The Weakly Interacting Universe

Joachim Kopp (CERN & JGU Mainz)

Munich • 14 June 2024


Gravity
Dark Matter
rotational velocity
(km/s)
measured
200
100
calculated
50000
100000
distance from center (light years)
Weak Force
Neutrinos
Strong &
Electromagnetic forces
Hadrons / Atoms


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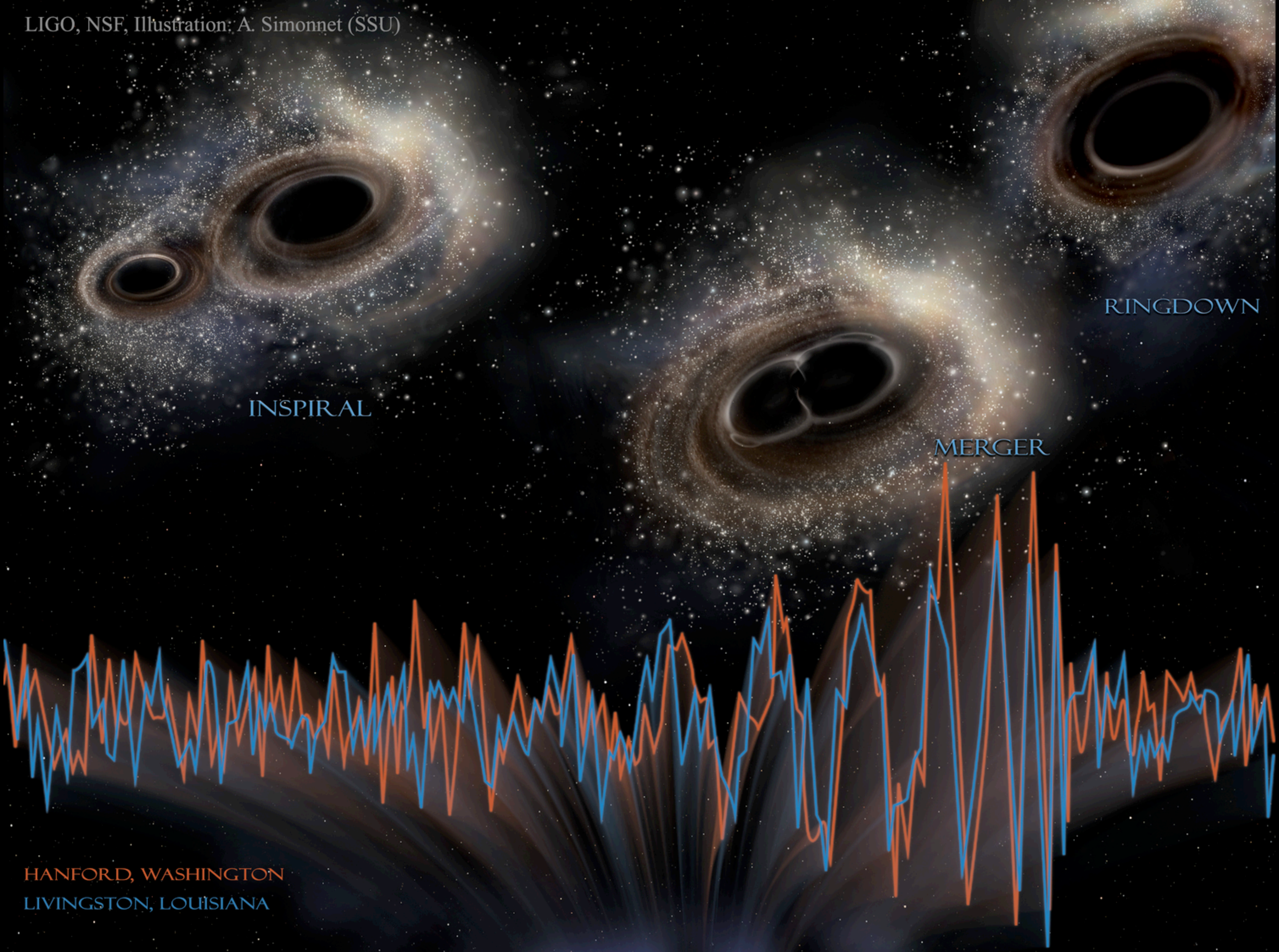
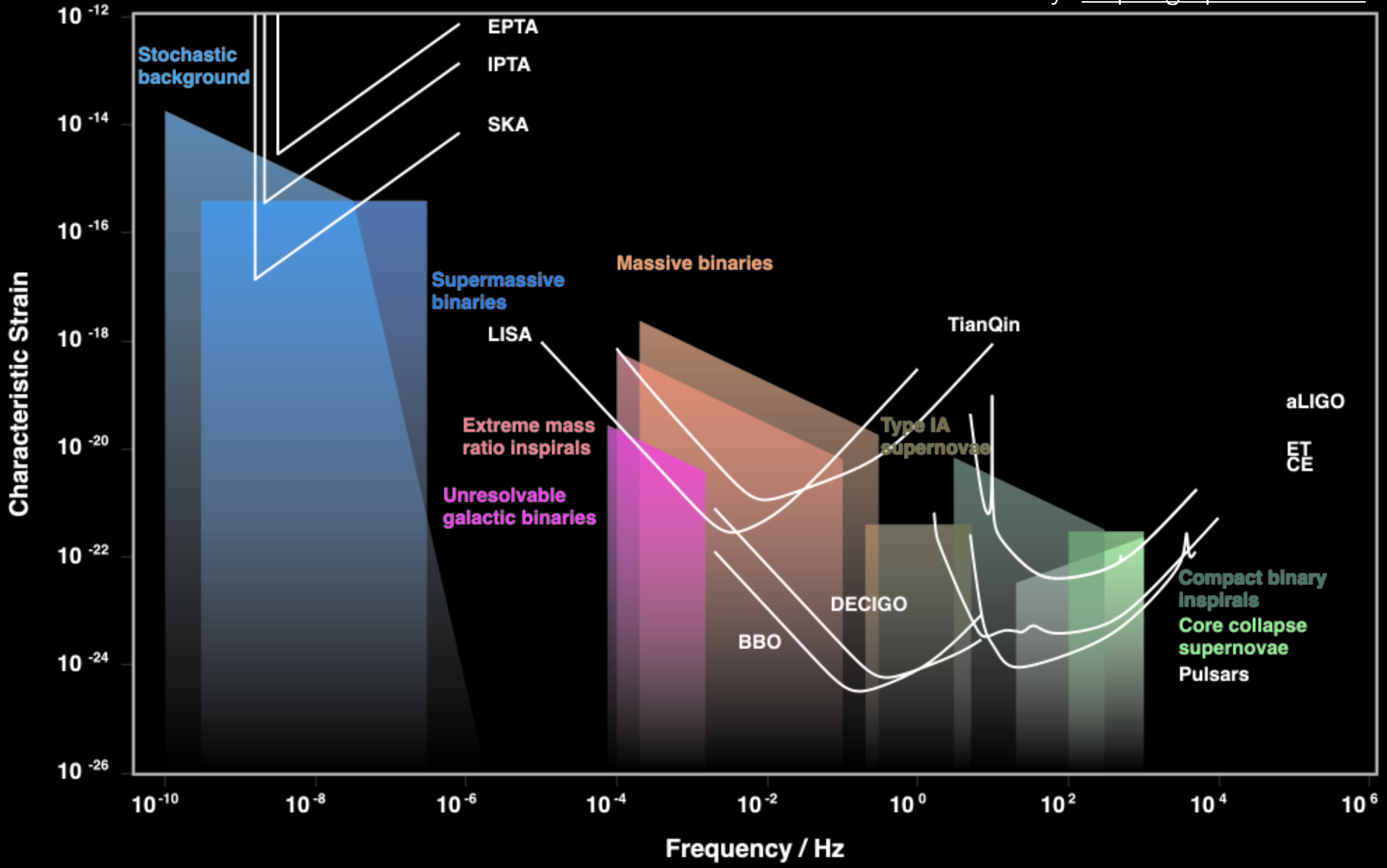

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

Moore Cole Berry http://gwplotter.com/



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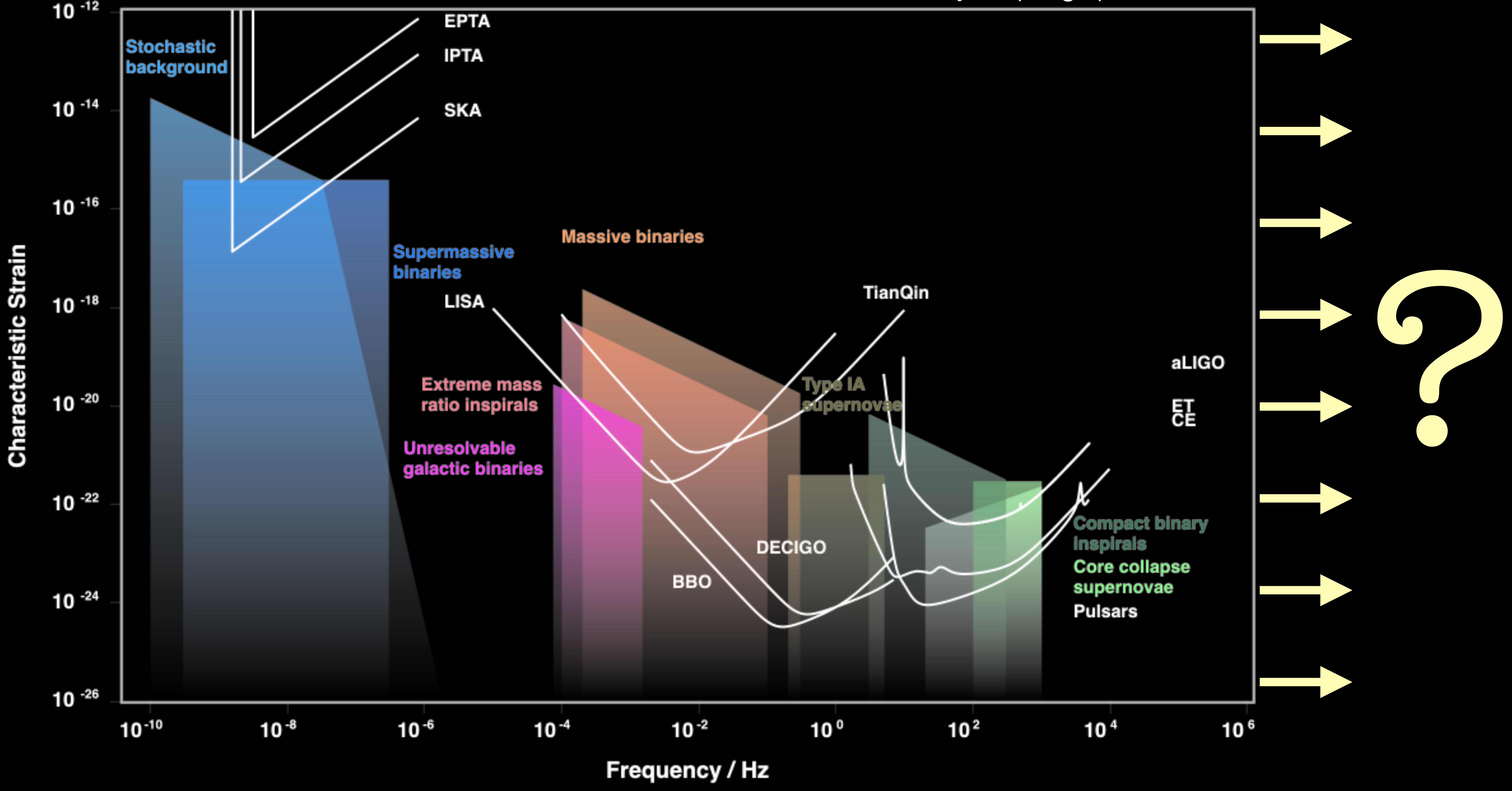


High-Frequency Gravitational Wave Sources

Cosmological
Phase Transitions

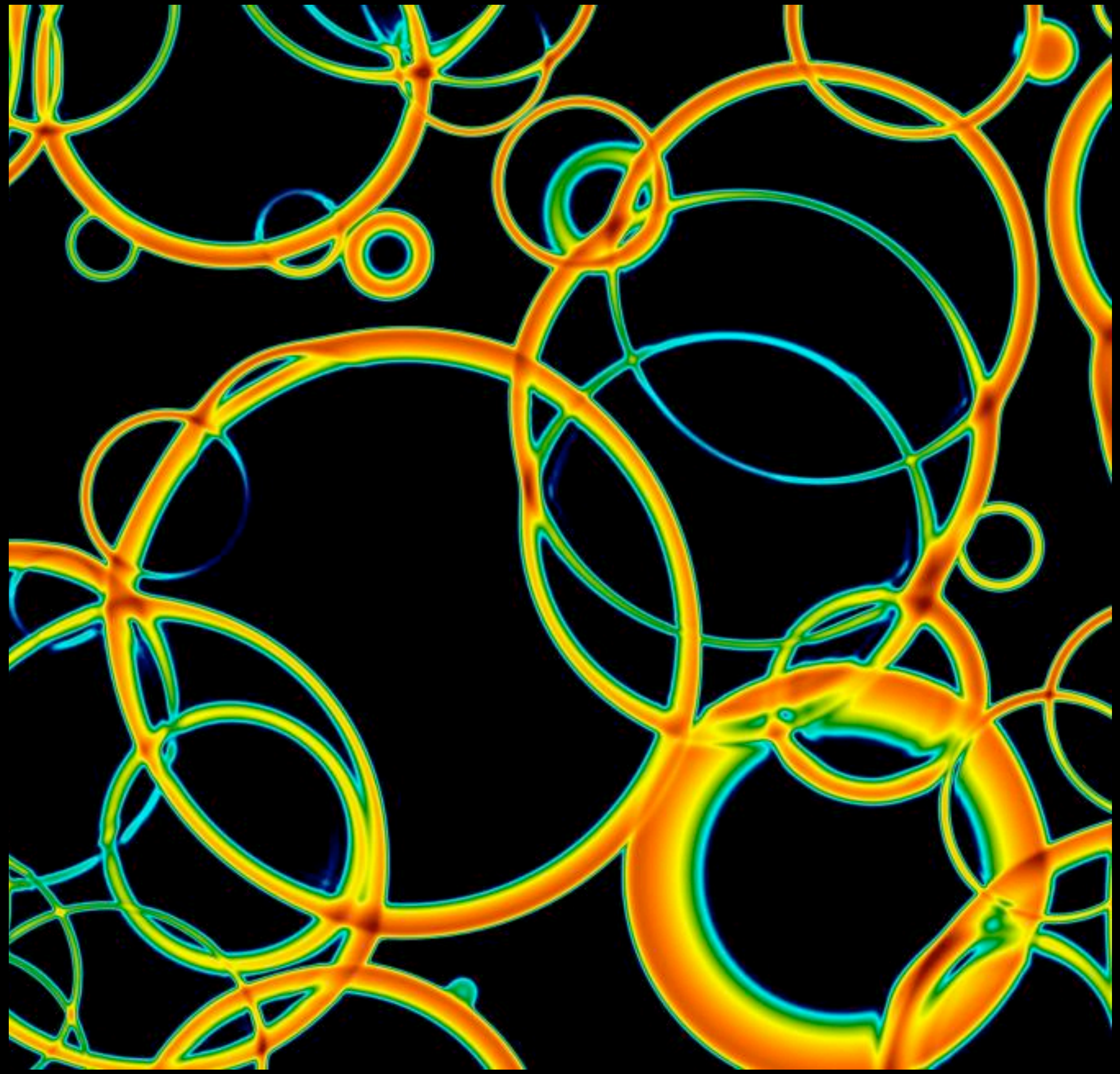


Image: D. Weir

Primordial
Black Hole Mergers

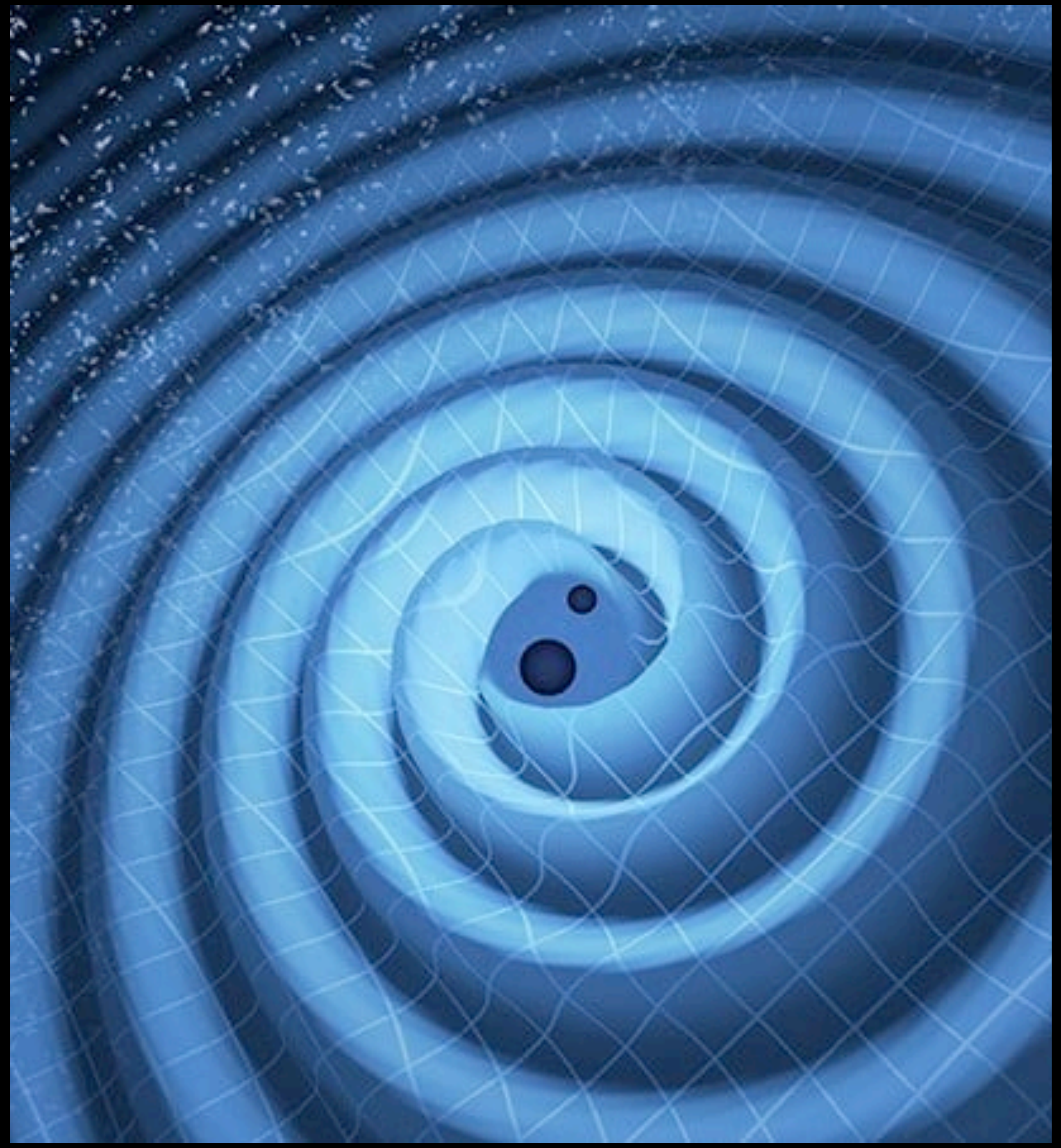
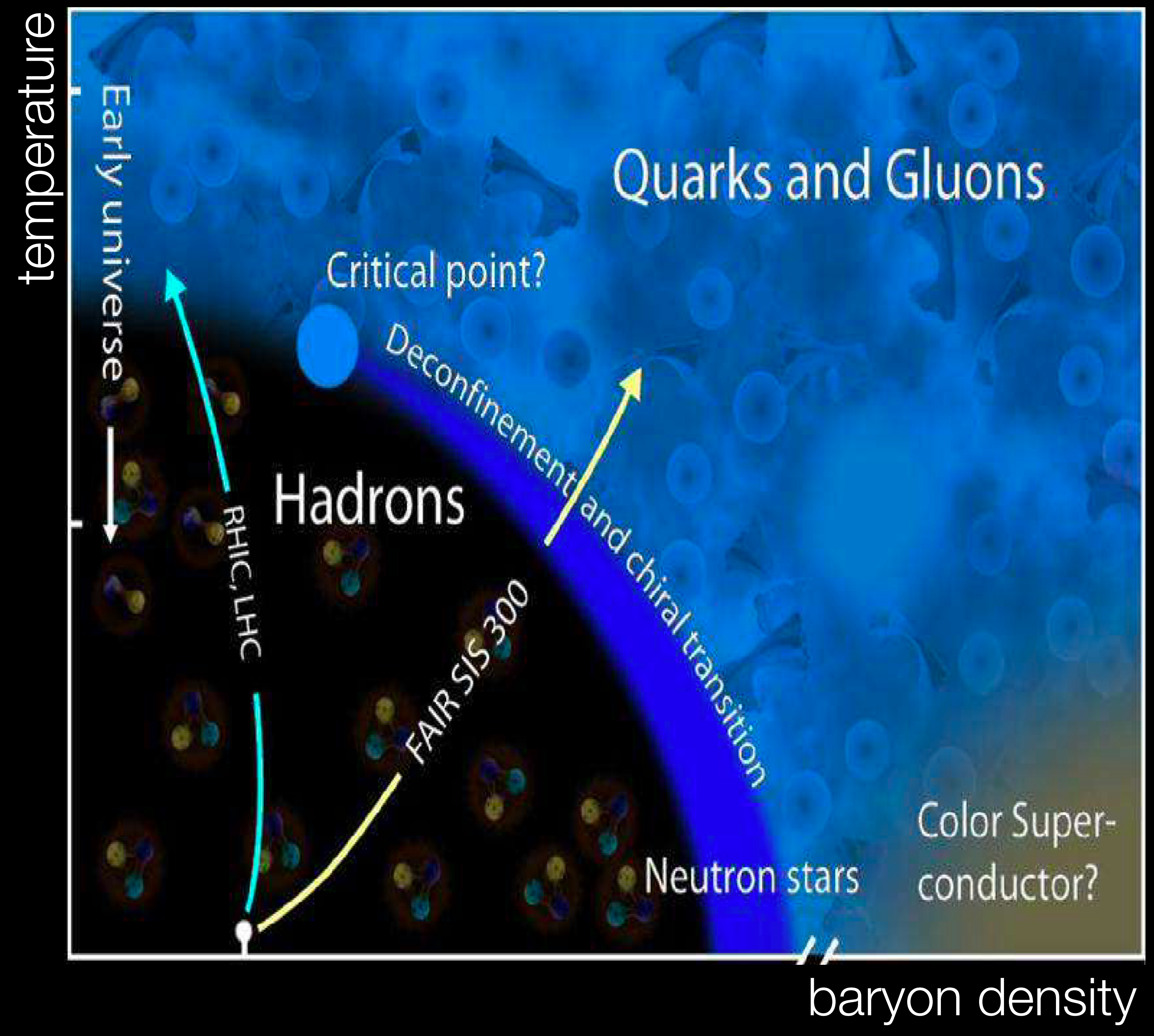
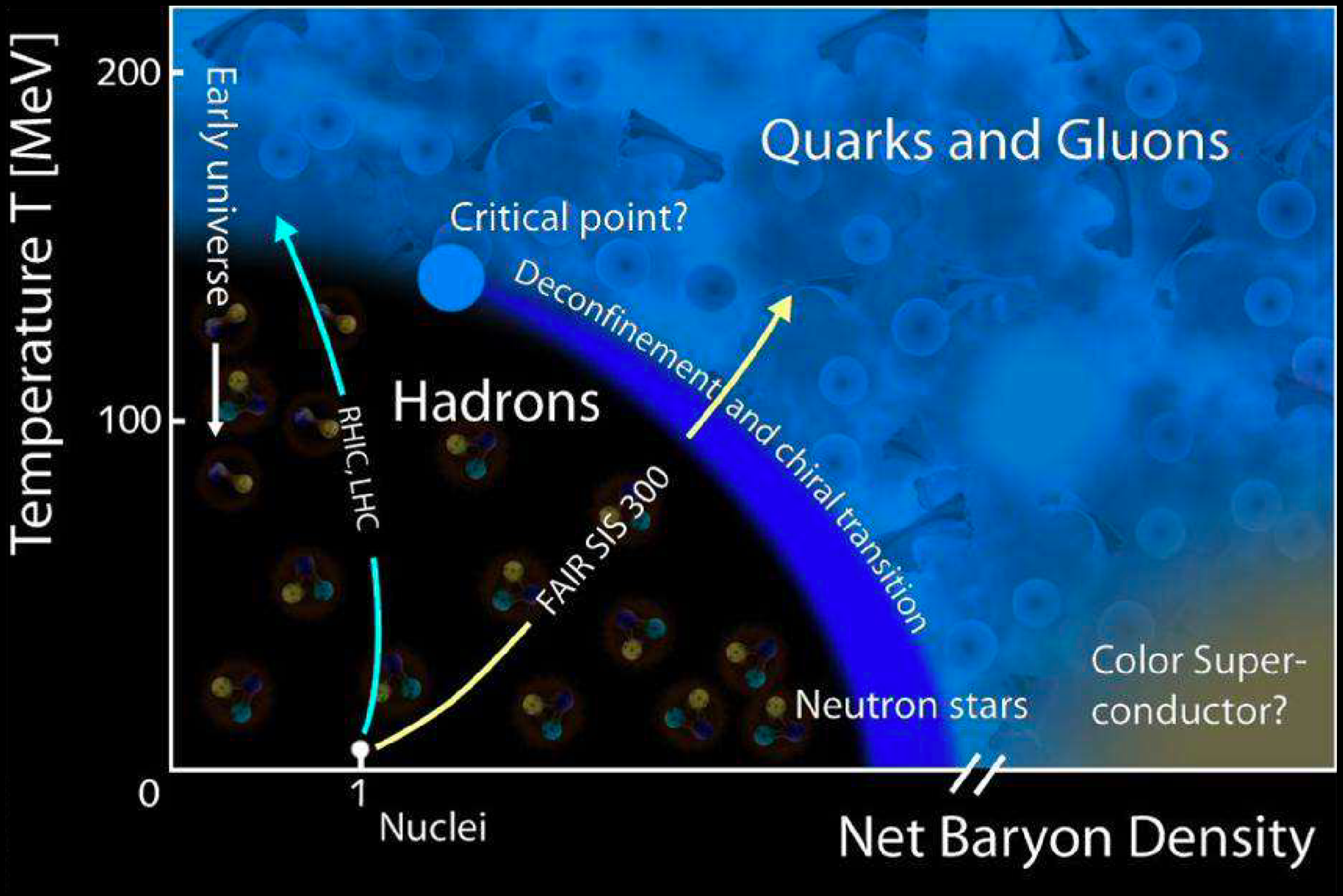


Image: LIGO / T. Pyle

QCD Phase Transitions
during NS mergers



MHz Gravitational Waves from Neutron Star Mergers



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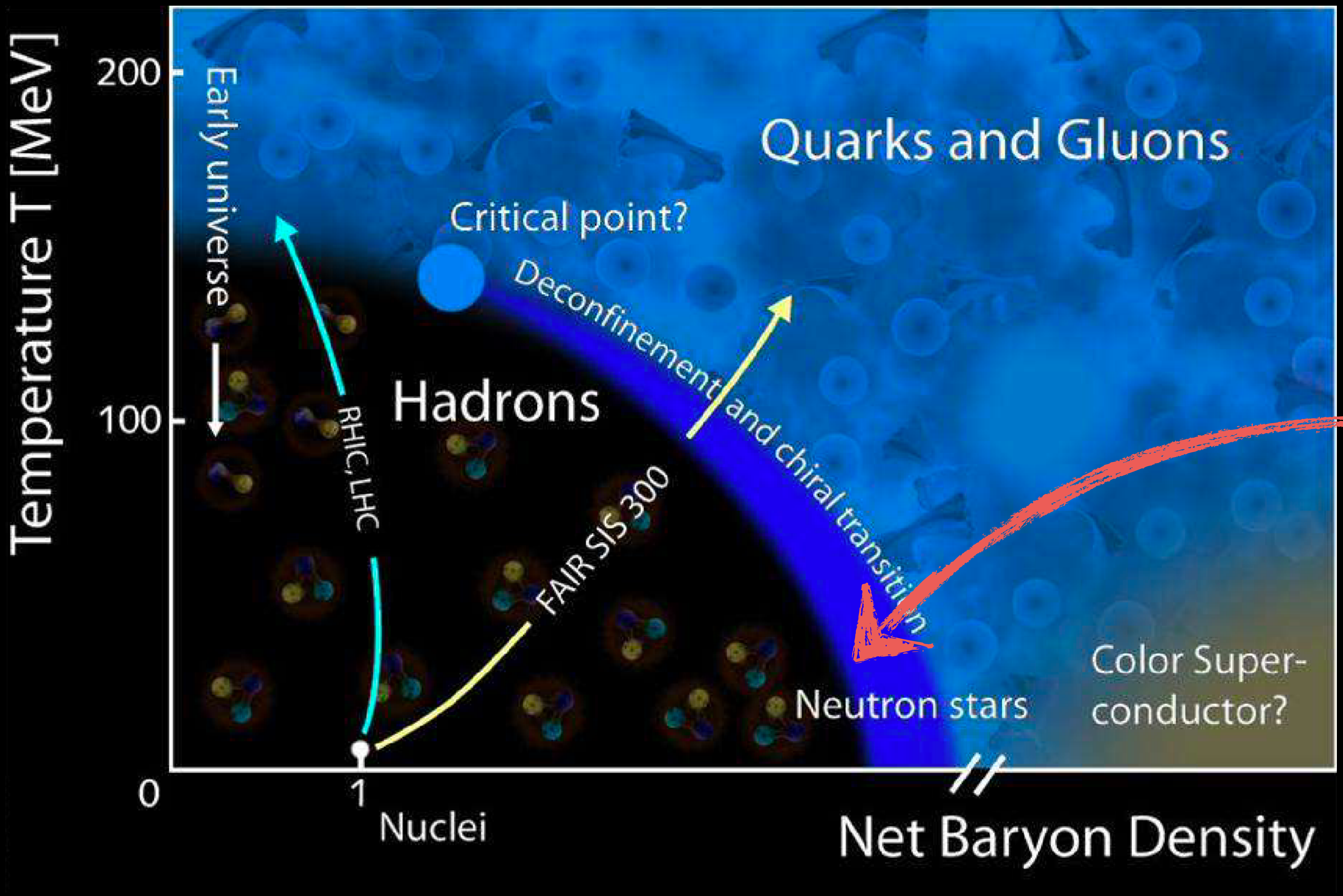

PT between hadrons
and quark matter?

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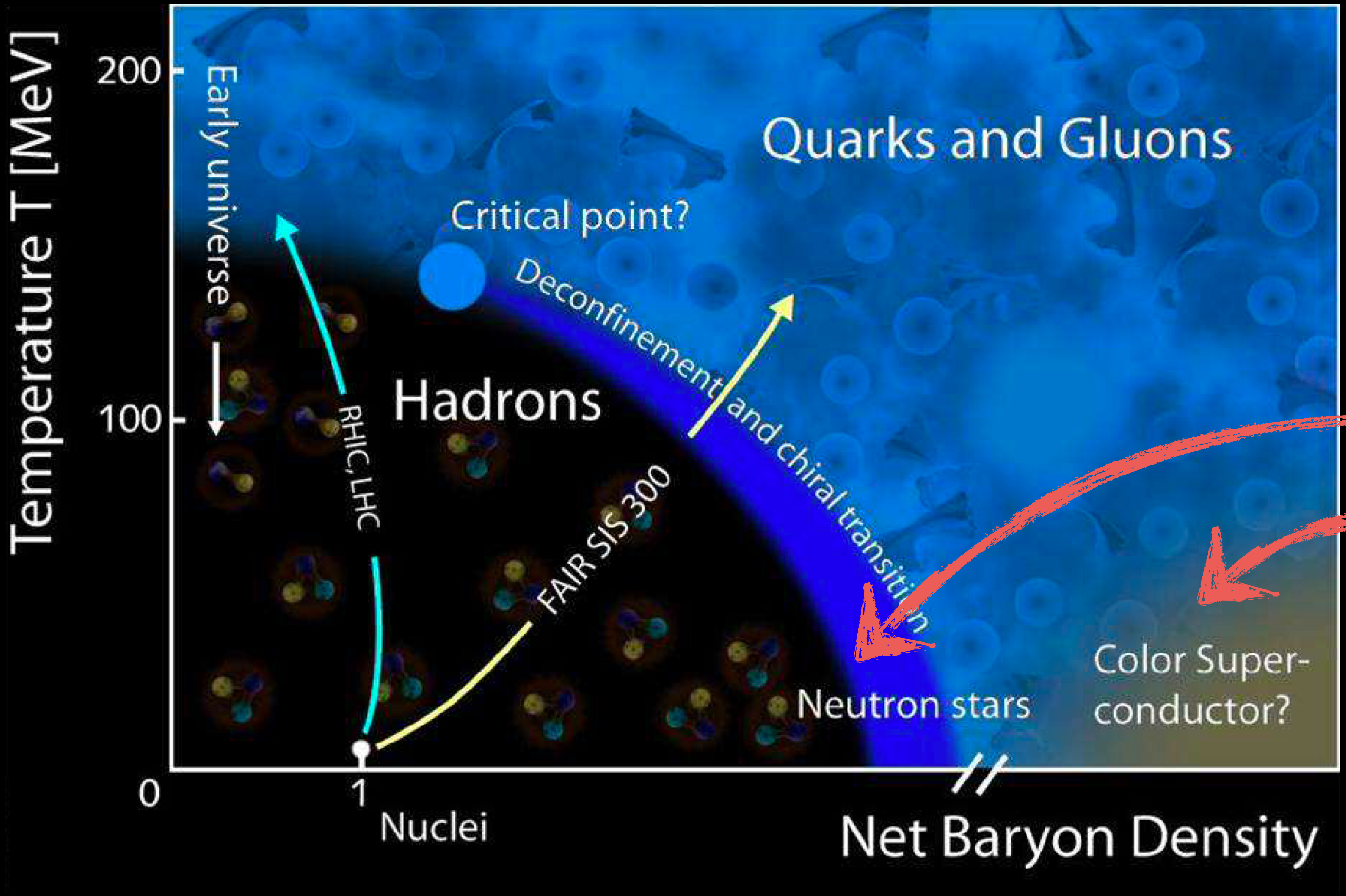

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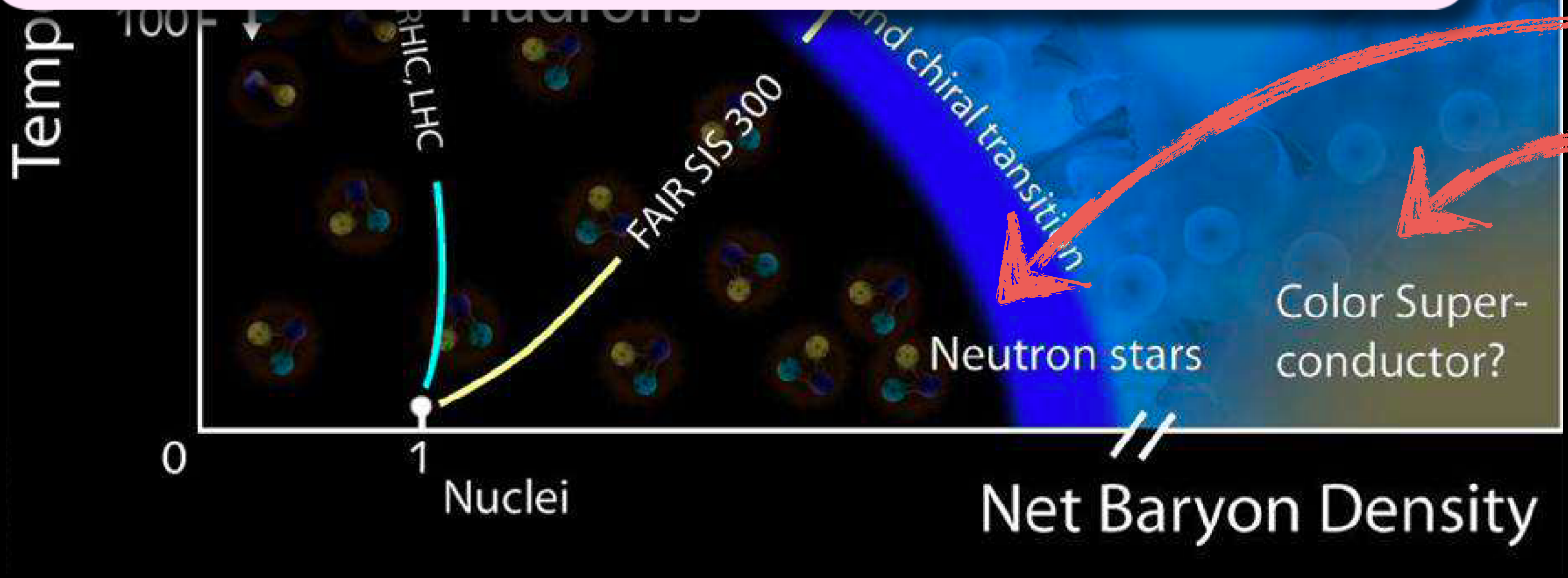
PT to color superconducting phase?

MHz Gravitational Waves from Neutron Star Mergers

- ☐ if a 1st order PT exists
- ☐ and if it lies in the T and μ range accessible in NS mergers

then such mergers would emit GW at f ~ MHz

Casalderrey-Solana Mateos Sanchez-Garitaonandia 2022



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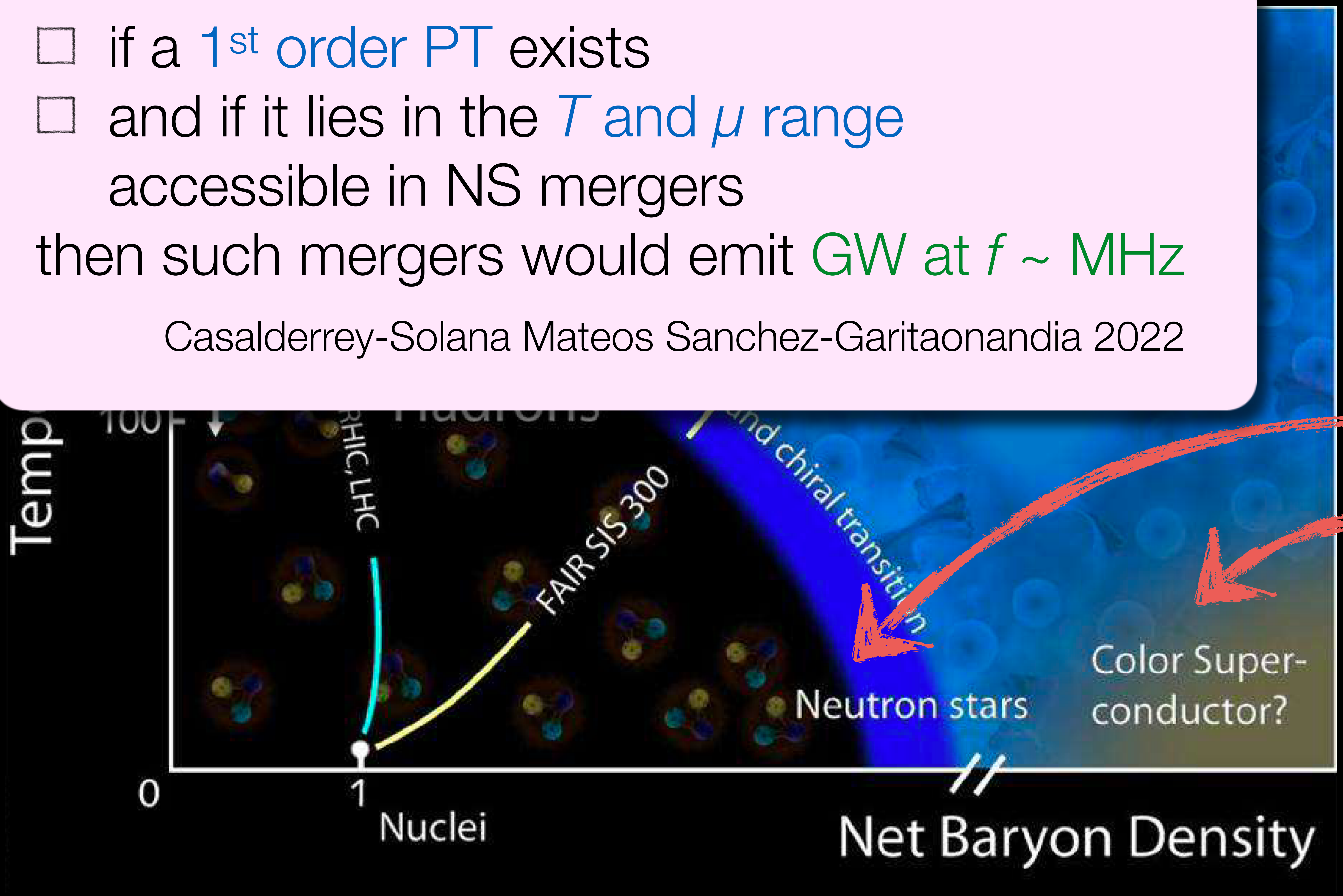


A **Standard Model** source of **MHz gravitational waves!**

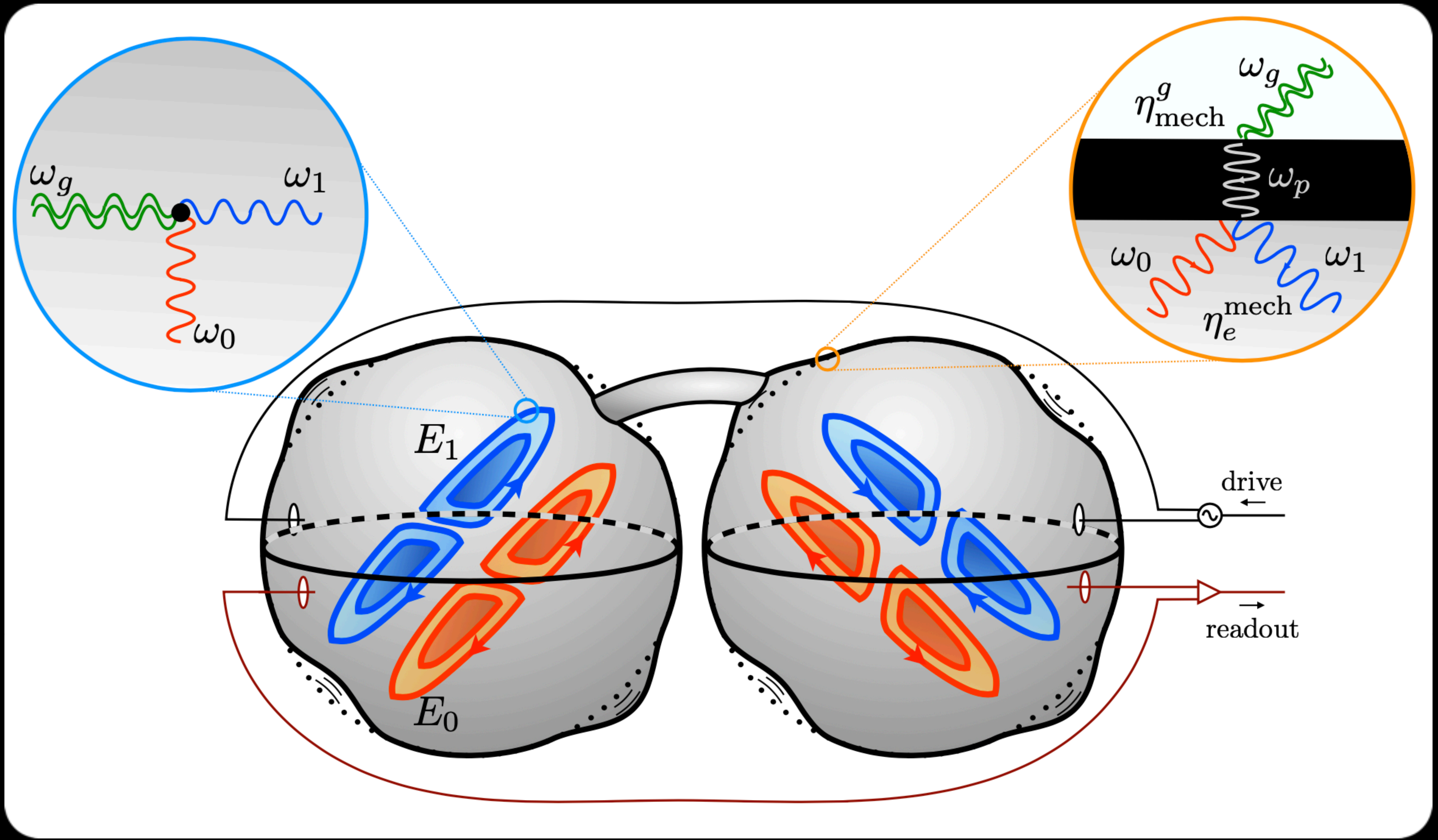
PT between hadrons and quark matter?

PT to color superconducting phase?

Cavities for High-Frequency GW Detection

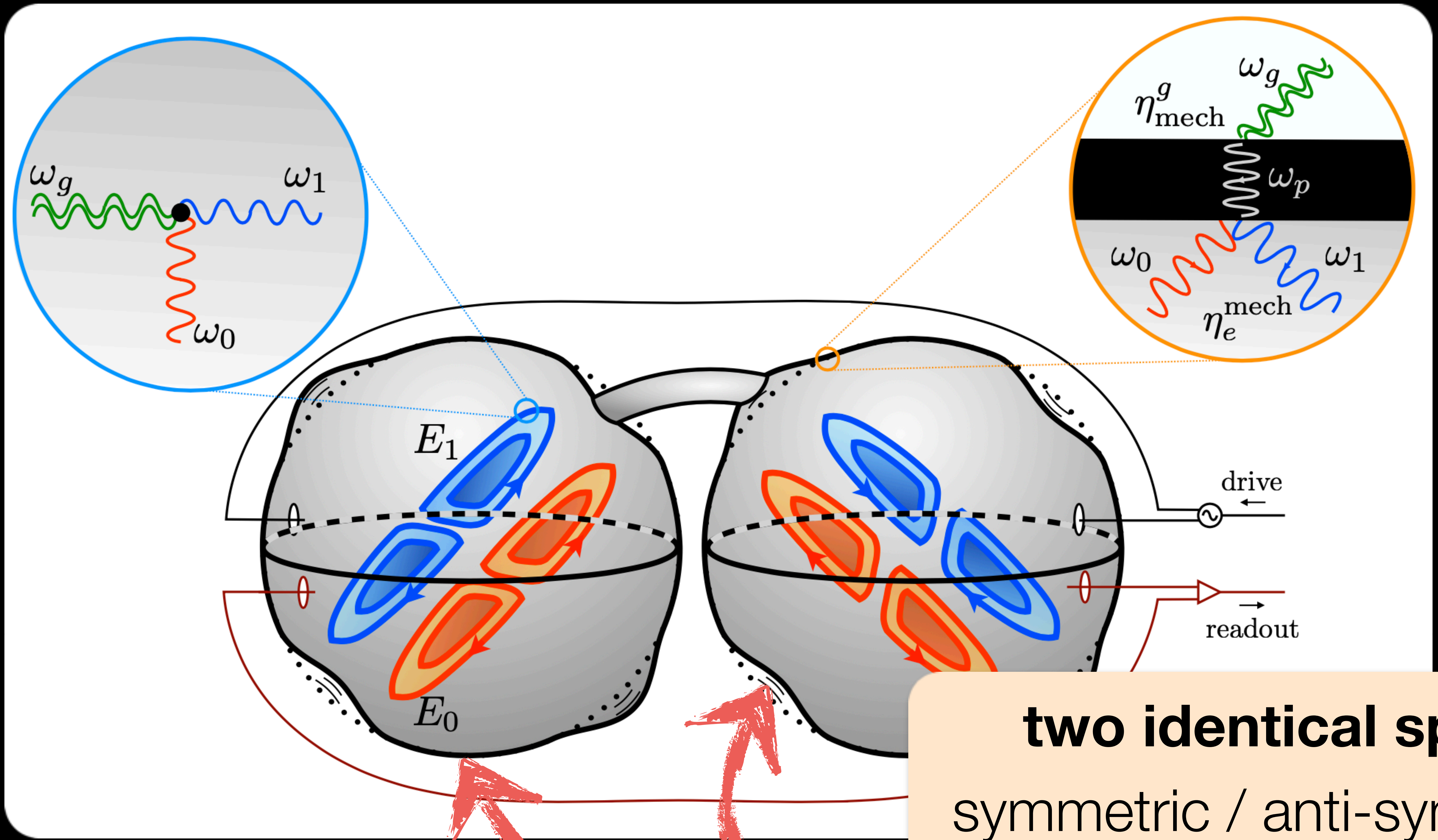
MAGO prototype (Ballantini et al. 2005)
basic idea by Bernard et al. 2001

The MAGO Concept



Berlin *et al.* 2023

The MAGO Concept



Berlin *et al.* 2023

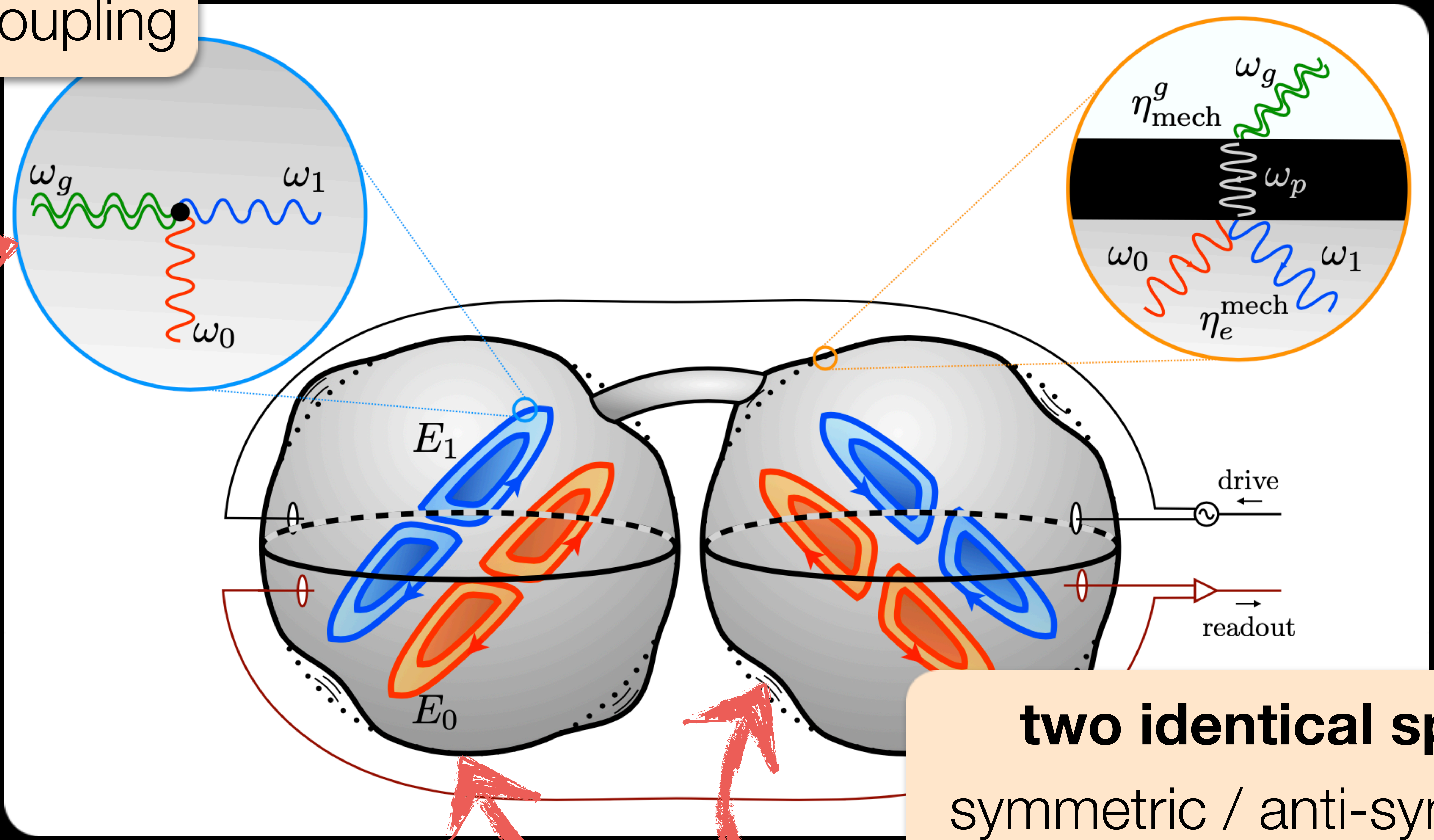
two identical spherical cavities

symmetric / anti-symmetric e.m. modes are nearly equal in energy

pump symmetric mode,
detect anti-symmetric mode excited by GW

The MAGO Concept

direct **GW–photon coupling**



Berlin *et al.* 2023

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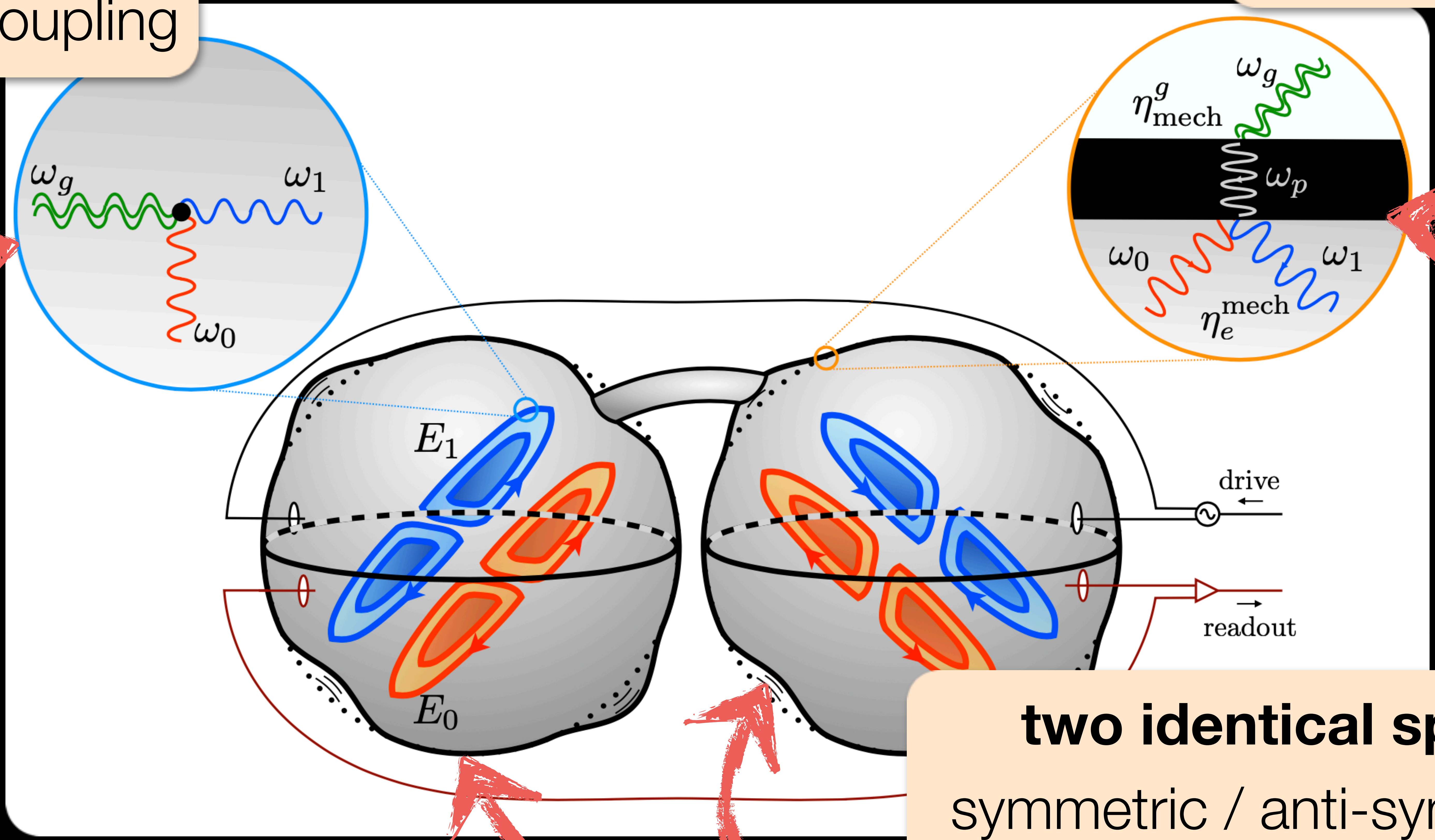
The MAGO Concept

GW coupling to **mechanical mode** + **electro–mechanical** coupling

direct **GW–photon** coupling



Berlin *et al.* 2023

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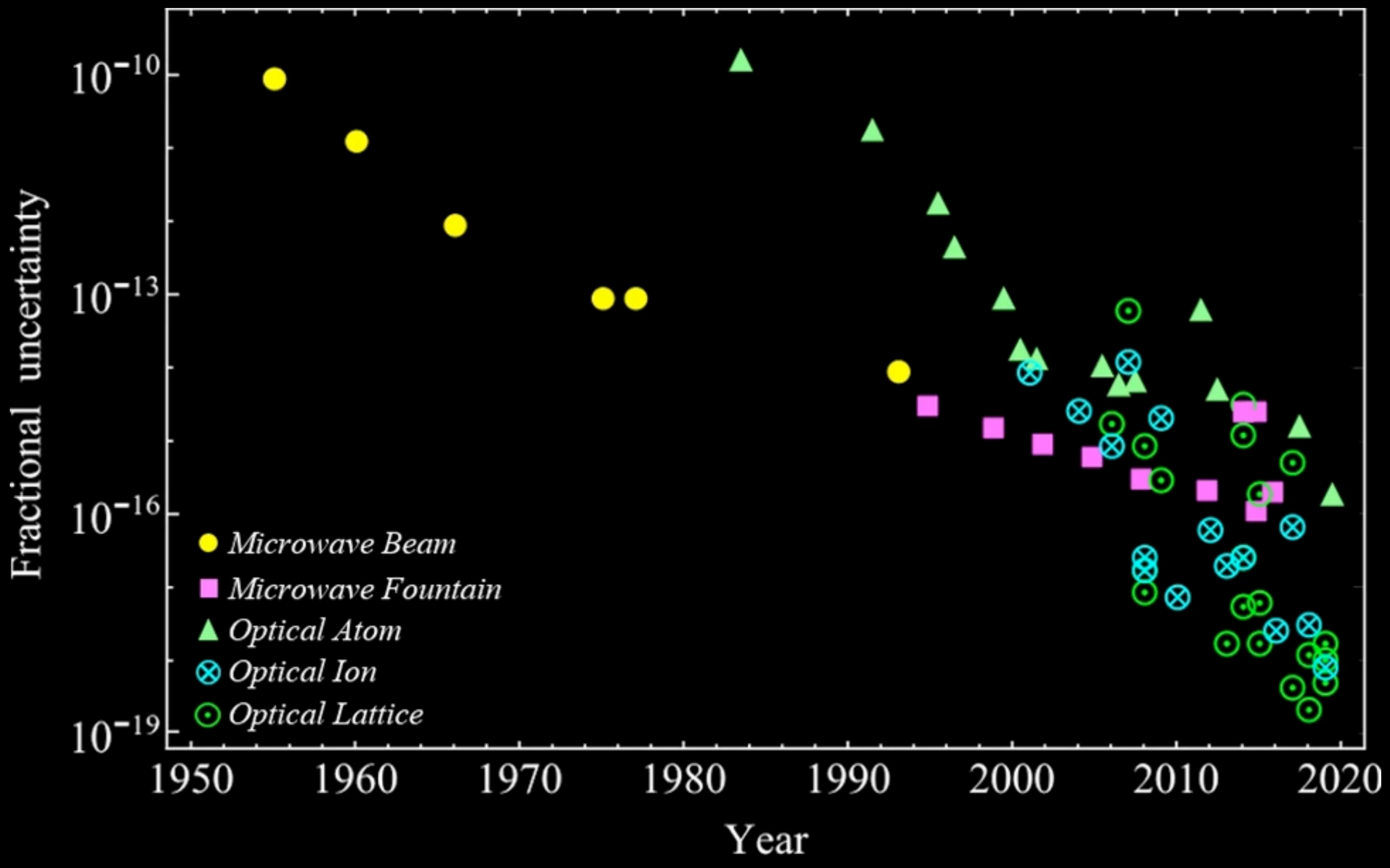
Atomic Clocks are Amazing

Sharma *et al.* 2023



Atomic Clocks are Amazing

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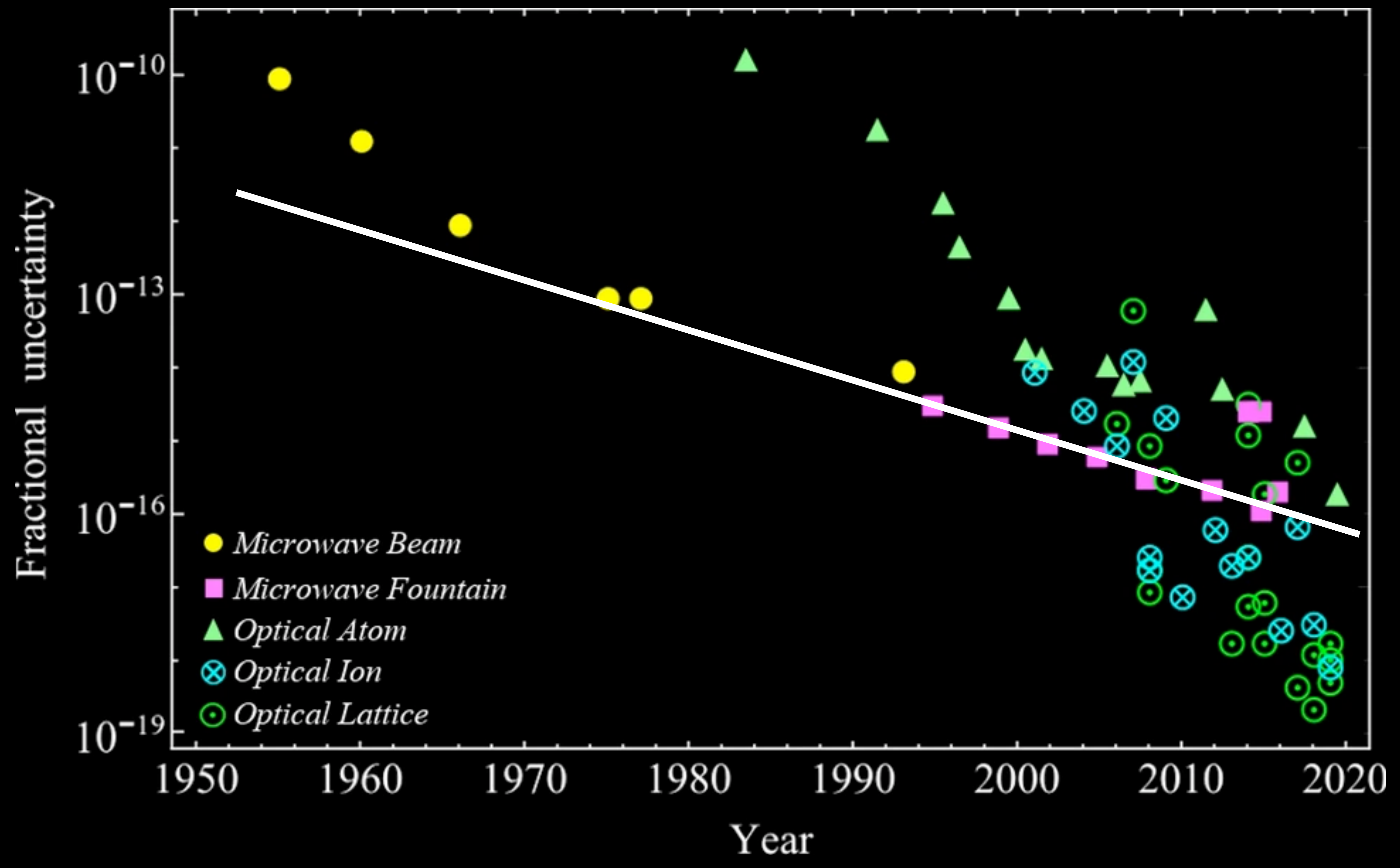

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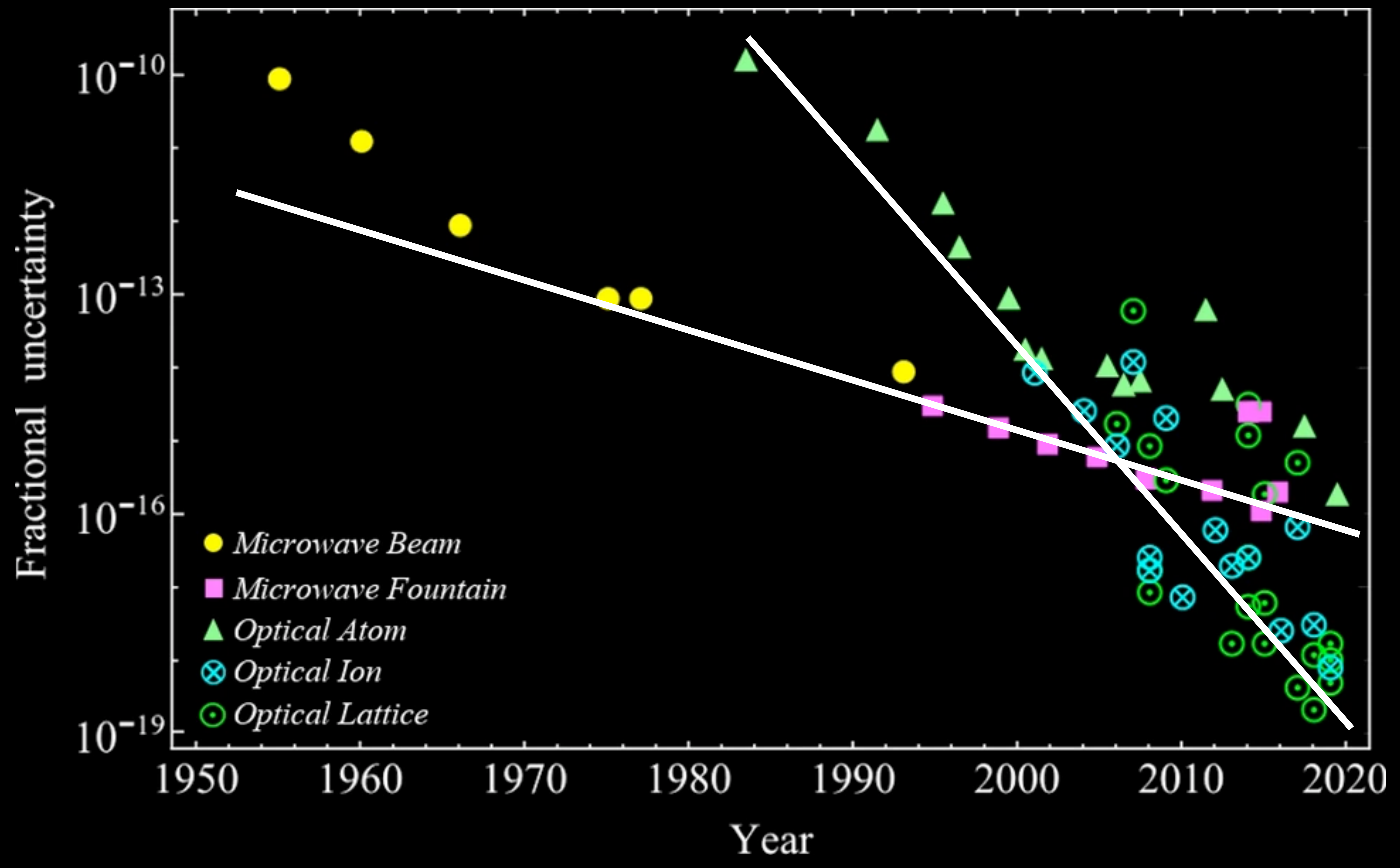


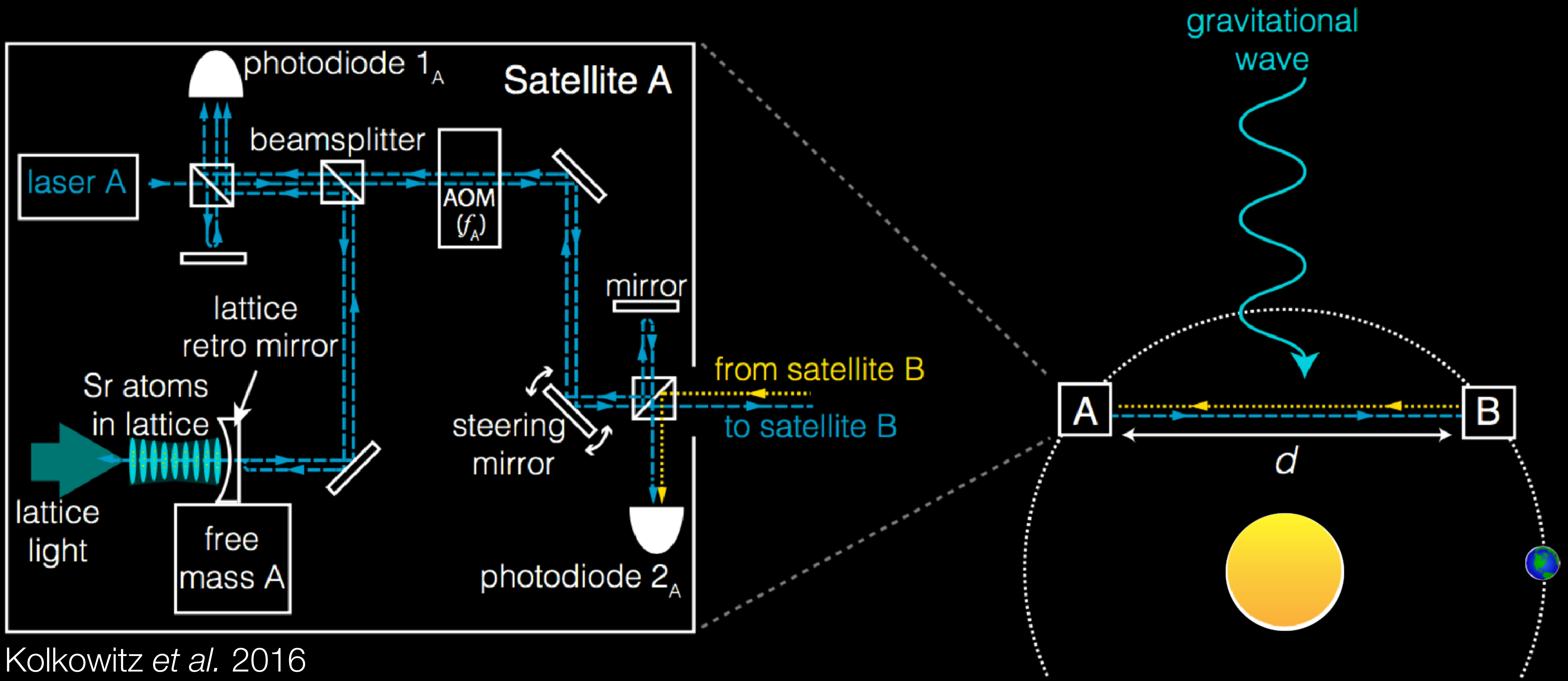
Atomic Clock Technology for GW Detection

"The only quantity you should ever measure is frequency"

source unknown

photons traveling through GW background
experience **frequency shift**

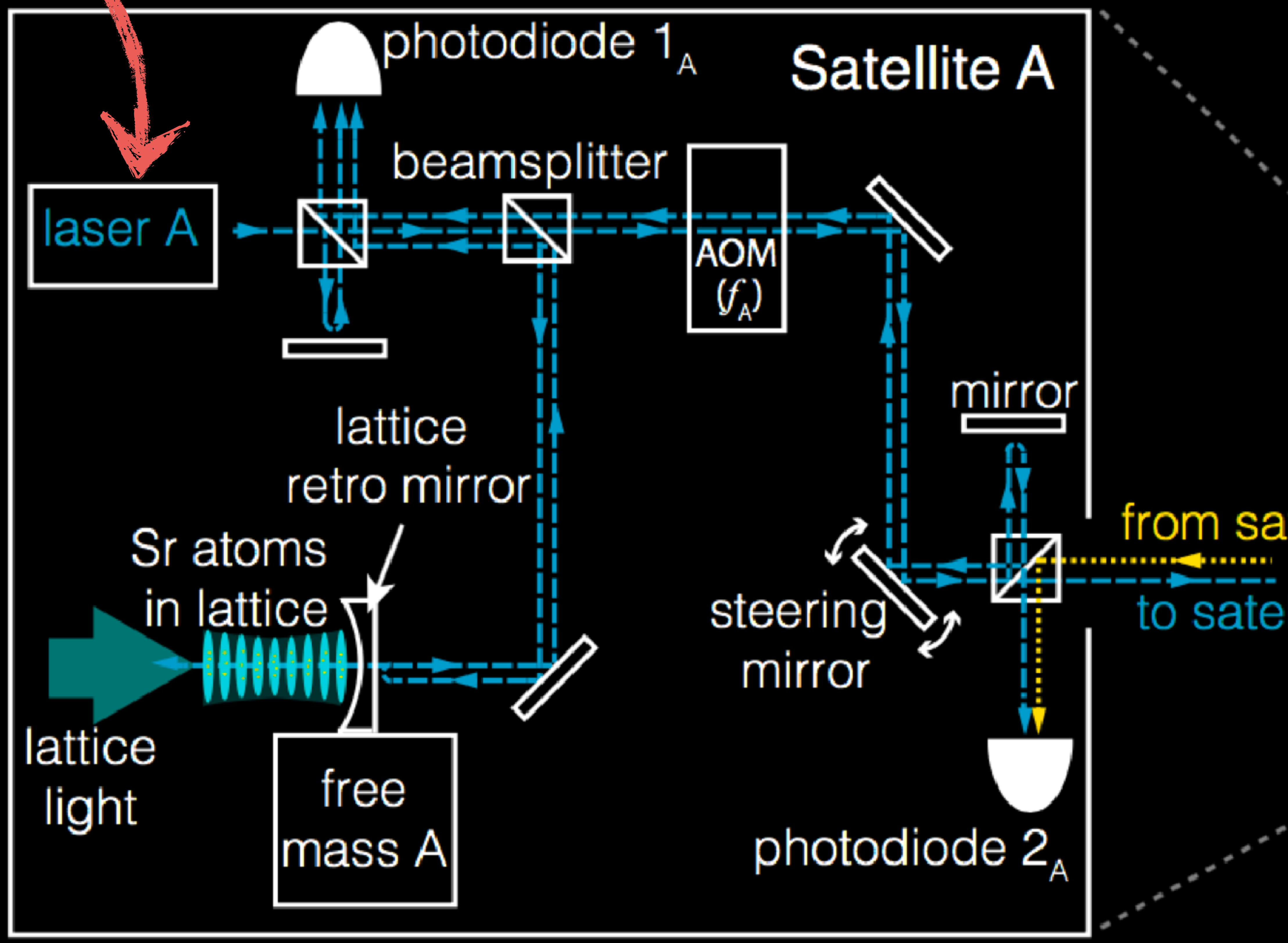
Low-Frequency GW Detection Using Atomic Clocks



Kolkowitz *et al.* 2016

Low-Frequency GW Detection Using Atomic Clocks

ultra-stable laser



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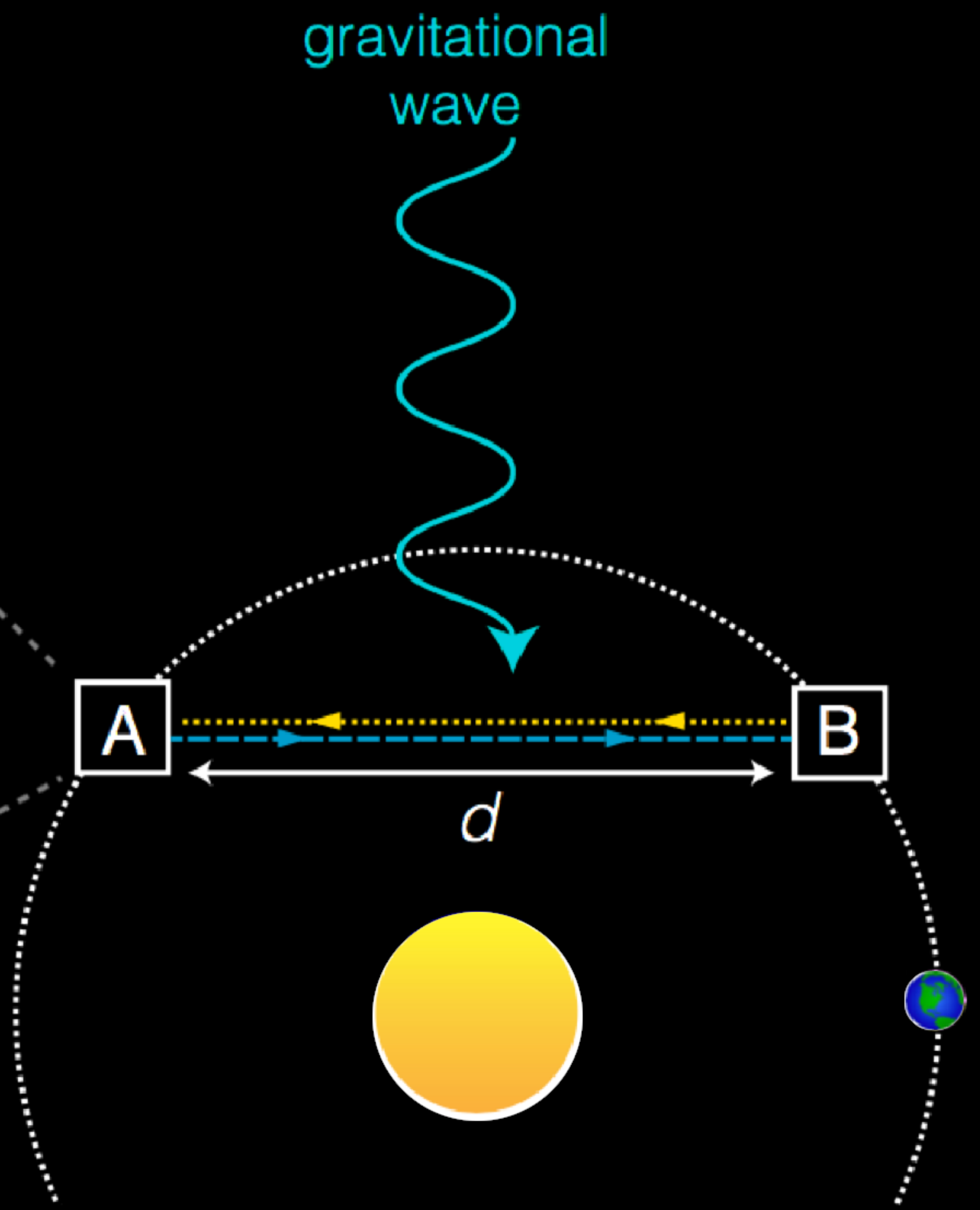

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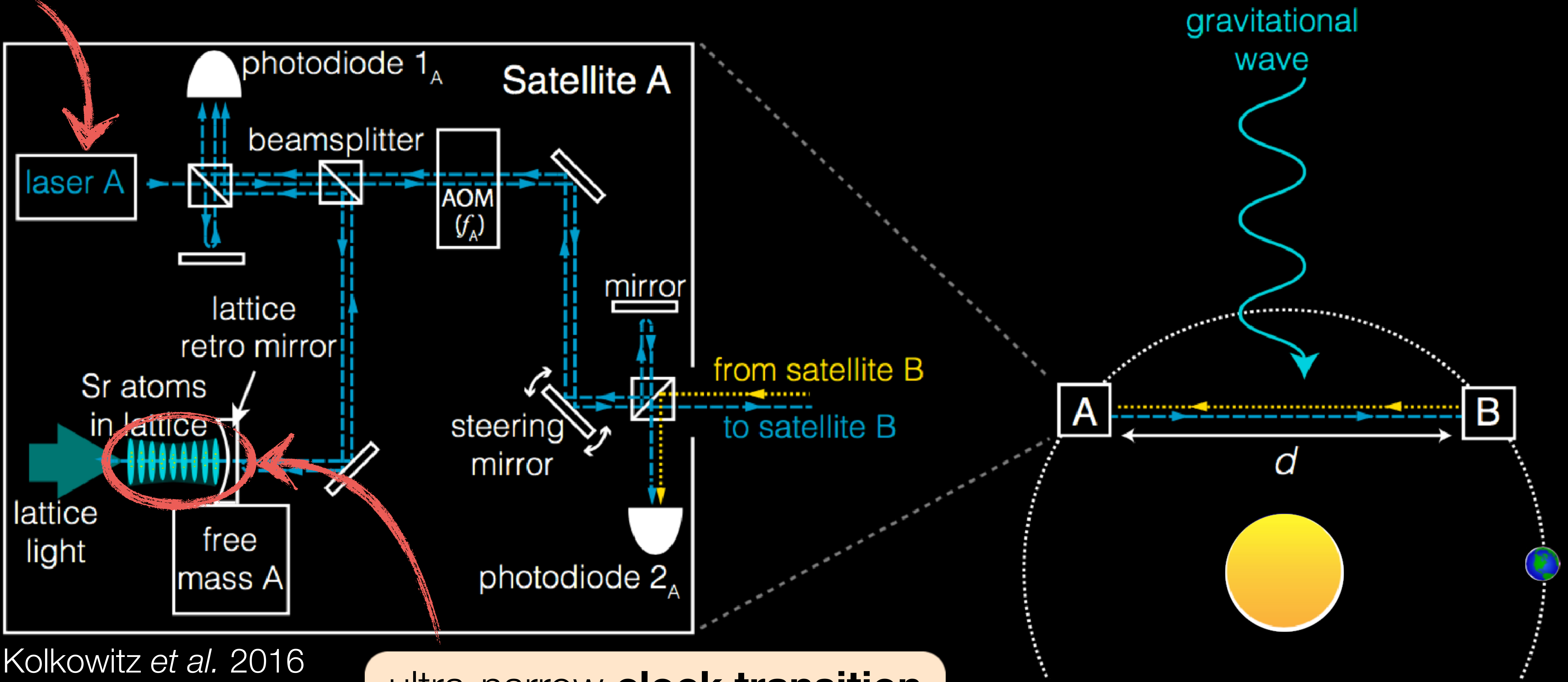


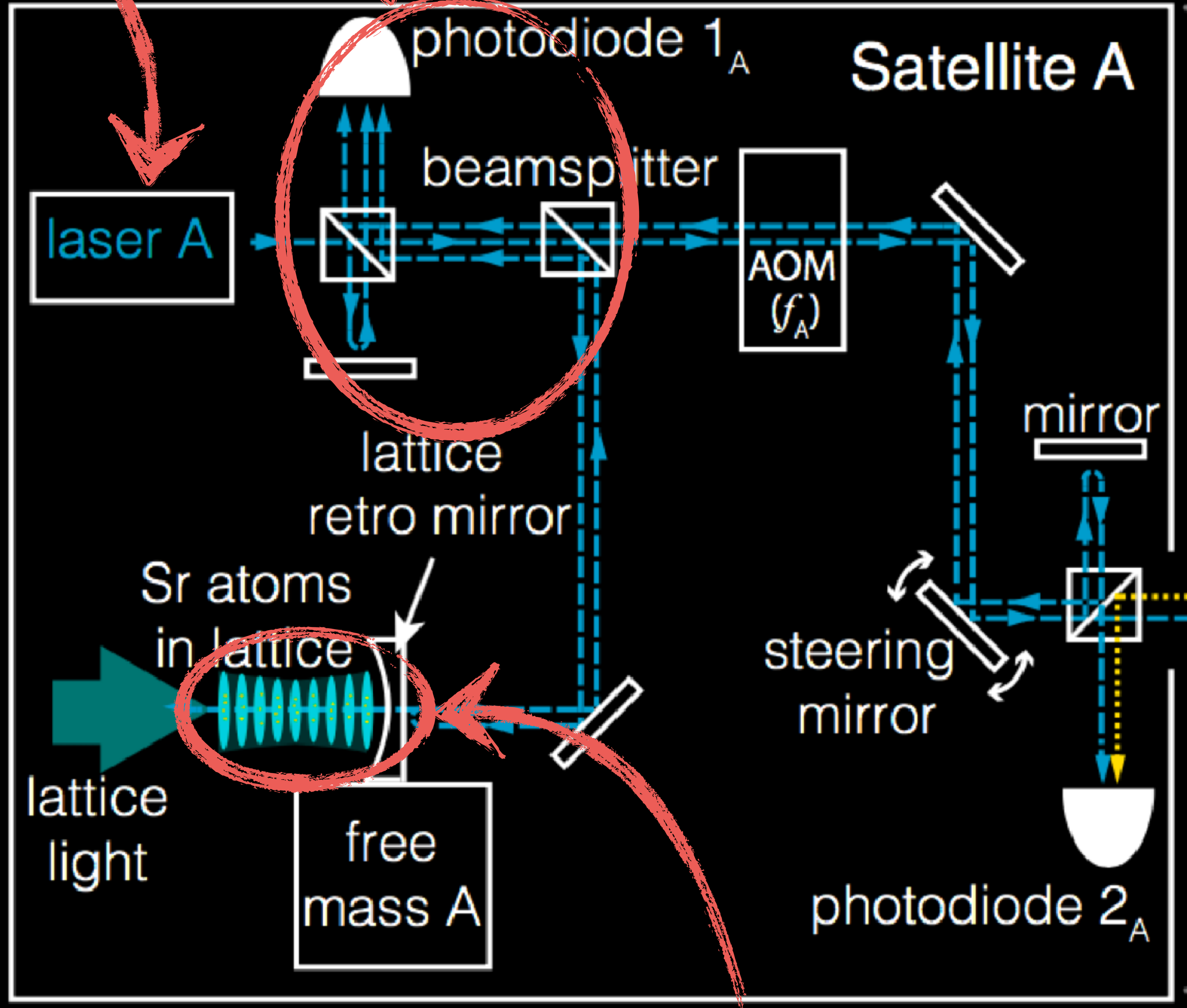
Kolkowitz *et al.* 2016

ultra-narrow **clock transition**
in free-falling atoms
provides **frequency reference**

Low-Frequenc Jsing Atomic Clocks

ultra-stable laser

interferometer measures relative motion between satellite and test mass



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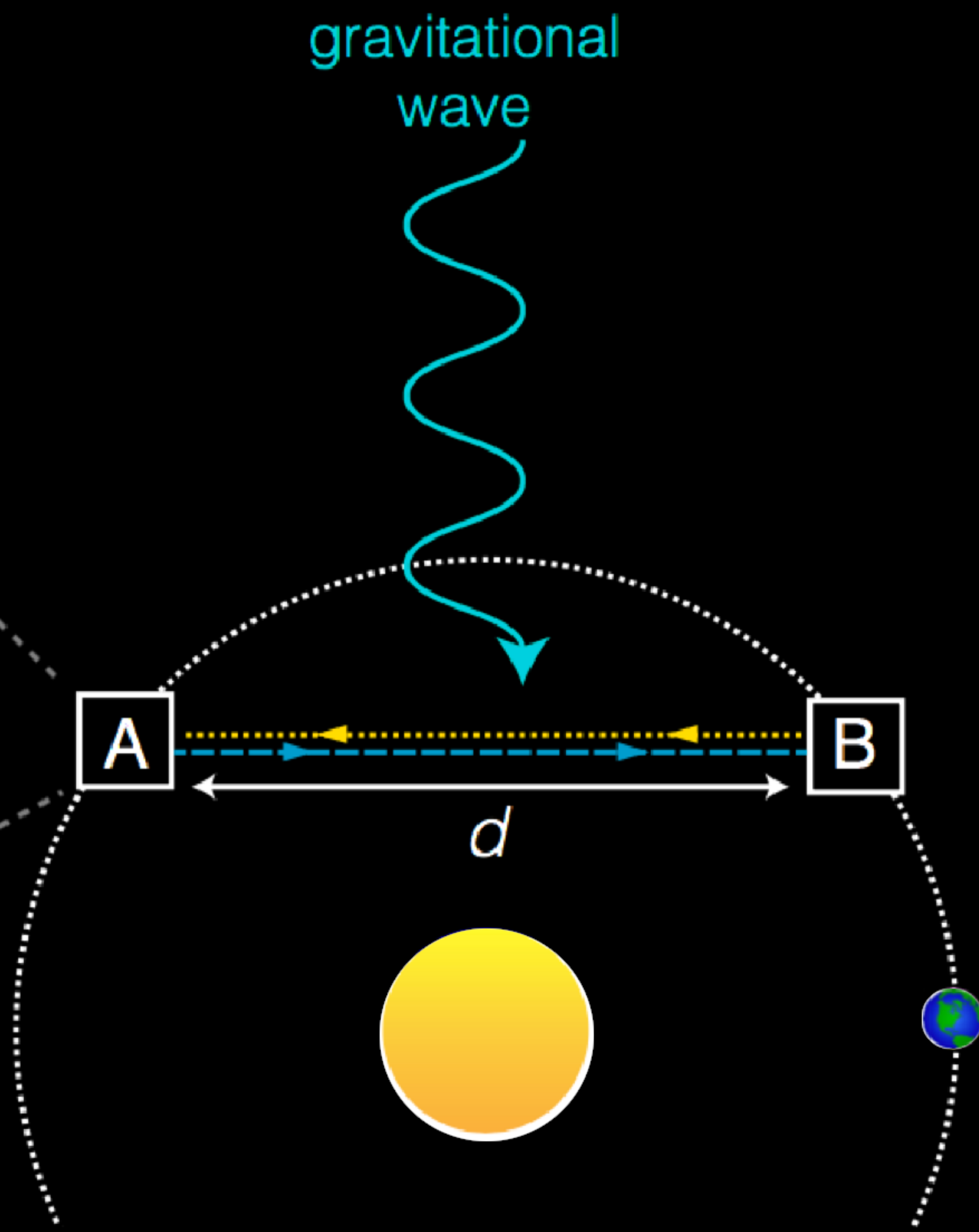

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Low-Frequenc… Using Atomic Clocks

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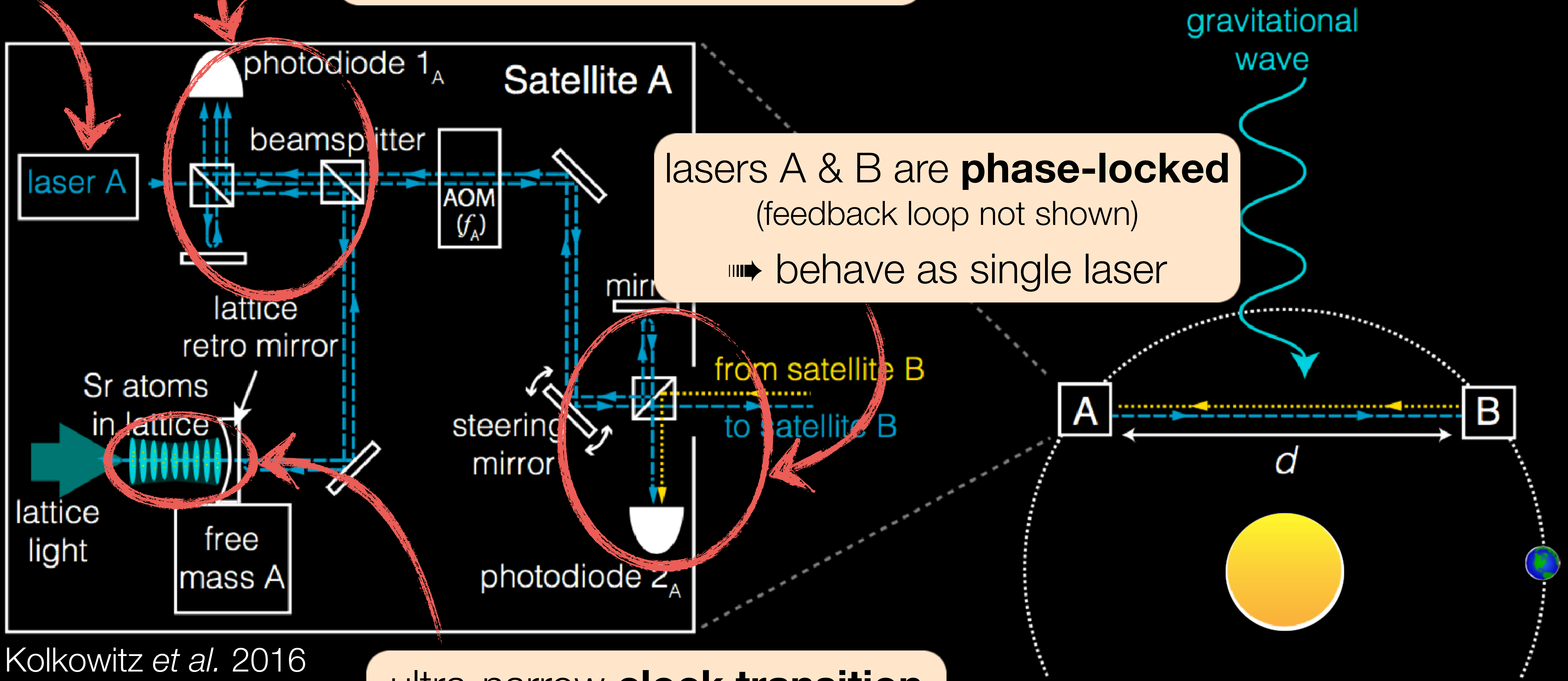


Kolkowitz *et al.* 2016

lasers A & B are **phase-locked**
(feedback loop not shown)
➠ behave as single laser

ultra-narrow **clock transition** in free-falling atoms provides **frequency reference**

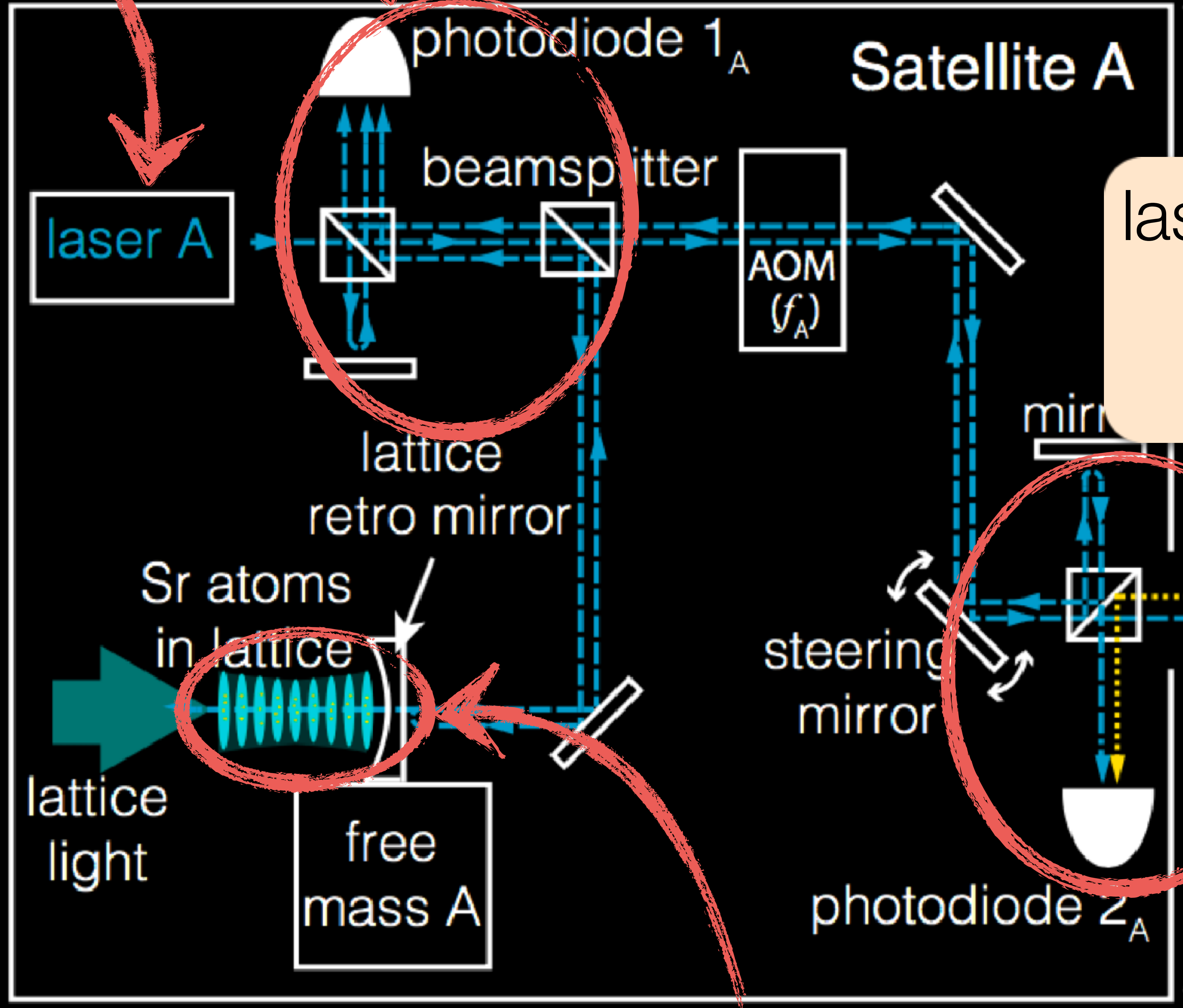
Low-Frequenc ... Using

ultra-stable laser

interferometer measures relative motion between satellite and test mass

clock readout (not shown) on both satellites compares laser frequency to clock transition.

GW causes differences between satellites A and B



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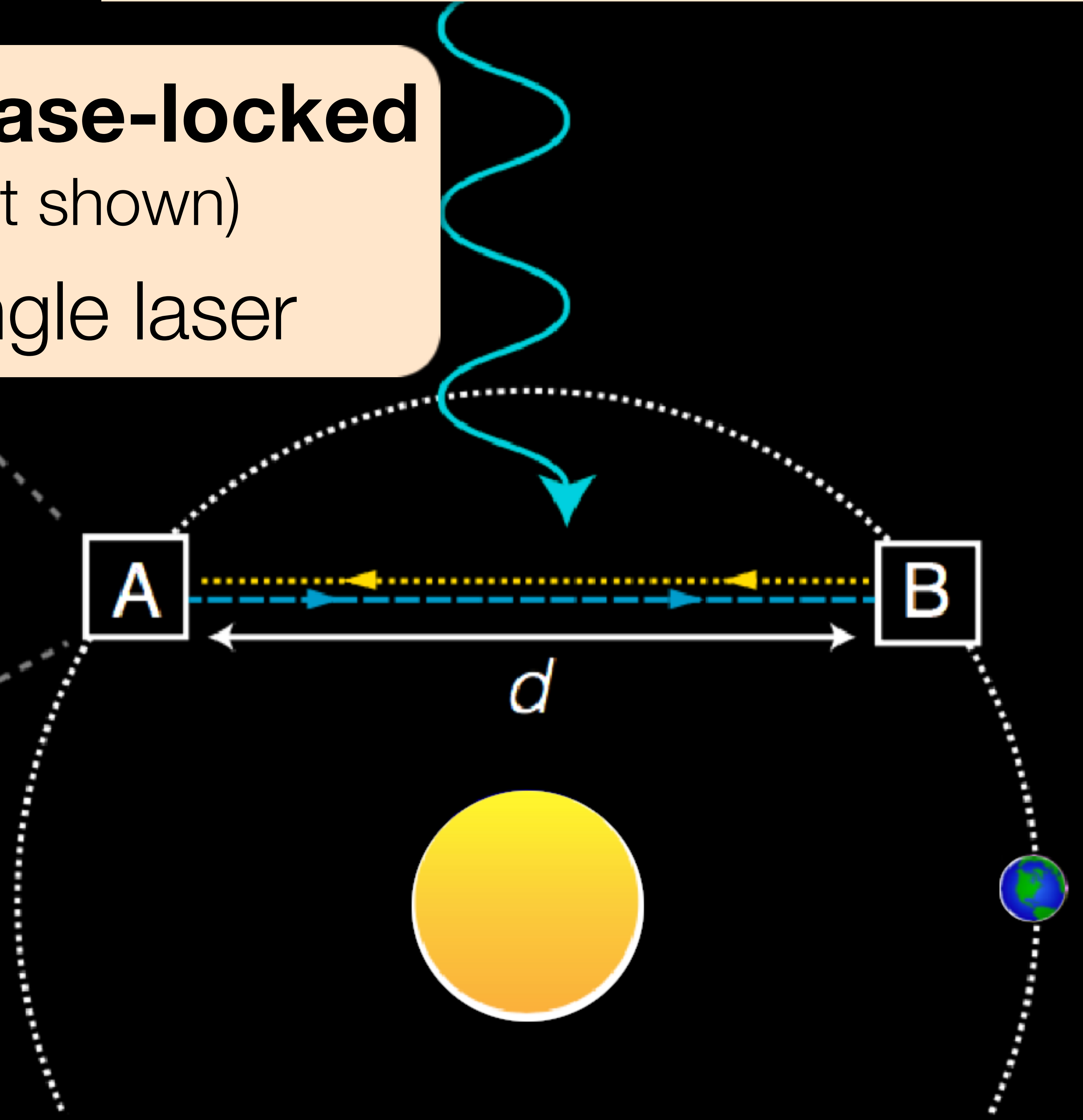

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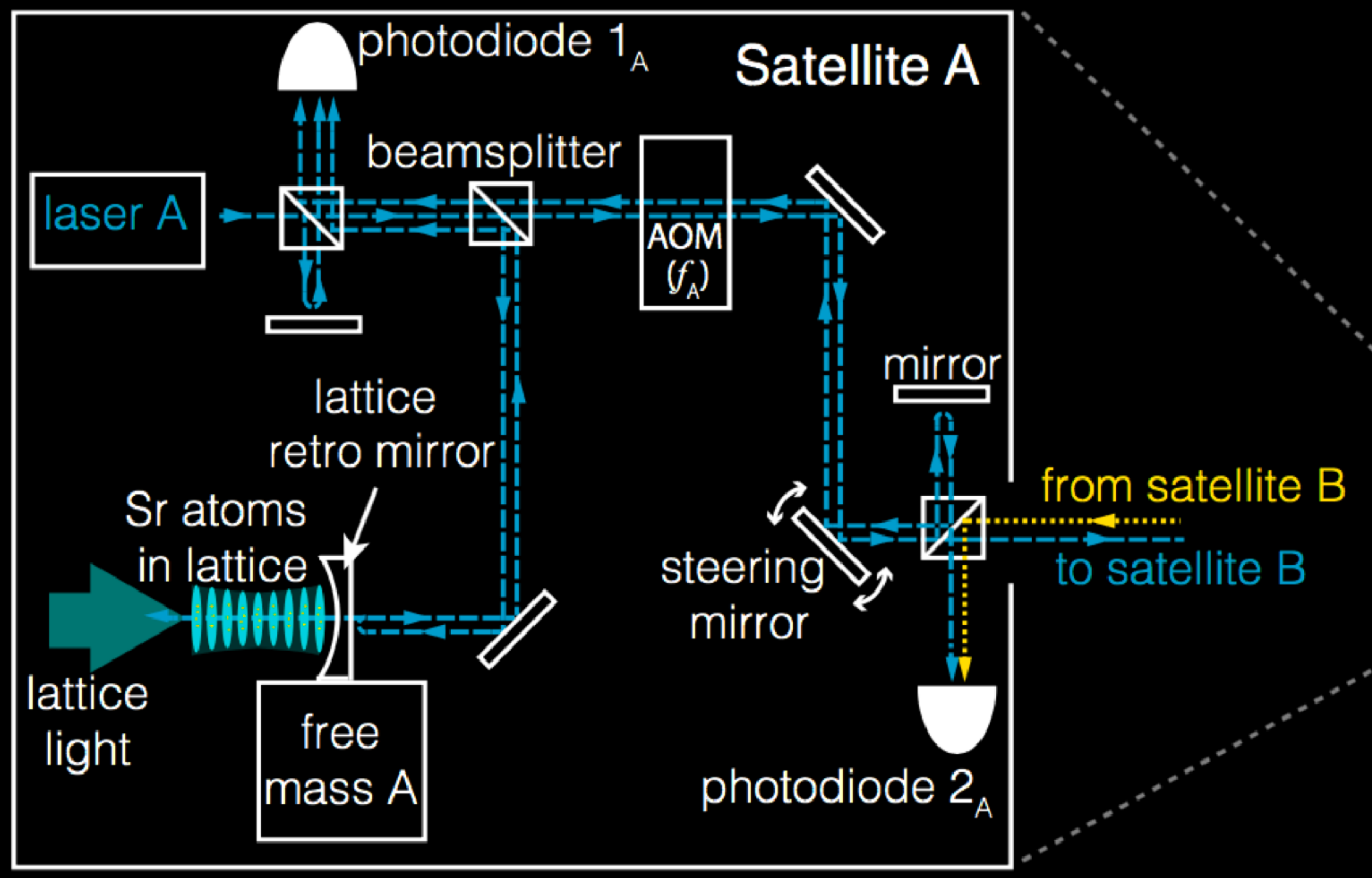
High-Frequency GW Detection Using Atomic Clocks

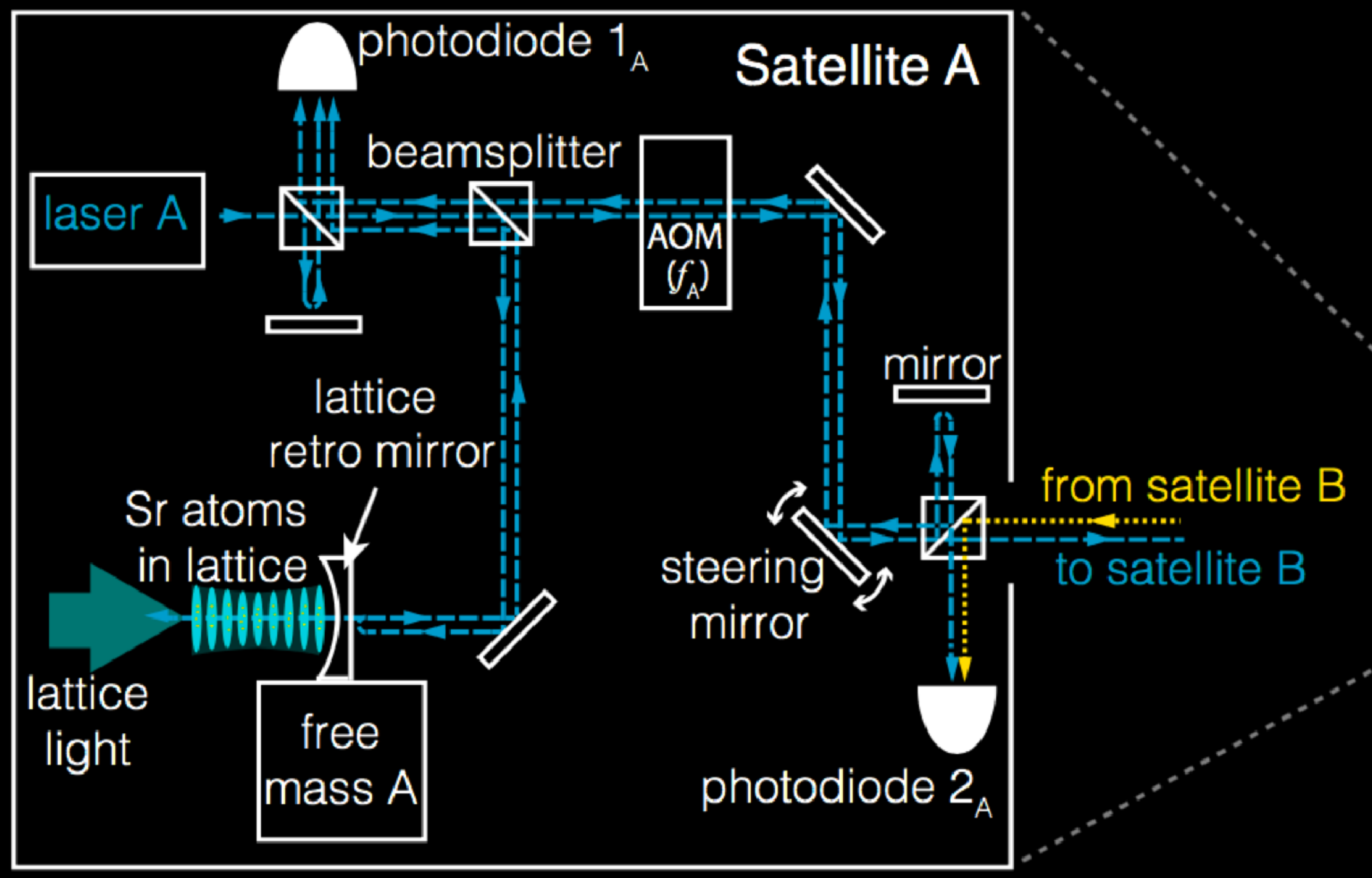
- scale the system *down* to laboratory scales



High-Frequency GW Detection Using Atomic Clocks

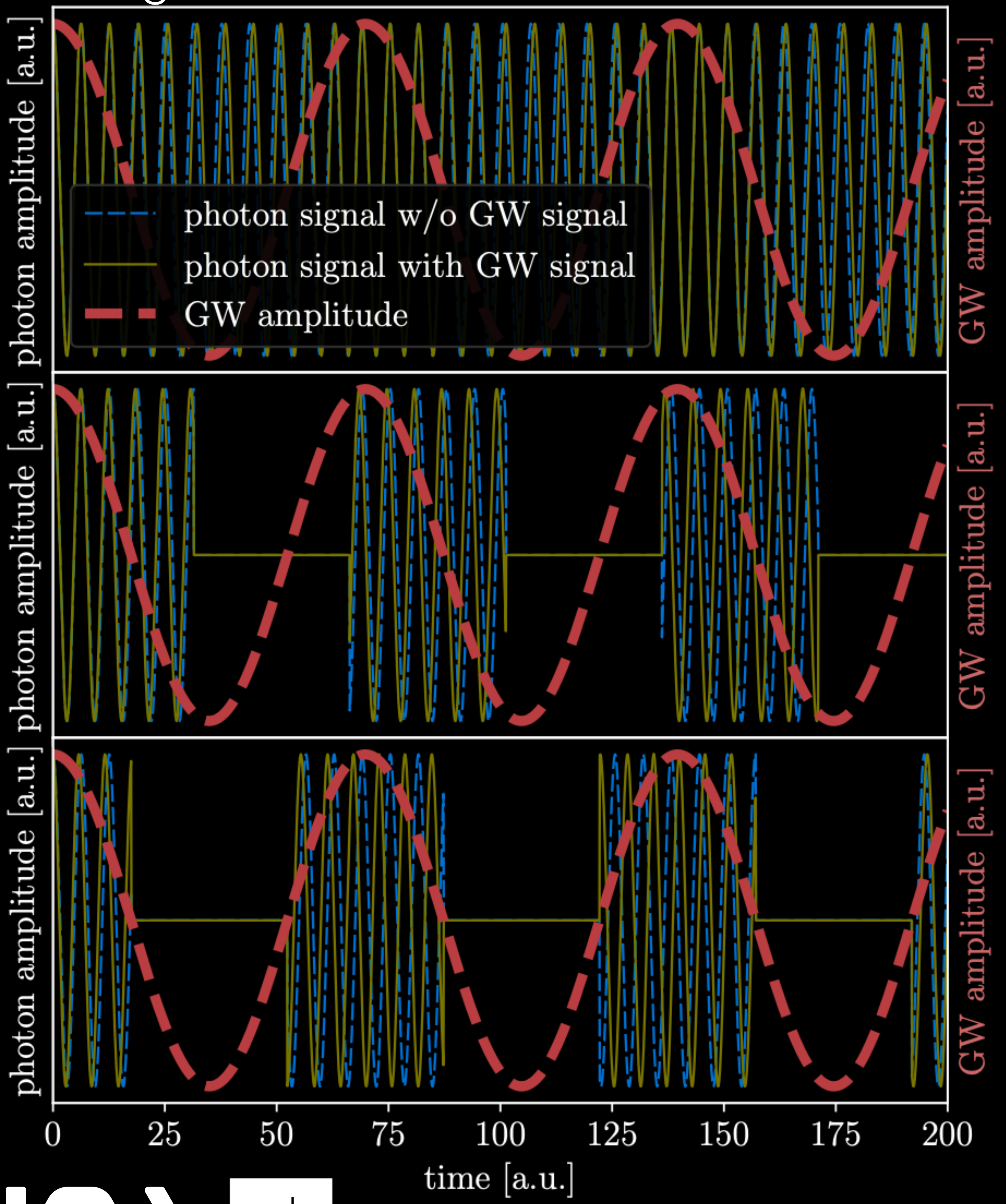
- scale the system *down* to laboratory scales
- high precision requires long interrogation times …
- … but leads to averaging of the signal

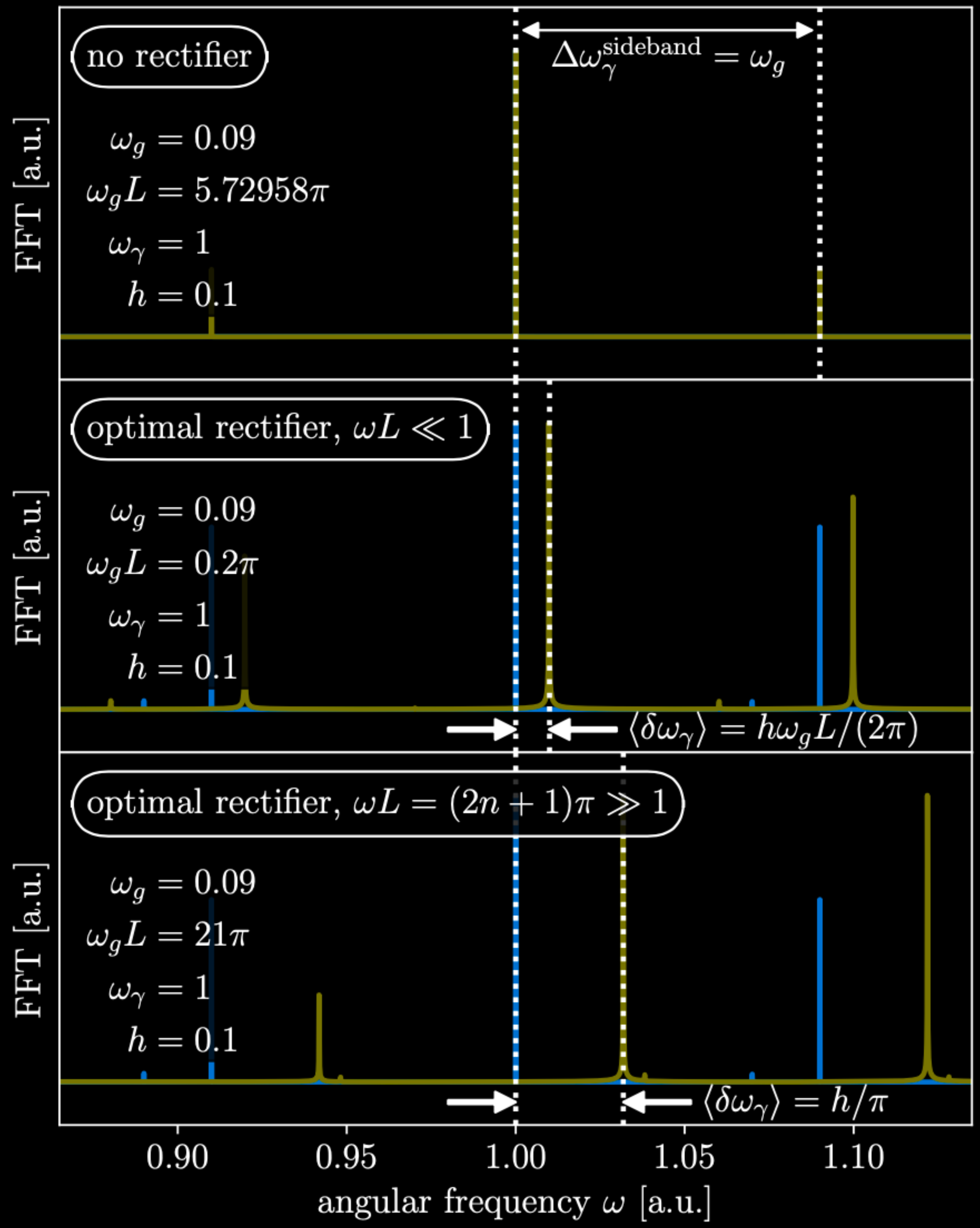
Proposal: **“optical rectifier”**



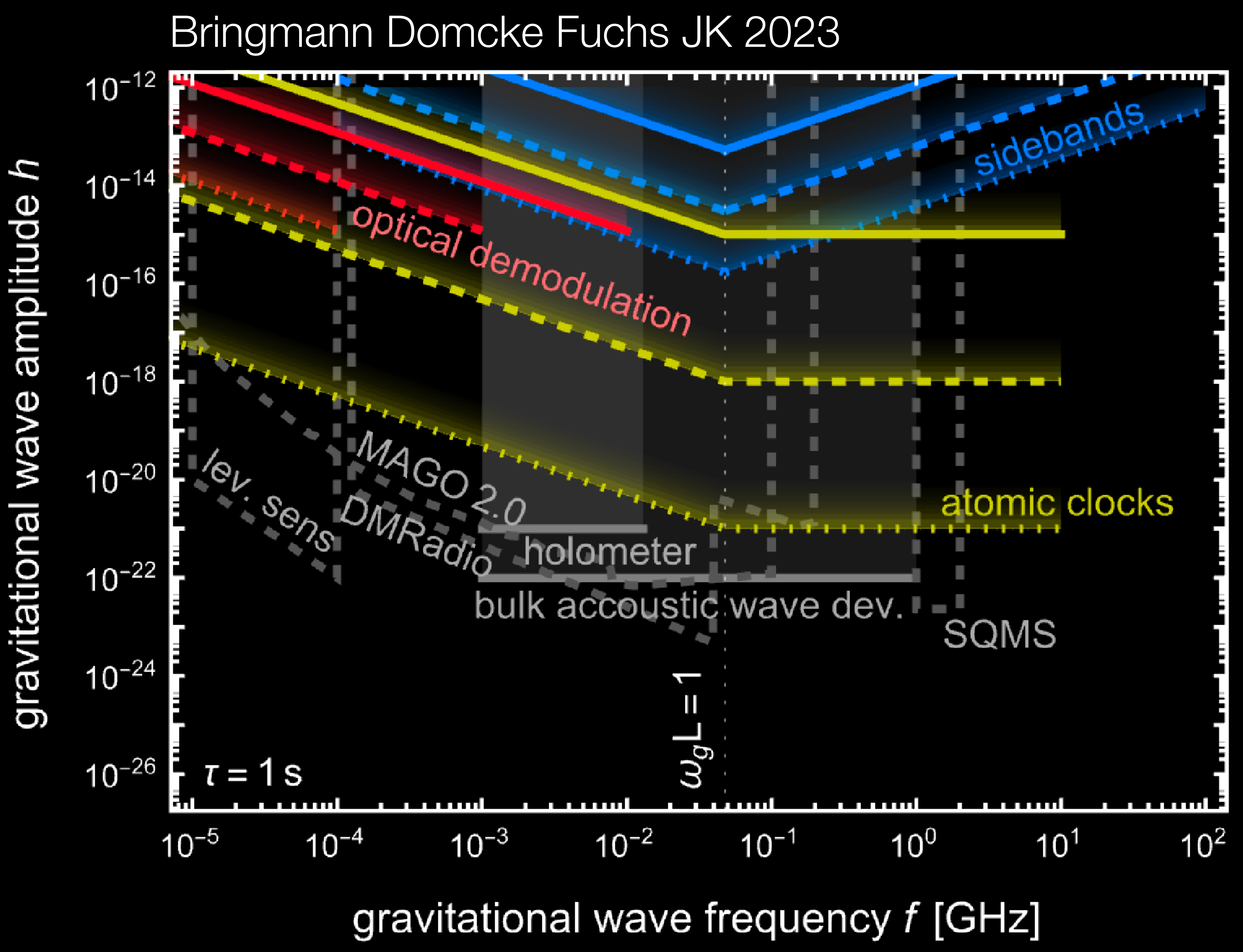
High-Frequency GW Detection Using Atomic Clocks

Bringmann Domcke Fuchs JK 2023





Sensitivity Projections



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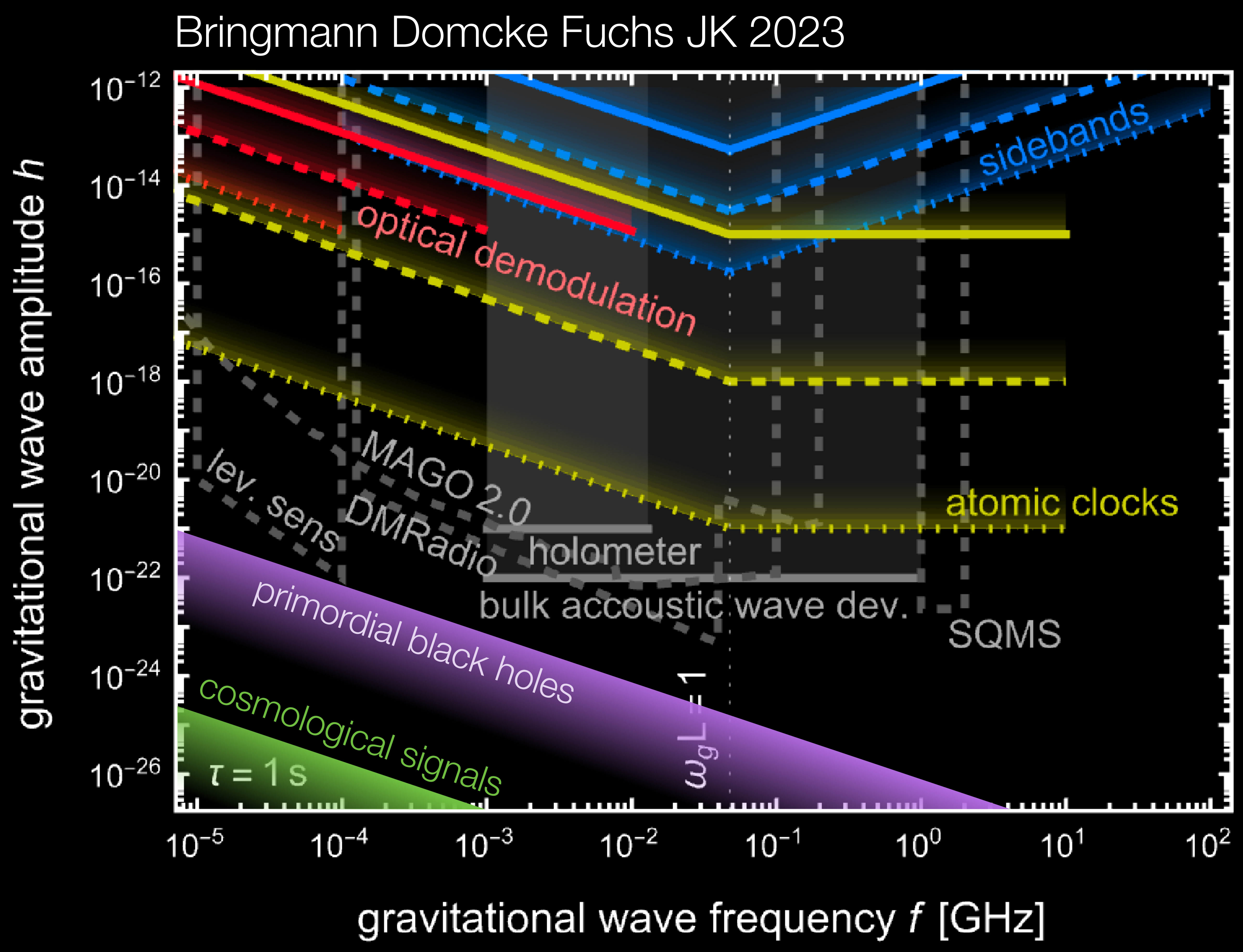
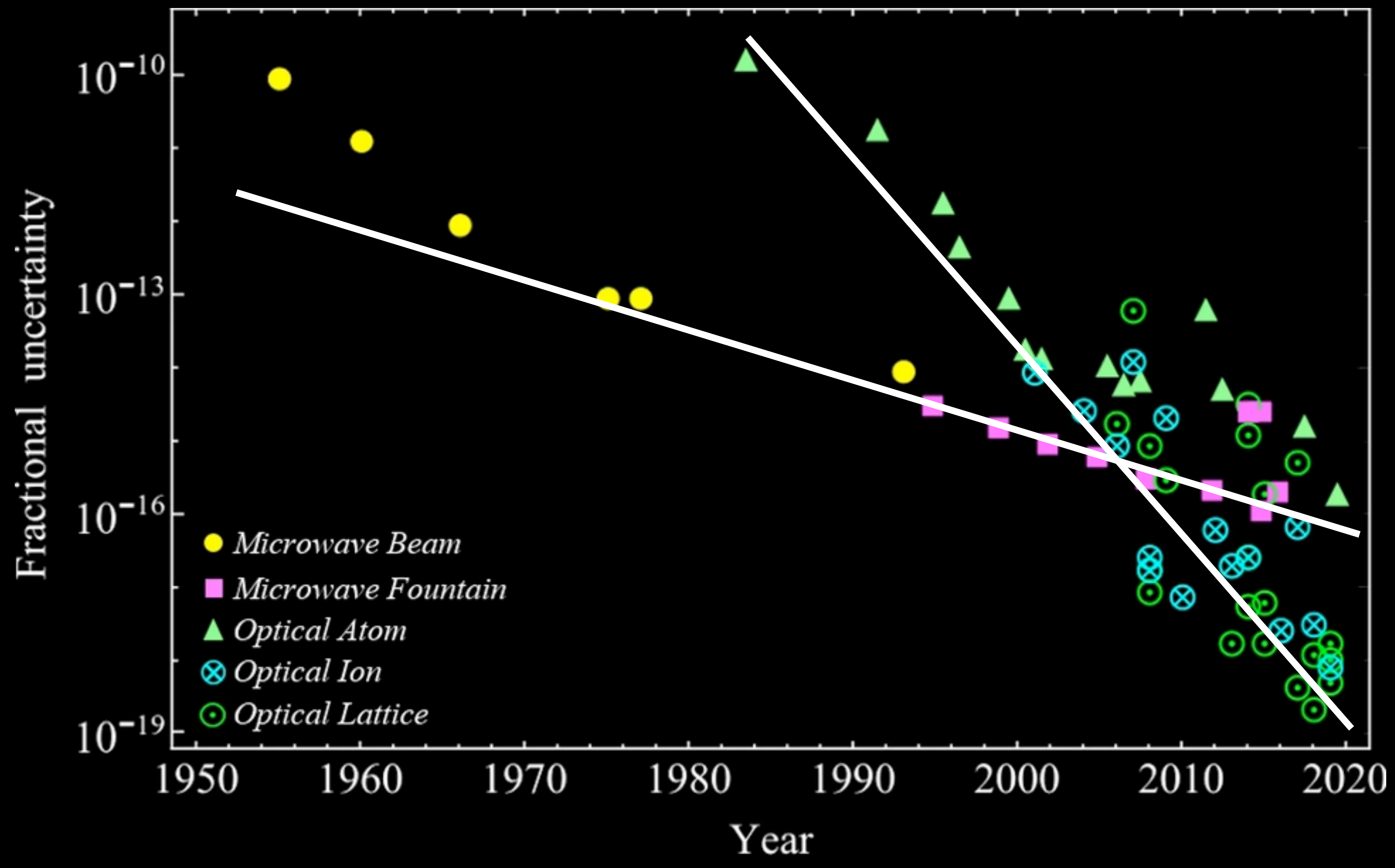


Atomic Clocks are Amazing

Sharma *et al.* 2023



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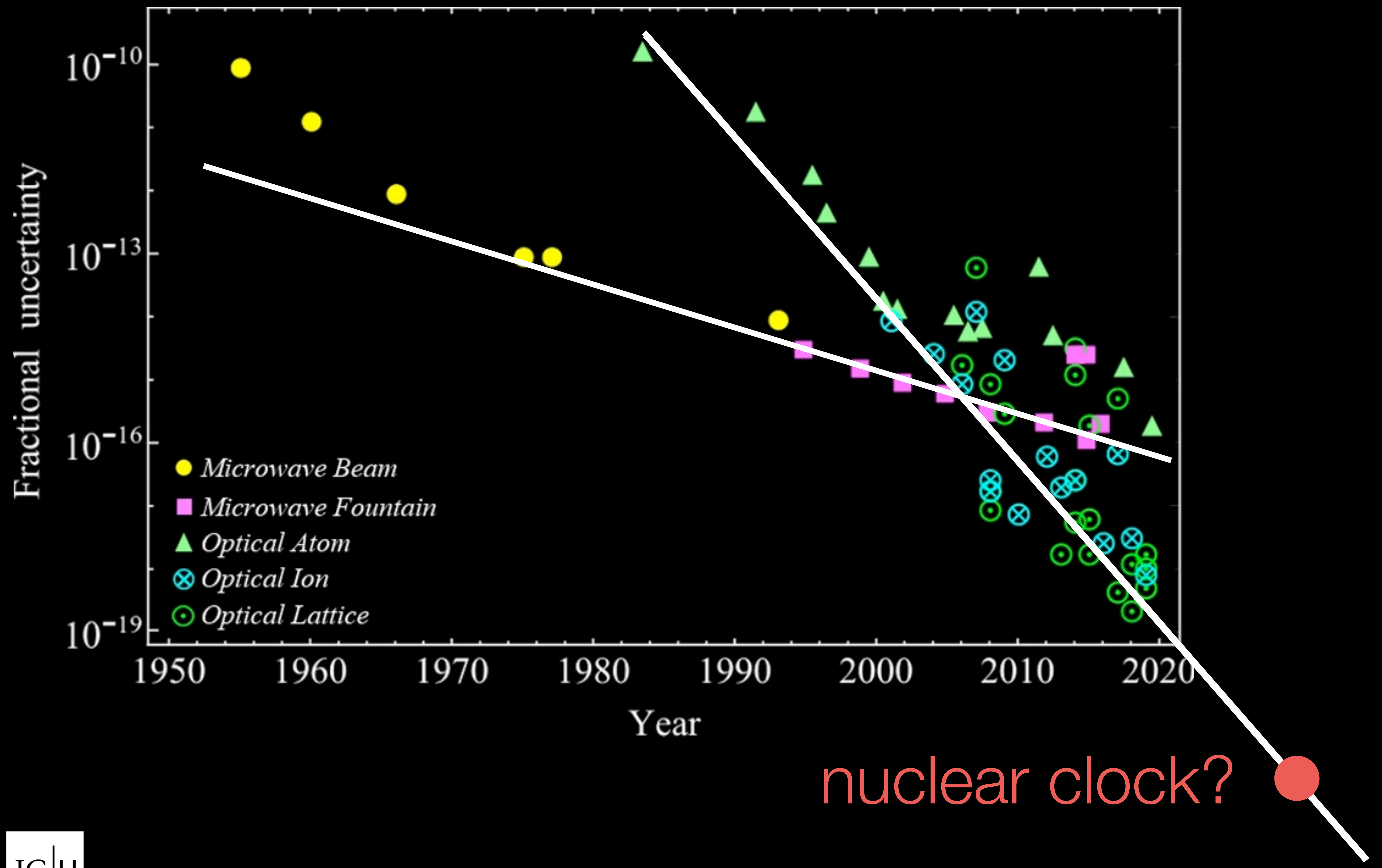
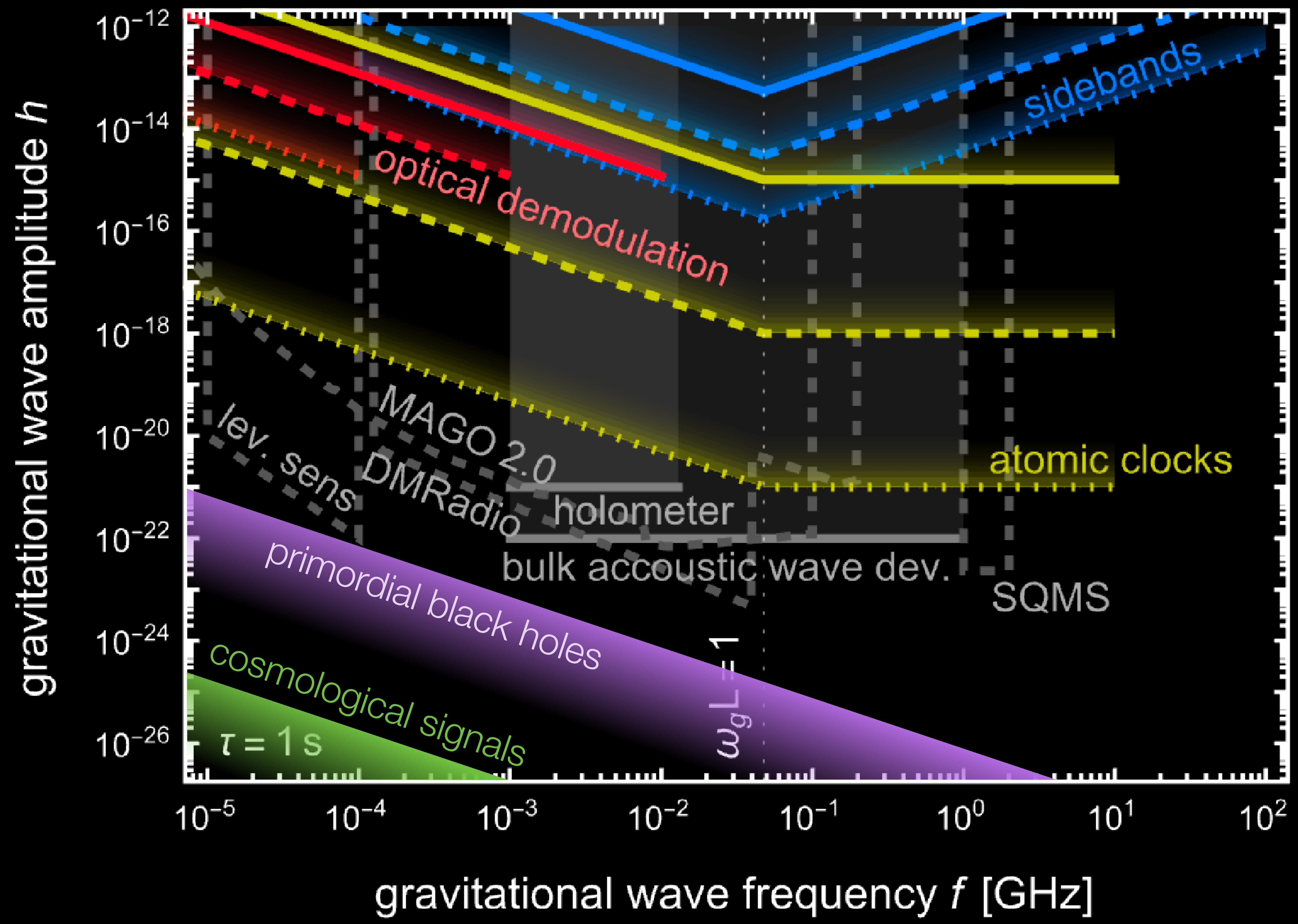


Other HF-GW Detection Techniques



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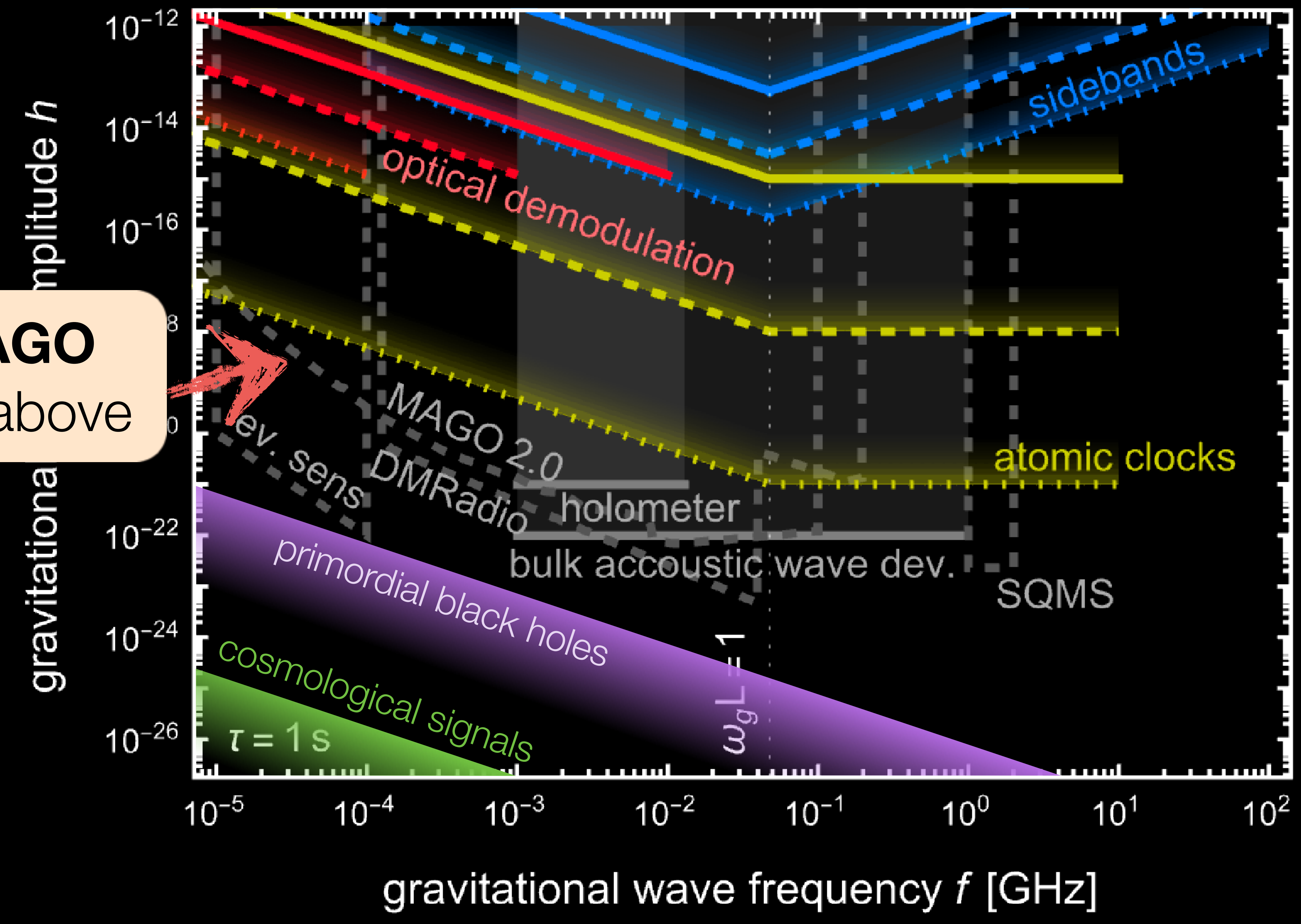

MAGO
see above

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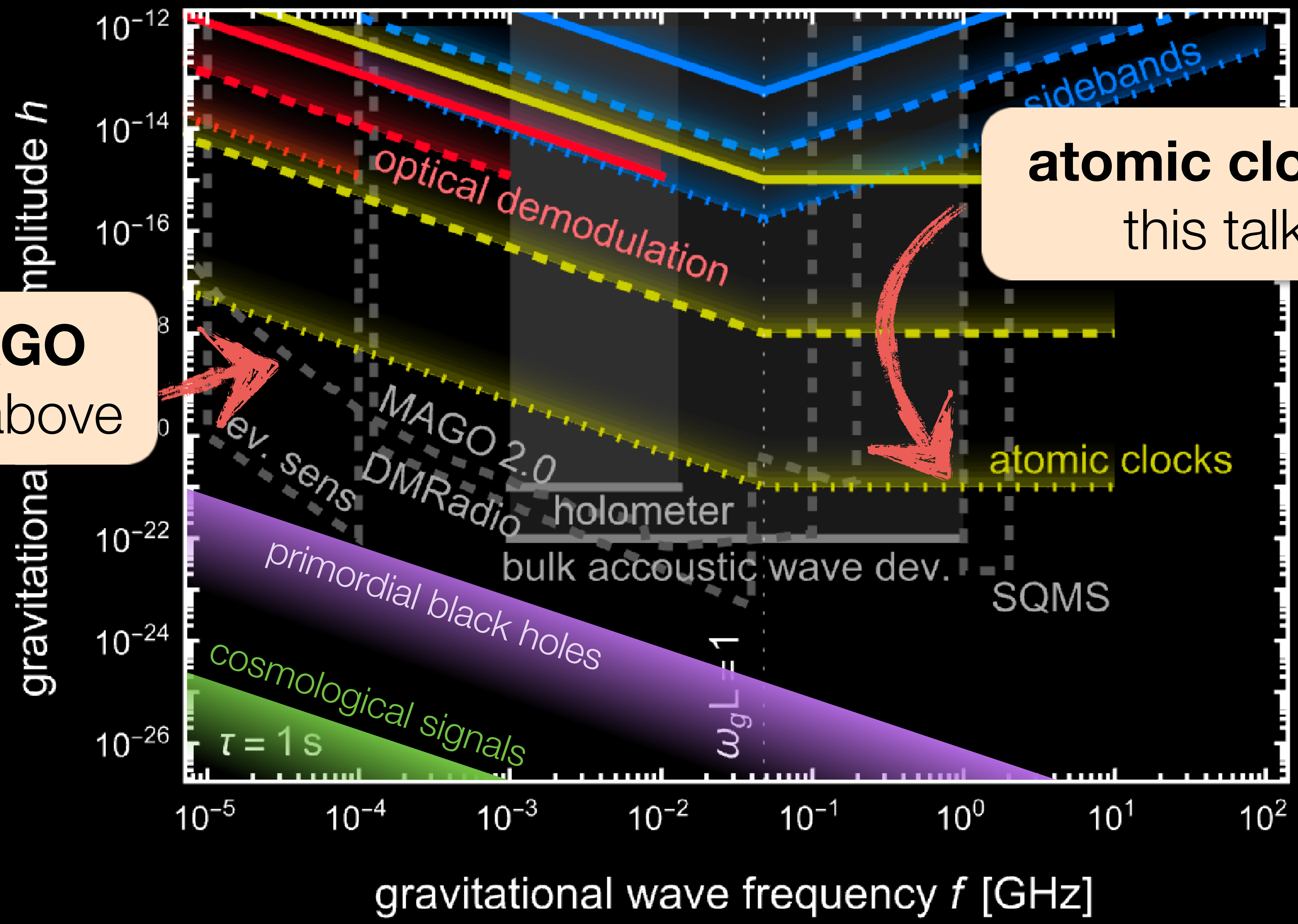

atomic clocks
this talk

MAGO
see above

Other Detection Techniques

levitated sensors

nano-particle trapped by standing optical waves; passing GW stretches cavity;

➠ particle moves

Aggarwal et al. 2020

MAGO

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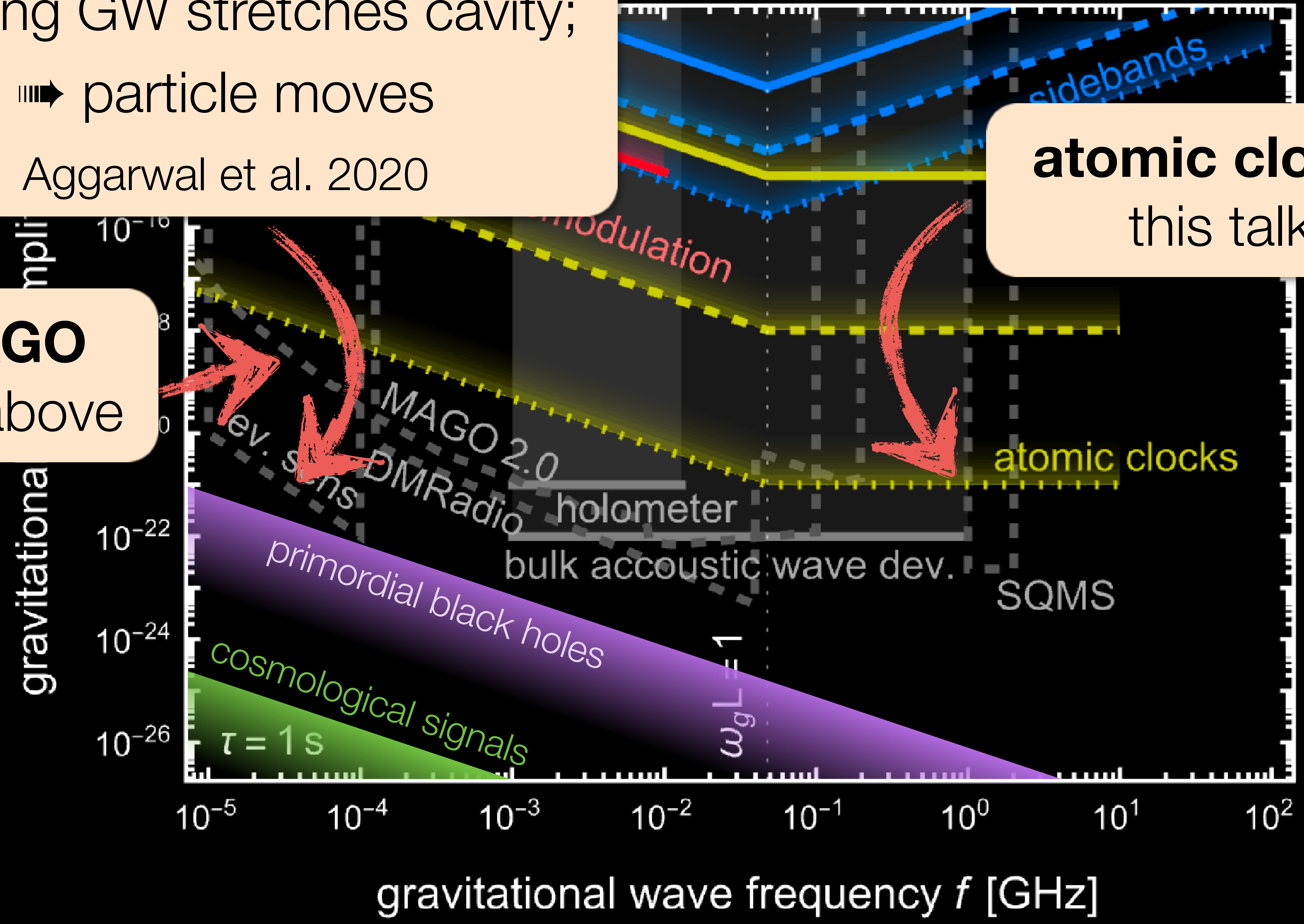
atomic clocks

this talk



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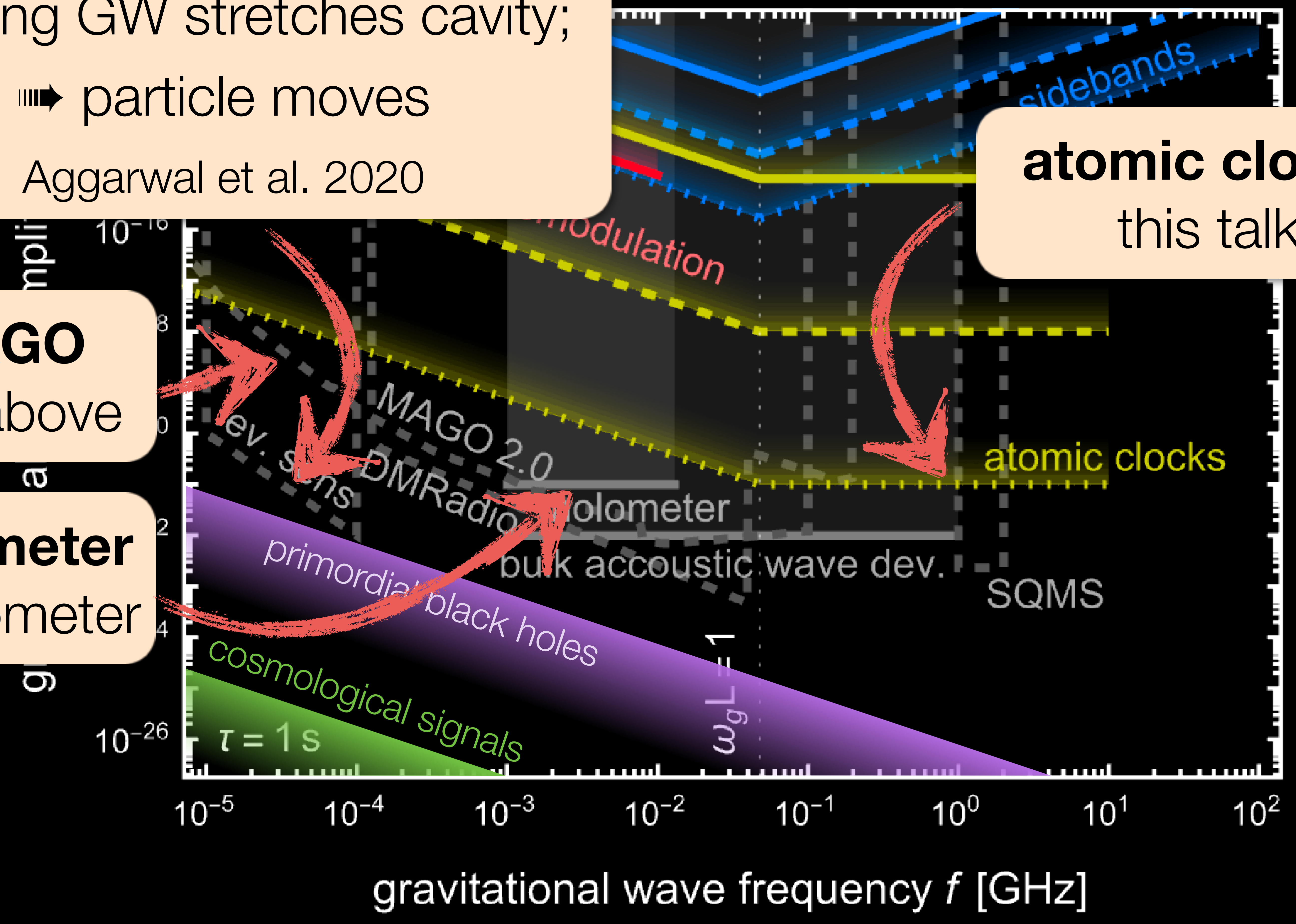

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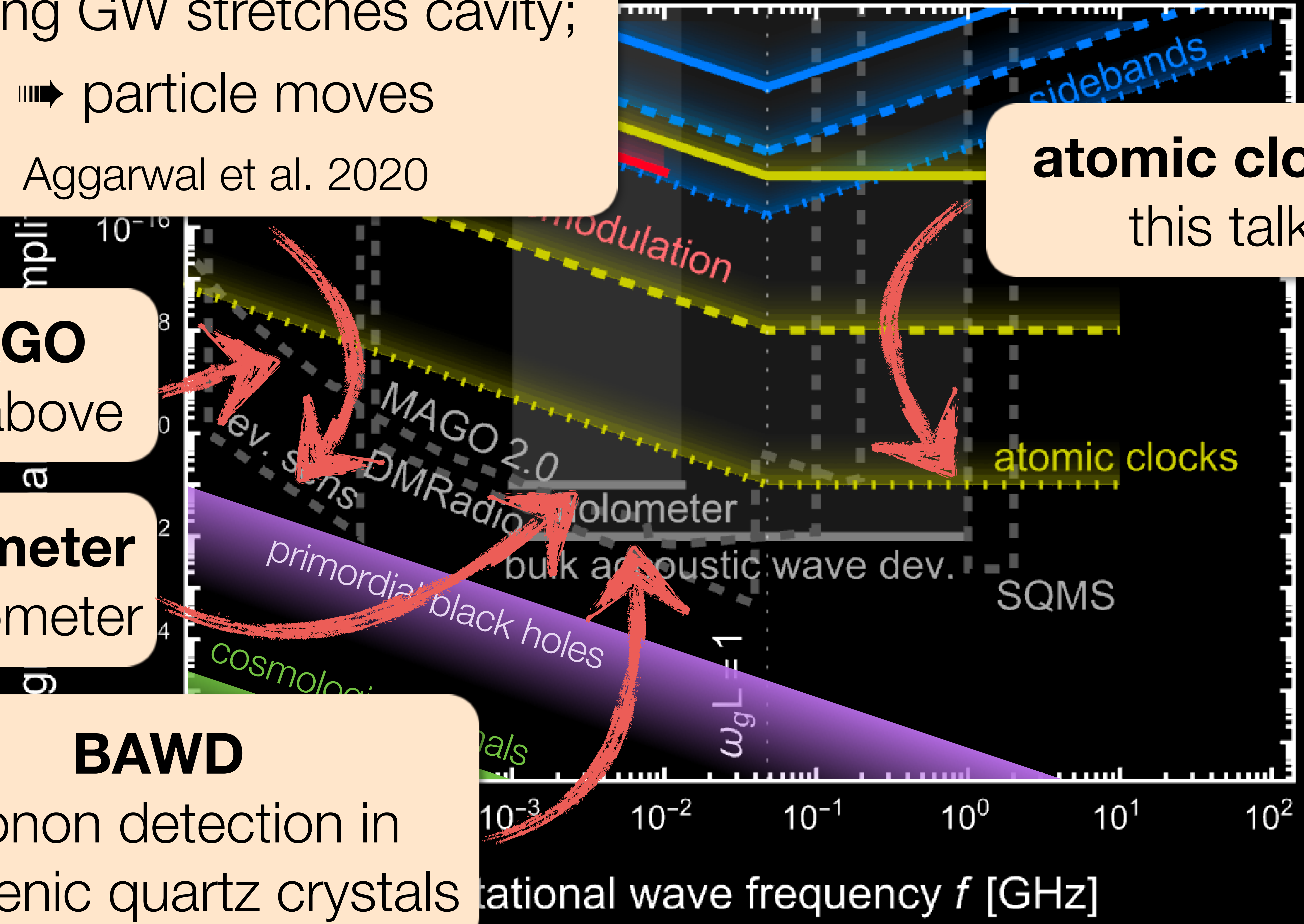

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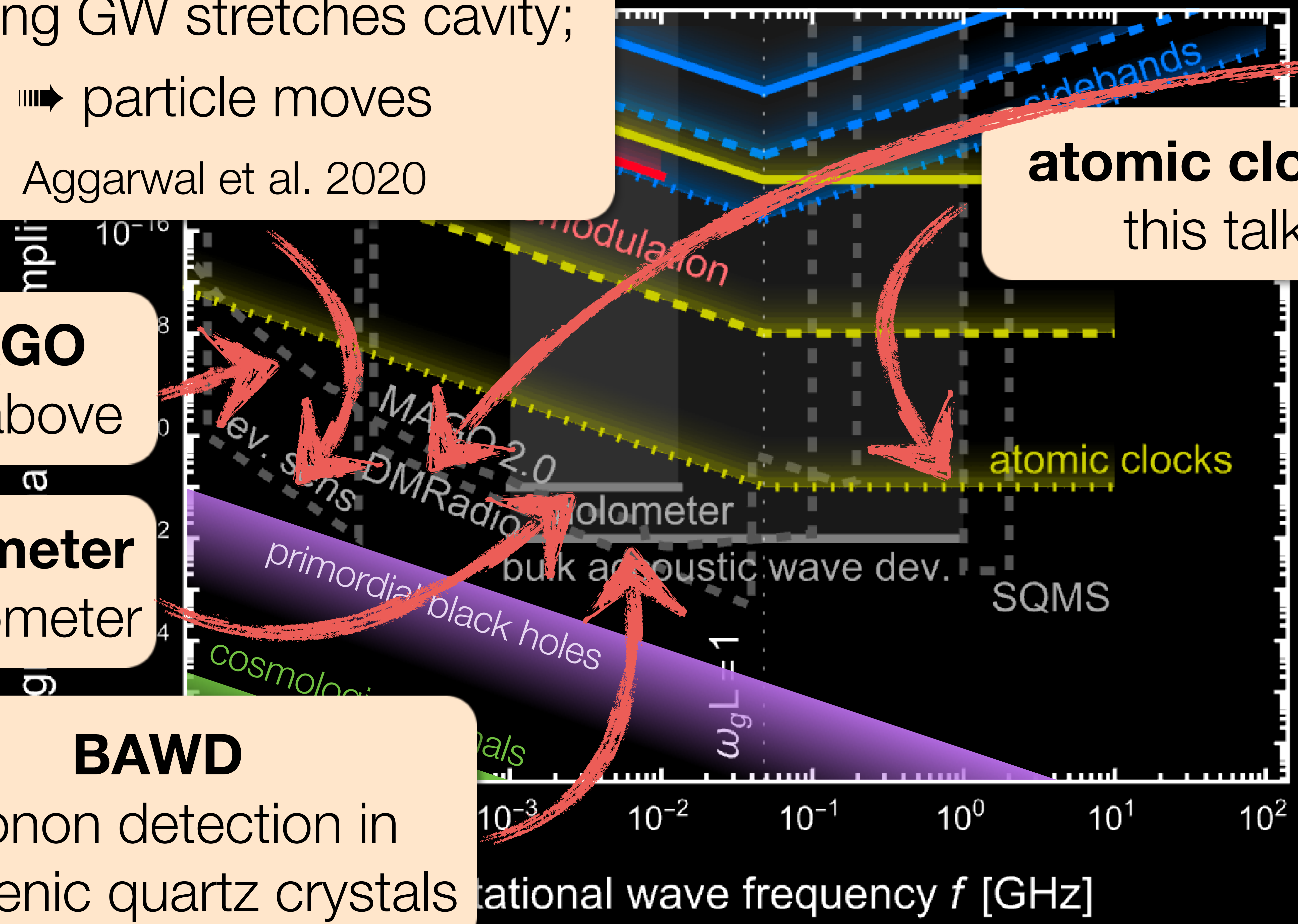

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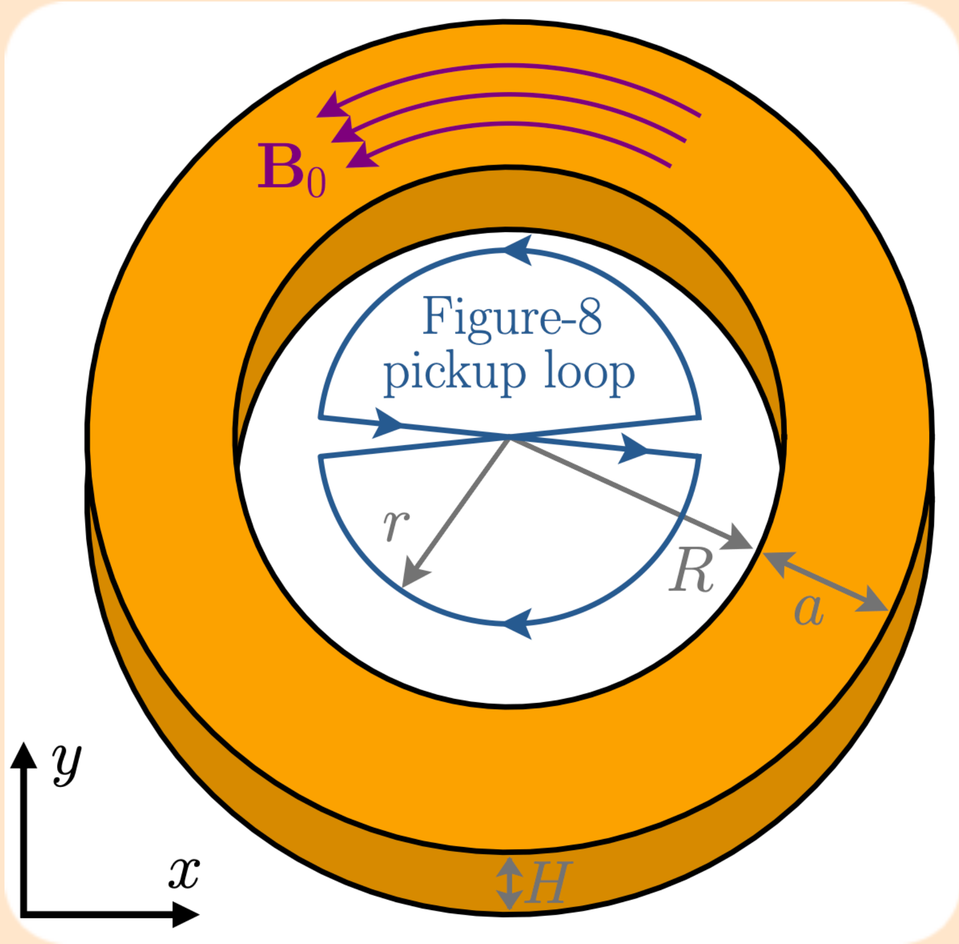
DMRadio

GW + B_0 field leads to magnetic flux in pickup loop



Domcke Garcia-Cely Rodd 2023

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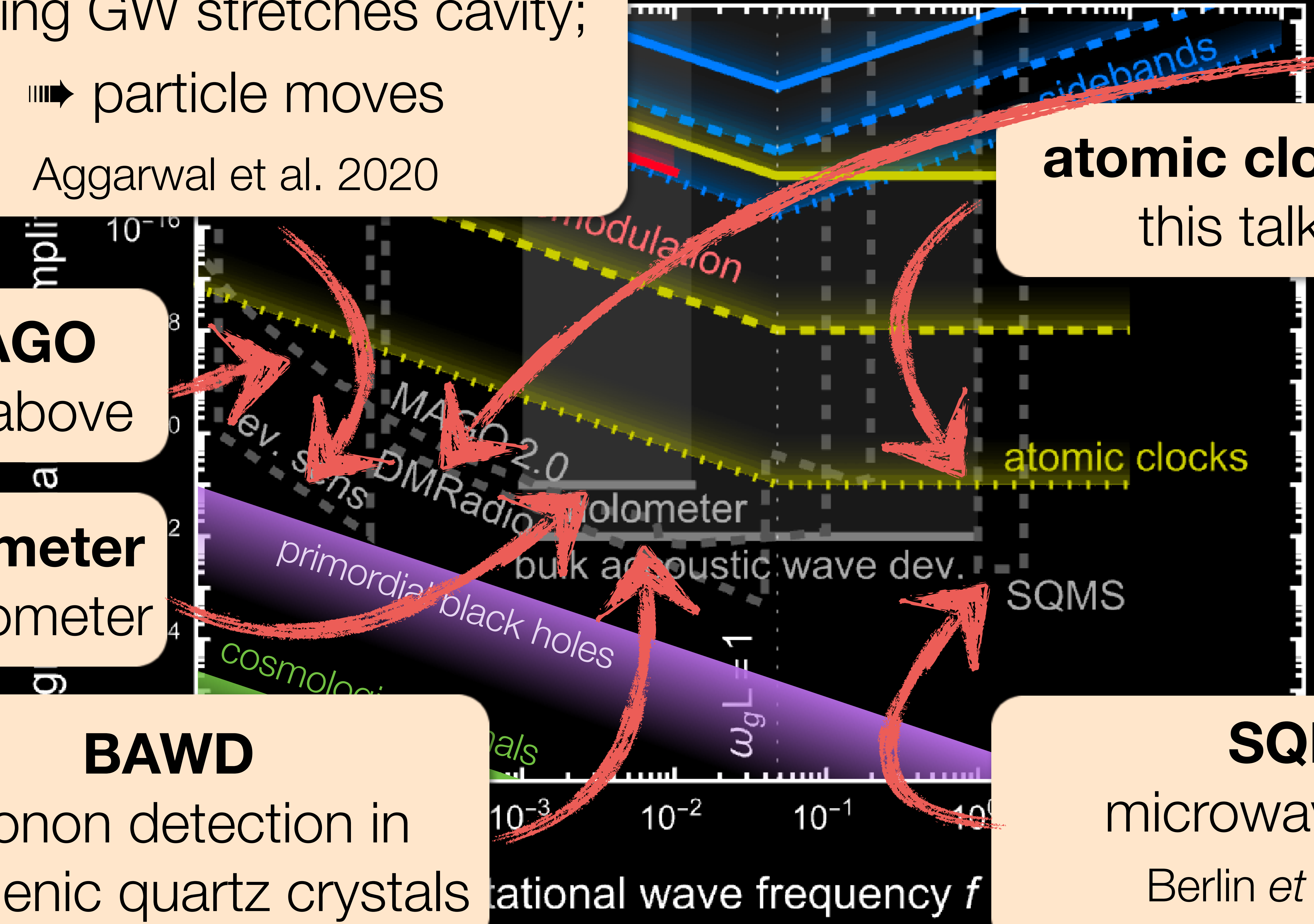

atomic clocks

this talk

SQMS

microwave cavity

Berlin *et al.* 2021

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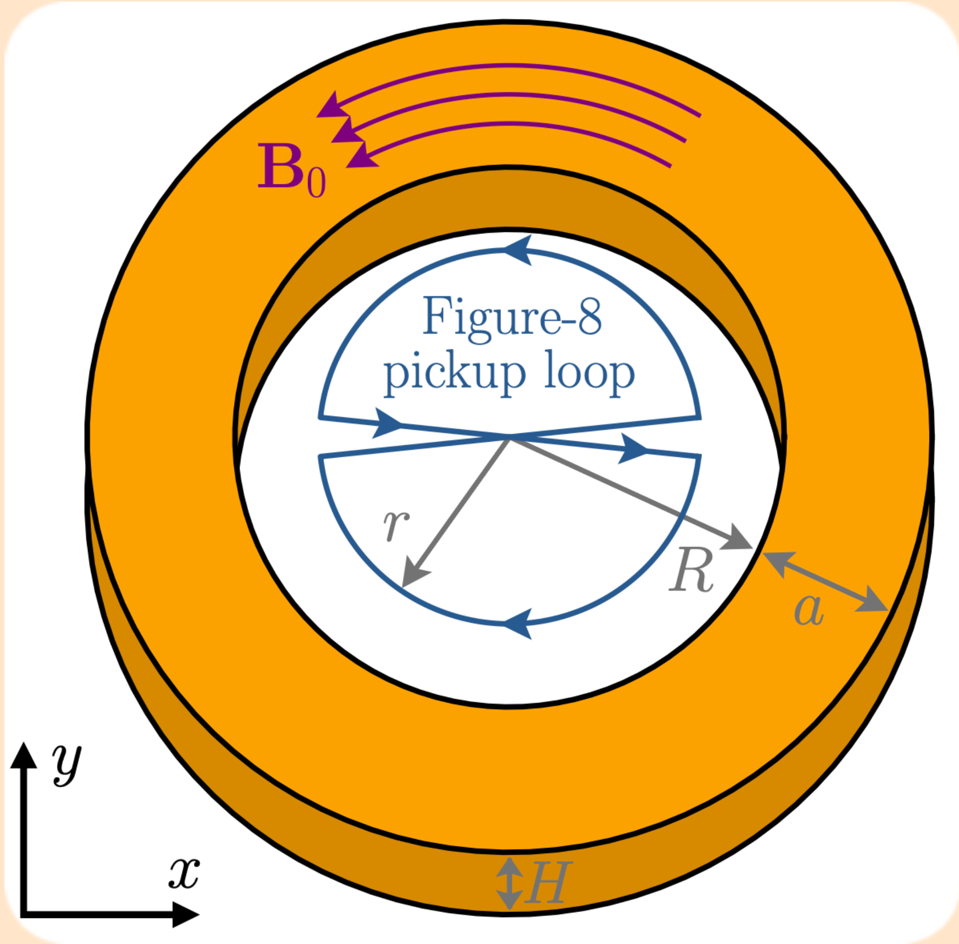

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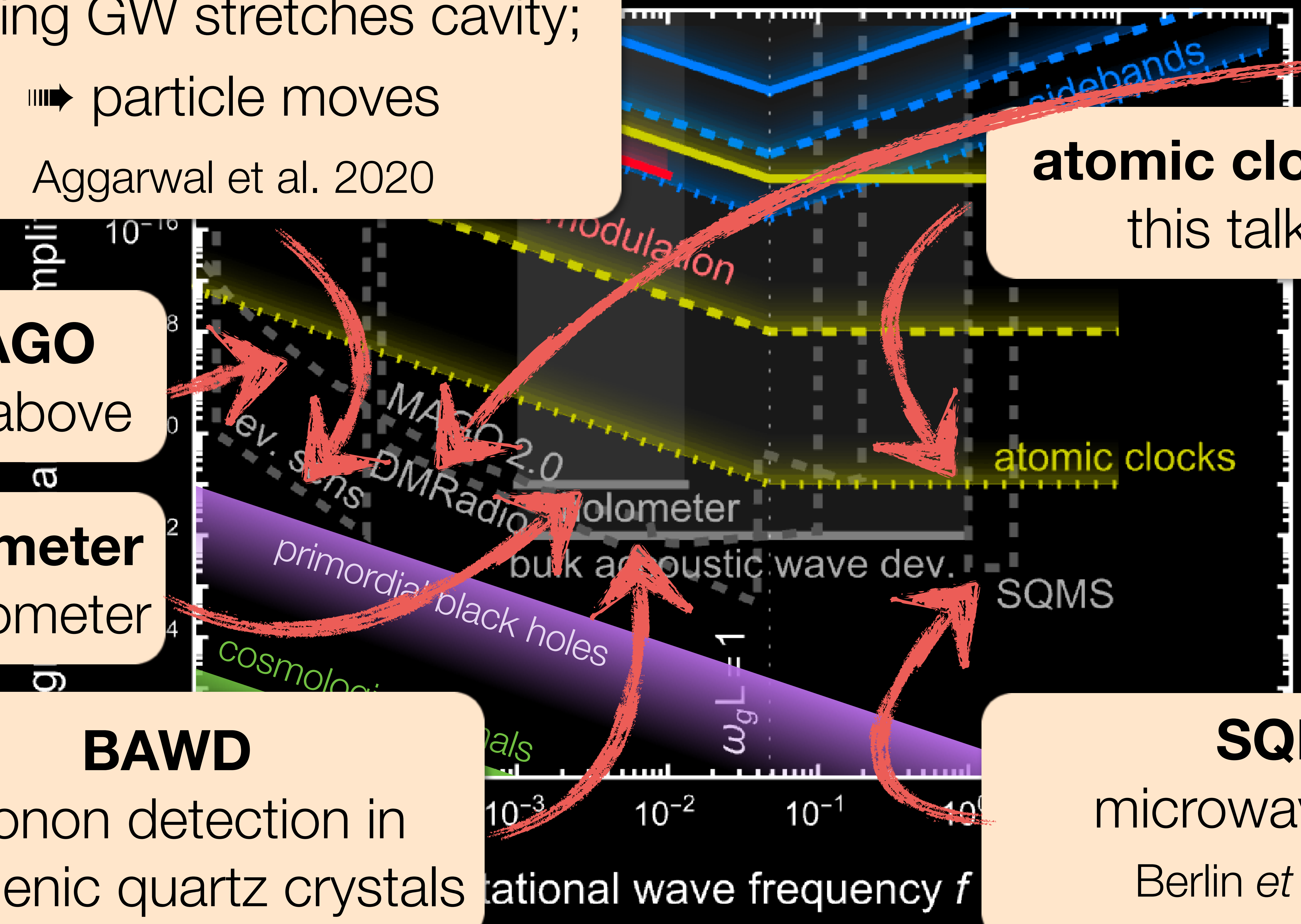

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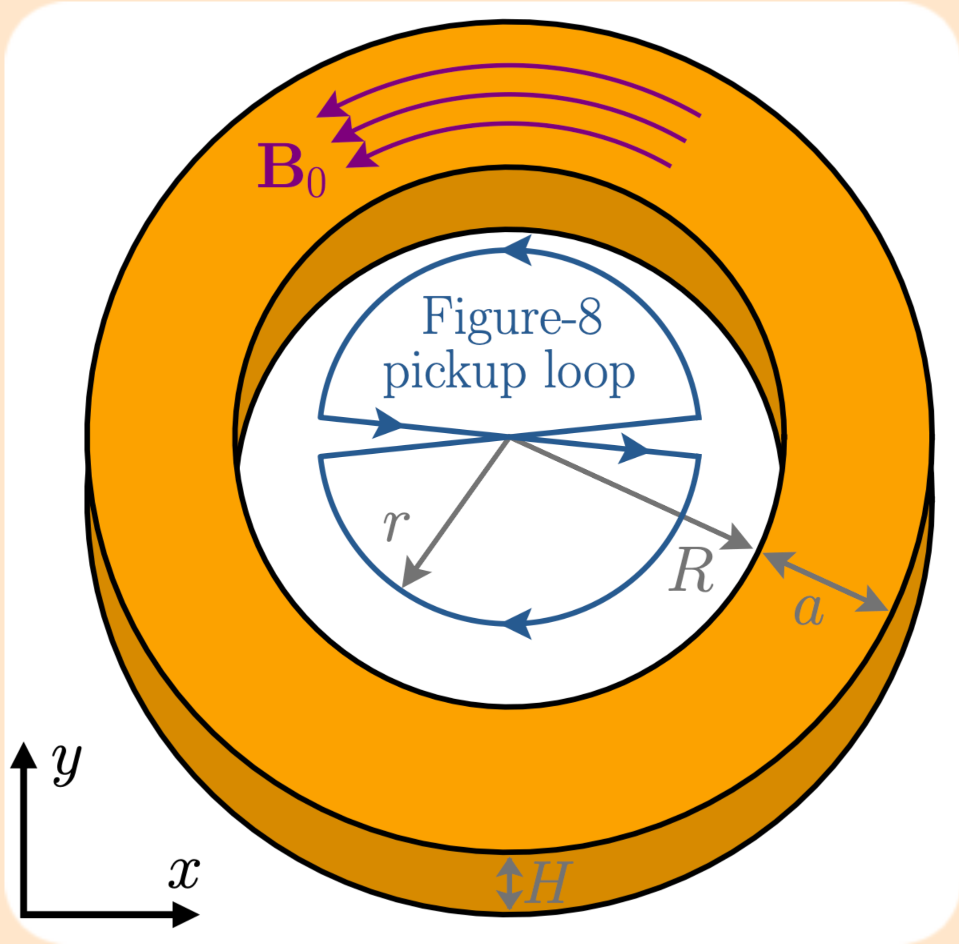
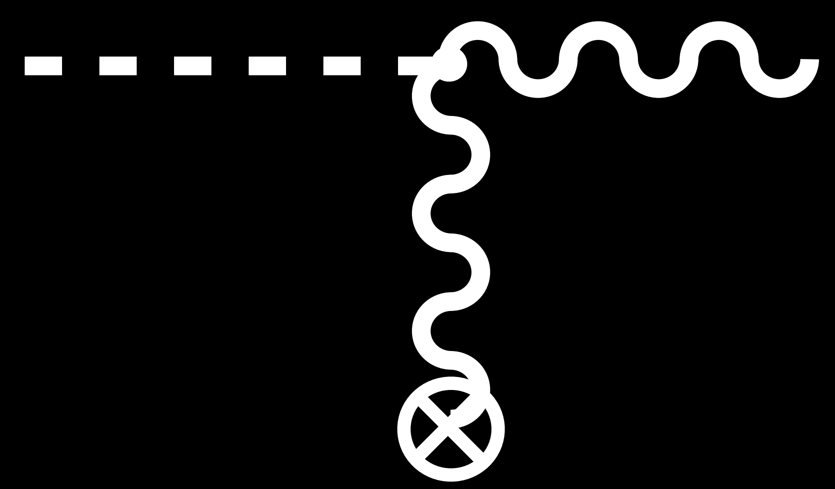


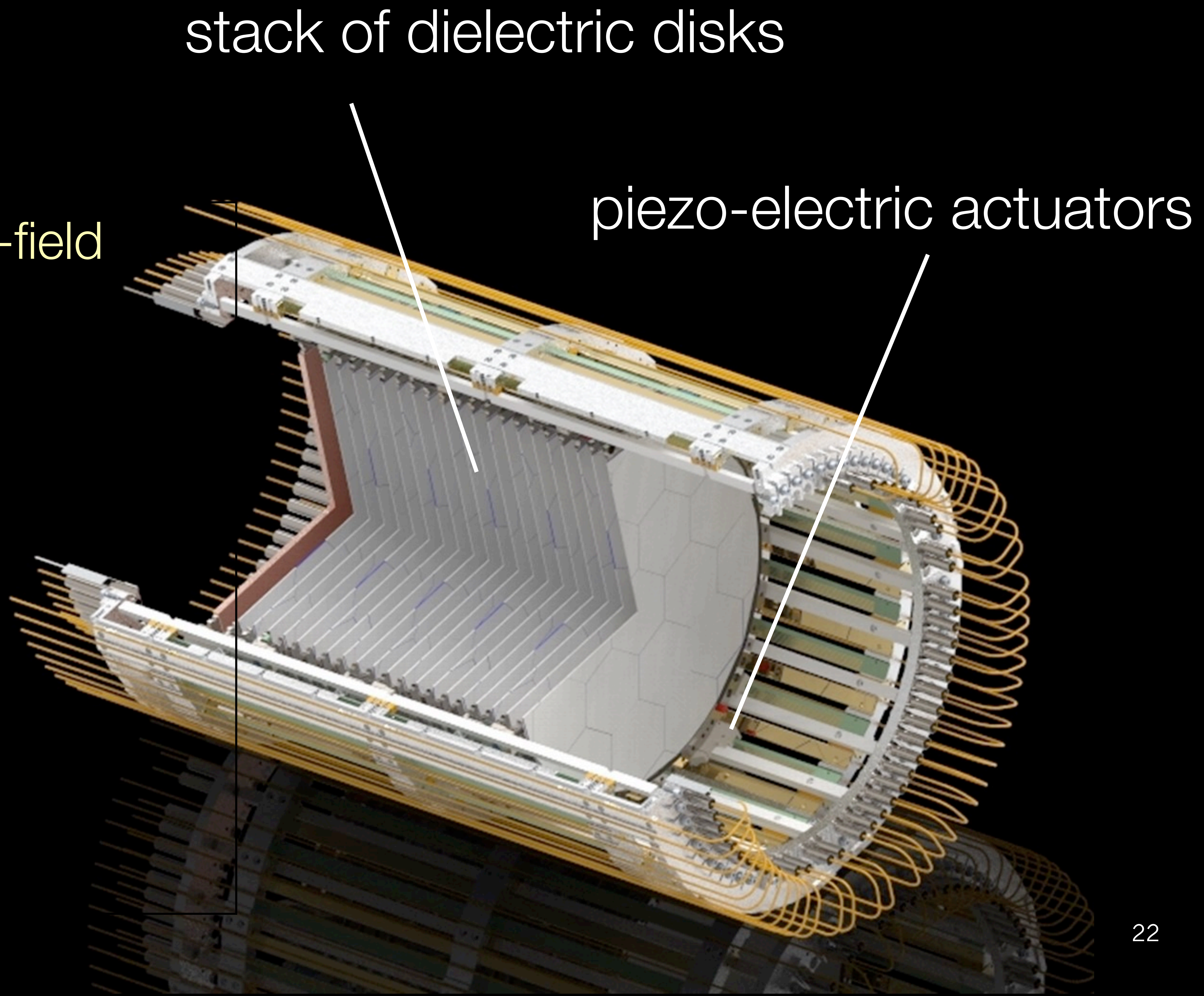
Domcke Garcia-Cely Rodd 2023

Realistic Signals

typically several orders of magnitude below current sensitivities.

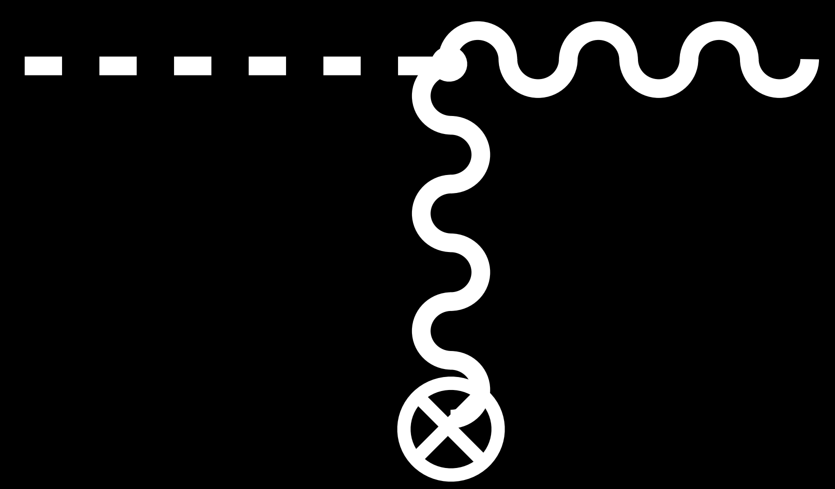
- stack of dielectric disks in *B*-field
- exploits axion–γ–γ coupling



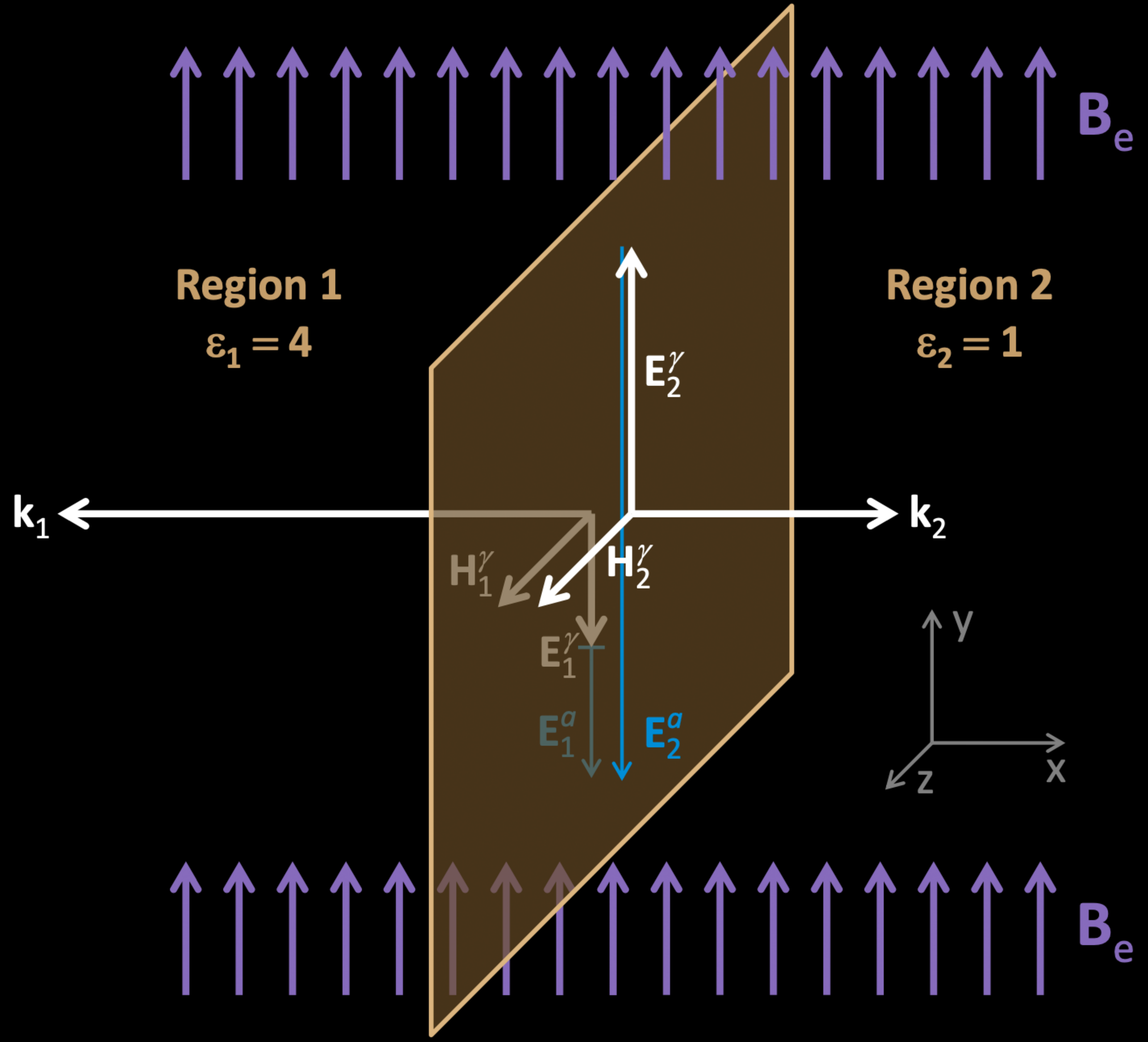


MADMAX

- stack of dielectric disks in *B*-field
- exploits axion–γ–γ coupling

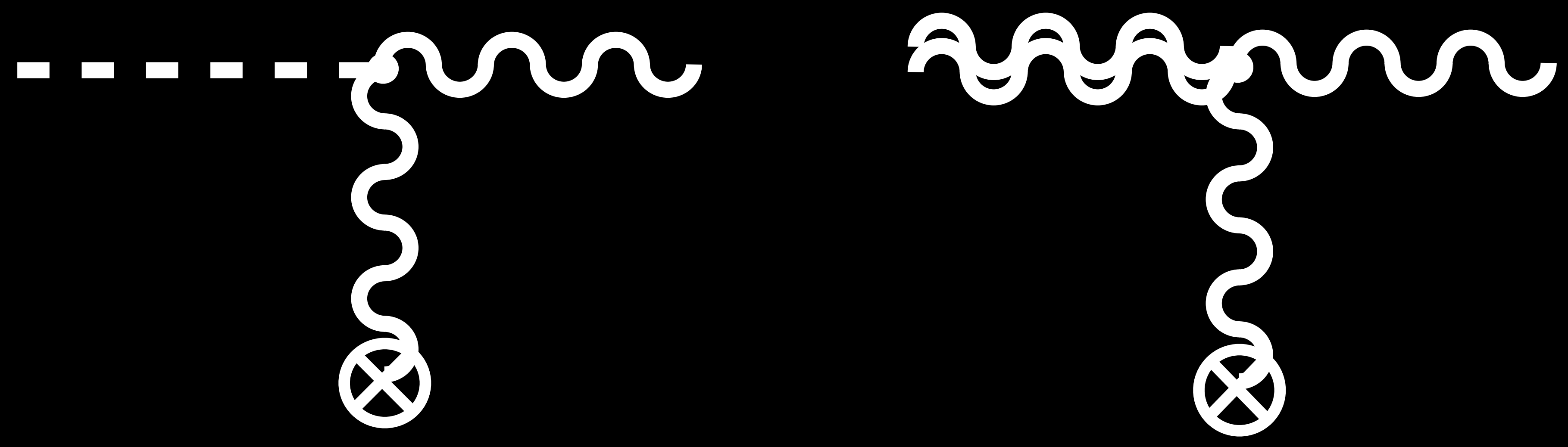


- *E* and *B* fields need to satisfy boundary conditions at disk surfaces
- generation of photons at the surfaces
- signal enhanced by number of disks

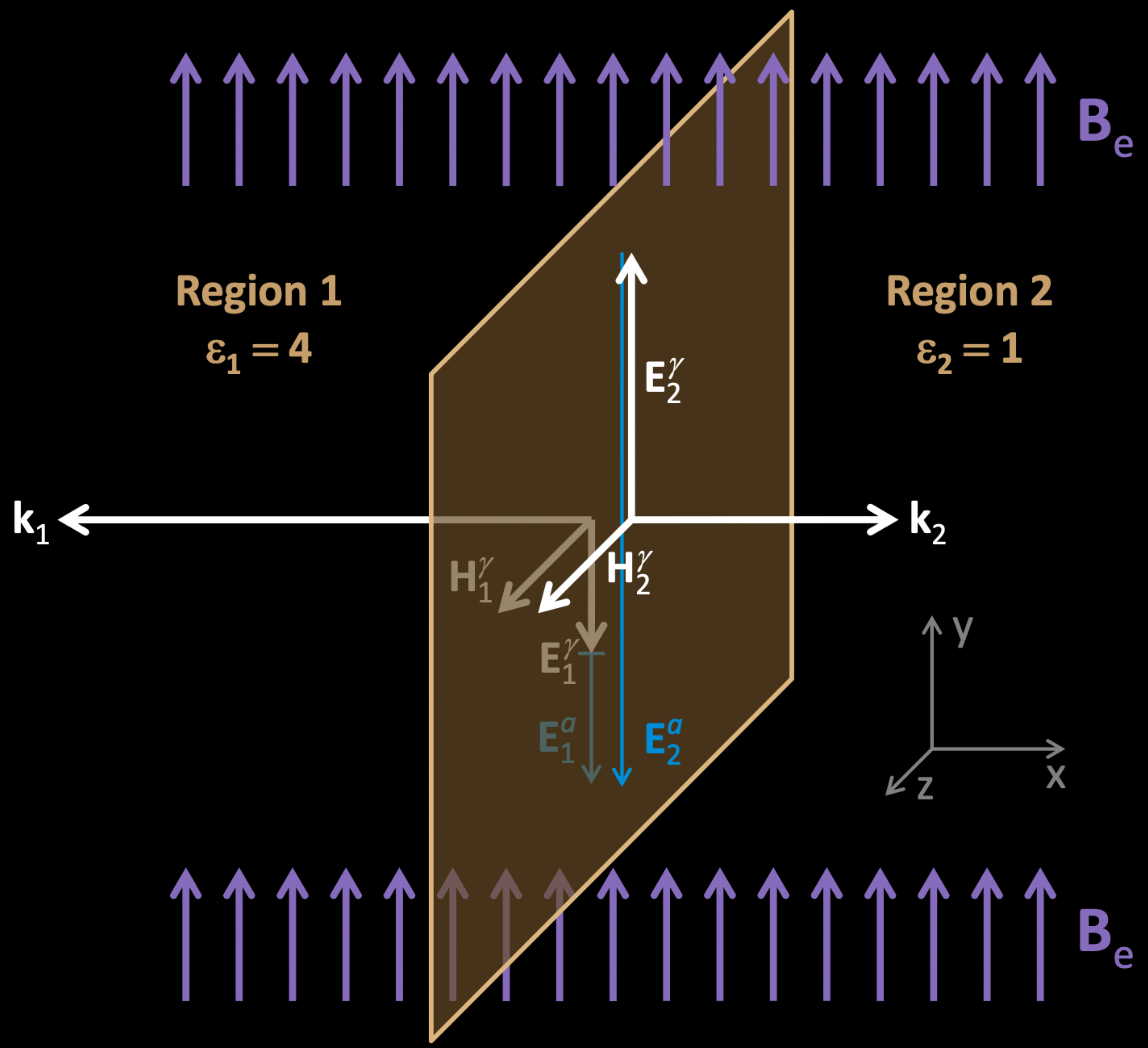


MADMAX

- stack of dielectric disks in *B*-field
- exploits axion–γ–γ coupling
- analogously: graviton–γ–γ coupling (inverse Gertsenshtein effect)



Domcke Ellis JK, *in preparation*



MADMAX will have excellent sensitivity

to gravitational waves

at frequencies of 10–100 GHz.

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- optimization of disk thickness / spacing is different than for axions
- photons travel in the direction of the GW
- relaxed requirements on disk smoothness

Domcke Ellis JK, *in preparation*


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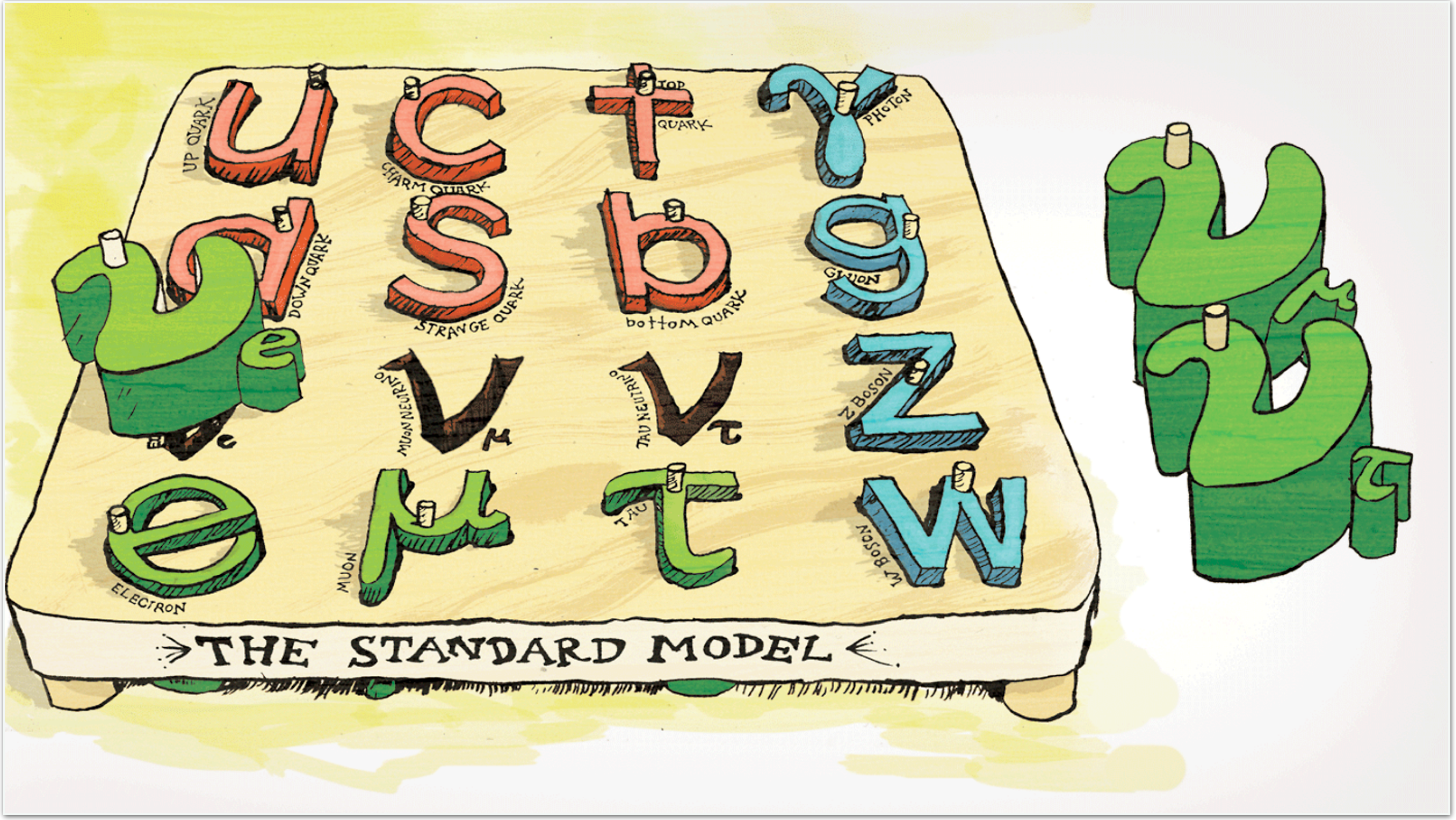
SHOCK WAVE

Three Neutrino Flavors



Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

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Mass Eigenstate
(well-defined energy)

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Mass Eigenstate
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Flavor Eigenstate
(well-defined coupling)

Mixing Matrix
(*3*x*3*, unitary)

Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

During propagation, different mass eigenstates acquire different phases ➠ **oscillations**

$$P_{\alpha\to\beta} = \Big|\langle\nu_\beta|e^{-i\hat{H}T}|\nu_\alpha\rangle\Big|^2$$
$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\Big[-i\big(E_j - E_k\big)T\Big]$$

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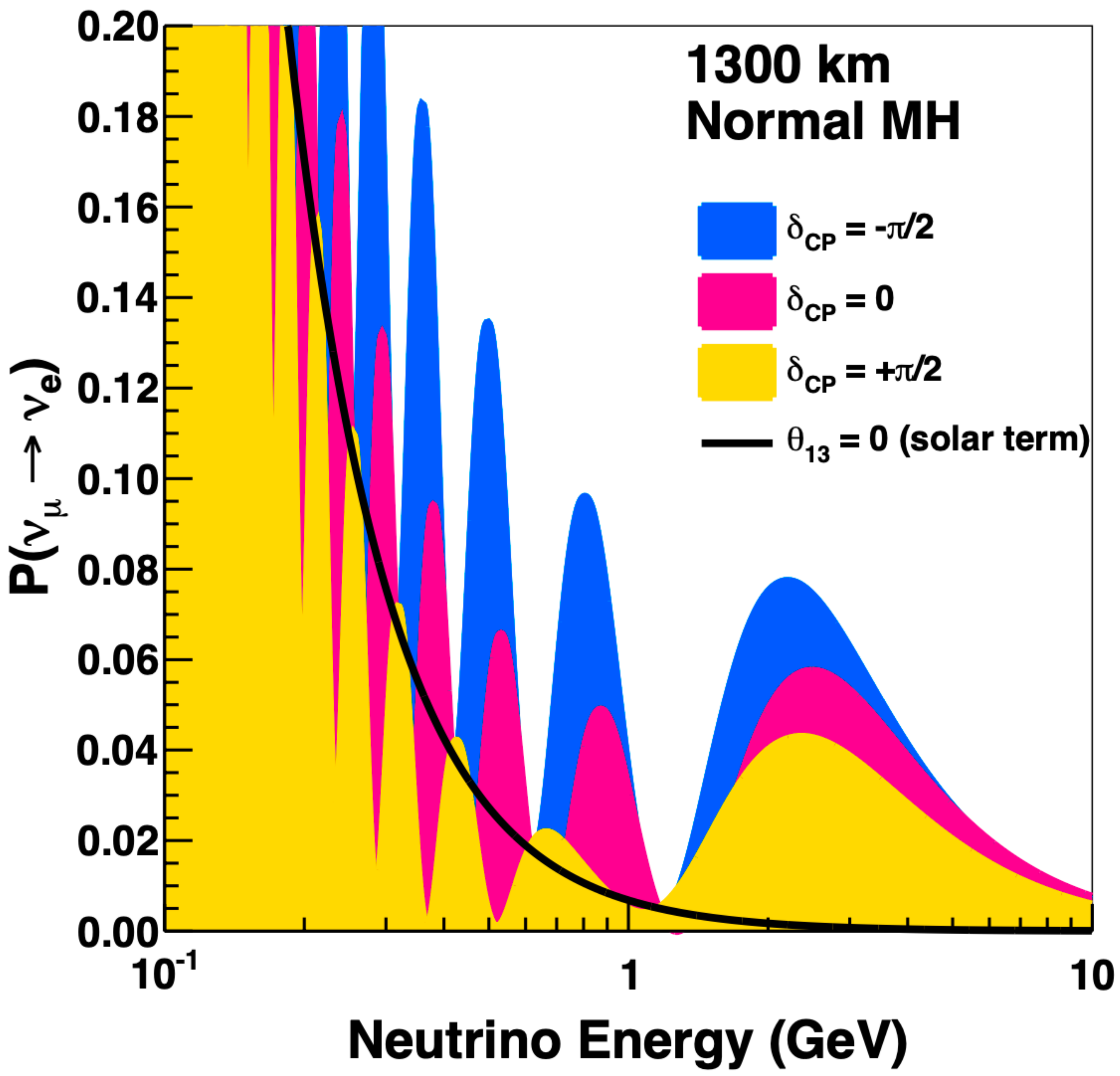
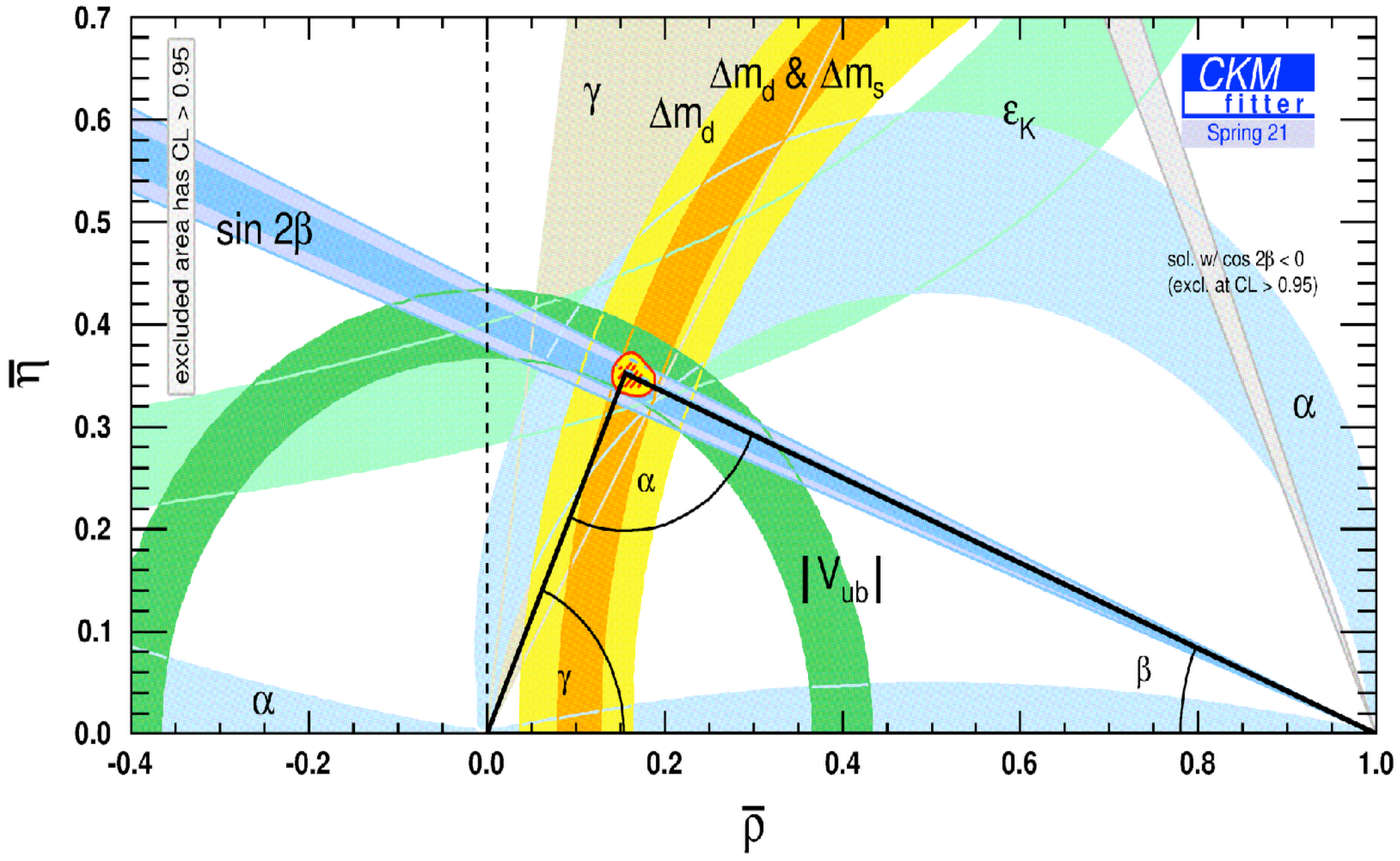
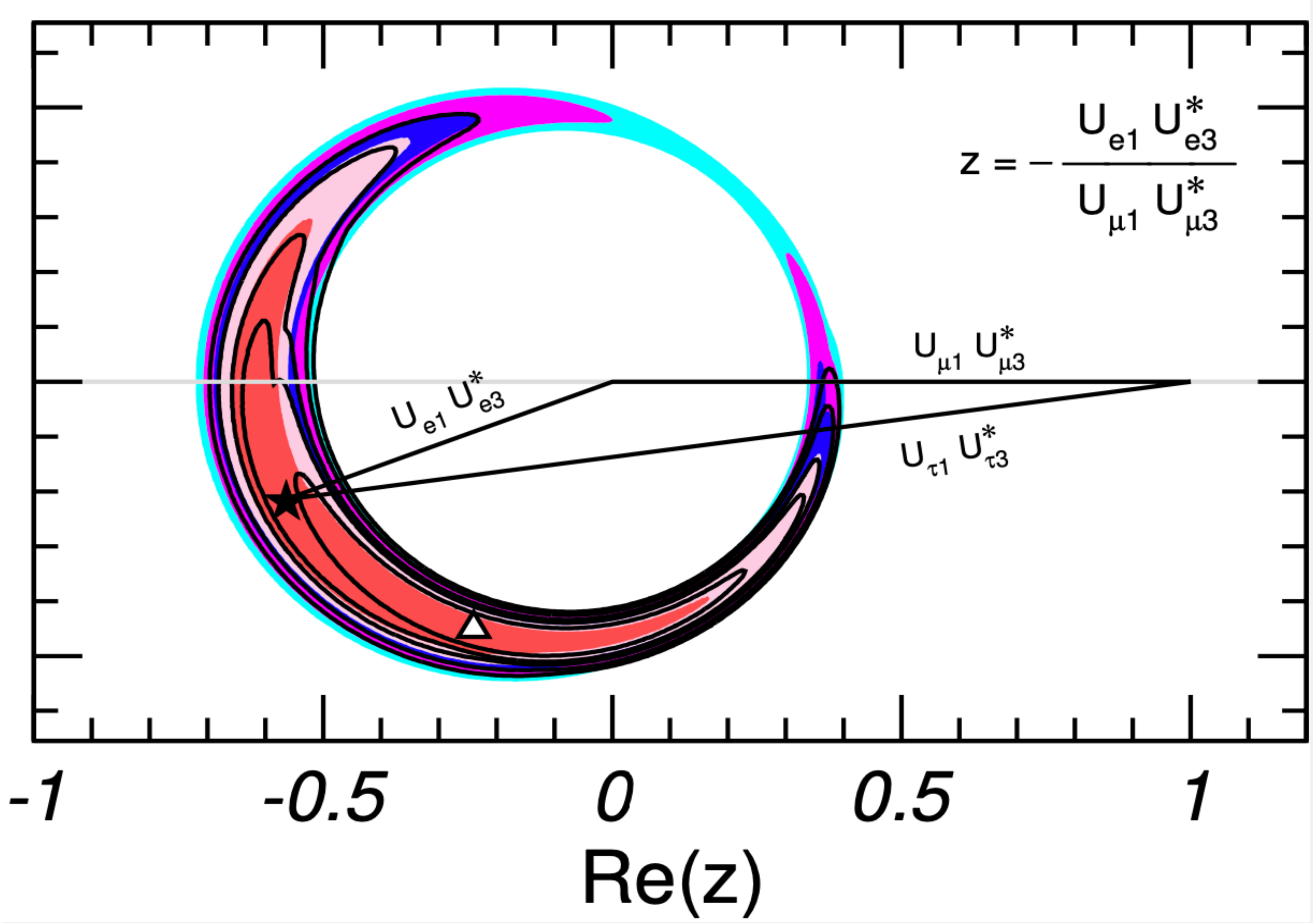


Precision Neutrino Physics

Quarks



Leptons



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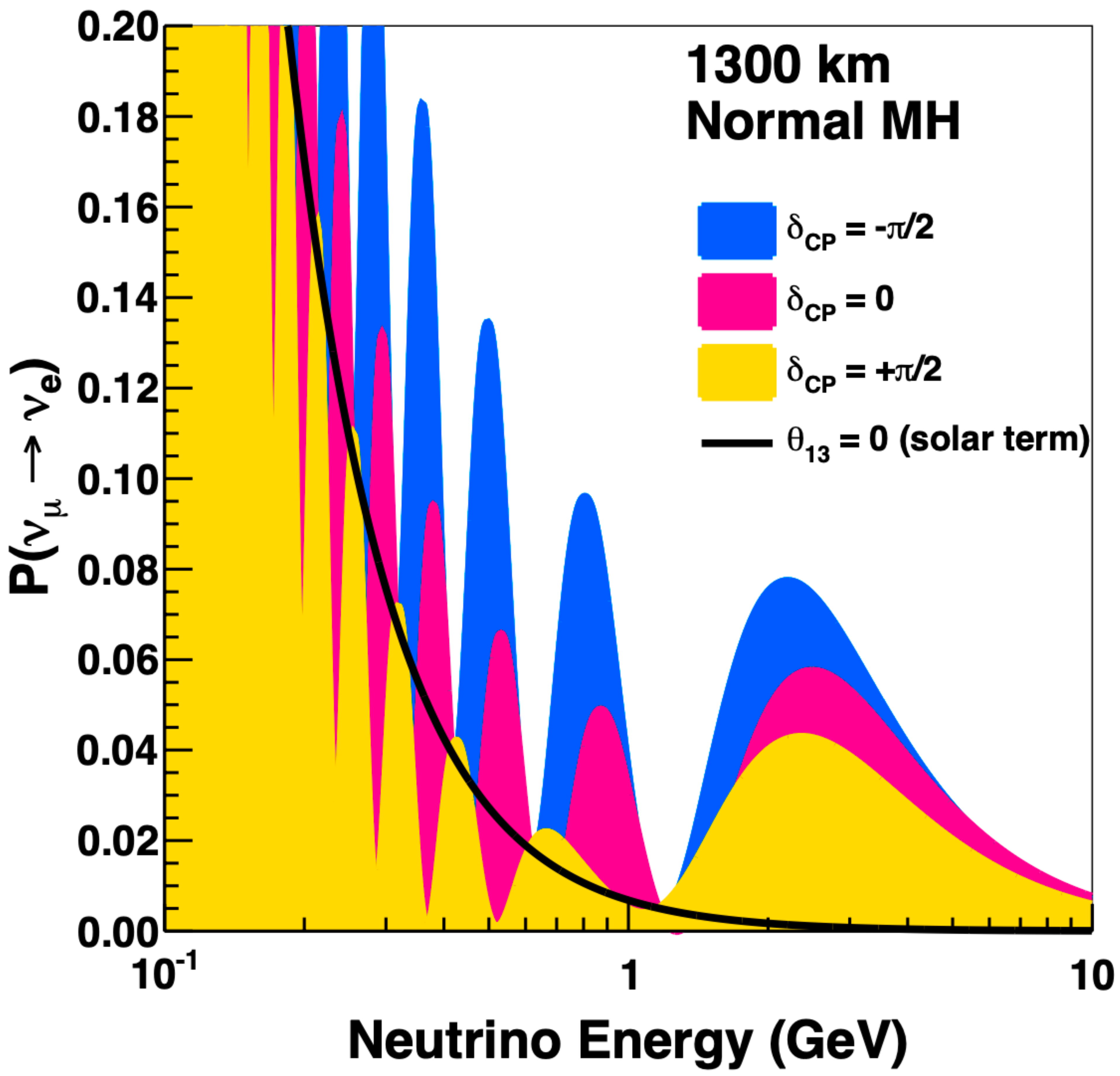

Long-Baseline Neutrino Oscillation Experiments

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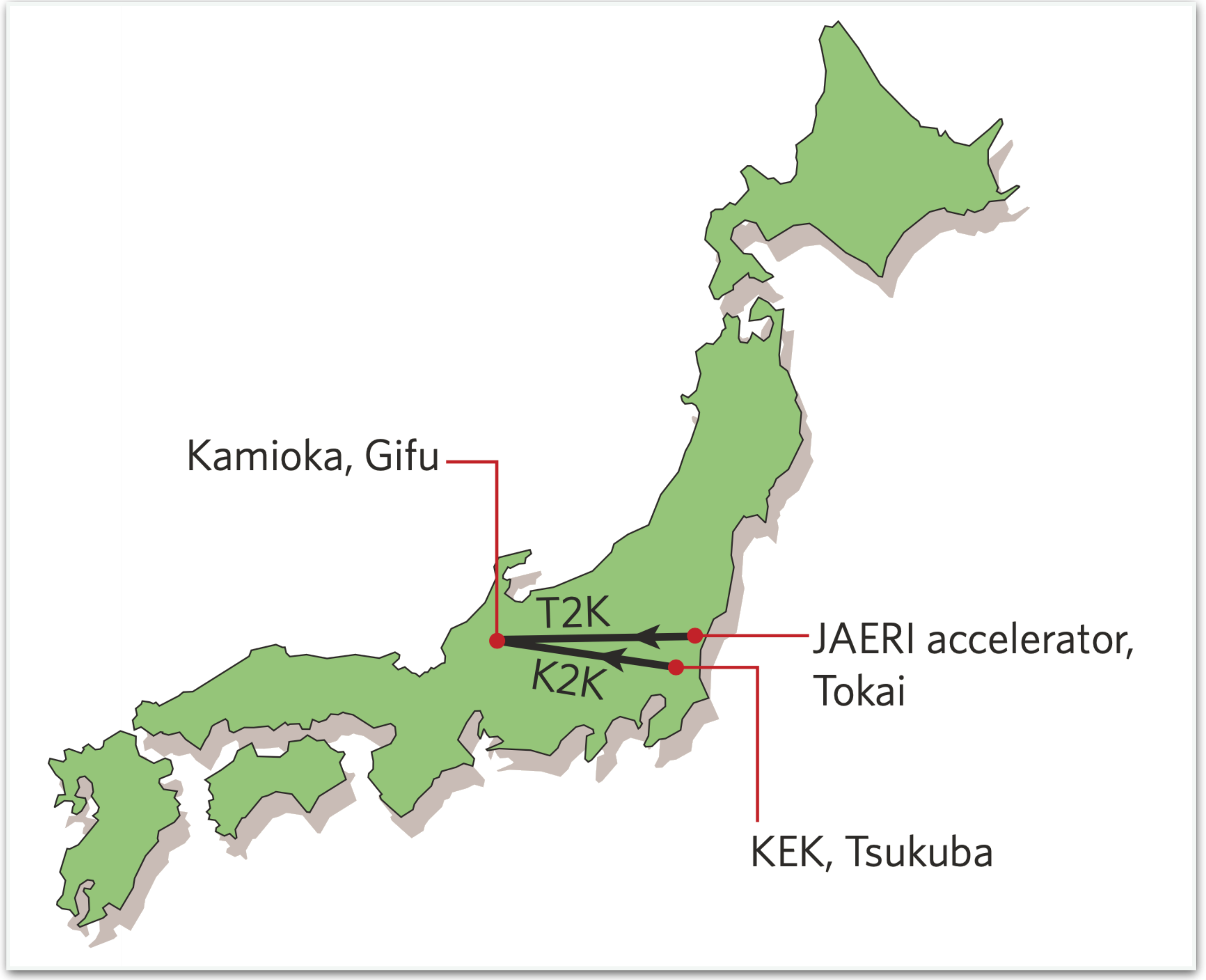

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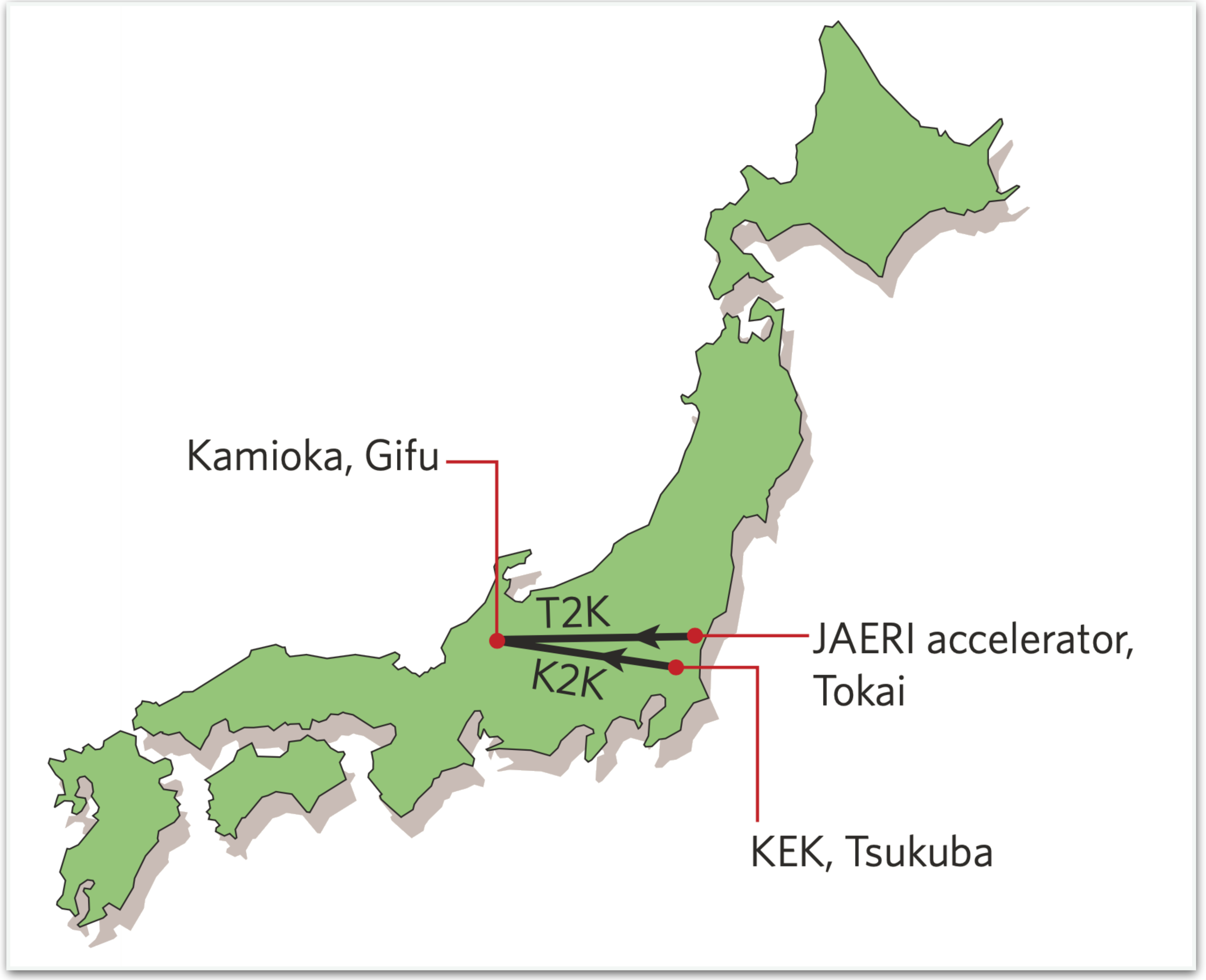

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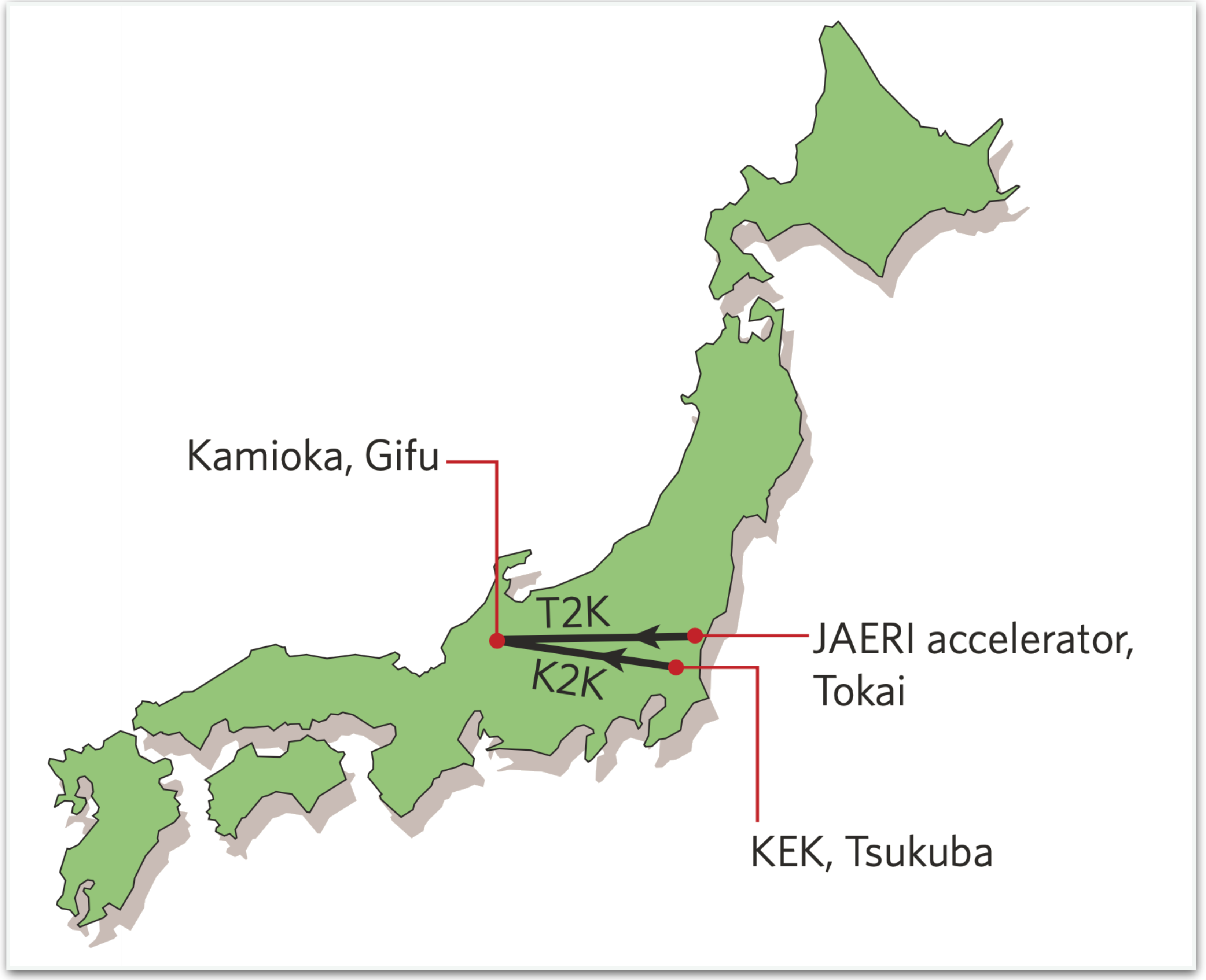

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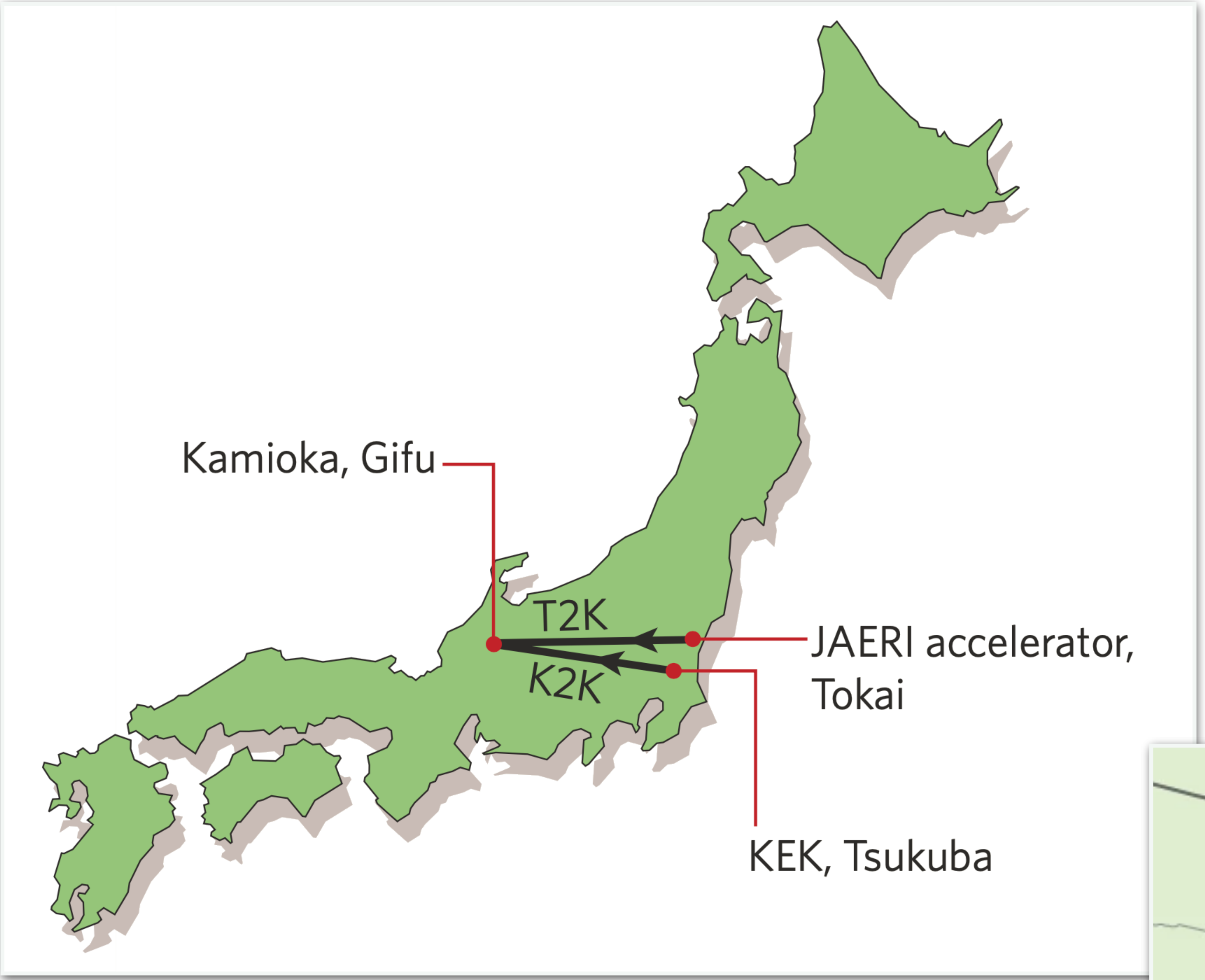
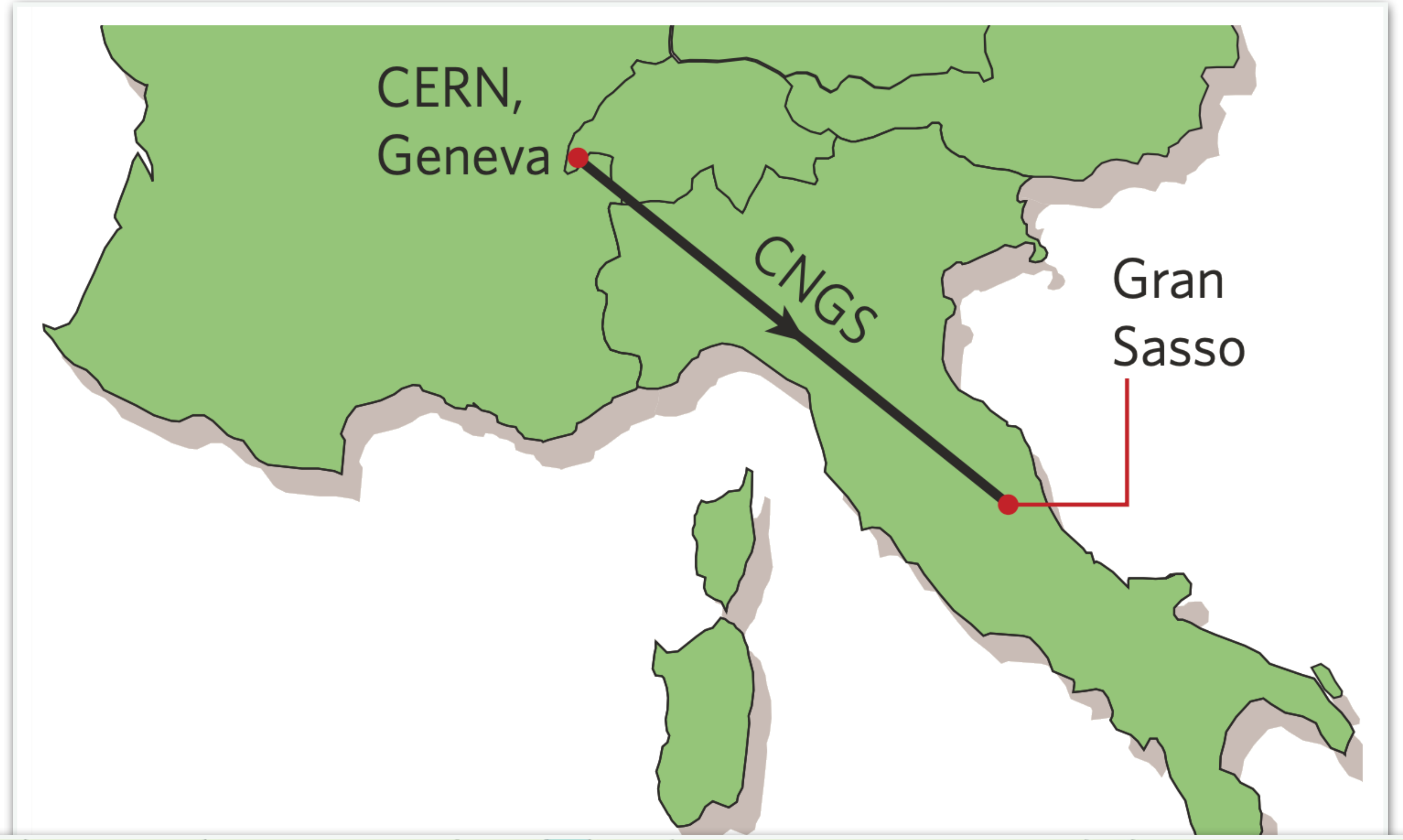
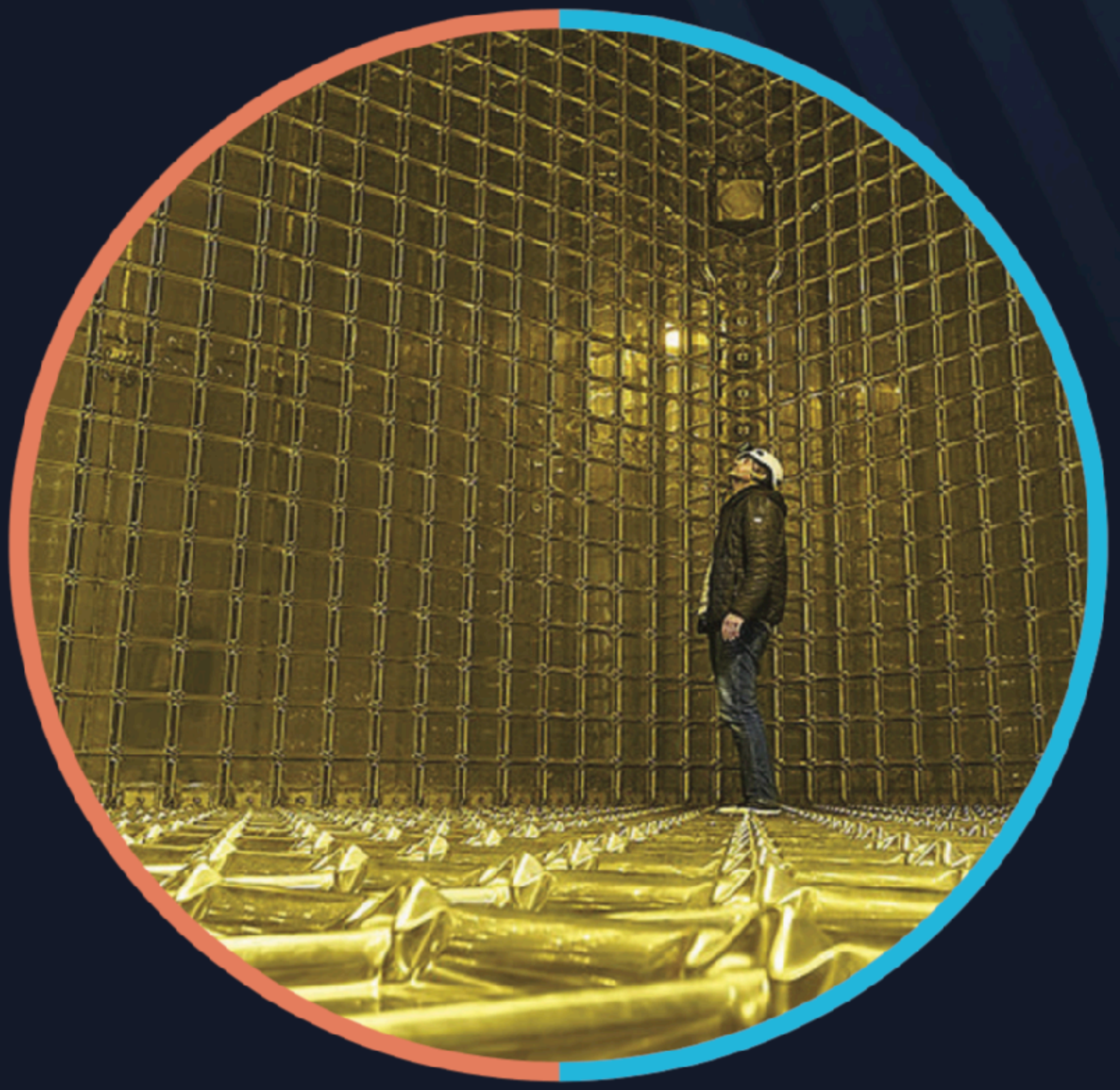


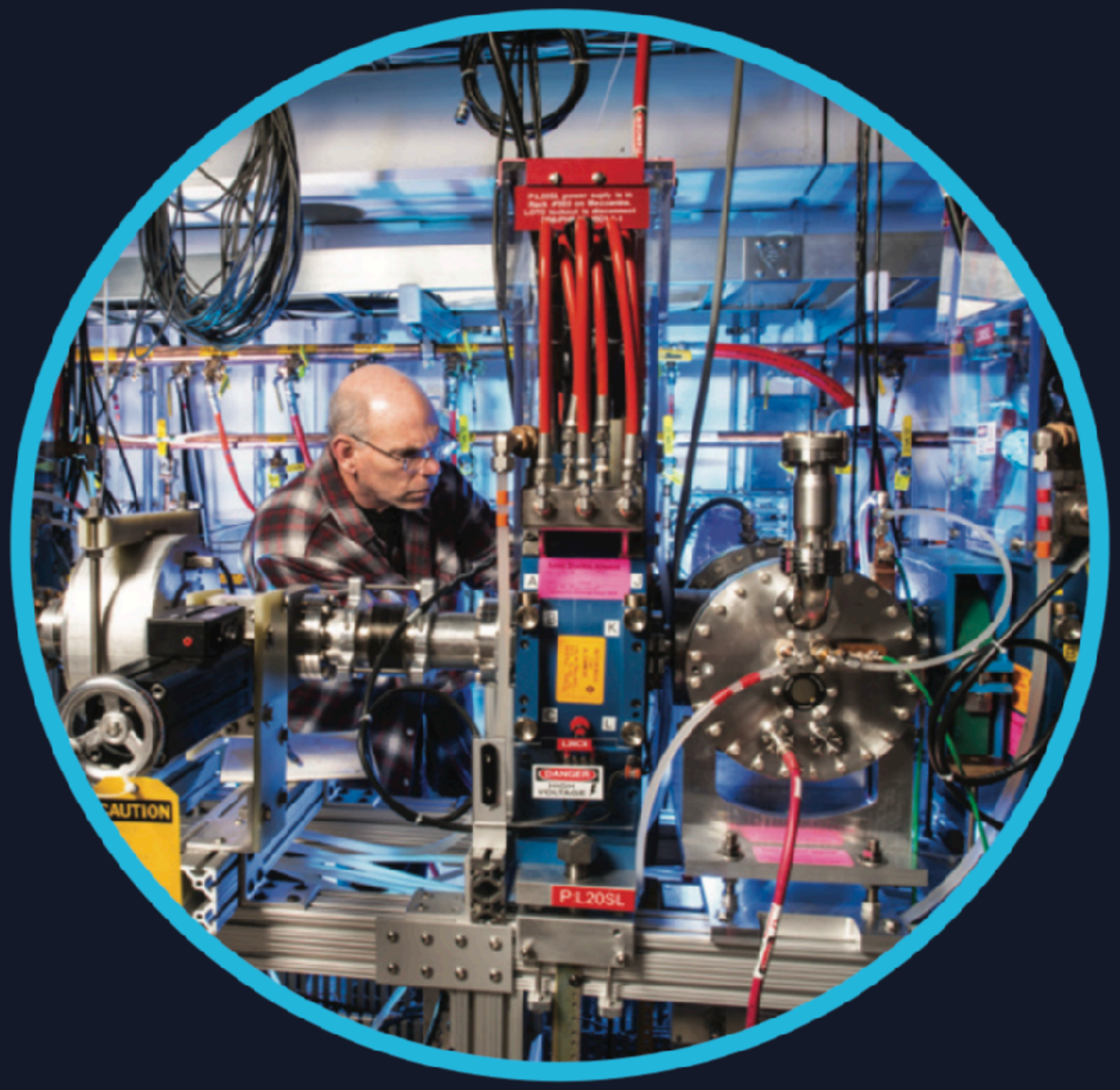


Next-Generation Long-Baseline Experiments



Far Detectors
(measure oscillations)

Near Detectors
(measure unoscillated flux & x-secs)



Neutrino source

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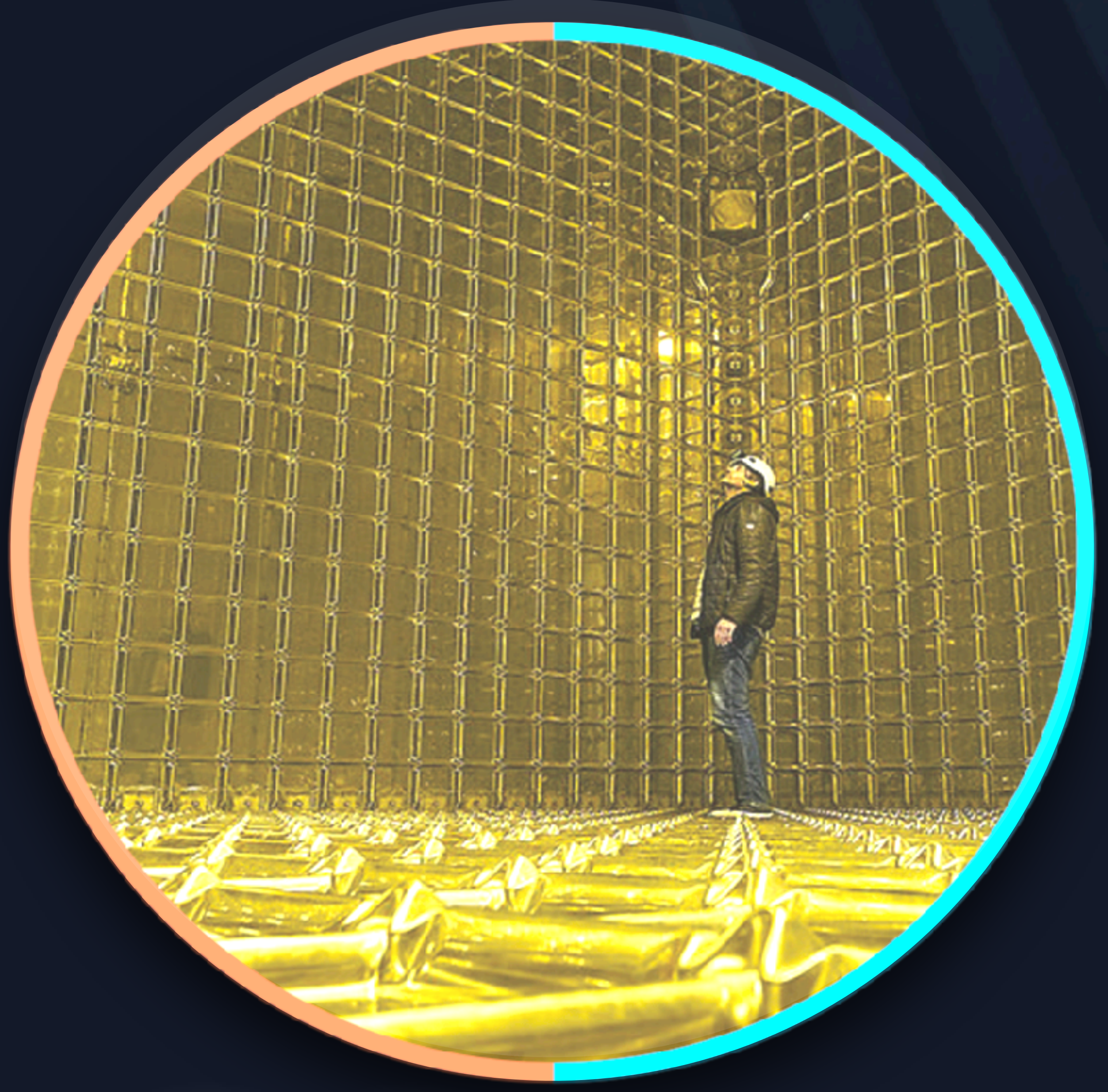

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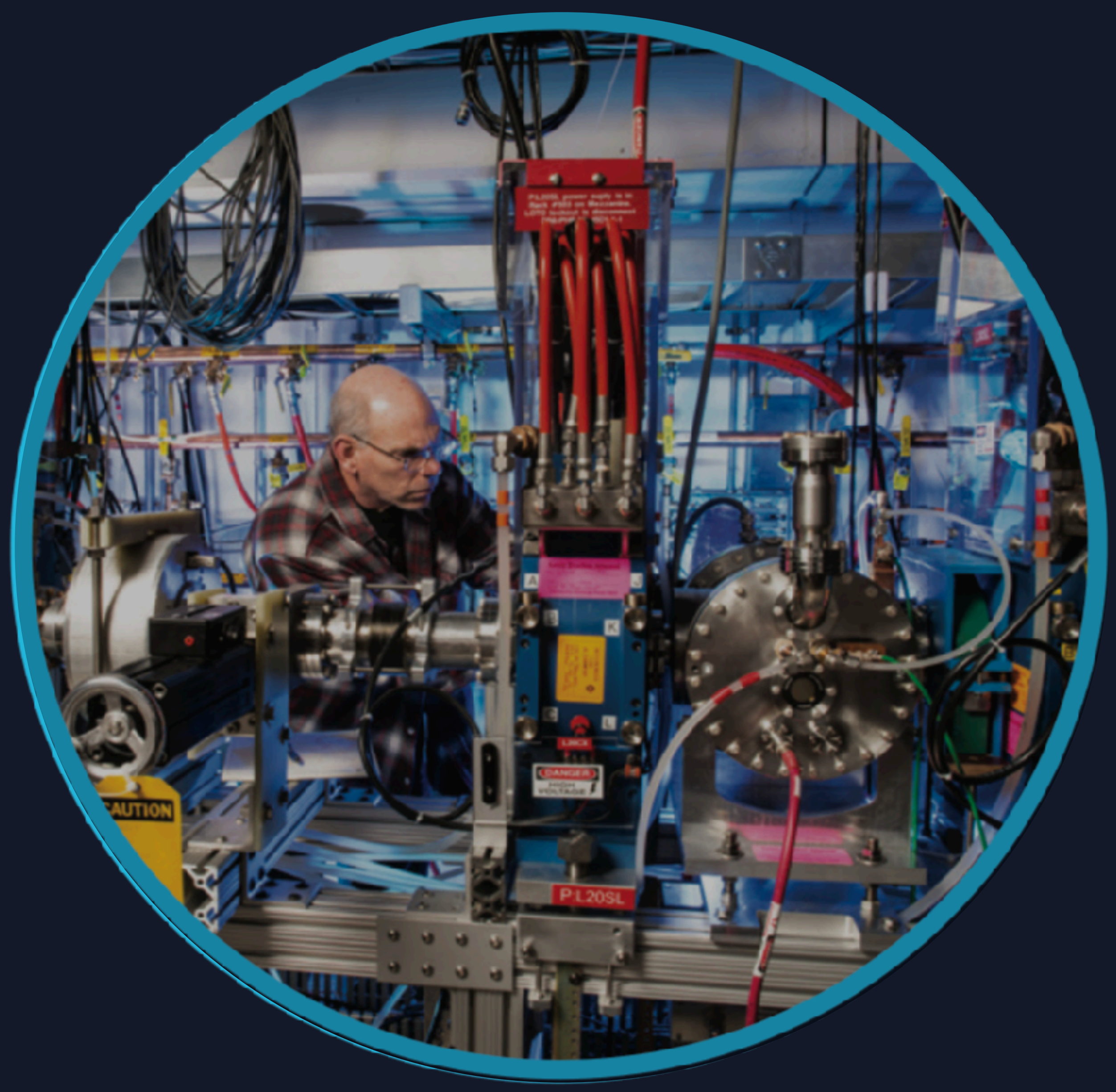

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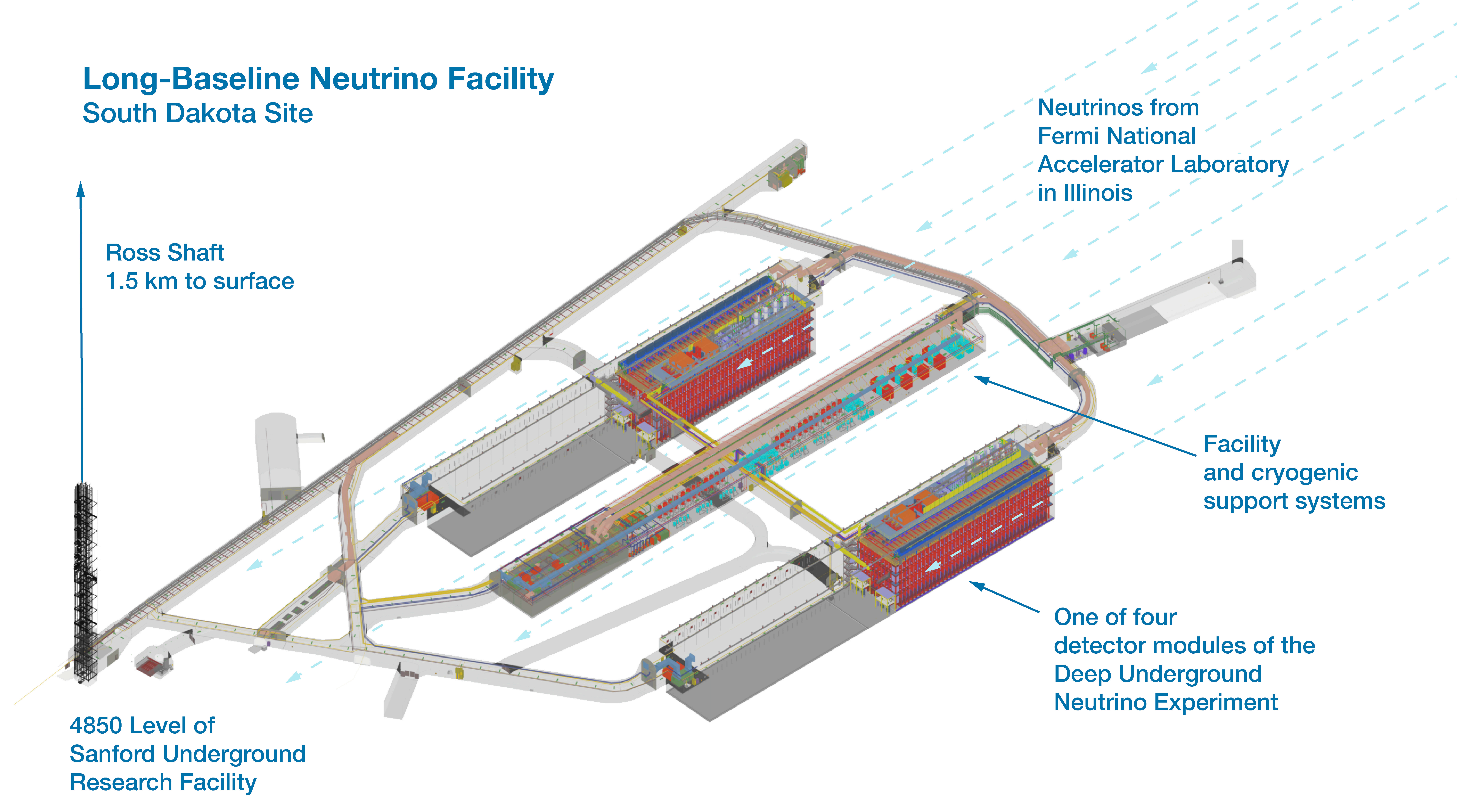
Long-Baseline Neutrino Facility
South Dakota Site
Neutrinos from Fermi National Accelerator Laboratory in Illinois
Ross Shaft 1.5 km to surface
Facility and cryogenic support systems
One of four detector modules of the Deep Underground Neutrino Experiment
4850 Level of Sanford Underground Research Facility

Yes, But Why?

- Connection between leptonic CP violation and baryogenesis
- Portal to new physics
- Precise knowledge of particle physics is indispensable for using neutrinos as astrophysical messengers
- Hints for the origin of flavour
- Multi-purpose detectors with lots of secondary opportunities (supernova neutrinos, light dark sectors, proton decay, …)
- …

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Neutrinos as Astrophysical Messengers

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solar neutrinos

- ⋆ stellar evolution

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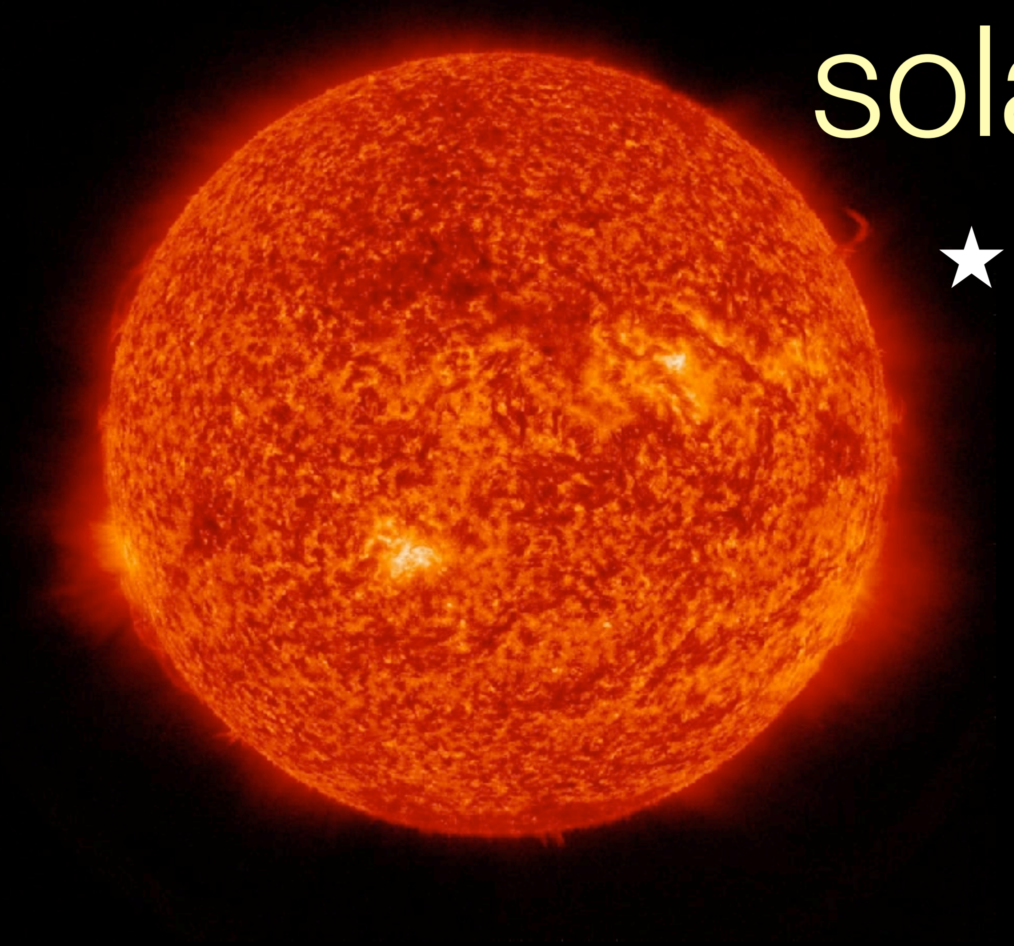

solar neutrinos

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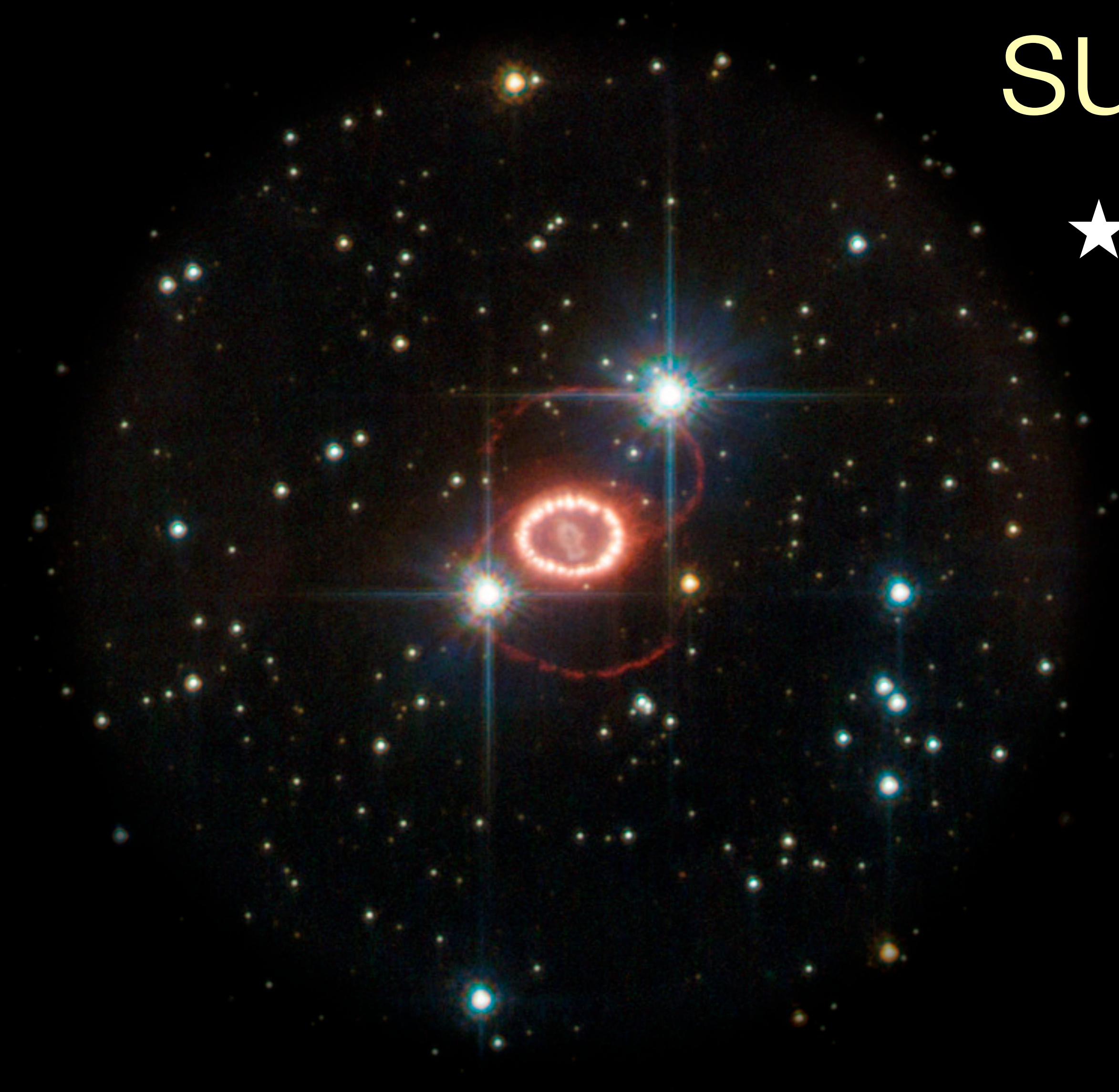

supernova neutrinos

- ⋆ death throes of massive stars
- ⋆ nucleosynthesis
- ⋆ matter under extreme conditions

Neutrinos as Astrophysical Messengers

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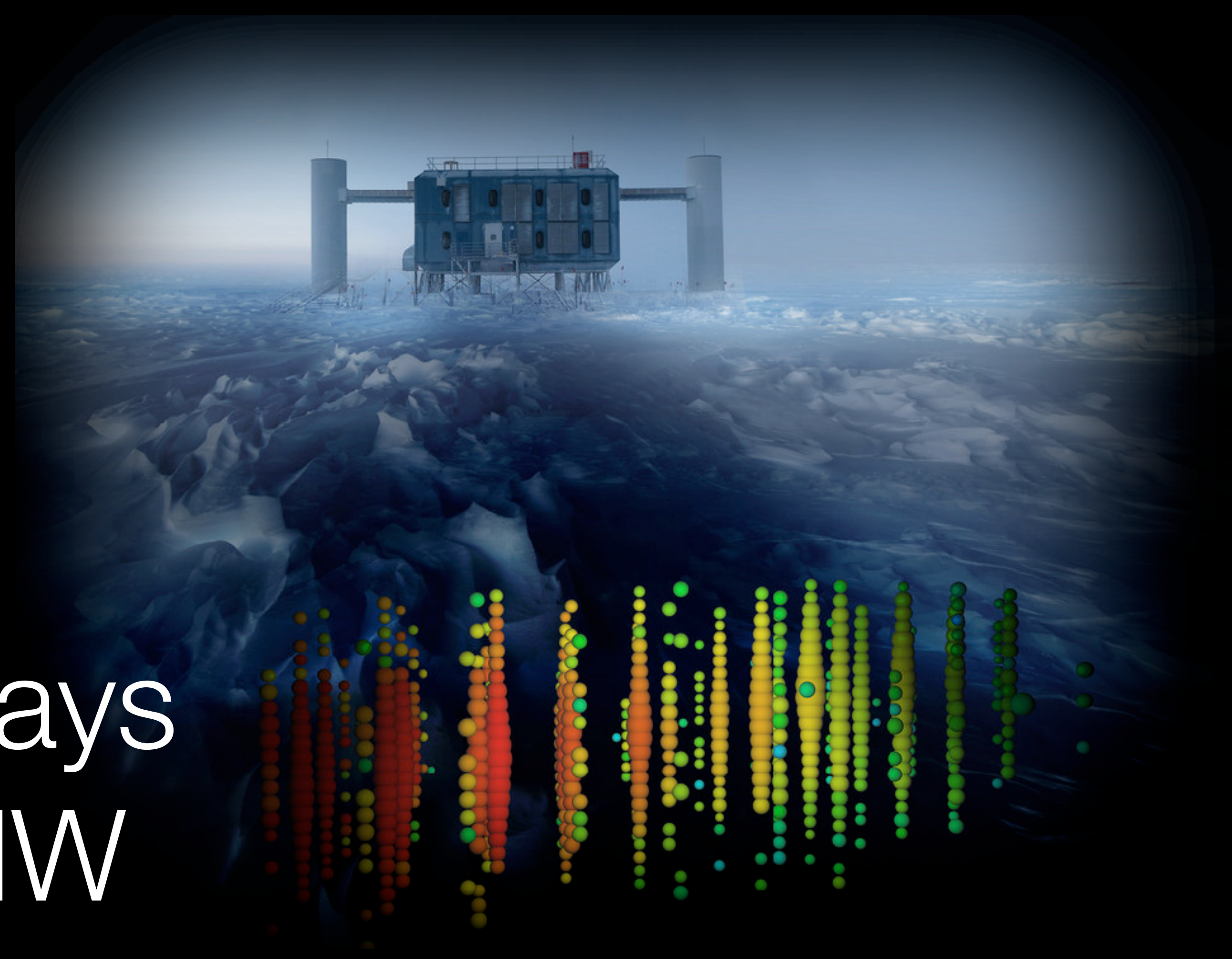
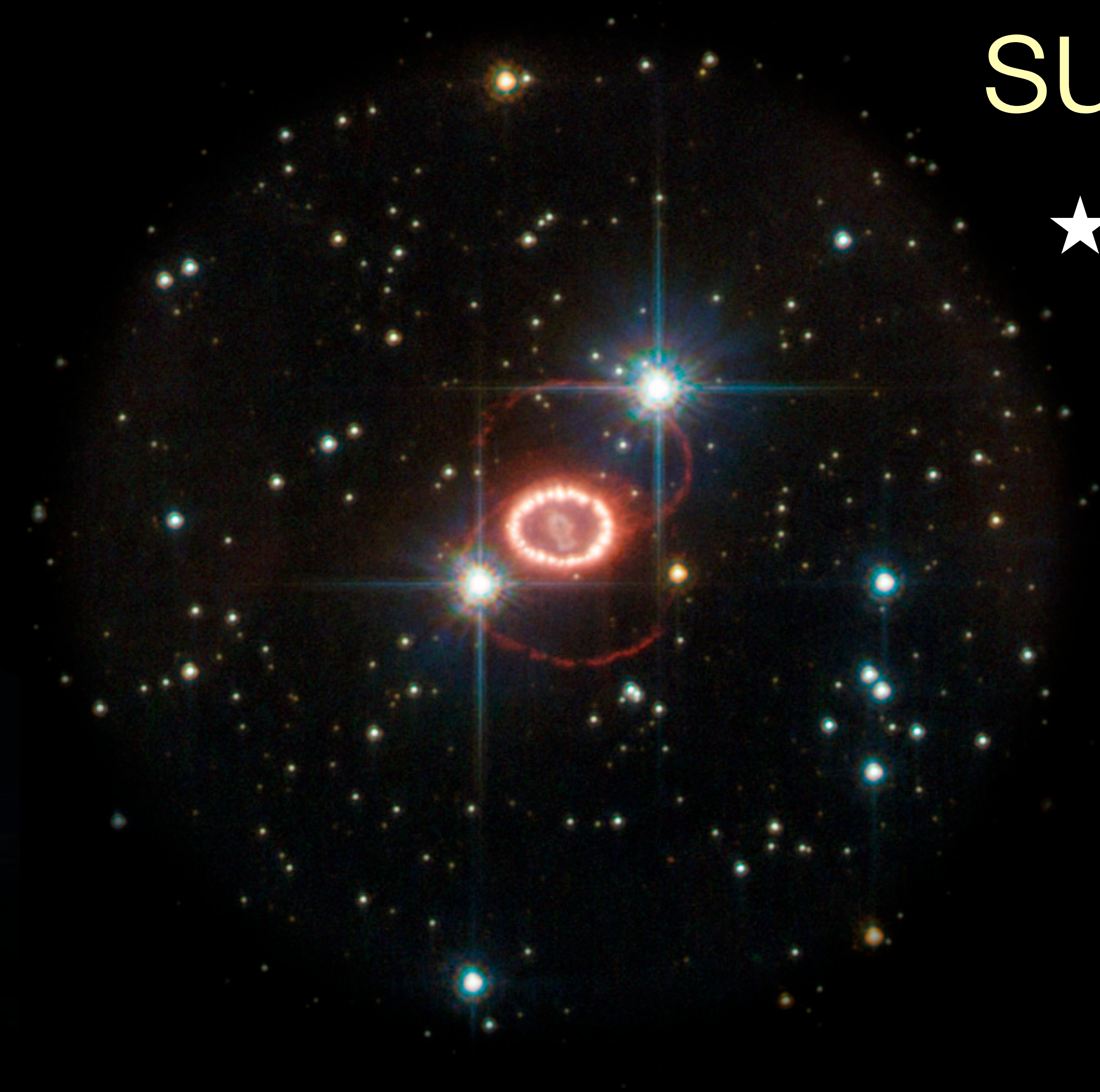


high-E neutrinos

- ★ origin of cosmic rays
- ★ AGNs, blazars, MW



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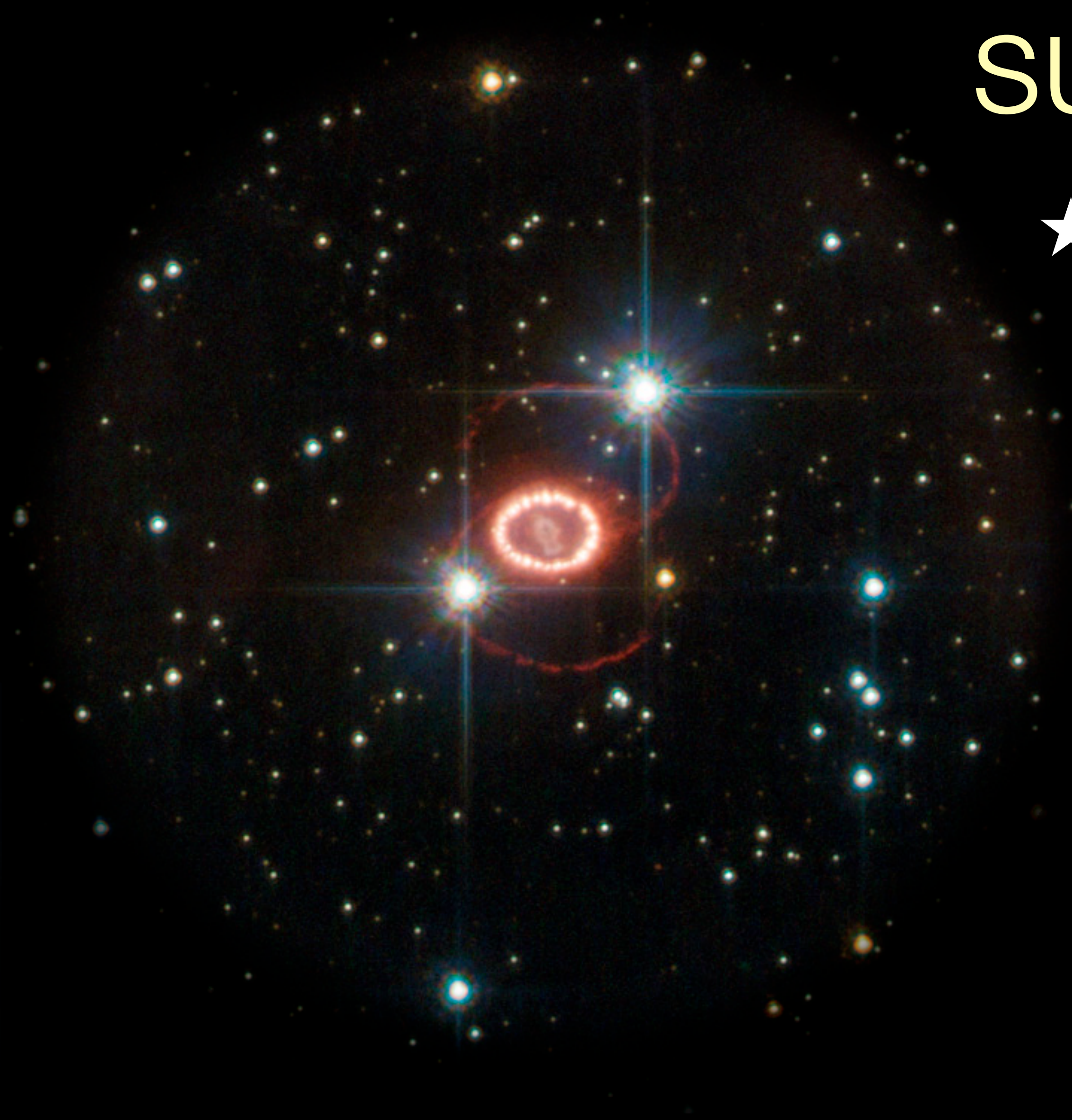

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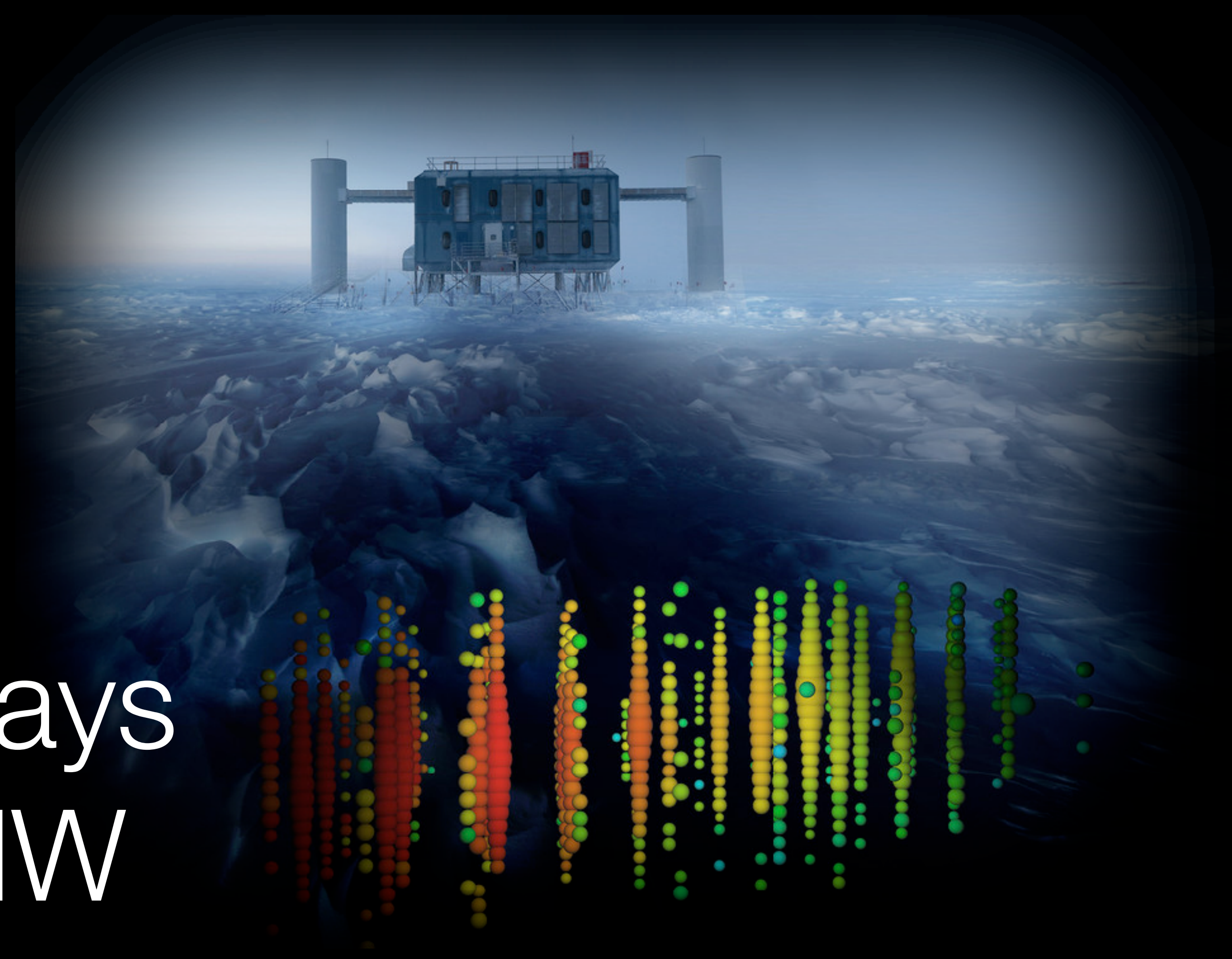

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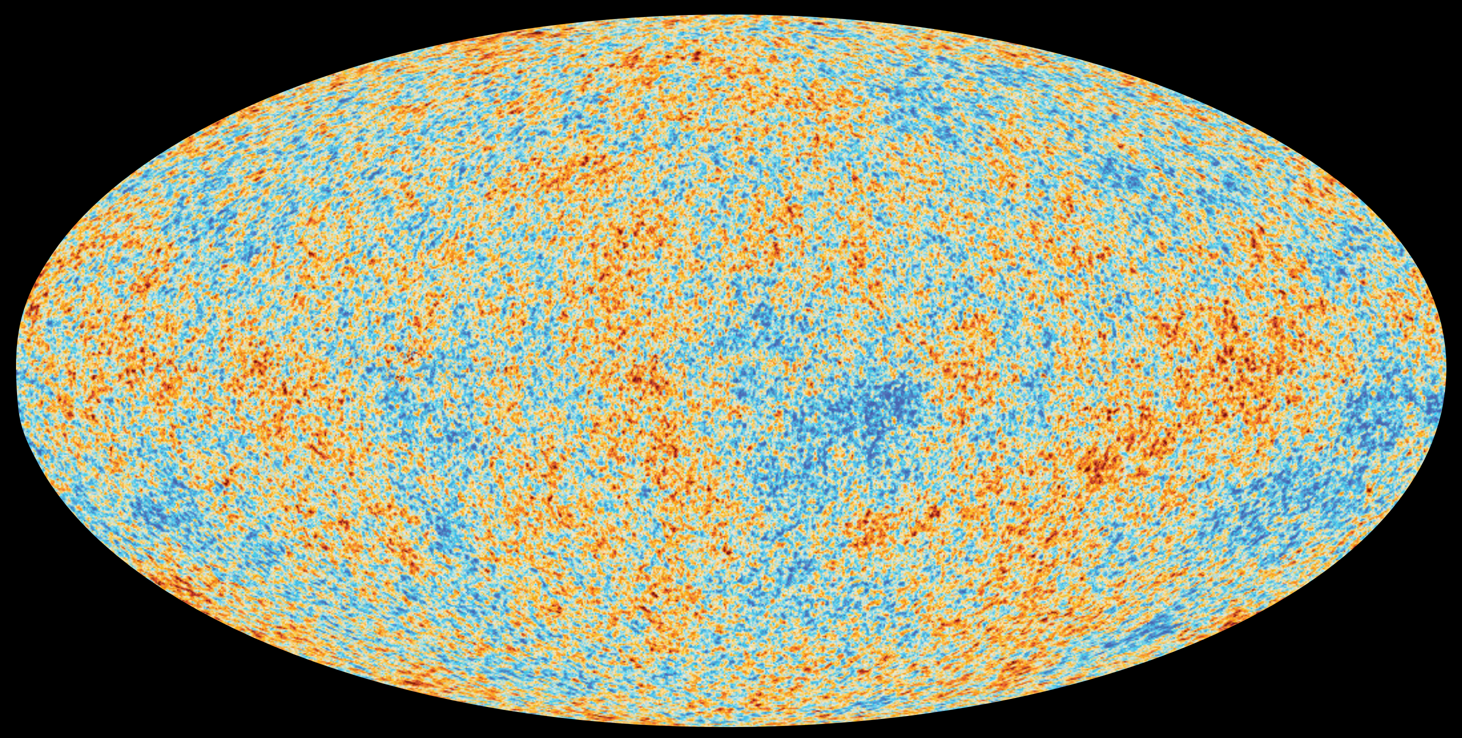

cosmology

- ★ early Universe

Neutrinos as Astrophysical Messengers

solar neutrinos

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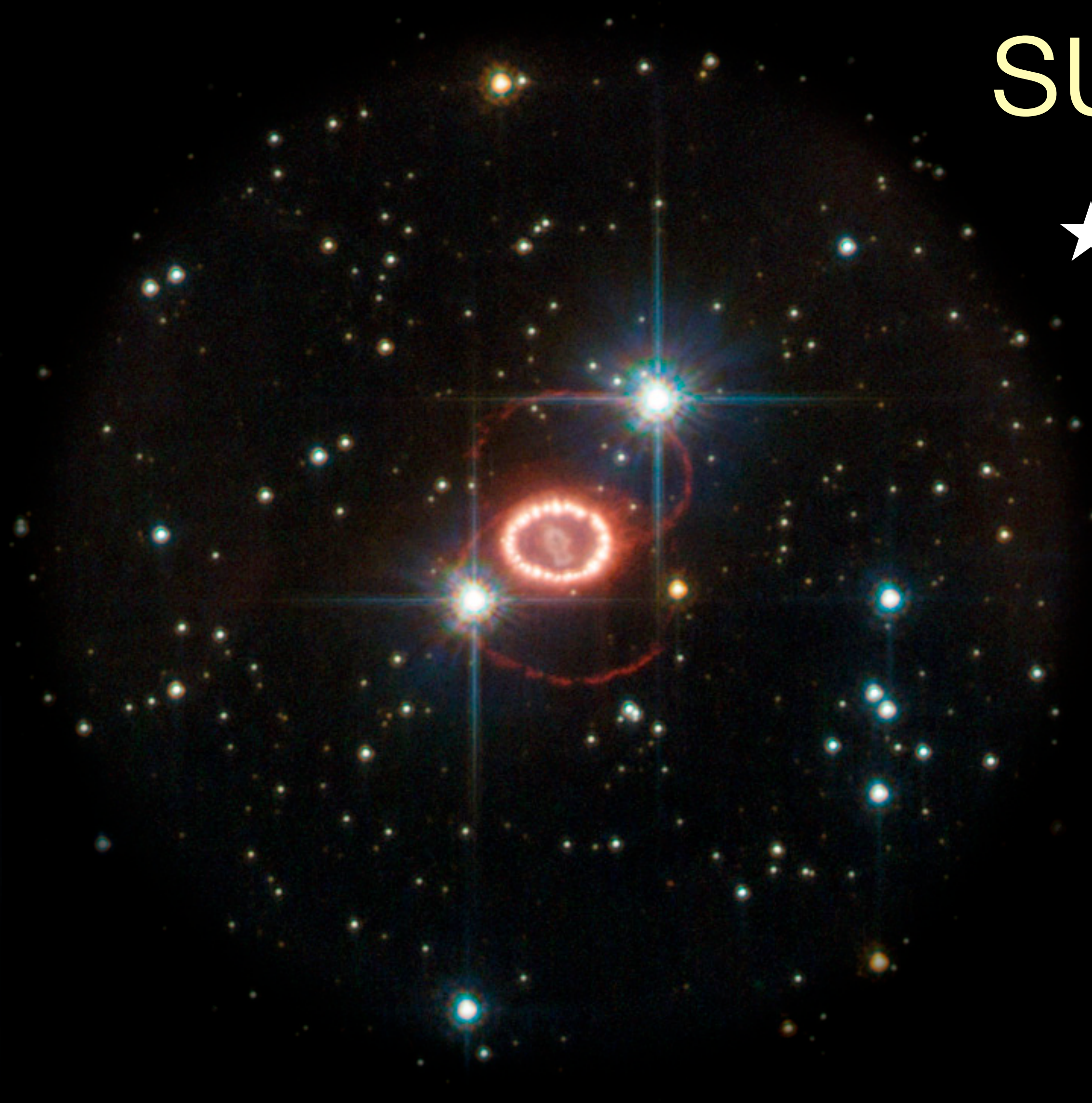

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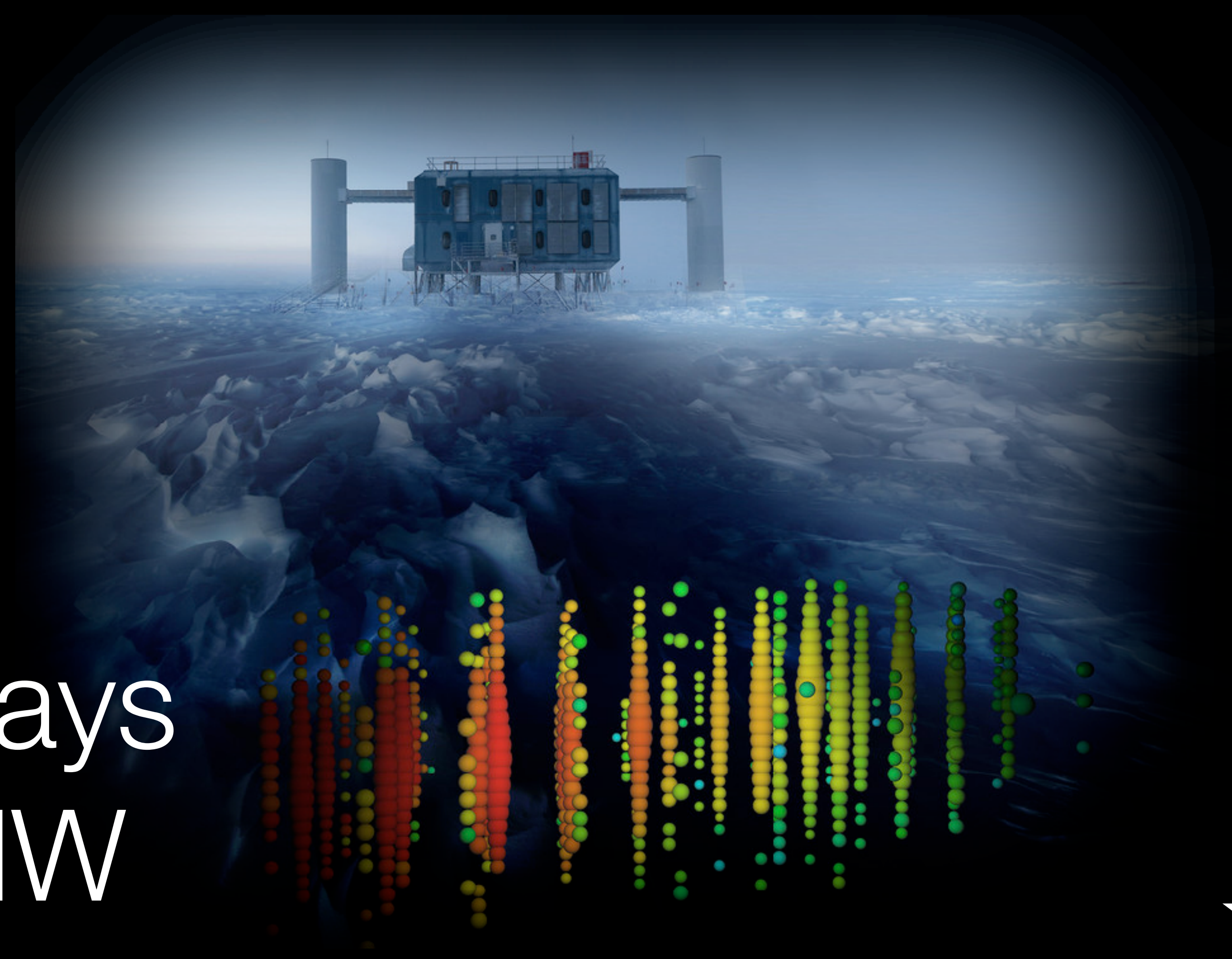

high-*E* neutrinos

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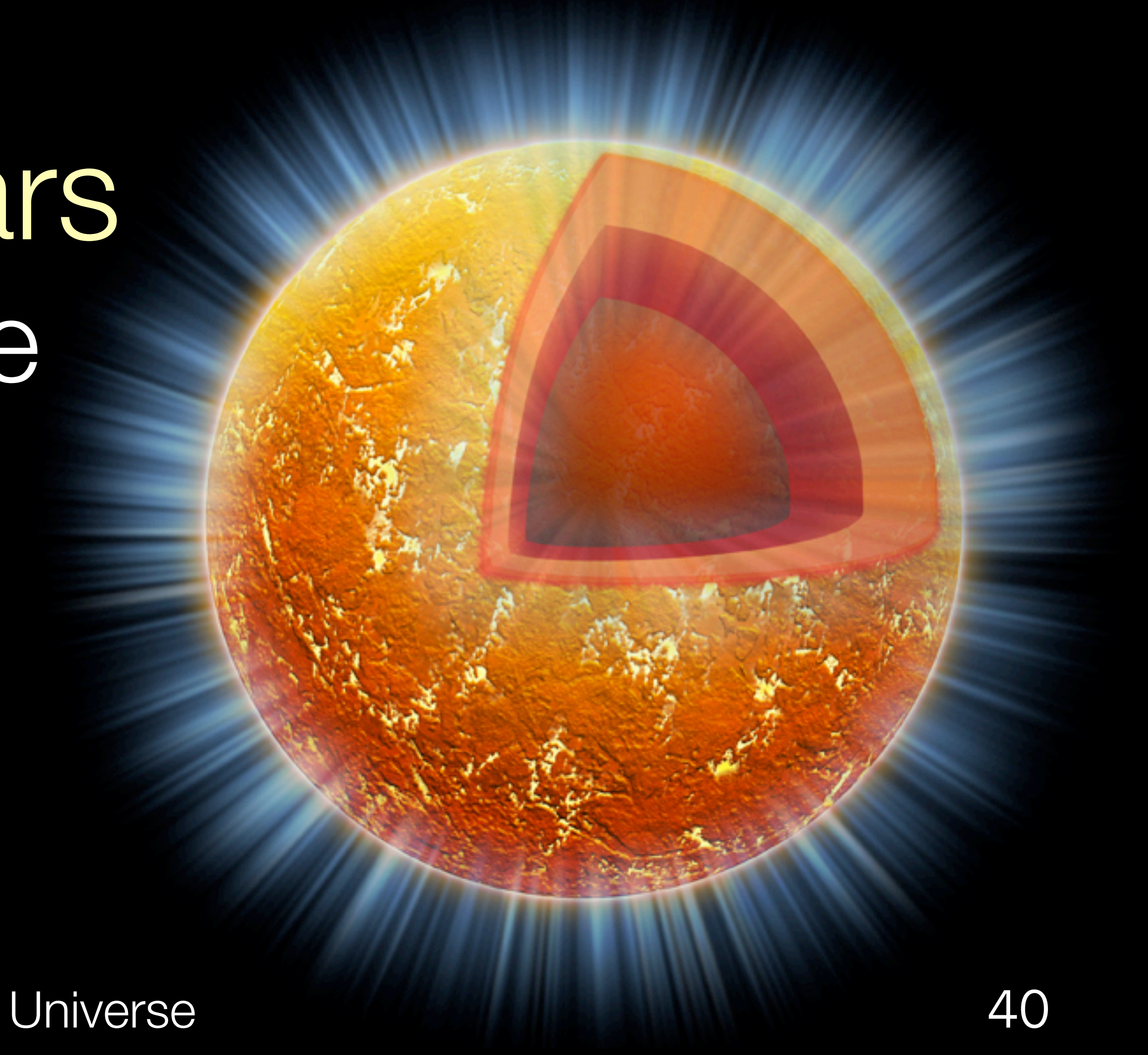
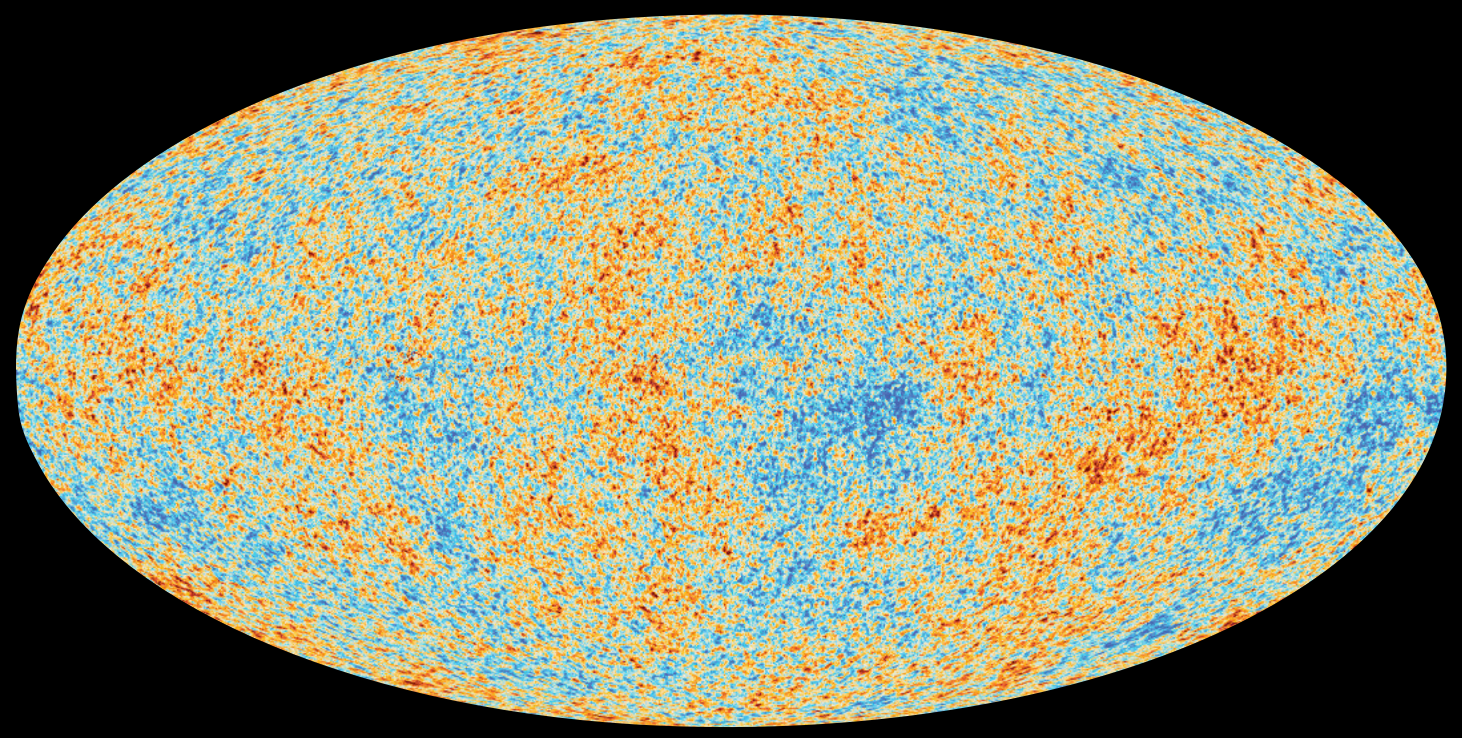
neutron stars

- ★ common-envelope systems
- ★ muon decays





cosmology

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Common-Envelope Evolution

- compact star (neutron star, black hole, white dwarf, …) enters companion star
- significant friction
- gigantic accretion rates (up to 0.1 $M_\odot$/yr for several months)
- crucial for the formation of gravitational wave sources
- **never observed**

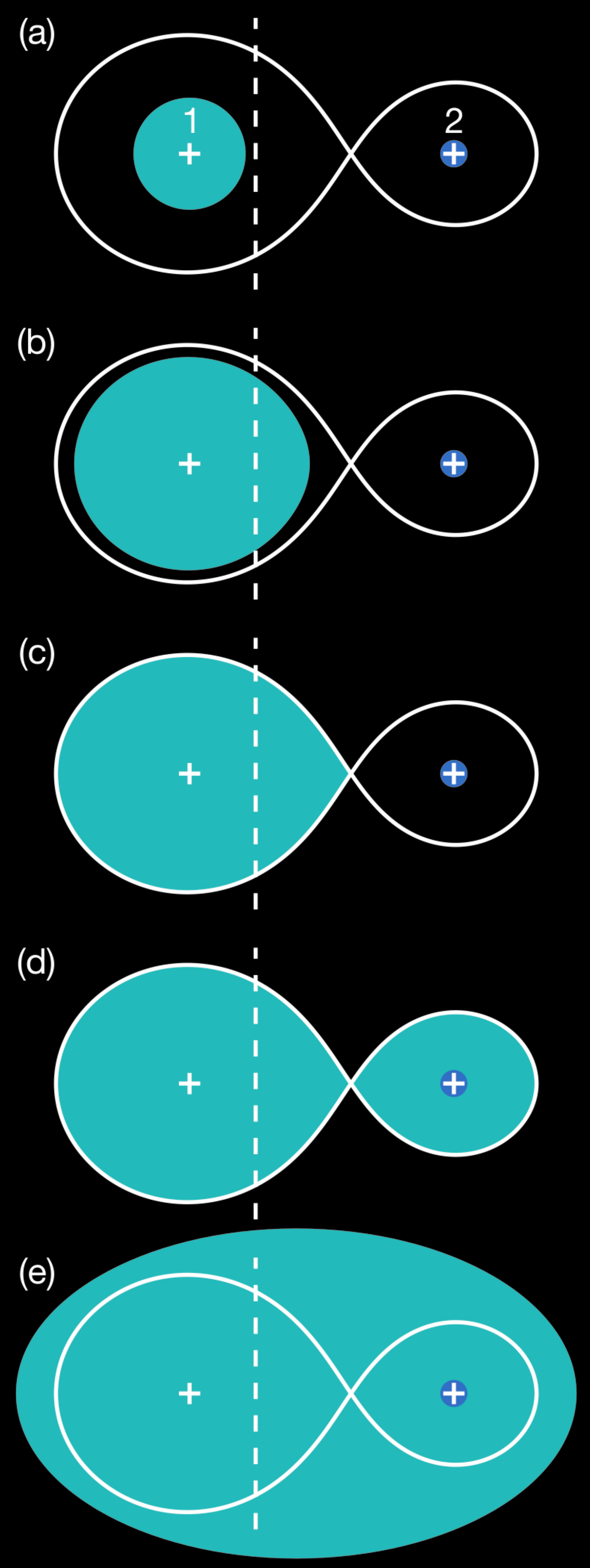
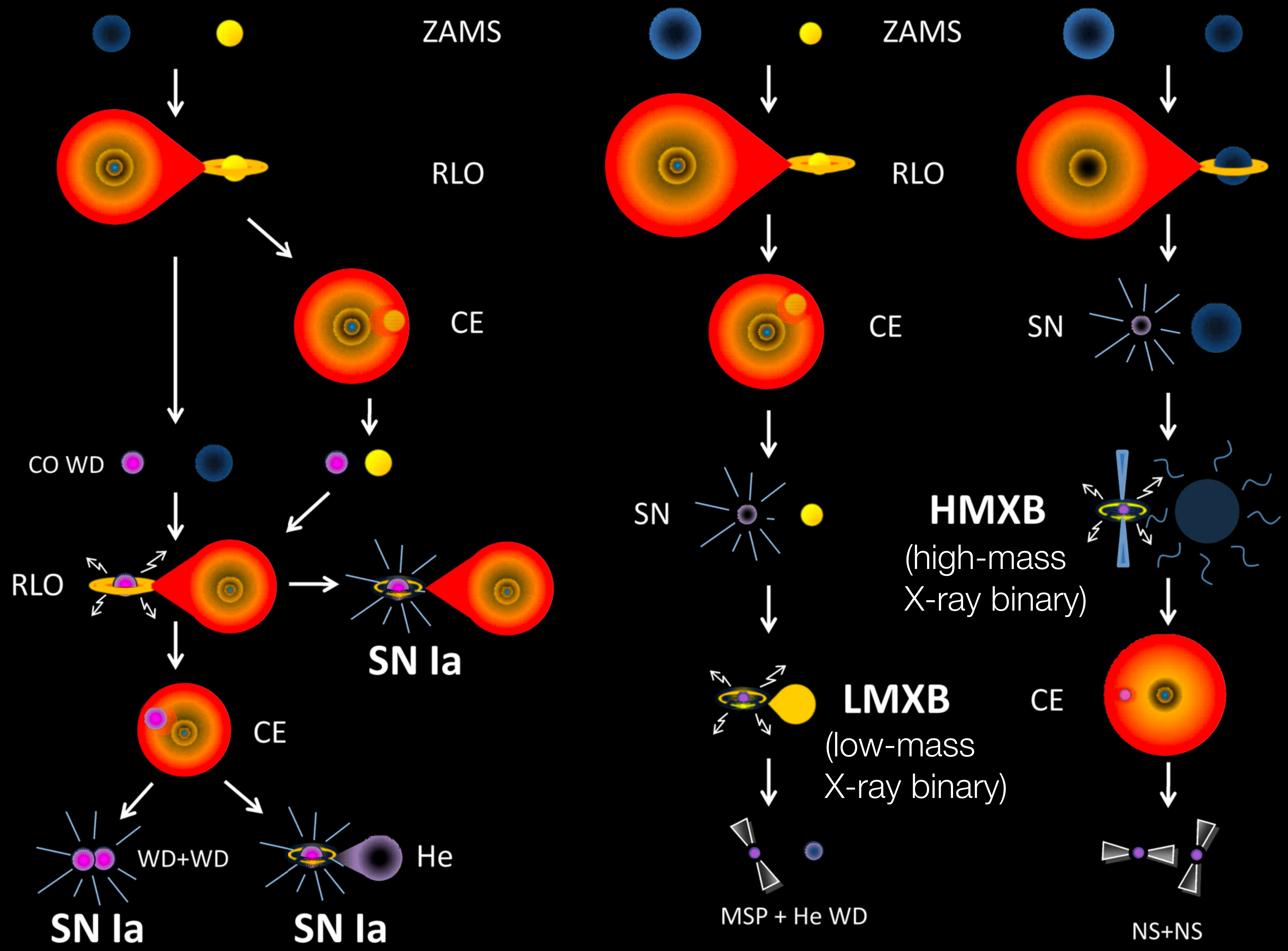


Image: Wikimedia Commons

Common-Envelope Evolution – Examples

Ivanova *et al.* 2012



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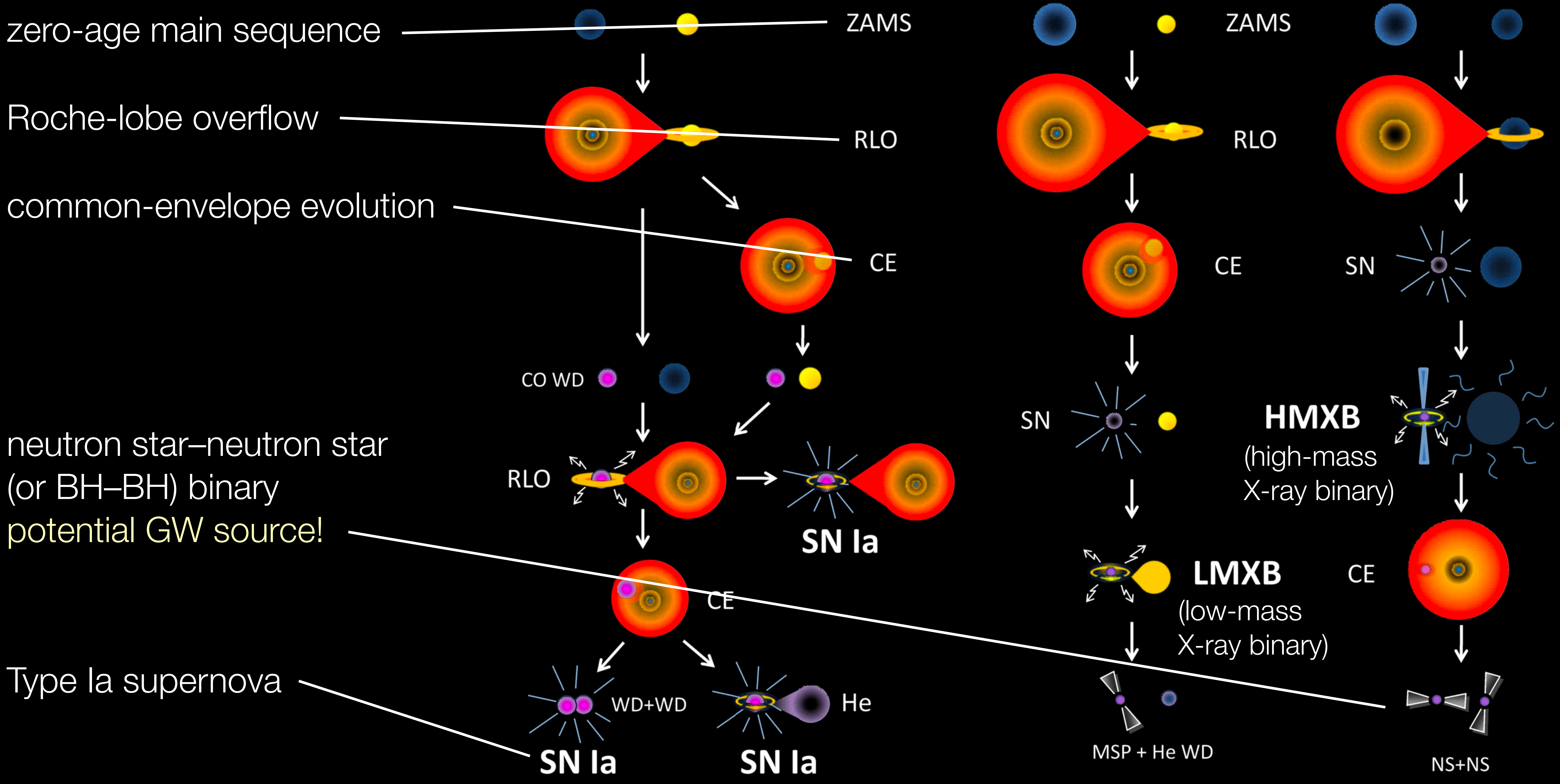
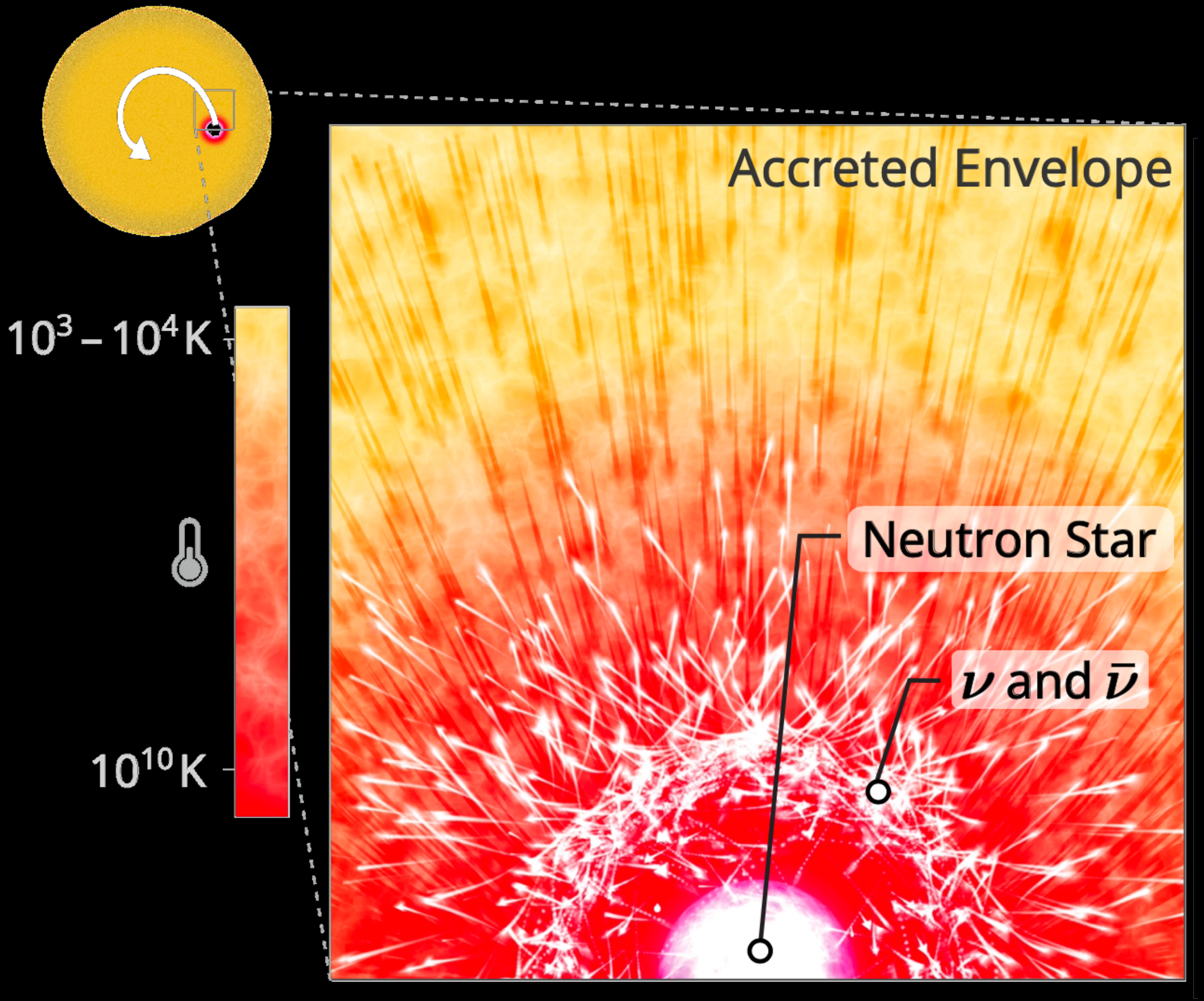


Common-Envelope Evolution – Neutrino Emission



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 $M_\odot$/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Esteban Beacom JK 2023

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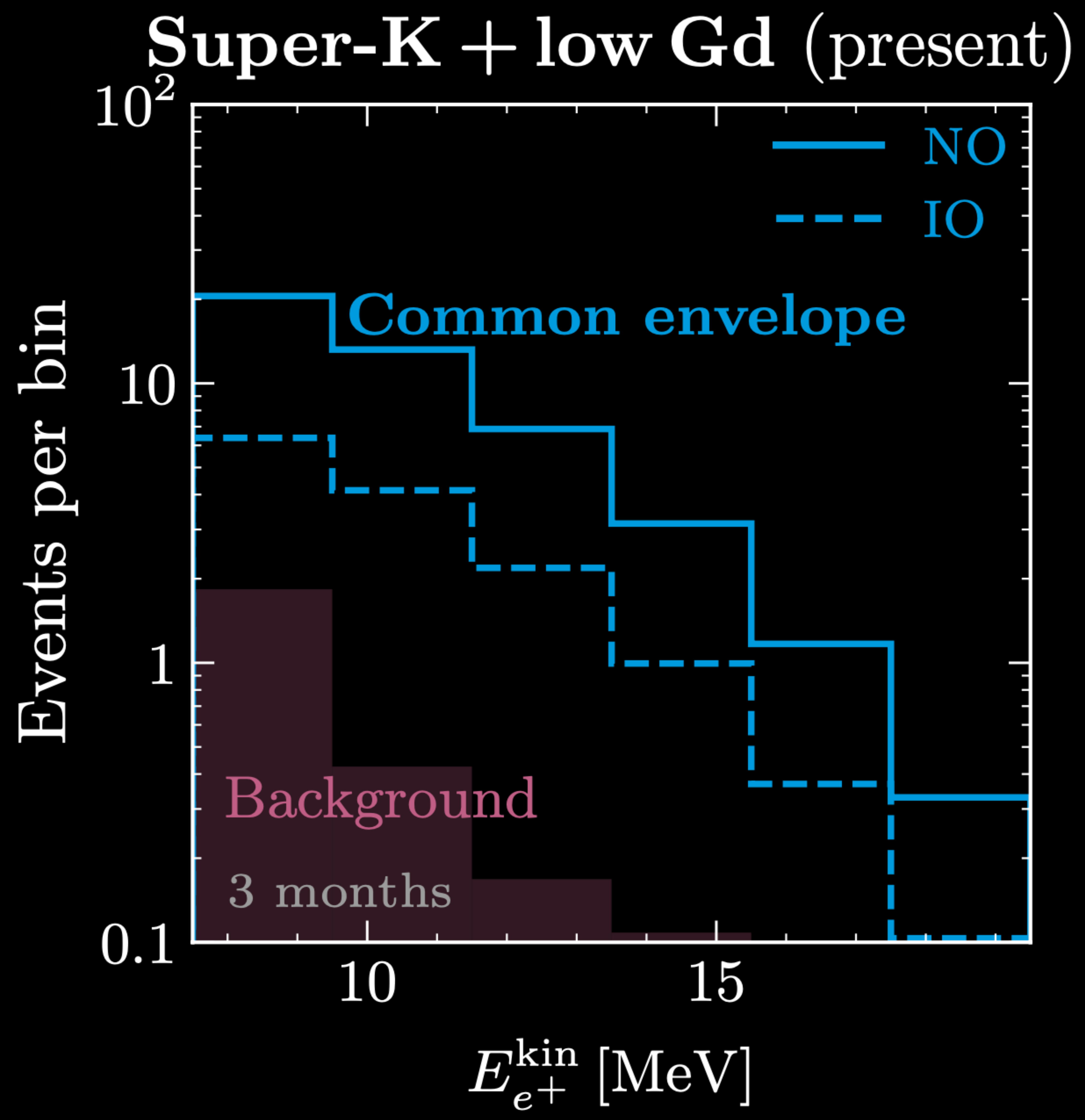

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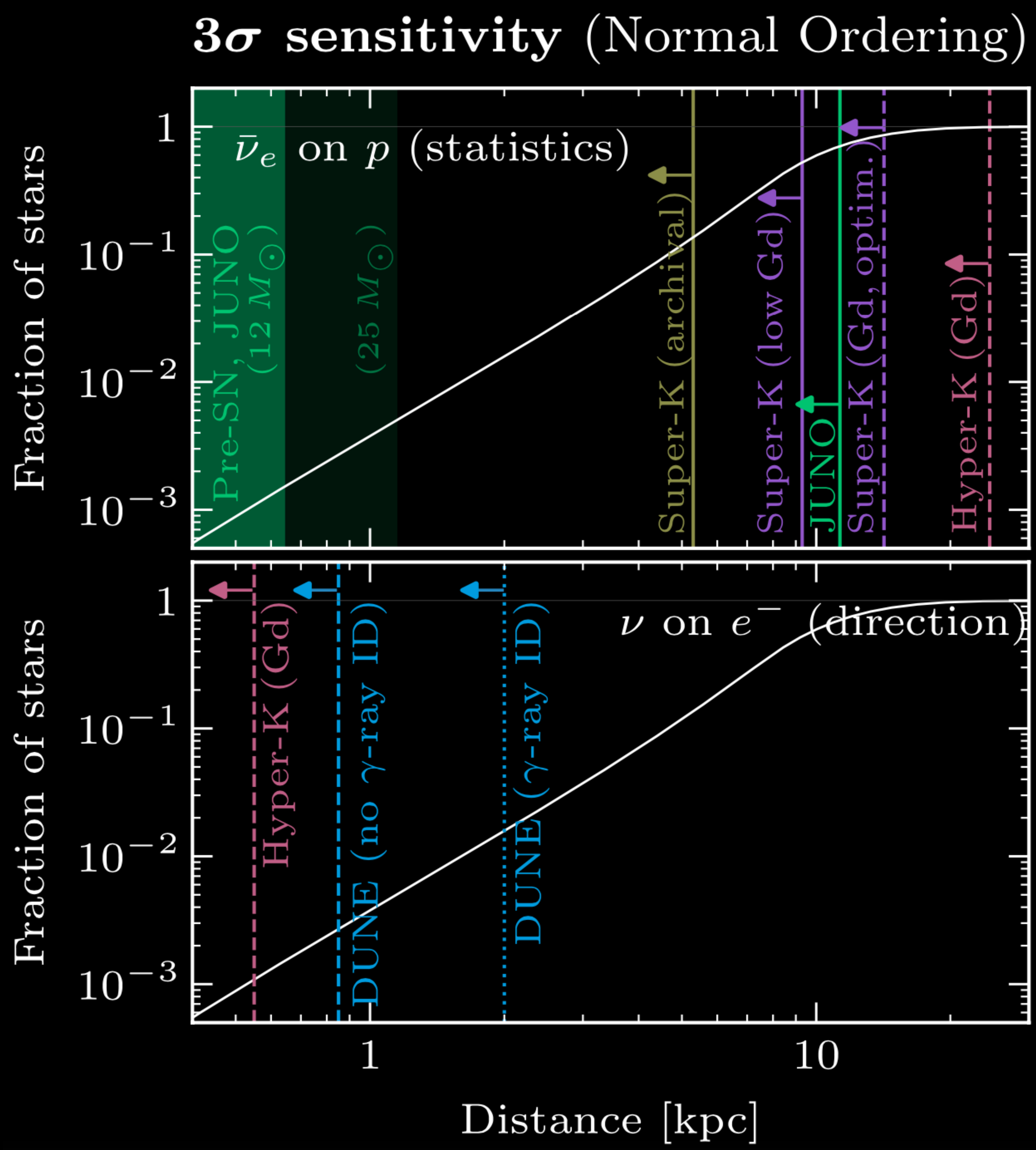

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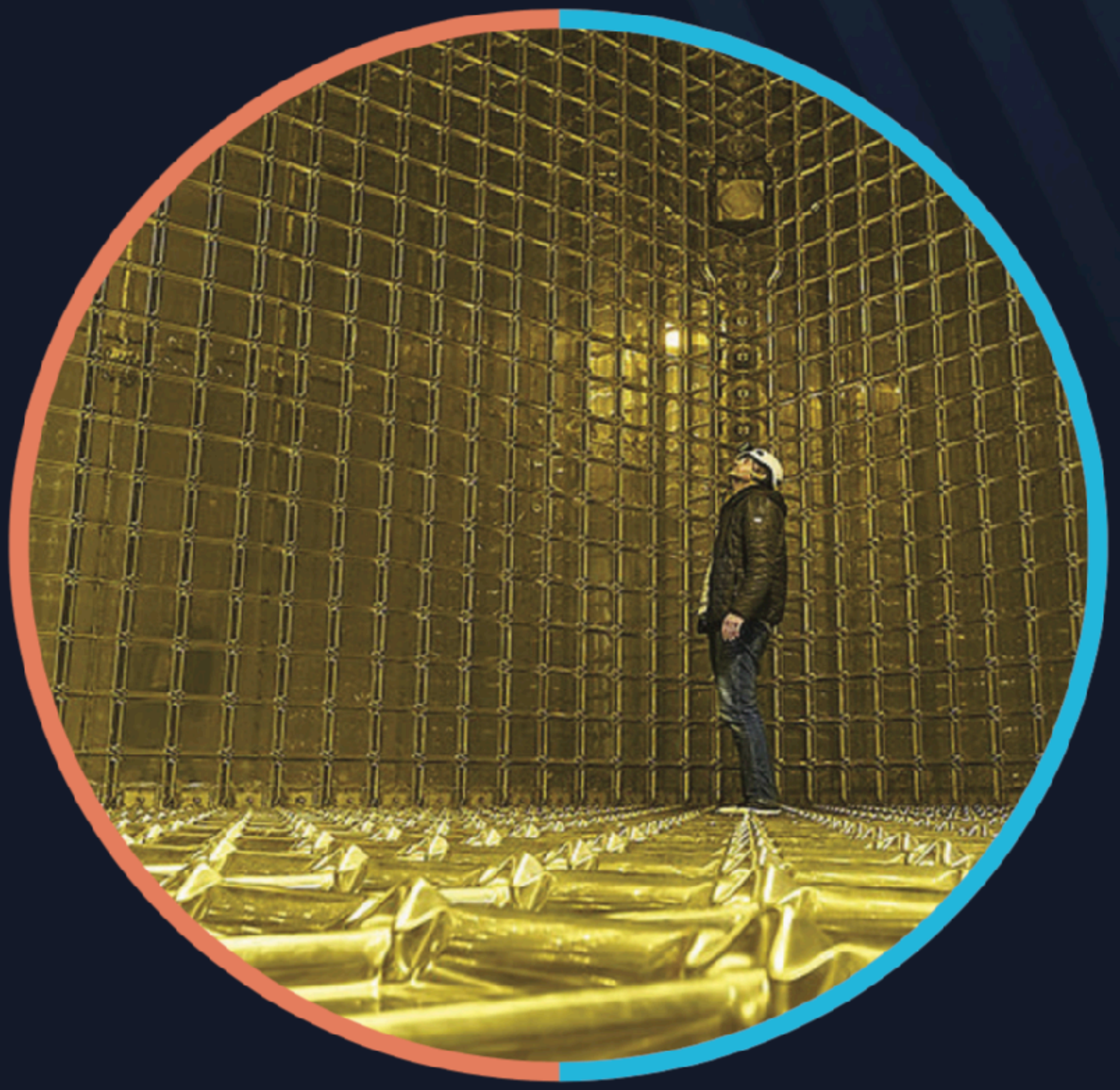
Next-Generation Long-Baseline Experiments



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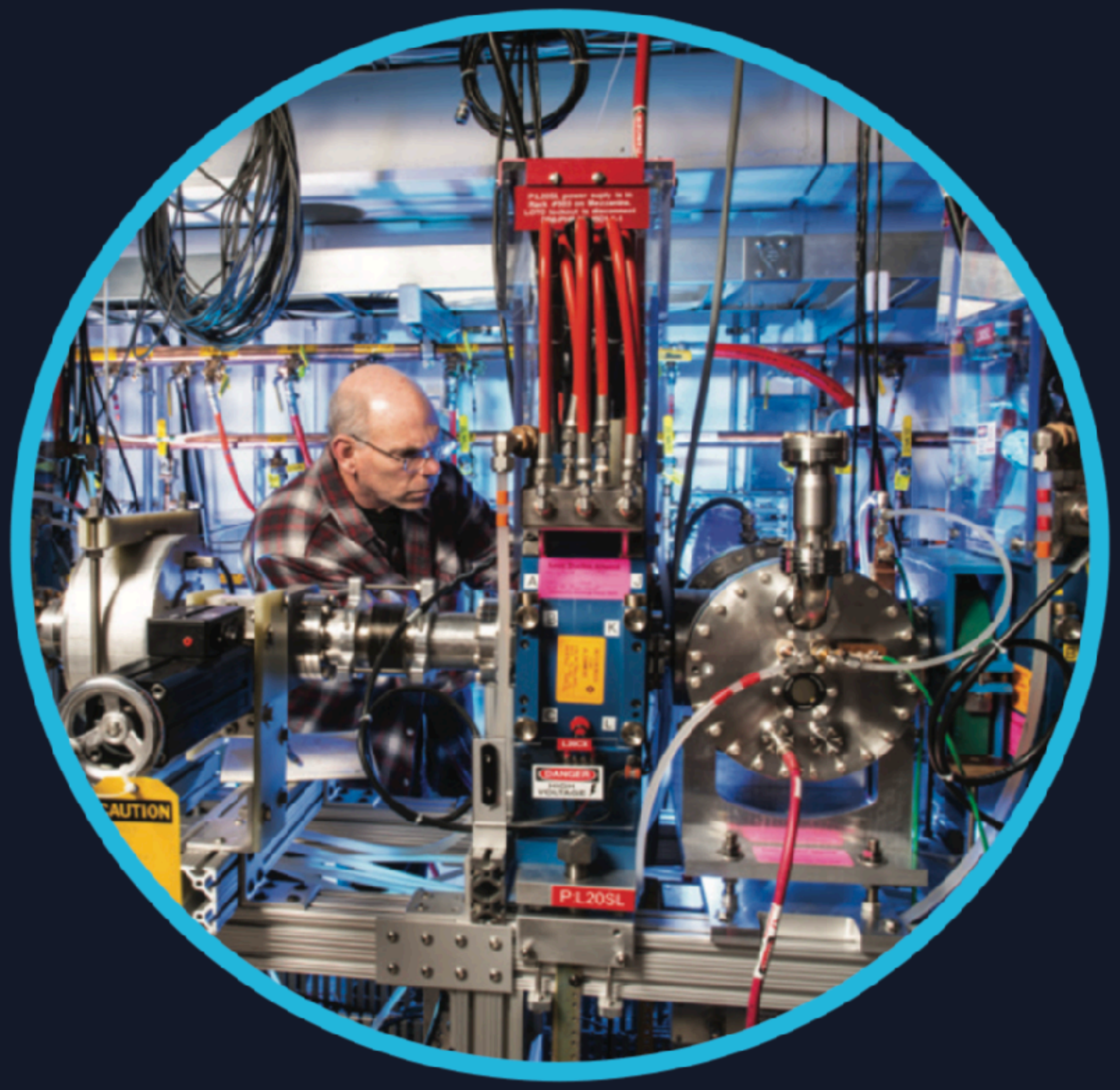

Neutrino source

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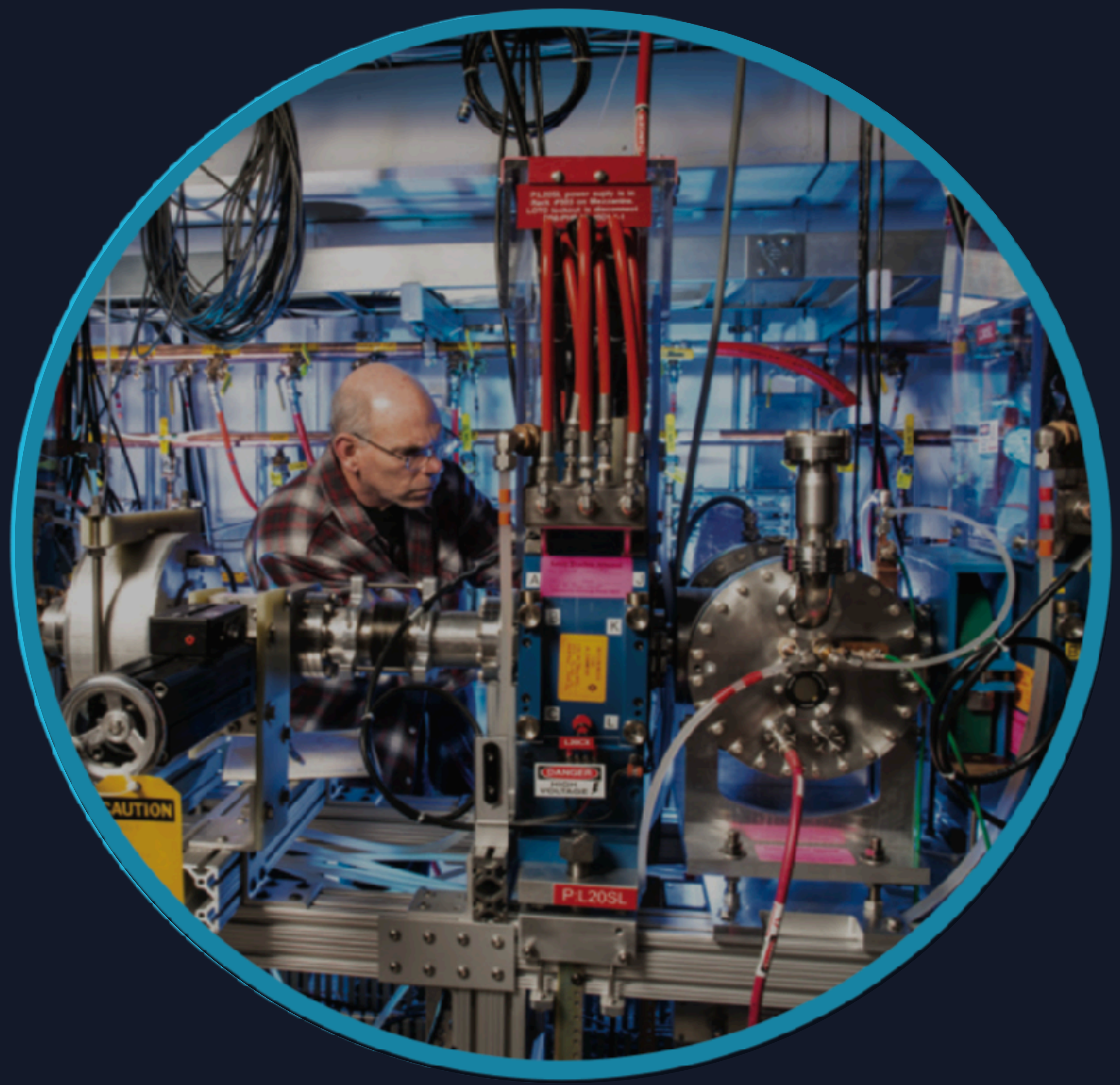
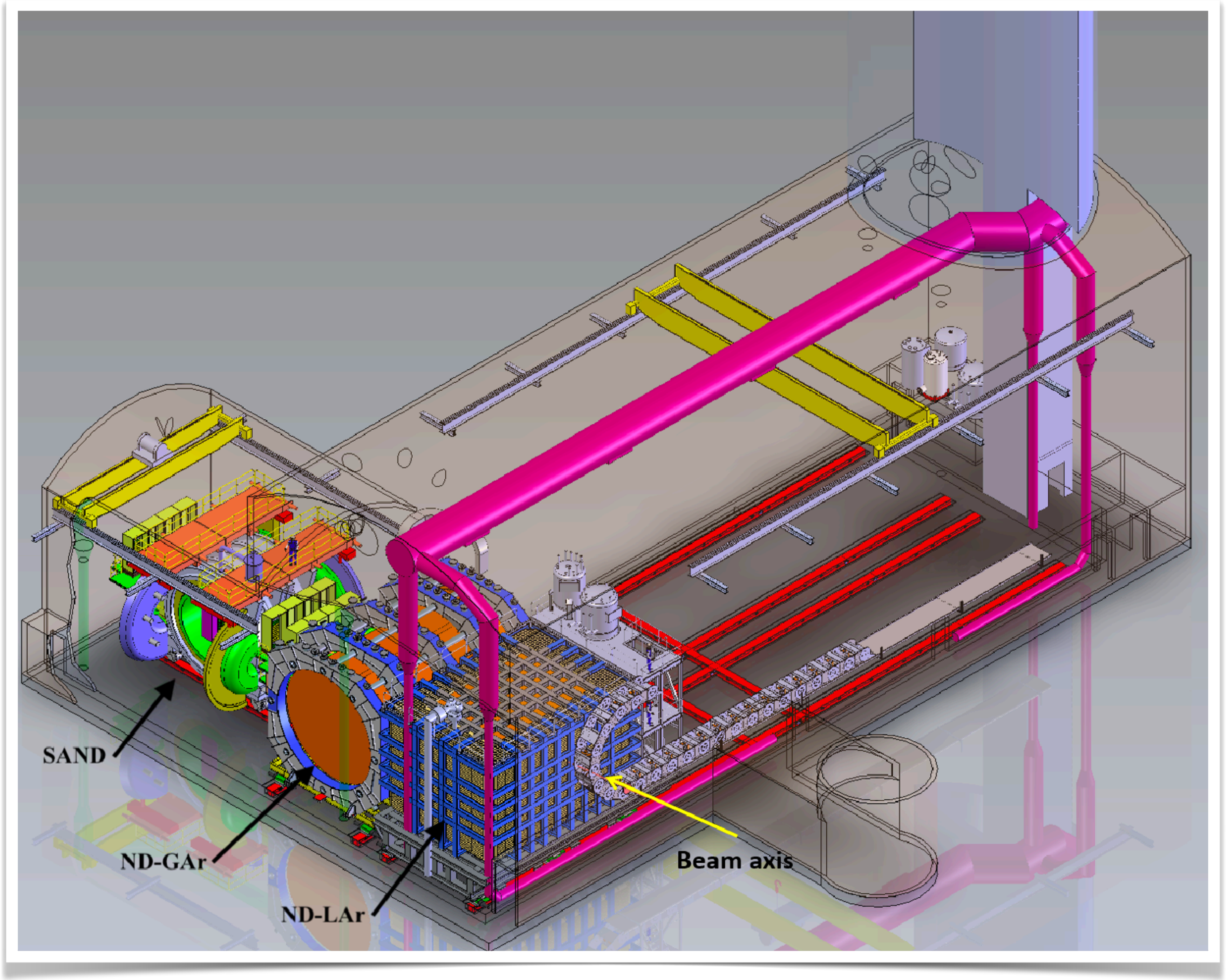


Neutrino source

The DUNE Near Detectors



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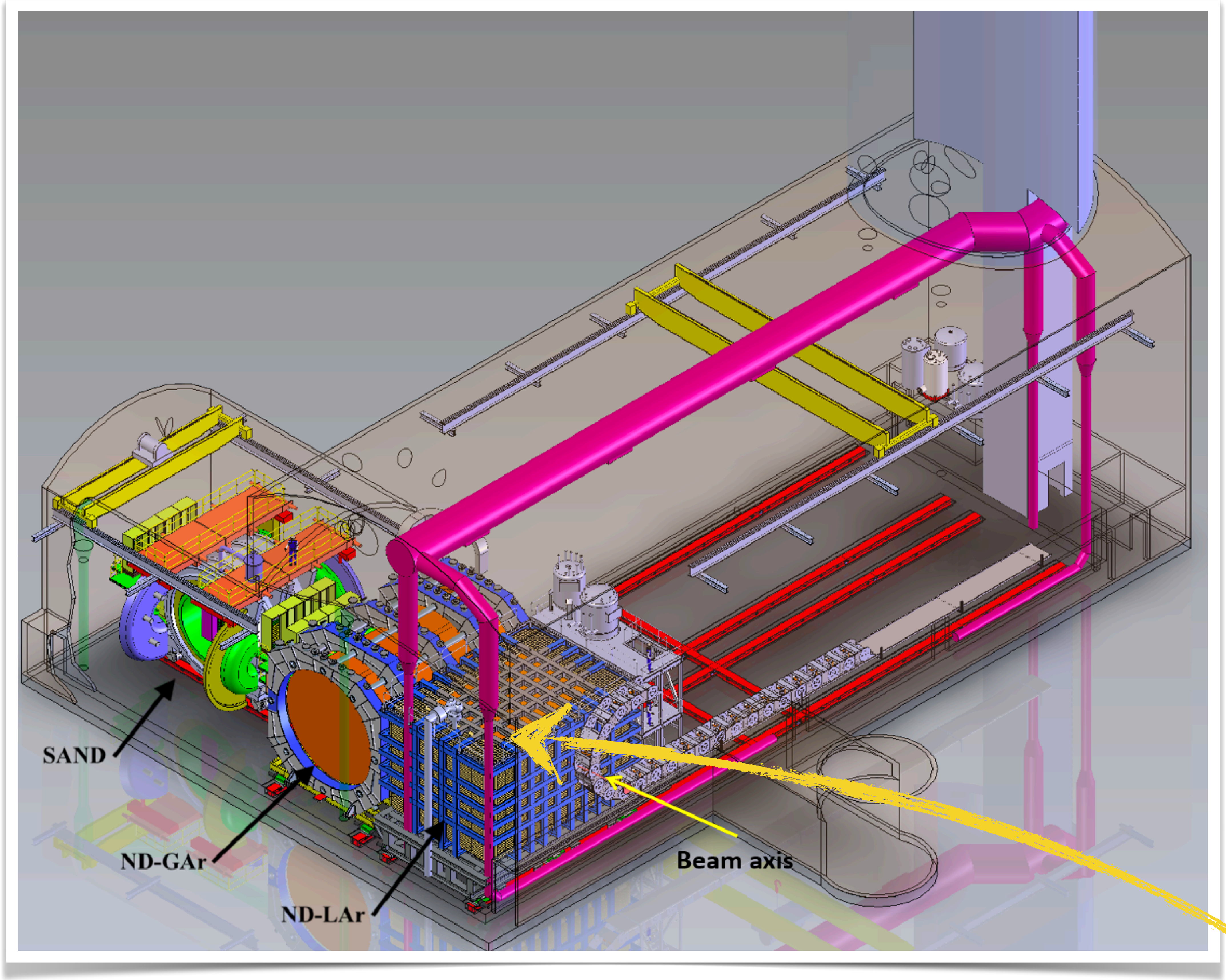

Liquid Argon TPC ("ND-LAr")

- similar to far detector (cancel systematic uncertainties)

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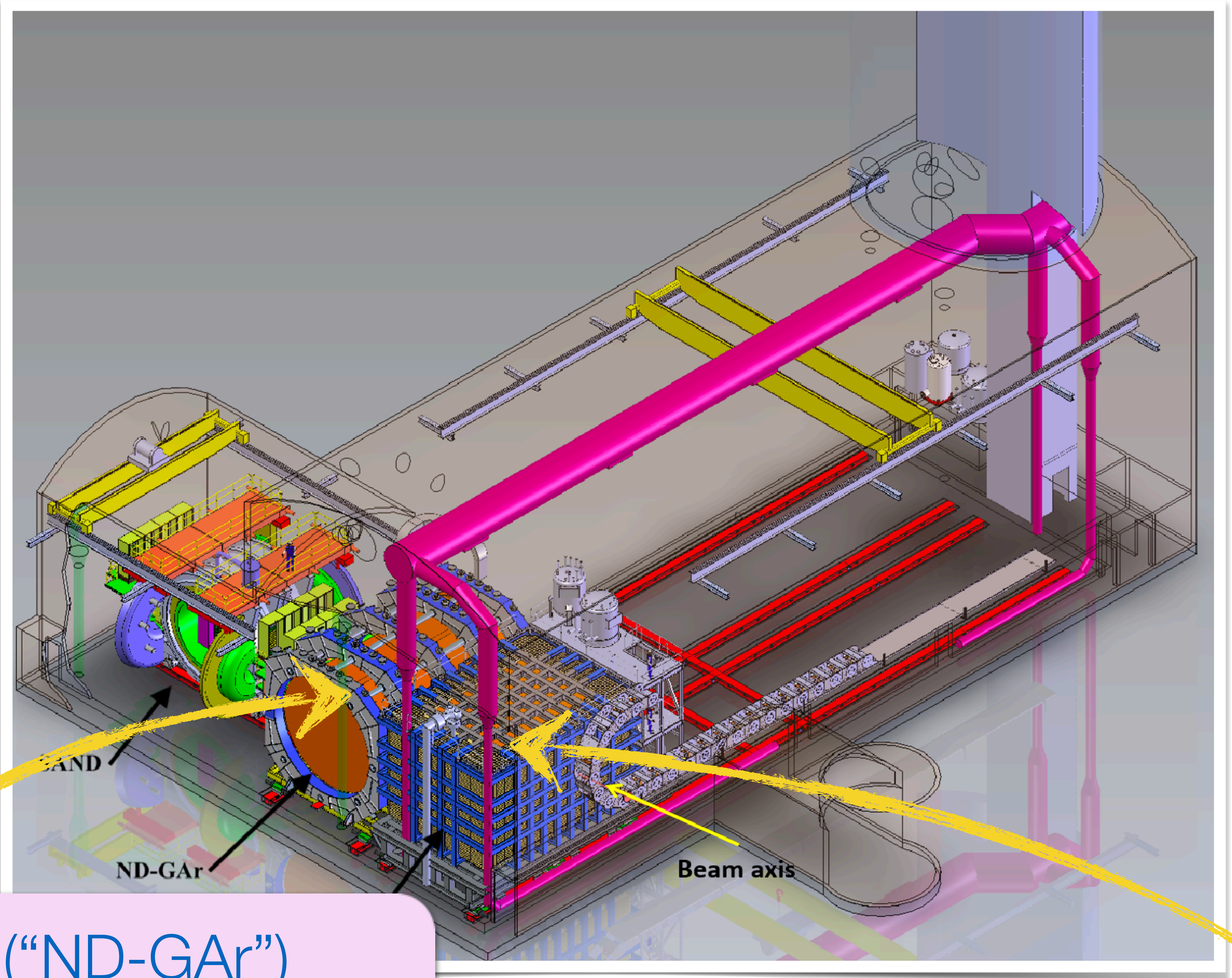

HP Gas TPC + ECal ("ND-GAr")
- excellent event reconstruction
- magnetic field

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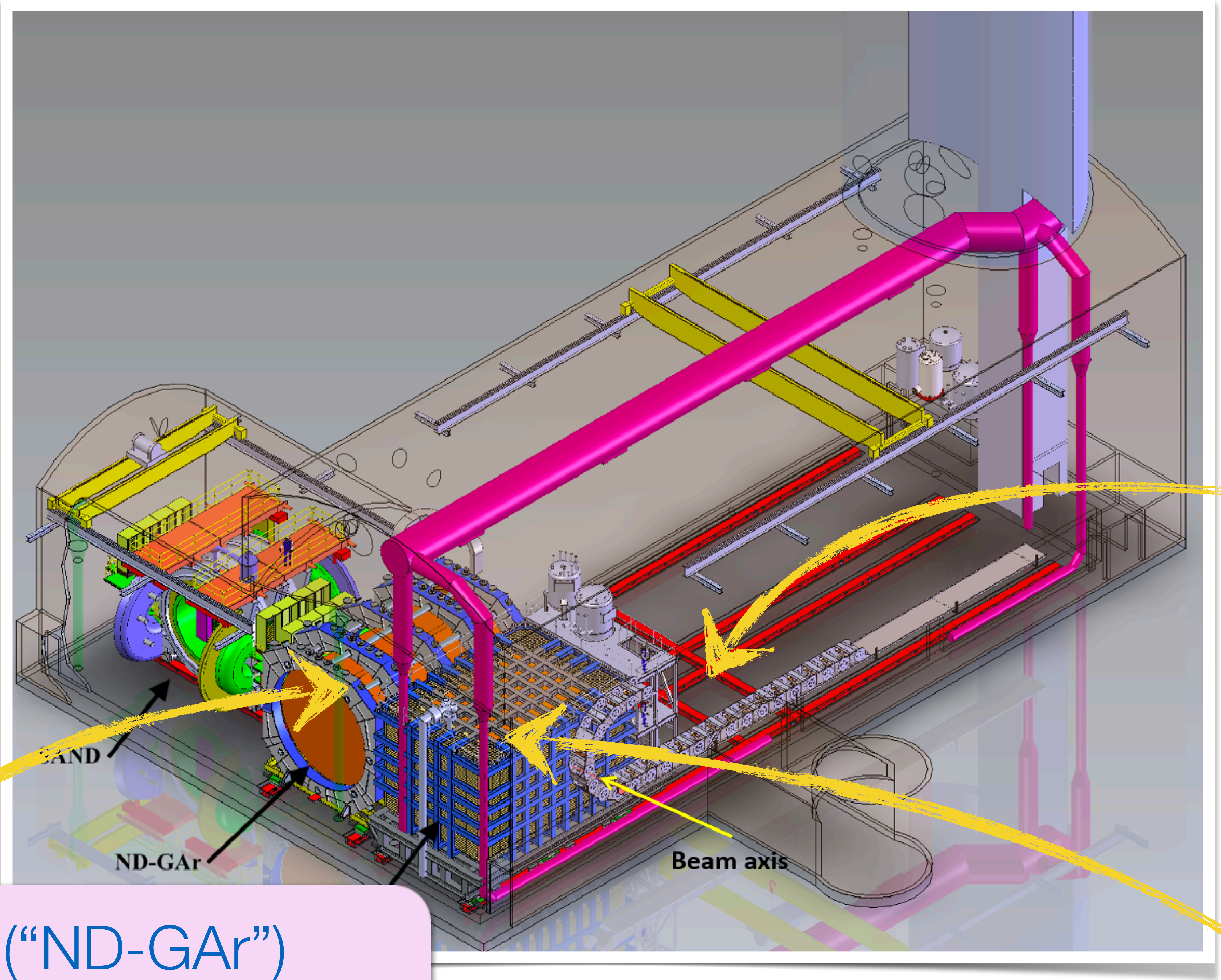

Movable Platform ("PRISM")
to take data both on-axis and off-axis (different beam spectra)

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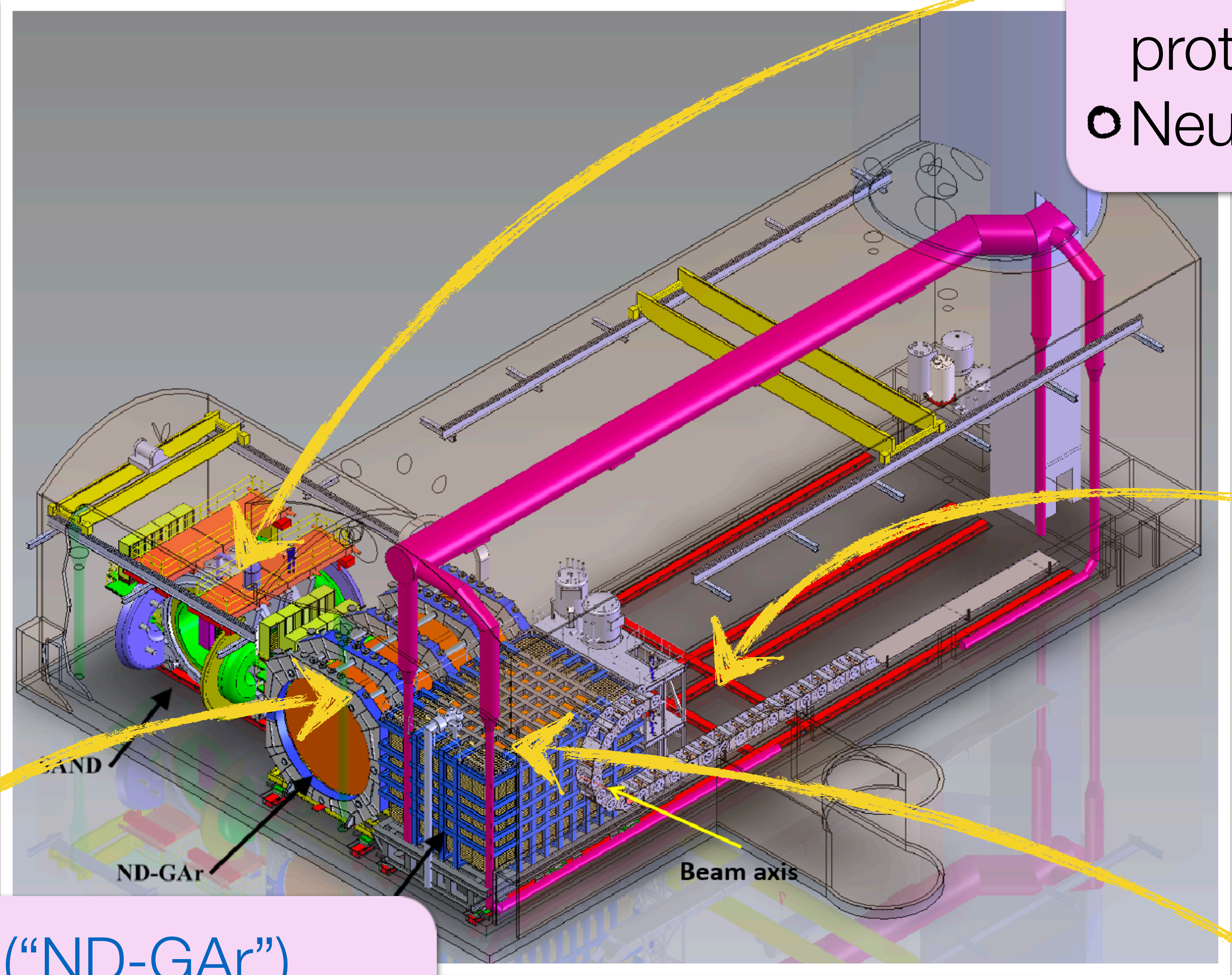


On-Axis Beam Monitor ("SAND")

- CH_2 → neutrino interactions on free protons (no nuclear physics)
- Neutron tagging

Movable Platform ("PRISM")

to take data both on-axis and off-axis (different beam spectra)

Liquid Argon TPC ("ND-LAr")

- similar to far detector (cancel systematic uncertainties)

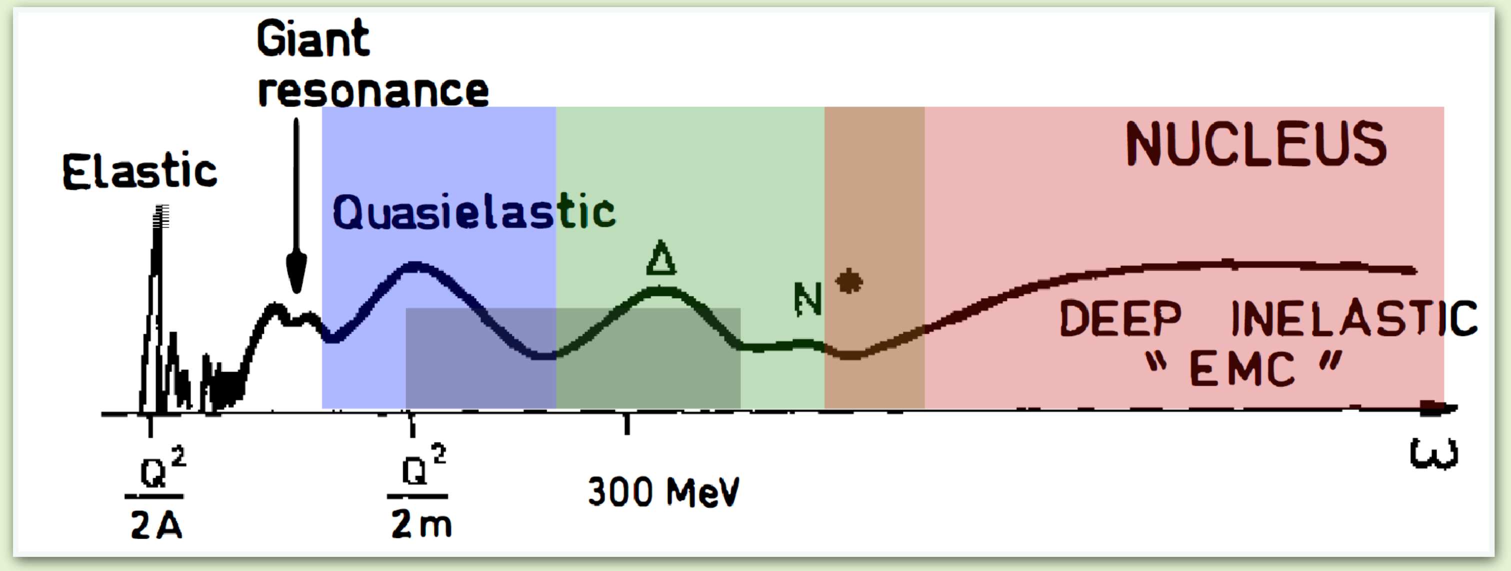
HP Gas TPC + ECal ("ND-GAr")

- excellent event reconstruction
- magnetic field

Physics with the DUNE Near Detectors

Neutrino Cross-Sections

- superb event reconstruction capabilities
- detailed separation of different interaction channels
- neutrino interactions on relatively heavy target (Ar-40)
- on-axis and off-axis
  (for disentangling flux and cross-section uncertainties)



Understanding Neutrino Interactions

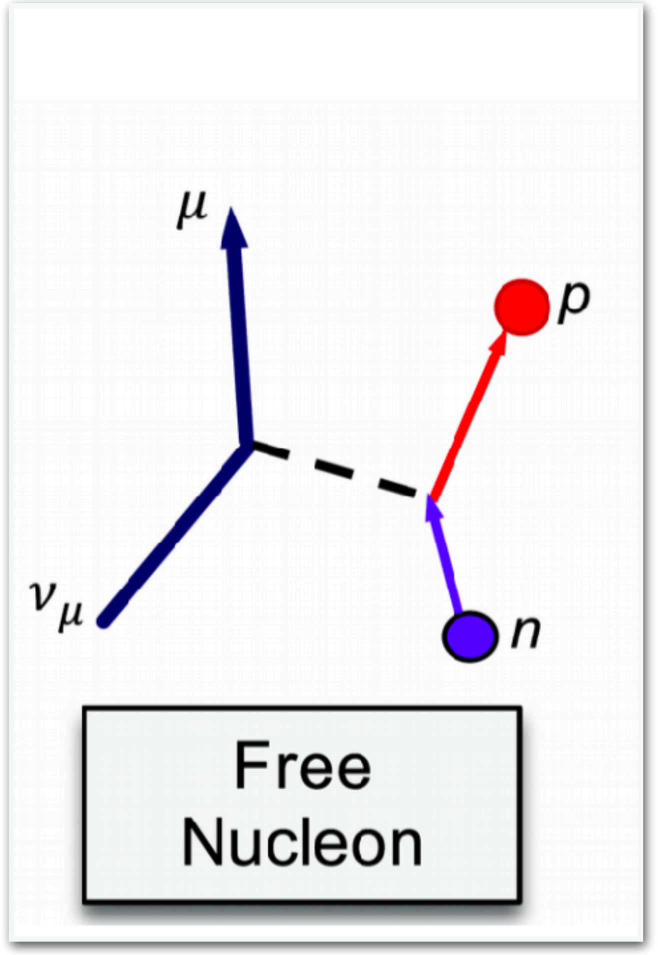


Image Credit: Callum Wilkinson

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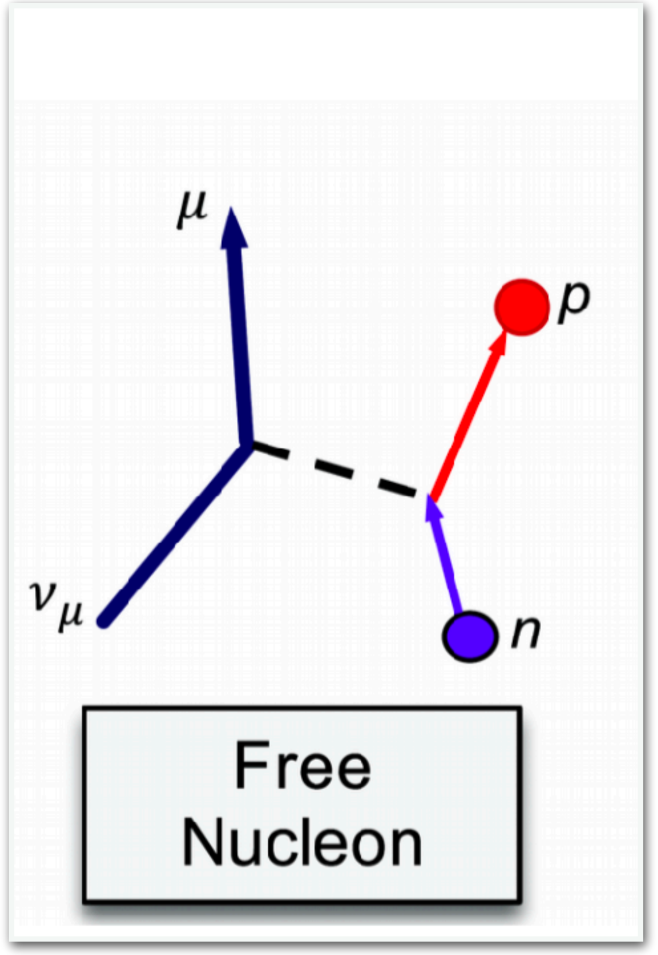

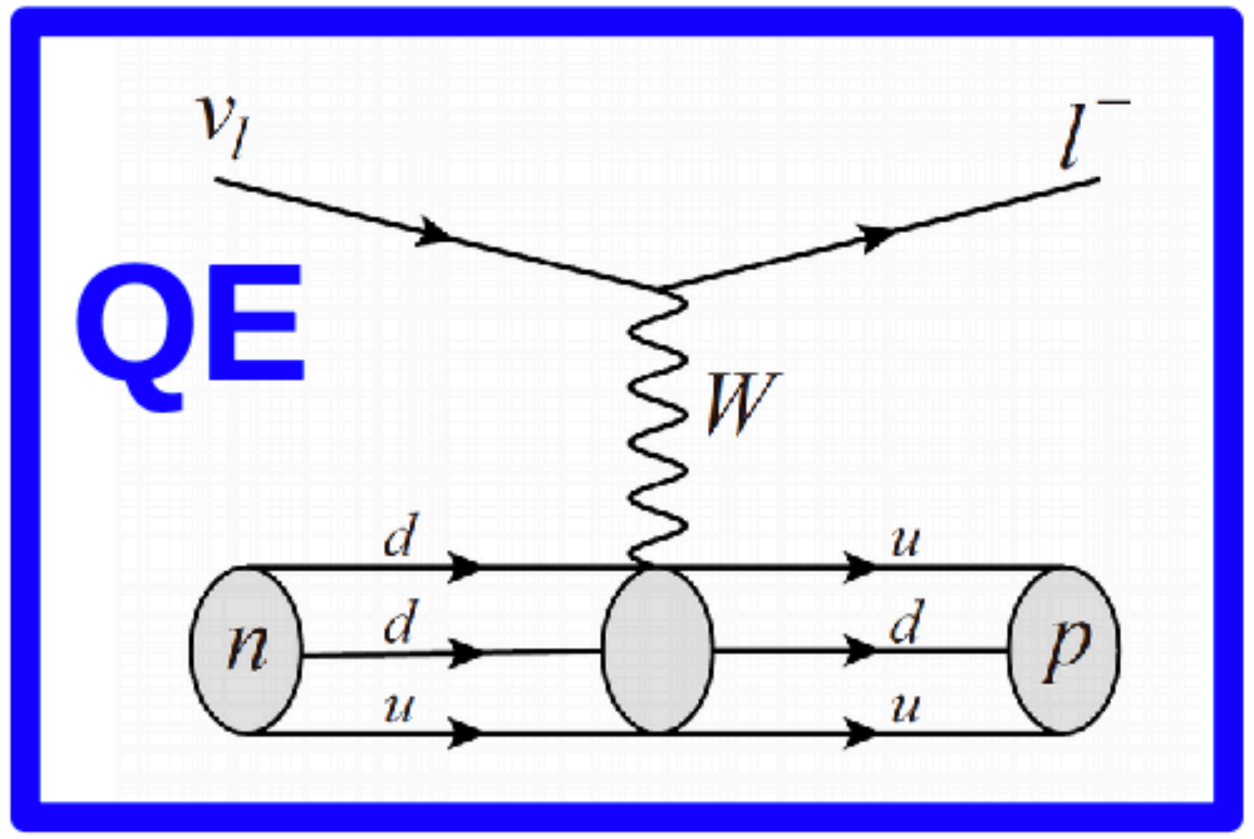

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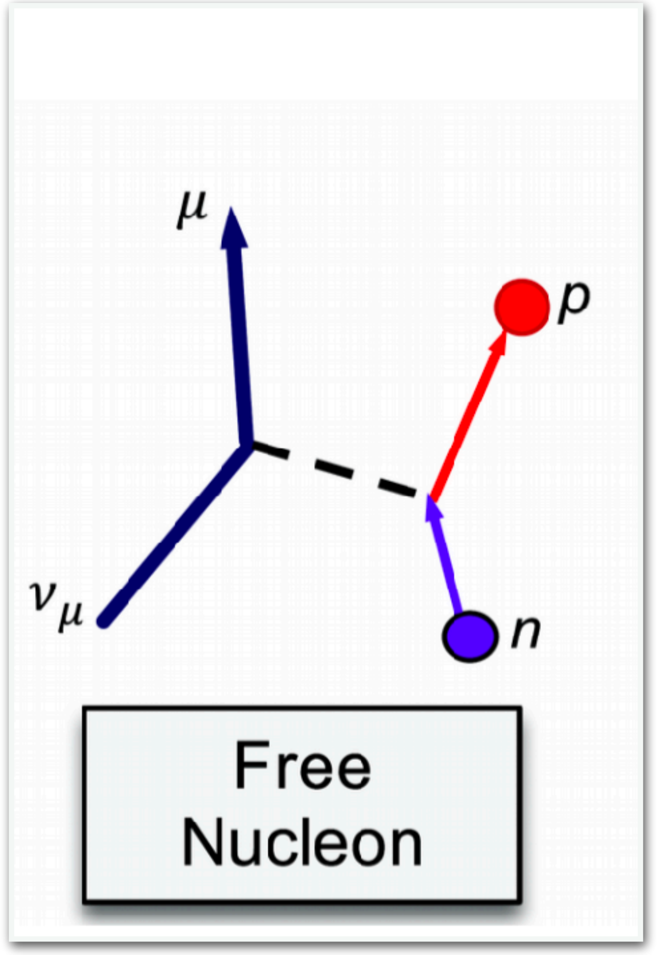

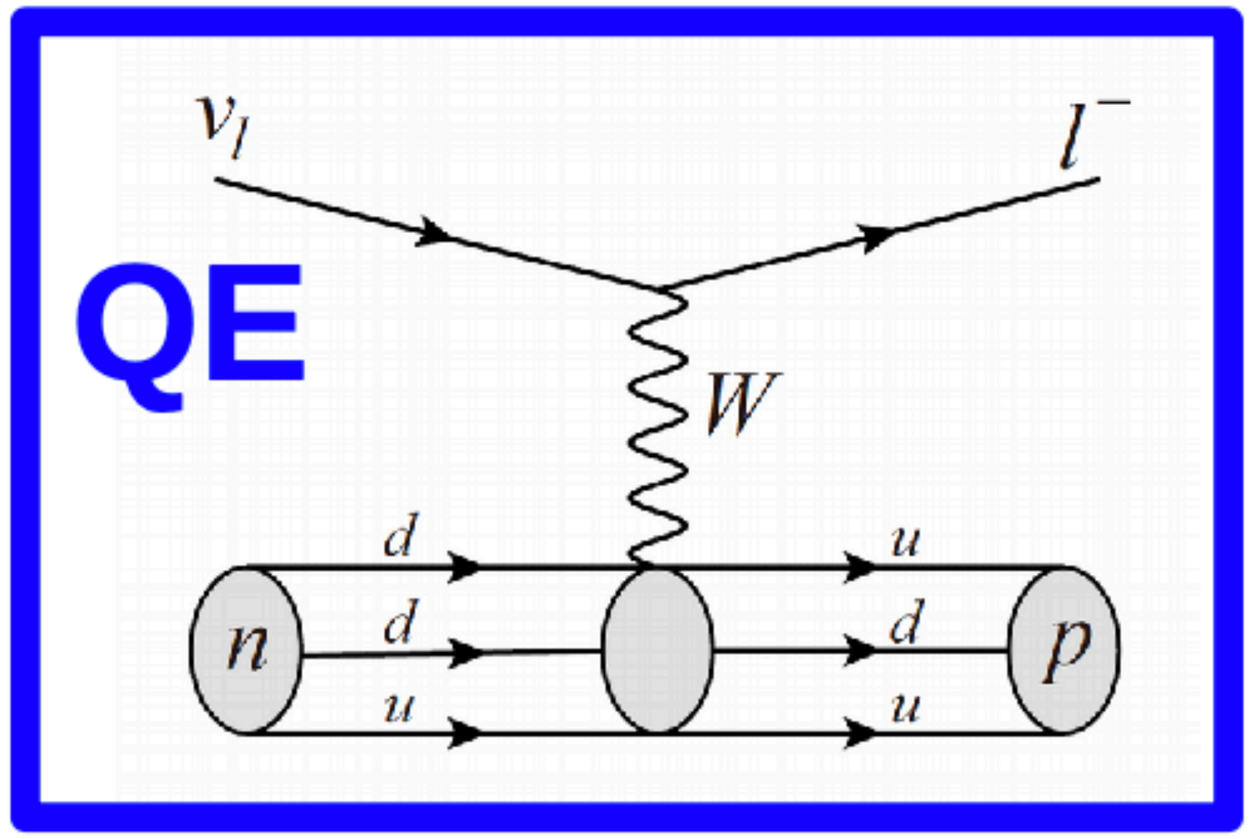

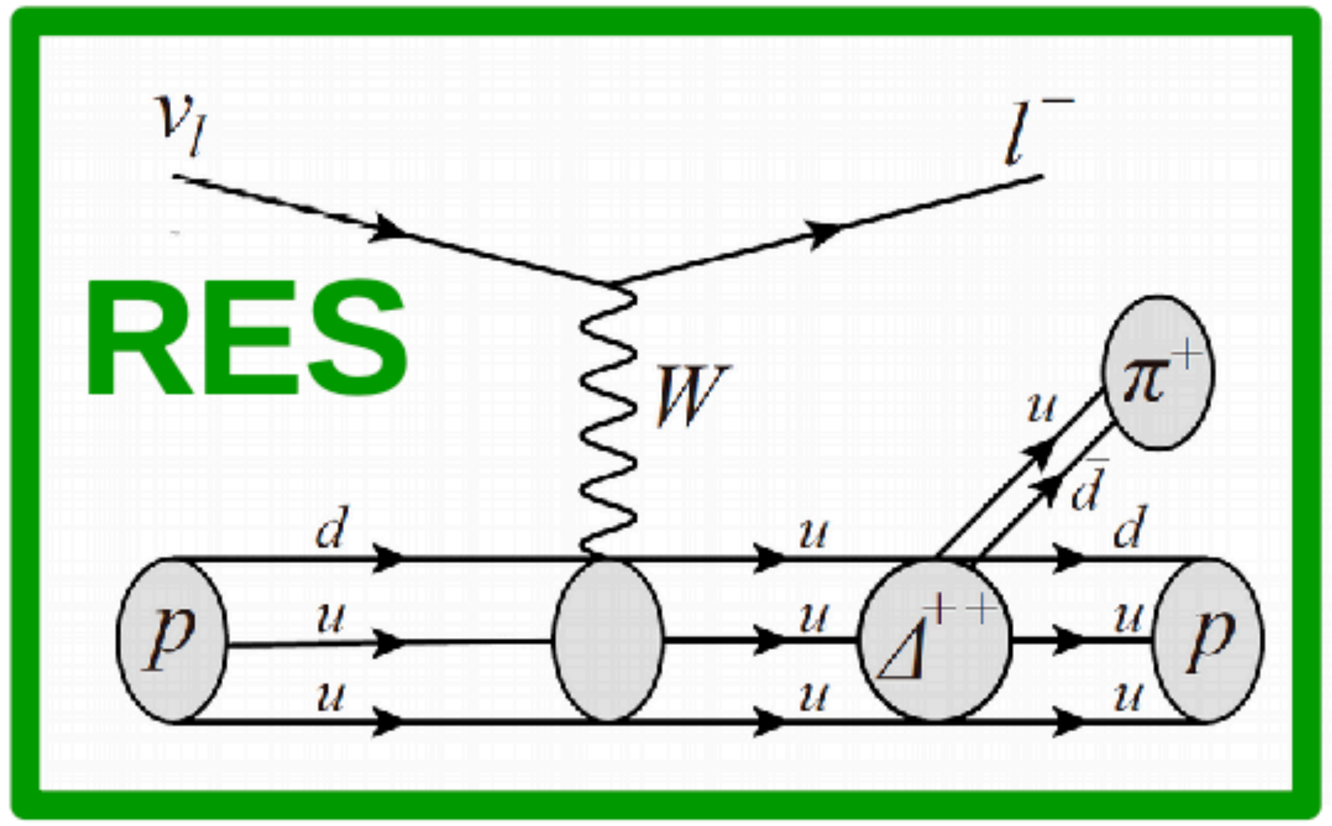

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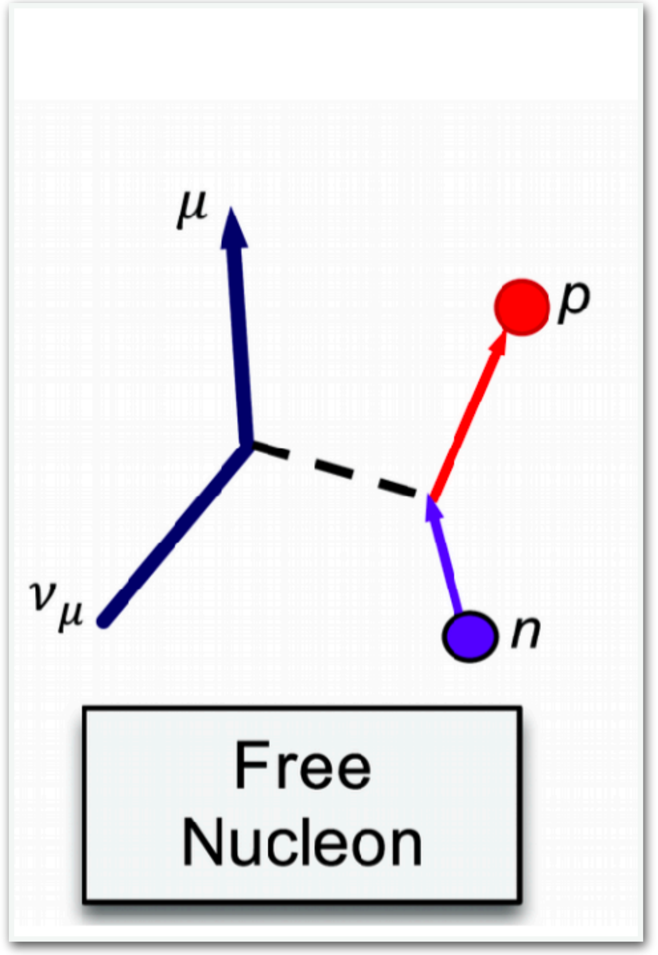

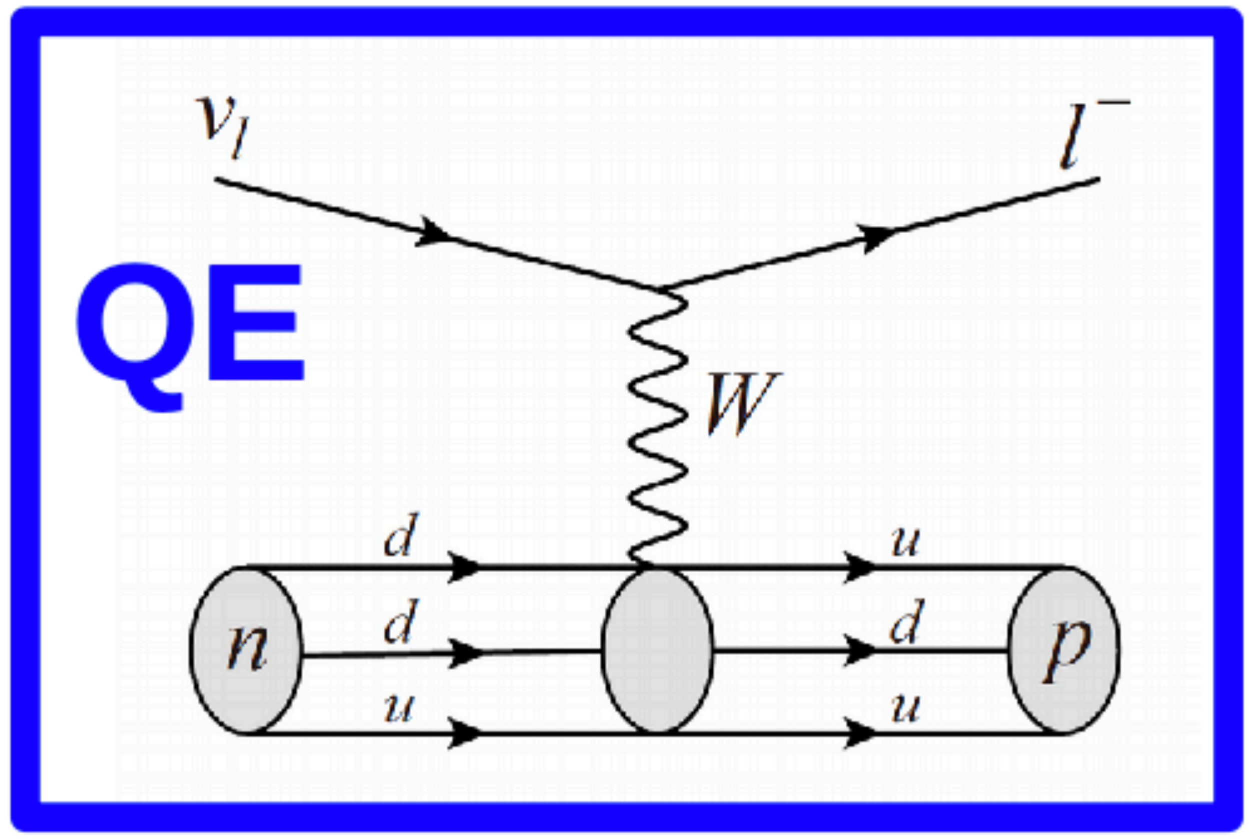

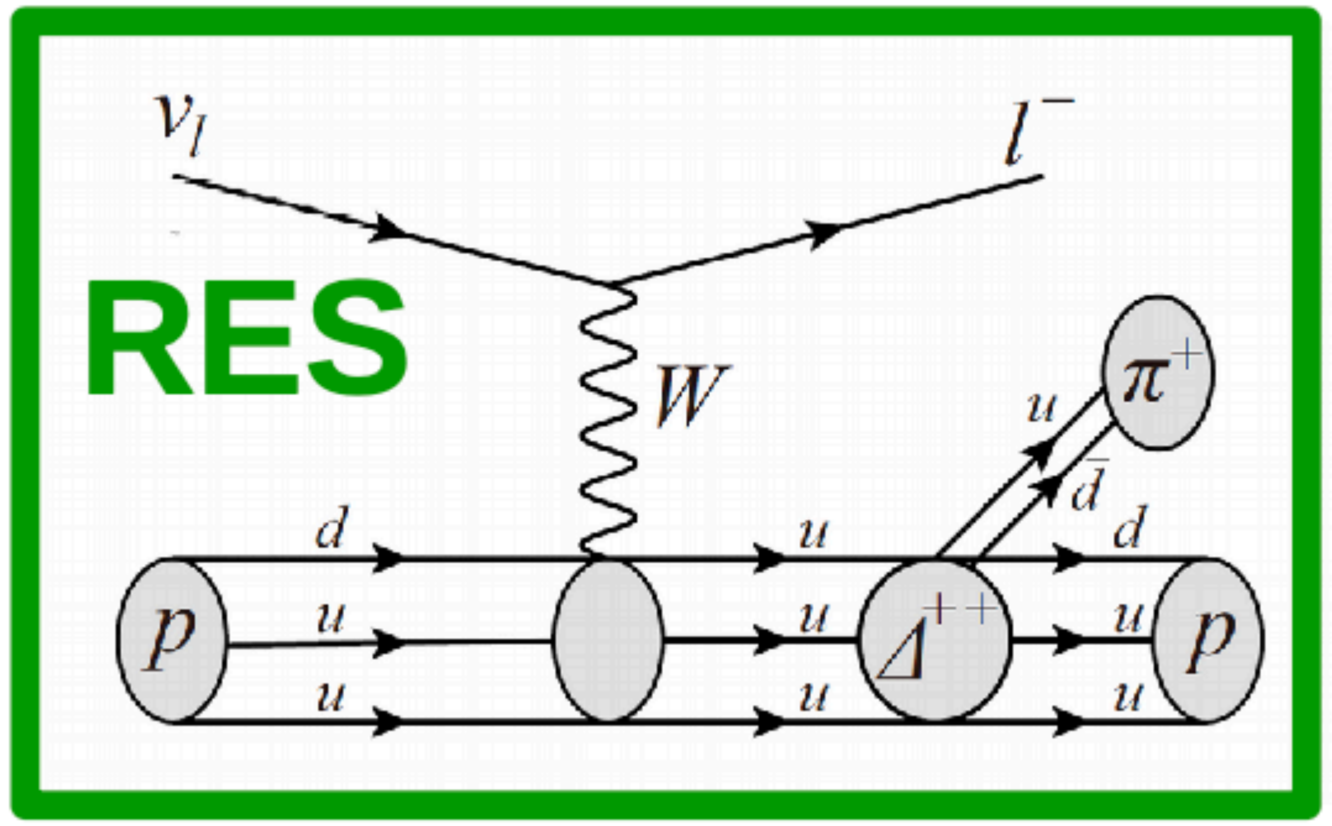

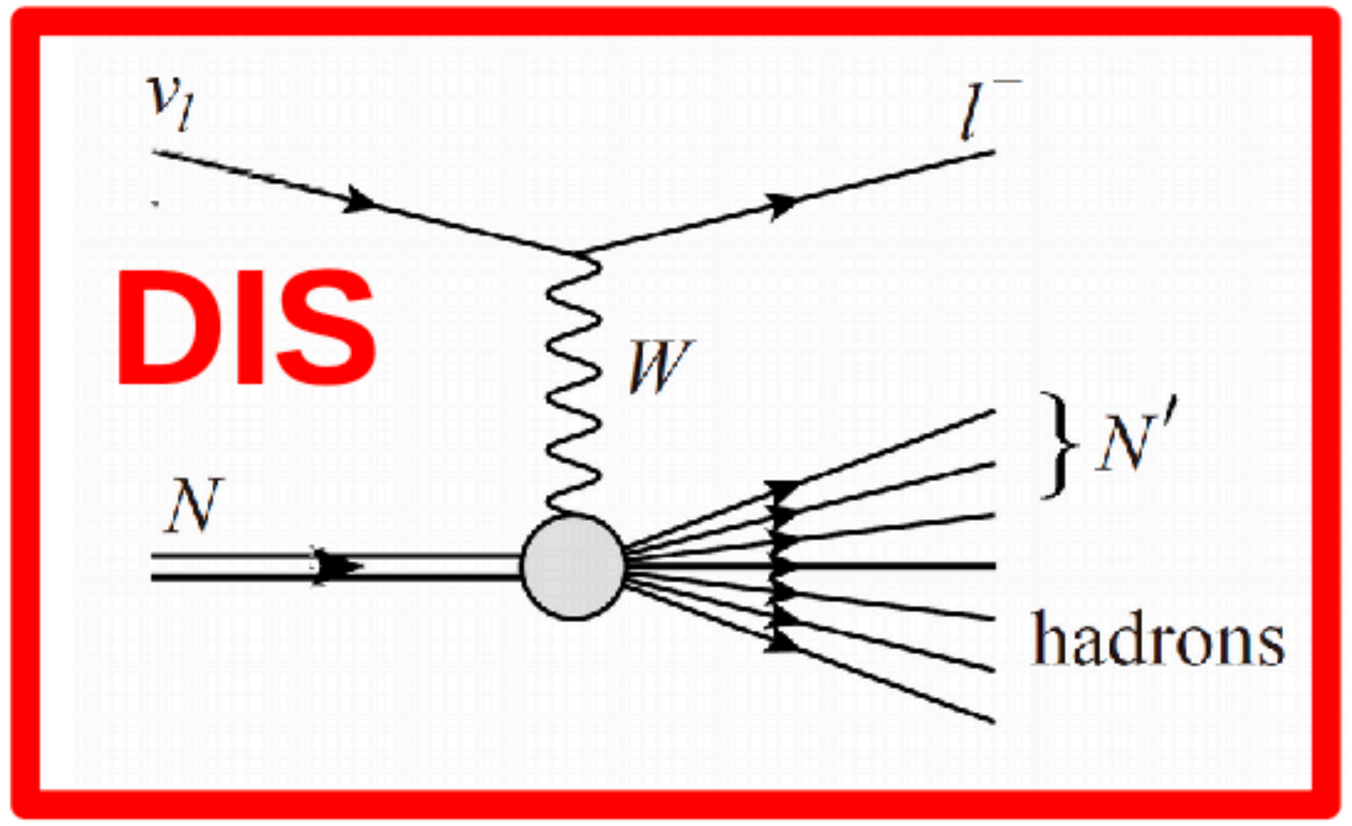

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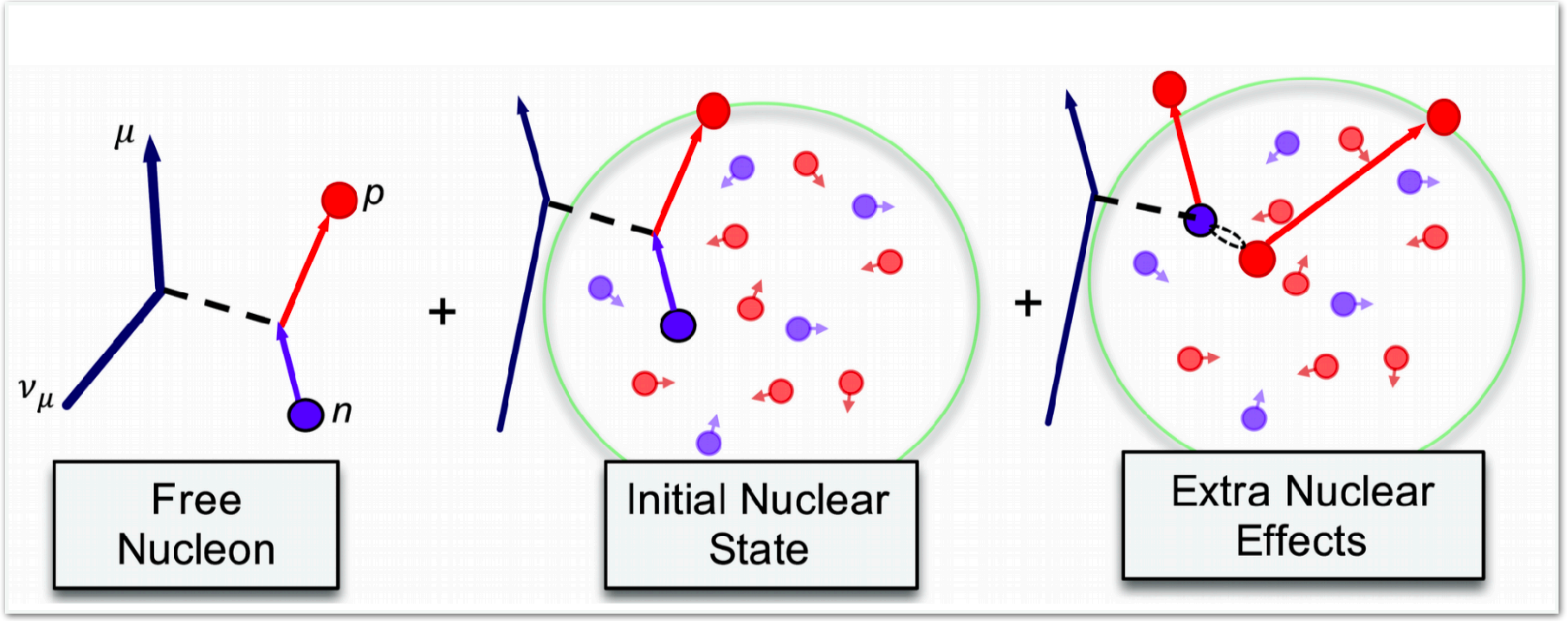
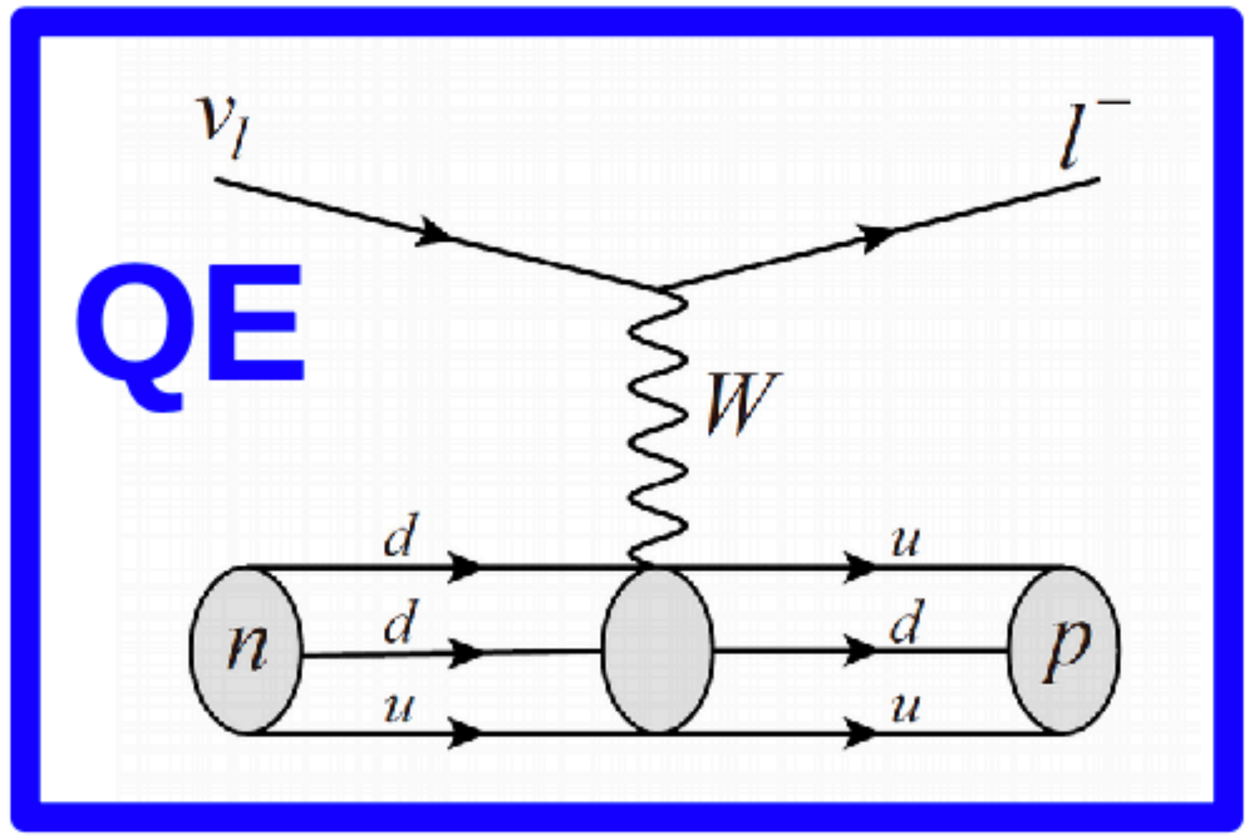
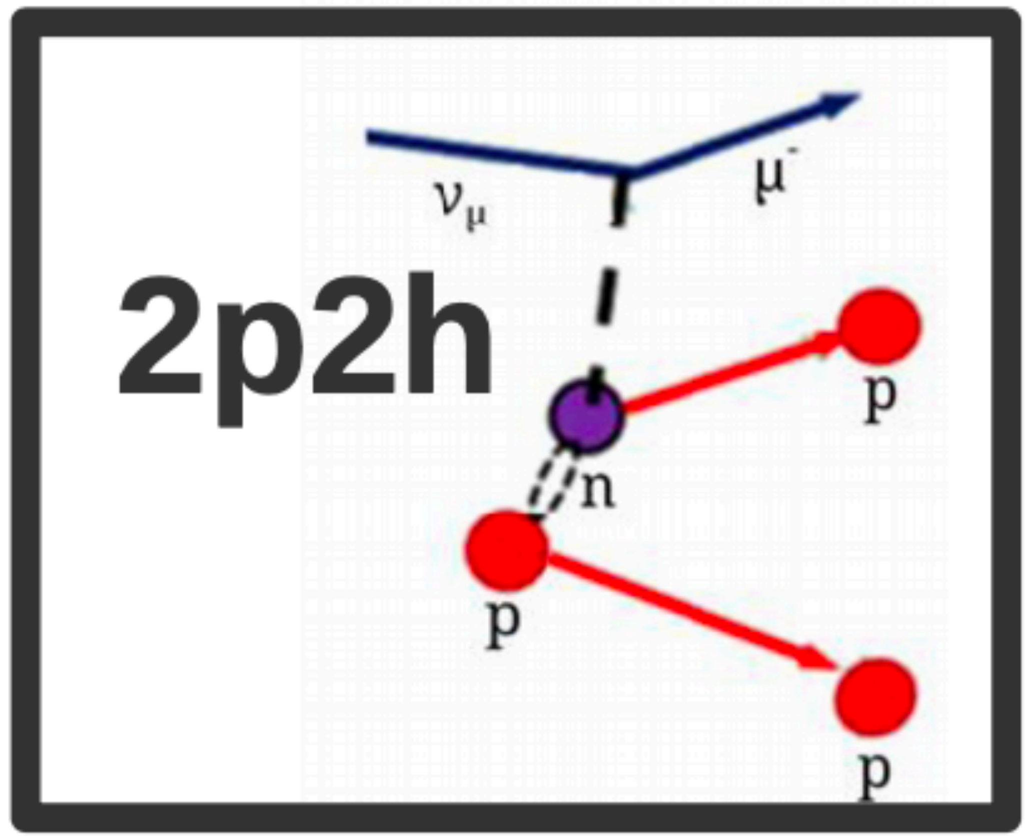
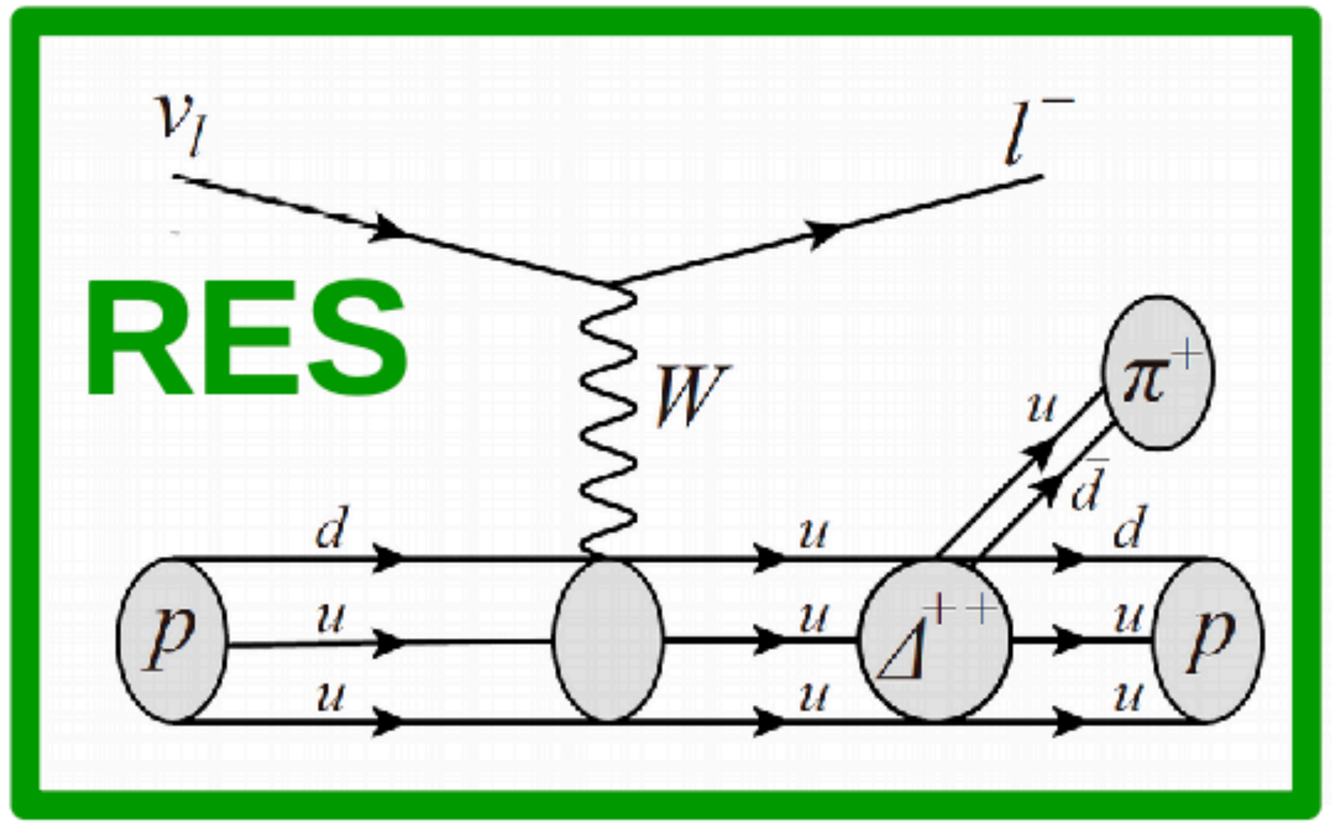








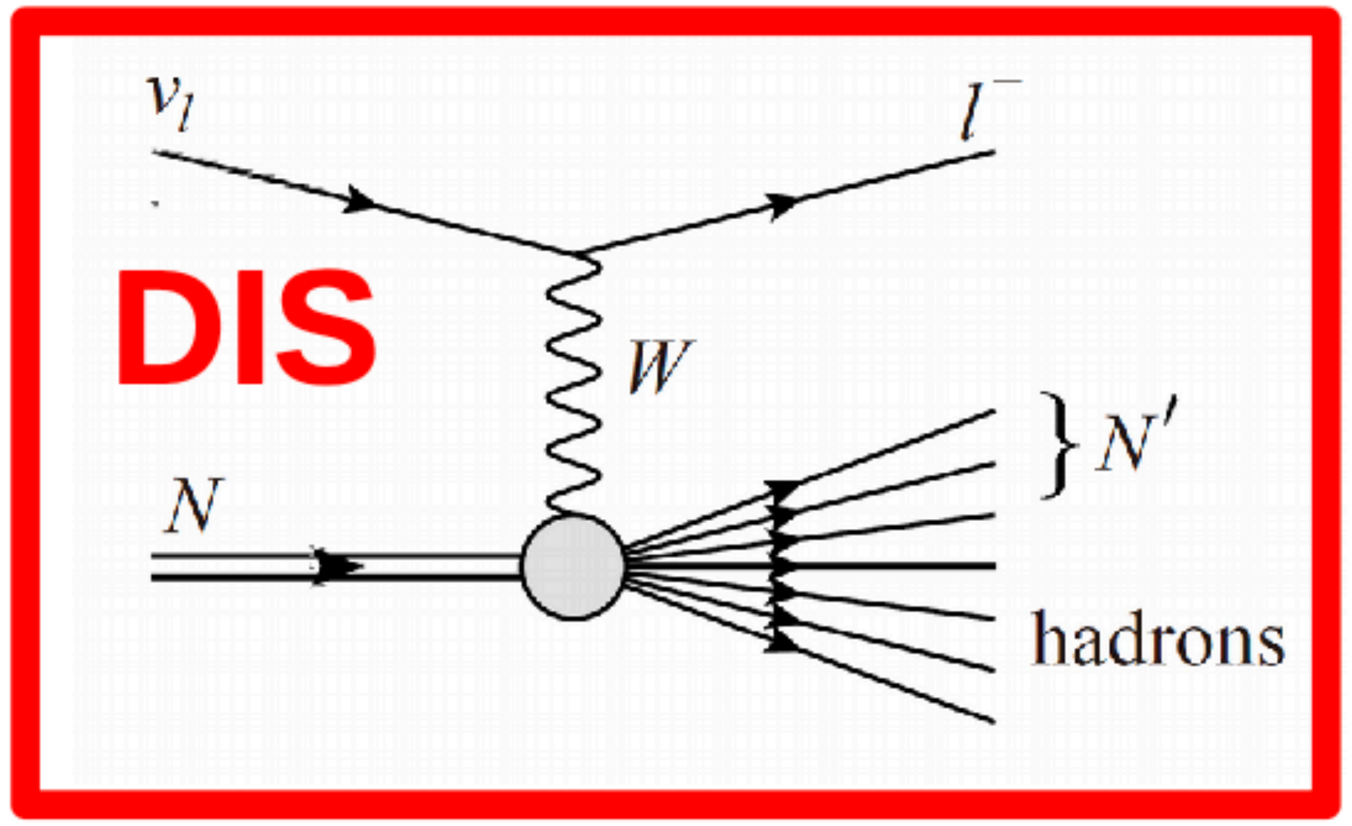
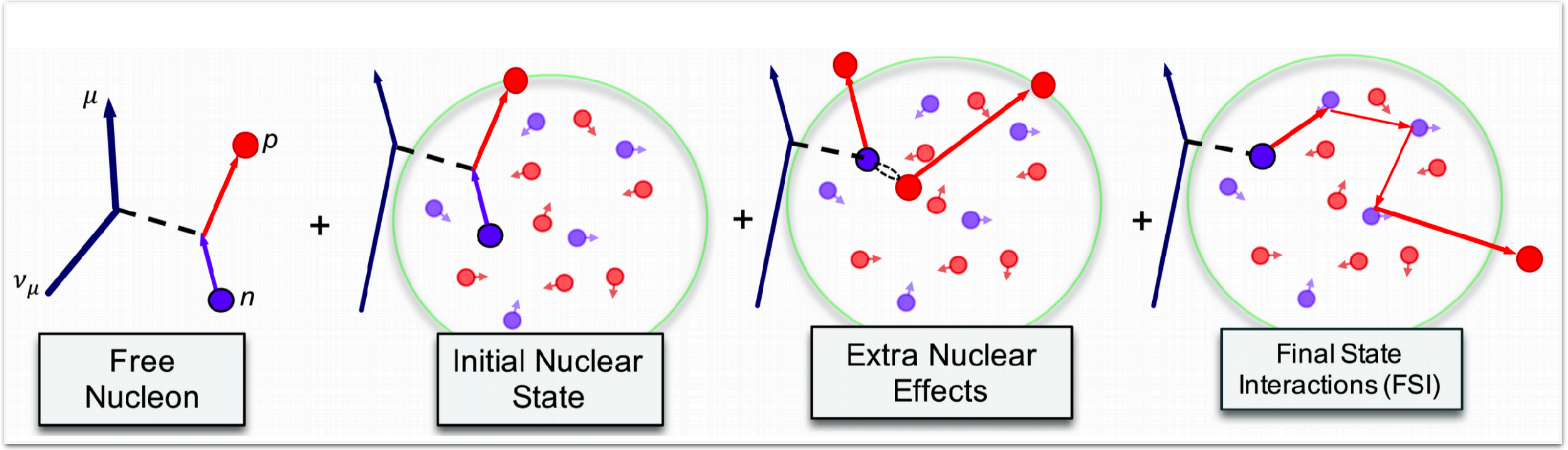
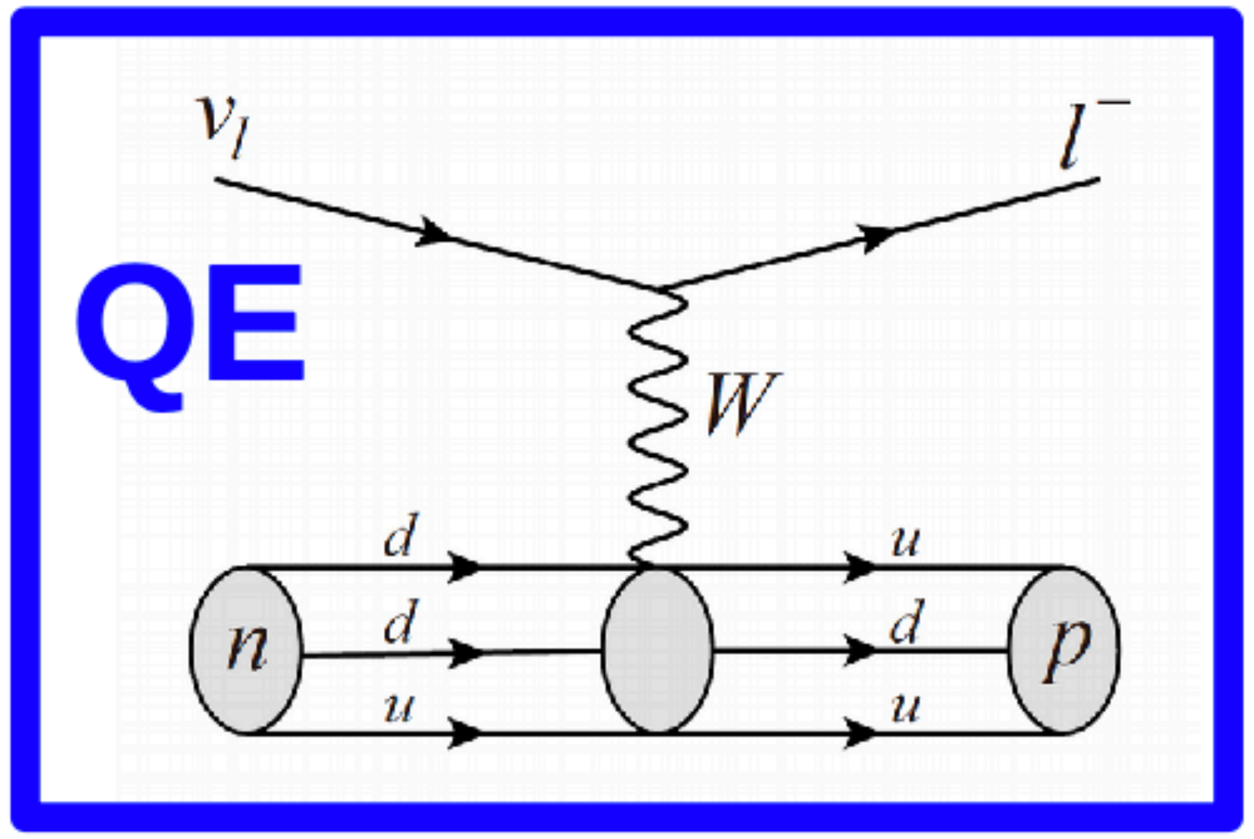
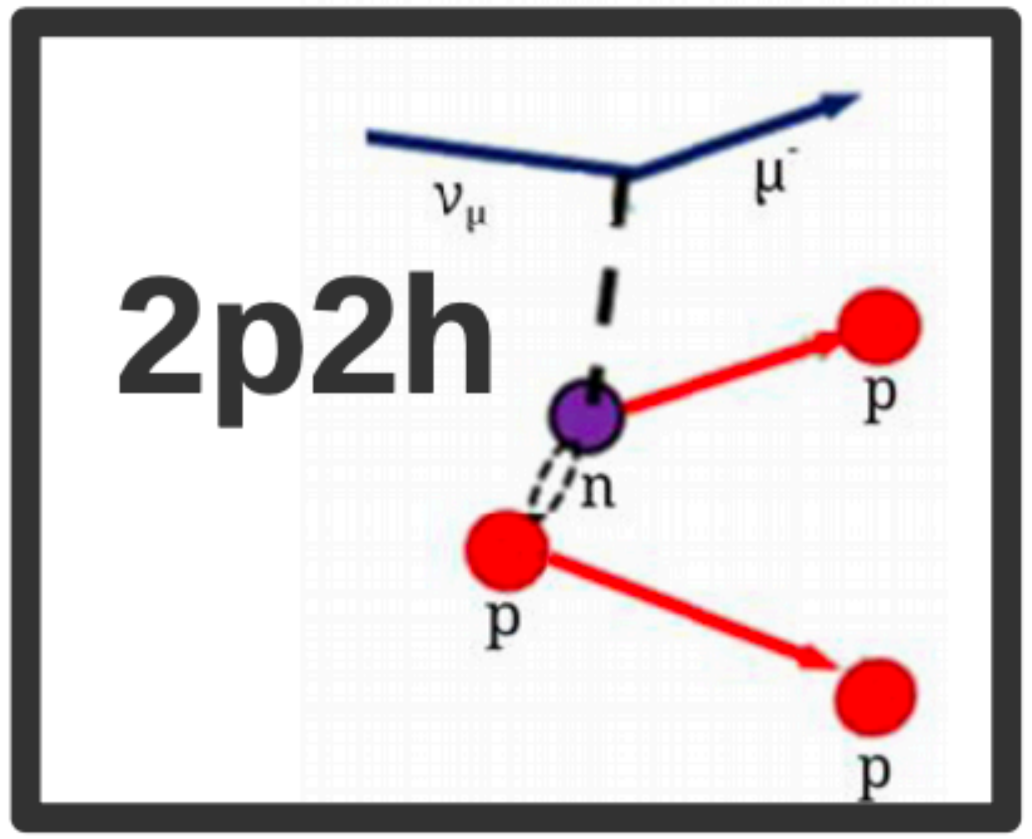


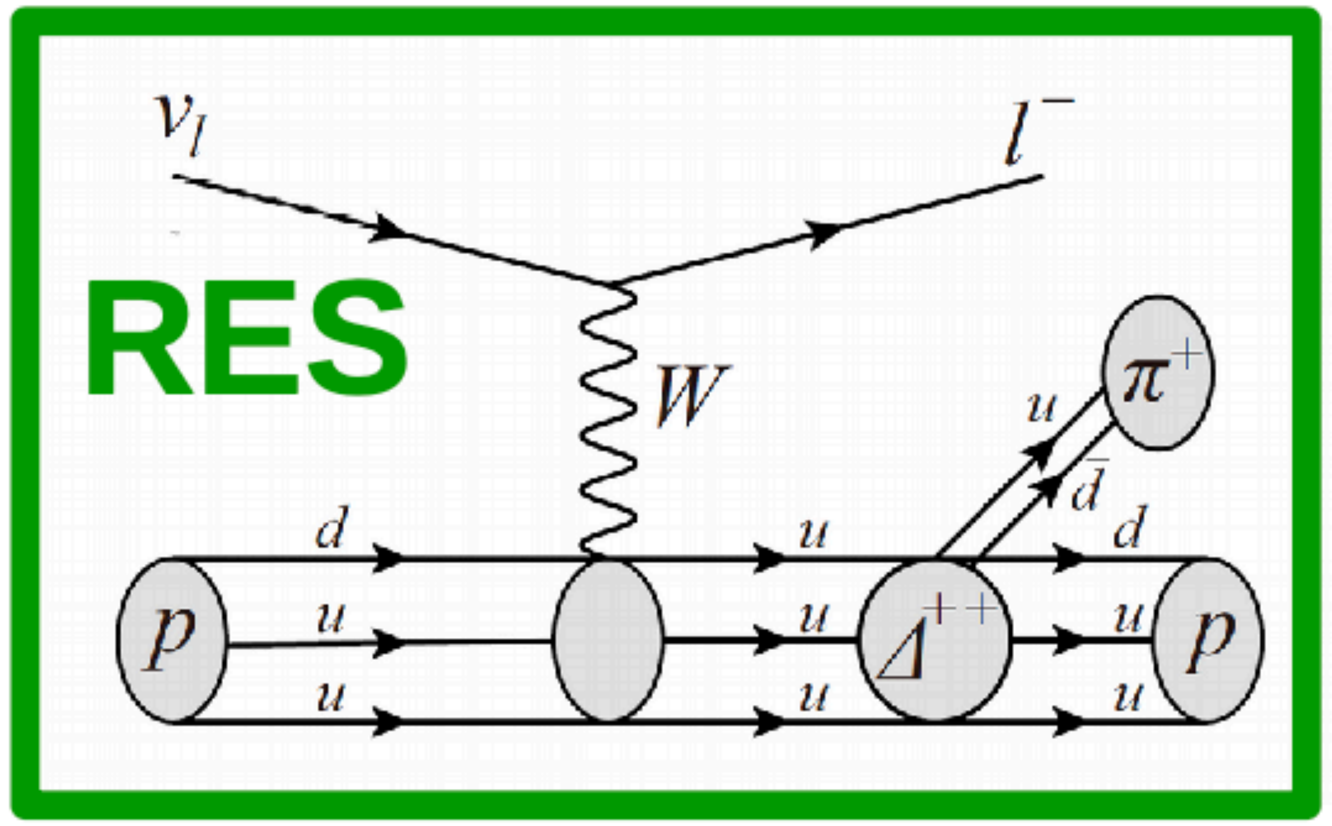
Image Credit: Callum Wilkinson

Understanding Neutrino Interactions









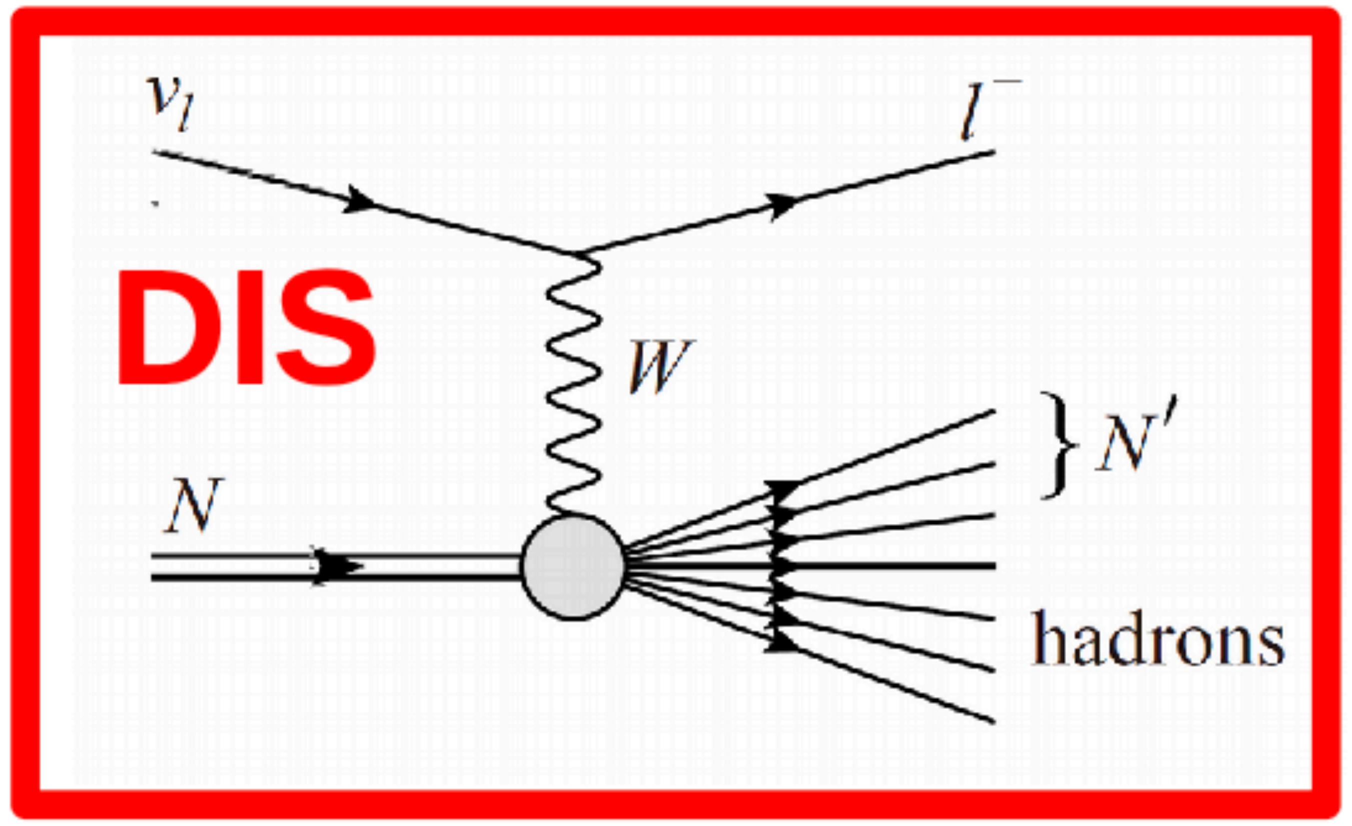
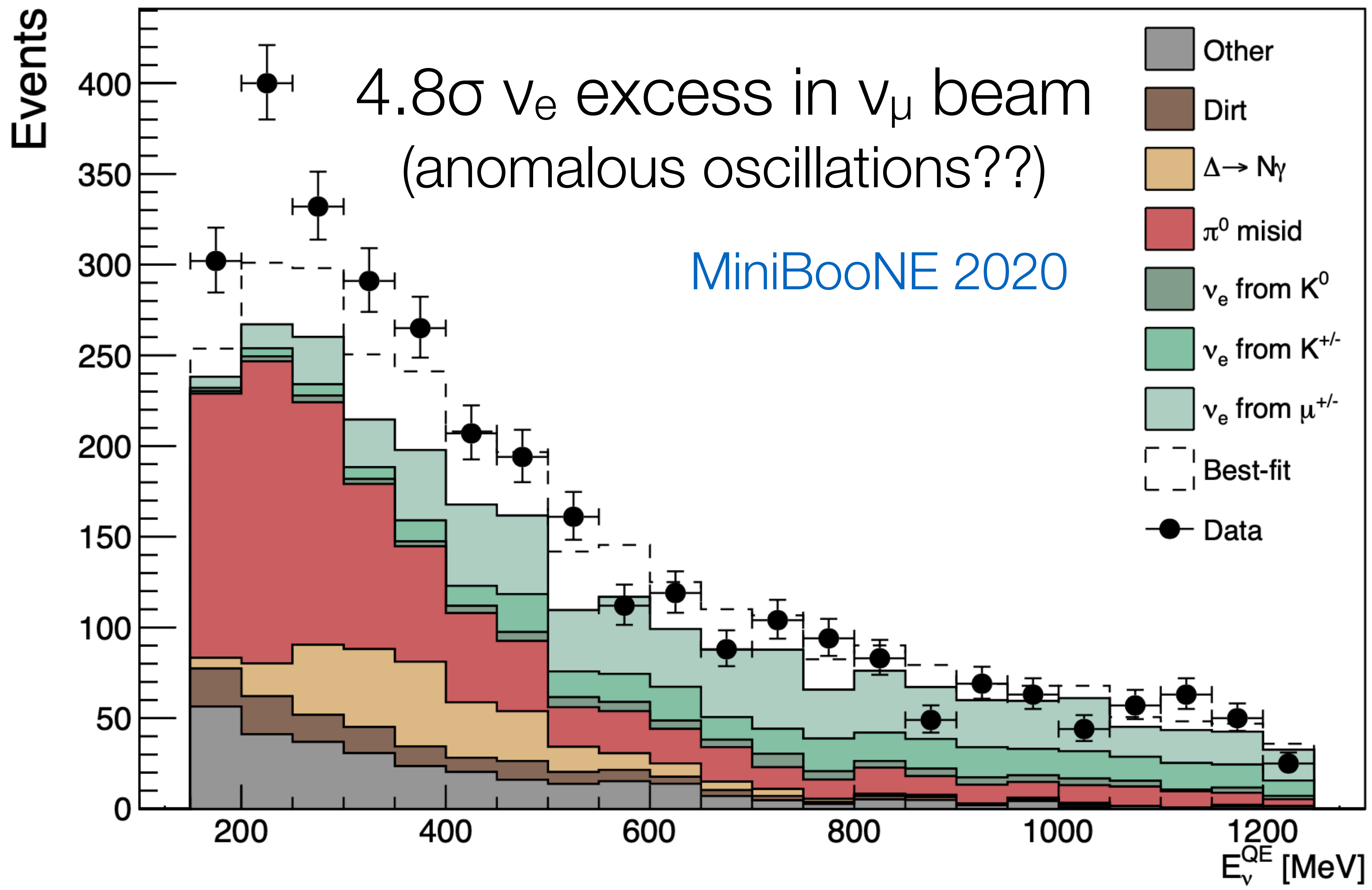
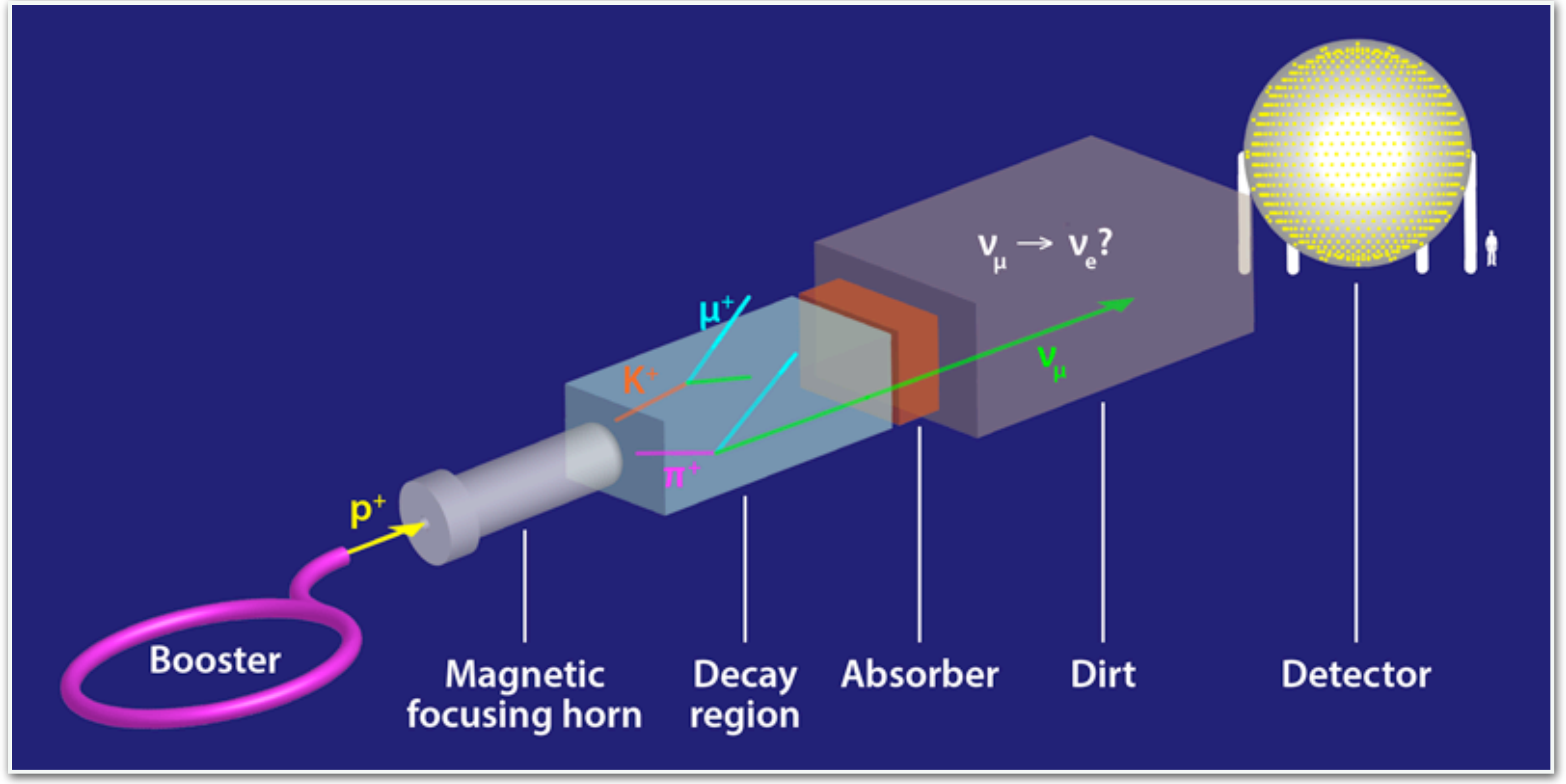


Image Credit: Callum Wilkinson

Why Neutrino Cross-Sections Matter: MiniBooNE





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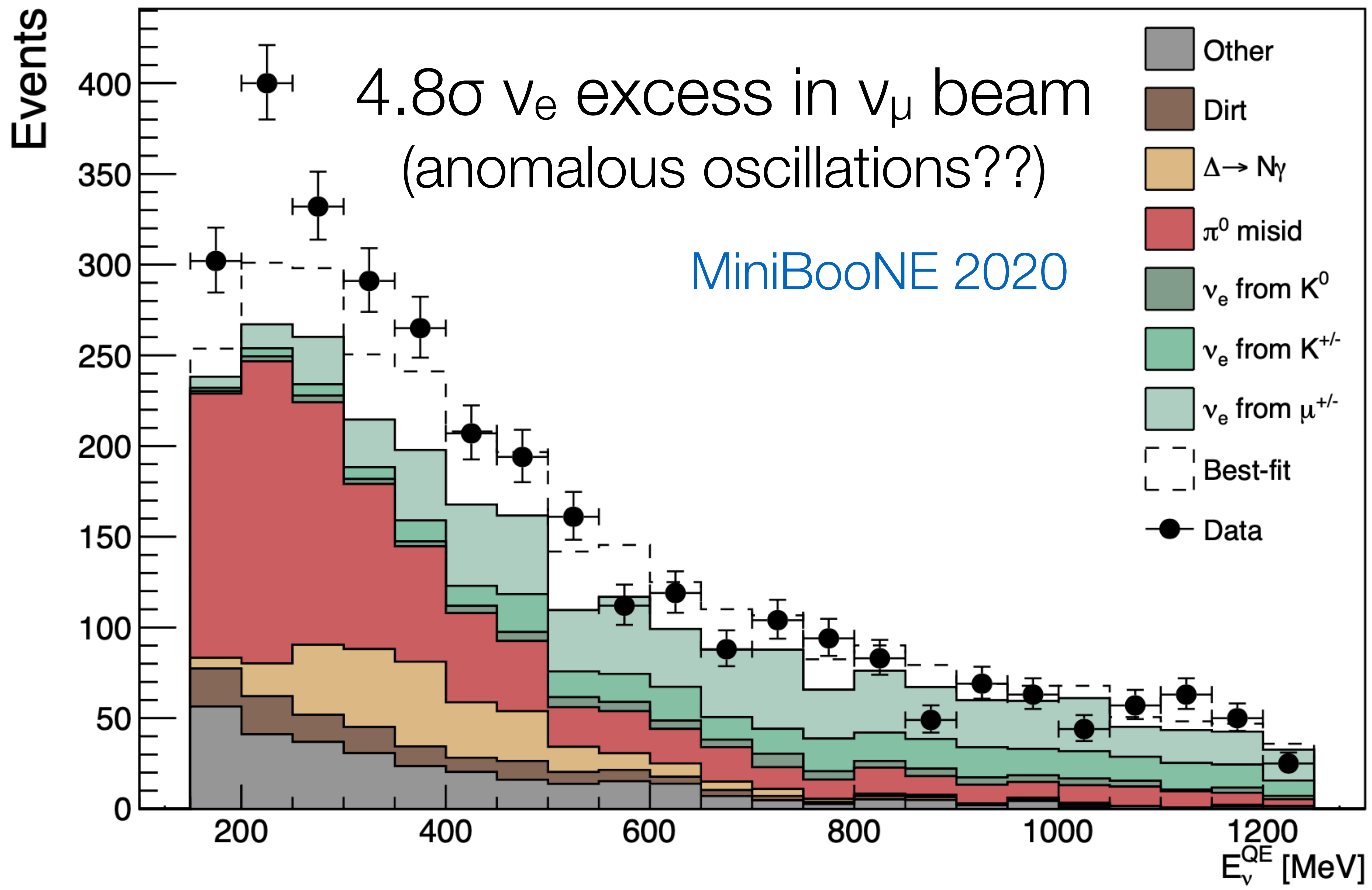
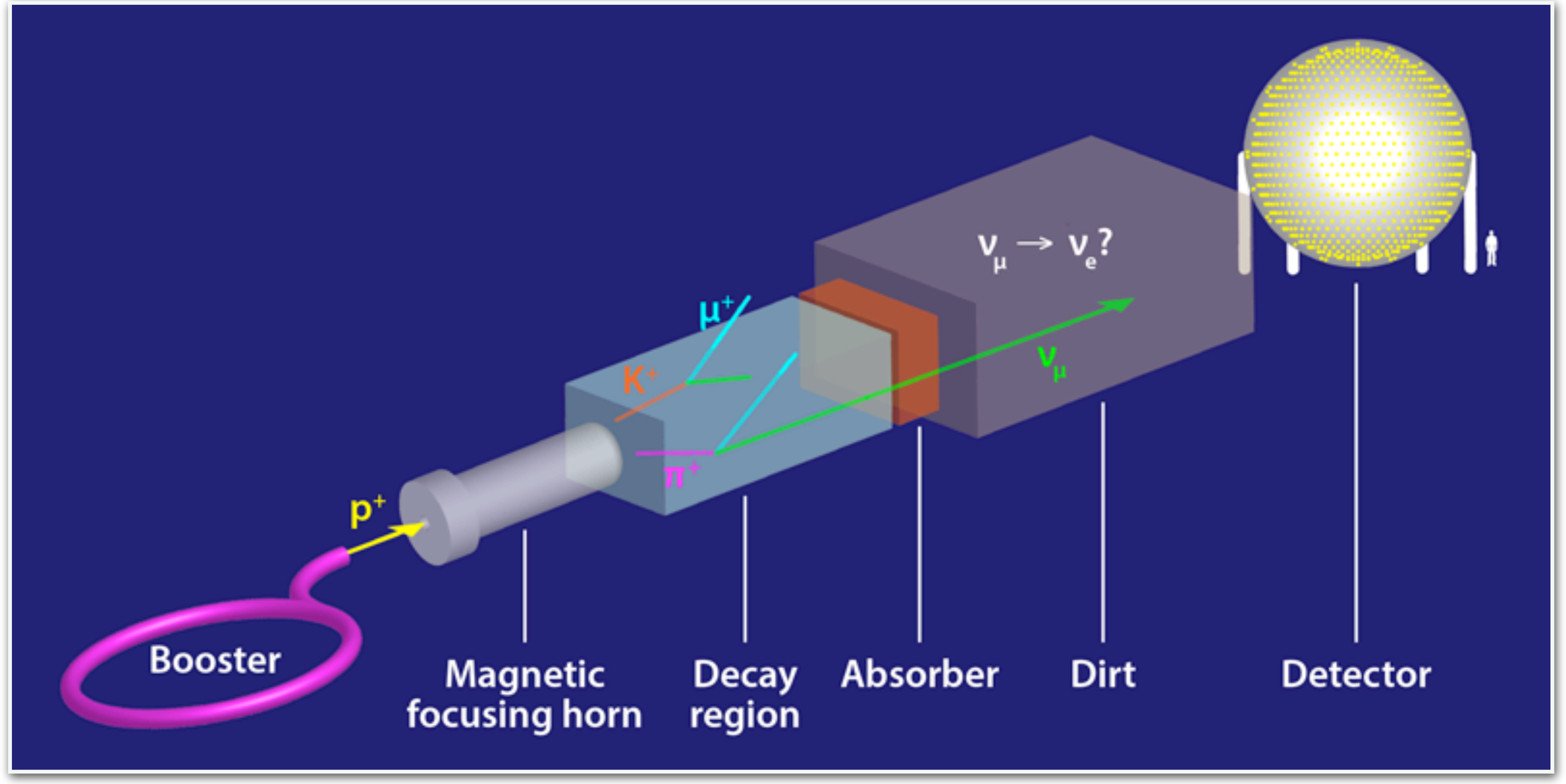




MiniBooNE

MiniBooNE

Experiment wrong.

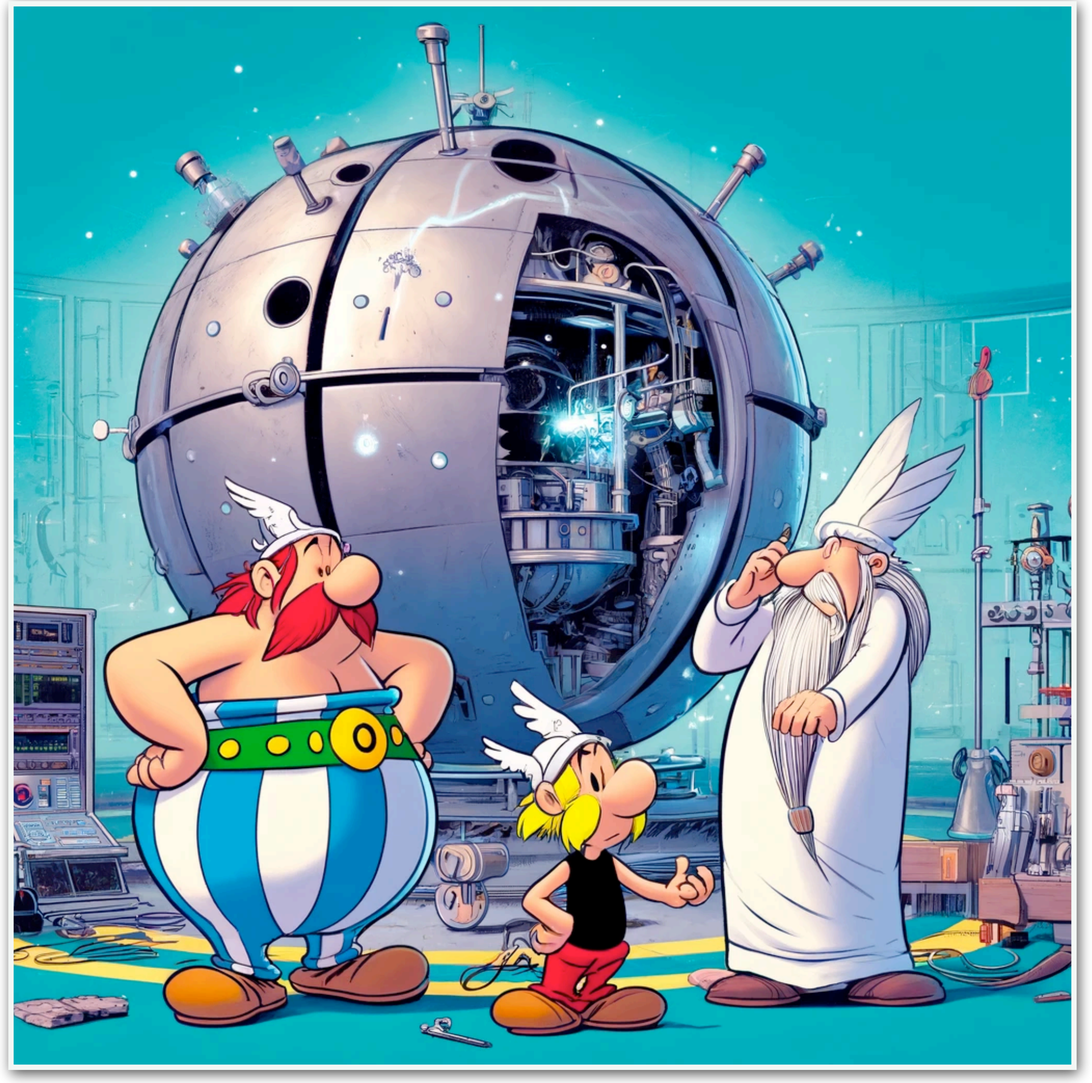


Image: GPT / DALL-E

MiniBooNE

Experiment wrong.

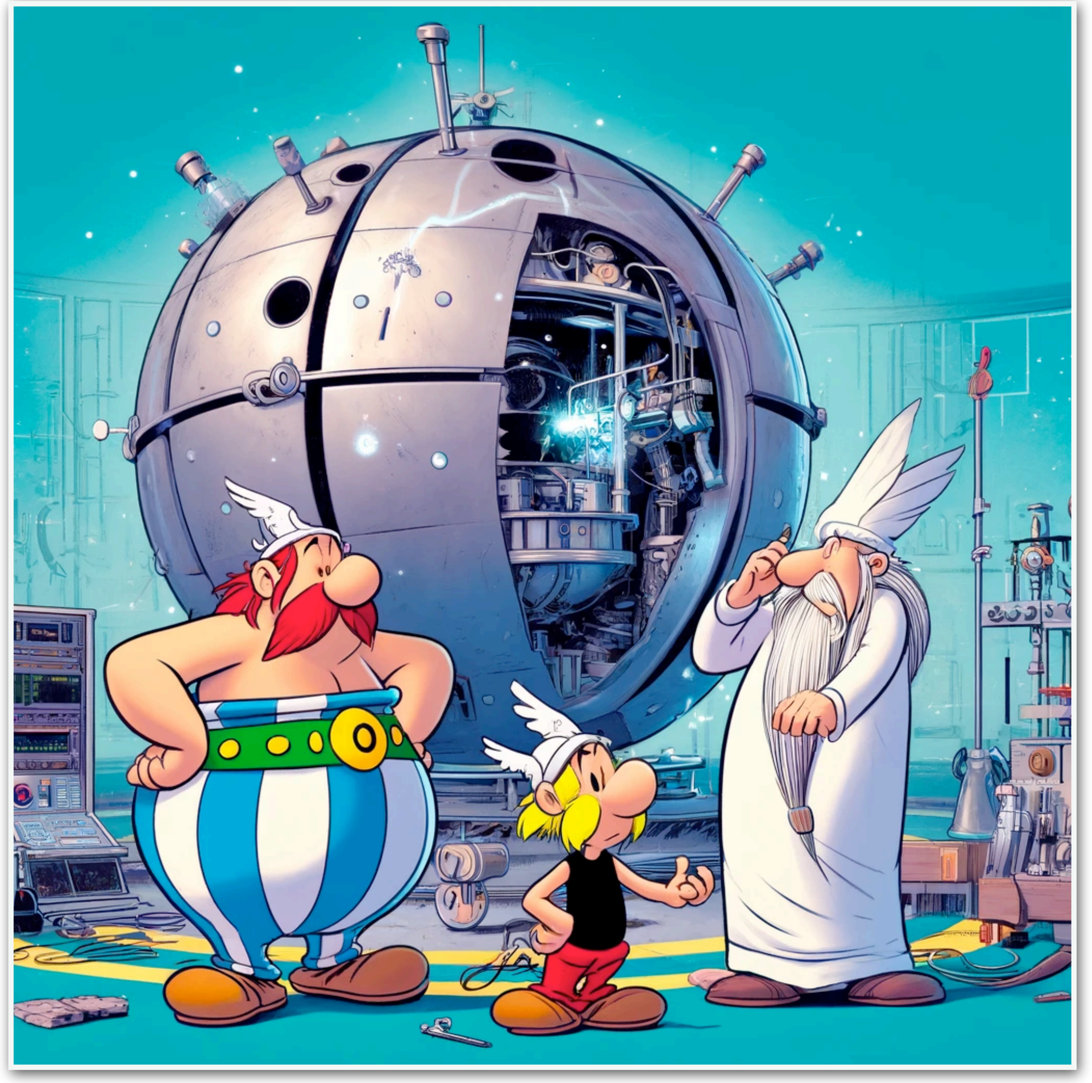


Image: GPT / DALL-E

Theory wrong.

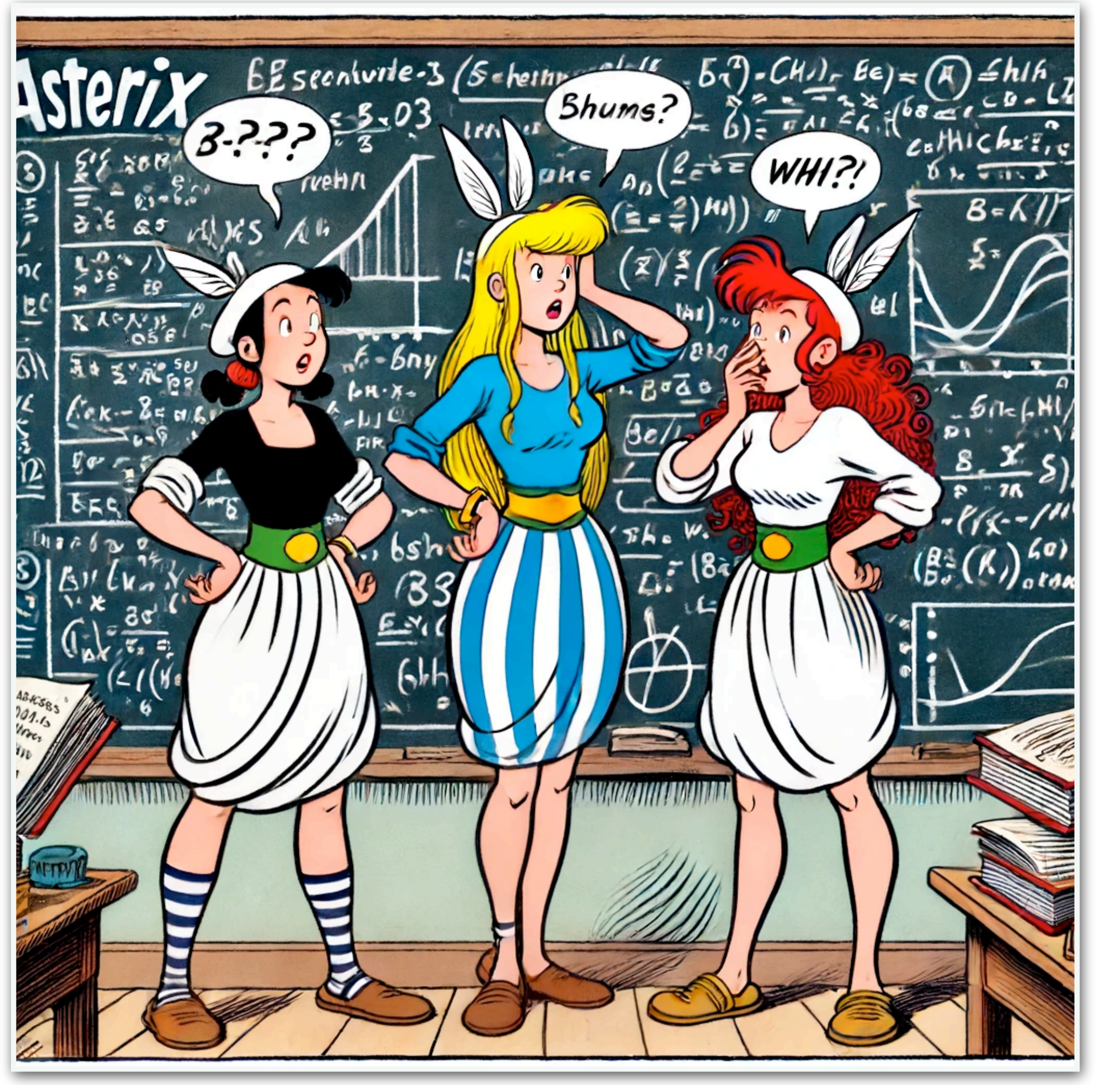
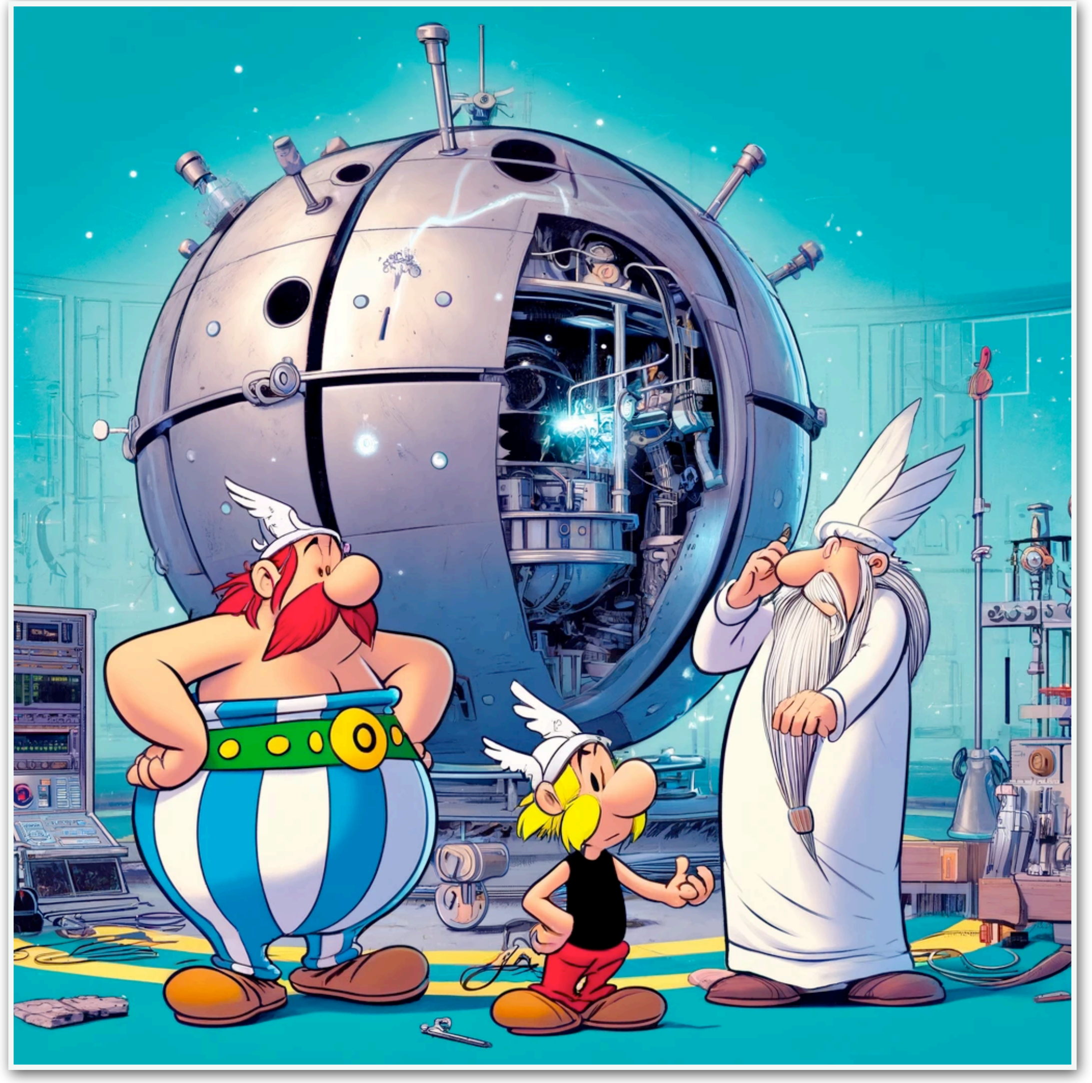


Image: GPT / DALL-E

MiniBooNE

Both wrong. Shut up.

Experiment wrong.



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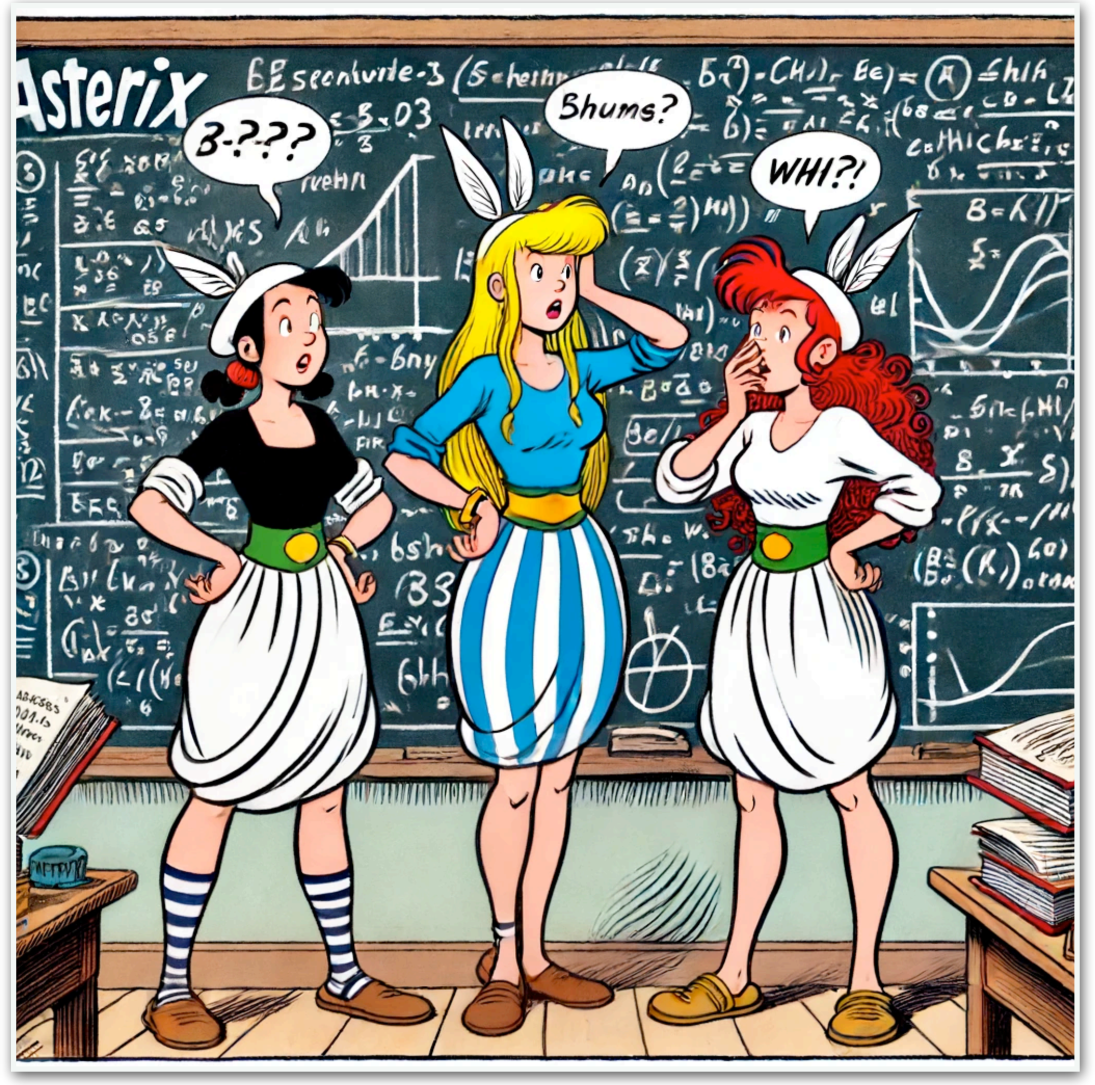

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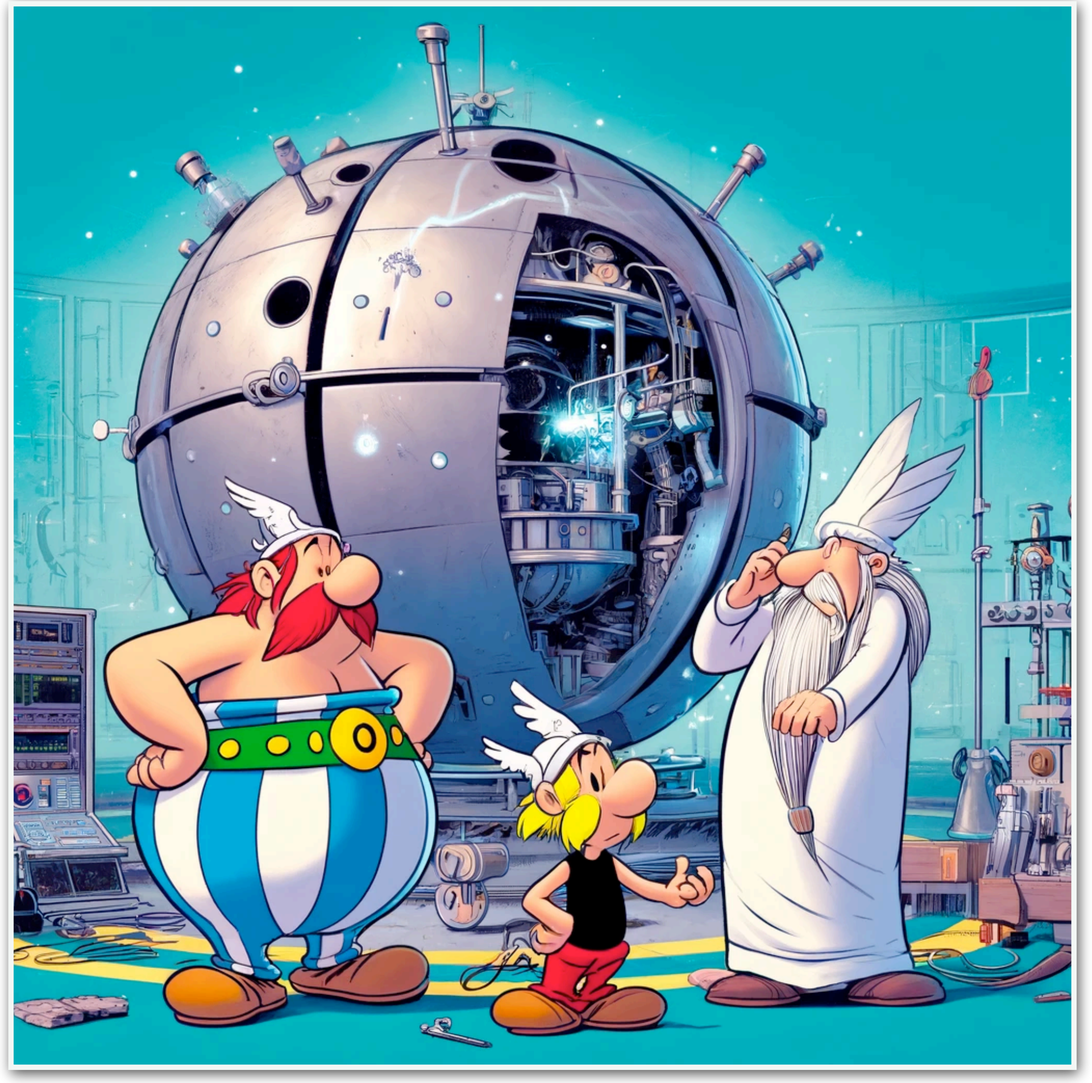

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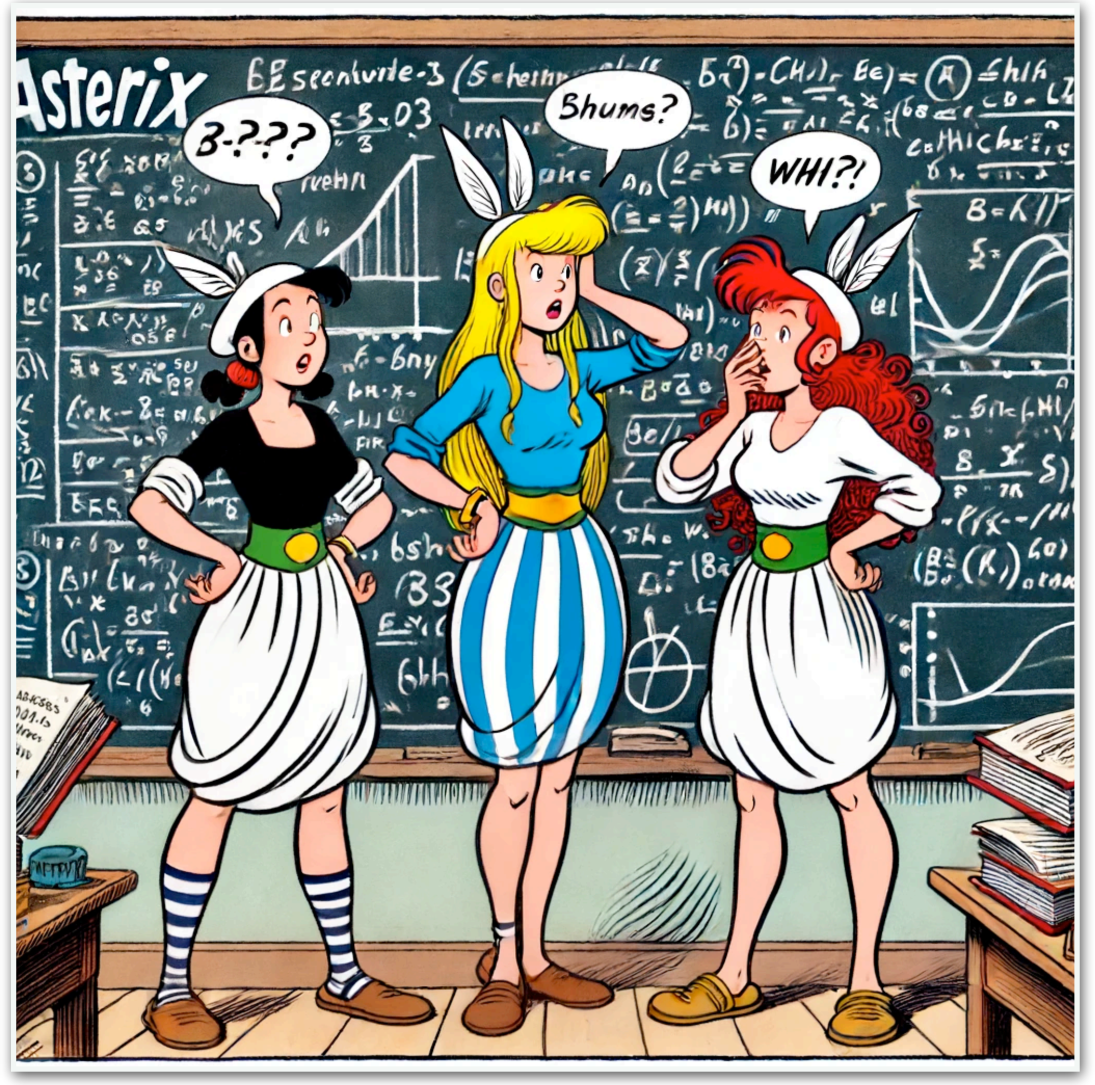
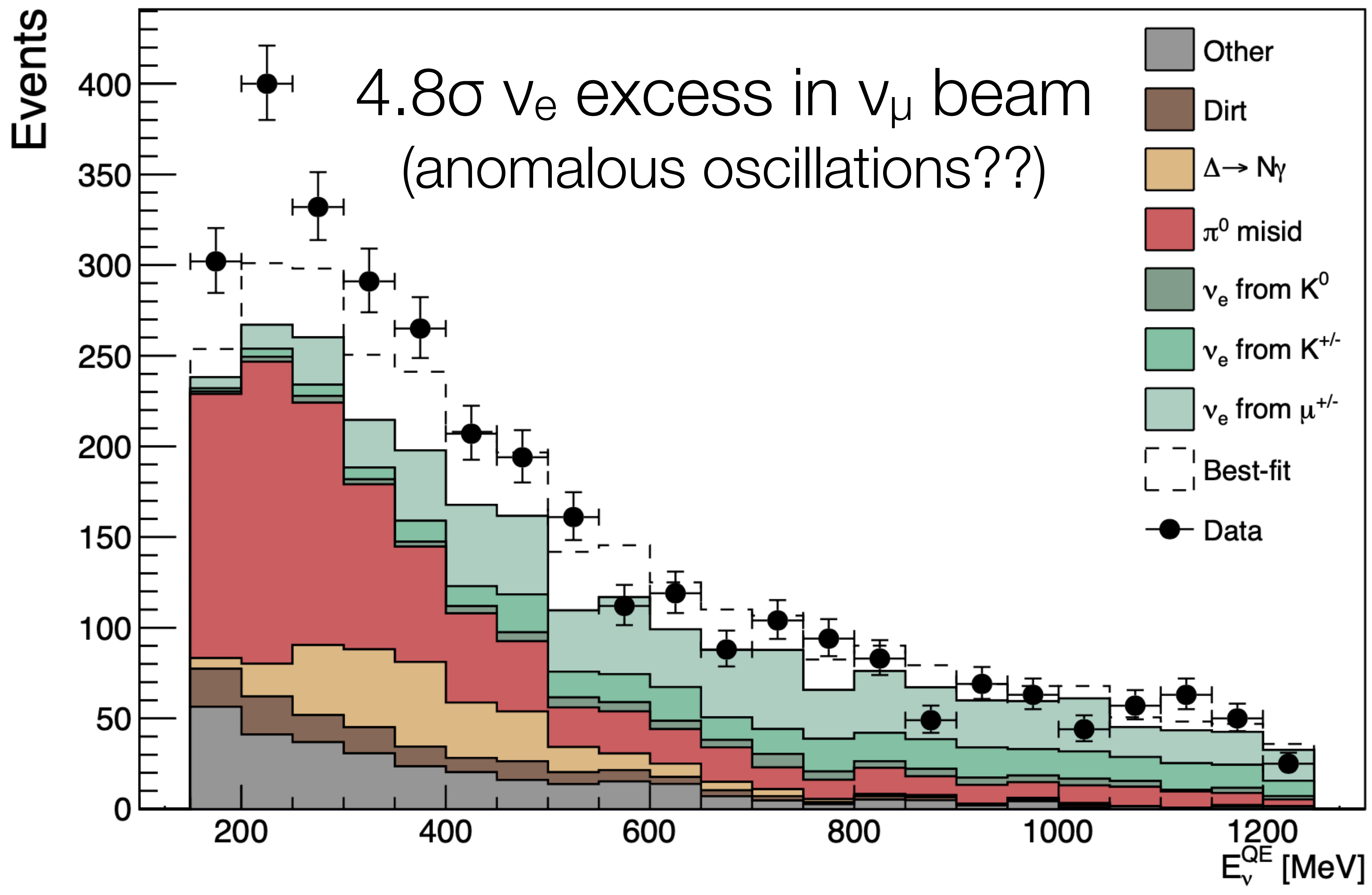


Image: GPT / DALL-E

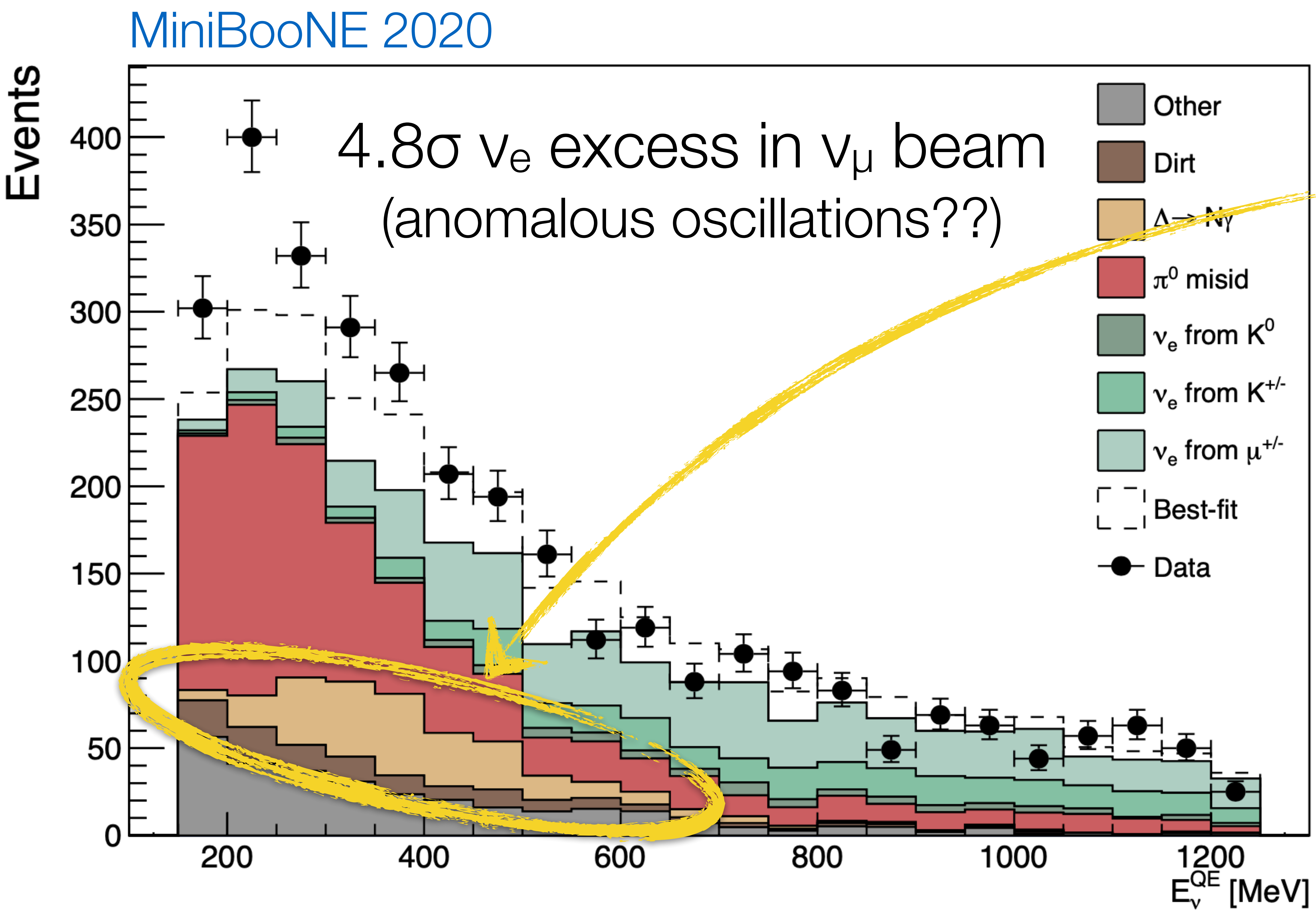
Let's build BSM models!

Why Neutrino Cross-Sections Matter: MiniBooNE

MiniBooNE 2020



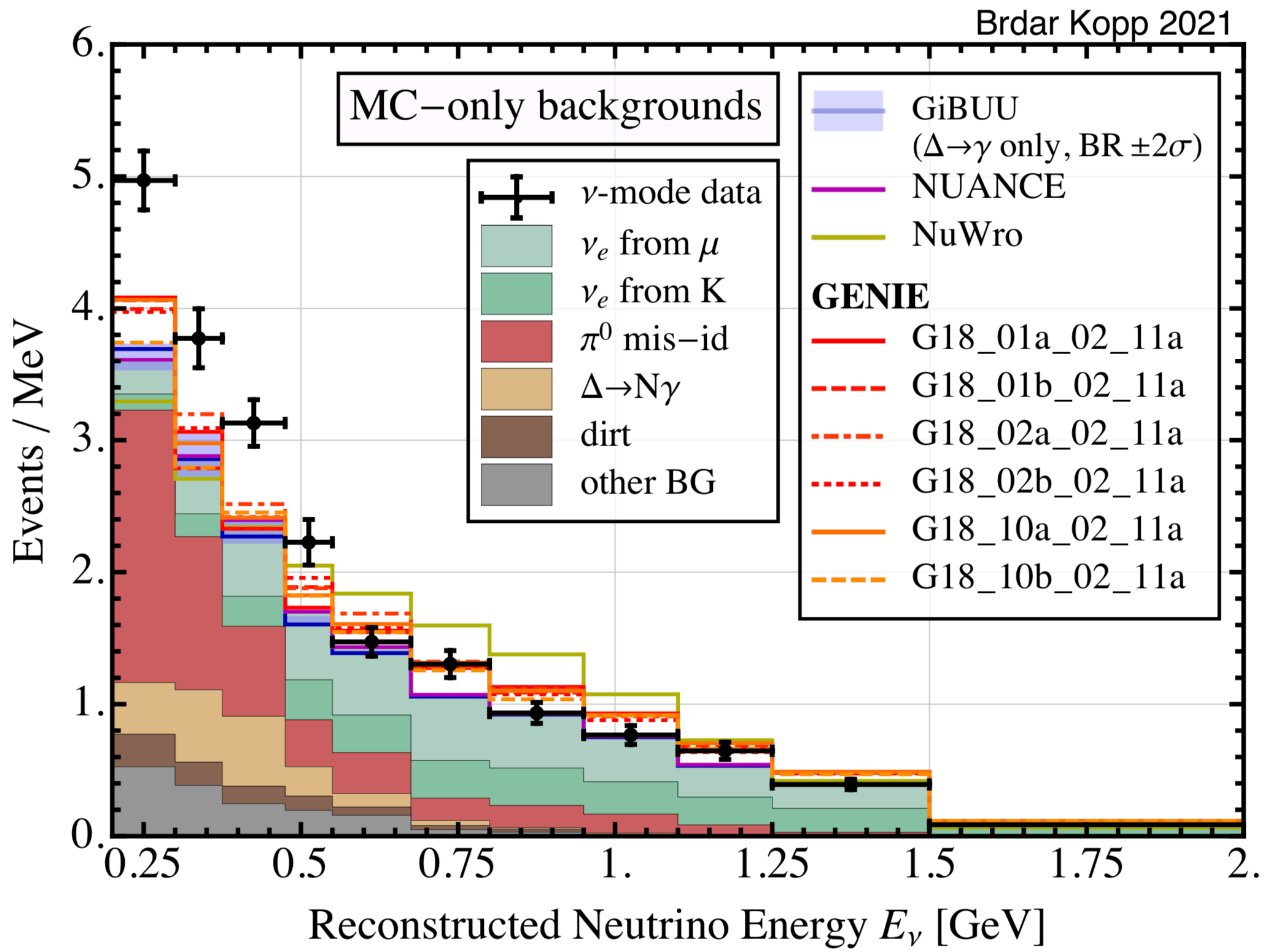
Why Neutrino Cross-Sections Matter: MiniBooNE



- NC interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- Most $\Delta(1232)$ decay to $\pi + N$, but rare decay exists to $\gamma + N$
- MiniBooNE cannot distinguish single-γ BG from CC ν_e signal
- Δ production rate from $\Delta \rightarrow \pi N$ (data-driven)
- Pions may be absorbed on their way out of the nucleus
  - may excite another $\Delta(1232)$
    ➠ $\Delta \rightarrow \gamma N$ enhanced
  - or may be absorbed
    ➠ control region suppressed

➠ dependence on theoretical modeling

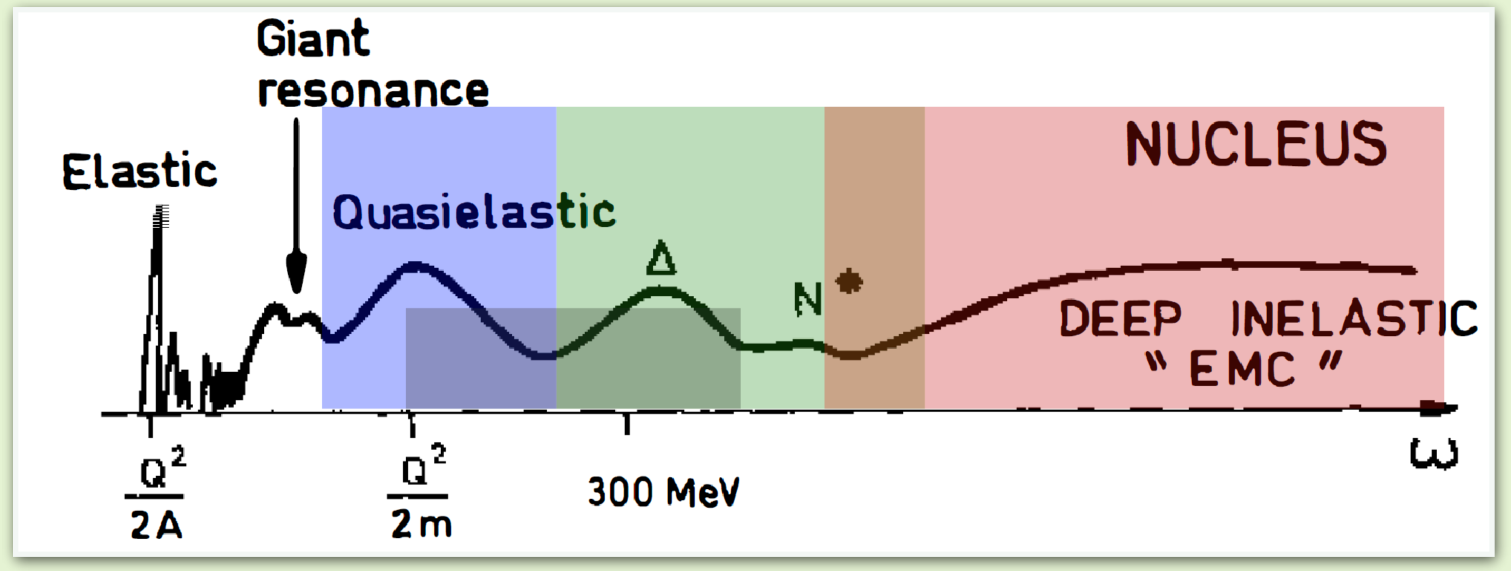
Why Neutrino Cross-Sections Matter: MiniBooNE



Physics with the DUNE Near Detectors

Neutrino Cross-Sections

- superb event reconstruction capabilities
- detailed separation of different interaction channels
- neutrino interactions on relatively heavy target (Ar-40)
- on-axis and off-axis
  (for disentangling flux and cross-section uncertainties)



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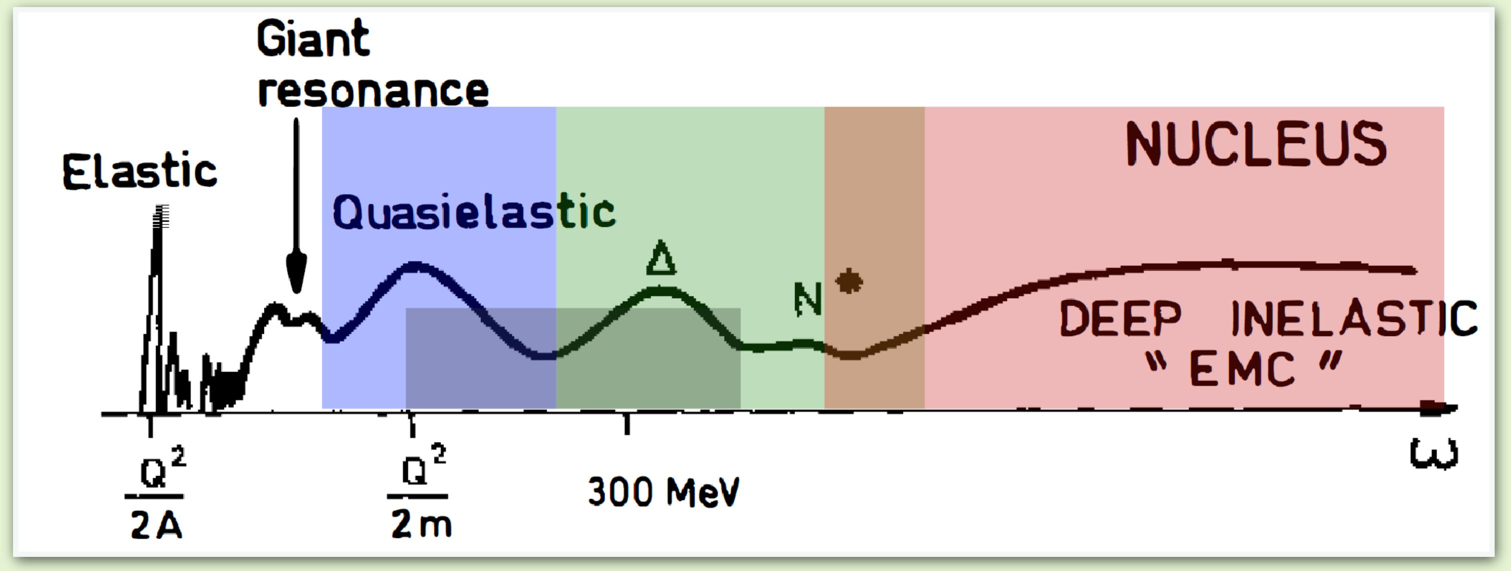
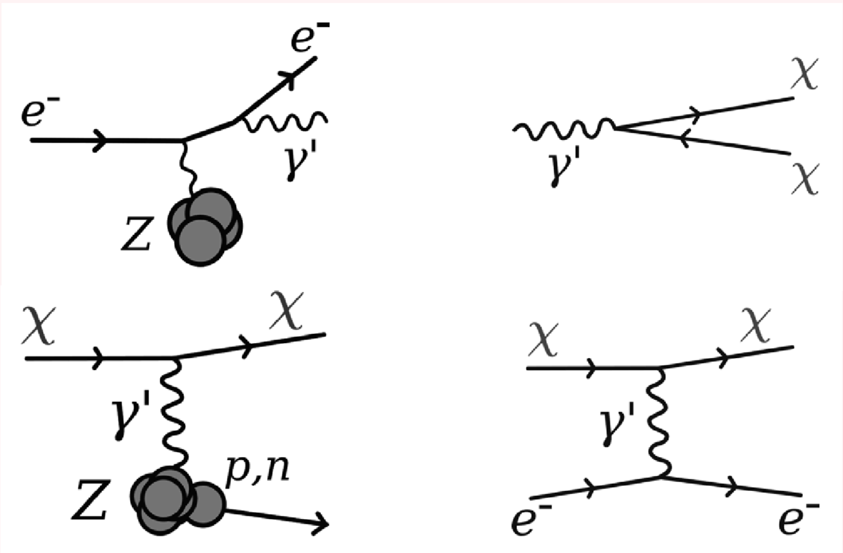
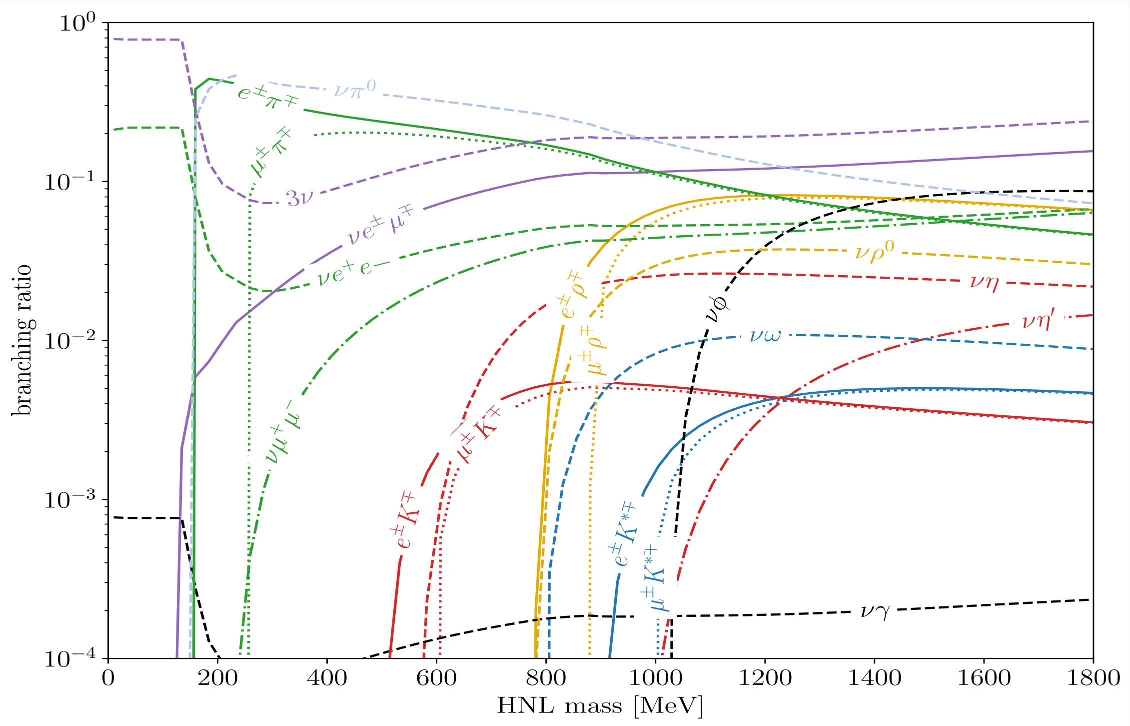


Physics Beyond the SM

- Light Dark Matter



- Heavy Neutral Leptons



- Light Sterile Neutrinos
  (anomalous short-baseline oscillations)

Physics with the DUNE Near Detectors

Neutrino Cross-Sections

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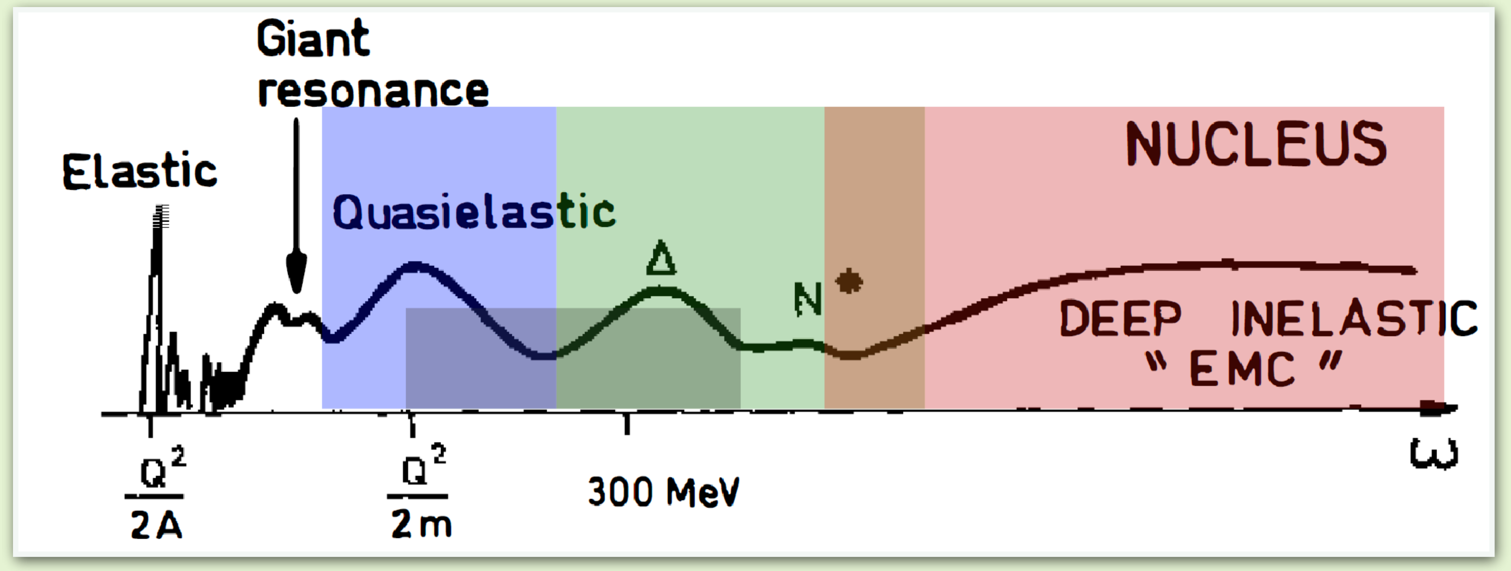

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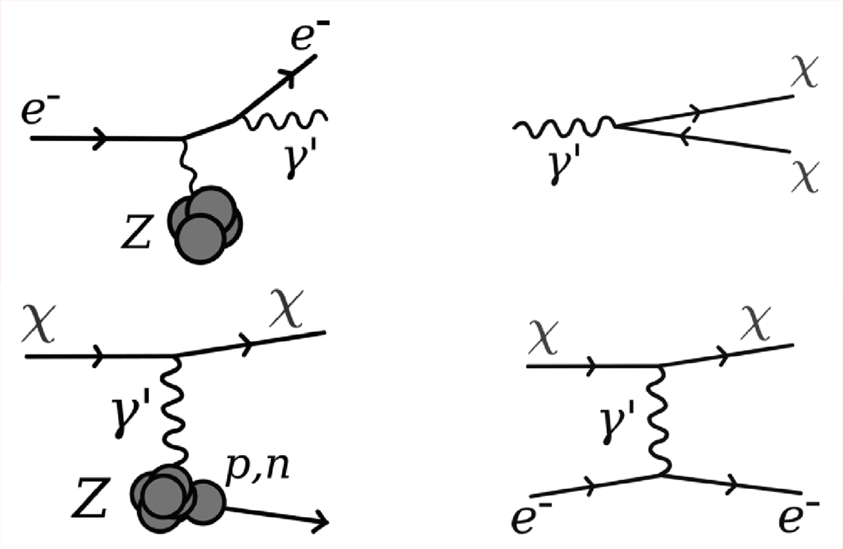

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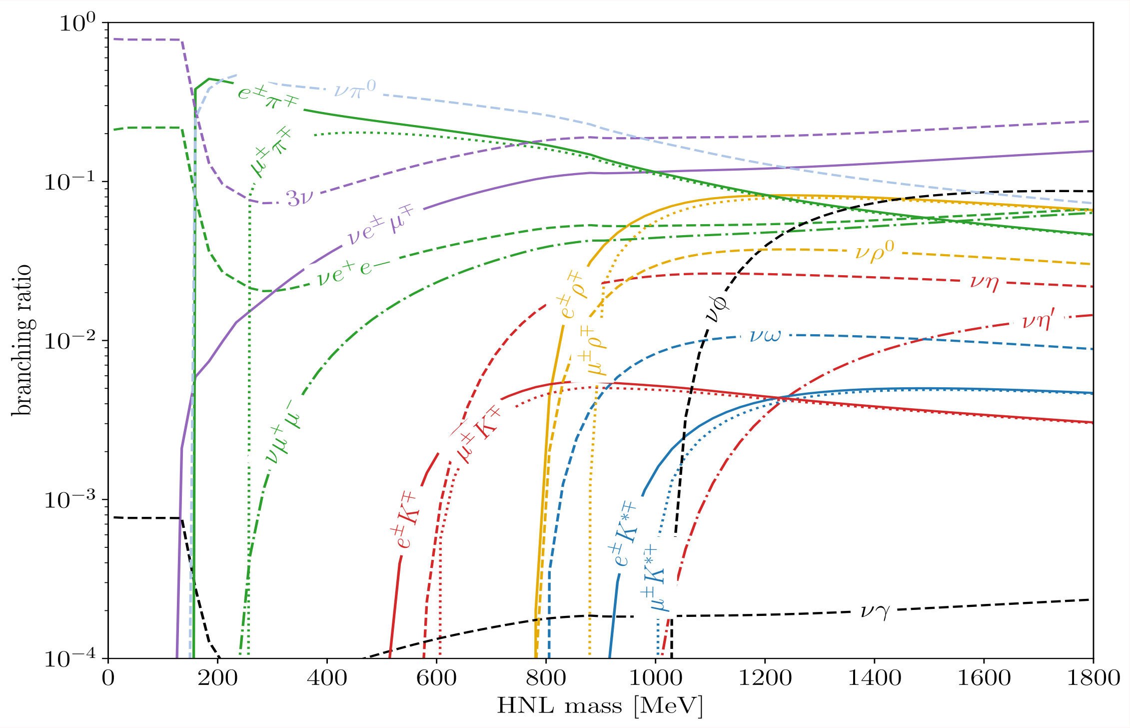
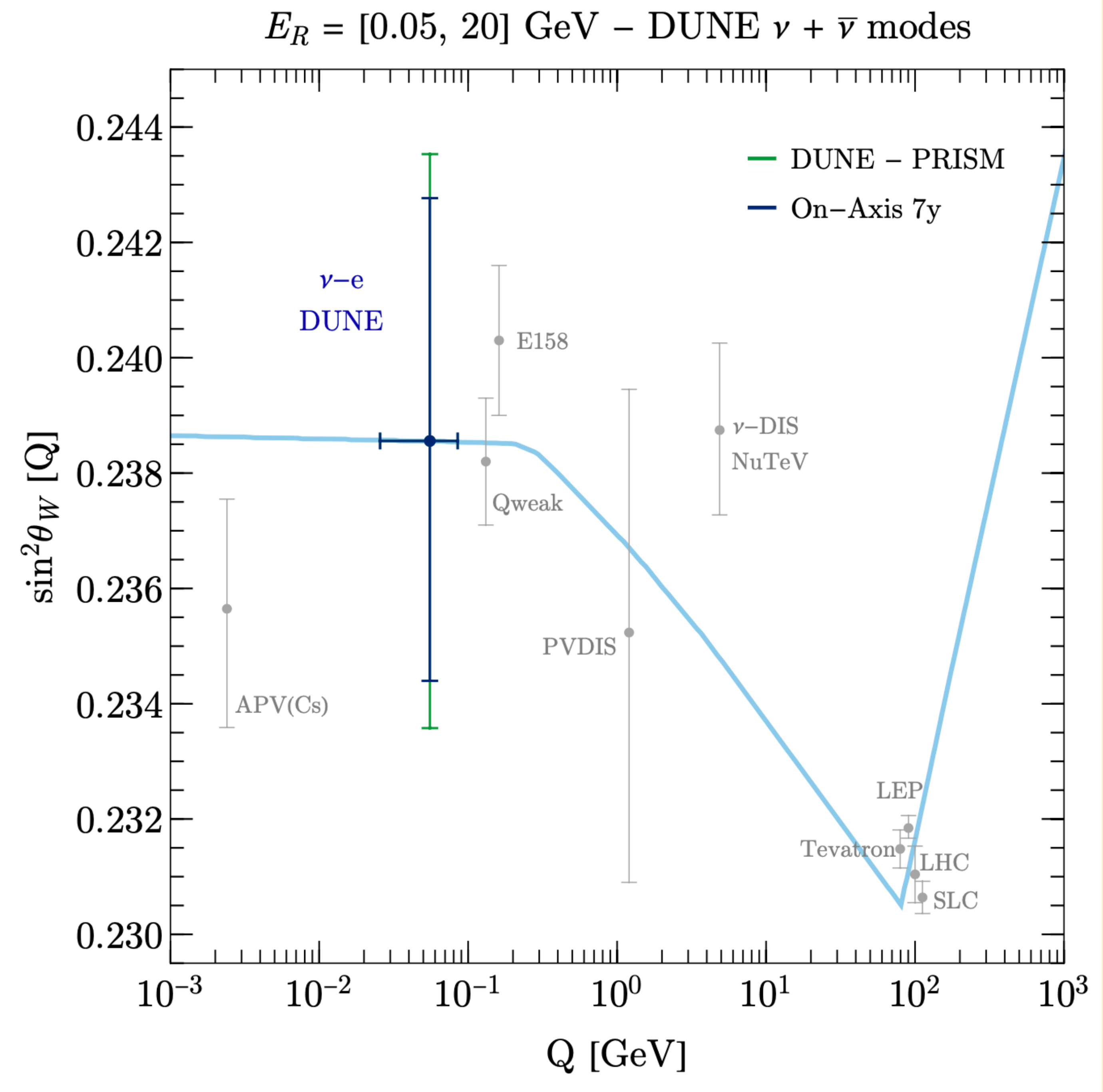


- Light Sterile Neutrinos
  (anomalous short-baseline oscillations)

The Weak Mixing Angle

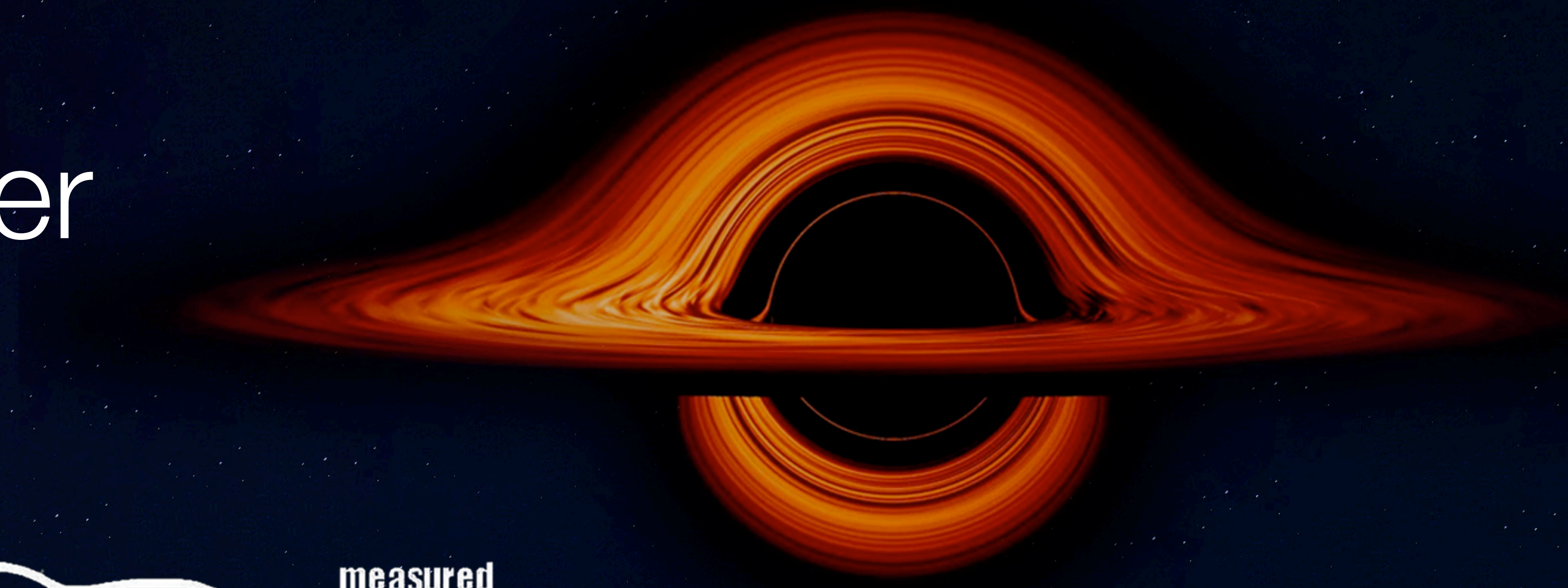
Measurement of $\sin^2\theta_W$ at low energy

de Gouvea et al. 2019

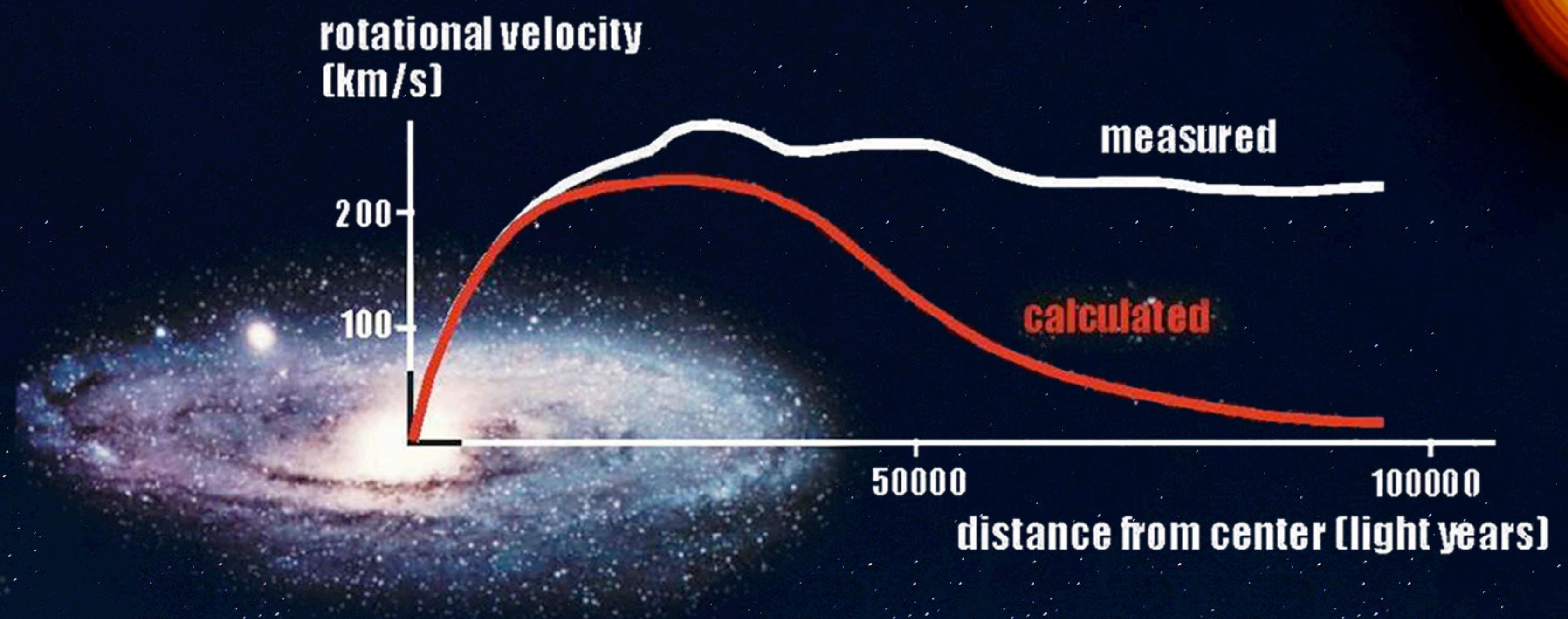


Summary & Outlook

Gravity



Dark Matter



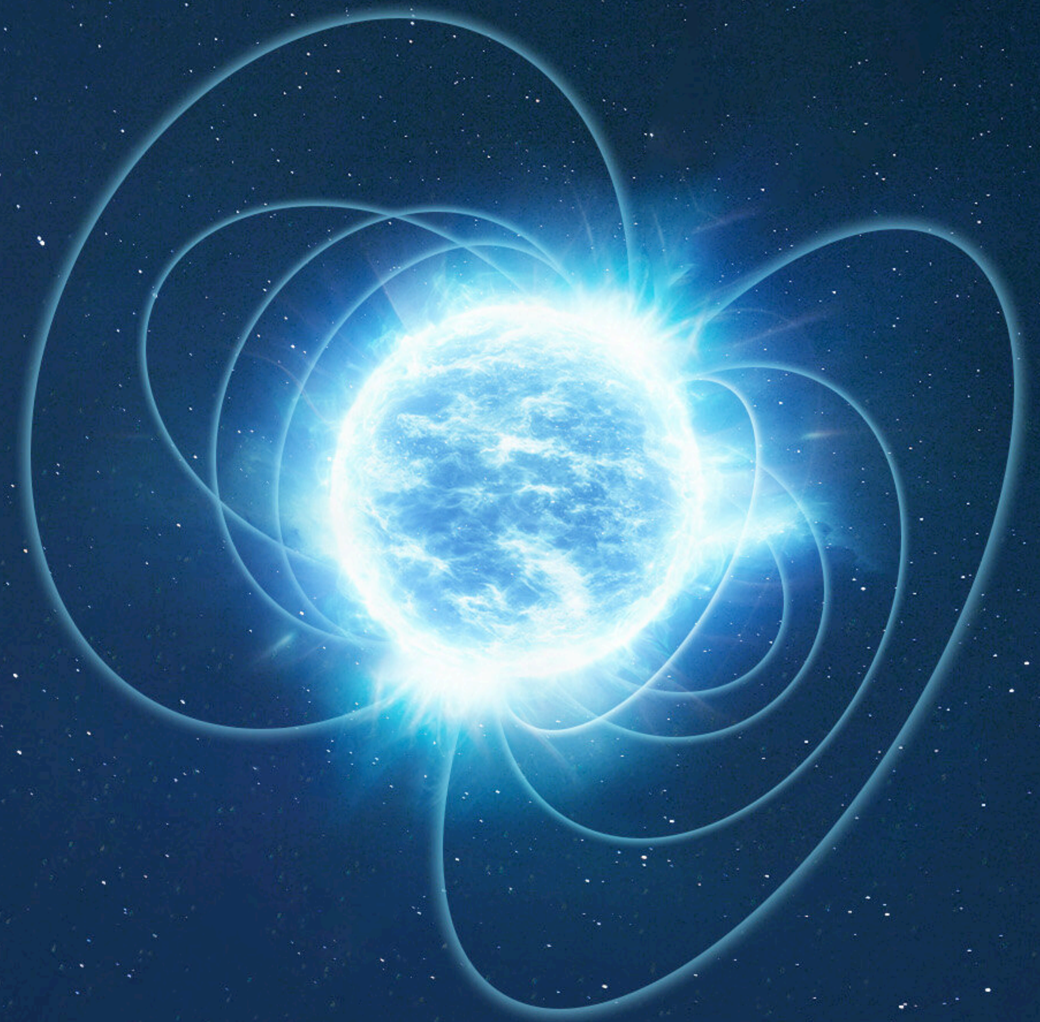
Weak Force

Neutrinos

Strong &

Electromagnetic forces

Hadrons / Atoms

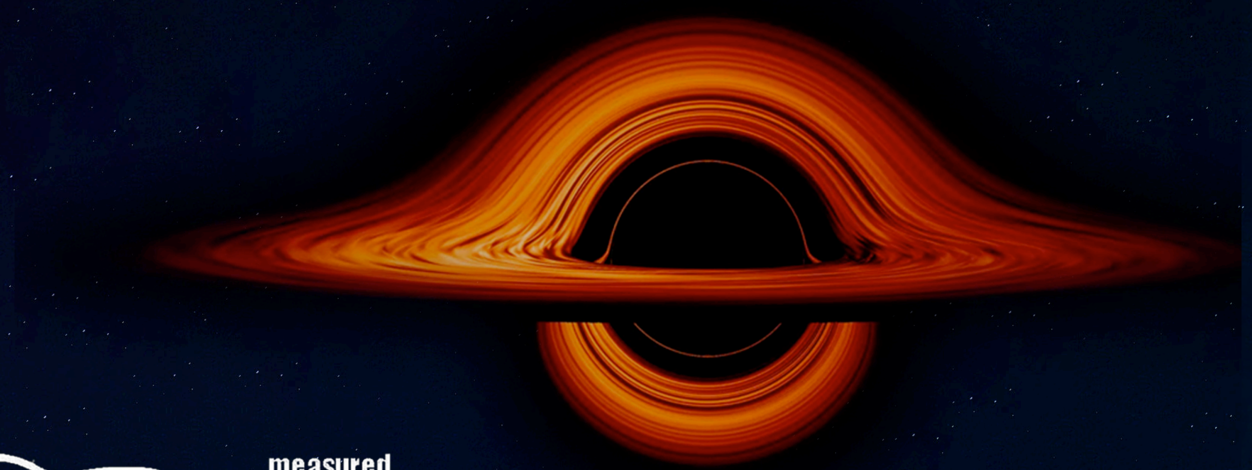


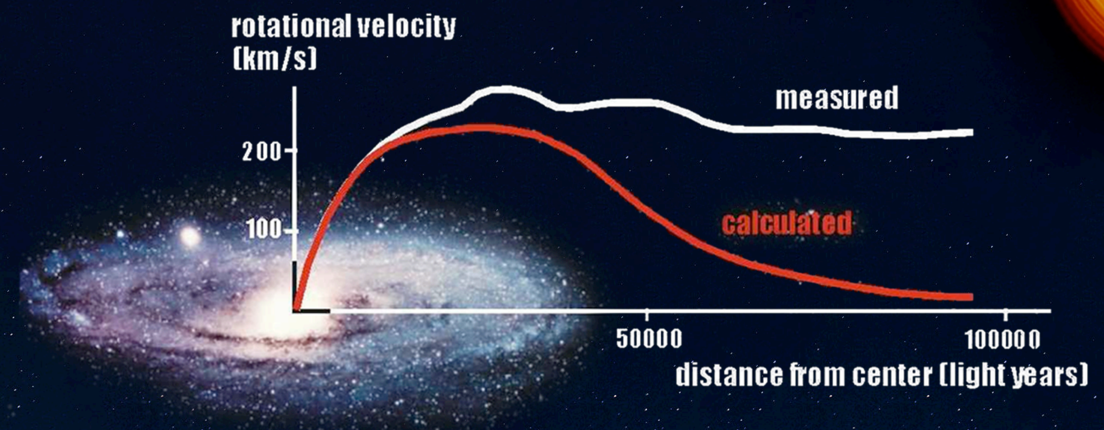
Weak Force

Unique Opportunities at the **Near Detectors** of long-baseline oscillation experiments

Gravity

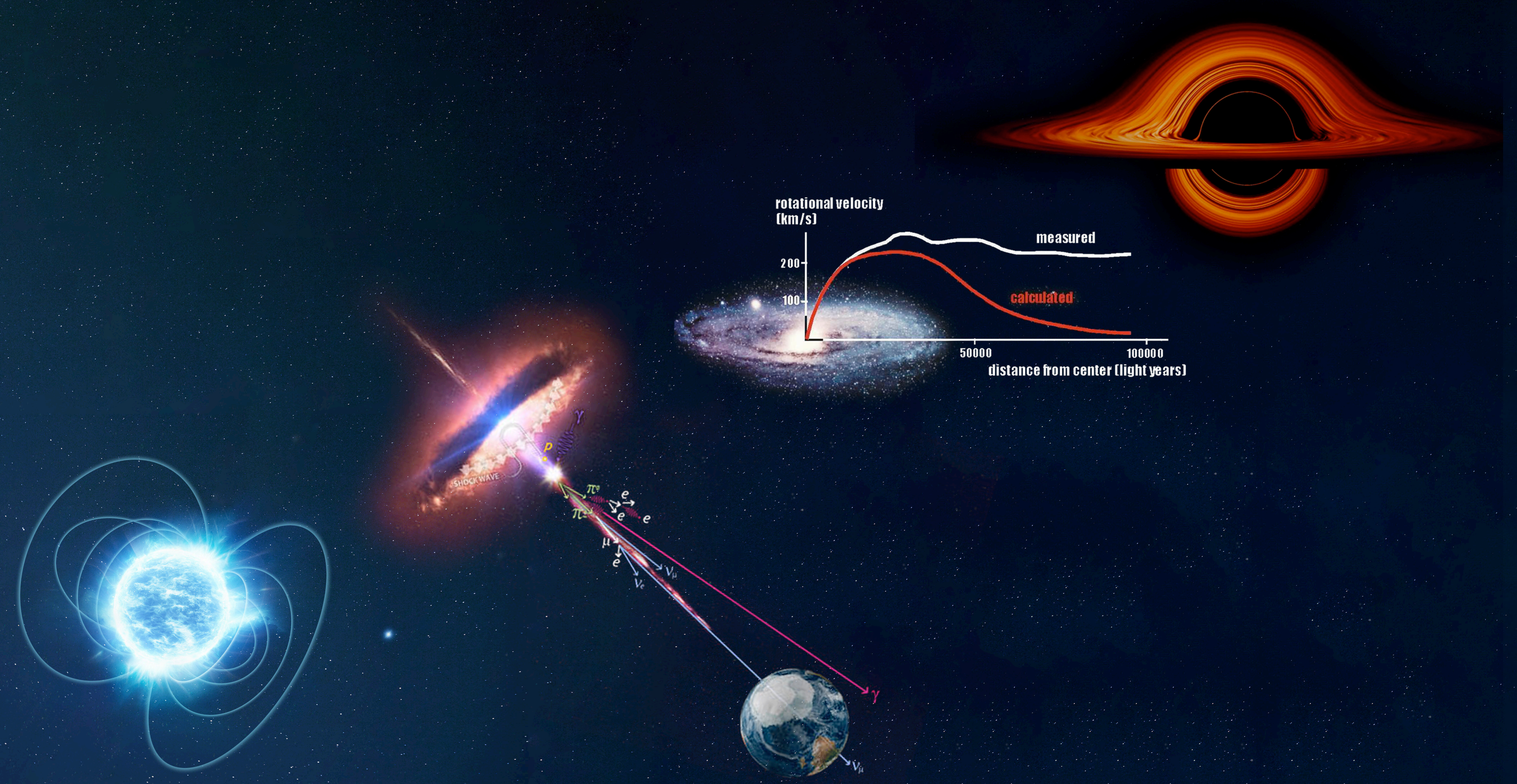
Quantum Sensors for probing **high-frequency gravitational waves**.





What next?

- ☐ MADMAX-like detector re-optimised for gravitational waves?
- ☐ miniaturised quantum sensors (e.g. on a silicon chip)?
- ☐ DUNE “module of opportunity”?



Thank You!

Bonus Slides

High-Frequency Gravitational Waves

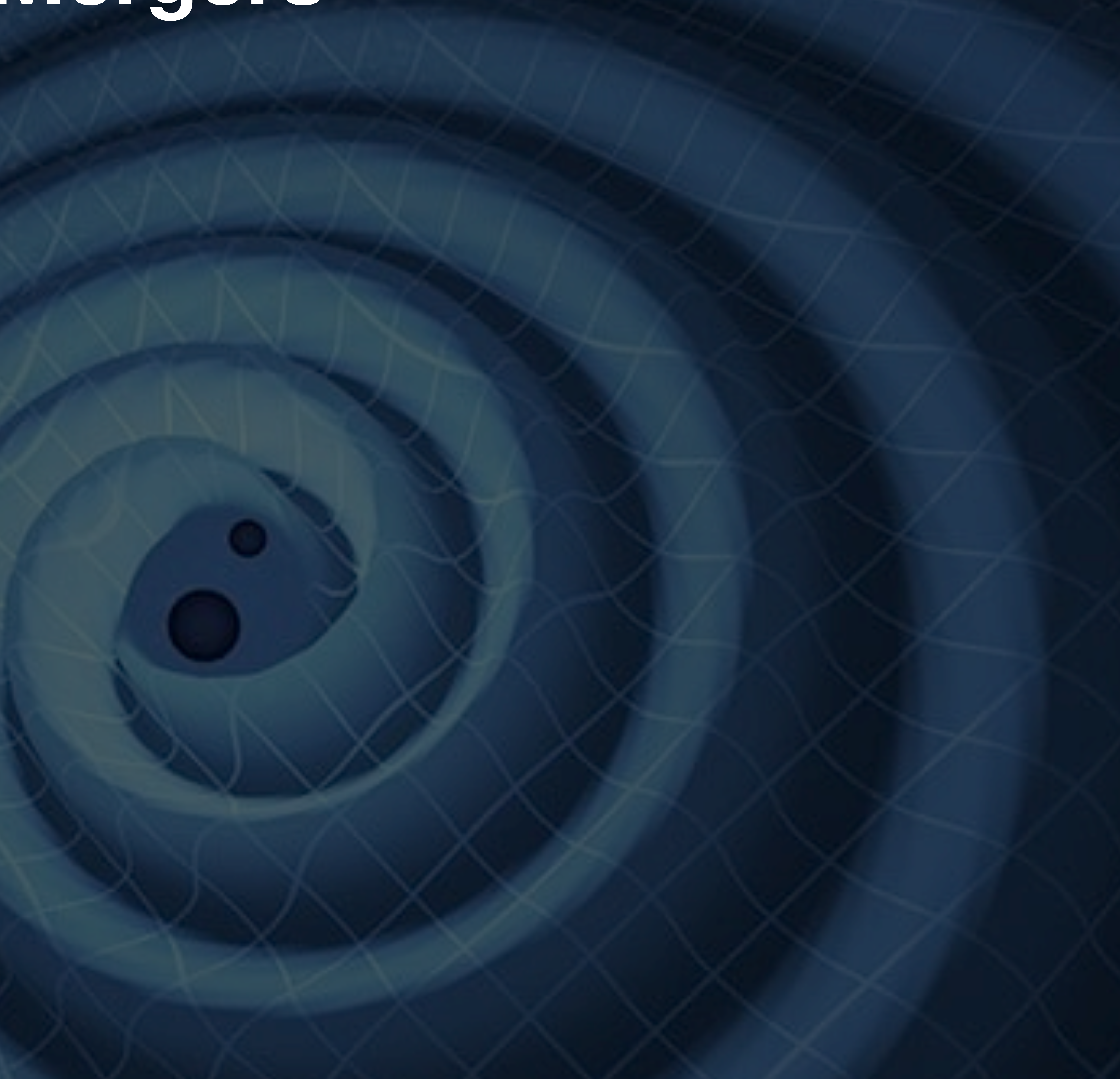
Light Primordial Black Hole Mergers

- completely analogous to regular BH mergers
- but smaller mass means higher frequency

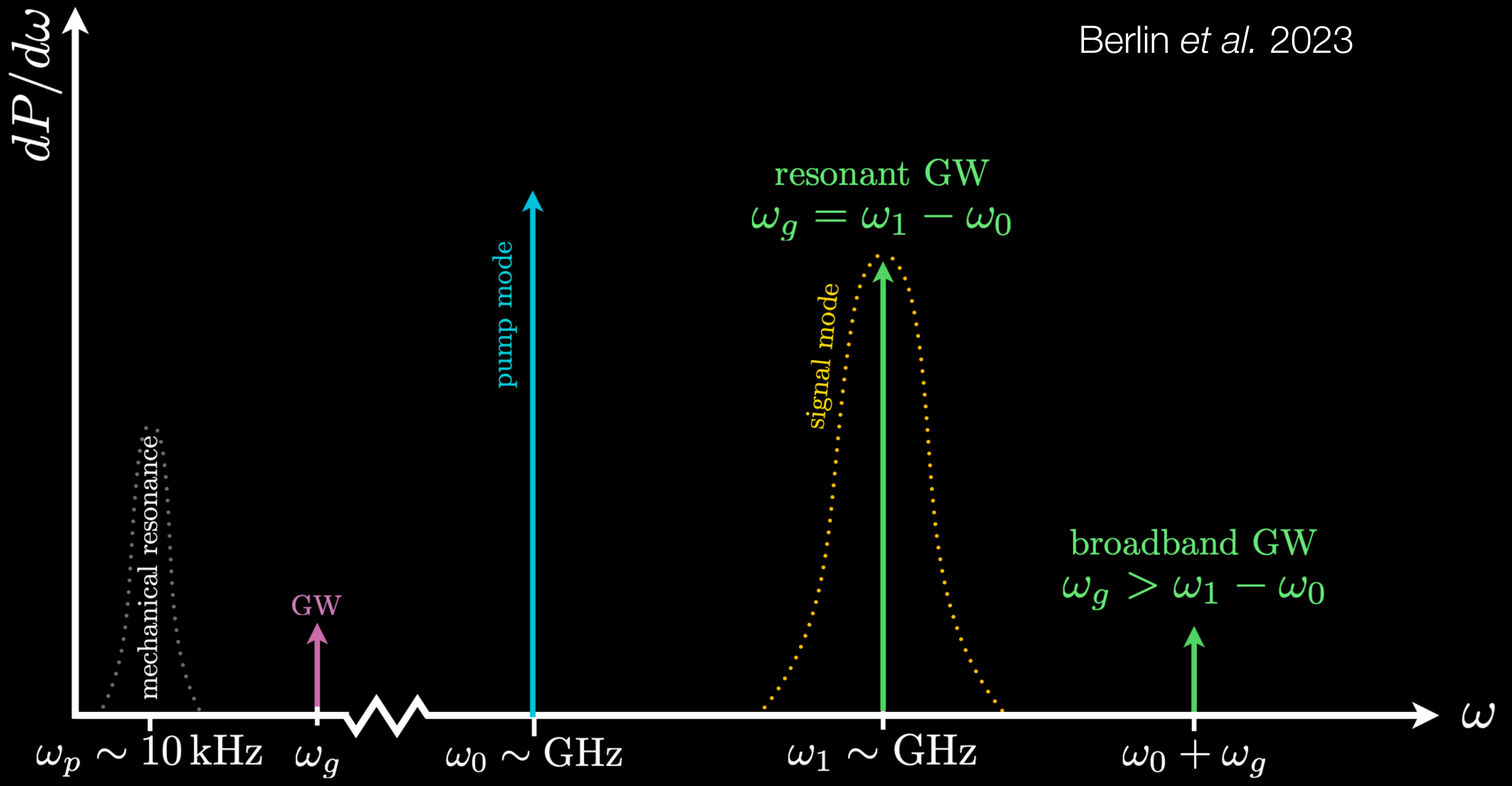
$$f_{\mathrm{gw}}(\tau) \simeq 134\,\mathrm{Hz}\left(\frac{1.21 M_\odot}{M_c}\right)^{5/8}\left(\frac{1\,s}{\tau}\right)^{3/8}$$

Maggiore 2007

- transient
- large amplitude only for last few cycles (≪ 1 sec)

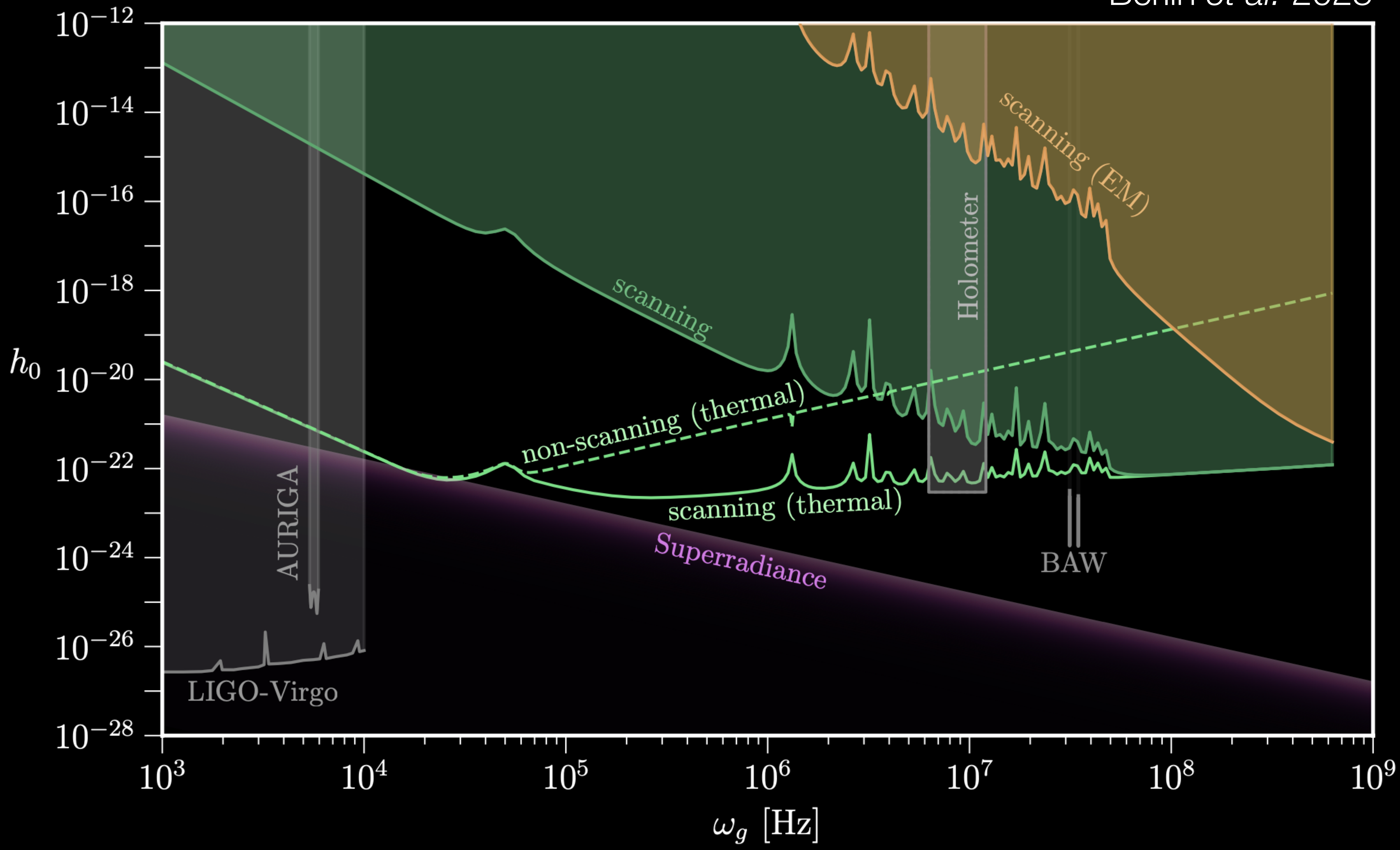


MAGO Frequency Spectrum



MAGO 2.0 Sensitivity Estimates

Berlin *et al.* 2023



Gravitational Wave Electrodynamics

Bringmann Domcke Fuchs JK 2023

Photons traveling in a GW background experience **frequency shift**

$$\omega_\gamma = -g_{\mu\nu} p^\mu u^\nu$$

linearisation

$$\begin{aligned} g_{\mu\nu} &= \eta_{\mu\nu} + h_{\mu\nu} \\ p^\mu &= (\omega_0, \omega_0, 0, 0) + \delta p^\mu \\ u^\mu &= (1, 0, 0, 0) + \delta u^\mu \,, \end{aligned}$$

leads to

$$\omega_\gamma = \omega_0 (1 + \delta u^0 - \delta u^1 - h_{00} - h_{01}) + \delta p^0 + \mathcal{O}(h^2)$$

Gravitational Wave Electrodynamics

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leads to

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- *h* depends on GW source parameterization for coherent source (in TT gauge):

$$h_{11}^{TT}(x^\mu) = h_+ s_\vartheta^2 \, \cos\left[\omega_g (x^0 - c_\vartheta x^1 - s_\vartheta x^3) + \varphi_0\right]$$

- δp^0 from geodesic equation

$$\frac{dp^0}{d\lambda} = -\Gamma^0_{\mu\nu} p^\mu p^\nu = -\omega_0^2 \left(\Gamma^0_{00} + 2\Gamma^0_{10} + \Gamma^0_{11}\right) + \mathcal{O}(h^2)$$

- δu^0, δu^1 depend on experimental conditions.
For free-falling observers (in TT gauge):
$\delta u^0 = \delta u^1 = 0$

Photon Frequency Shift in GW Background

$$\frac{\omega_\gamma^D - \omega_\gamma^S}{\omega_\gamma^D} = h_+ c_{\vartheta/2}^2 \Big\{ \cos\varphi_0 - \cos\big[\omega_g L (1 - c_\vartheta) + \varphi_0\big] \Big\}$$

Bringmann Domcke Fuchs JK 2023

Side Note: Rigid Detectors

Discussion so far was for
free-falling detectors

What about rigid setups?

$$\frac{\omega_\gamma^D - \omega_\gamma^S}{\omega_\gamma^D} = \frac{h_+}{2}\left\{\cos\varphi_0 - \omega_g L \sin(\omega_g L + \varphi_0)\right.$$
$$\left. + \left(\frac{1}{2}\omega_g^2 L^2 - 1\right)\cos(\omega_g L + \varphi_0)\right\}$$

Bringmann Domcke Fuchs JK 2023

Side Note: Rigid Detectors

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enhancement for large GW frequencies / large detectors?

Bringmann Domcke Fuchs JK 2023

Side Note: Rigid Detectors

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$$\frac{\omega_\gamma^D - \omega_\gamma^S}{\omega_\gamma^D} = \frac{h_+}{2}\Big\{\cos\varphi_0 - \omega_g L \sin(\omega_g L + \varphi_0) + \Big(\frac{1}{2}\omega_g^2 L^2 - 1\Big)\cos(\omega_g L + \varphi_0)\Big\}$$

enhancement for large GW frequencies / large detectors?

it is **fundamentally impossible** to construct a **mechanical system** that is **rigid** at **arbitrarily high** vibration **frequencies**.

Consider harmonic oscillator driven by GW:

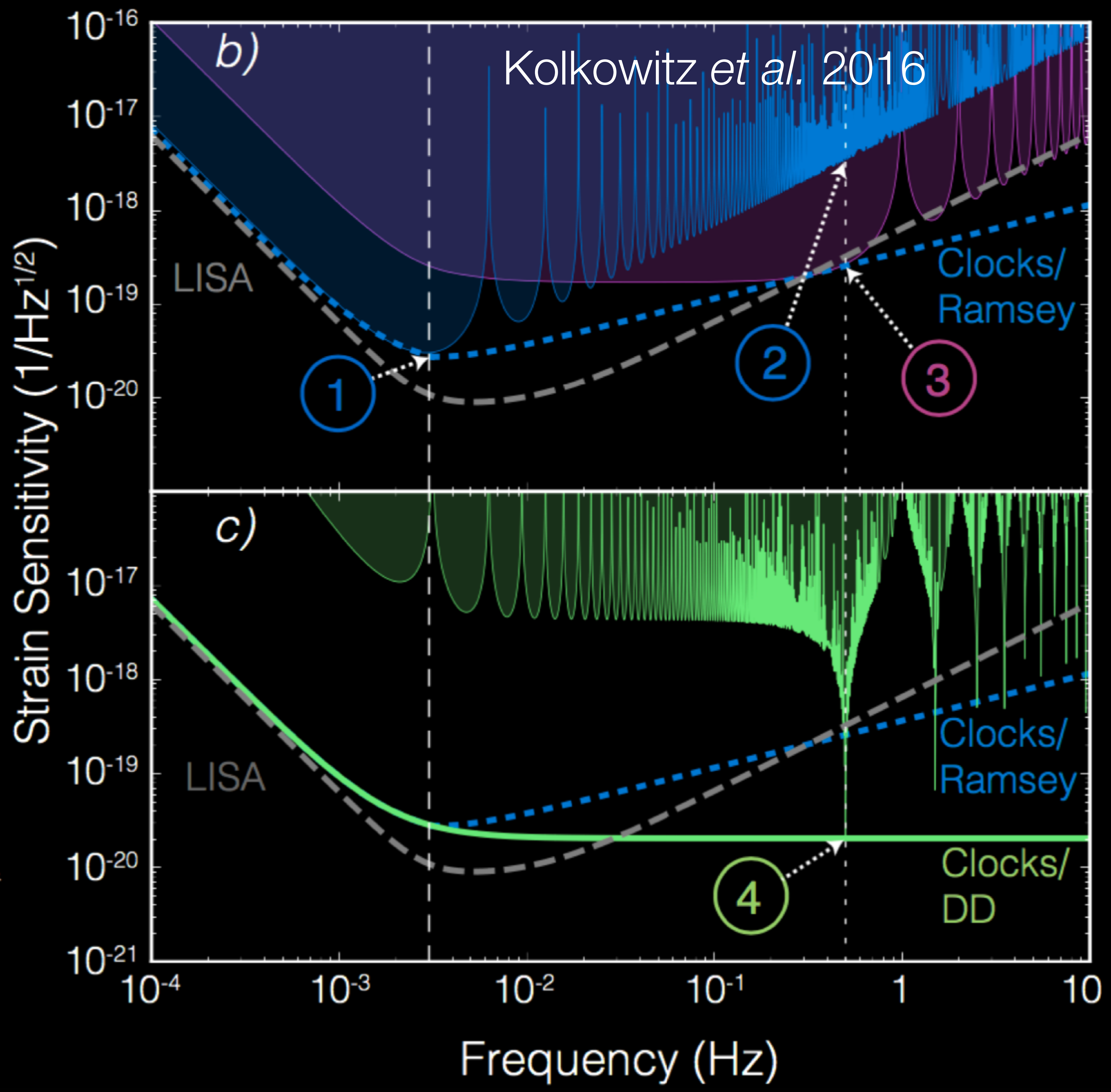
$$\ddot{\xi} - \frac{\omega_0^2 L^2}{\pi^2}\xi'' + \gamma\dot{\xi} = \frac{1}{2}x^1 \ddot{h}_{11}^{TT}$$

at $\omega_g \gg \omega_0$, terms containing $\dot{\xi}$ and ξ'' are negligible

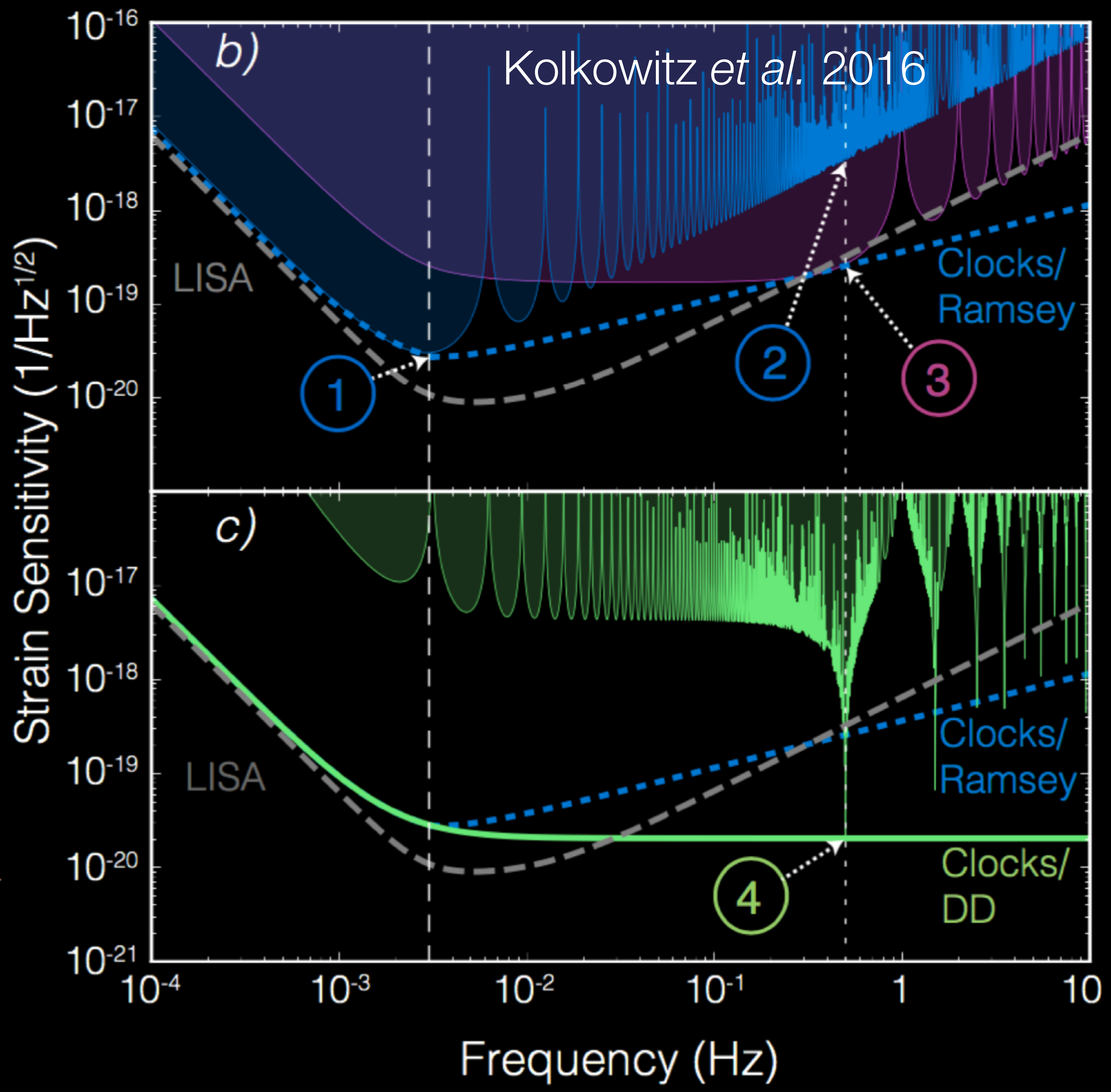
➠ recover **free oscillator**

Bringmann Domcke Fuchs JK 2023

Low-Frequency GW Detection Using Atomic Clocks



Low-Frequency GW Detection Using Atomic Clocks

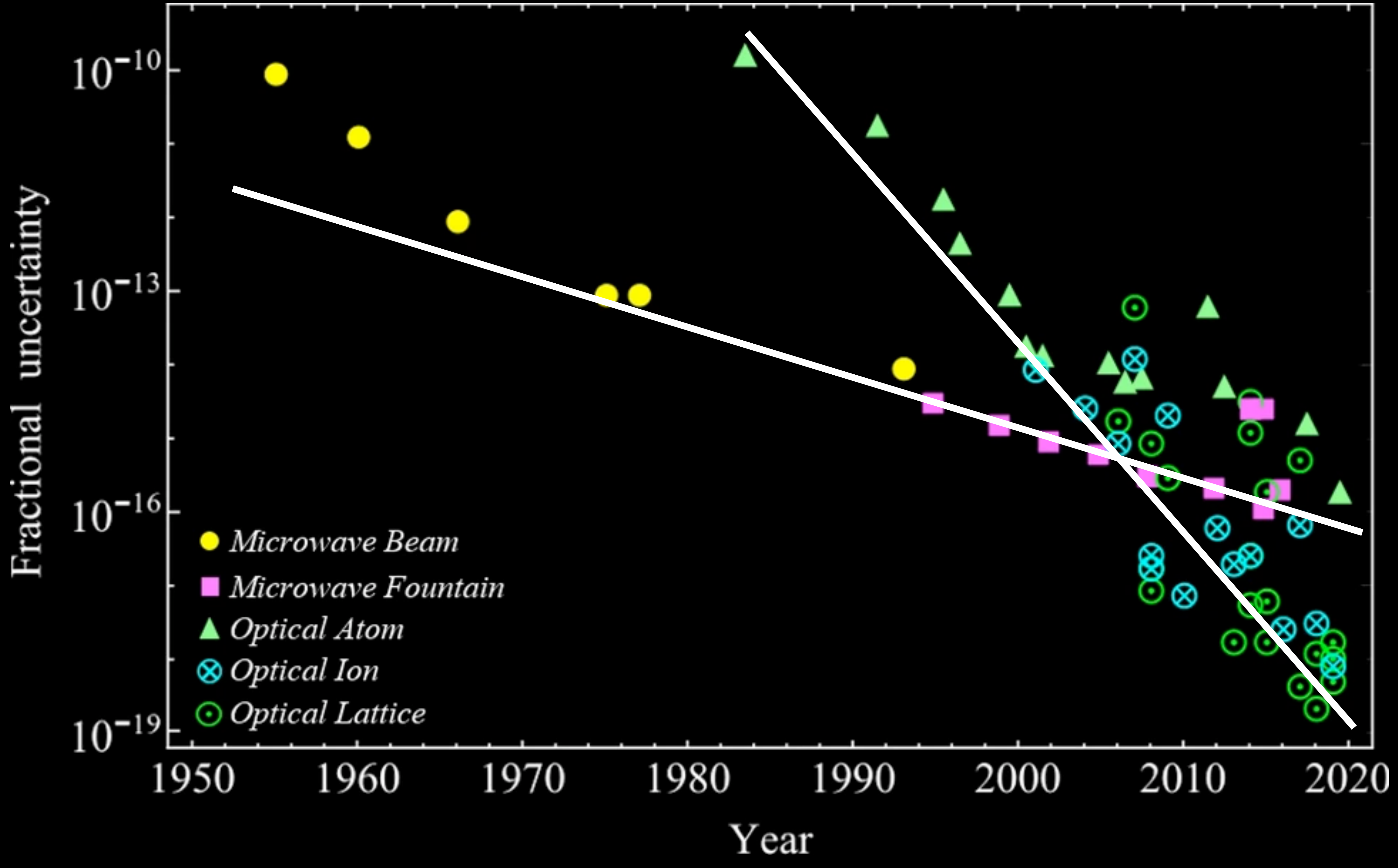


①, ②	different interrogation times T
	(large T ➟ better sensitivity at low frequencies, but signal averages out at high ω_g)
③	sensitivity envelope (optimal T for each ω_g)

④ readout optimized for specific ω_g

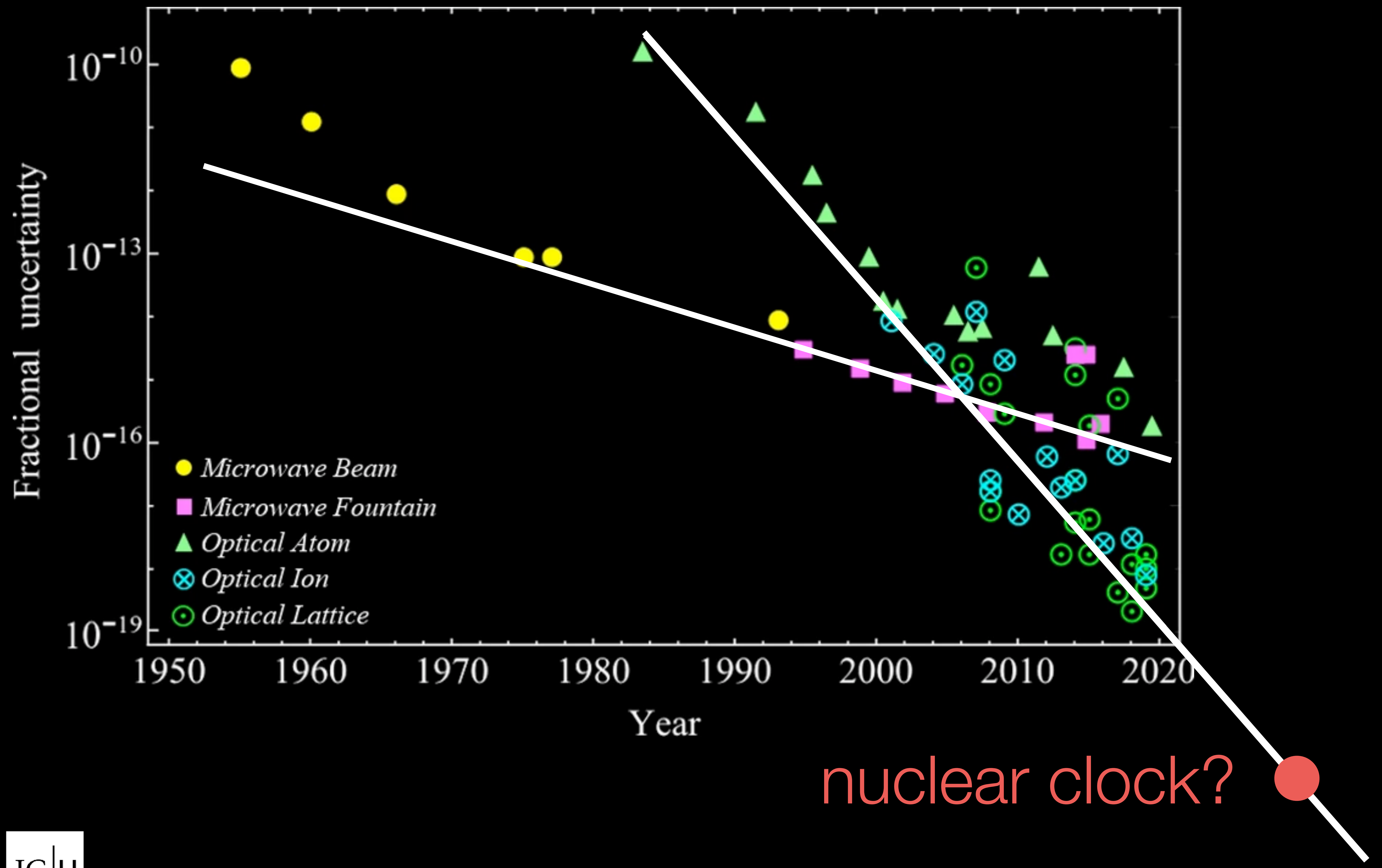
Atomic Clocks are Amazing

Sharma *et al.* 2023



Nuclear Clocks would be Even More Amazing

Sharma *et al.* 2023



Atomic Clocks vs. Nuclear Clocks

Sr-87 atomic clock

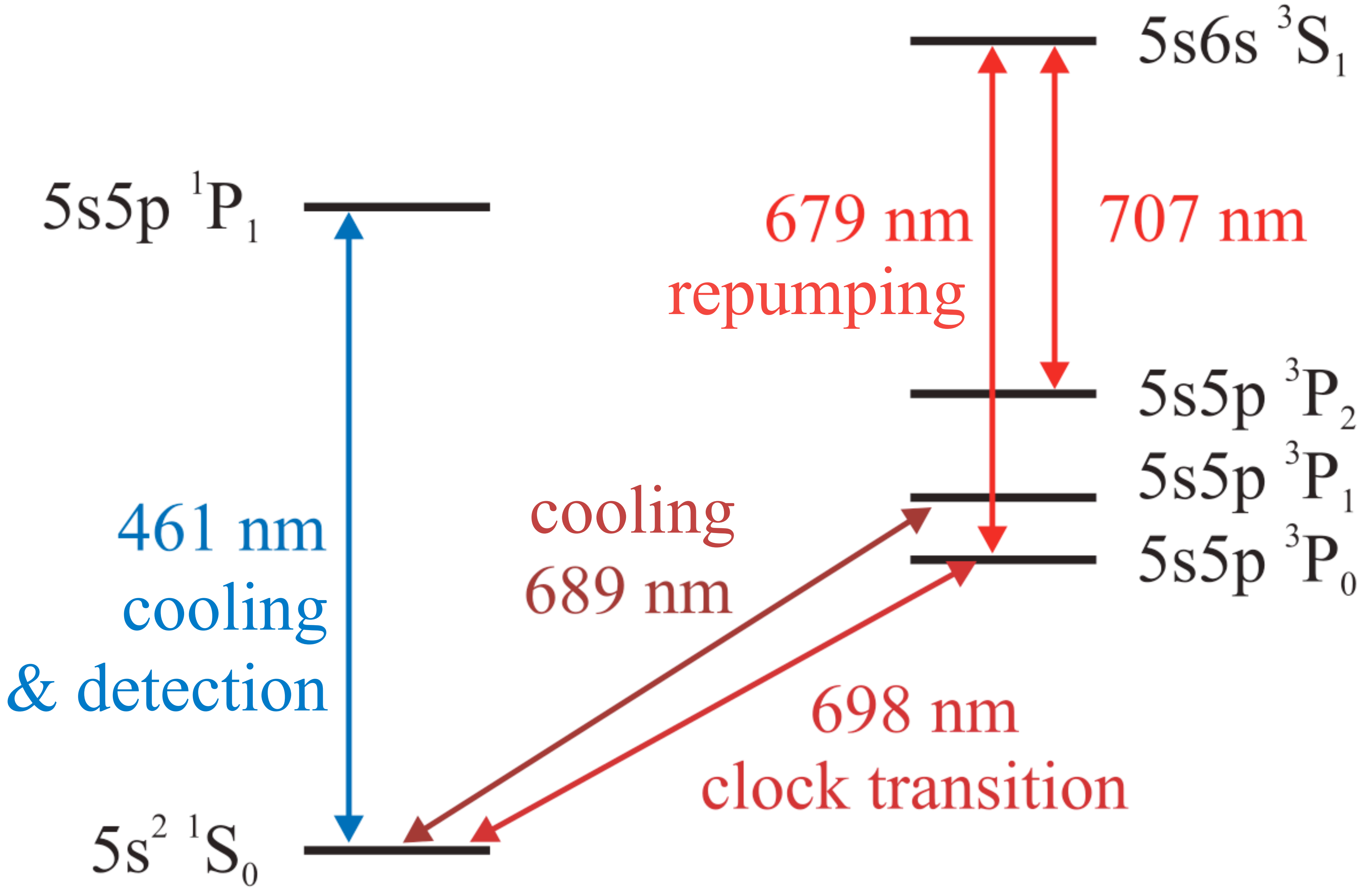


Image: Wikimedia Commons

Atomic Clocks vs. Nuclear Clocks

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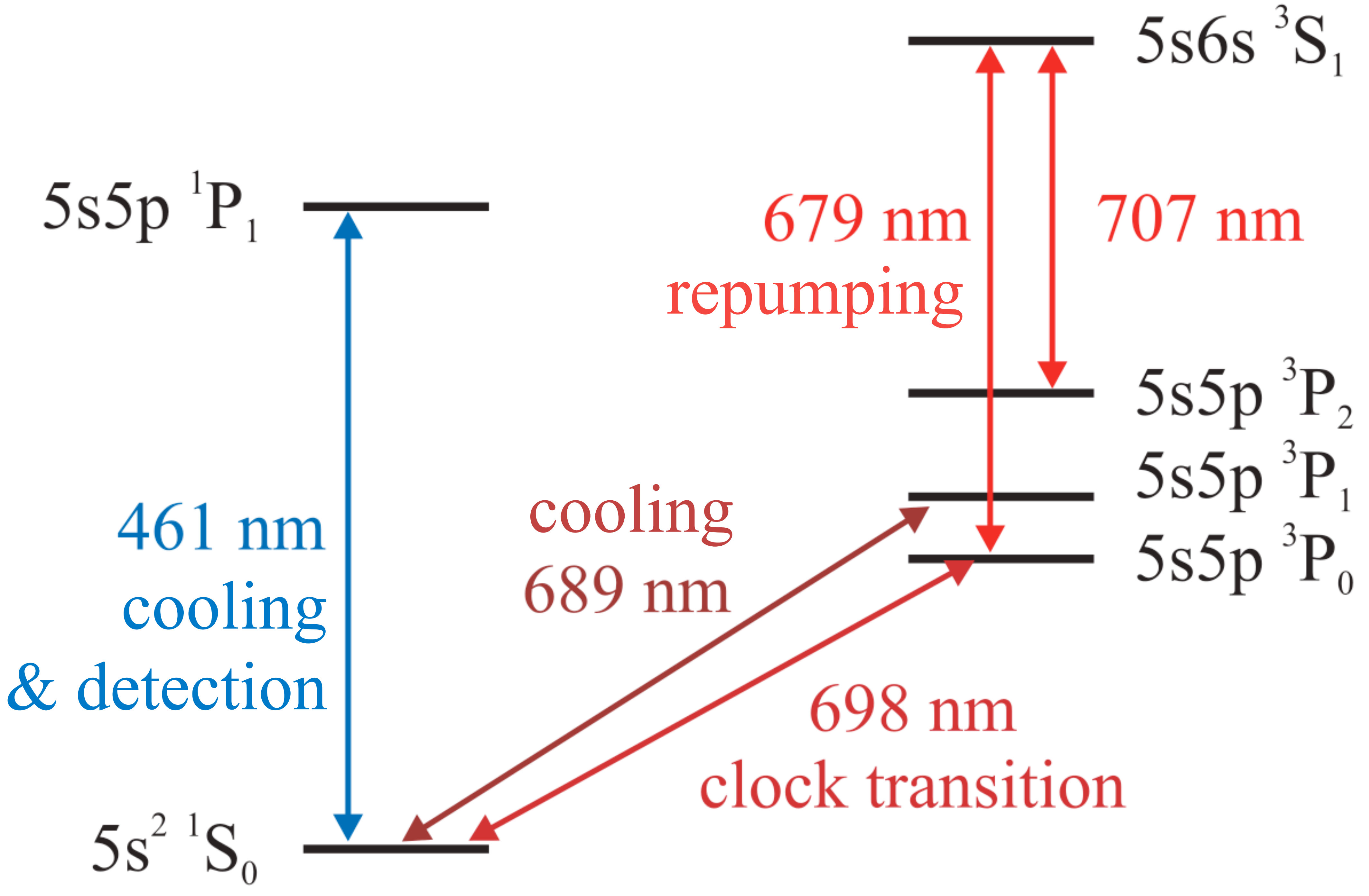


Image: Wikimedia Commons

Th-229 nuclear clock

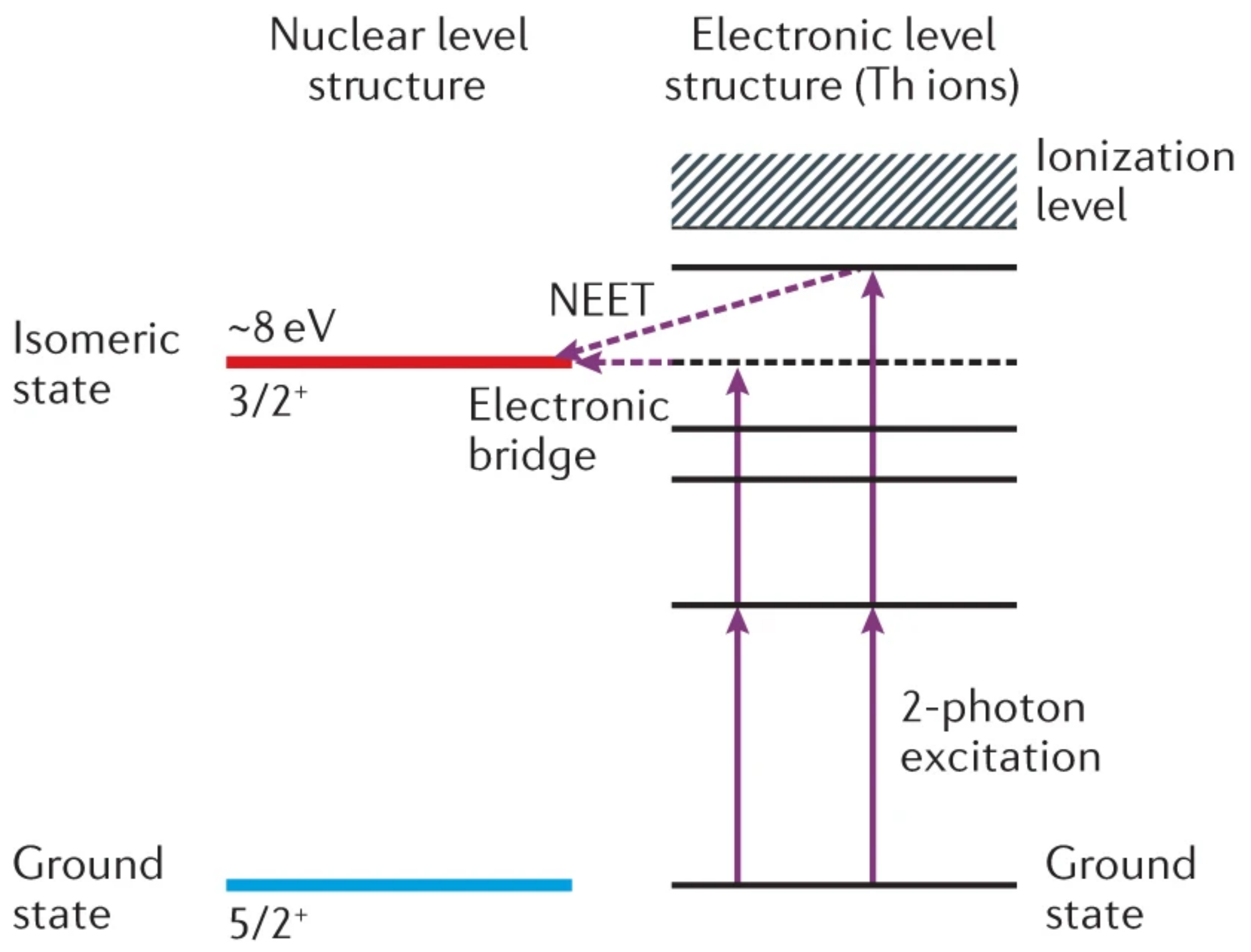


Image: Beeks *et al.* 2021

Aside: New Physics Searches with Nuclear Clocks

- Low transition energy presumably due to **fine-tuned cancellation** between strong and electromagnetic contribution
- new physics that effects one but not the other break this tuning
  ➠ hugely enhanced sensitivity

Th-229 nuclear clock

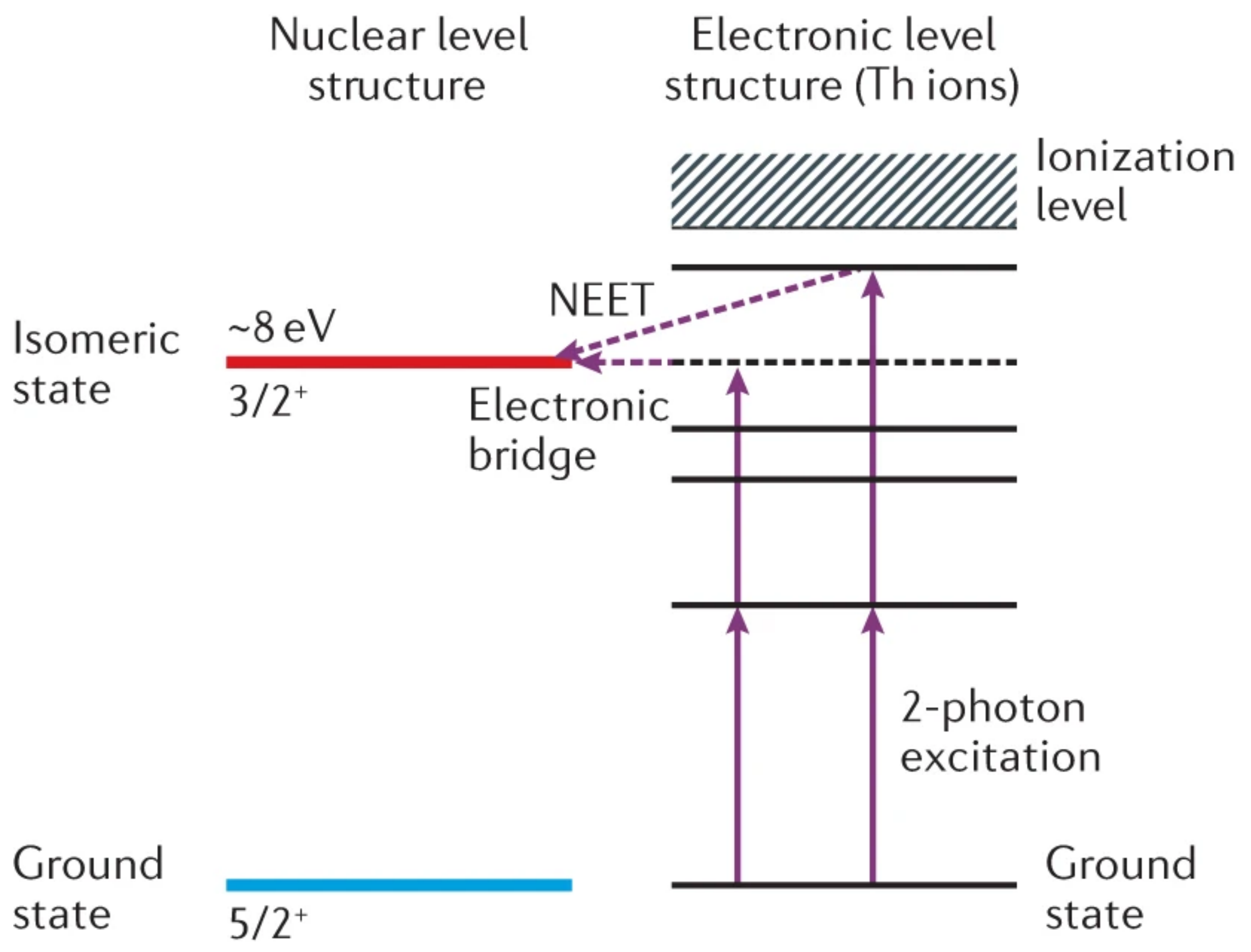


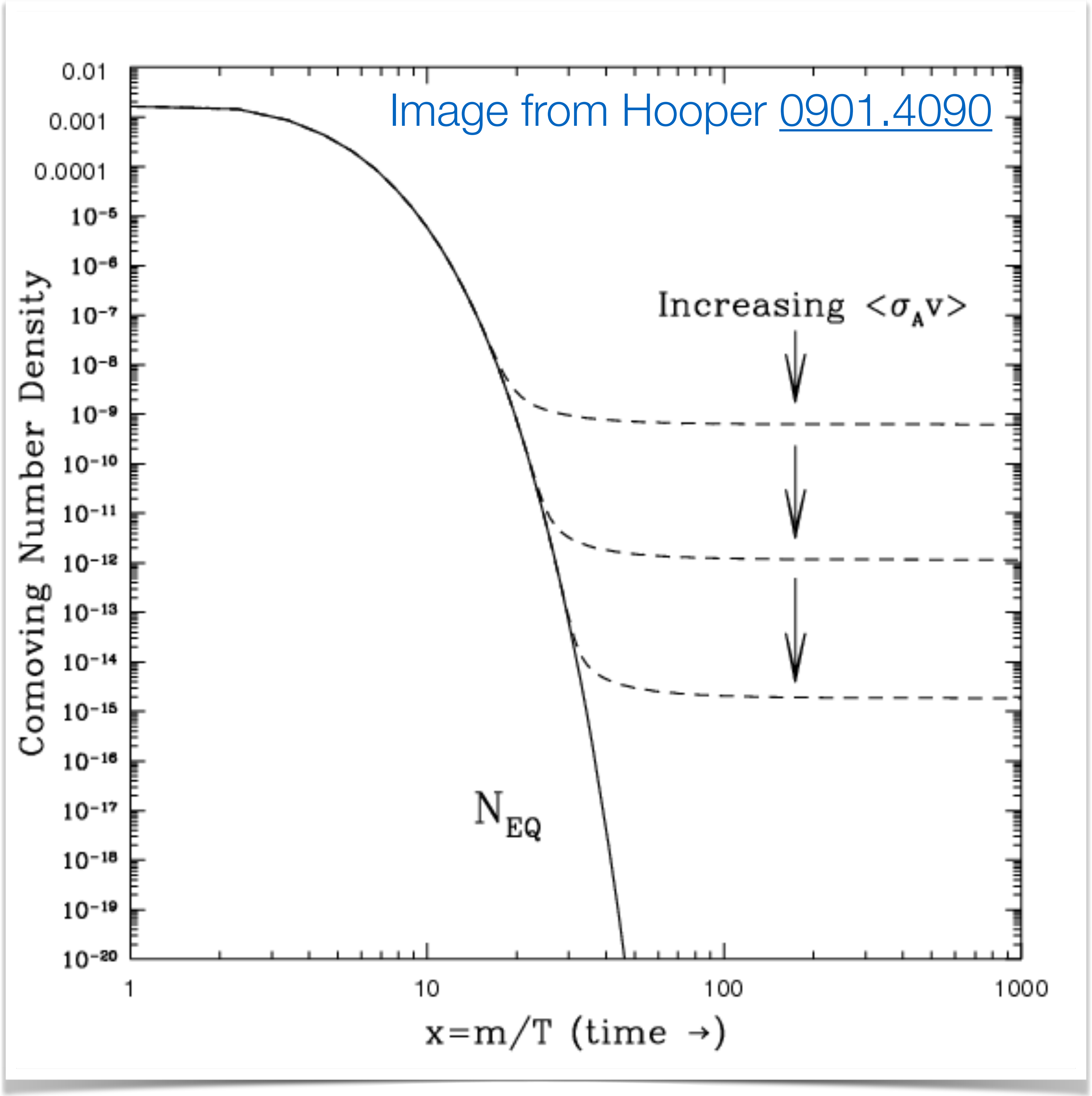
Image: Beeks *et al.* 2021

Dark Matter

Gravity
Dark Matter
Weak Force
Neutrinos
Strong &
Electromagnetic forces
Hadrons / Atoms
rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)
SHOCK WAVE

The Dark Matter Abundance in the Universe

- Observed DM abundance requires a mechanism that depletes DM by several orders of magnitude, then stops
- Idea: phase transitions



Phase Transitions in Everyday Life

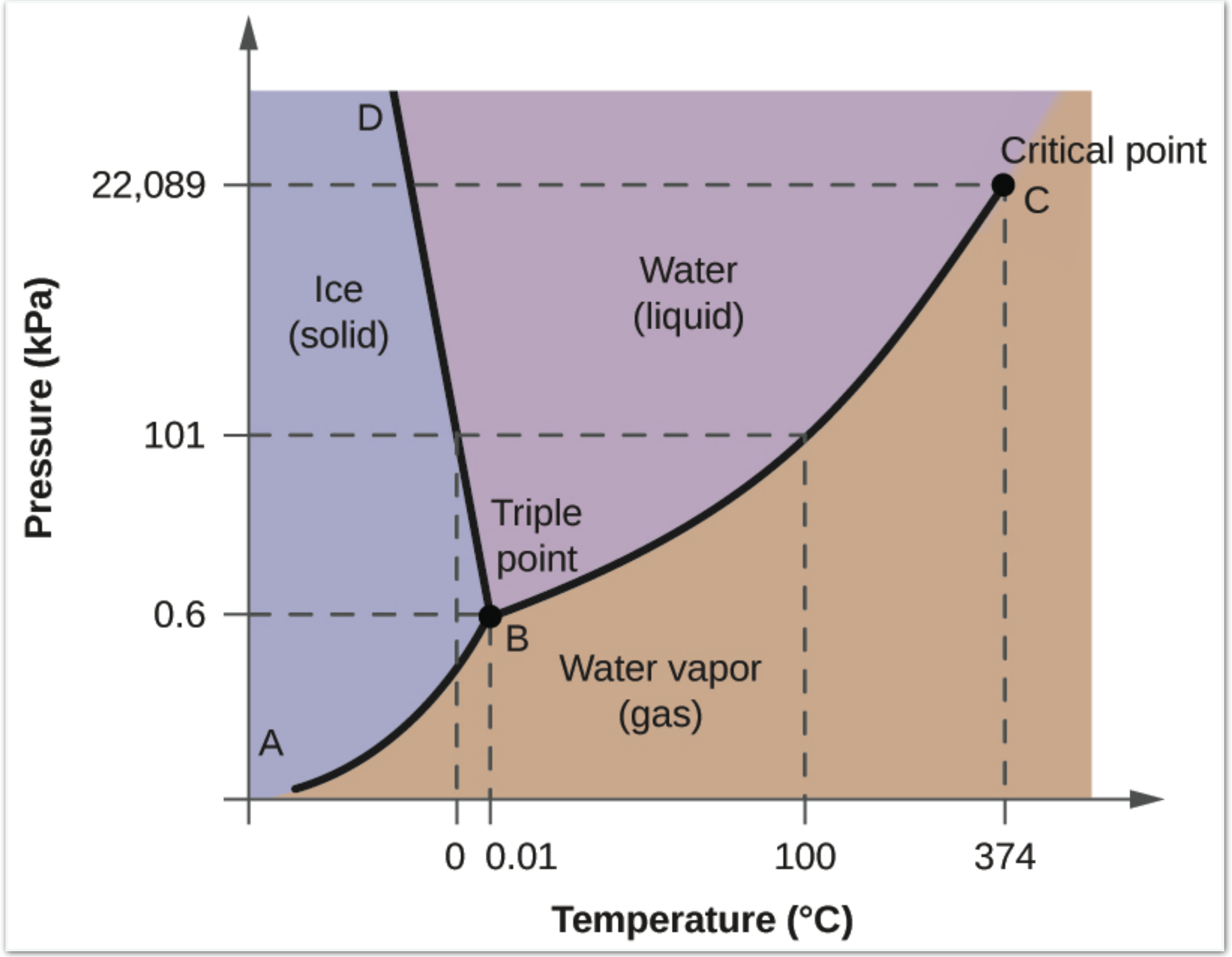


Image Credit: libretexts.org

Phase Transitions in a Physicist's Everyday Life

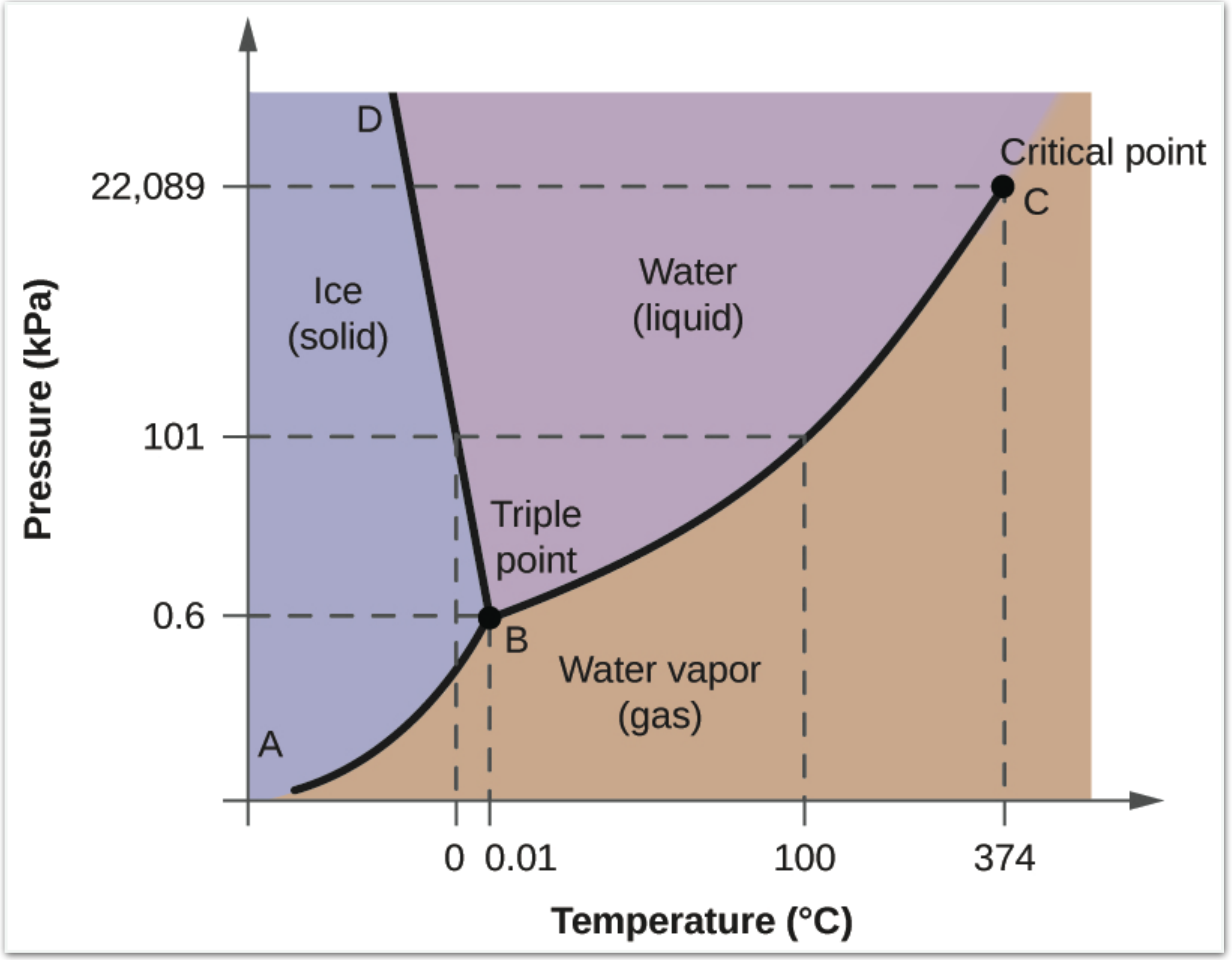


Image Credit: libretexts.org

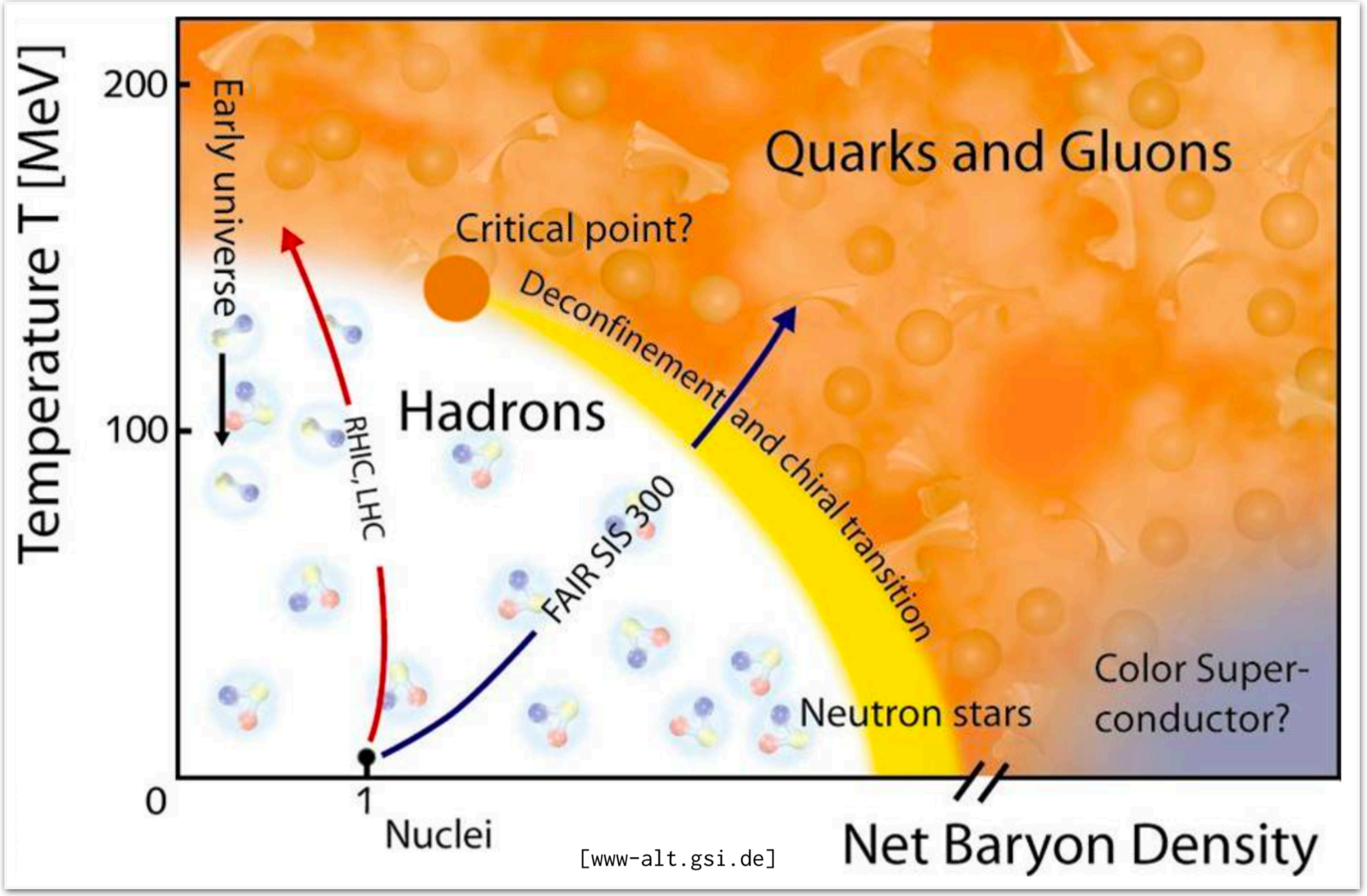


Image Credit: Ralf-Arno Tripolt

Phase Transitions in a Physicist's Everyday Life

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- Order Parameter Q: a quantity measuring the change in the system across the phase transition

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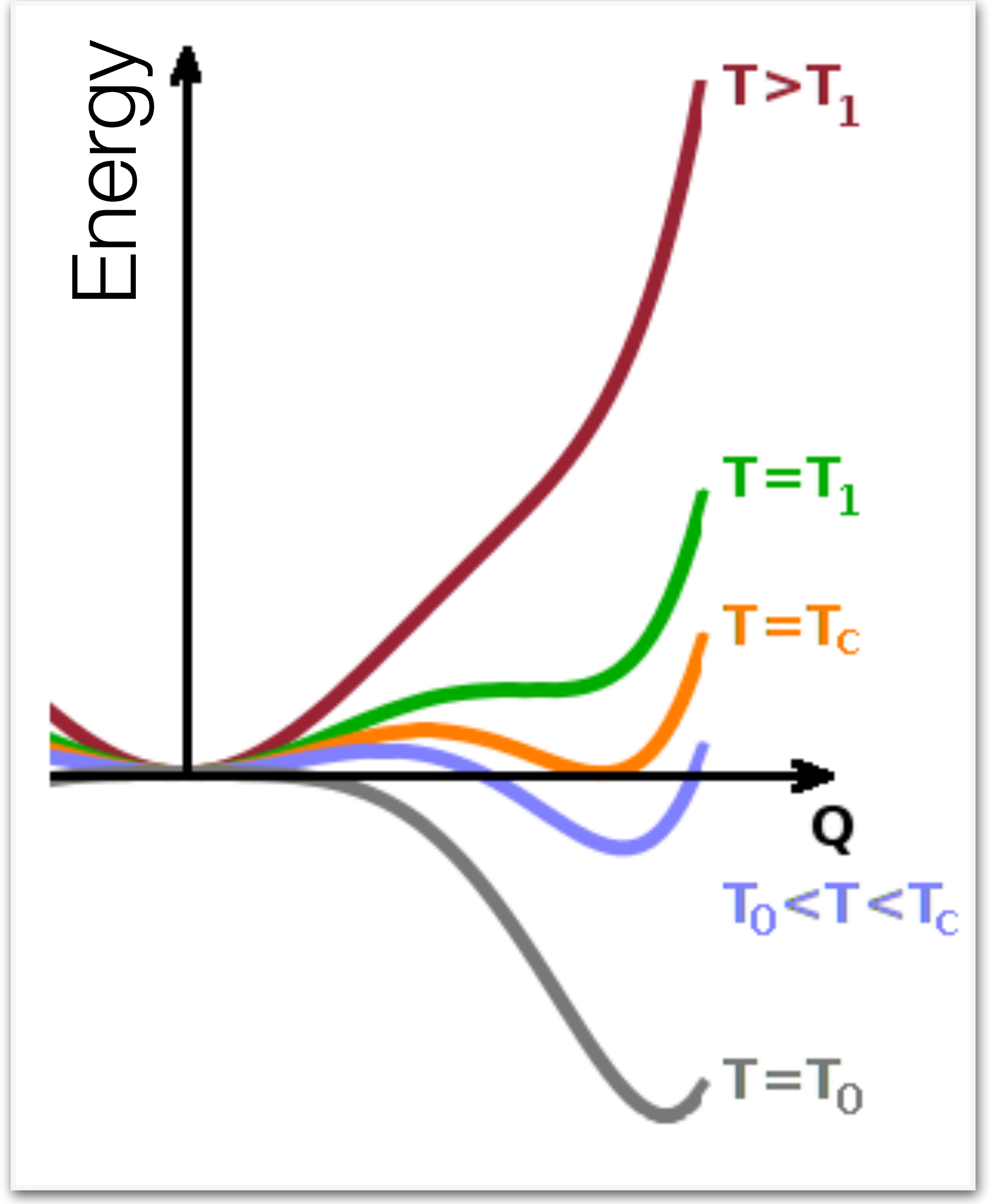
1st order transition
order parameter changes discontinuously



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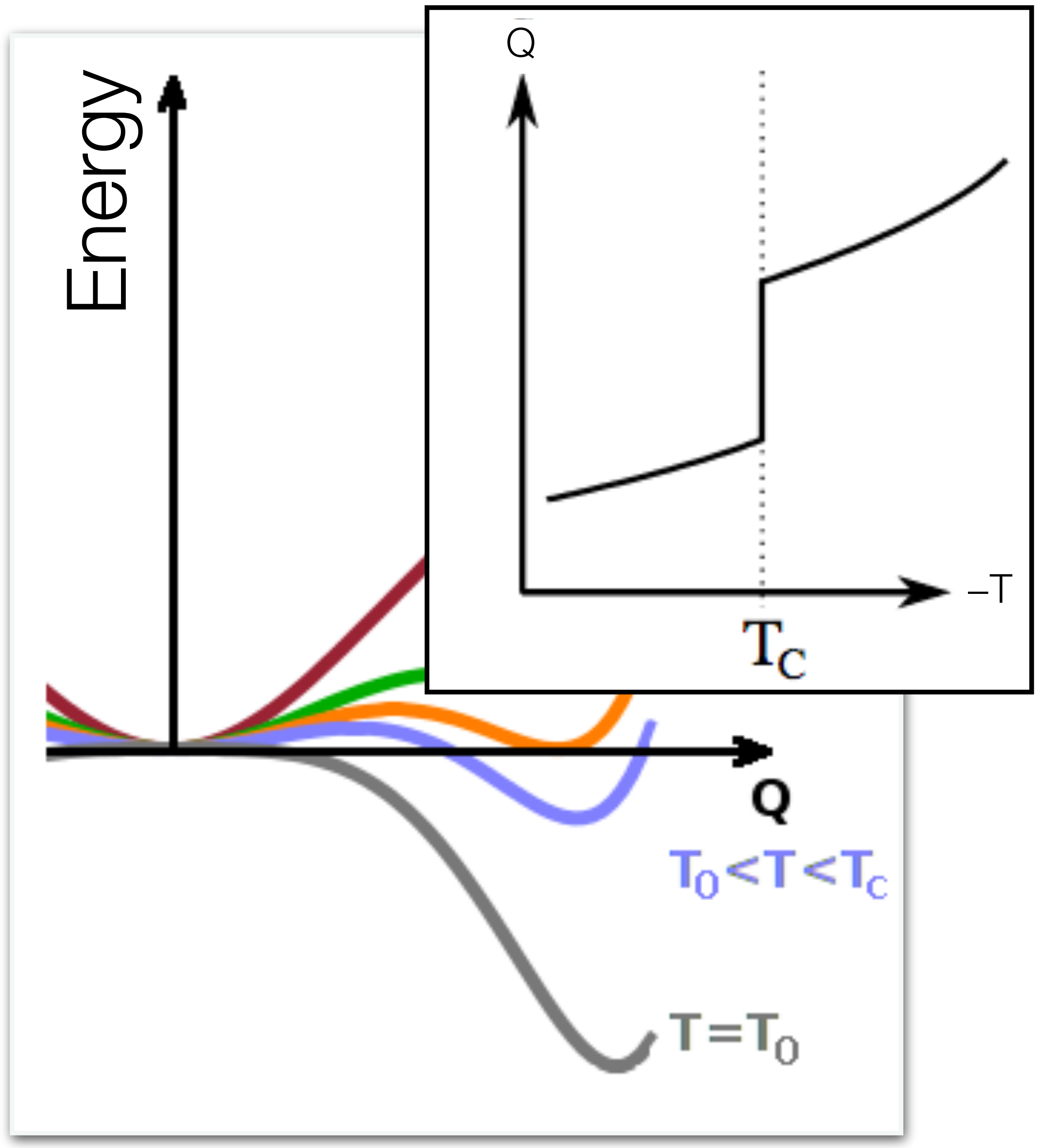

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2nd order transition / crossover
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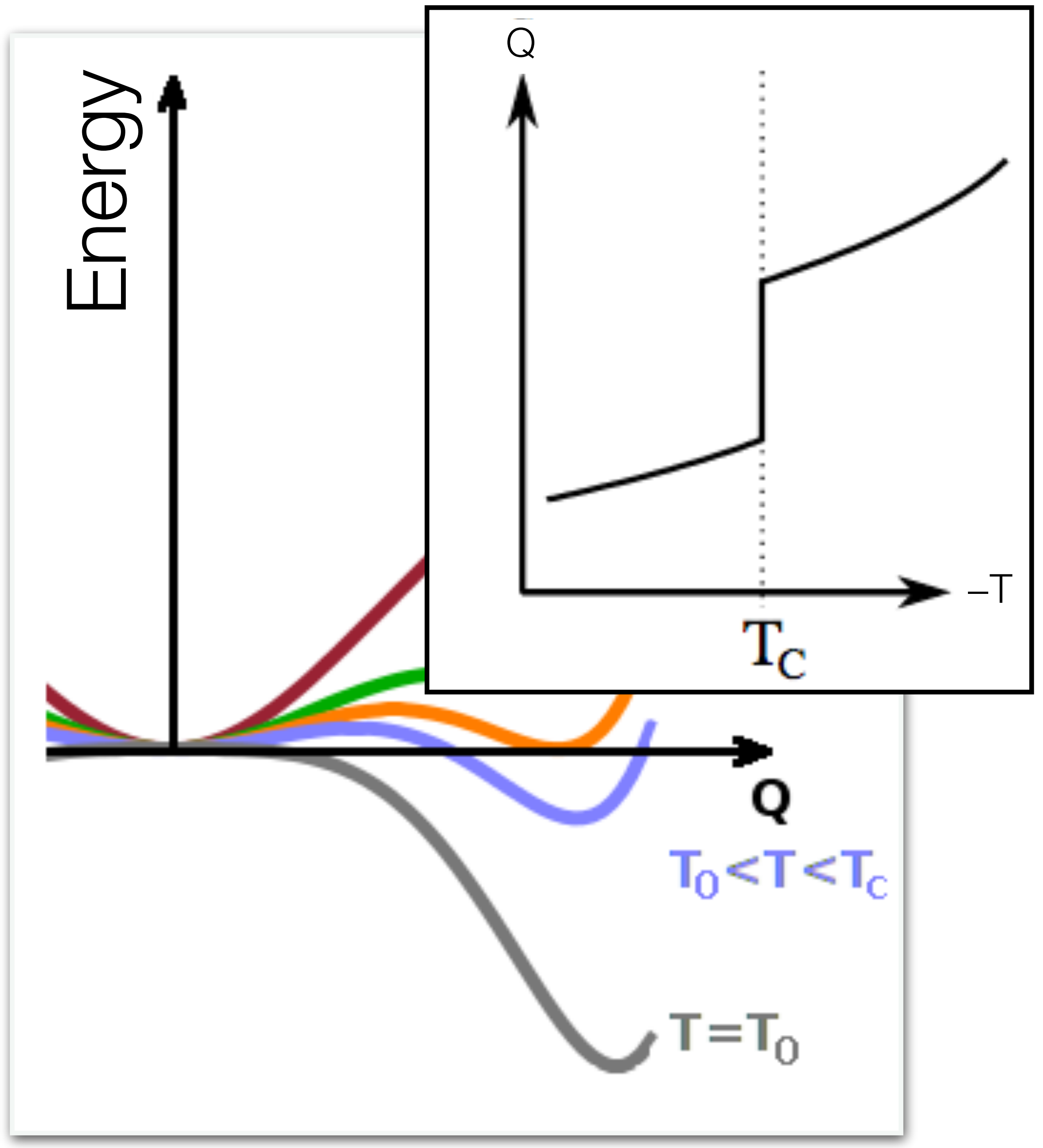

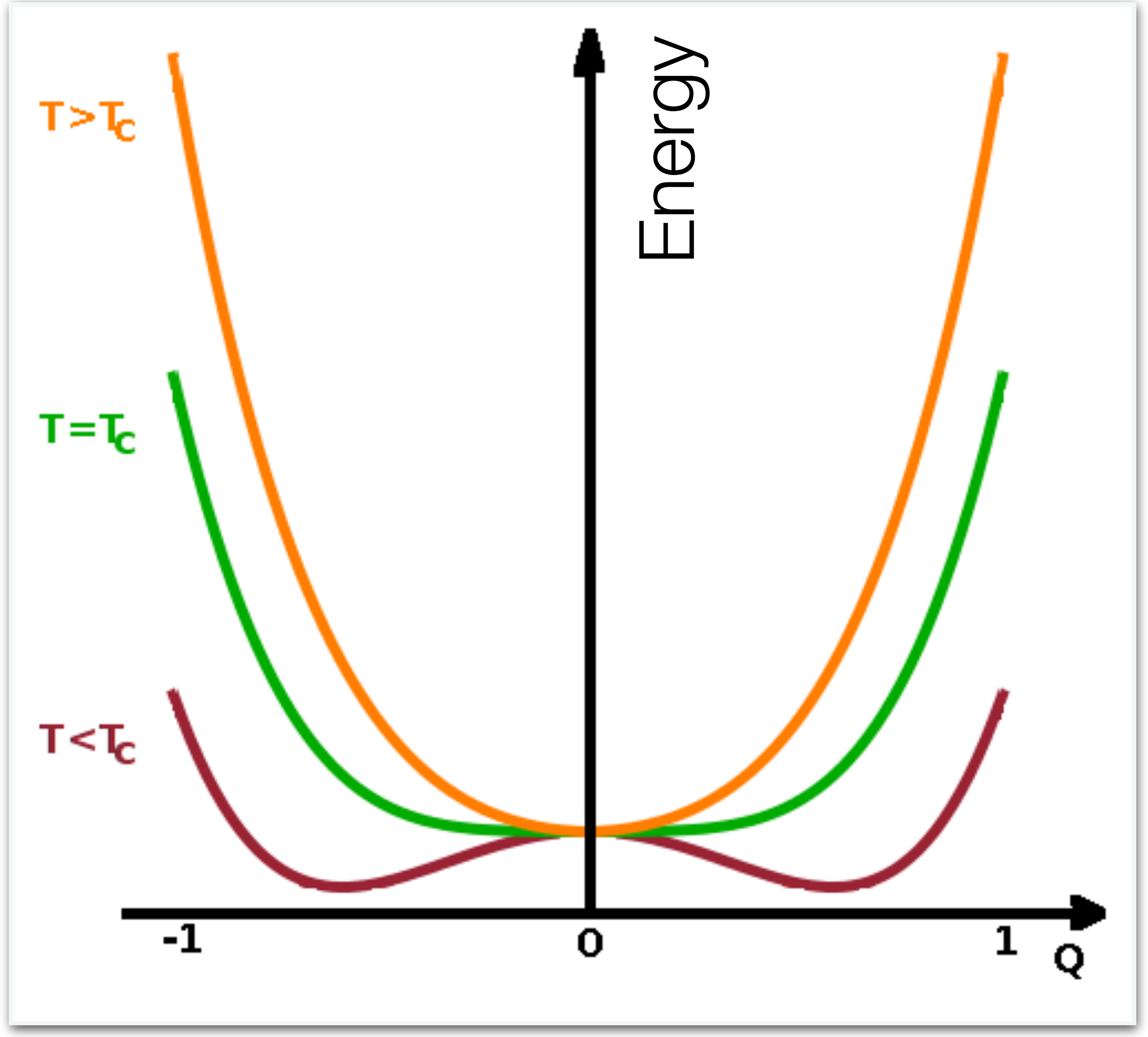

Images: Rudi Winter, Caroline Röhr and Heinz Gericke

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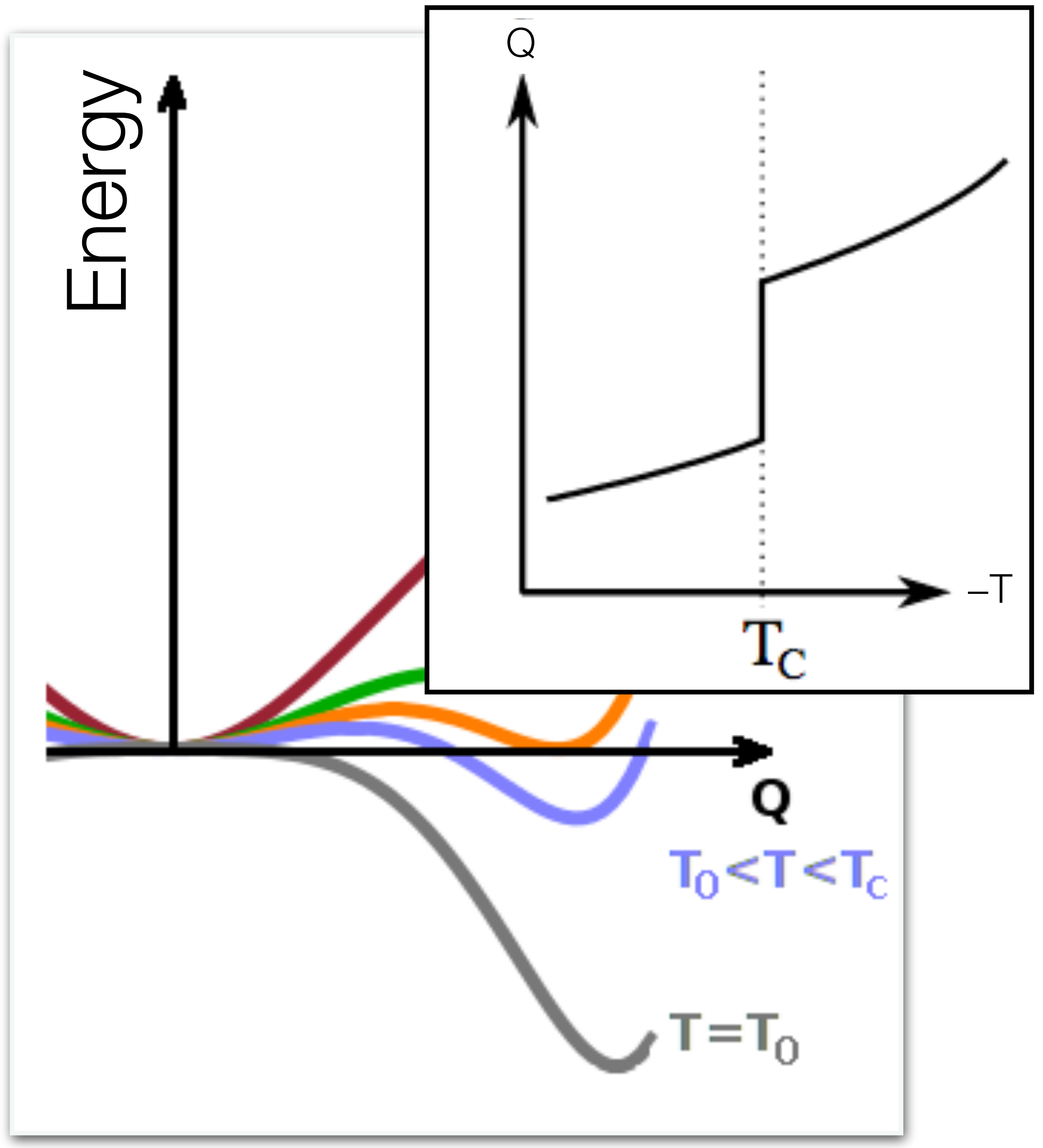
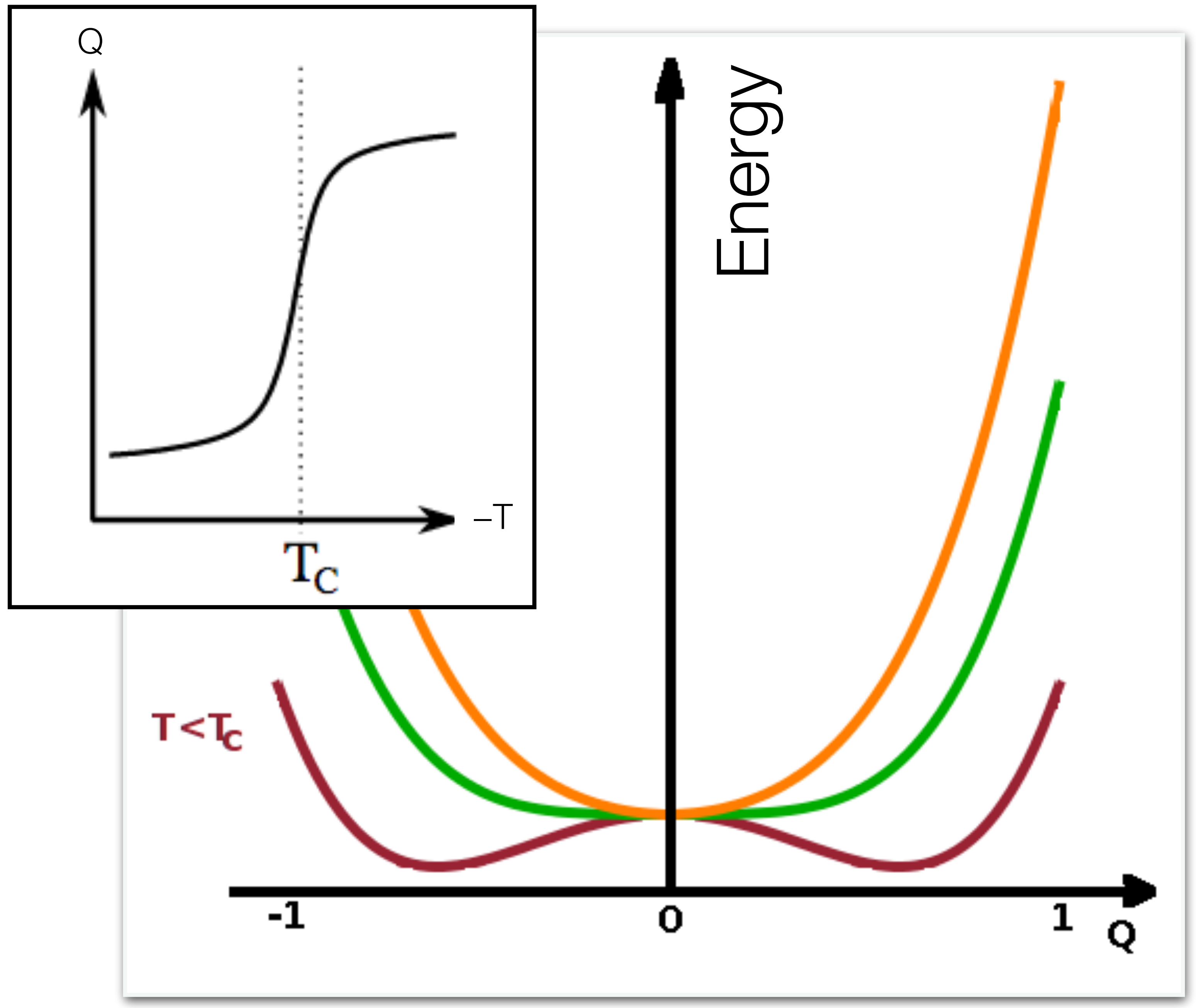
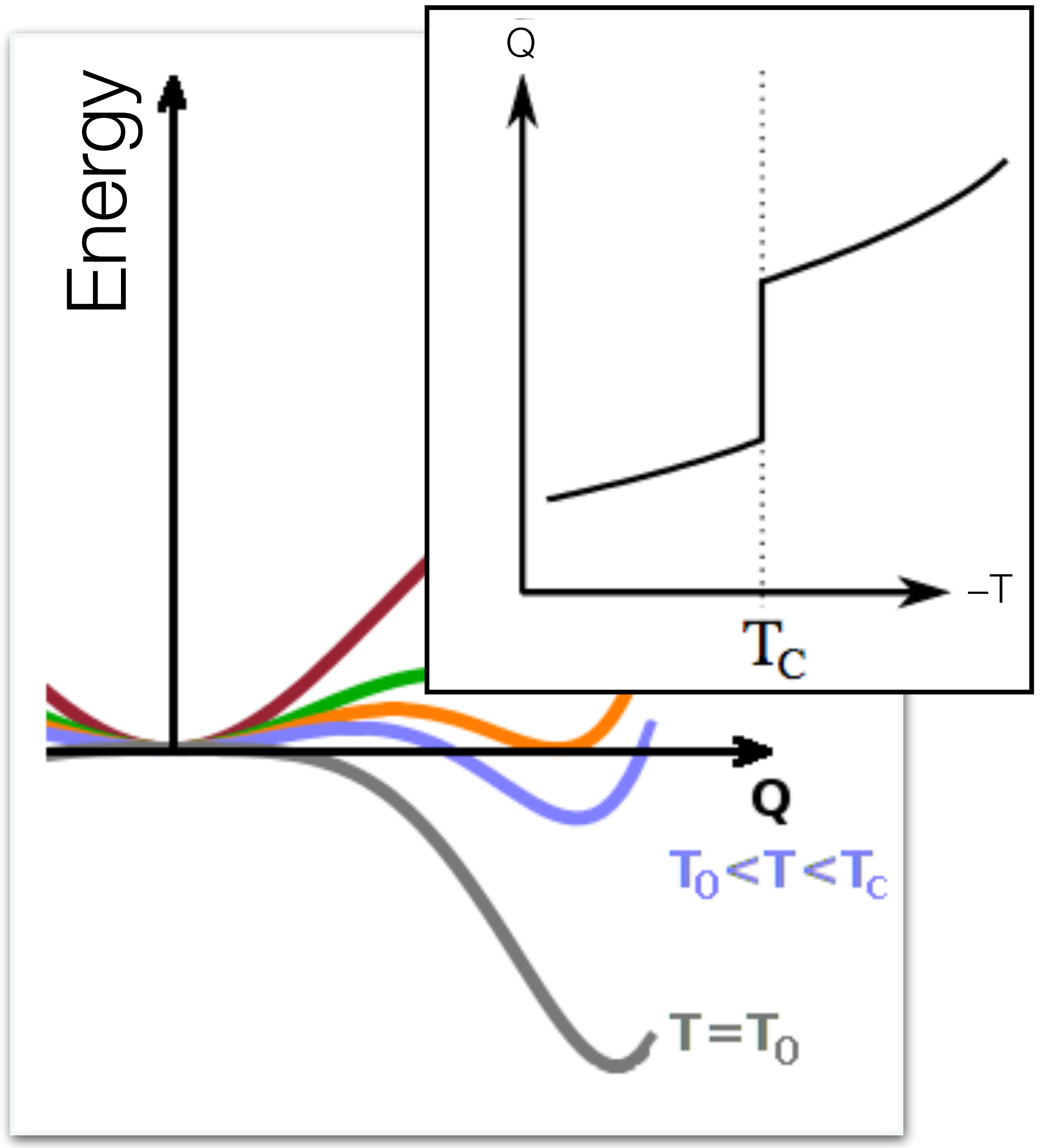


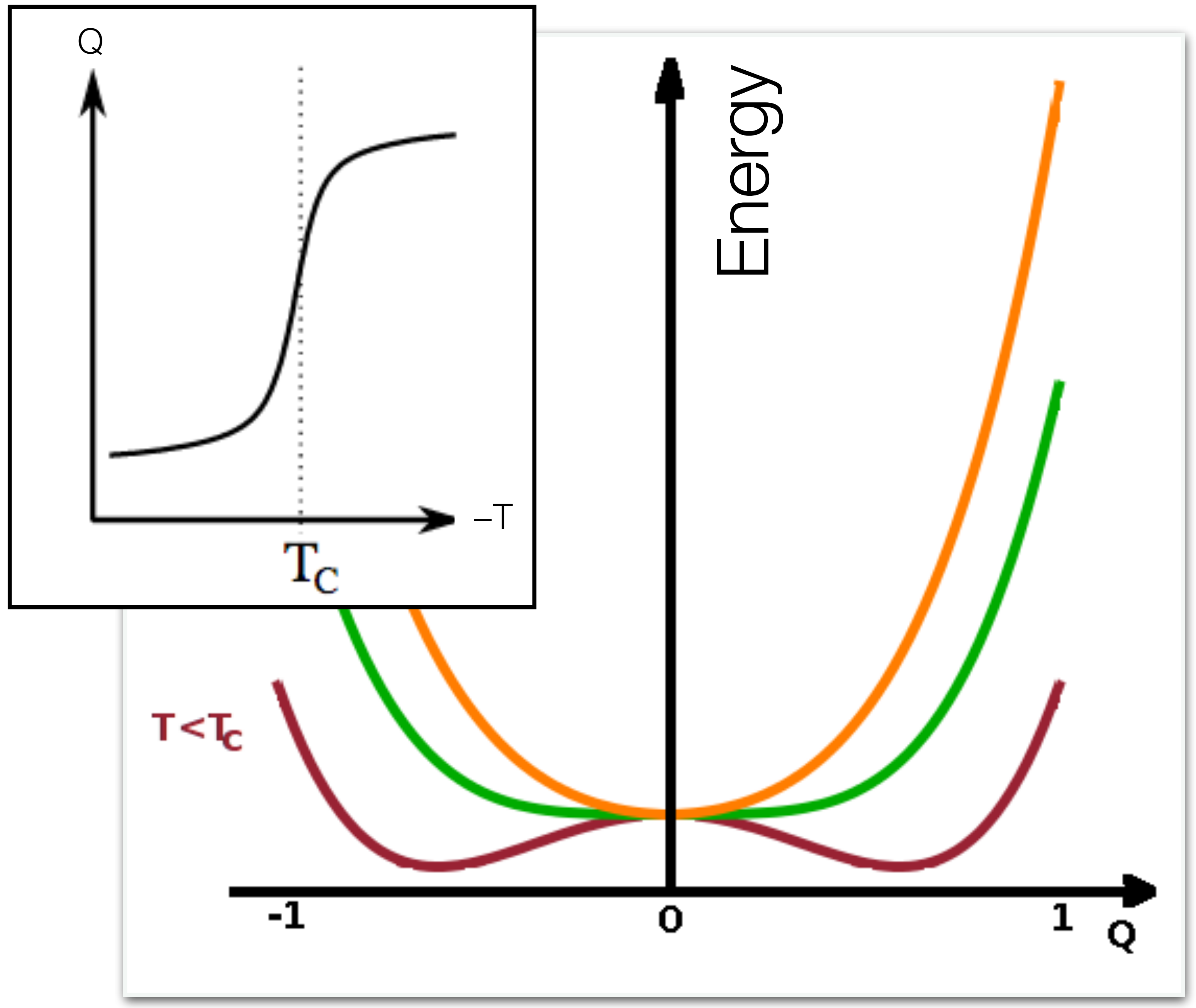


Images: Rudi Winter, Caroline Röhr and Heinz Gericke

Phase Transitions in a Physicist's Everyday Life

- Order Parameter Q: a quantity measuring the change in the system across the phase transition
  - for liquid–gas transition: density ρ
  - for QCD phase transition: chiral condensate $\langle \bar{q}_L q_R \rangle$





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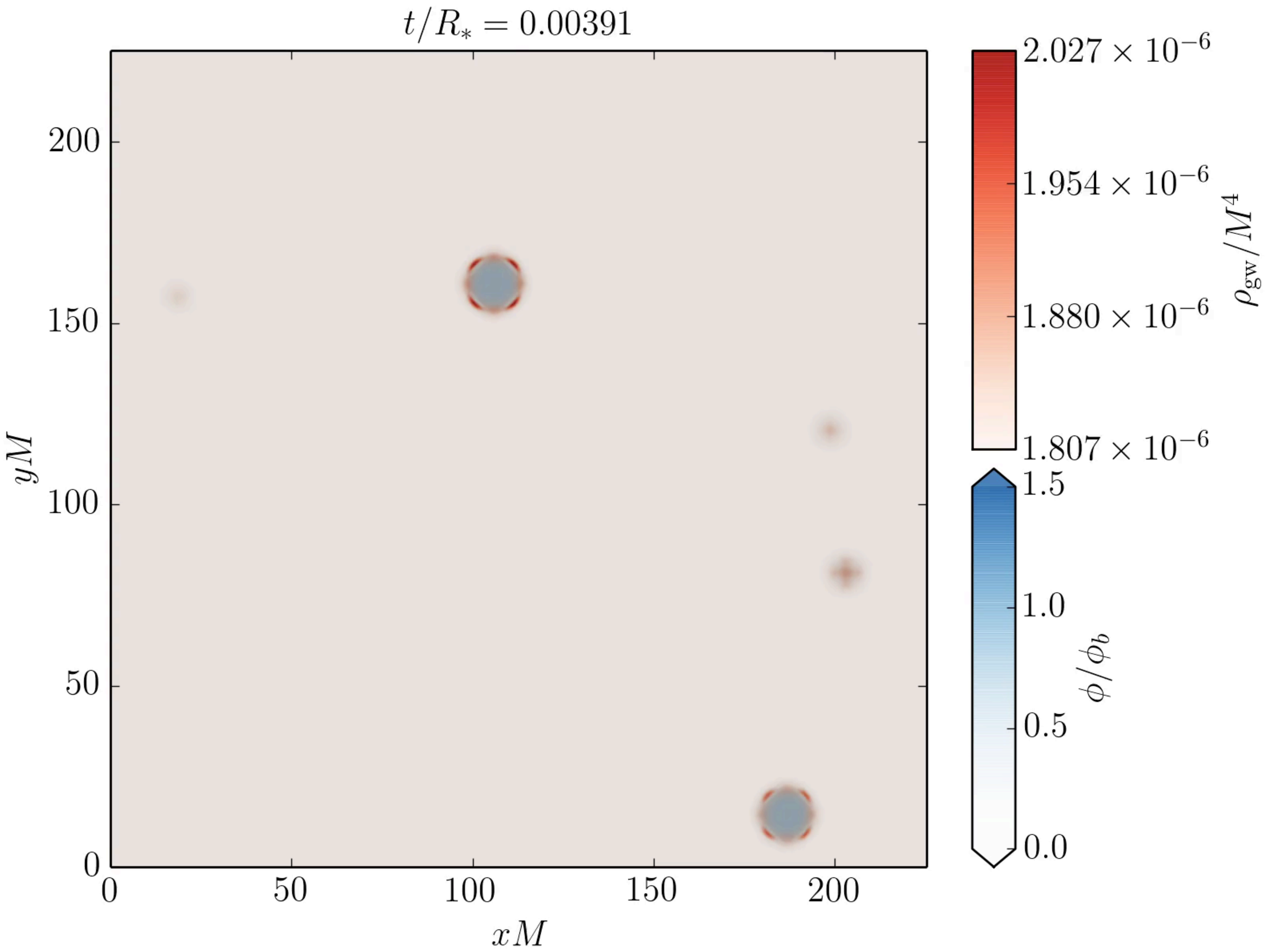
Gravitational Waves from Phase Transitions



Witten 1984, Cutting Hindmarsh Weir 2018

Gravitational Waves from Phase Transitions

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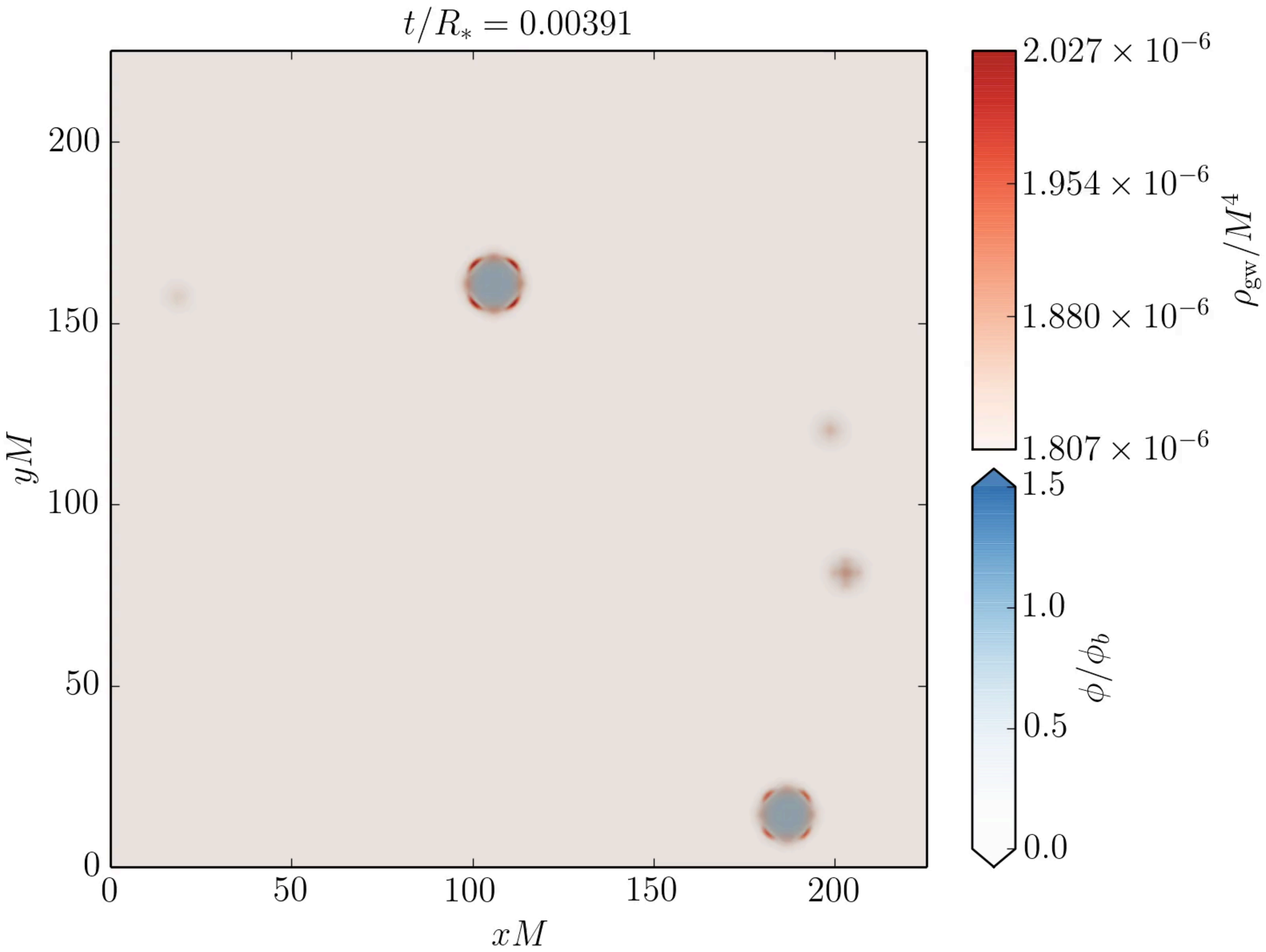


Phase Transitions and Dark Matter

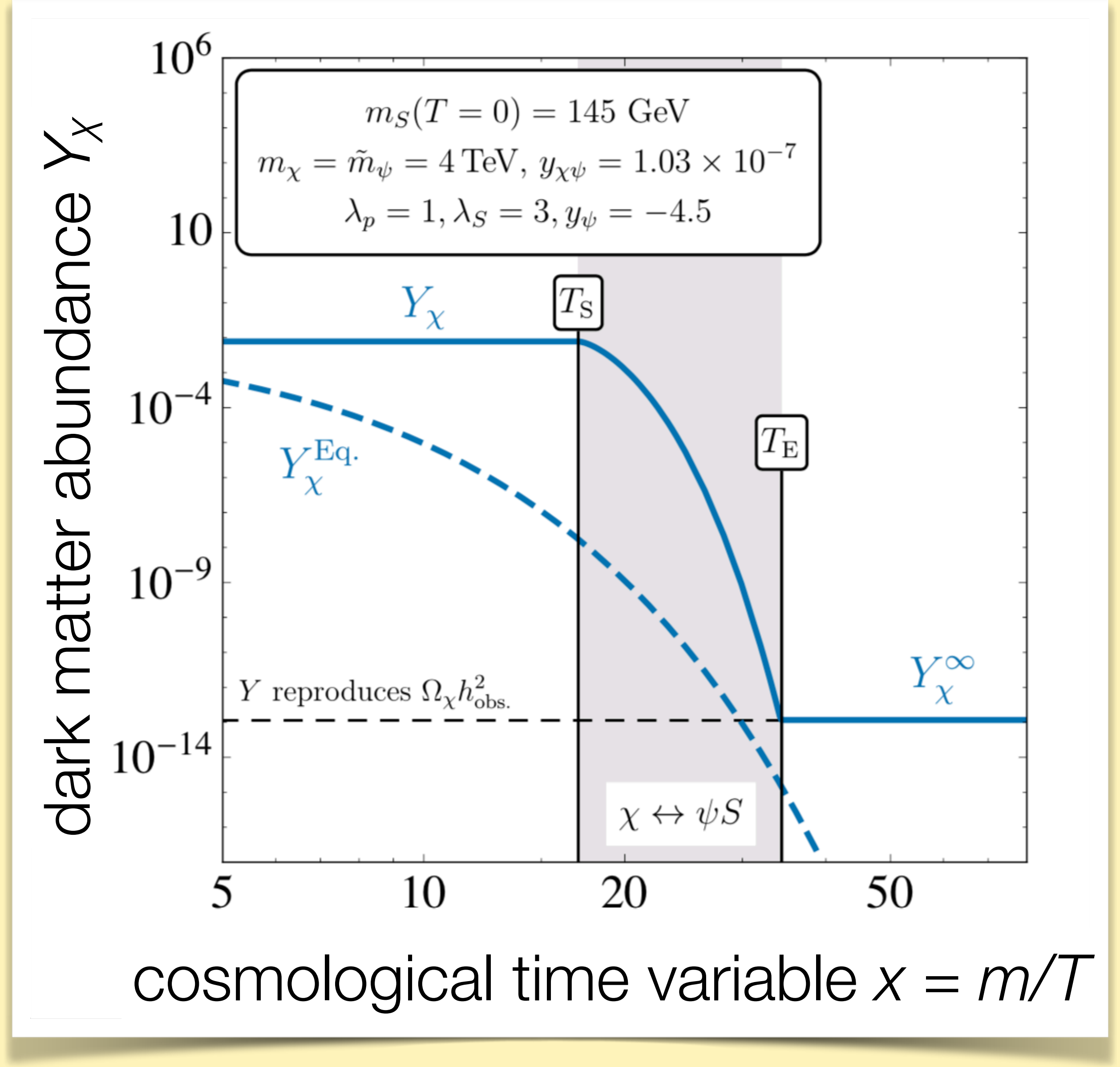
Phase Transitions and Dark Matter

DM Decay Between PTs

Phase Transitions (PTs) can

- break/restore symmetries,
- change particle masses.

DM can be temporarily unstable in the early Universe Baker JK 2016



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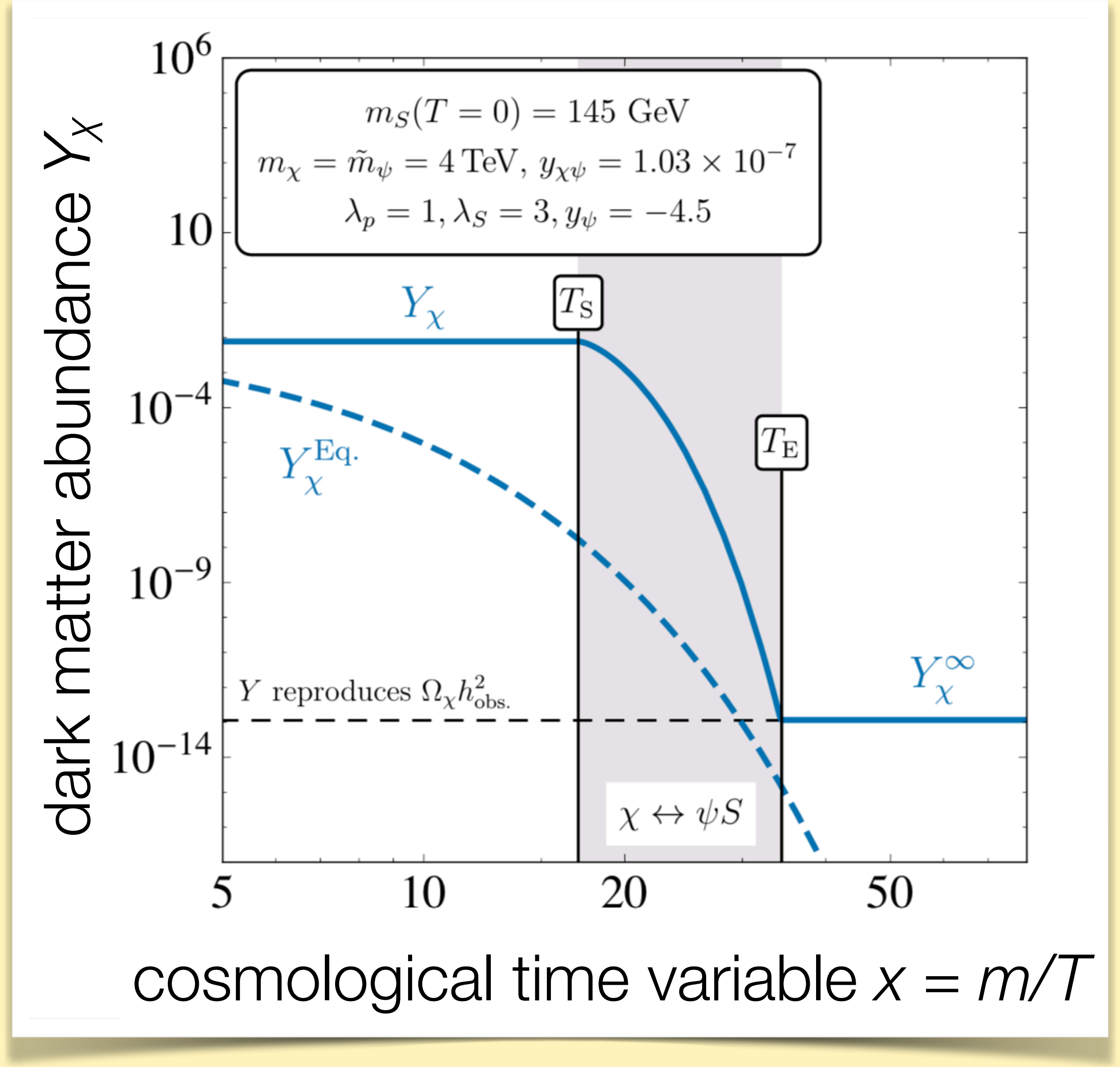

DM Filtering

- PT gives mass to DM particle
- only a fraction of initially massless DM particles can enter the true vacuum
- the rest annihilates

➠ efficient depletion

Baker JK Long 2019

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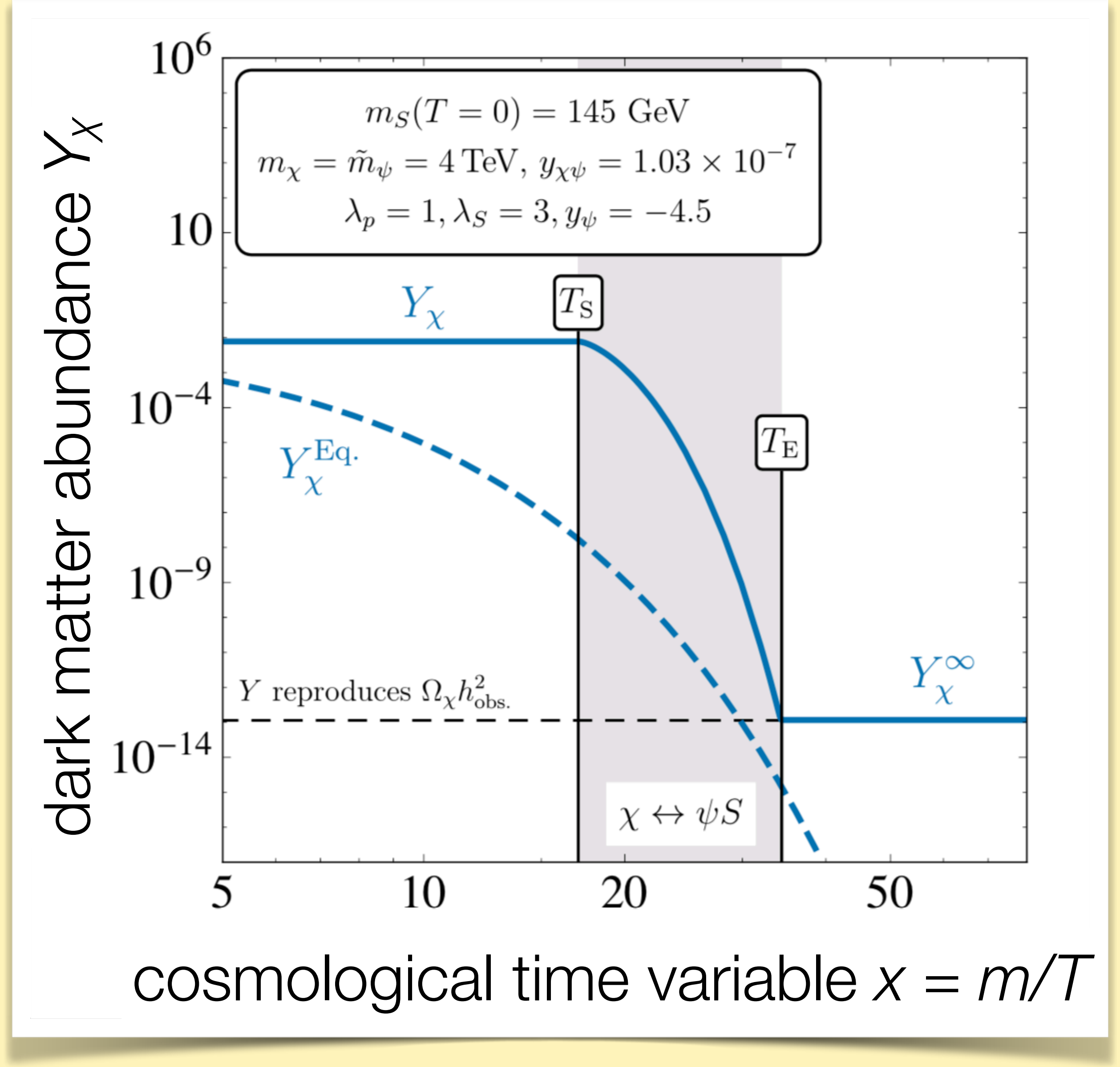

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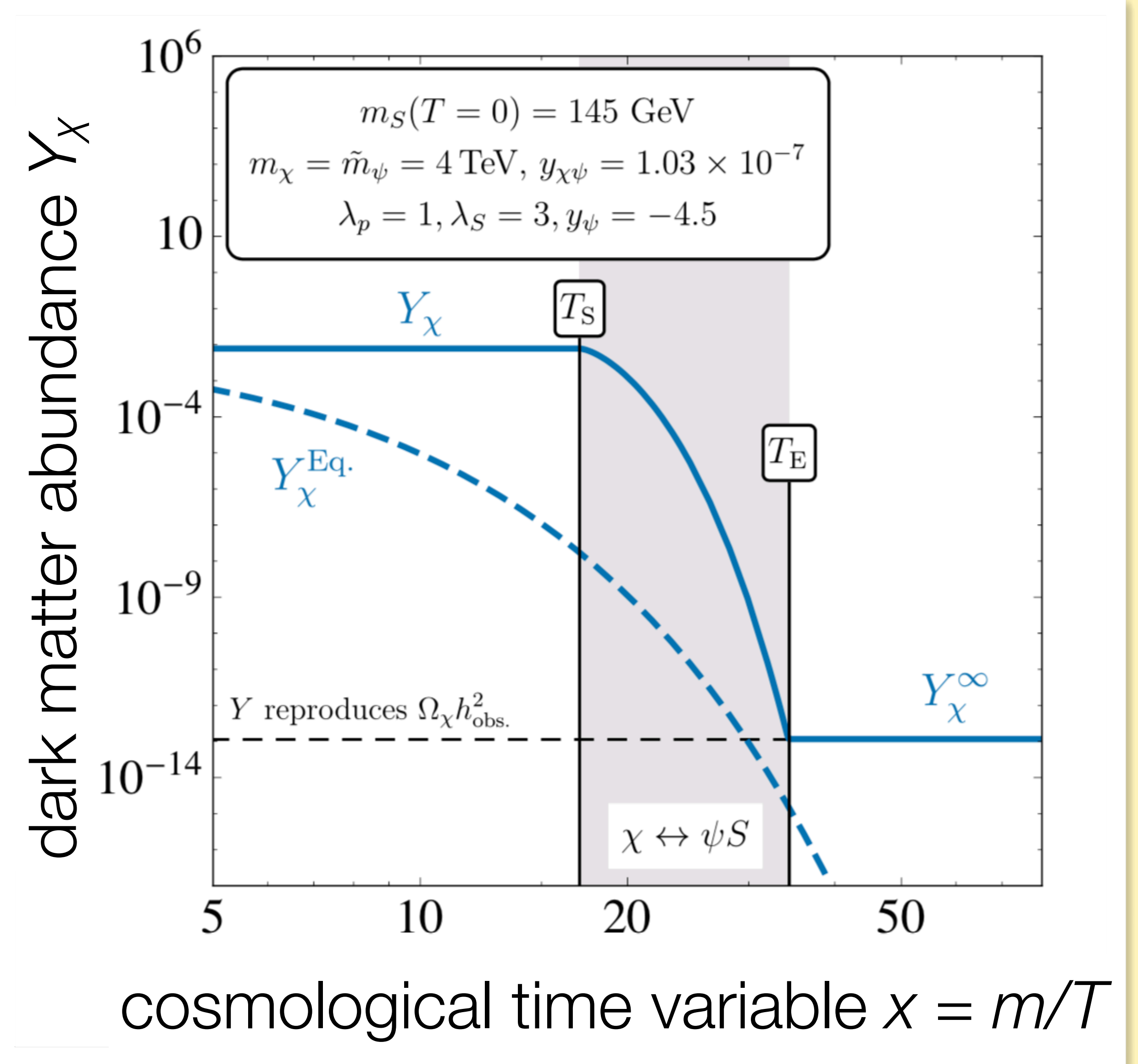

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Primordial Black Holes

- bubble wall collisions

Hawking Moss Stuart 1982, Moss 1994

- collapse of inflating false-vacuum pockets

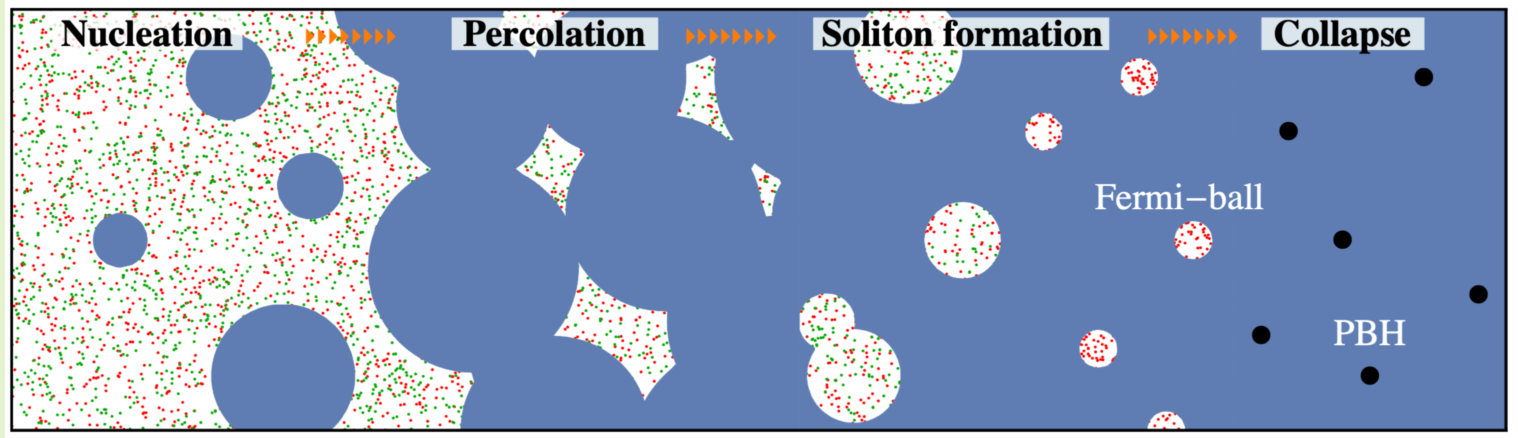
Sato Sasaki Kodama Maeda 1981
Gouttenoire Volansky 2305.04942

- collapse of "Fermi balls"
(particles acquire mass in PT, cannot enter true vacuum, form overdense pockets)

Gross *et al.* 2021, Kawana Xle 2021

- compression / direct collapse

Breitbach *et al.* 2105.07481, 2110.00005



Gravitational Waves from Phase Transitions

- Three contributions
  - bubble collisions
  - collisions of sound waves (generated during bubble collisions)
  - turbulence

Gravitational Waves from Phase Transitions

- Four relevant parameters
  - bubble nucleation temperature T^{nuc}
  - strength of the phase transition

$$\alpha \equiv \frac{\epsilon}{\rho_R} = \frac{1}{\rho_R}\left(- \Delta V + T^{\text{nuc}} \frac{\partial \Delta V}{\partial T}\bigg|_{T^{\text{nuc}}} \right)$$

  - inverse duration of the phase transition

$$\frac{\beta}{H} = T_h^{\text{nuc}} \frac{\mathrm{d}S_E(T)}{\mathrm{d}T}\bigg|_{T_h^{\text{nuc}}}$$

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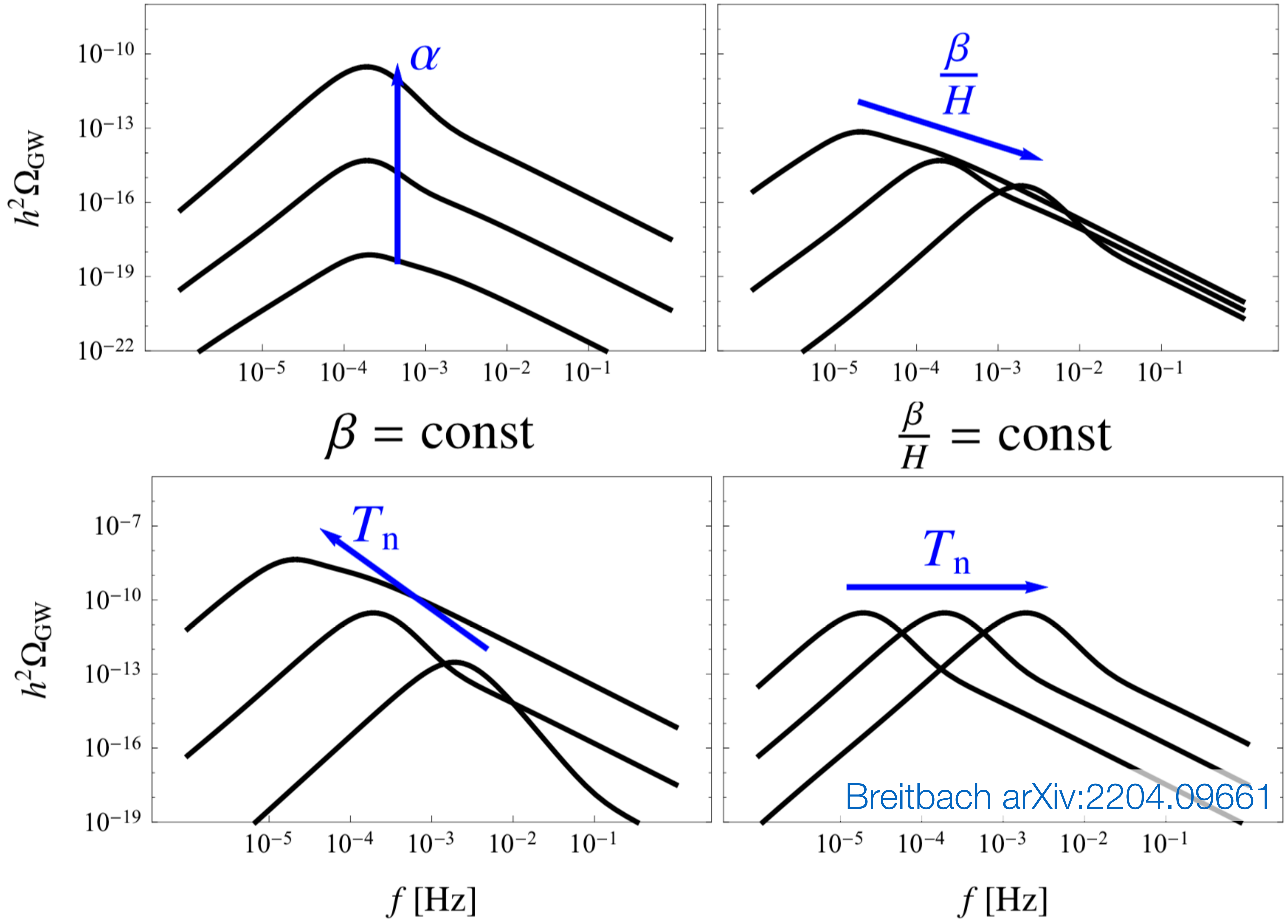
Euclidean action
corresponding to the
transition path in field space

  - bubble wall velocity v_w

Gravitational Waves from Phase Transitions



DM Filtering at Bubble Walls

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- Assume DM (χ) acquires mass during a phase transition

$$\mathcal{L} \supset -y_{\rm DM}\, \phi \bar{\chi} \chi$$

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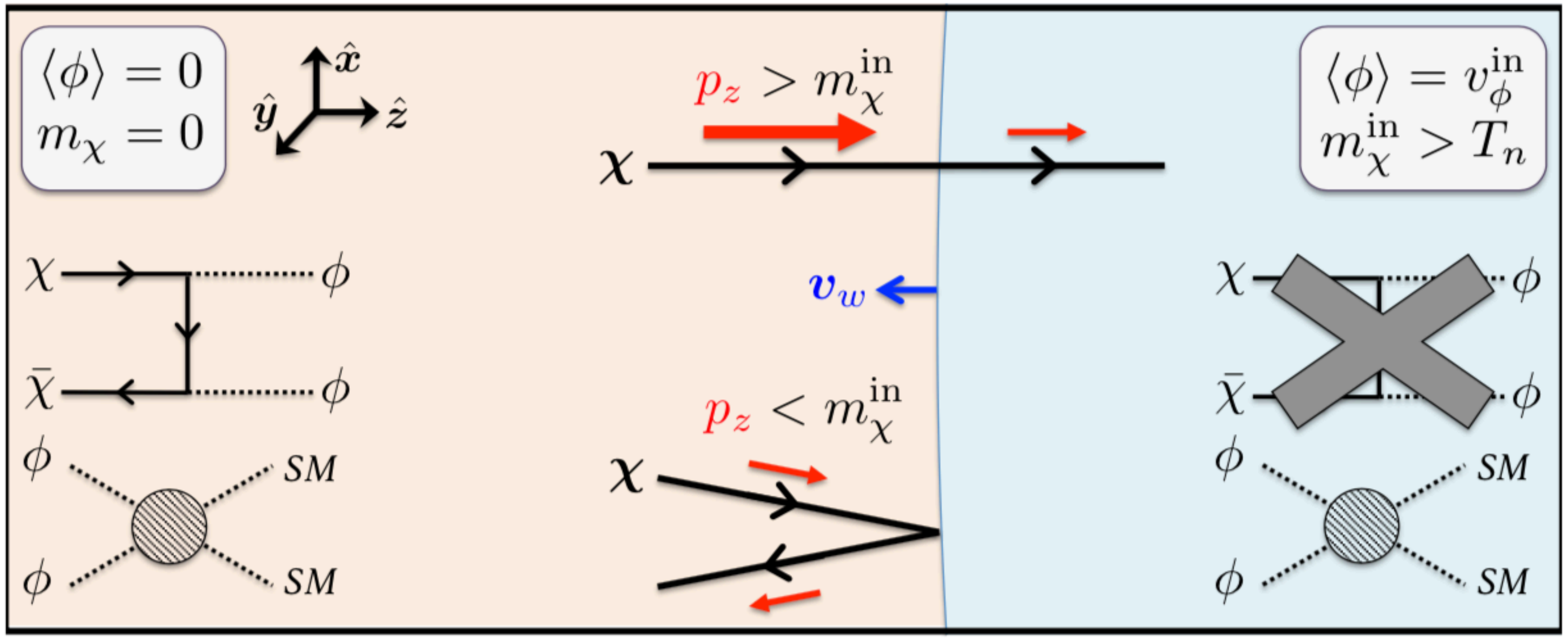

Baker JK Long, arXiv:1912.02830

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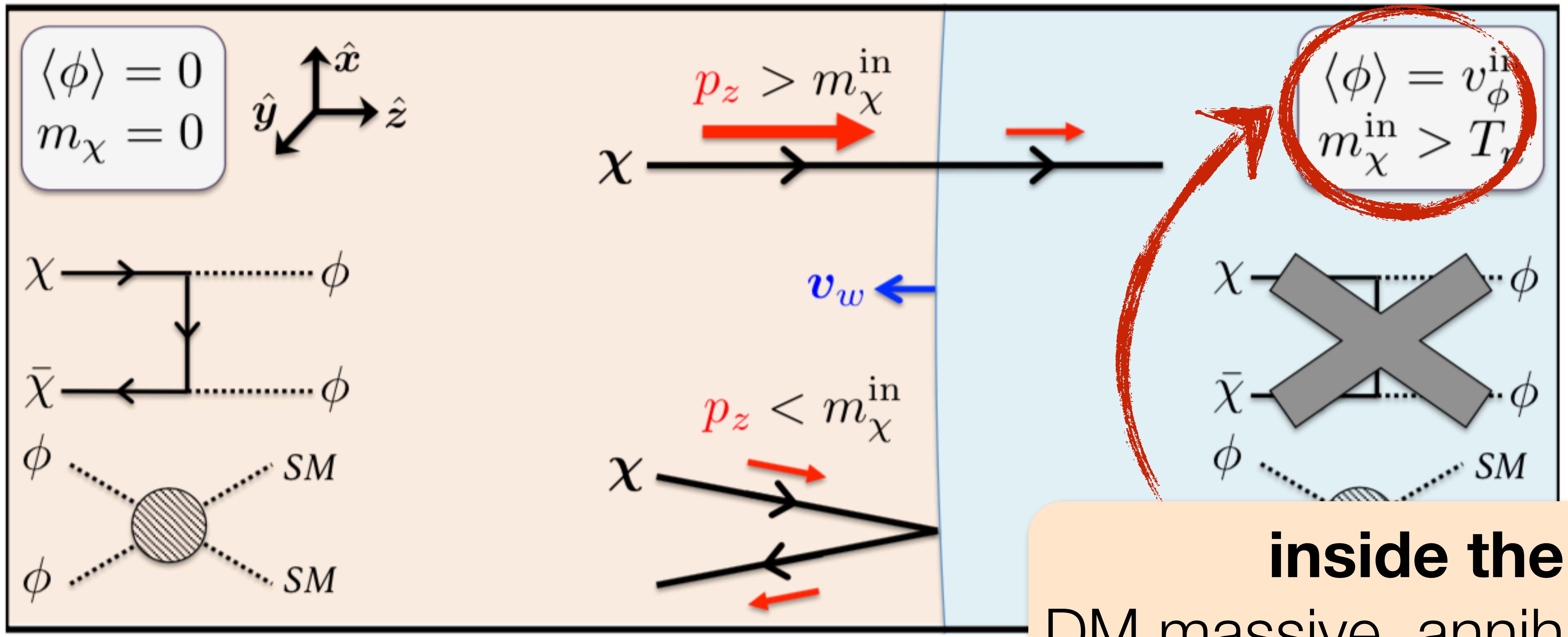

inside the bubble
DM massive, annihilation frozen out

Baker J

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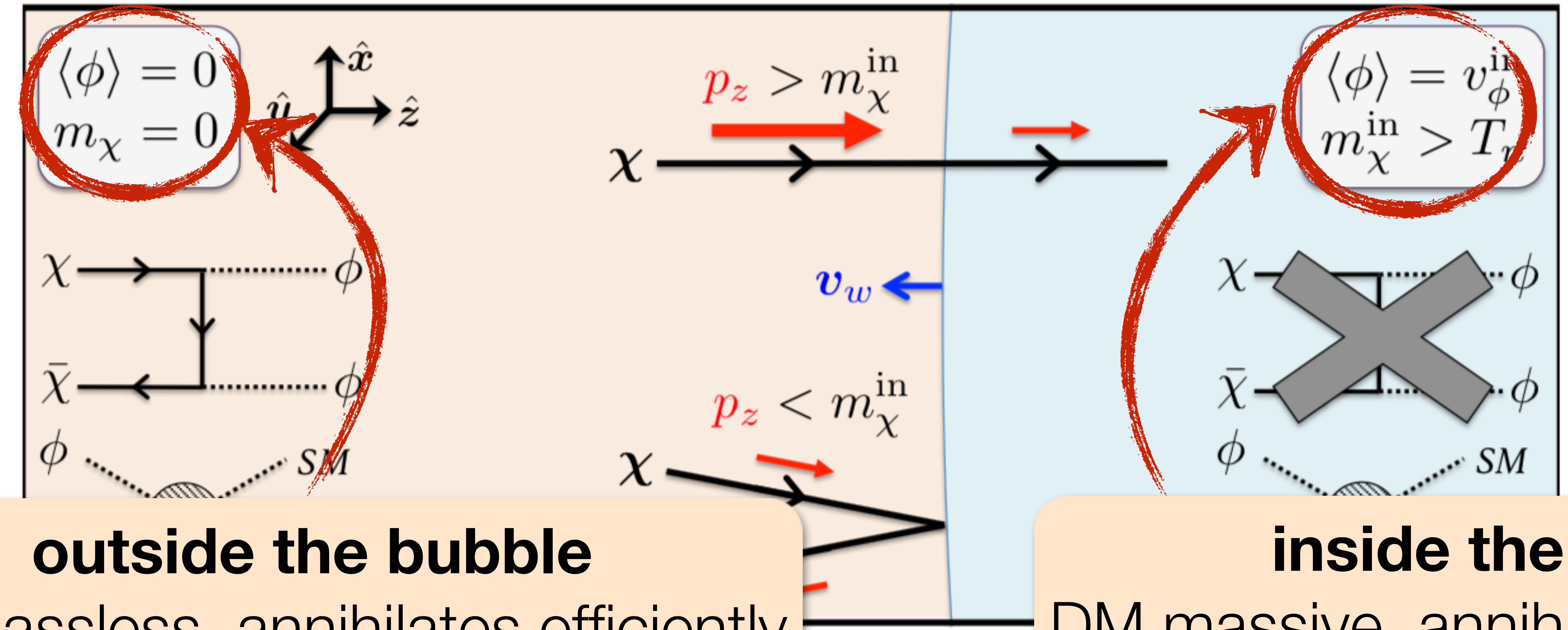

outside the bubble
DM massless, annihilates efficiently

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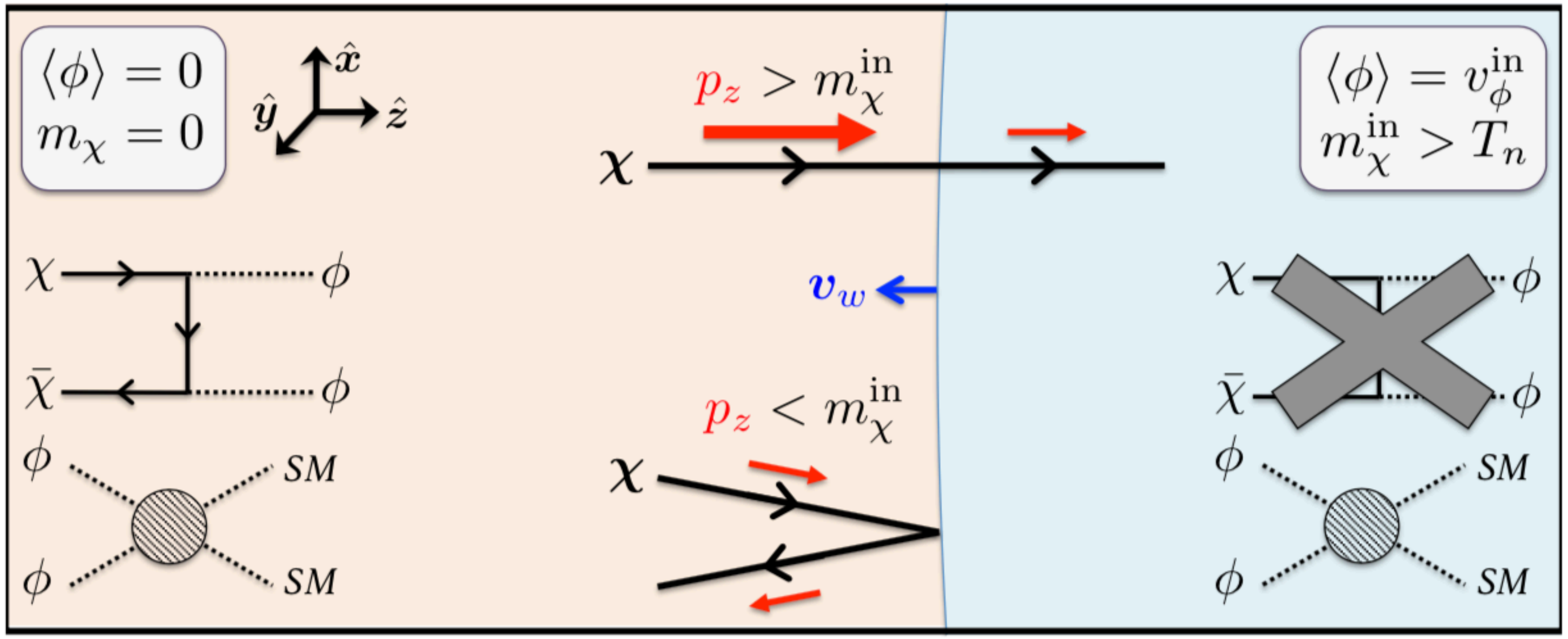

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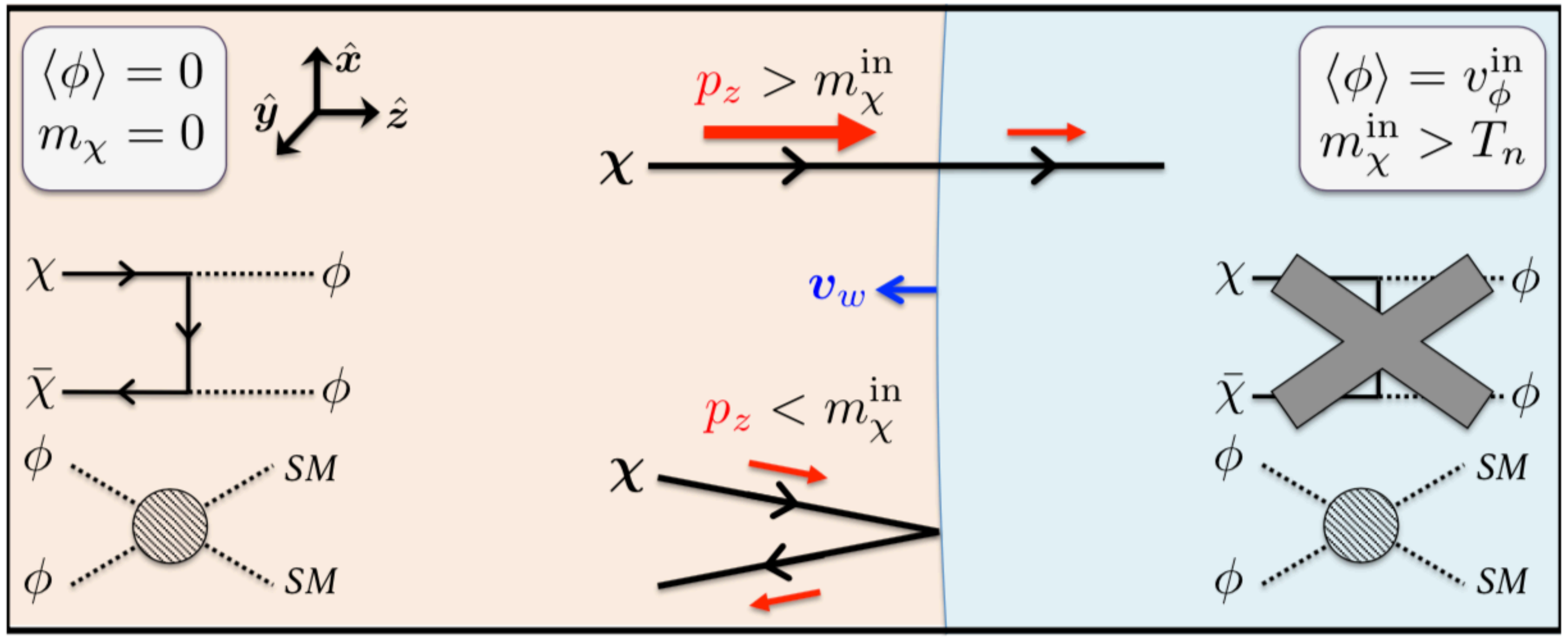

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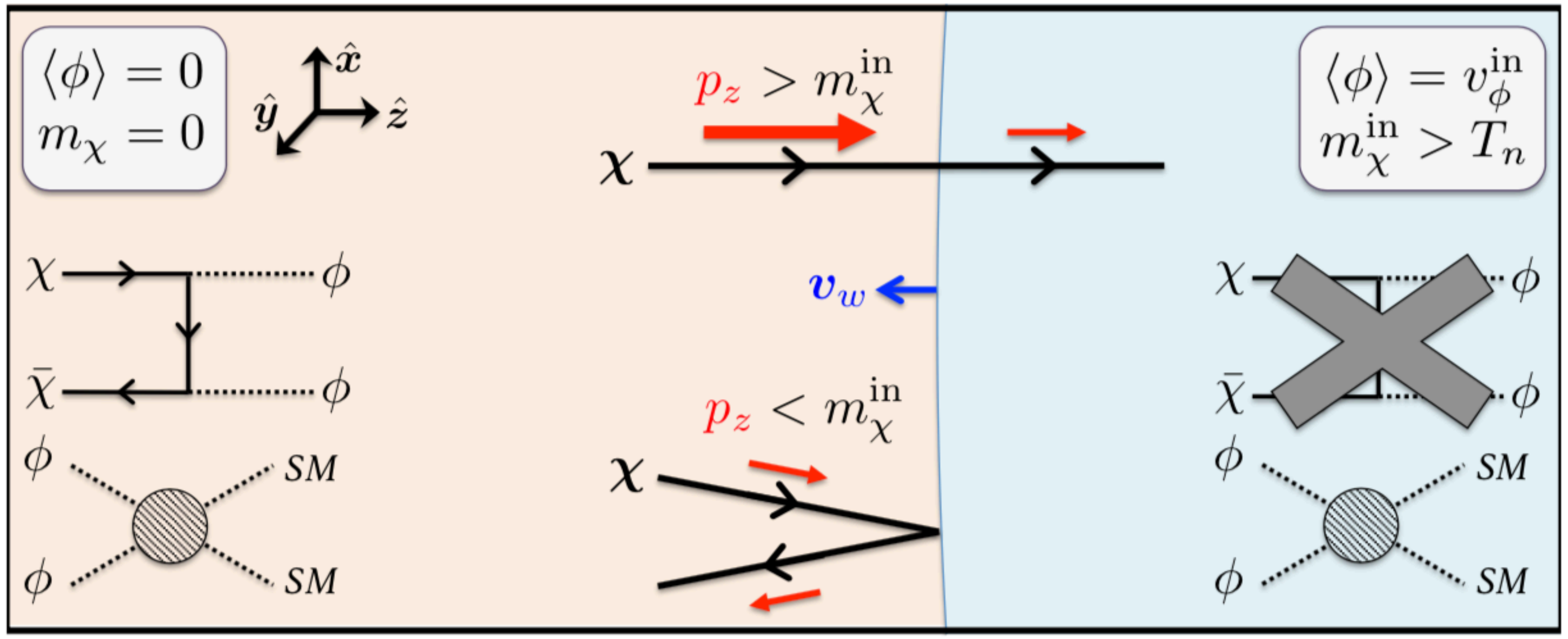

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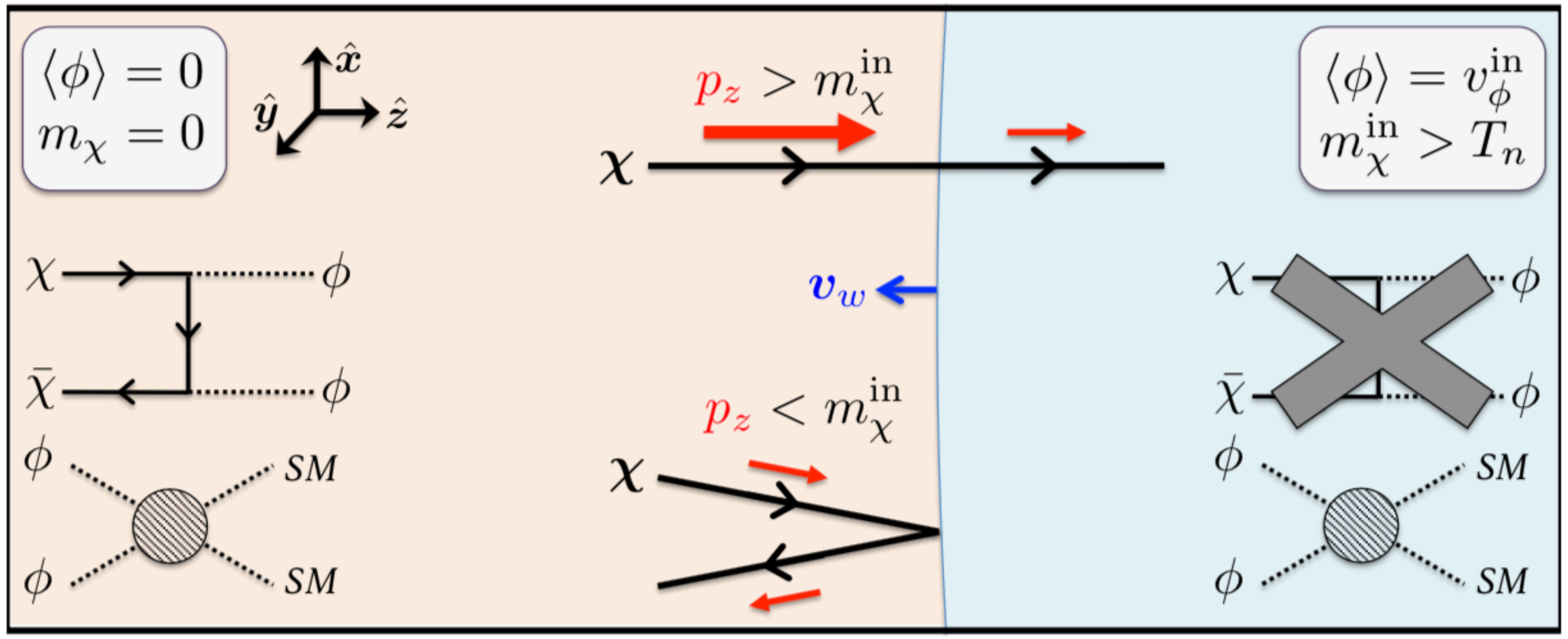

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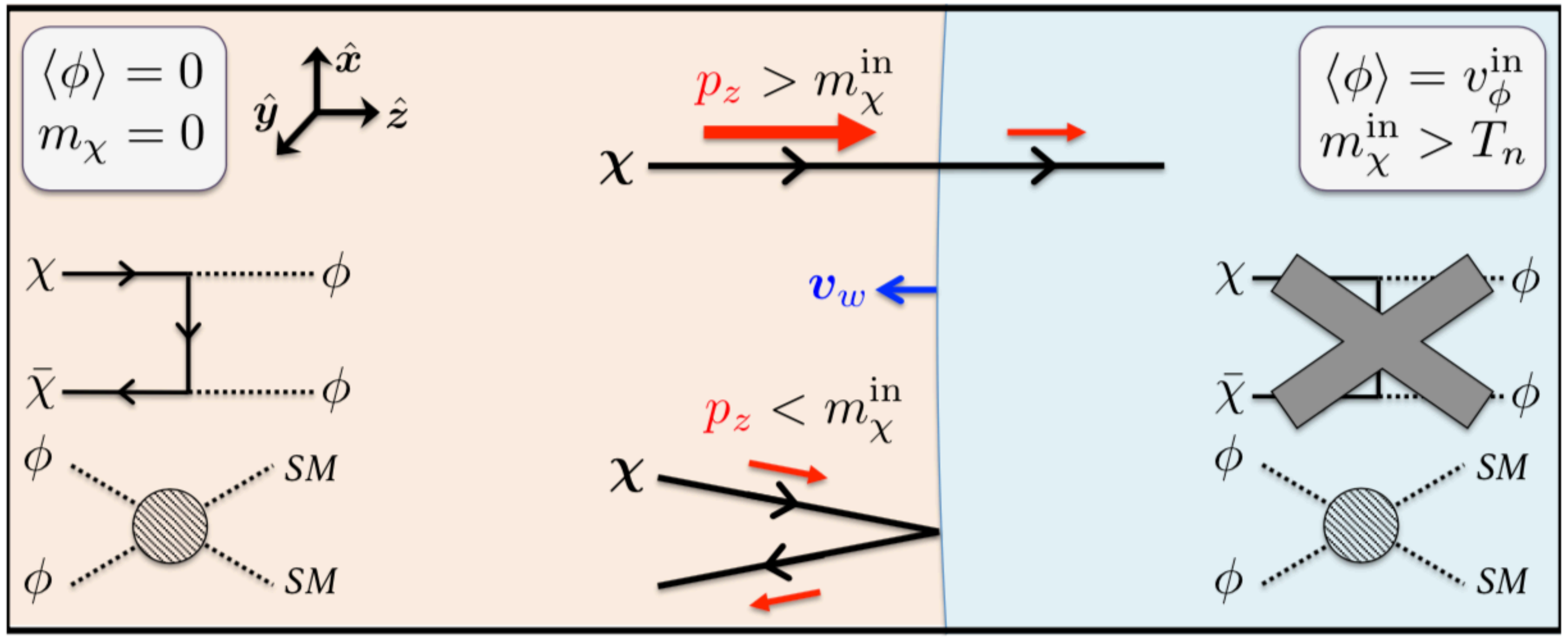

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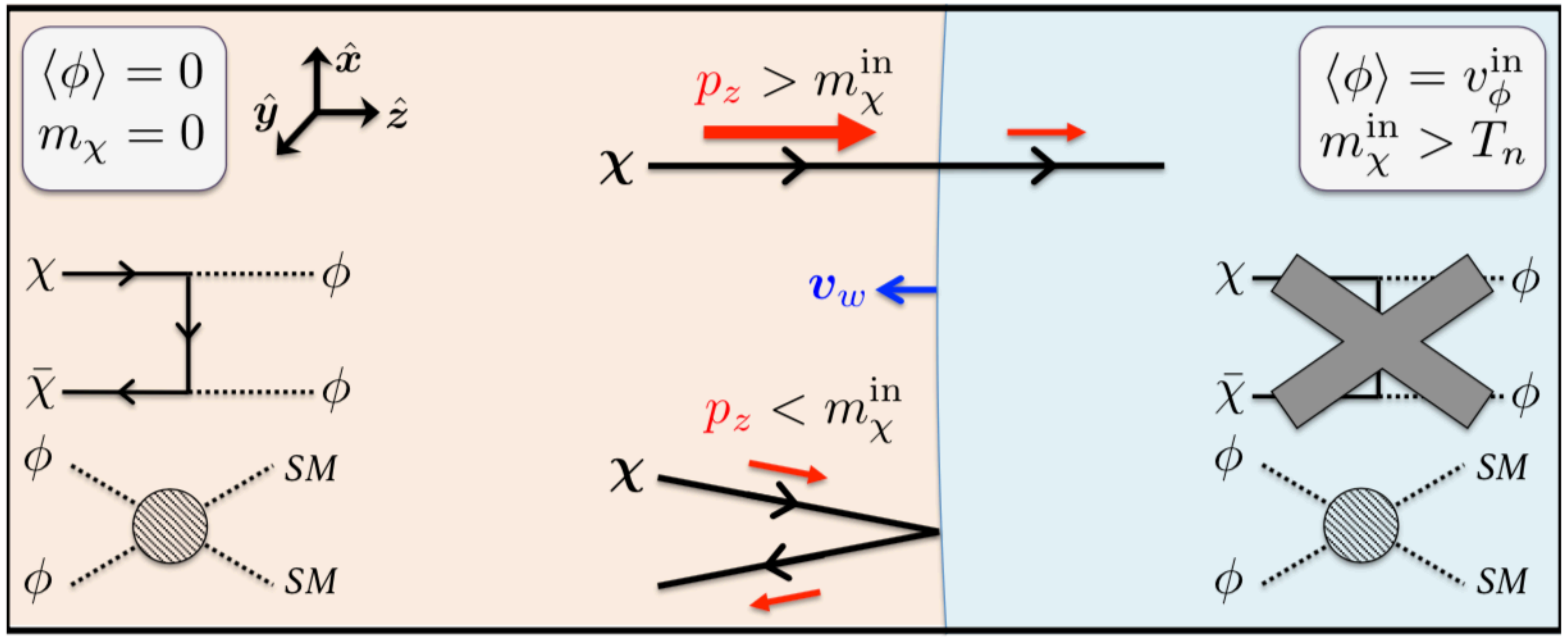

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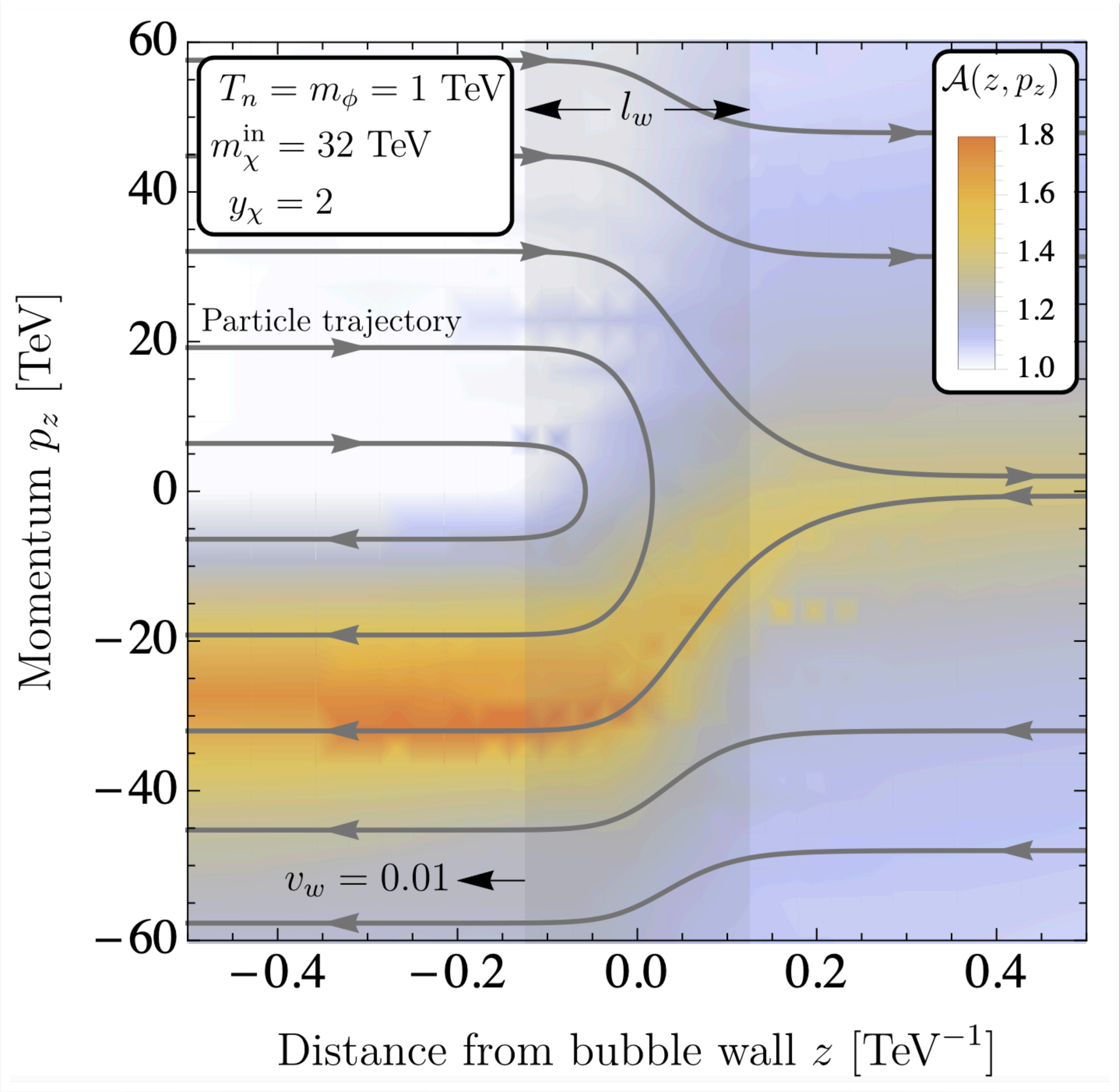
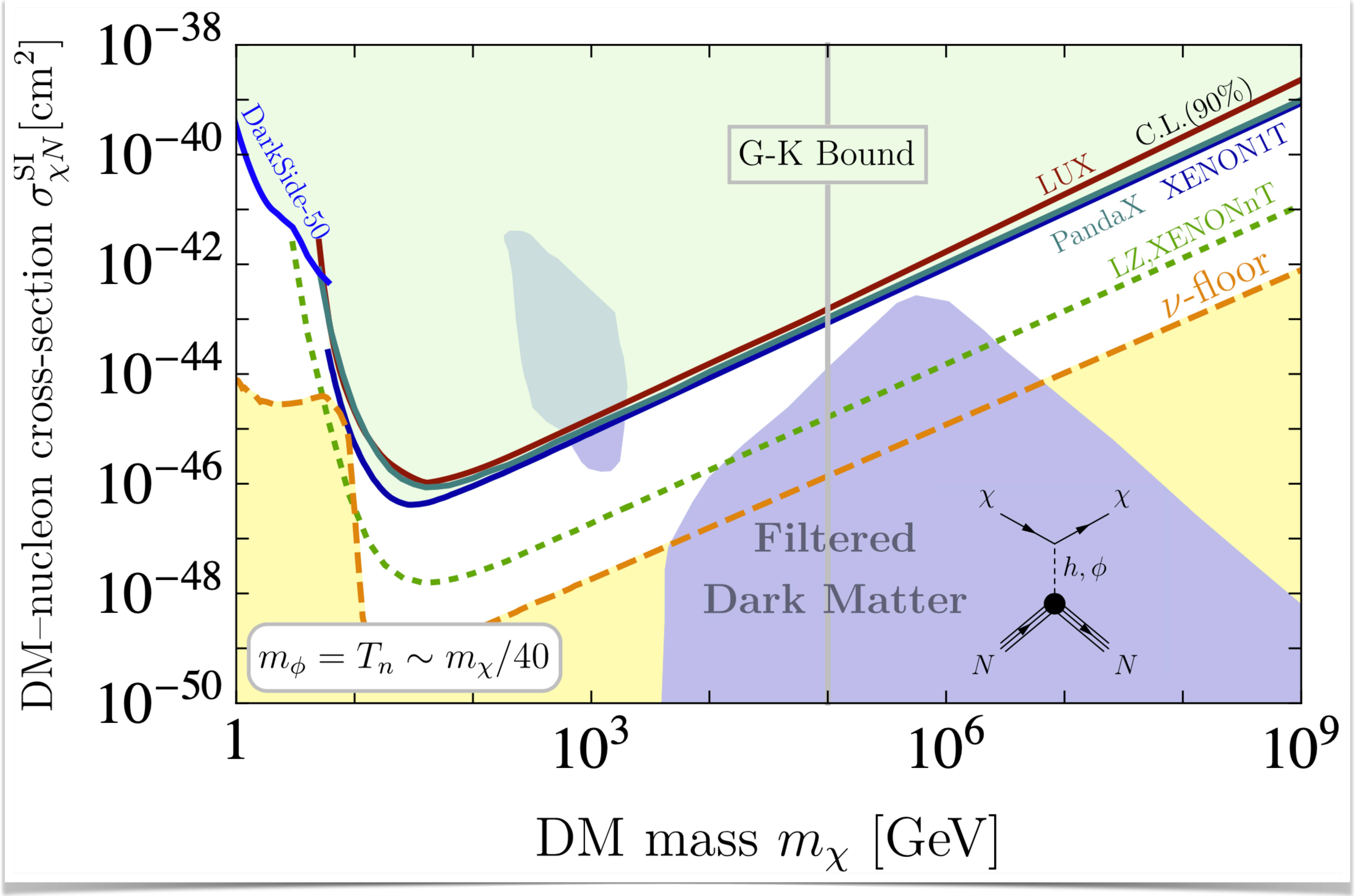
- quantitative description: Boltzmann transport equations
- **DM density set by phase transition dynamics**

Dark Matter at Bubble Walls



DM Filtering at Bubble Walls



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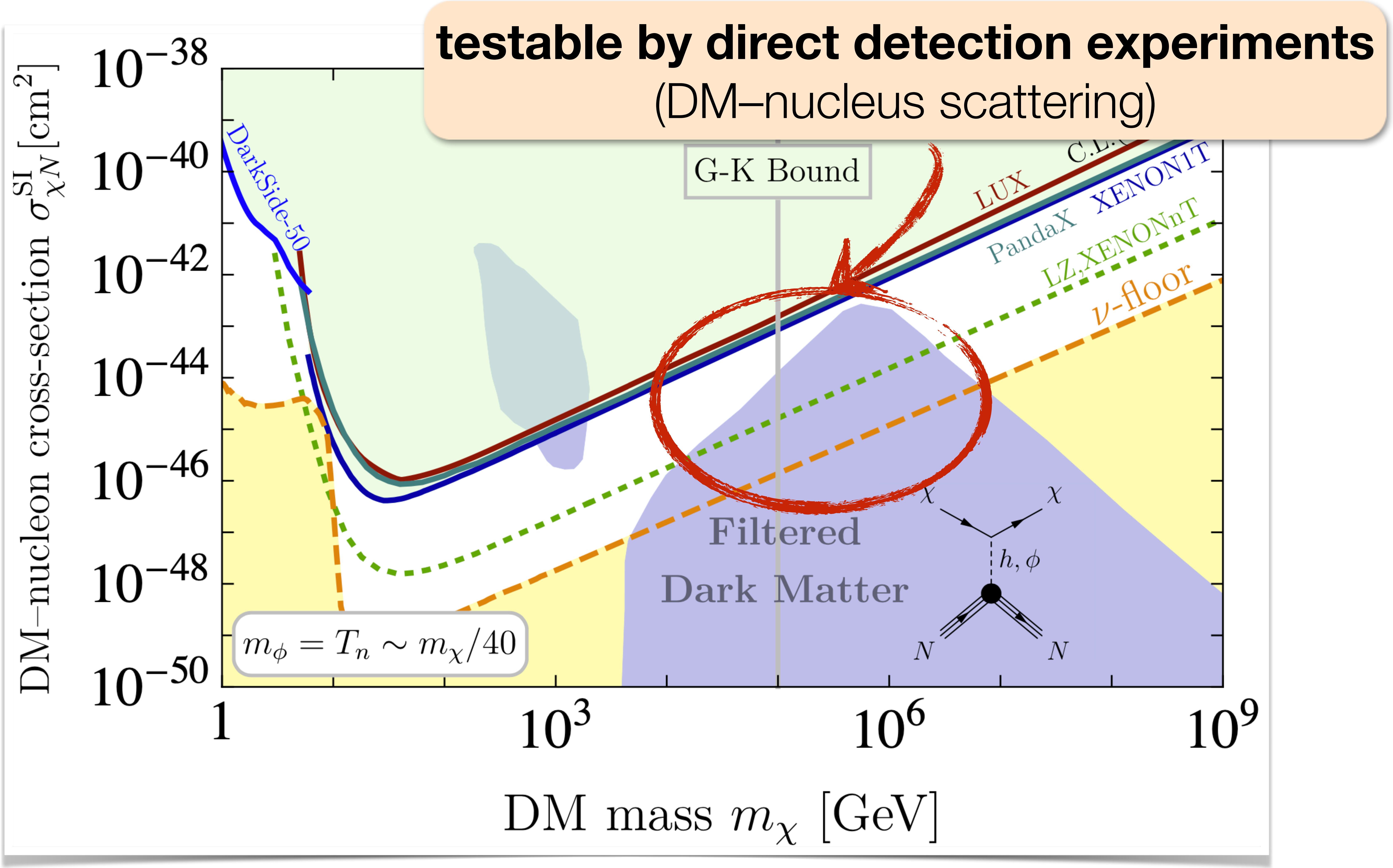

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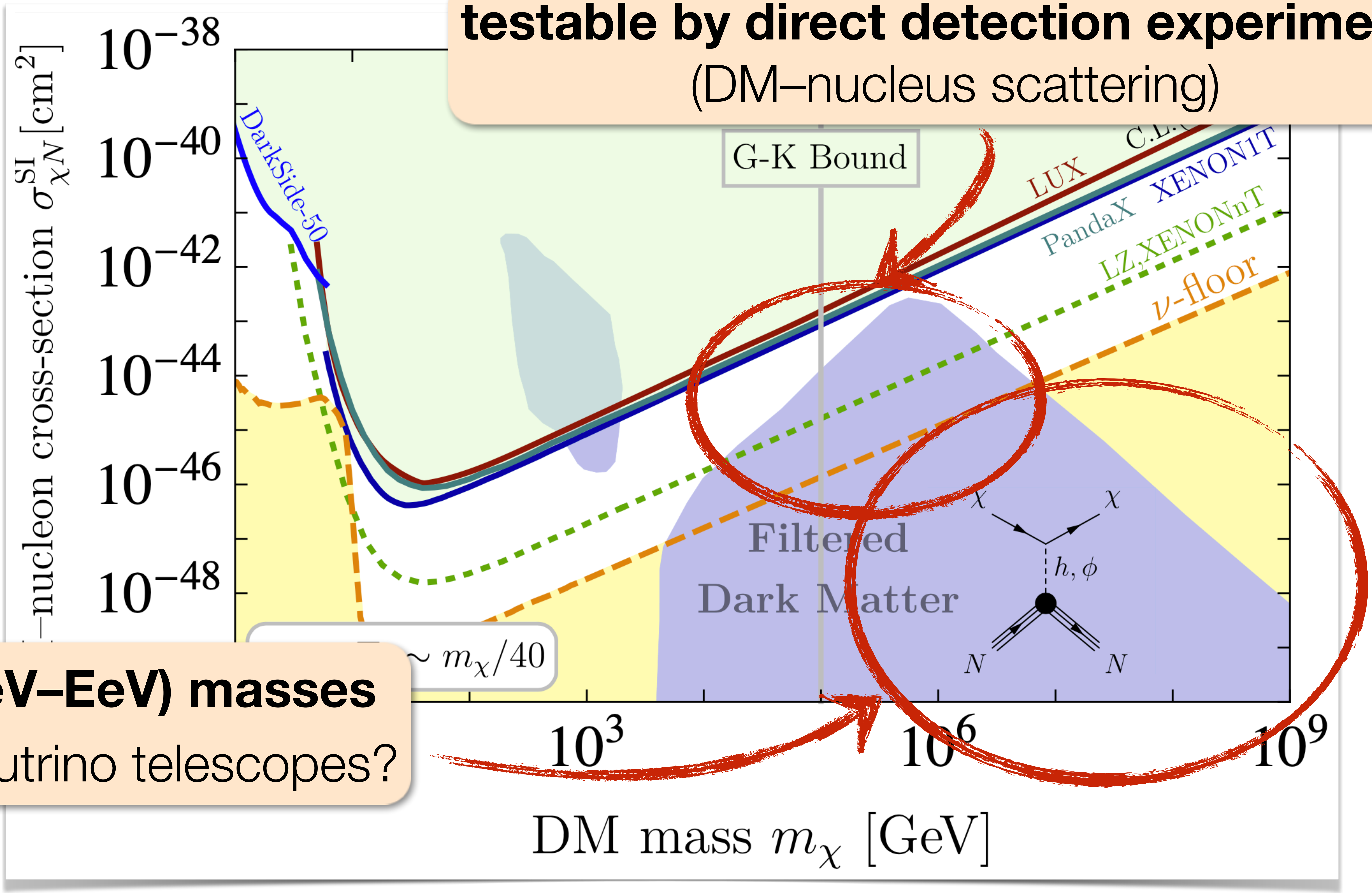


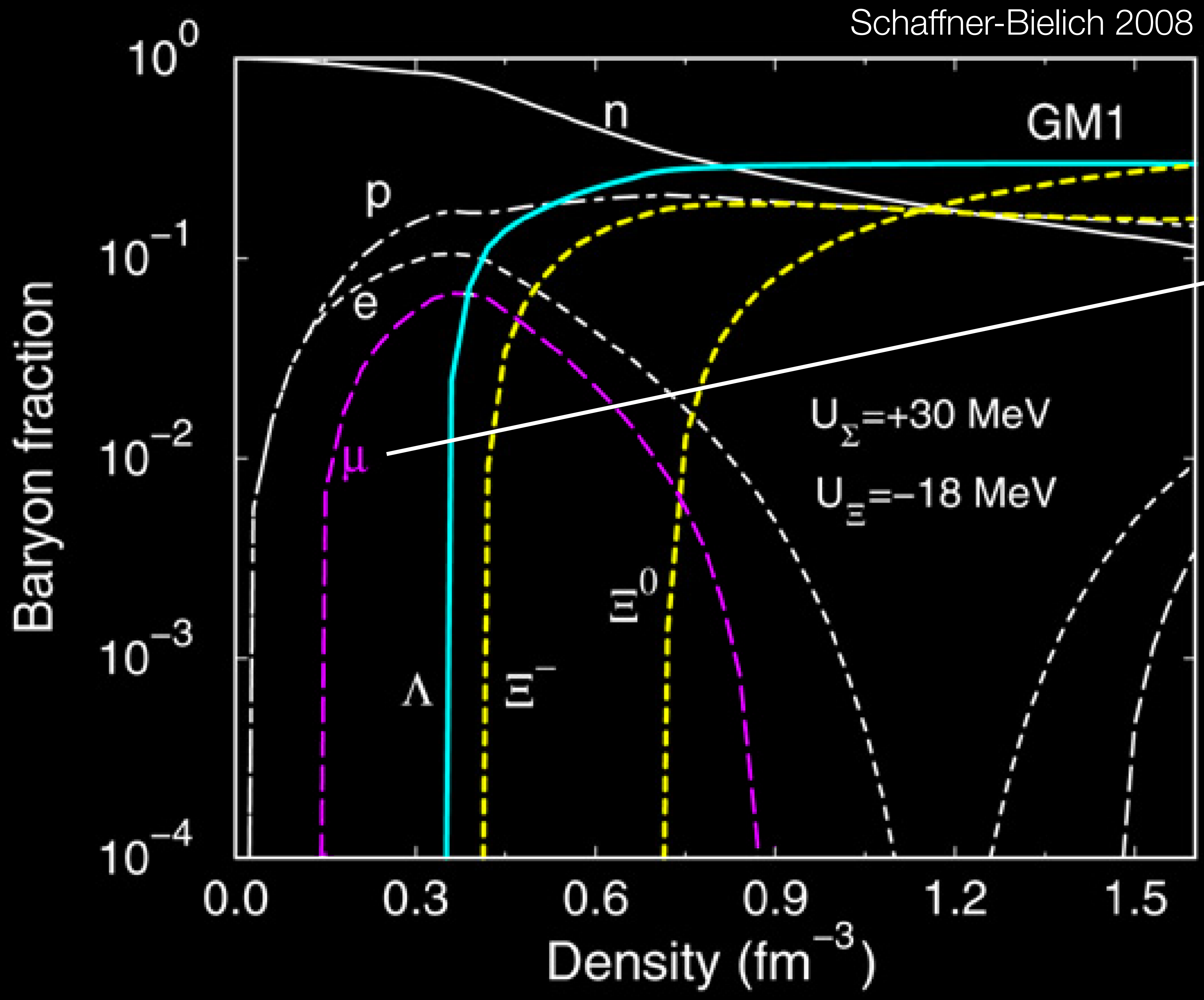
testable by direct detection experiments
(DM–nucleus scattering)

works for $\mathcal{O}$(PeV–EeV) masses
➠ searches in neutrino telescopes?

Baker JK Long, arXiv:1912.02830

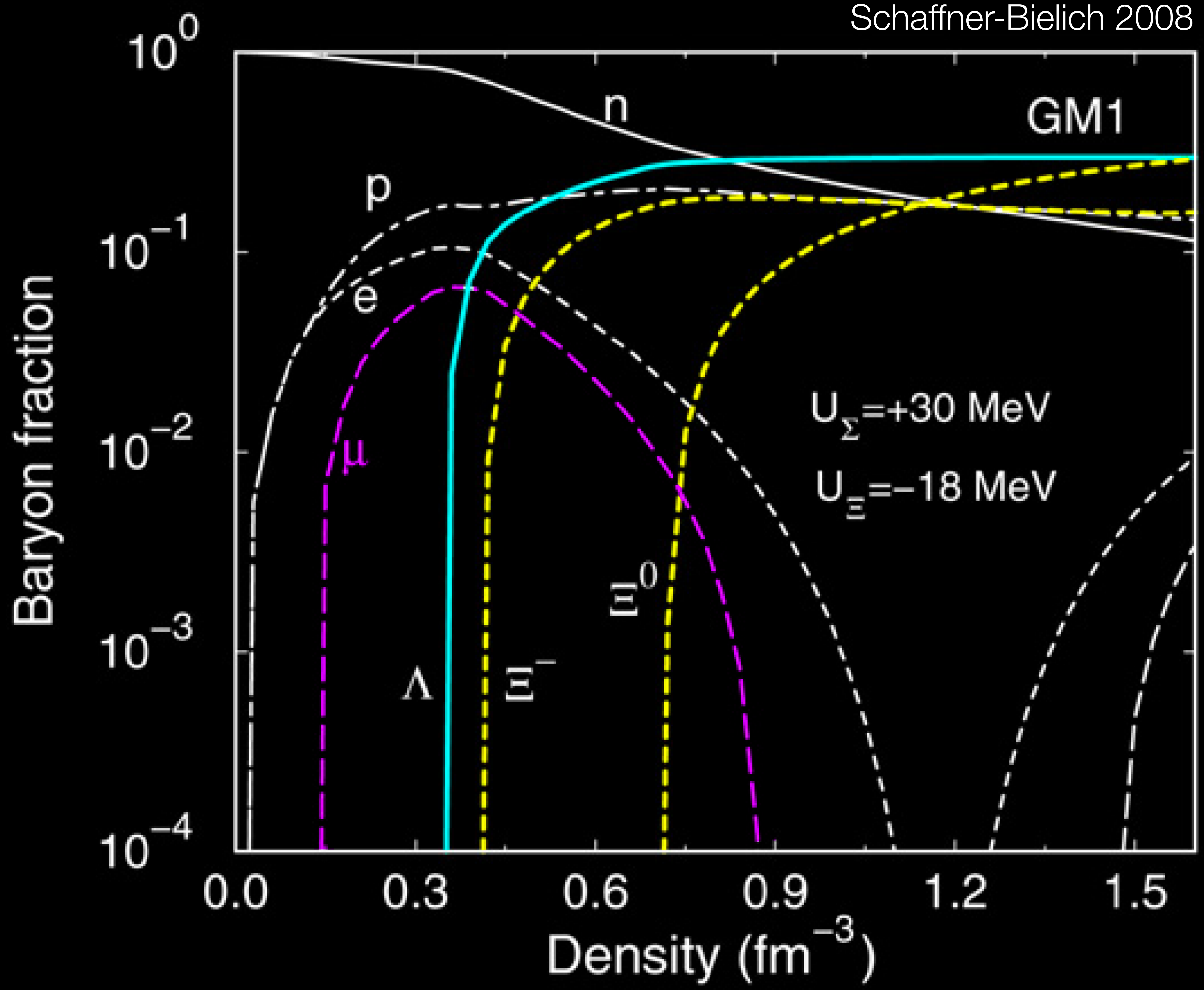
Neutrinos from Neutron Stars

Muons in Neutron Stars



neutron stars harbor abundant quantities of muons

Muons in Neutron Stars

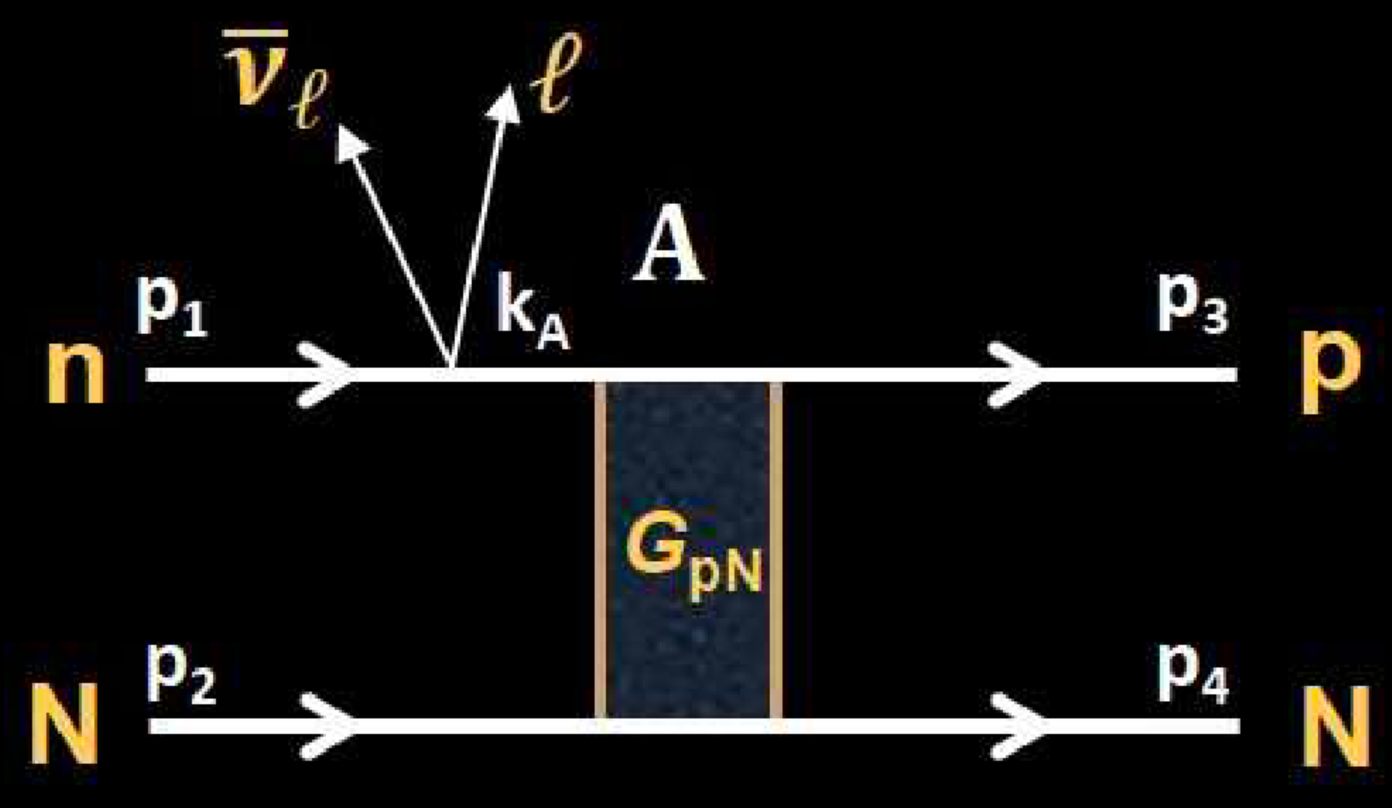


- in the core: μ decay Pauli-blocked
- drop in core density may reduce equilibrium μ abundance
- at $t \gtrsim 10^4$ yrs, Urca interactions too slow to maintain equilibrium
- muons diffuse outward and decay ➠ neutrinos!
- observable signal requires $\mathcal{O}(0.001)$ change in μ abundance

major caveat

- equilibrium μ abundance typically *increases* over time

Neutrinos from Neutron Stars



thermal flux

- from “Urca” processes
- low energy
- undetectable after ~10 sec

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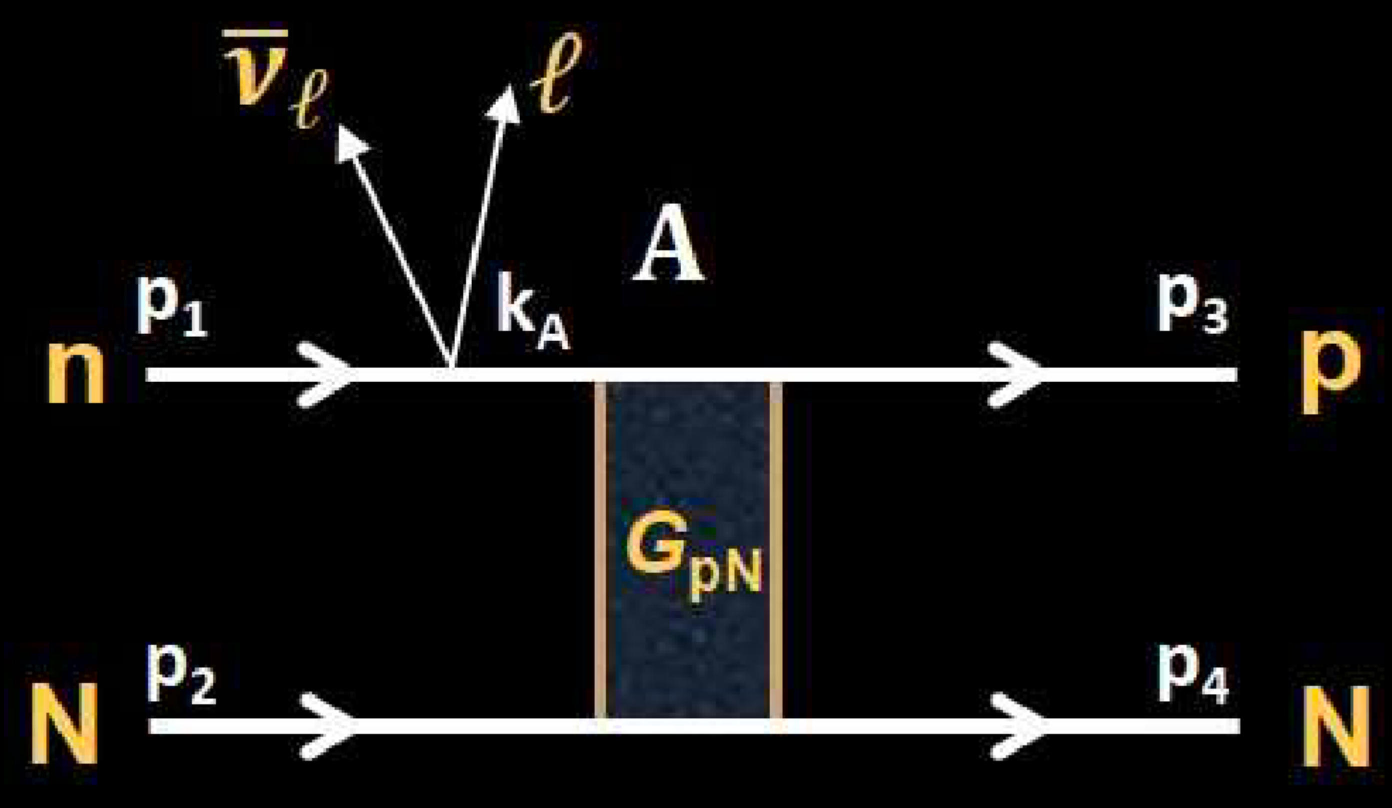

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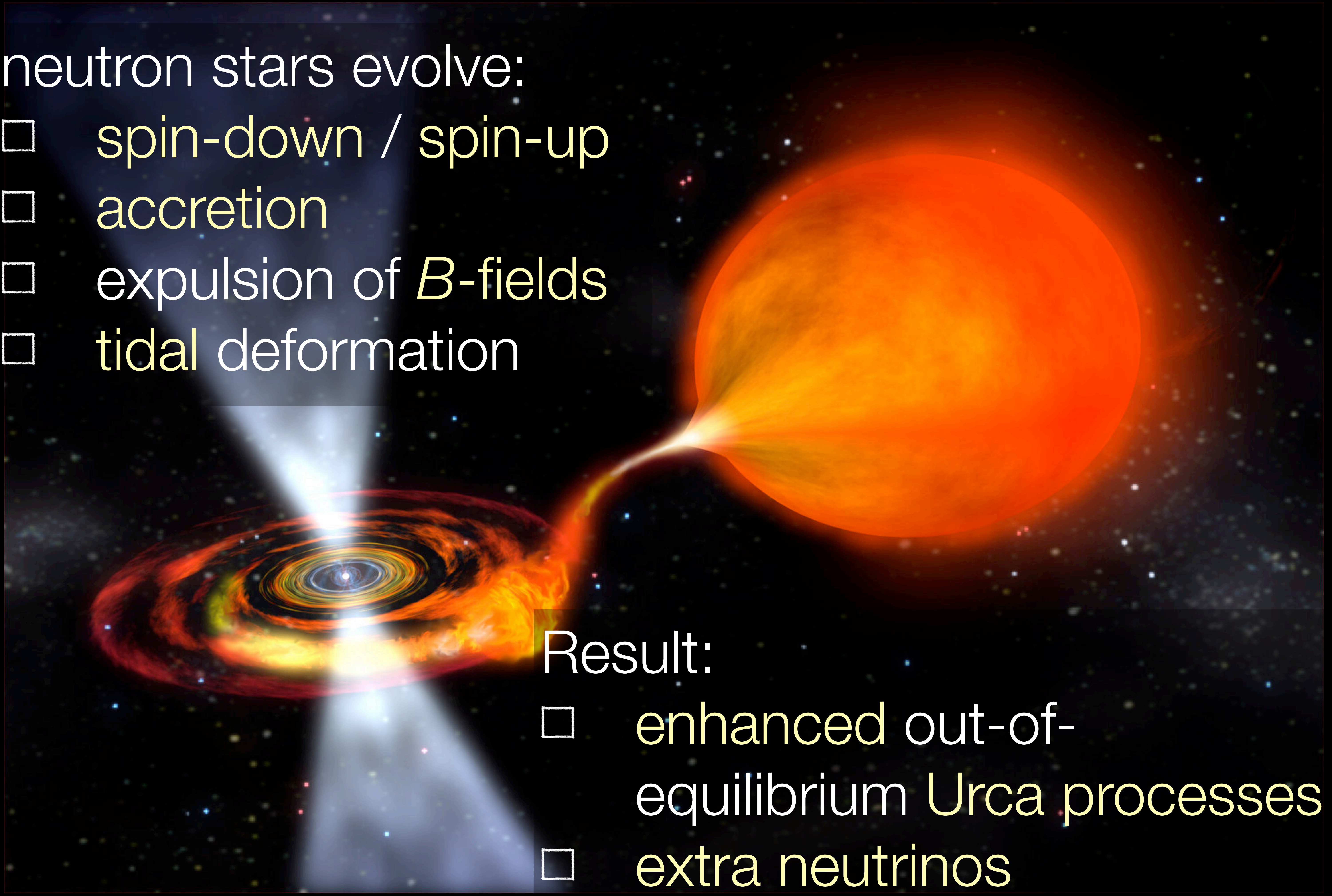


neutron stars evolve:

- spin-down / spin-up
- accretion
- expulsion of B-fields
- tidal deformation

Result:

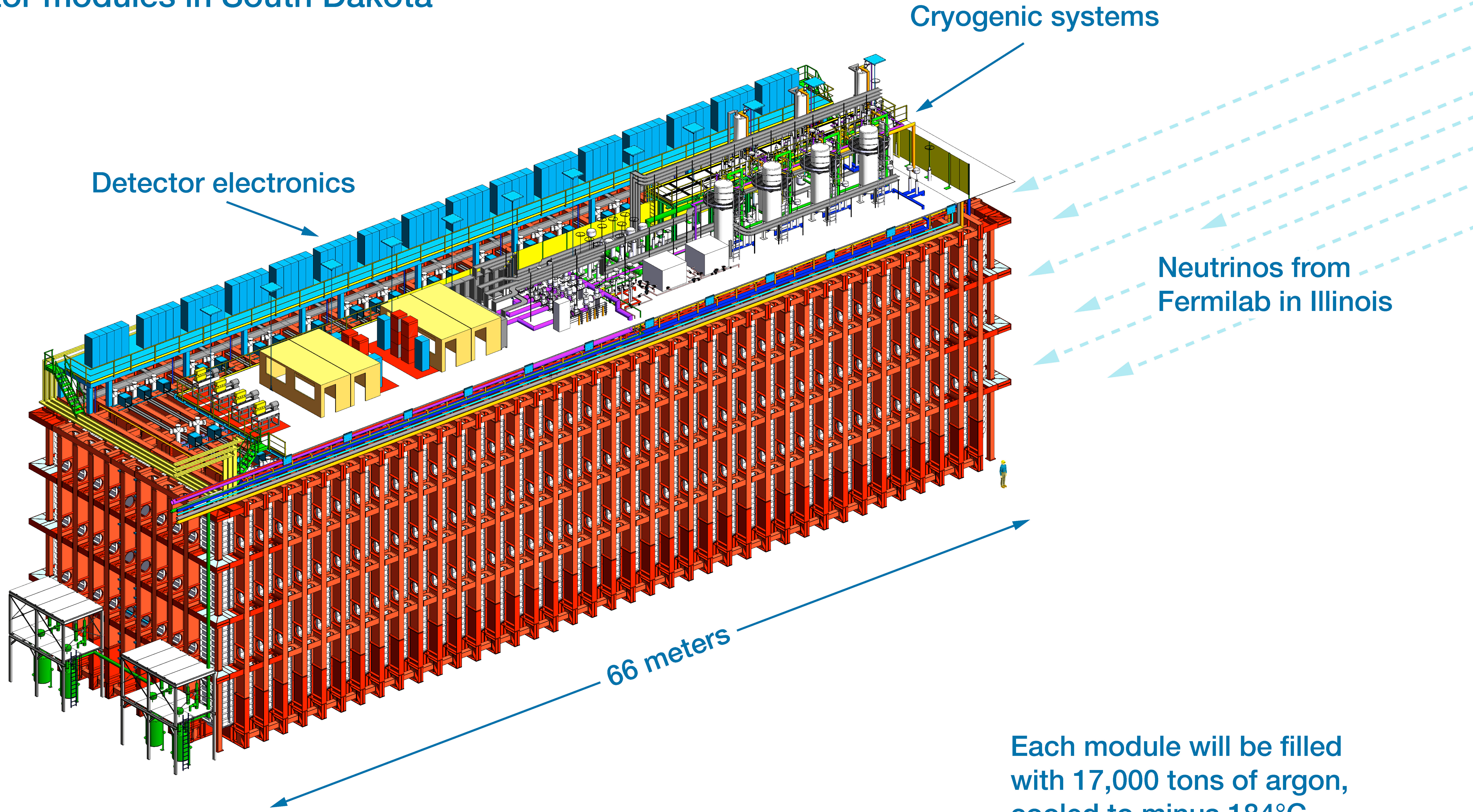
- enhanced out-of-equilibrium Urca processes
- extra neutrinos

JK Opferkuch arXiv:2312.08457

DUNE

Deep Underground Neutrino Experiment

One of four detector modules in South Dakota



Detector located
1.5 kilometers
underground at
Sanford Lab

Each module will be filled
with 17,000 tons of argon,
cooled to minus 184°C

Neutrino Detection in Liquid Argon TPCs