

# The Nature and Variety of Dark Matter

## Lecture III: light particle dark matter

Tracy Slatyer



SLAC Summer Institute 2025  
Pathways to New Physics  
30 July 2025

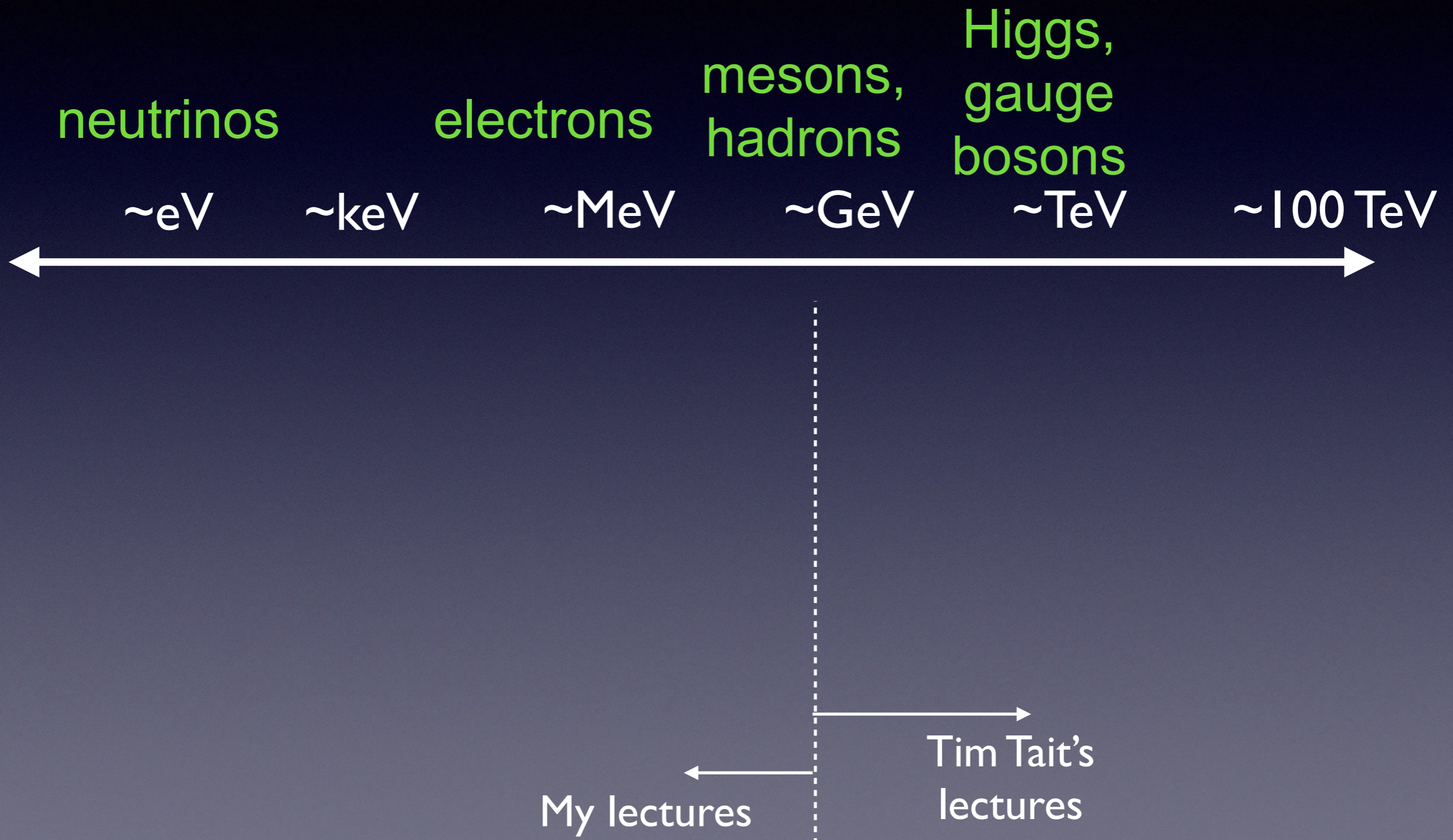
# Goals (Lecture 3)

- Today's focus:  $\sim$ keV-GeV DM (following up on Tim Tait's lectures focused on the GeV+ scale)
- Discuss the classification of MeV-GeV dark sectors
- Outline constraints on their properties
- Briefly discuss thermal freezeout benchmarks and variations on this scenario
- Discuss sterile neutrinos as a dark matter candidate and limits on keV-scale DM

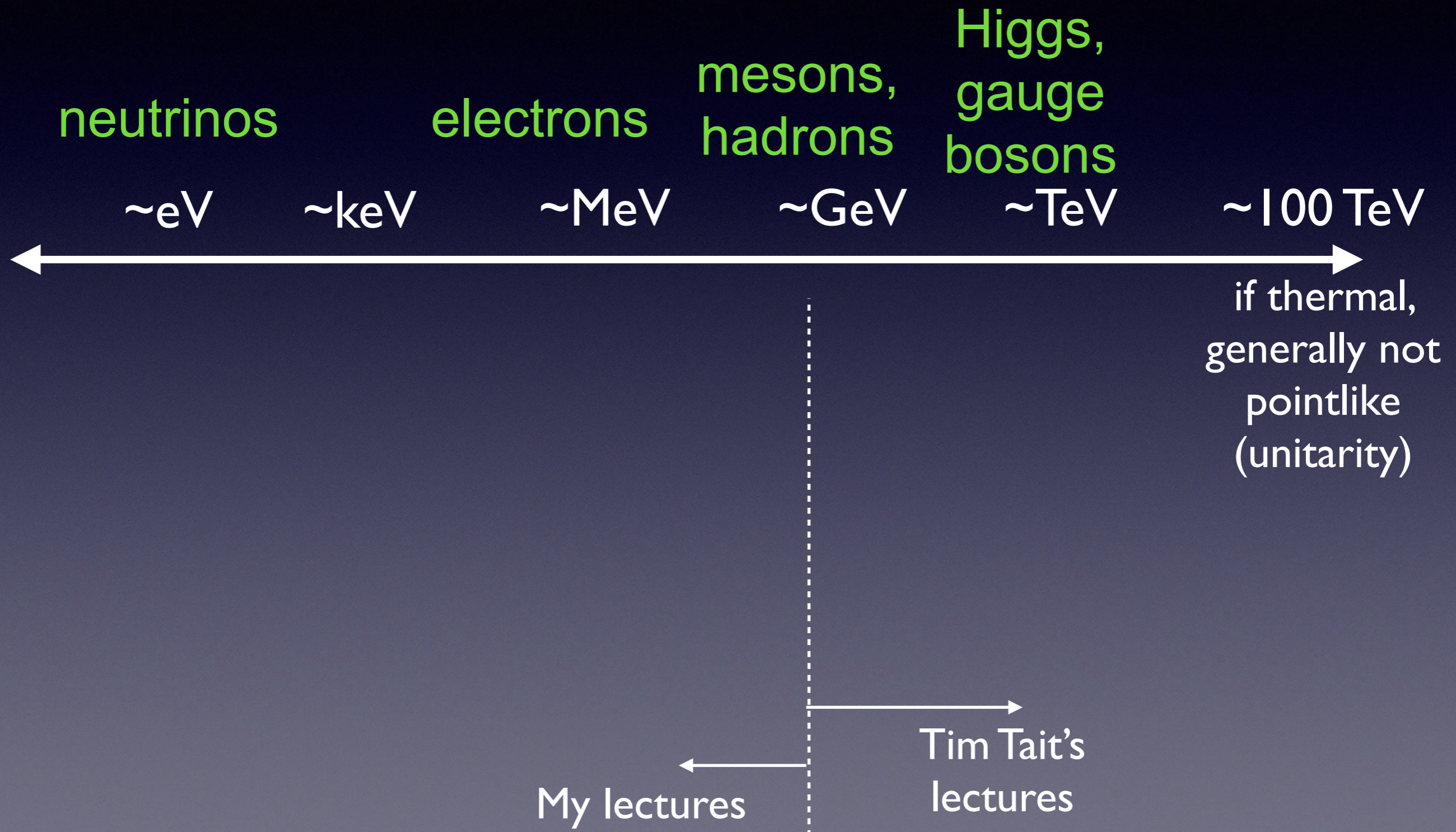
# What is the DM mass?



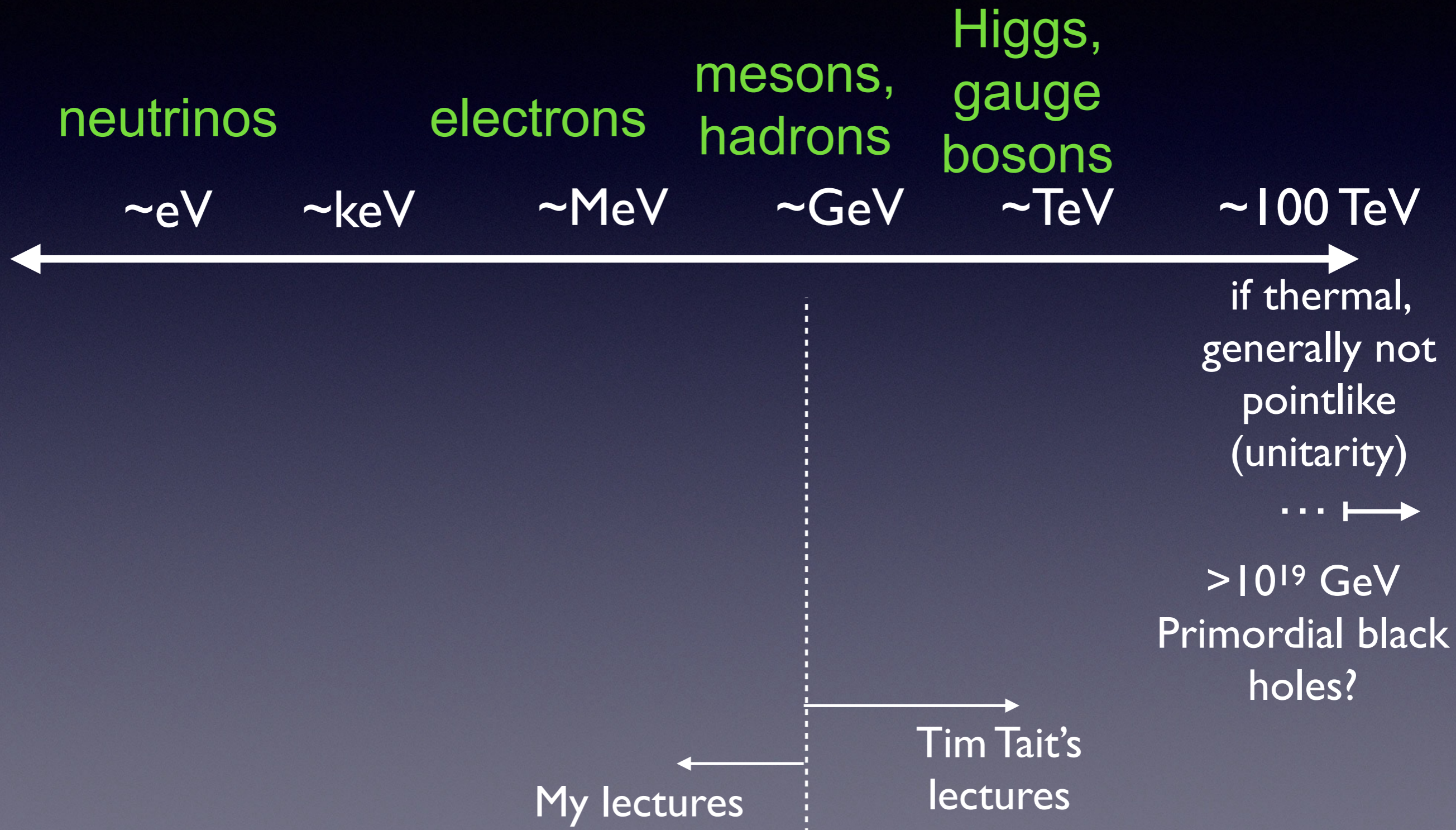
# What is the DM mass?



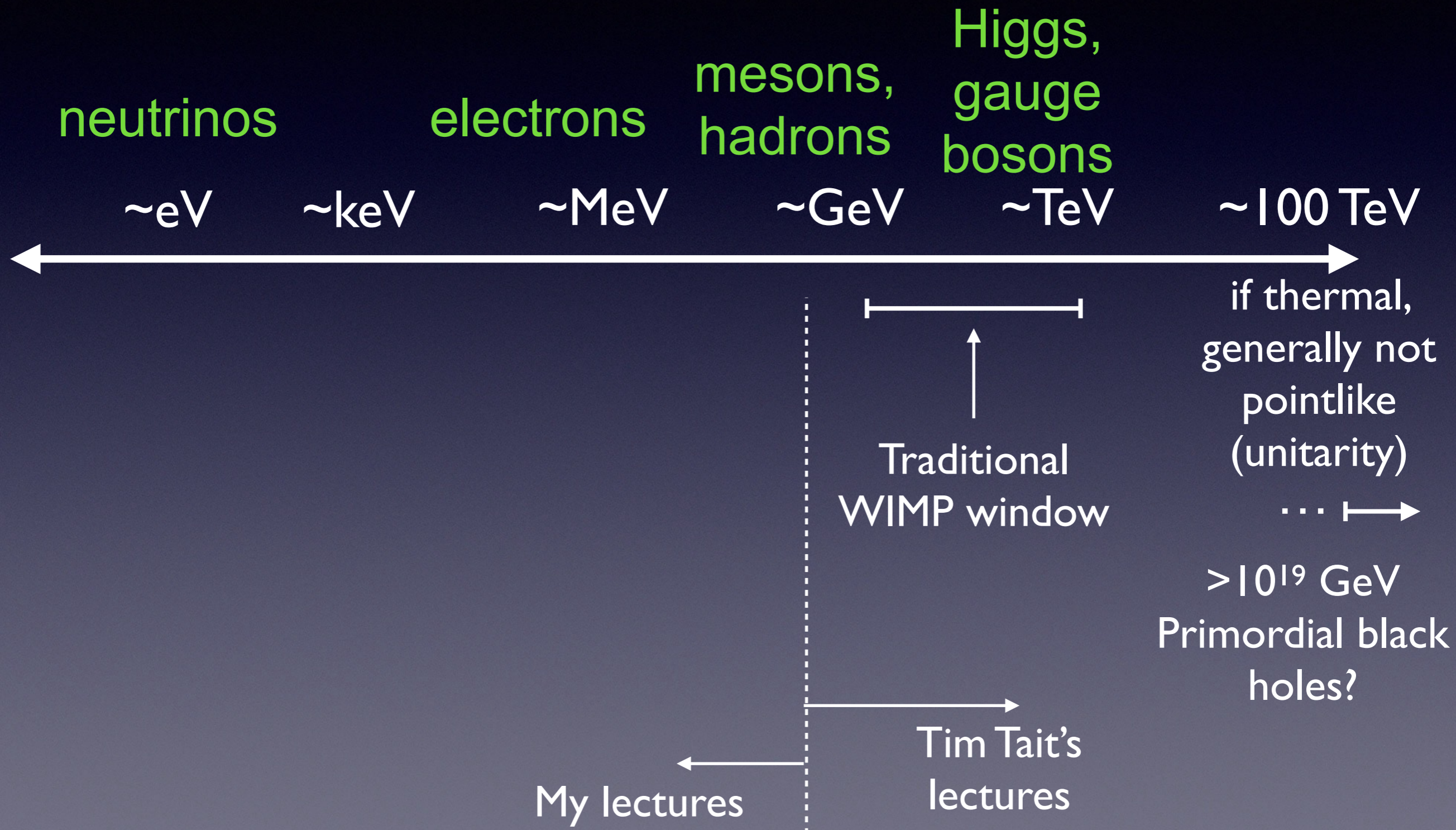
# What is the DM mass?



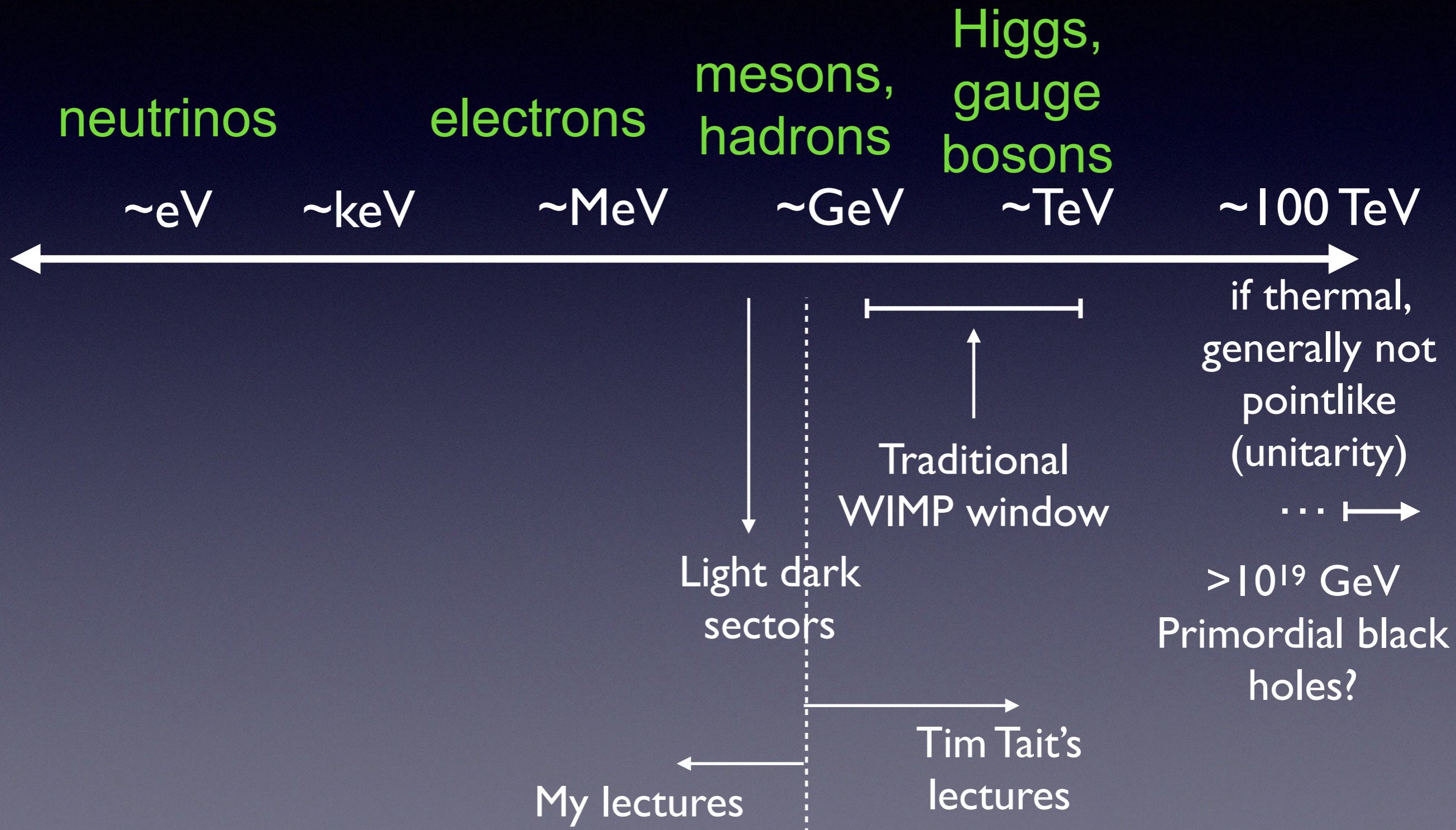
# What is the DM mass?



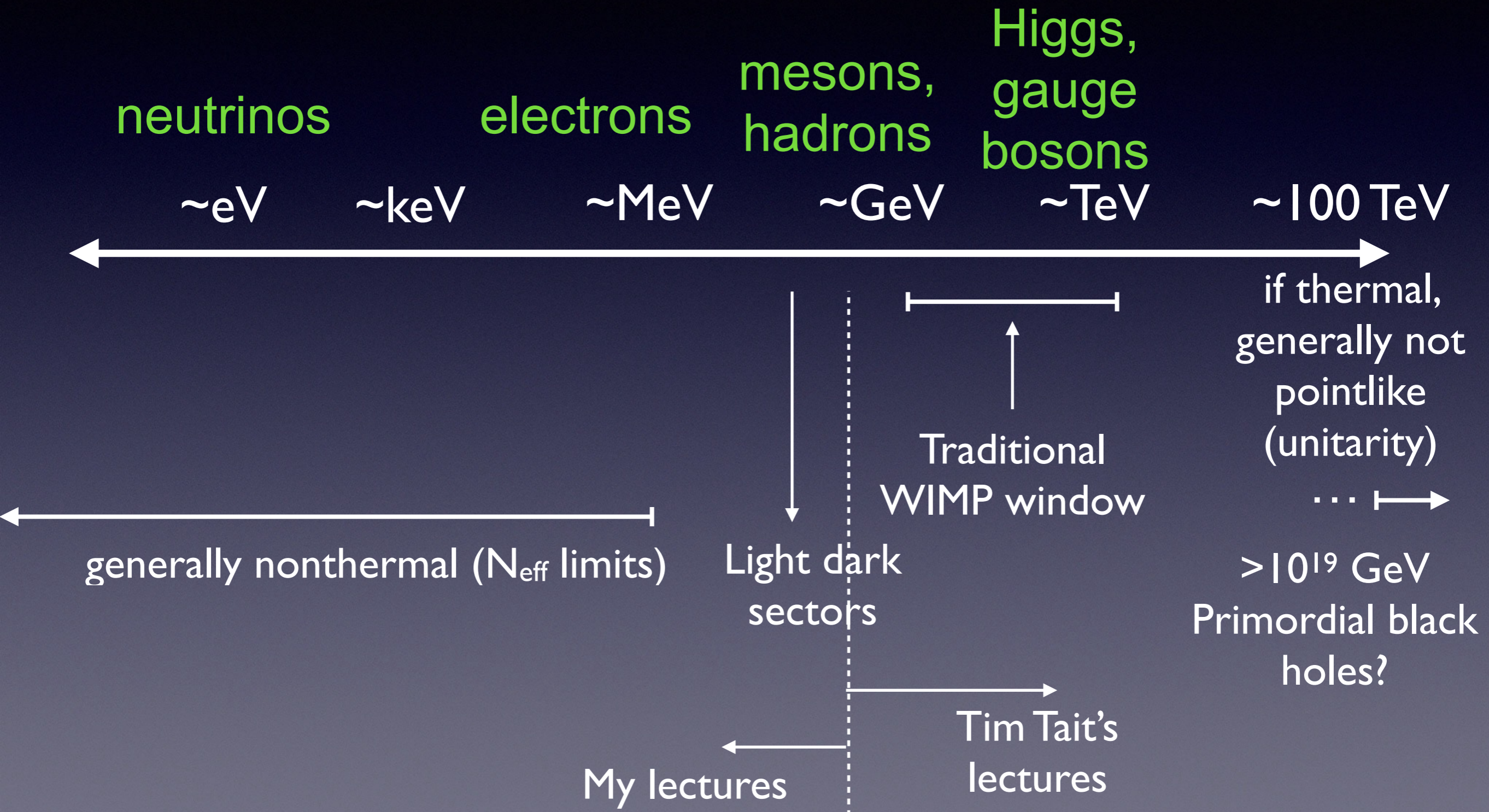
# What is the DM mass?



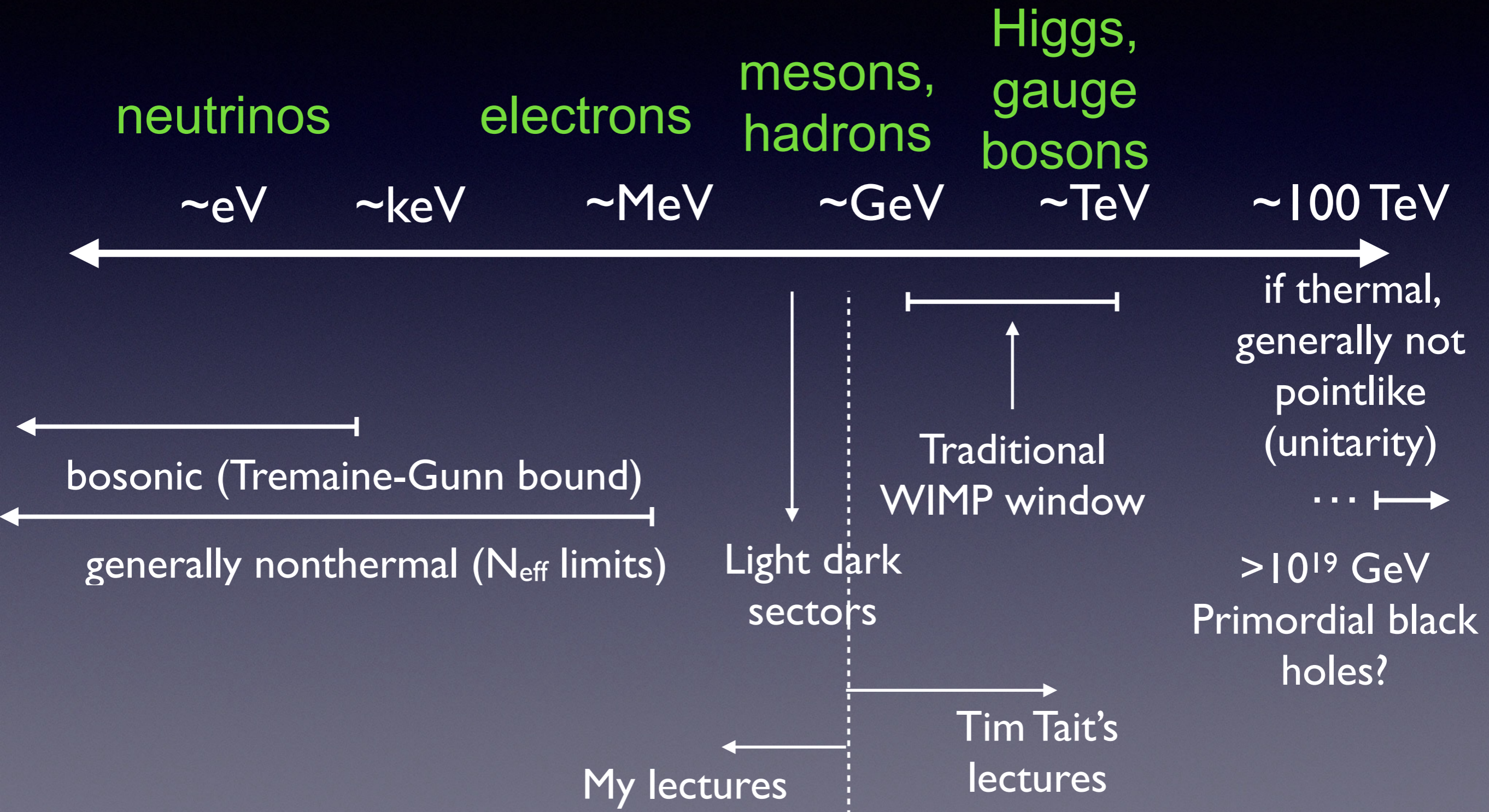
# What is the DM mass?



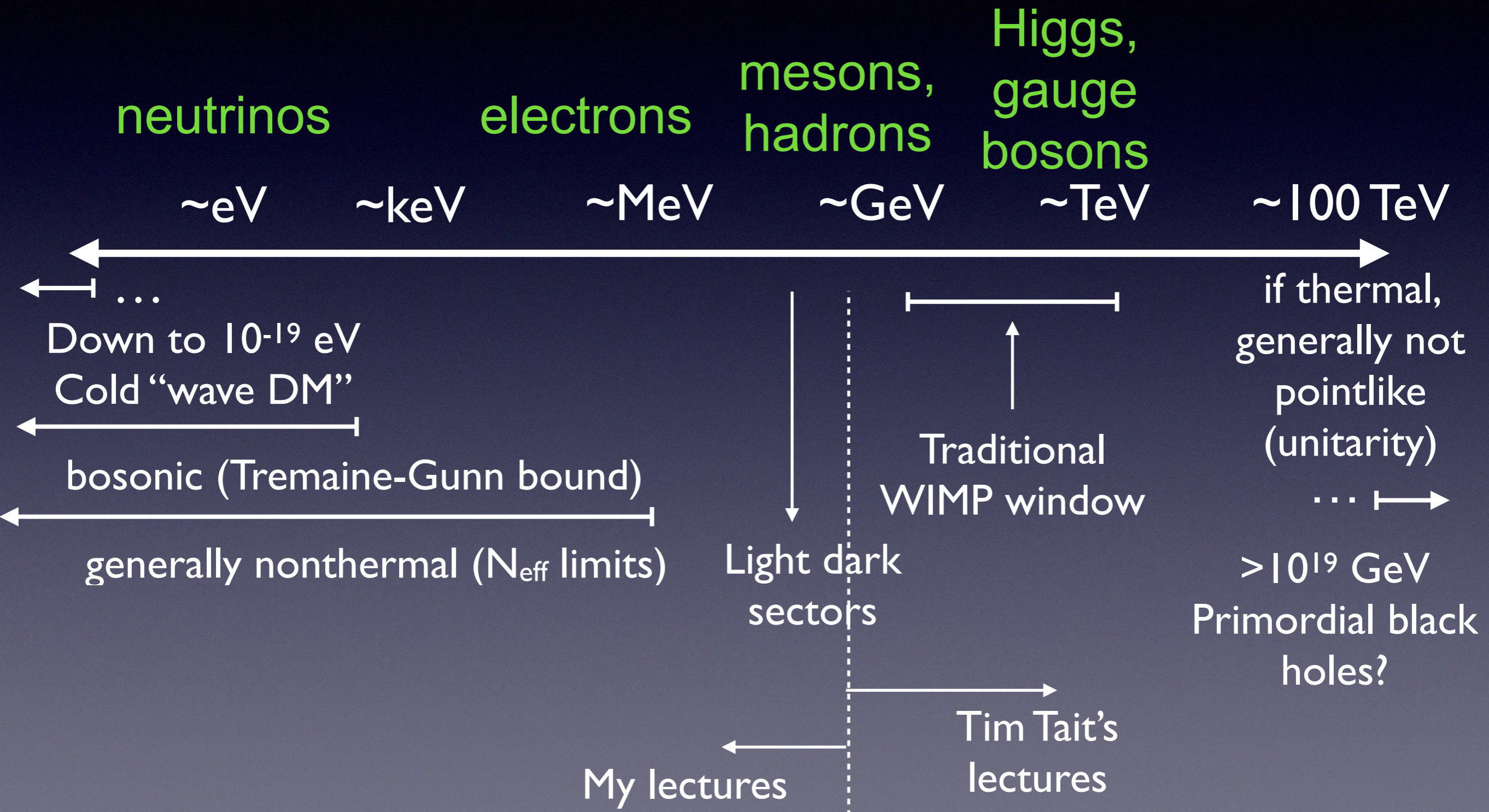
# What is the DM mass?



# What is the DM mass?



# What is the DM mass?



# Key points from earlier

- Thermal freezeout is a dynamical mechanism to produce the DM abundance
  - Implies significant couplings between dark-sector particles and Standard Model
  - Multi-faceted search strategy with direct detection, indirect detection, accelerators
- Not the only mechanism - multiple variations on freezeout
- One major variation is freeze-in - abundance set by couplings, but DM never reaches full equilibrium

Is there a characteristic mass  
scale for freezeout?

# Is there a characteristic mass scale for freezeout?

- If the DM is weakly-coupled and annihilates at tree-level, and there are no large hierarchies in the problem, we might expect  $\sigma v_{\text{rel}} \sim \alpha^2 / m_{\text{DM}}^2$  for some coupling  $\alpha$

# Is there a characteristic mass scale for freezeout?

- If the DM is weakly-coupled and annihilates at tree-level, and there are no large hierarchies in the problem, we might expect  $\sigma v_{\text{rel}} \sim \alpha^2 / m_{\text{DM}}^2$  for some coupling  $\alpha$

- One way to characterize the cross-section needed to obtain the right relic density is:

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{m_{\text{DM}} / T_f}{m_{\text{Pl}} T_{\text{MRE}}}$$

# Is there a characteristic mass scale for freezeout?

- If the DM is weakly-coupled and annihilates at tree-level, and there are no large hierarchies in the problem, we might expect  $\sigma v_{\text{rel}} \sim \alpha^2 / m_{\text{DM}}^2$  for some coupling  $\alpha$

- One way to characterize the cross-section needed to obtain the right relic density is:

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{m_{\text{DM}} / T_f}{m_{\text{Pl}} T_{\text{MRE}}}$$

**f: freezeout**  
**MRE: matter-radiation equality**

# Is there a characteristic mass scale for freezeout?

- If the DM is weakly-coupled and annihilates at tree-level, and there are no large hierarchies in the problem, we might expect  $\sigma v_{\text{rel}} \sim \alpha^2 / m_{\text{DM}}^2$  for some coupling  $\alpha$

- One way to characterize the cross-section needed to obtain the right relic density is:

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{m_{\text{DM}} / T_f}{m_{\text{Pl}} T_{\text{MRE}}}$$

**f: freezeout**  
**MRE: matter-radiation equality**

- From Tim's first lecture, numerator is  $O(40)$ , denominator is  $\sim (1 \text{ eV})(10^{19} \text{ GeV}) \sim (100 \text{ TeV})^2$

# Is there a characteristic mass scale for freezeout?

- If the DM is weakly-coupled and annihilates at tree-level, and there are no large hierarchies in the problem, we might expect  $\sigma v_{\text{rel}} \sim \alpha^2 / m_{\text{DM}}^2$  for some coupling  $\alpha$

- One way to characterize the cross-section needed to obtain the right relic density is:

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{m_{\text{DM}} / T_f}{m_{\text{Pl}} T_{\text{MRE}}}$$

**f: freezeout**  
**MRE: matter-radiation equality**

- From Tim's first lecture, numerator is  $O(40)$ , denominator is  $\sim (1 \text{ eV})(10^{19} \text{ GeV}) \sim (100 \text{ TeV})^2$
- Putting these together suggests  $m_{\text{DM}} \sim \alpha \times 20 \text{ TeV}$ , so a weak-scale coupling  $\alpha \sim 10^{-2}$  would correspond to  $m_{\text{DM}} \sim 200 \text{ GeV}$

# Exercise

- For 2-body annihilation, derive the approximate relation

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{m_{\text{DM}}/T_f}{m_{\text{PI}} T_{\text{MRE}}}$$

- Show that if the annihilation involves  $N$  dark matter particles instead of 2, and is described by a rate coefficient  $R$  so the annihilation term in the Boltzmann equation is  $dn_{\text{DM}}/dt = -Rn_{\text{DM}}^N$  then the relation becomes:

$$R \approx \frac{m_{\text{DM}}^{N-1} T_f^{5-3N}}{m_{\text{PI}} T_{\text{MRE}}^{N-1}}$$

- Use this to estimate the relationship between the coupling and the DM mass scale for  $N$ -body annihilation, assuming  $T_f \sim m_{\text{DM}}$ , and  $R$  scales as  $\alpha^N$  and the only relevant mass scale for  $R$  is  $m_{\text{DM}}$

# Thermal relics below the GeV scale

# Thermal relics below the GeV scale

- Weak-scale mass+coupling works (WIMP miracle), but this suggests lower masses are also fine, just require weaker coupling

# Thermal relics below the GeV scale

- Weak-scale mass+coupling works (WIMP miracle), but this suggests lower masses are also fine, just require weaker coupling
- **Lee-Weinberg bound**: DM must be above 2 GeV in mass

# Thermal relics below the GeV scale

- Weak-scale mass+coupling works (WIMP miracle), but this suggests lower masses are also fine, just require weaker coupling
- **Lee-Weinberg bound**: DM must be above 2 GeV in mass
  - Assumptions: DM obtained its abundance through freezeout and the mediator is the Z

# Thermal relics below the GeV scale

- Weak-scale mass+coupling works (WIMP miracle), but this suggests lower masses are also fine, just require weaker coupling
- **Lee-Weinberg bound:** DM must be above 2 GeV in mass
  - Assumptions: DM obtained its abundance through freezeout and the mediator is the Z
- If the DM is relatively light but annihilates through the Z boson (which we can integrate out), we expect the cross section to be parametrically bounded above by  $\sigma v_{\text{rel}} \lesssim m_{\text{DM}}^2/m_Z^4$ .

But then matching the relic density needs:

$$40/(100\text{TeV})^2 \lesssim m_{\text{DM}}^2/m_Z^4 \Rightarrow m_{\text{DM}} \gtrsim 6m_Z(m_Z/100\text{TeV}) \sim \text{GeV}$$

# Thermal relics below the GeV scale

- Weak-scale mass+coupling works (WIMP miracle), but this suggests lower masses are also fine, just require weaker coupling
- **Lee-Weinberg bound:** DM must be above 2 GeV in mass
  - Assumptions: DM obtained its abundance through freezeout and the mediator is the Z
- If the DM is relatively light but annihilates through the Z boson (which we can integrate out), we expect the cross section to be parametrically bounded above by  $\sigma v_{\text{rel}} \lesssim m_{\text{DM}}^2/m_Z^4$ .  
But then matching the relic density needs:  
 $40/(100\text{TeV})^2 \lesssim m_{\text{DM}}^2/m_Z^4 \Rightarrow m_{\text{DM}} \gtrsim 6m_Z(m_Z/100\text{TeV}) \sim \text{GeV}$
- DM below this mass scale is fine - but if it is a thermal relic, likely requires new (lighter) mediators between the DM and the SM

# Dark sectors

- This leads us to a class of models where the DM interacts with a new “mediator” particle, which in turn has a small coupling to the SM
- Requires at least one new particle beyond DM - dark sector
- One possible classification: nature of the mediator + its interactions with SM, summarized as the “portal”
- This does not tell us everything - still need to specify how the DM couples to the mediator, plus properties of any other dark-sector particles
- Notes:
  - Thermal freezeout is a key benchmark, but not the only viable production mechanism for dark sectors (e.g. freeze-in also works)
  - Implies the existence of DM self-interactions through the new mediator

# Portals to the dark sector

- One question we might ask: does the mediator carry any SM quantum numbers?
- If not, what renormalizable (dim 4 or less) operators can we build from a gauge-singlet mediator and a gauge-singlet combination of SM fields?
- This leads us to the vector, scalar & neutrino portals

Portal	Interactions
Dark Photon, $A'_\mu$	$-\epsilon F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, $S$	$(\mu S + \lambda S^2) H^\dagger H$
Heavy Neutral Lepton, $N$	$y_N L H N$

There is also the axion portal which is dim-5

# Exercise

- Suppose there is a dark photon with mass  $m_A$  coupled to the Standard Model only through the kinetic mixing term given on the last slide (note  $B^{\mu\nu}$  is the hypercharge field strength). For the purposes of this problem you may ignore the Z boson (harder version: include the Z boson. If you get stuck, e.g. [1712.03974](#) may be helpful.)
- Show that you can always perform a field redefinition that removes the kinetic mixing term, while keeping the Standard Model photon massless. How will the redefined dark photon field couple to the Standard Model matter fields?
- Now suppose there is also a dark Dirac fermion  $\chi$  charged under the dark U(1). After the field redefinition to remove the kinetic mixing, does  $\chi$  couple to the photon?
- Now consider the case where the dark photon mass is set to zero. Show that we can perform an additional field redefinition to completely decouple the dark photon field from the SM (without re-establishing a kinetic mixing). What happens to the couplings of the  $\chi$  field in this case?

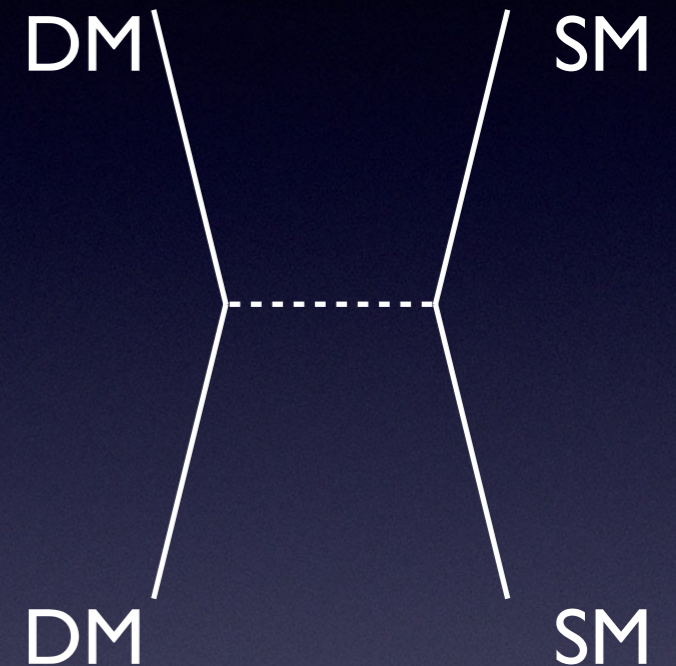
# Freezeout for portal dark matter

# Freezeout for portal dark matter

- Two general scenarios:
  - (1) DM annihilates through off-shell mediators into SM particles
  - (2) DM annihilates to (lighter) on-shell mediators, which subsequently decay to SM particles

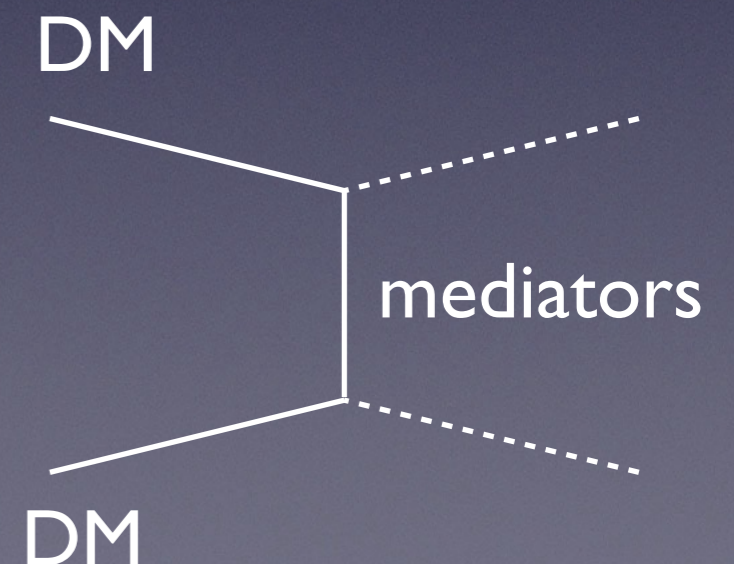
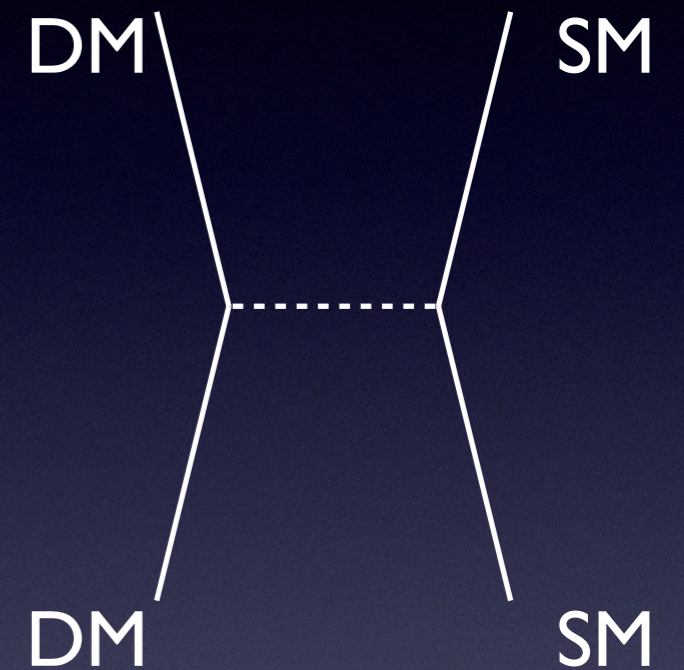
# Freezeout for portal dark matter

- Two general scenarios:
  - (1) DM annihilates through off-shell mediators into SM particles
  - (2) DM annihilates to (lighter) on-shell mediators, which subsequently decay to SM particles
- (1) same calculation as before, annihilation is controlled by the mediator couplings + mass
  - If the mediator mass is heavy, behaves like contact interaction: same effective DM-SM coupling relevant for accelerators and direct detection



# Freezeout for portal dark matter

- Two general scenarios:
  - (1) DM annihilates through off-shell mediators into SM particles
  - (2) DM annihilates to (lighter) on-shell mediators, which subsequently decay to SM particles
- (1) same calculation as before, annihilation is controlled by the mediator couplings + mass
  - If the mediator mass is heavy, behaves like contact interaction: same effective DM-SM coupling relevant for accelerators and direct detection
- (2) Do the mediators remain in equilibrium with the SM through freezeout? If so, requires a minimum SM-mediator coupling. If not, see e.g. [Bringmann et al 2103.01944](#) for tools to treat this case.



# Variations on freezeout

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)
- Fully or partially secluded dark sectors (mediator not in equilibrium with SM throughout freezeout), see e.g. [Bringmann et al 2103.01944](#)

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)
- Fully or partially secluded dark sectors (mediator not in equilibrium with SM throughout freezeout), see e.g. [Bringmann et al 2103.01944](#)
  - “cannibalism” occurs when the DM number density falls while conserving entropy, increasing temperature [[e.g. Carlson et al '92](#)]

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)
- Fully or partially secluded dark sectors (mediator not in equilibrium with SM throughout freezeout), see e.g. [Bringmann et al 2103.01944](#)
  - “cannibalism” occurs when the DM number density falls while conserving entropy, increasing temperature [[e.g. Carlson et al '92](#)]
  - more generally, presence of a non-zero chemical potential can modify the equilibrium abundance curve, e.g. “bouncing dark matter” [[Puetter et al 2208.08453](#)]

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)
- Fully or partially secluded dark sectors (mediator not in equilibrium with SM throughout freezeout), see e.g. [Bringmann et al 2103.01944](#)
  - “cannibalism” occurs when the DM number density falls while conserving entropy, increasing temperature [[e.g. Carlson et al '92](#)]
  - more generally, presence of a non-zero chemical potential can modify the equilibrium abundance curve, e.g. “bouncing dark matter” [[Puetter et al 2208.08453](#)]
  - ELastically DEcoupling Relic (ELDER) [[Kuflik et al 1512.04545](#)]: abundance controlled by kinetic decoupling during freezeout & hence by scattering cross section

# Variations on freezeout

- More than two DM particles in the initial state - e.g. Strongly Interacting Massive Particles (SIMPs) [[Hochberg et al 1402.5143](#)], “maximum” mass scale goes from  $O(100)$  TeV to sub-GeV
- Partner particles in the initial state - can be DM and anti-DM, or DM + a slightly heavier excited state (inelastic or pseudo-Dirac DM)
- Fully or partially secluded dark sectors (mediator not in equilibrium with SM throughout freezeout), see e.g. [Bringmann et al 2103.01944](#)
  - “cannibalism” occurs when the DM number density falls while conserving entropy, increasing temperature [[e.g. Carlson et al '92](#)]
  - more generally, presence of a non-zero chemical potential can modify the equilibrium abundance curve, e.g. “bouncing dark matter” [[Puetter et al 2208.08453](#)]
  - ELastically DEcoupling Relic (ELDER) [[Kuflik et al 1512.04545](#)]: abundance controlled by kinetic decoupling during freezeout & hence by scattering cross section
  - Interconversion between DM and other dark sector states (possibly followed by out-of-equilibrium decay of those states) may control the abundance [[e.g. Dror et al 1607.03110](#), [Tito d’Agnolo et al 1705.08450](#), [Garny et al 1705.09292](#)]

# Cosmological and astrophysical bounds

# Cosmological and astrophysical bounds

- Indirect searches for annihilation can be very stringent at these masses; higher DM number density compared to WIMPs

# Cosmological and astrophysical bounds

- Indirect searches for annihilation can be very stringent at these masses; higher DM number density compared to WIMPs
- In the thermal freezeout scenario, annihilation at early times is  $\sim$ fixed by the DM abundance

# Cosmological and astrophysical bounds

- Indirect searches for annihilation can be very stringent at these masses; higher DM number density compared to WIMPs
- In the thermal freezeout scenario, annihilation at early times is  $\sim$ fixed by the DM abundance
- However, annihilation at late times can be either suppressed or enhanced relative to the early universe

# Cosmological and astrophysical bounds

- Indirect searches for annihilation can be very stringent at these masses; higher DM number density compared to WIMPs
- In the thermal freezeout scenario, annihilation at early times is  $\sim$ fixed by the DM abundance
- However, annihilation at late times can be either suppressed or enhanced relative to the early universe
- Suppression: typically either originates from a low-velocity suppression (e.g. p-wave annihilation, kinematically forbidden final states [e.g. [Tito d'Agnolo et al 1505.07107](#)]) or the absence of a needed partner particle (asymmetric DM, coannihilation).

# Cosmological and astrophysical bounds

- Indirect searches for annihilation can be very stringent at these masses; higher DM number density compared to WIMPs
- In the thermal freezeout scenario, annihilation at early times is  $\sim$ fixed by the DM abundance
- However, annihilation at late times can be either suppressed or enhanced relative to the early universe
- Suppression: typically either originates from a low-velocity suppression (e.g. p-wave annihilation, kinematically forbidden final states [e.g. [Tito d'Agnolo et al 1505.07107](#)]) or the absence of a needed partner particle (asymmetric DM, coannihilation).
- Enhancement: low-velocity enhancement can occur from Breit-Wigner resonance or Sommerfeld enhancement [e.g. [Hisano et al hep-ph/0307216](#)] - generic in the presence of scalar/vector mediators much lighter than the DM

# Cosmological history of thermal relic DM

# Cosmological history of thermal relic DM

- For calibration, let us consider the “standard” case with (1) standard freezeout + (2) annihilation cross-section is unchanged post-freezeout

# Cosmological history of thermal relic DM

- For calibration, let us consider the “standard” case with (1) standard freezeout + (2) annihilation cross-section is unchanged post-freezeout
- One way to estimate effects is calorimetric: look at the fraction of DM that annihilates per Hubble time,  $n_{\text{DM}}\langle\sigma v\rangle H^{-1}$  ( $\sim 1$  at freezeout, by definition)

# Cosmological history of thermal relic DM

- For calibration, let us consider the “standard” case with (1) standard freezeout + (2) annihilation cross-section is unchanged post-freezeout
- One way to estimate effects is calorimetric: look at the fraction of DM that annihilates per Hubble time,  $n_{\text{DM}}\langle\sigma v\rangle H^{-1}$  ( $\sim 1$  at freezeout, by definition)
- After freezeout,  $n_{\text{DM}} \propto (1+z)^3 \sim T^3$ . During radiation domination  $H \propto T^2$ , so this ratio falls linearly with  $T$ ; during matter domination  $H \propto T^{3/2}$  so the ratio falls as  $T^{3/2}$  (and then as  $T^3$  during dark energy domination).

# Cosmological history of thermal relic DM

- For calibration, let us consider the “standard” case with (1) standard freezeout + (2) annihilation cross-section is unchanged post-freezeout
- One way to estimate effects is calorimetric: look at the fraction of DM that annihilates per Hubble time,  $n_{\text{DM}}\langle\sigma v\rangle H^{-1}$  ( $\sim 1$  at freezeout, by definition)
- After freezeout,  $n_{\text{DM}} \propto (1+z)^3 \sim T^3$ . During radiation domination  $H \propto T^2$ , so this ratio falls linearly with  $T$ ; during matter domination  $H \propto T^{3/2}$  so the ratio falls as  $T^{3/2}$  (and then as  $T^3$  during dark energy domination).
- During radiation domination, energy injected per baryon over a Hubble time is roughly  $(5 \text{ GeV})T/T_f$ :  
i.e. for  $T_f \sim 5 \text{ GeV}$  ( $m_{\text{DM}} \sim 100 \text{ GeV}$ ), the energy injected is sufficient to change the energy of the baryons by an  $O(1)$  factor (more for lighter DM)

# An example: perturbing the CMB

# An example: perturbing the CMB

- After recombination, a significant fraction of this injected power can go into ionizing hydrogen

# An example: perturbing the CMB

- After recombination, a significant fraction of this injected power can go into ionizing hydrogen
  - Temperature at recombination  $T \sim 0.2$  eV  
1 eV ( $1 \text{ GeV}/T_f$ ) power injected per baryon over a Hubble time (note CMB is emitted not long after matter-radiation equality)  
 $O(10)$  eV to ionize one H

# An example: perturbing the CMB

- After recombination, a significant fraction of this injected power can go into ionizing hydrogen
  - Temperature at recombination  $T \sim 0.2$  eV  
1 eV ( $1 \text{ GeV}/T_f$ ) power injected per baryon over a Hubble time (note CMB is emitted not long after matter-radiation equality)  
 $O(10)$  eV to ionize one H
  - Suggests that  $T_f \sim 0.1 \text{ GeV}$  (so  $m \sim \text{few GeV}$ ) provides power to ionize all hydrogen over a Hubble time

# An example: perturbing the CMB

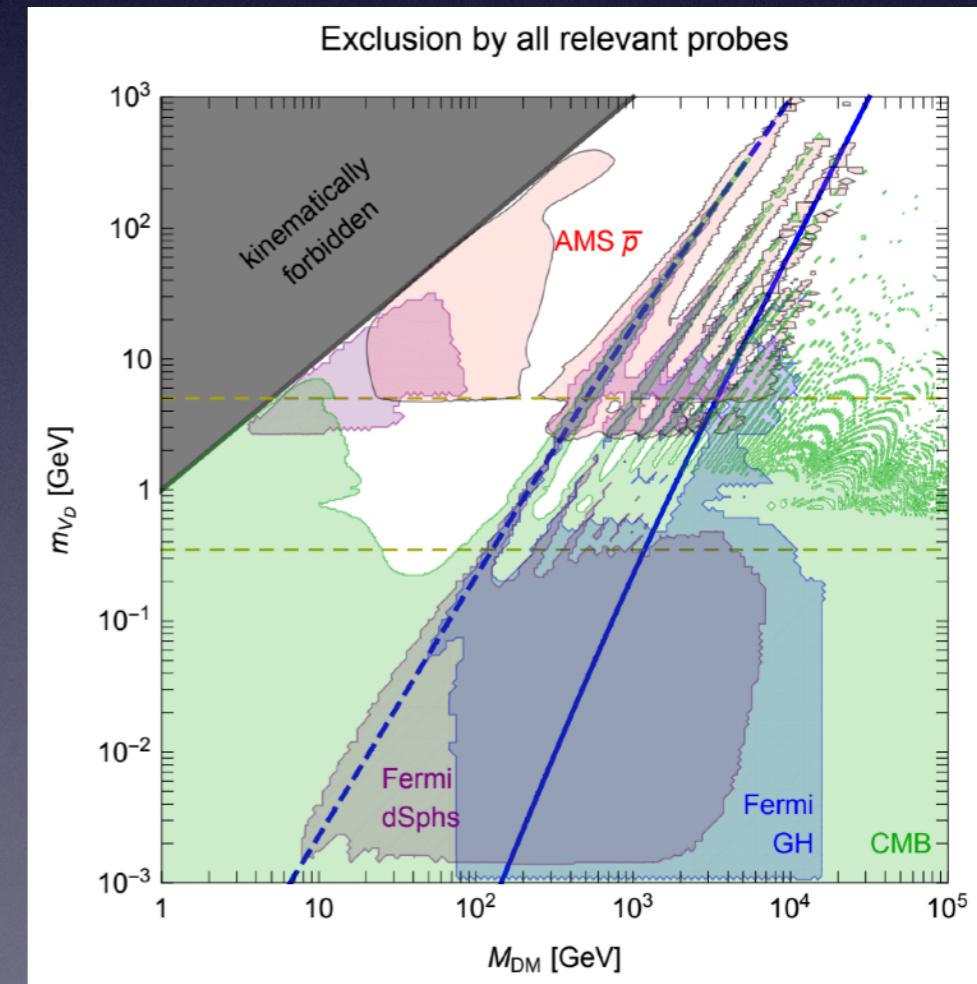
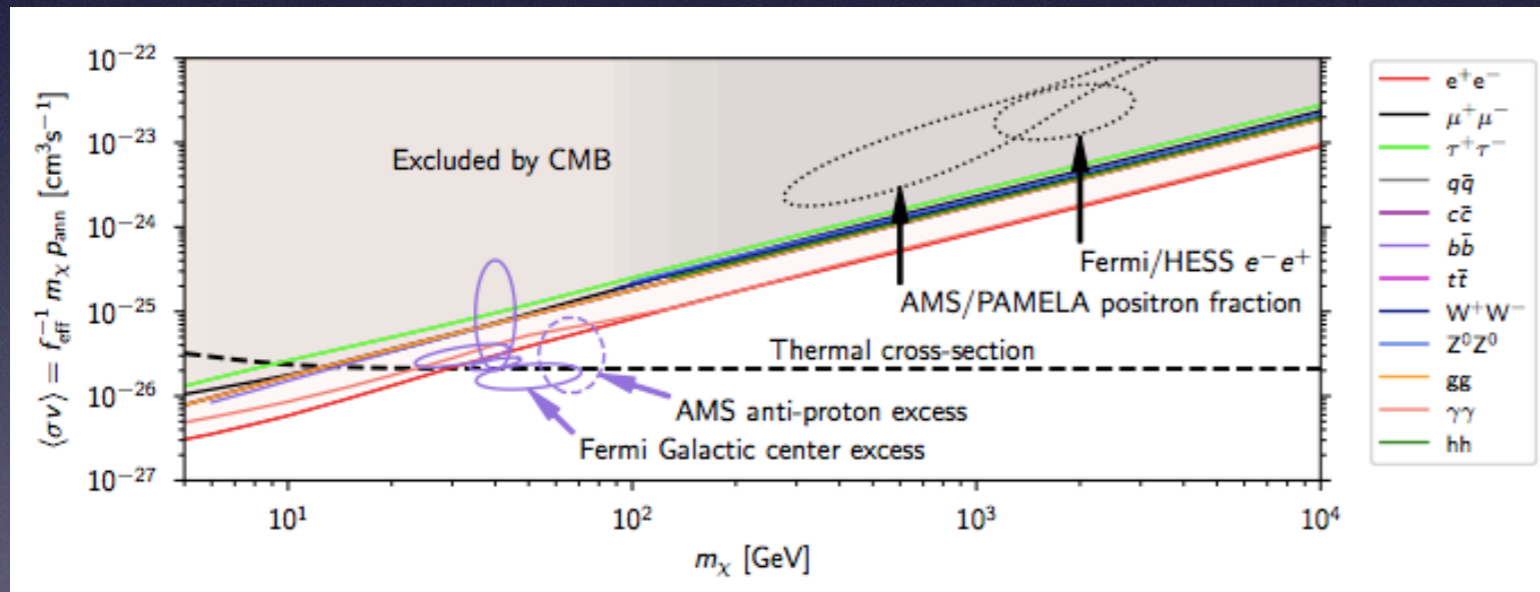
- After recombination, a significant fraction of this injected power can go into ionizing hydrogen
  - Temperature at recombination  $T \sim 0.2$  eV  
1 eV ( $1 \text{ GeV}/T_f$ ) power injected per baryon over a Hubble time (note CMB is emitted not long after matter-radiation equality)  
 $O(10)$  eV to ionize one H
  - Suggests that  $T_f \sim 0.1 \text{ GeV}$  (so  $m \sim \text{few GeV}$ ) provides power to ionize all hydrogen over a Hubble time
  - CMB constrains changes to the ionization level post-recombination of order  $10^{-3} \Rightarrow$  potential sensitivity to TeV-scale and lighter thermal DM

# An example: perturbing the CMB

- After recombination, a significant fraction of this injected power can go into ionizing hydrogen
  - Temperature at recombination  $T \sim 0.2$  eV  
1 eV ( $1 \text{ GeV}/T_f$ ) power injected per baryon over a Hubble time (note CMB is emitted not long after matter-radiation equality)  
 $O(10)$  eV to ionize one H
  - Suggests that  $T_f \sim 0.1 \text{ GeV}$  (so  $m \sim \text{few GeV}$ ) provides power to ionize all hydrogen over a Hubble time
  - CMB constrains changes to the ionization level post-recombination of order  $10^{-3} \Rightarrow$  potential sensitivity to TeV-scale and lighter thermal DM
- Detailed calculation finds this excludes DM annihilating to  $\sim$ all SM final states (except neutrinos) with thermal relic  $x_{\text{sec}}$  after emission of the CMB, for masses below 10 GeV

# CMB limits

- Detailed calculation finds this excludes DM annihilating to  $\sim$ all SM final states (except neutrinos) with thermal relic xsec after emission of the CMB, for masses below 10 GeV
- Model-building favors scenarios with p-wave annihilation, asymmetry, or a coannihilation partner that is absent at late times
- Even more stringent constraints if annihilation is instead enhanced at late times, e.g. for DM coupled to light dark photon



Planck Collaboration '18

1807.06209

Cirelli et al

1612.07295

based on results of TRS PRD '16

Where do the portal  
models stand?

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars
- Annihilation of scalar DM through a vector mediator, or fermionic DM annihilating to two scalars, is p-wave suppressed [e.g. Battaglieri et al 1707.04591].

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars
- Annihilation of scalar DM through a vector mediator, or fermionic DM annihilating to two scalars, is p-wave suppressed [e.g. Battaglieri et al 1707.04591].
- Annihilation of pseudo-Dirac or inelastic scalar DM through an off-shell vector mediator requires a partner particle ( $\chi\chi^* \rightarrow A' \rightarrow \text{SM}$ ): suppressed at late times

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars
- Annihilation of scalar DM through a vector mediator, or fermionic DM annihilating to two scalars, is p-wave suppressed [e.g. Battaglieri et al 1707.04591].
- Annihilation of pseudo-Dirac or inelastic scalar DM through an off-shell vector mediator requires a partner particle ( $\chi\chi^* \rightarrow A' \rightarrow \text{SM}$ ): suppressed at late times
- Neutrino portal models vary, but can arrange for the dominant annihilation channels to be to neutrinos, e.g. Bell et al 2412.02994

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars
- Annihilation of scalar DM through a vector mediator, or fermionic DM annihilating to two scalars, is p-wave suppressed [e.g. Battaglieri et al 1707.04591].
- Annihilation of pseudo-Dirac or inelastic scalar DM through an off-shell vector mediator requires a partner particle ( $\chi\chi^* \rightarrow A' \rightarrow \text{SM}$ ): suppressed at late times
- Neutrino portal models vary, but can arrange for the dominant annihilation channels to be to neutrinos, e.g. Bell et al 2412.02994
- For the surviving model classes, searches in direct detection and at accelerators can be powerful; e.g. for scalar-portal models, the thermal relic case where the mediator is heavier than the DM is largely excluded by a combination of such bounds [Krnjaic 1512.04119]

# Where do the portal models stand?

- CMB constraints are powerful for Dirac fermion DM + vector portal (or pseudo-Dirac DM + vector portal provided  $m_{\text{DM}} < m_{A'}$ ), or scalar DM annihilating to two scalars
- Annihilation of scalar DM through a vector mediator, or fermionic DM annihilating to two scalars, is p-wave suppressed [e.g. Battaglieri et al 1707.04591].
- Annihilation of pseudo-Dirac or inelastic scalar DM through an off-shell vector mediator requires a partner particle ( $\chi\chi^* \rightarrow A' \rightarrow \text{SM}$ ): suppressed at late times
- Neutrino portal models vary, but can arrange for the dominant annihilation channels to be to neutrinos, e.g. Bell et al 2412.02994
- For the surviving model classes, searches in direct detection and at accelerators can be powerful; e.g. for scalar-portal models, the thermal relic case where the mediator is heavier than the DM is largely excluded by a combination of such bounds [Krnjaic 1512.04119]
- A useful reference is Kumar & Marfatia 1305.1611: classifies all effective interaction structures by whether their annihilation/scattering is suppressed at low velocity

# Exercise

- Consider the vector portal scenario with DM being a Dirac fermion  $\chi$  charged under the dark U(1). Show that if  $m_\chi < m_{A'}$  (the dark photon mass),  $\alpha_D$  is the dark sector gauge coupling, and  $\epsilon$  is the kinetic mixing, both the direct detection signal and the cross section for freezeout are controlled by the parameter combination  $\epsilon^2 \alpha_D^2 m_\chi^2 / m_{A'}^4$ .
- Consider the scenario where  $m_\chi < m_{A'} < 2m_\chi$ . Note that in this case it is possible to have a purely dark-sector annihilation  $\chi\chi\bar{\chi} \rightarrow A'\chi$ . Under what circumstances would you expect this channel to dominate freezeout?

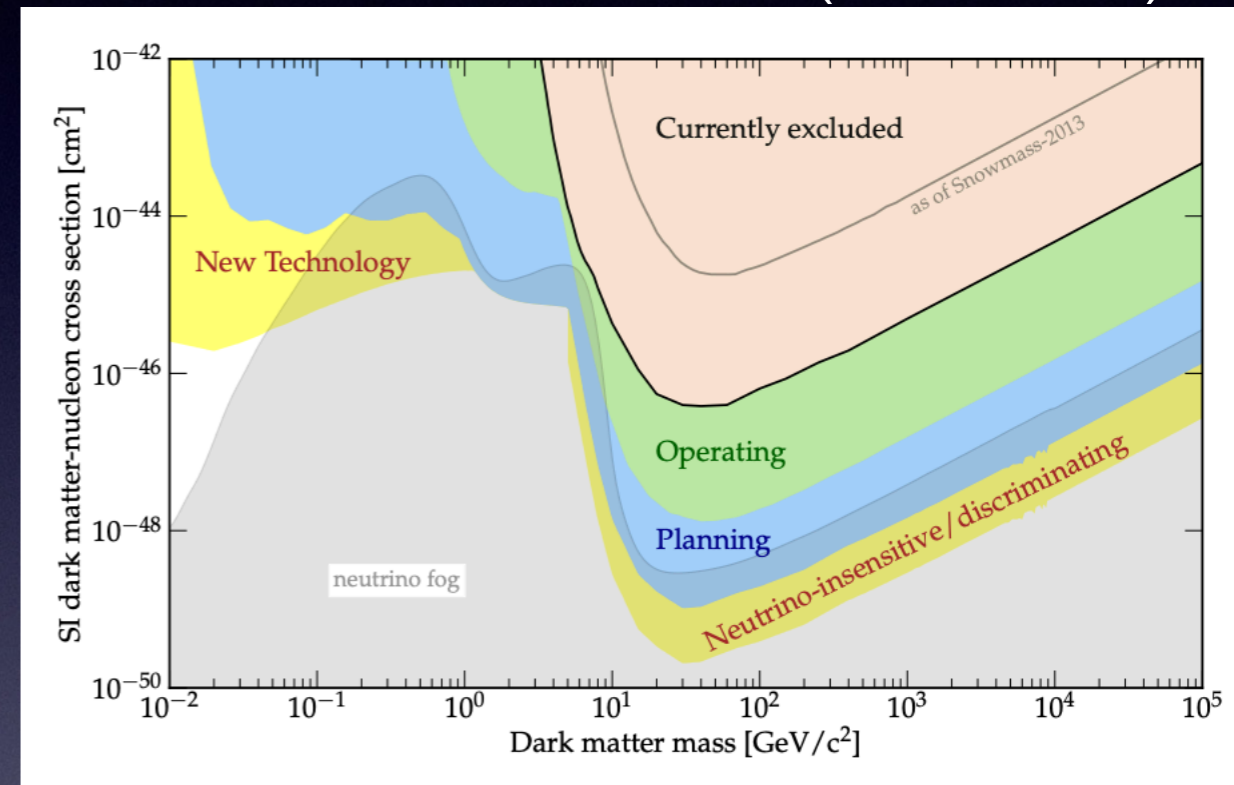
# Direct detection: general considerations

Cooley et al '22  
(Snowmass)

- Classic nuclear recoil searches: measure energy recoil given by:

$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta}{m_N} \quad (\mu = \text{reduced mass, } m_N = \text{target nuclear mass})$$

- When  $\mu \ll m_N$ , recoil energy of the nucleus becomes very small relative to its mass
- This causes a sharp loss of sensitivity once the DM mass is small compared to all target nuclei



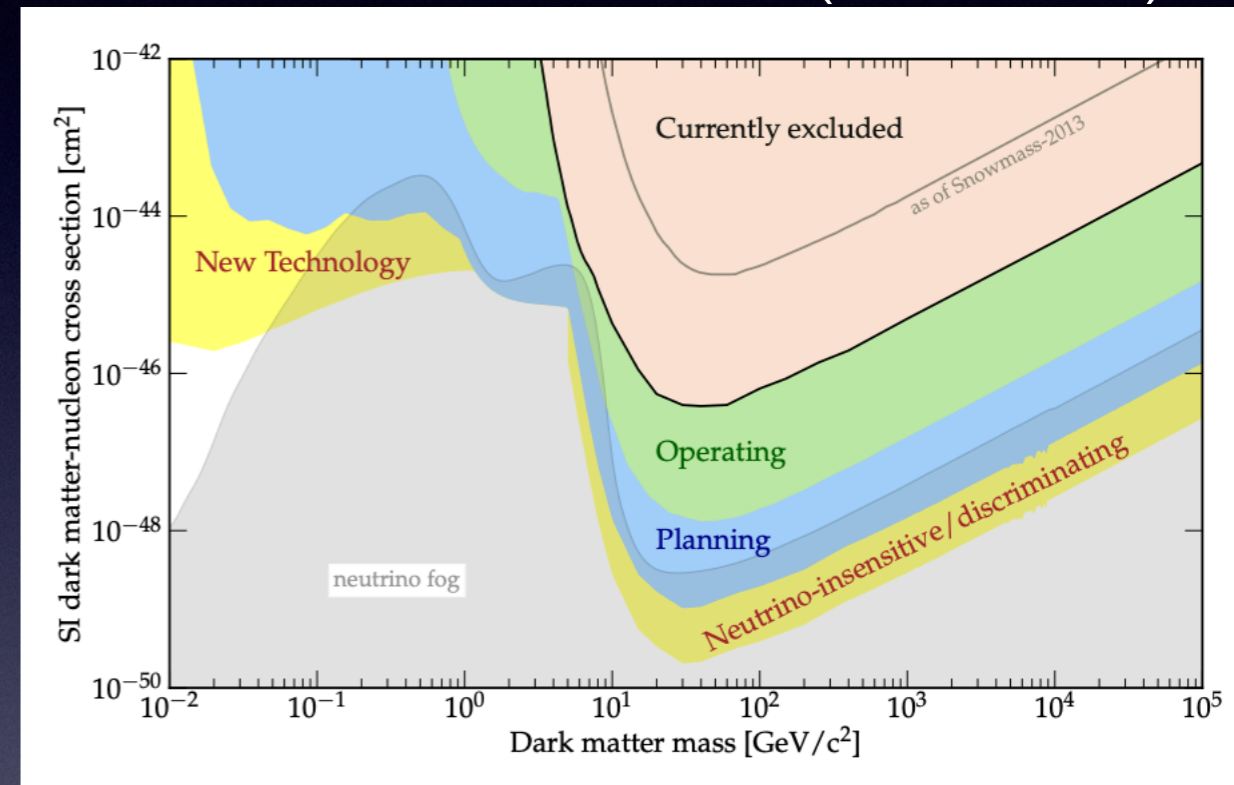
# Direct detection: general considerations

Cooley et al '22  
(Snowmass)

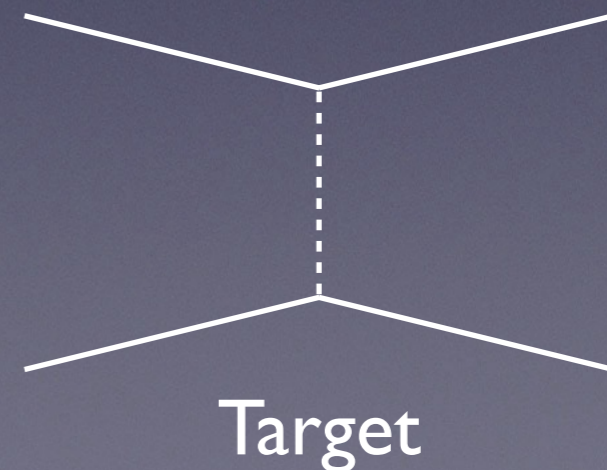
- Classic nuclear recoil searches: measure energy recoil given by:

$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta}{m_N} \quad (\mu = \text{reduced mass, } m_N = \text{target nuclear mass})$$

- When  $\mu \ll m_N$ , recoil energy of the nucleus becomes very small relative to its mass
- This causes a sharp loss of sensitivity once the DM mass is small compared to all target nuclei



incoming DM



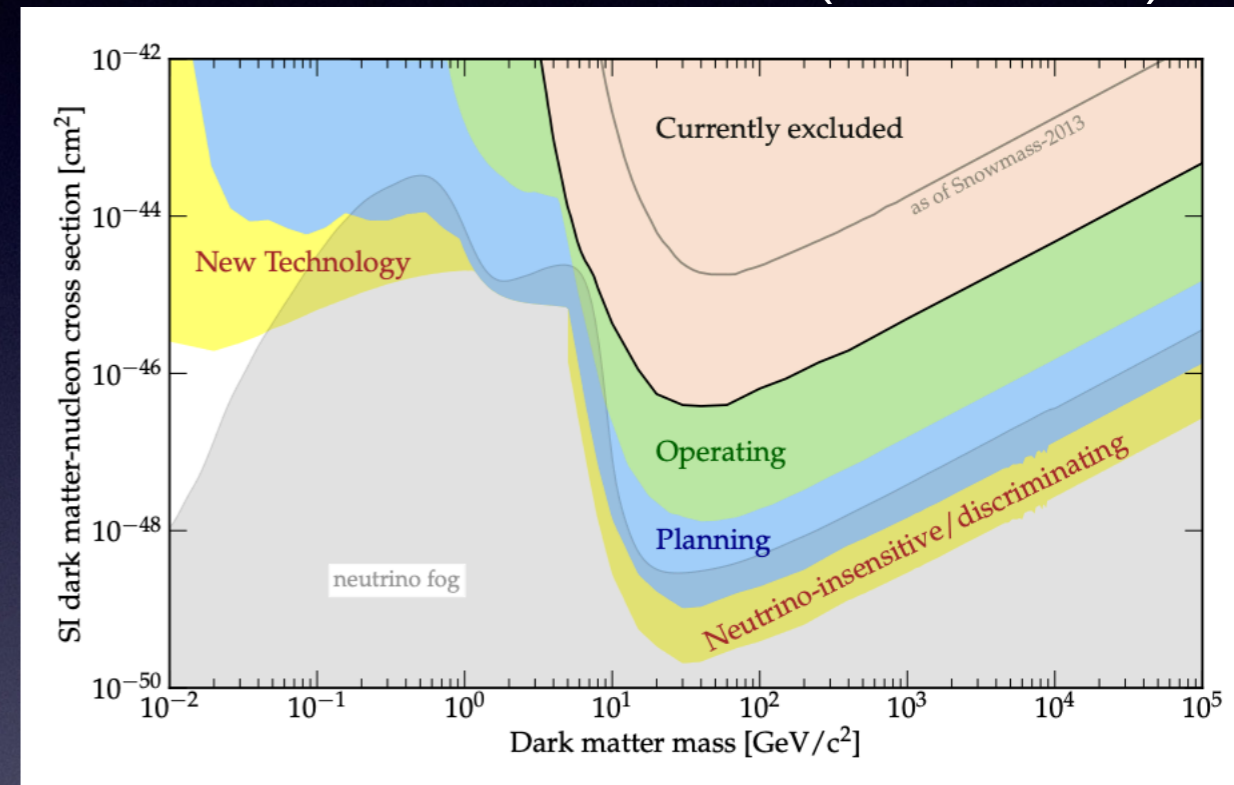
# Direct detection: general considerations

Cooley et al '22  
(Snowmass)

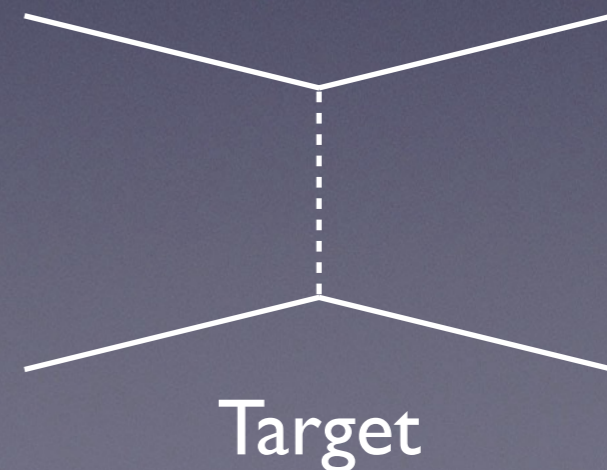
- Classic nuclear recoil searches: measure energy recoil given by:

$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta}{m_N} \quad (\mu = \text{reduced mass, } m_N = \text{target nuclear mass})$$

- When  $\mu \ll m_N$ , recoil energy of the nucleus becomes very small relative to its mass
- This causes a sharp loss of sensitivity once the DM mass is small compared to all target nuclei
- Direct detection is low-velocity ( $v \sim 10^{-3}$ )



incoming DM



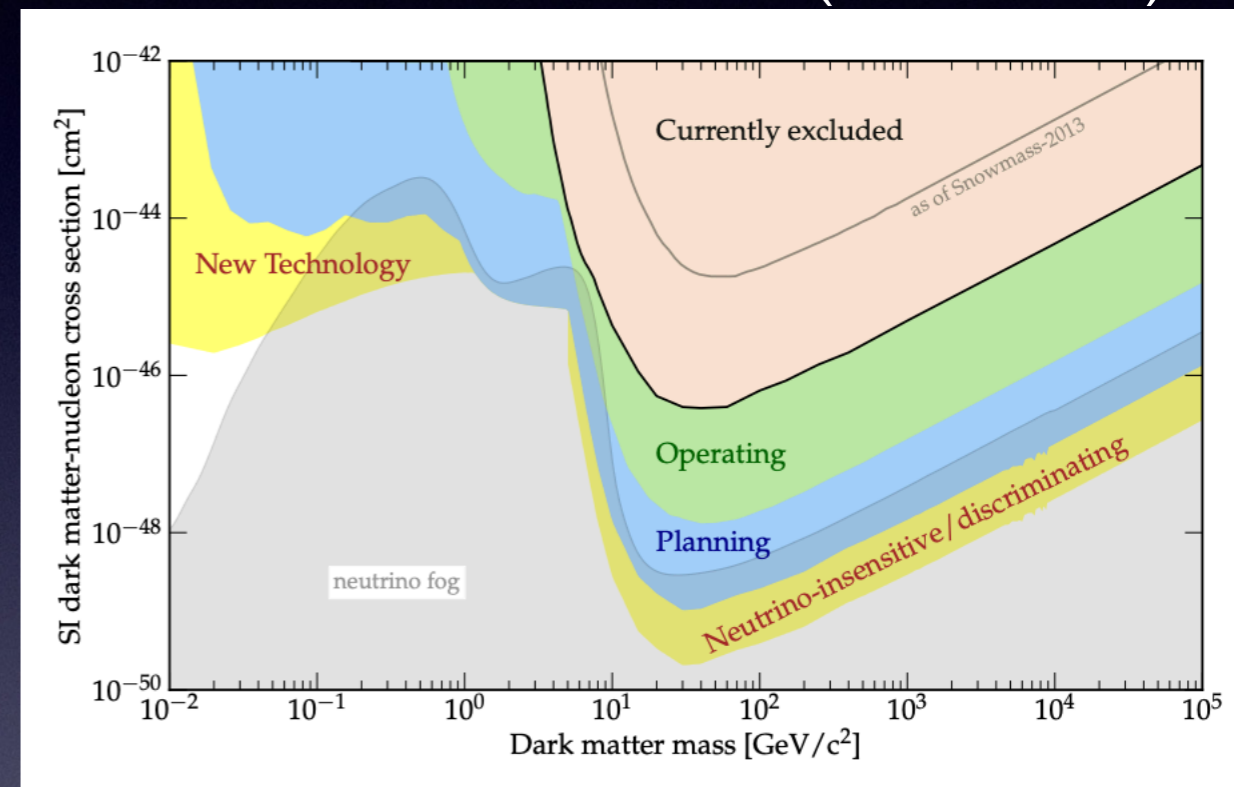
# Direct detection: general considerations

Cooley et al '22  
(Snowmass)

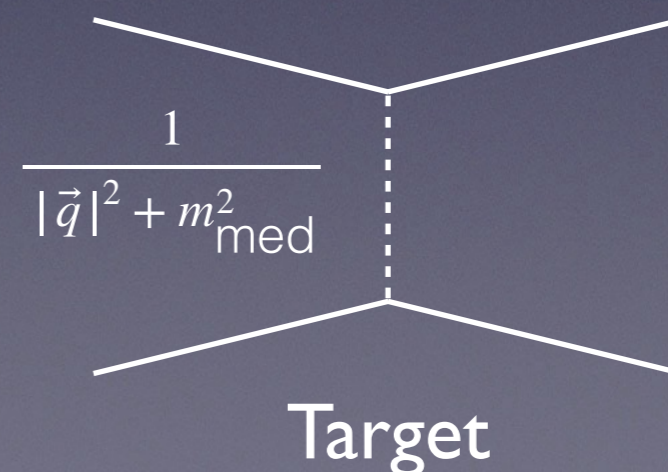
- Classic nuclear recoil searches: measure energy recoil given by:

$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta}{m_N} \quad (\mu = \text{reduced mass, } m_N = \text{target nuclear mass})$$

- When  $\mu \ll m_N$ , recoil energy of the nucleus becomes very small relative to its mass
- This causes a sharp loss of sensitivity once the DM mass is small compared to all target nuclei
- Direct detection is low-velocity ( $v \sim 10^{-3}$ )
  - Enhanced in the presence of a light mediator



incoming DM



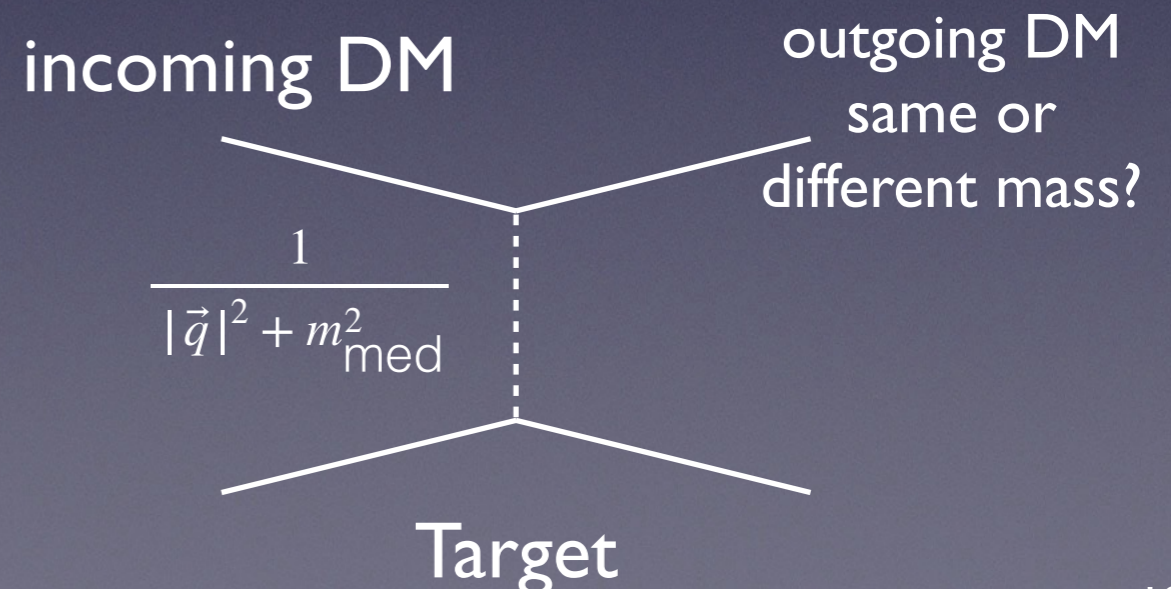
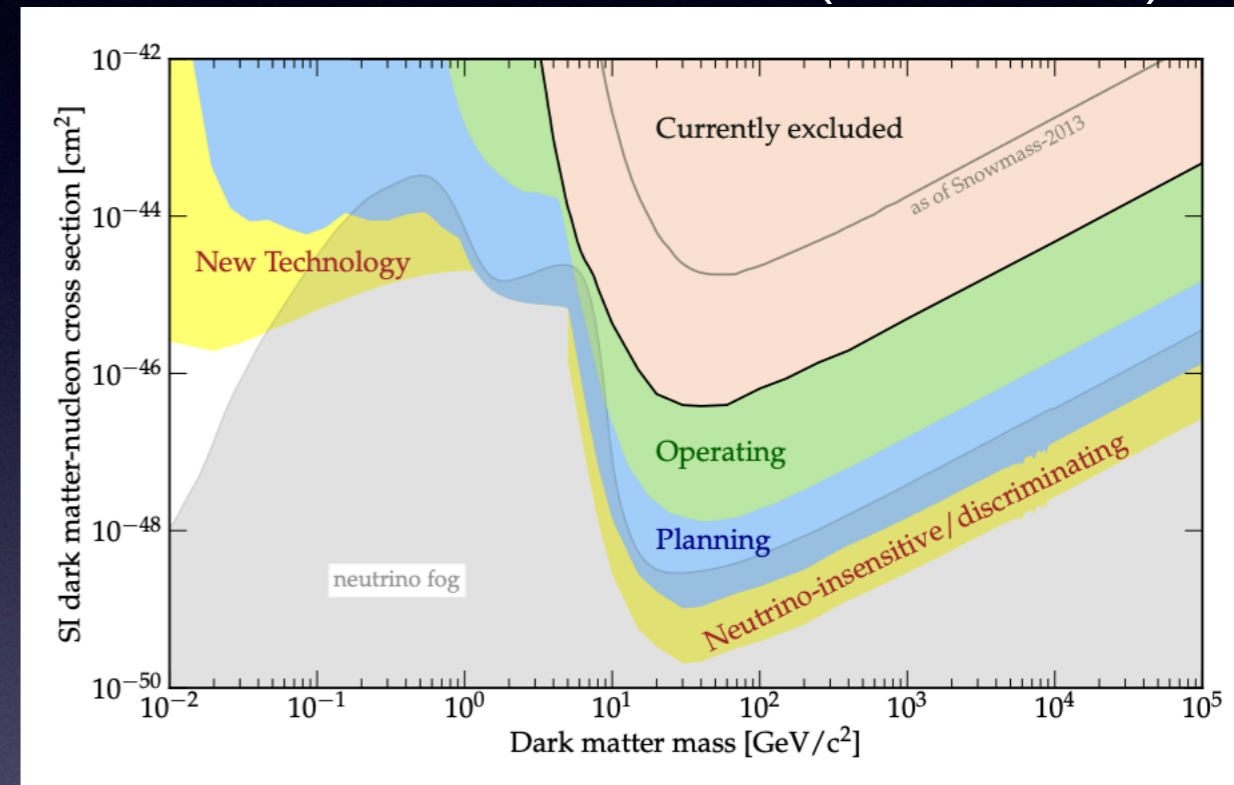
# Direct detection: general considerations

Cooley et al '22  
(Snowmass)

- Classic nuclear recoil searches: measure energy recoil given by:

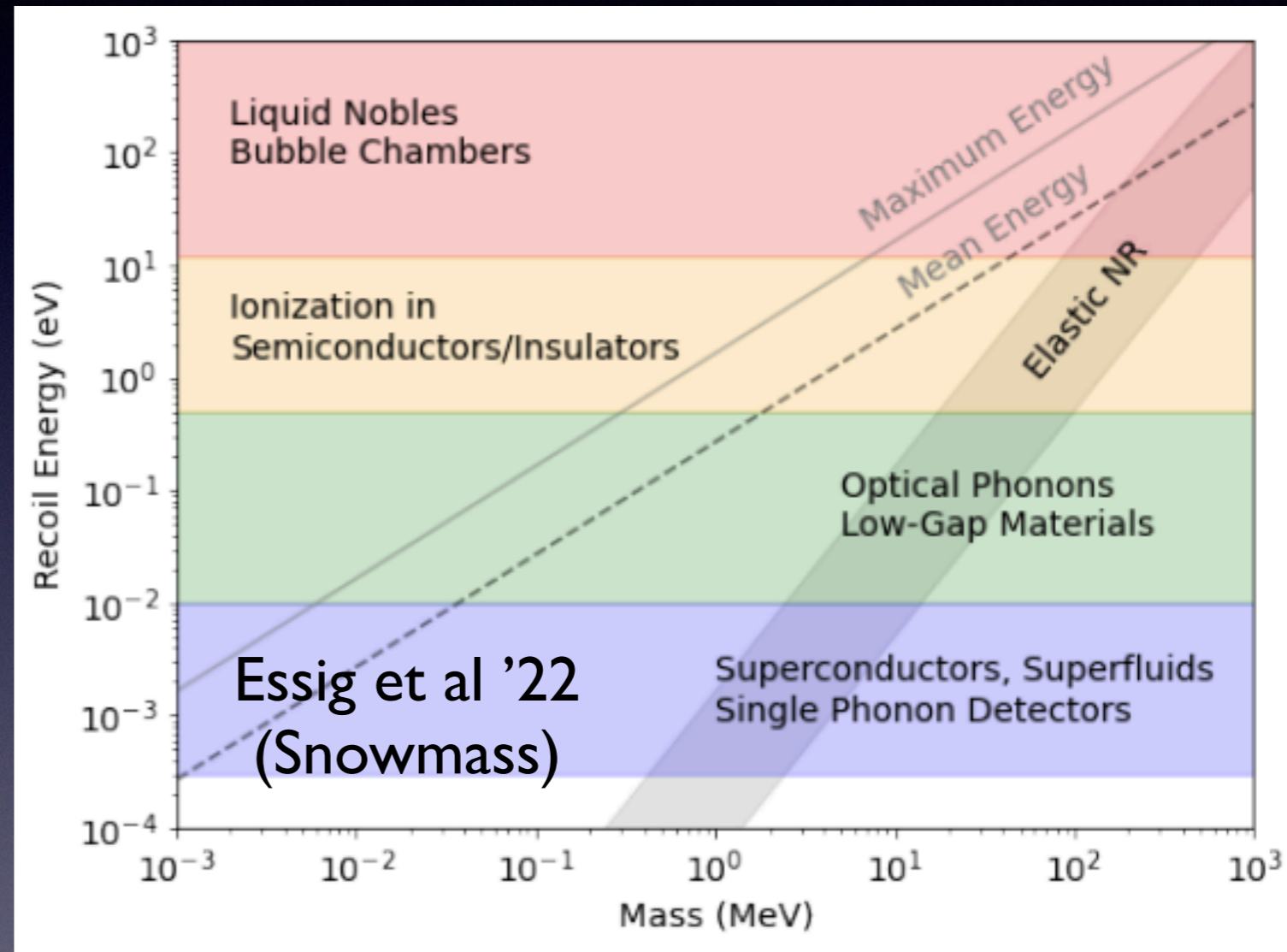
$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta}{m_N} \quad (\mu = \text{reduced mass, } m_N = \text{target nuclear mass})$$

- When  $\mu \ll m_N$ , recoil energy of the nucleus becomes very small relative to its mass
- This causes a sharp loss of sensitivity once the DM mass is small compared to all target nuclei
- Direct detection is low-velocity ( $v \sim 10^{-3}$ )
  - Enhanced in the presence of a light mediator
  - Can be suppressed by powers of exchanged momentum or kinematic suppression (e.g. tree-level scattering is inelastic), + spin-dependent scattering causing cancellations



# Direct detection

- Searches for elastic nucleus-DM scattering are often inefficient for light DM due to the kinematic mismatch
  - However, secondary photons/electrons produced in conjunction with nucleus-DM scattering, via bremsstrahlung or “Migdal effect”, can be detectable [e.g. [Kouvaris et al 1607.01789](#), [Ibe et al 1707.07258](#)]
- Searching for electron recoils provides sensitivity to lighter DM albeit at the cost of higher background
- If DM is absorbed onto SM particles, energy transfer is  $O(\text{DM mass})$  rather than  $O(\text{kinetic energy})$  or less - absorption searches allow sensitivity to much lighter DM

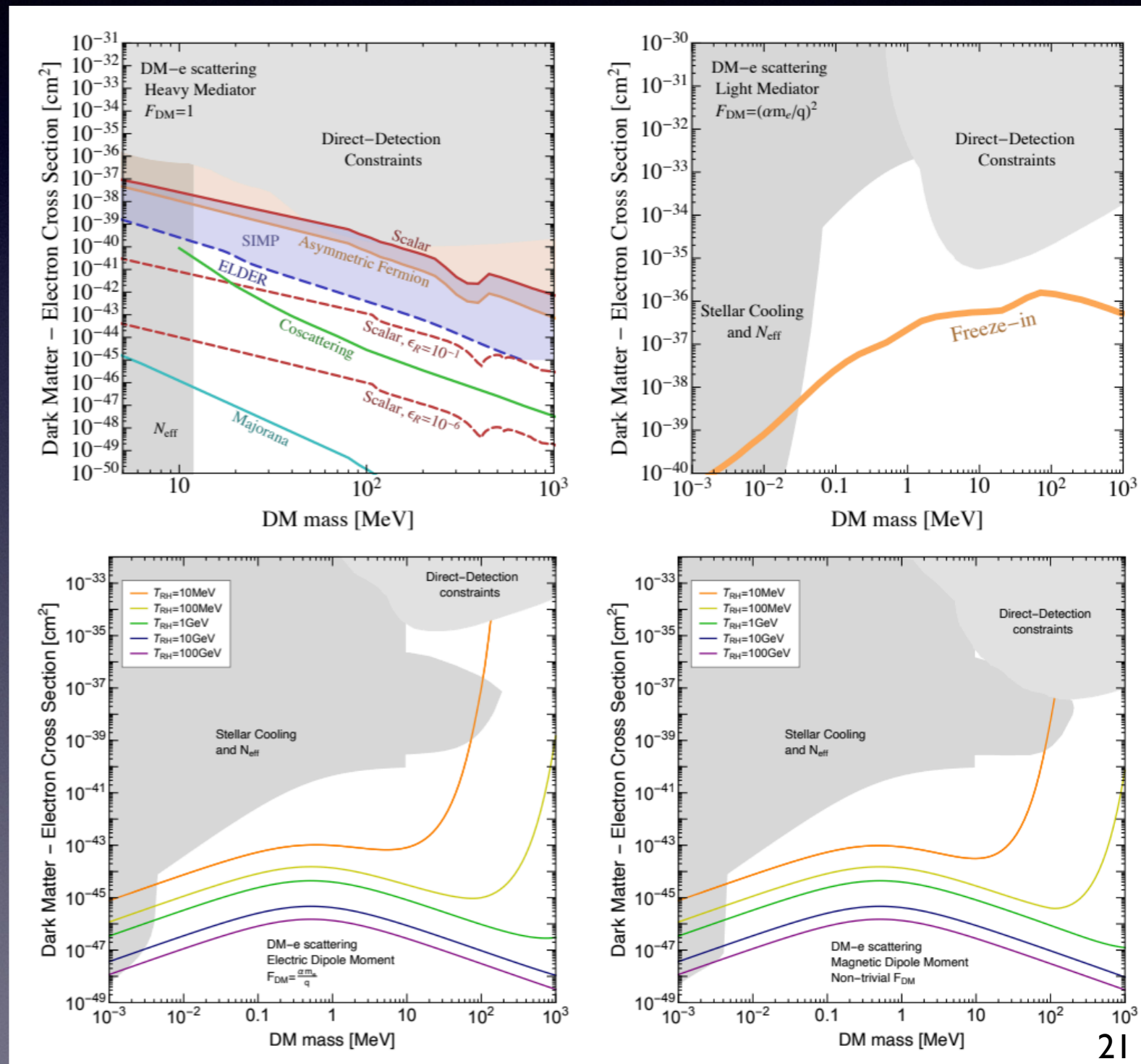


- Very active research program underway to work out possibly observable signatures of tiny energy depositions, often using special features of carefully-chosen target materials, e.g. tiny bandgaps (see [Essig et al 2203.08297 \(Snowmass\)](#) for a review)
- Collective/in-medium effects are often critically important

# Example benchmarks for direct detection

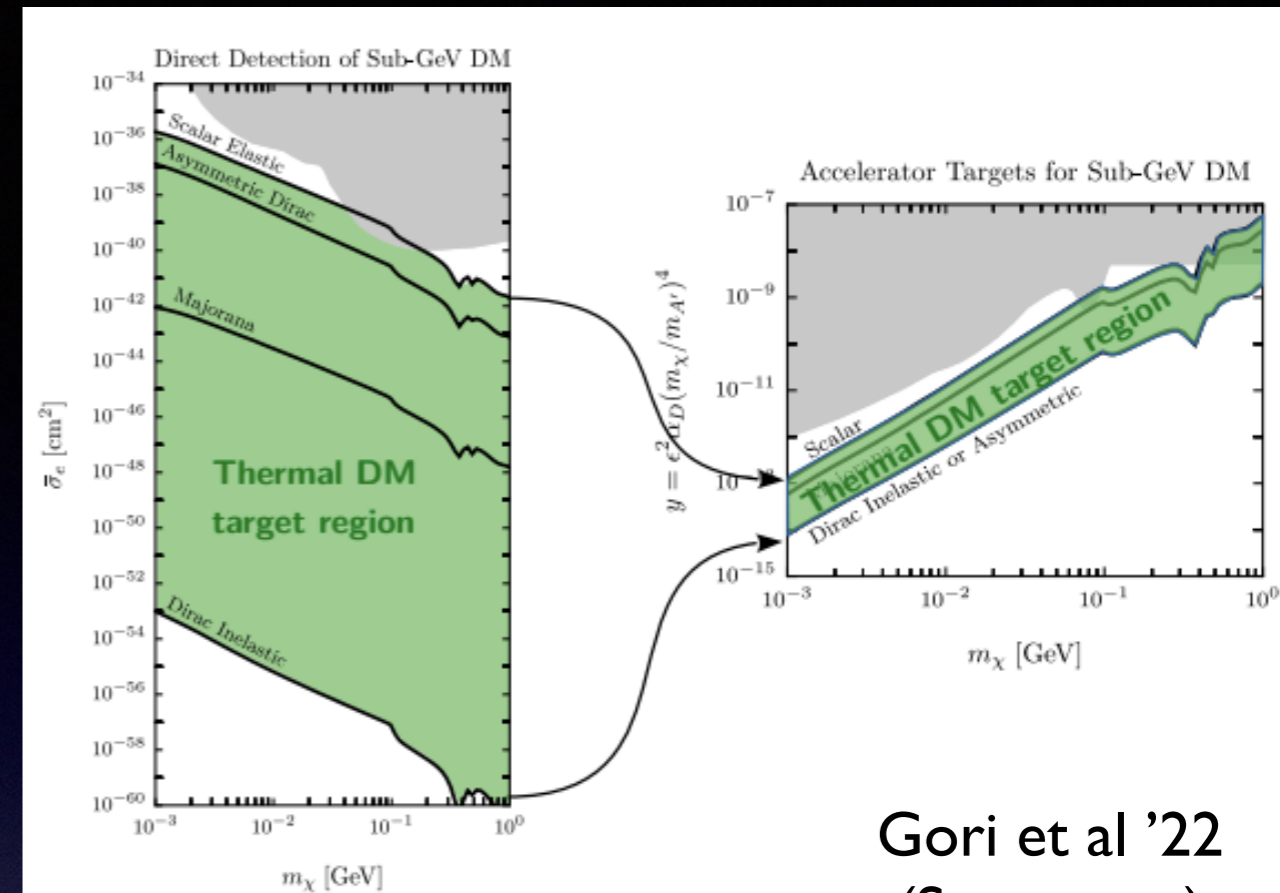
Essig et al '22  
(Snowmass)

- Examples of how different production mechanisms manifest as different benchmarks in direct-detection searches for electron scattering
- Benchmarks in upper left panel are variations on freezeout; other panels show variations of freeze-in

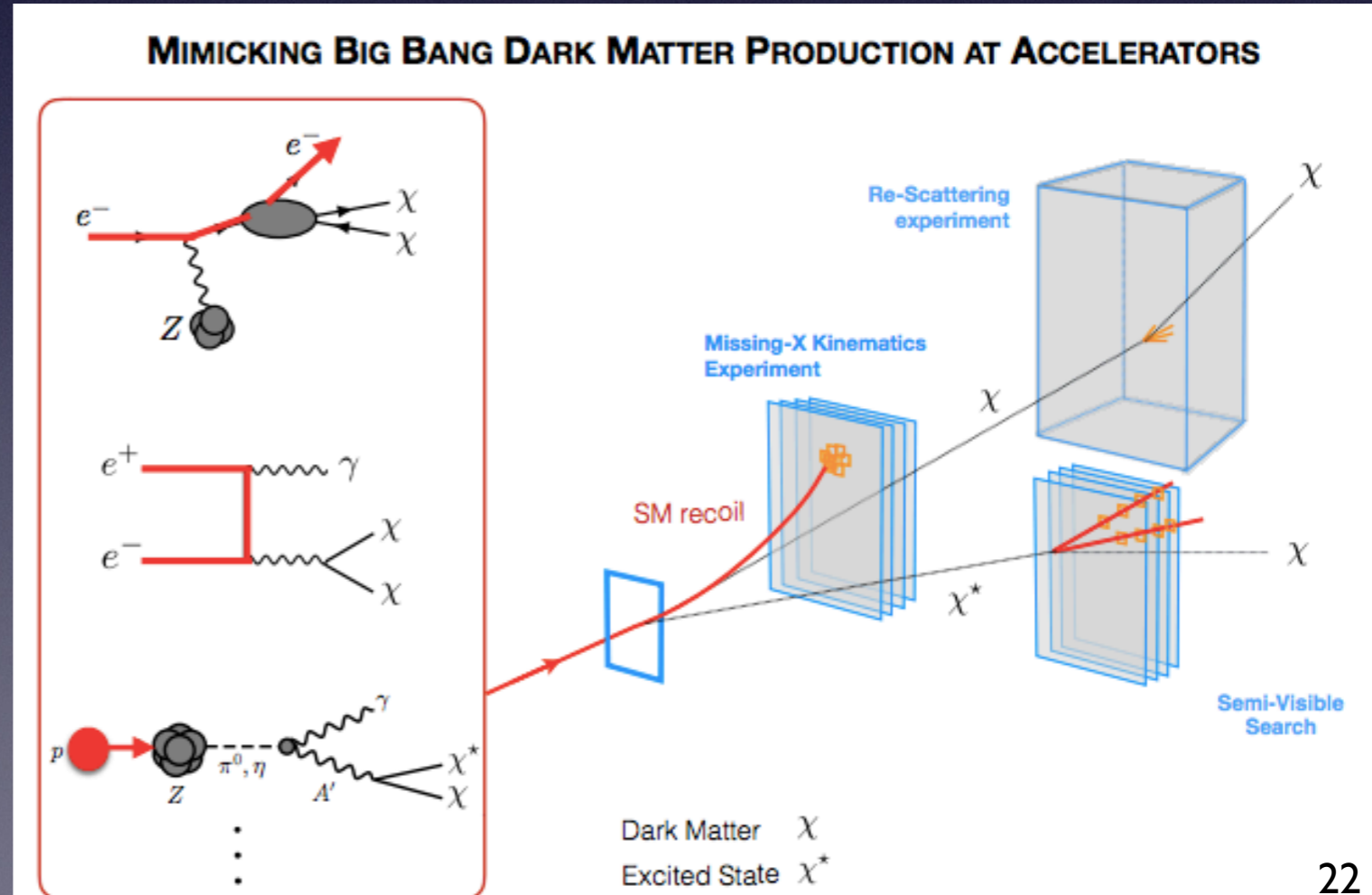


# Accelerators & thermal targets

- General argument: direct/indirect detection largely measure DM interactions in the present-day halo,  $v \sim 10^{-3}$
- Accelerators allow reproduction of conditions in the freezeout epoch (relativistic or near-relativistic DM)
- Can lead to relatively narrow range of expected accelerator signals for simple portal models with thermal freezeout
- Multiple channels to probe DM production

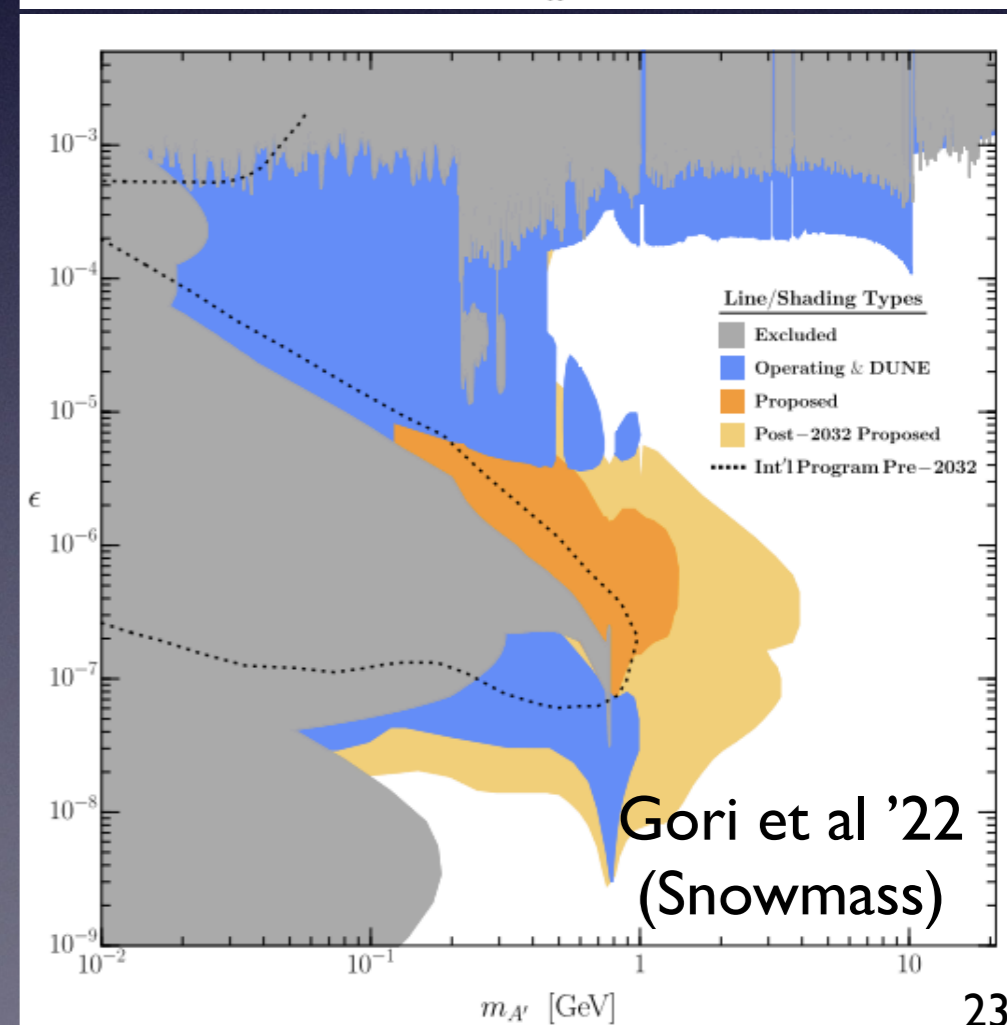
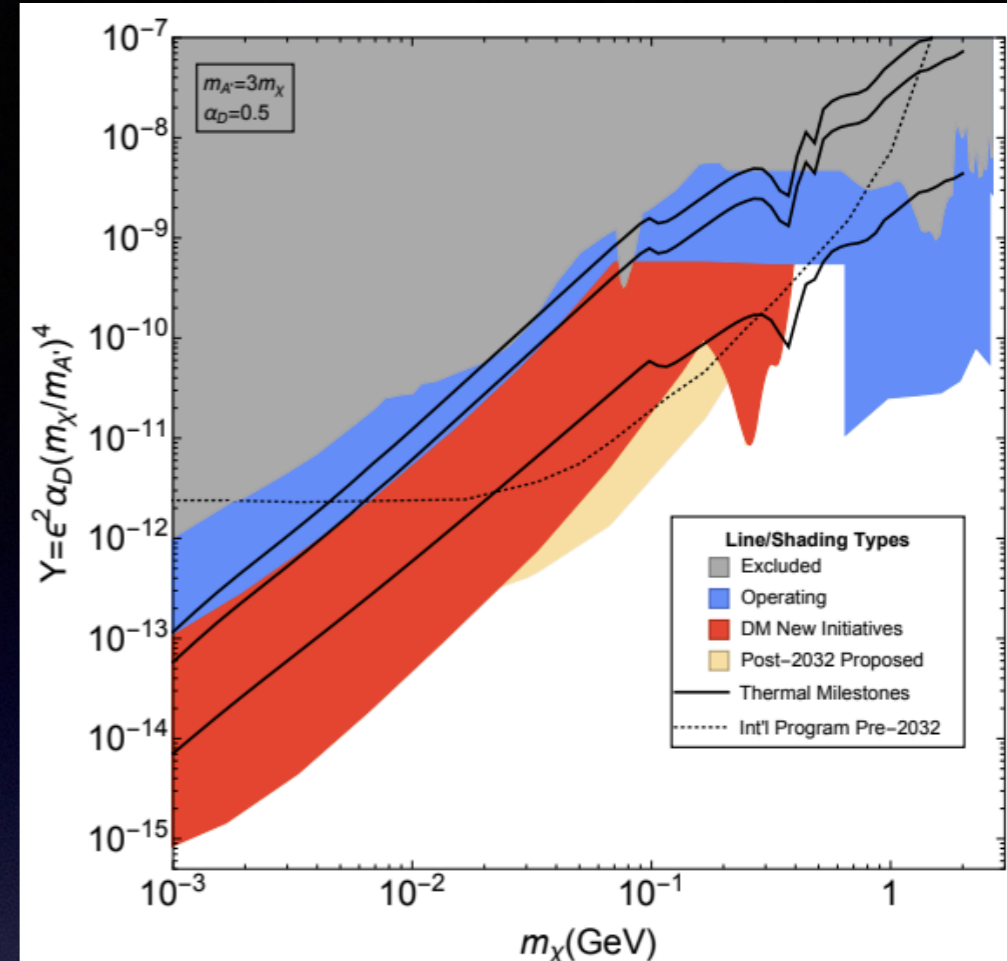


Gori et al '22  
(Snowmass)



# Accelerator searches

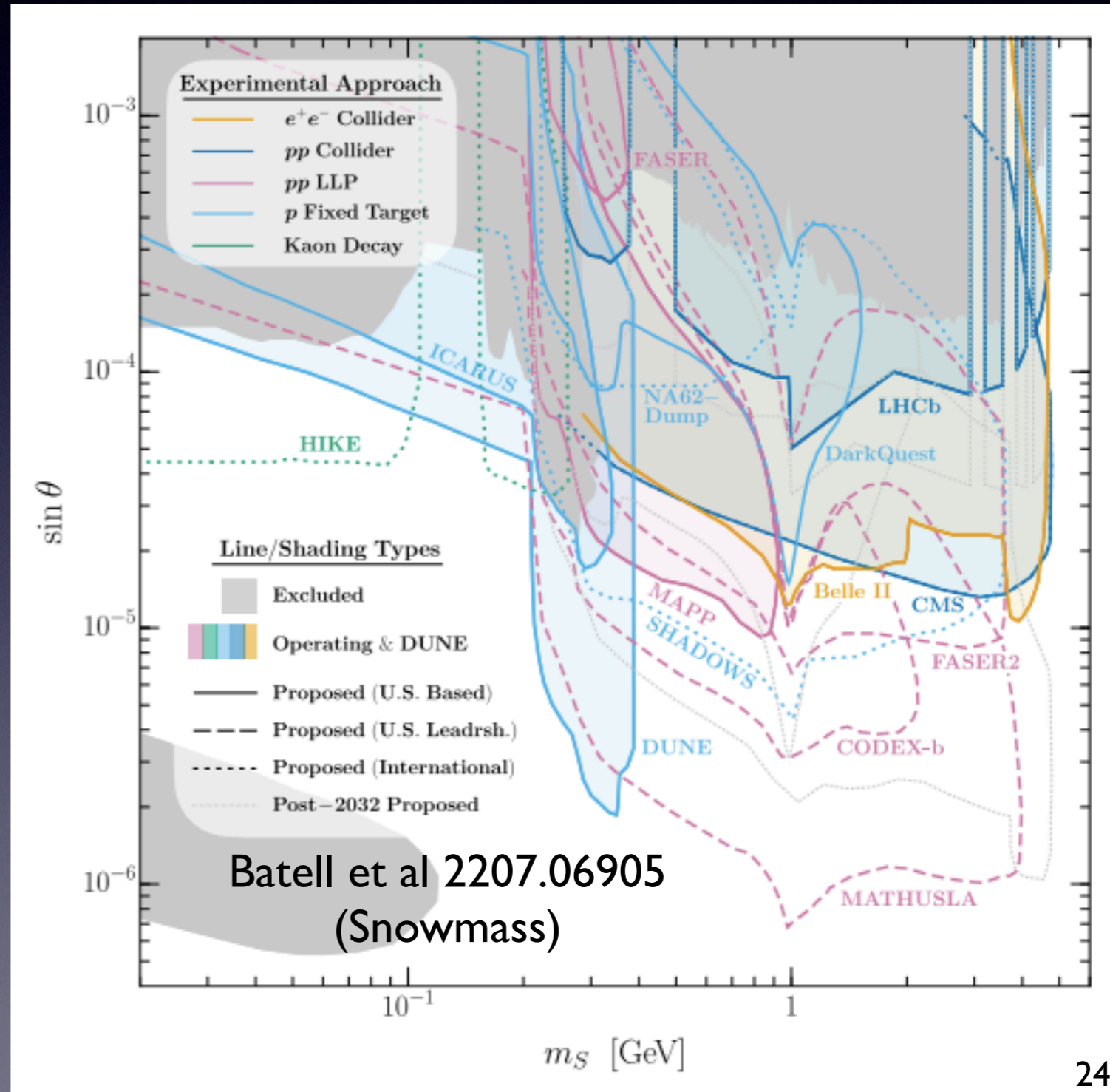
- For light DM or DM that interacts with the SM through new light weakly-coupled particles, high luminosity may be more important than high energy
- Active program of fixed-target and collider experiments to search for both DM annihilating through new mediators + new mediators themselves
- Immediate target: “full exploration of the range of interaction strengths compatible with light DM thermal freeze-out via the simplest mechanism of s-channel annihilation to SM particles mediated by a dark photon”
- [Gori et al 2209.04671 \(Snowmass, RF6 topical report\)](#) provides an in-depth discussion



# Mediator searches

- Mediators coupled to the SM through minimal portals could exist whether or not they relate to DM
- In some cases, may be our first clue to the existence of a dark sector
- Mediators can decay to SM particles or invisibly into the dark sector - can search for both
- Can use existing accelerators (including the LHC) as a source of long-lived particles - search for their displaced decays with additional detectors (e.g. FASER, CODEX-b, MATHUSLA)

Example: status of Higgs portal with visible decays



# BBN limits

- Big Bang nucleosynthesis (BBN) occurs around  $T \sim 0.1 - 1$  MeV
- Constrained by observations of light-element abundances
- Annihilation can produce energetic particles that catalyze or inhibit reaction network that produces nuclei
- BBN allows measurement of photon-to-baryon ratio and provides a “clock” for the cosmic expansion  $H$  at this time
  - Once  $T$  drops below the neutron-proton mass difference ( $\sim 1.3$  MeV), neutrons are depleted by decays/scatterings that convert them into protons, and must bind into helium to be stable
  - Final abundance of helium is sensitive to the relative timescale for neutron-proton interconversion via weak interactions and cosmic expansion  
 $\Rightarrow$  allows sensitive measurement of  $H$
- BBN occurs during radiation domination:  $H$  is sensitive to the number and temperature of relativistic species

# BBN limits from $N_{\text{eff}}$

- The contribution of relativistic species to the energy density is expressed in terms of the number of effective neutrino species,  $N_{\text{eff}}$

$$\frac{\rho_i}{\rho_\gamma} = \frac{7}{8} N_{\text{eff}} \left( \frac{4}{11} \right)^{4/3}$$

- Measured value of  $N_{\text{eff}}$  from BBN is  $2.889 \pm 0.229$  [Yeh et al 2207.13133]

- Expected SM value is 3.044

$$\rho_i = \frac{7}{8} g_i \frac{\pi^2}{30} T^4$$

- Changing the temperature of the neutrinos relative to the photons also affects their contribution to  $N_{\text{eff}}$

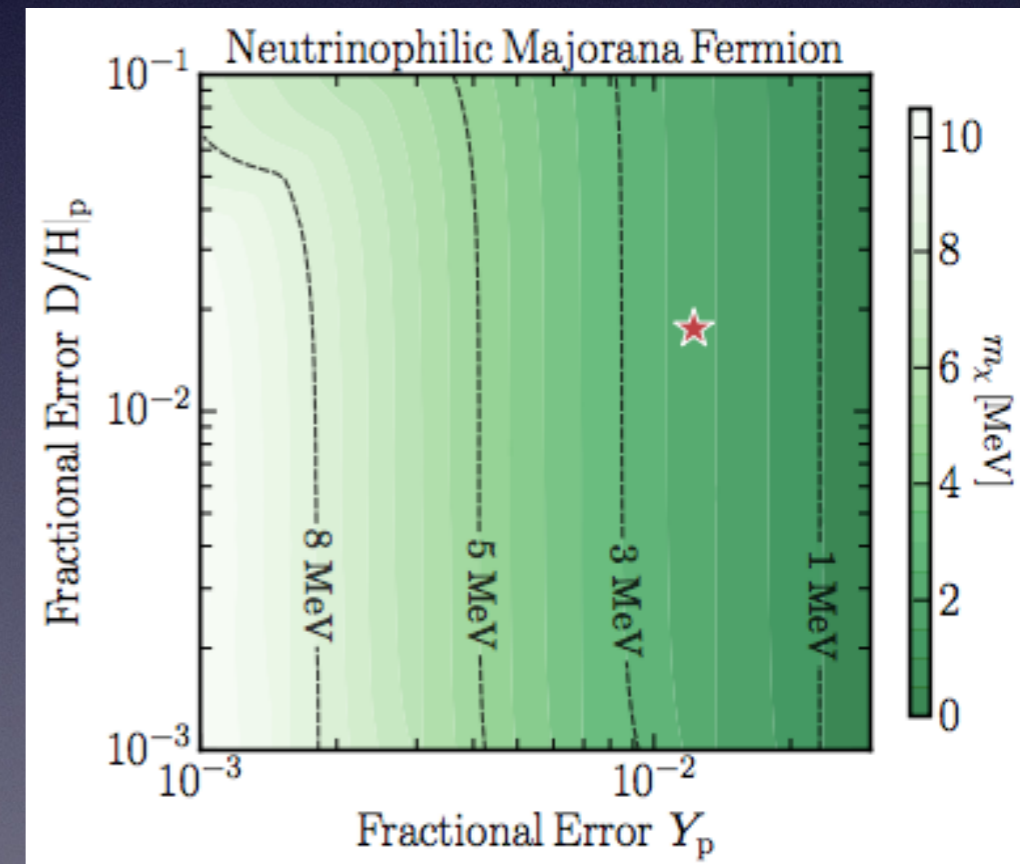
- If DM is still relativistic at the start of BBN, it can itself contribute to  $N_{\text{eff}}$

- If the DM annihilates to some invisible “dark radiation”, that will contribute to  $N_{\text{eff}}$

- If the DM annihilates to neutrinos and/or other SM particles after neutrinos decouple from the main SM bath ( $T \sim 2$  MeV), it will generically modify  $N_{\text{eff}}$  from neutrinos via changing  $T_{\text{neutrinos}}/T_\gamma$

- All of these effects constrain thermal relic DM that becomes non-relativistic and freezes out around the BBN epoch

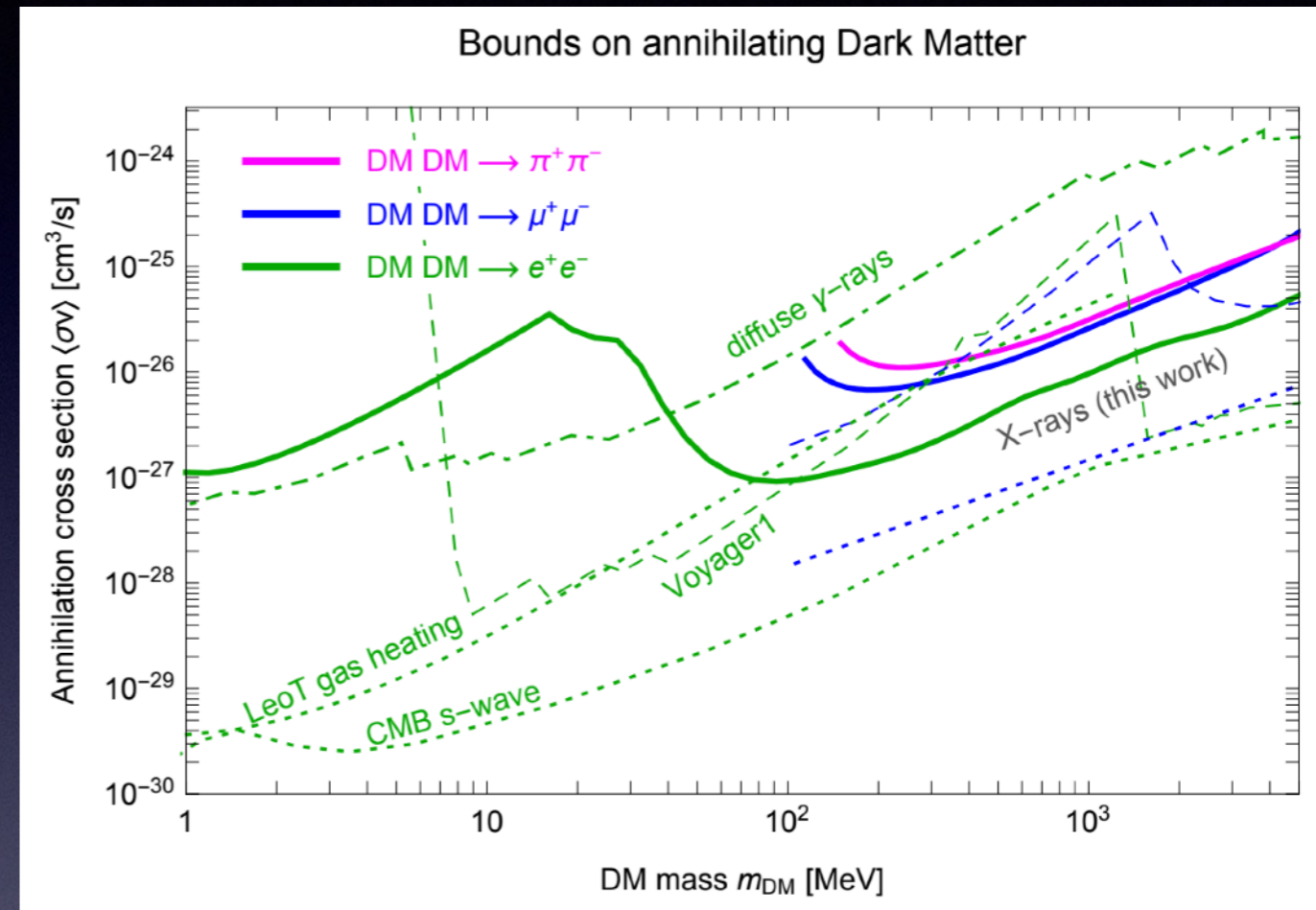
- Lower limits on DM mass vary depending on the DM spin and annihilation channels, but lie in the  $\sim 4$ - $14$  MeV range [Sabti et al 1910.01649, An et al 2202.03515]



# Indirect detection

Cirelli et al  
2303.08854

- Note that BBN bounds primarily constrain DM freezing out around BBN - no large extrapolation of annihilation  $\sigma v$  to later times (vs CMB)  $\rightarrow$  fewer loopholes
- Most focus on sub-GeV thermal relics focuses on MeV-GeV mass range (although see e.g. [Berlin et al 1706.07046](#) for a counter-example)
- In this energy range, can search for annihilation signals in gamma-rays, X-rays, positrons; especially competitive (vs CMB) for annihilation suppressed at low velocities



- Similar searches apply for decaying DM signals, where dedicated indirect searches typically beat the CMB
- There is currently a “MeV gap” in sensitivity and prospects for significant sensitivity improvements with future telescopes

# Below the MeV scale

- Due to BBN constraints, below the MeV scale we typically need alternate production mechanisms to freeze-out
- Freeze-in is still OK
- Archetypal example of keV-scale dark matter is the sterile neutrino - fermion that is a singlet under the SM gauge group (such states could also be relevant for neutrino masses)
- One might also want to think about other cases where the ‘mediators’ we discussed previously are themselves the DM, e.g. a SM-singlet scalar or vector
  - These cases are largely excluded as thermal relics but could have other production mechanisms; we will return to them next lecture

# What is the DM mass?

