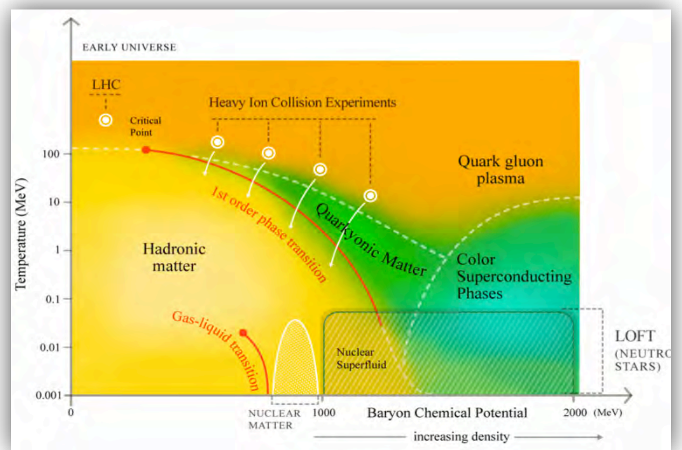
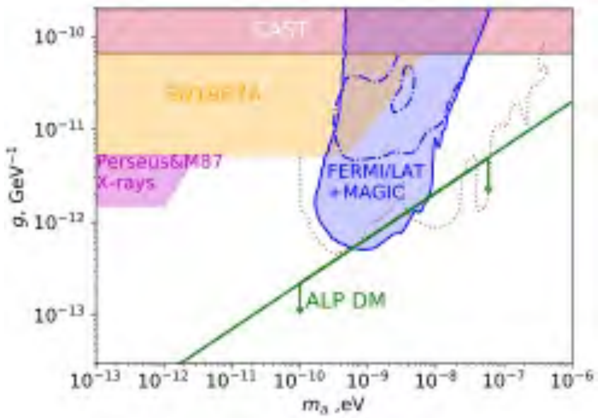
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT

Institute of Astronomy and Astrophysics





A new frontier of X-ray+ astrophysics: unveiling fundamental physics.

Andrea Santangelo* IAAT Kepler Center Tübingen

Also at IHEP, CAS, Beijing

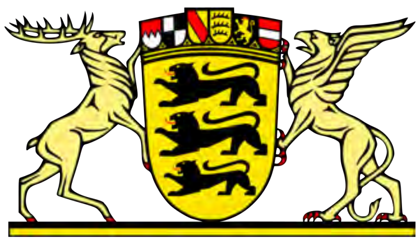
Seminar at IPMU, November 22, Tokyo Japan

Preamble

In Southwest Germany, heart of Europe

Population 85,000
University city

"Land" is Baden-Württemberg, Capital Stuttgart



Population 10.6 Million
Area about 36,000 km^2

Eberhard Karls Universität* was founded in *1477


Lichtenstein
MARQUART
GLAS-PORZELLAN

Perhaps Tübingen's most famous student

Johannes Kepler
(1571-1630)

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X-ray observatories: a bright future

eROSITA

2019

IXPE
Imaging X-Ray Polarimetry Explorer

2020

ATHENA

2028 (?)

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

2032 (?)

2023 (?)

ARCUS

2021

XRISM
X-RAY IMAGING AND SPECTROSCOPY MISSION

SVOM

2021

exploring transients and variability in the dynamic X-ray Universe
Einstein Probe

2020

And this list is not exhaustive… eXTP will be presented later, Strobe X is missed

Rationale of the talk

Topics of fundamental Physics that can be addressed **in High energy Astrophysics:**

Mainly X-rays but with a touch of GeV Gamma rays.

- **EOS of ultradense matter: NSs studies**
- **Dark Matter search: sterile neutrinos, ALPS**
- Unveiling QED effects (only if time left)

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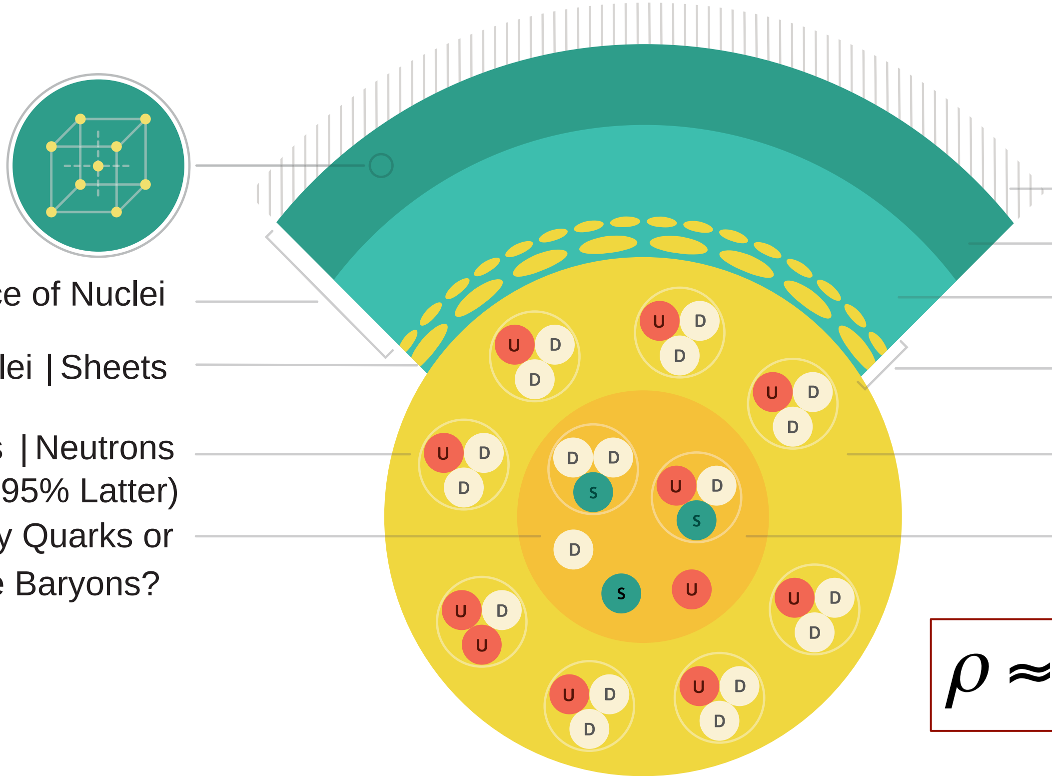
Part I

Dense Matter Studies
(DM stands for Dense Matter)

A. L. Watts, W. Yu, J. Poutanen, S. Zhang, et al Sci. China-Phys. Mech. Astron (2018)

The interior of a NS (2)



$$\rho \approx 10\,\rho_{sat}$$

In the simplest picture: core is a uniform charge-neutral fluid of neutrons *n*, protons *p*, electrons e^-, and muons μ^- (equilibrium with respect to the weak interaction, β-stable nuclear matter)

$$\rho_{sat} \approx 2\times10^{14}\,\mathrm{gcm}^{-3}$$

Anna L. Watts et al. Rev. Mod. Phys. ***88****, 021001 (2016)*

Interior of Neutron Star (3)

196 F. Weber / Progress in Particle and Nuclear Physics 54 (2005) 193–288

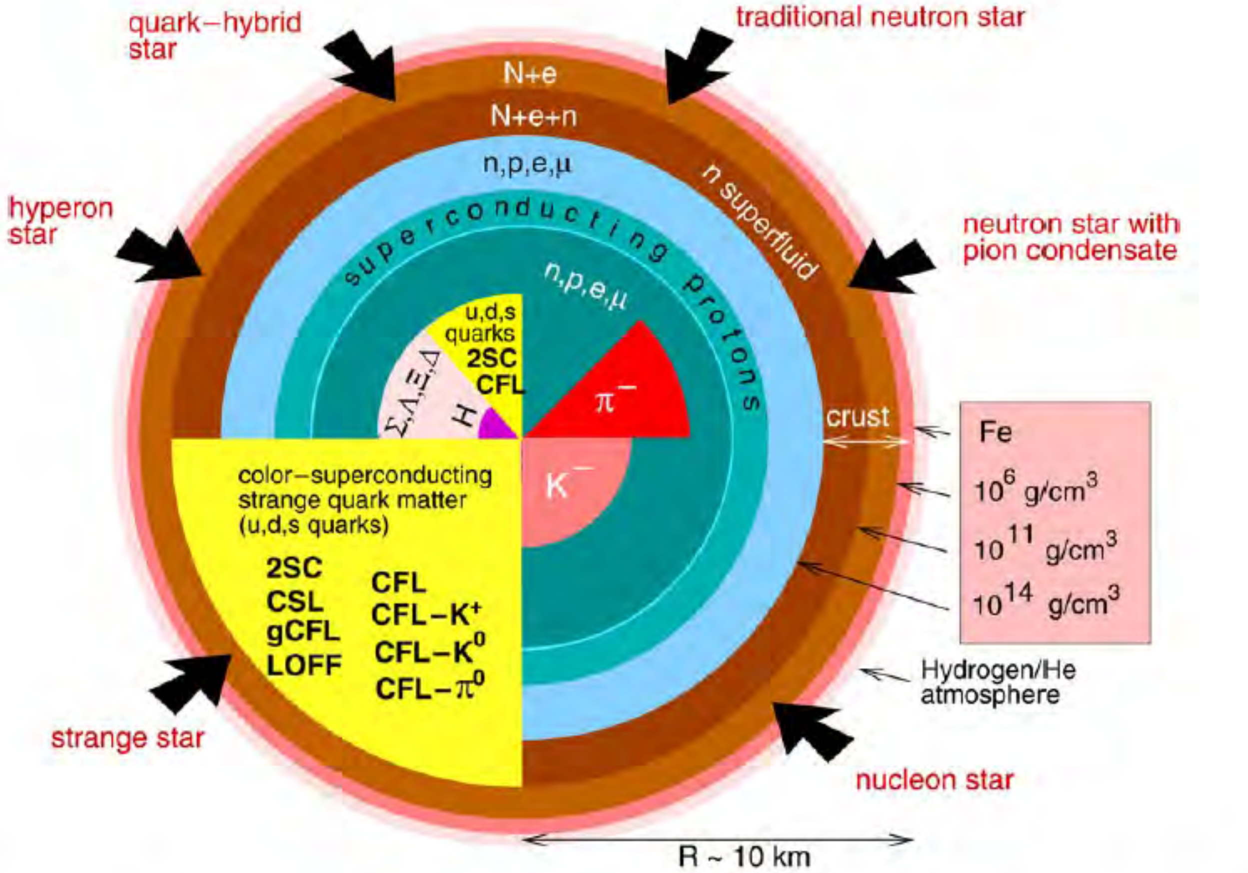
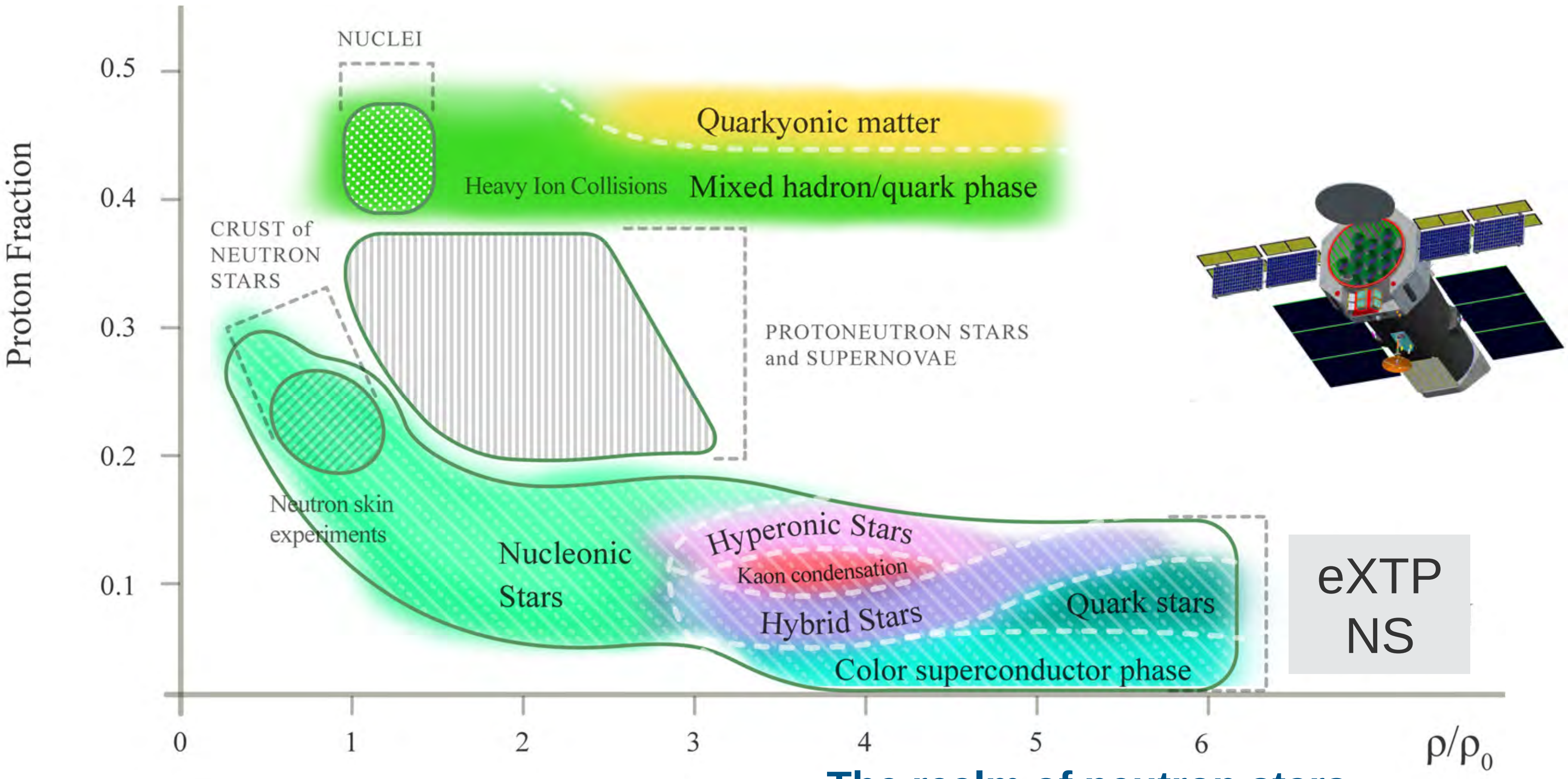


Fig. 1. Competing structures and novel phases of subatomic matter predicted by theory to make their appearance in the cores ($R \lesssim 8$ km) of neutron stars [1].

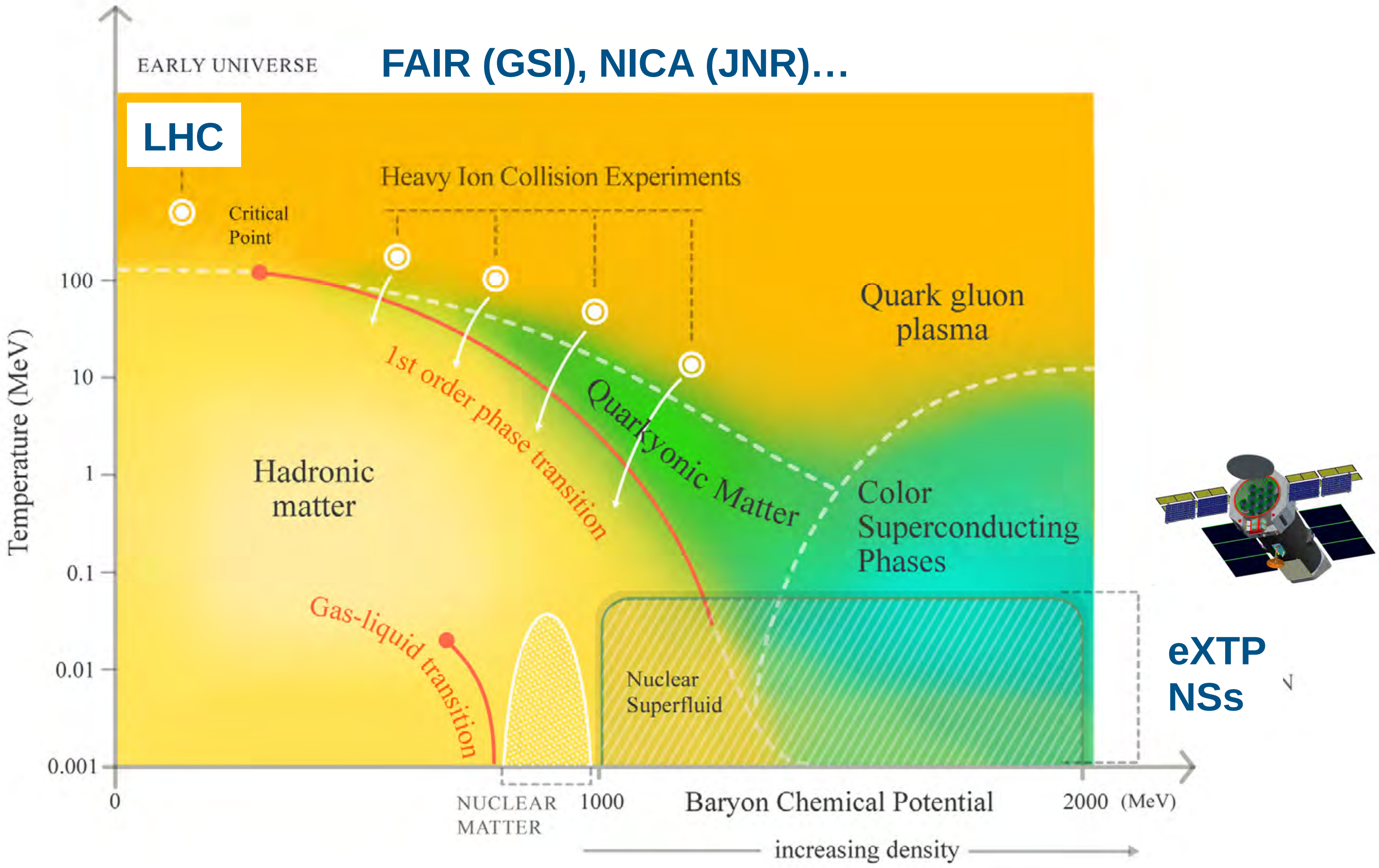
Stable states of strange matter in deconfined quark or baryonic form.

Studying Baryonic matter



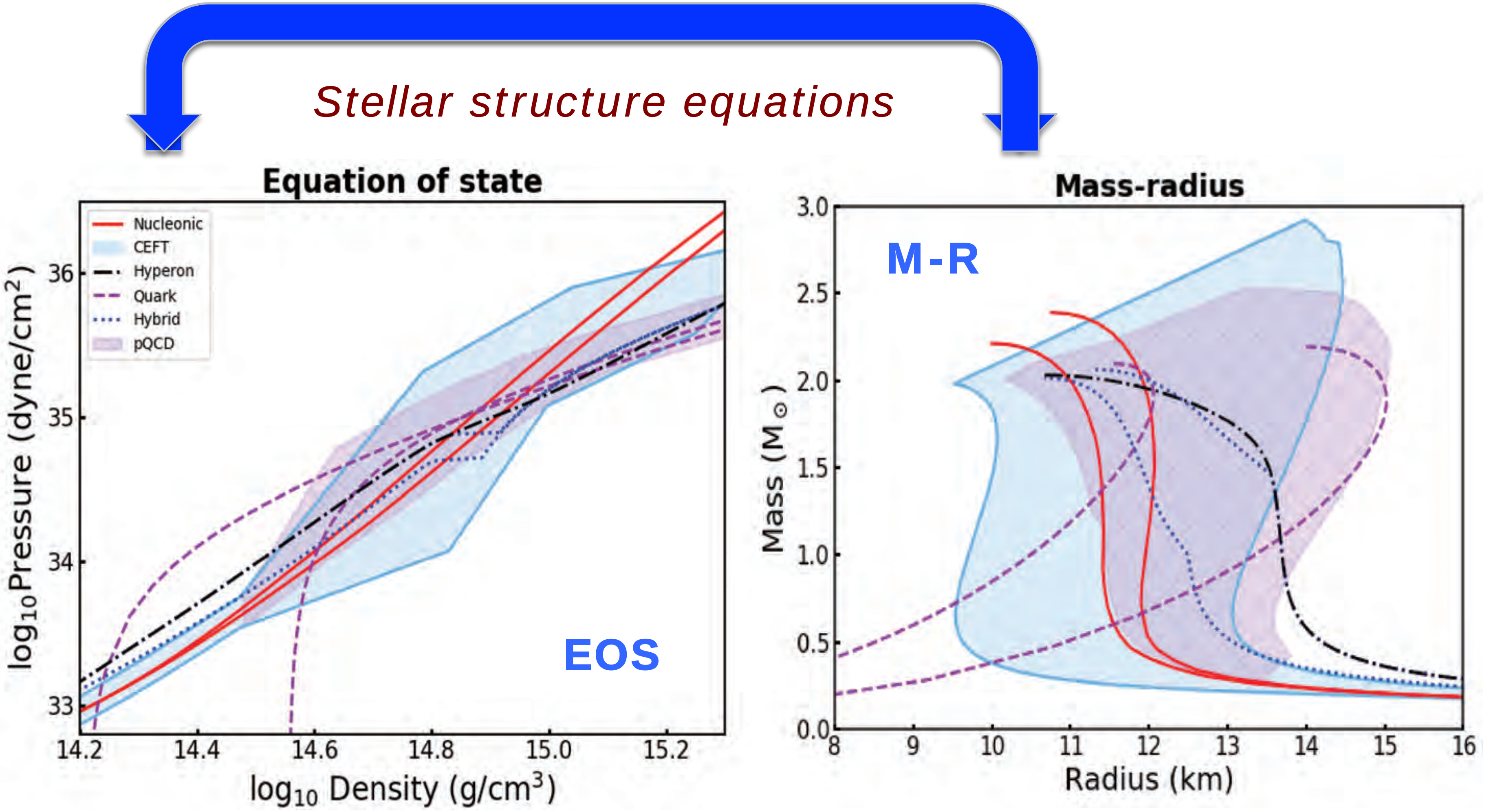
The realm of neutron stars

States of Baryonic Matter



NSs access a unique region at T<<1 MeV, highest density

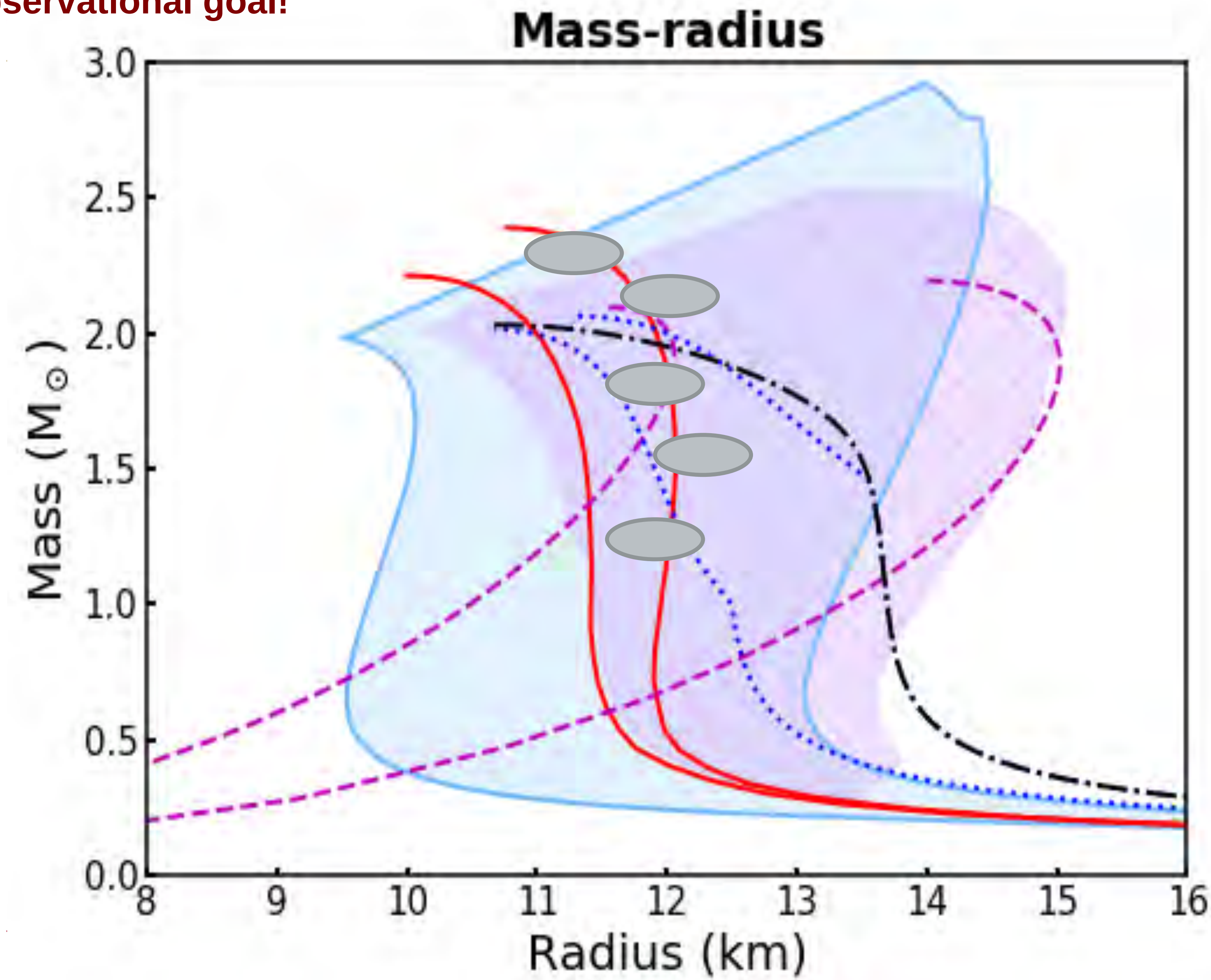
Strong force, EOS, and mass-radius relation



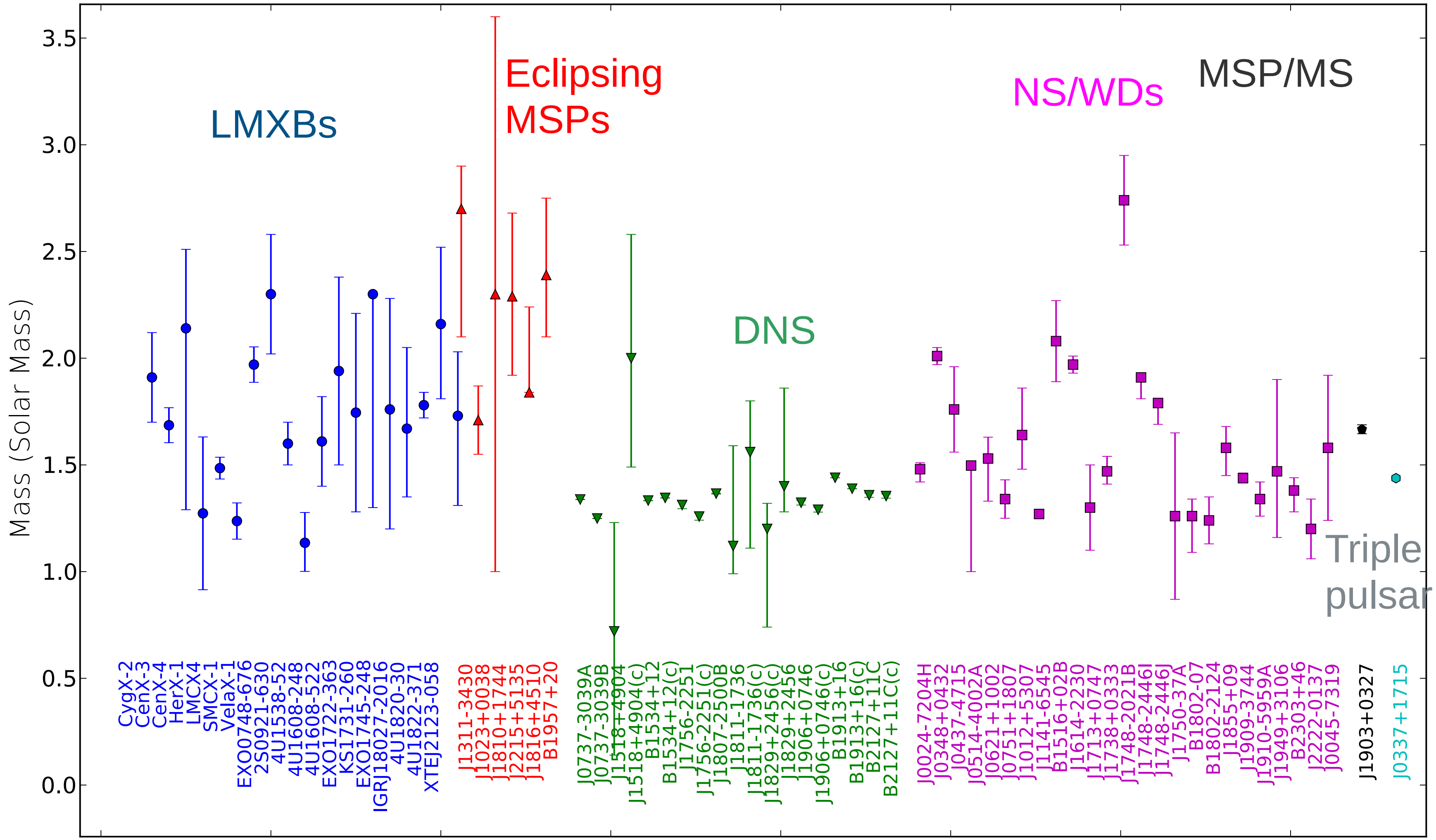
The Equation of state of Neutron Stars: *core-collapse supernovae, binary neutron star mergers…*

Watts A L, Yu W, Poutanen J, Zhang S, et al Sci. China-Phys. Mech. Astron (2018)

Observational goal!

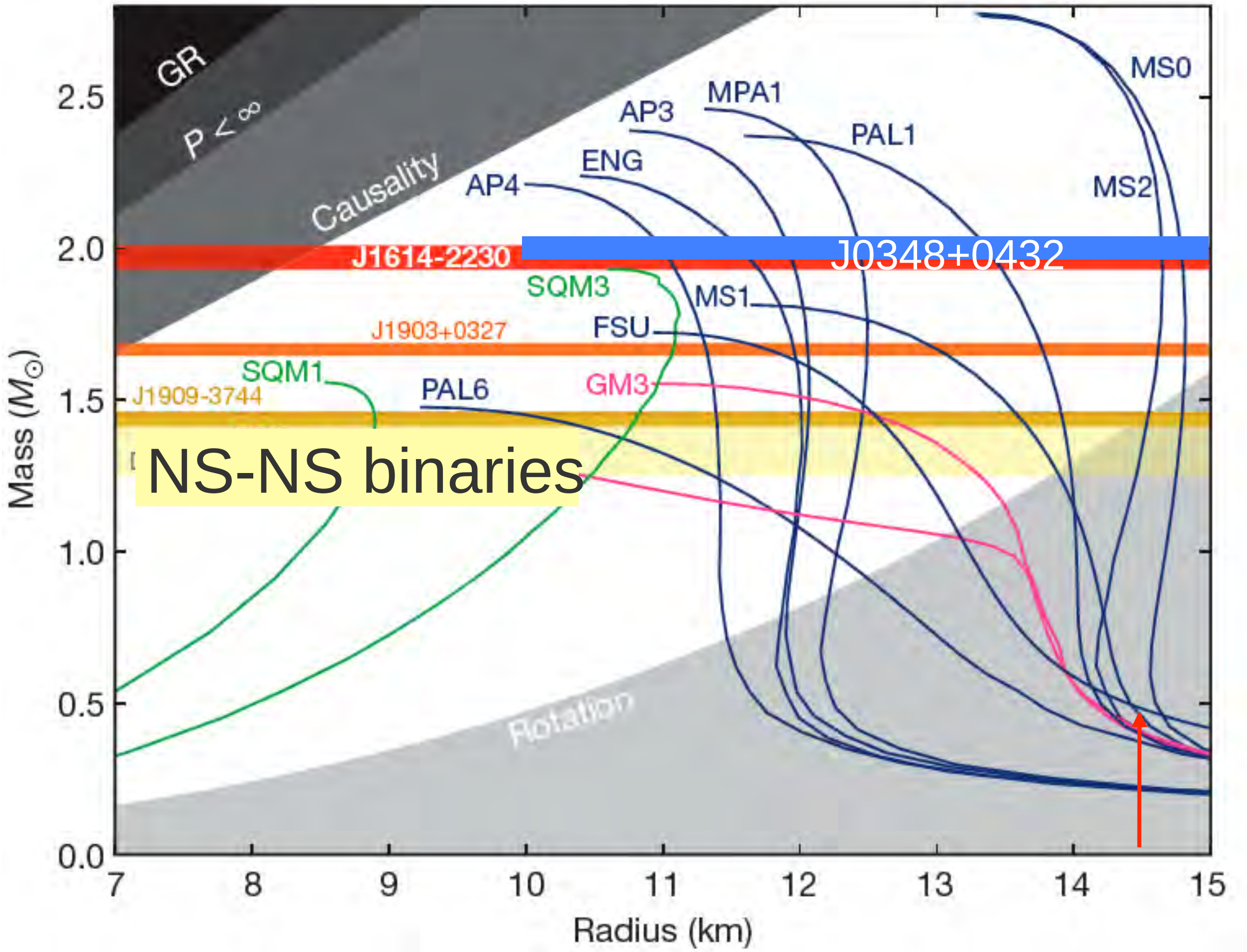


Current mass measurements



see J.Antoniadis website for updates, slide credits: A. Watts

Limits from maximum mass



Antoniadis et al. (2013)
Demores et al. (2010)
Fonseca et al. (2016)
...

The hyperon problem

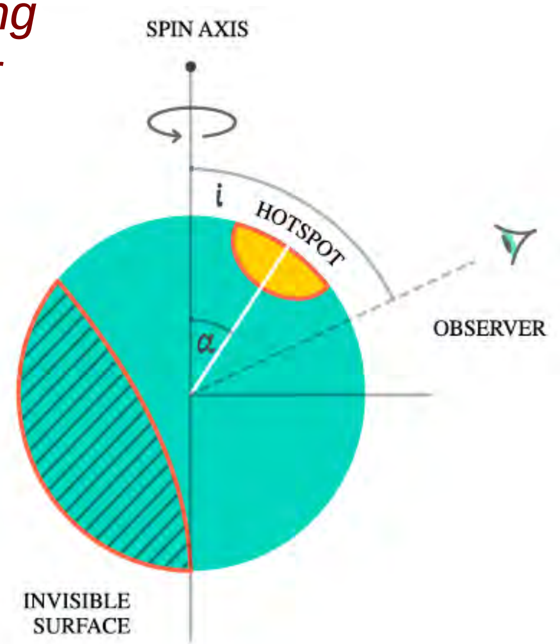
Spectra from thermonuclear bursts, weak constrains, model uncertainties

Suleymanov et al. (2011)
Nättila et al. (2016)
Nättila et al. (2017)
...

Masses from radio pulsars. Radii can be determined from thermal spectra and pulse profiles of accreting millisecond pulsars.

Technique: Pulse profile modeling

Spacetime around a fast spinning compact star



A Hotspot forms on the surface of the neutron star and radiates:

Relativistic effects: Llight-bending, Gravitational Redshift, Doppler redshift, aberration, local time dilation

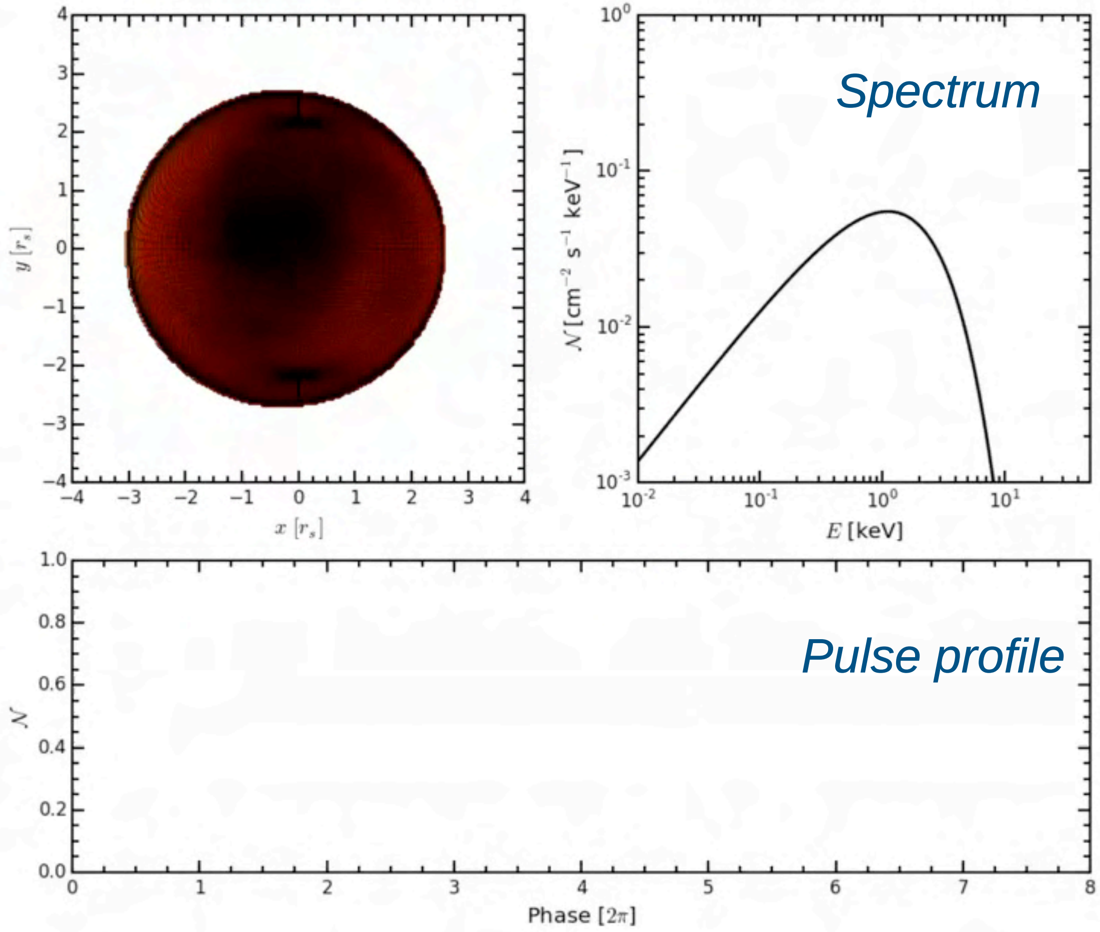
→ encode information about mass M and radius R in the pulse profile.

I can measure energy dependent pulse profiles!

M and R can be recovered from the energy-dependent pulse profile, but: **1) curved space-time around a fast spinning compact star, 2) Geometry unknown**

For 1: Embedding an oblate star in Schwarzschild spacetime

Pulse Profile Modelling (2)

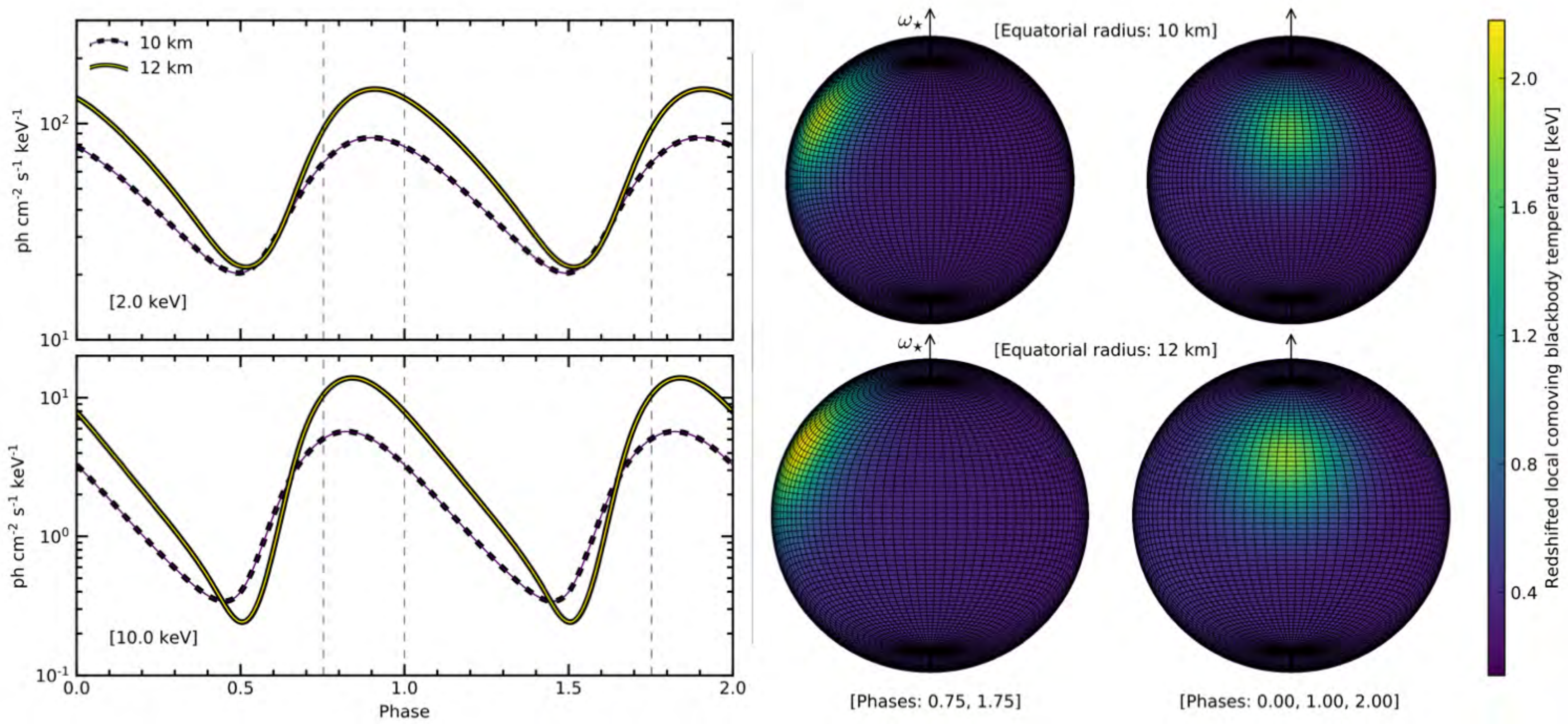


Simulations (Hartle-Thorne spacetime) by Thomas Riley

Ray-tracing papers:
Pechenick et al. 83,
Poutanen & Gierlinski 03,
Viironen & Poutanen 04,
Poutanen & Beloborodov 06,
Morsink et al. 07,
Bogdanov et al. 07,
Baubock et al. 12, 13,
Lo et al. 13,
Psaltis et al. 14,
Miller & Lamb 15

By fitting the pulse profiles we can reconstruct mass and radius…

Pulse Profile Modelling (3)

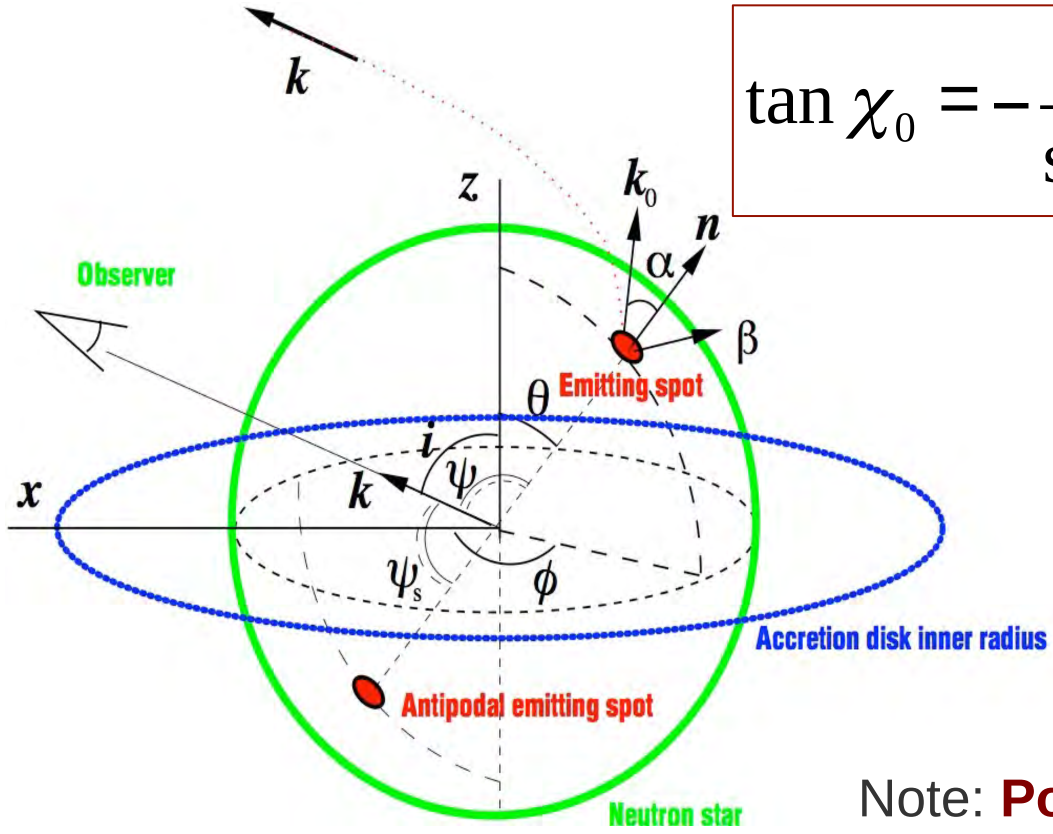


Key astrophysics questions:

- Model for emission (pattern, beaming) required
- **Geometry of the emission?**

Riley, Raaijmakers & Watts 2018; Raaijmakers, Riley & Watts 2018

Phase dependence of the polarisation angle



(Viironen & Poutanen 04)

$$\tan\chi_0 = -\frac{\sin\theta\sin\phi}{\sin i\cos\theta - \cos i\sin\theta\cos\phi}$$

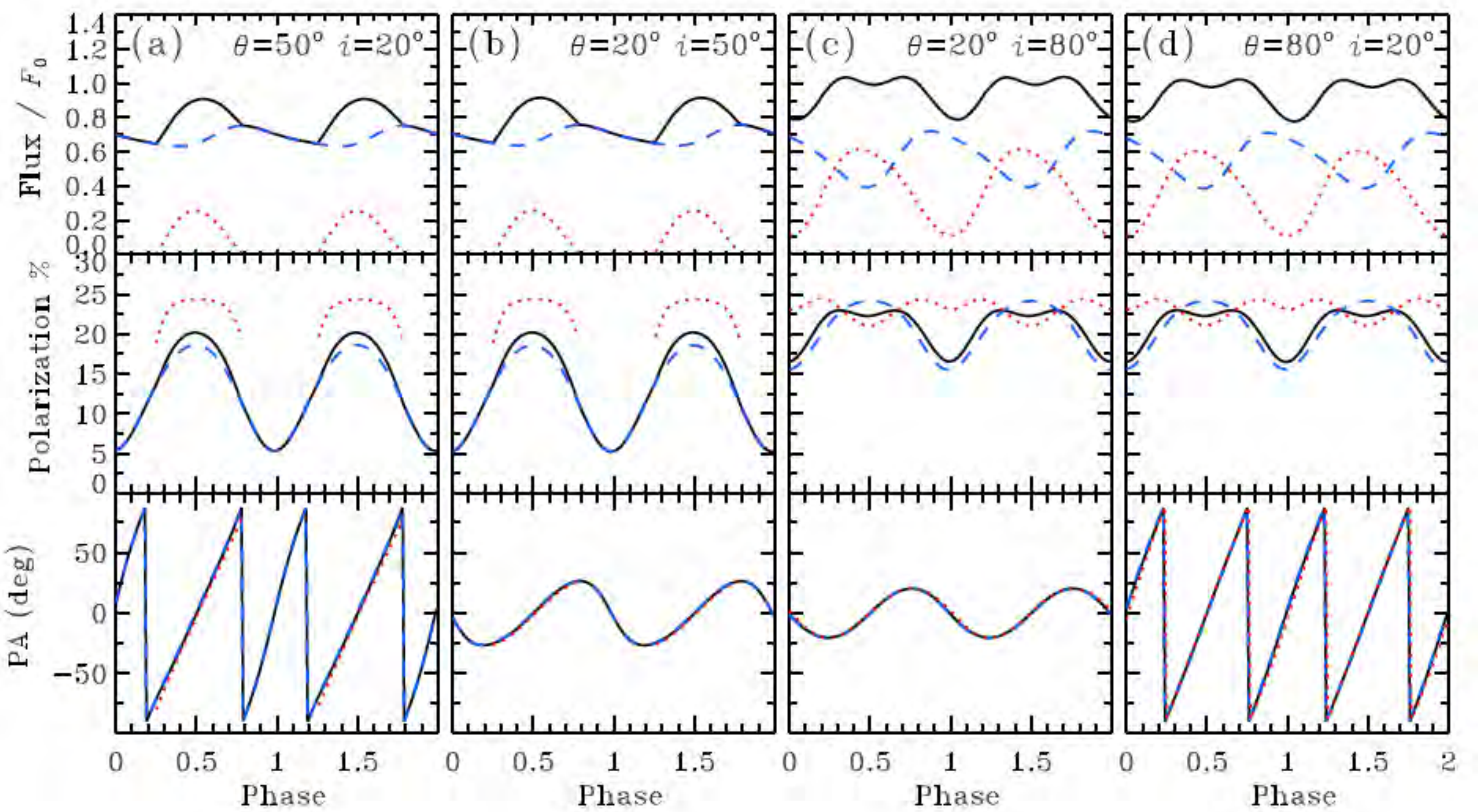
$i \rightarrow$ inclination

$\theta \rightarrow$ colatitude

$\phi \rightarrow$ pulse phase

Note: **Polarization degree** is **Lorentz invariant**: computed in the spot comoving frame accounting for light bending and relativistic aberration

Fixing the geometry



Pulse profile and polarization properties as function of rotational phase: **black line (2 antipodal spots)**, **blue/red** lines (each individual spot), adapted from *Viironen & Poutanen (2004).*

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Parenthesis: eXTP

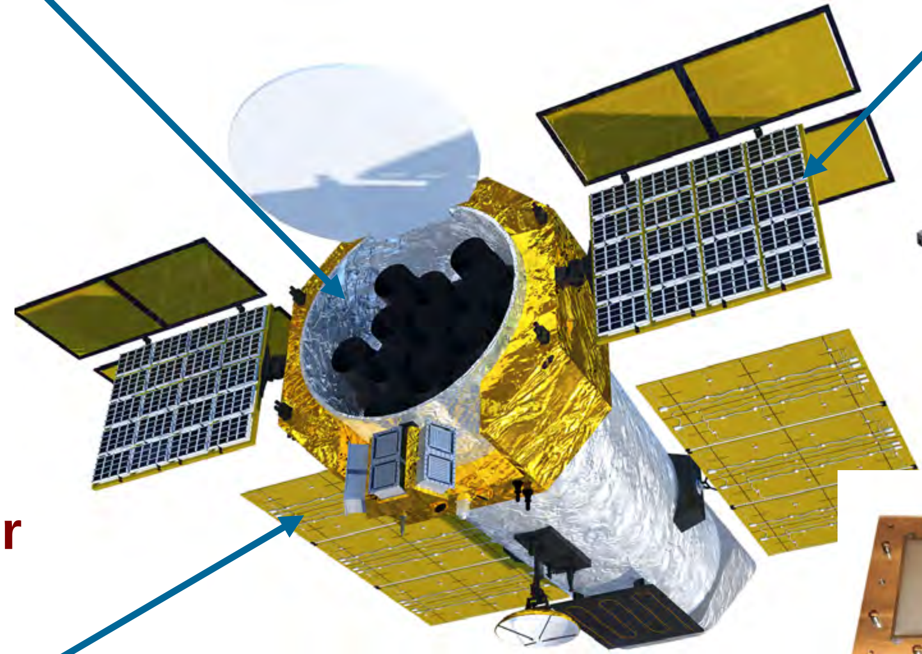
The enahnced X-ray Timing and Polarimetry mission

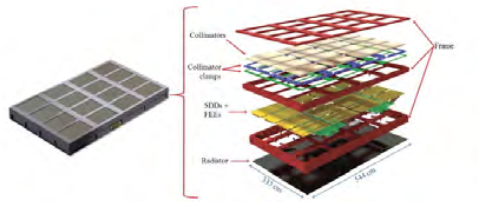
S.N. Zhang, A. Santangelo, M. Feroci, F. Lu, et al Sci. China-Phys. Mech. Astron (2018)

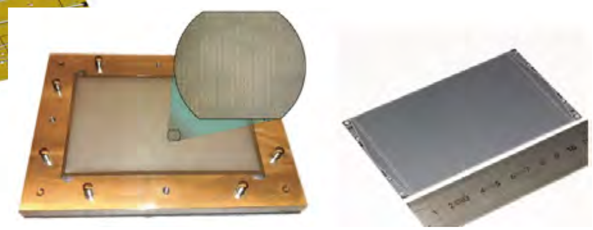
eXTP current configuration

9 Tel. Spectroscopy Focusing Array
4 Tel. Polarimetry Focusing Array

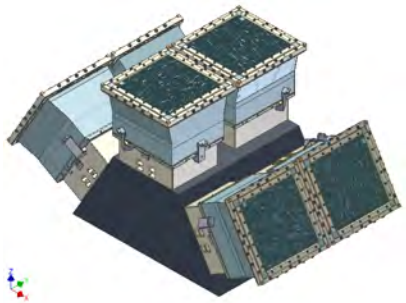
Large Area Detector







Wide Field Monitor



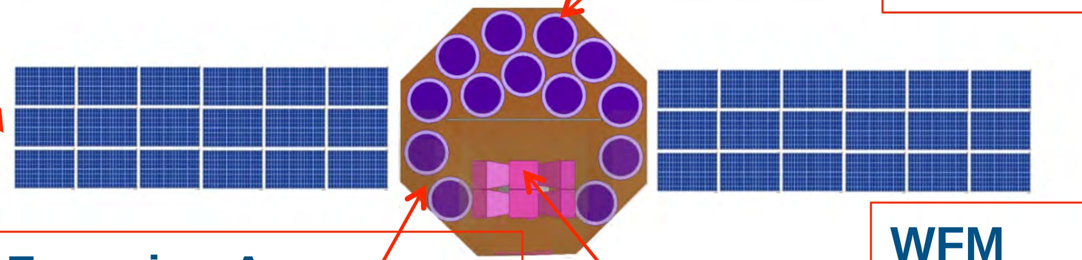
4.5 ton, lifetime 8 years, launched with LM-7, Orbit 550km, 0 deg

Zhang, Santangelo et al., 2019 (special issue of Science China)

Payload

LAD
40 modules SDDs, MCP coll.
Energy band: 2- 30 (50) keV
FoV: 1° (FWHM)
Time resolution: 10 μs
Energy res.: <250eV@ 6keV
Sensitivity: 10 μCrab (10^4s)
Effective area: 3.4m²@8keV

Soft Focusing Array
9 telescopes: FL5.25m, FoV 12′, SDD
Energy range: 0.5-10(12) keV
Energy resolution: 180eV@6keV
Time resolution: 10μs
Angular resolution: 1′ (HPD)
Sensitivity: 0.16μCrab (10^4s)
Effective area: 0.8m²@2 keV



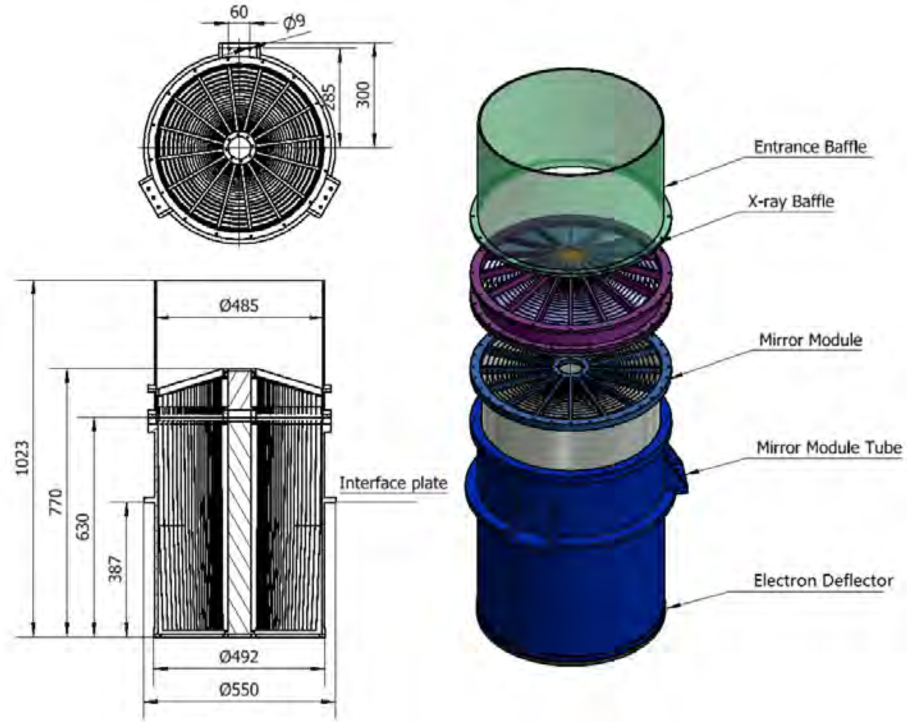
Polarimetry Focusing Array
4 telescopes: FL5.25m, FoV8′, GPD
Energy range: 2-8 keV
Energy res.: 1.8keV@6keV
Time resolution: 500μs
Angular resolution: 30″ (20”) (HPD)
Sensitivity: 5μCrab(10^4s)
Effective area: >700 cm²@2keV

WFM
3 units: 1.5D coded mask, SDD
Energy range: 2-50keV
Energy res.: 500 eV@6keV
Field of view: 3.2 Sr
Location accuracy: 1′
Angular resolution: 5′
Time resolution: 10μs
Sensitivity: 4mCrab(1day)
Effective area: 170cm²@6keV

Electro-formed Nickel replication optics

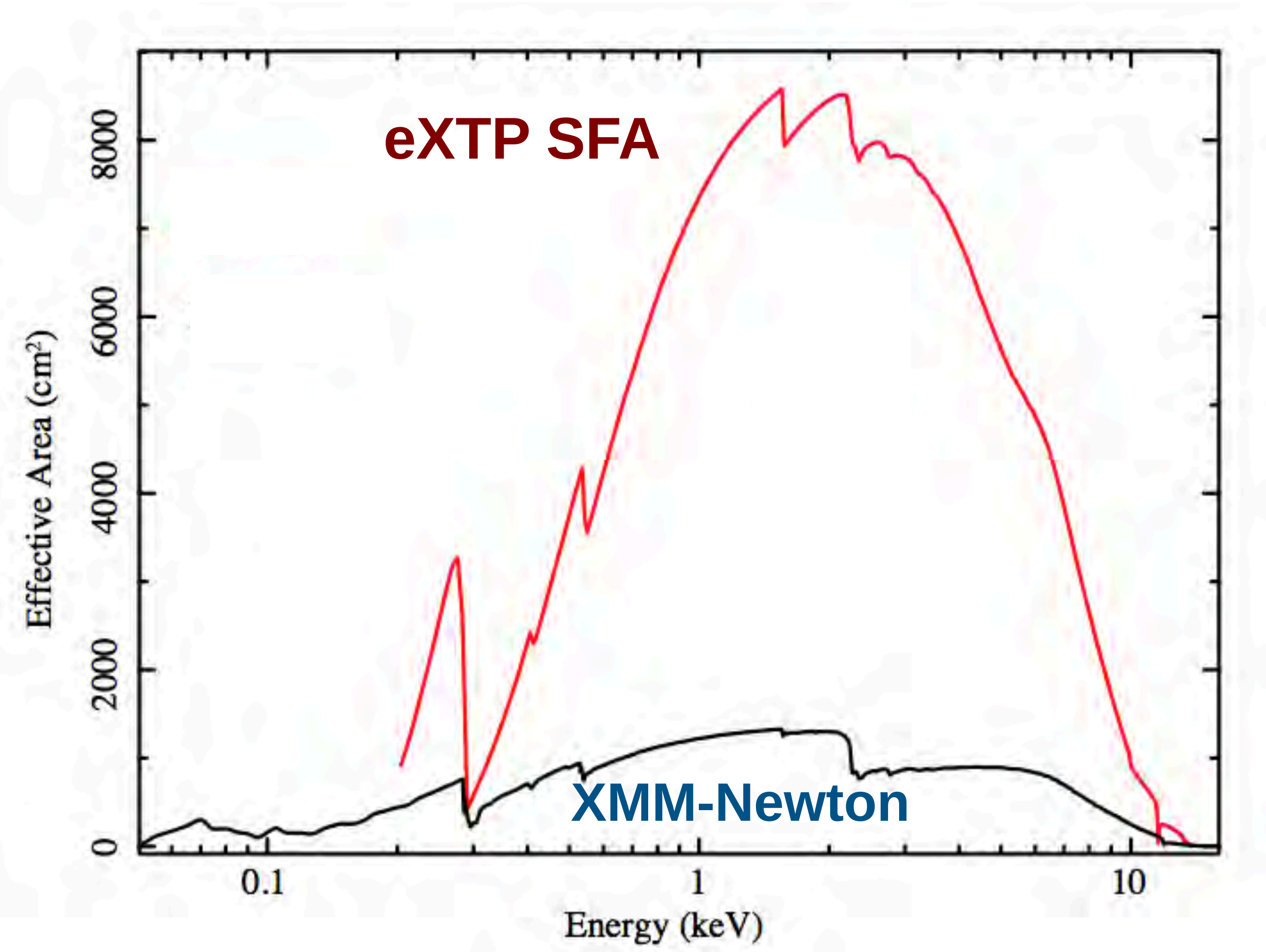
- **Nested Wolter-I system**
- Focal length: 5.25 m
- Field of view: 12′
- Angular resolution: 30″(15″)

- Status:
  - A proven technology in Italy,
  - XMM and eROSITA (OAB & Media Lario)
  - TRL = 7~8
  - A study team had been formed at IHEP, for the optical design, mechanical design, metrology and calibration.



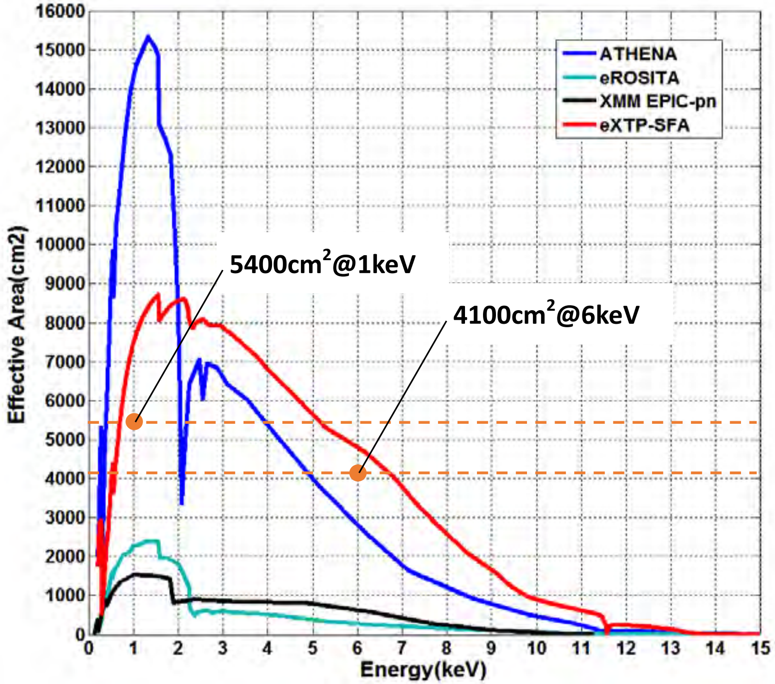
Preliminary design of the polarimetry focusing mirror assembly

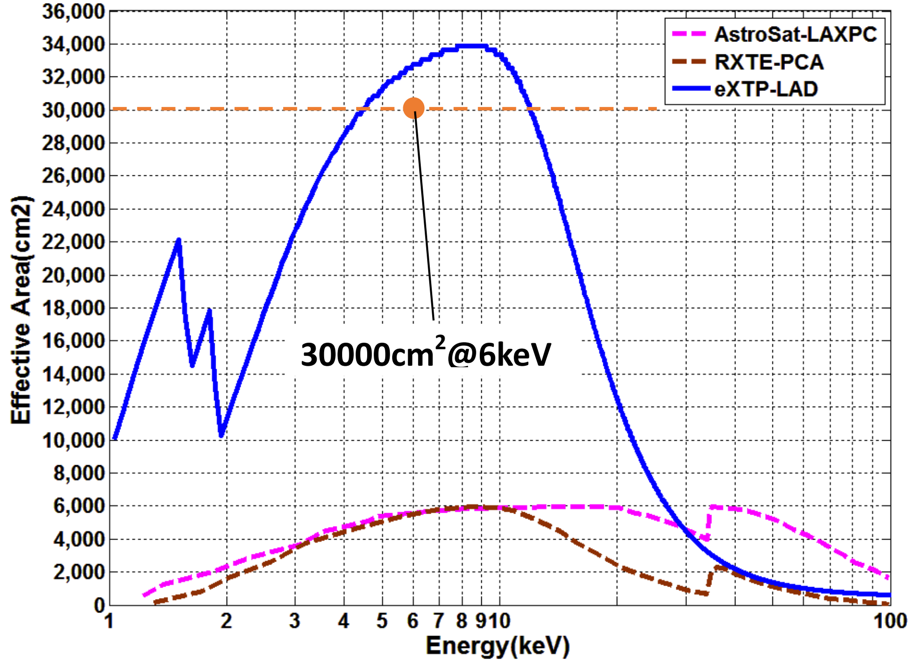
SFA vs. XMM-Newton- pn



Very large increase in effective area…

SFA and LAD effective area





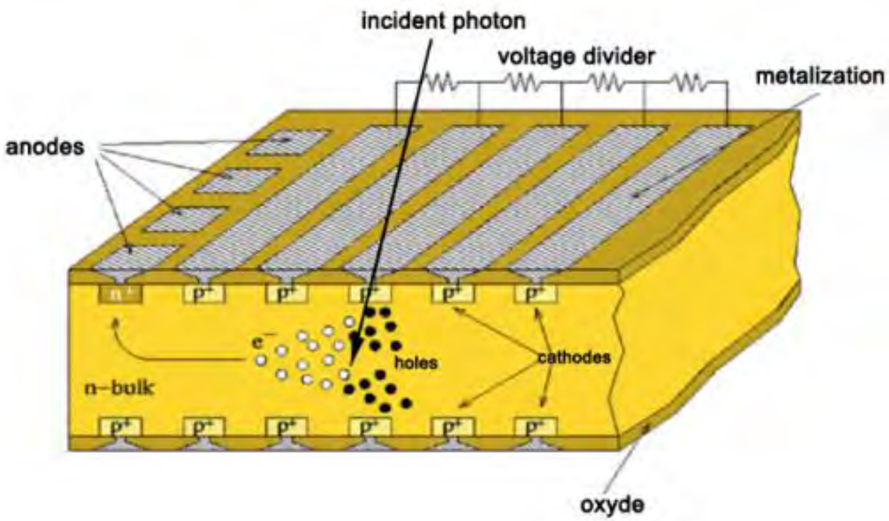
SFA: a factory for soft photons, ready to operate in 2025.

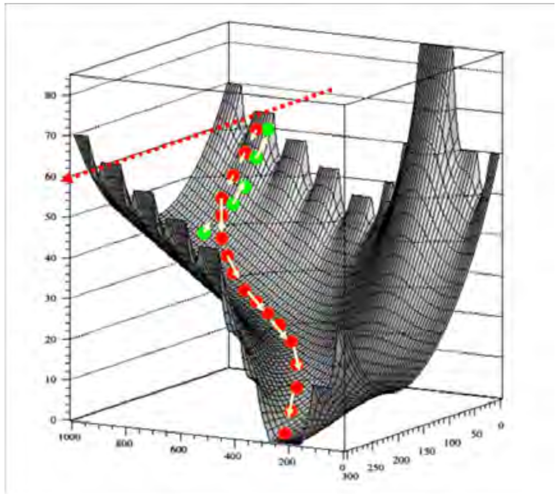
LAD: a transformational instrument of exceptionally high photon throughput in the 2-30 keV range ready to operate in 2025.

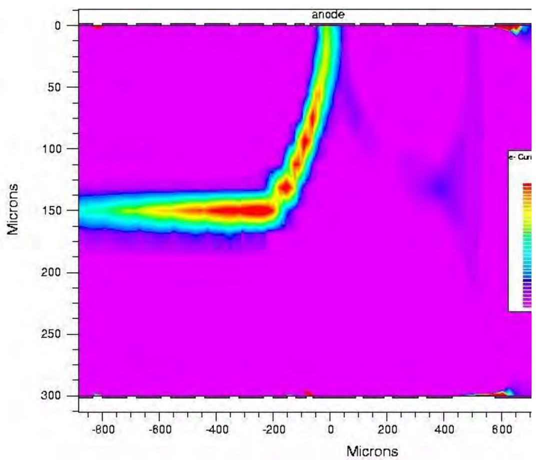
Transformational payload for spectral- timing studies!

Silicon Drift Detector (ESA's LOFT study)

Neutron Transmutation Doped (NTD) silicon wafers





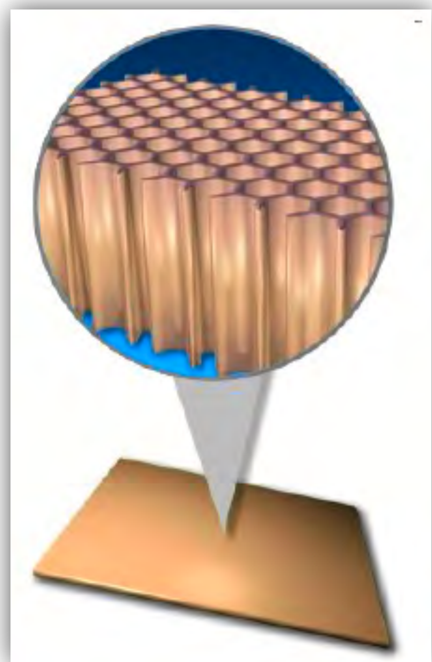


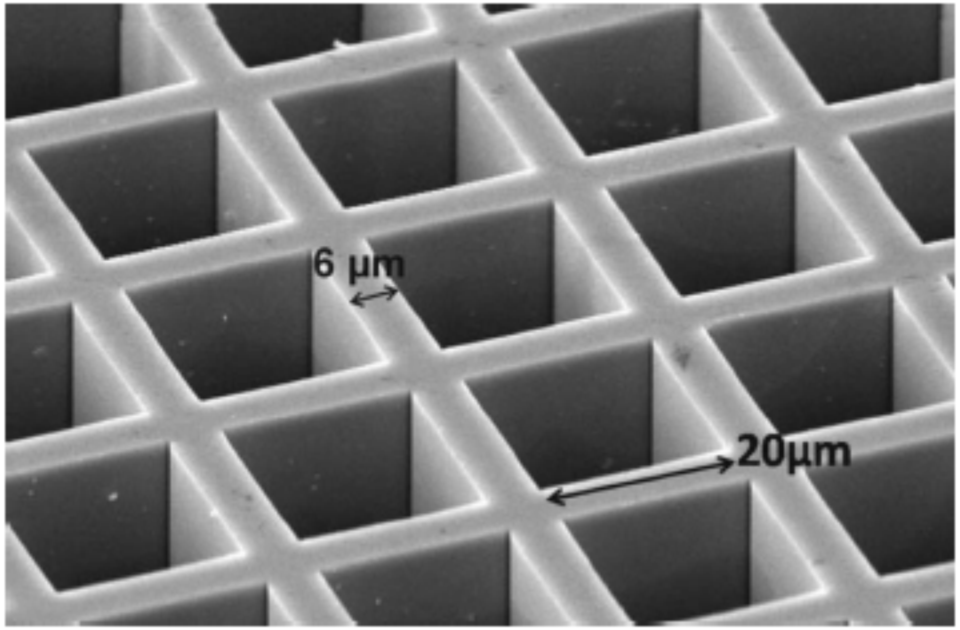
Heritage of ALICE-D4 SDD developed for the ITS. Designed by **INFN TS, Produced by Canberra Semiconductor Belgium**

LAD sensors: INFN Trieste, INAF, FBK (Fondazione Bruno Keller), PoliMi, University of Pavia and University of Bologna.

LAD: collimated instrument

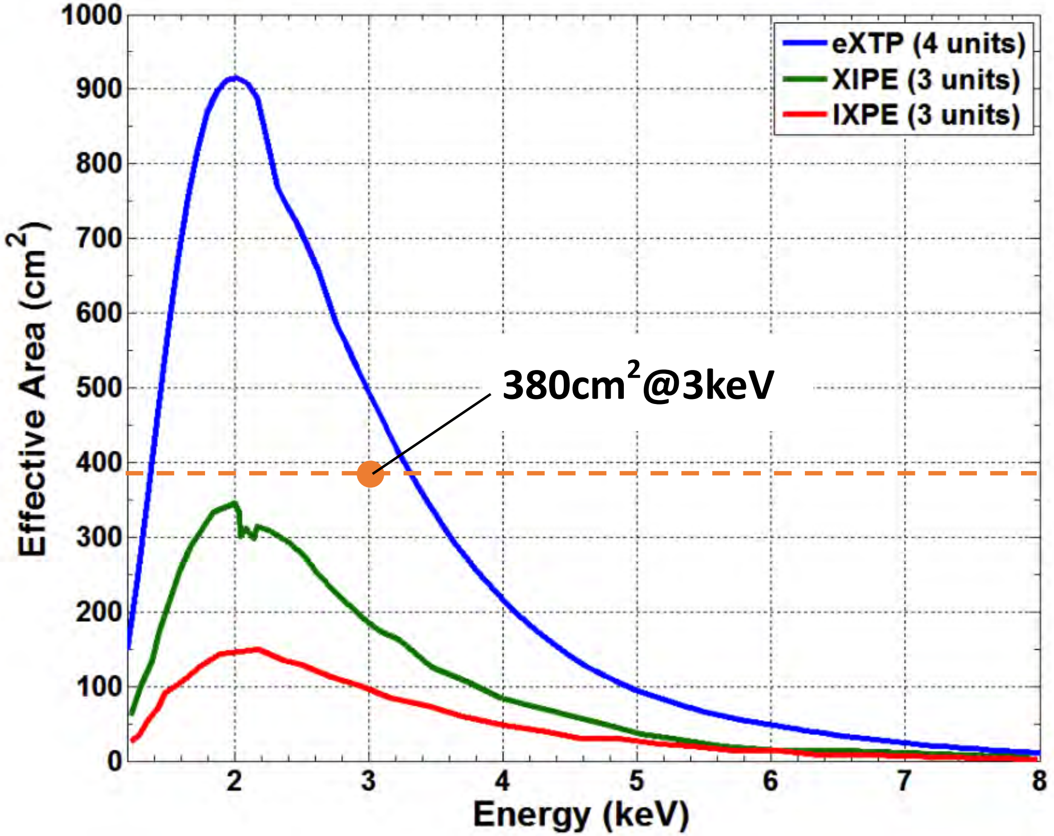
A micropore collimator made of ***non-contaminated* lead glass** will restrict the **field of view to about 1 degree.**





Microchannel Plate Collimators (widely used in space)

PFA a game changer in polarimetry



The PFA will bring studies of X-ray polarimetry to a mature stage

In addition PFA Baseline: low angular resolution! → better than 30” and possibly 20”

Based on the GPD

Area (cm^2)	2 keV	3 keV	4 keV	6 keV
eXTP	915	495	216	48
IXPE	151	101	52	16

5-6 times IXPE

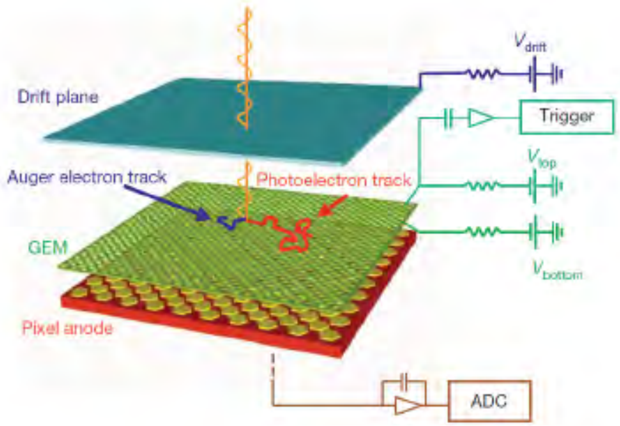
Dashed line current requirement, lower than the expected performance

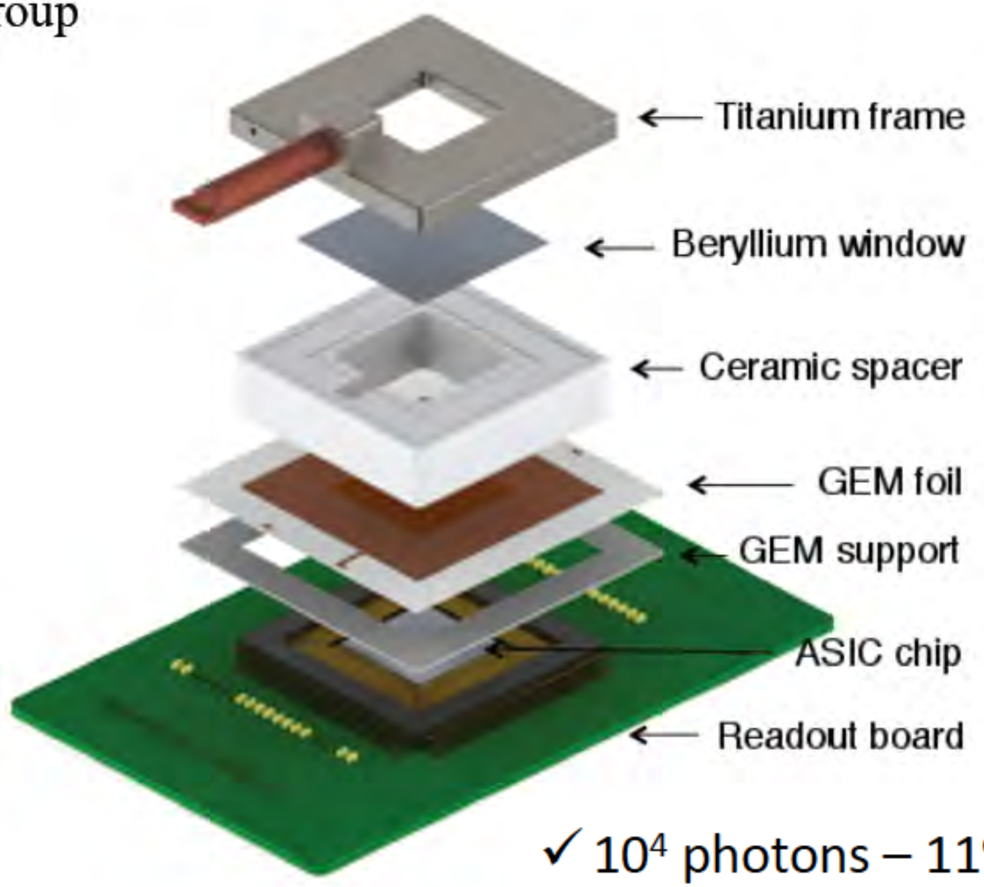
Gas Pixel Detector

- Designed by the INFN-Pisa group (Bellazzini et al.)

Sensitive volume
- ✓ **DME (CH3-O-CH3)**
- ✓ **1cm depth**
- ✓ **0.8 atm**

Window
- ✓ **50 µm Beryllium**





- ✓ 10^4 photons – 11%
- ✓ 10^5 photons – 3.5%
- ✓ 10^6 photons – 1.1%

Courtesy of H. Feng

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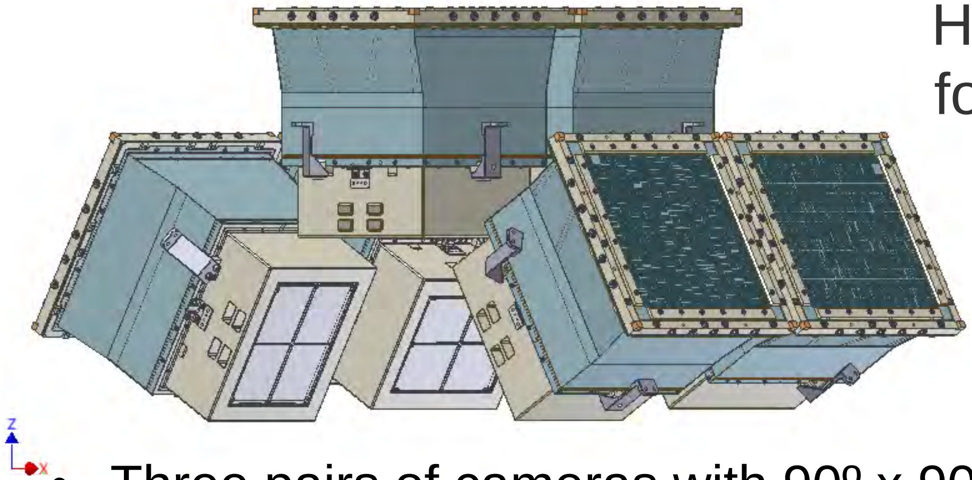
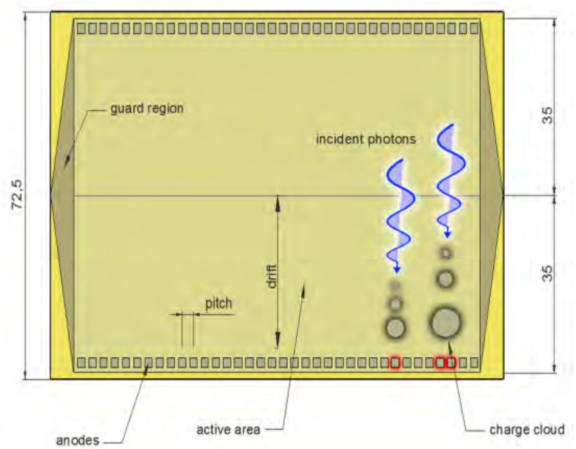
WFM on eXTP



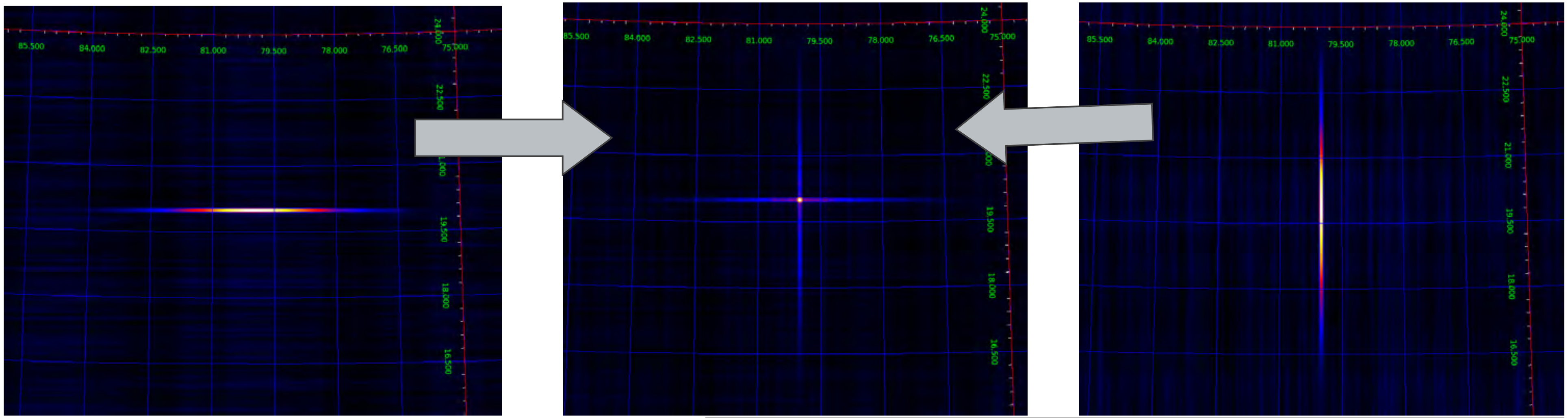
Heritage from LOFT feasibility study for ESA-M3 and ESA-M4 proposal:
a coded mask instrument

- Three pairs of cameras with 90º x 90º FoV
- Configuration with 3 Camera Pairs (-60º, 0, 60º)

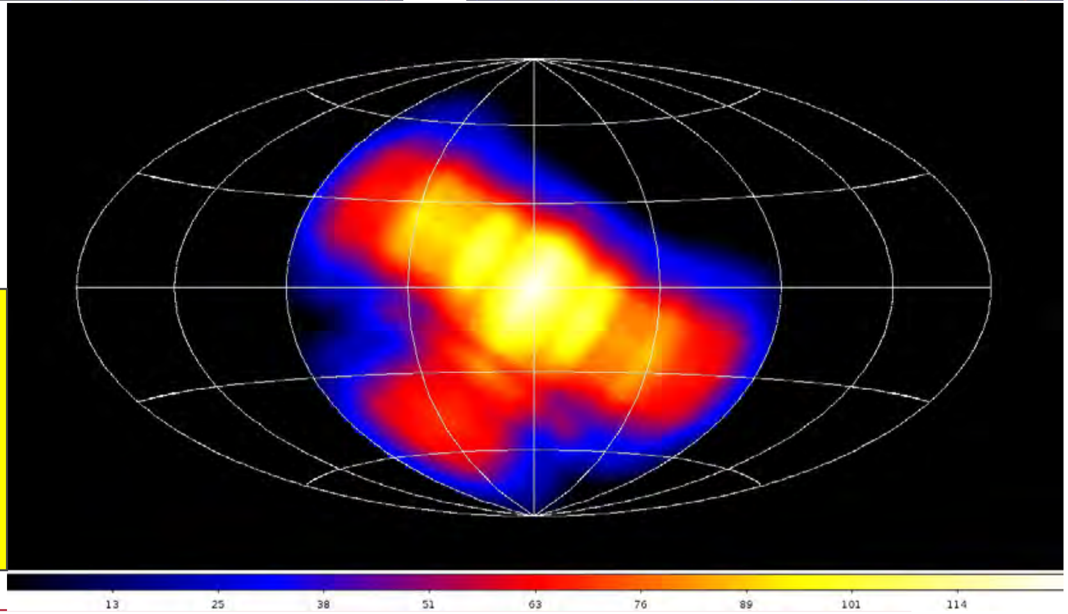


Same detector as the LAD but with smaller anode pitch, to get better spatial resolution

WFM performance



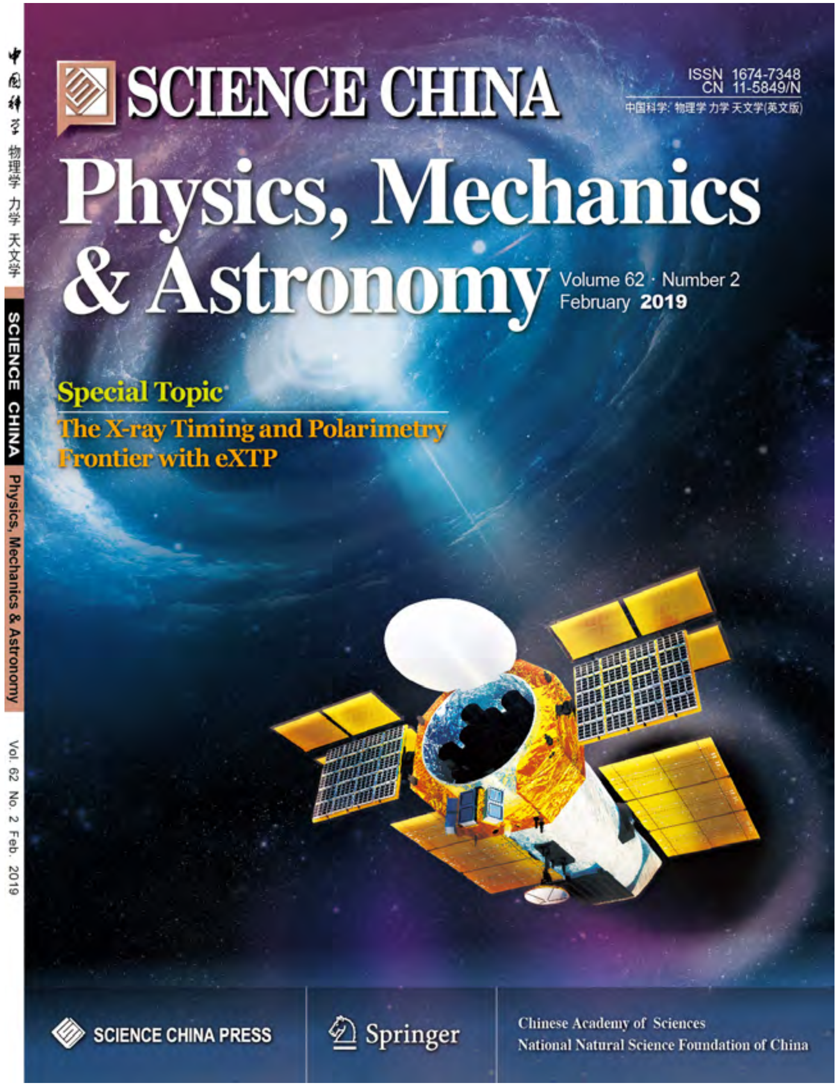
Each WFM camera produces a shadowgram convolved sky image with PSF ~5 arcmin x 5 degrees: "1.5D image"



~1.4 π steradian (~35% of the sky) at zero response

~1.1 π steradian (~27% of the sky) at 20% of peak response

Special issue of Science China



5 papers

Zhang et al. , "The enhanced X-ray Timing and Polarimetry mission—*eXTP*"

In 't Zand et al., "Observatory science with eXTP"

Watts et al., "Dense Matter with eXTP"

Santangelo et al., "Physics and astrophysics of strong magnetic field systems with eXTP"

De Rosa et al., "Accretion in Strong Field Gravity with eXTP"

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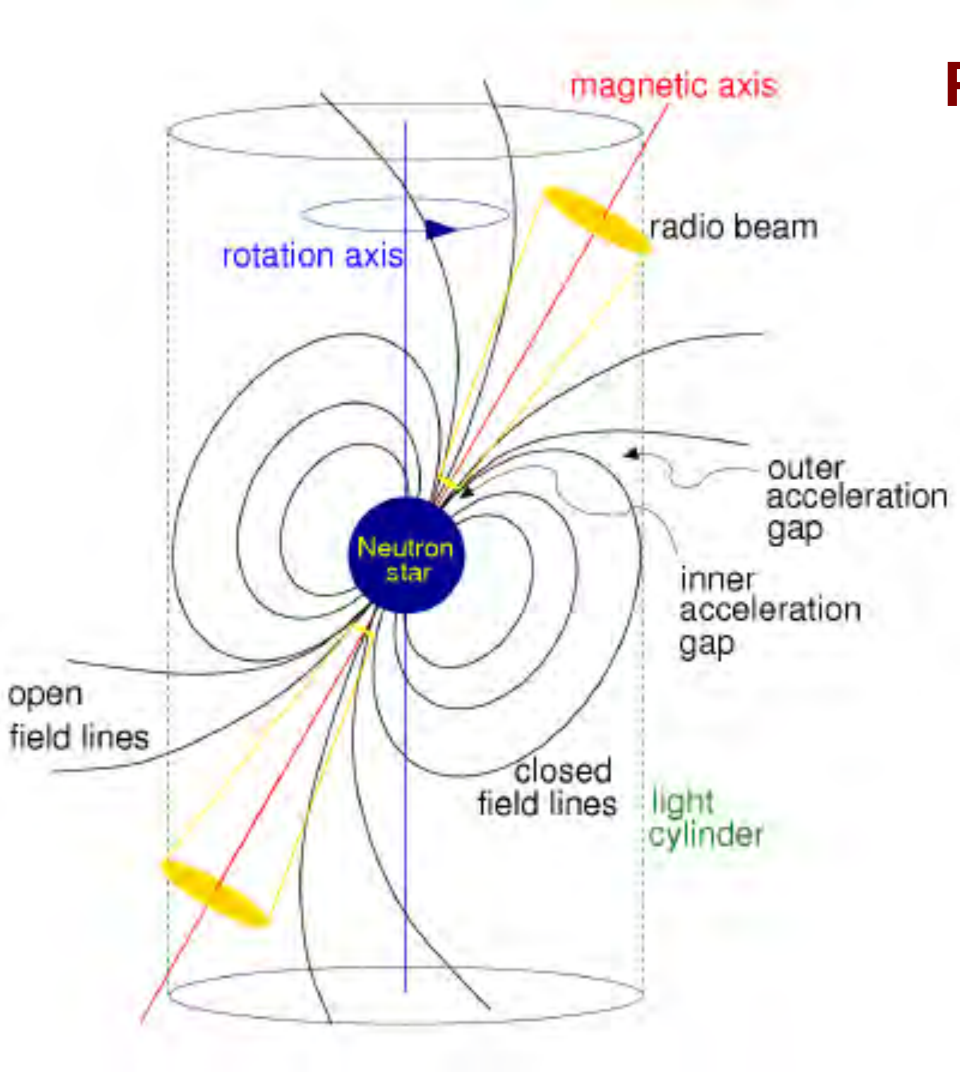
Sources: Rotation Powered Pulsars



Rotation powered MSPs

Primary targets:

PSR J0437-4715
PSR J0030+0451 (NICER results?)

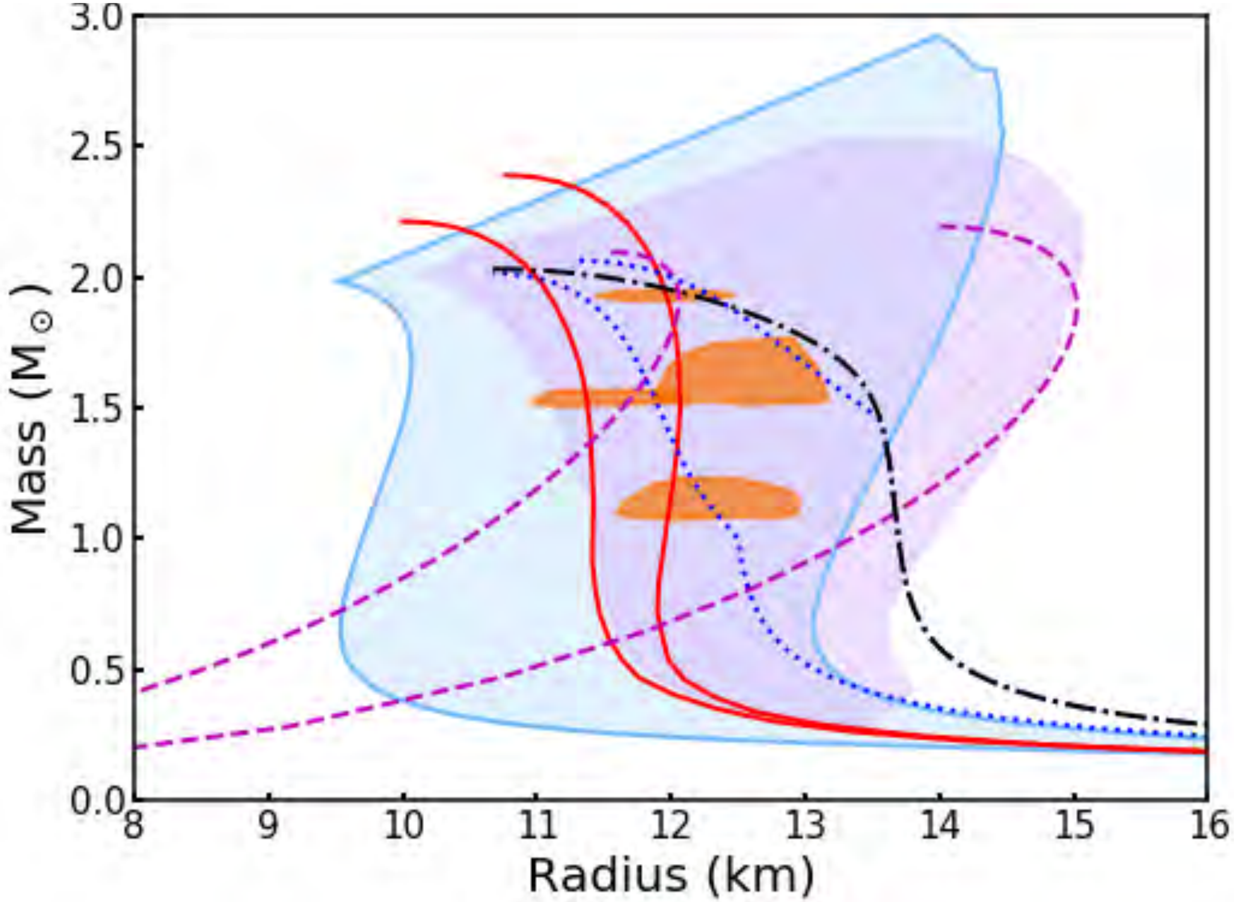
- **Several targets with known masses** will be observed by eXTP:

PSR J1614-2230
PSR J2222-0137
PSR J0751+1807
PSR J1909-3744

These sources are faint (not Nicer targets) and mass is know from radio

Sources (1): Rotation Powered Pulsars

Stable – ephemeris well known.



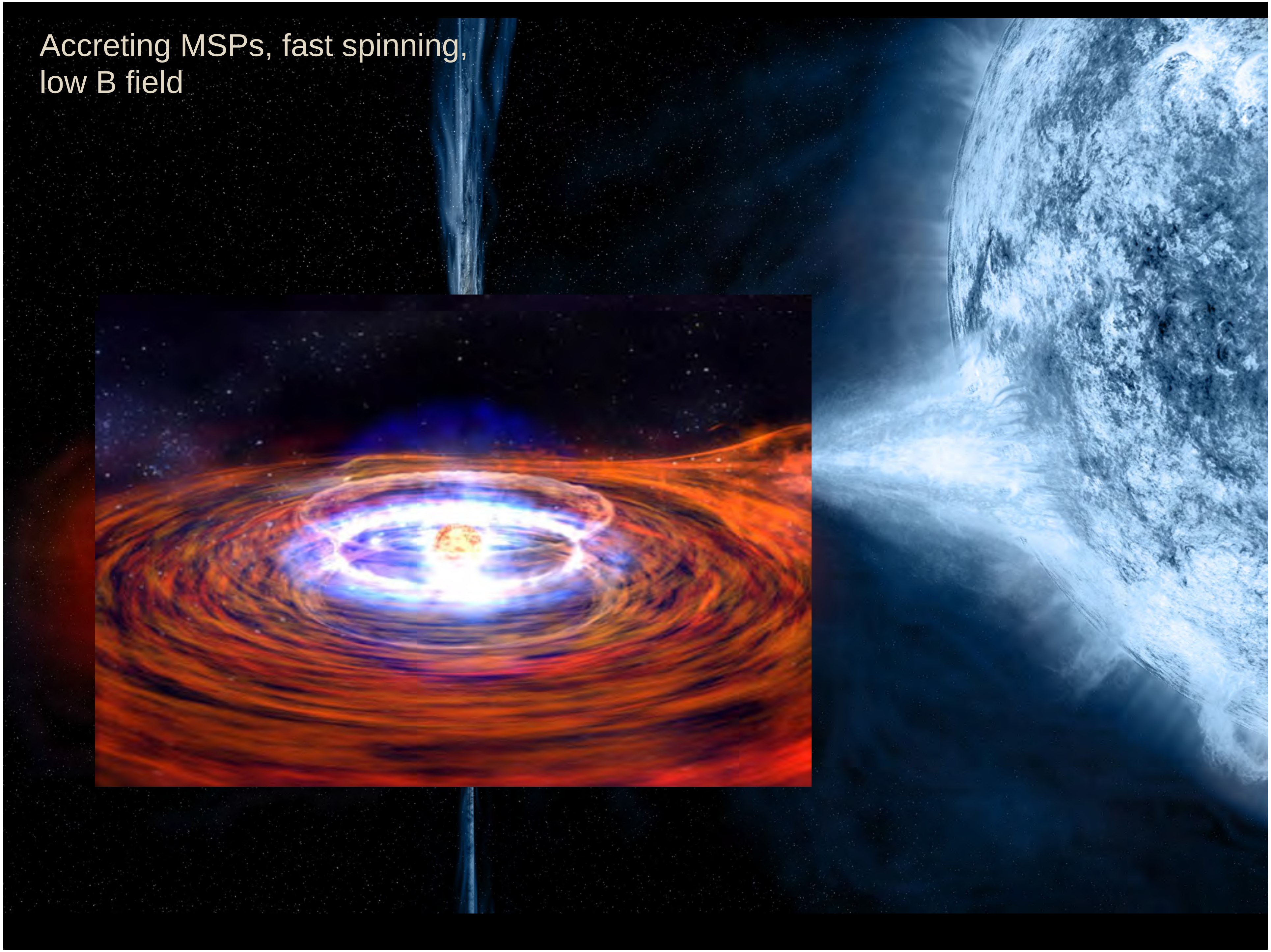
Several % accuracy needs ~10^6 photons: large area crucial → ~ 1 Ms

The orange error contours are for the four MSPs for which masses are known precisely, see previous slides

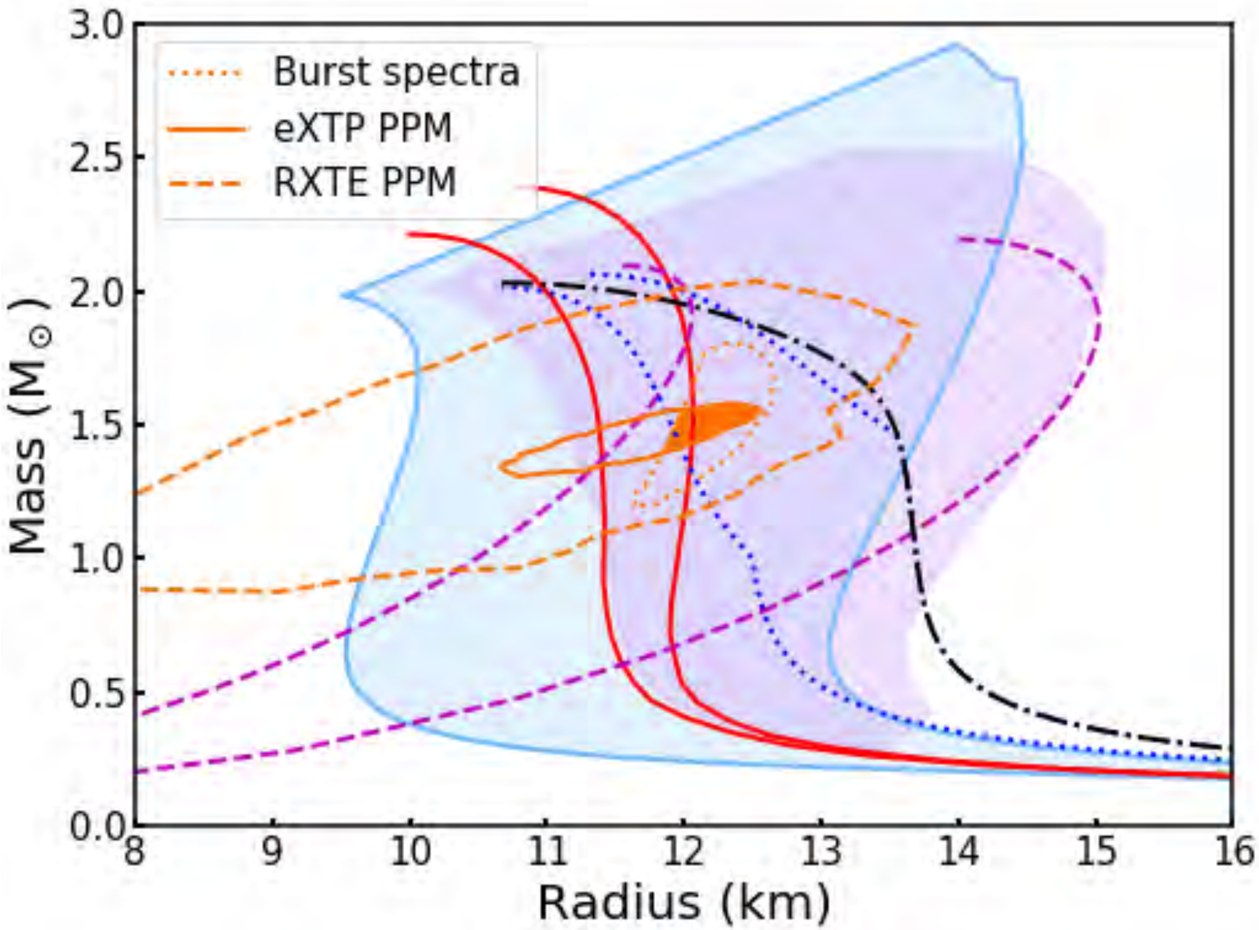
- **Polarimetry for RPPs?**

Watts A L, Yu W, Poutanen J, Zhang S, et al Sci. China-Phys. Mech. Astron (2018)

Accreting MSPs, fast spinning,
low B field



AMXP regular outbursts



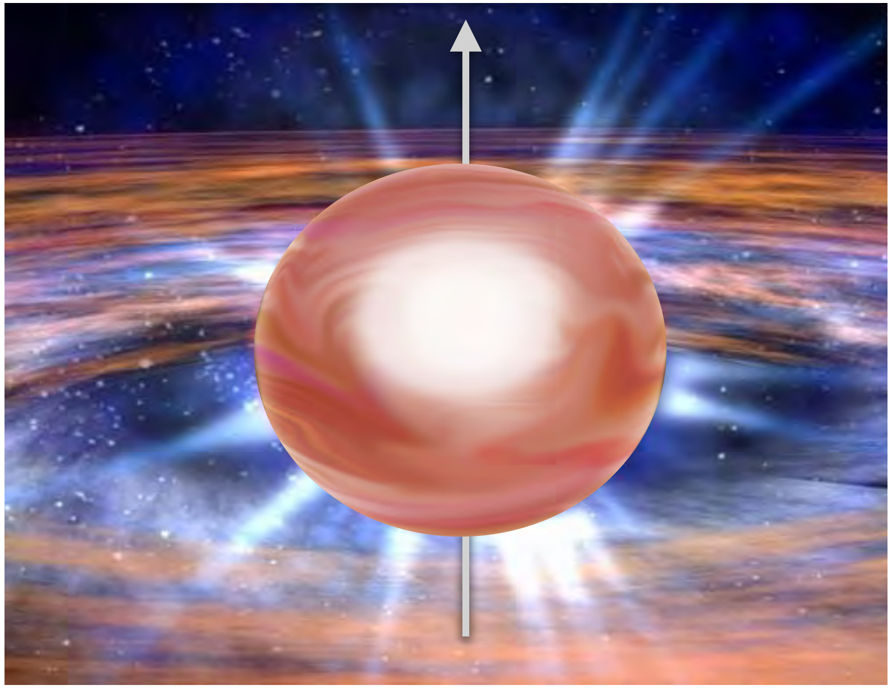
SAX J1808.4–3654
or
XTE J1751–305

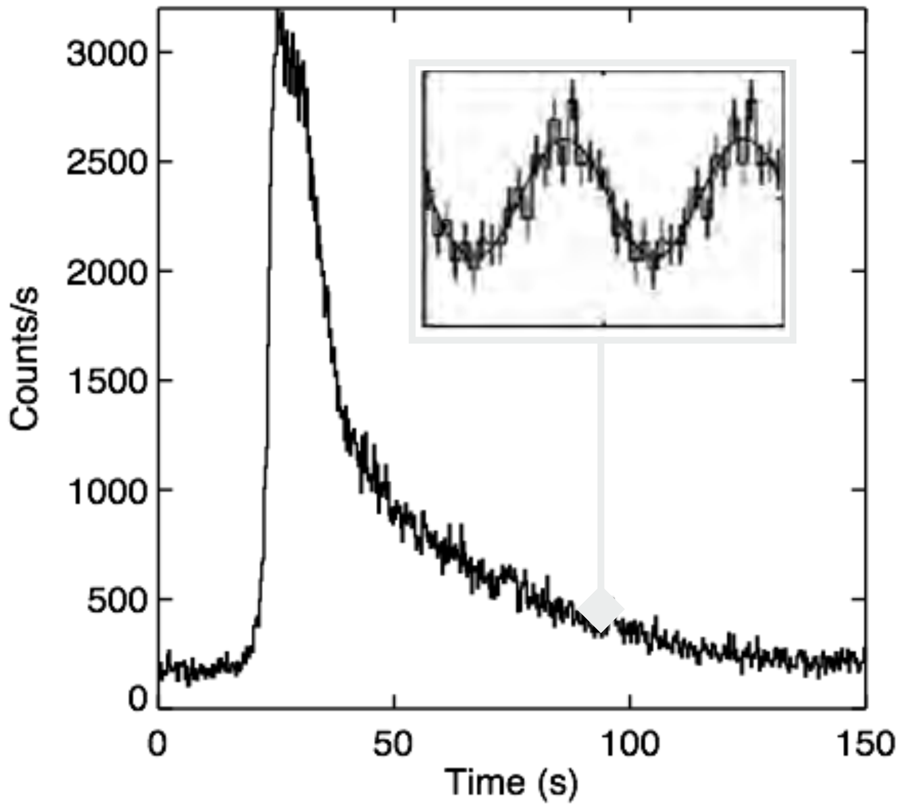
Few % accuracy needs ~10^6 photons: large area crucial →a few – several 100 ks

Combining eXTP PPM modeling and polarimetry we **get the solid orange contour (dashed is for RXTE!).**

Bursts and Bursts Oscillations

Spin axis



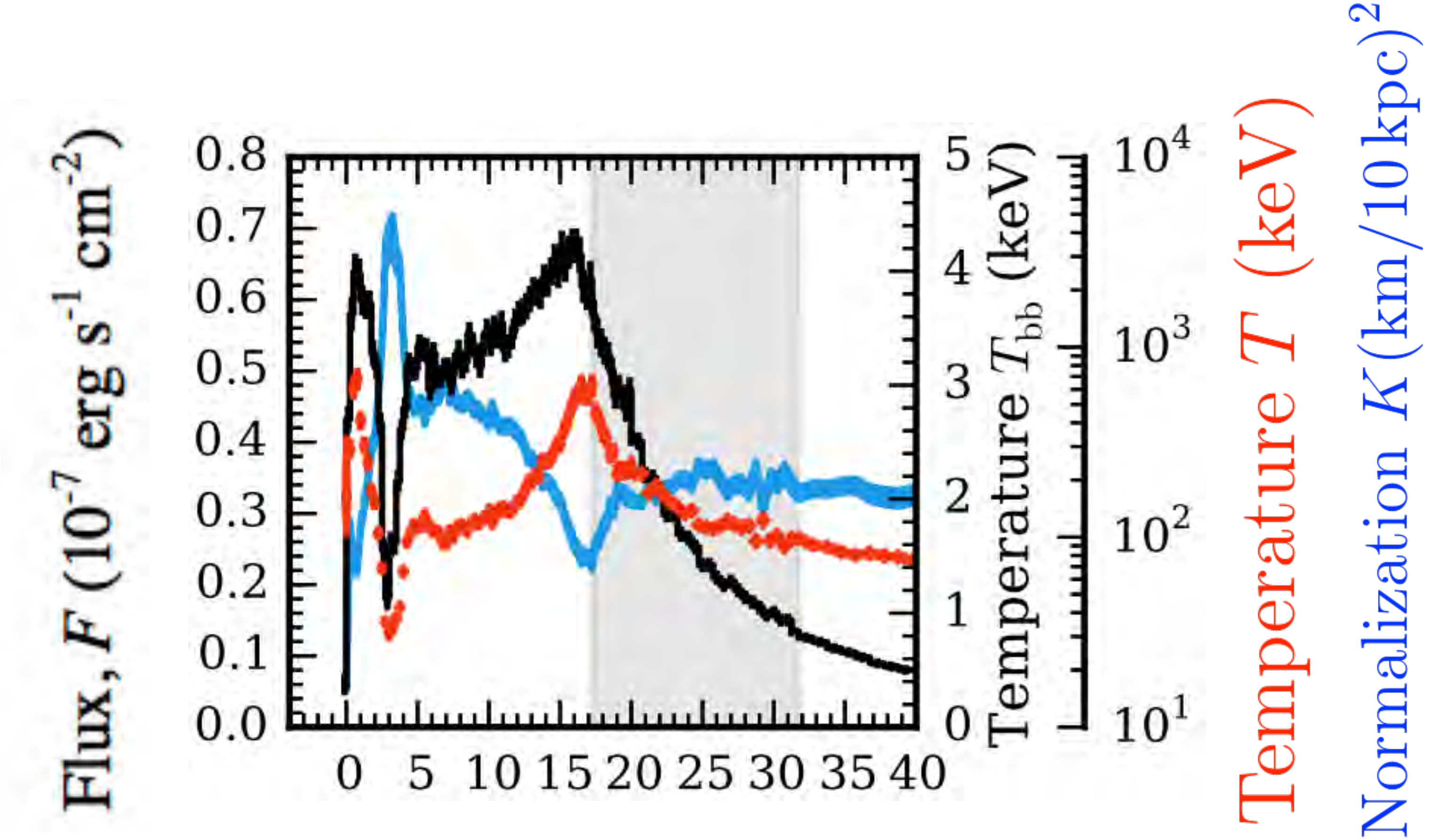


In some bursts anomalously bright patches form.
There are known as burst oscillations.

Strohmayer et al., 1996.

Another method: fitting burst spectra

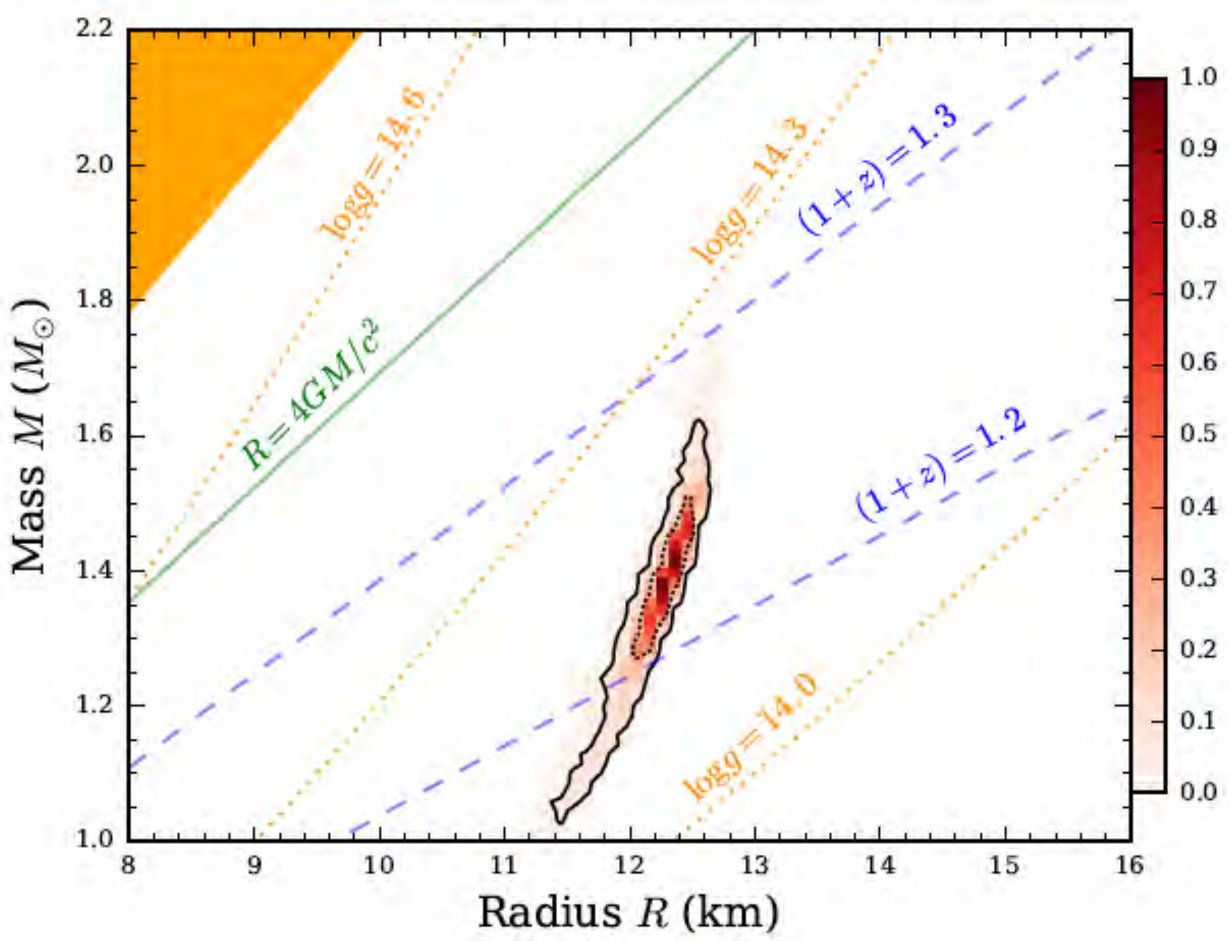
Thermal spectra from type I X-ray bursts



$$R_\infty = R_{bb} f_c^2 = D_{10}\sqrt{K} f_c^2$$

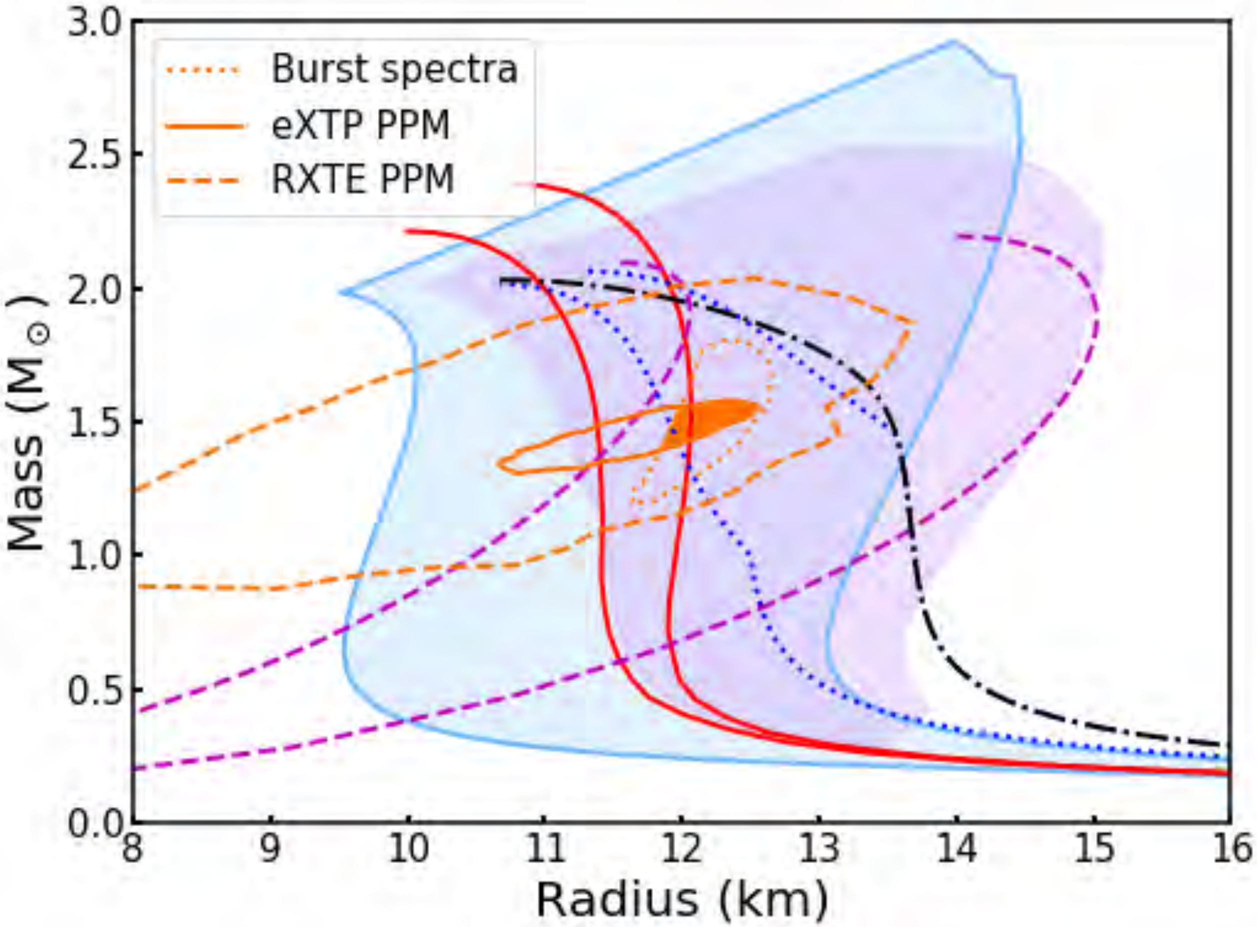
Recent measurement

M-R constraints for 4U 1702-429



Nättilä et al. 2017

A better look…

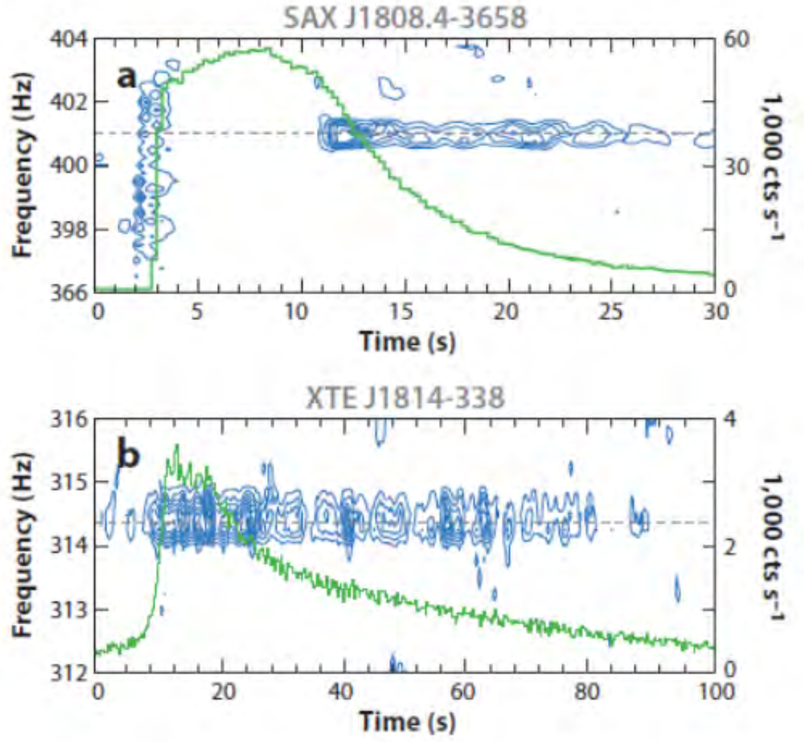


Few per cents accuracy on both M and R!

Combining PPM modelling and polarimetry, and burst spectra we get the orange solid spot!

Sources (3): AMXP burst oscillations

AMXP show burst oscillations

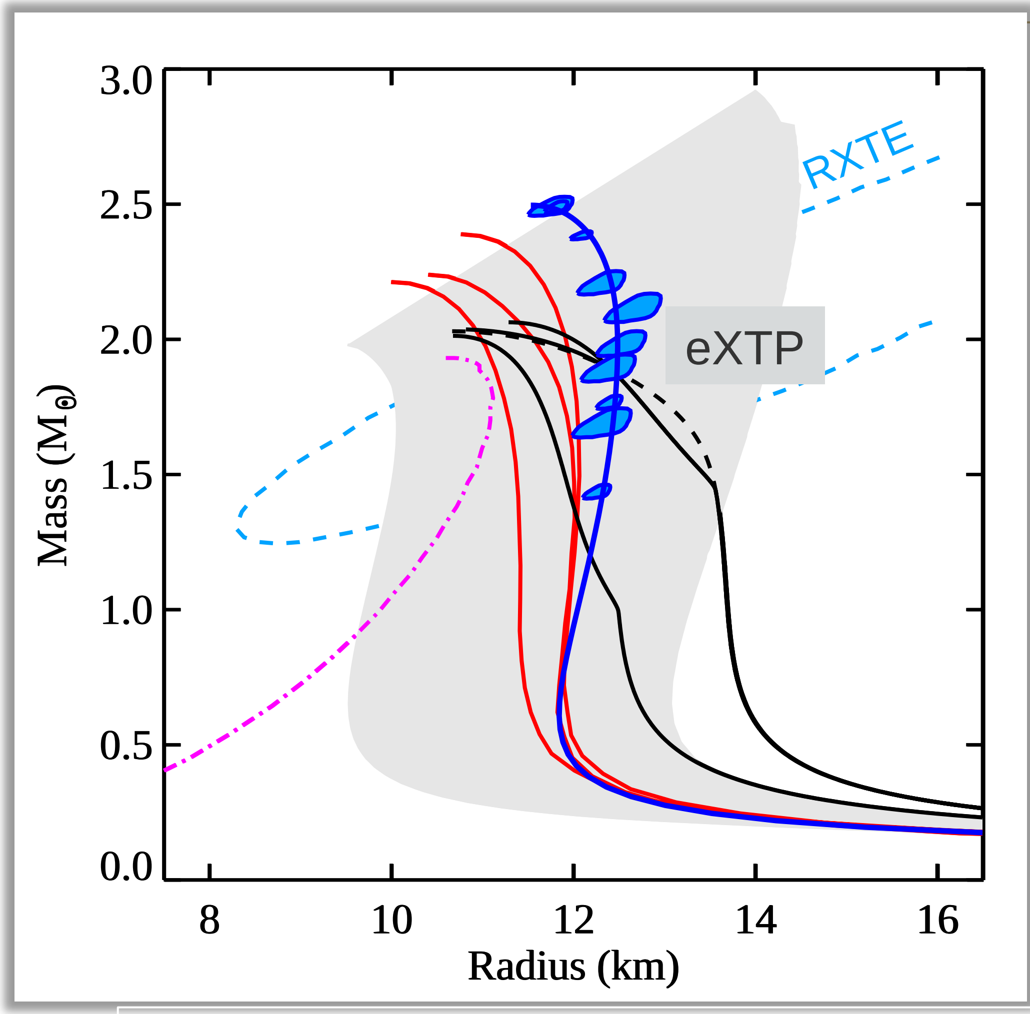


Vital cross-check on accretion powered pulsation fitting.

- **Spectra and PPM modeling!**
- Need more time than for APPs alone, ~500ks, to guarantee catching sufficient bursts

Best targets are (~500 ks observations): **XTE J1814-338** (very stable frequency), **SAX J1808.4-3658** (more frequency drift), most prolific known burst oscillation sources: **4U 1636-536, 4U 1728-34, Aql X-1** (high level of variability).

Pulse profile modeling of AMSPs



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

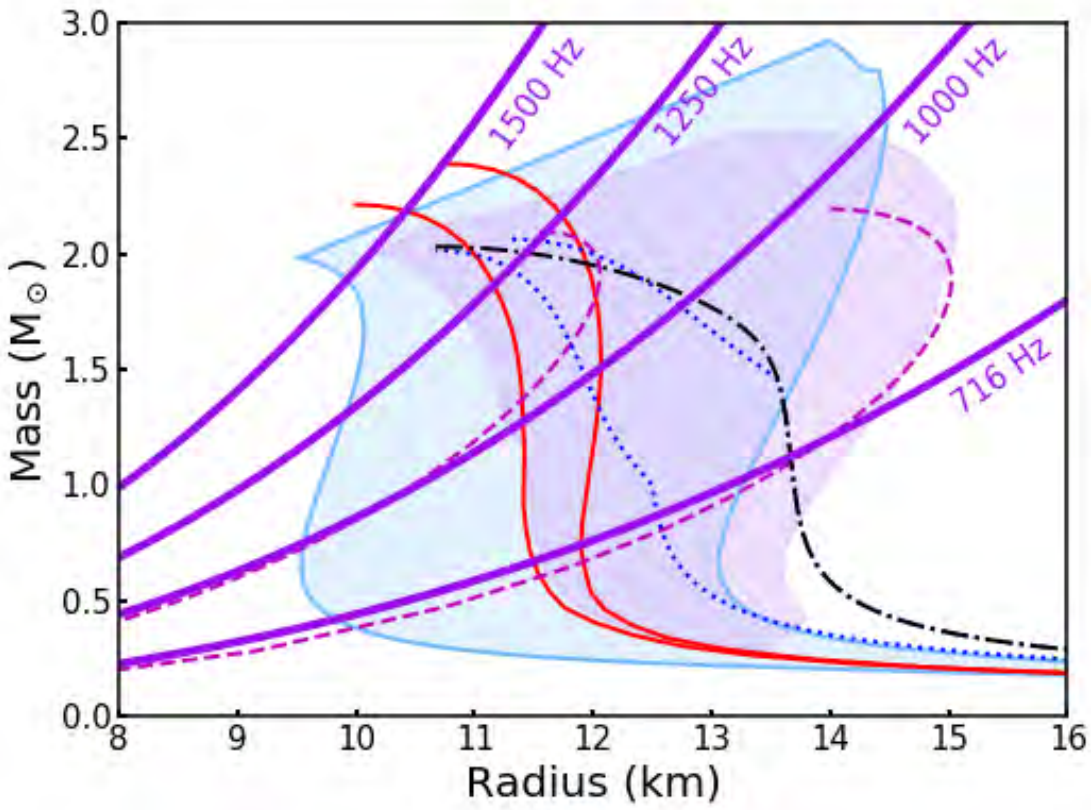
Few % accuracy needs ~10^6 photons: large area crucial →a few – several 100 ks

Multiple same-source cross-checks.

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

M-R to EOS inversion makes no model assumptions except continuity

Technique: Spin searches

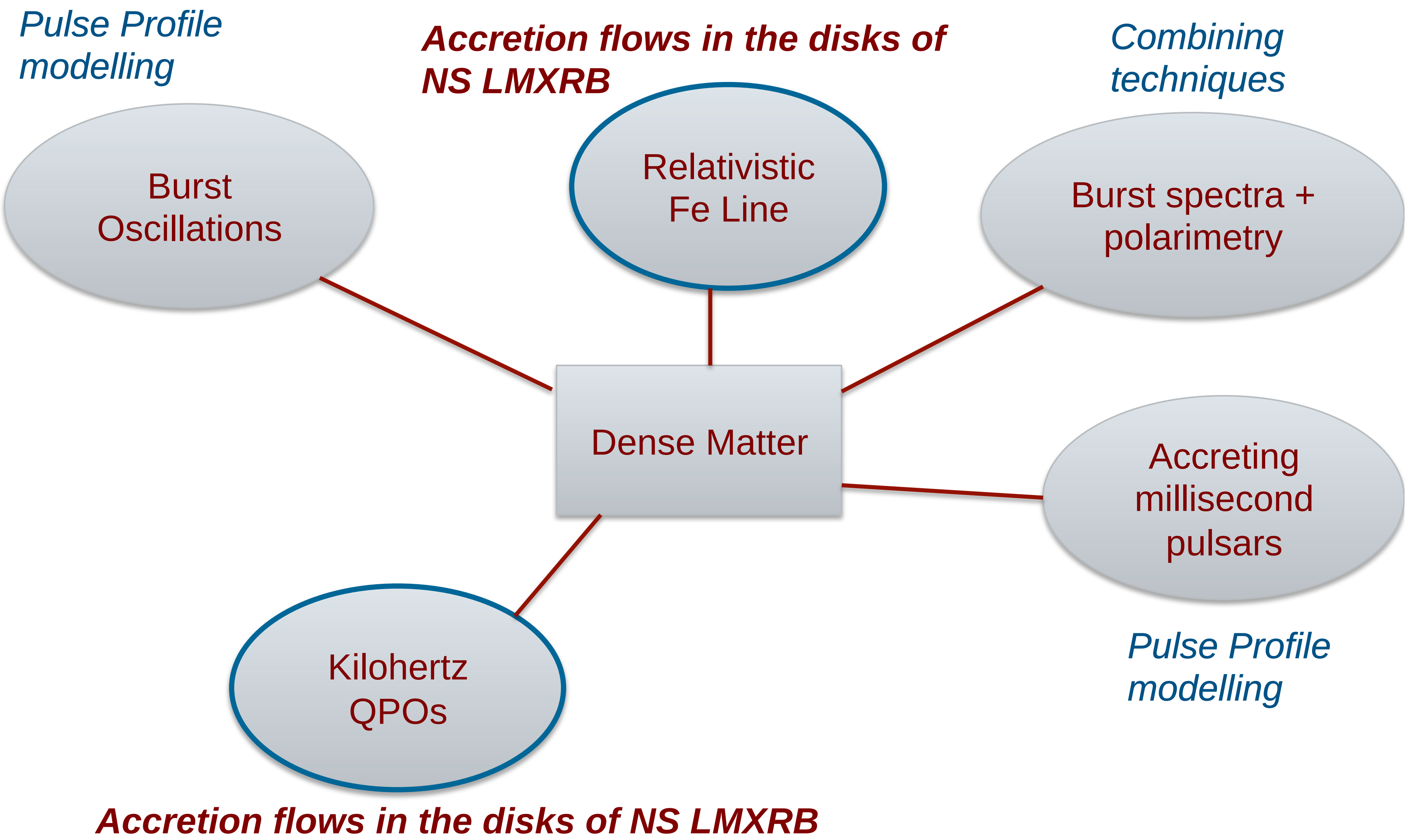


Searching for rapidly spinning stars is a very clean constraint on EOS.

- Fully sample spin distribution of accreting NS.

Two options: (1) target all accreting NS sources with unknown spin, (2) prioritise using RXTE sub-threshold results, or brightest sources where tightest amplitude constraints are Expected.

Dense matter (DM): synopsis



A. L. Watts, W. Yu, J. Poutanen, S. Zhang, et al Sci. China-Phys. Mech. Astron (2018)

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Part II

Dark matter search in the X-rays and more

Initial Remarks

– In astrophysics there is ***no way to directly measure*** the parameters (e.g. mass) of DM particle.

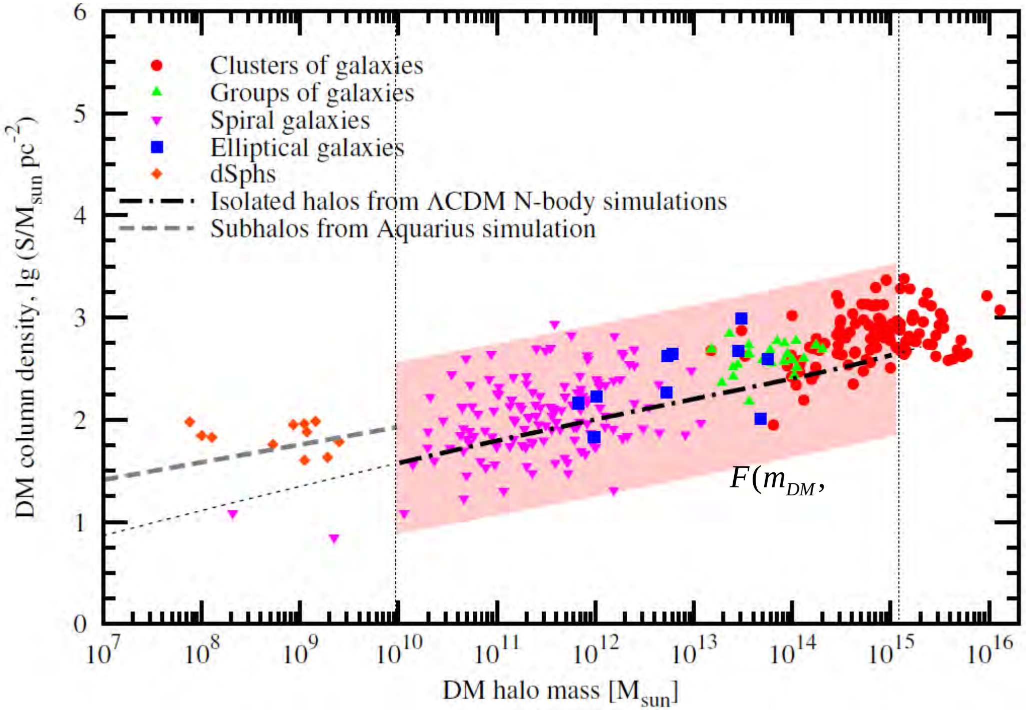
– Then? **To *deduce* these parameters *from observations*** that do not have convenient astrophysical explanations.

– The idea? **To detect decaying/annihilating dark matter** observing the corresponding feature in DM-dominated objects' ***(photon) spectra***.

The signal depends on the DM amount (and spatial distribution in annihilating DM case) in the instrument's FoV

Where to look for DM signals?

Boyarsky et al 2012



- Our Galaxy?
- Clusters of Galaxies?
- Dwarf spheroidals?
- Some other object?

Expected flux F from DM decay **proportional to the DM column density**:

$$F(m_{DM},\Gamma) = \frac{\Gamma}{4\pi m_{DM}} \int_{l.o.s.} \rho_{DM} d\ell = \frac{\Gamma}{4\pi m_{DM}} \frac{M_{DM.FoV}}{d^2}$$

Warning: lower astrophysical background and good quality of the knowledge of DM density distribution!

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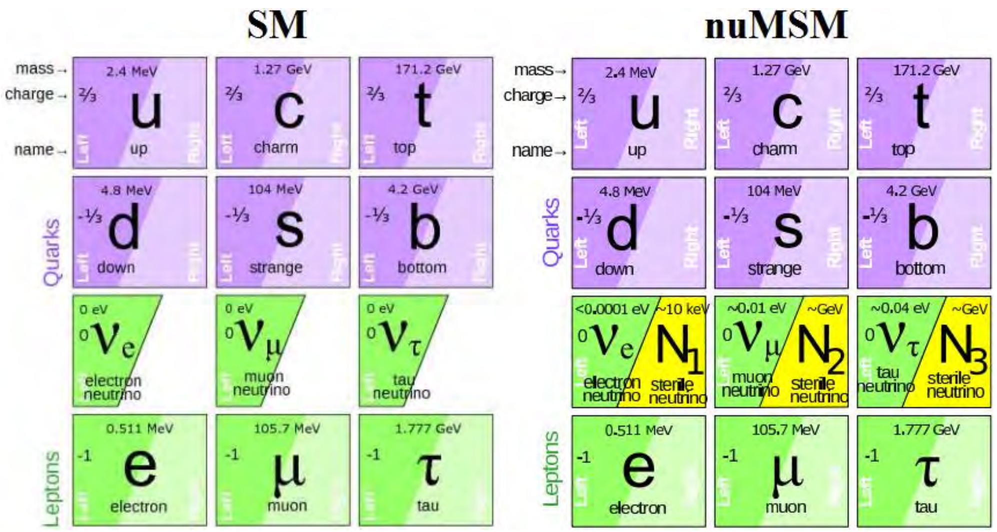
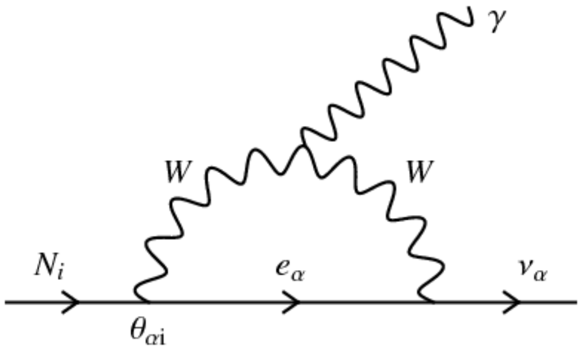
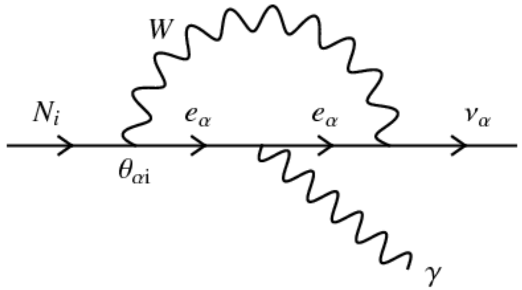
Sterile neutrino Dark Matter



SM particles have positive («right handed») and negative («left-handed») projection of the spin onto their momentum.
Standard neutrinos can be only left-handed.

νMSM proposes to add right-handed «sterile» companions to the neutrinos.





Radiative decay channel suggests a narrow line at energy $E=M_s/2$

Sterile Neutrinos (2)

νMSM is "nice" because:

– it is a «natural» extension of the SM
– It can explain low neutrino masses (seesaw mechanism) / neutrino oscillations
– gives candidate(s) for the Dark Matter
– help to explain perhaps pulsar kicks
…

$$F_{DM} \approx 1.4 \times 10^{-7} \left[\frac{\sin^2(2\theta)}{10^{-11}}\right] \left[\frac{m_{DM}}{10\mathrm{keV}}\right]^4 \left[\frac{d}{100\mathrm{kpc}}\right]^{-2} \left[\frac{M_{DM,FoV}}{10^7 M_\odot}\right] \frac{\mathrm{ph}}{\mathrm{cm}^2\mathrm{s}}$$

the decay width Γ can be expressed in terms of sterile neutrino mass m_{DM} and the mixing angle between the sterile and standard neutrinos.

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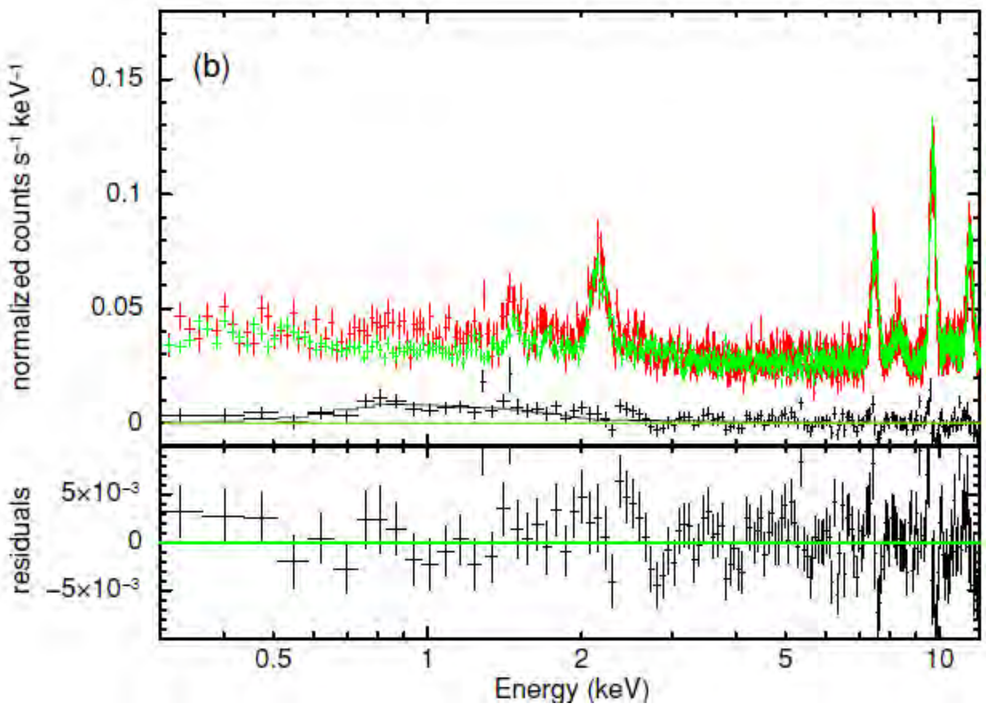
Detection of a keV line?

Lowenstein&Kusenko (2009)



2.5 keV line from Willman 1 dSph

– Based on 100 ks Chandra observations of ***Willman 1 dSph*** (low astrophysical background!)

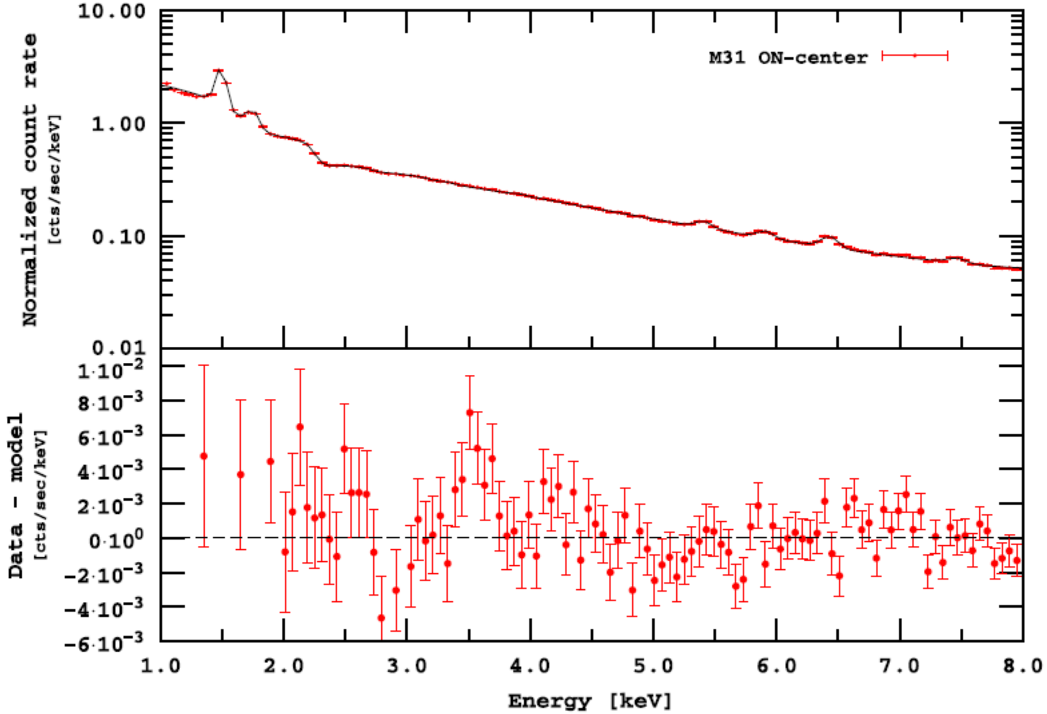
– ***Consistent*** with the previous Ursa Minor and Draco dSph Suzaku and Chandra (non-) observations of DM decay line

– *No 2.5 keV line in M31 and Fornax dSph (XMM); no line in Sculptor dSph (Chandra)*

– Total exclusion significance ~20 sigma!
– Possible reason – poor modeling of Chandra effective area...

Boyarsky et al (2010)

Again another line: 3.55 keV line!



Bulbul et. al. (2014) 1402.2301 – unidentified line in the staked XMM observations of 73 clusters. Detection in Chandra observations of Perseus cluster.

Boyarsky et al.(2014) 1402.4119 – same line in Andromeda galaxy and Perseus cluster.

Well we have to be cautious…

Followed by the avalanche of papers:

Riemer-Sorencen (1405.7943) – No line in GC/Chandra, upper limits are consistent
Jeltema & Profumo(1408.1699)– 3.55 = plasma line?
Boyarsky et al. (1408.2503) – 3.55 keV line from the GC/XMM
Malyshev et al. (1408.3531) – No line in dSphs/XMM
Anderson et al. (1408.4115) – No line in 89 stacked galaxy groups/Chandra/XMM
Tamura et al. (1412.1869) – No line in Perseus cluster (weak tension) / Suzaku
Sekiya et al. (1504.02826) – No line in Suxaku/XIS XRB
Ruchayskiy et al. (1512.07217) – marginal detection in deep, 1Msec, XMM Draco dSph observations (PN only detection)
Jeroen et al. (1604.01759) – radial profile for 3.55 keV line in Perseus cluster / Suzaku
Bulbul et al. (1605.02034) – marginal detection in 47 galaxy clusters/Suzaku (weak tension)
Hoffman et al (1606.04091) – no line in 33 high-mass clusters stacking/Chandra

Research to be continued…

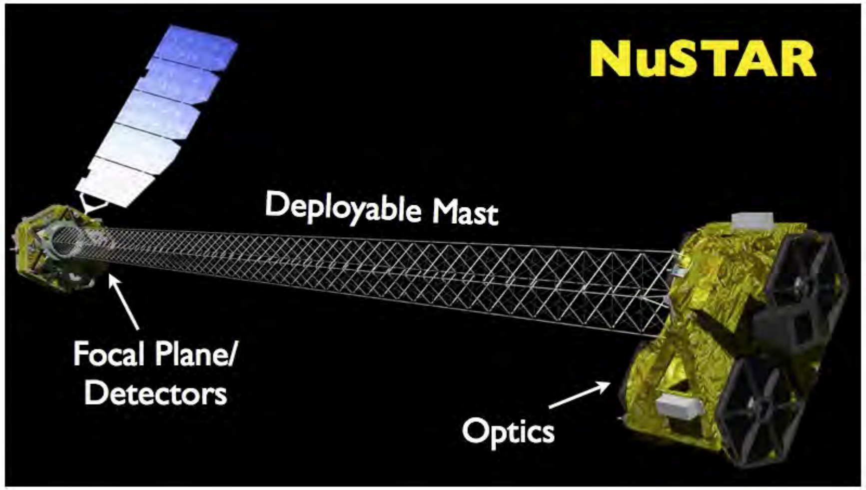
Caveats (Warnings!!)

– DM profiles can have ***large uncertainties***, especially near the centers of DM dominated objects

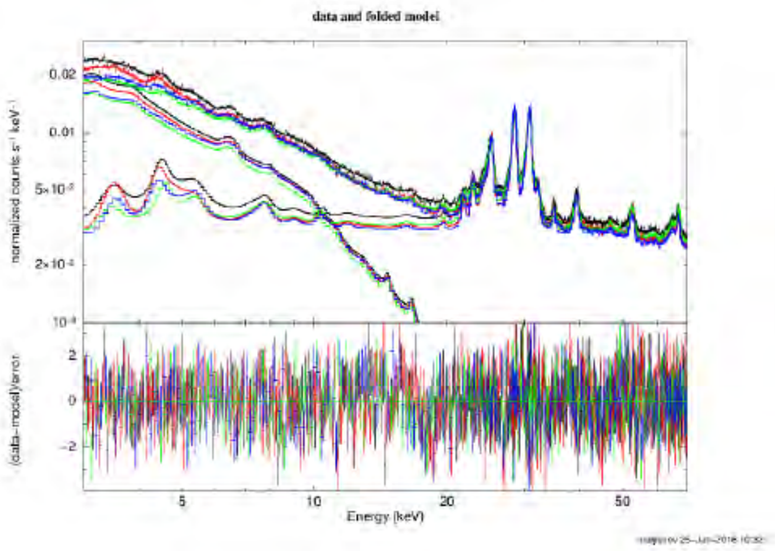
– DM decay/annihilating spectral feature can be confused with an ***astrophysical line/feature*** or with ***instrumental feature***.

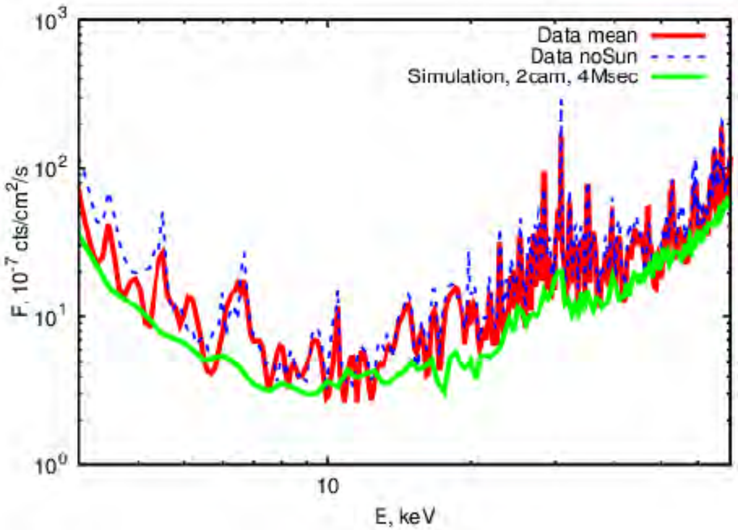
– The expected feature is generally weak and requires the analysis of a large amount of the data. At this step one can encounter previously ***unknown instrument systematic*** effects.

Also work at IAAT



Analysis regions – **2 “blank sky fields”** -- **COSMOS** (~1deg2 @ (l,b) = (236 ; 42) ; ~5 Msec) and **ECDFS** (~0.3deg2 @ (l,b) = (223 ; -54) ; ~2.5 Msec).





A. Neronov, D. Malyshev, D. Eckert, Phys Rev. 94, 2016

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Plenty of lines!

Line energy, keV	Significance σ	Width, keV	F, 10^{-6} cts/cm^2/s	F_{noSun}, 10^{-6} cts/cm^2/s	Sun?	Ghost?	Comments
$3.51^* \pm 0.02$	11.1	0.08 ± 0.05	7.7 ± 1.3	10 ± 2.5			lower edge of sensitivity band
$4.46^* \pm 0.05$	15.7	0.12 ± 0.03	5.9 ± 0.5	3.7 ± 0.5	Y		Ti $K\alpha$
$4.7^* \pm 0.1$	9.8	0.6 ± 0.1	8.9 ± 1.8	8.2 ± 1.9			
6.32 ± 0.08	6.7	0.	1.2 ± 0.2	0.66 ± 0.23	Y		Fe $K\alpha$?
7.96 ± 0.06	4.0	0.	0.5 ± 0.1	0.23 ± 0.18	Y		Cu $K\alpha$?
$10.44^* \pm 0.05$	8.9	0.2 ± 0.05	1.4 ± 0.2	1.7 ± 0.3			W L-edge residuals [50]
14.2 ± 0.1	3.3	0.	0.51 ± 0.18	0.6 ± 0.2			Sr $K\alpha$?
14.75 ± 0.05	5.9	0.	0.9 ± 0.2	1.0 ± 0.2		Y?	23 keV ghost?
15.7 ± 0.1	3.7	0.	0.57 ± 0.16	0.6 ± 0.2		Y?	24.5 keV ghost, Zr $K\alpha$?
16.7 ± 0.1	5.5	0.	0.9 ± 0.2	1.2 ± 0.2		Y?	25.3 keV ghost, Nb $K\alpha$?
$19.66^* \pm 0.06$	9.3	0.06 ± 0.14	1.3 ± 0.3	1.3 ± 0.3		Y?	28.5 keV ghost?

11 high-significance lines (>3sigma) were detected at energies <20 keV.

Ghost lines – due to poor RMF modeling – can be residuals from strong higher-energy instrumental lines.

3.55 keV line is there?..

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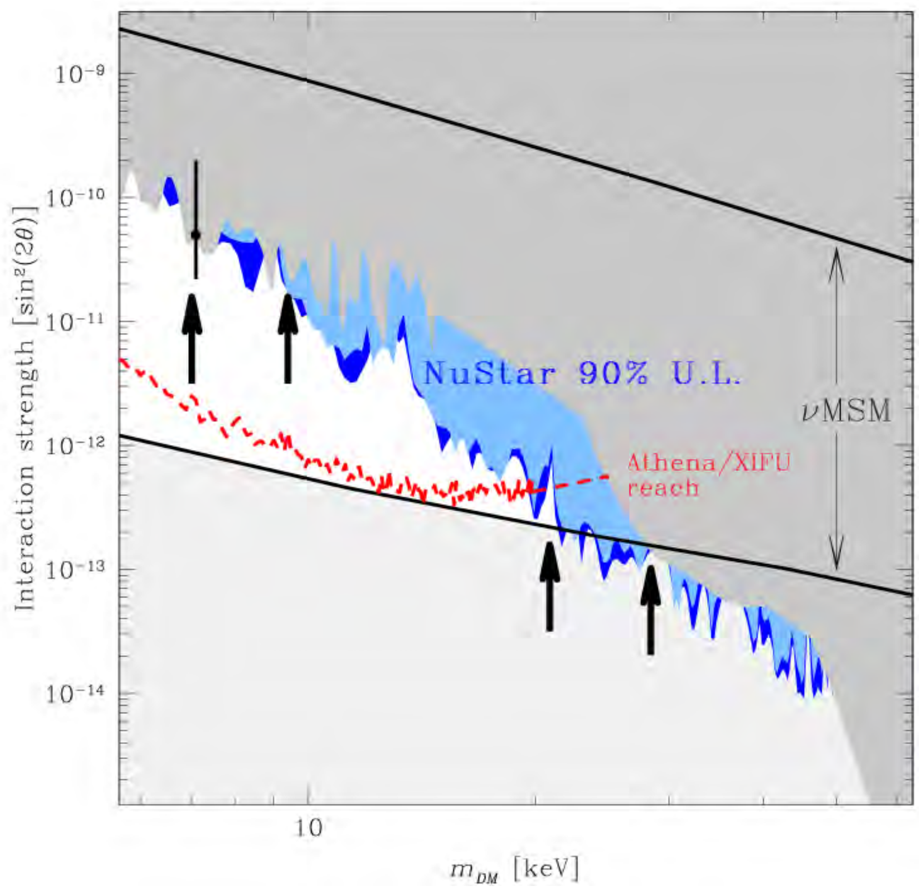
Tighter constrains



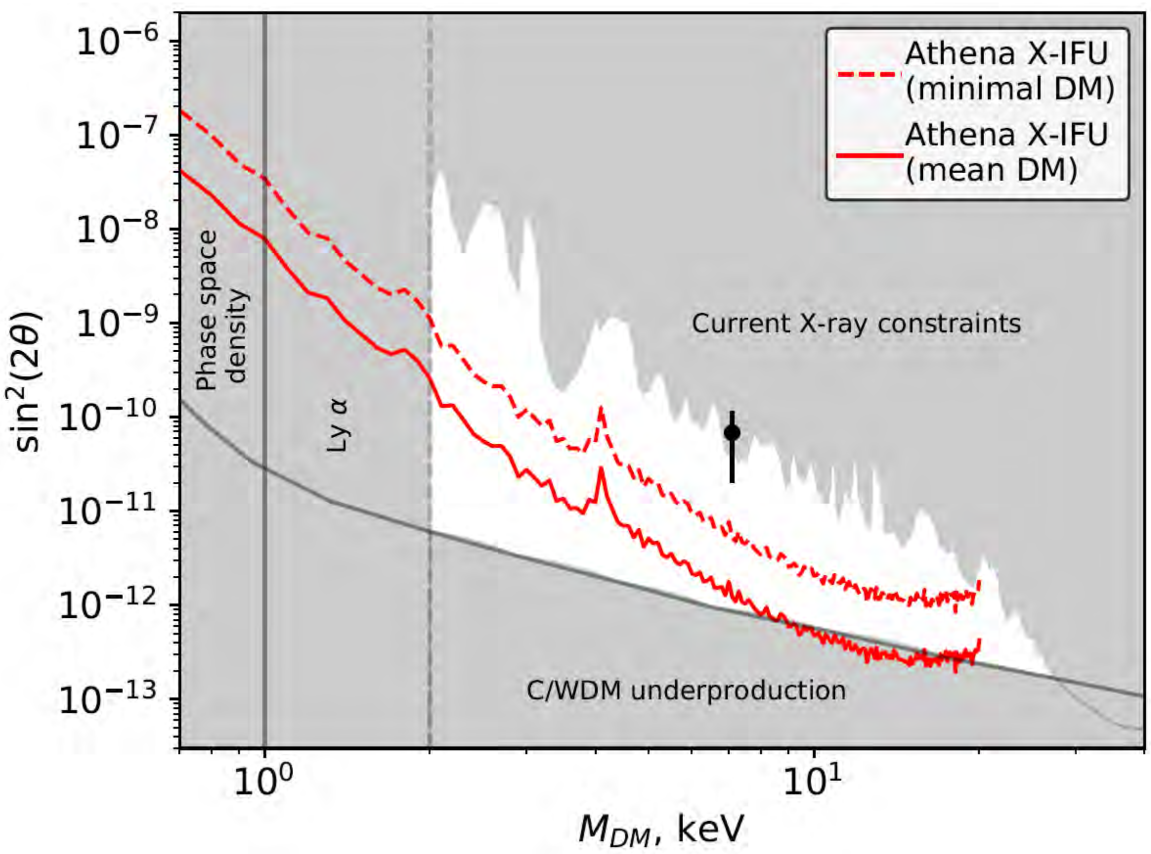
Model independent flux constraints in the case of sterile neutrino DM can be converted to the ***constraints on interaction strength – sterile neutrino mass.***

With NuStar observations*: improve the constraints on sterile neutrino DM by a factor of ~4 for sterile neutrino masses <10 keV.*

Deep exposure of the selected DM dominated objects (e.g. dSphs) can improve the shown bounds by a factor of few.

Sterile neutrino forecast: Athena

1 Msec Segue 1 dSph, instrument Athena X-IFU



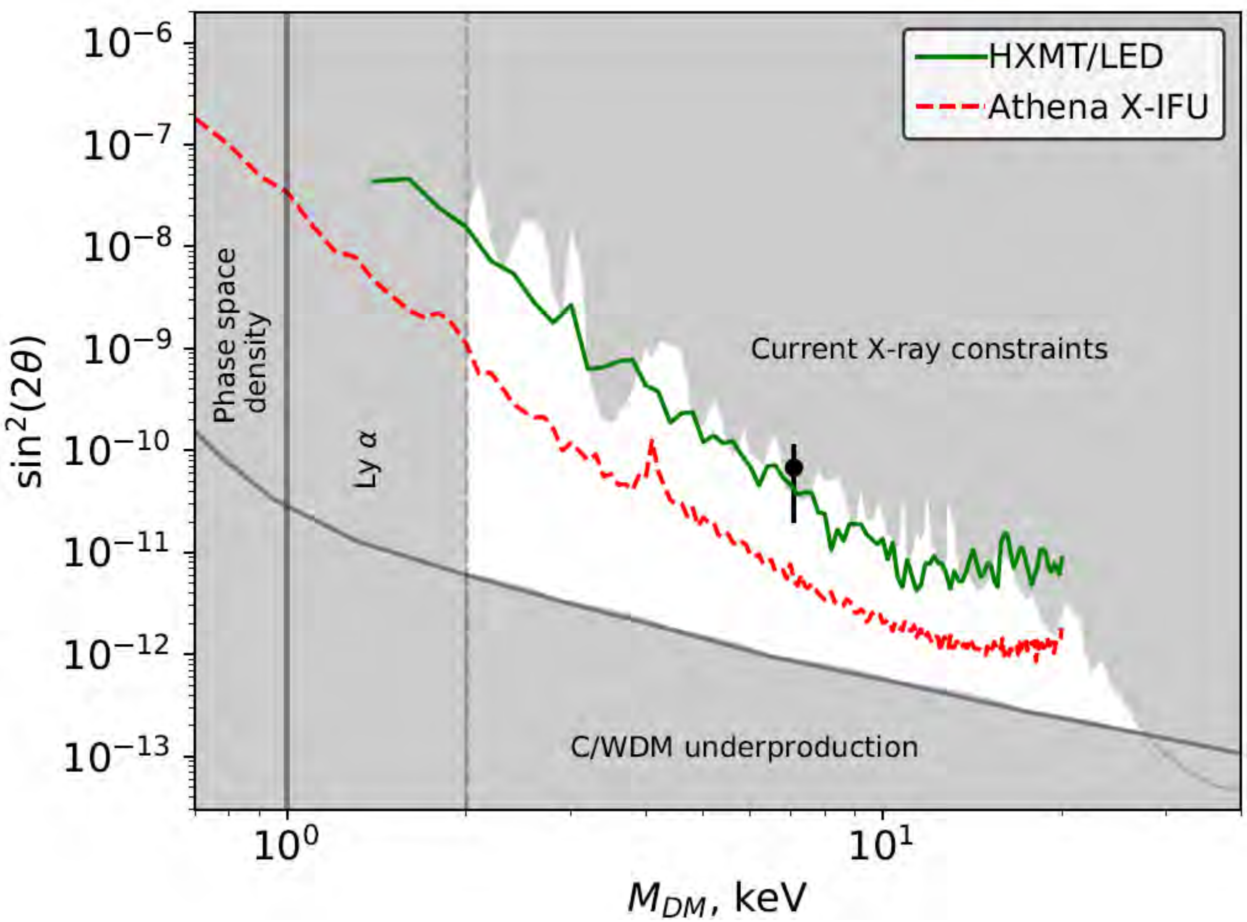
Solid (dashed) lines correspond to mean (minimal) DM column density profiles in Segue 1 (See details in 2016PhRvD.. 93f3518N)

Black point shows "3.5 keV sterile neutrino detection" point from Bulbul (2014)

- Grey shaded regions show currently excluded sterile neutrino parameter space
- Black point shows "3.5 keV sterile neutrino detection" point from Bulbul (2014)

Sterile neutrino forecast: HXMT

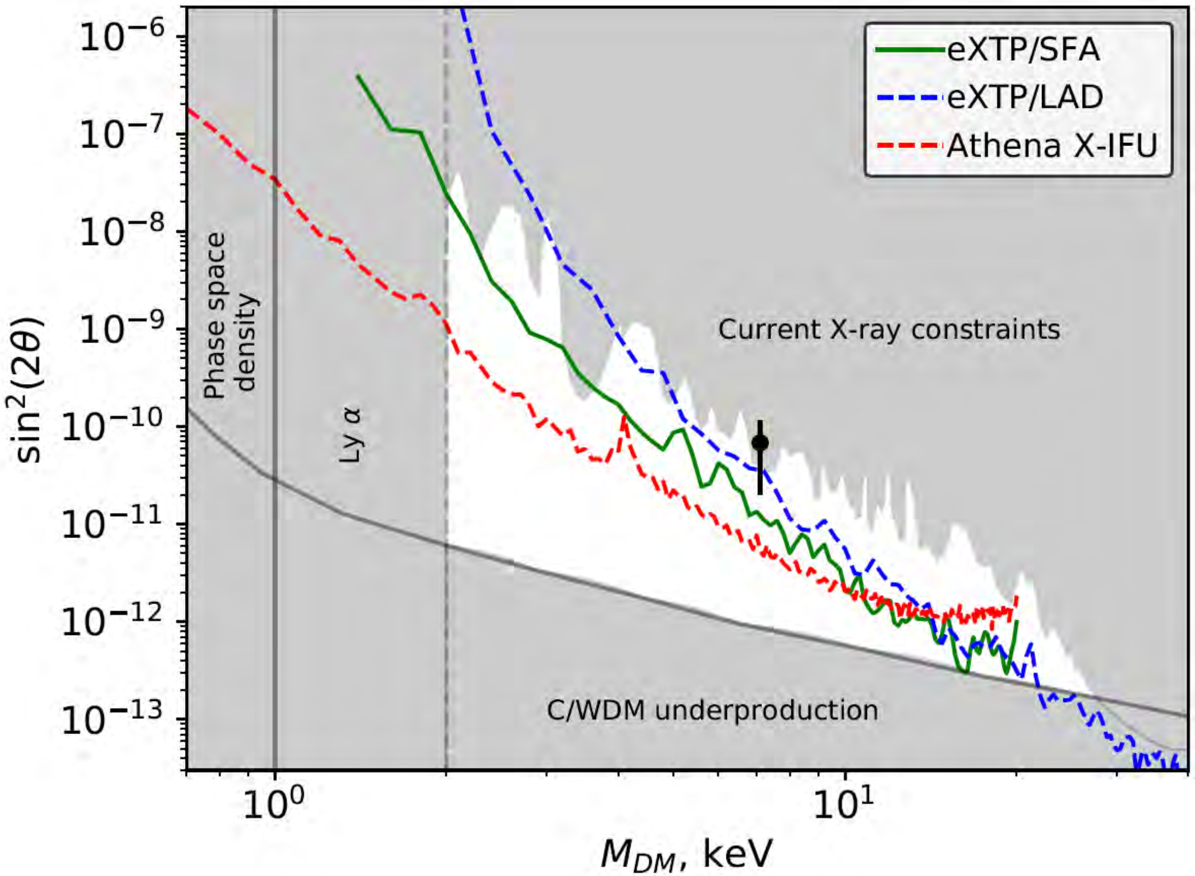
1 Msec Segue 1 dSph, instrument LE HXMT (minimal DM profile)



Based on simulations of HMXT/LE background by fit_grped.tcl script provided by HMXT team

Sterile neutrino forecast: eXTP

1 Msec Segue 1 dSph, instrument eXTP SFA (minimal DM profile)



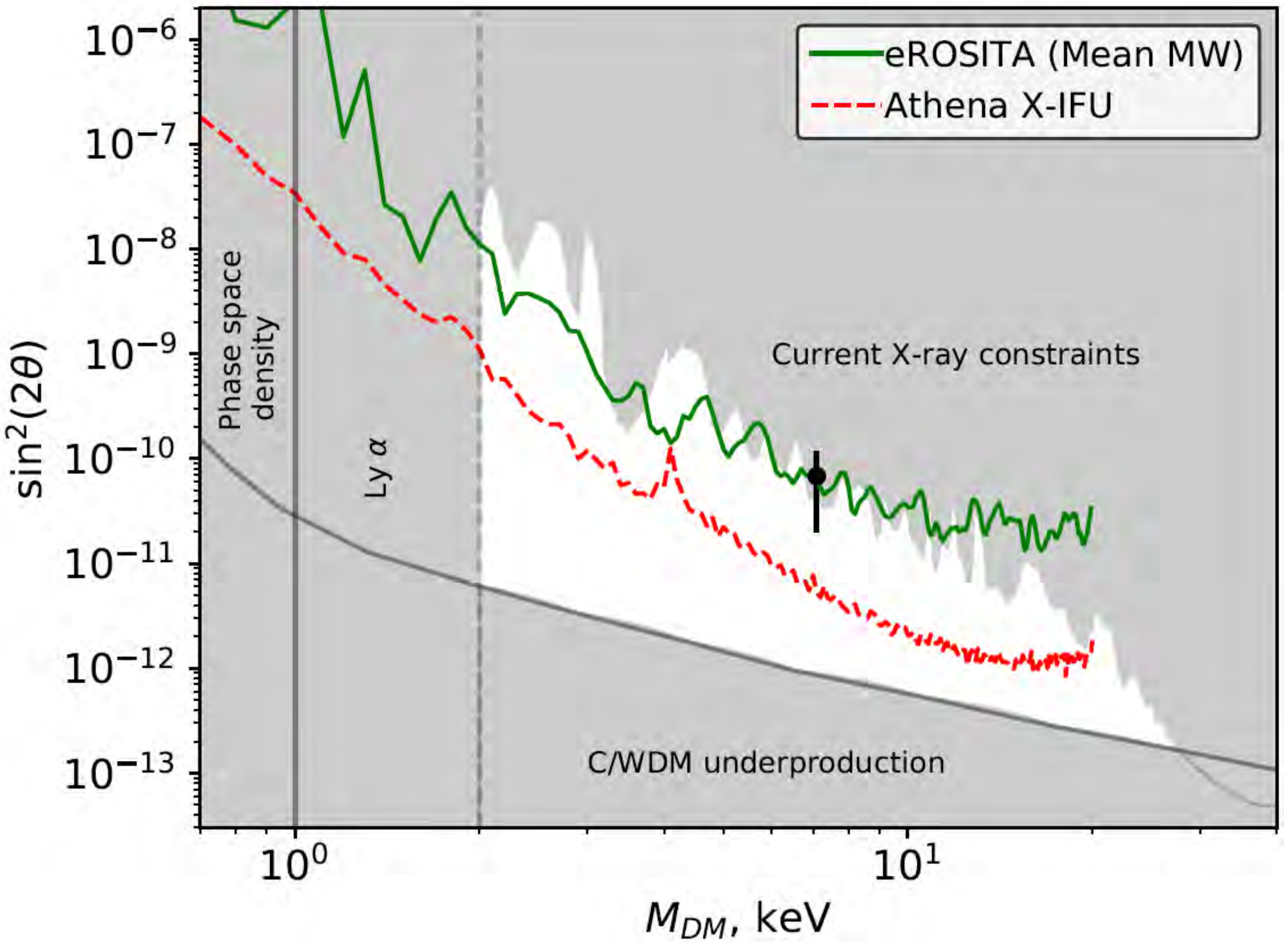
eXTP Limits comparable to Athena for M_{DM} > 10 keV

For lower M_{DM} eXTP can improve current constraints by a factor of few

Based on XTP_sfa_v6.bkg and LAD_40mod_300eV.bkg background templates provided by eXTP collaboration

Sterile neutrino forecast: eROSITA

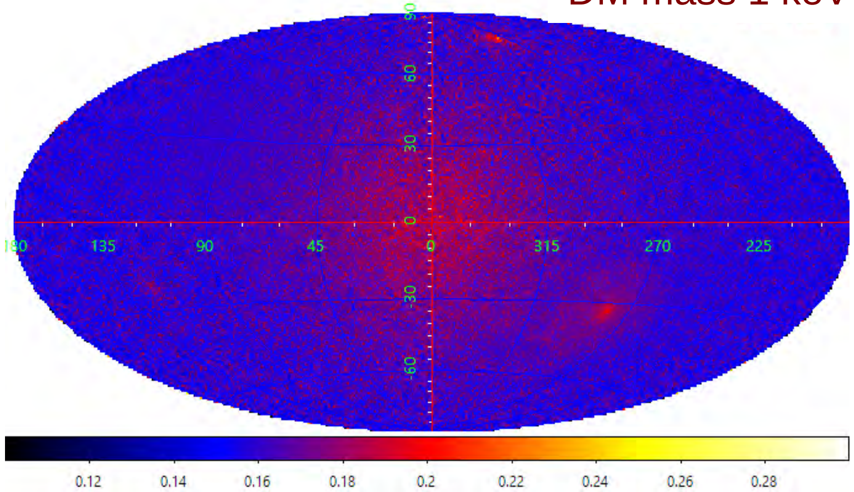
1 Msec Segue 1 dSph, instrument eROSITA (minimal DM profile)



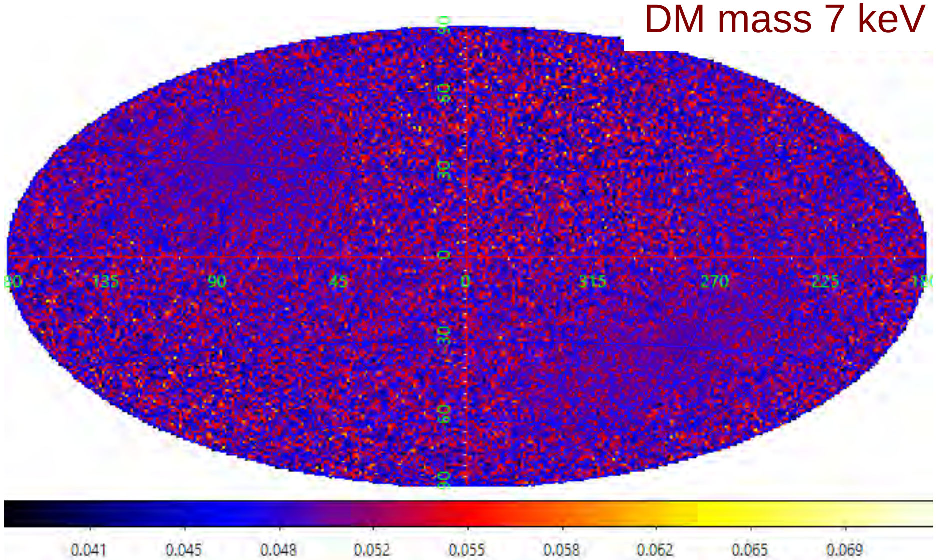
- 1 Msec simulations of “mean MW” (corresponding to mean Milky Way DM density at the position of Segue 1) observations by eROSITA

Sterile neutrino forecast: eROSITA (2)

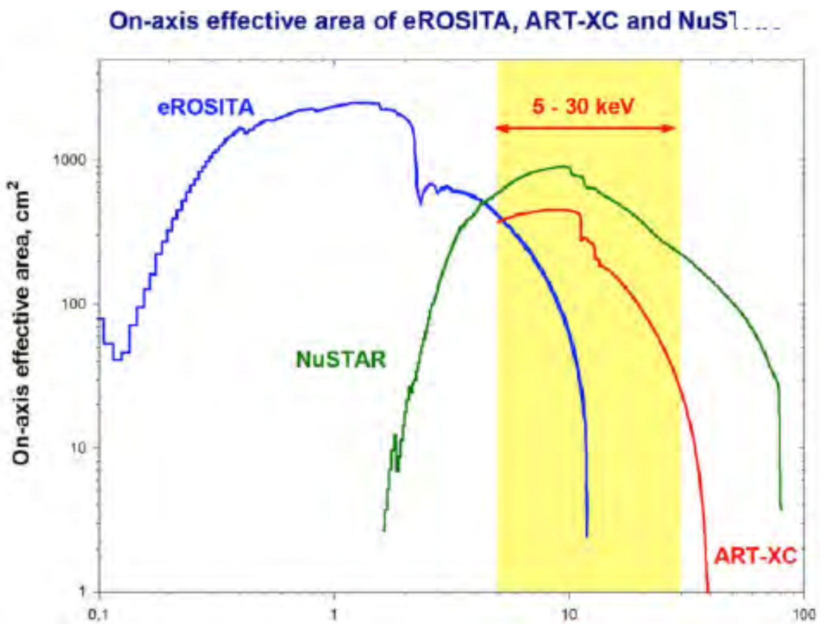
DM mass 1 keV



DM mass 7 keV



eROSITA view of sterile neutrino dark matter for m_{DM} = 1.0 keV and m_{DM} = 7.0 keV (assuming the DM parameters from existing upper bounds)



A second candidate: Axions

Axions invented to solve strong CP problem in QCD but a good candidate to be DM, see e.g. *Marsh, 2015* for a review.

Despite the low mass of the axion, there are ways to make it cold – «misalignment mechanism»

QCD axion → particle with specific m_a-g_a relation

More general type of particles - **ALPs** (axion-like particles)

ALPs are (generally) **light**, since CP violation is tiny

ALPs are **WISPs**: *Weakly Interacting Sub-eV Particles*

Axions (2): good candidates?

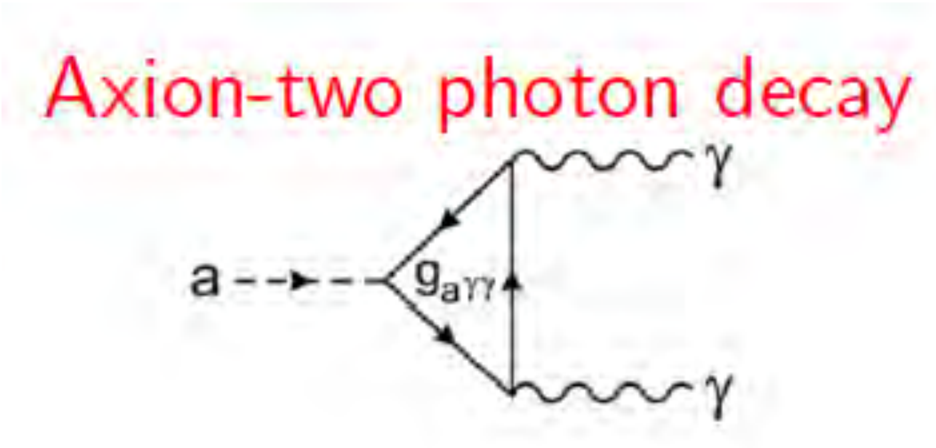
- **Massive particles**
- **Non relativistic (CDM/WDM)**
- **Produced in the early Universe**
- **Weakly interacting to survive cosmological times**

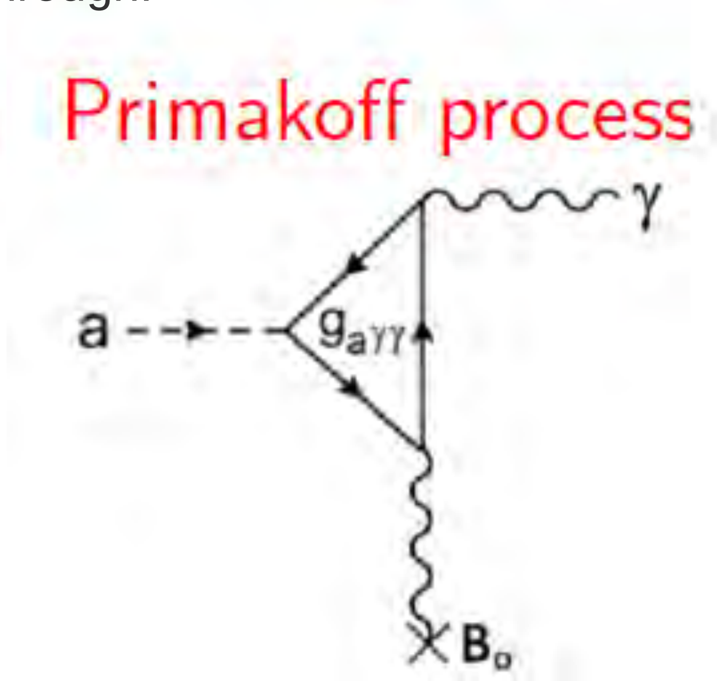
Despite of low mass ALPs can be indeed produced in the early Universe out of of thermal equilibrium via vacuum realignment or topological production mechanisms

Marsh, 2017; Duffy & Biber, 2009.

How to detect them?

Axions are coupled to direct observables through:





One-to-one correspondence between photon energy *E* and axion mass m_a:

$$E_\gamma = m_a/2$$

$$\Gamma = 7.6 \cdot 10^{-26} \left(\frac{g_a}{10^{-10}\,\mathrm{GeV}^{-1}} \right)^2 \left(\frac{m_a}{1\mathrm{eV}} \right)^3 \mathrm{s}^{-1}$$

In a presence of (electro)-magnetic field axions can be converted to a photon and viceversa: photon-axion oscillations

SN 1987A	2015JCAP...02..006P	– Detected neutrino implies high intrinsic gamma-ray flux – Some of gamma-rays inside SN can be converted to axions (high electron plasma density + magnetic field) – Axions travel trough the galactic magnetic field and can be converted back to gammas (Primakoff process) – No gamma-rays from SN 987A detected → *upper* limit on axion-photon coupling constant
Transparency of the Universe	2013PhRvD.. 87c5027M (VHE γ-rays)	– TeV photons from distant AGNs have to be EBL-absorbed – gamma → axion (no EBL absorption) → gamma conversion hint? In both cases gamma ↔ axion conversion is on extragalactic magnetic field (Primakoff process) – *lower* bound on axion-photon coupling
AGN in a cluster	2017ApJ...847..101B (Perseus/X-rays) 2017JCAP...12..036M (M87/X-rays) 2016PhRvL. 116p1101A and 1805.04388 (Perseus/ γ-rays) 2018PhRvD..97f3009Z (PKS 2155/γ-rays)	– AGN in a galaxy cluster with intrinsically smooth spectrum – gamma/X-rays converted to axions in cluster's magnetic field in energy-dependent way – irregularities (oscillations) expected in observed gamma/X-ray spectrum – non-detection of irregularities → upper bound on photon-axion coupling
Pulsars spectrum	2018JCAP...04..048M 1807.10773	– gamma – ray converted into axion close to pulsar (high magnetic field and plasma density) – axion → gamma-ray in galactic magnetic field – spectral irregularities expected; non-detection → upper bound on photon-axion coupling – additional polarization of the signal expected → a window for polarimetry missions?
Modified stellar evolution	2016PhRvD.. 93f5044S 2018MNRAS. 478.2569I 1995PhRvD.. 51.1495R hep-ph/9805400	– additional axion-cooling channel can affect evolution of certain types of stars, e.g. neutron stars, white dwarves, red giants

Primakoff process: Axion conversion

A prominent feature corresponding to the ***resonant* conversion of the photons**: its position/shape depends on the magnetic field strength/plasma density.

$$P_{\gamma\to a} = \left(\Delta_{a\gamma} s\right)^2 \frac{\sin^2\left(\Delta_{osc} s/2\right)}{\left(\Delta_{osc} s/2\right)^2}$$

Conversion probability has local maxima at certain photon energies *$E(B, n_e)$*

$$\Delta_{osc}^2 = (\Delta_{pl} - \Delta_a)^2 + 4\Delta_{a\gamma}^2$$

$$\Delta_{a\gamma}/Mpc^{-1} = 0.15 \cdot \frac{g_{a\gamma\gamma}}{10^{-10} GeV^{-1}} B_{nG}$$

$$\Delta_a/Mpc^{-1} = -7.7 \times 10^{28} \left(\frac{m_a}{1eV}\right)^2 \left(\frac{\omega}{1eV}\right)^{-1}$$

$$\Delta_{pl}/Mpc^{-1} = -11.1 \left(\frac{n_e}{10^{-7} cm^{-3}}\right) \cdot \left(\frac{\omega}{1eV}\right)^{-1}$$

At these energies we expect features in spectra of astrophysical objects.

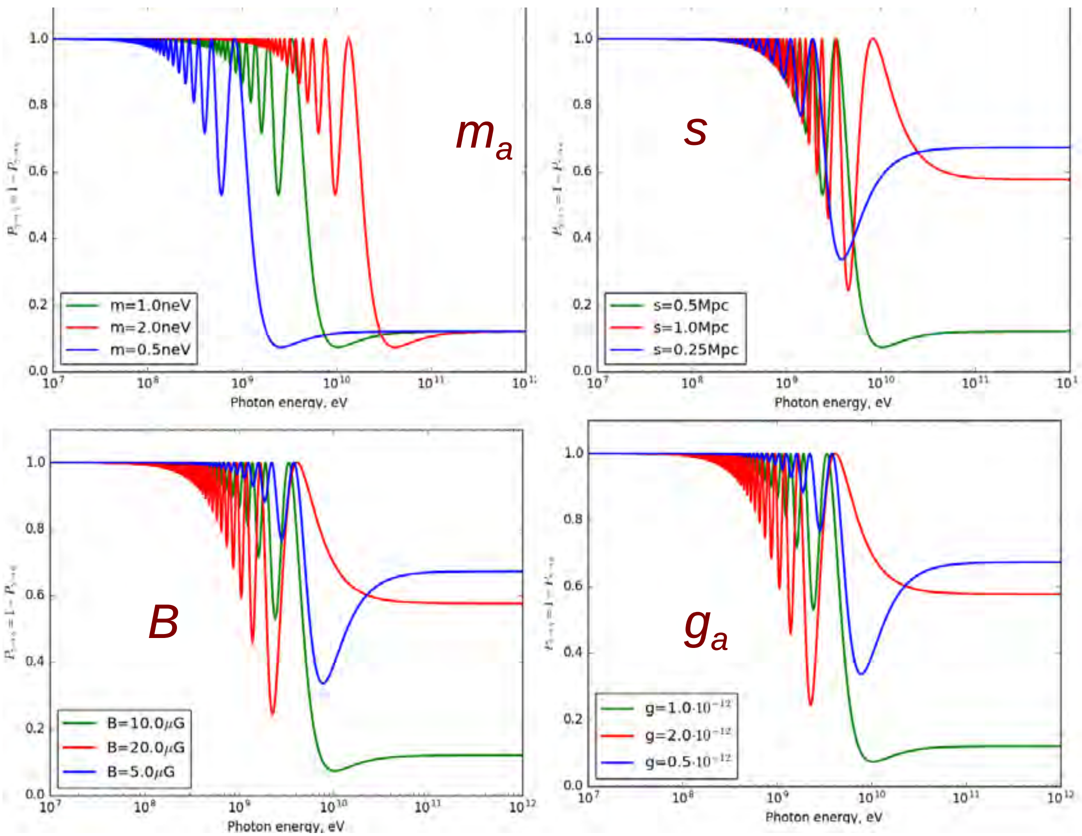
For objects with kown ***B*** and n_e we can probe the axion mass range for which *$E(B,n_e)$* happens to be in the keV-GeV range

Examples of $P_{\gamma \to a}$ in astrophysics

For most of astrophysical sources one of the two regimes: dominant *B* or dominant n_e:

$$E_{cr} \cong 72.5 \left[\frac{m_a}{1\ \mathrm{neV}}\right]^2 \left[\frac{g_a}{10^{-12}\,\mathrm{GeV}^{-1}}\right]^2 \left[\frac{B_T}{10\ \mu\mathrm{G}}\right]^{-1} \mathrm{GeV}$$

Magnetic field is dominant



Energy: 10^7 - 10^{12}

Oscillations' energy strongly correlate with m_a

strength with g_a and *B*

Two key features

Ideal targets Cluster of galaxies: n_e is negligible, dominated by B

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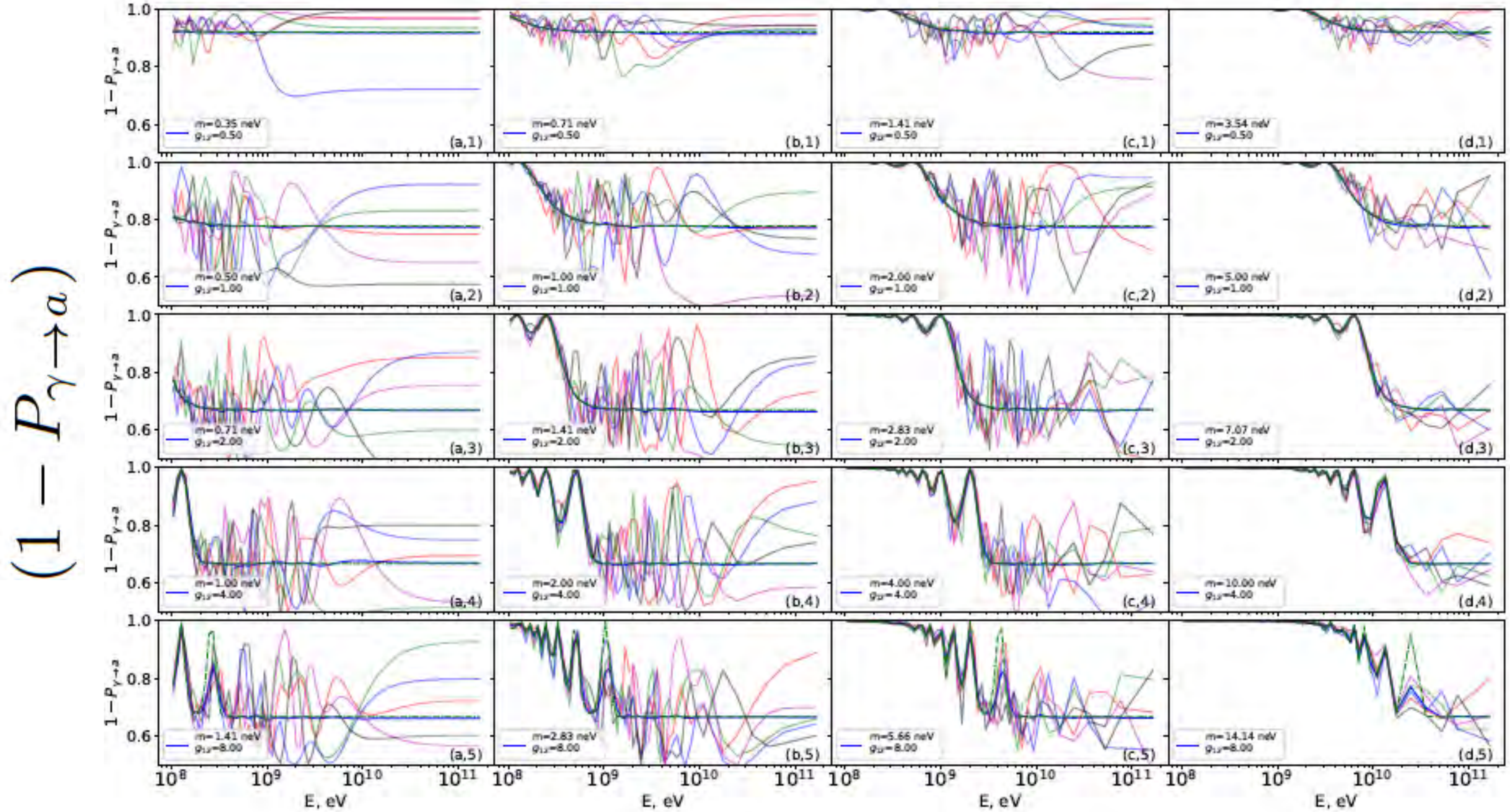
Simulating the spectrum…



$$g_a = 10^{-14} \ldots 10^{-9}\,\mathrm{GeV}^{-1} \quad m_a = 10^{-11} \ldots 10^{-7}\,\mathrm{eV}$$

Thick curves, average of several realizations

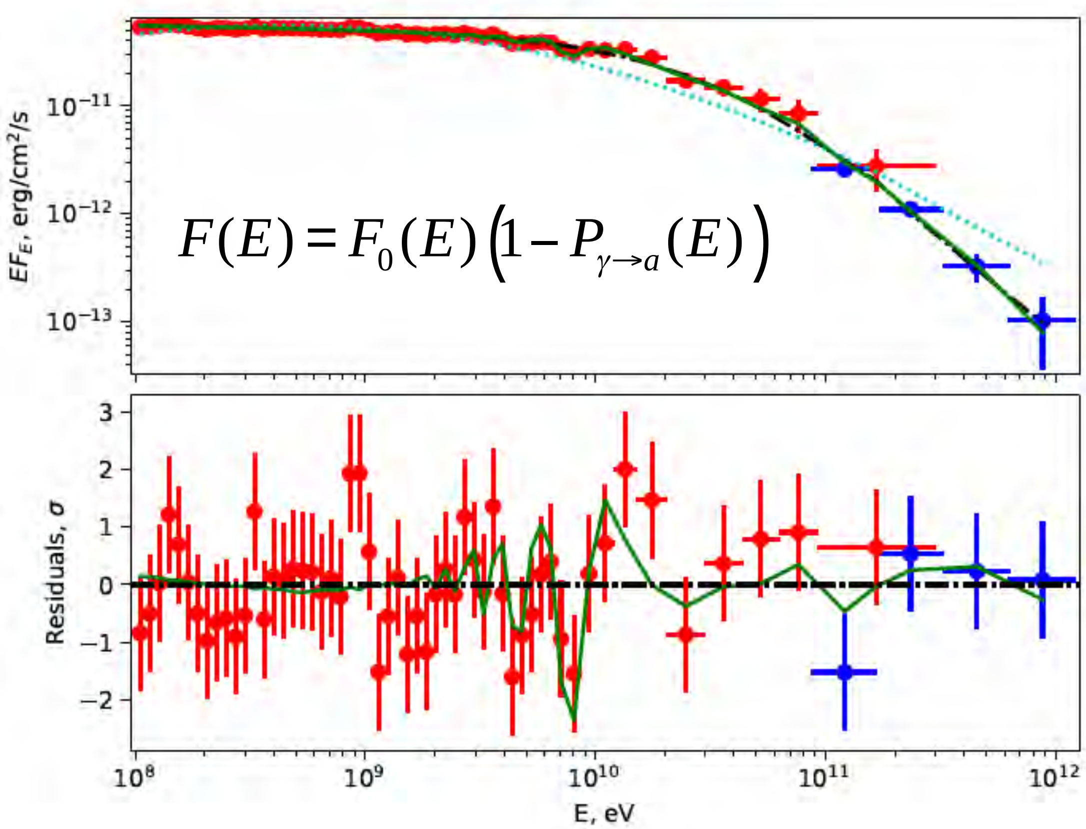
At the critical energy suppression in the spectra to about 2/3

Photon-Axion with NGC 1275 in Perseus

$$B(r) = \begin{cases} B_0 & if \quad r \le r_0 \\ B_0 \cdot (r/r_0)^{-0.5} & if \quad r > r_0 \end{cases} \qquad \delta z = 10 \text{ kpc}$$

$B_0 = 15\mu G; \quad r_0 = 40$ kpc

1000 realizations



Best fit broken powerlaw model (black dash dotted line).

Green curve: photon-ALP conversion into account

Cyan dashed line illustrates the best fit log-parabola model.

Improvement 2.2σ, but only statistics

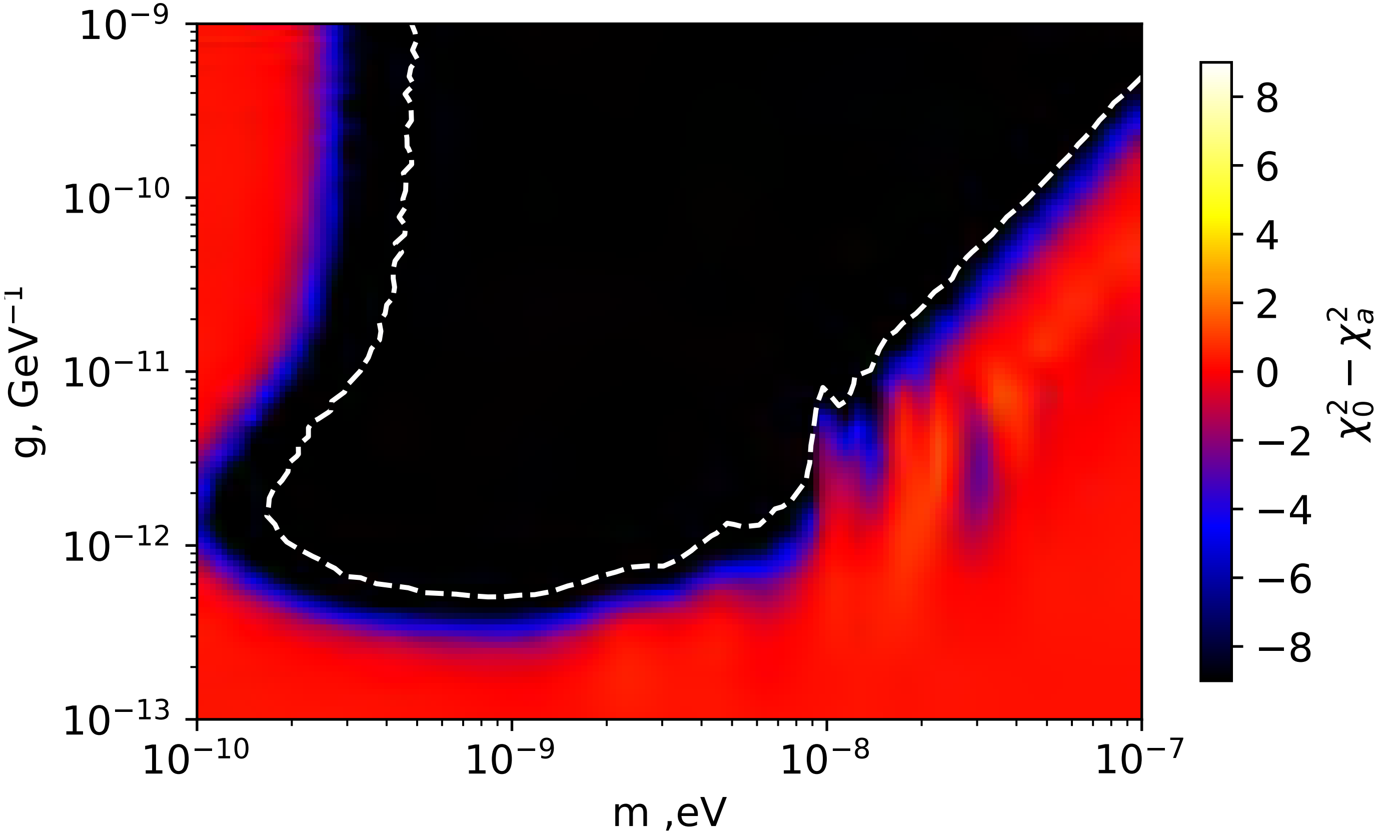
$$g_a = 4 \cdot 10^{-12}\,\text{GeV}^{-1}$$

$$m_a = 9.6 \cdot 10^{-9}\,\text{eV}$$

Combined **Fermi/LAT (red)** and **MAGIC (blue)** spectrum of NGC 1275

Malyshev et al., 2018

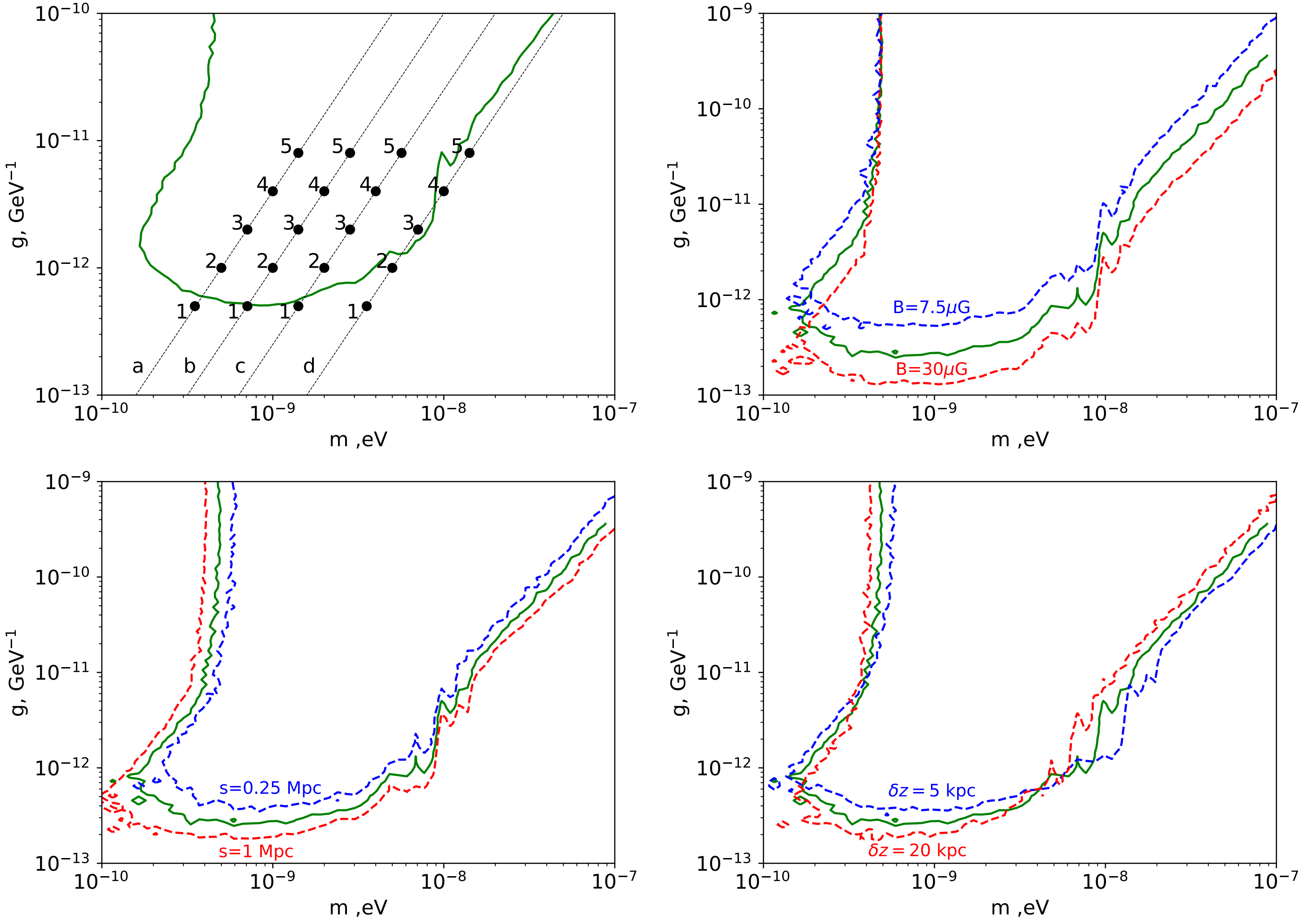
Results



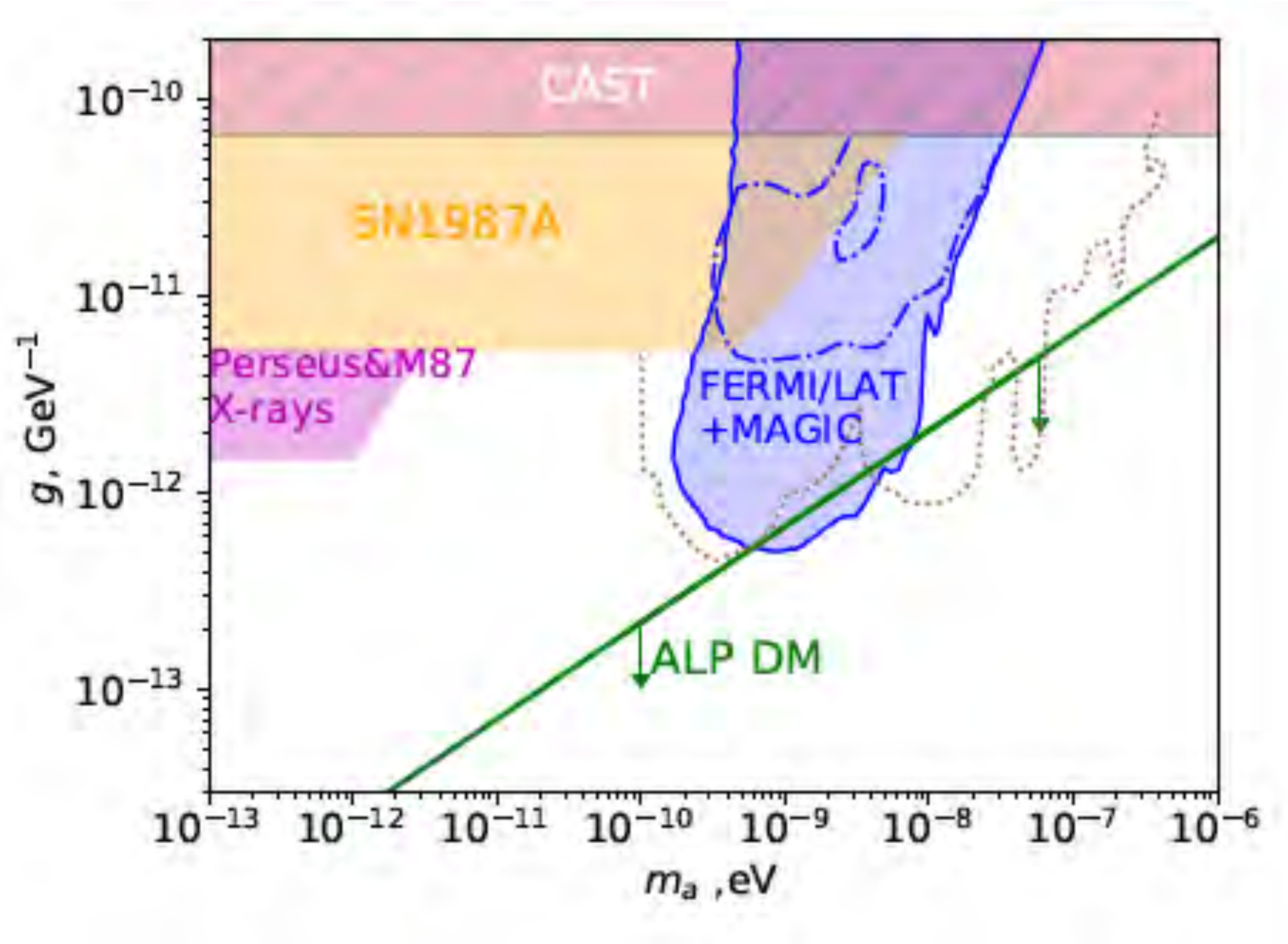
The map of median values χ_0^2-χ_a^2 distribution (over random realizations of the magnetic field) for different values of m_a, g_a.

The range for which photon-ALP conversion is incosistent with the data is delimited by the white dashed line.

Changing the parameter

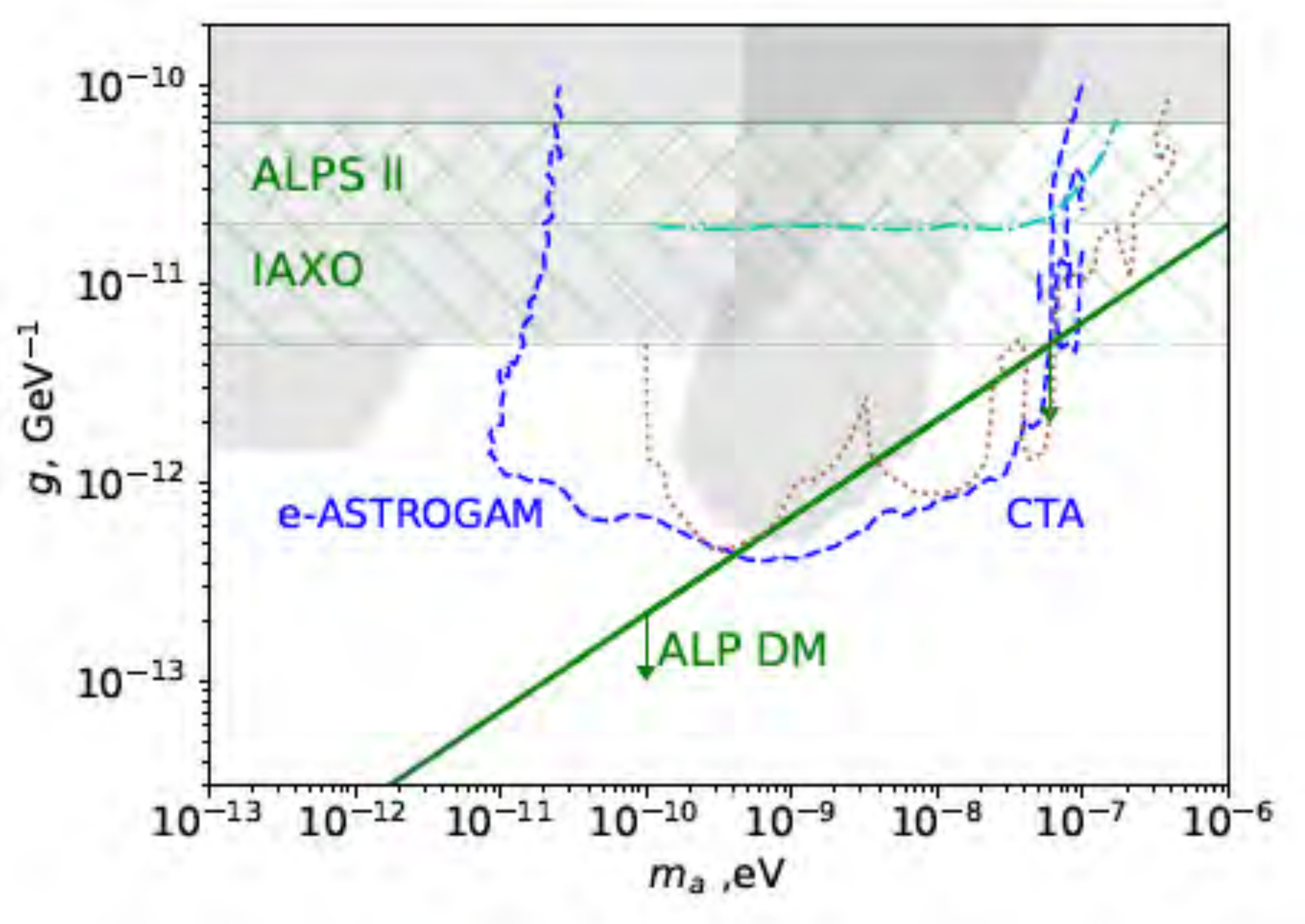


Limits (1)



Blu dot-dashed line: previous Fermi analysis *(Ajello et al., 2016)*
Brown dotted line: photon-ALP conversion effects could increase transparency of the Universe to TeV photons *(Meyer et al., 2013)*

Limits (2)



Cyan dash-dotted: CTA measurements on the transparency at TeV energies
Dashed blue line: Perseus cluster observations with e-Astrogam, Fermi (or HERD) and CTA

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Part IIc

Testing QED

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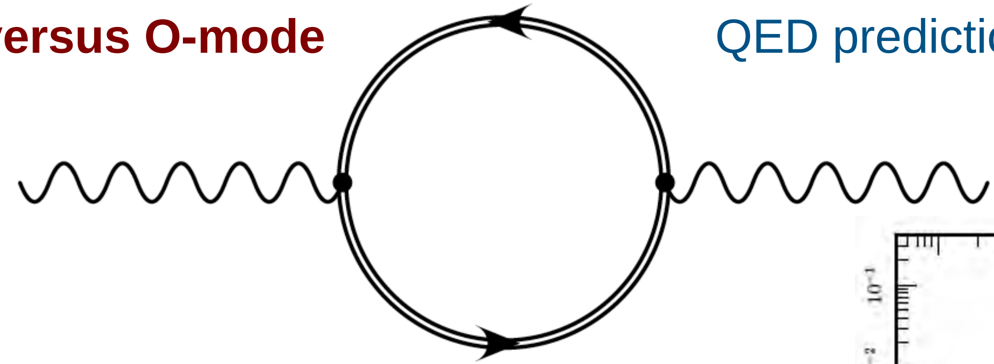
Physics: QED effects

X- versus O-mode

QED predictions: Birefringence of the vacuum

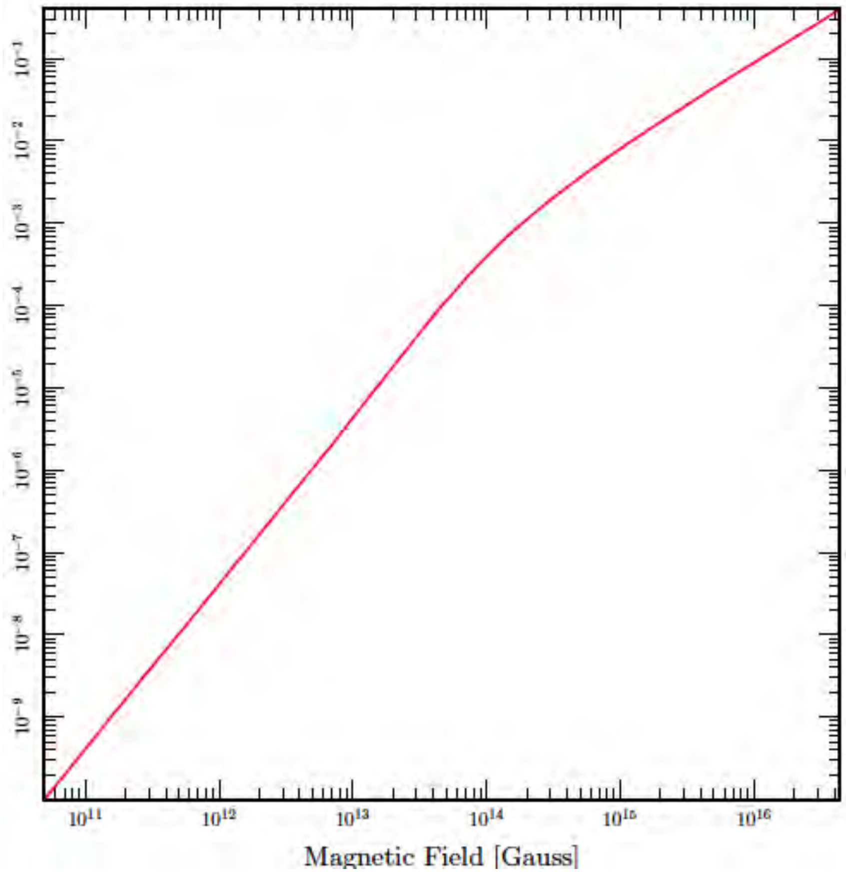


$$n_\perp - n_\parallel = \frac{\alpha_{\rm QED}}{30\pi}\left(\frac{B}{B_{\rm QED}}\right)^2 \sin^2\theta$$

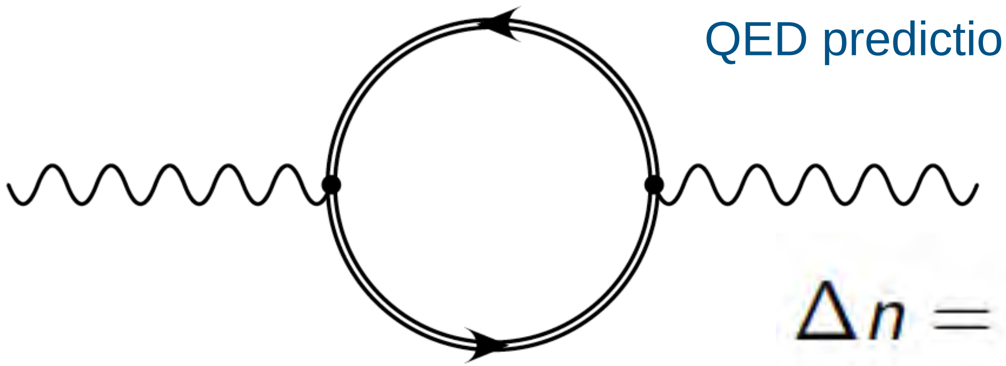
index of refraction between photons polarized in the O-mode and in the X-mode

$$\Delta n = 4 \times 10^{-24}\mathrm{T}^{-2}B^2$$

Interaction of light with magnetised vacuum



Physics: QED effects



QED predictions: Birefringence of the vacuum

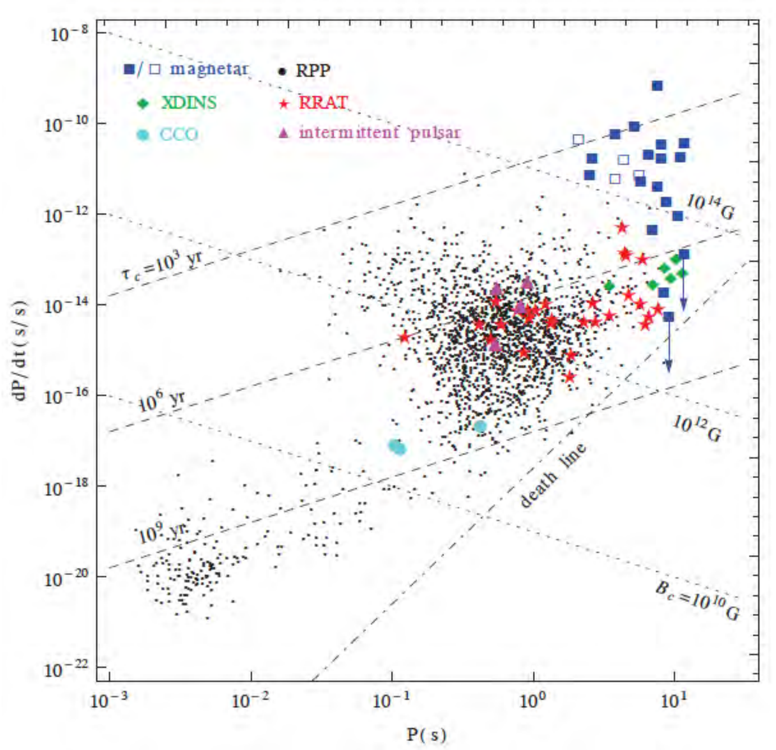
$$\Delta n = 4 \times 10^{-24}\mathrm{T}^{-2} B^2$$

For a strong enough B, **the polarization modes are decoupled, and the polarization direction follows the direction of the magnetic field.**
The radius at which the polarization stops following the magnetic field is called the polarization-limiting radius

$$r_{\rm pl} \sim 1.2 \times 10^7 \left(\frac{\mu}{10^{30}\ \mathrm{Gcm}^3}\right)\left(\frac{\nu}{10^{17}\ \mathrm{Hz}}\right)^{1/5} (\sin\theta)^{2/5}\ \mathrm{cm}$$

Sources: where to test QED effects?

- **Only neutron stars probably worth to be “key” targets**
- **BH or binaries that can be observed anyway**



Neutron Stars:

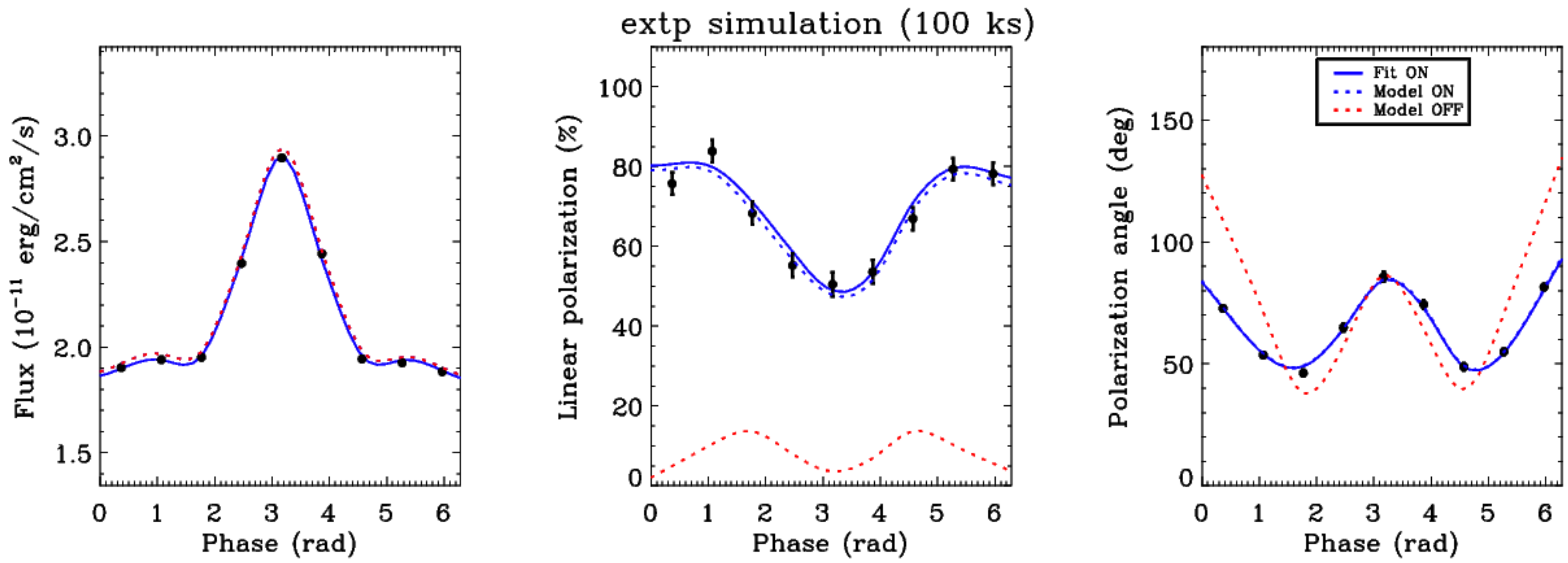
- Persistent thermal emission **magnetars** and others
- Magnetospheric emission: **magnetars**
- Outburst peak/ decay: **magnetars**

Magnetars hosts neutron stars with magnetic fields of $10^{13\text{-}15}$ Gauss

First evidence in optical by Mignani et al., (2017) on X-ray dim INS.

Magnetars persistent emission (2)

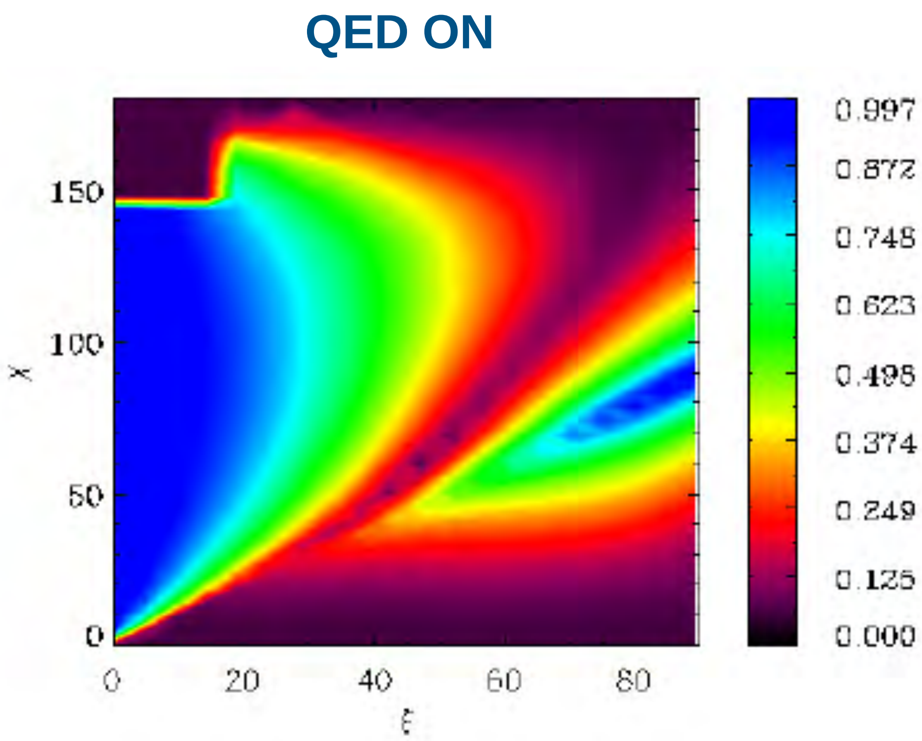
Non-Thermal emission: twisted magnetosphere model

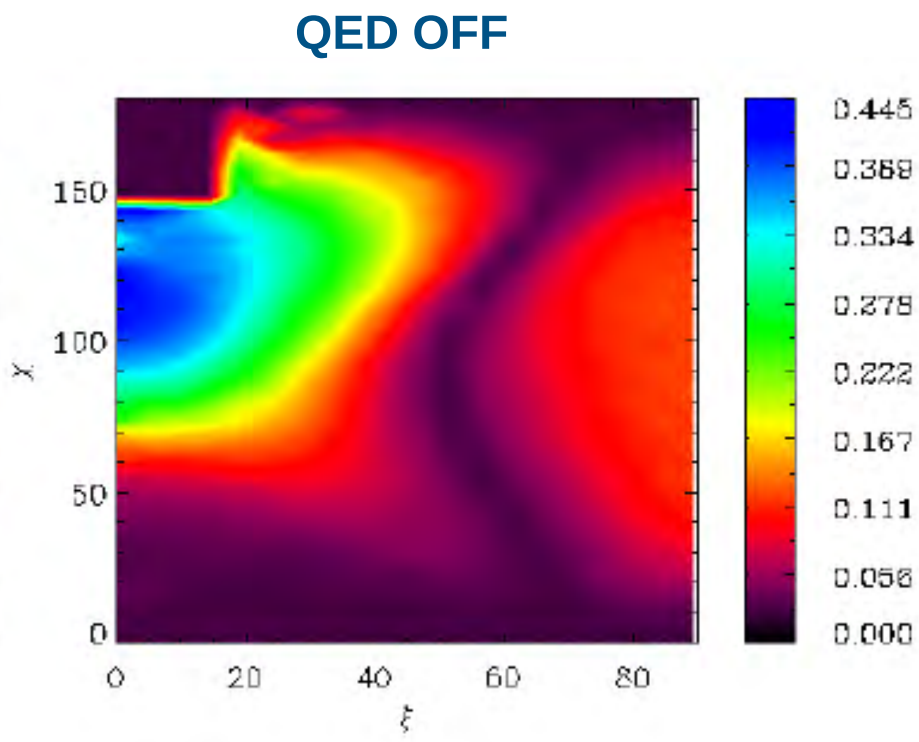


100 ks on AXP 1RXS J170849.0-400910

Angles:
ξ=90° between the magnetic axis and spin axis
χ =60°between the line of sight and spin axis

Different Geometries





Expected **phase averaged polarization fraction** for different values of the **angles ξ and χ**, assuming thermal emission, B =10^{14} G, for the two cases of QED on and QED off. Emission from one hot polar cap covering ~15% of the NS surface.

Thermal emission

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Conclusions

- The next generation of X-ray (and in general high energy observatories) will tackle a robust program of fundamental physics.

- The Equation of state of ultradense matter will, most likely be discovered, as well the properties of the dark matter particle. This was discussed here.

- However -not discussed here- test of Birefringence in magnetized vacuum and the test on the motion of matter in strong gravity around Black Holes will be also tested (core case of eXTP, Strobe-X…)

- The future of high energy astrophysics is bright: a new generation of X-rays (or high energy satellites) will be launched soon or is in preparation…

Stay Tuned for surprises!

Thank you.

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