BH VIII Workshop, IST 21-22 December 2015

Binary Pulsars as Dark-Matter Probes

based on arXiv:1512.01236 (PRD in press)

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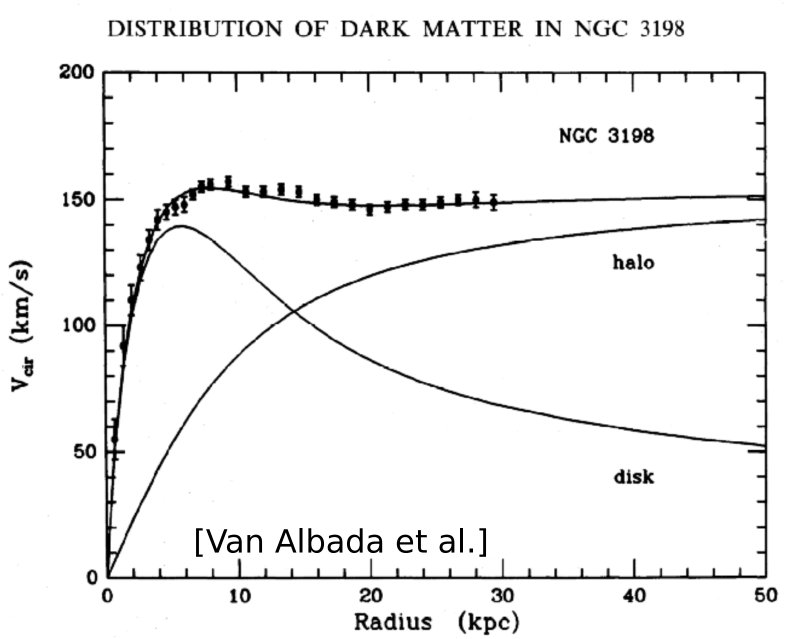
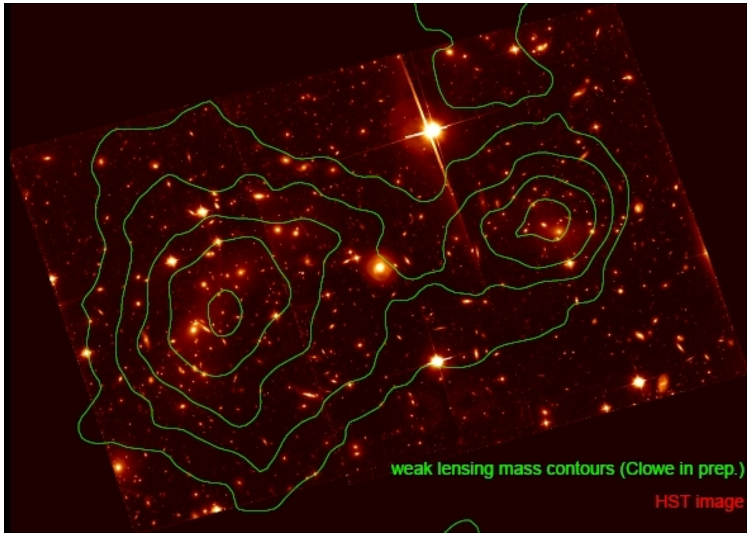
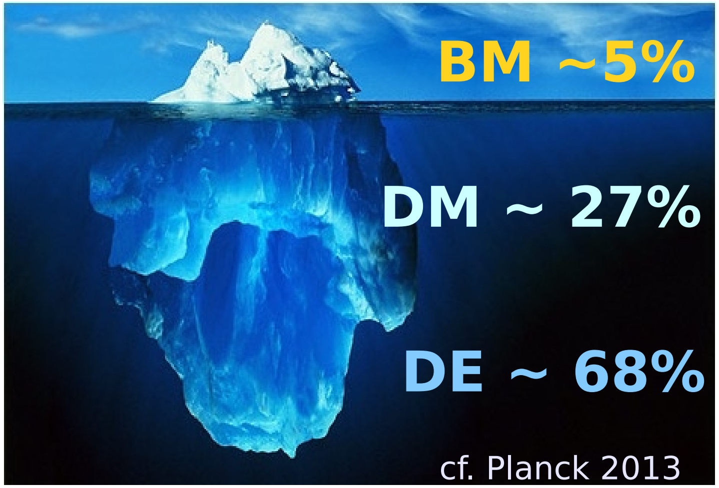
The Dark-Matter (DM) Problem

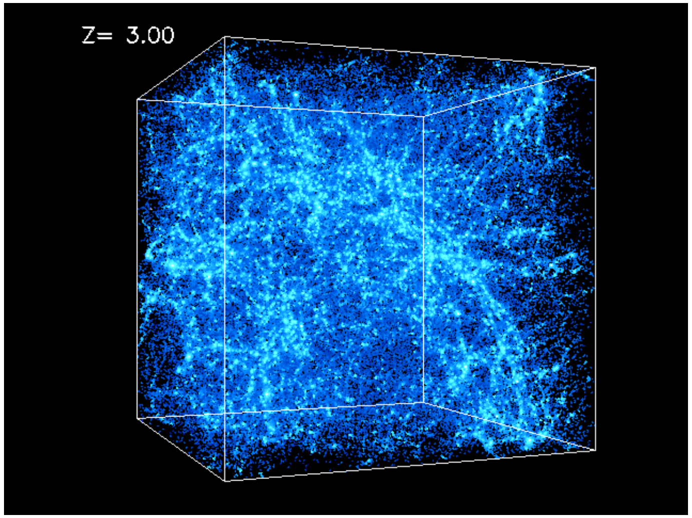




- Weak leansing

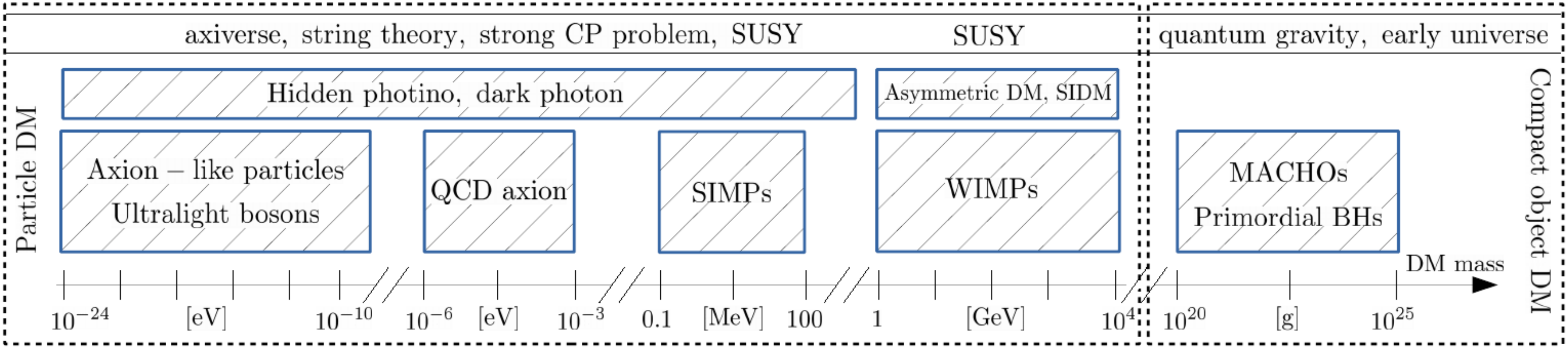


- Cosmology



- Structure formation

The DM candidate problem



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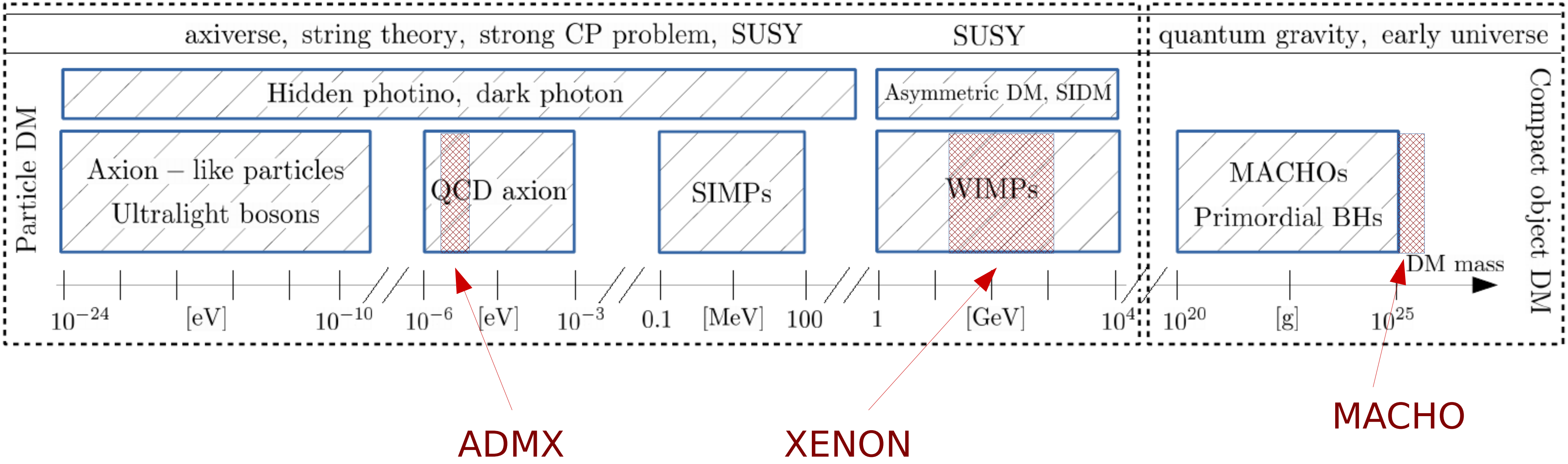

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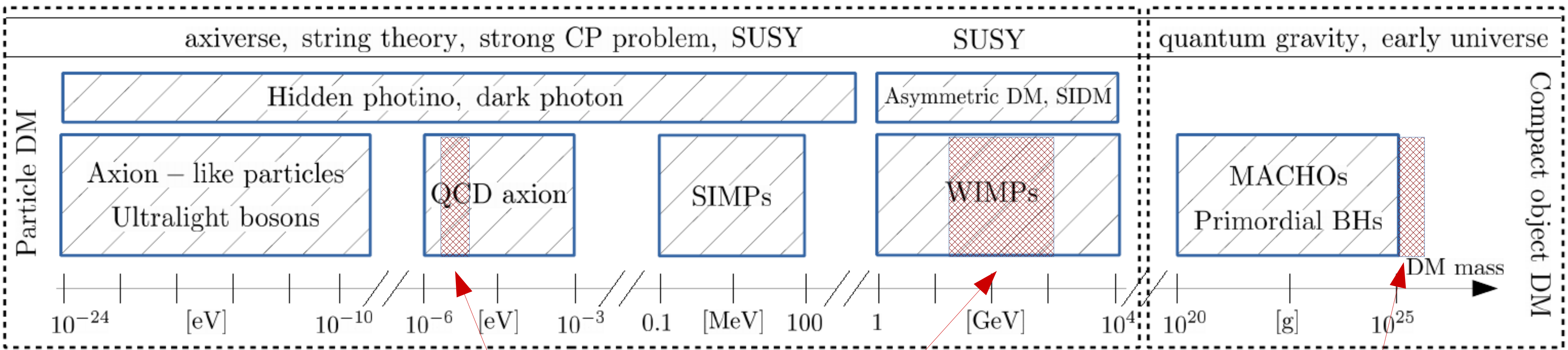


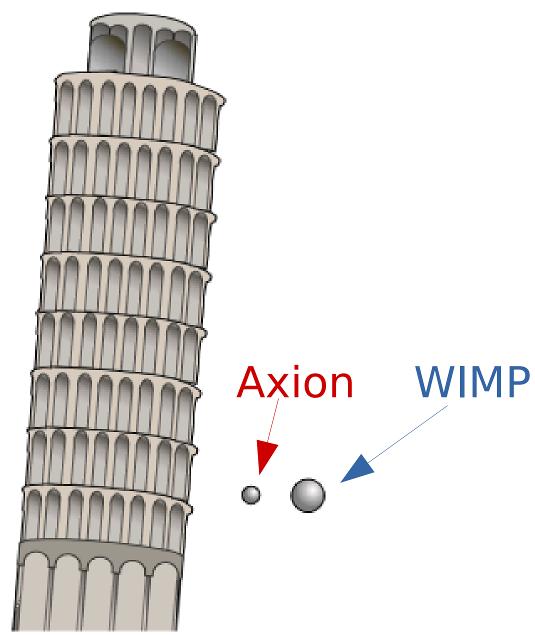
ADMX

XENON

MACHO

Diverse phenomenology,
but <u>same gravitational interaction</u>

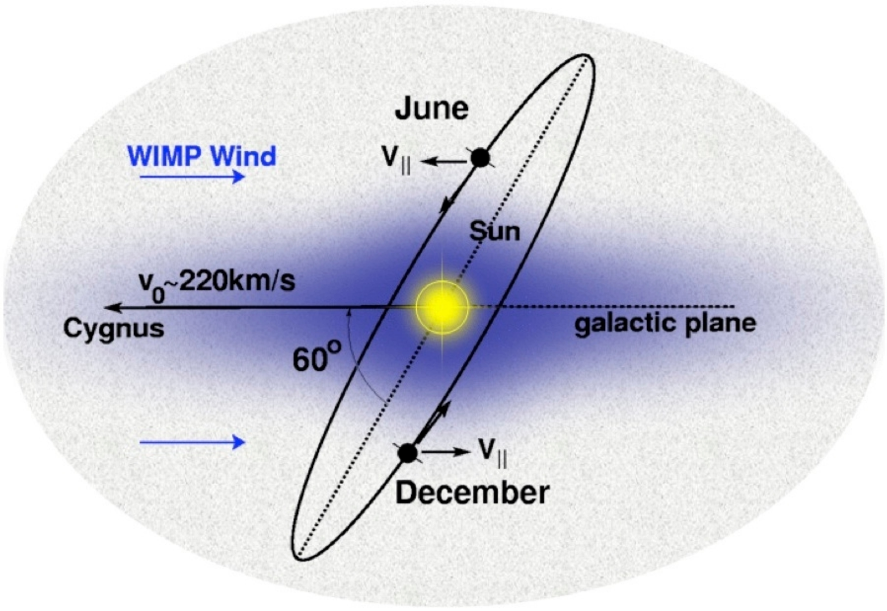
Model-independent tests

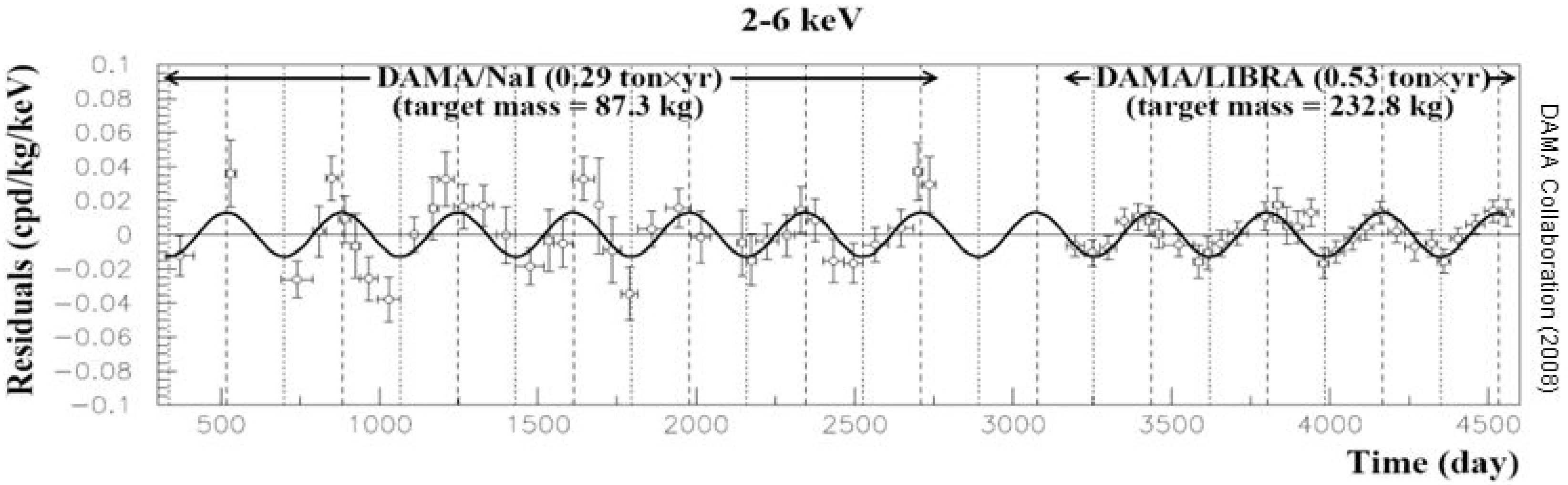


DM “monsoons” on Earth

[Drukier, Freese, Spergel, Phys.Rev. D33 (1986) 3495-3508, Freese Rev. Mod. Phys. 85, 1561 2013]

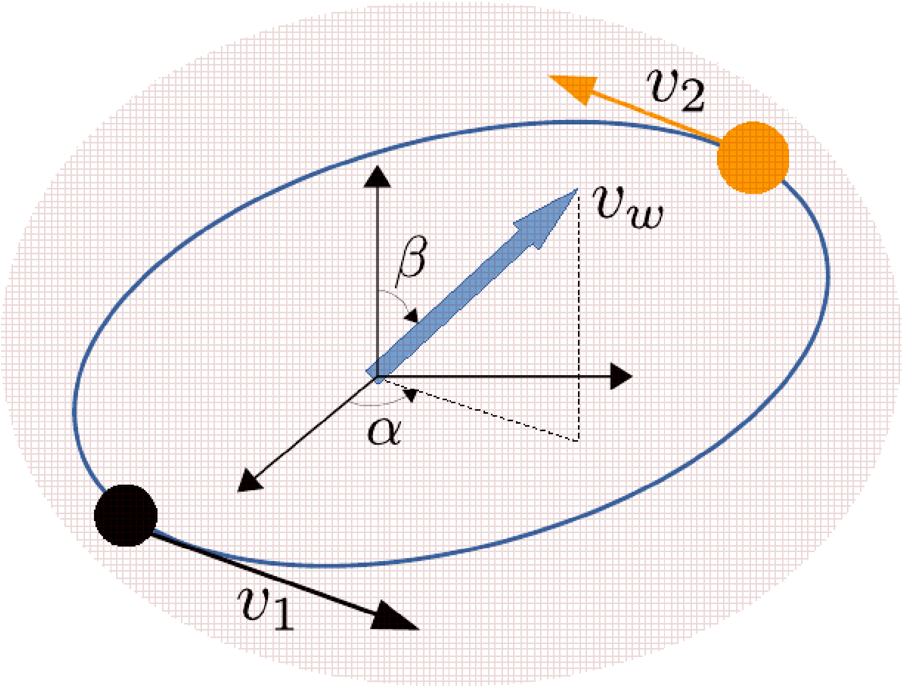
- Seasonal modulation
- Depends on DM distribution
- Velocity dependence

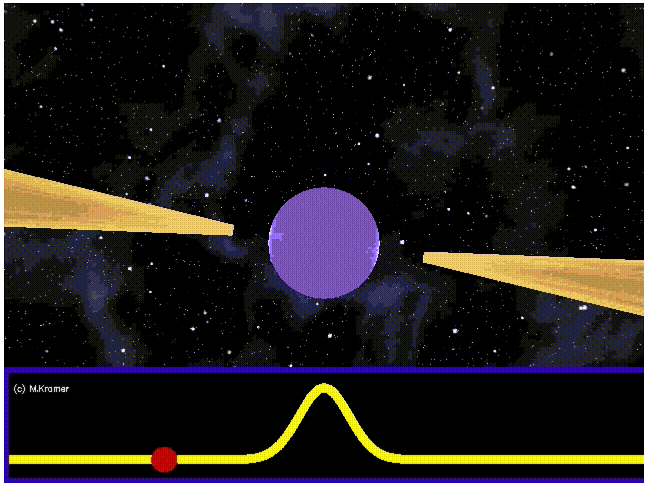




DM monsoons in pulsar binaries

$$m_i \ddot{\mathbf{r}}_i = \pm \frac{G m_1 m_2}{r^3}\mathbf{r} + \mathbf{F}_i^{\rm ext}$$





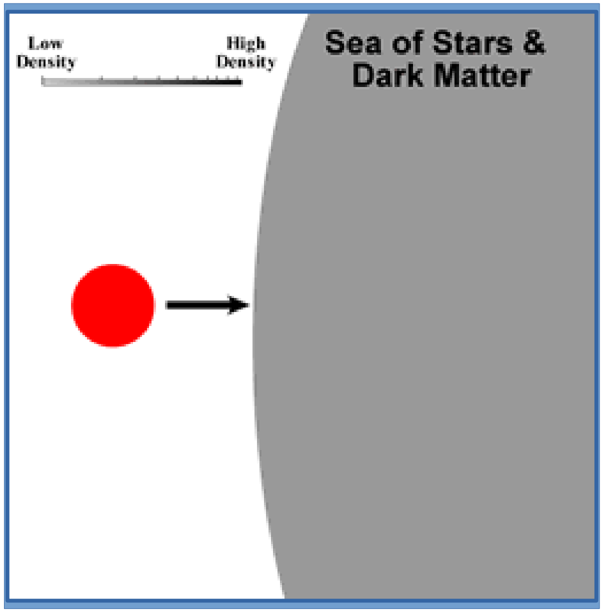
$$\mathbf{F}_i^{\rm DF} = -A b_i \frac{m_i^2}{M}\tilde{\mathbf{v}}_i \qquad \tilde{\mathbf{v}}_i = \dot{\mathbf{r}}_i + \mathbf{v}_w$$

$$\dot{\mathbf{v}} = -\frac{GM}{r^3}\mathbf{r} + a_1 \eta \mathbf{v} + a_2\left(\mathbf{v}_w + \mathbf{V}\right) \qquad \dot{\mathbf{V}} = a_2 \eta \mathbf{v} + a_3\left(\mathbf{v}_w + \mathbf{V}\right)$$

Dynamical friction

Chandrasekhar, 1940s, Binney & Tremain, “Galactic Dynamics”, 1987

$$\mathbf{F}_i^{\rm DF} = -4\pi\rho_{\rm DM}\lambda\frac{G^2m_i^2}{\tilde{v}_i^3}\left(\mathrm{erf}\left(x_i\right) - \frac{2x_i}{\sqrt{\pi}}e^{-x_i^2}\right)\tilde{\mathbf{v}}_i,$$



- Linear motion, collisionless medium
- Approximate for binary systems:

Bekenstein & Zamir, ApJ 1990

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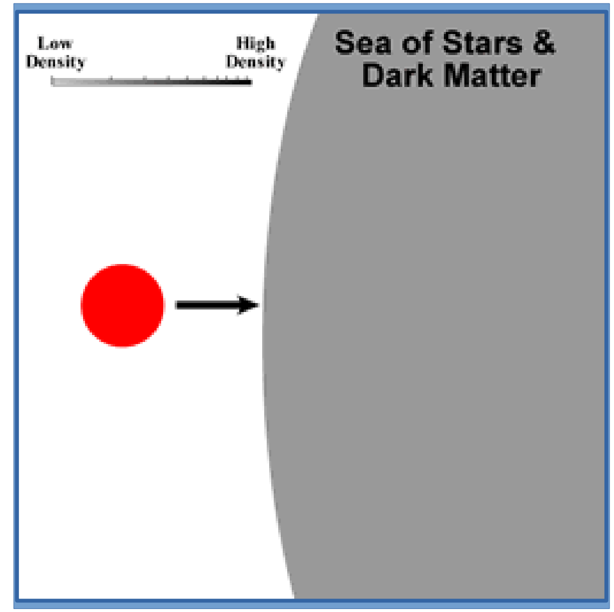

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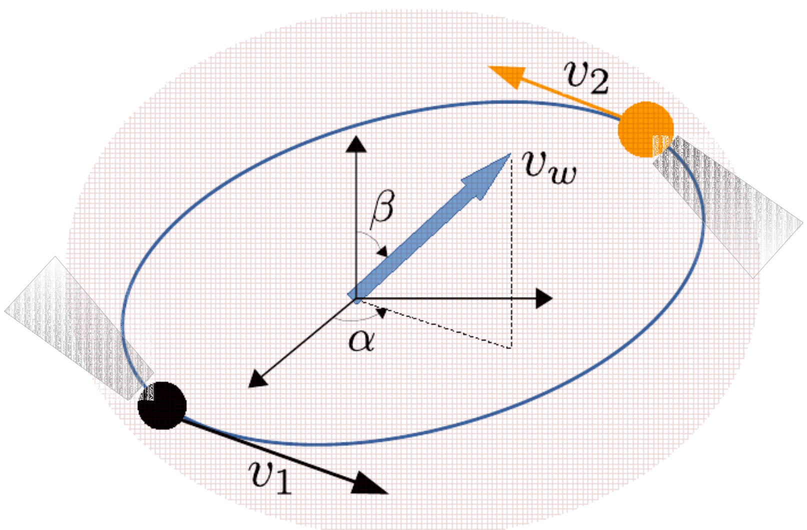


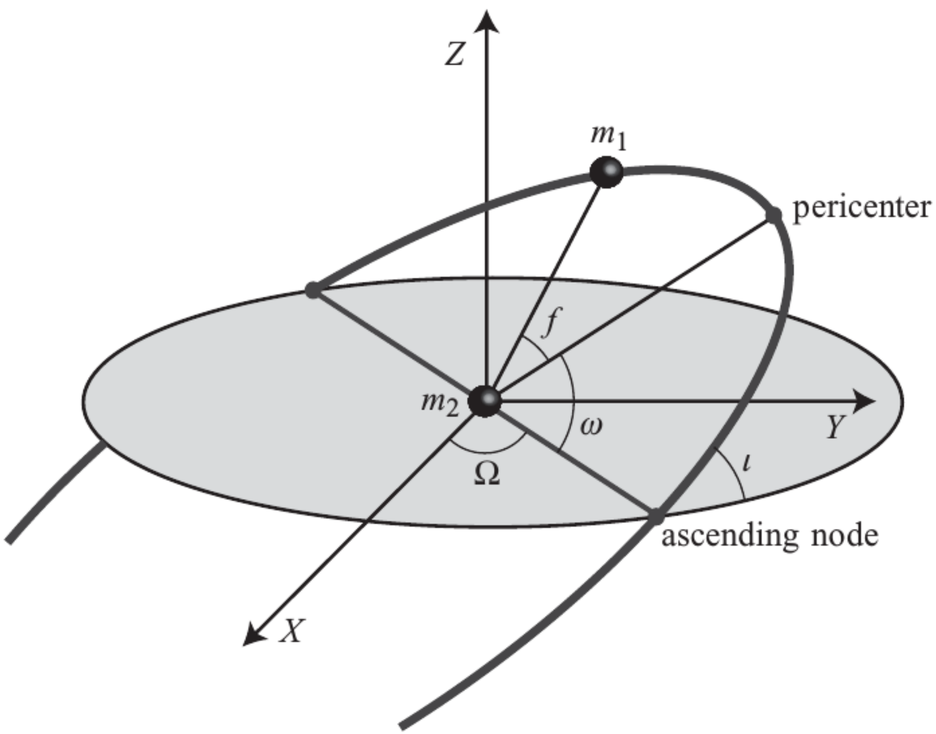
$$\frac{d\mathbf{v}}{dt} \sim -4\pi\frac{G^2(m_1+m_{\rm DM})m_{\rm DM}}{v^3}\mathbf{v} \times \left[\underbrace{\log(qv^2)\int_0^v d^3u f(u)}_{\text{Slow perturbers}} + \underbrace{\frac{2}{3}v^3\int_v^\infty d^3u\frac{f(u)}{u^3}}_{\text{Fast perturbers}}\right]$$

$$P_b \gg \frac{Gm_i}{\sigma^3} \sim 0.6\left(\frac{m_i}{1.3\,M_\odot}\right)\left(\frac{150\,\mathrm{km/s}}{\sigma}\right)^3 \mathrm{day}$$

Perturbed Newtonian dynamics

e.g. Poisson & Will "Gravity", 2014

$$\dot{\mathbf{v}} = -\frac{GM}{r^3}\mathbf{r} + a_1\eta\mathbf{v} + a_2\left(\mathbf{v}_w + \mathbf{V}\right) \qquad \dot{\mathbf{V}} = a_2\eta\mathbf{v} + a_3\left(\mathbf{v}_w + \mathbf{V}\right)$$



- Osculating orbits:

$$\dot{a} = 2\sqrt{\frac{r_0^3}{GM}}\mathcal{S}(t)\,,$$

$$\dot{e} = \sqrt{\frac{r_0}{GM}}\left[\mathcal{R}(t)\sin\Omega_0 t + 2\mathcal{S}(t)\cos\Omega_0 t\right]\,,$$

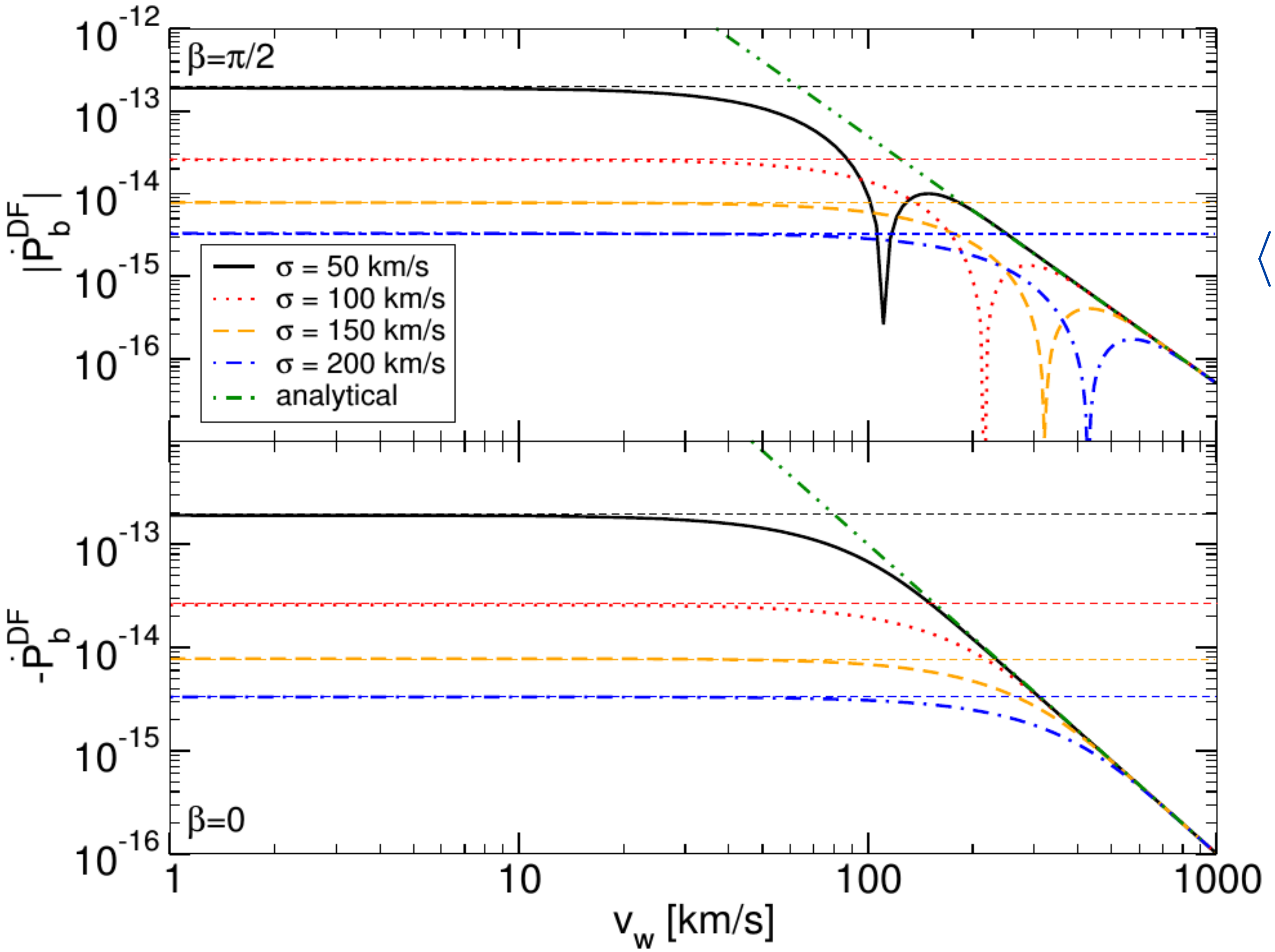
$$\dot{\iota} = \sqrt{\frac{r_0}{GM}}\mathcal{W}(t)\cos(\Omega_0 t + \omega)\,,$$

$$\dot{\Omega} = \frac{1}{\sin\iota}\sqrt{\frac{r_0}{GM}}\mathcal{W}(t)\sin(\Omega_0 t + \omega)\,,$$

$$\mathcal{R} := \mathbf{f}\cdot\mathbf{n} \quad \mathcal{S} := \mathbf{f}\cdot\lambda \quad \mathcal{W} := \mathbf{f}\cdot\mathbf{e}_z$$

- Secular changes: $\langle X\rangle := P_b^{-1}\int_0^{P_b} dt X(t)$

Secular changes of the orbital period



$$\langle \dot{P}_b^{\rm DM} \rangle = f(m_i, P_b, v_w, \alpha, \beta, \sigma)$$

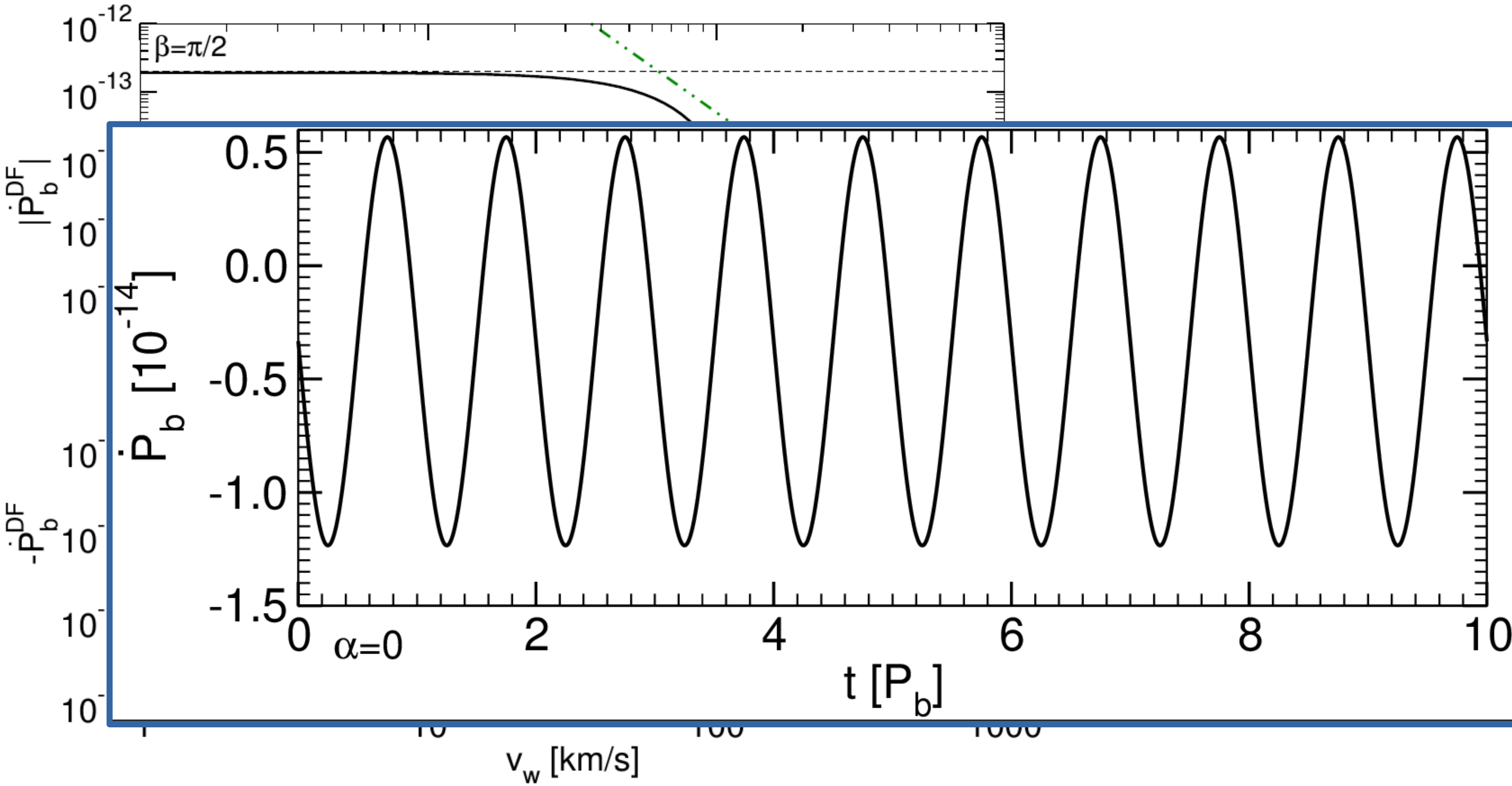
$$\langle \dot{P}_b^{\rm DF} \rangle \sim -8\sqrt{2\pi} G^2 \frac{\mu\lambda\rho_{\rm DM} P_b}{\sigma^3}$$

in the large-sigma limit

[Gould 1991]

$$\langle \dot{P}_b^{\rm DF} \rangle \approx -3\times 10^{-14} \left(\frac{\lambda}{20}\right)\left(\frac{\mu}{M_\odot}\right)\left(\frac{\rho_{\rm DM}}{2\times 10^3\,{\rm GeV/cm}^3}\right)\left(\frac{P_b}{100\,{\rm day}}\right)\left(\frac{150\,{\rm km/s}}{\sigma}\right)^3$$

Secular changes of the orbital period



$, \beta, \sigma)$

$_M P_b$

uld 1991]

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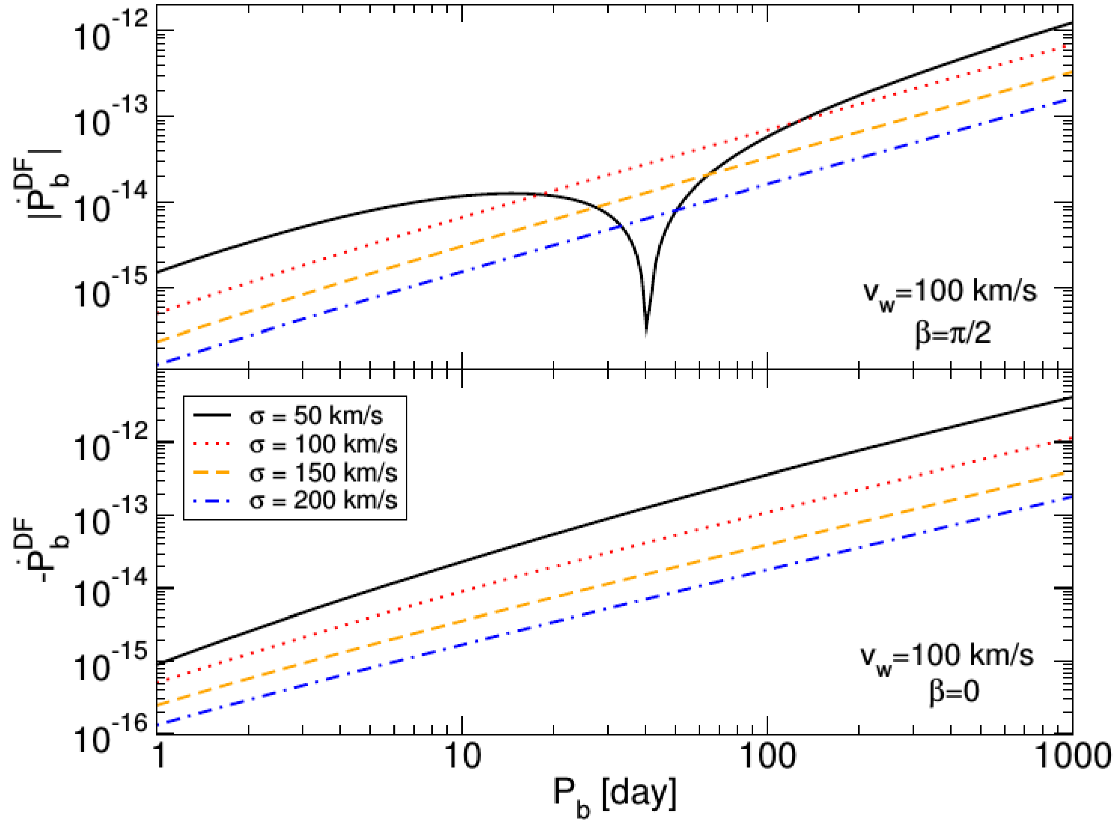
Secular changes of the orbital period



Other contributions:

$$\dot{P}_b^{\rm cm} = P_b \dot{\mathbf{V}} \cdot \mathbf{e}_Z$$

Center-of-mass acceleration

$$\dot{P}_b^{\iota} = \frac{3}{2} \tan \iota P_b \dot{i}$$

Apparent change due to inclination

$$55^\circ \lesssim \beta \lesssim 125^\circ \Rightarrow \langle \dot{P}_b^{\rm DF} \rangle > 0$$

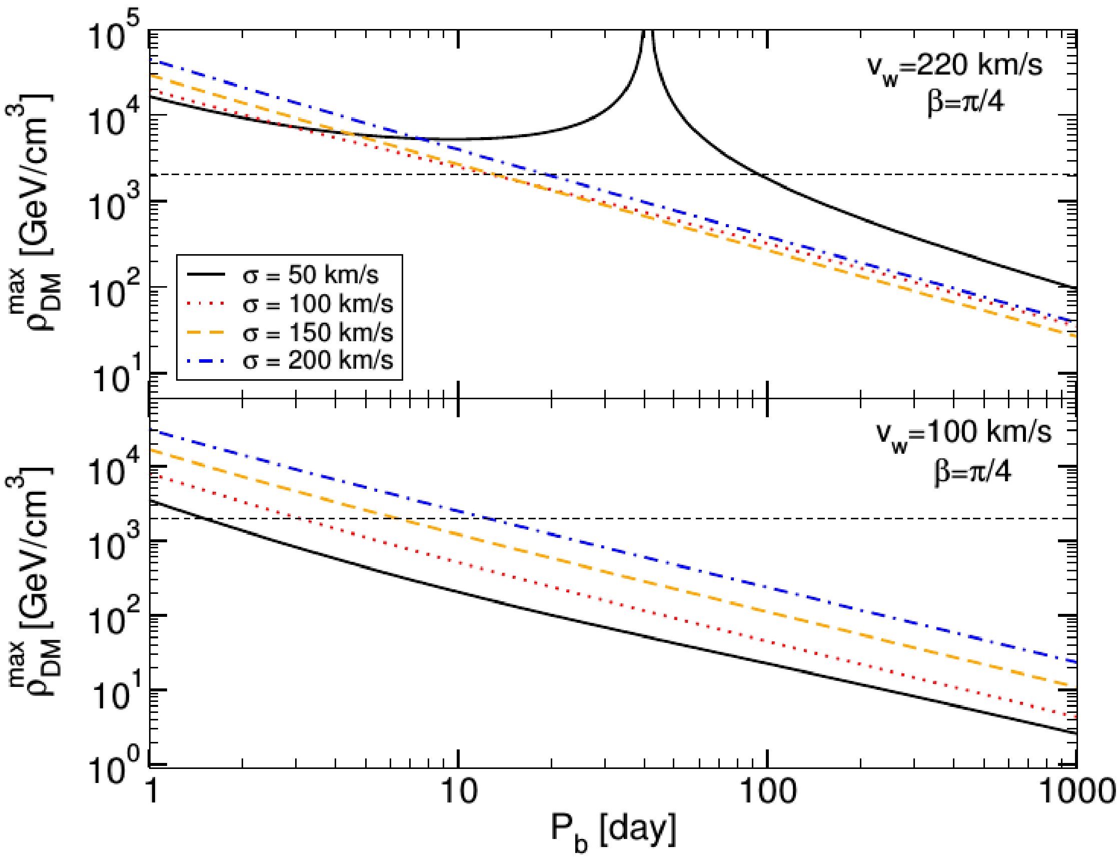
Violation of Heggie's law

"Hard binaries ($E_b \gg m_{\rm DM}\sigma^2$) get harder, soft binaries get softer"

[Heggie 1975]

Bounds on DM density at the GC

$$|\langle \dot{P}_b^{\rm DF} + \dot{P}_b^{\rm cm} + \dot{P}_b^{\iota}\rangle| \lesssim \dot{P}_b^{\rm xs} \Rightarrow \rho_{\rm DM} < \rho_{\rm DM}^{\rm max}$$



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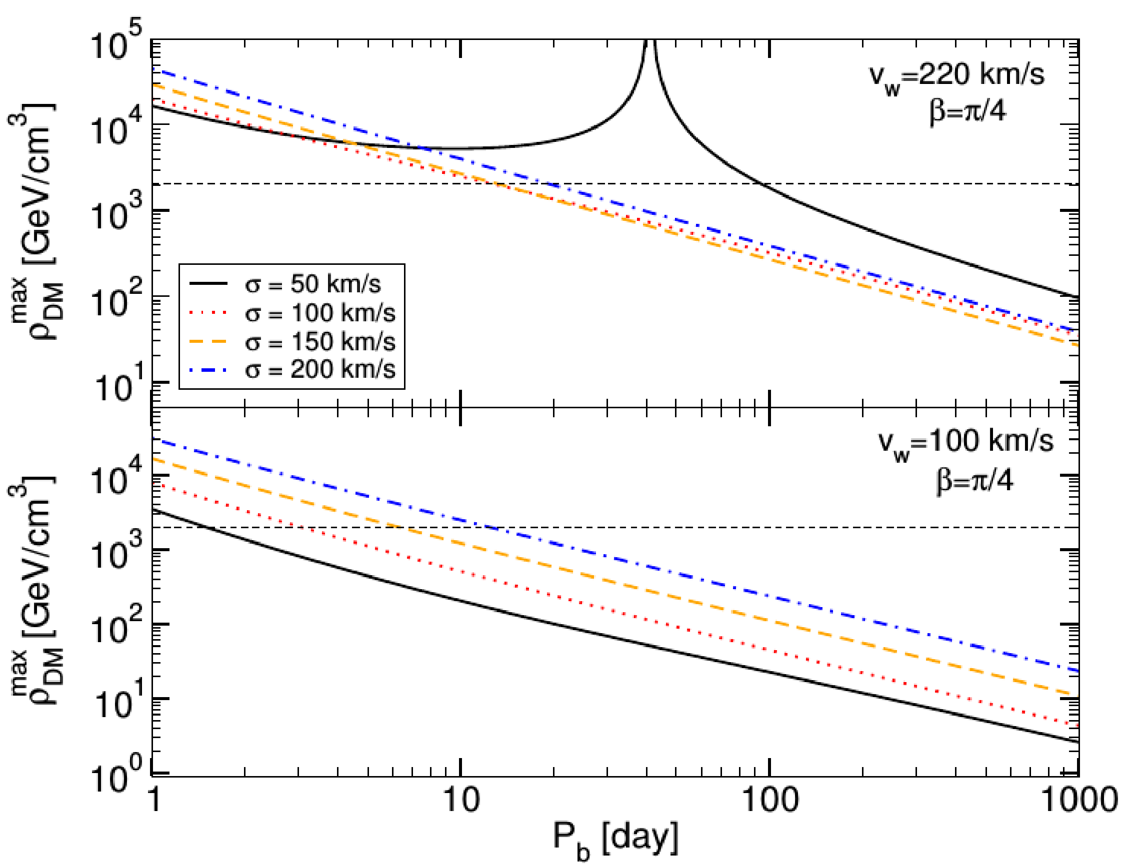

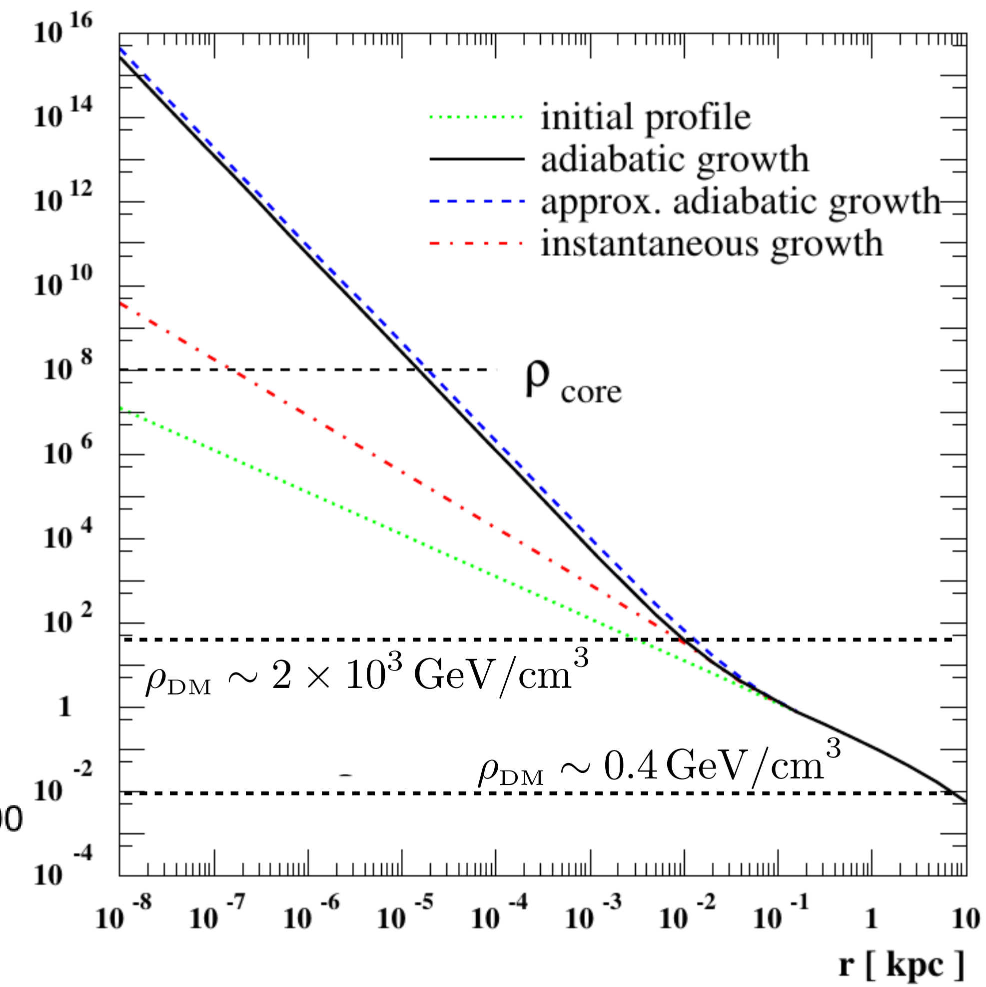

Navarro-Frenk-White profile

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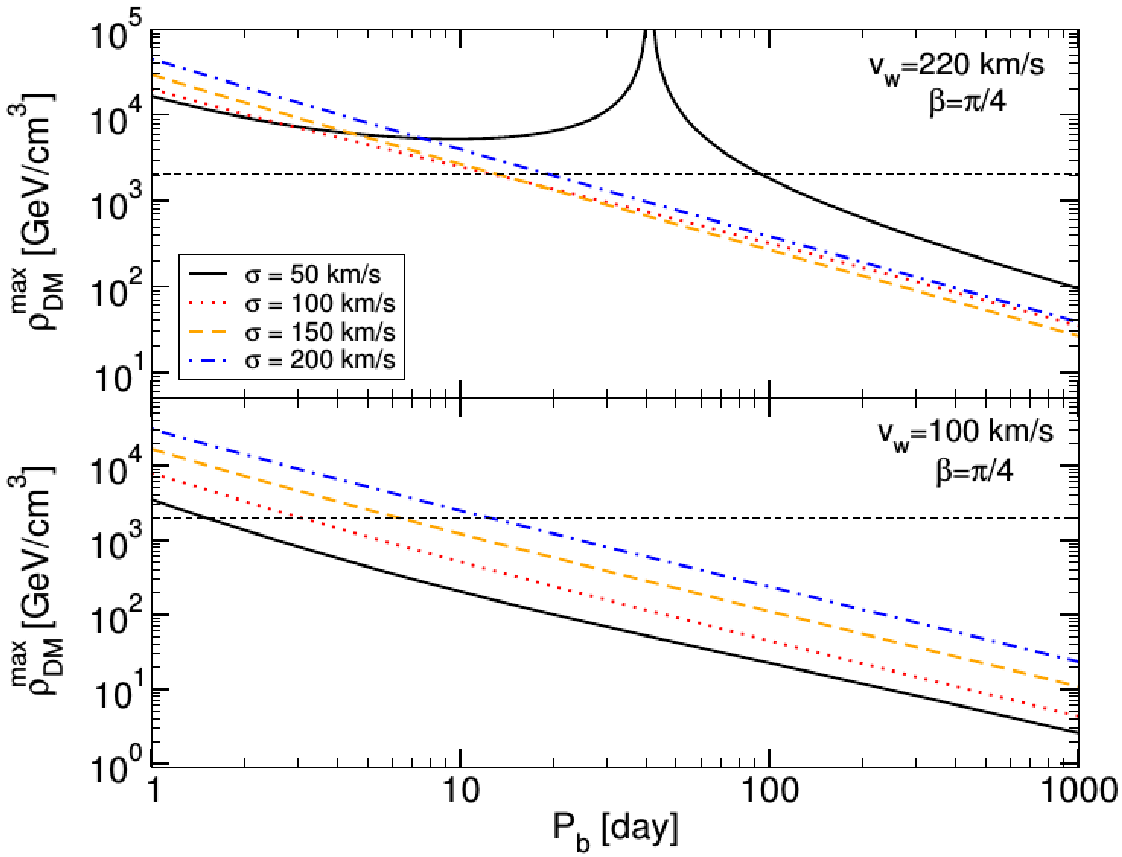
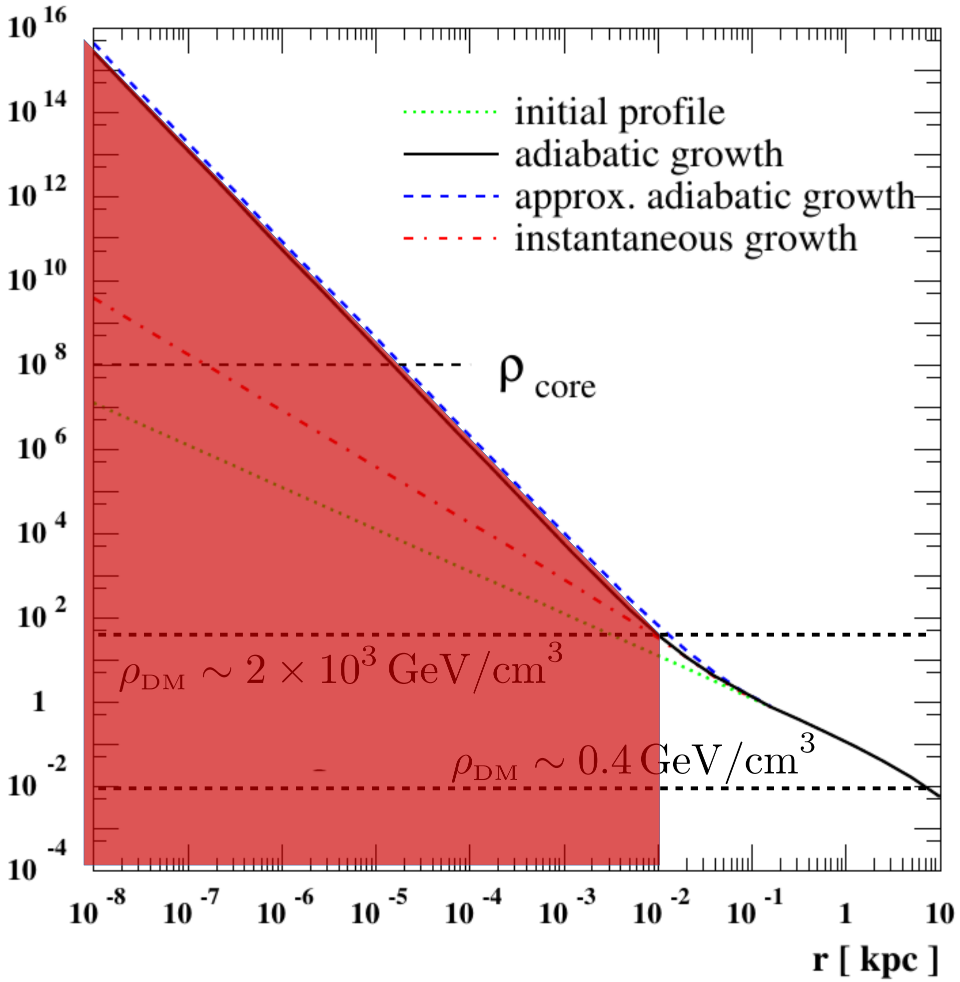




Navarro-Frenk-White profile

Bounds on local DM density

J1738+0333

$\langle \dot{P}_b^{\rm xs} \rangle \lesssim 2 \times 10^{-15}$ [Freire+, 2012]

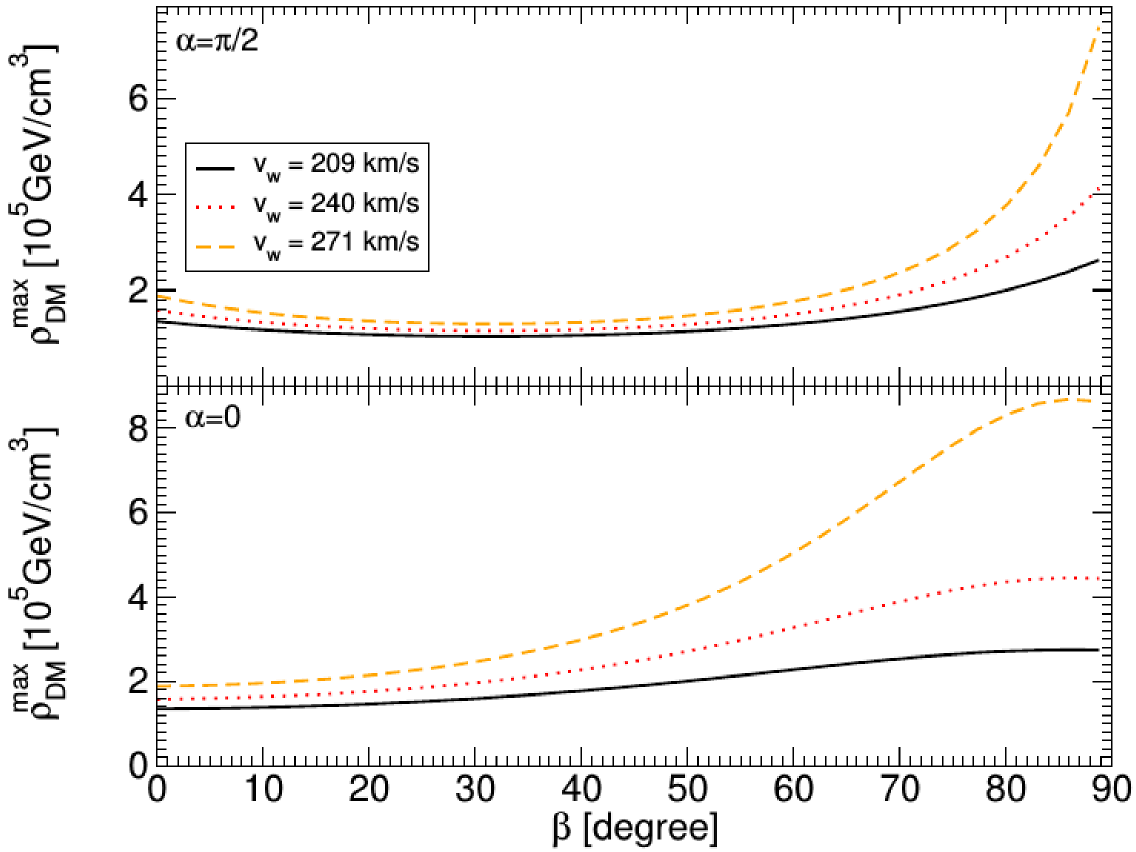
$P_b \sim 0.3547907398724(13)\,\text{day}$

J1713+0747

$\langle \dot{P}_b^{\rm xs} \rangle \lesssim 2 \times 10^{-13}$ [Zhu+, 2015]

$P_b \sim 67.82513682426(16)\,\text{day}$

$\dot{P}_b^{\rm GW} \approx -6 \times 10^{-18}$



Conclusions & work in progress

- Probing DM with binary pulsars *is* possible
- SKA will improve current bounds by 2 orders of magnitude
- Pulsars near SgrA*
  - constraints on DM profiles, DM spikes, clumps
  - Model independent
- Work in progress:
  - Accretion, eccentricity
  - Generic orbital period
  - DM interactions
  - Timing model (e.g. TEMPO)

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MARIE CURIE ACTIONS

IF INVESTIGADOR FCT

QUALIFICAR É CRESCER.