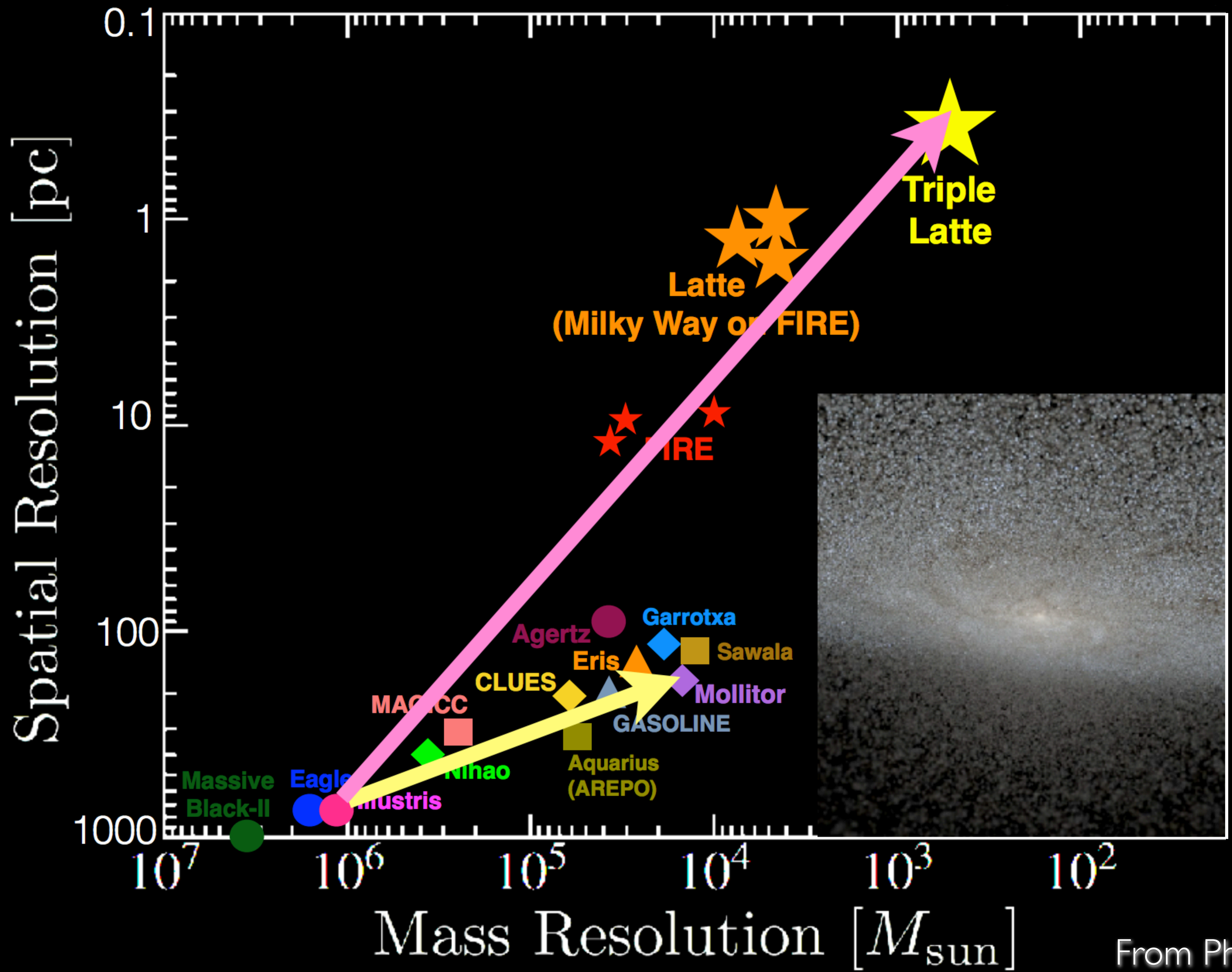
Searching for Light and Ultralight Dark Matter
The SENSEI and NASDUCK Experiments

May 2022

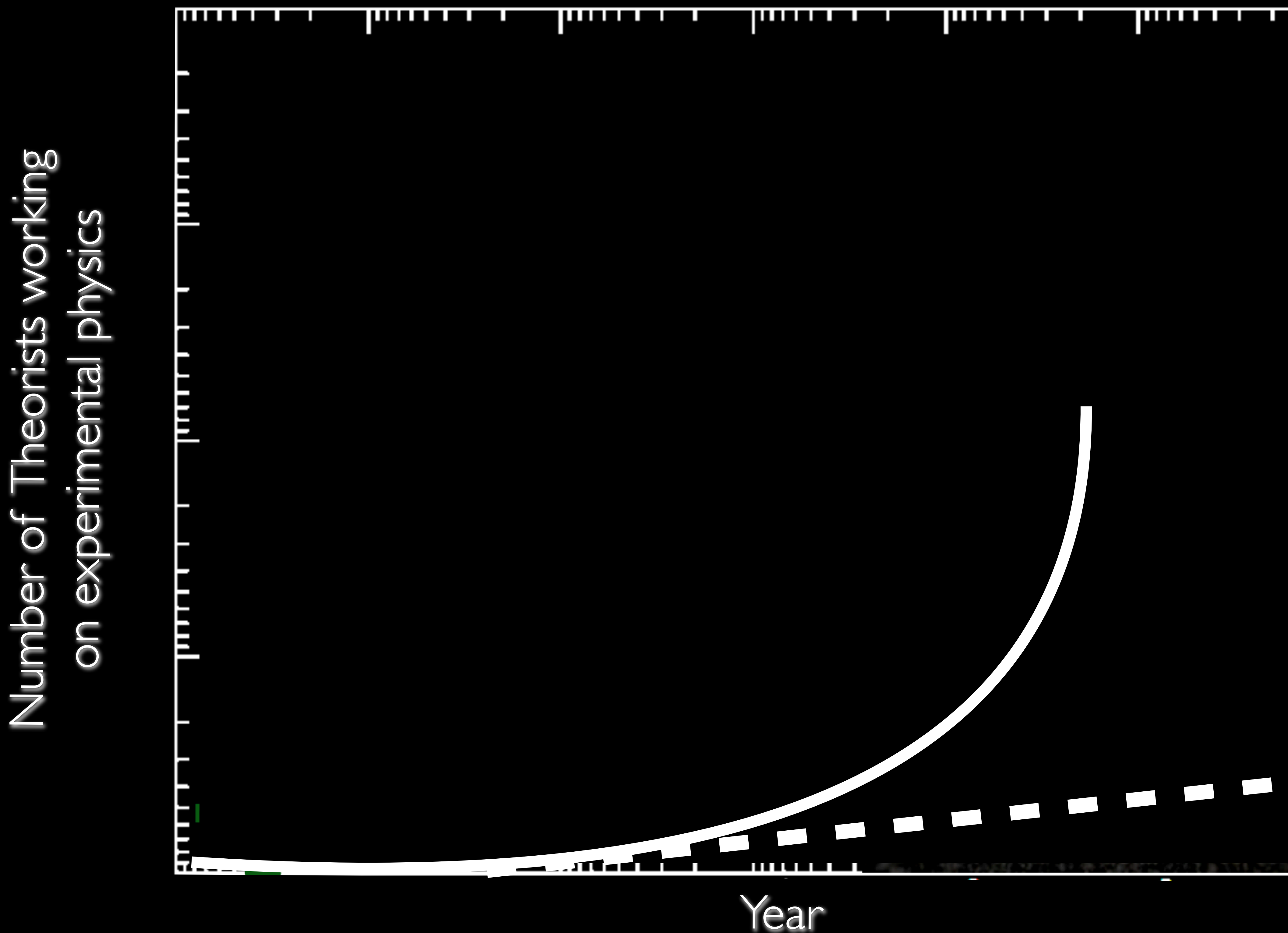
Tomer Volansky
Tel-Aviv University

Moore's law in N-body simulations

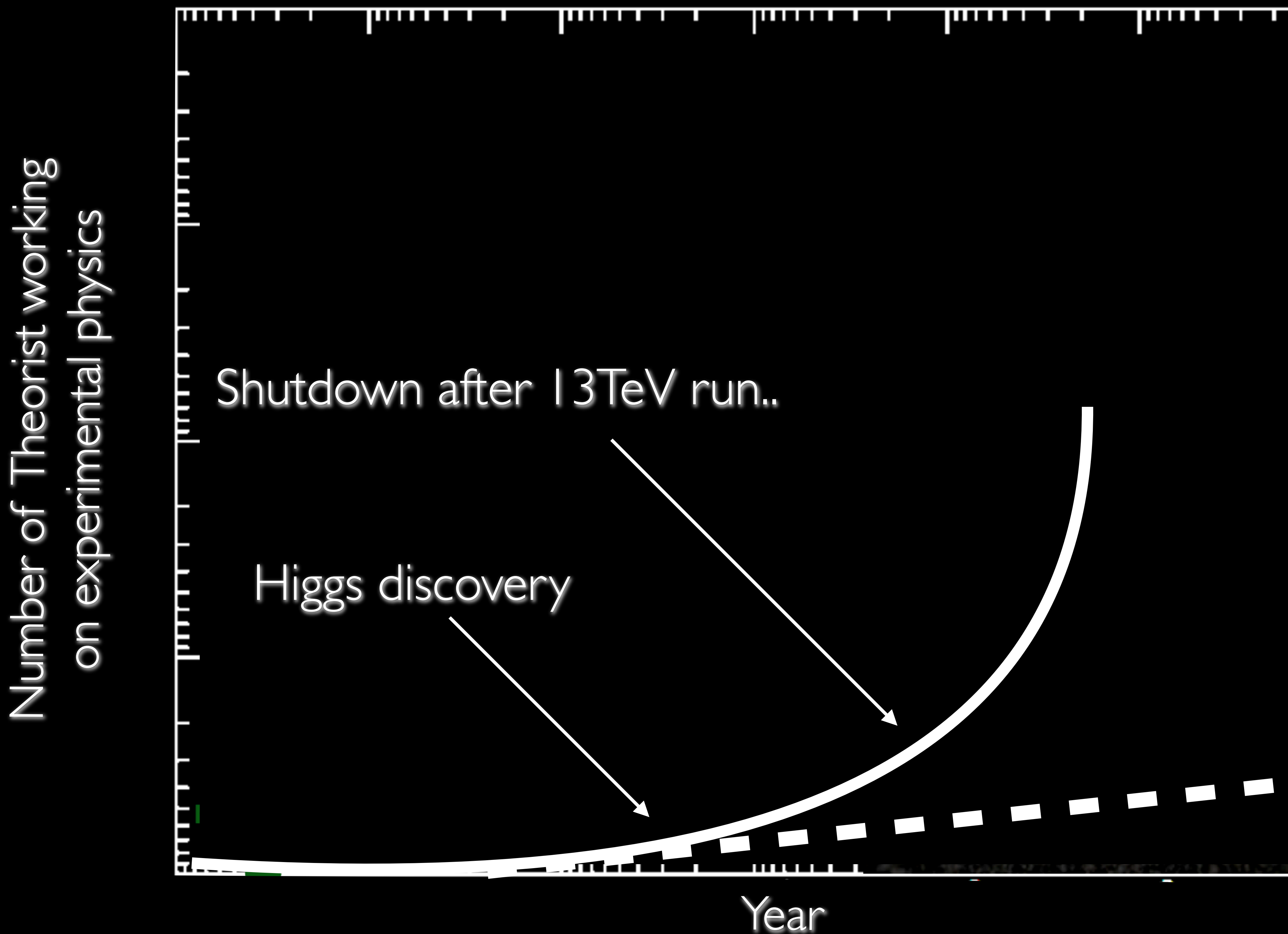


From Phil Hopkins

Moore's law in theoretical particle physics



Moore's law in theoretical particle physics



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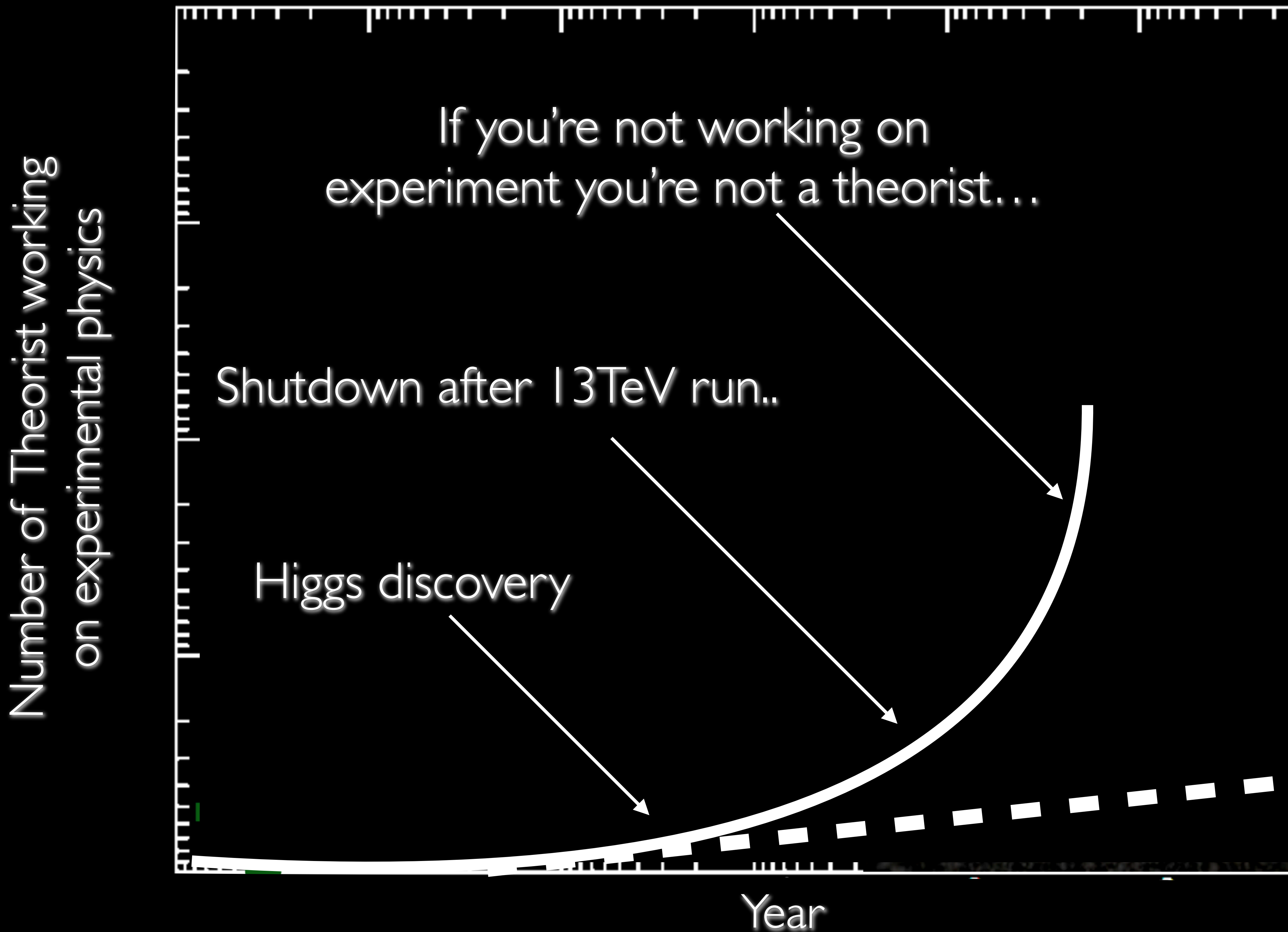
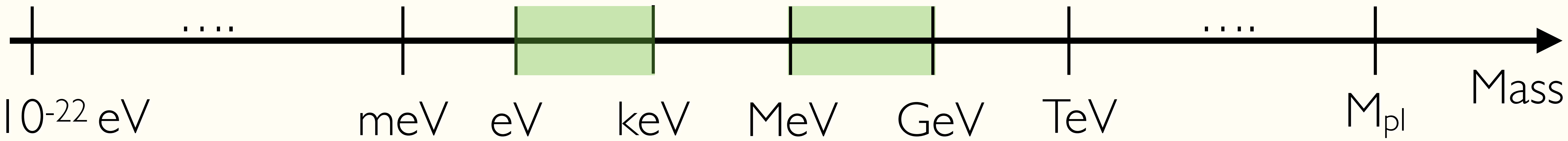
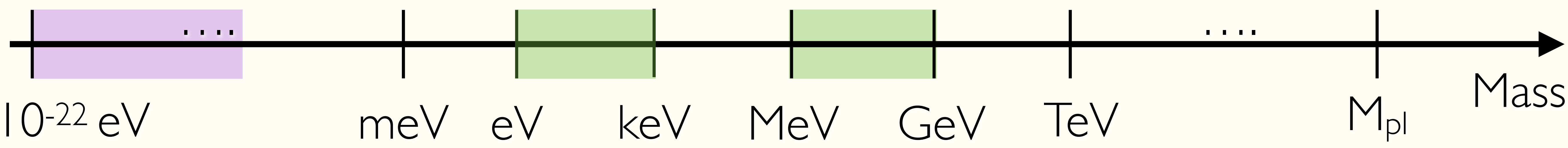


Outline



- Direct Detection of Light Dark Matter
  - Electron ionisation
  - The SENSEI experiment

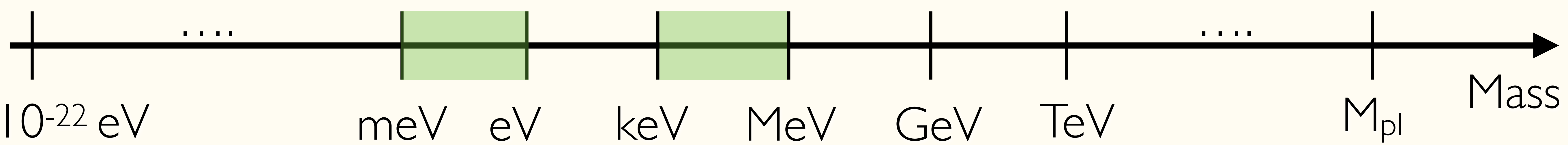
Outline



- Direct Detection of Light Dark Matter
  - Electron ionisation
  - The SENSEI experiment
- Detection of Ultralight Dark Matter
  - Axion-like particles
  - The NASDUCK experiment

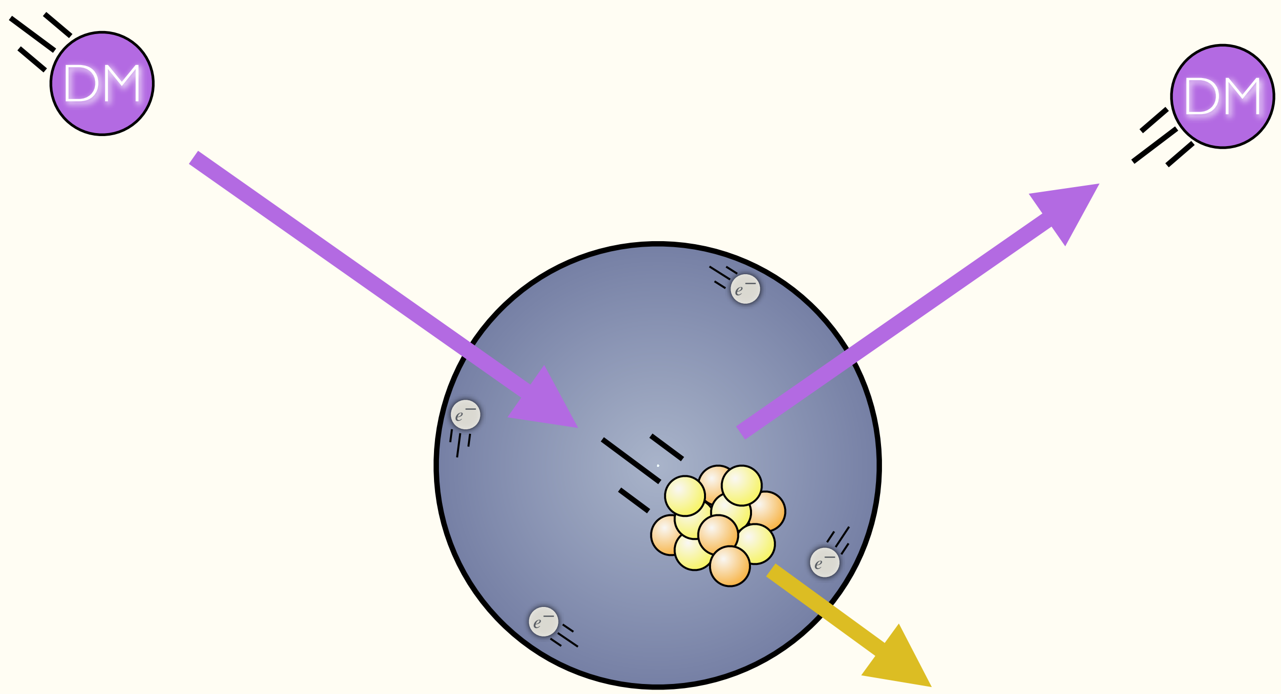
The Direct Detection Frontier

Sub-GeV Dark Matter



Direct Detection: Kinematics

Conventional direct detection experiments search for elastic scattering:



$$E_{\mathrm{R}} = \frac{q^2}{2m_N} \sim \frac{(m_{\mathrm{DM}}v)^2}{2m_N}$$

$$\sim 20\,\mathrm{eV} \times \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_N}\right)$$

Recoil energy drops fast

Can't go much below ~ GeV

Negligible recoil energy

Direct Detection: Kinematics

How do we extract more energy?

Low Threshold Inelastic Processes

Essig, Mardon, TV, 2011

Direct Detection: Kinematics

How do we extract more energy?

Low Threshold Inelastic Processes

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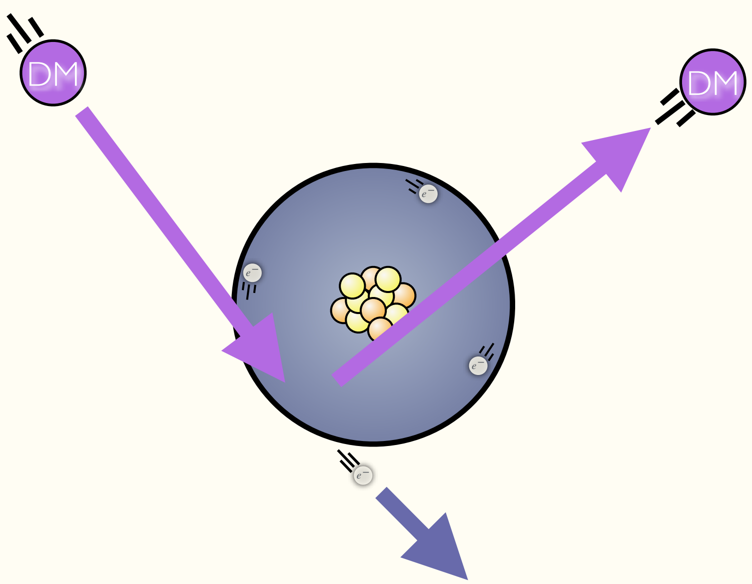

Electron Scattering

Essig, Mardon, TV, 2011

Essig, Manalaysay, Mardon, Sorensen, TV; Essig, Fernandez-Serra, Mardon, Soto, TV, Yu; Derenzo, Essig, Massari, Soto, Yu; Essig, TV, Yu; Essig, Sholarpurkar, Yu; Emken, Essig, Kouvaris, Sholarpurkar; Derenzo, Bourret, Hanrahan, Bizarri; Graham, Kaplan, Rajendran, Walters; Lee, Lisanti, Mishra-Sharma, Safdi; XENON1T; Berggren, Hochberg, Kahn, Kurinsky, Lehmann, Yu;Knapen, Kozaczuk, Lin;

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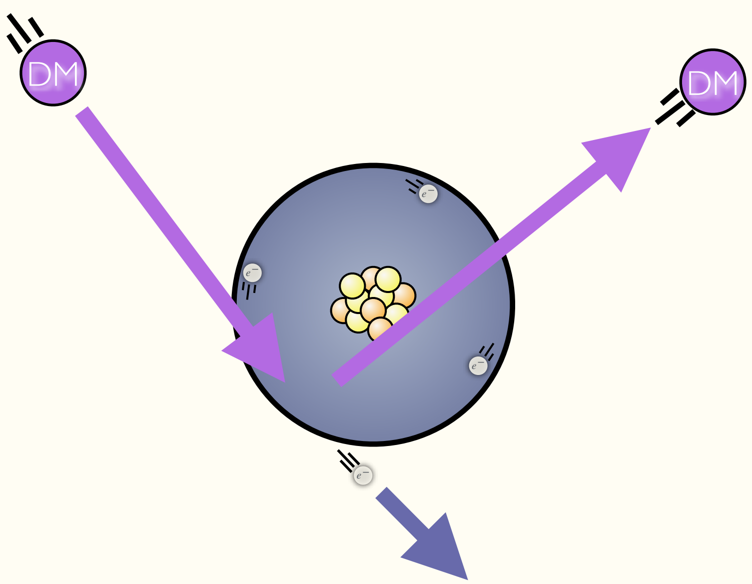

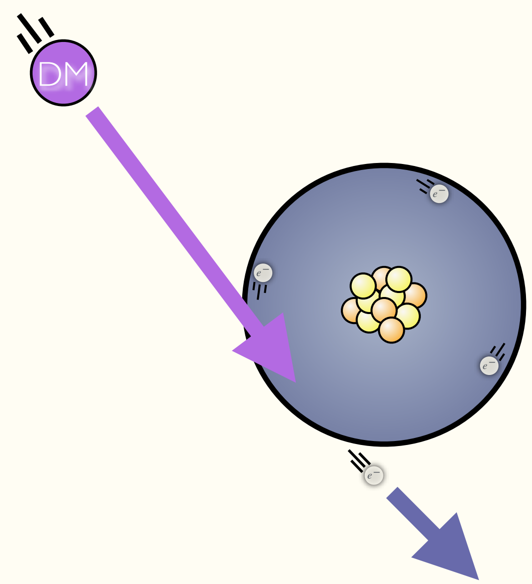

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DM Absorption

Dimopoulos, Starkman, Lynn, 1986
An, Pospelov, Pradler, Ritz, 2014

Avignone et al.; Pospelov, Ritz, Voloshin; Raffelt, Redondo; Hochberg, Lin,. Zurek; Bloch, Essig, Tobioka, TV. Yu; Bloch, Caputo, Essig, Redigolo, Sholapurkar, TV; Knapen, Lin, Zurek; XENON1T; DAMIC;

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Direct Detection: Kinematics

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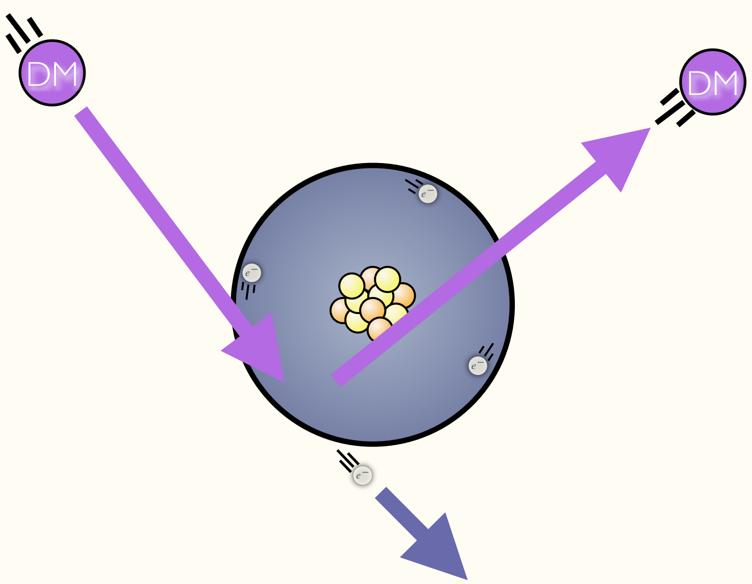

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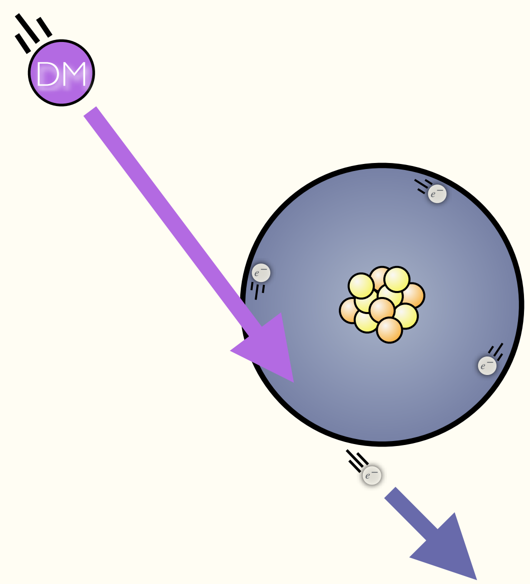

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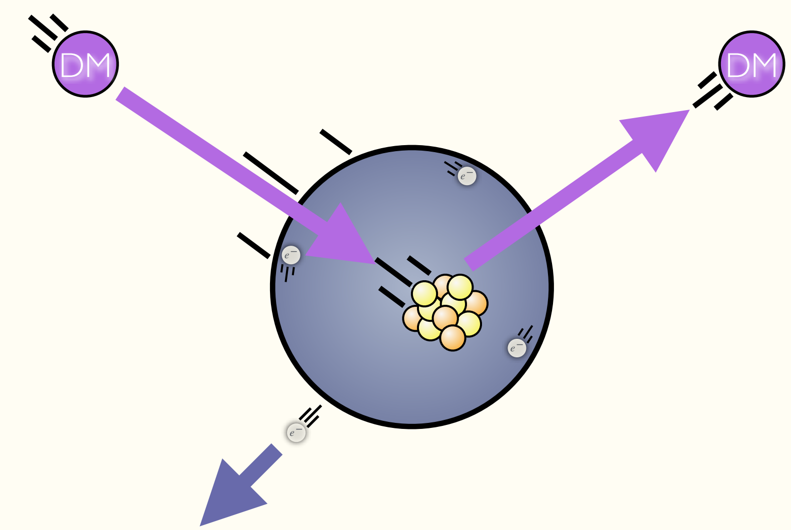

Migdal Scattering

Ibe, Nakano, Shoji, Suzuki, 2017

Ibe, Nakano, Shoji, Suzuki; Baxter, Kahn, Krnjaic; Essig, Pradler, Sholapurkar, Yu; Liang, Zhang, Zheng, Zhang; Liu, Wu, Chi, Chen; Kahn, KKrnjaic, Mandava; Knapen, Kozaczuk, Li; Liang, Mo, Zheng, Zhang;
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Direct Detection: Kinematics

How do we extract more energy?

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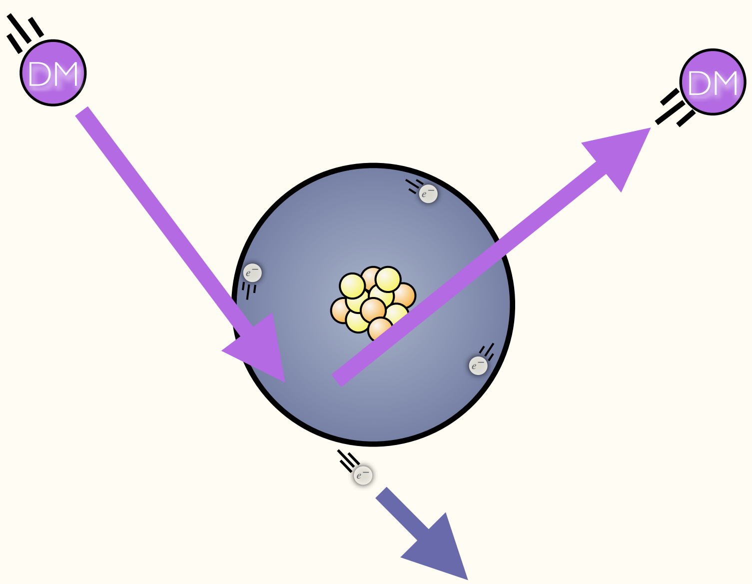
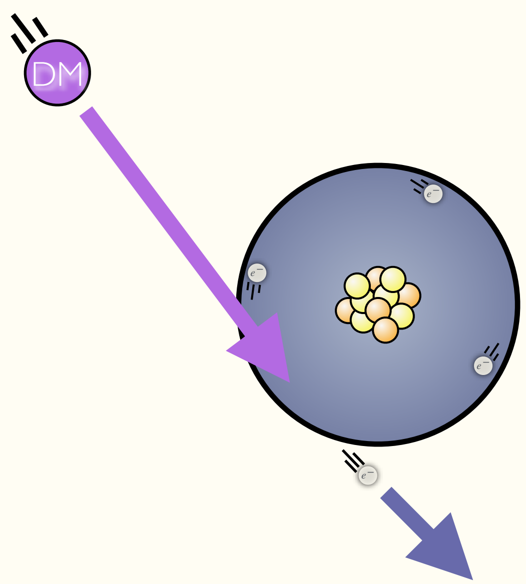


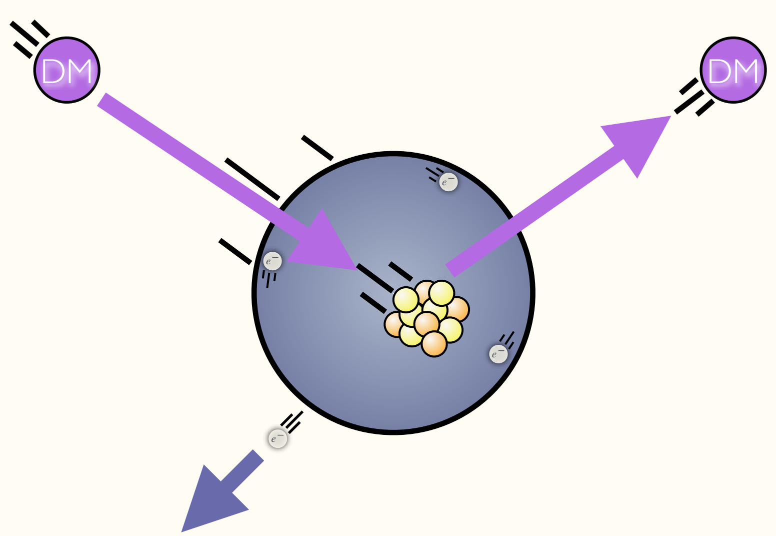
Electron Scattering

$$\Delta E_e = \mathbf{q}\cdot\mathbf{v} - \frac{\mathbf{q}^2}{2\mu_{\chi N}}$$



DM Absorption

$$E_R \sim m_{\rm DM}$$



Migdal Scattering

$$\Delta E_e = \mathbf{q}\cdot\mathbf{v} - \frac{\mathbf{q}^2}{2\mu_{\chi N}}$$

$$v_{\rm DM} \lesssim 2\times 10^{-3}\,c \ll v_{\rm e} \sim \alpha_{\rm EM} \sim \frac{1}{137}$$

Direct Detection: Kinematics

How do we extract more energy?

Low Threshold Inelastic Processes

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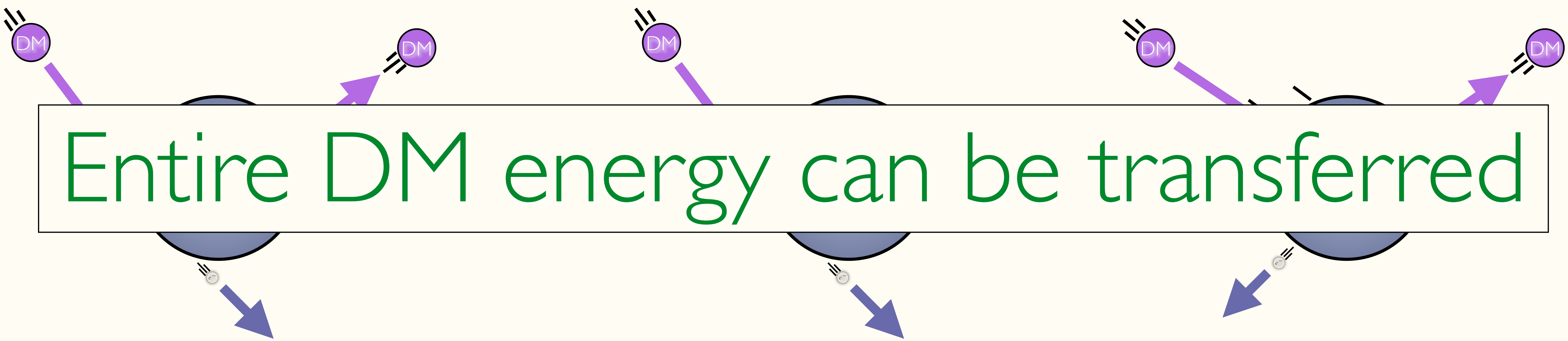


Entire DM energy can be transferred

Electron Scattering

$$\Delta E_e = \mathbf{q} \cdot \mathbf{v} - \frac{\mathbf{q}^2}{2\mu_{\chi N}}$$

$$v_{\rm DM} \lesssim 2 \times 10^{-3}\, c \ll v_{\rm e} \sim \alpha_{\rm EM} \sim \frac{1}{137}$$

DM Absorption

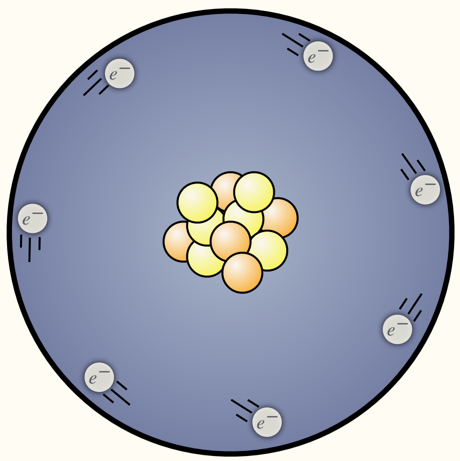
$$E_R \sim m_{\rm DM}$$

Migdal Scattering

$$\Delta E_e = \mathbf{q} \cdot \mathbf{v} - \frac{\mathbf{q}^2}{2\mu_{\chi N}}$$

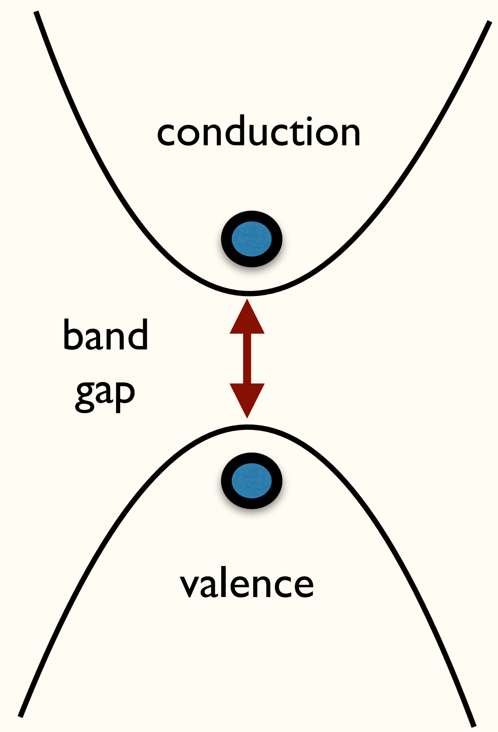
Direct Detection: Targets

Requires sensitivity to single- or few ionized electrons



noble liquids

$$\Delta E \sim 10 \text{ eV}$$
$$m_{\text{DM}} \gtrsim 5 \text{ MeV}$$

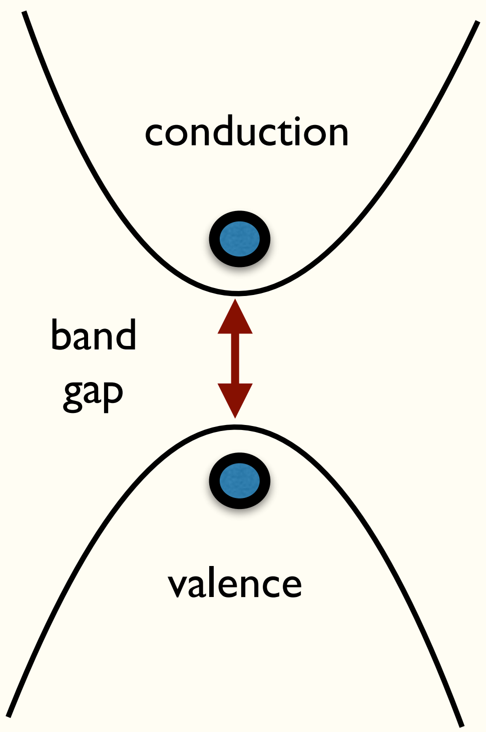


semiconductors
scintillators

$$\Delta E \sim 1 \text{ eV}$$
$$m_{\text{DM}} \gtrsim 500 \text{ keV}$$

Direct Detection: Targets

Requires sensitivity to single- or few ionized electrons



semiconductors
scintillators

$$\Delta E \sim 1 \text{ eV}$$

$$m_{\text{DM}} \gtrsim 500 \text{ keV}$$

Electron Ionization: Rates

Low threshold implies:

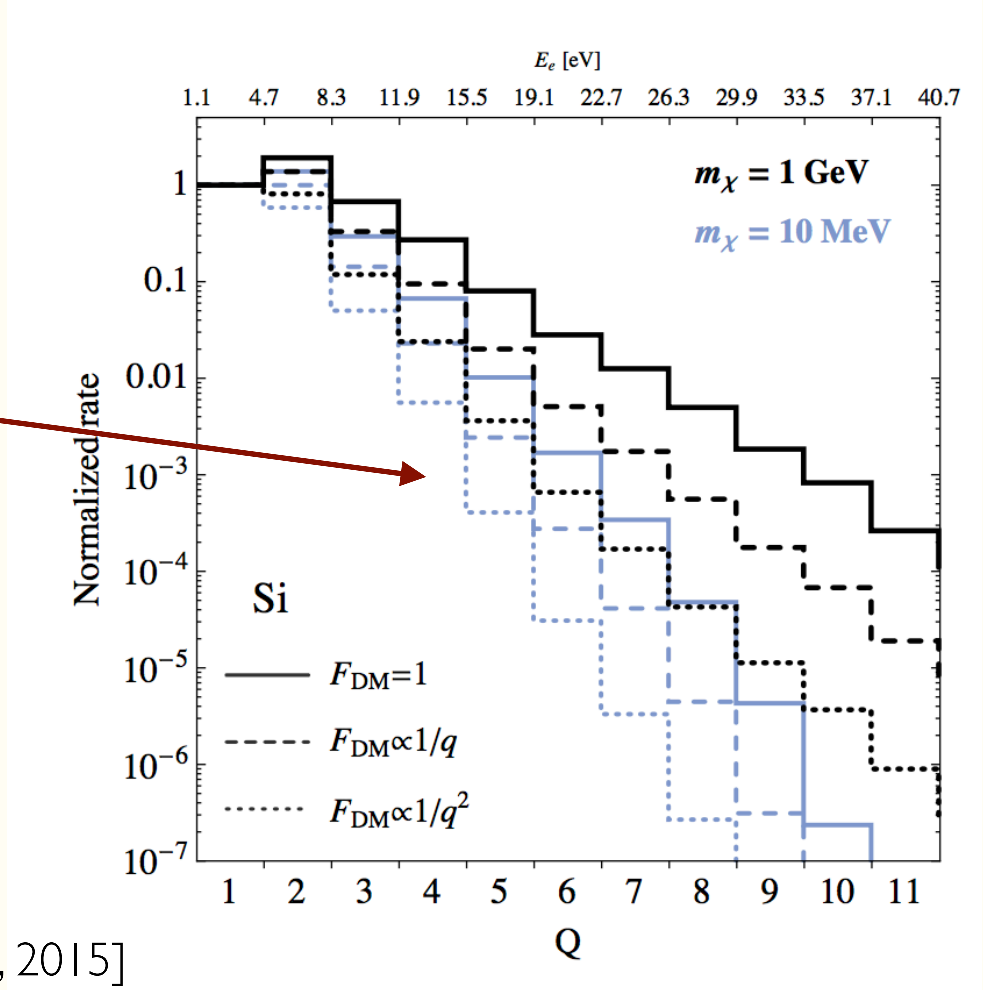
Sensitivity to low mass

Exponentially larger rates

Excellent sensitivity with small targets

1 tonne (WIMP) vs. 100 gram (Light DM)

Rapid drop-off in rate!

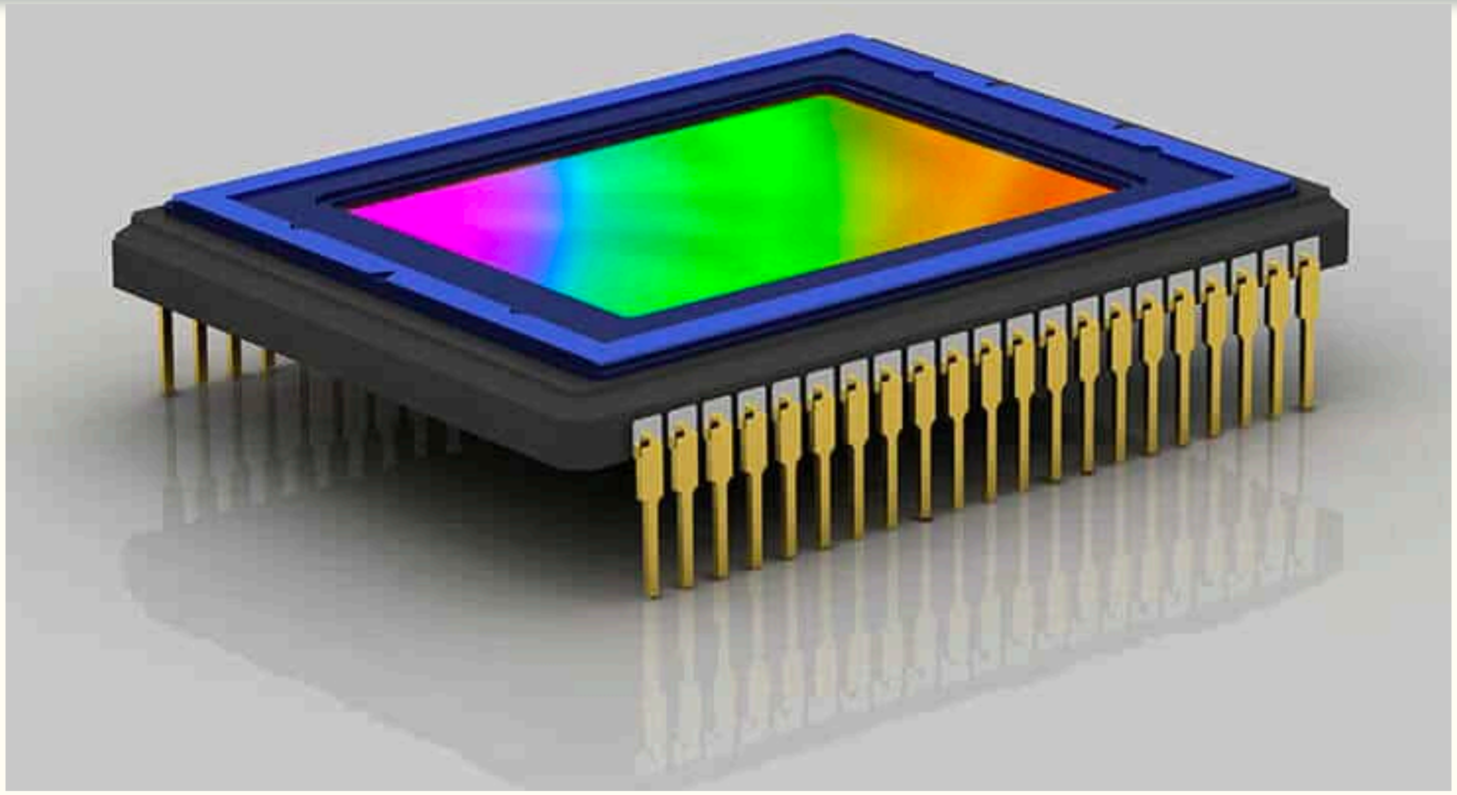


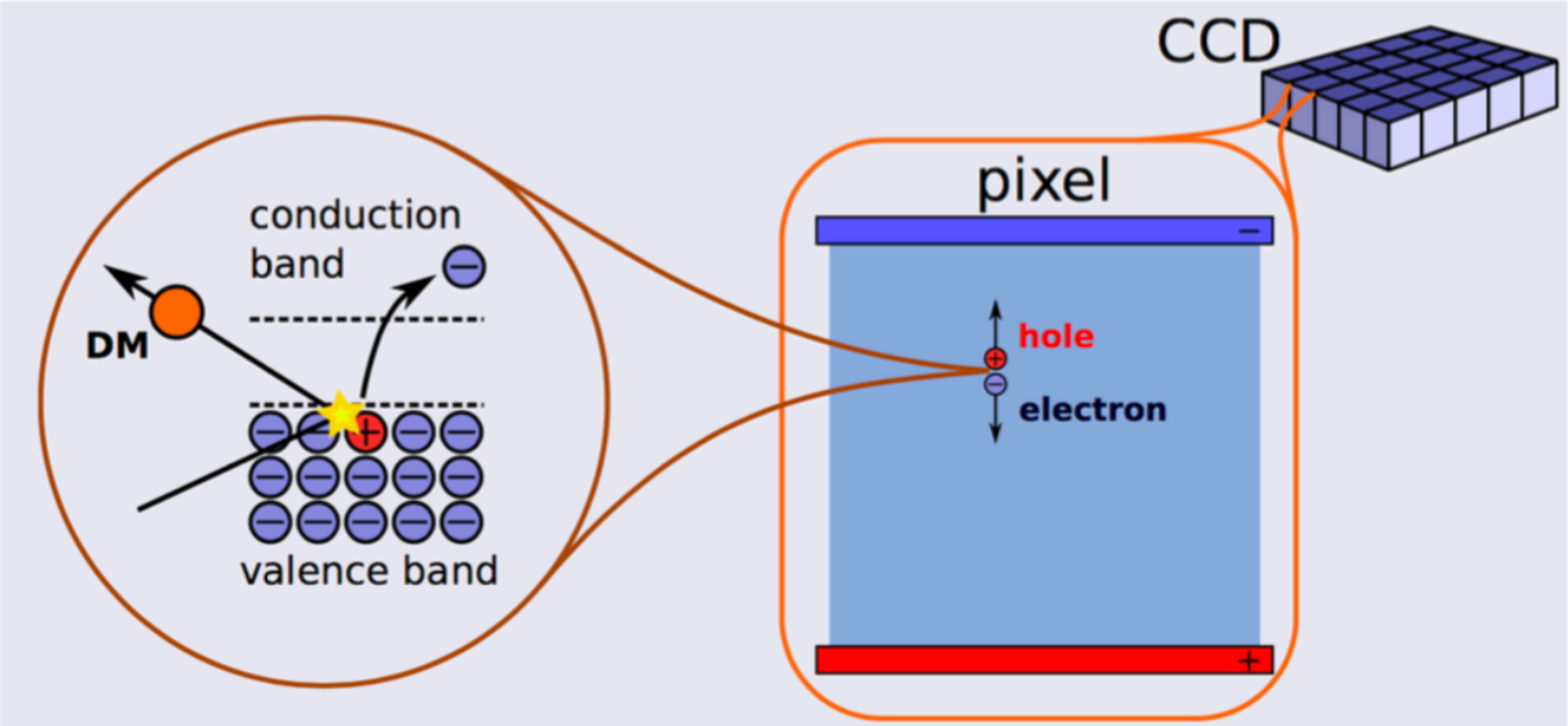
[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015]

SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument

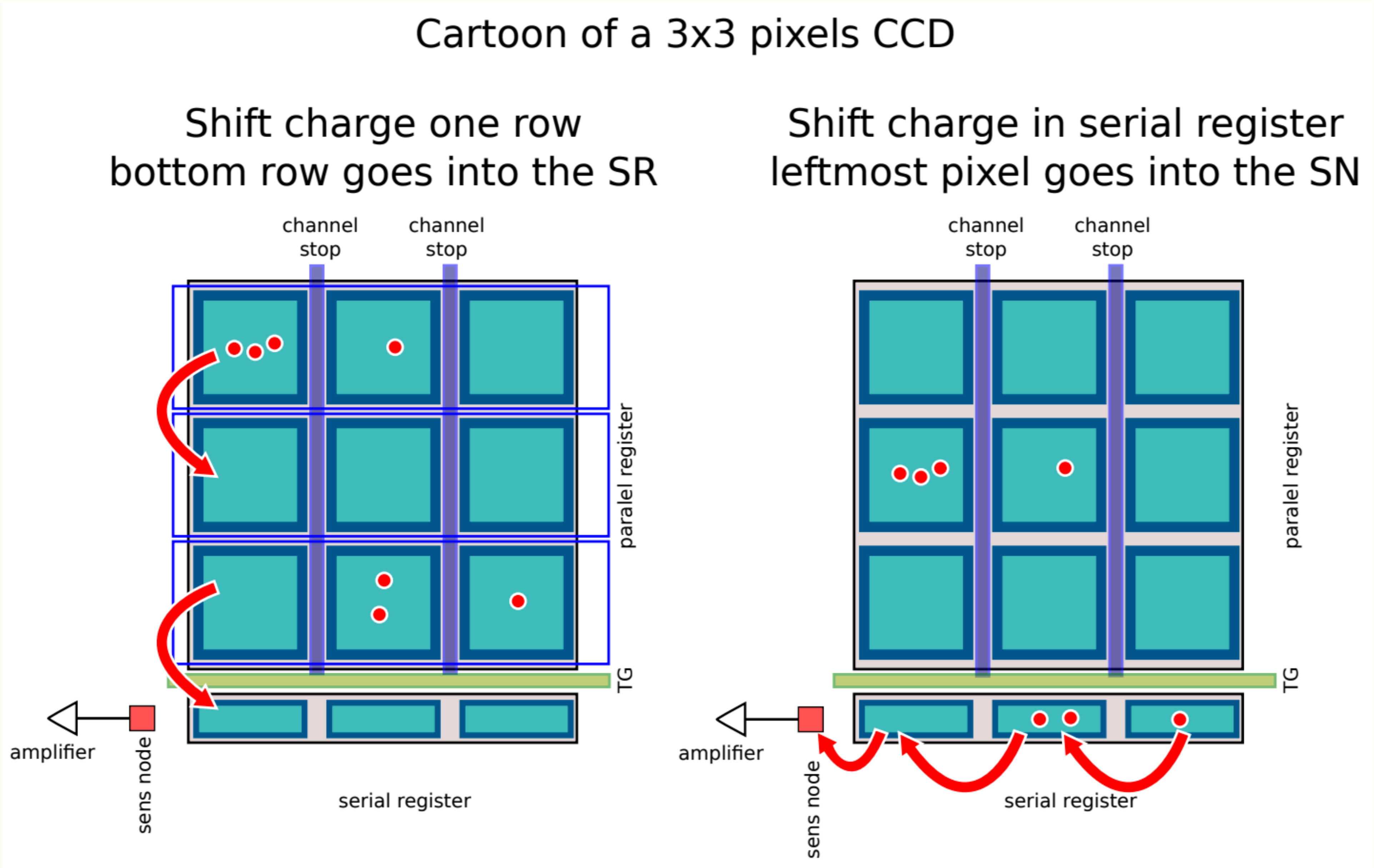
Semiconductors: CCDs





Semiconductors: CCDs

[Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, TV, Yu, 2017]



Pictures from a talk by Tiffenberg

Skipper-CCDs: Single-Electron Frontier

- Ordinary CCDs have two sources that limit sensitivity:
  - Readout noise: 2 e^-/pixel with ordinary science-grade CCDs.
  - Dark current: currently $<10^{-3}$ e^-/pixel/day.
- Readout noise dominates and requires 11e^- threshold.

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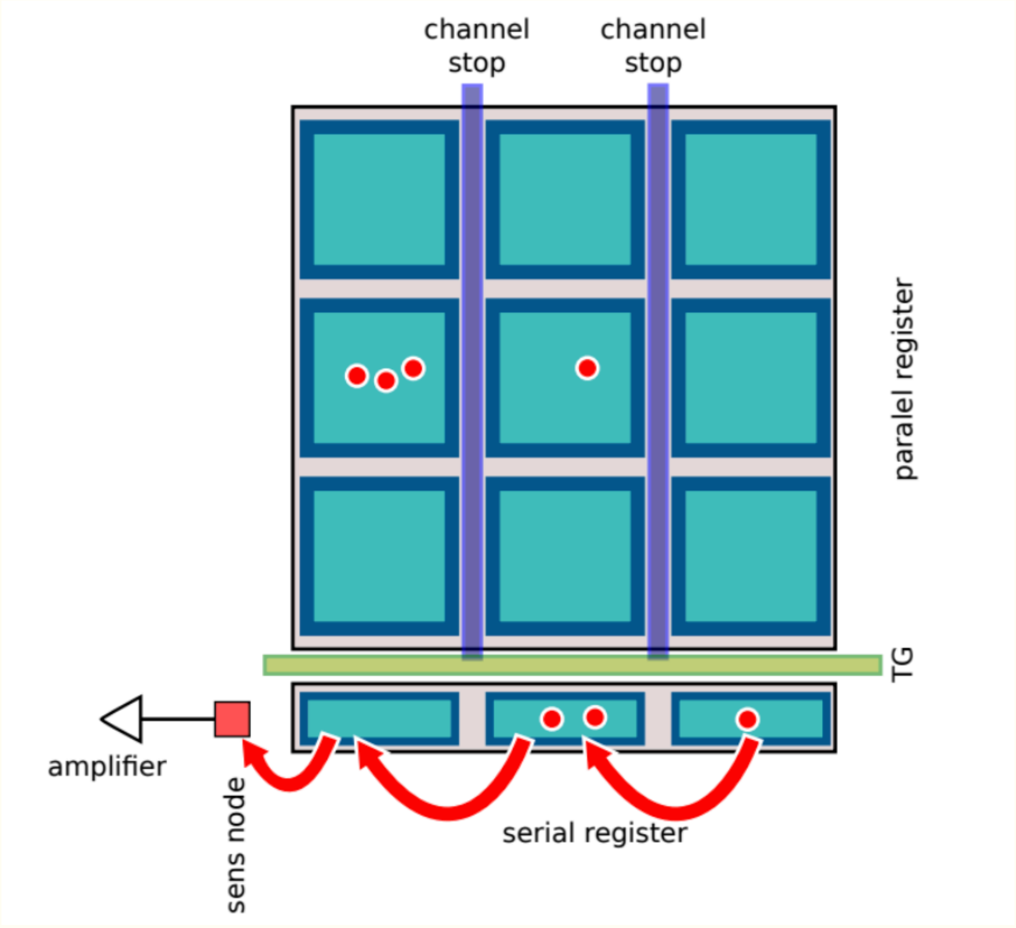
  - Readout noise: 2 e^-/pixel with ordinary science-grade CCDs.
  - Dark current: currently $<10^{-3}$ e^-/pixel/day.
- Readout noise dominates and requires 11e^- threshold.
- SENSEI technology: Skipper-CCD.

[Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, TV, Yu, 2017]

- Developed at LBNL and Fermilab. Allows multiple reading of each pixel.

Skipper-CCDs: Single-Electron Frontier

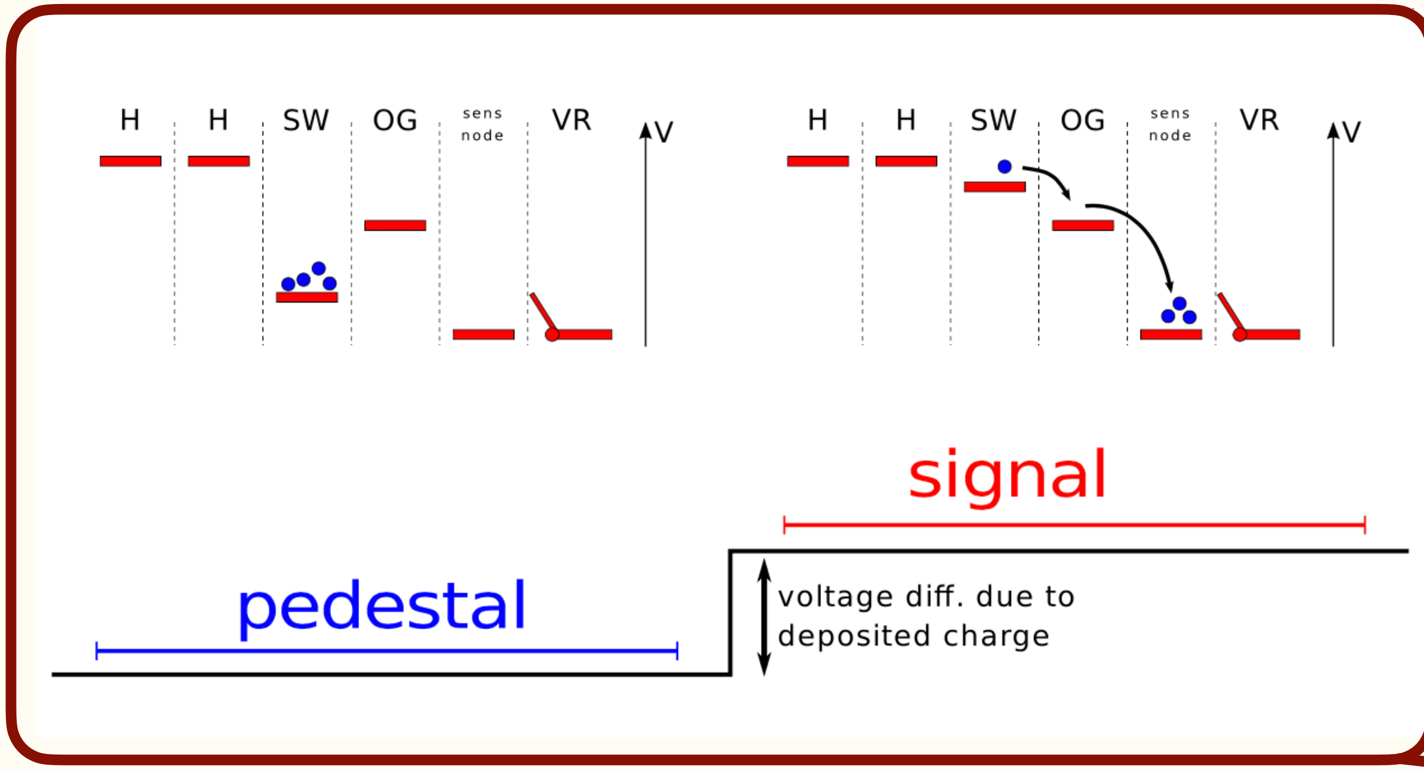
[Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, TV, Yu, 2017]



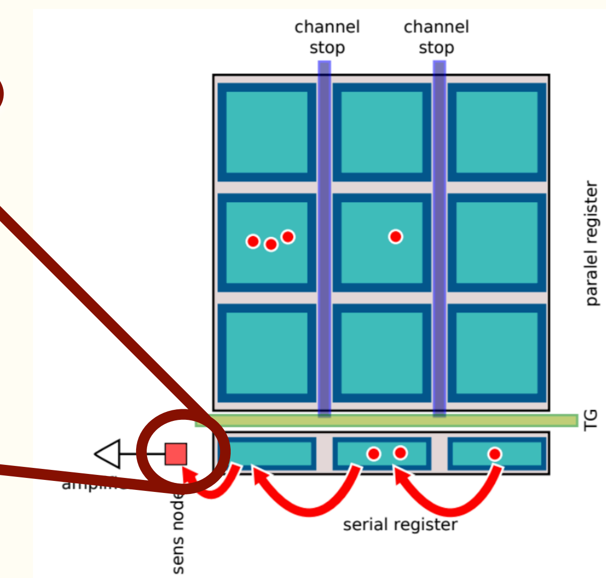
Pictures from a talk by Tiffenberg

Skipper-CCDs: Single-Electron Frontier

[Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, TV, Yu, 2017]



Regular CCD



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Skipper-CCDs: Single-Electron Frontier

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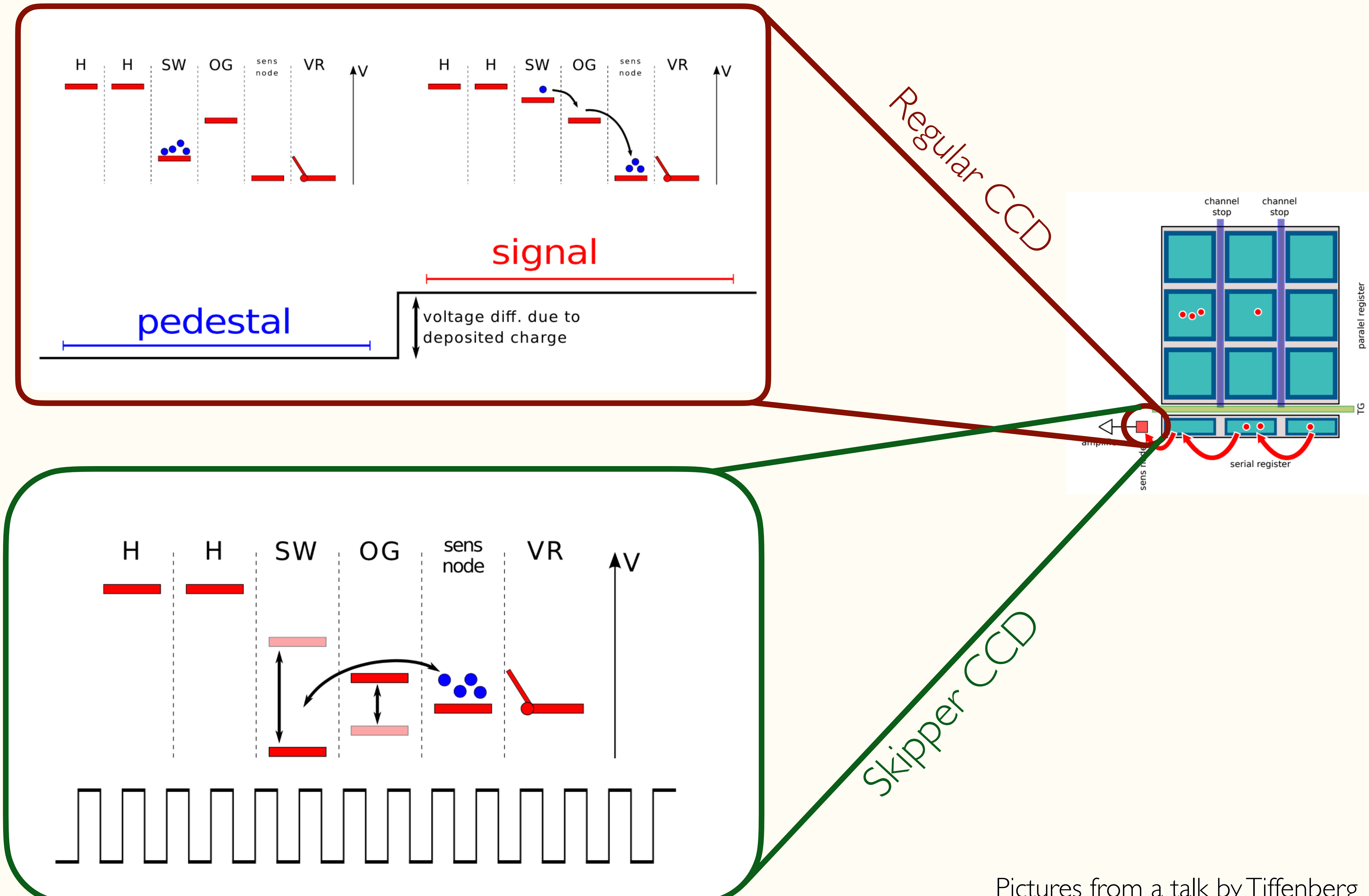

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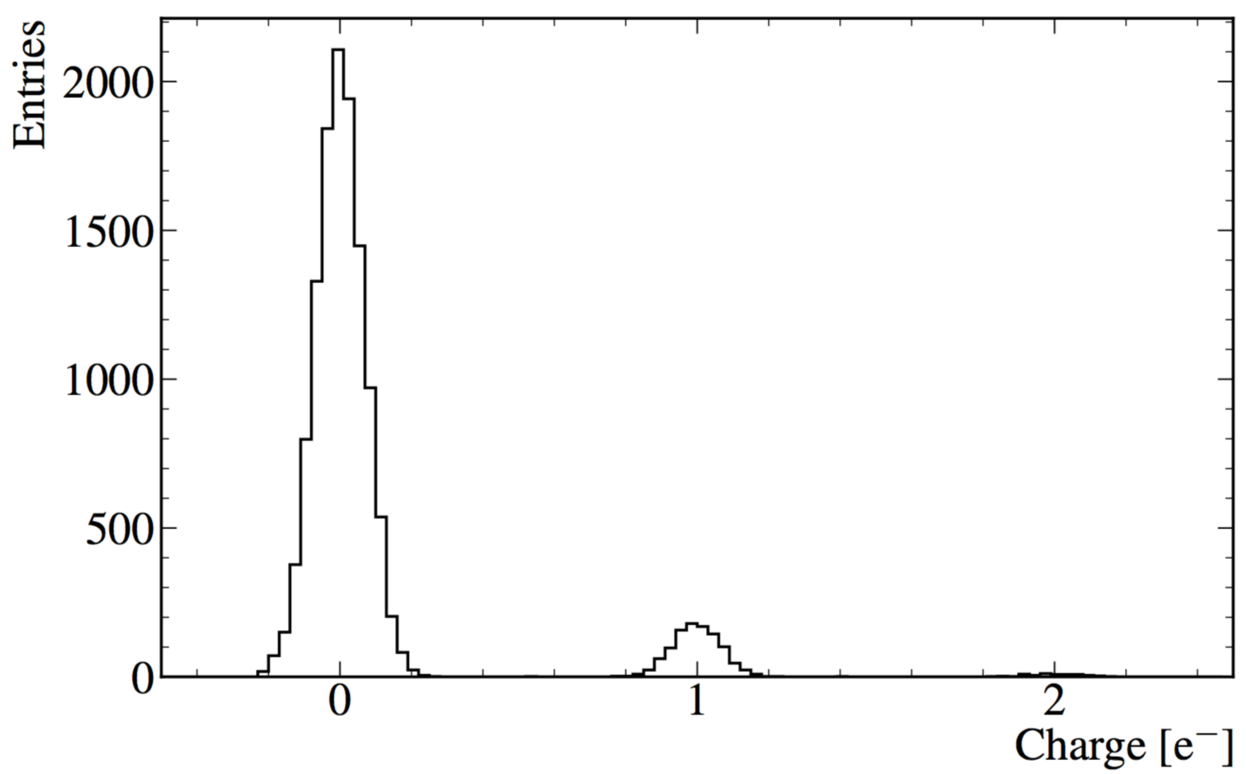
Skipper-CCDs: Single-Electron Frontier

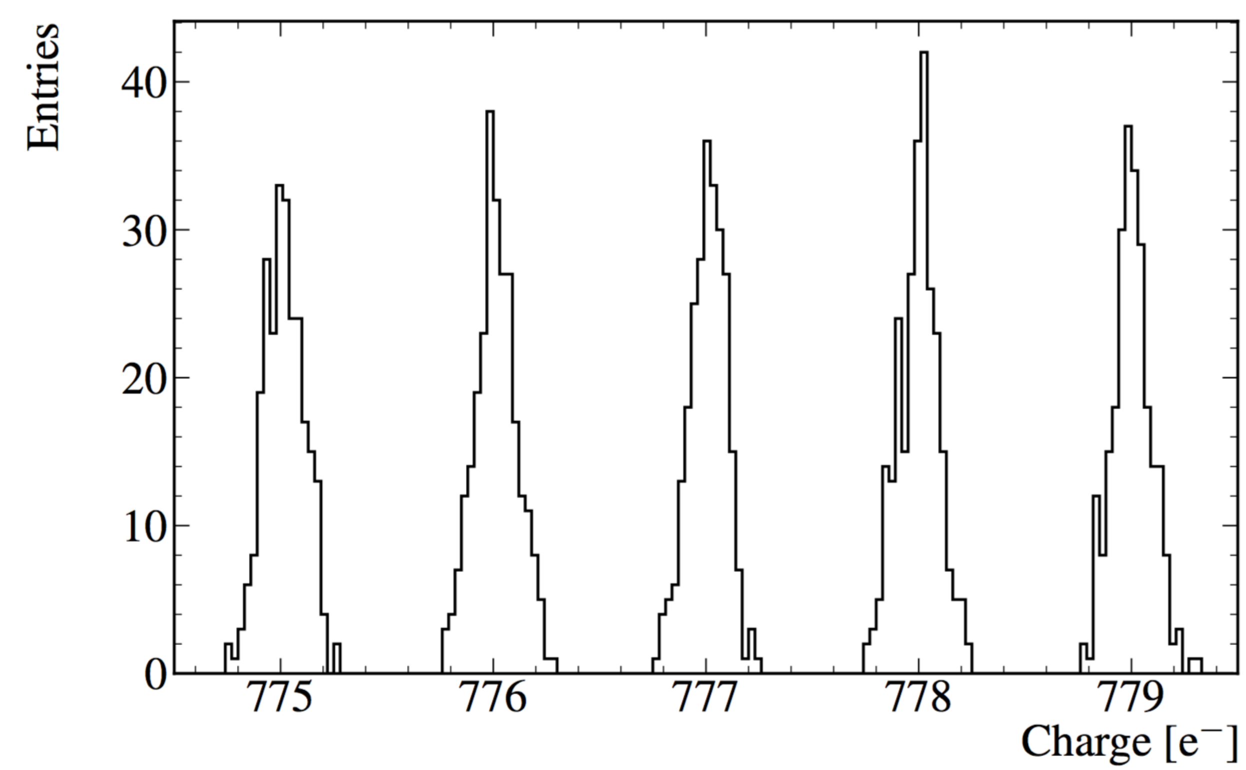
[Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, TV, Yu, 2017]

Skipper CCDs Highly reduced readout noise (~0.068 e-/pixel)

$$\text{Pixel Value} = \frac{1}{N}\sum_{i}^{N}(\text{pixel sample})_i$$

Large dynamical range (up to 1500 e-'s per pixel)





The SENSEI Collaboration

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Fermilab

Stony Brook University

UNIVERSITY OF OREGON

universidad de buenos aires - exactas departamento de física Juan José Giambiagi

SNOLAB

Liron Barak
Yonathan Ben Gal
Itay Bloch
Erez Etzion
Yaron Korn
Aviv Orly
Tomer Volansky

Ana Botti
Gustavo Cancelo
Fernando Chierchie
Michael Crisler
Alex Drilca-Wagner
Juan Estrada
Guillermo Fernandez
Miguel Sofo-Haro
Leandro Stefanazzi
Sho Uemura
Javier Tiffenberg

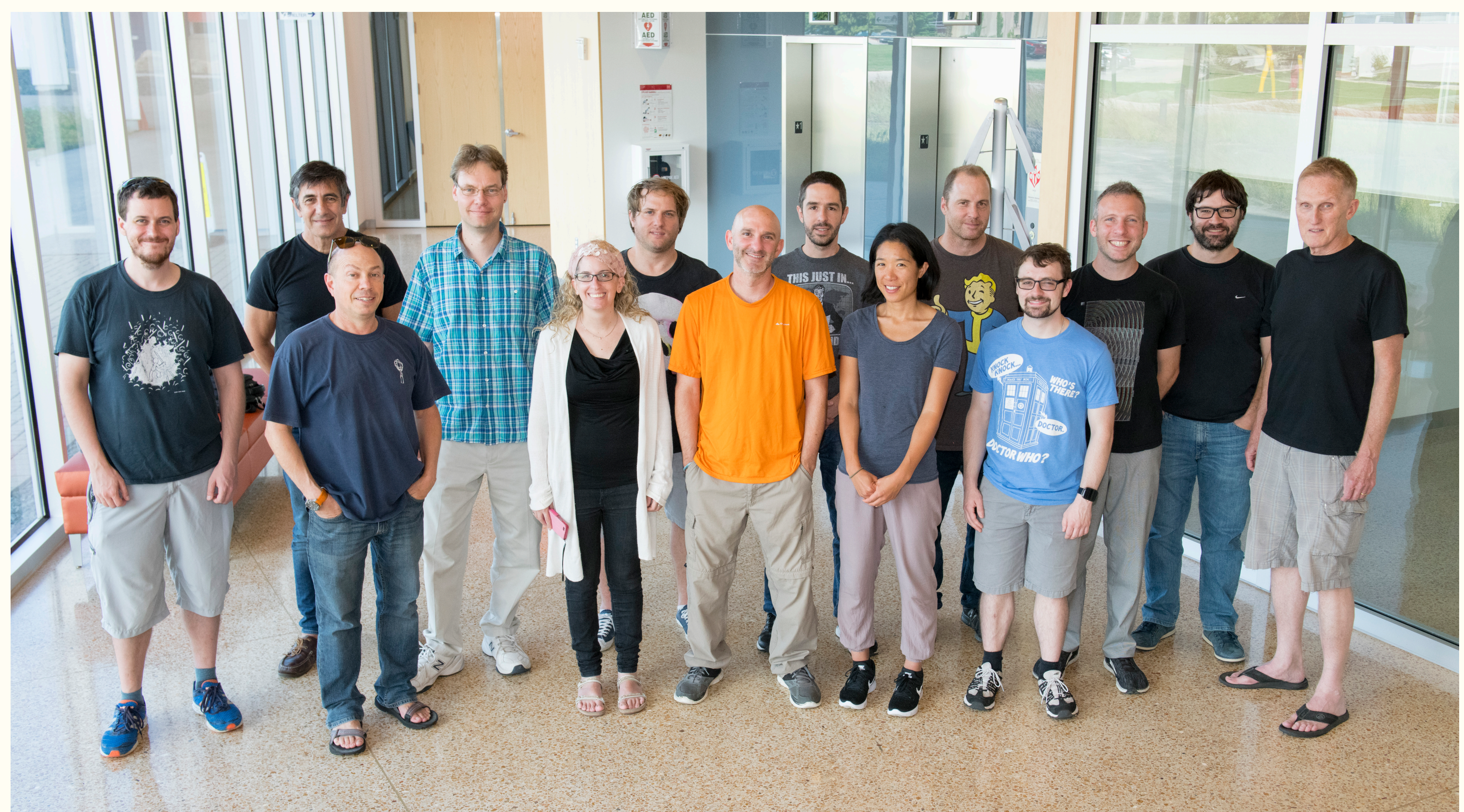
P. Adari
A. Desai
Rouven Essig
Aman Singal

Tien-Tien Yu

Mariano Cababie
Dario Rodrigues

Ian Lawson
Silvia Scorza
Steffon Luoma

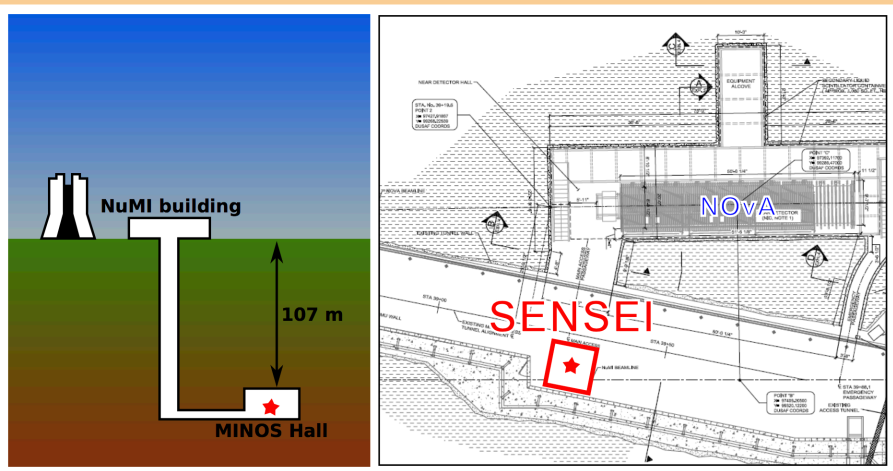
HEISING-SIMONS FOUNDATION



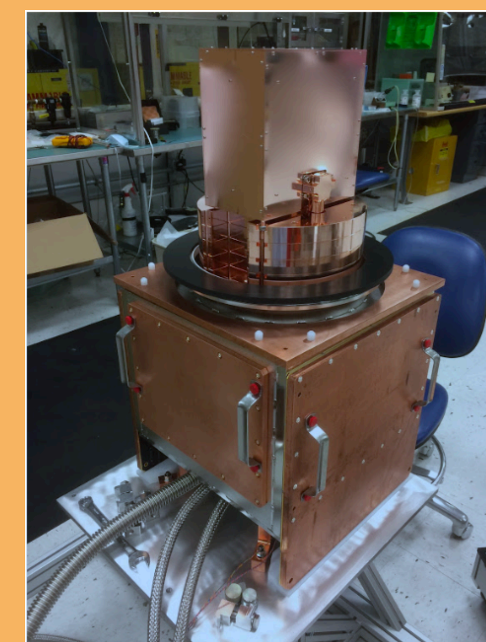
The SENSEI Collaboration

Skipper-CCDs in 4 locations

Fermilab (MINOS Cavern)



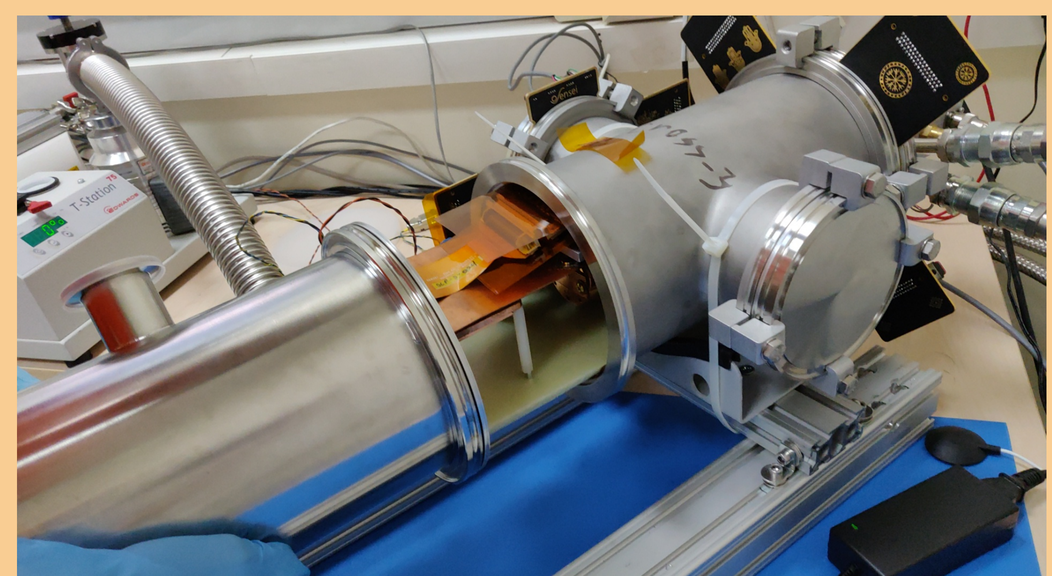
SNOLAB



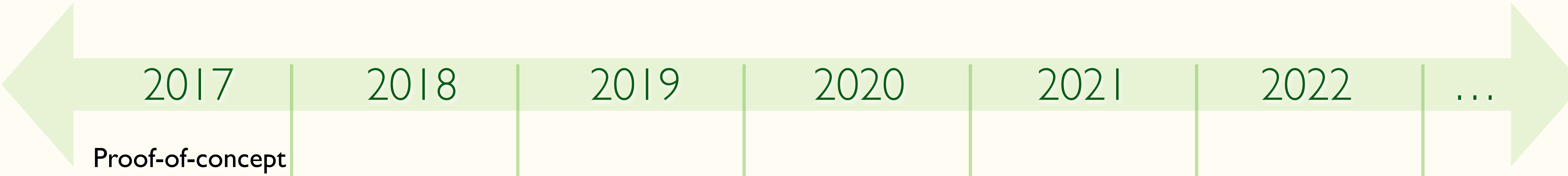
DAMIC Vessel (SNOLAB)
(currently not working)


From talk by Alex Piers

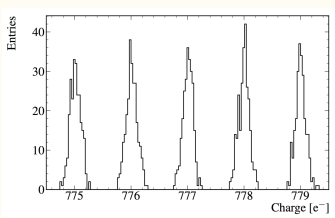
Tel Aviv University



The SENSEI Collaboration



Proof-of-concept
Single-electron
Sensitivity



The SENSEI Collaboration

2017 | 2018 | 2019 | 2020 | 2021 | 2022 | ...

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Single-electron
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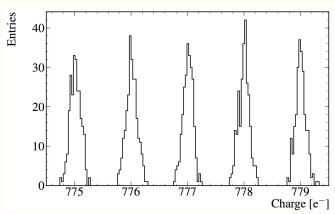
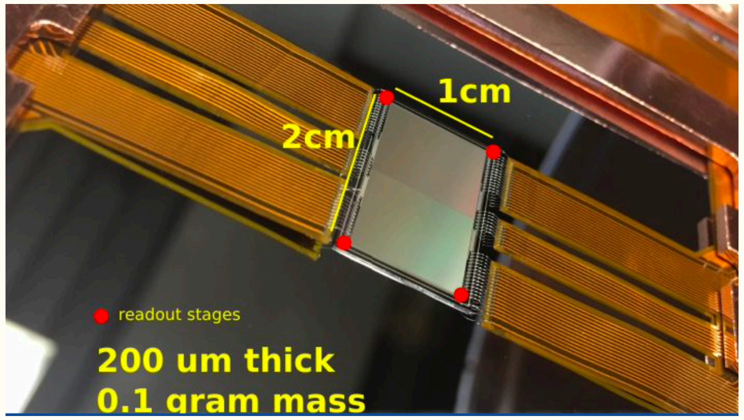
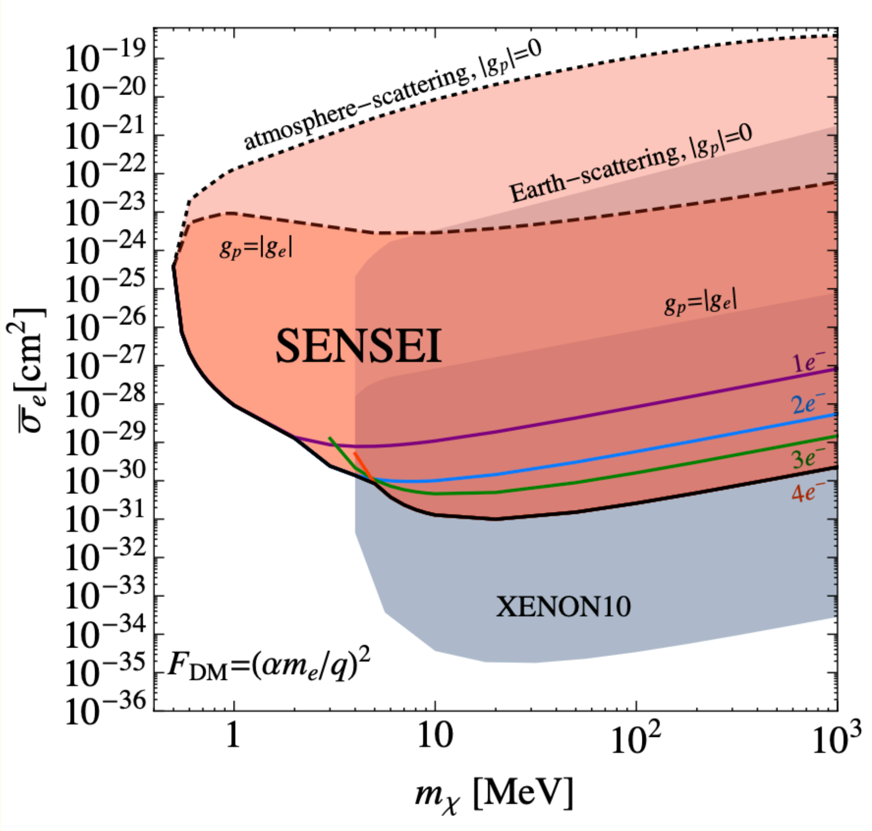


DM Surface run
w/ proto-SENSEI





The SENSEI Collaboration

2017 | 2018 | 2019 | 2020 | 2021 | 2022 | ...

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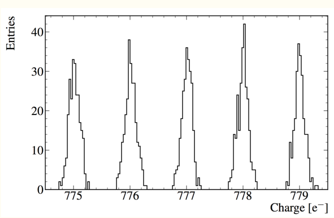
Single-electron Sensitivity



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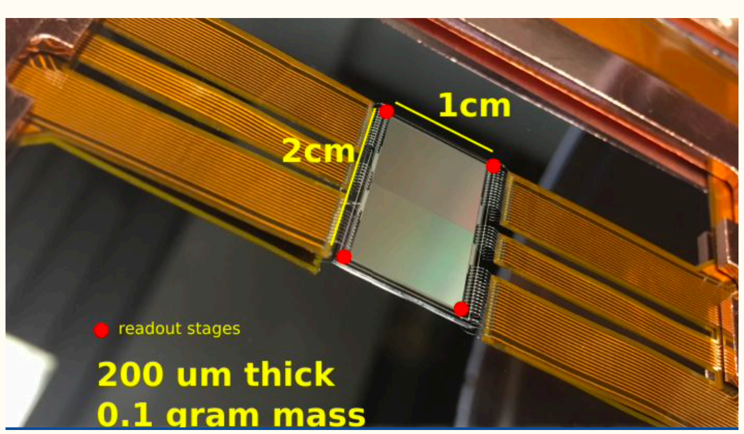
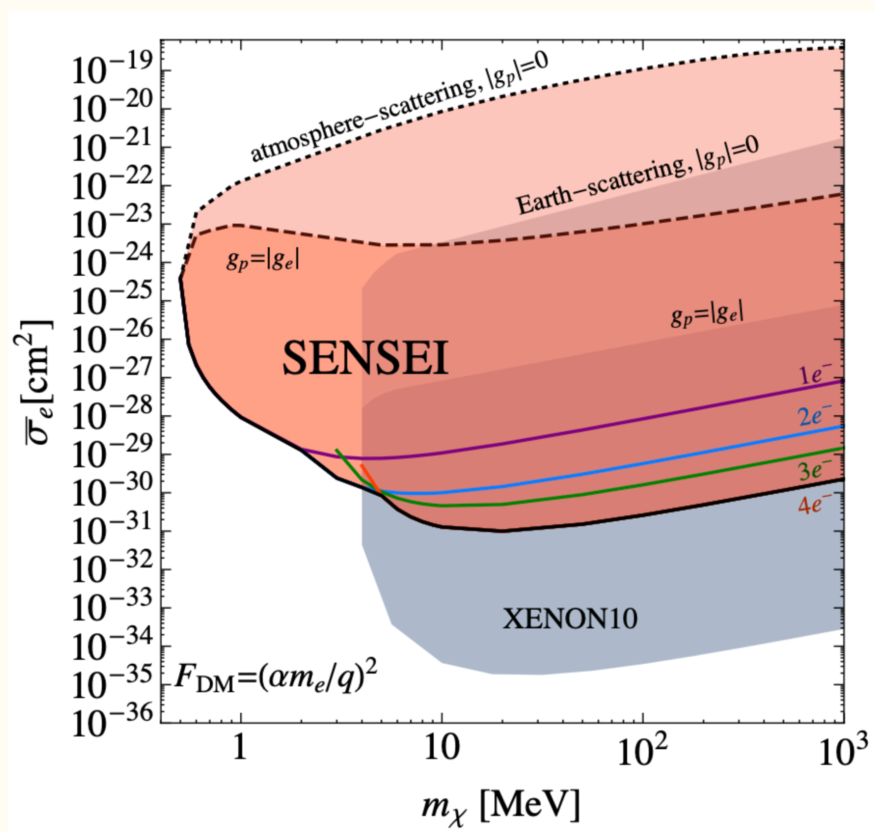
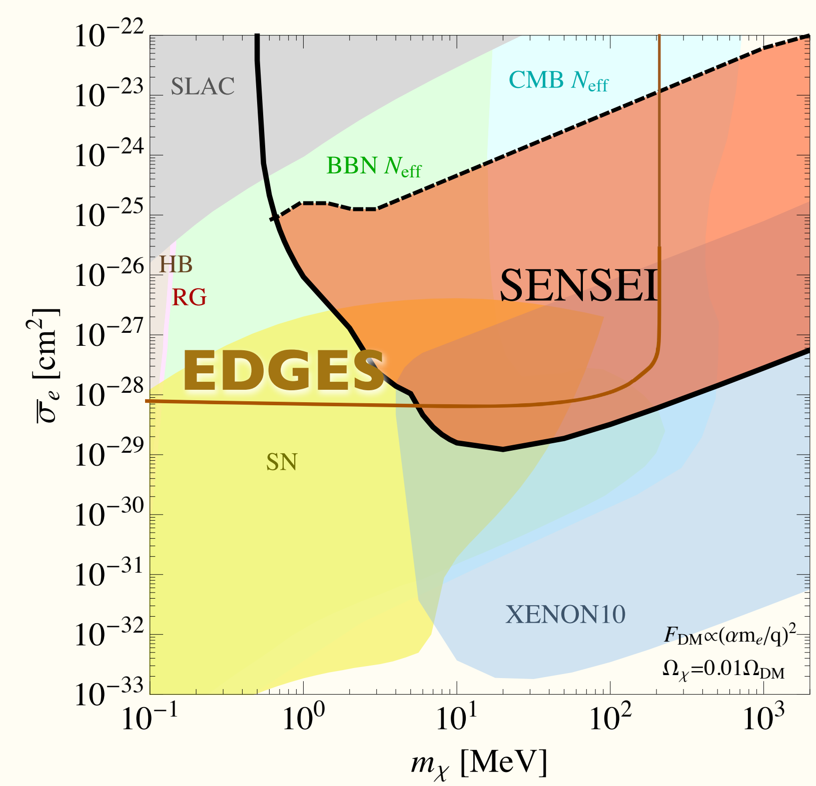


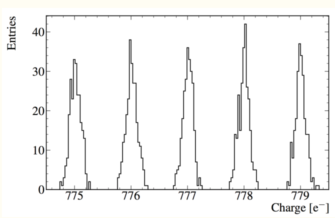




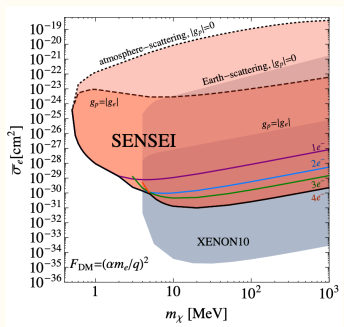
The SENSEI Collaboration

2017 | 2018 | 2019 | 2020 | 2021 | 2022 | ...

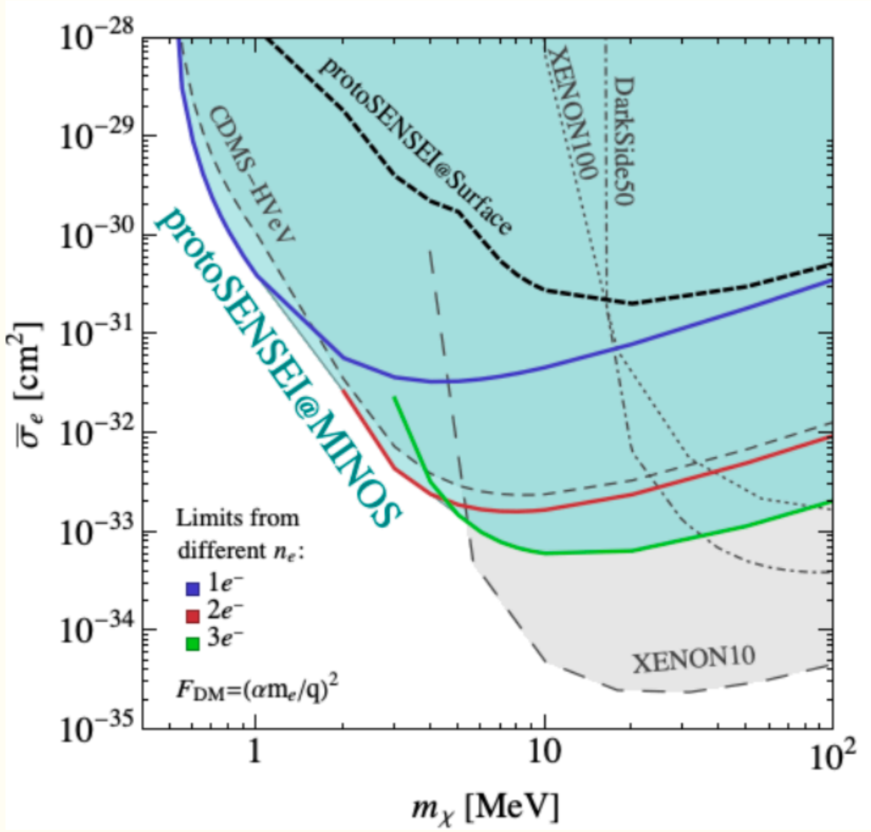
2017 — Proof-of-concept
Single-electron Sensitivity



2018 — DM Surface run
w/ proto-SENSEI

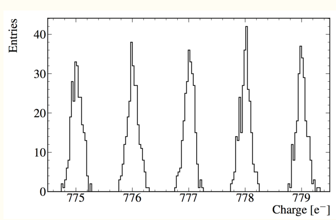


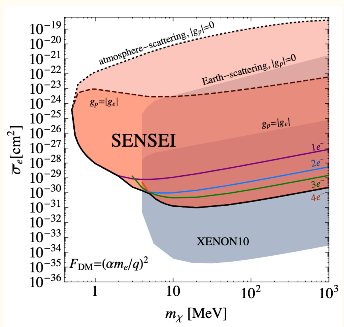
2019 — DM MINOS run
w/ proto-SENSEI

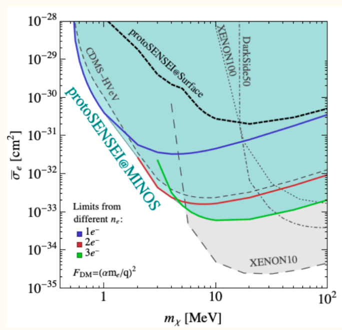


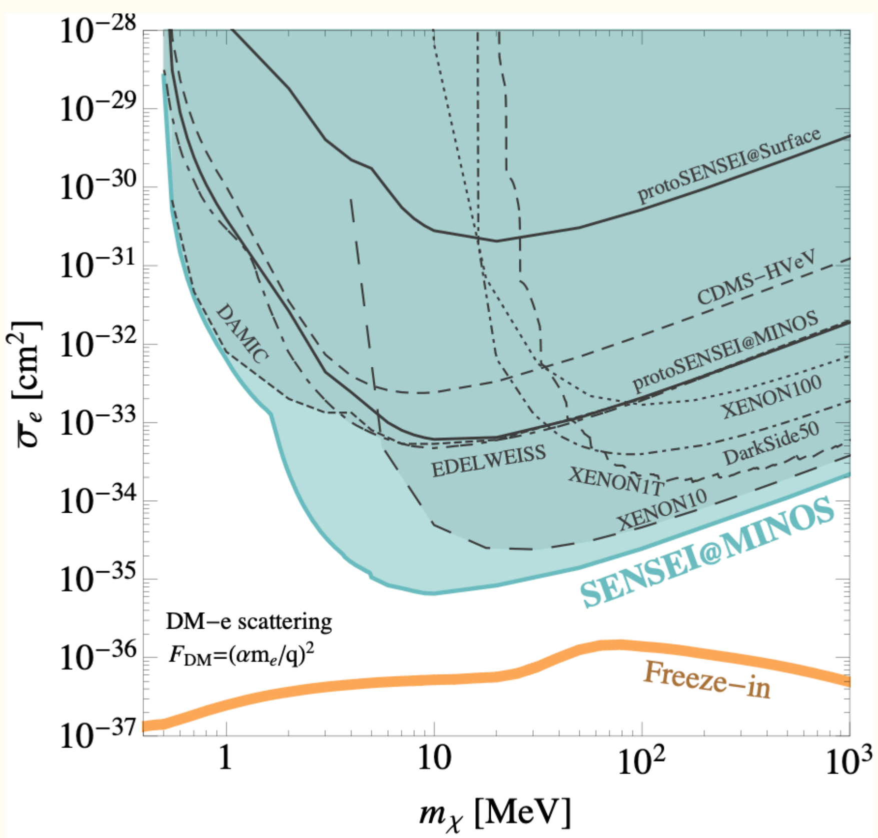
The SENSEI Collaboration

2017	2018	2019	2020	2021	2022	...
Proof-of-concept Single-electron Sensitivity	**DM Surface run** *w/ proto-SENSEI*	**DM MINOS run** *w/ proto-SENSEI*	**DM MINOS run** *w/ science-grade* SENSEI			



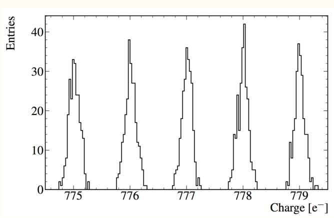


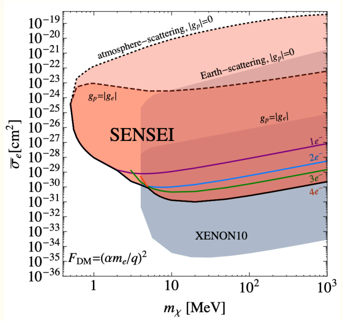


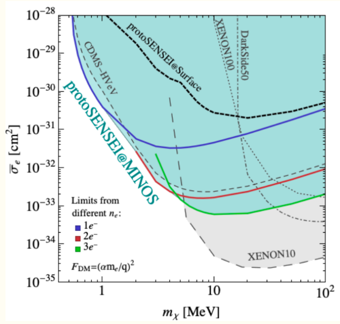


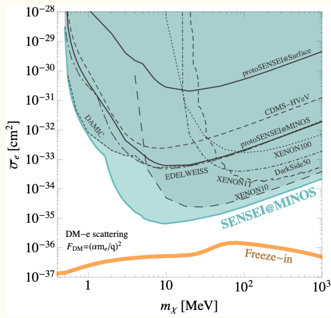
The SENSEI Collaboration

2017	2018	2019	2020	2021	2022	…
Proof-of-concept Single-electron Sensitivity	**DM Surface run** w/ *proto-SENSEI*	**DM MINOS run** w/ *proto-SENSEI*	**DM MINOS run** w/ *science-grade* SENSEI	**Background Characterization** w/ *science-grade SENSEI*		



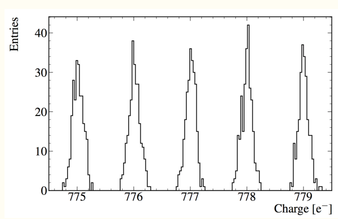


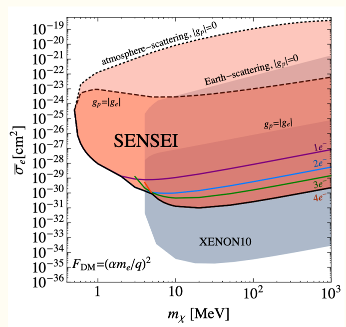


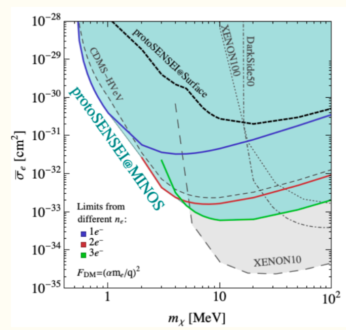


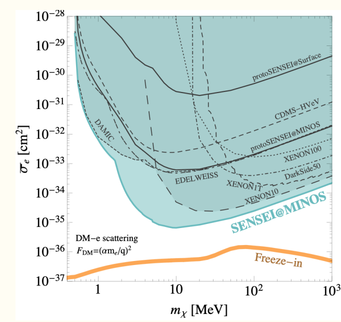
The SENSEI Collaboration

2017	2018	2019	2020	2021	2022	. . .
Proof-of-concept Single-electron Sensitivity	**DM Surface run** *w/ proto-SENSEI*	**DM MINOS run** *w/ proto-SENSEI*	**DM MINOS run** *w/ science-grade* SENSEI	**Background Characterization** *w/ science-grade SENSEI*	**Compton and Fano-Factor** *w/ science-grade* **DM MINOS run** *w/ science-grade* SENSEI **DM MINOS Modulation run** *w/ science-grade* SENSEI **DM SNOLAB-10 run** *w/ science-grade* SENSEI	





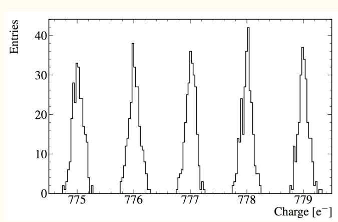




The SENSEI Collaboration

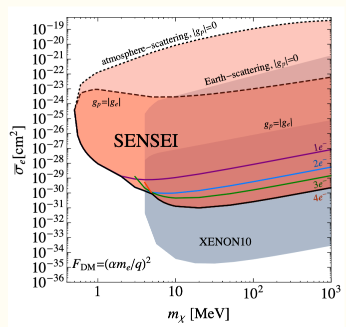
2017

Proof-of-concept
Single-electron Sensitivity



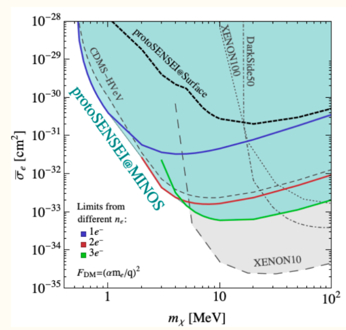
2018

DM Surface run
w/ proto-SENSEI



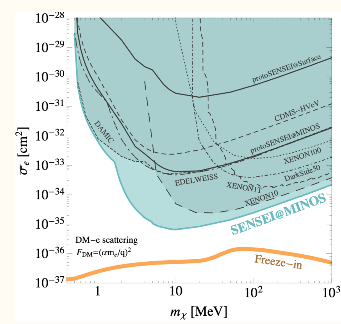
2019

DM MINOS run
w/ proto-SENSEI



2020

DM MINOS run
w/ science-grade
SENSEI



2021

Background Characterization
w/ science-grade SENSEI

2022

Compton and Fano-Factor
w/ science-grade

DM MINOS run
w/ science-grade
SENSEI

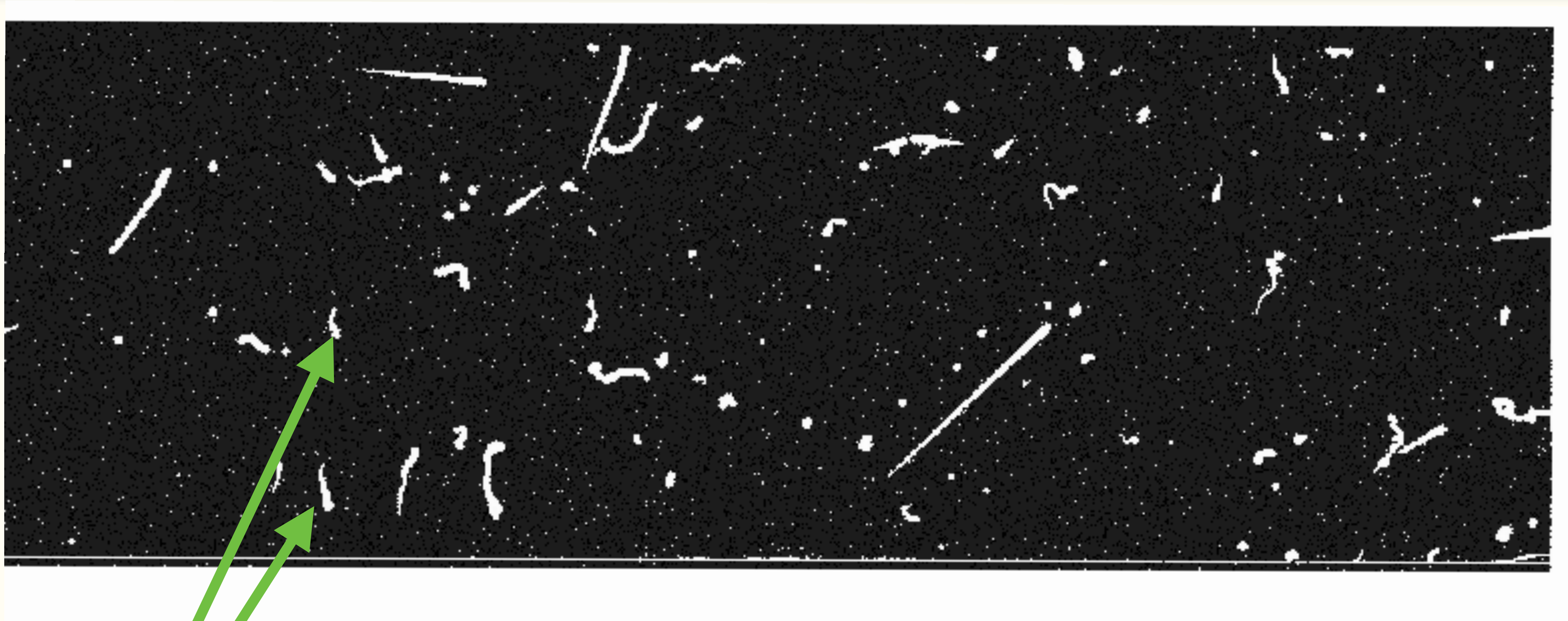
DM MINOS Modulation run
w/ science-grade
SENSEI

DM SNOLAB-10 run
w/ science-grade
SENSEI

. . .

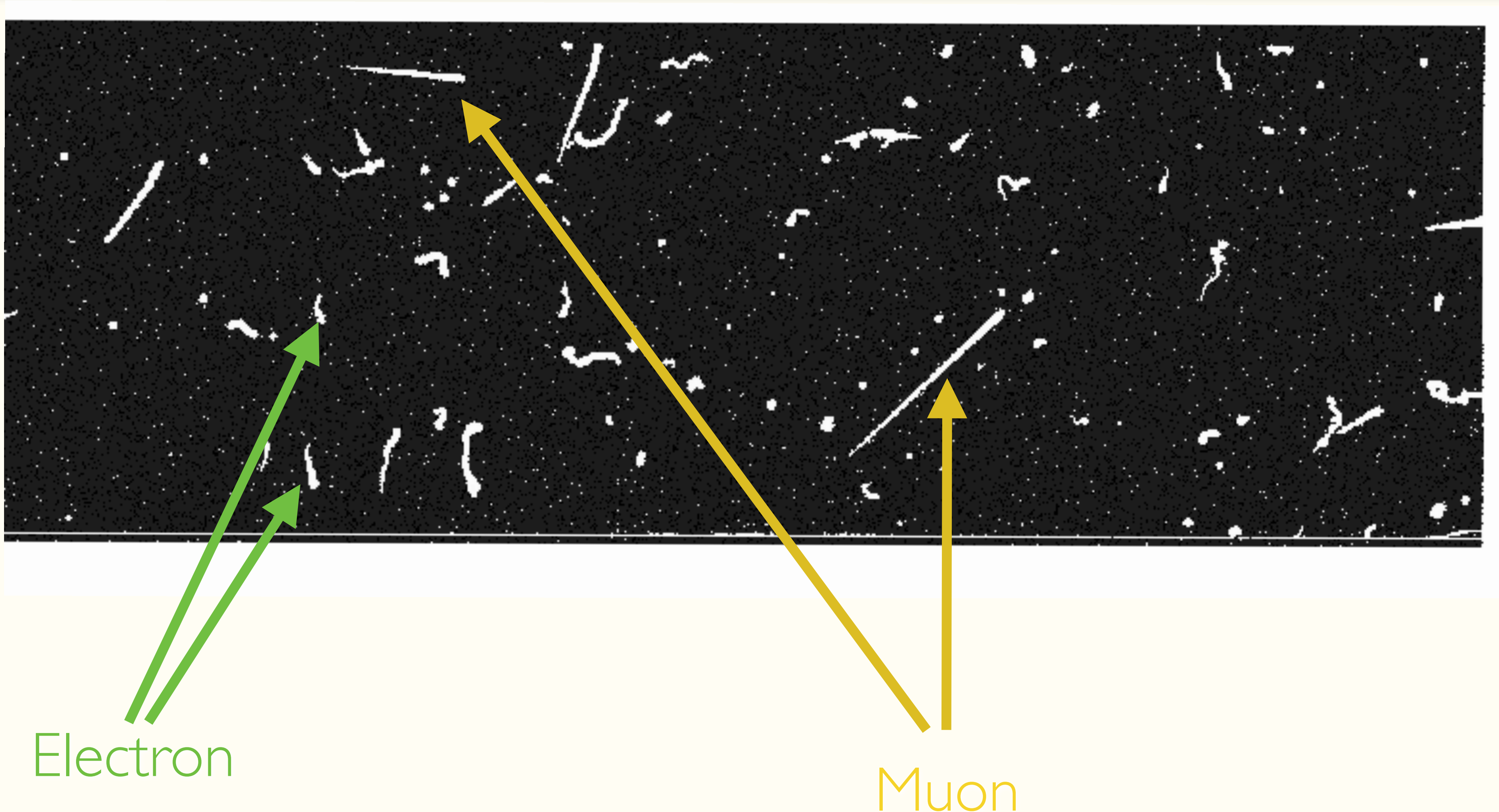
SENSEI: 2020 DM Result

SENSEI: 2020 DM Result

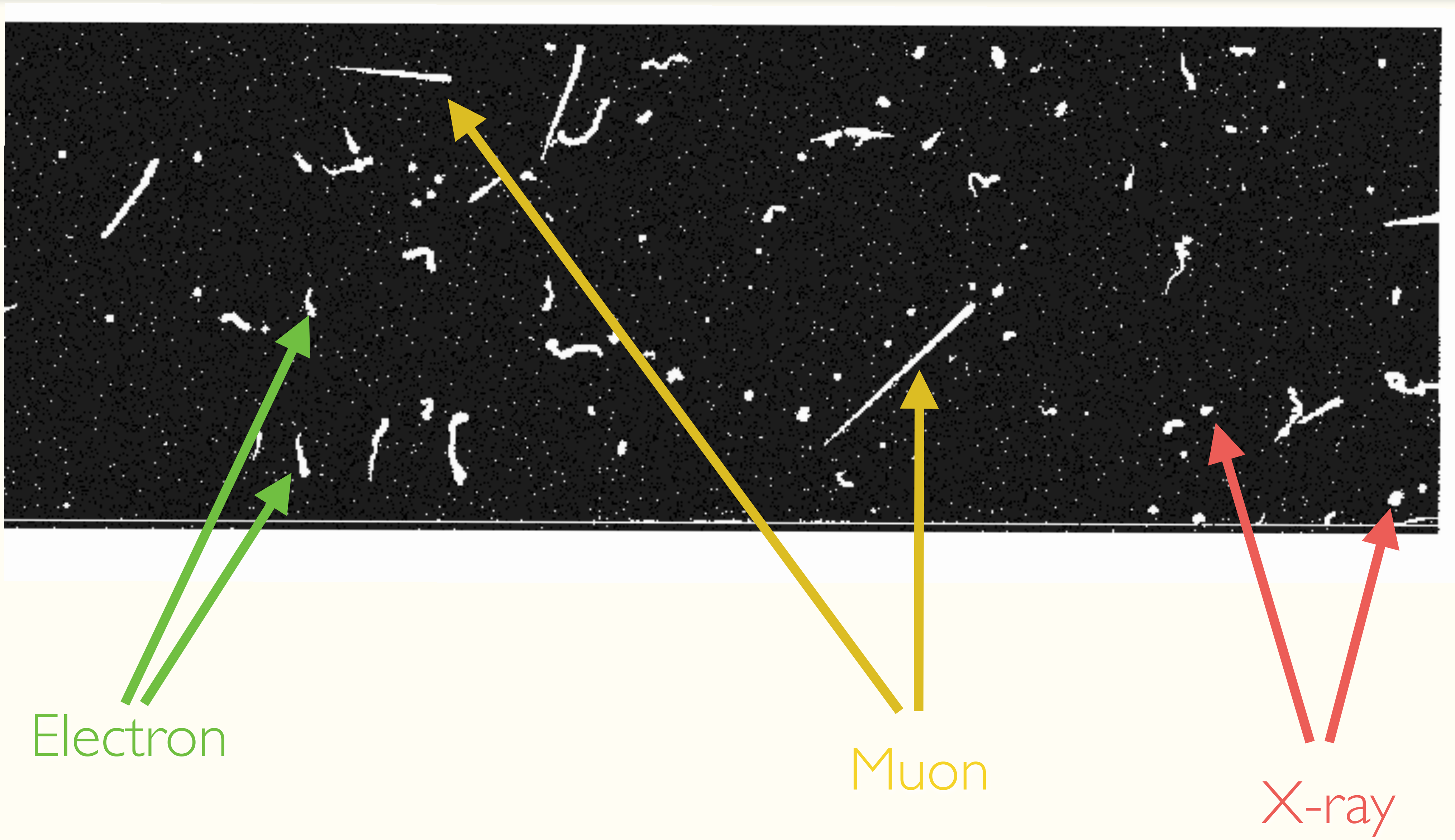


Electron

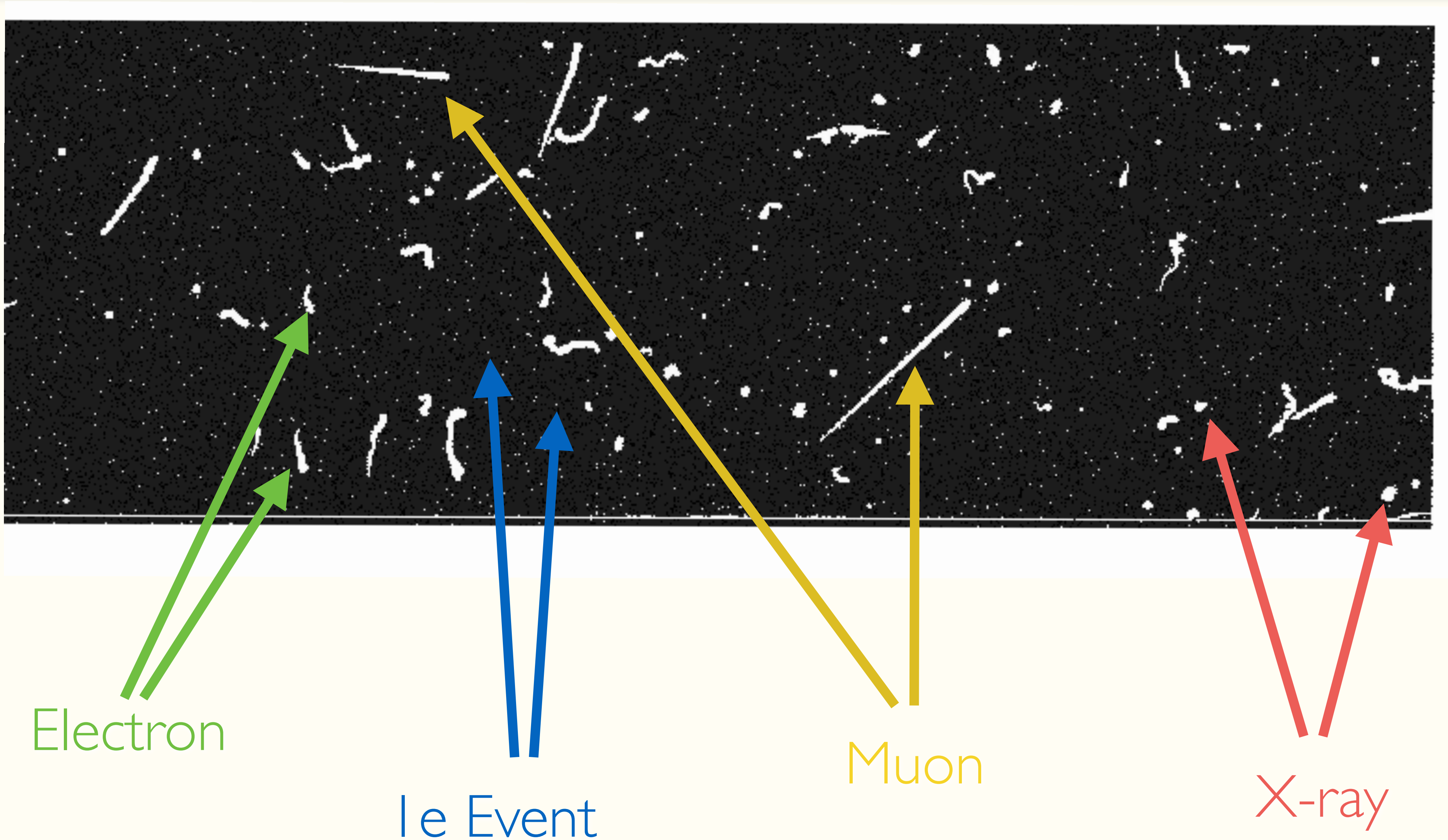
SENSEI: 2020 DM Result



SENSEI: 2020 DM Result



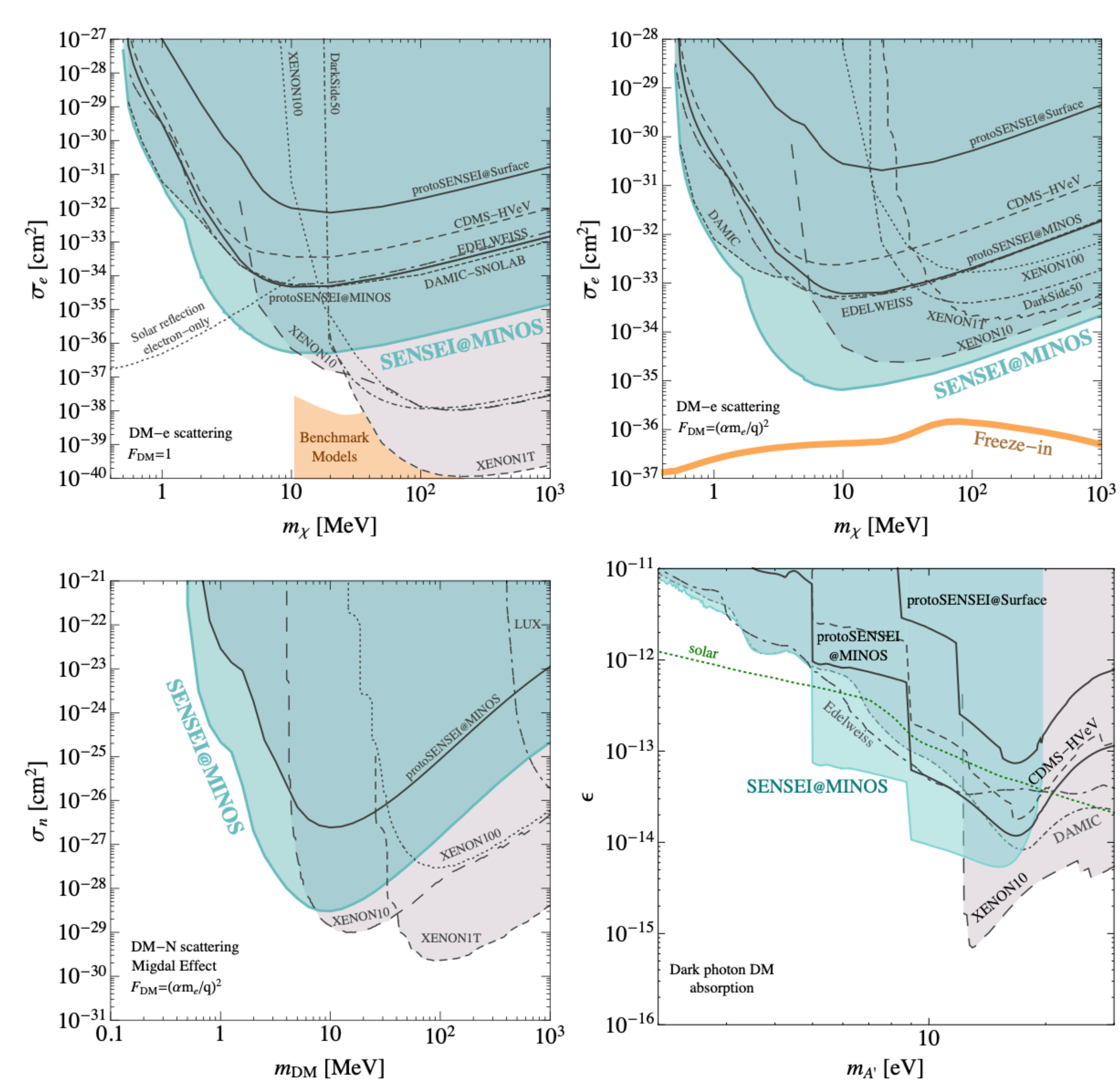
SENSEI: 2020 DM Result



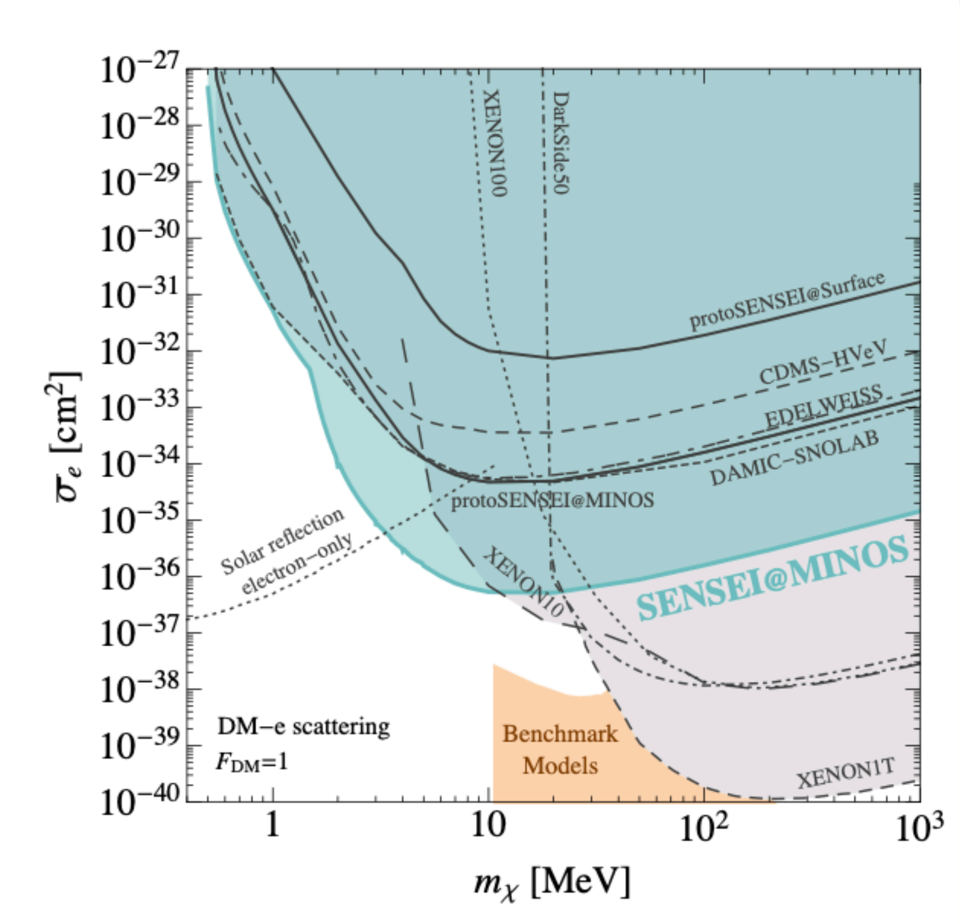
SENSEI: 2020 DM Result

Cuts \ N_e	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	0.69	35	0.69	7
6. Edge	0.70	25585	0.90	70	0.93	8	0.93	2
7. Bleeding Zone	0.60	11317	0.79	36	0.87	7	0.87	2
8. Bad Pixel/Col.	0.98	10711	0.98	24	0.98	2	0.98	0
9. Halo	0.18	1335	0.81	11	~ 1	2	~ 1	0
10. Loose Cluster	N/A		0.89	5	0.84	0	0.84	0
11. Neighbor	~ 1	1329	~ 1	5	N/A			
Total Efficiency	0.069		0.105		0.341		0.349	
Eff. Efficiency	0.069		0.105		0.325		0.327	
Eff. Exp. [g-day]	1.38		2.09		9.03		9.10	
Observed Events	1311.7$^{(*)}$		5		0		0	
90%CL [g-day]$^{-1}$	525.2$^{(*)}$		4.449		0.255		0.253	

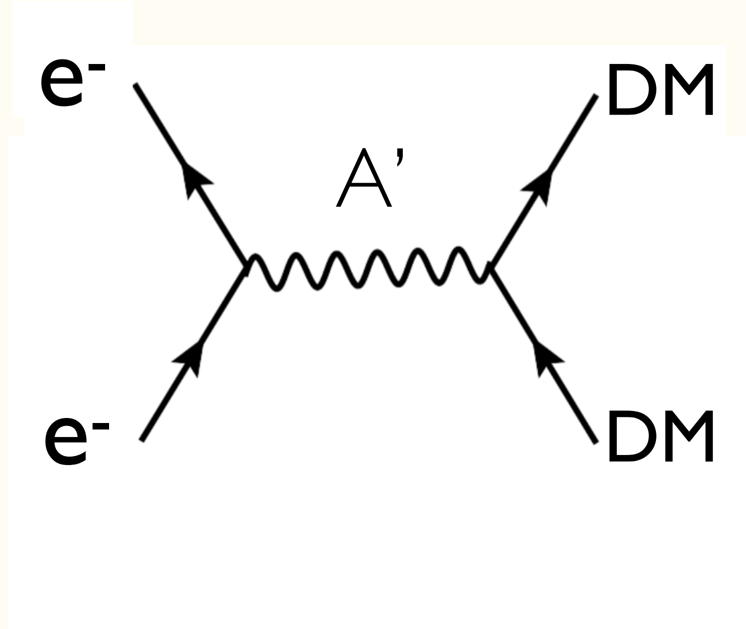
SENSEI: 2020 DM Result

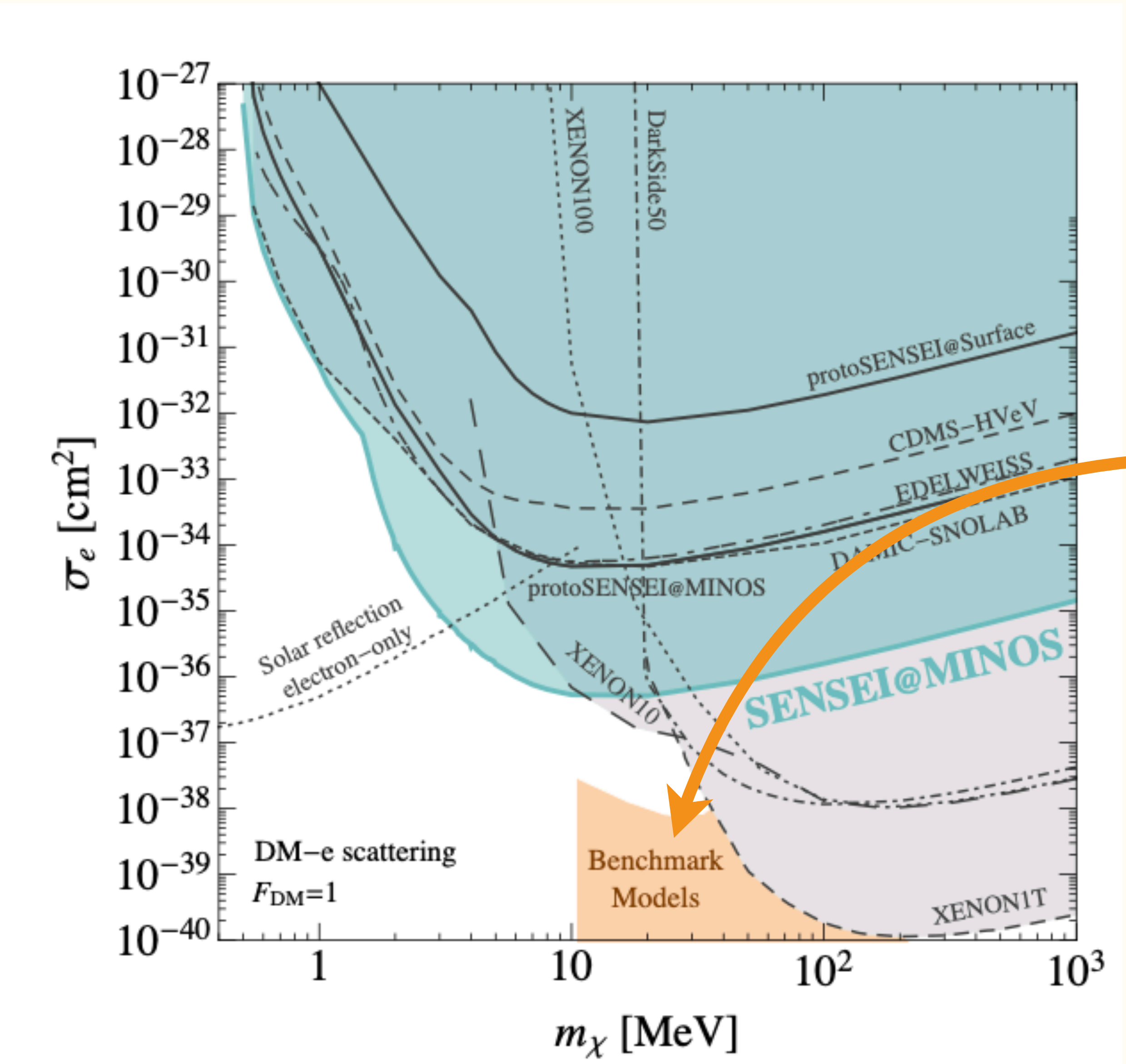


SENSEI: 2020 DM Result



SENSEI: 2020 DM Result



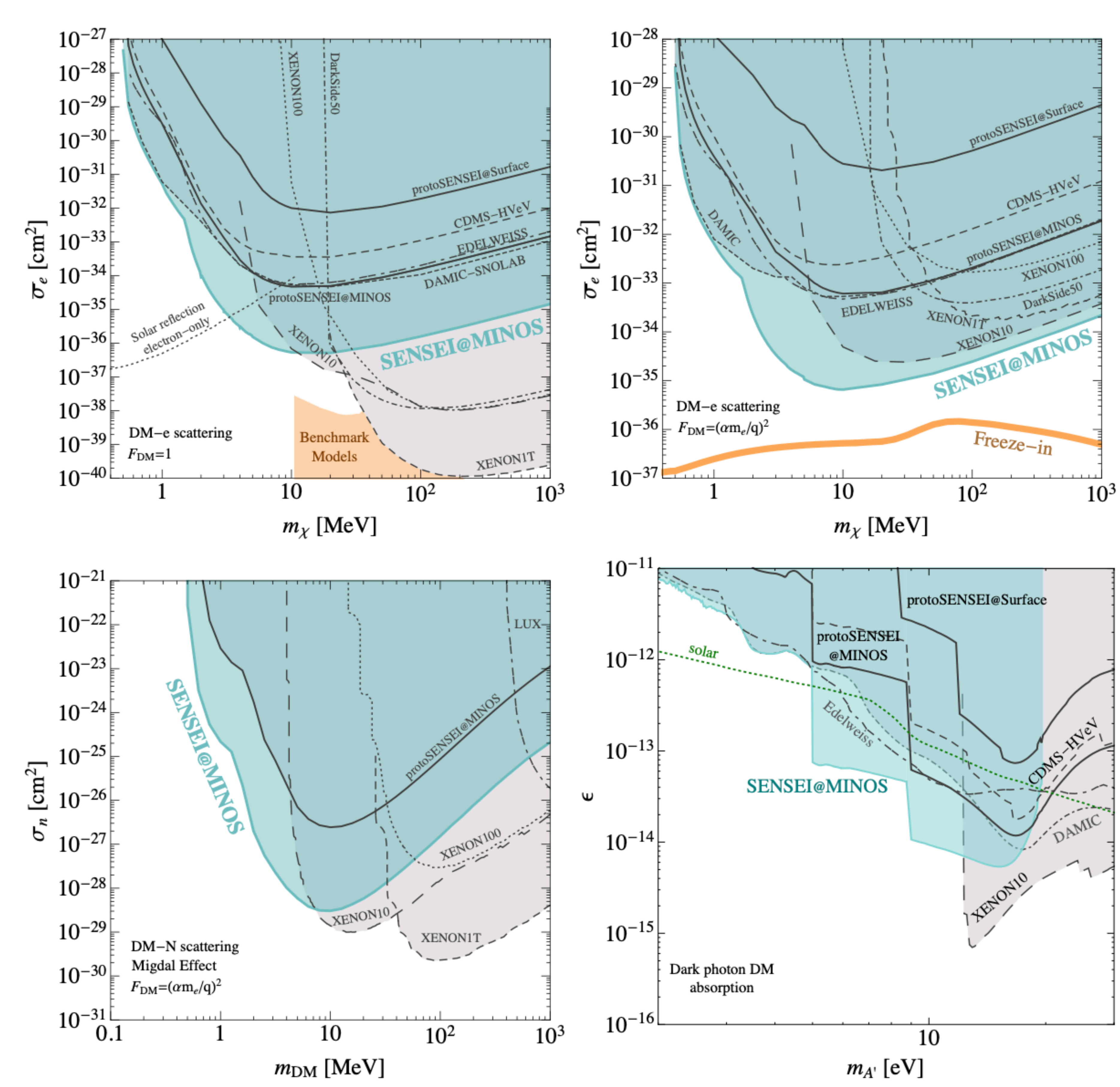


Heavy mediator models

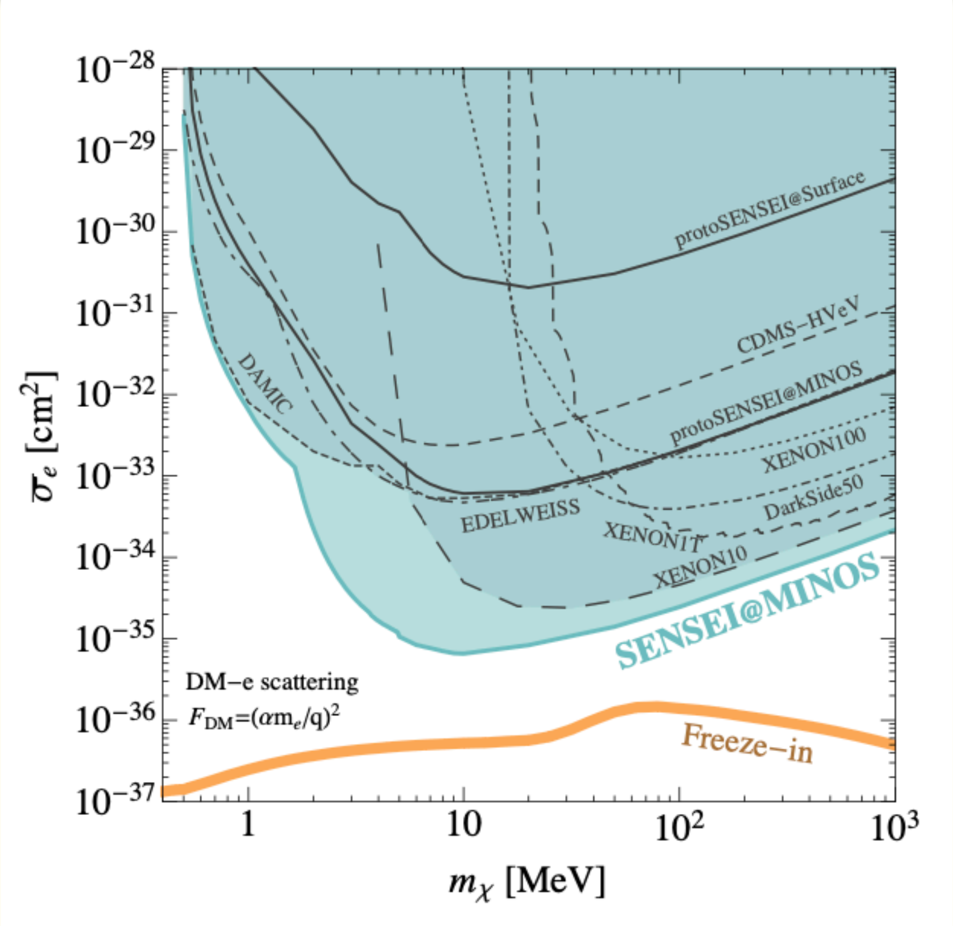
Many production mechanisms:
asymmetric, 2-2 & 3-2 freeze-out, etc.

Boehm, Fayet 2003
Essig, Mardon, TV 2011
Essig, Fernandez-Serra, Soto, Mardon, TV, Yu 2015
Hochberg, Kuflik, TV, Wacker, 2014
Kuflik, Perelstein, Lorier, Tsai, 2017
D'Agnolo, Pappadopulo, Ruderman, 2019
…

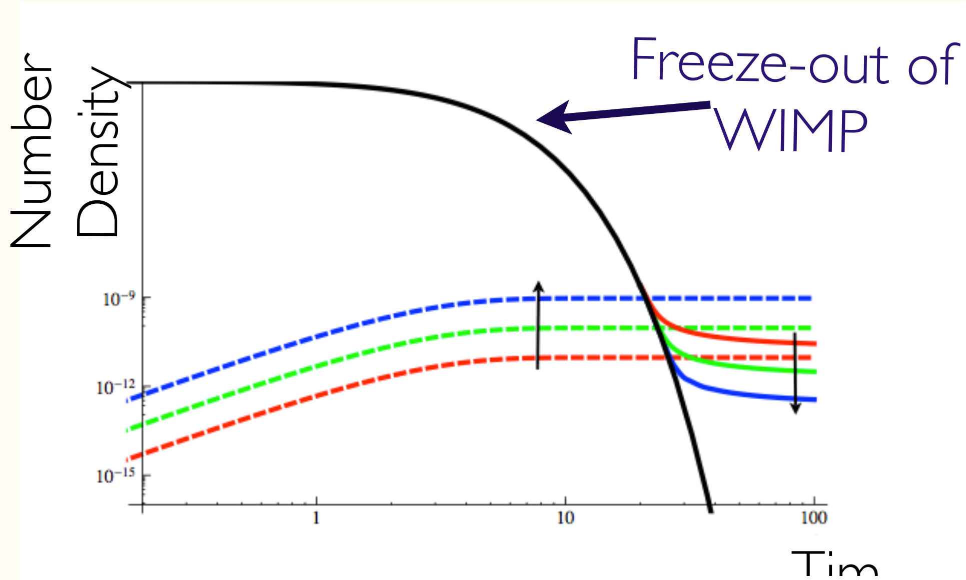
SENSEI: 2020 DM Result

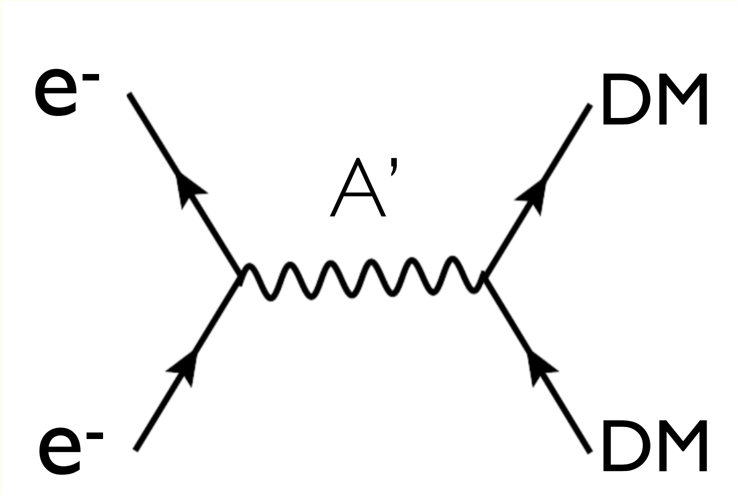


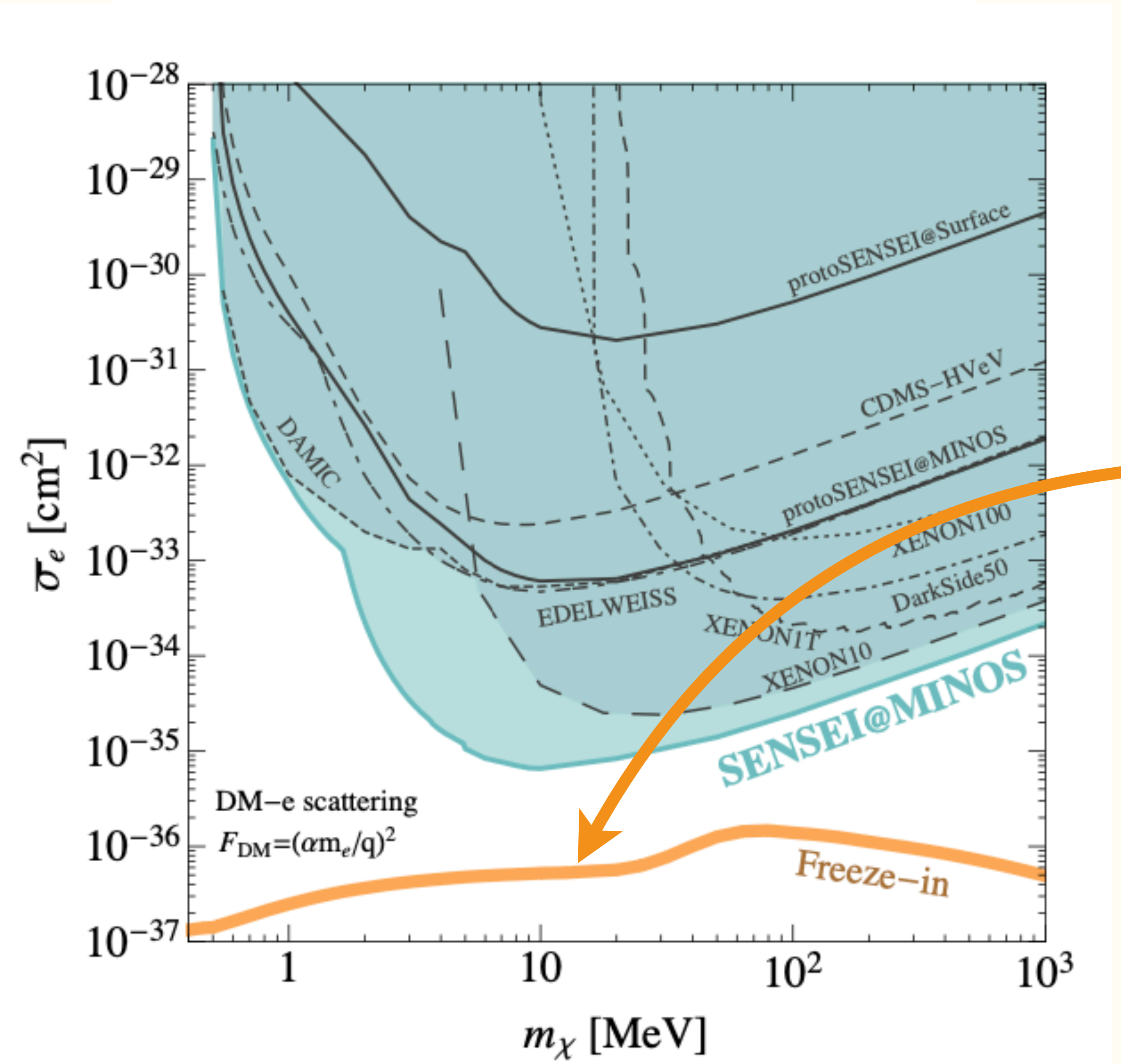
SENSEI: Latest results



SENSEI: Latest results





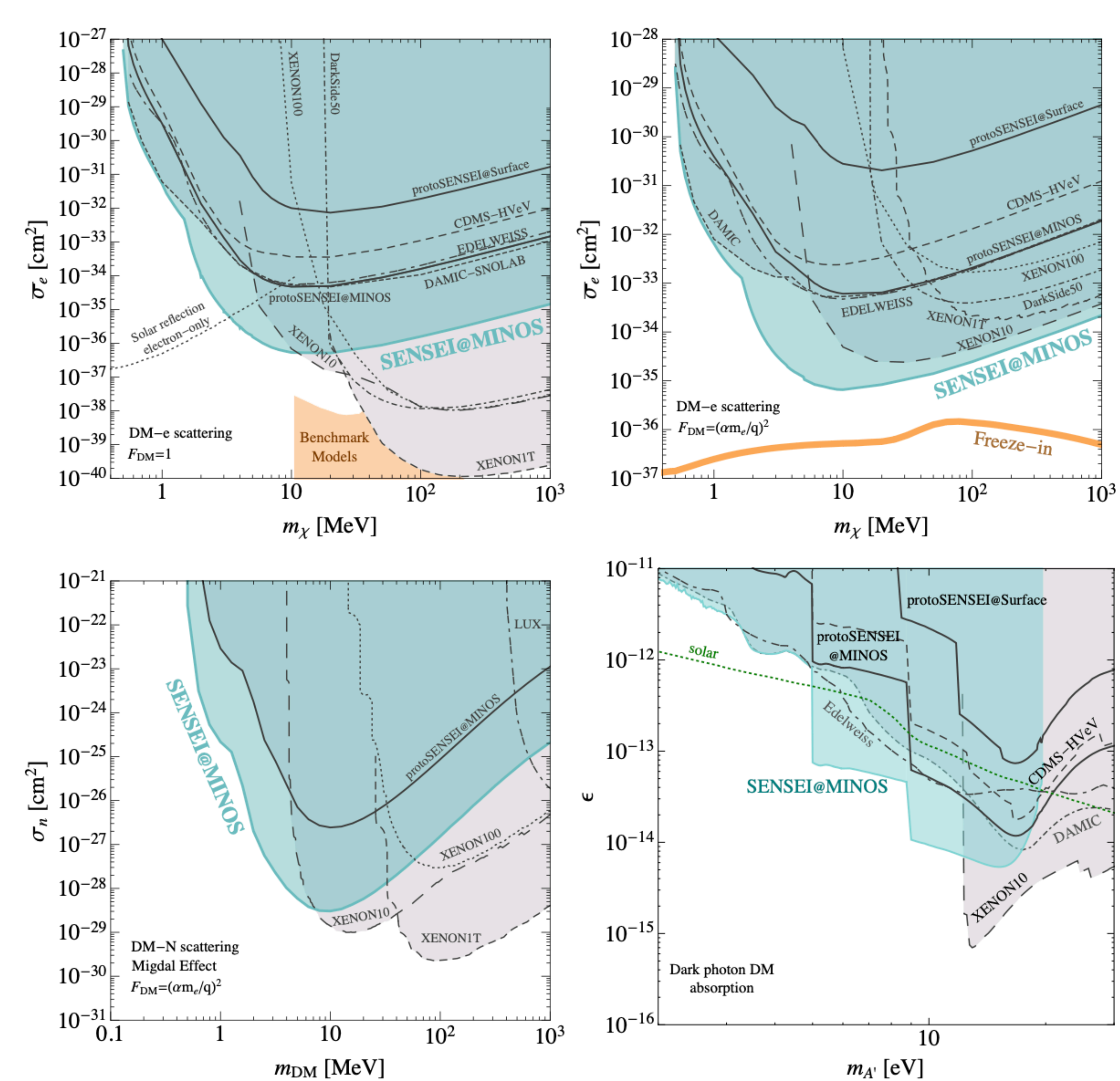


Freeze-In

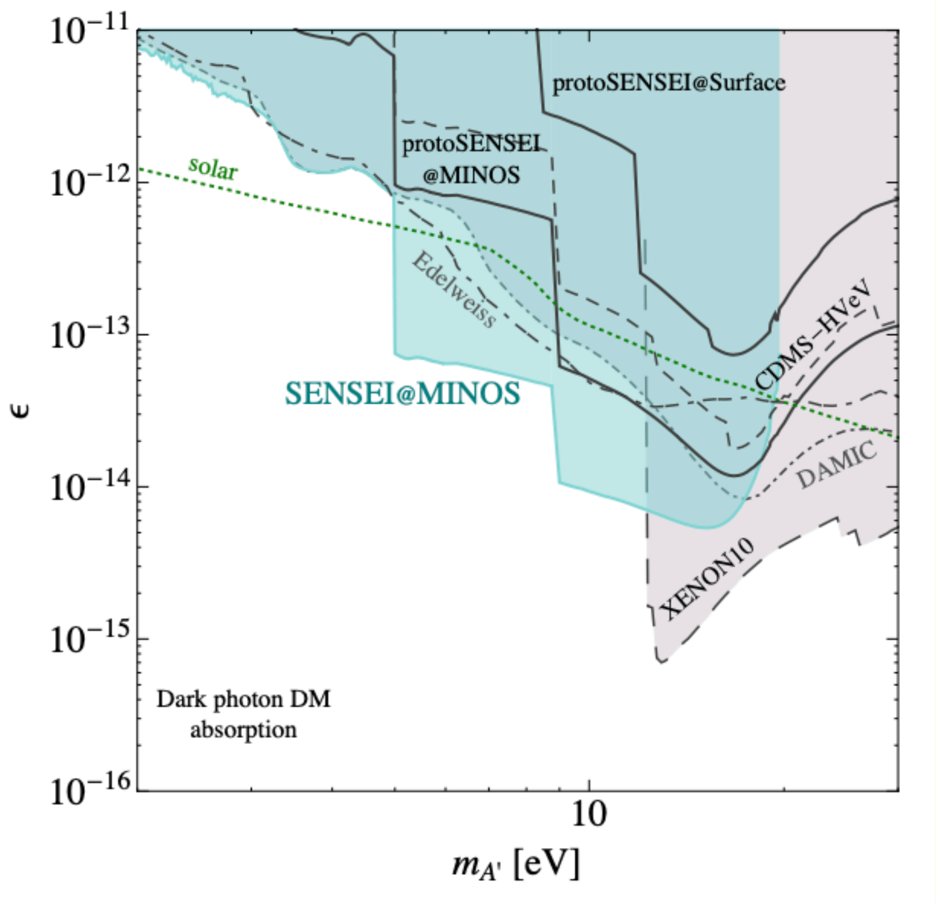
Essig, Mardon, TV 2011
Chu, Hambye, Tytgat, 2011
Essig, Fernandez-Serra, Soto, Mardon, TV, Yu 2015

- Very light mediator.
- Couplings very small.
- DM never thermalizes.
- Irreducible production mechanism.

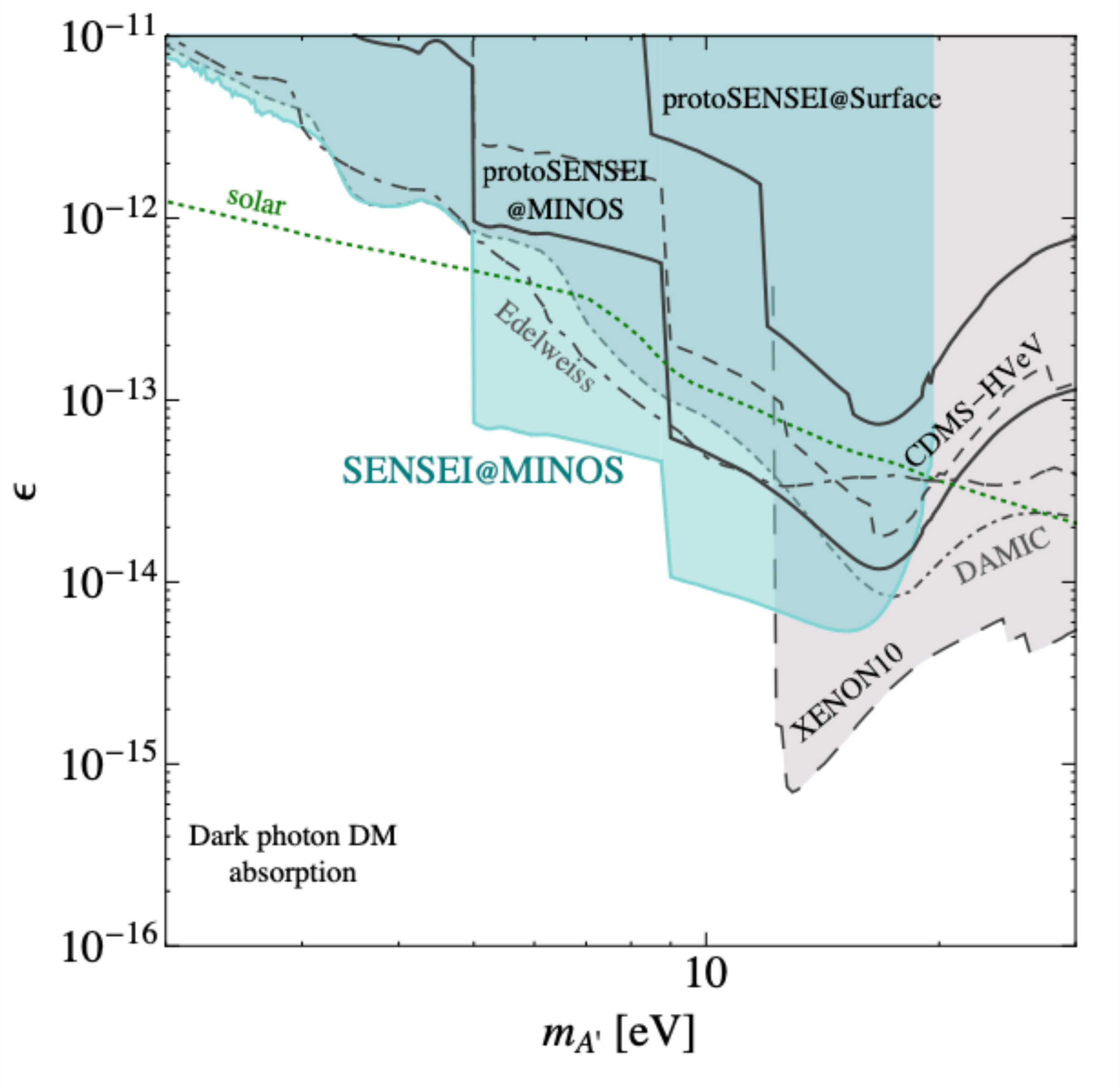
SENSEI: 2020 DM Result

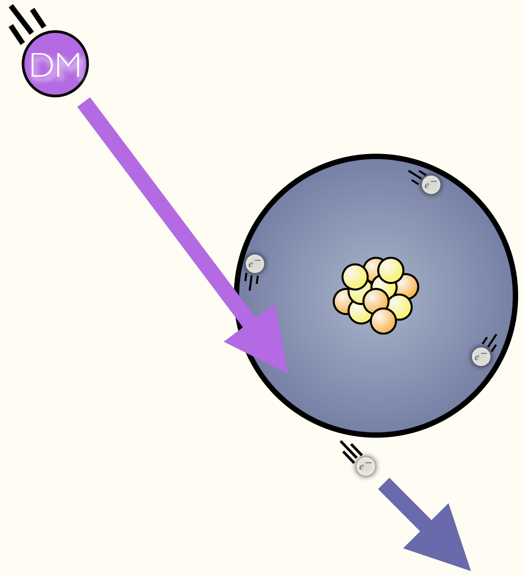


SENSEI: 2020 DM Result



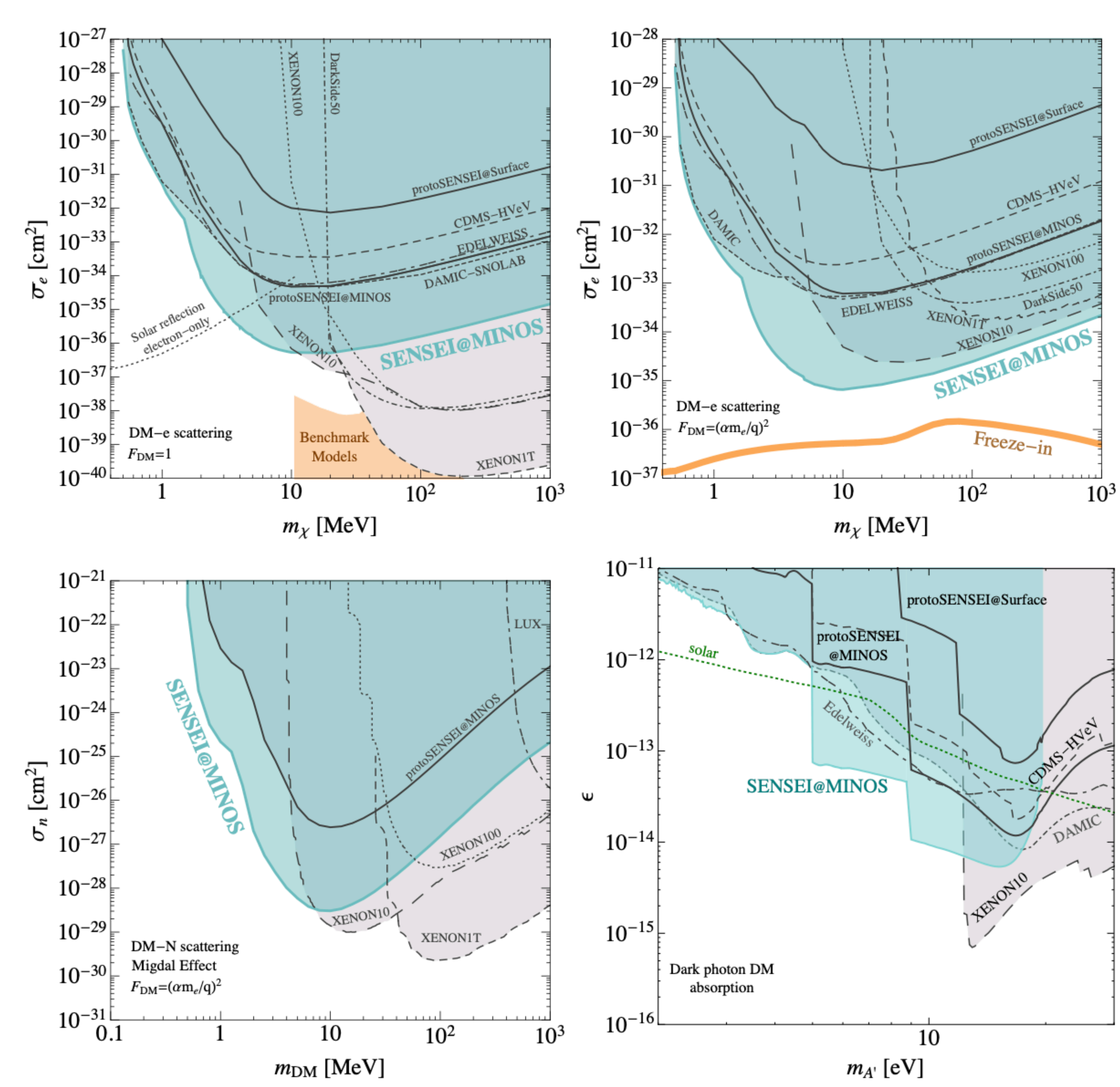
SENSEI: 2020 DM Result



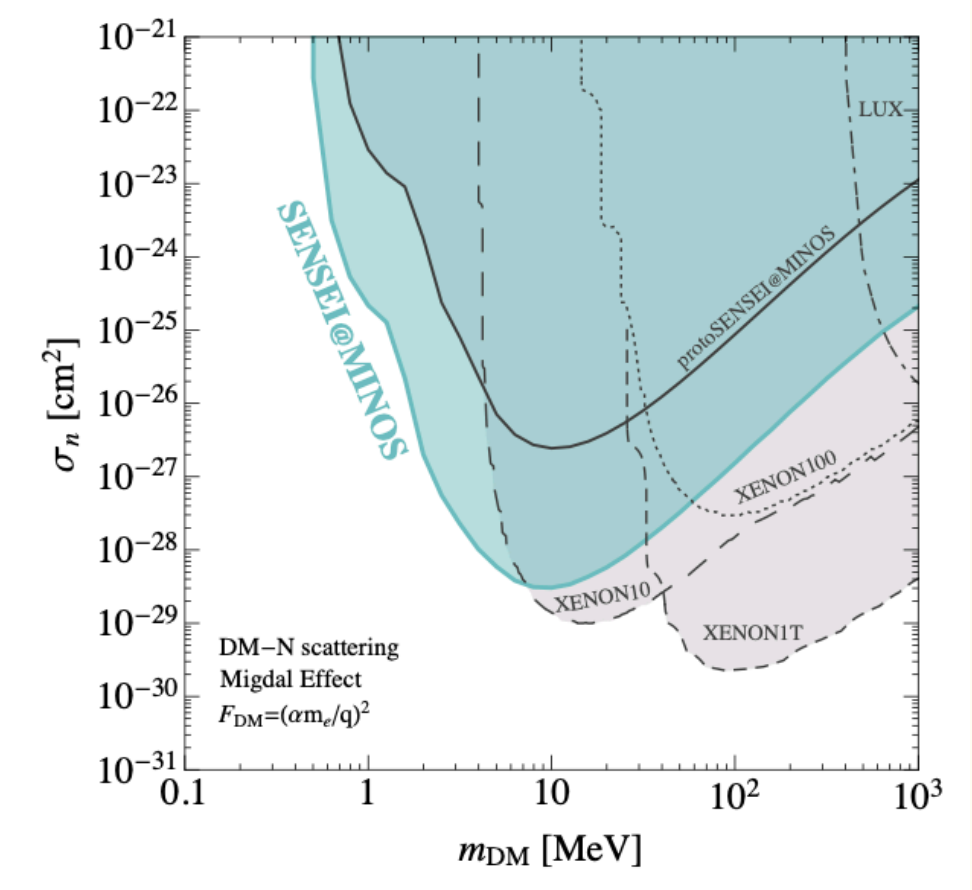


DM Absorption

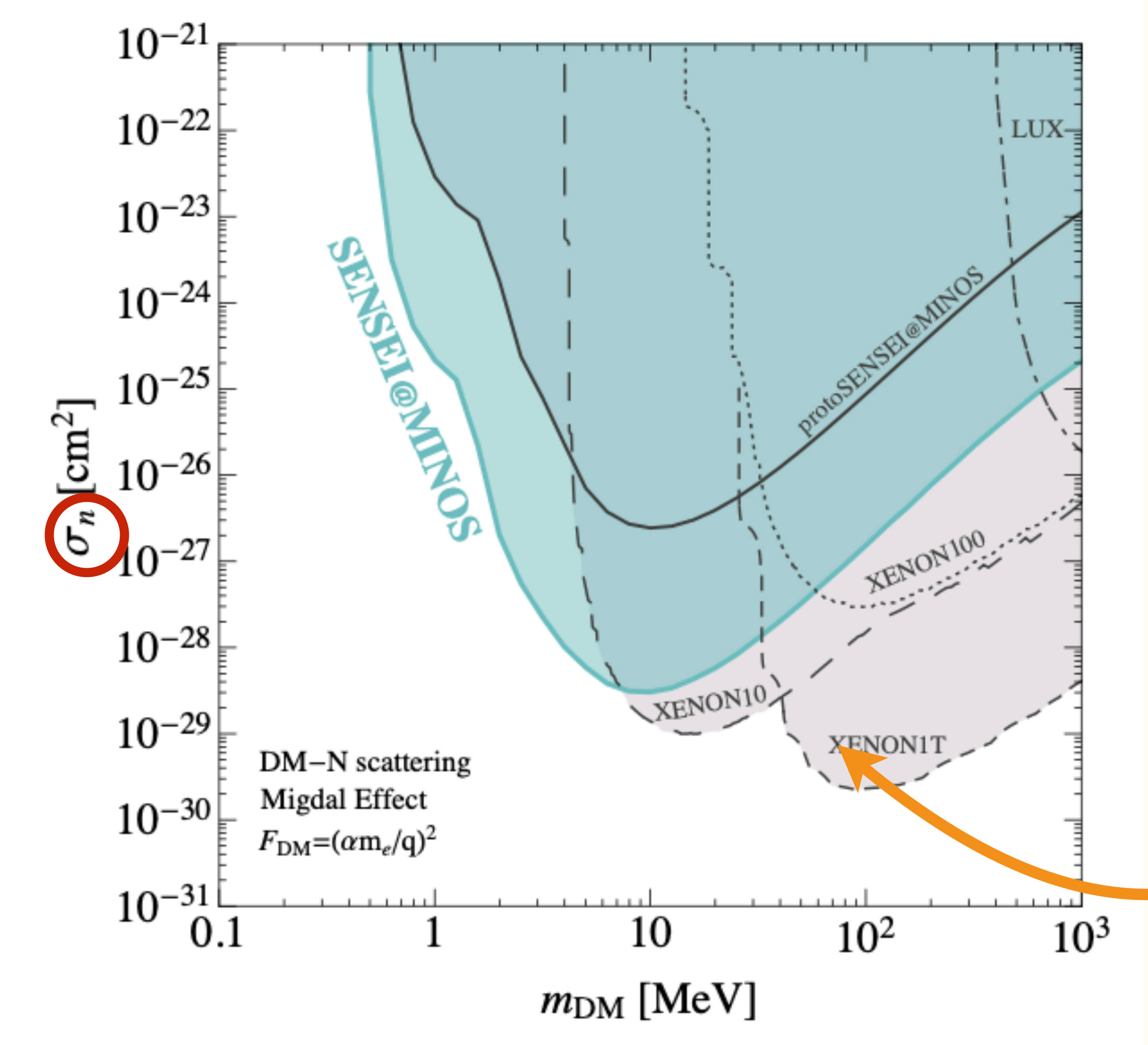
SENSEI: 2020 DM Result



SENSEI: 2020 DM Result



SENSEI: 2020 DM Result

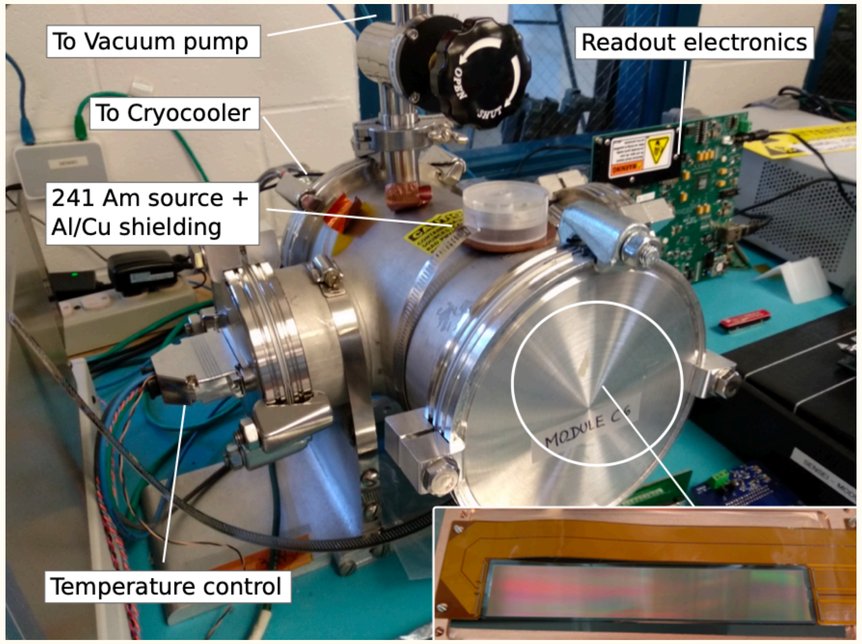


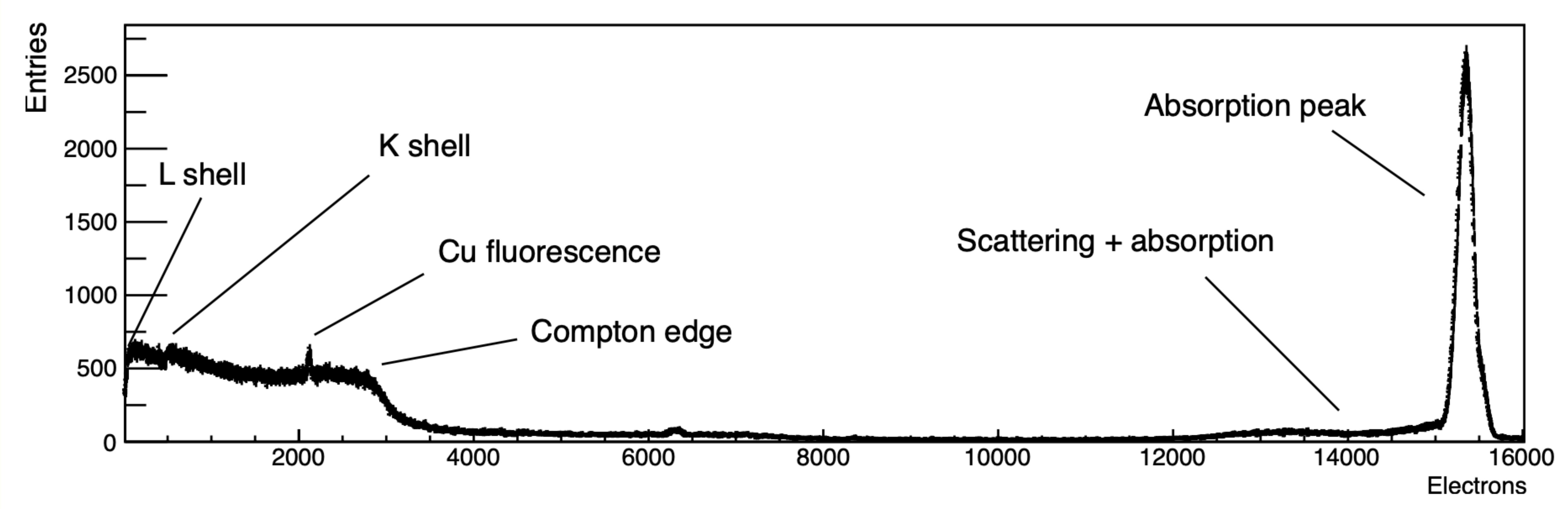
The Migdal Scattering

Scattering with nucleons

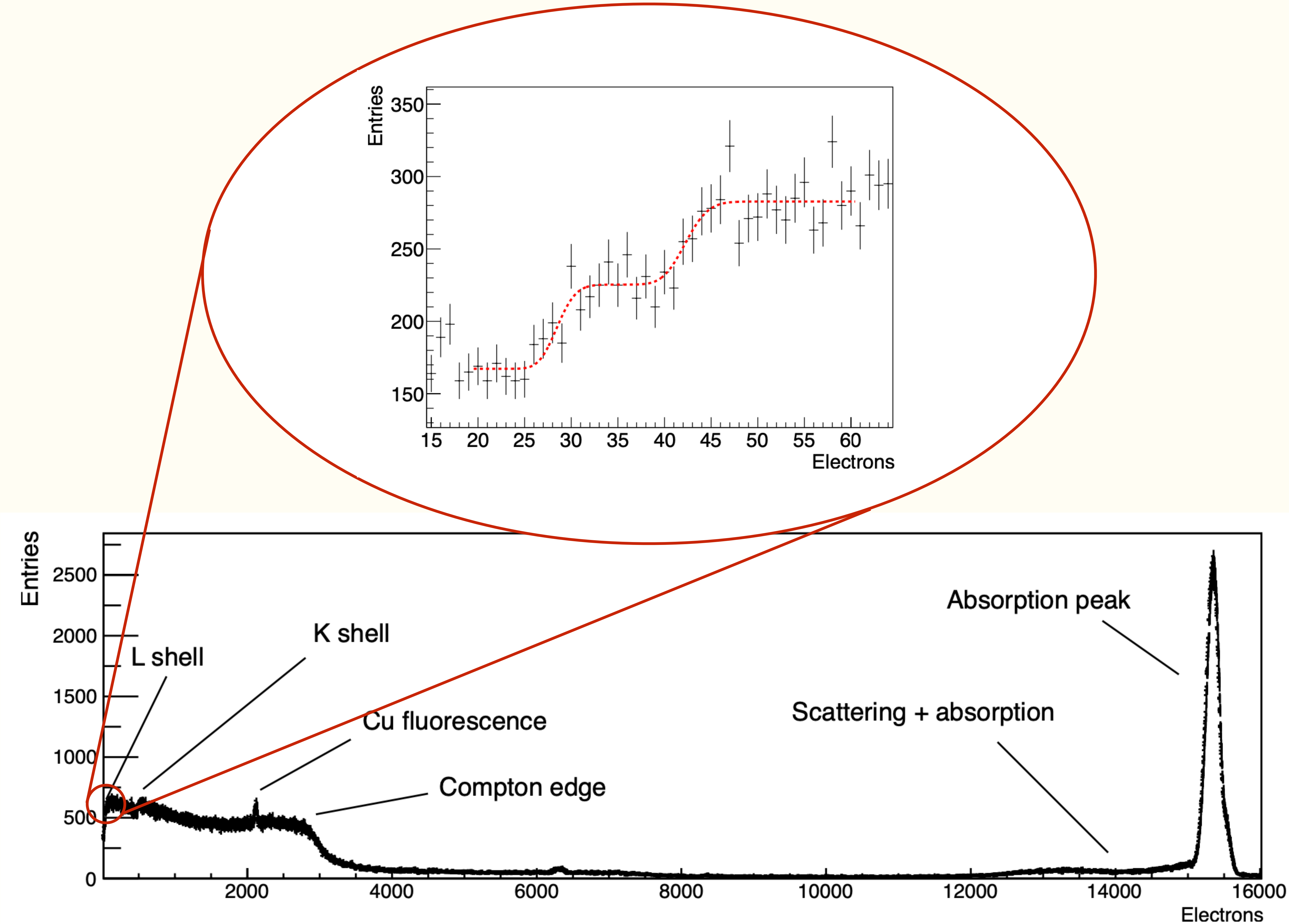
SENSEI(-related): Compton and Fano Factor

- Compton scattering is a background: high-energy photons can deposit small ionizing energy.
- Until recently, was never measured at low energy.

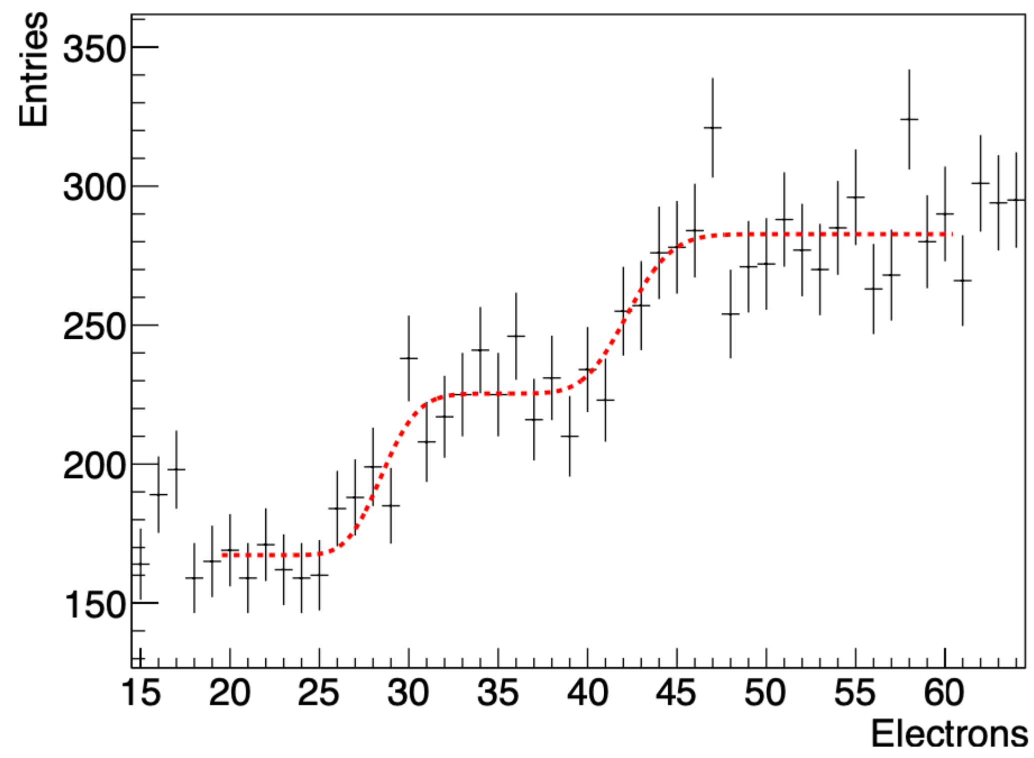




SENSEI(-related): Compton and Fano Factor



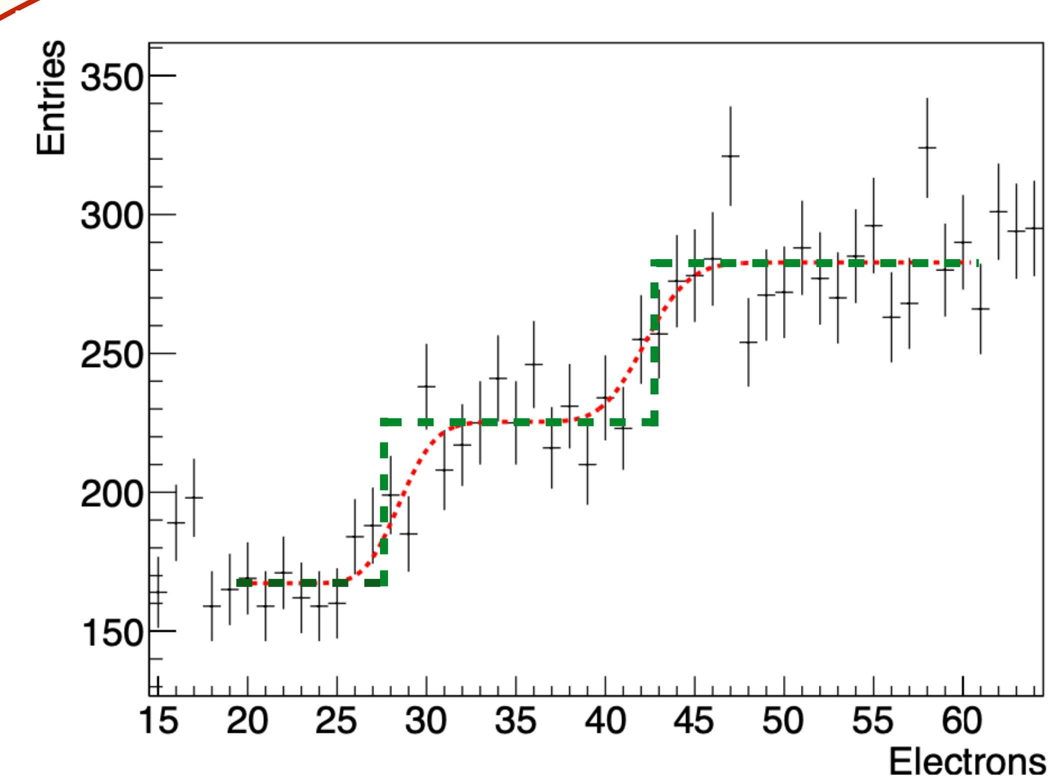
SENSEI(-related): Compton and Fano Factor



$$Q(E_e) = 1 + \left[(E_e - E_{gap})/\epsilon\right]$$

$E_{gap} = 1.11$ eV
$\epsilon = 3.71$ eV

SENSEI(-related): Compton and Fano Factor

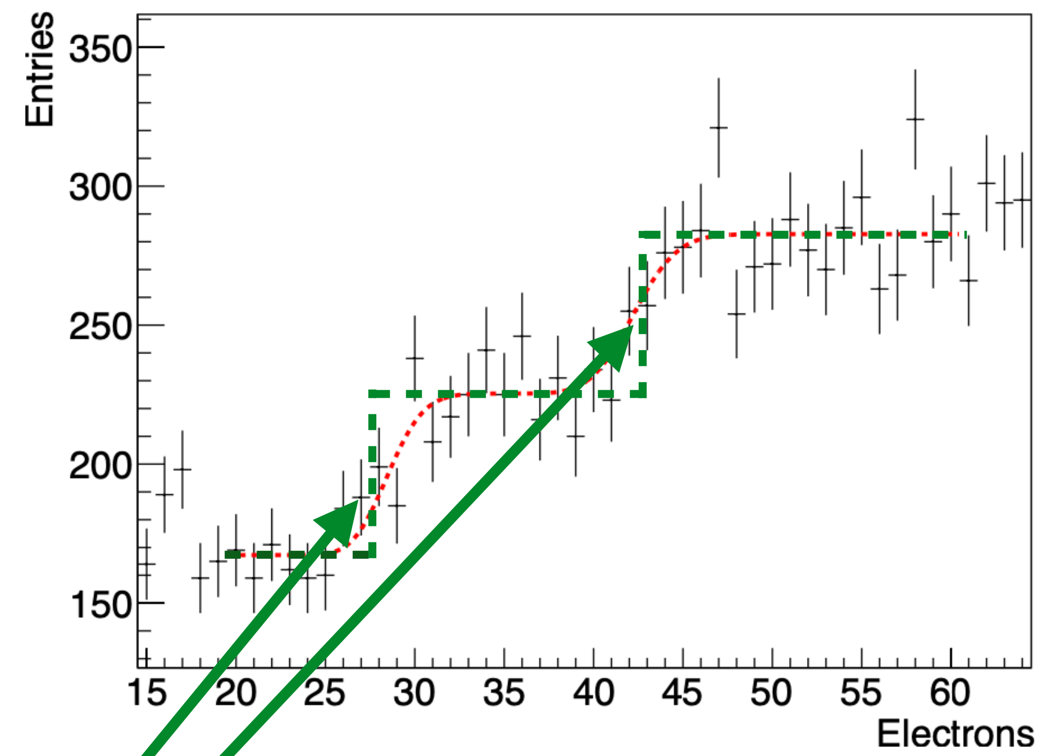


$$Q(E_e) = 1 + \left[(E_e - E_{\text{gap}})/\epsilon \right]$$

$E_{\text{gap}} = 1.11$ eV

$\epsilon = 3.71$ eV

SENSEI(-related): Compton and Fano Factor

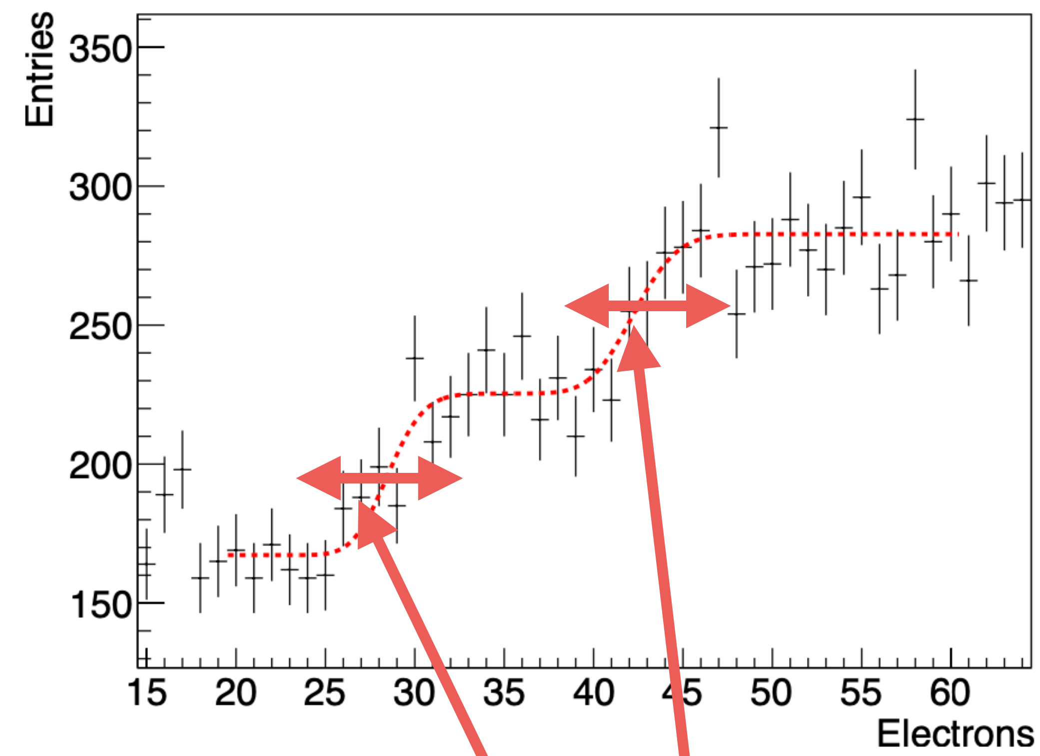


$$Q(E_e) = 1 + \left[(E_e - E_{gap})/\epsilon \right]$$

$E_{gap} = 1.11$ eV
$\epsilon = 3.71$ eV

Known energy levels. Location can be used to extract ϵ

SENSEI(-related): Compton and Fano Factor



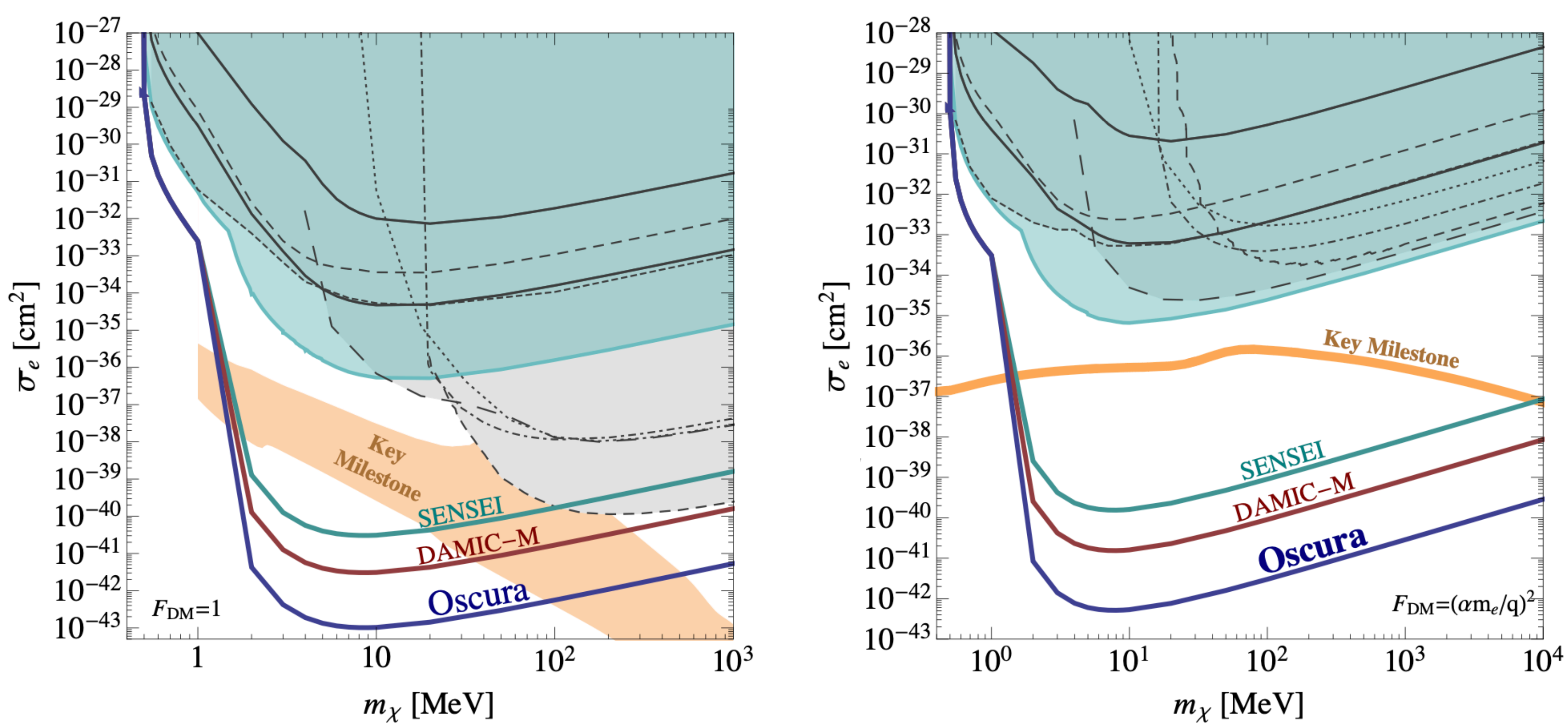
$$Q(E_e) = 1 + \left[(E_e - E_{gap})/\epsilon\right]$$

$$E_{gap} = 1.11 \text{ eV}$$
$$\epsilon = 3.71 \text{ eV}$$

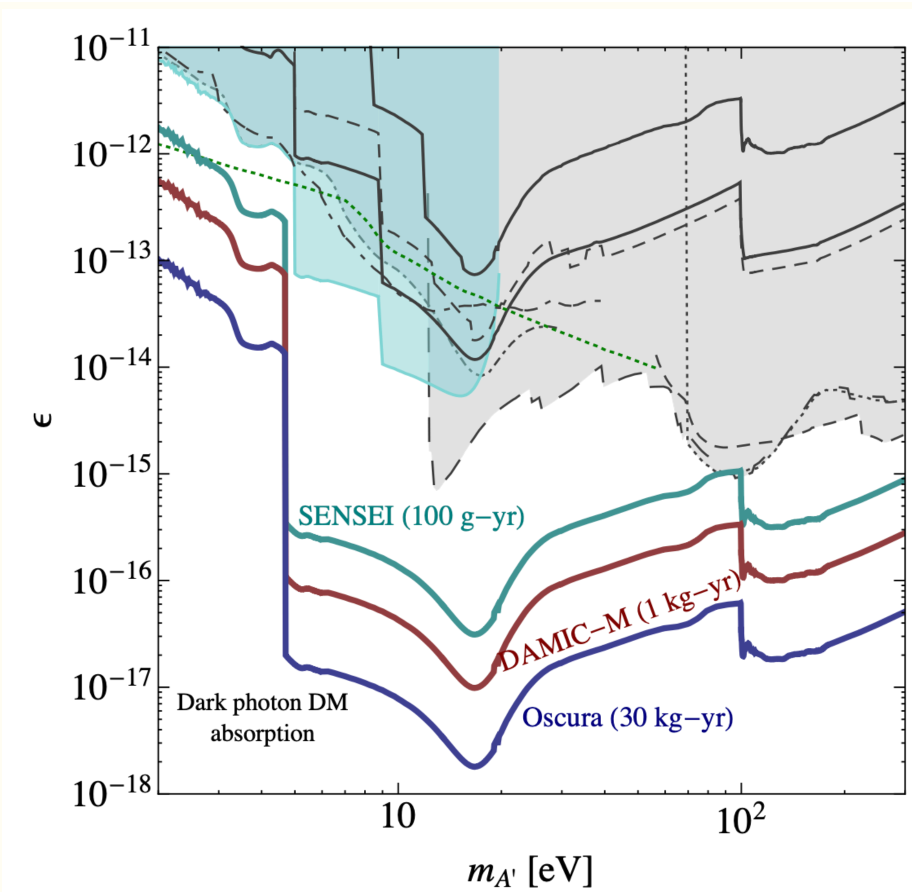
Width is related to the fluctuations around mean ionization: Fano factor

$$F = \frac{\sigma_Q^2}{\langle Q \rangle} \leq 0.31 \quad (90\,\%\,\mathrm{CL})$$

SENSEI and Beyond

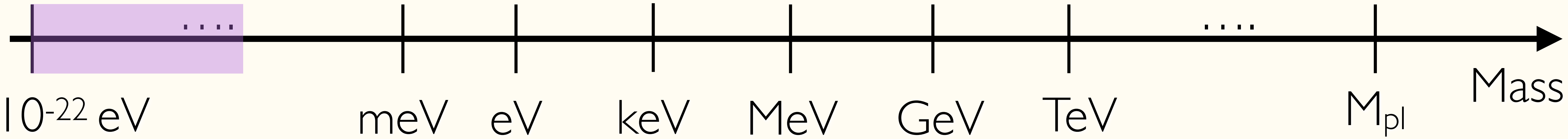


- SENSEI: 100 gram-yr (funded, SNOLAB, 2023-2025)
- DAMIC-M: 1 kg-year (funded, Modane, ~2023-..)
- Oscura: 30 kg-yr (R&D funded by DoE)



Direct Detection Frontier

Ultralight Dark Matter



Ultralight Dark Matter

We measure the DM mass density:

$$\rho_{\rm DM} \simeq 0.4\frac{\rm GeV}{\rm cm^3}$$

For DM with mass below eV:

$$0.4\frac{\rm GeV}{m_{\rm DM}{\rm cm}^3} \simeq n_{\rm DM} > 1/\lambda^3_{\rm de-Broglie} \sim m^3_{\rm DM}v^3$$

DM can be treated as a classical wave:

$$a \sim a_0 e^{ix^\mu p_\mu}$$

DM Scattering on targets is not what we want to search for!

Utilize coherent interactions

Ultralight Dark Matter: ALPs

DM with low mass must be a boson

Motivated example: the **Axion**

Why is the neutron dipole moment so small (the Strong CP Problem)

$$d_n < 1.8 \times 10^{-26}\,\mathrm{e\,cm}$$

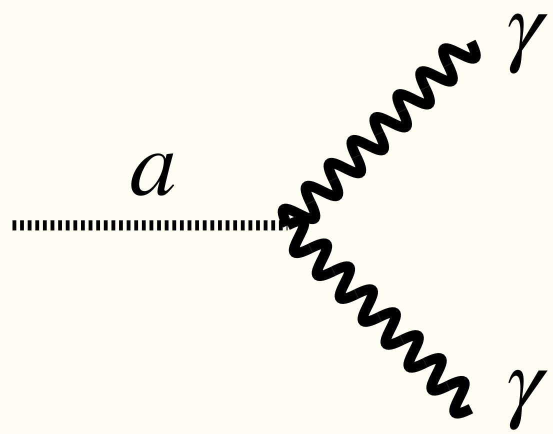
More motivated examples: Axion-like Particles (**ALPs**)

Found in many high-energy particle theories

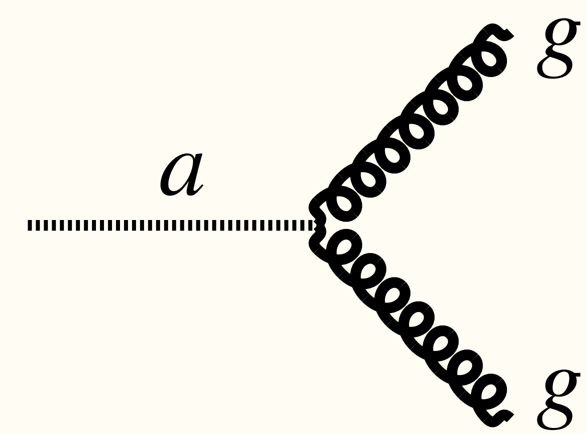
Can be very light

May have intricate implications on structure formation

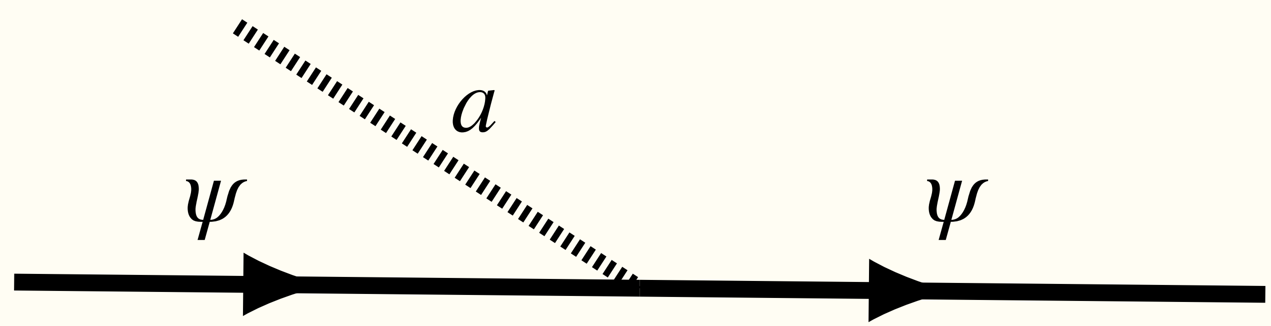
Ultralight Dark Matter: ALPs



$$-\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F}$$

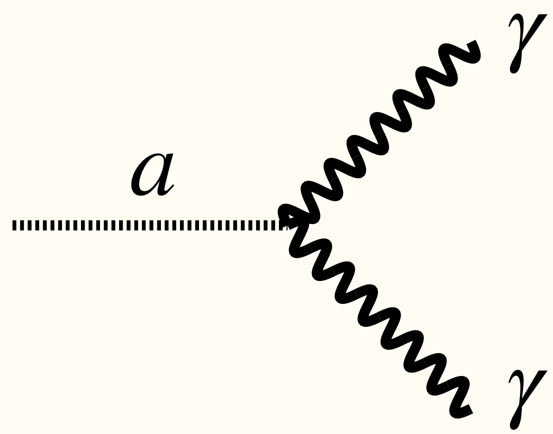


$$-\frac{a}{f_a}\frac{G\tilde{G}}{32\pi^2}$$

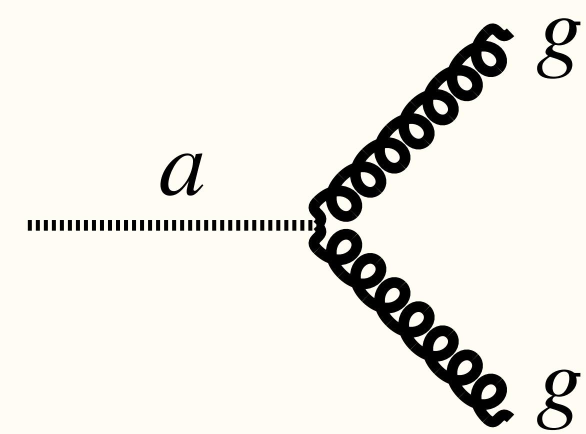


$$g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$$

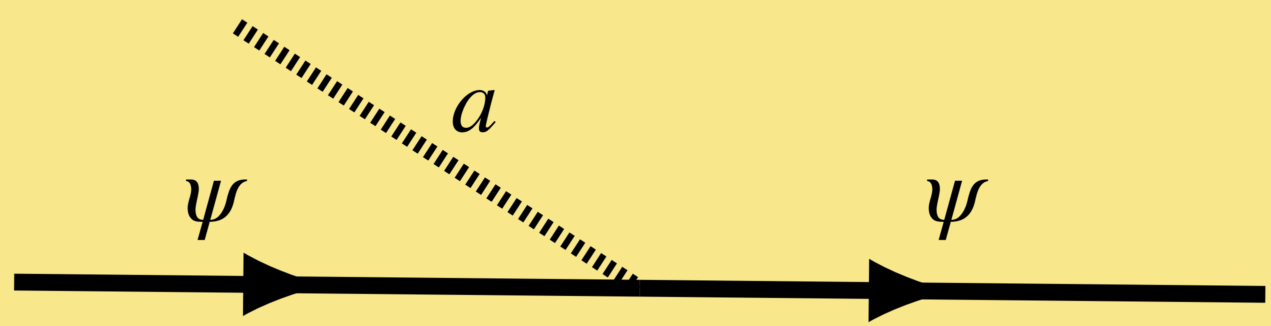
Ultralight Dark Matter: ALPs



$$-\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F}$$



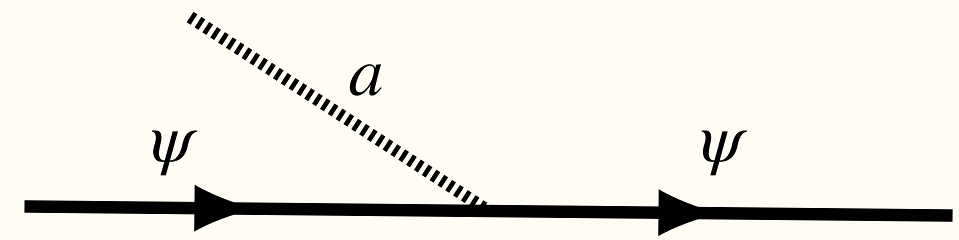
$$-\frac{a}{f_a}\frac{G\tilde{G}}{32\pi^2}$$



$$g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$$

Ultralight Dark Matter: ALPs

What is the effect of ALP interactions?



$$g_{a\psi\psi}\, \partial_\mu a \cdot \bar{\psi}\gamma^\mu \gamma_5 \psi$$

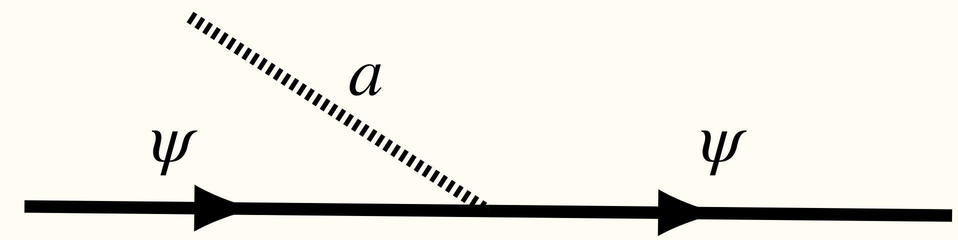
Non-relativistic limit:

$$H_{a\psi\psi} = -\, g_{a\psi\psi}\, \vec{b}_a \cdot \vec{S}_\psi = -\, \vec{b}_{a-\psi} \cdot \vec{S}_\psi$$

$$\vec{b}_{a-\psi} = g_{a\psi\psi} \sqrt{2\rho_a} \cos(m_a t) \cdot \vec{v}_{a-\psi}$$

Ultralight Dark Matter: ALPs

What is the effect of ALP interactions?



$$g_{a\psi\psi}\, \partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$$

Non-relativistic limit:

$$H_{a\psi\psi} = -g_{a\psi\psi}\, \overrightarrow{b}_a \cdot \overrightarrow{S}_\psi = -\overrightarrow{b}_{a-\psi} \cdot \overrightarrow{S}_\psi$$

$$\overrightarrow{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t) \cdot \overrightarrow{v}_{a-\psi}$$

Recall for regular magnetic field:

$$H = -\gamma \overrightarrow{B} \cdot \overrightarrow{S}$$

Ultralight Dark Matter: ALPs

Dark Matter ALPs act as time-dependent anomalous magnetic background

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Ultralight Dark Matter: ALPs

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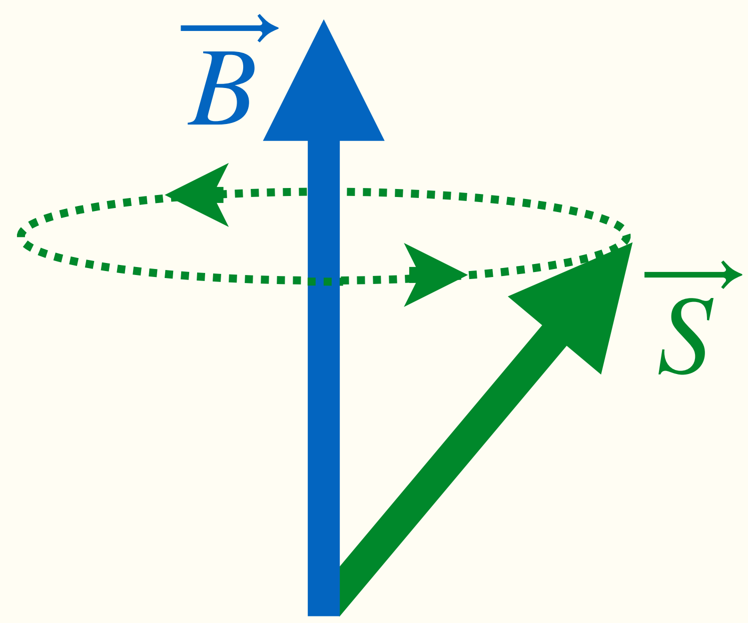
Larmor Precession



$$\dot{\vec{S}} = \gamma \vec{S} \times \vec{B}$$

Ultralight Dark Matter: ALPs

Dark Matter ALPs act as time-dependent anomalous magnetic background

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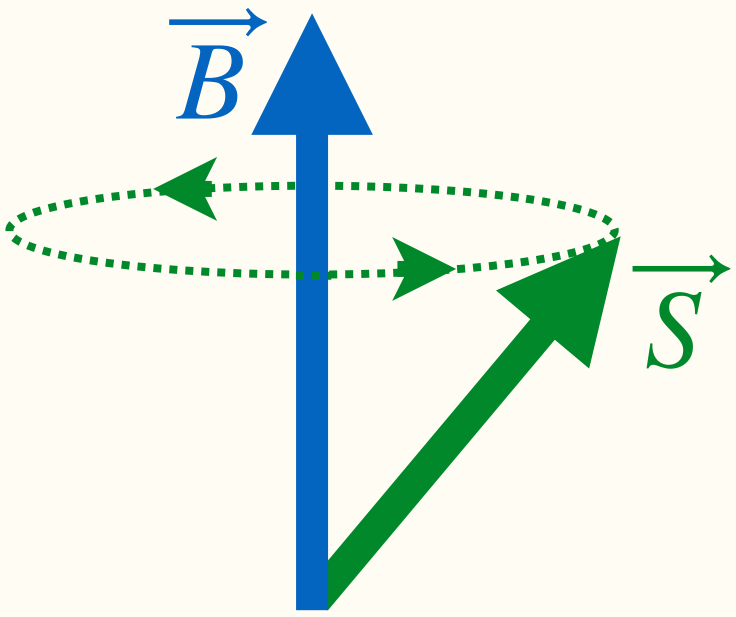


$$\dot{\vec{S}} = \gamma \vec{S} \times \vec{B}$$

How do we measure this?

NASDUCK

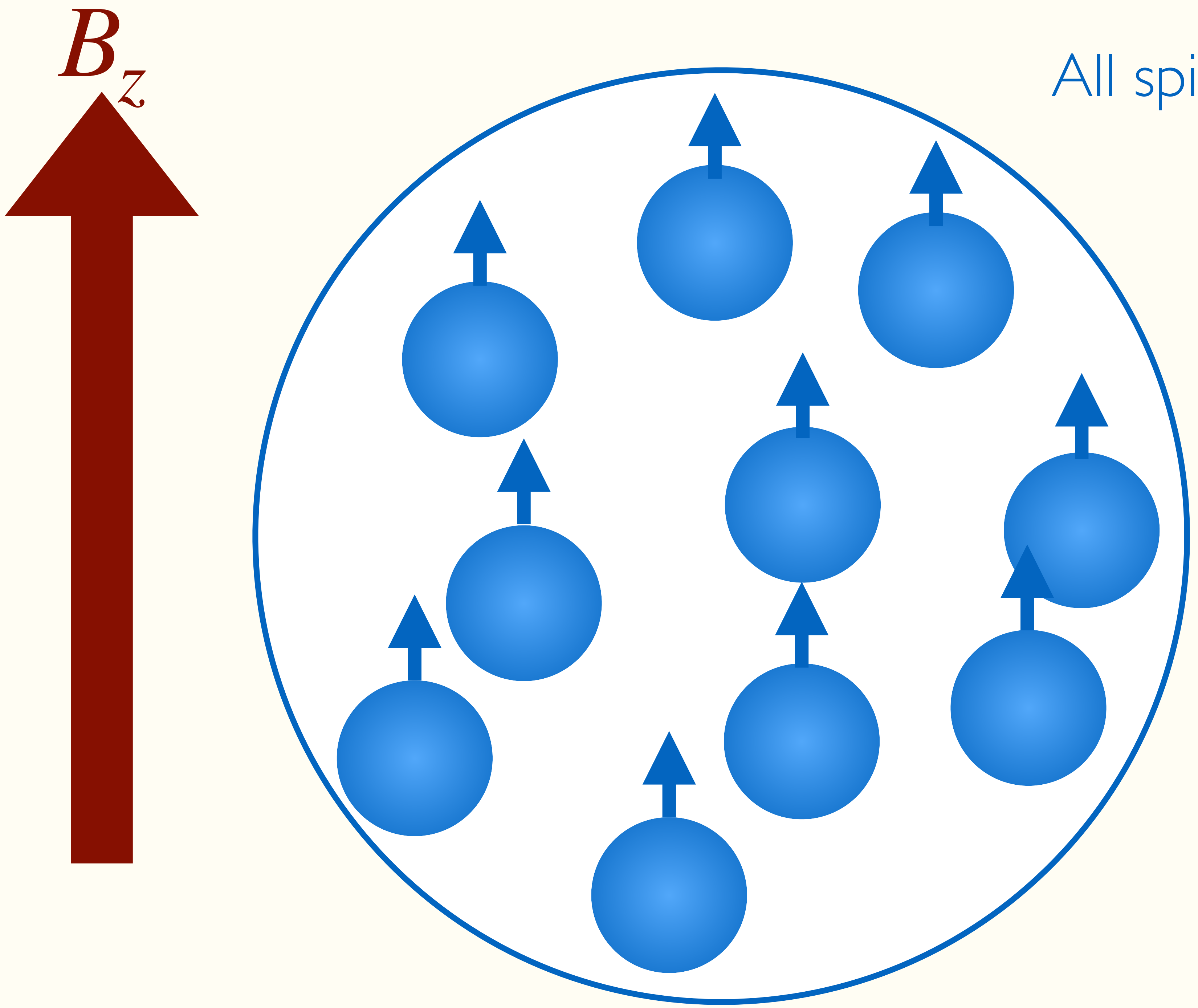
Noble and Alkali Spin Detectors for Ultralight Coherent darK matter

Itay Bloch, Or Katz, Ori Katz, Gil Ronen, Roy Shaham, TV

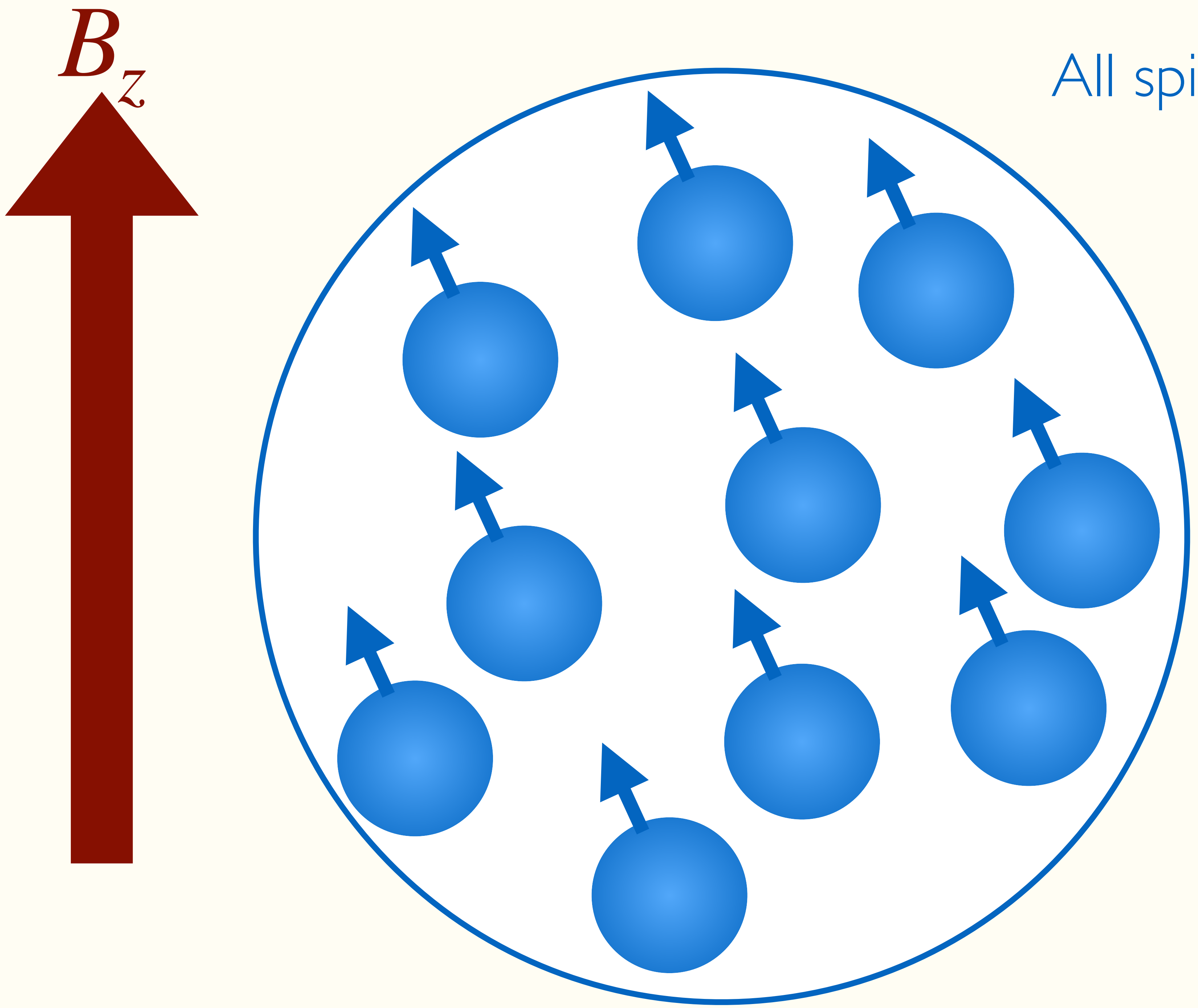
[Science Advances, 2022]

Atomic (Co-)Magnetometers

Atoms in a cell
All spins pointing in the z-direction



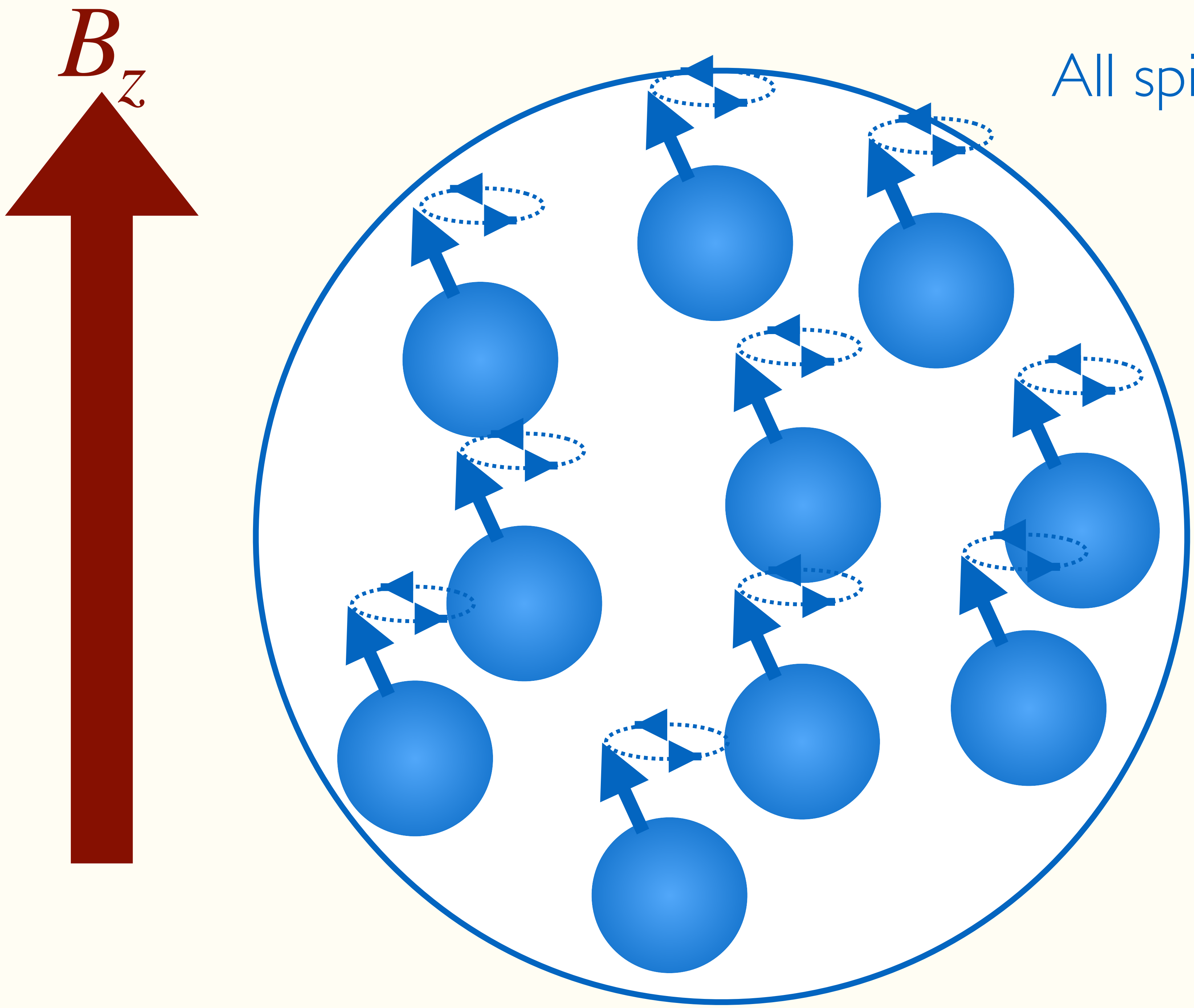
Atomic (Co-)Magnetometers



Atoms in a cell
All spins pointing in the z-direction

Perturb spins

Atomic (Co-)Magnetometers

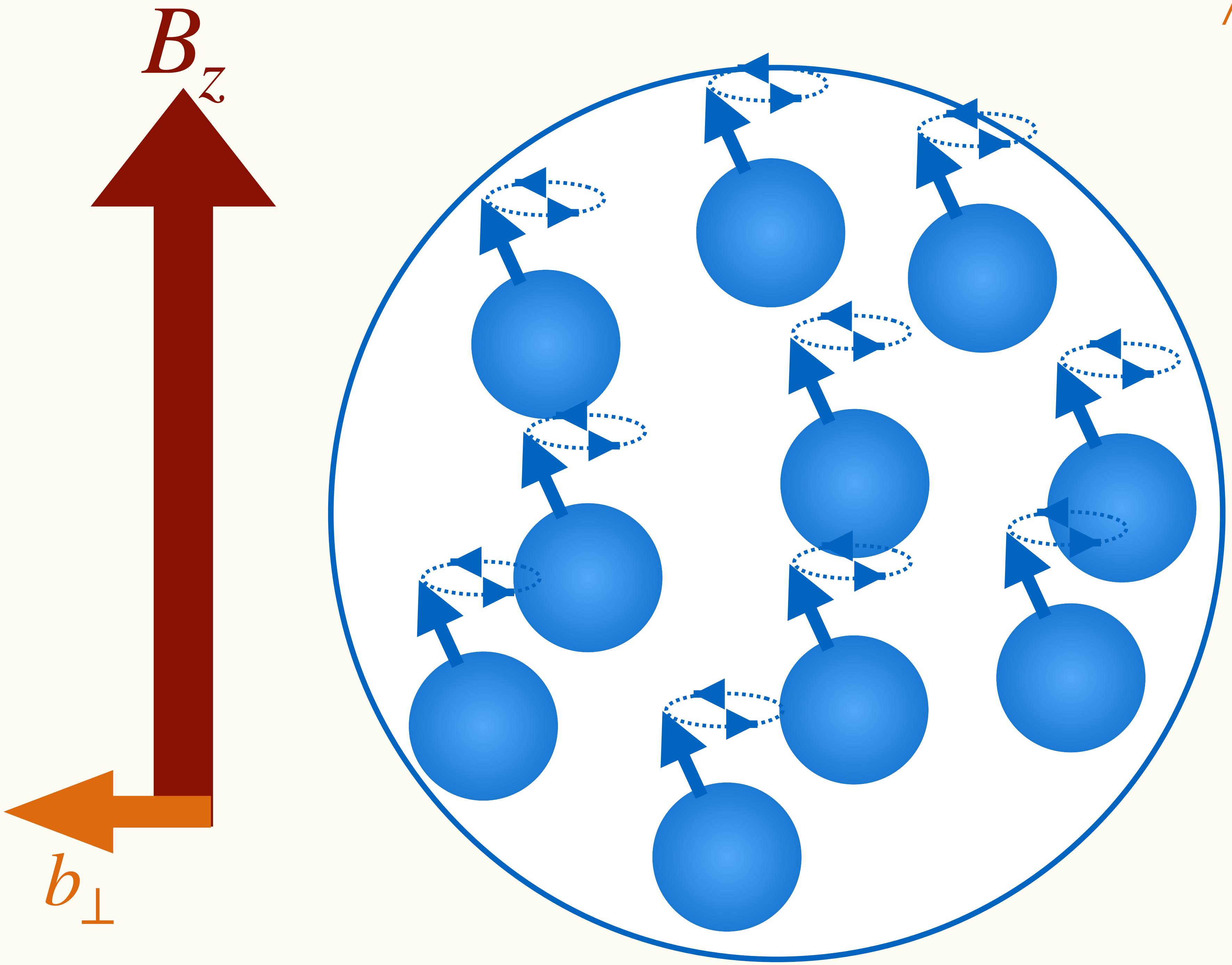


Atoms in a cell
All spins pointing in the z-direction

Perturb spins

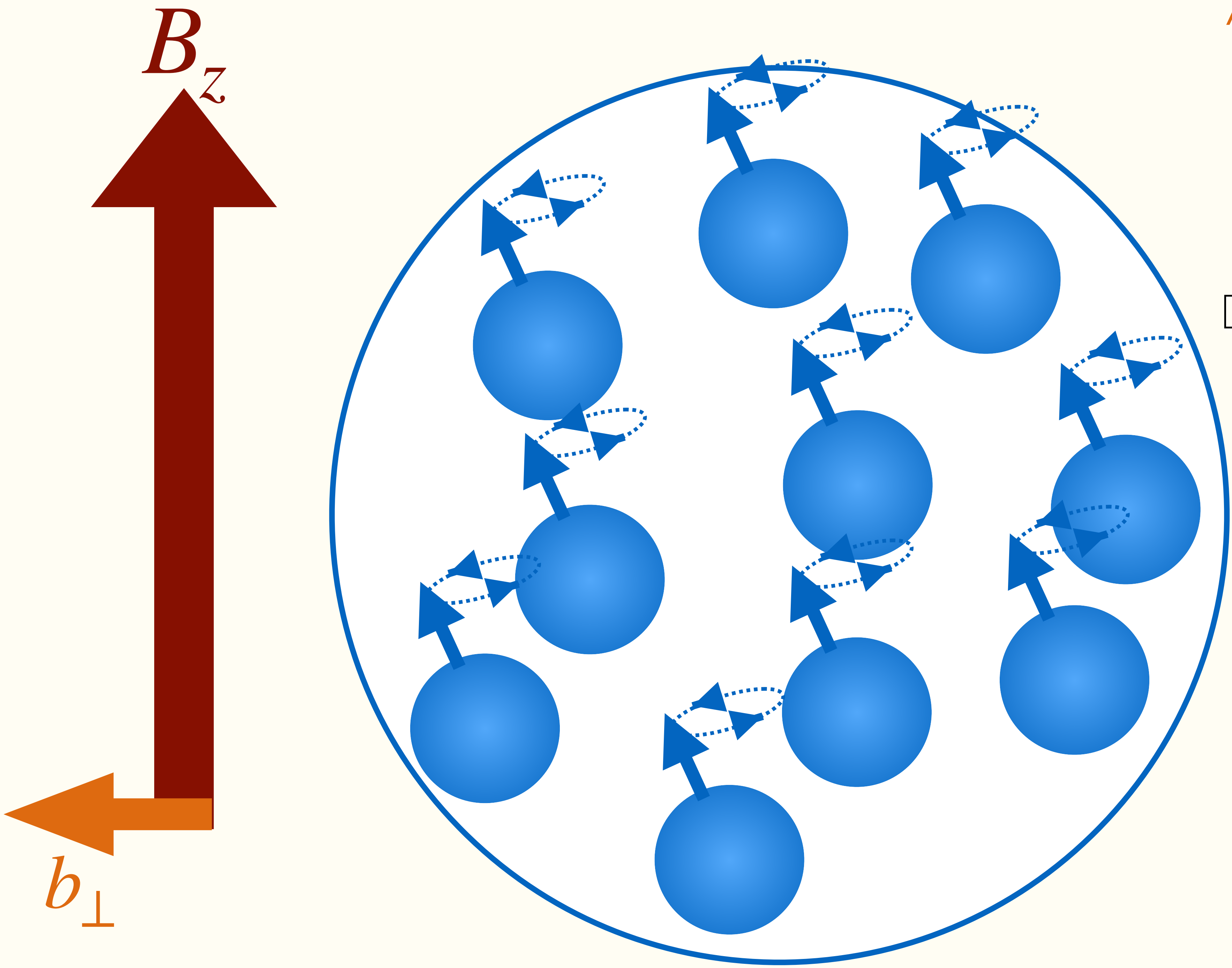
Spins will precess

Atomic (Co-)Magnetometers



Add now a small anomalous magnetic field

Atomic (Co-)Magnetometers



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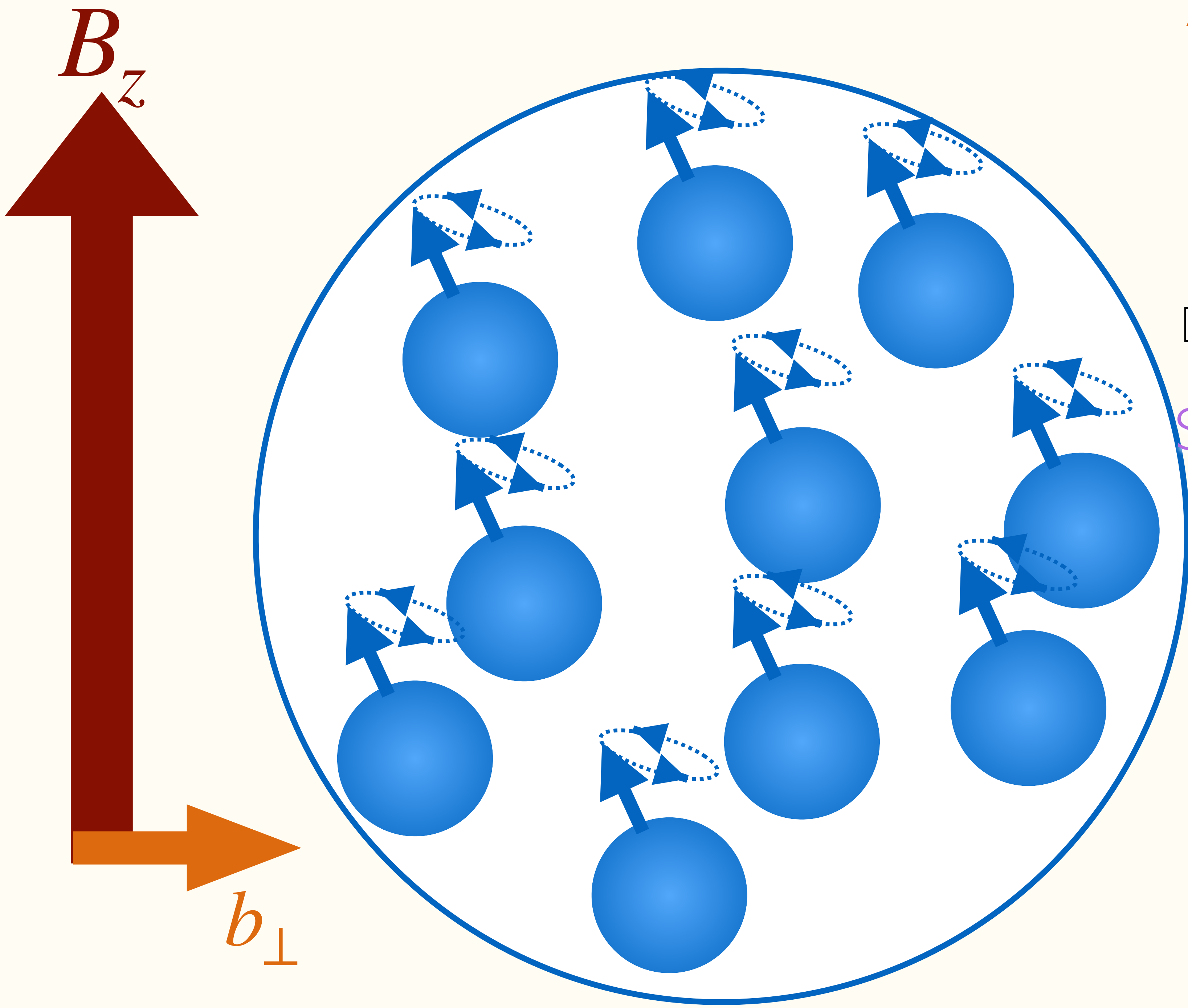
Precession will shift

[Kolokolov, Vorobev, 1995; Budker et al., 2013]

Atomic (Co-)Magnetometers



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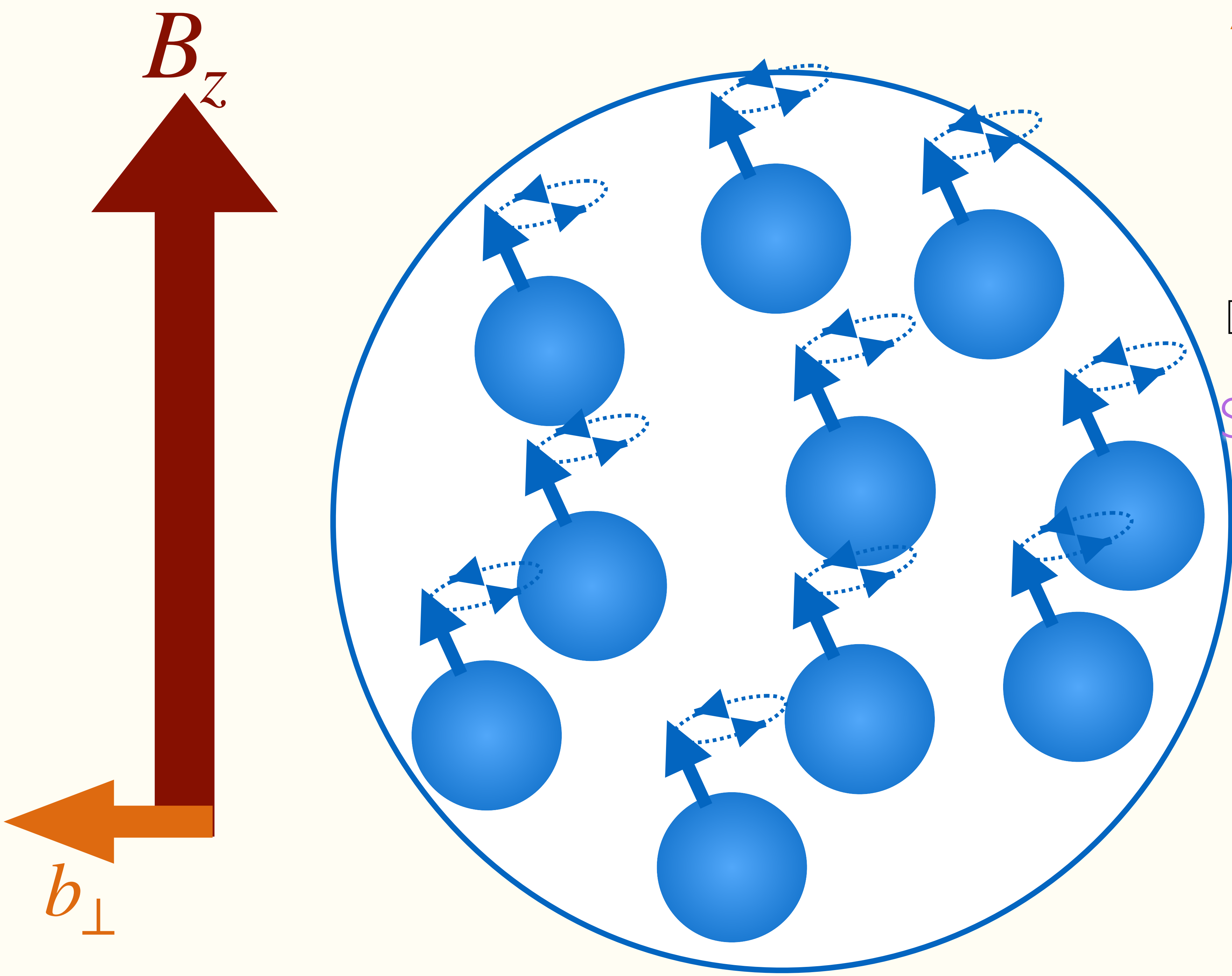
Since anomalous field changes Spins will try to follow

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t)\cdot\vec{v}_{a-\psi}$$

Atomic (Co-)Magnetometers



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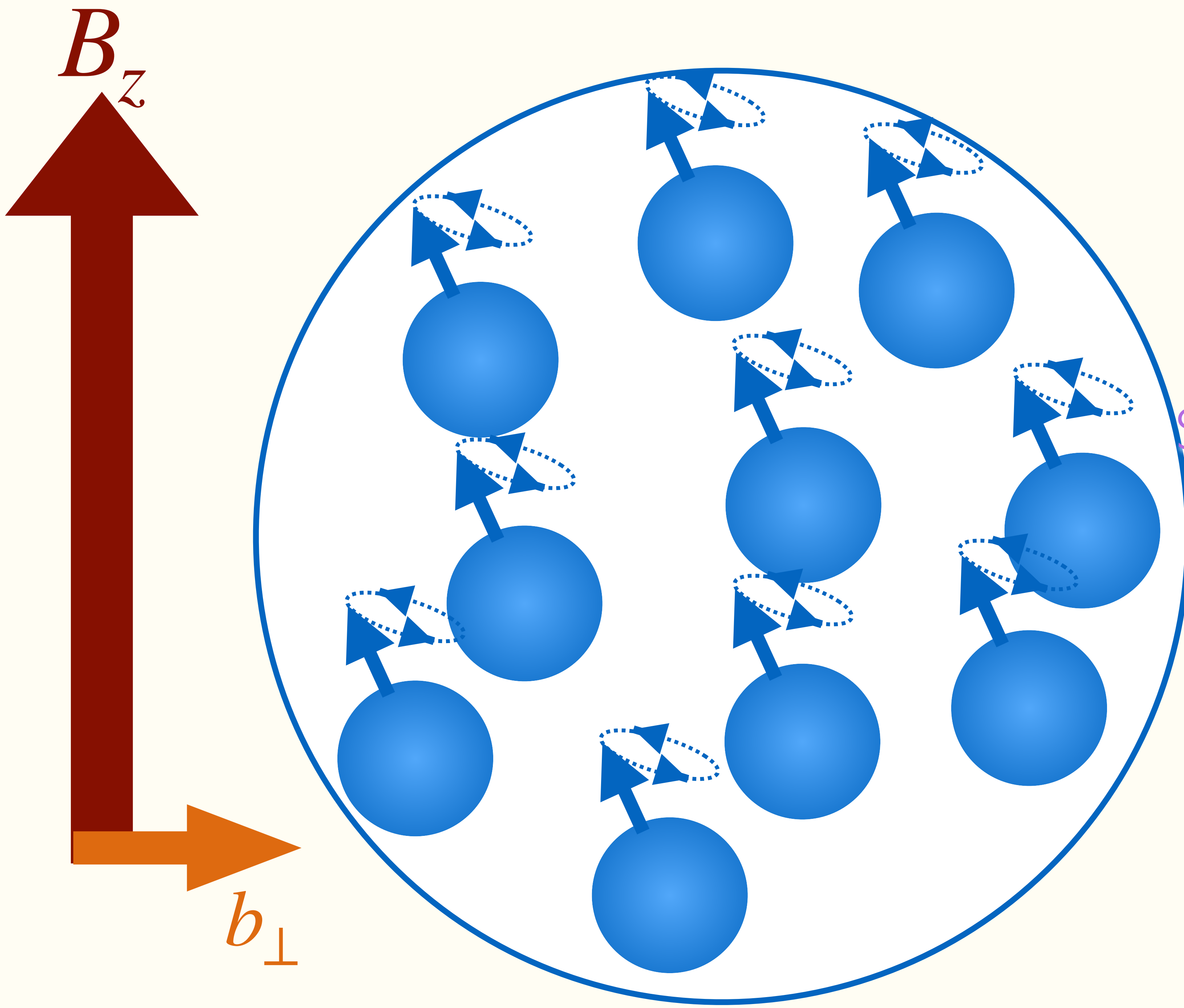
Atomic (Co-)Magnetometers



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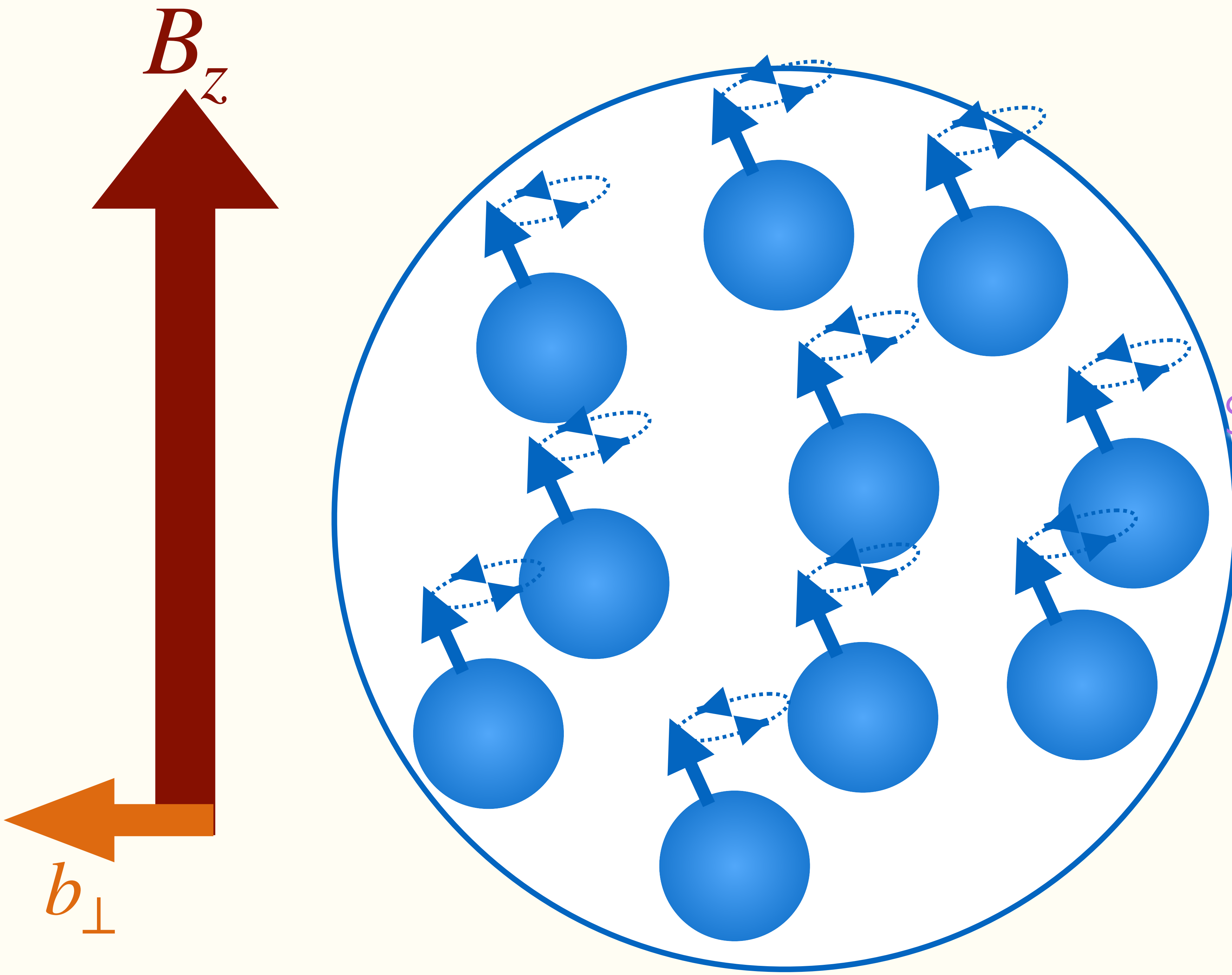

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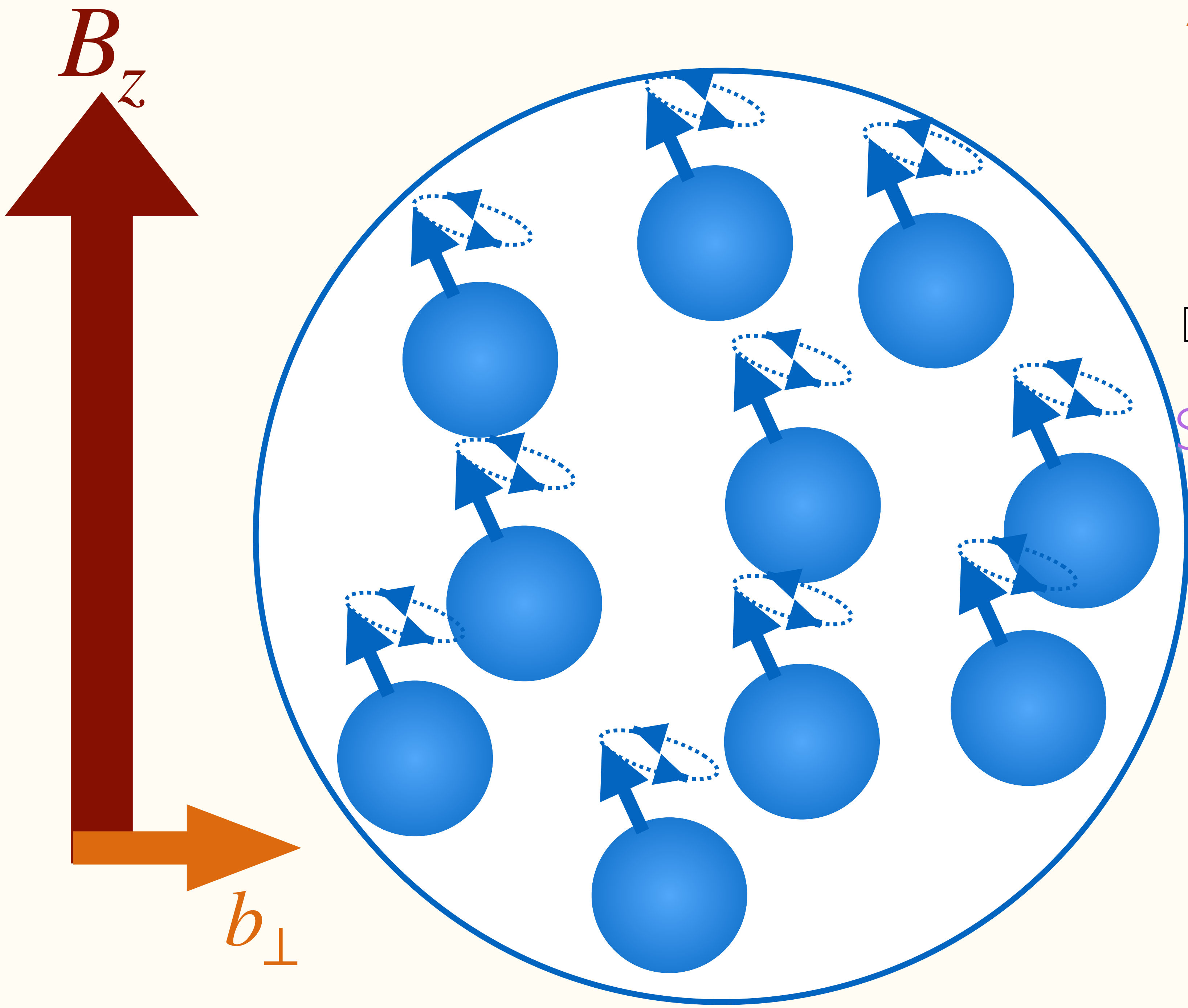

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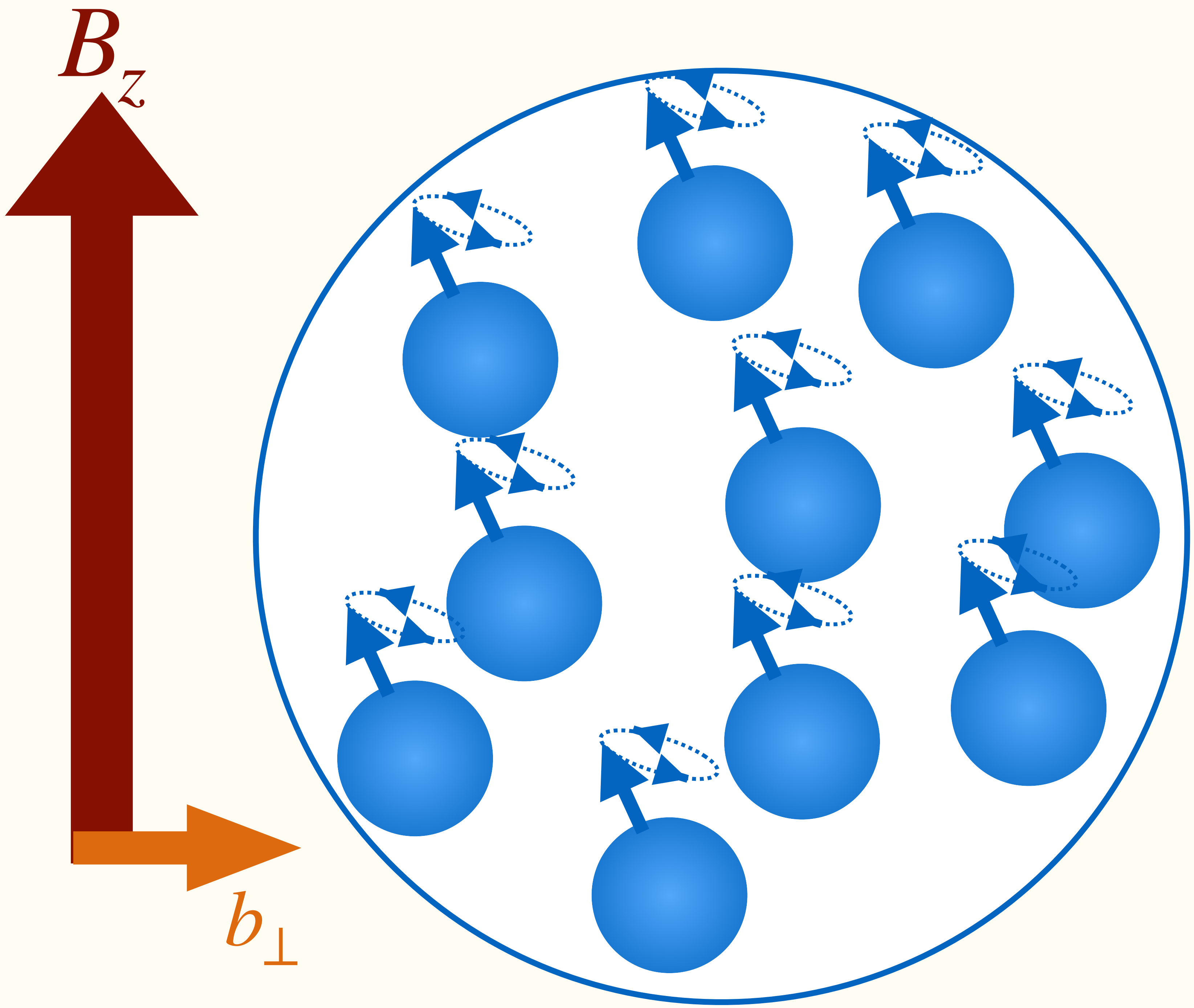
Anomalous field act as driving force

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t)\cdot\vec{v}_{a-\psi}$$

Atomic (Co-)Magnetometers



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Atomic (Co-)Magnetometers

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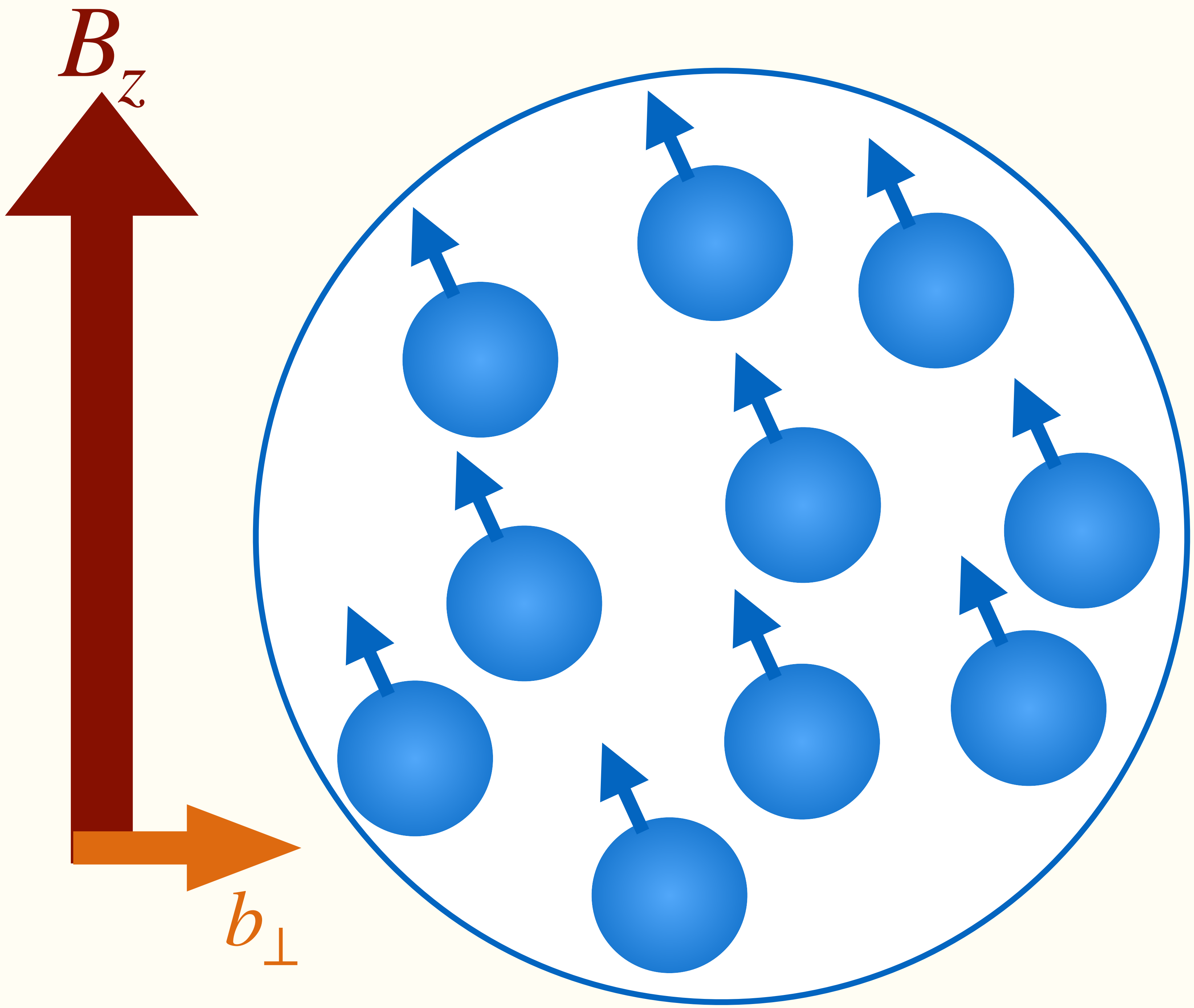
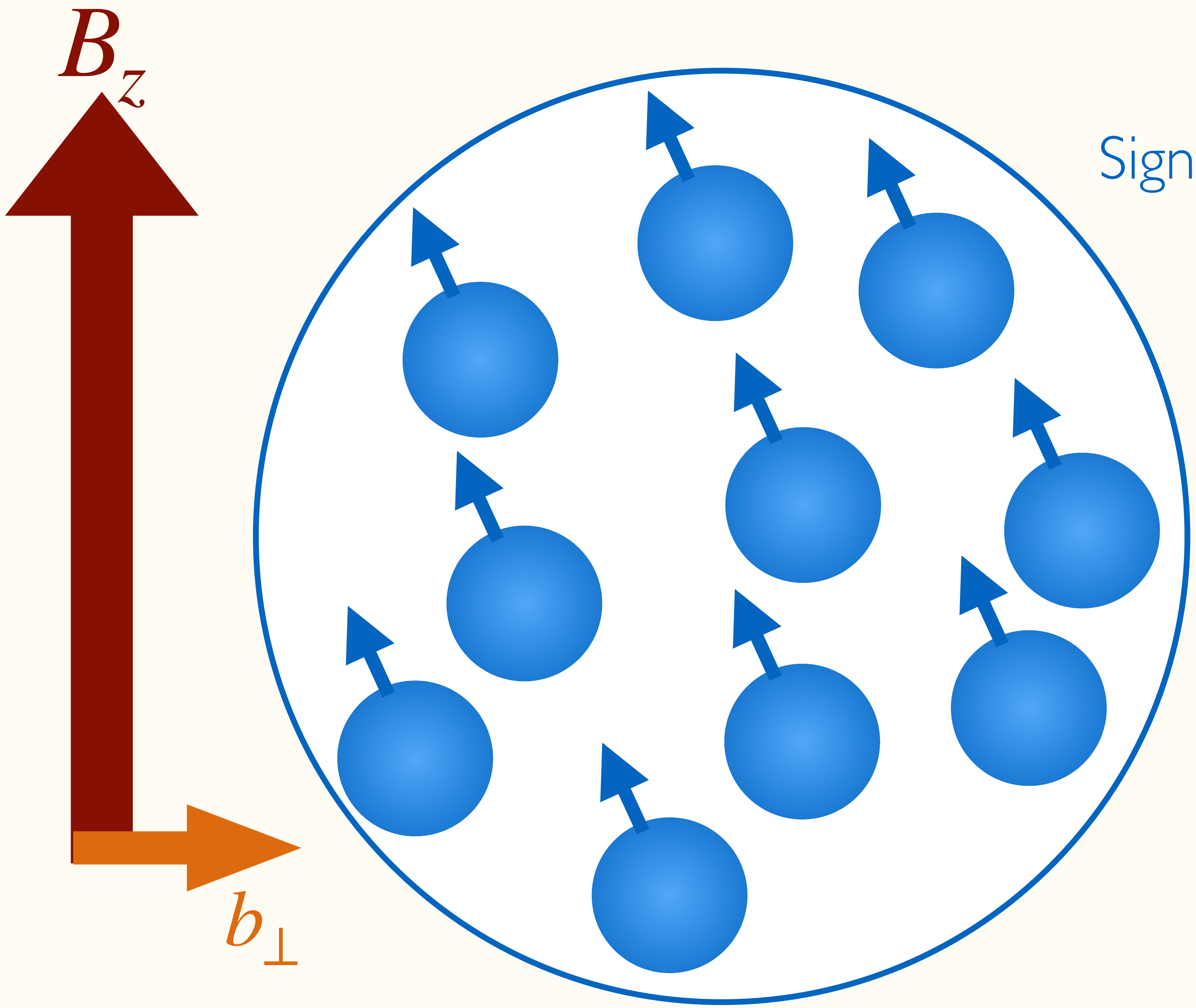


$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z$$

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t)\cdot\vec{v}_{a-\psi}$$

Atomic (Co-)Magnetometers

Anomalous field act as driving force



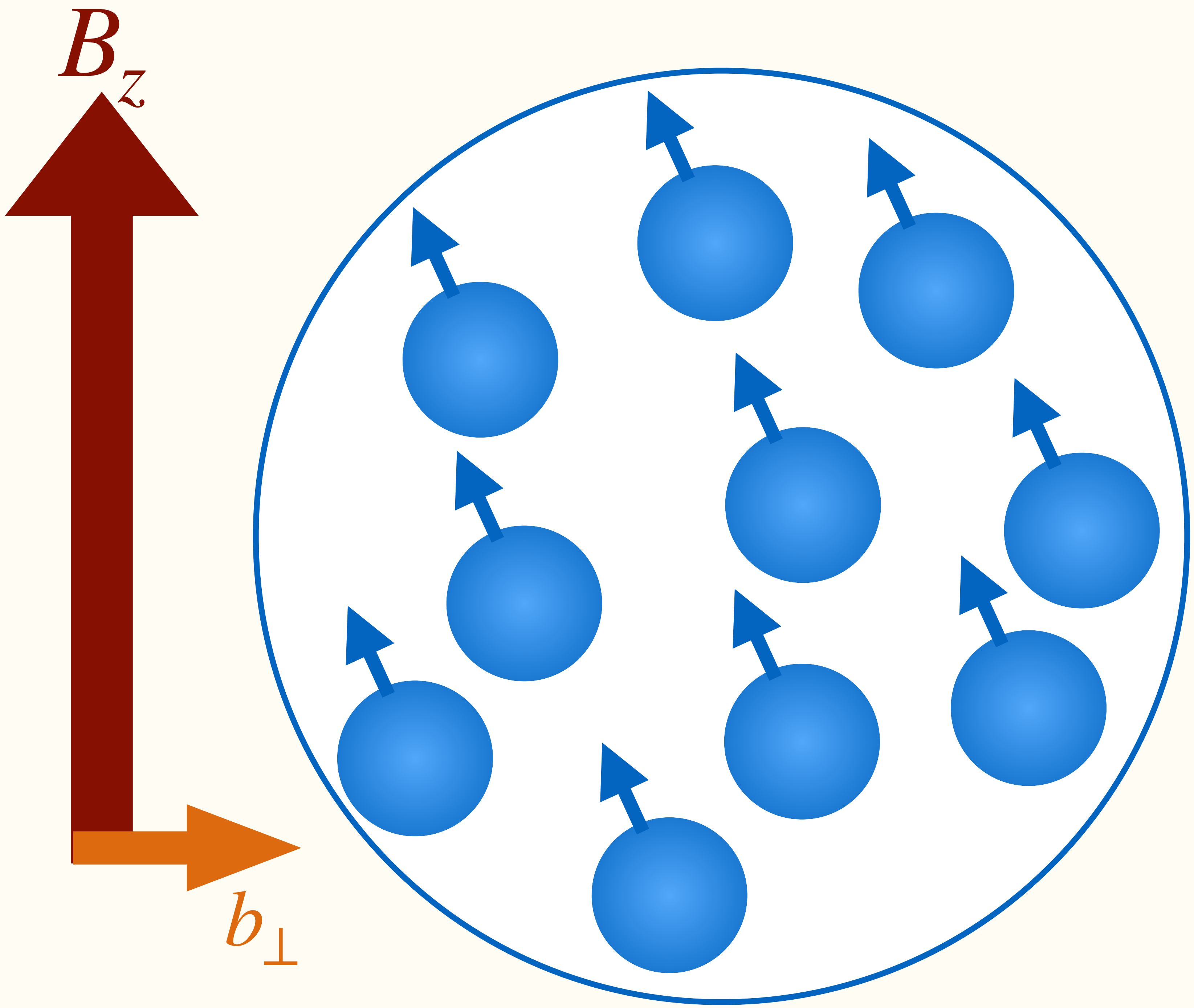
Signal

Noise

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z$$

$$\vec{b}_{a-\psi} = g_{a\psi\psi} \sqrt{2\rho_a} \cos(m_a t) \cdot \vec{v}_{a-\psi}$$

Atomic (Co-)Magnetometers



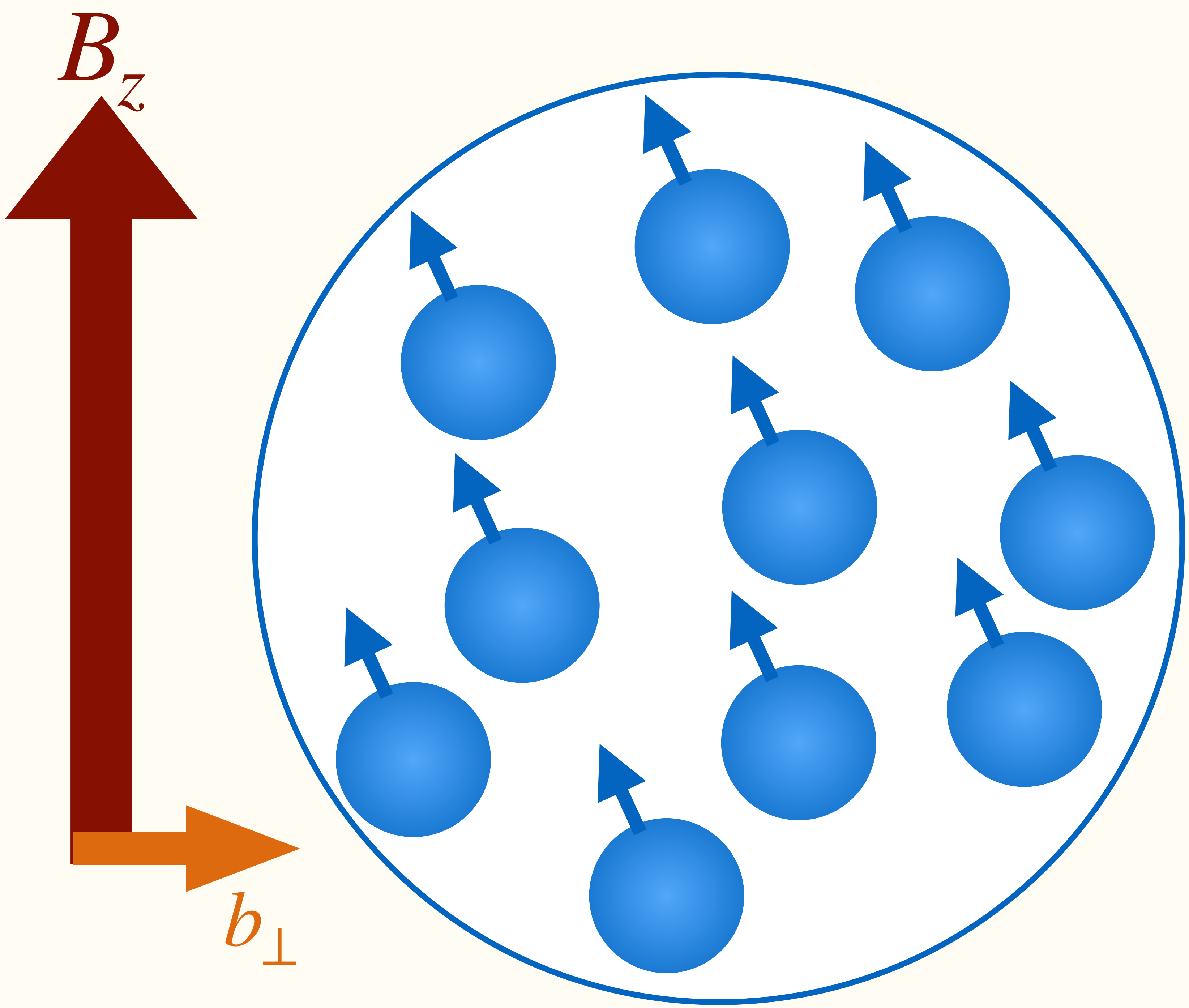
Anomalous field act as driving force

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z$$

Resonance Effect!!

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t)\cdot \vec{v}_{a-\psi}$$

Atomic (Co-)Magnetometers



Anomalous field act as driving force

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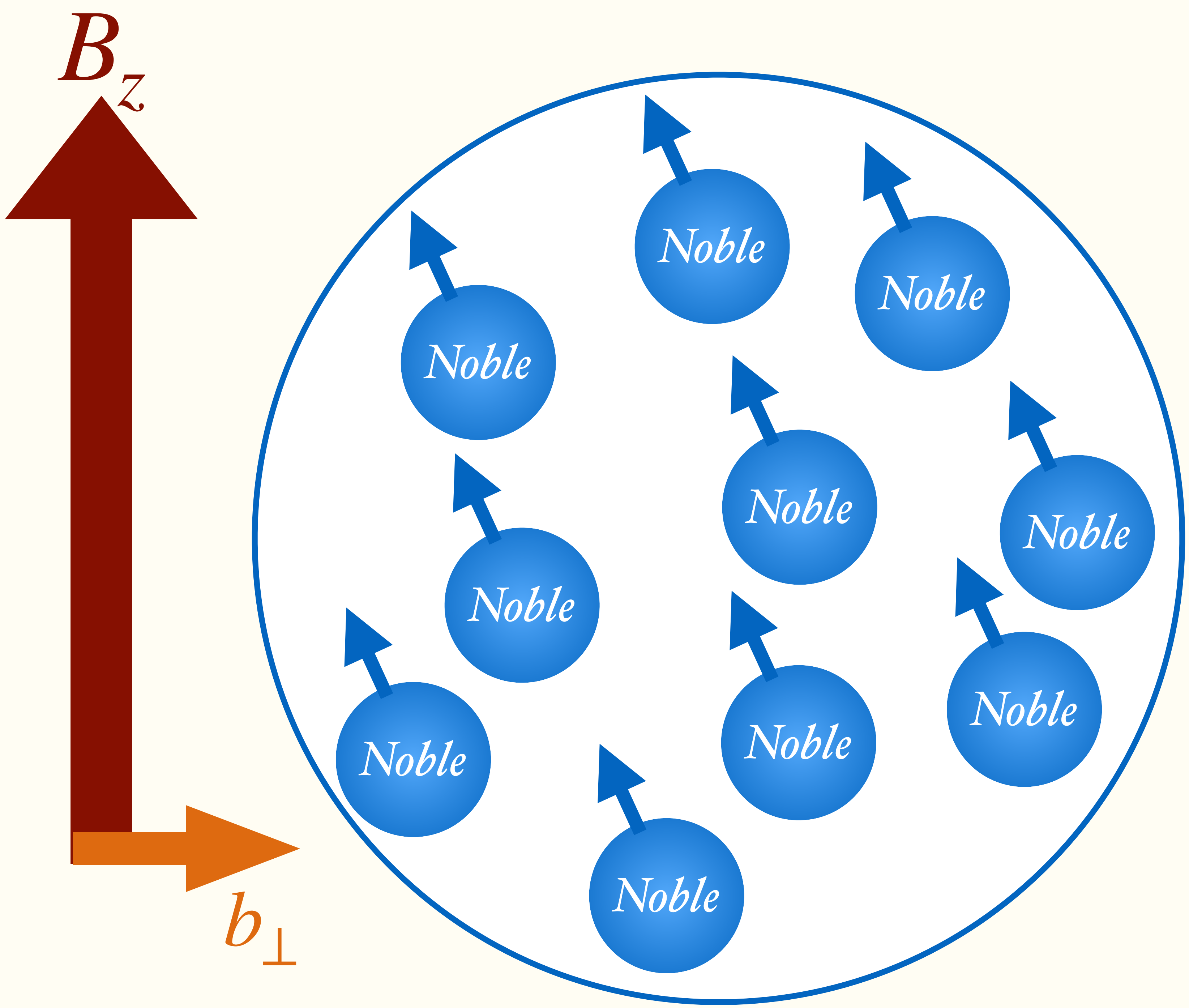
PROBLEM:

Susceptible to magnetic noise

Atomic (Co-)Magnetometers



Anomalous field act as driving force

$$S_\perp = \frac{b_\perp + \cancel{\gamma B_\perp}}{i\Gamma + (\gamma B_z - m_a)} S_z$$

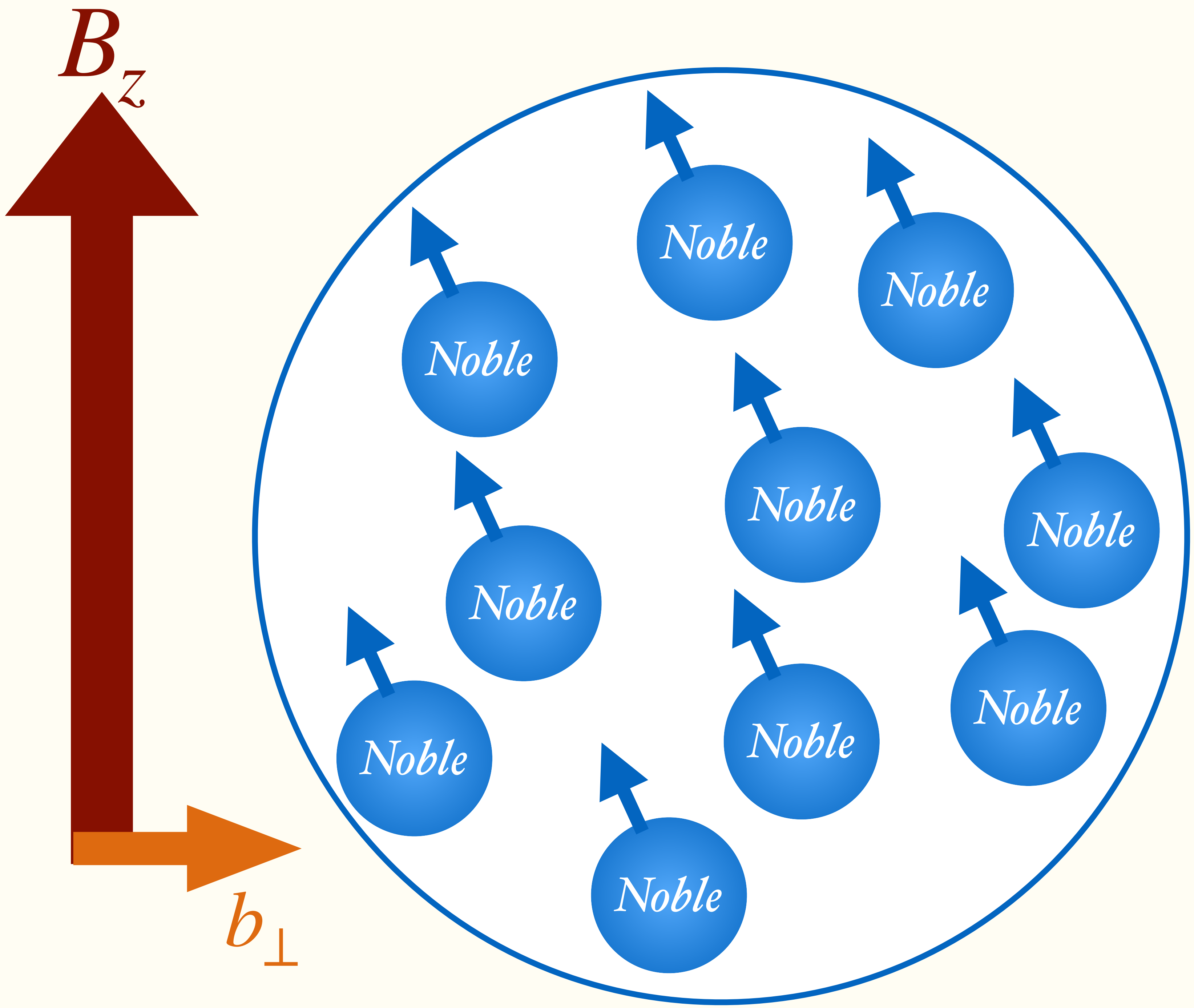
PROBLEM:

Susceptible to magnetic noise

SOLUTION:

Take Noble atoms which have small γ

Atomic (Co-)Magnetometers

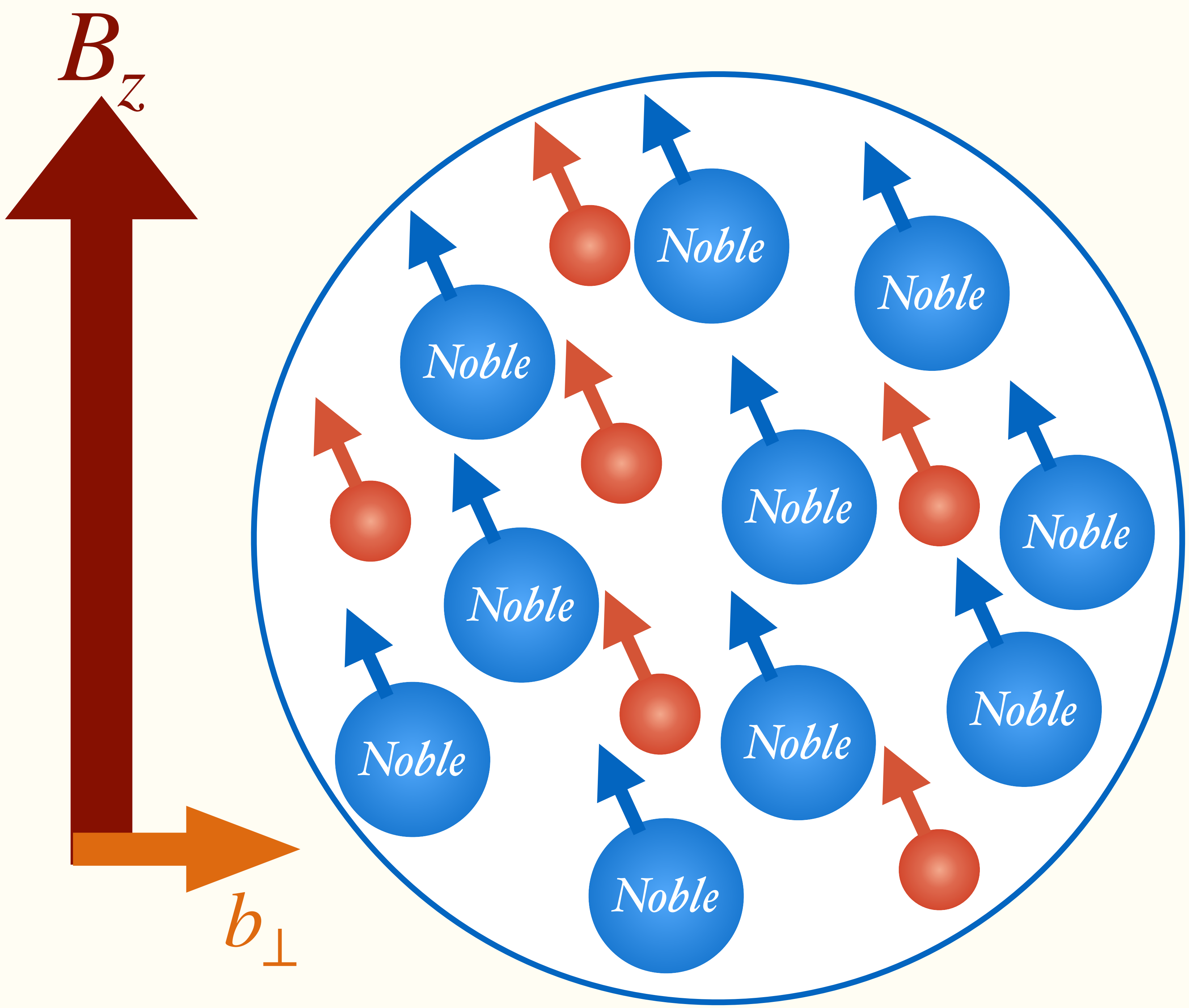


For Noble atoms, spin is nuclear

PROBLEM:

How can we read their spin?

Atomic (Co-)Magnetometers



For Noble atoms, spin is nuclear

PROBLEM:

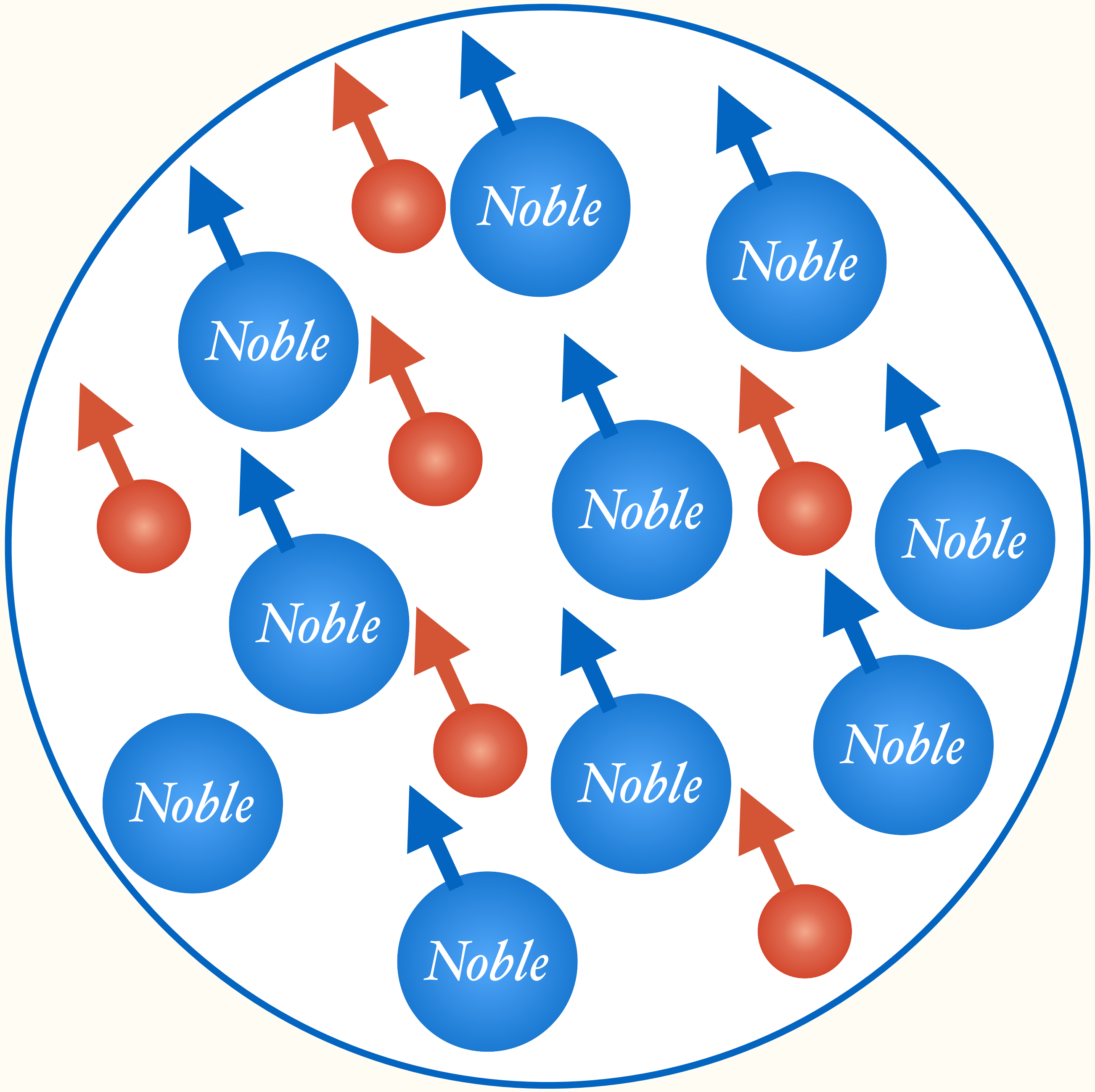
How can we read their spin?

SOLUTION:

Add another in-situ optical magnetometer (typically Alkali metal)

Atomic (Co-)Magnetometers

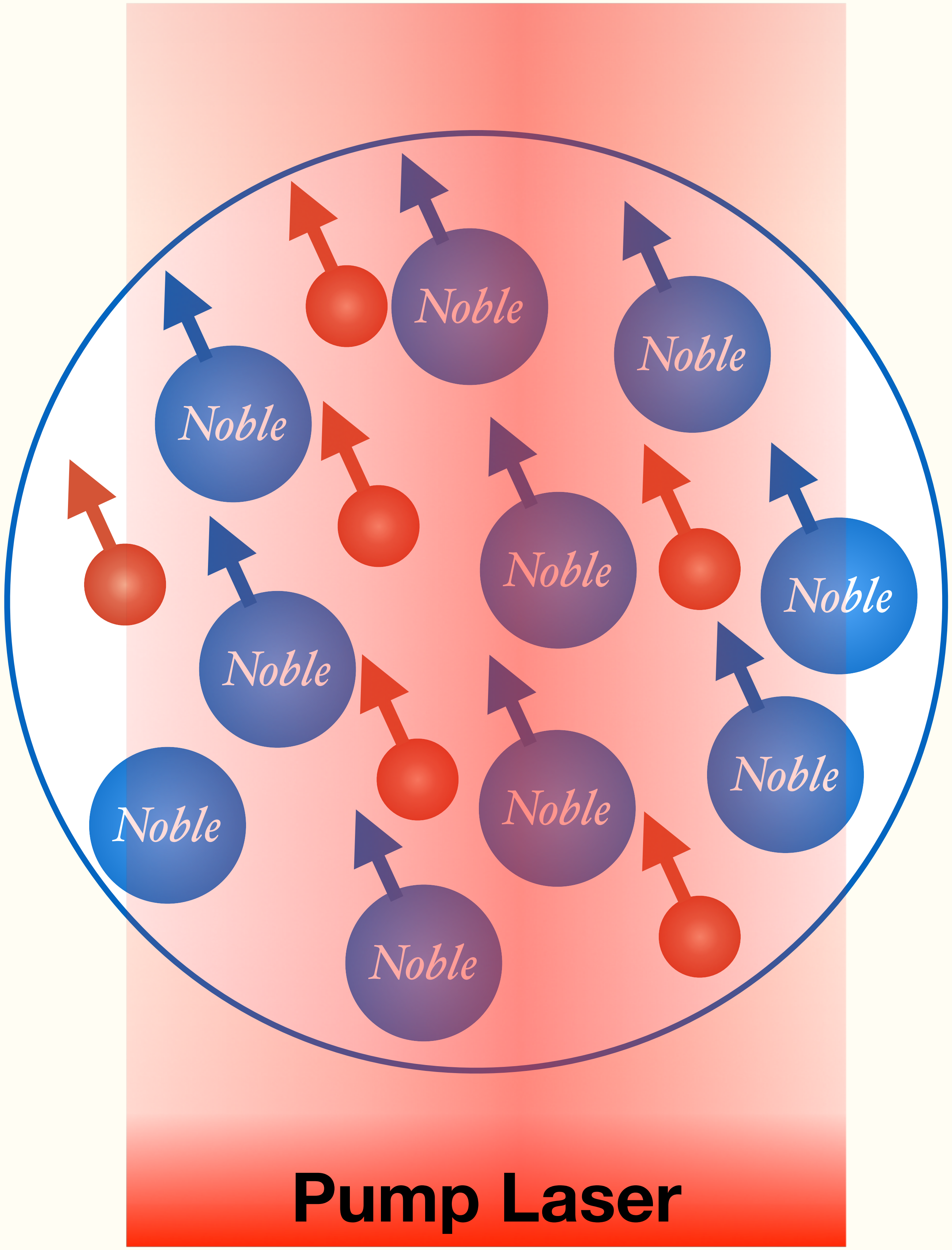
Skip



Lasers interact only
with Alkali

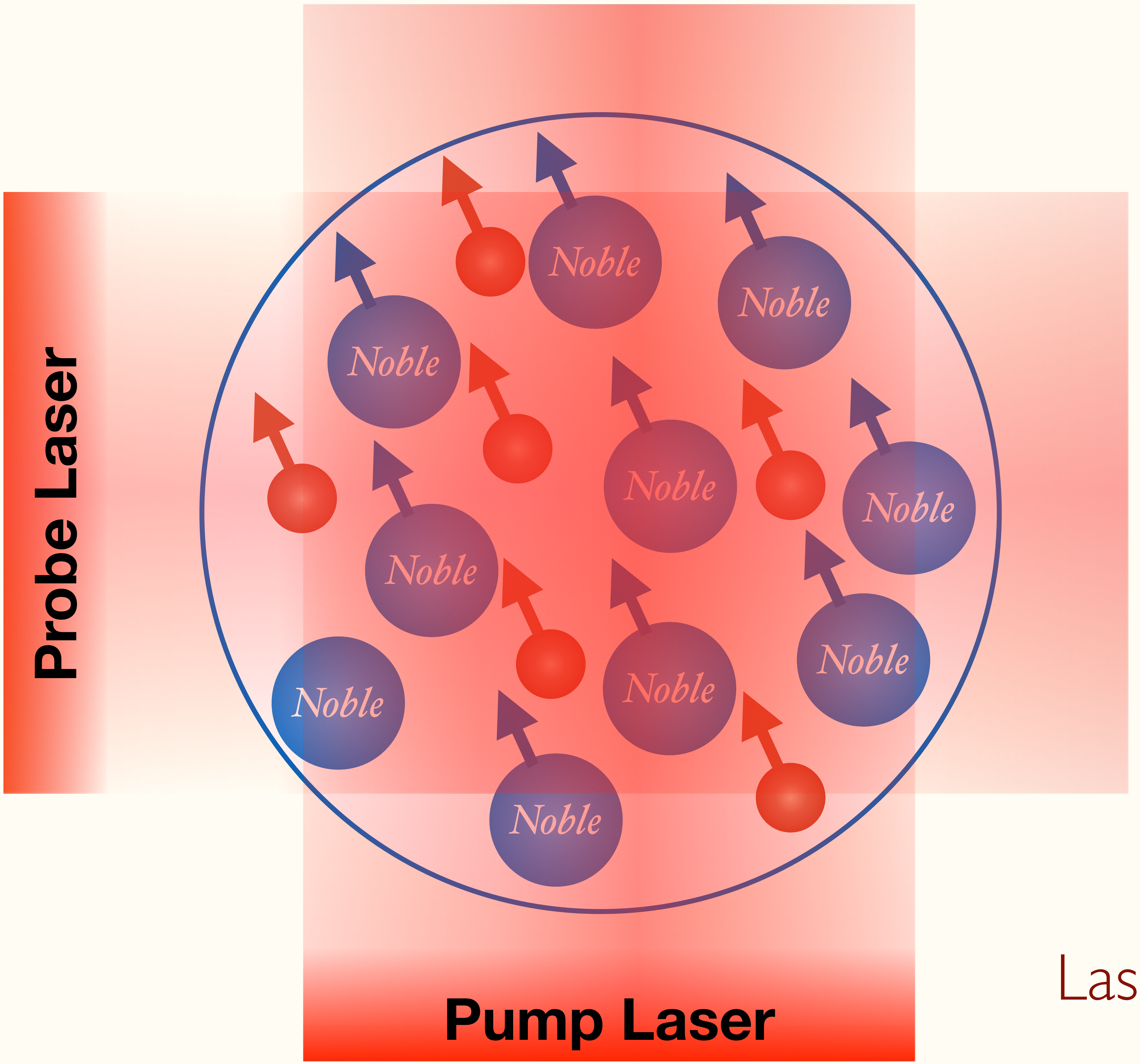
Atomic (Co-)Magnetometers

Skip



Lasers interact only with Alkali

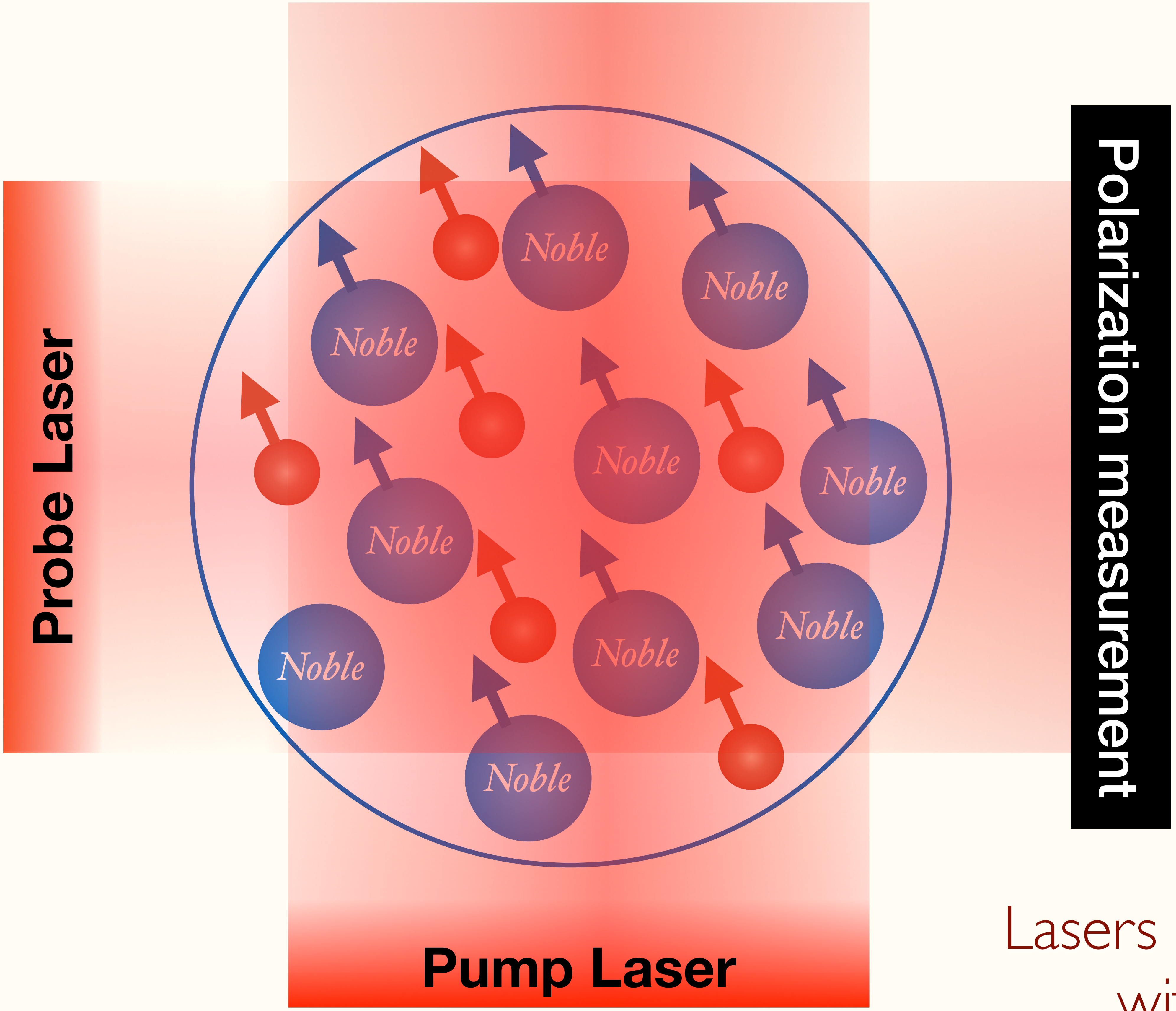
Atomic (Co-)Magnetometers



Lasers interact only with Alkali

Atomic (Co-)Magnetometers

Skip

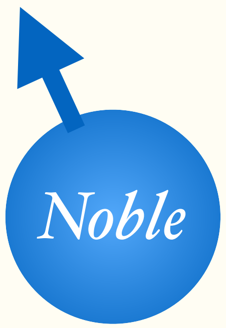


Lasers interact only with Alkali

Atomic (Co-)Magnetometers

^{129}Xe

Nuclear spin
(NMR)



$$S_\perp^{\mathrm{Xe}} = \frac{b_\perp}{i\Gamma_{\mathrm{Xe}} + (\gamma_{\mathrm{Xe}} B_z - m_a)} S_z$$

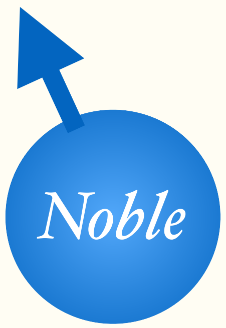
$$\gamma_{\mathrm{Xe}} = -\,1.18\,\mathrm{kHz/G}$$

$$\Gamma_{\mathrm{Xe}} = 0.3\,\mathrm{kHz}$$

Atomic (Co-)Magnetometers

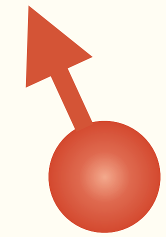
^{129}Xe

Nuclear spin
(NMR)



Two interacting
resonating systems

^{85}Rb



Electronic spin
(EPR)

$$S_\perp^{\mathrm{Xe}} = \frac{b_\perp}{i\Gamma_{\mathrm{Xe}} + (\gamma_{\mathrm{Xe}} B_z - m_a)} S_z$$

$$S_\perp^{\mathrm{Rb}} = \frac{\kappa_0 \gamma_{\mathrm{Rb}} b_{\mathrm{Xe}}}{i\Gamma_{\mathrm{Rb}} + (\gamma_{\mathrm{Rb}} B_z - m_a)} S_\perp^{\mathrm{Xe}}$$

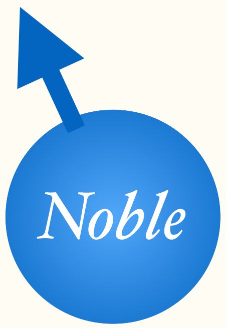
$\gamma_{\mathrm{Xe}} = -1.18\,\mathrm{kHz/G}$ $\ll$ $\gamma_{\mathrm{Rb}} = 467\,\mathrm{kHz/G}$

$\Gamma_{\mathrm{Xe}} = 0.3\,\mathrm{kHz}$ $\ll$ $\Gamma_{\mathrm{Rb}} = 6.6\,\mathrm{kHz}$

$\kappa_0 = 518$

Atomic (Co-)Magnetometers

^{129}Xe



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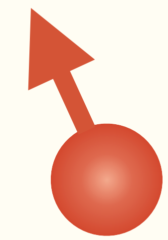

$$S_\perp^{\mathrm{Xe}} = \frac{b_\perp}{i\Gamma_{\mathrm{Xe}} + (\gamma_{\mathrm{Xe}} B_z - m_a)} S_z \qquad S_\perp^{\mathrm{Rb}} = \frac{\kappa_0\, \gamma_{\mathrm{Rb}} b_{\mathrm{Xe}}}{i\Gamma_{\mathrm{Rb}} + (\gamma_{\mathrm{Rb}} B_z - m_a)} S_\perp^{\mathrm{Xe}}$$

To search for large m_a one needs large B_z
but two systems are no longer in resonance

Floquet Field Enhancement

To search for large m_a one needs large B_z
but two systems are no longer in resonance

A solution is to Floquet-modulate the magnetic field

$$B_z = B_{z,0} + B_F \cos(\omega_F t)$$

Floquet Field Enhancement

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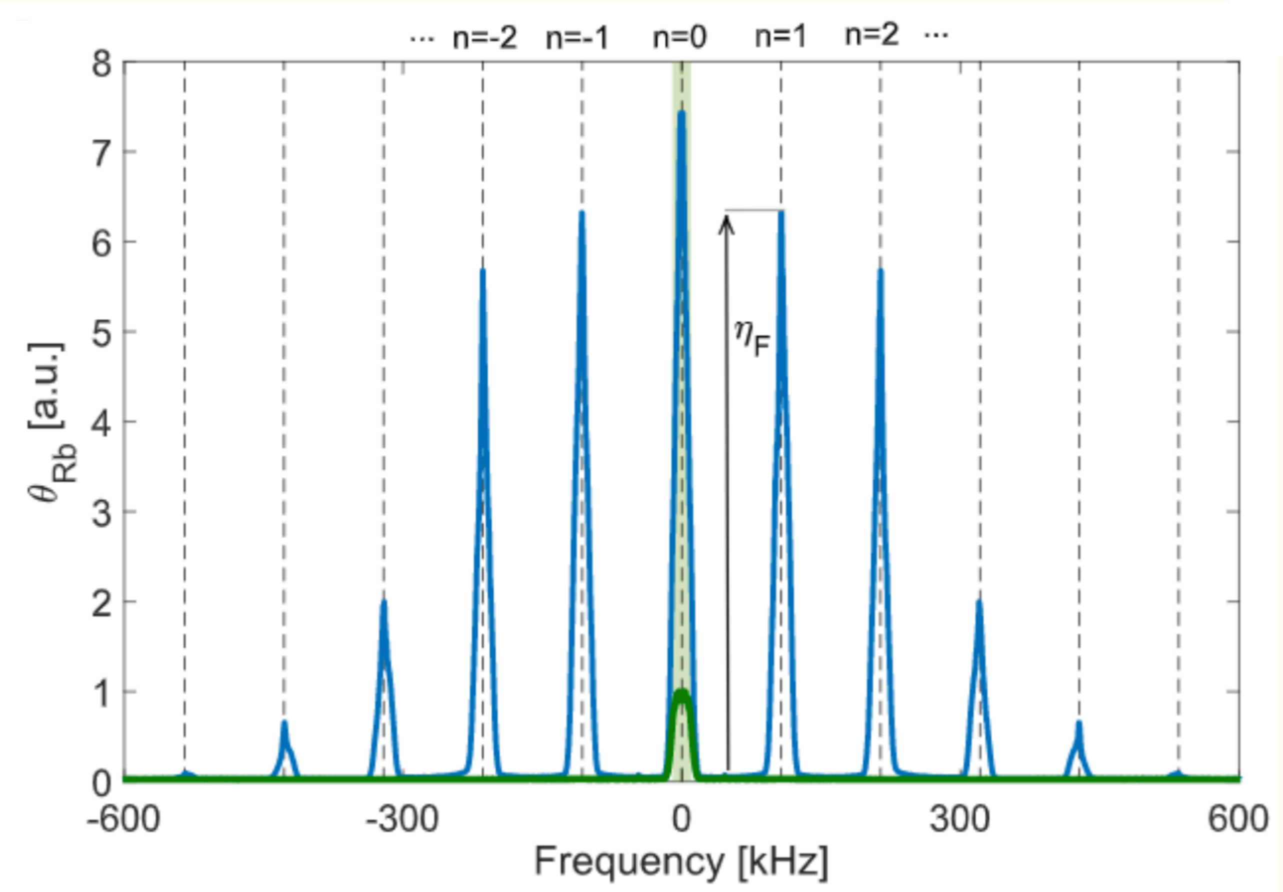
$$B_z = B_{z,0} + B_F \cos(\omega_F t)$$

$$\Downarrow$$

$$S^{\mathrm{Rb}}_{\mathrm{floquet}}(m_a + n\omega_F) = \eta_F^{(n)} S^{\mathrm{Rb}}_{\perp}(m_a)$$



Floquet Field Enhancement

To search for large m_a one needs large B_z

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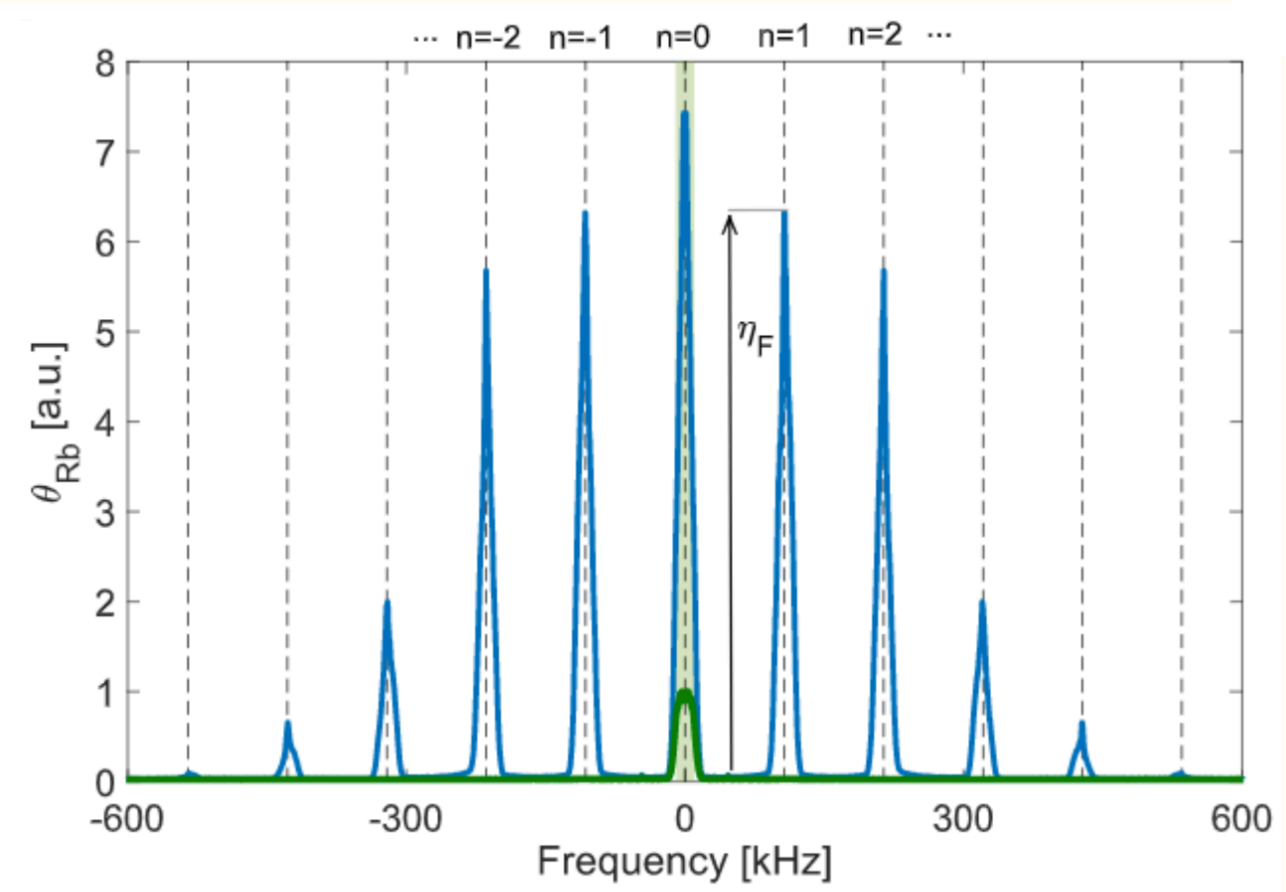
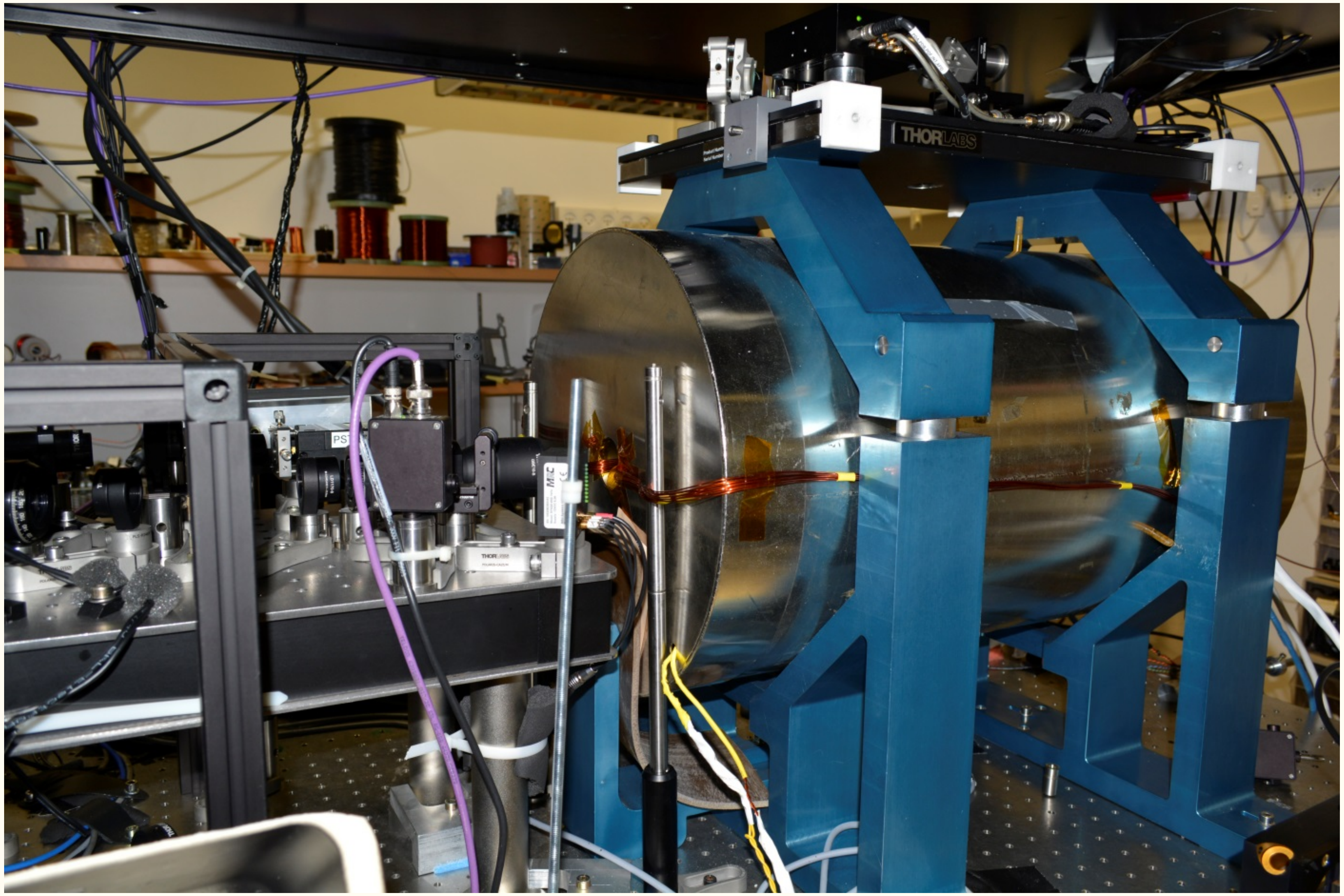
A solution is to Floquet-modulate the magnetic field

$$B_z = B_{z,0} + B_F \cos(\omega_F t)$$

$$S^{\mathrm{Rb}}_{\mathrm{floquet}}(m_a + n\omega_F) = \eta_F^{(n)} S^{\mathrm{Rb}}_{\perp}(m_a)$$



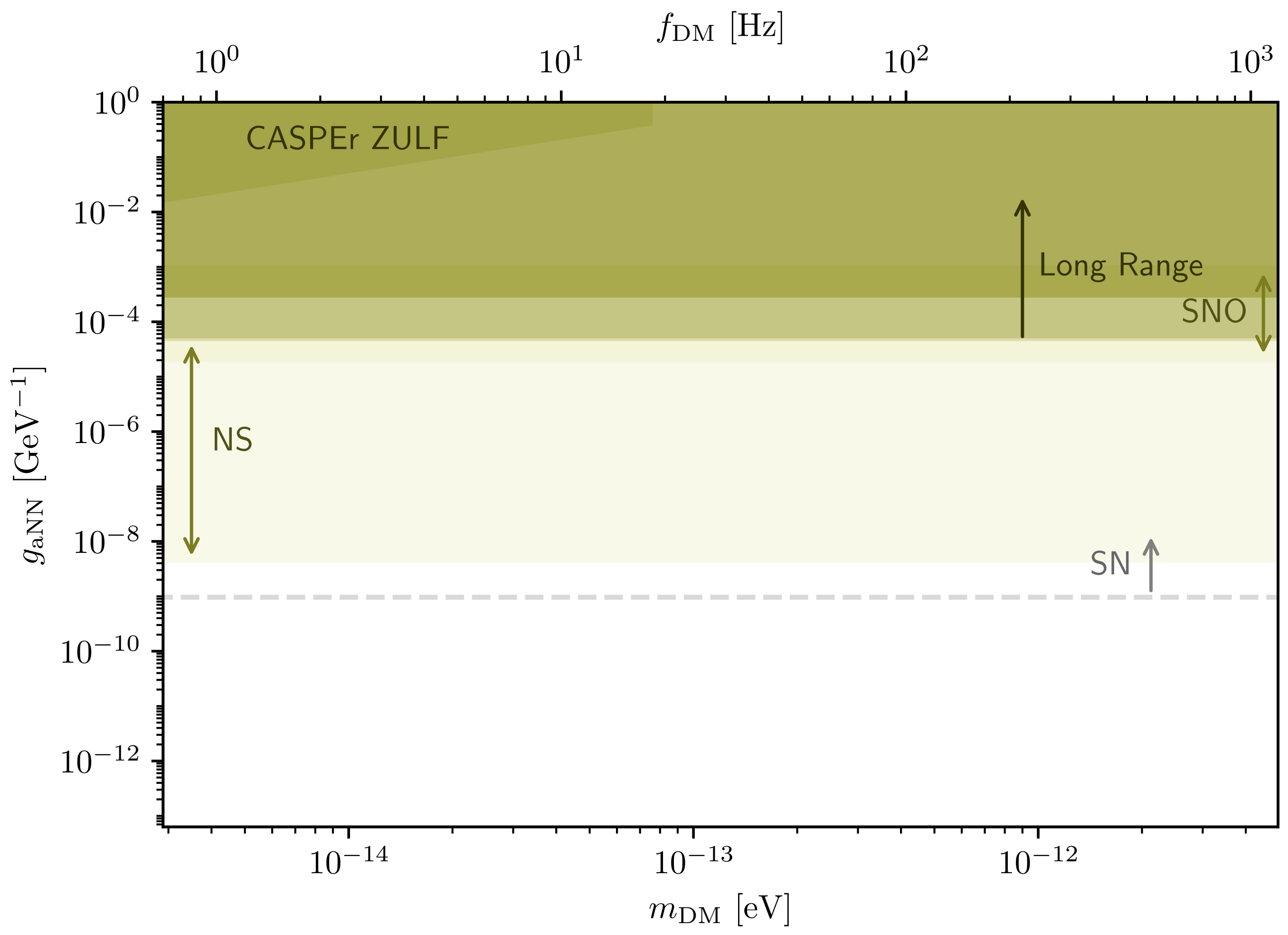
Tuning the Floquet frequency both systems can be brought to resonance!



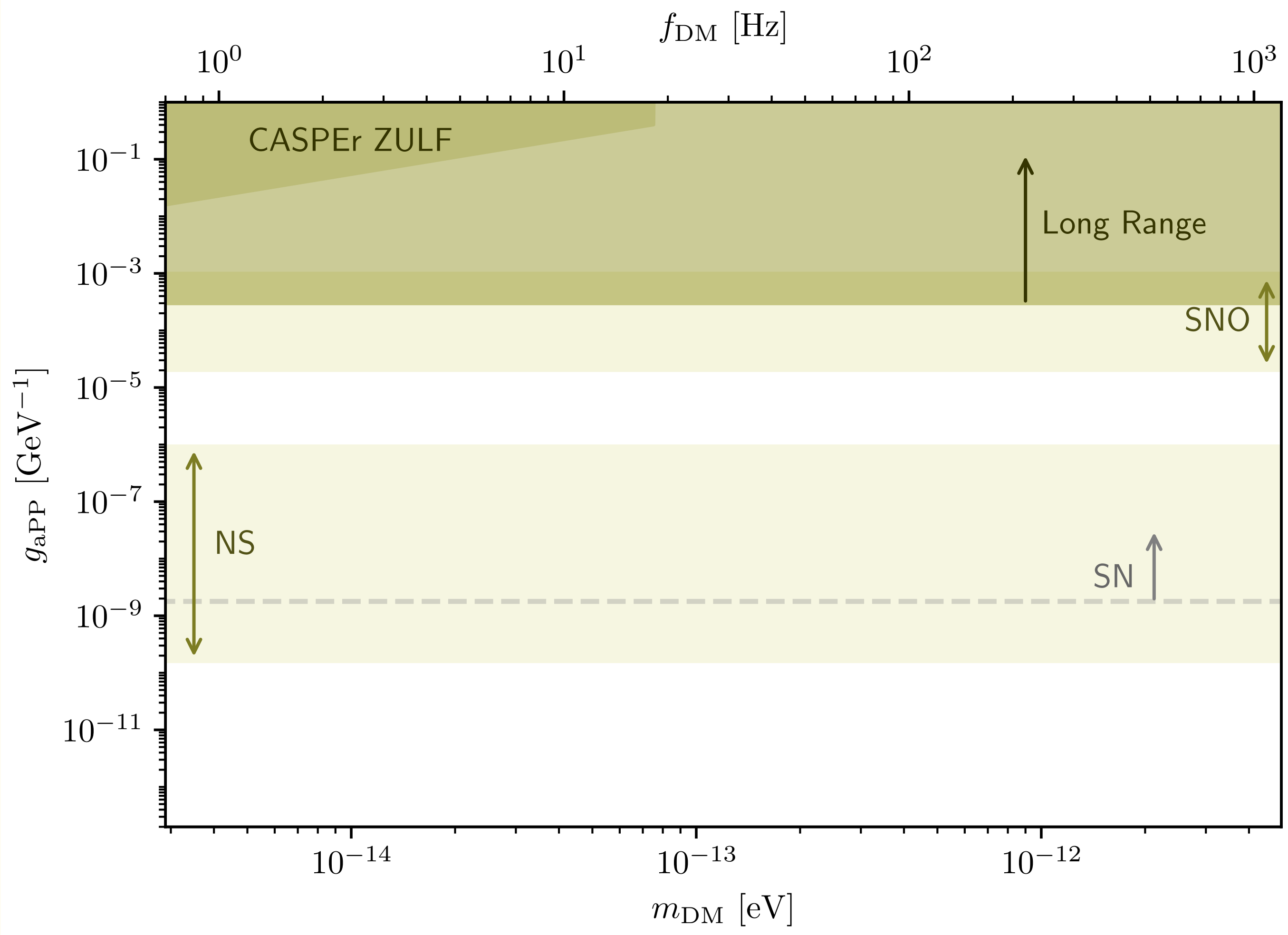
First results from NASDUCK:
Floquet quantum sensor

Floquet Quantum Sensor: Results

ALP-Neutron

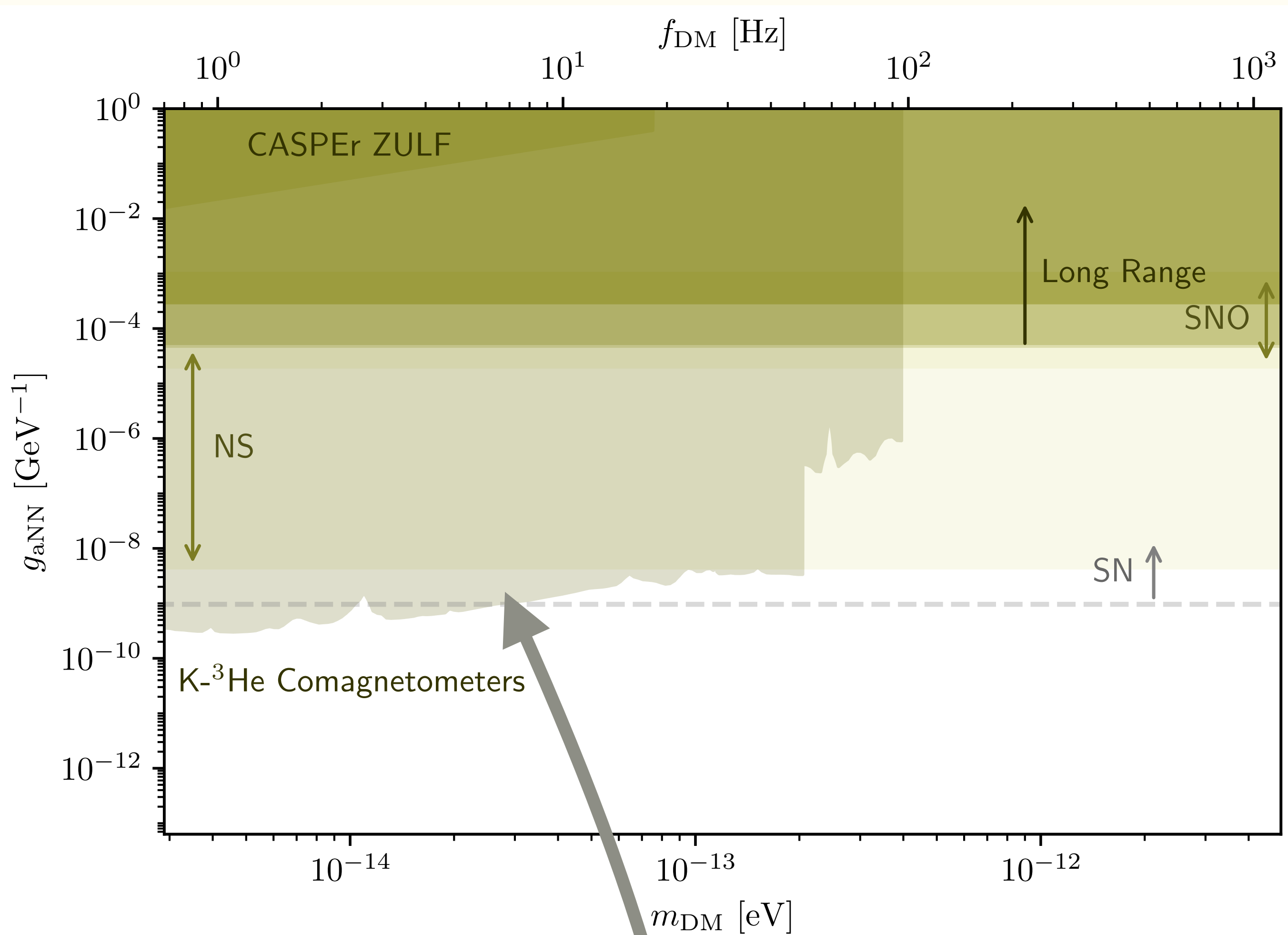


ALP-Proton

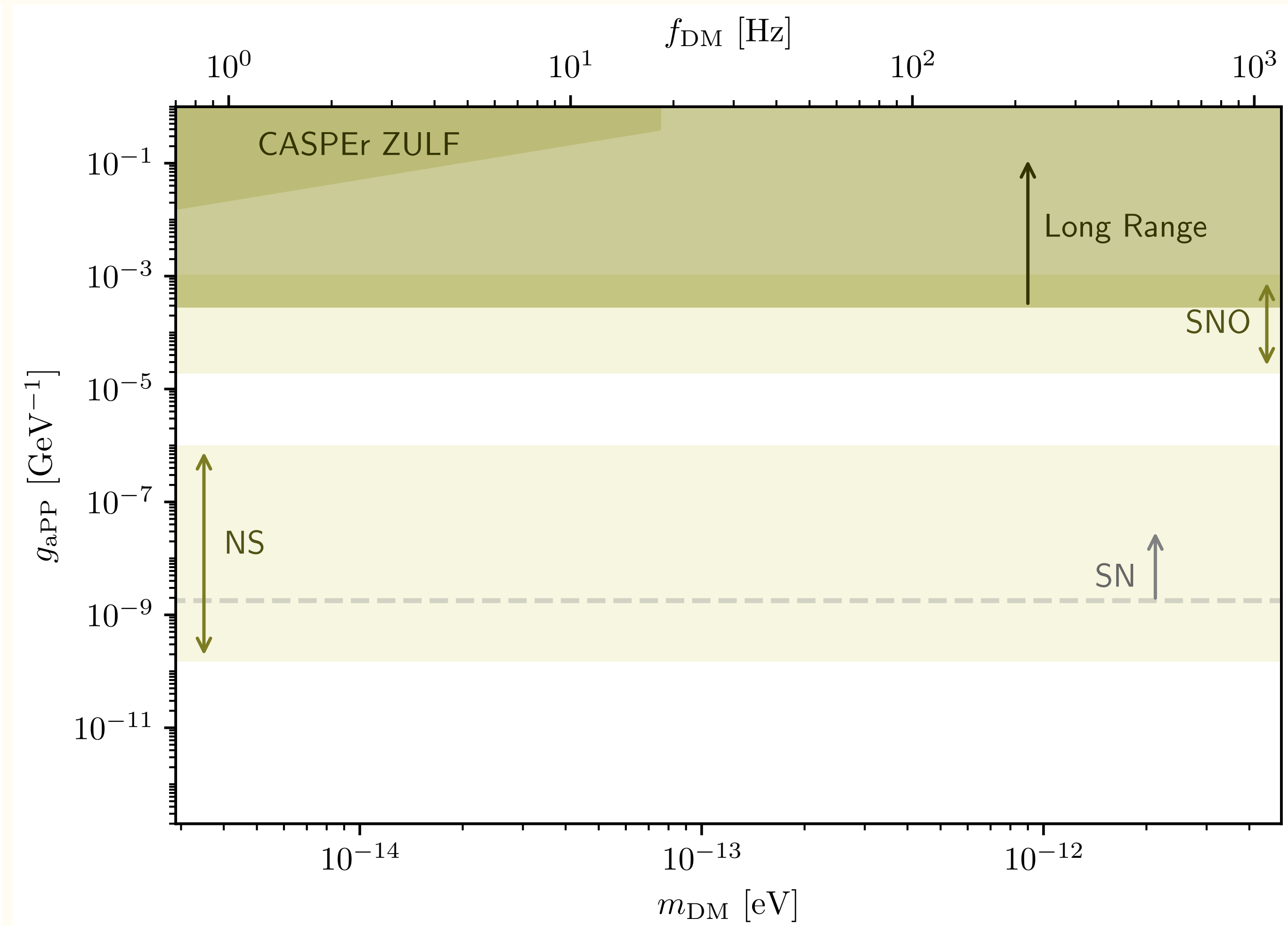


Floquet Quantum Sensor: Results

ALP-Neutron



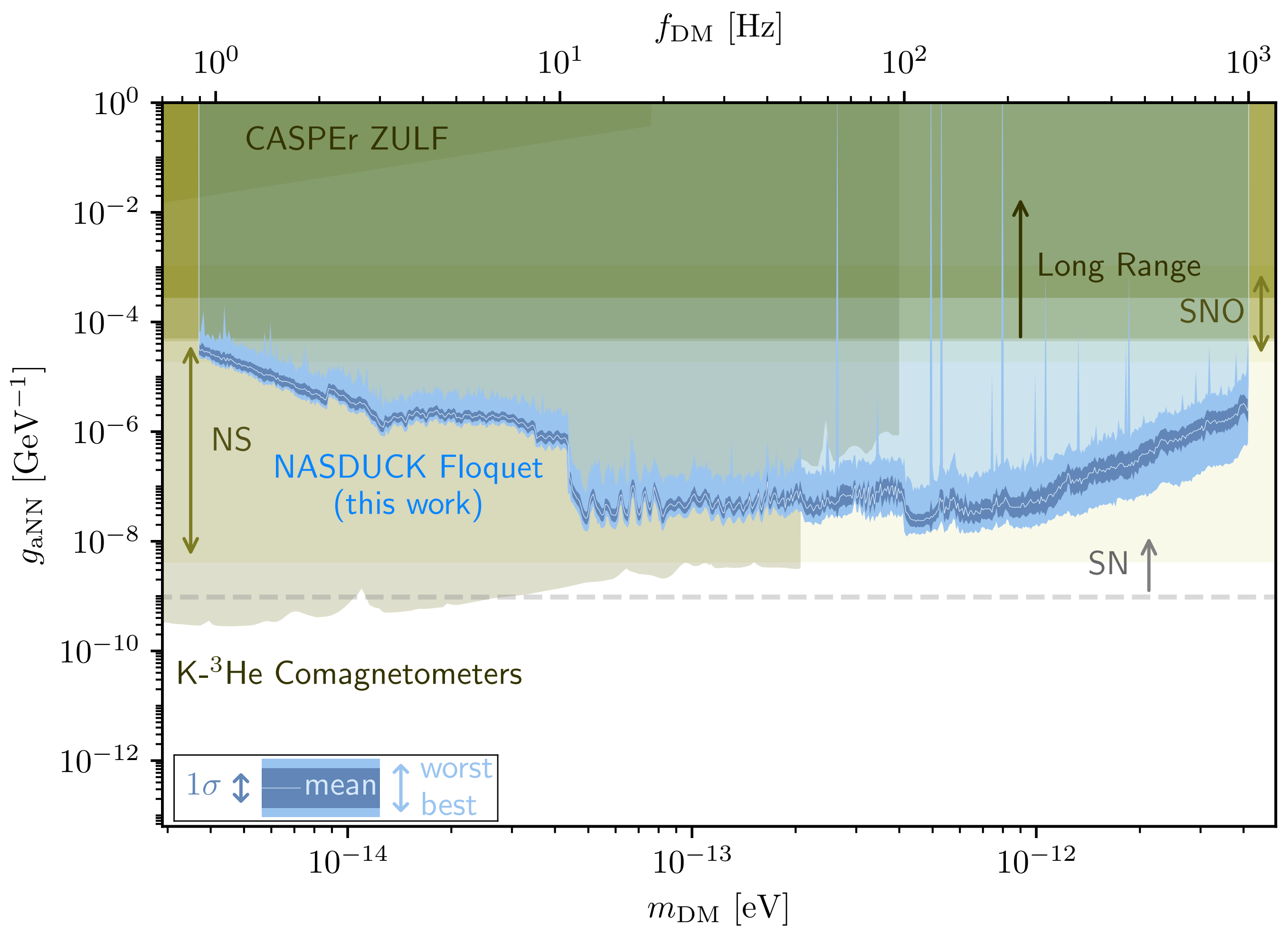
ALP-Proton



[Bloch,Kuflik,Hochberg,TV, 2019]

Floquet Quantum Sensor: Results

ALP-Neutron



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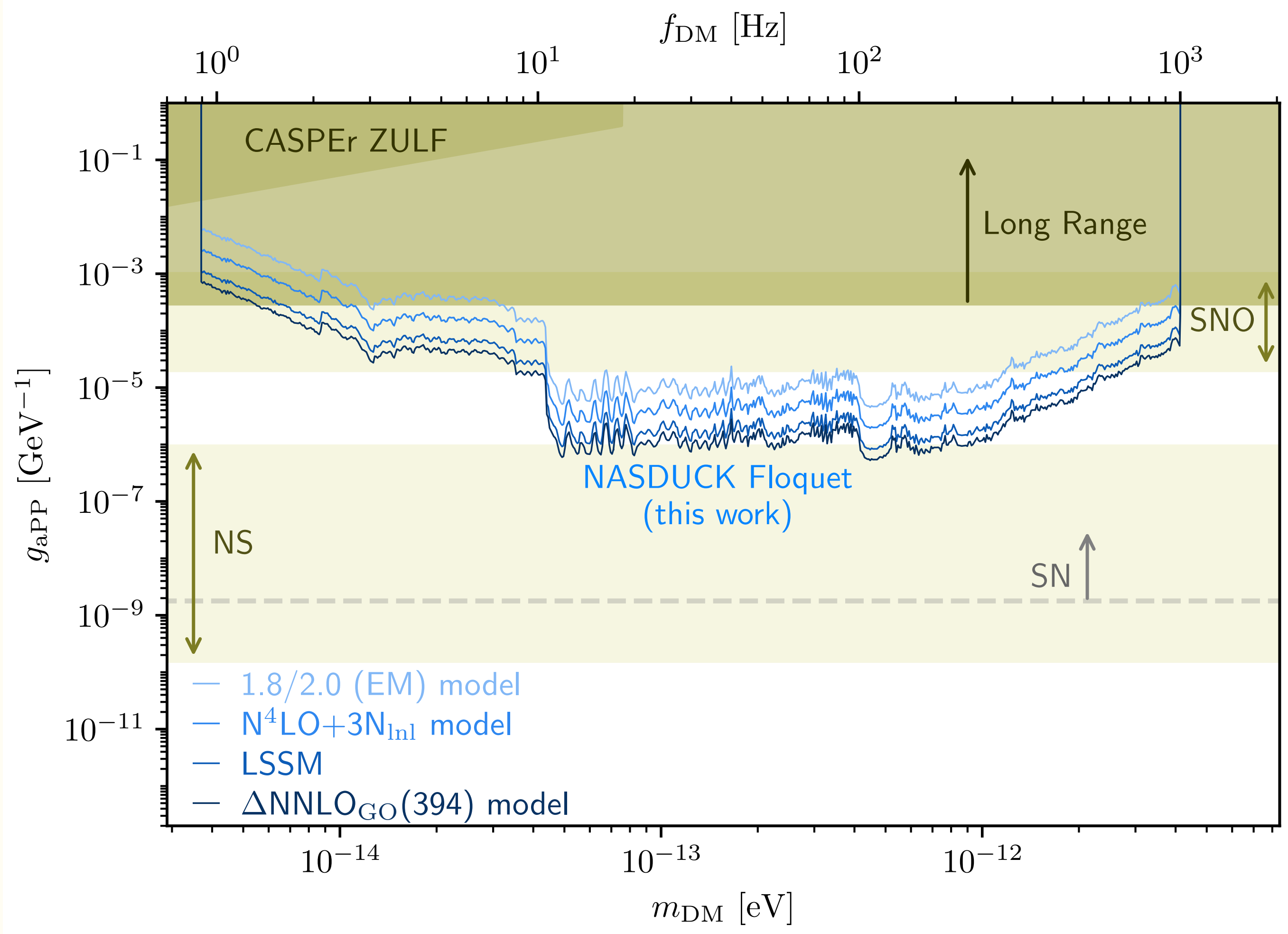
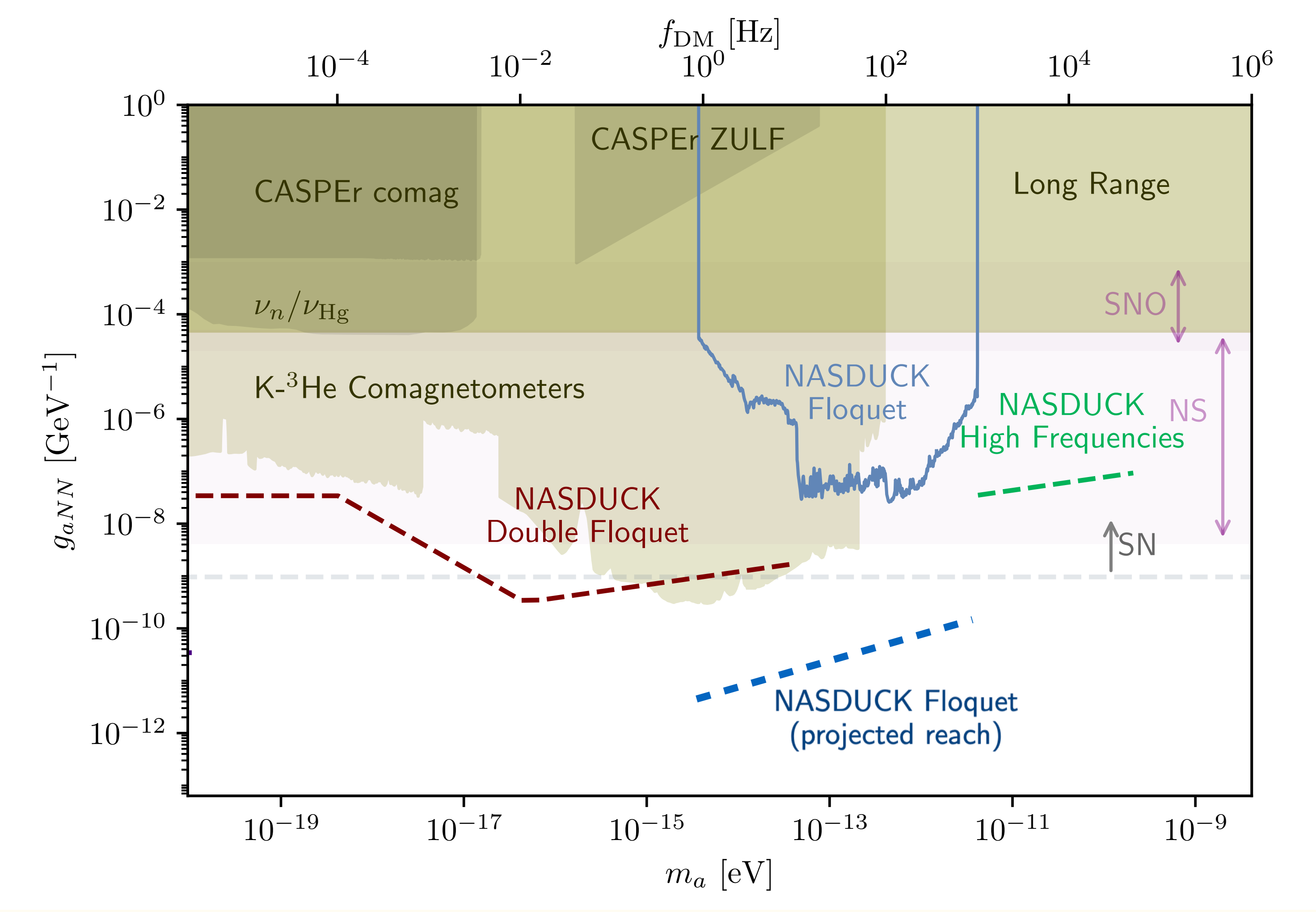


[NASDUCK Floquet, Science Advances 2022]

Limits are the result of 3000 measurements over a 5-month period

The Many experiments of NASDUCK

1. NASDUCK Improved Floquet
2. NASDUCK Double Floquet
3. NASDUCK High Frequency
4. NASDUCK Modulated
5. NASDUCK CoComag
6. …



Conclusions

SENSEI

Leading Light-DM experiment

Probes: DM-electron scattering
DM absorption
Migdal Scattering

Upcoming: Constraints from SNOLAB & MINOS
First modulation analysis

NASDUCK

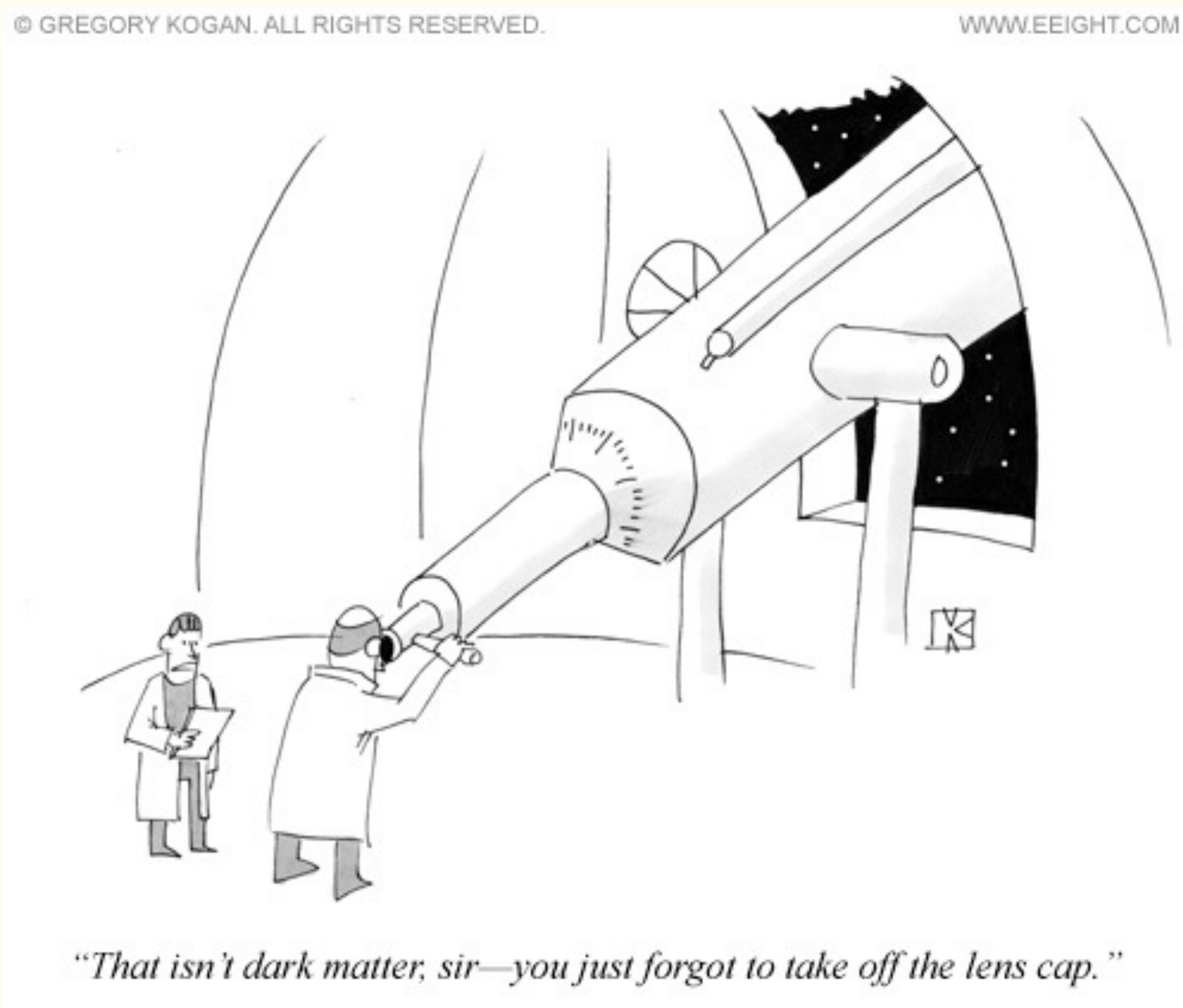
Leading Ultralight DM experiment

Upcoming: Many new co-magnetometer experiments probing a wide range of masses

Many new results coming up soon!!

Far too many mysteries to solve.
Can't stop now!

To be continued...



Israeli search for dark matter…