ALBA

# On the Benefits of Small Emittance

## An X-ray Experimentalist Perspective

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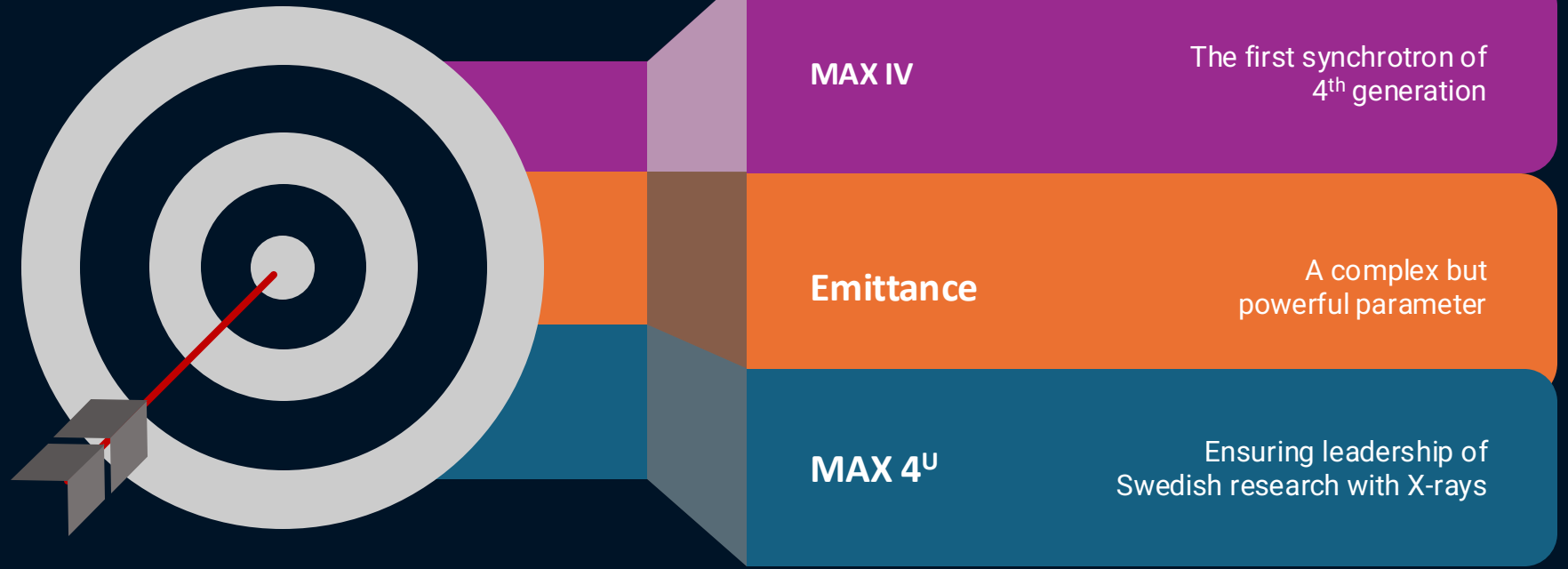
NOVEMBER 2024

MAX IV

# Outline / Goals



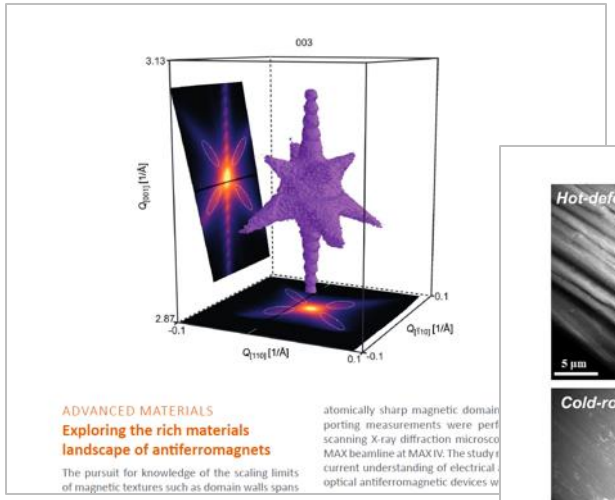
# This is MAX IV

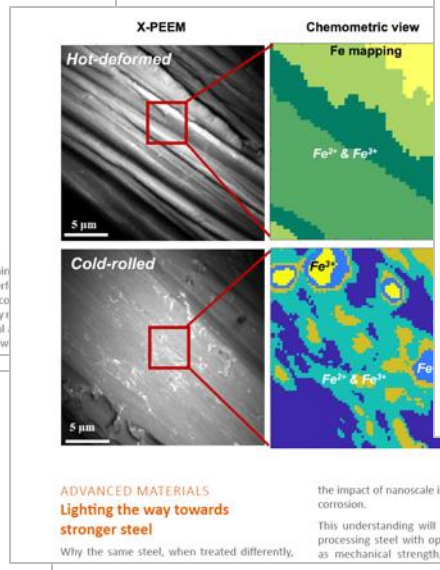
- The world's first 4th-generation light source
- 16 beamlines in user operation

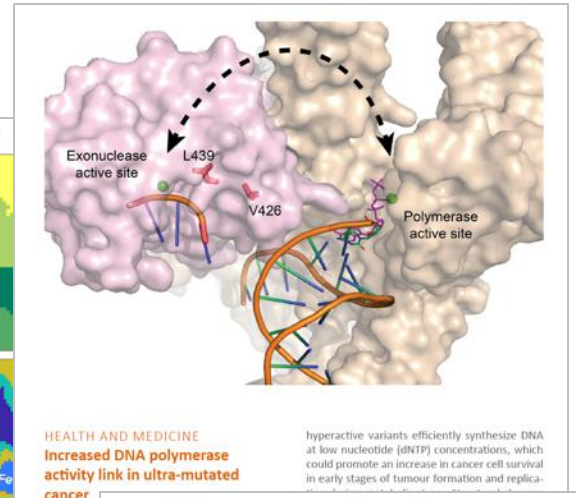
- **MAX IV in numbers** (in 2023)
  - 1700 users
    - principally from the nordic and baltic region
    - from 280 research institutions
    - across 34 countries
  - ~40000 beamtime hours available for user projects
  - 5000 hours of user scientific projects connected with industry

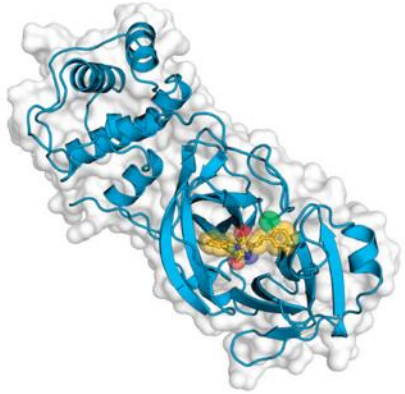

# Science Highlights

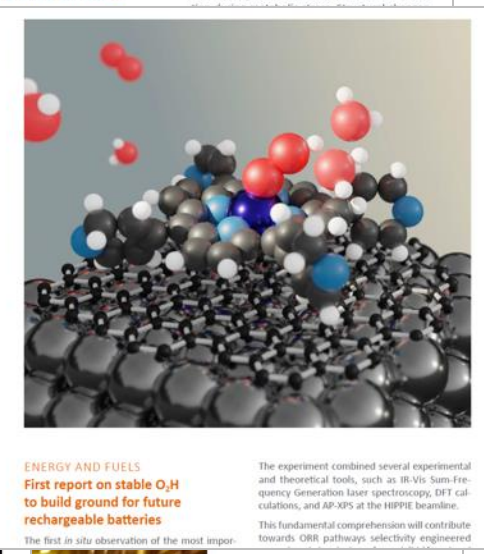
Download our
Science Highlights

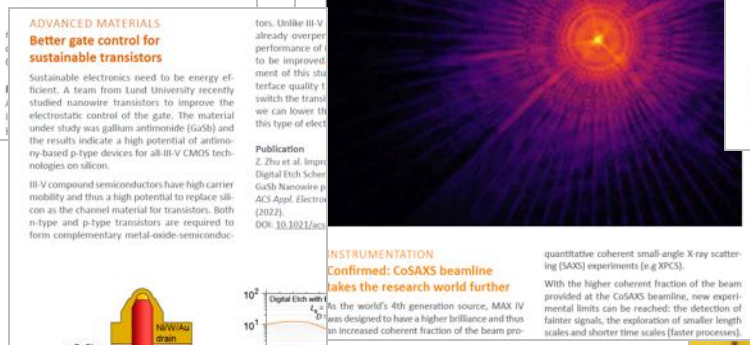






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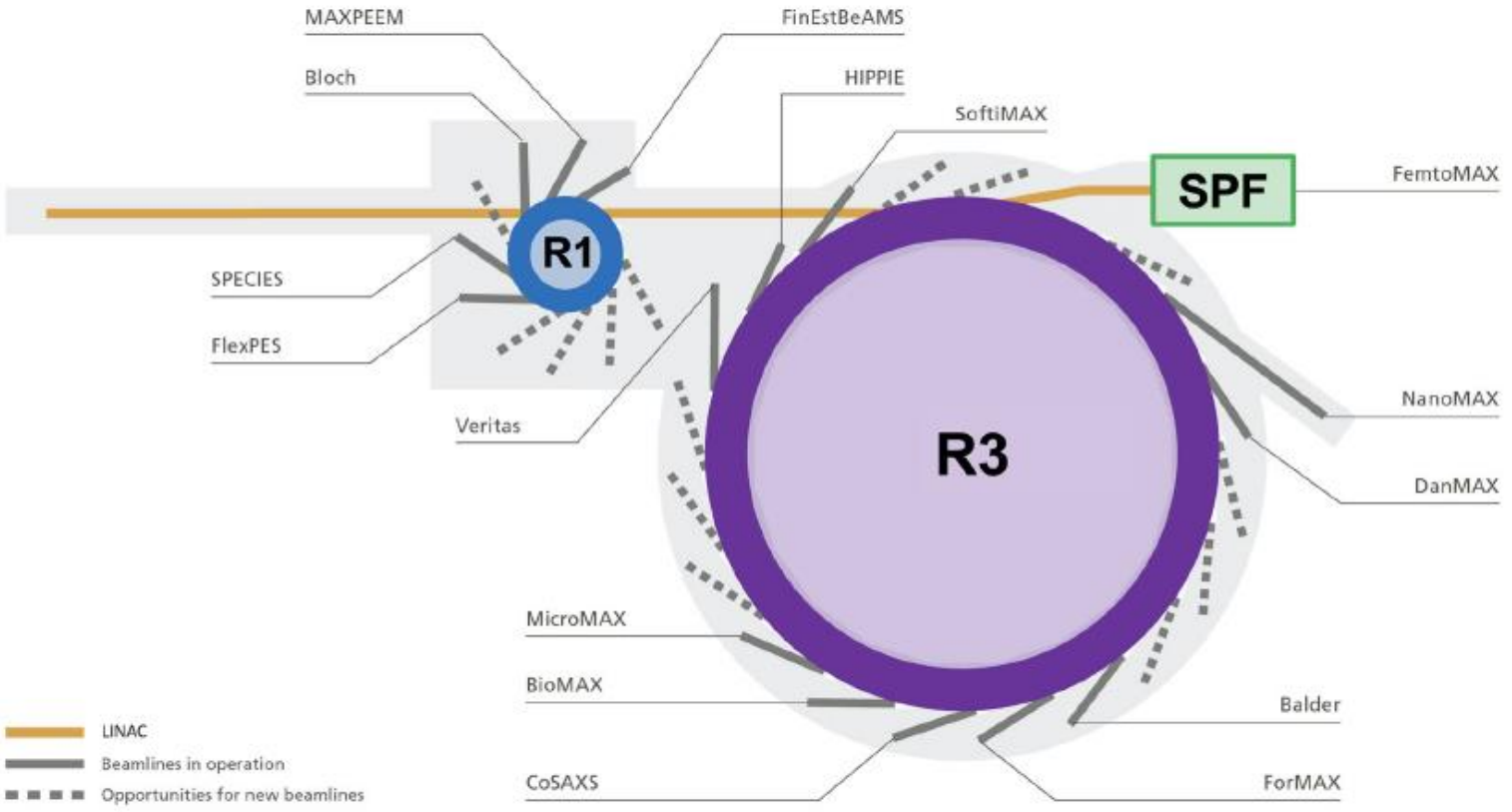
# This is MAX IV !

## 3 Accelerators

**Linac** – Linear Accelerator
**R1** - 1.5GeV storage ring
**R3** - 3GeV storage ring

www.maxiv.lu.se



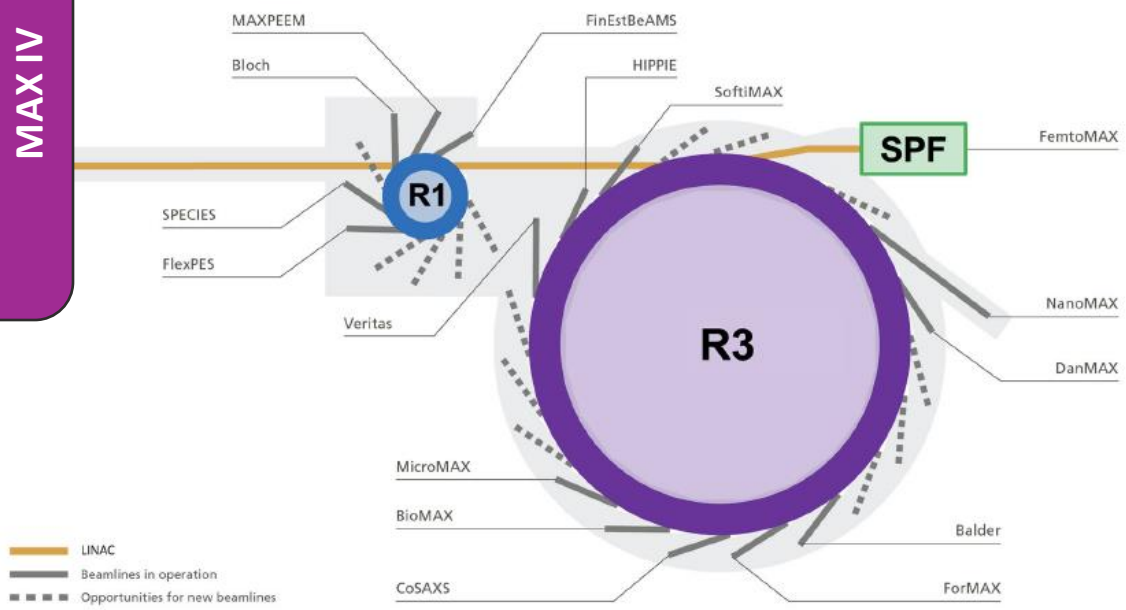

# 16 Beamlines in operation

**Opportunities for 10-14 new BLs**

A. Robert *et al.*, "MAX IV Laboratory", *Eur. Phys. J. Plus* **138**, 495 (2023).

MAX IV

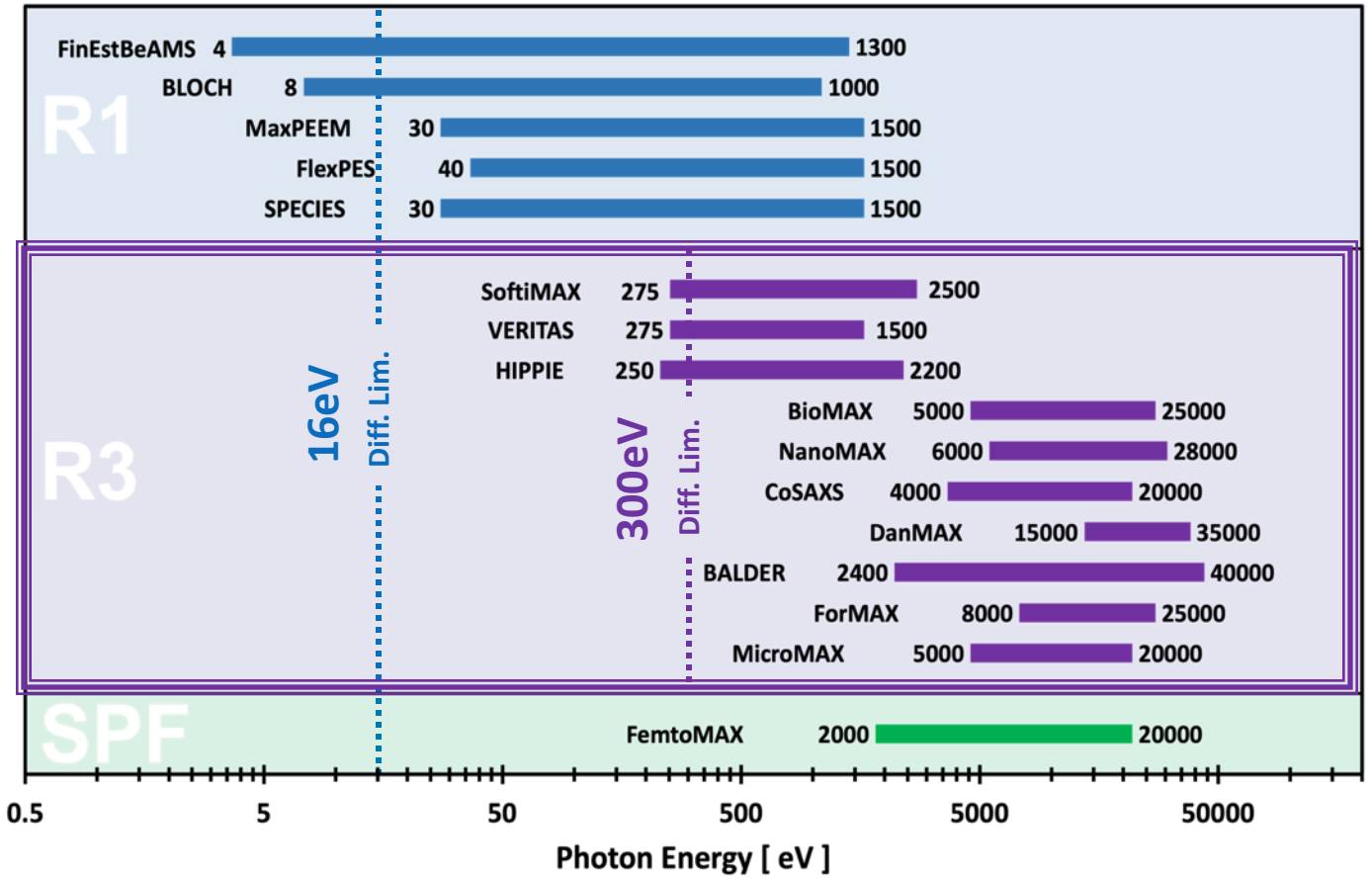
# Beamline Portfolio




**16 beamlines in operation covering a broad X-ray energy range from 4 eV to 40 keV**

**3GeV storage ring**

**The first 4th gen. synchrotron source with a 328 pmrad emittance**




A. Robert *et al., Eur. Phys. J. Plus* ***138,*** *495 (2023)*

# Accelerators

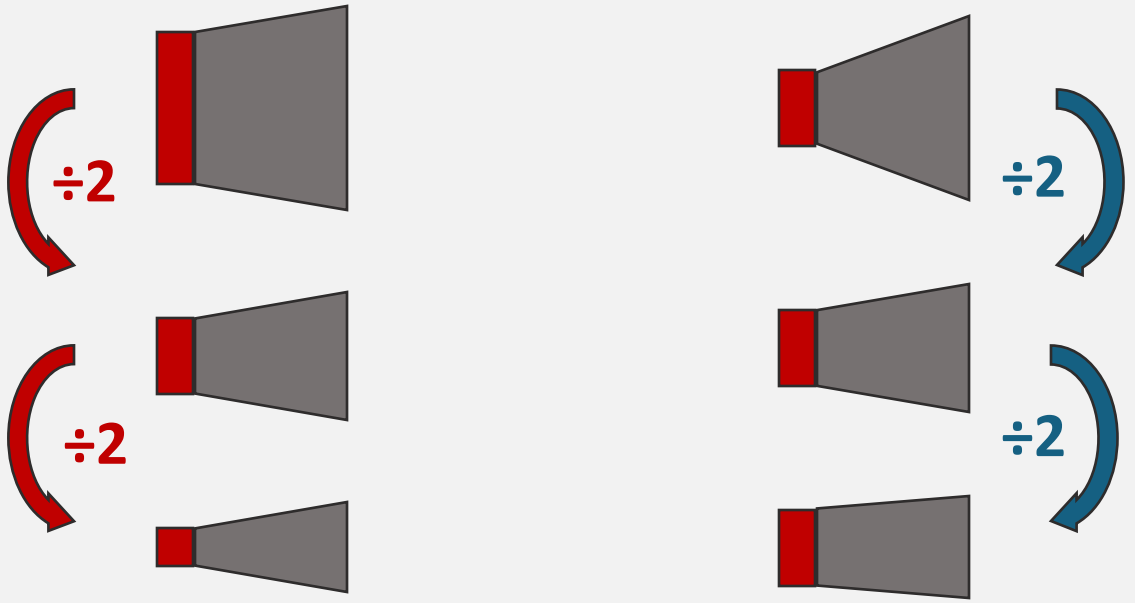
- **R1** - E=1.5 GeV Storage Ring
  - **C = 96m**
  - **$\varepsilon_x \sim 6$ nmrad, $\varepsilon_y \sim 60$ pmrad**
  - Diffraction-limited X-rays at 16 eV
  - World-leading source of soft X-rays

- **R3** - E=3 GeV Storage Ring
  - **C = 528m**
  - **$\varepsilon_x \sim 330$ pmrad, $\varepsilon_y \sim 8$ pmrad**
  - Diffraction-limited X-rays at 300eV
  - First 4th generation storage ring

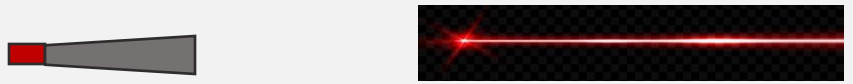
## Emittance $\varepsilon_{H,V}$ in [pm rad]

**Source Size [micro-meter]** × **Angular Size [micro-radian]**

$10^{-6}$ m × $10^{-6}$ rad = $10^{-6} \times 10^{-6}$ m rad = $10^{-12}$ m rad = pm rad




**We want to minimize both size and divergence**



MAX IV

Emittance

# Accelerators

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- C = 100m , $\mathcal{E}\backsim$6 nmrad
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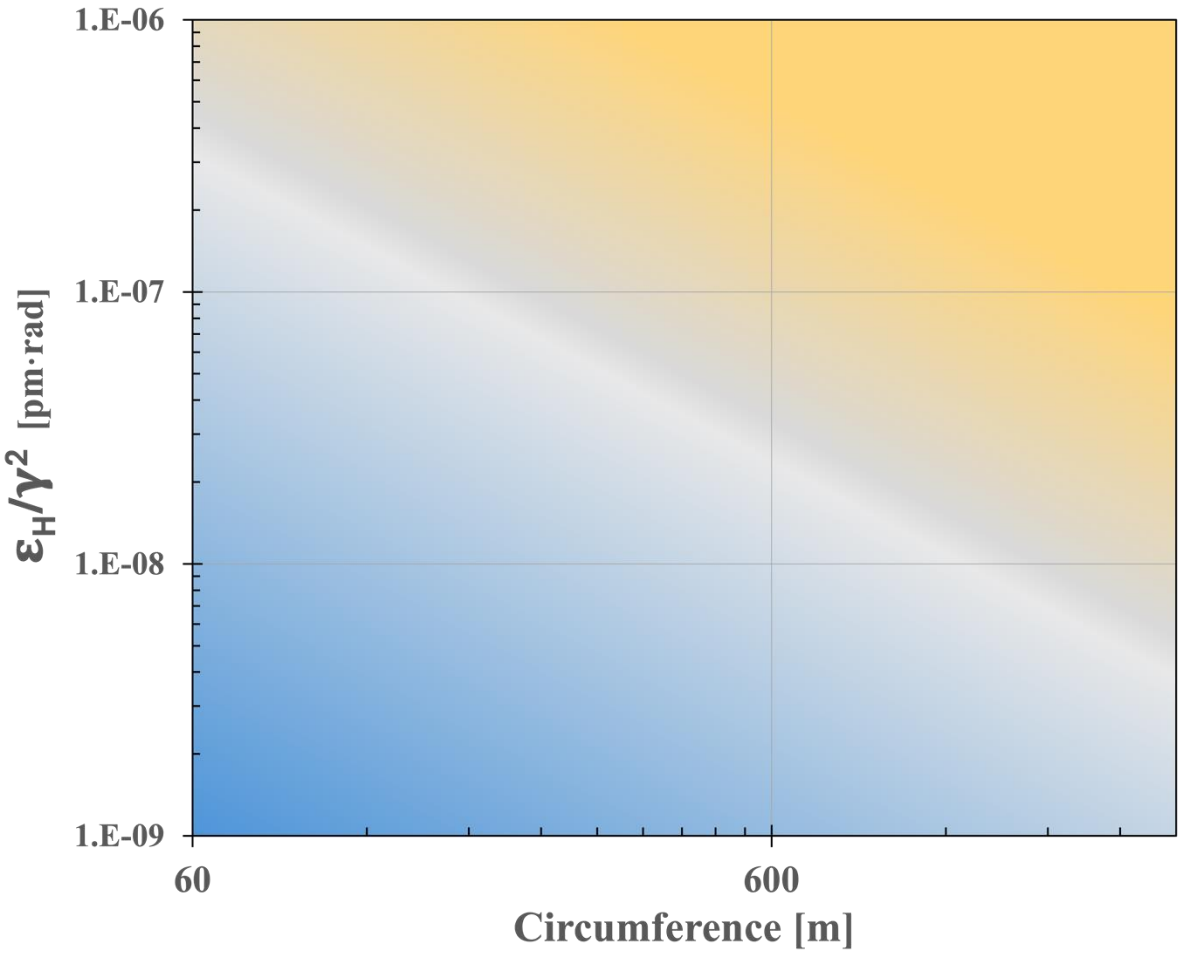

MAX IV

Emittance

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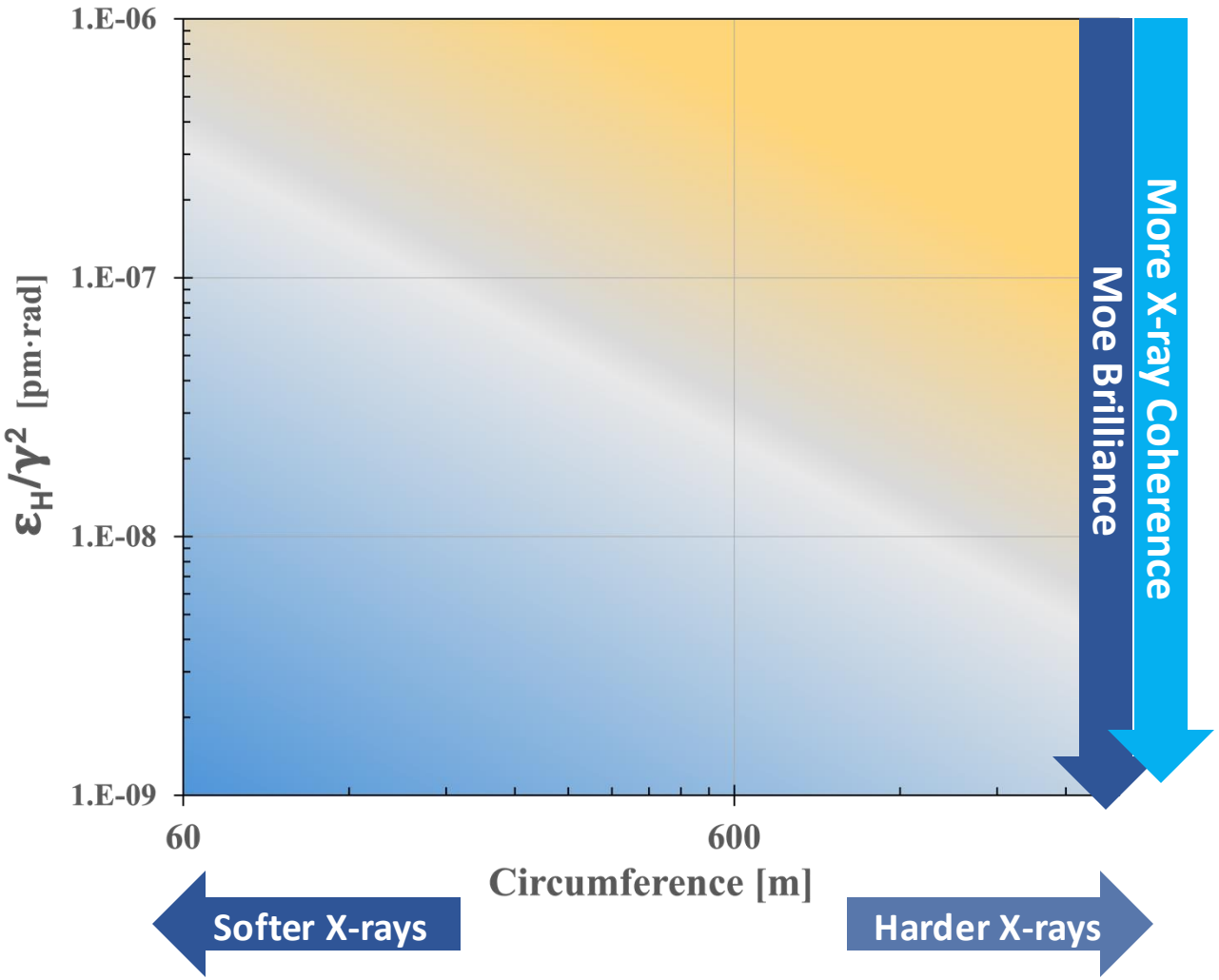

MAX IV

Emittance

# Accelerators

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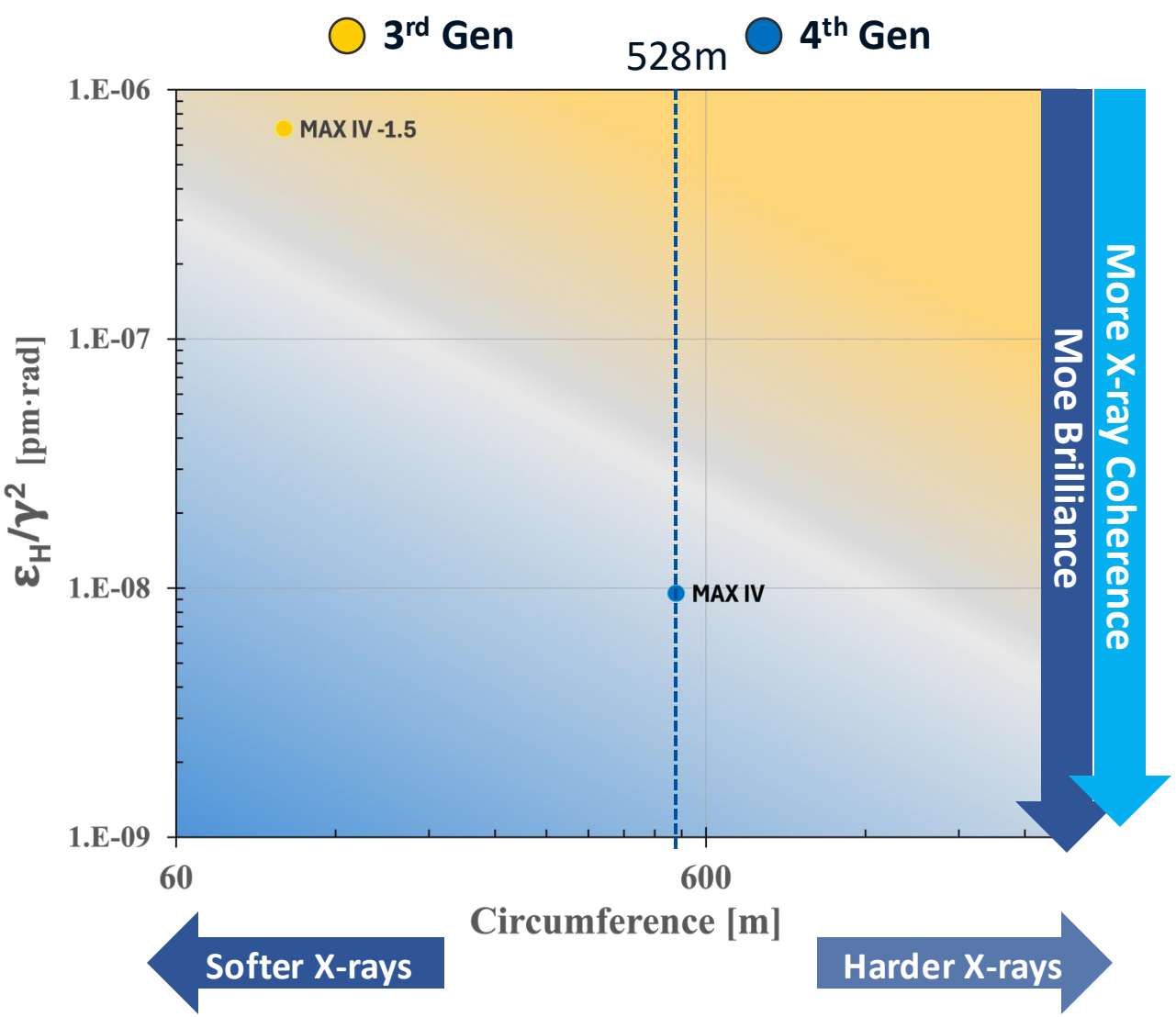

MAX IV

Emittance

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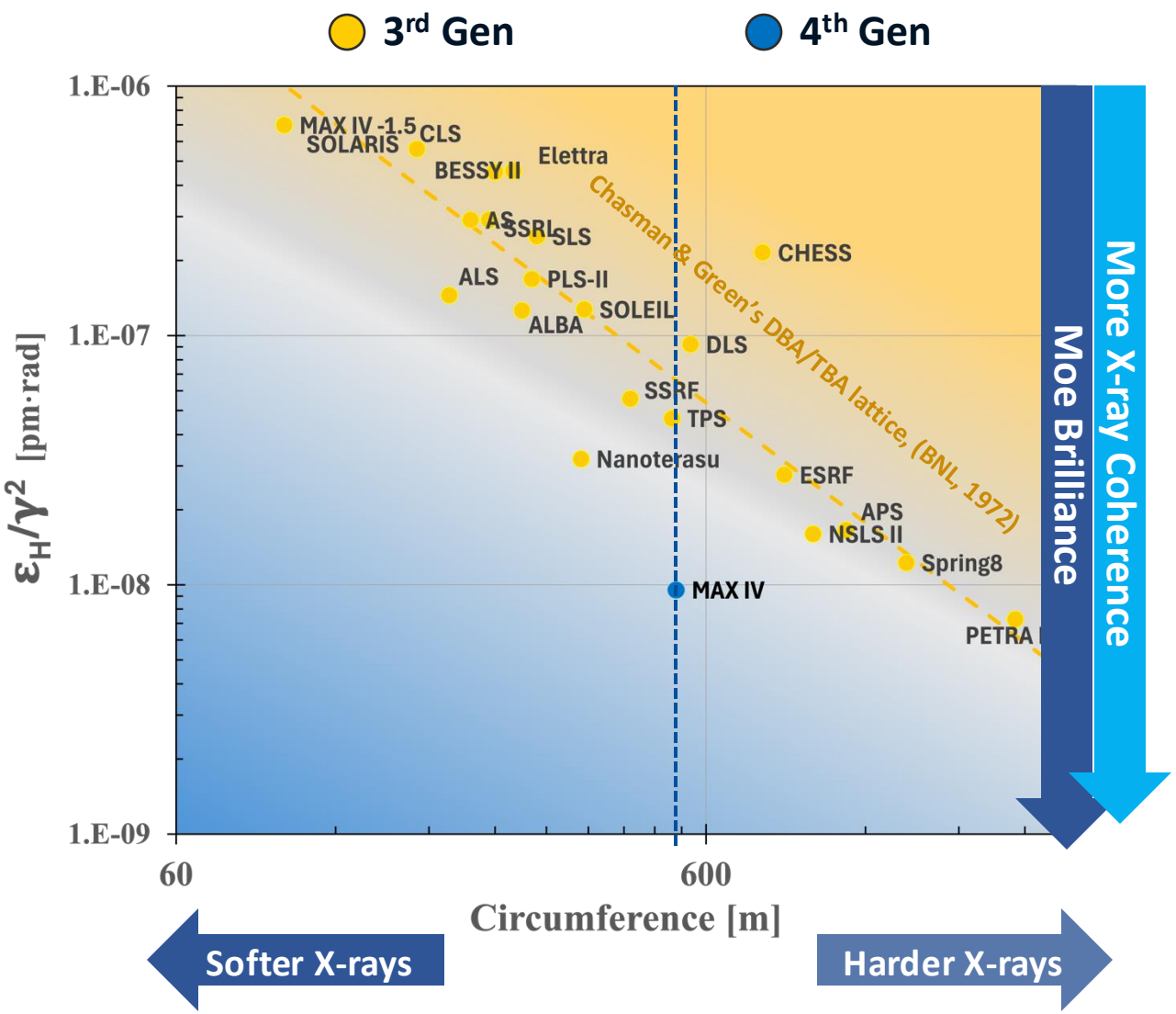


Before 2016

# Accelerators

MAX IV

Emittance

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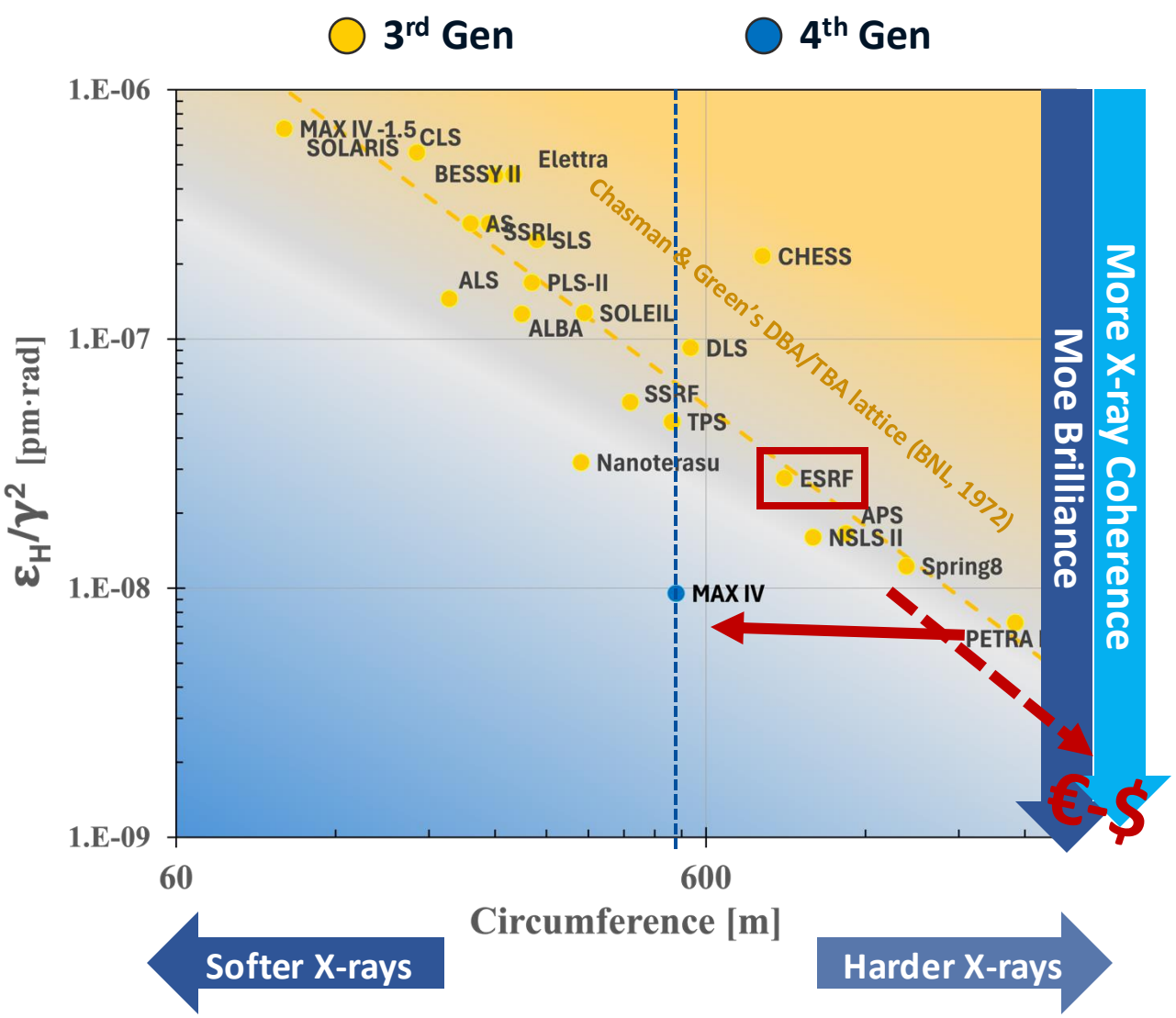



$$\varepsilon_H/\gamma^2 \propto \theta^3 \cdot F$$

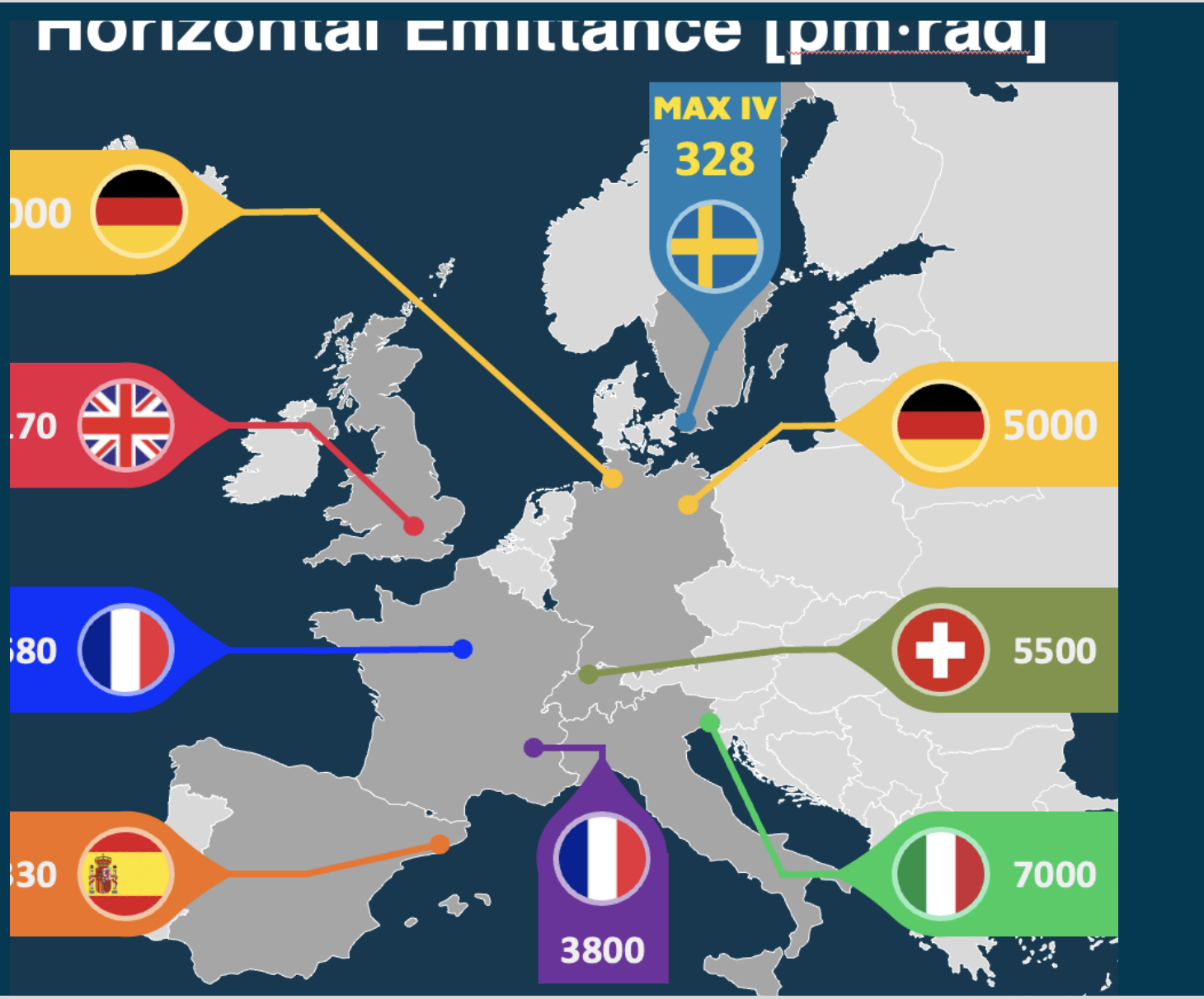

# MAX IV

*European context in 2016*

MAX IV

## MAX IV 3GeV Ring: The first 4th generation synchrotron Source

*Breaking down the emittance glass ceiling with world record emittance of 328pmrad*




**A factor 3 to 20 better than a ALL ghtsources**

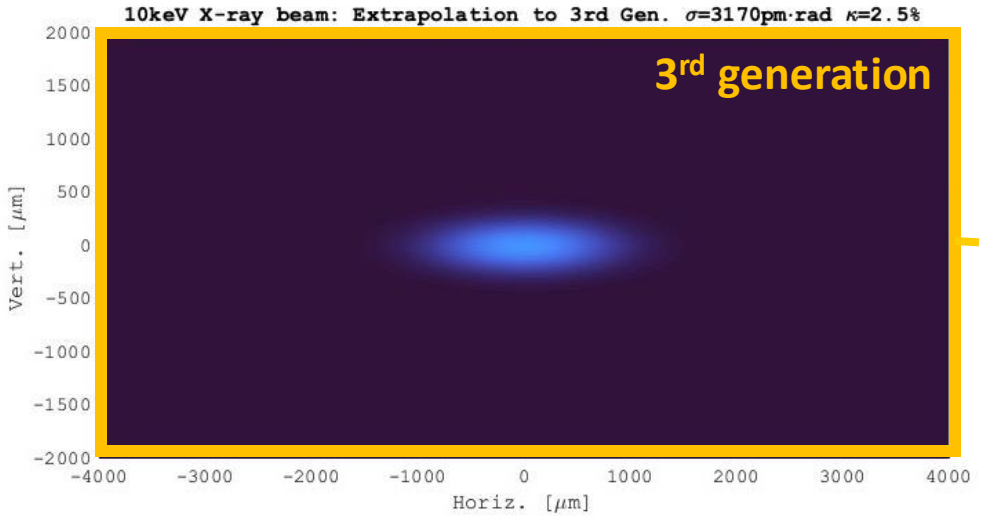
# Accelerators

MAX IV

Emittance

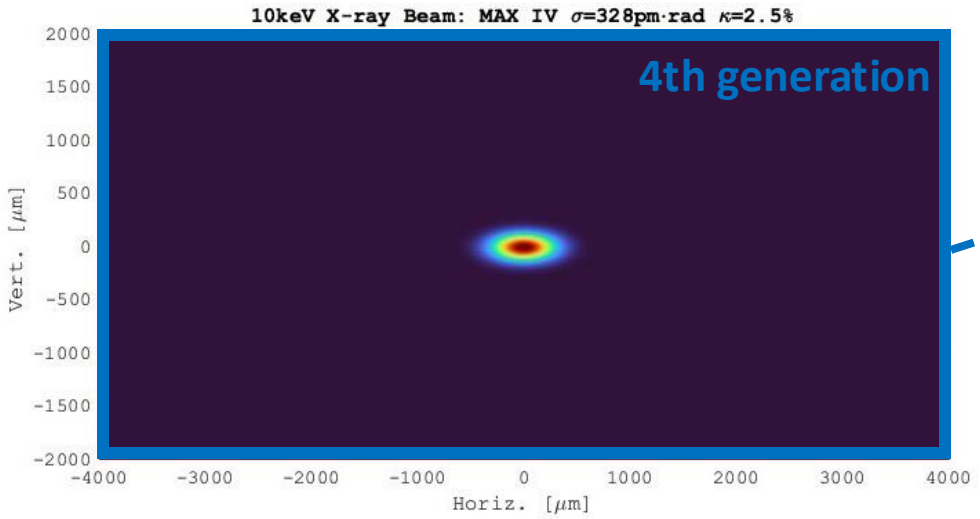
1.5

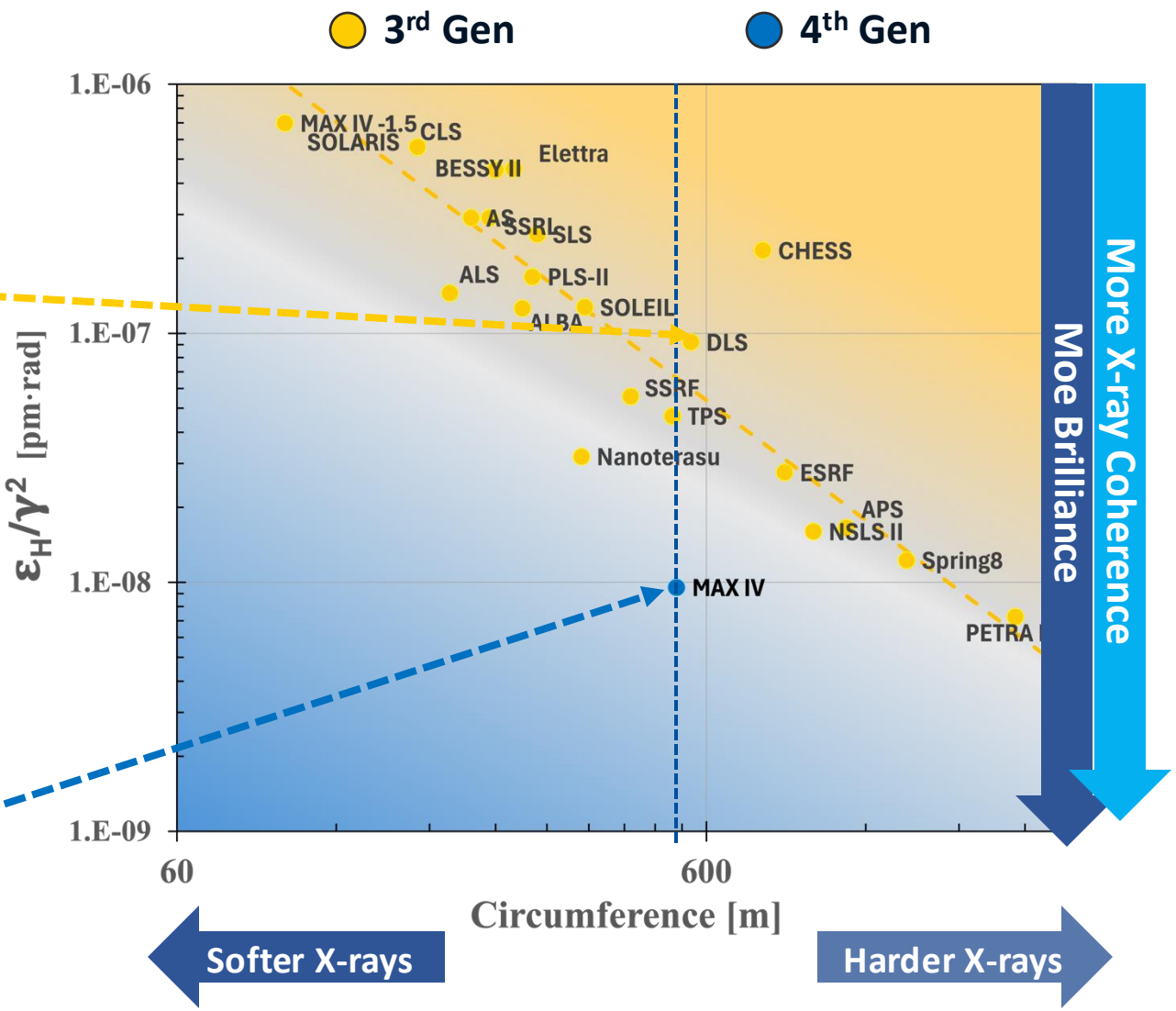
- 
- 
- 




3 G

- 
- 
- 




*10 keV beam profile 20 meters from the source, same scale*

**In 2016**

# Accelerators

MAX IV

Emittance

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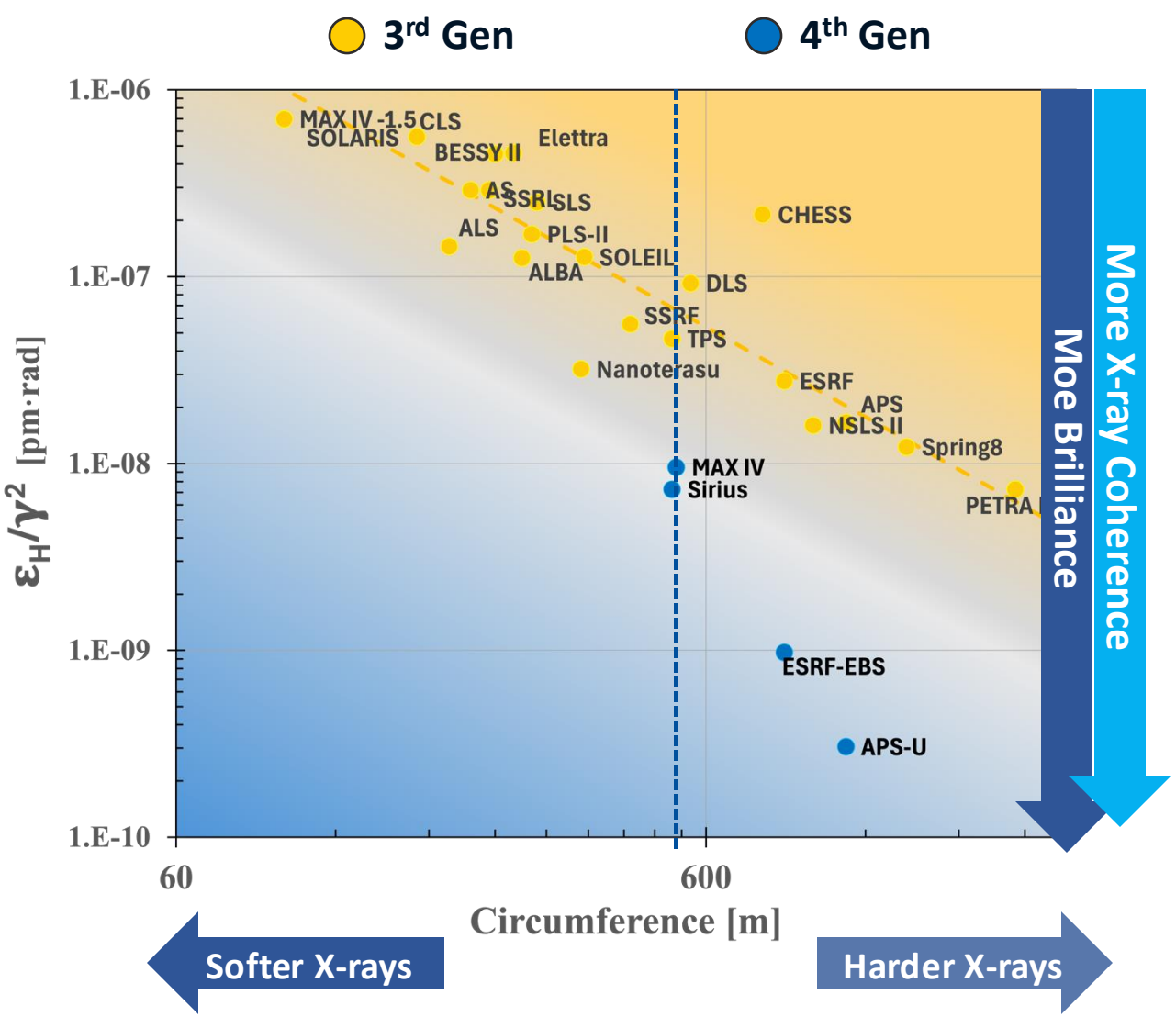
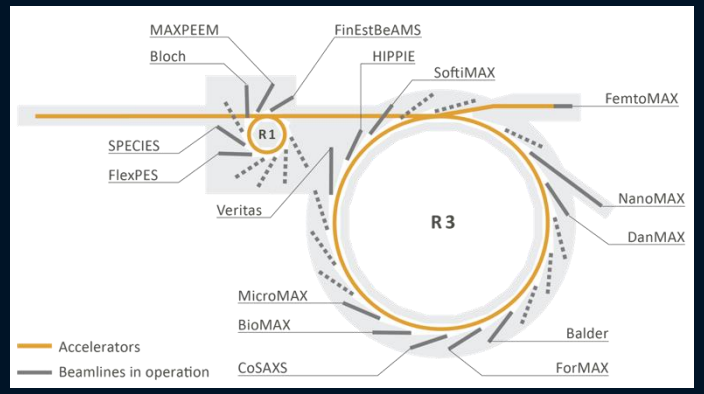



Today

MAX §


MAXPEEM
Bloch
FinEstBeAMS
HIPPIE
SoftiMAX
FemtoMAX
SPECIES
FlexPES
R1
Veritas
R3
NanoMAX
DanMAX
MicroMAX
BioMAX
Balder
ForMAX
CoSAXS
Accelerators
Beamlines in operation

MAX IV


Future
2019
2020
2023
2022
2018
2021
2024
2025

# Accelerators

MAX 4U

Emittance

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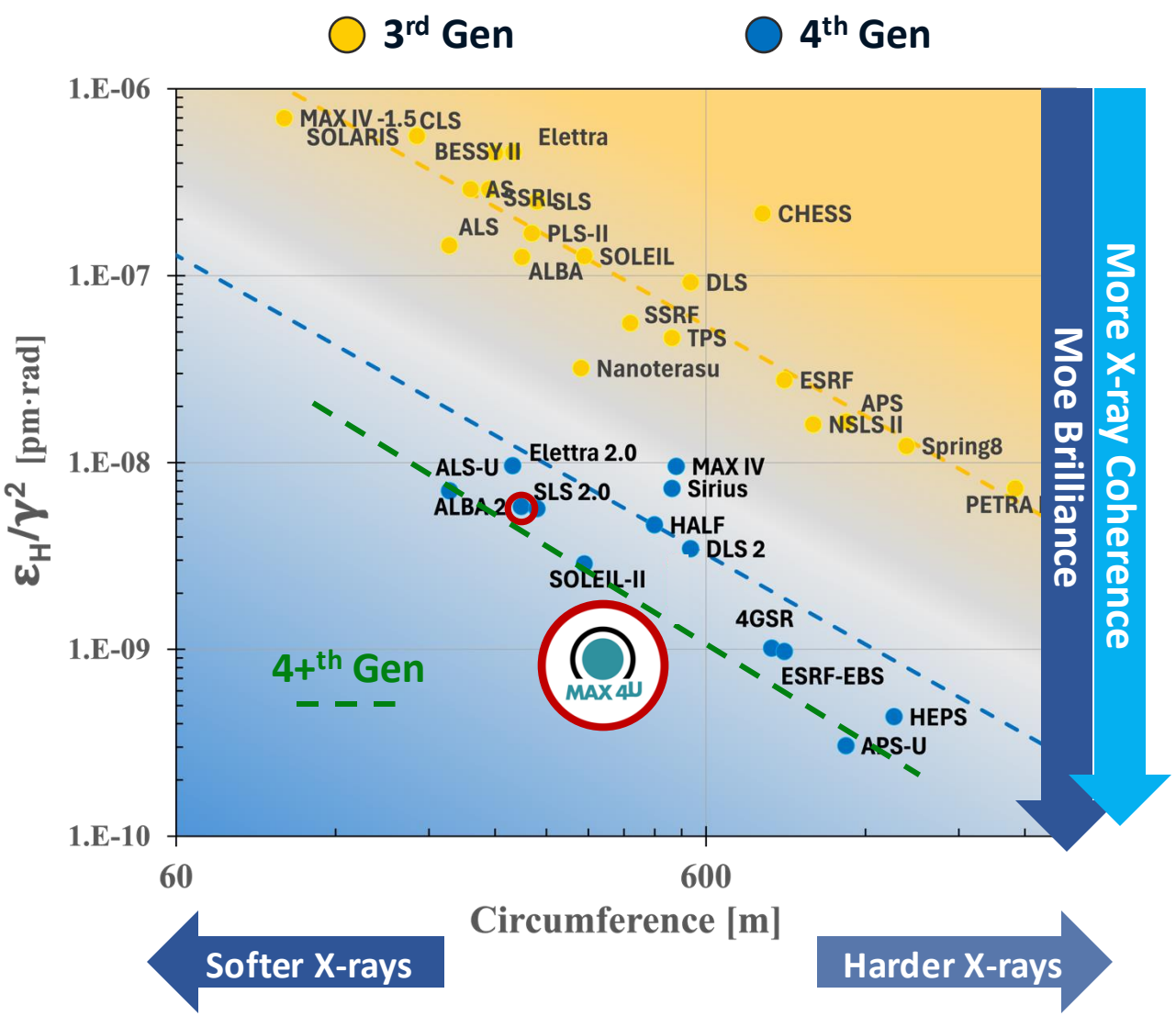



**Most 4th generation light sources will be fully operational by the end of the decade**

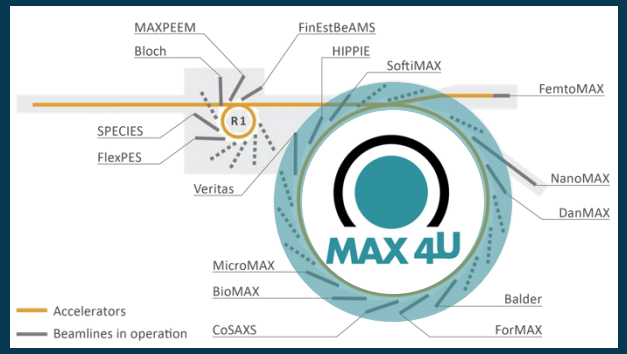
**Toward early 2030 ⇒ MAX §**

# MAX § – A ”**surgical**” upgrade of our 3GeV ring

MAX §

**Ensuring leadership of Swedish research with X-rays for the next decades**

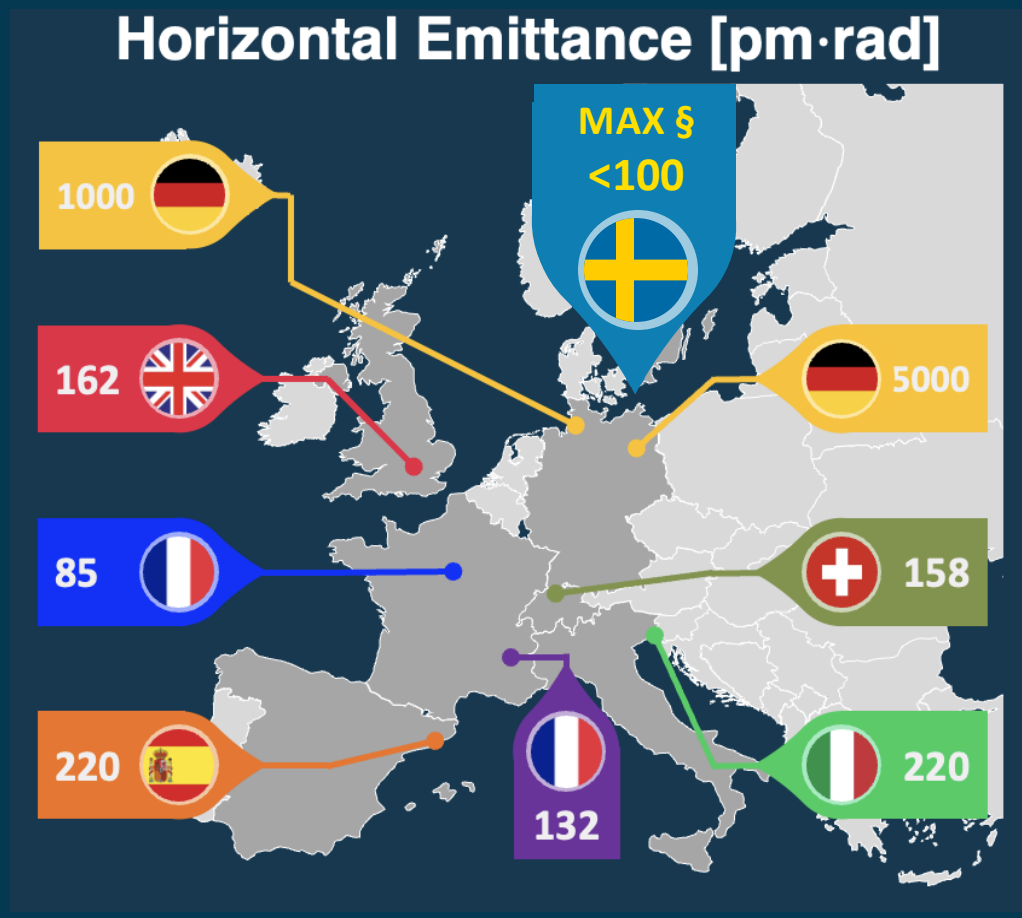
# MAX §




**Optics parameters for a candidate MAX § lattice**

| Parameter | Value |
|---|---|
| Energy | 3 GeV |
| Circumference | 528 m |
| Bare Lattice Emittance | **<100 pmrad** |



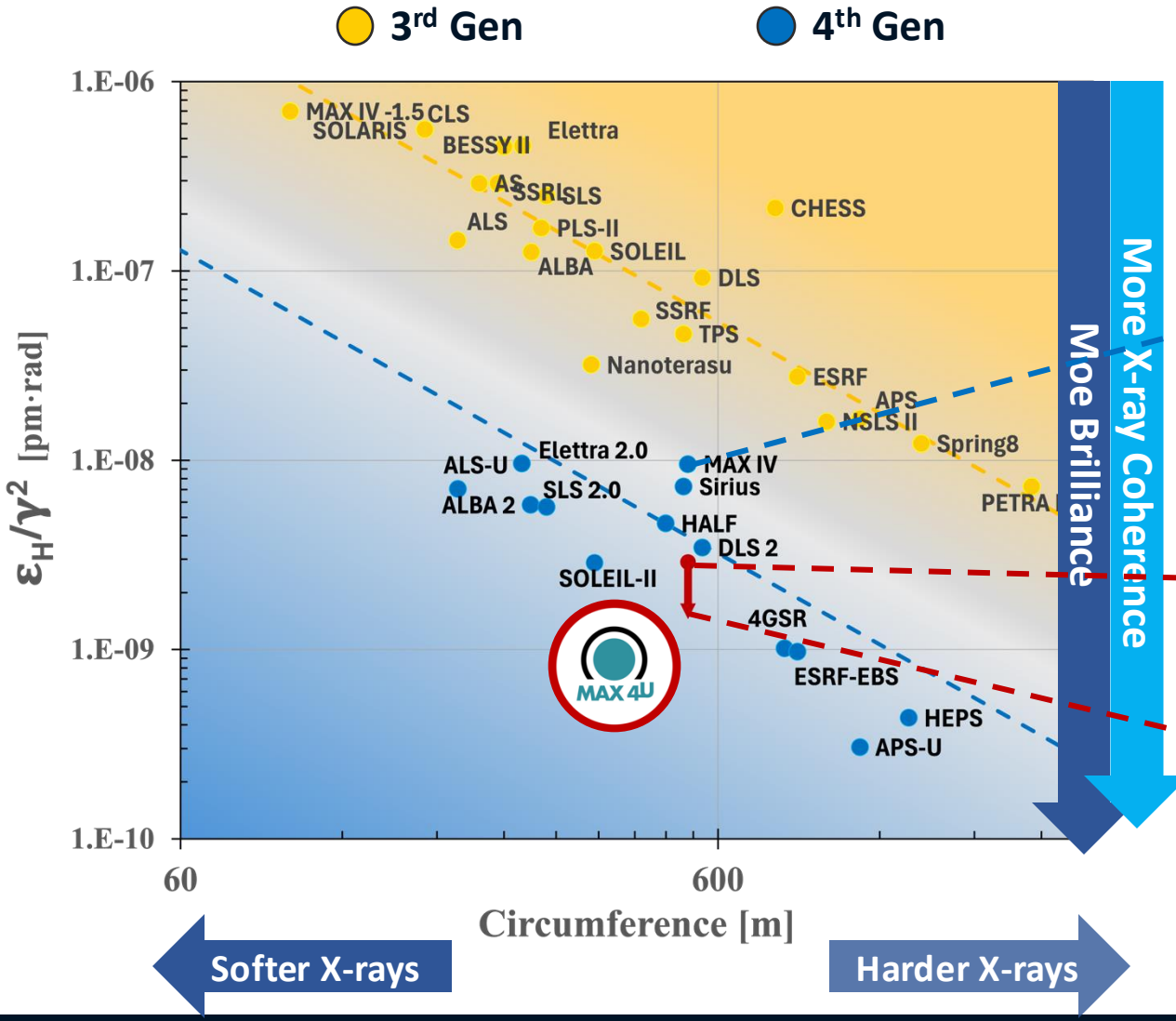


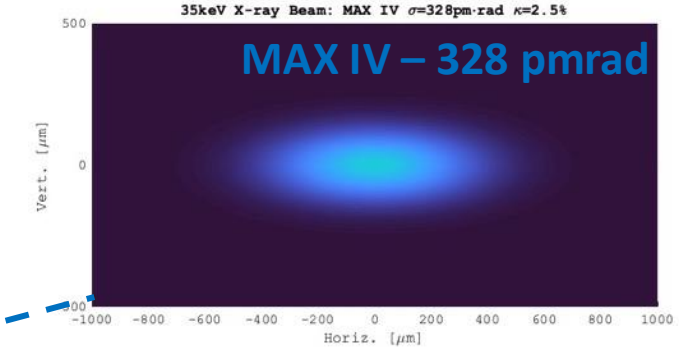
# Enough with e-, what about X-ray photons ?

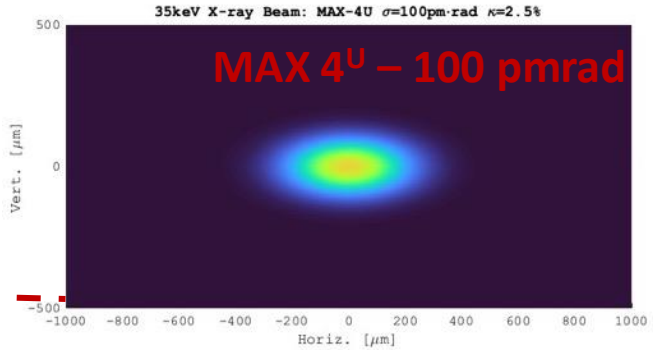
# What does it mean for X-ray beams ?

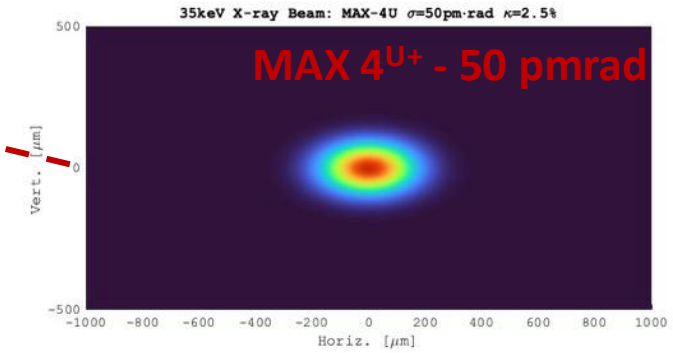
MAX 4U

Emittance



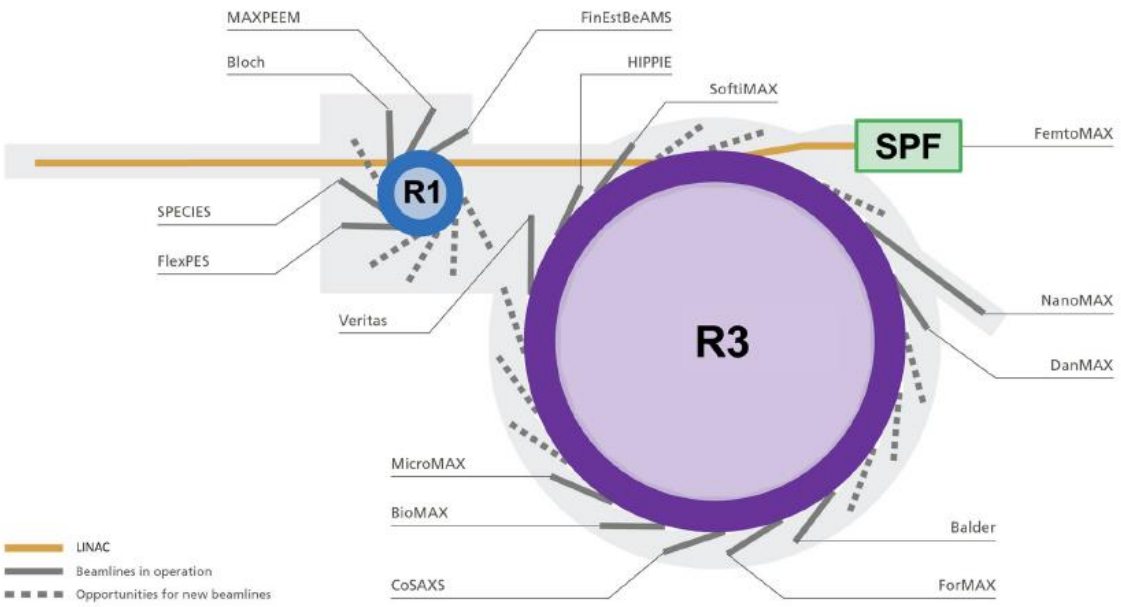



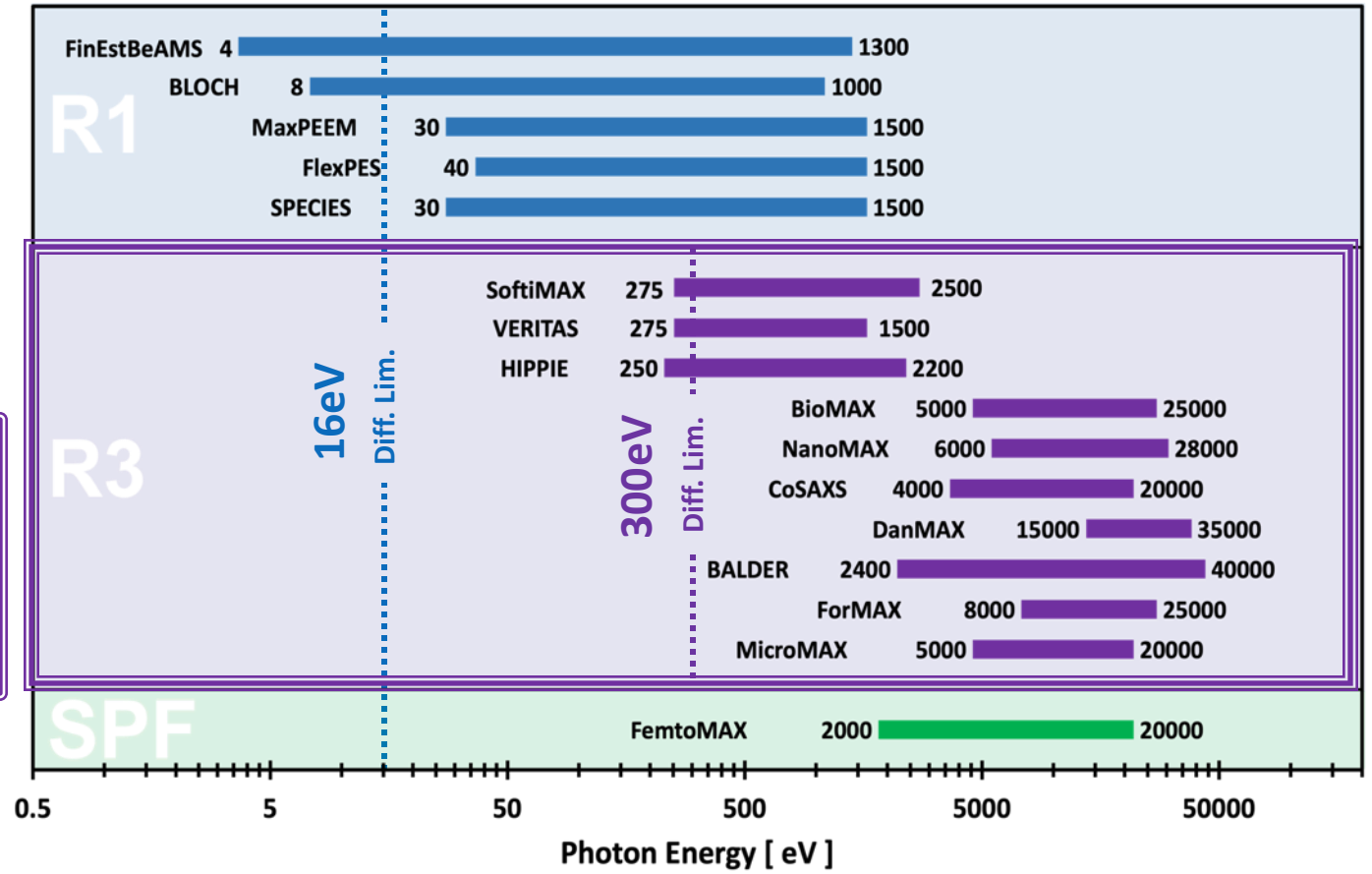

[20 m : 35keV]

# Beamline Portfolio




**16 beamlines in operation covering a broad X-ray energy range from 4 eV to 40 keV**

Opportunities for 10-14 more




## 3GeV ring

**The first 4th gen. synchrotron source** with a 328 pmrad emittance

A. Robert *et al., Eur. Phys. J. Plus* ***138,*** *495 (2023)*

# How will the X-ray beam change at the beamlines ?

MAX 4U

SoftiMAX
HIPPIE
Veritas

-HAXPES

CoSAXS
NanoMAX

-HAXPES

DanMAX

-Tomo

MAX IV

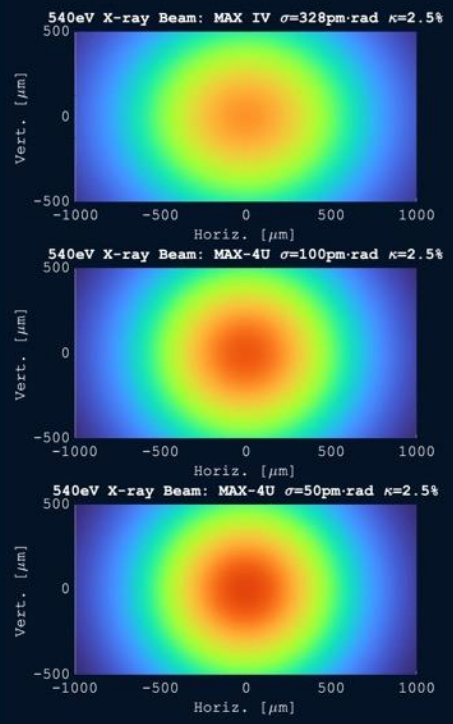
MAX 4U

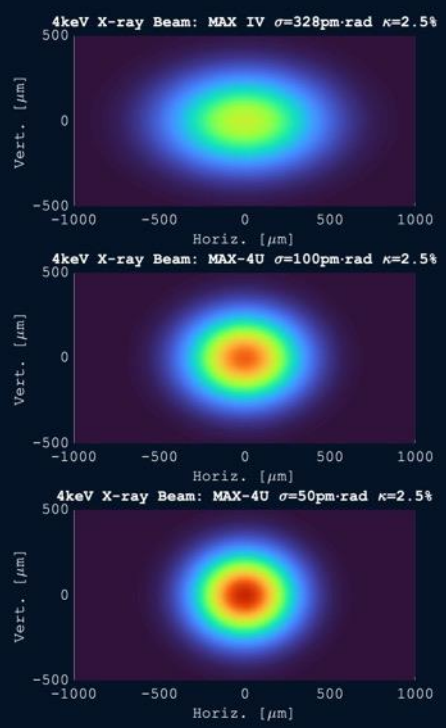
MAX 4U+

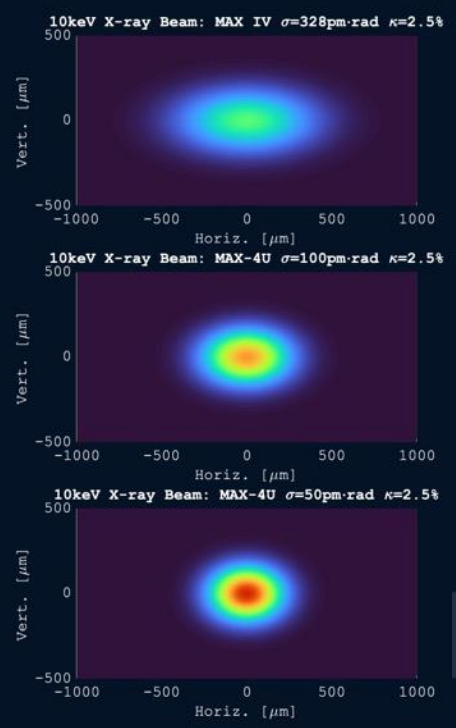
328 pmrad

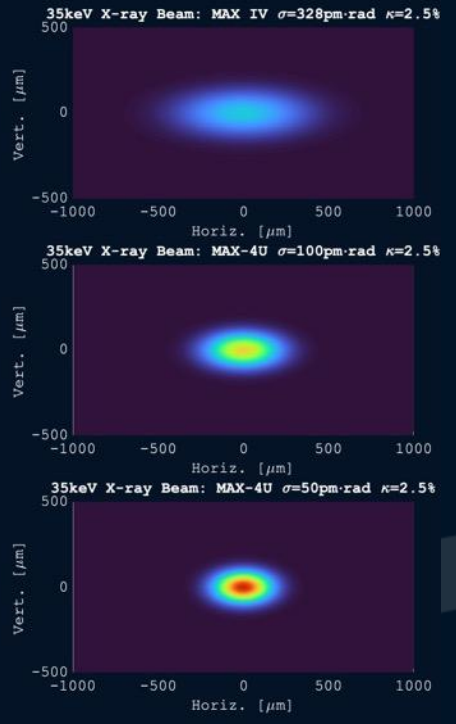
100 pmrad

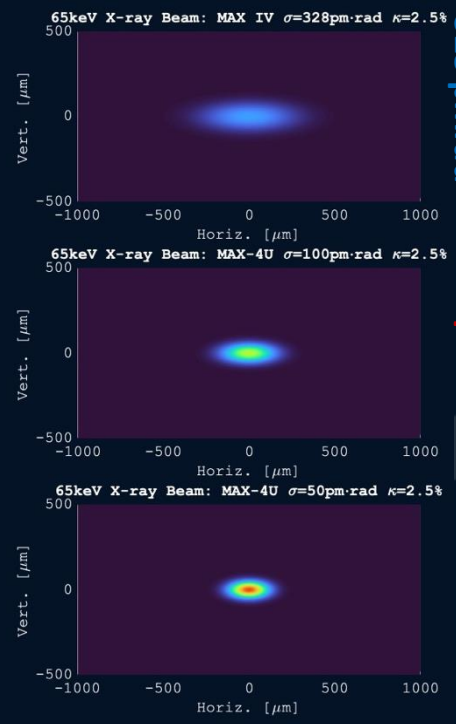
50 pmrad




540eV

4keV

10keV

35keV

65keV

*D=30m, L=3m*

# Accelerators

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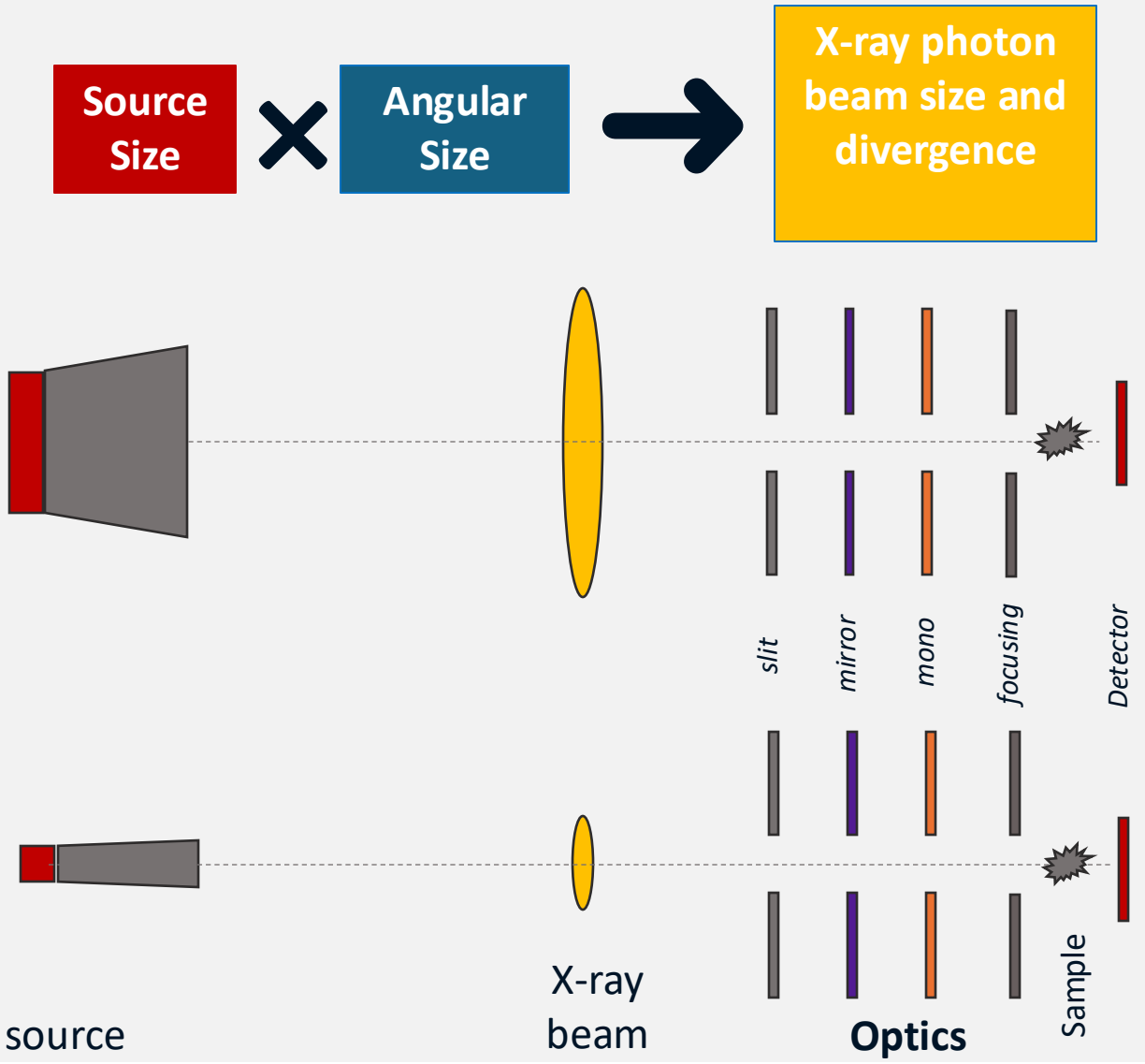
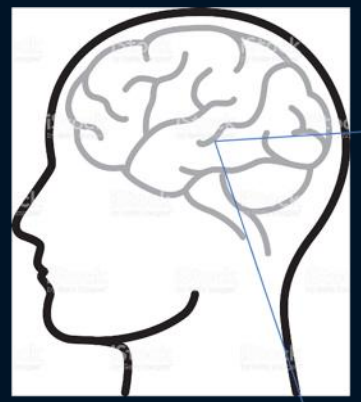
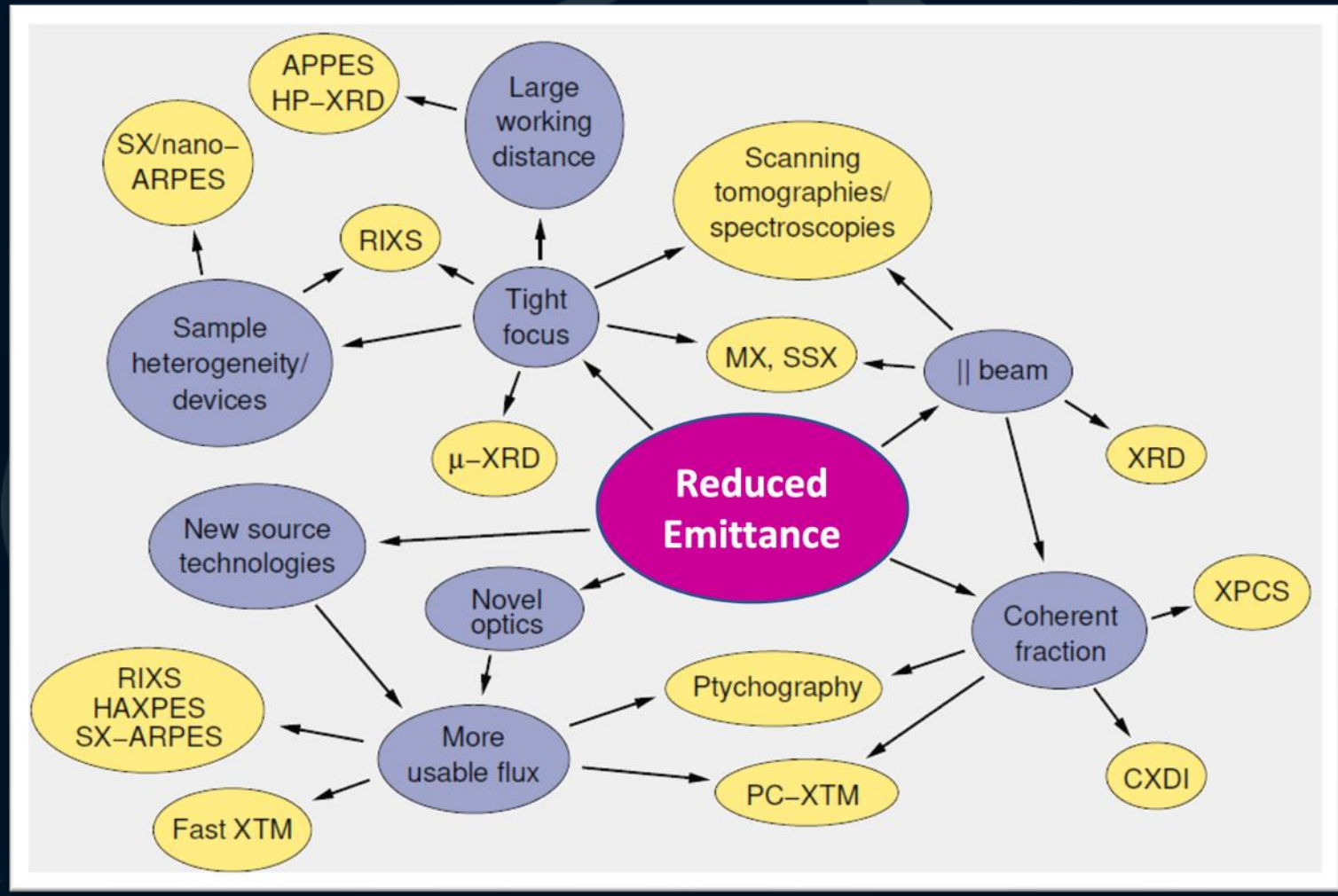
## Emittance, beam size and Optics



# Use and Explore opportunities with reduced Emittance



Adapted from SLS 2.0 – Beamline Conceptual Design Report - Jan 20, 2021




Property

X-ray Technique

Adapted from SLS 2.0 – Beamline Conceptual Design Report Jan 2021

# Use and Explore opportunities with reduced Emittance

## Reduced emittance ➛ increase in Brilliance

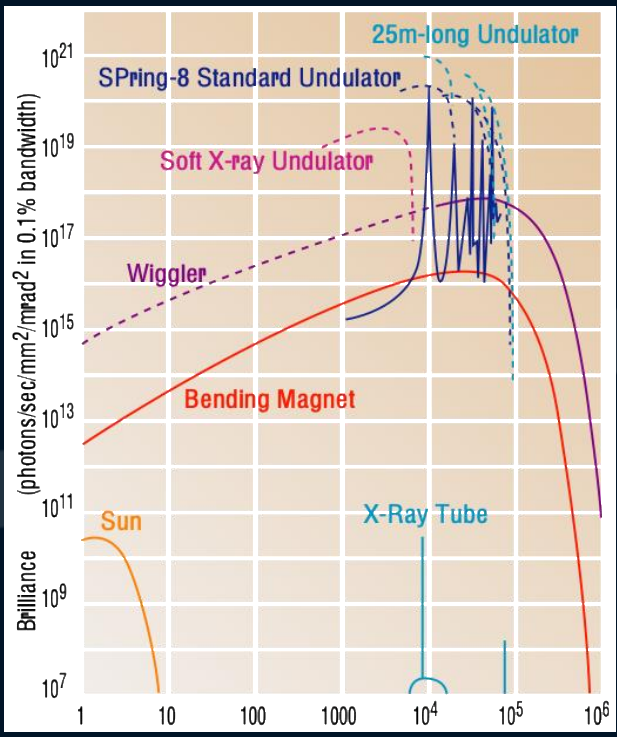
Brilliance in units of photon $s^{-1}$ $mm^{-2}$ $mrad^{-2}$ 0.1%$BW^{-1}$

photon $s^{-1}$ $mm_H^{-1}$ $mm_V^{-1}$ $mrad_H^{-1}$ $mrad_V^{-1}$ 0.1%$BW^{-1}$

photon $s^{-1}$ $mm_H^{-1}$ $mrad_H^{-1}$ $mm_V^{-1}$ $mrad_V^{-1}$ 0.1%$BW^{-1}$

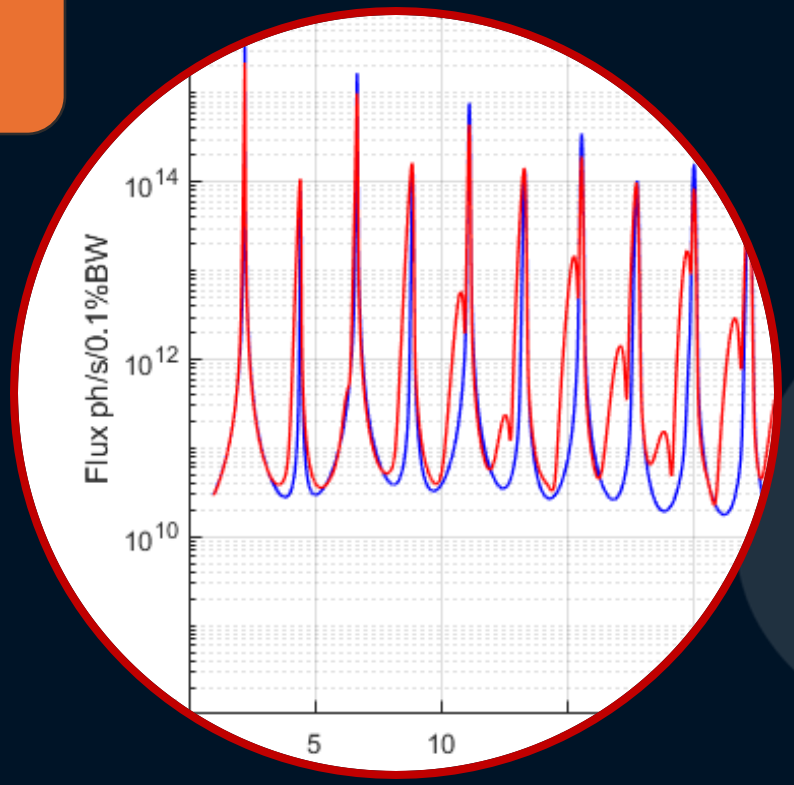
$(\varepsilon_H)^{-1}$ $(\varepsilon_V)^{-1}$

**1/Emittance**



# Small Emittance - More Research Opportunities

*Not ”more” photons, … but ”better” photons*



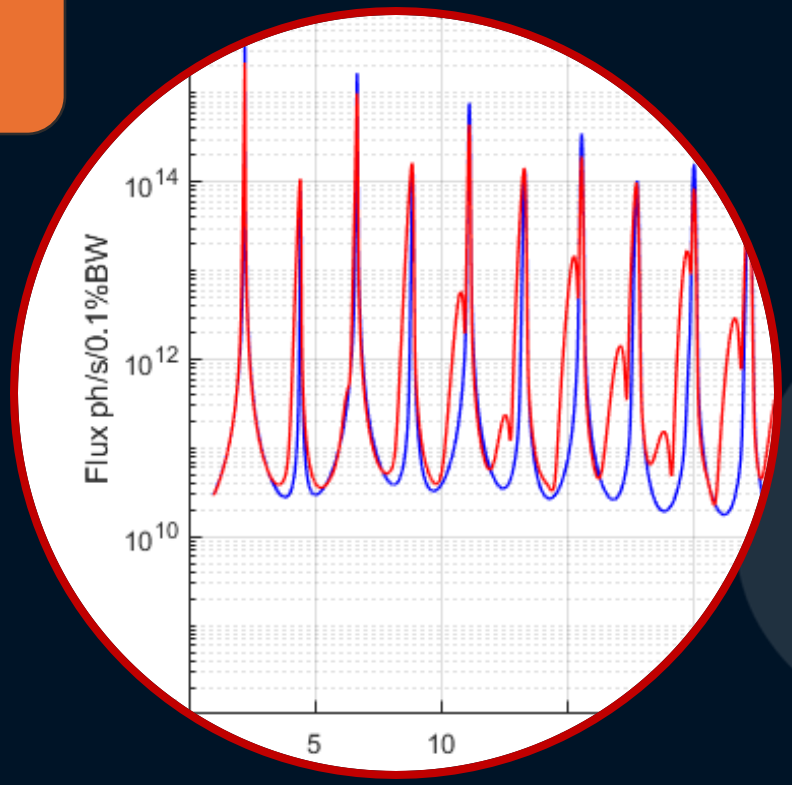

More Photons per EV

- Increase monochromator transmission
- Possibility of using pink beam to boost incident flux with multilayer monochromator
- Boost for inelastic X-ray scattering techniques

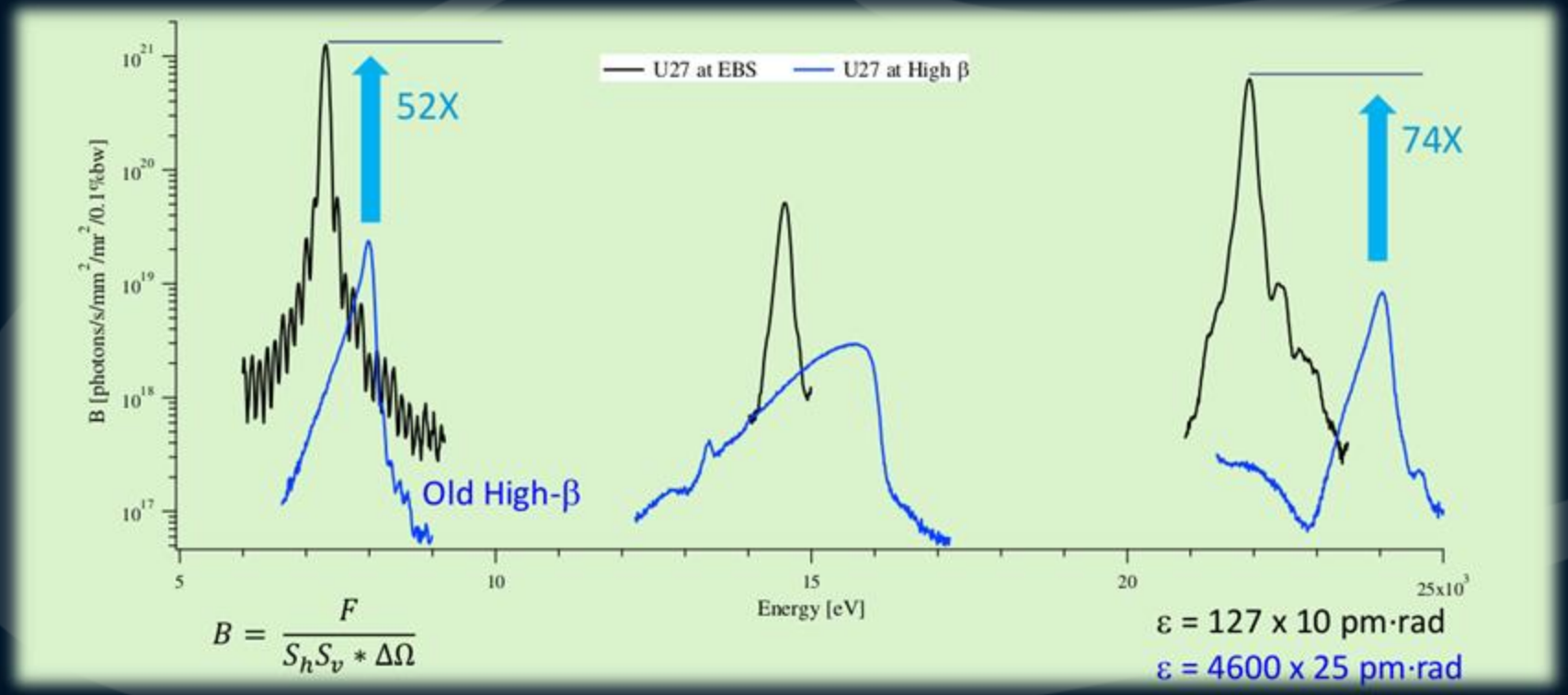
| | | | | | | |
|---|---|---|---|---|---|---|
| MicroMAX ✓ | Veritas ✓ | NanoMAX ✓ | Balder ✓ | CoSAXS ✓ | WISE | Imaging Life Sciences ✓ |
| HIPPIE ✓ | SoftiMAX ✓ | DanMAX ✓ | ForMAX ✓ | BioMAX ✓ | Spectro ✓ / Imaging ✓ | |

# Small Emittance - More Research Opportunities

*Not ”more” photons, … but ”better” photons*




More Photons per EV




Spectral flux of a U27 undulator through a 0.15x0.15 mm$^2$ aperture at 27m

Courtesy of Zontone & Chushkin, ESRF- ID10 beamline

P. Raimondi *et at.*, Communications Physics **6**, 82, (2023)

| | | | | | | |
|---|---|---|---|---|---|---|
| MicroMAX ✓ | Veritas ✓ | NanoMAX ✓ | Balder ✓ | CoSAXS ✓ | WISE | Imaging Life Sciences ✓ |
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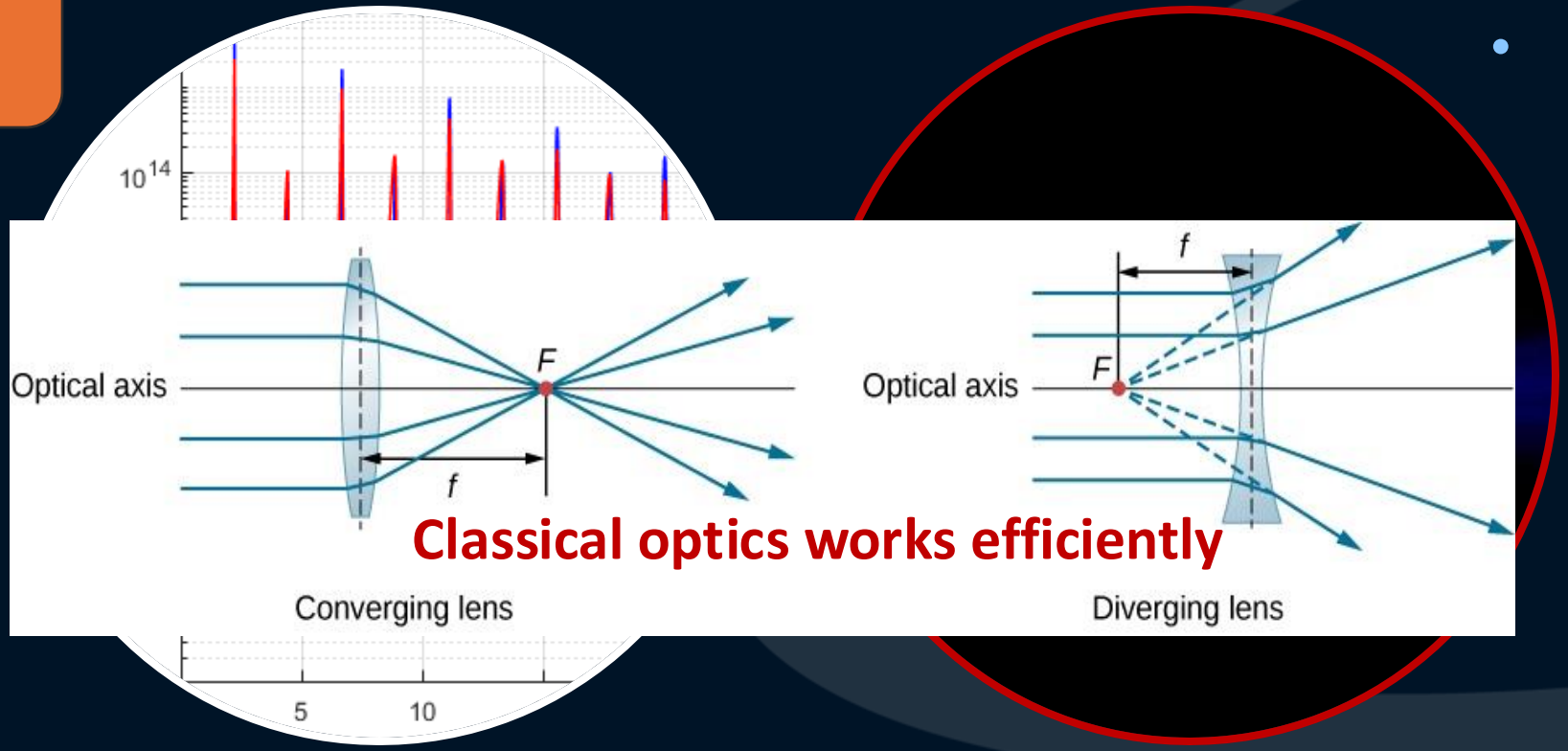
# Small Emittance - More Research Opportunities

*Not "more" photons, … but "better" photons*




**Classical optics works efficiently**

More Photons per EV

Access to micron and submicron size beams

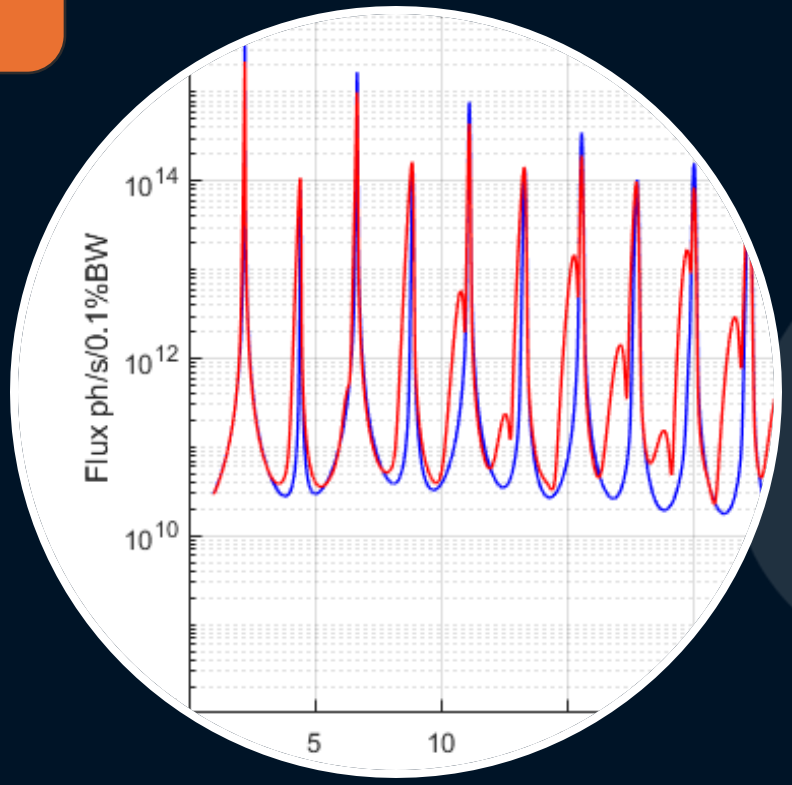
- Transformational for
- **Getting X-ray beam size you need!**
- X-ray microscopy (STXM)
- Spectro- & Diffraction- microscopy
- Coherent X-ray Diffraction Imaging- CXDI
- Ptychography
- SAXS-Tomography

| | | | | | | |
|---|---|---|---|---|---|---|
| MicroMAX ✓ | Veritas ✓ | NanoMAX ✓ | Balder ✓ | CoSAXS ✓ | WISE | Imaging Life Sciences ✓ |
| HIPPIE ✓ | SoftiMAX ✓ | DanMAX ✓ | ForMAX ✓ | BioMAX ✓ | Spectro ✓ Imaging ✓ | |

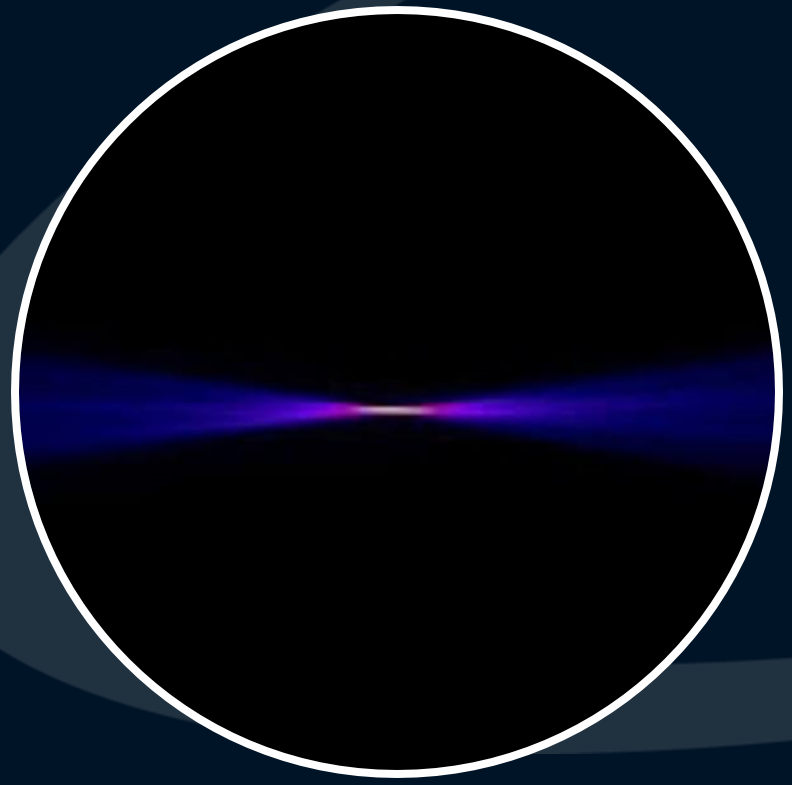
Emittance

# Small Emittance - More Research Opportunities

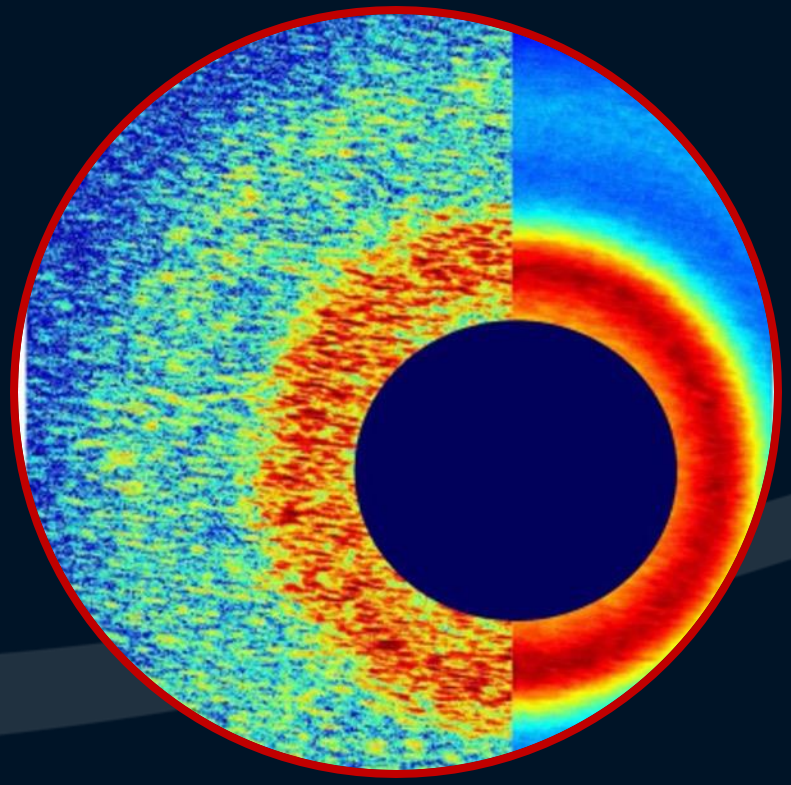
*Not ”more” photons, … but ”better” photons*




More Photons per EV



Access to micron and submicron size beams



More transverse coherence and coherent flux

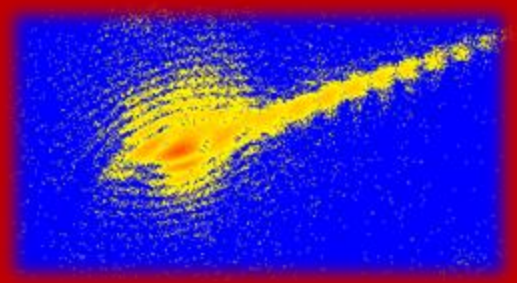
| | | | | | | |
|---|---|---|---|---|---|---|
| MicroMAX | Veritas | NanoMAX ✓ | Balder | CoSAXS ✓ | WISE | Imaging Life Sciences ✓ |
| HIPPIE | SoftiMAX ✓ | DanMAX ✓ | ForMAX ✓ | BioMAX | Spectro / Imaging ✓ | |

Emittance

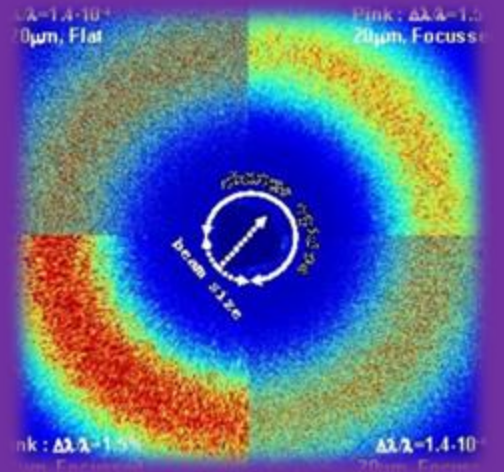
# Use and Explore Opportunities with X-ray Coherence

**Phase Contrast Imaging/Tomography**

**Coherent X-ray Diffraction Imaging**



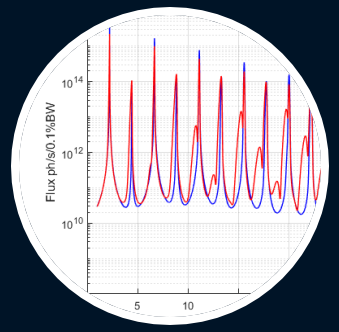
**Speckle Spectroscopy**

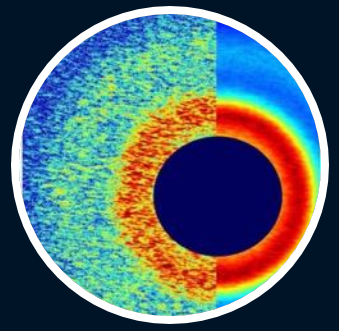


X-ray Imaging Techniques

# Small Emittance - More Research Opportunities

*Not "more" photons, … but "better" photons*



- **Getting intense and coherent X-ray beams w/ the size you need**

- **Translates into better resolution**
  - Better **energy** resolution
  - Better **spatial** resolution
  - Better **time** resolution

- **Opportunities to/for**
  - Study dynamics, kinetics
  - Operando and in-situ studies

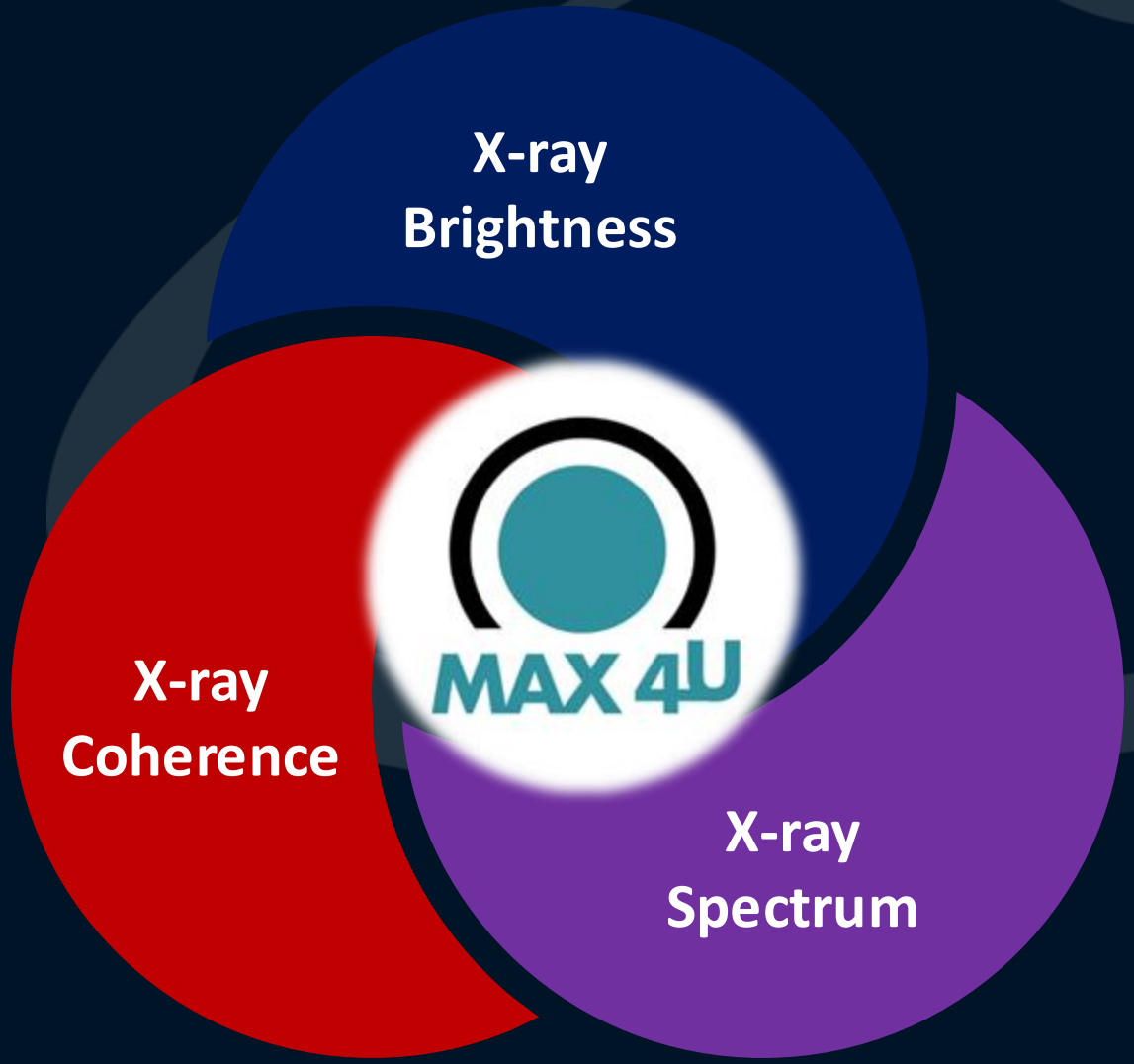
  - Perfect X-ray optics performs optimally
  - Use X-ray coherence as a diagnostics (e.g., ptychographic focus optimization)

  - *Use and explore opportunities with X-ray coherence*

# MAX §

## Ensuring leadership of Swedish research with X-ray for the next decades

### Understanding the structure and dynamics of matter on relevant time- and length-scales



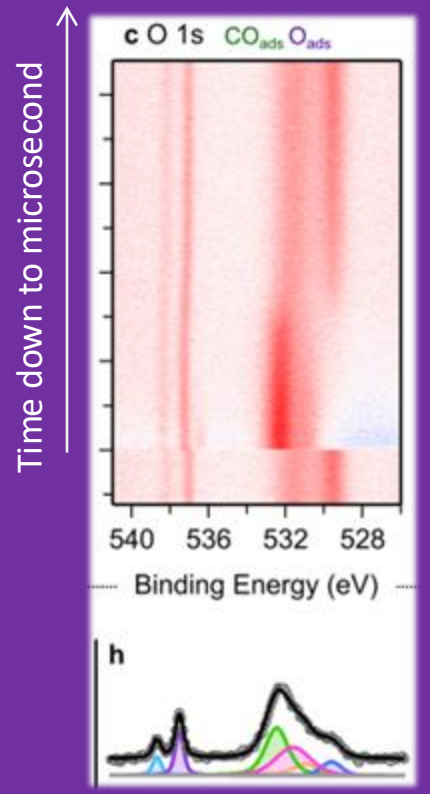
# MAX § Strengths

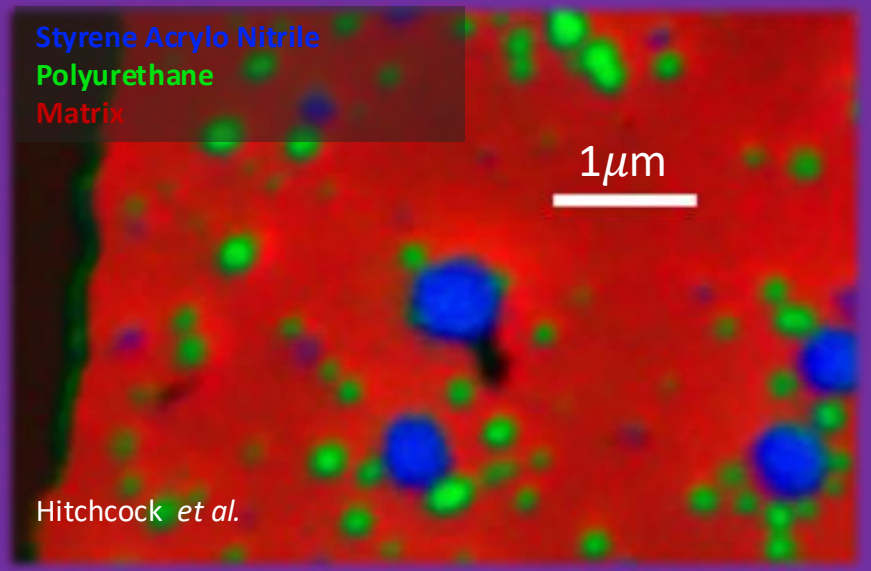
**Understanding the structure and dynamics of matter on relevant time- and length-scales**

## X-ray Spectrum

Probing surface and bulk properties of real matter in-situ and operando

- **Broad X-ray photon energy range from 250eV to 65keV**
- Powerhouse for soft, tender and hard X-ray spectroscopy down to the Carbon K-edge
- Enabling chemical imaging
- Opportunities for exploiting tender X-rays
- Enabling X-ray science up to 65keV



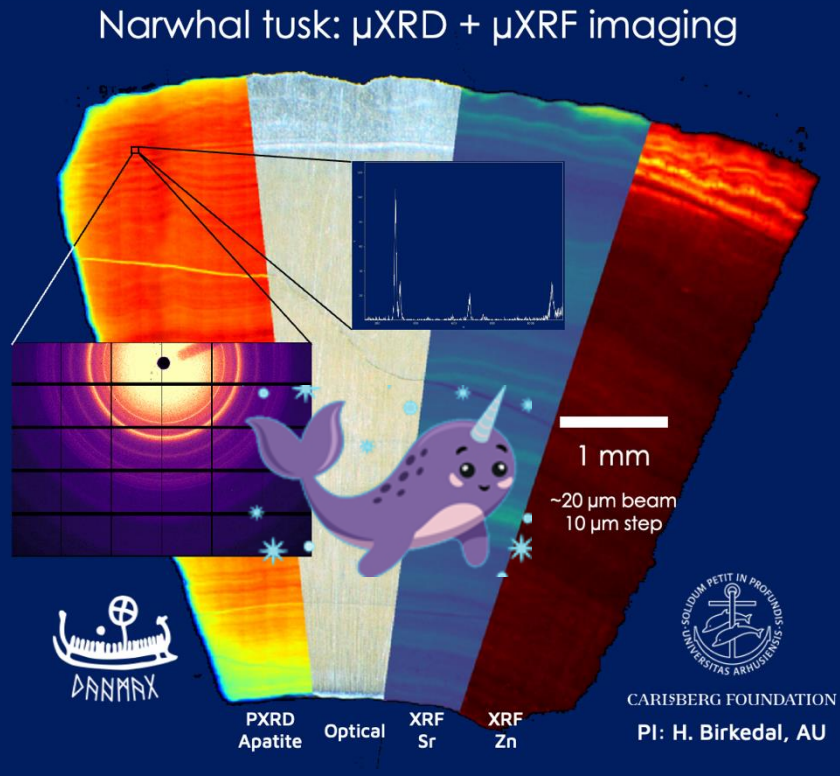
# MAX § Strengths

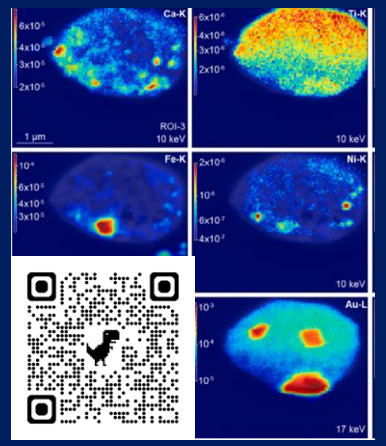
**Understanding the structure and dynamics of matter on relevant time- and length-scales**

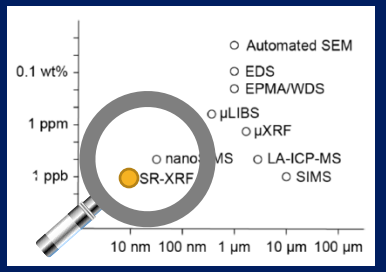
## X-ray Brightness

Understanding macroscopic objects with 10s of nanometer resolution

- **Maximizing the photon flux in the beam size you need**
- Multi-scale and multi-modal imaging by connecting spectroscopy and diffraction with high resolution
- Measuring fast changes in samples in action with structural, chemical, and electronic sensitivity
- Enabling sensitivity to detect small/ dilute samples



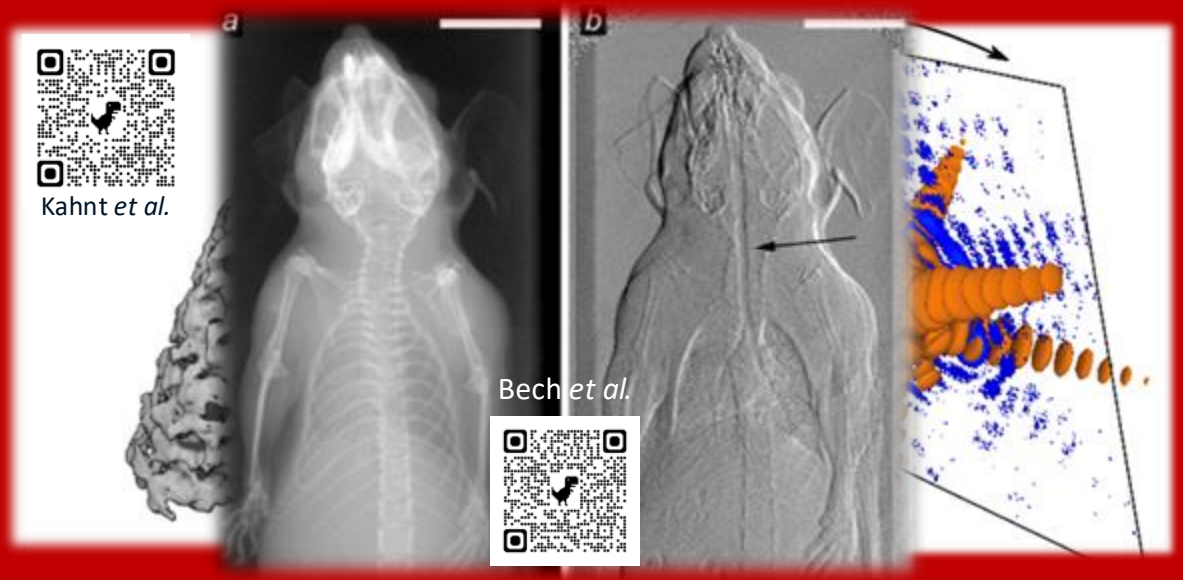
# MAX § Strengths

**Understanding the structure and dynamics of matter on relevant time- and length-scales**

## X-ray Coherence

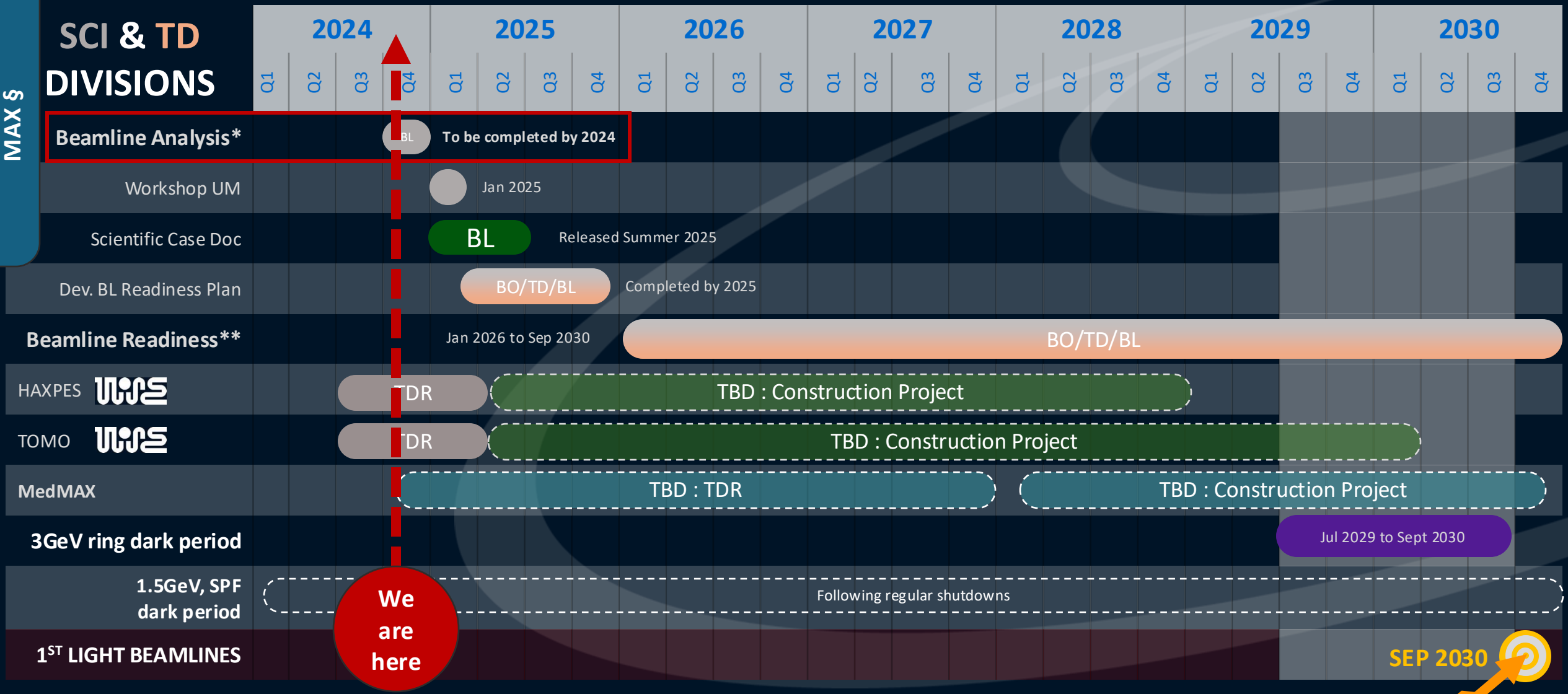
Understanding disordered matter with the highest spatial- and time-resolutions

- **Maximizing the coherent photon flux in the beam size you need**
- Improved phase contrast imaging for fast or high-resolution full-field imaging
- Imaging in 2- and 3-dimensions with resolutions down to 1nm with coherent imaging
- Improving time resolution for correlation techniques



MAX §

# SCI & TD DIVISIONS



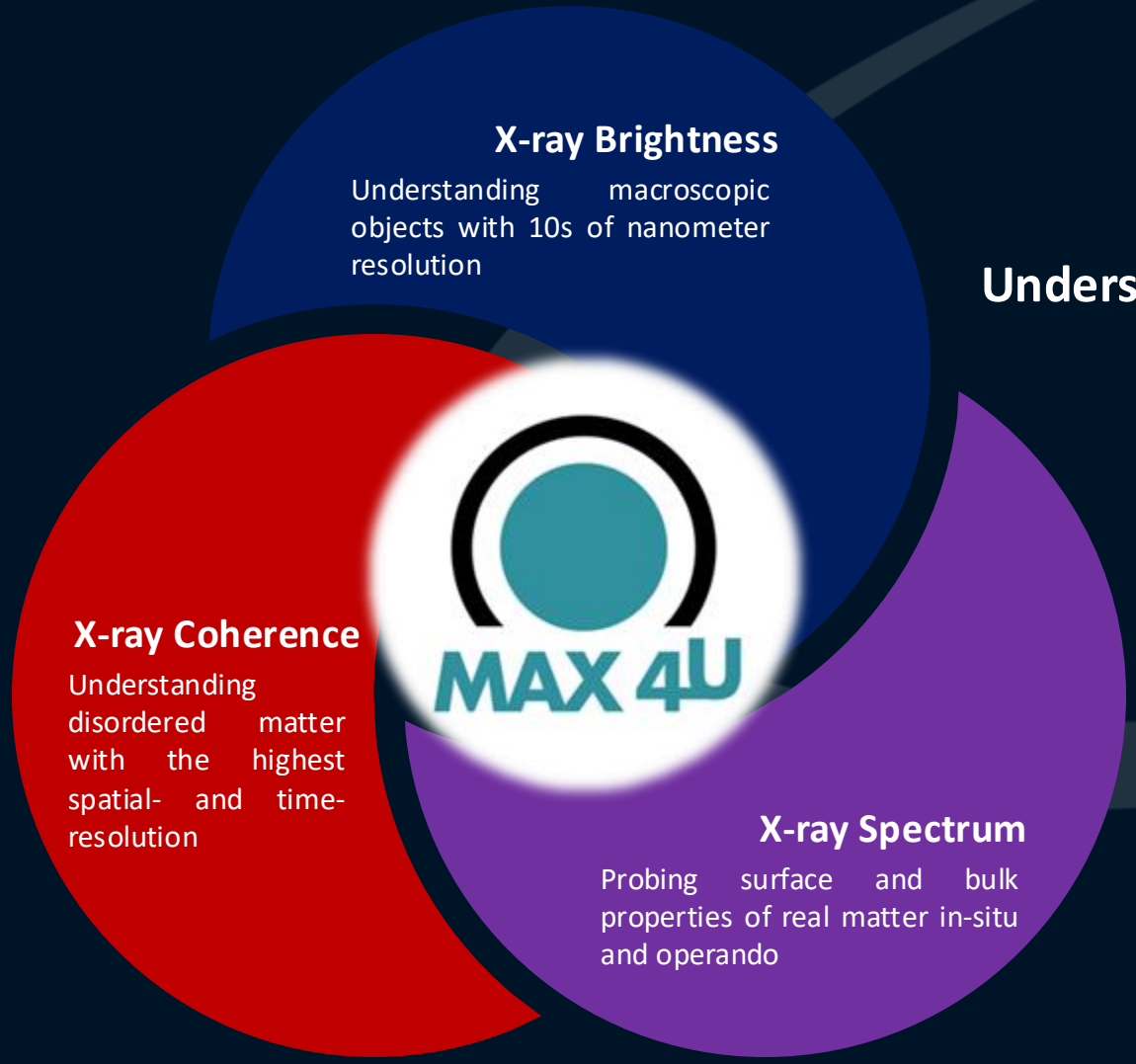

***Beamline Analysis**
Understand at the beamline level the effect of MAX §, whereas improvement or degradation of beamline performance. Quantification of effects. Discuss mitigations

****Beamline Readiness**
Translate Beamline Analysis into a concrete plan for ensuring and optimizing the performances of R3 beamlines (source, optics, instrumentation, detector, software. Input to Opportunity Studies program and financing.

MAX IV

# MAX §

## Ensuring leadership of Swedish research with X-ray for the next decades




**Understanding the structure and dynamics of matter on relevant time- and length-scales**

| Parameter | Value |
|---|---|
| Energy | 3 GeV |
| Circumference | 528 m |
| Bare Lattice **Emittance** | **<100 pmrad** |