University of Southern Denmark

The Hunt for Dark Matter:

From stars to detectors

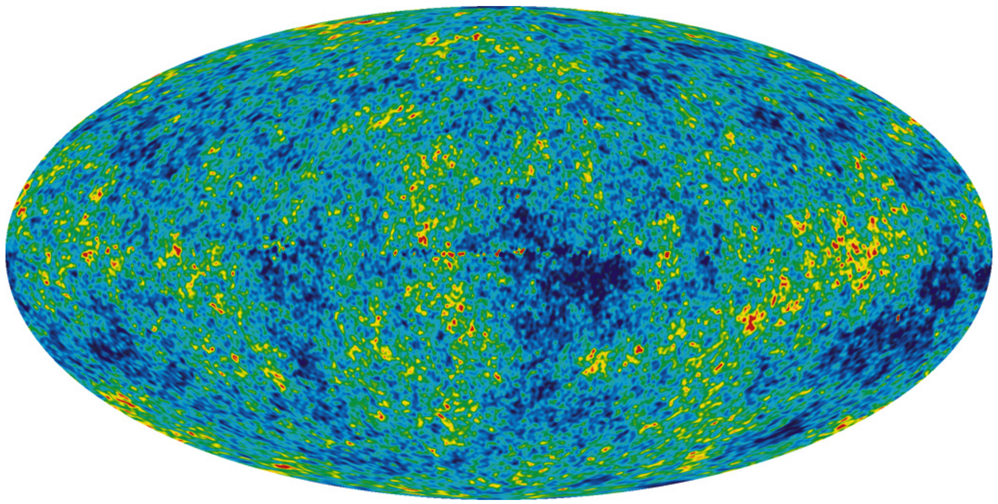
Chris Kouvaris

CP3 - Origins

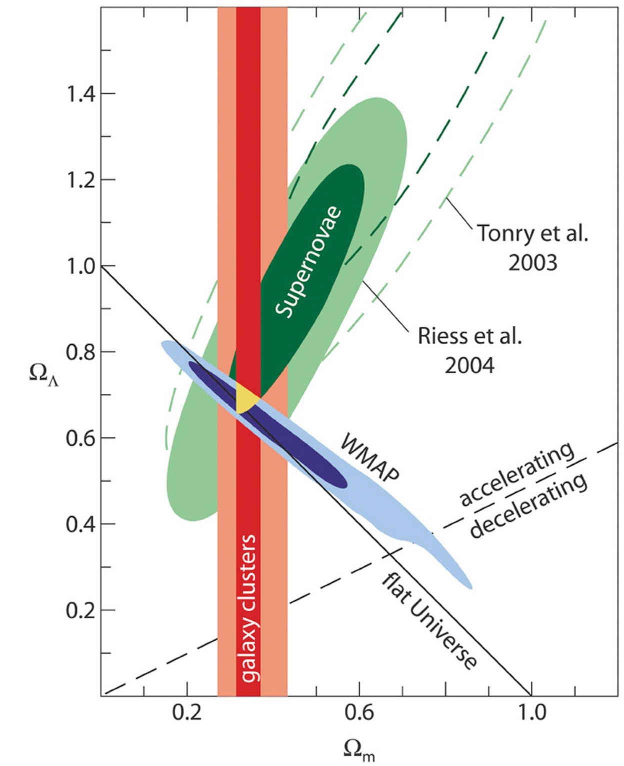
Particle Physics & Origin of Mass

Oslo, 10 May 2017

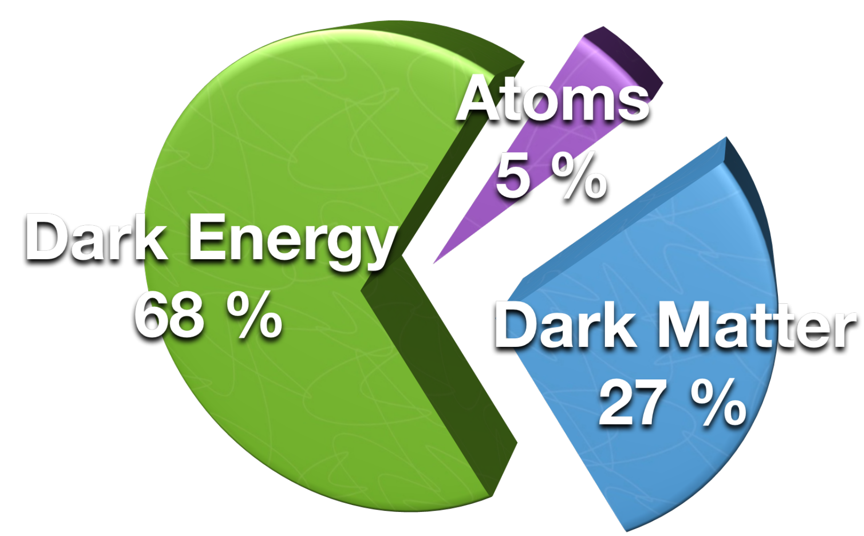
Dark Matter



Microwave Background Radiation



Bullet Cluster



Asymmetric Dark Matter

- Asymmetric DM can emerge naturally in theories beyond the SM
- Alternative to thermal production
- Possible link between baryogenesis and DM relic density

Nussinov ’85, Barr Chivukula Farhi ’90, Gudnason CK Sannino ’06
Khlopov CK ’07, CK ’08, Ryttov Sannino ’08, Kaplan Luty Zurek ’09, Buckley Randall ’10
Dutta Kumar ’10, Taoso ’10, Falkowski Ruderman Volansky ’11, Petraki Volkas ’13, Zurek ‘13

Light WIMP ~GeV

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{n_{TB}}{n_B}\frac{M_{TB}}{M_p}$$

$$n_{TB} = n_B$$

$$M_{TB} = 5\mathrm{GeV}$$

$$1 \times 5 = 5$$

Why Dark Matter Self-Interactions?

Problems with Collisionless Cold Dark Matter

- Core-cusp profile in dwarf galaxies
- Number of Satellite galaxies
- "Too big to fail"

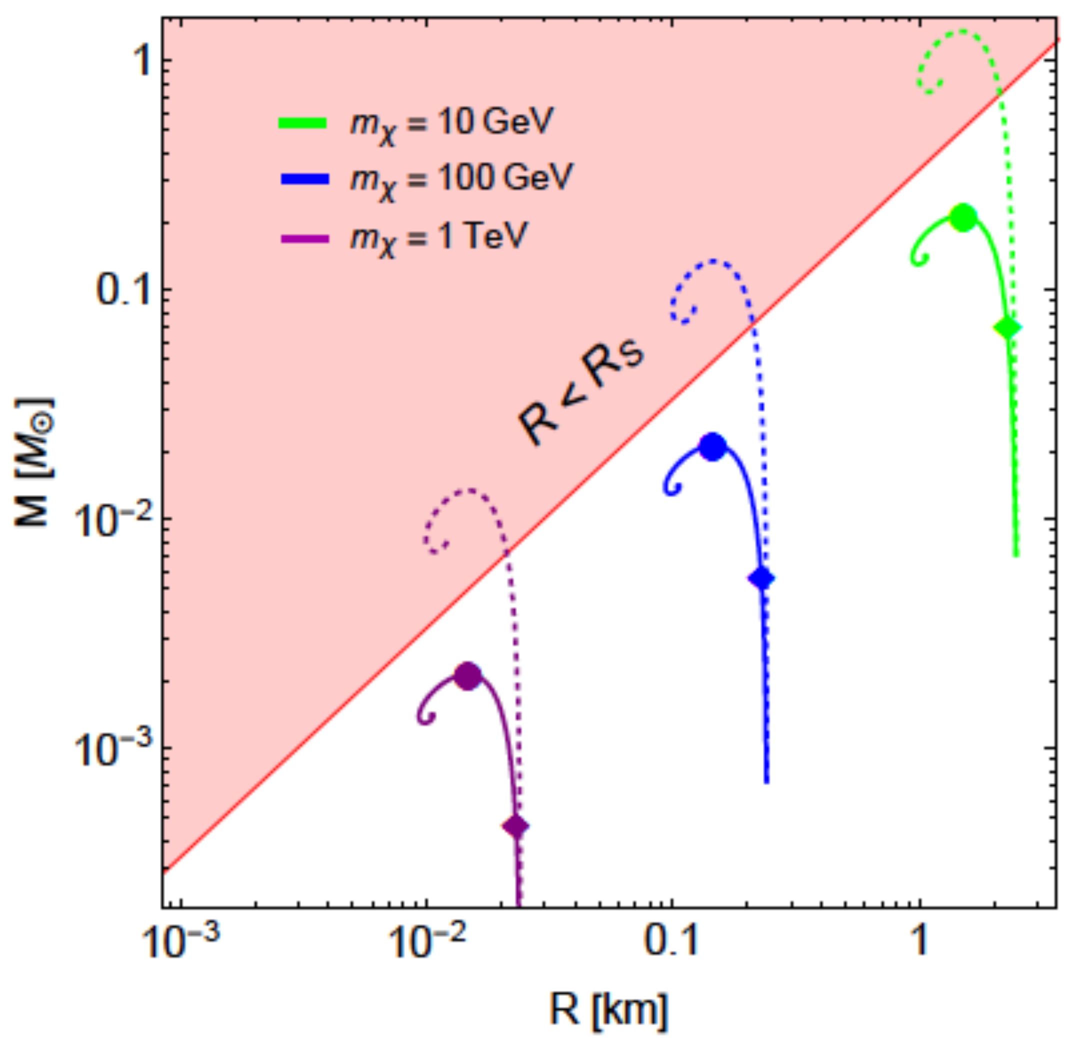
Numerical Simulations suggest $0.1\,cm^2/g < \sigma/m < 1\,cm^2/g$

Extra motivation:
Provide seeds for the Supermassive Black hole at the center of galaxy
Pollack Spergel Steinhardt '15

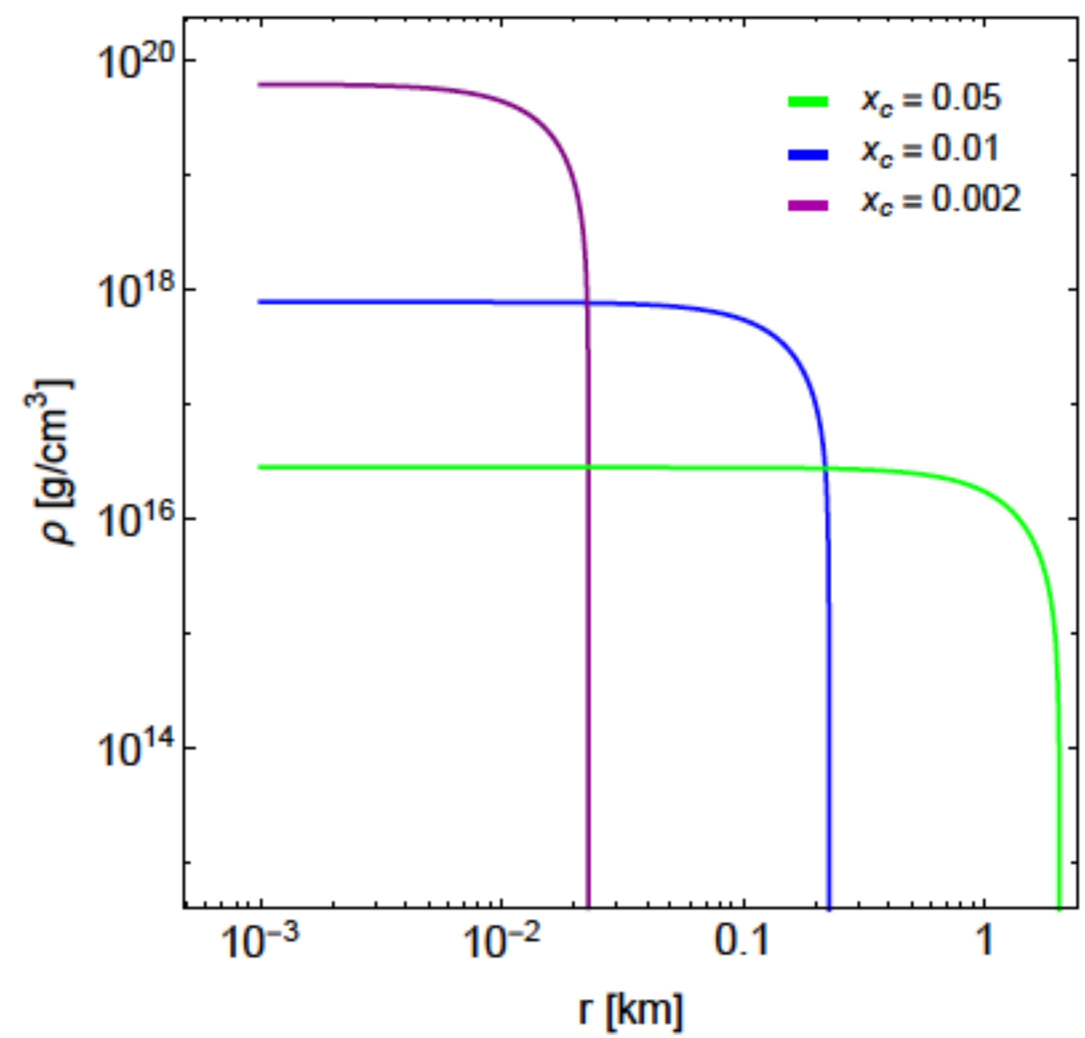
Asymmetric Fermionic Dark Stars

Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}\frac{\left[1+\frac{P}{\rho}\right]\left[1+\frac{4\pi r^3 P}{M}\right]}{\left[1-\frac{2GM}{r}\right]}$$



(a) $M(R)$ for repulsive interactions



(b) $\rho(r)$ for repulsive interactions

CK, Nielsen ‘15

Asymmetric Bosonic Dark Stars

BEC Bosonic DM with $\lambda\phi^4$

Repulsive Interactions: Solve Einstein equation together with the Klein-Gordon

Attractive Interactions: We can use the nonrelativistic limit solving the the Gross-Pitaevskii with the Poisson

$$E\psi(r) = \Big(-\frac{\vec{\nabla}^2}{2m} + V(r) + \frac{4\pi a}{m}|\psi(r)|^2\Big)\psi(r) \qquad \vec{\nabla}^2 V(r) = 4\pi G m \rho(r)$$

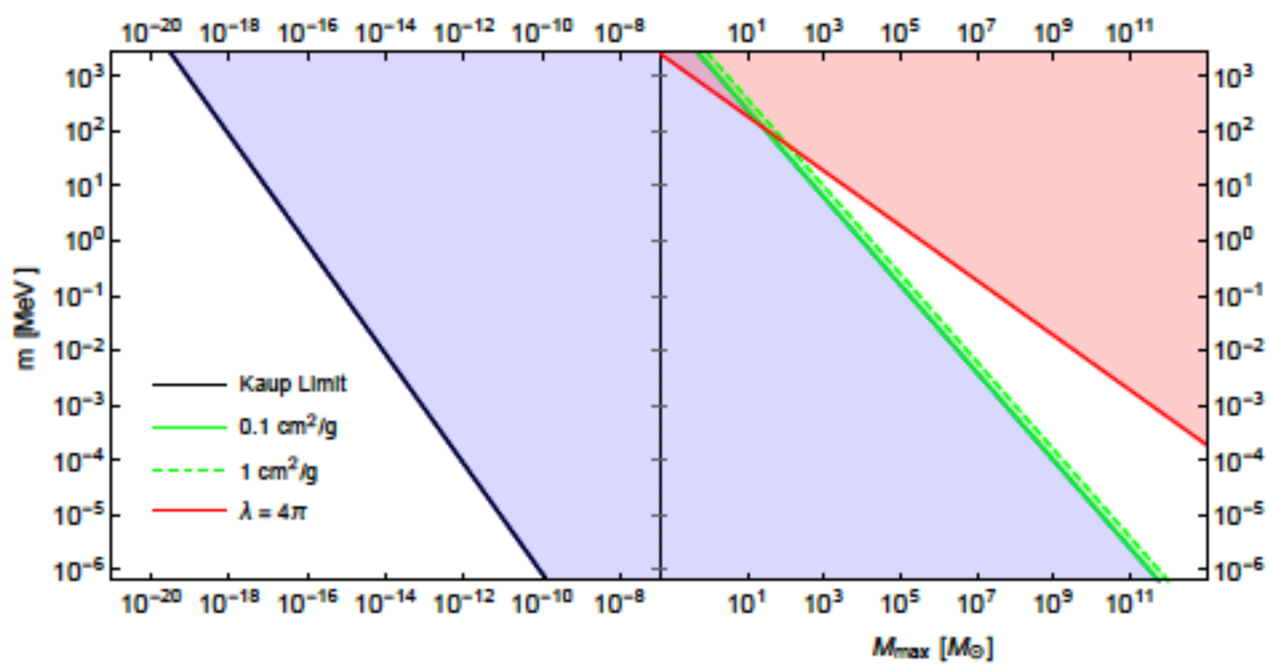
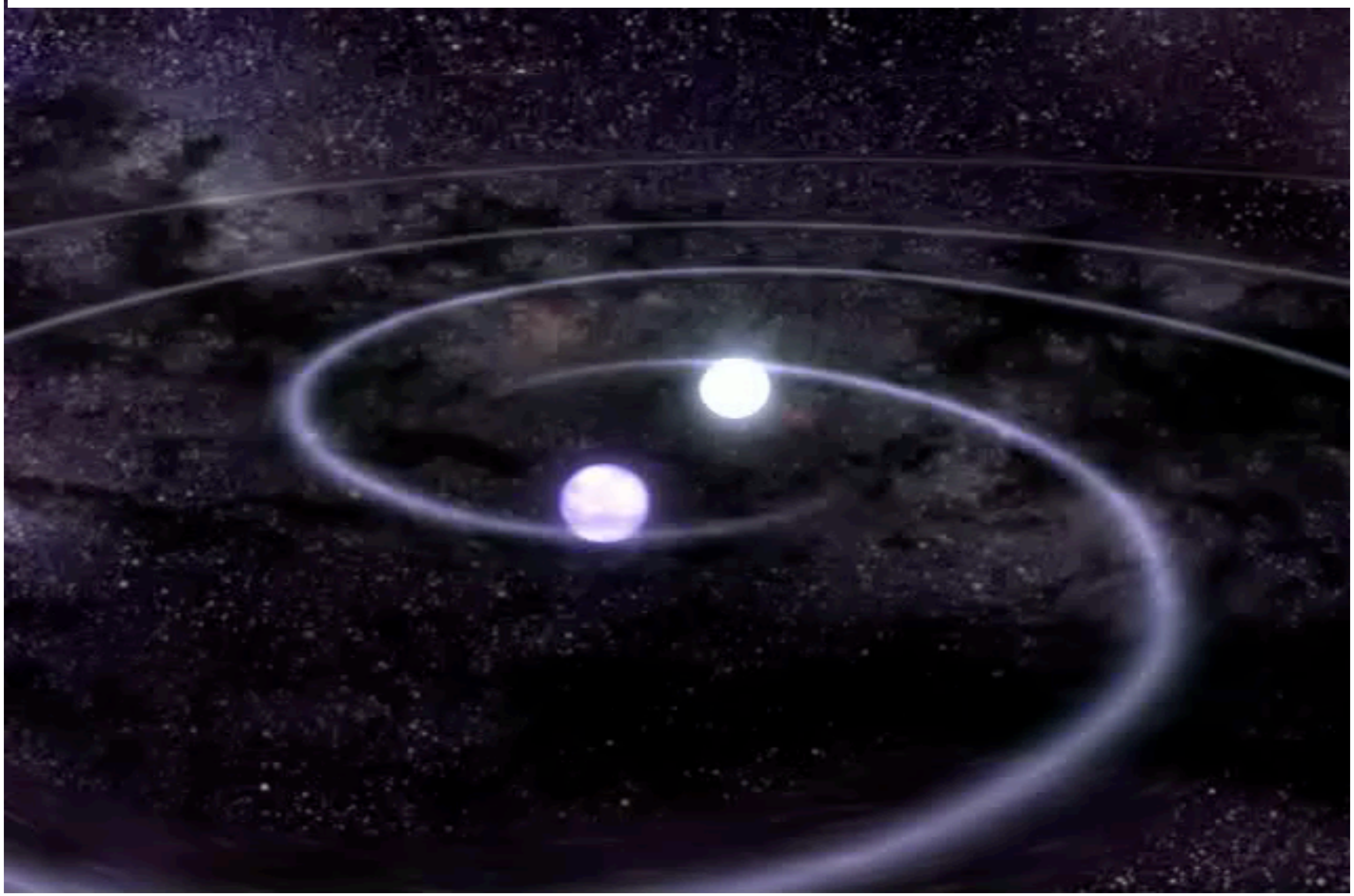


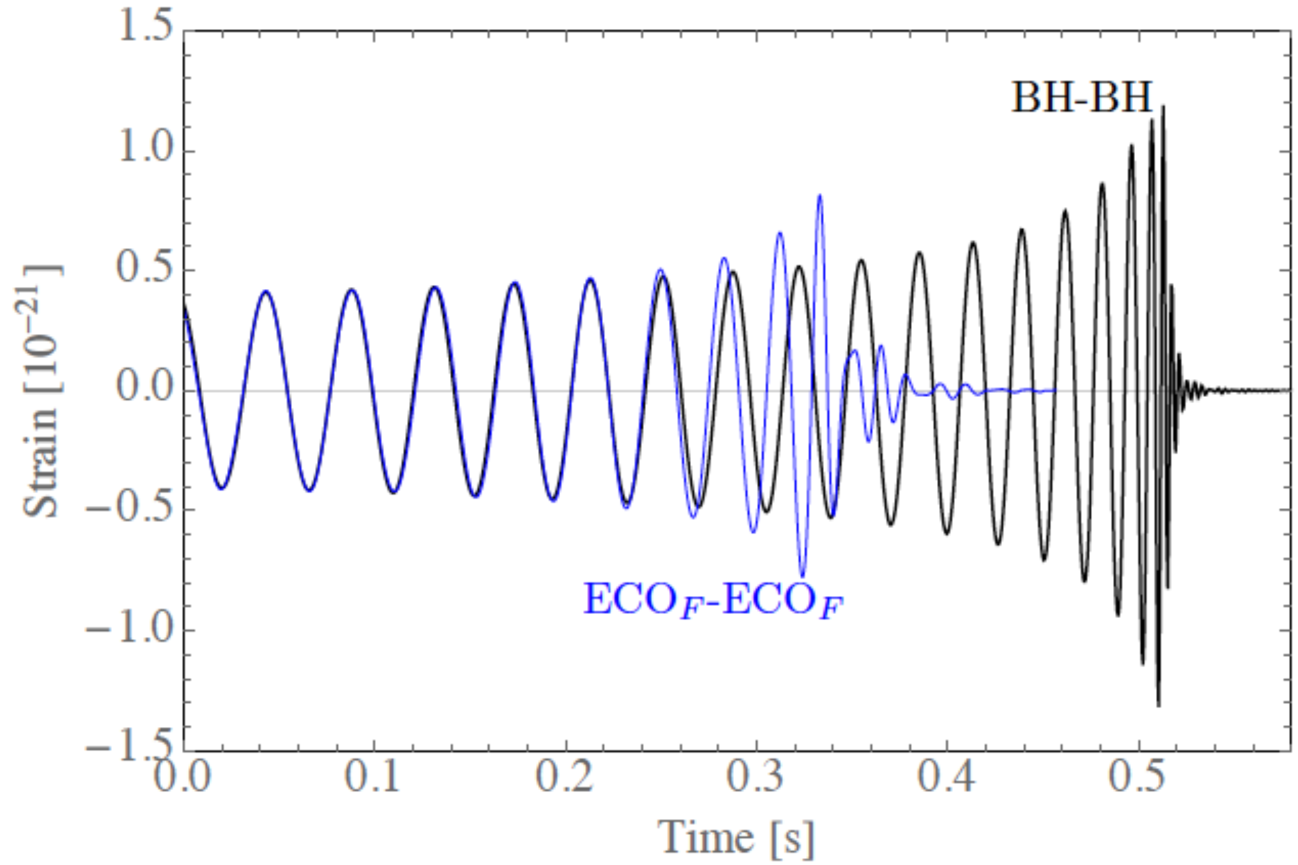
Figure 3: The maximum mass of a boson star with *repulsive* self-interactions satisfying Eq. (4), as a function of DM particle mass m. The green band is the region consistent with solving the small scale problems of collisionless cold DM. The blue region represents generic allowed interaction strengths (smaller than 0.1 cm^2/g) extending down to the Kaup limit which is shown in black. The red shaded region corresponds to $\lambda \gtrsim 4\pi$. Note that the horizontal axis is measured in solar masses $M_\odot$.

Eby, CK, Nielsen, Wijewardhana '15

Gravitational Waves of Dark Stars



“Odd Neutron Stars & Weird Black Holes”



Giudice, McCullough, Urbano ‘16

Observation

- Gravitational Waves: DS+DS->DS or BH (Solving numerically Einstein’s equations) with K.Kokkotas (Univ. of Tubingen)

  DS+NS-> DS*

  DS+BH->BH

  Spinning DS
- Gravitational Lensing (with L. Moustakas Caltech/JPL and K. Mack Melbourne)

Tidal Deformations of Dark Stars

How stars deform in the presence of an external gravitational field?

$$V=-(1/2)\varepsilon_{ij}x^i x^j$$

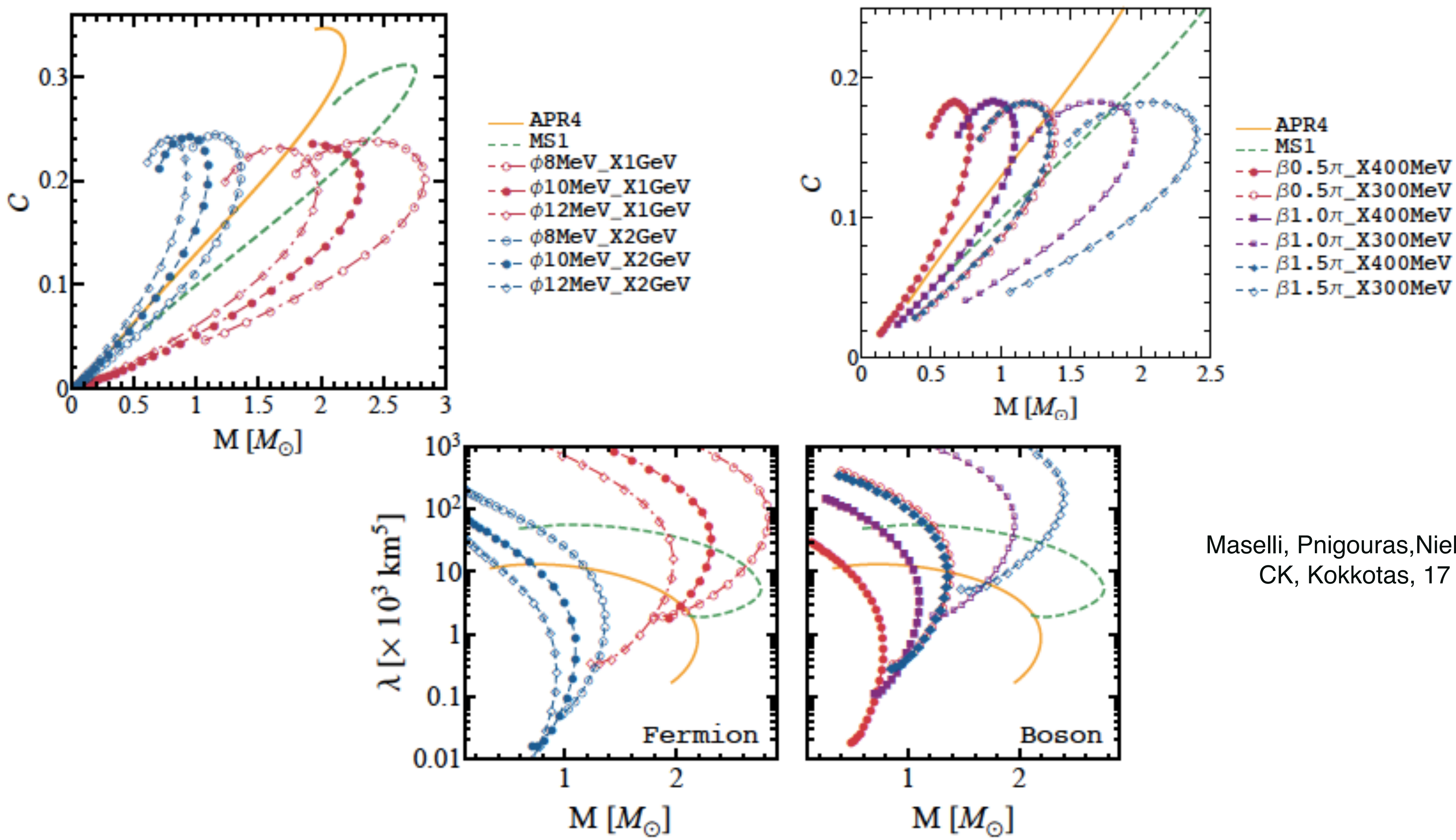
$$Q_{ij}=-\lambda\varepsilon_{ij}$$

$$\lambda=\frac{2}{3}k_2R^5$$

Love number

Similalry we can estimate the deformation due to rotation

I-Love-Q for Dark Stars



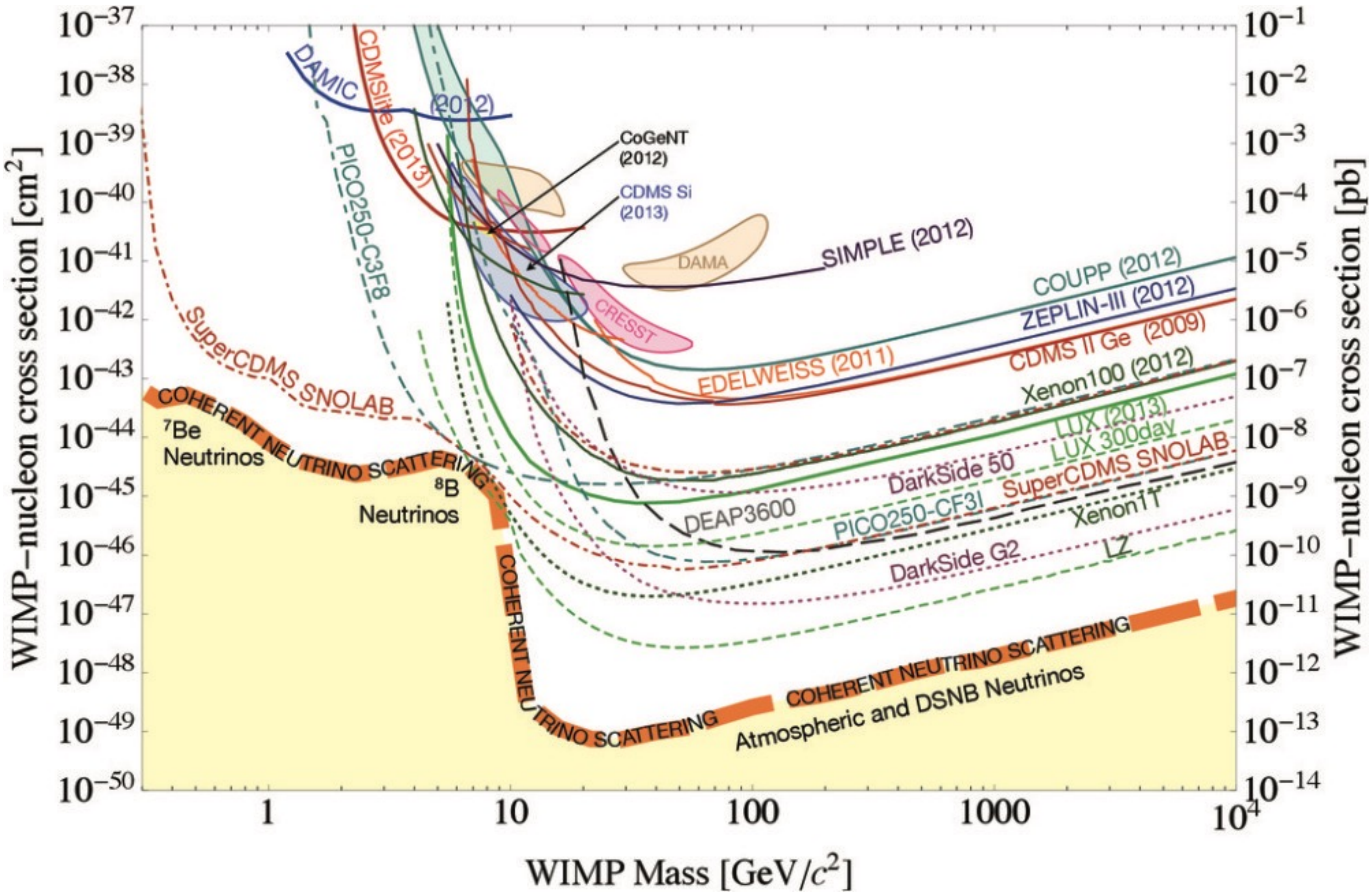
Maselli, Pnigouras,Nielsen, CK, Kokkotas, 17

I-Love-Q relations

$$\ln y = a + b \ln x + c(\ln x)^2 + d(\ln x)^3 + e(\ln x)^4$$

$$\bar{I} = \frac{I}{M^3} \quad , \quad \bar{Q} = -\frac{Q}{M^3\chi^2} \quad , \quad \bar{\lambda} = \frac{\lambda}{M^5}$$

Probing New Territory in Dark Matter Direct Detection

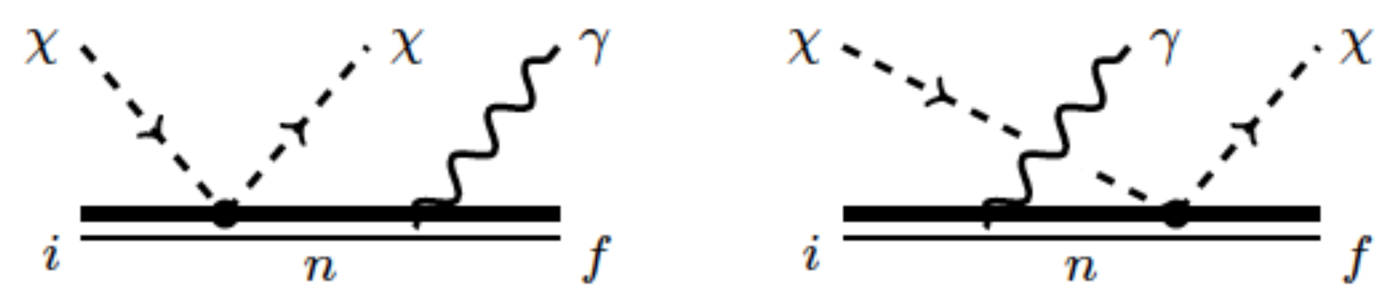


Probing sub-GeV Dark Matter

A given nuclear recoil requires a minimum velocity $v_{\rm min} = \sqrt{\dfrac{m_N E_R}{2\mu_N^2}}$

$$E_R \leq 2\mu_N^2 v^2/m_N$$

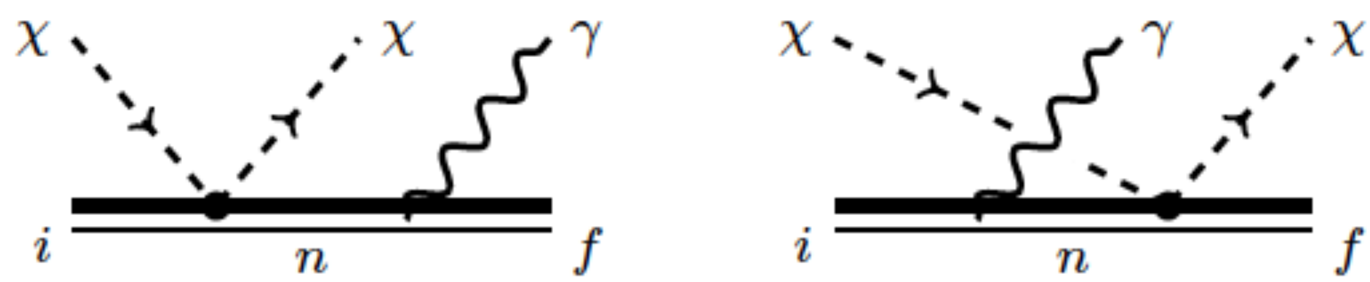
Inelastic Scattering



$$\omega \leq \mu_N v^2/2$$

The photon energy can be much larger than the nuclear recoil

Probing sub-GeV Dark Matter

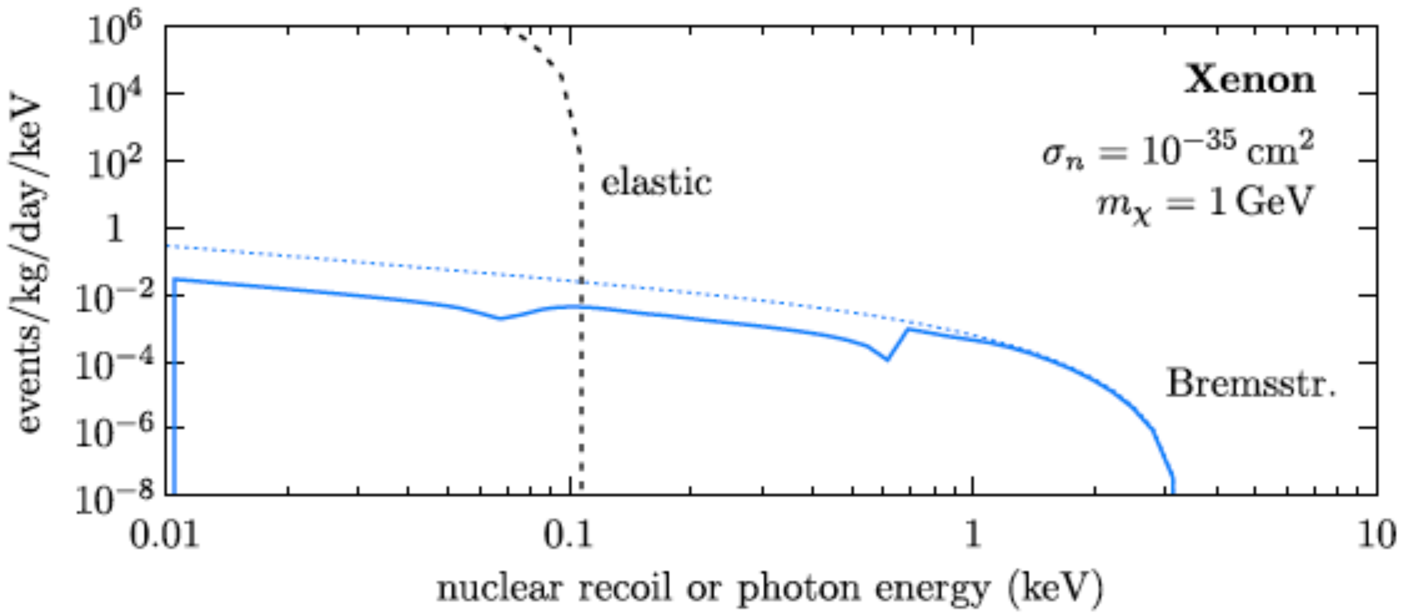


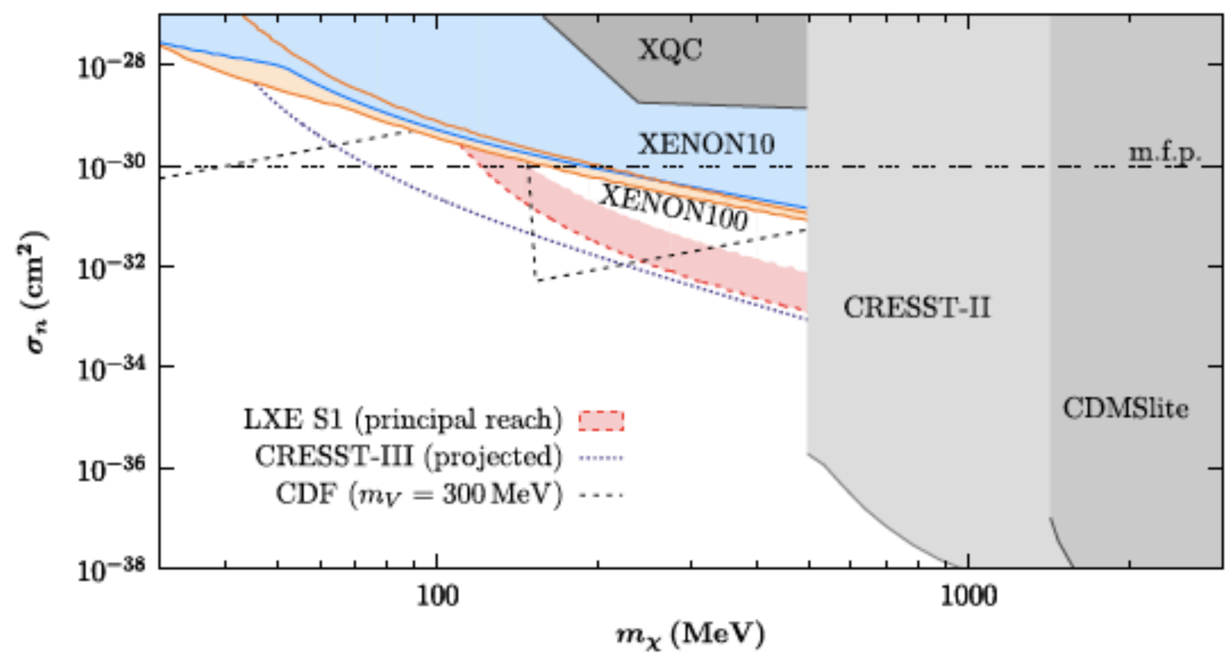
$$|V_{fi}|^2 = 2\pi\omega|M_{\rm el}|^2 \left| \sum_{n,n\neq i} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\,\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\,\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|n\rangle}{\omega_{ni}+\omega} \right] \right|^2$$

atomic state after nucleus has been boosted

$$\frac{d\sigma}{d\omega dE_R} = \frac{4\omega^3}{3\pi}\frac{E_R}{m_N}\frac{m_e^2|\alpha(\omega)|^2}{\alpha} \times \frac{d\sigma}{dE_R}\Theta(\omega_{\rm max}-\omega)$$

New Limits on Dark Matter

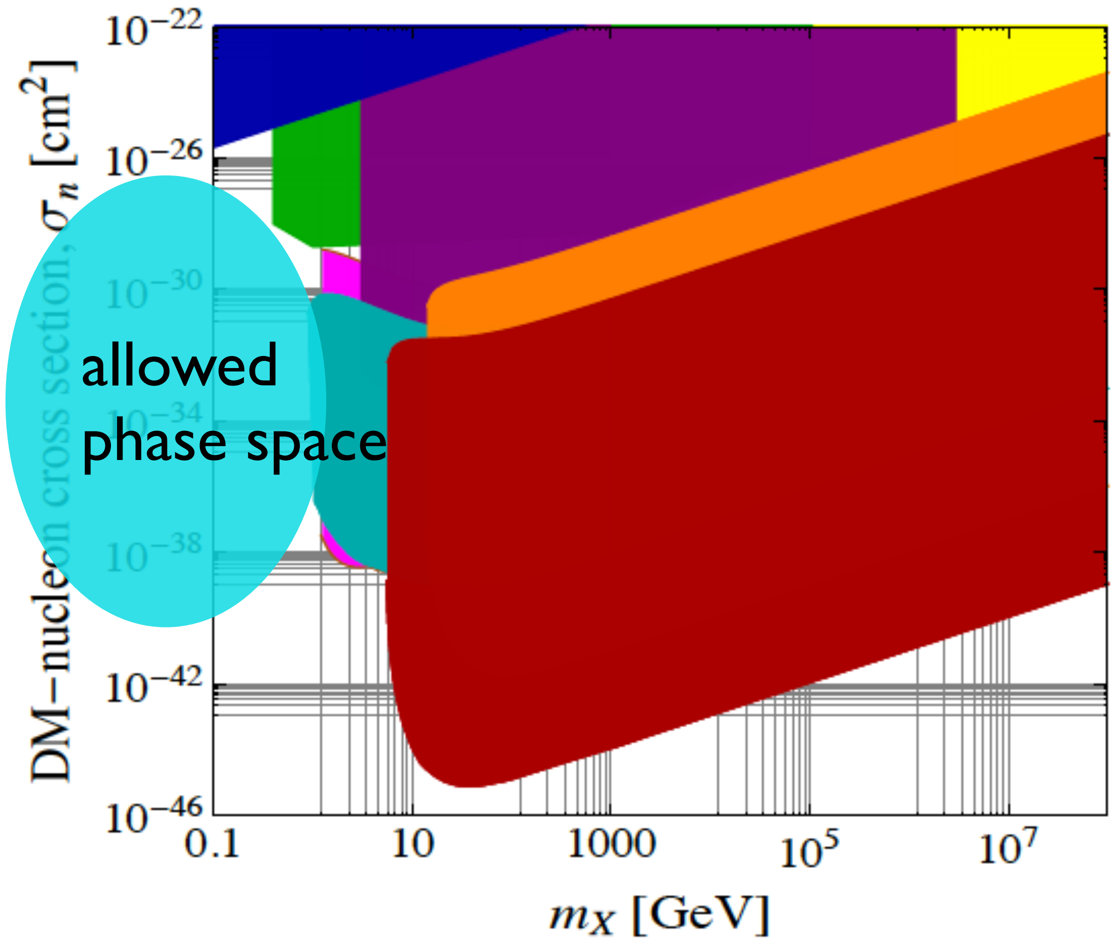




CK, Pradler PRL '17

- First time limits on sub-GeV DM with DM-nucleon interactions
- "Converting" a conventional detector to a directional one
- Generalize to final states that leave the atom excited
- Different DM-nucleon operators

Looking for Dark Matter in the Earth's Shadow



CK, Shoemaker '14

There is light dark matter phase space that will not be covered by underground experiments even if they lower their energy threshold due to effective stopping by the rock.

Need for detectors in shallow sites or on surface
However this would increase the background!

Observing a daily varying dark matter signal
CK, Shoemaker '14, Foot Vagnozzi '15

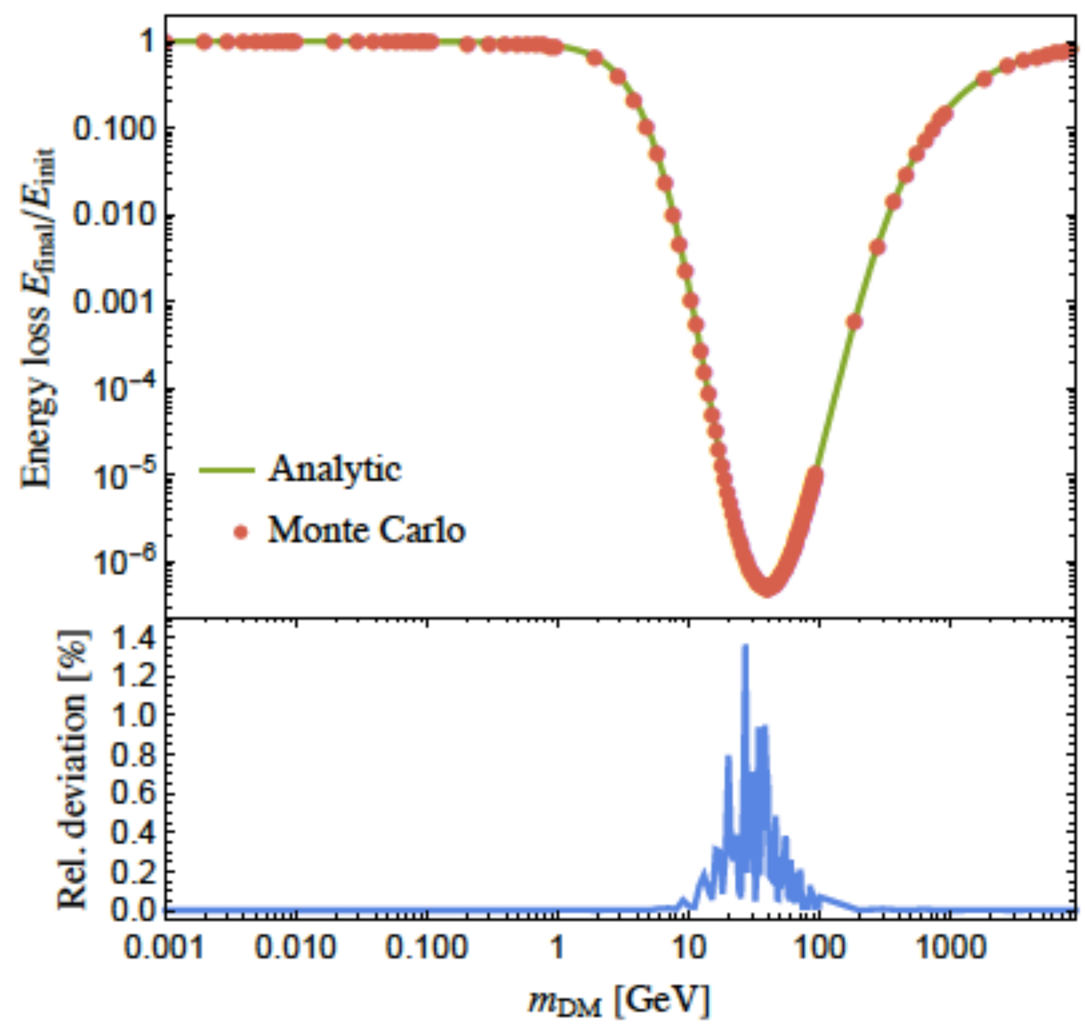
- Ideal for portable detectors like DAMIC can be placed either on the surface or in shallow sites
- Best latitude at the south hemisphere ~43 degrees. Chile, Argentina, Australia, New Zealand

The effect can be probed also in directional detectors manifesting itself as a top-down asymmetry CK'15

Re-visiting Direct Detection Limits

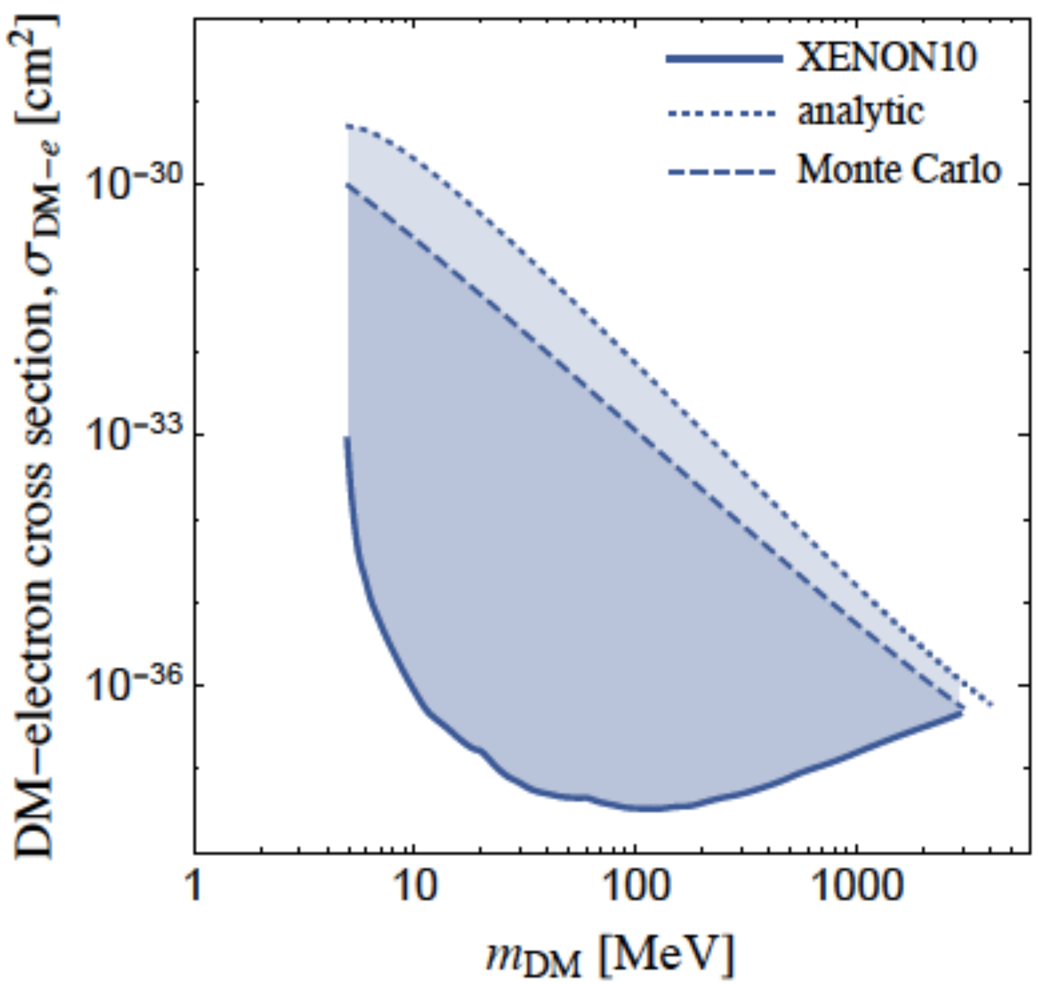
$$\mathscr{L} \supset g_X \bar{X}\gamma^\mu X A'_\mu + \varepsilon F_{\mu\nu} F'^{\mu\nu} + m_\phi^2 A'_\mu A'^\mu$$

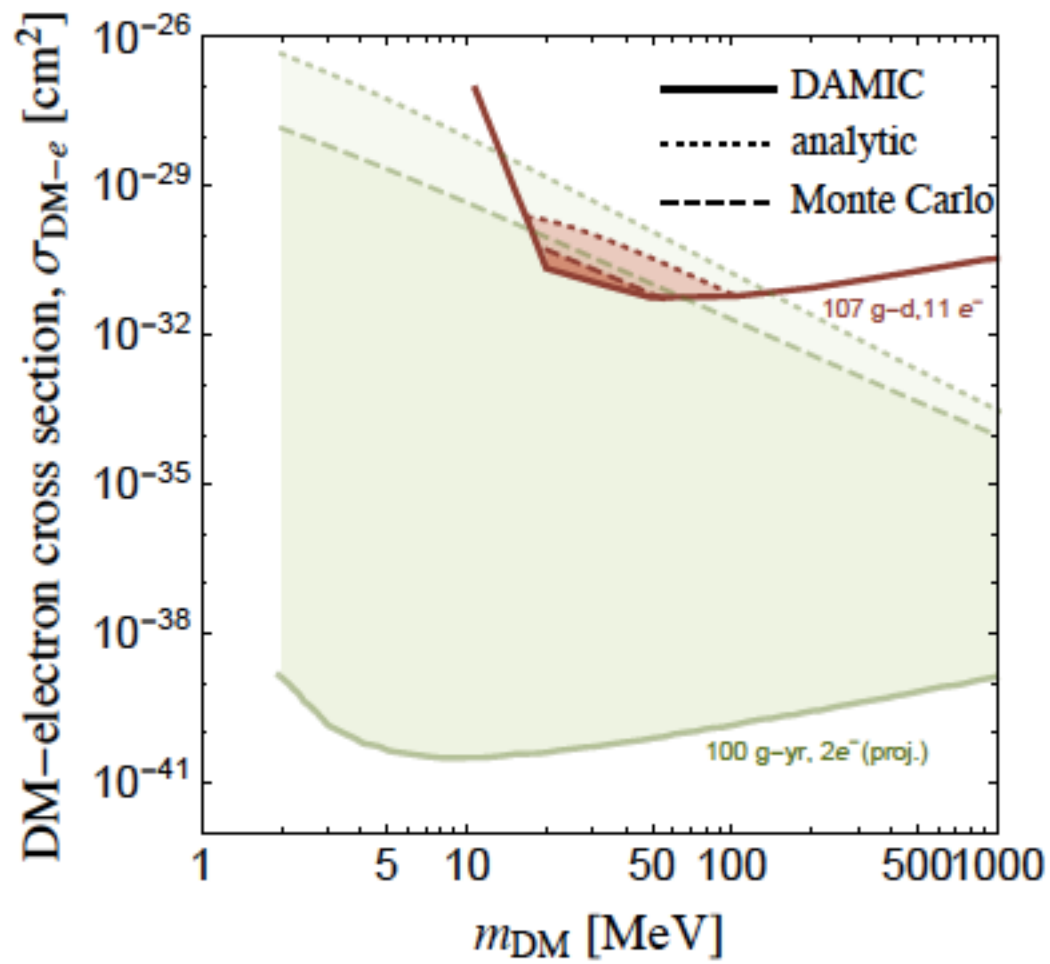
$$\frac{\mathrm{d}E}{\mathrm{d}x} = -n_N \int_0^{E_R^{\max}} \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} E_R \, \mathrm{d}E_R \qquad \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_N \sigma_N}{2\mu_N^2 v^2} = \frac{m_N \sigma_p Z^2}{2\mu_p^2 v^2} \qquad \log\left(\frac{E_{\mathrm{in}}}{E_{\mathrm{f}}}\right) = \frac{2 n_N \sigma_p Z^2 \mu_N^4 L}{m_X m_N \mu_p^2}$$



Emken, CK, Shoemaker '17

Re-visiting Direct Detection Limits





Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, '16, Emken, CK, Shoemaker '17

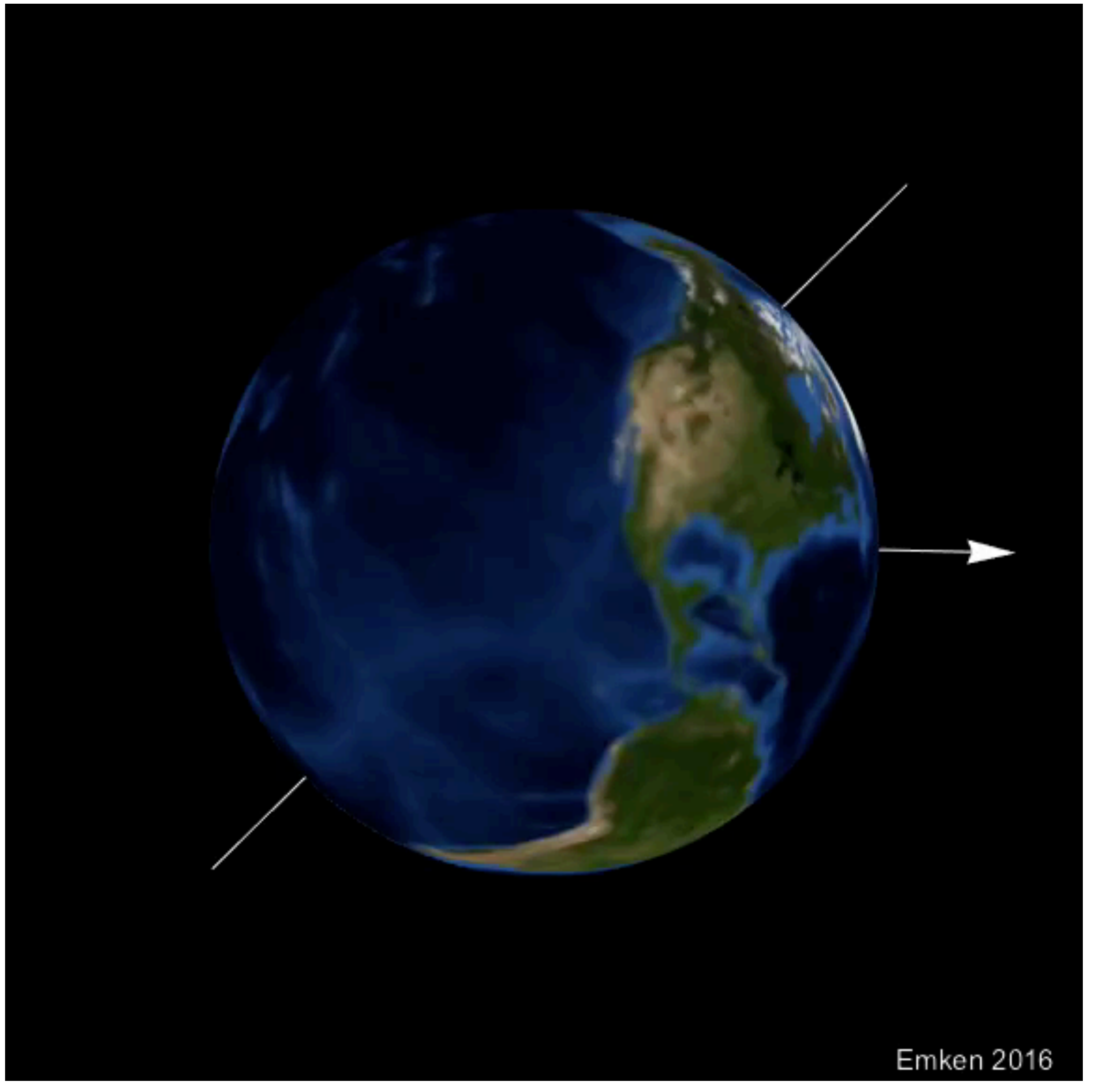
Experiment	Depth [m]	E_{thr}[eV]
XENON10	1400	12.4
DAMIC	100	40
DAMIC (proj.)	100	$\sim 1-2$

Constraints weaken significantly

Daily Modulation in the Dark Matter Signal

The dark matter signal in underground detectors has three types of diurnal modulation:

- Shadowing effect
- Gravitational focusing
- Rotational velocity of the Earth



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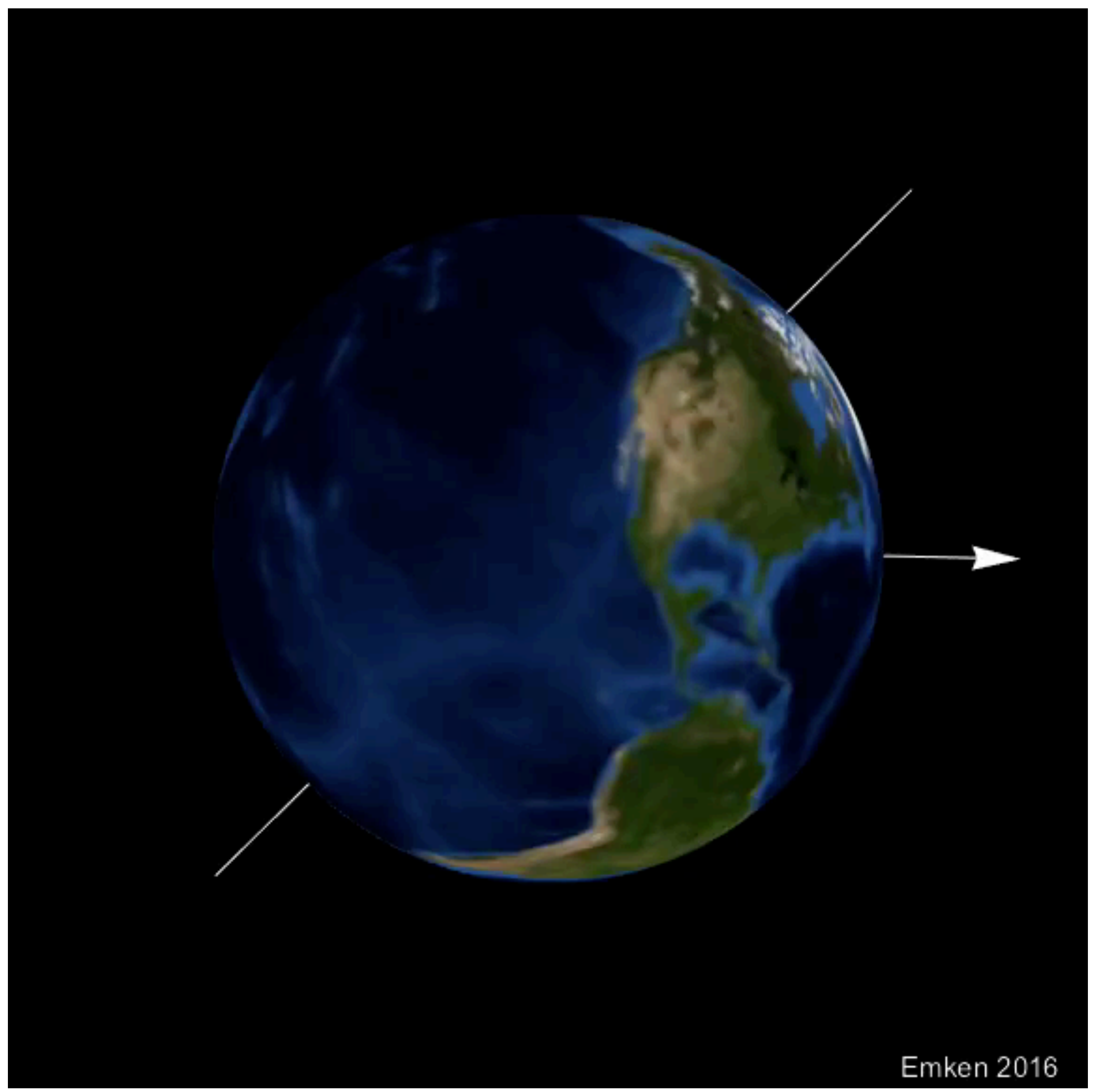
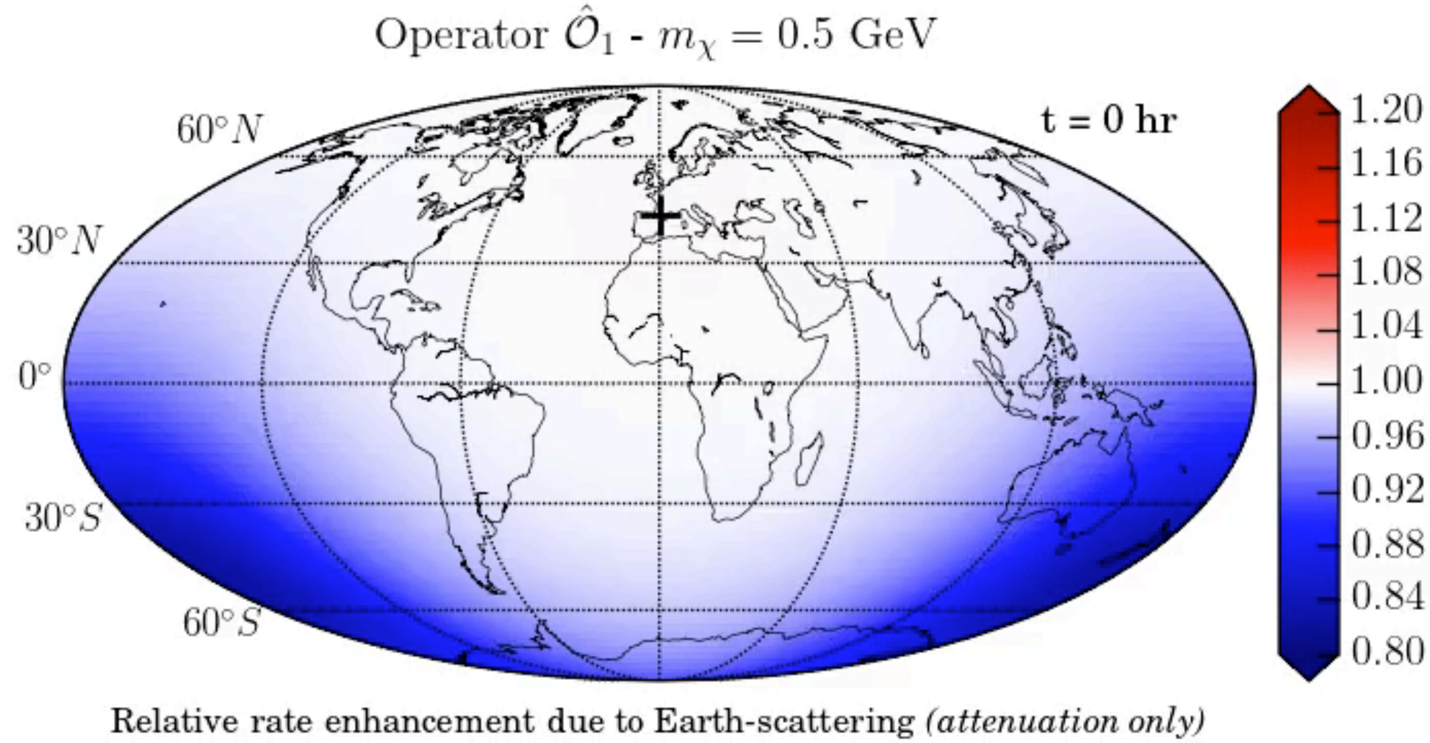
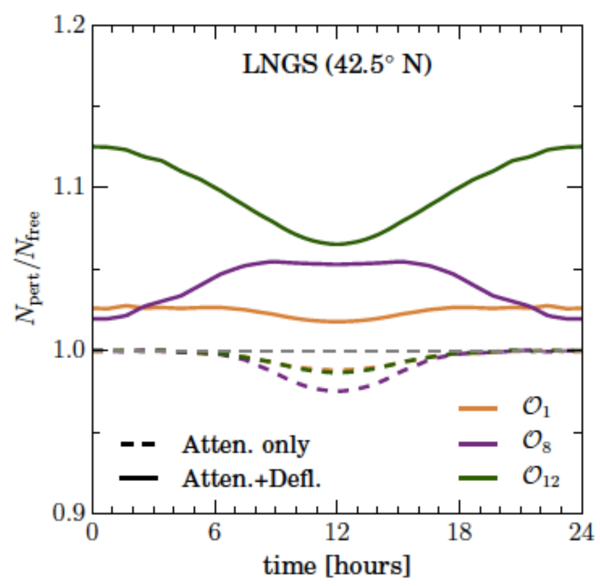
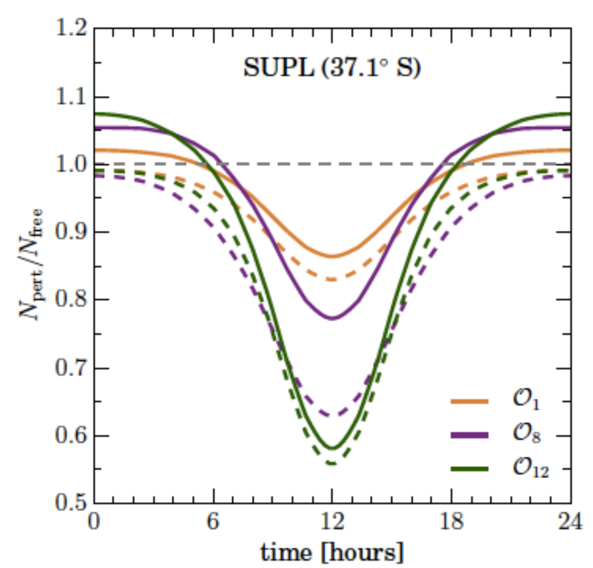


The Shadow of the Earth



(Kavanagh, CK, Catena '17)

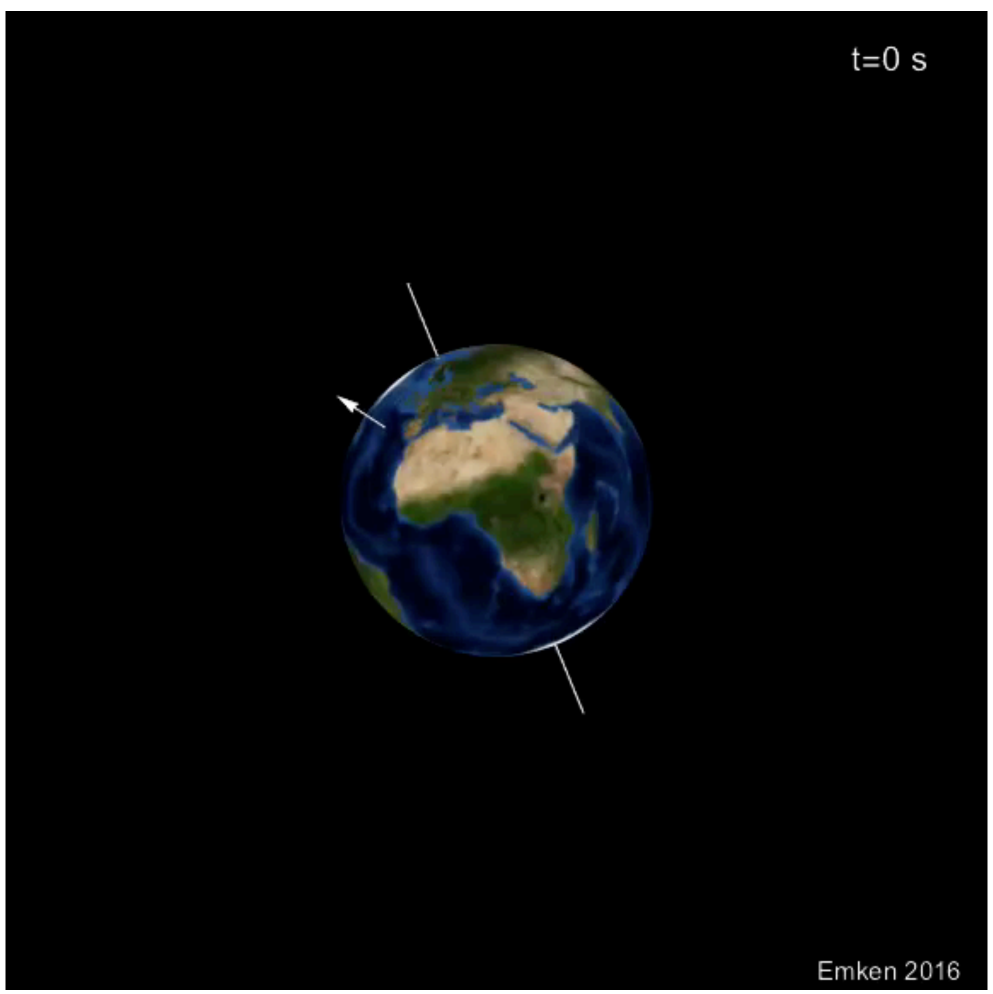


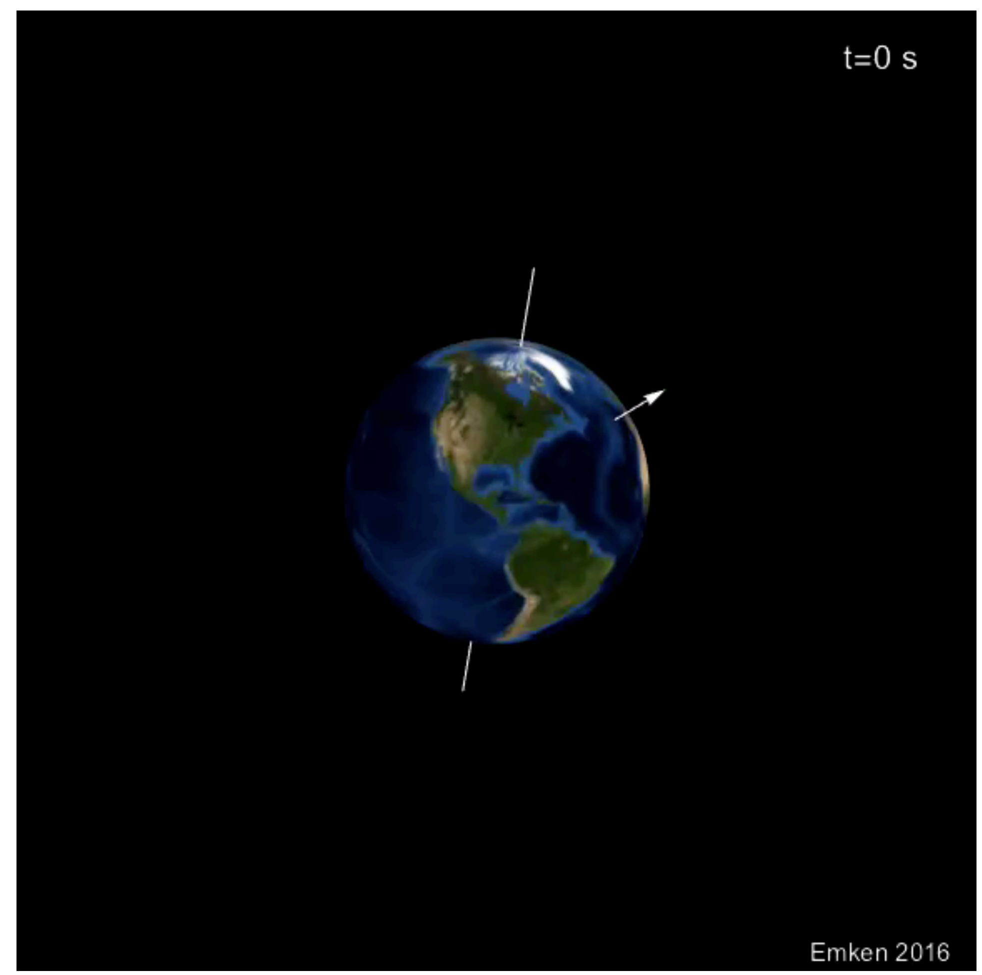


DAMASCUS: Dark Matter on Supercomputers

Performing a simulation of trillions of DM particles on ABACUS

- fully parallelized code
- Precise Recoil Spectrum
- Test self-consistency of experiments
- Probe Currently Elusive Dark Matter





Conclusions

Discovering Dark Stars

- Gravitational Waves LIGO
- Gravitational Lensing

Probing Light Dark Matter in Direct detection via Inelastic processes

- New Limits
- Reducing effectively the energy threshold of current detectors
- “Converting” non-directional detectors to directional ones

Probing Light Dark Matter using the daily modulation DM signals from

- Earth’s shadowing effect
- Gravitational Focusing
- Rotational velocity of the Earth