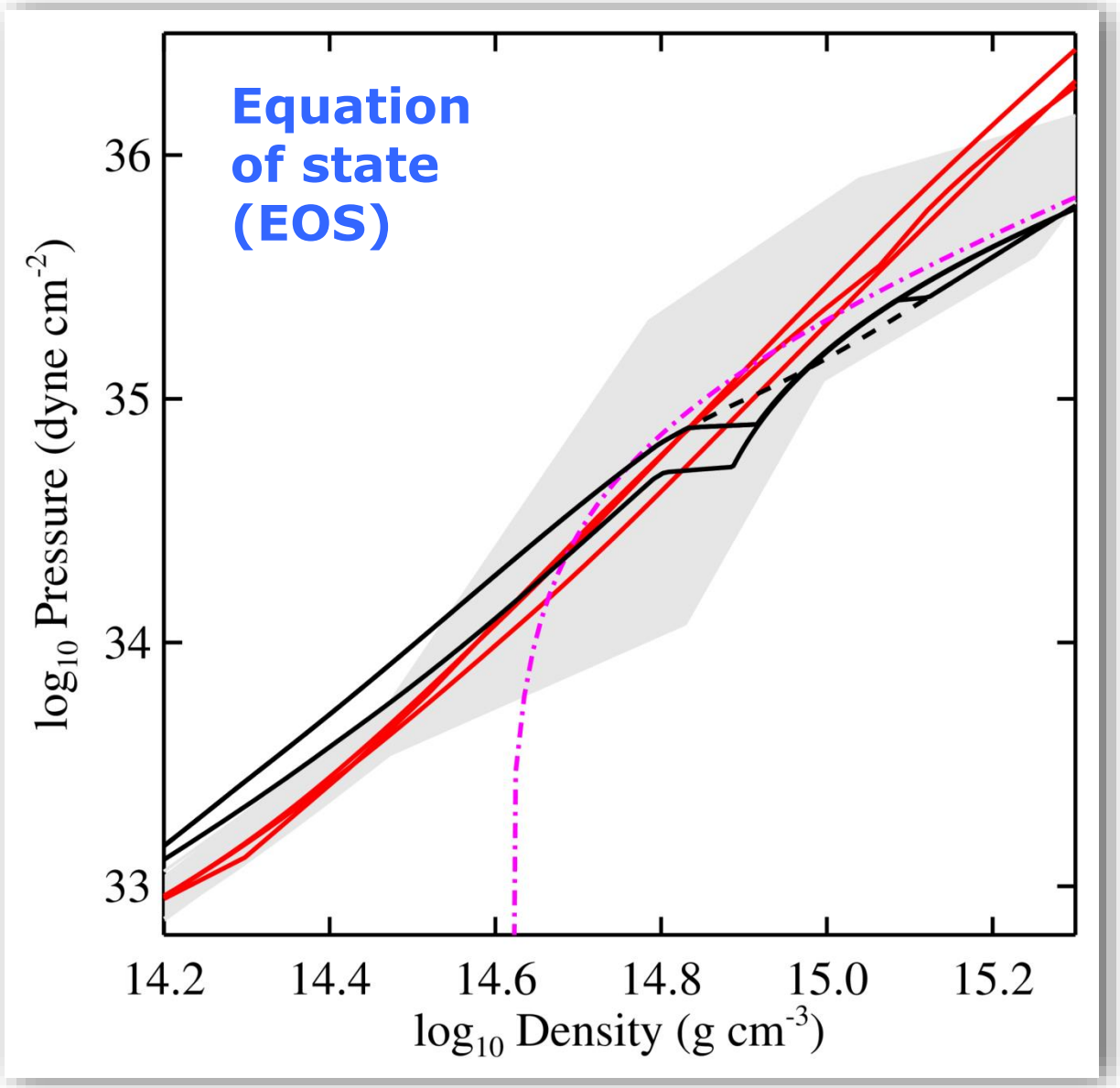



EARLY UNIVERSE
LHC
Heavy Ion Collision Experiments
Critical Point
Quark gluon plasma
1st order phase transition
Quarkyonic Matter
Hadronic matter
Color Superconducting Phases
Gas-liquid transition
Nuclear Superfluid
Neutron Stars
LOFT
Temperature (MeV)
100
10
1
0.1
0.01
0.001
0
NUCLEAR MATTER
1000
Baryon Chemical Potential
2000 (MeV)
increasing density



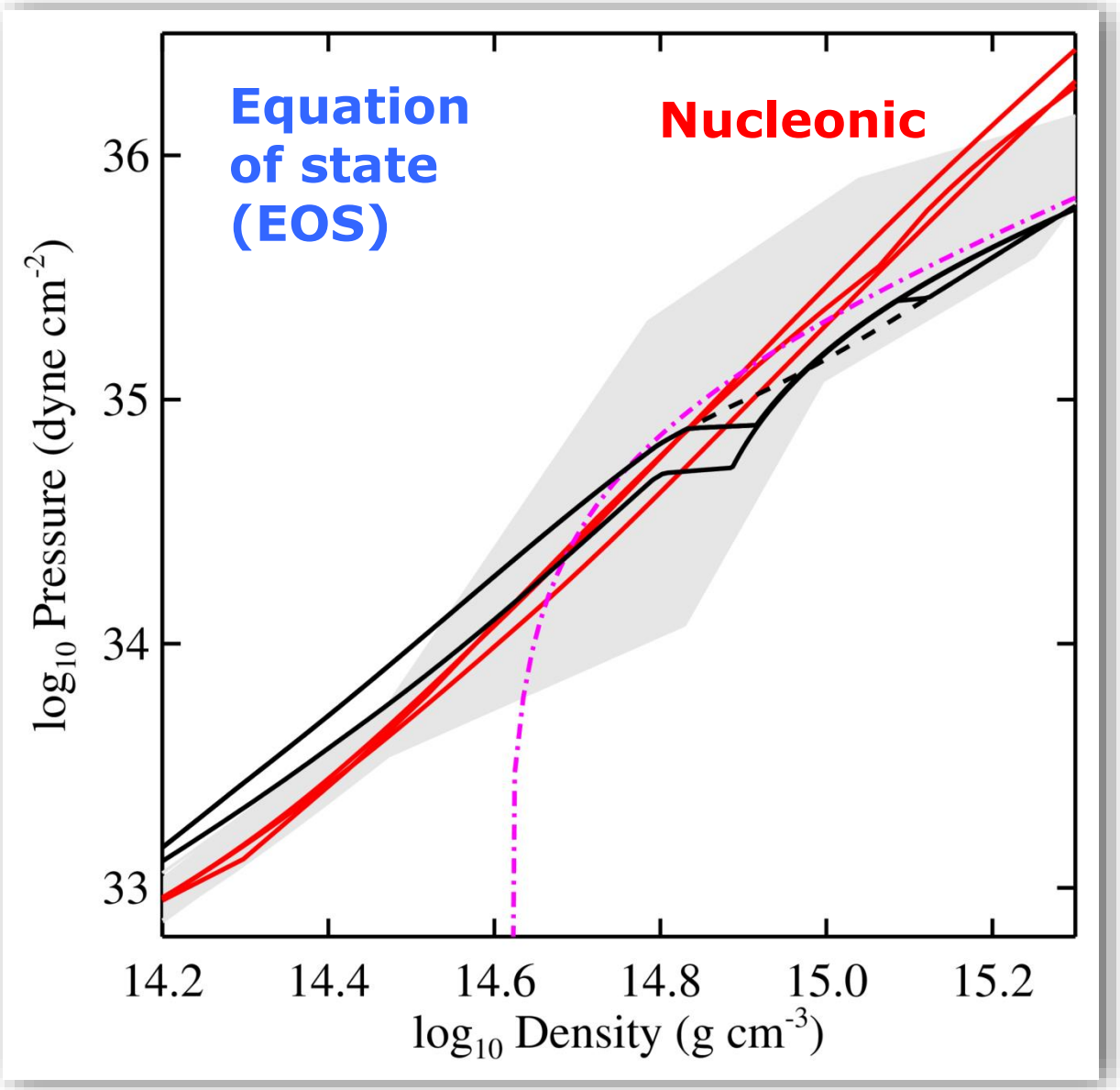
Neutron stars contain the **densest** and most **neutron-rich** matter **in the Universe**.

LOFT WILL STUDY **NUCLEONIC MATTER IN A UNIQUE REGIME,** AND **EXOTIC STATES OF MATTER** THAT COULD NEVER EXIST IN THE LABORATORY.



The strong force determines the 'stiffness' of neutron star matter.

This is encoded in the **EQUATION OF STATE**.



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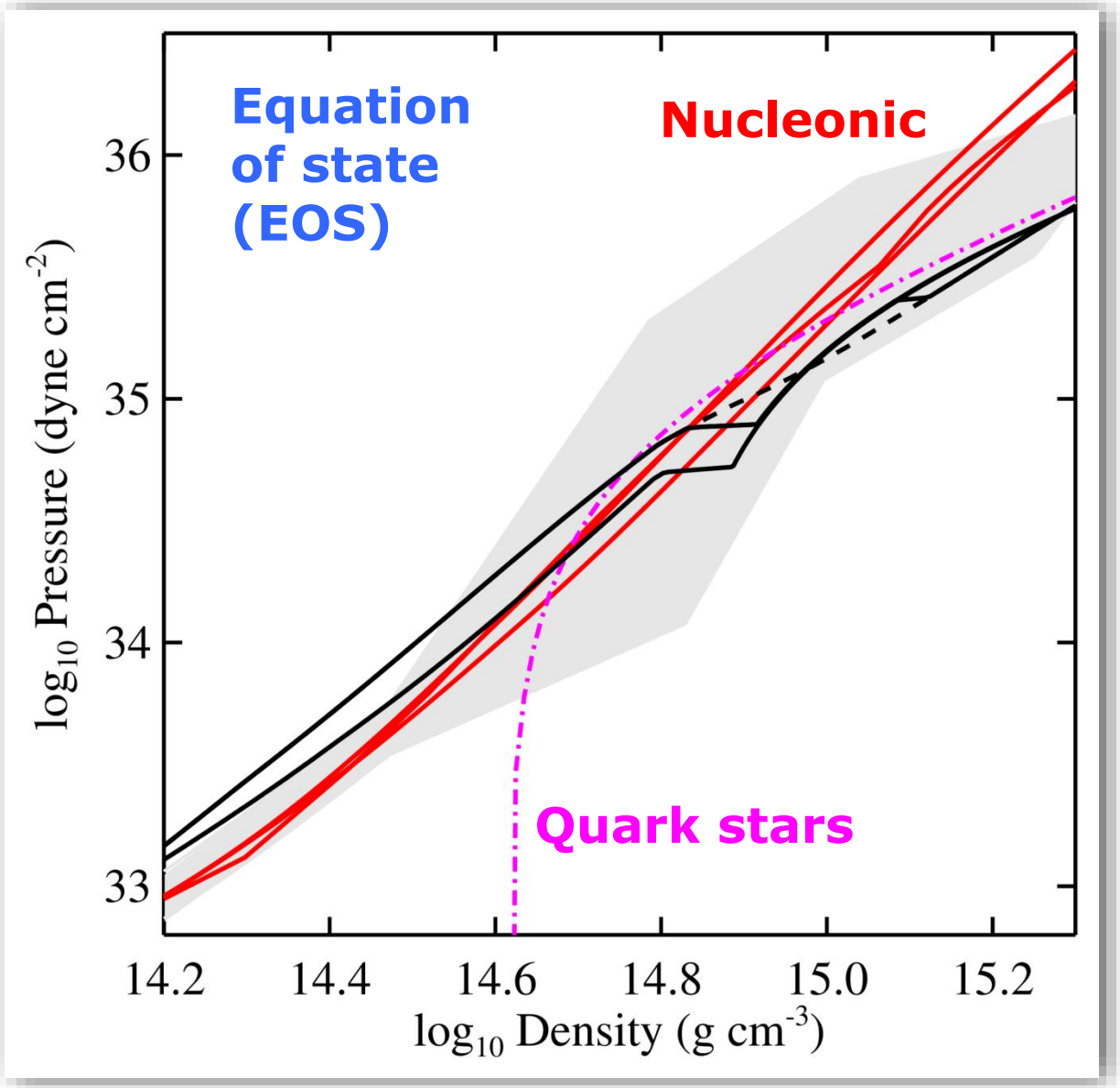

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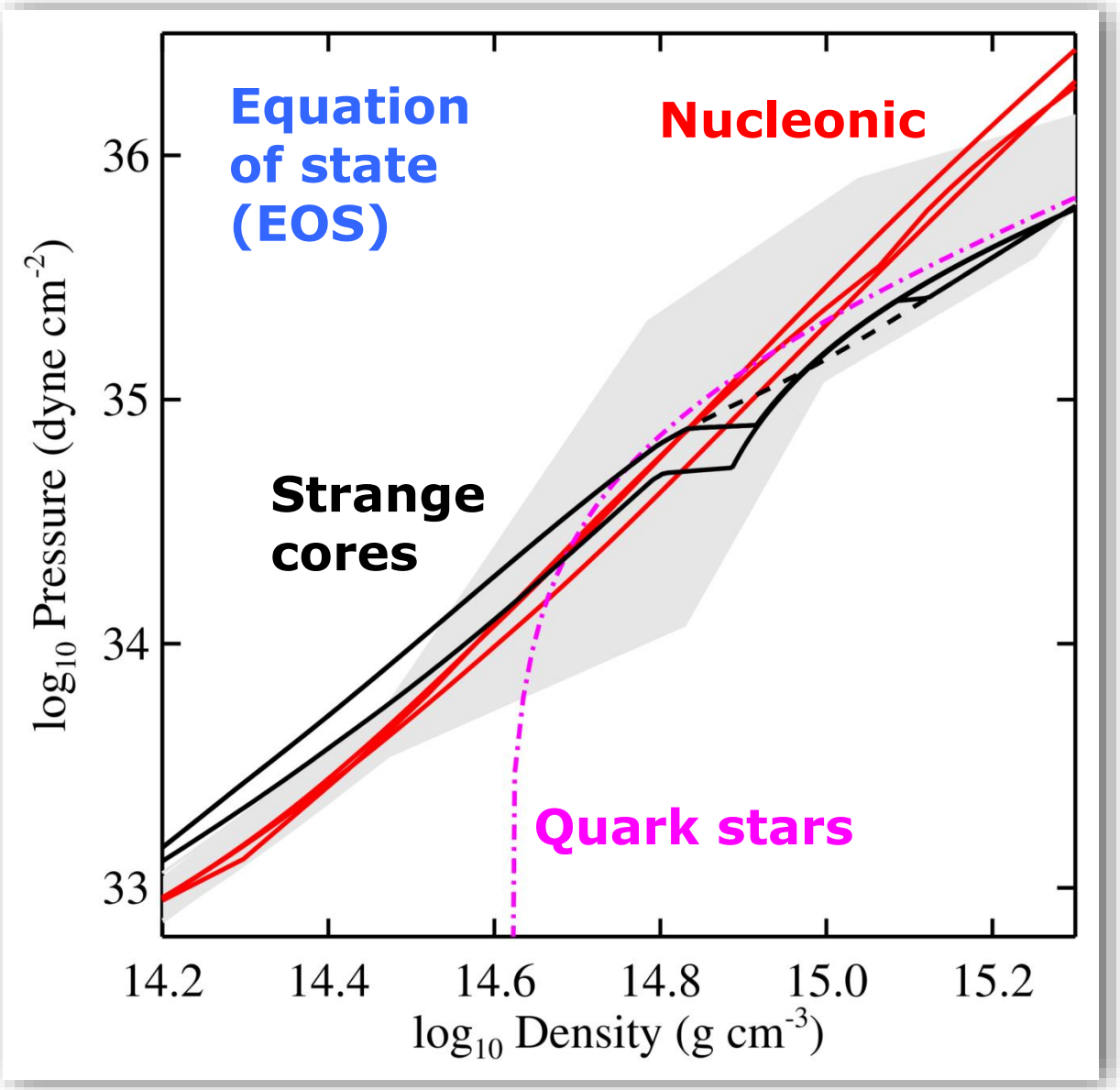

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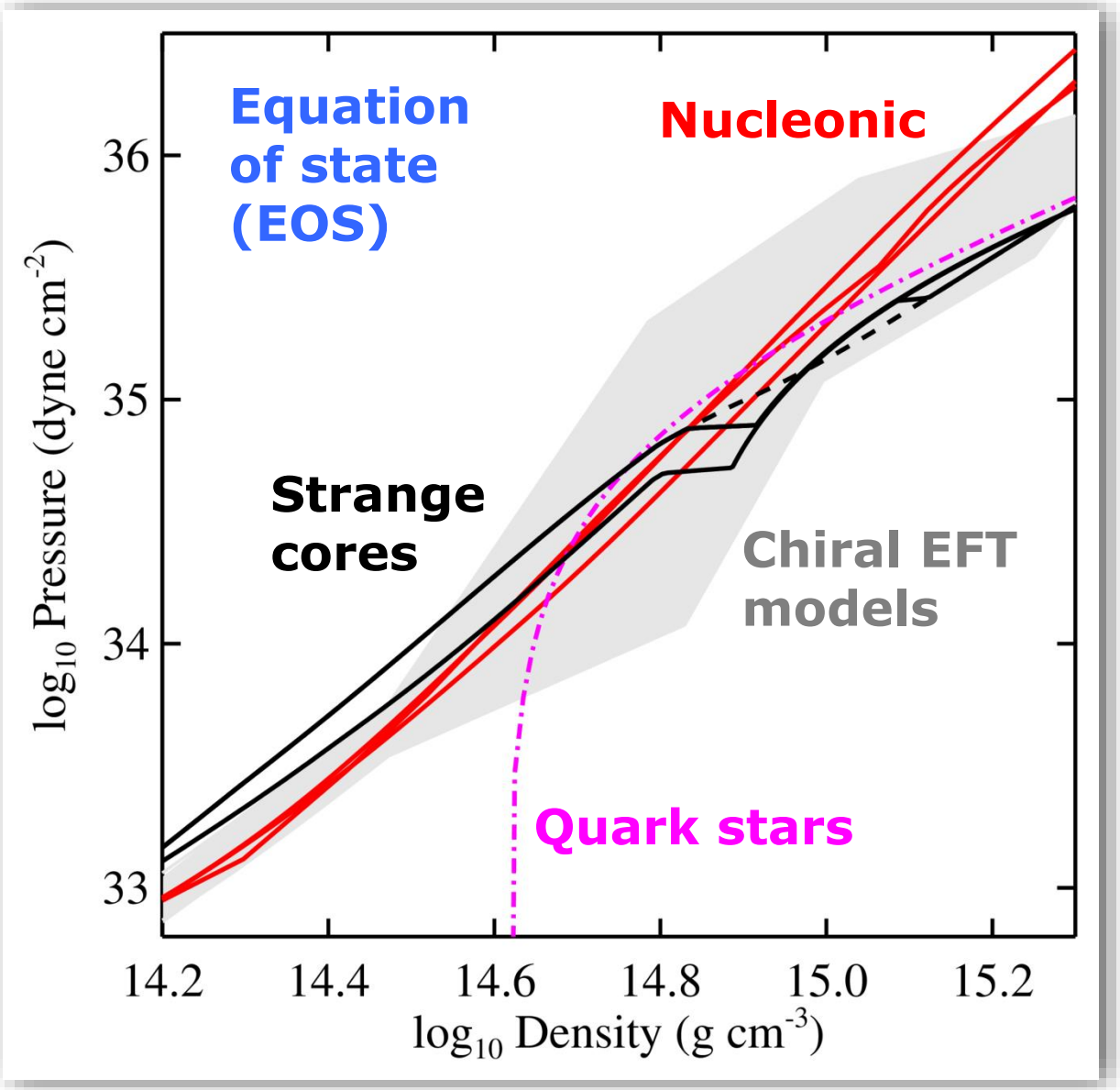

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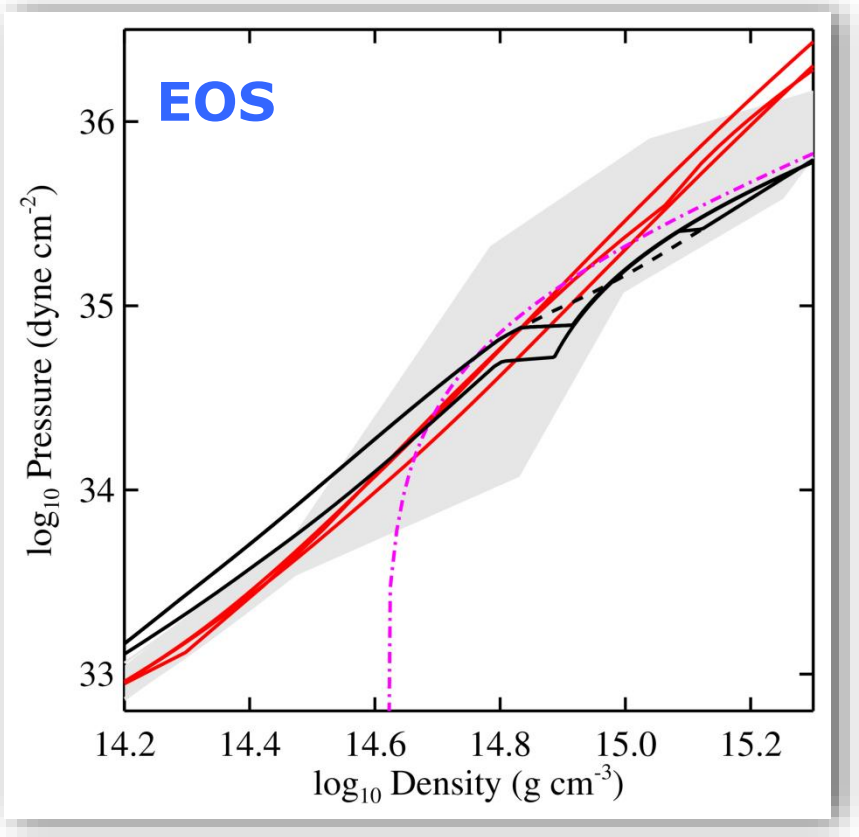
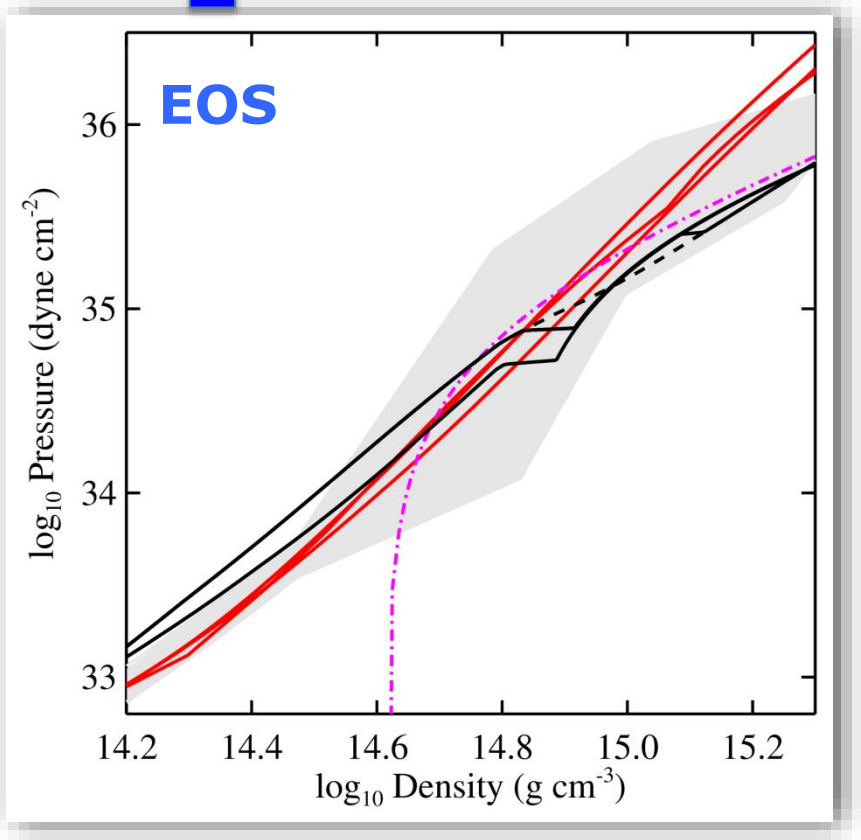
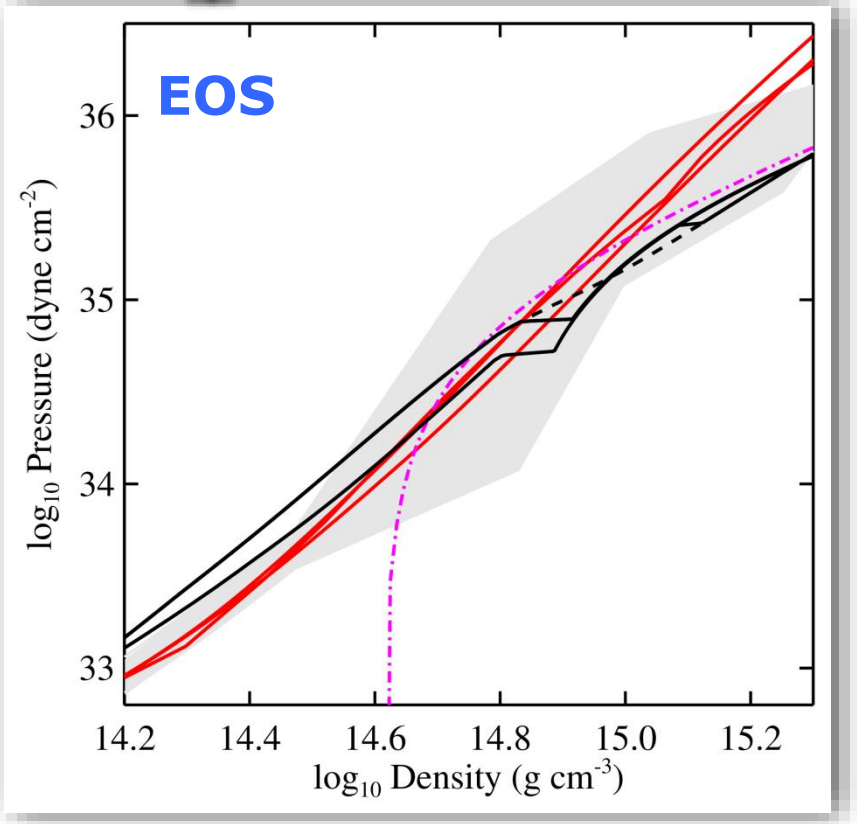
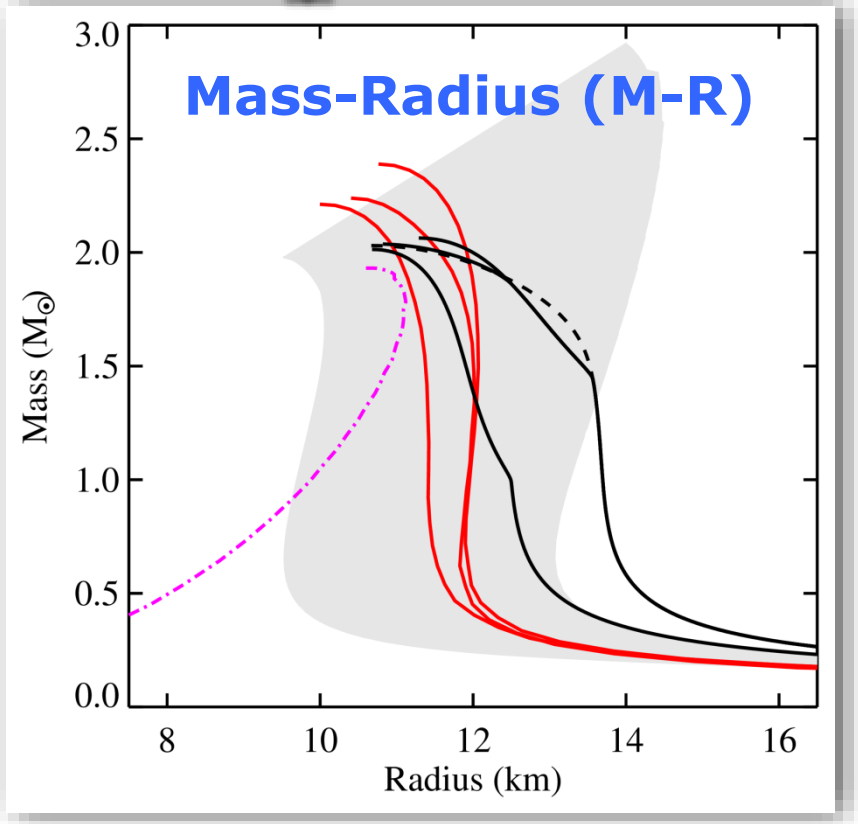

EOS
36
35
34
33
log10 Pressure (dyne cm-2)
14.2
14.4
14.6
14.8
15.0
15.2
log10 Density (g cm-3)

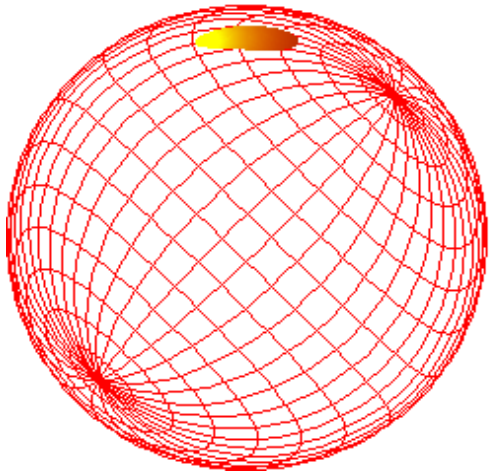

EOS
36
35
34
33
log10 Pressure (dyne cm-2)
14.2
14.4
14.6
14.8
15.0
15.2
log10 Density (g cm-3)

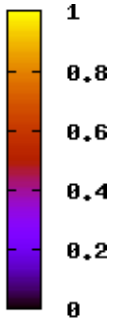
Stellar structure equations

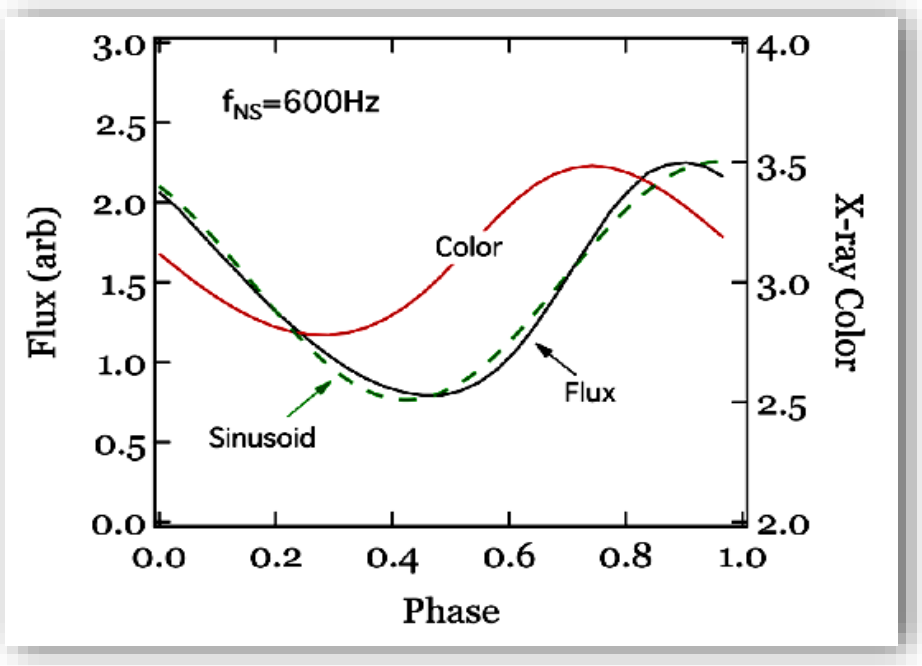


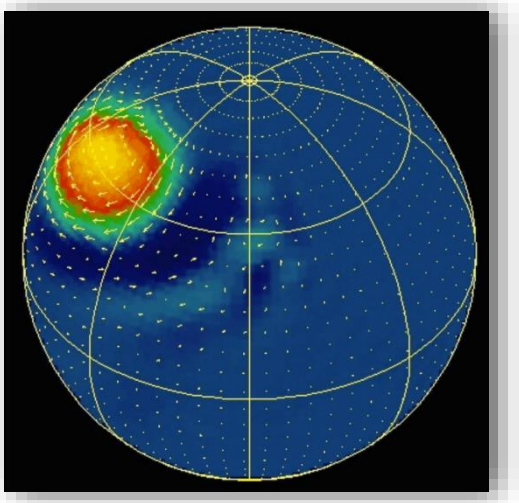


LOFT MUST MEASURE **BOTH M AND R** TO **HIGH PRECISION**
(LOW STATISTICAL AND SYSTEMATIC ERRORS) FOR A **RANGE OF M**.







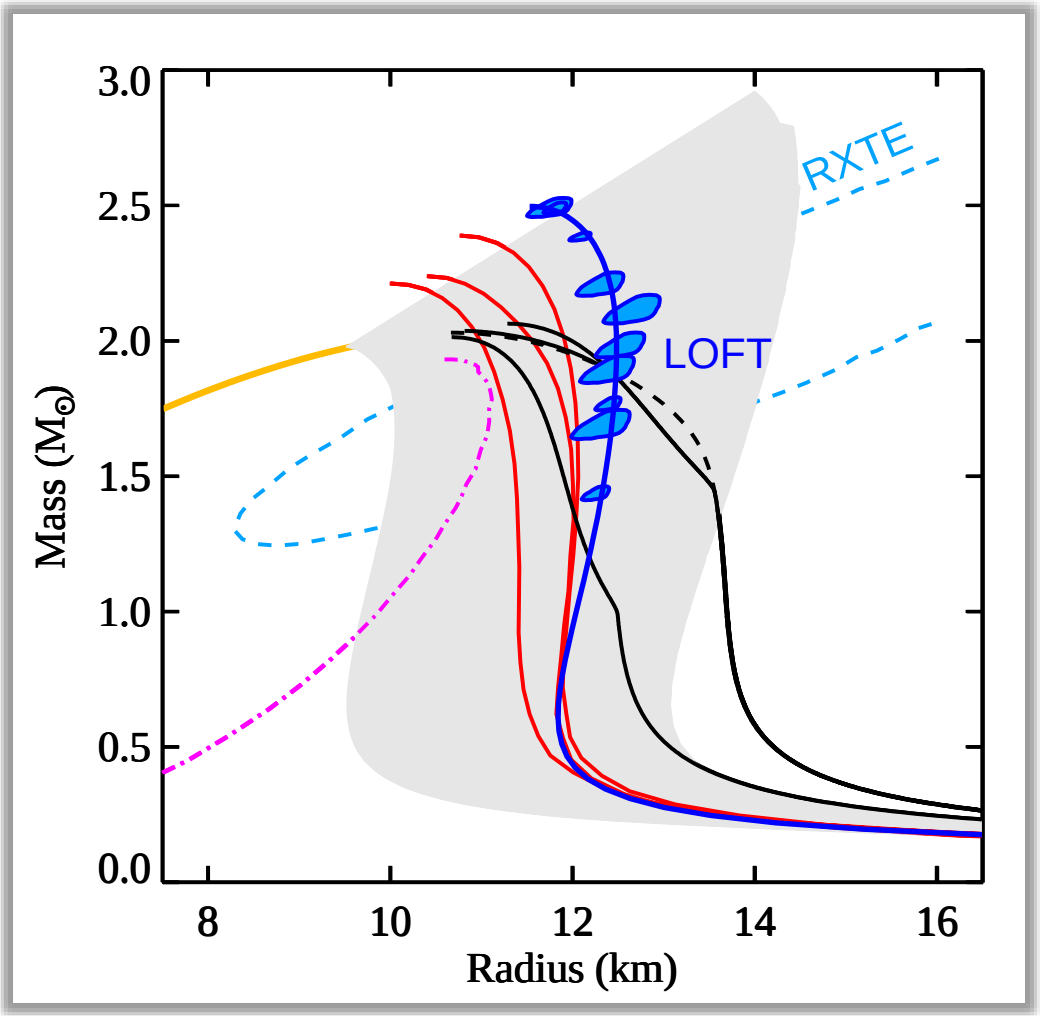


Hotspot in thermonuclear burst (Spitkovsky et al. 2002)

Hotspots on accreting neutron stars generate pulsations.

Relativistic effects (light-bending, redshifts, aberration) encode information about M and R.

LOFT WILL RECOVER M AND R FROM THE PHOTON ENERGY-DEPENDENT PULSE PROFILE.

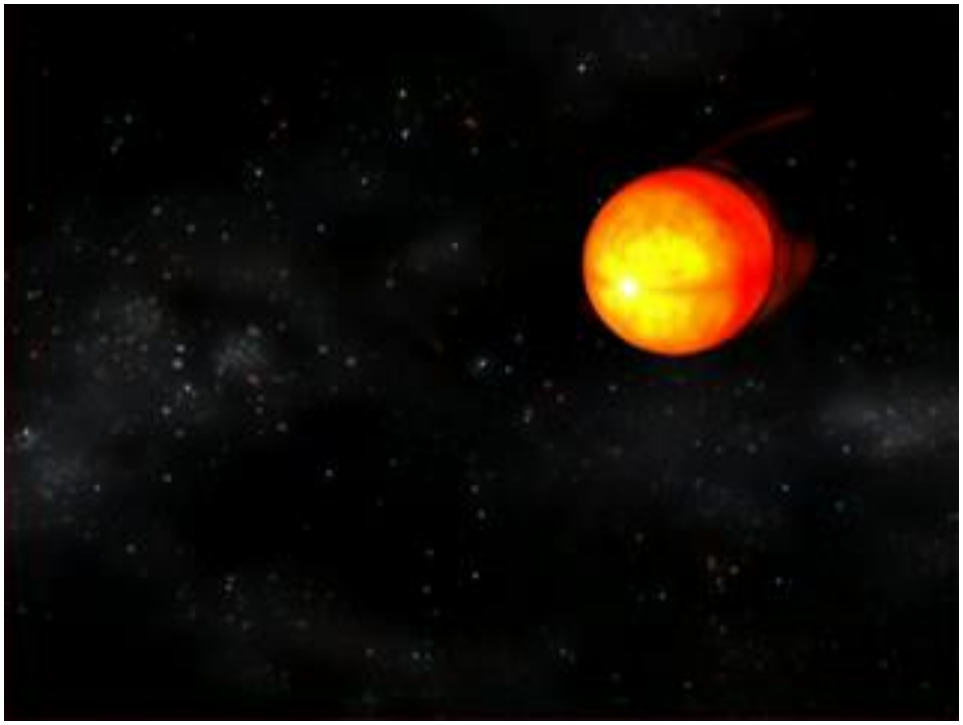


Detailed simulations carried out to evaluate fitting procedure and accuracies (Lo et al. 2013, ApJ).

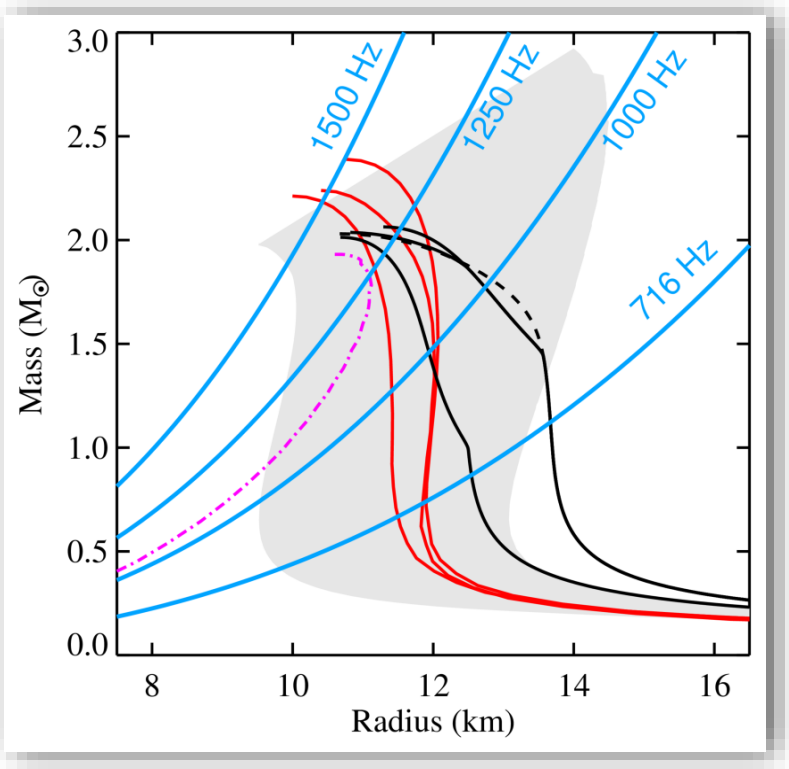
Few % accuracy needs ~10^6 photons: $10m^2$ area crucial.

Multiple same-source cross-checks.

USING ONLY KNOWN SOURCES, LOFT'S PULSE PROFILE MODELLING MEASUREMENTS WILL MAP THE M-R RELATION AND HENCE THE EOS.

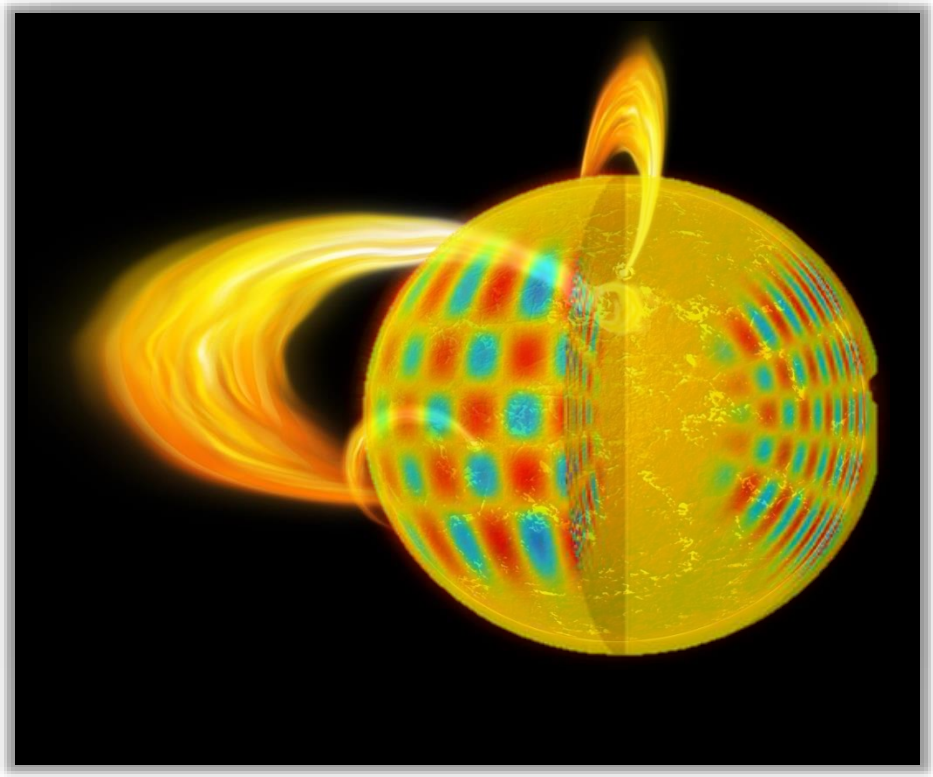


For most accreting NS spin is not yet known. Pulsations (especially for high accretion rate sources) are weak or intermittent.

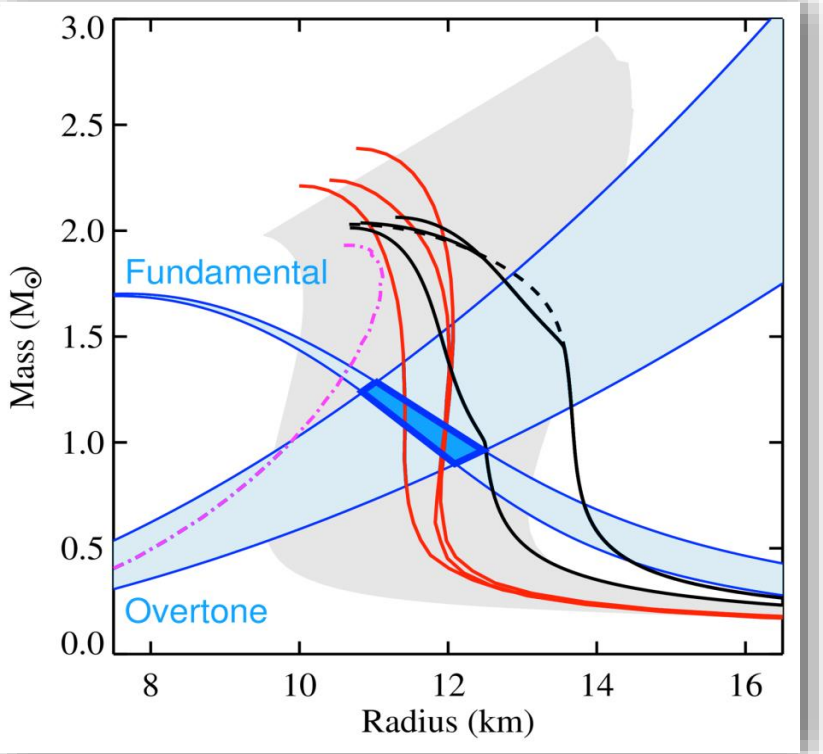


Spin rates constrain EOS via mass-shedding limit.

LOFT'S EXQUISITE SENSITIVITY WILL ALLOW FULL CHARACTERIZATION OF THE SPIN DISTRIBUTION OF ACCRETING NEUTRON STARS.

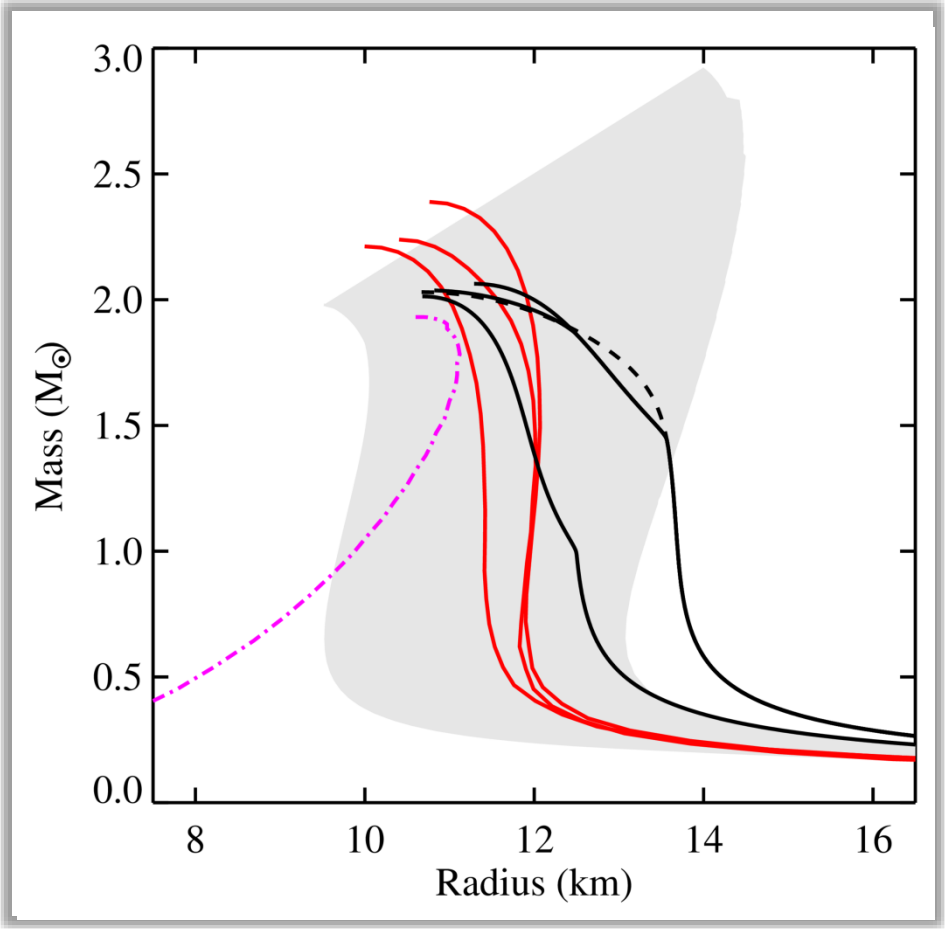


Starquakes on magnetars trigger global seismic vibrations. Current data come from the rarest, most energetic events.



Magneto-elastic seismic vibration models constrain M-R and hence the EOS.

LOFT WILL BE SENSITIVE TO SEISMIC VIBRATIONS FROM SMALLER STARQUAKES, DRIVING THE EMERGING FIELD OF NEUTRON STAR ASTEROSEISMOLOGY.



LOFT

- **measures both M and R.**
- **minimises statistical error** with its large effective area.
- **minimises systematic error** with complementary methods and same source cross-checks.
- **relies only on known sources** to deliver the required number of data points.

No other facility does this.

LOFT WILL MEASURE THE EOS OF DENSE MATTER, THE KEY TO UNDERSTANDING THE STRONG FORCE.

Dense matter

Strong field gravity

Observatory science

Near the event horizon

Astrophysics near black holes: strong field effects

- Inner Stable Circular Orbit
- Orbital motion near ISCO
  - Orbital and epicyclic frequencies
- Frame dragging, light deflection, Shapiro effect

Astrophysical impact

- Black hole masses and spins
- AGN feedback
- Relativistic jets
- Supernova core collapse
- Accretion physics

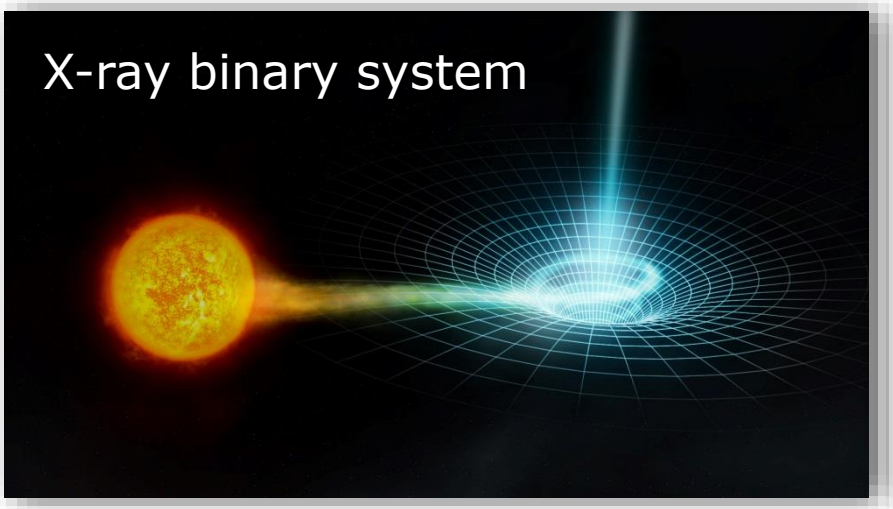
Current best tests
of General Relativity:
millisecond radiopulsars

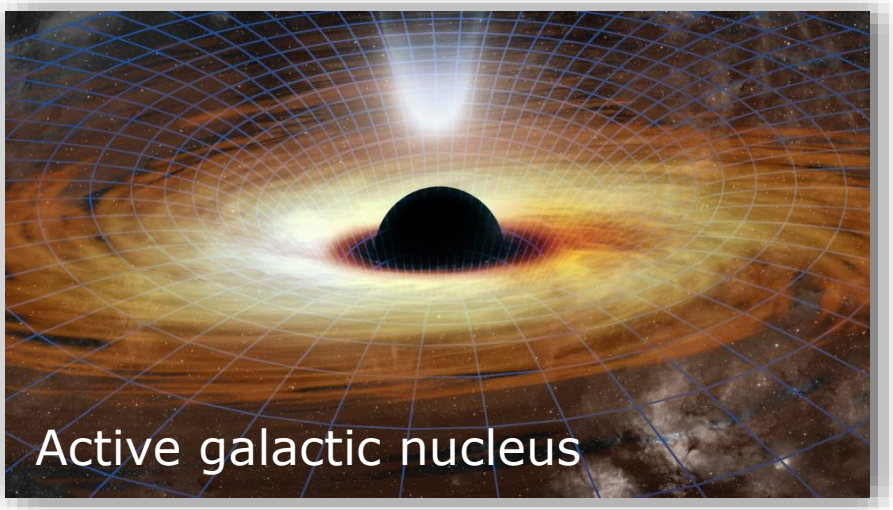
LOFT: near the event horizon

Relativistic effects dominate

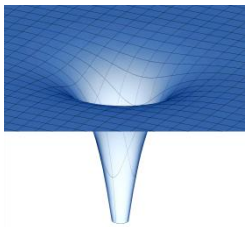
Factor 100,000 closer
to the black hole

Relativistic effects are small perturbations



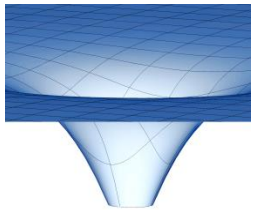


LOFT covers wide mass range in uniform setting



Stellar mass black hole
(or neutron star)

Strongly curved spacetime.
(10^{16} times Solar)

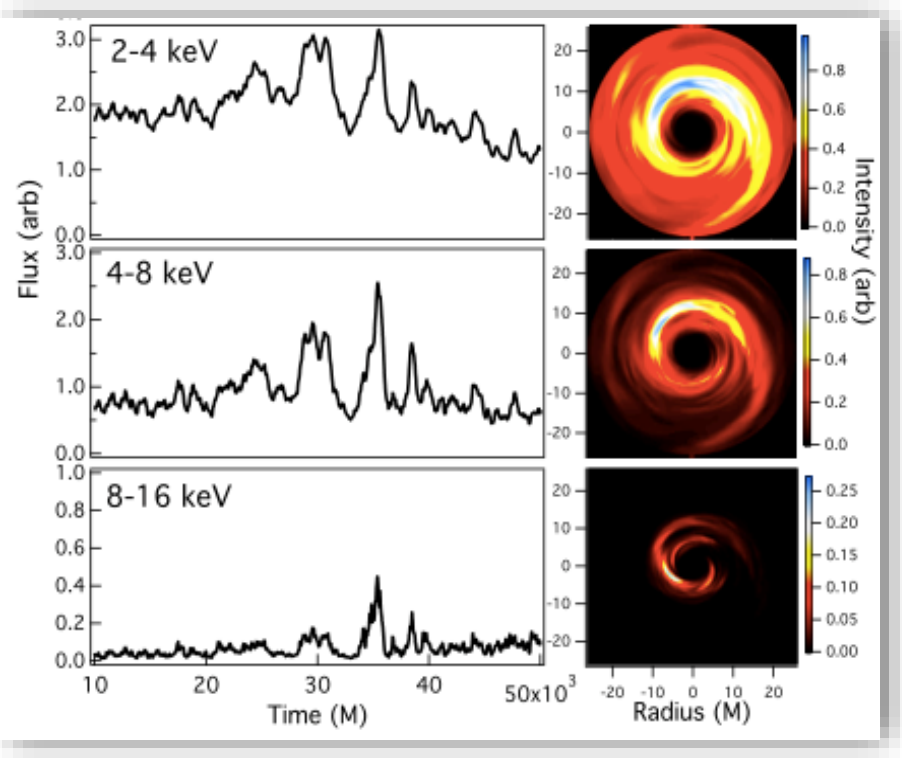


Supermassive black hole

Weakly curved spacetime
(~Solar)

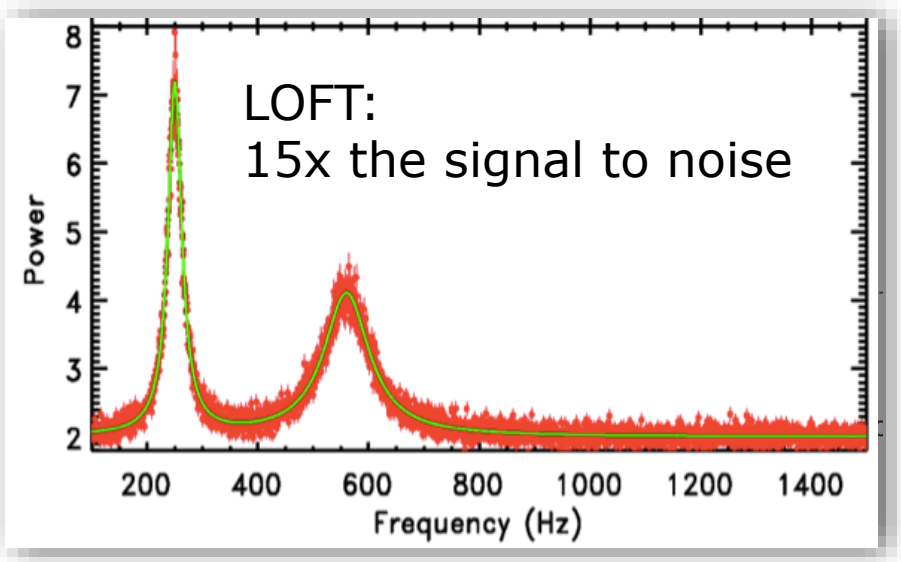
COMPLEMENTARY TO GRAVITATIONAL WAVE EXPERIMENTS:
LOFT PROBES STATIONARY SPACETIMES

General Relativity predicts precise orbital and epicyclic frequencies at each radius



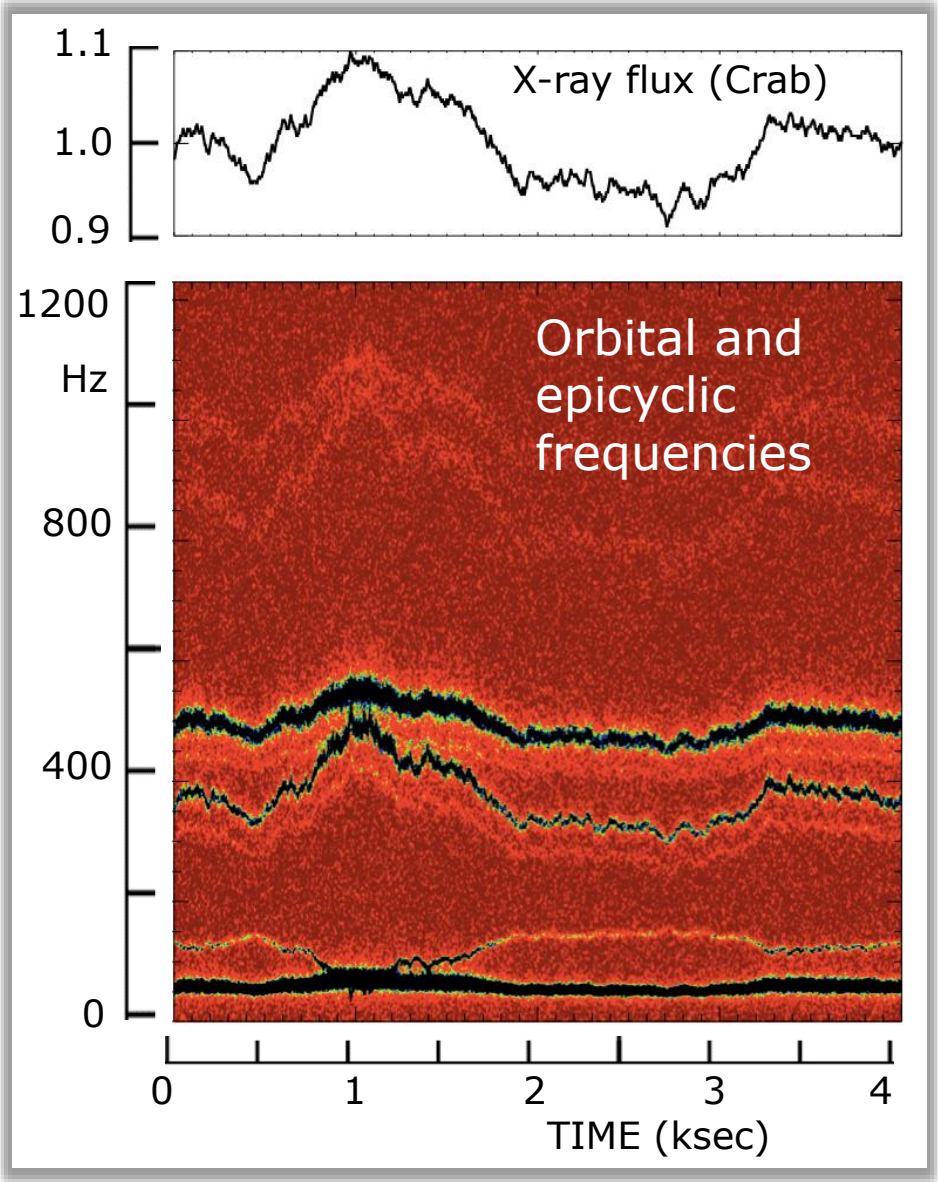
Wellons et al. 2013

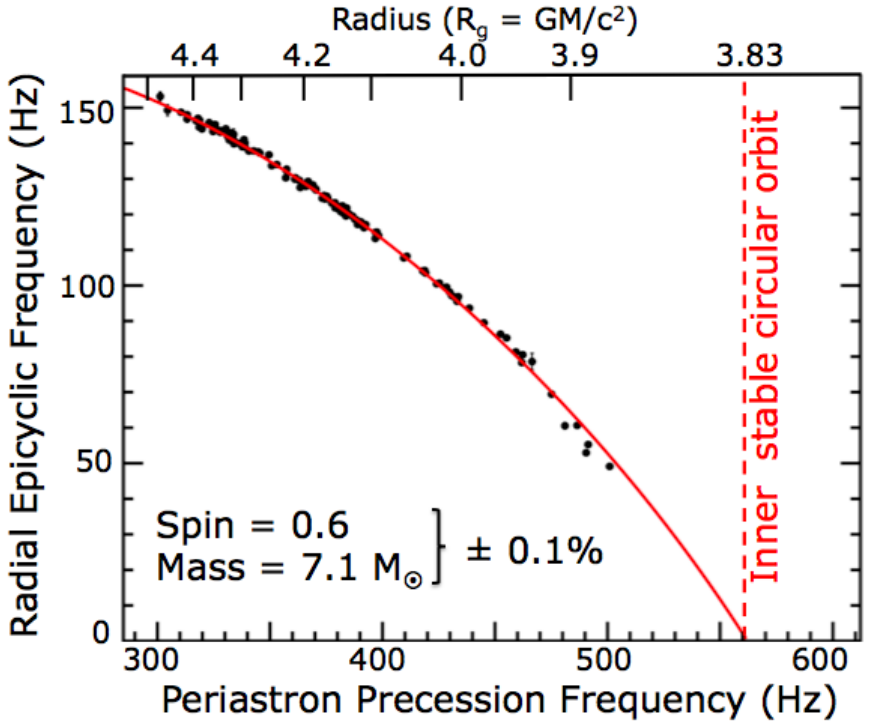
Orbiting inhomogeneities make frequencies observable



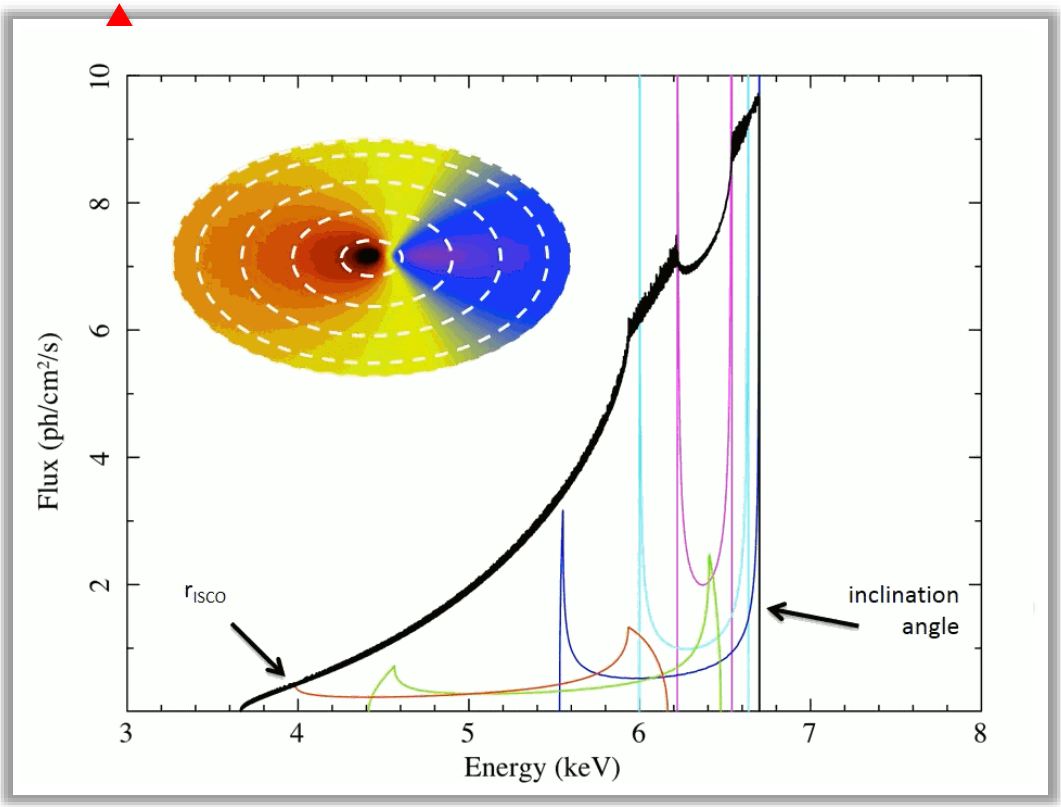
- Strong gravity dynamical frequencies <u>just</u> detected in current (RXTE) data
- LOFT diagnoses strong field gravity very precisely by:
  - timing of the <u>flux variations</u>
  - time resolved <u>spectroscopy</u>

  at very high signal to noise
- Uses known phenomena



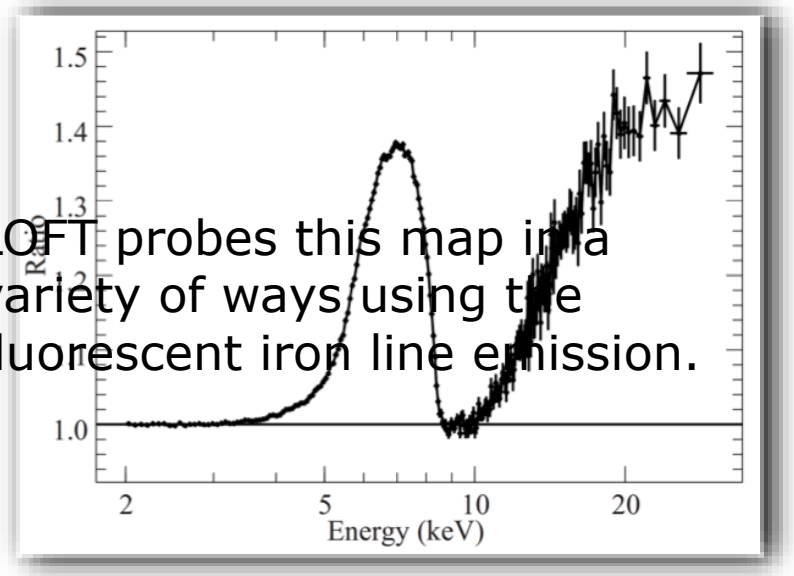


- Precisely measure orbital and epicyclic frequencies at each radius
- Compare curve to GR predictions
- Measure black hole mass and spin to 0.1% precision



Line profile integrated over entire flow

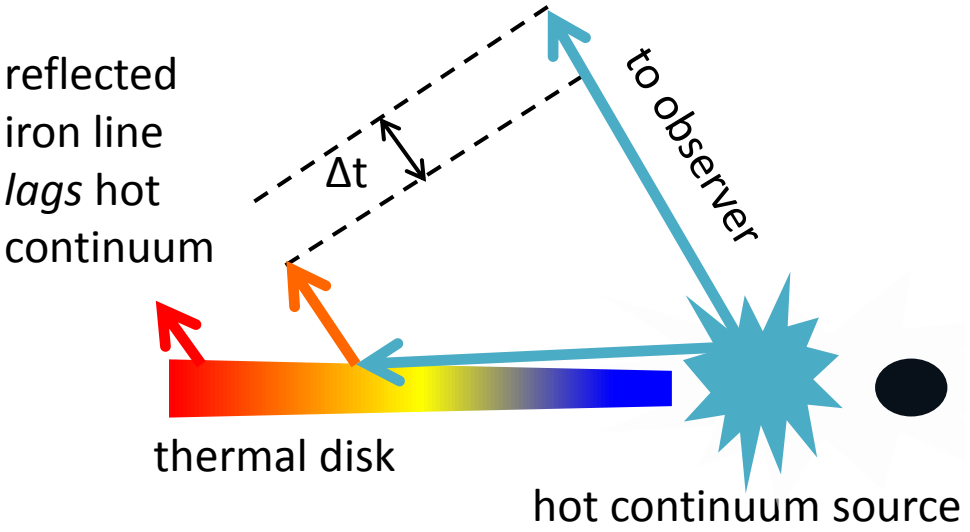
LOFT probes this map in a variety of ways using the fluorescent iron line emission.

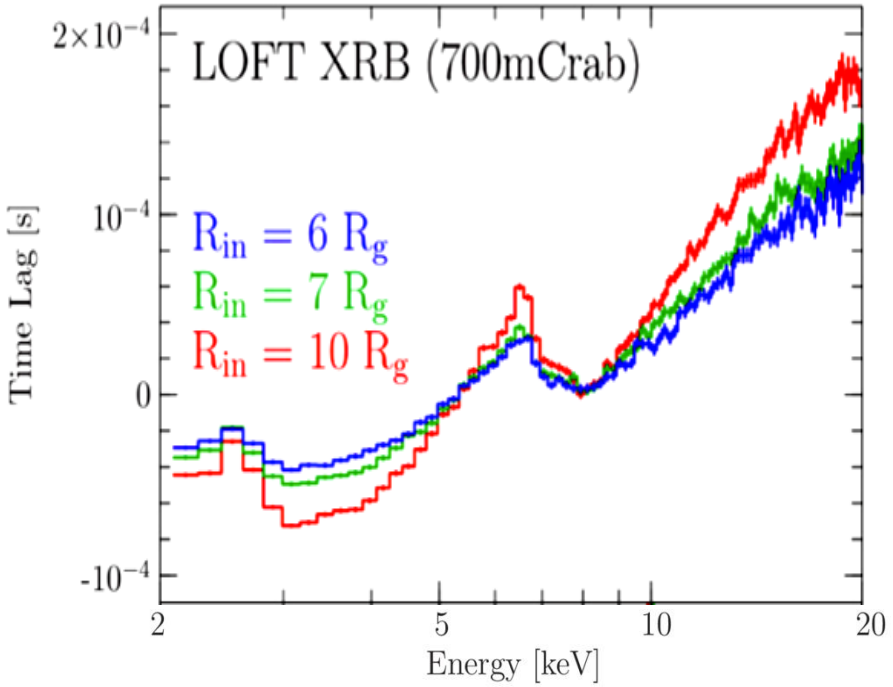


XMM 23 ks integration

LOFT simulation of black hole X-ray binary
100 sec integration
a* = 0.967±0.003

Reverberation





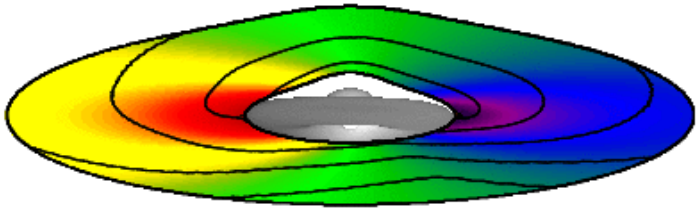
- Variable hot inner flow irradiates disk
- Probe disk velocity/redshift map as radiation fronts propagate over the disk
- Obtain strong field velocities and relativistic effects as a function of absolute radius

Reverberation (barely) detected in XMM data

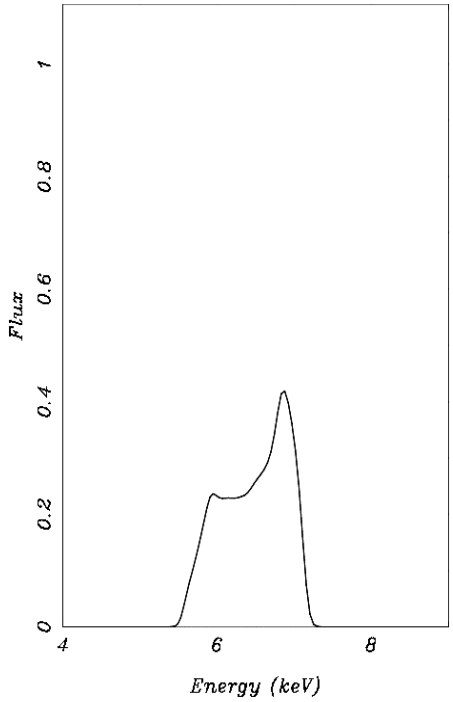
LOFT improves S/N by
- factor ~6 in AGN
- factor >200 in X-ray binaries!

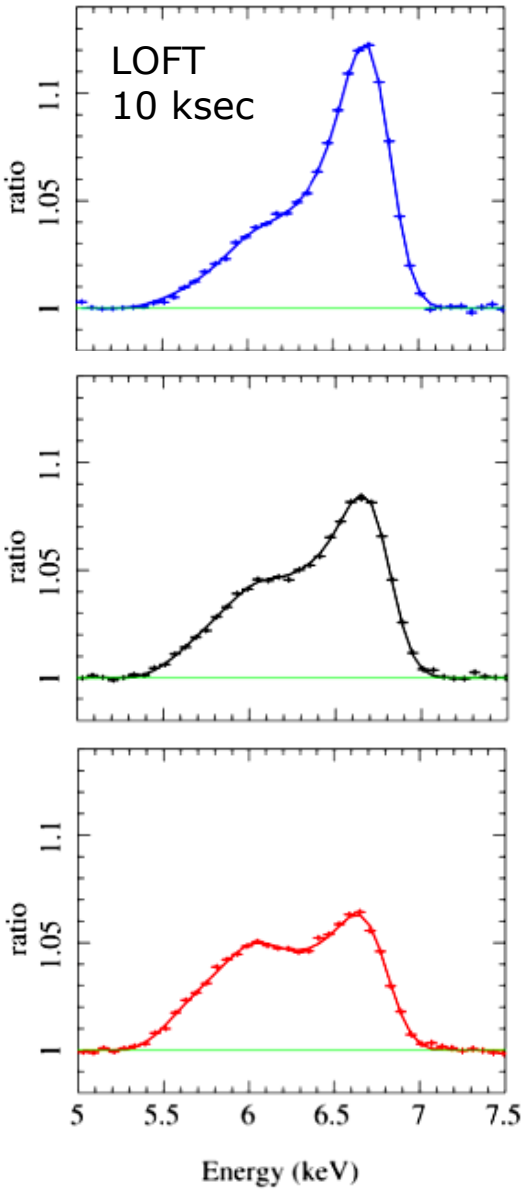
➔ Breakthrough capability ←

Precessing hot torus



Ingram, Done, Fragile
2009, 2012



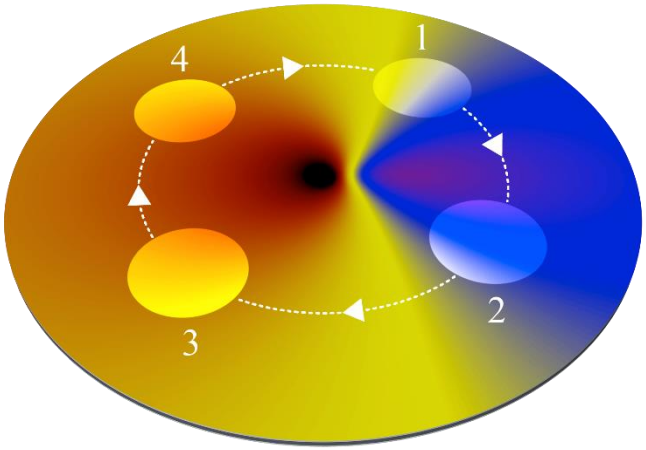


- Frame dragging: central hot torus <u>precesses</u>
- Hard radiation sweeps around over disk
- Reflection line profile varies periodically

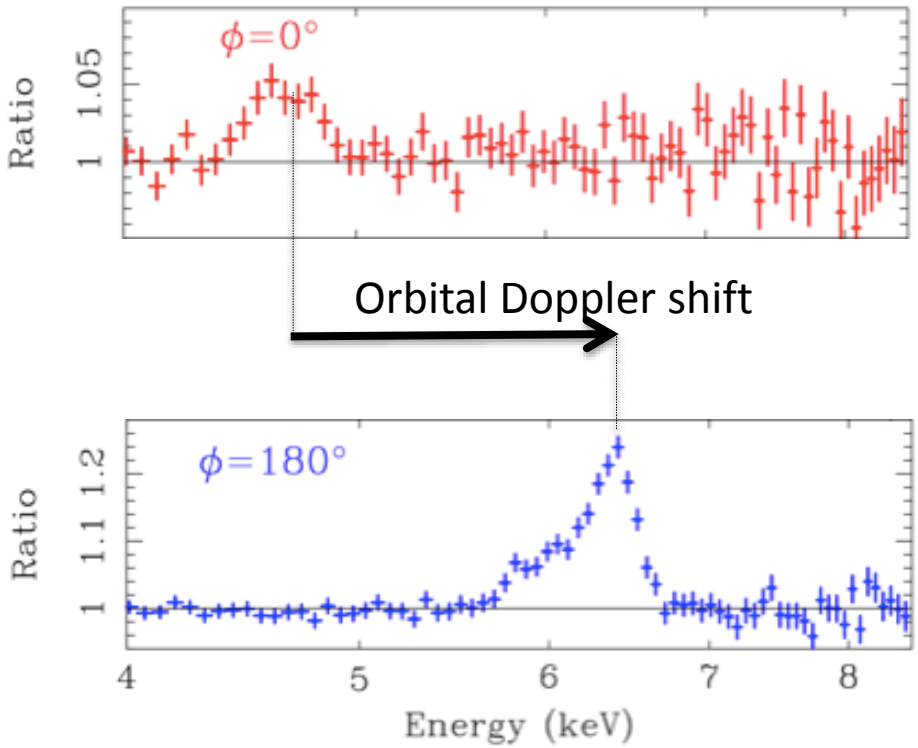
LOFT observations:

- Confirm black hole frame dragging
- Track the line profile, probing the disk velocity and redshift map

Supermassive black hole



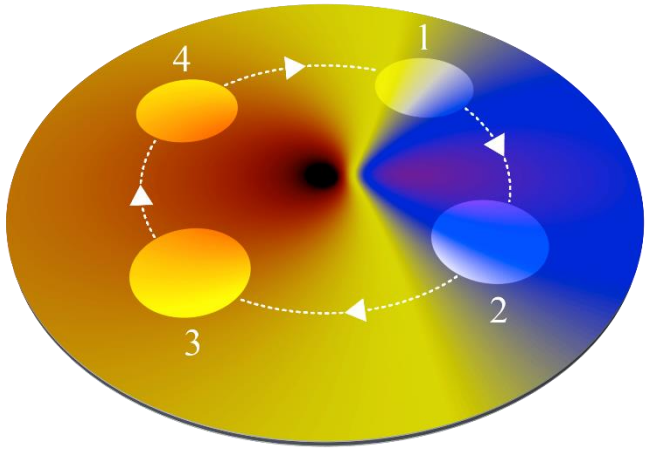
LOFT 3 ksec integrations



Doppler shifting for orbits closely around a supermassive black hole

Depending on precise pattern of inhomogeneities

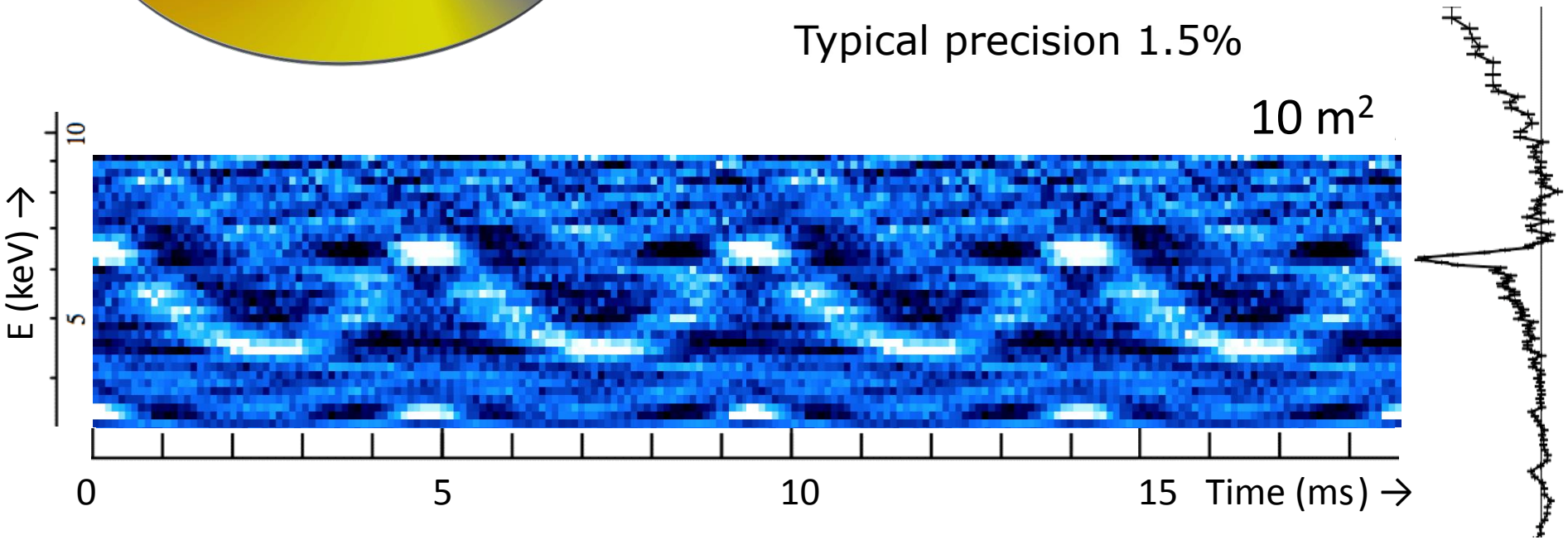
Stellar-mass black hole



Orbital radial velocity curve at ISCO, closely around a stellar mass black hole

Doppler tomography of disk velocity & redshift map.

Typical precision 1.5%



Uses known amplitude of quasi-periodic dynamic signals

Dense matter

Strong field gravity

Observatory science

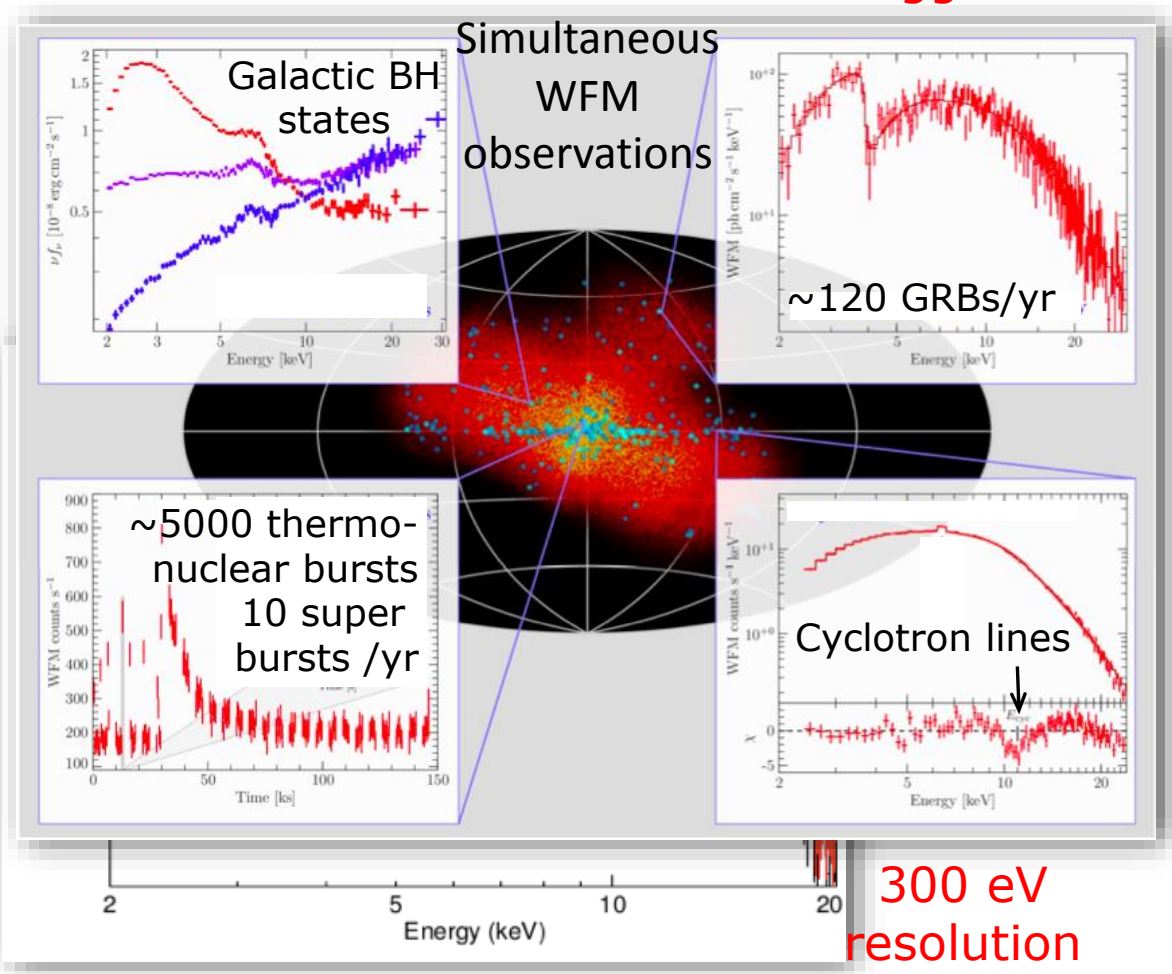
- EXTREME-THROUGHPUT SPECTROSCOPY WITH LAD
- VERY WIDE ANGLE MONITORING WITH WFM

30 s triggers

2-50 keV bandwidth

- Accretion physics
- Magnetospheric physics
- Thermonuclear bursts
- Magnetars
- Gamma ray bursts
- Tidal disruptions
- Cataclysmic variables
- Terrestrial γ-ray flashes
- Flare stars
- …

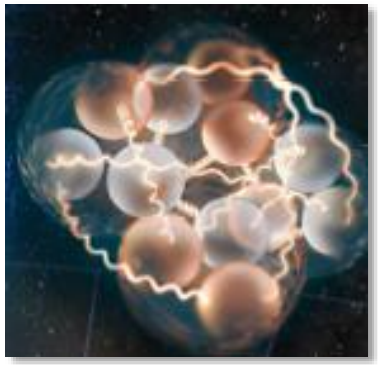
- 180 science papers
- 580 LOFT supporters



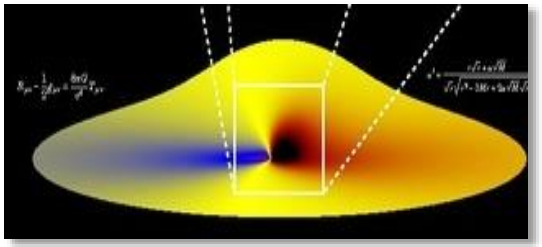
300 eV resolution

By the mid-2020's with LOFT we will have:

Measured the equation of state of supranuclear density matter



Mapped out the motions of matter in strong field gravity



Exploited the discovery space of

- LAD high throughput spectroscopy
- WFM sensitive sky monitoring & triggering