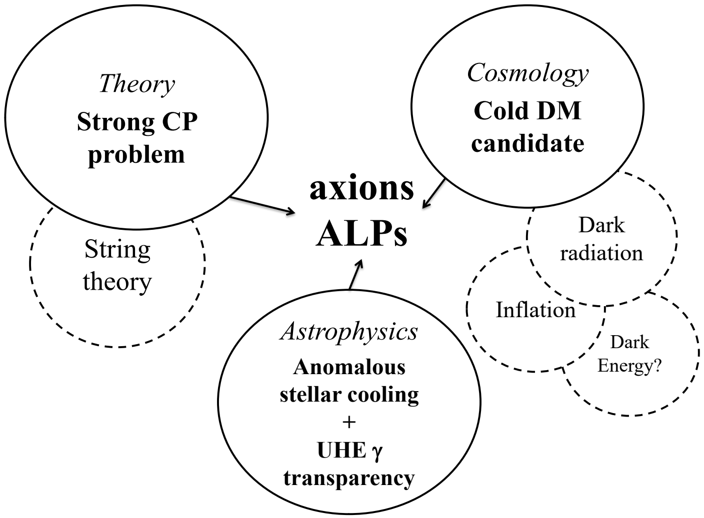
Supernovae & axions

Maurizio Giannotti,
Barry University

SN neutrinos at the crossroads:
astrophysics, oscillations, and detection
ECT, May 15, 2019

Axions



Most compelling solution of the Strong CP problem of the SM

Axion-like particles (ALPs) predicted by many extensions of the SM (e.g. string theory)

May solve the DM problem for free

–Transparency of the Universe to UHE gammas

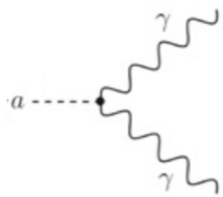
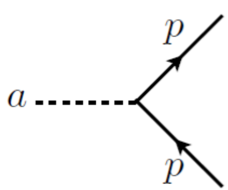
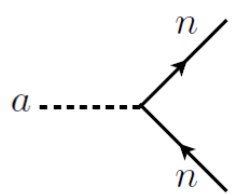
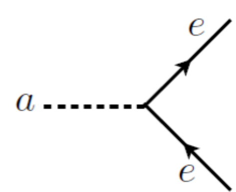
–Stellar anomalous cooling

Relevant parameter space at reach of current and near-future experiments

Experimental efforts growing fast

Axions

Axions interact with matter and photons.
Model dependence in the C_{ai} constants.

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			

$$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a} \qquad g_{ap} = C_{ap}\frac{m_p}{f_a} \qquad g_{ap} = C_{an}\frac{m_n}{f_a} \qquad g_{ap} = C_{ae}\frac{m_e}{f_a}$$

Axion mass

$$m_a = \frac{(5.70 \pm 0.07)\,\mu\mathrm{eV}}{f_a/10^{12}\,\mathrm{GeV}}$$

Grilli di Cortona et al., JHEP 1601 (2016)

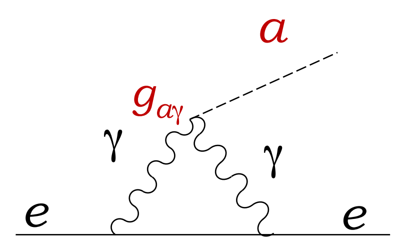
Benchmark QCD axion models

KSVZ (Hadronic):

$$C_{a\gamma} = \frac{E}{N} - 1.92$$

$$C_{ae} \simeq \frac{3\alpha^2}{2\pi}\left(\frac{E}{N}\ln\frac{f_a}{m_e} - 1.92\ln\frac{\Lambda}{m_e}\right) \approx 10^{-3}$$

$$C_{an} = -0.02(3) \qquad C_{ap} = -0.47(3)$$



Small coupling to electrons.
No coupling with neutron.
Photon coupling controlled by E/N

DFSZ:

$$C_{a\gamma} = \frac{8}{3} - 1.92 \qquad C_{ae} = \frac{1}{3}\sin^2\beta$$

$$C_{ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)$$

$$C_{an} = 0.414\sin^2\beta + (-0.16 \pm 0.025)$$

DFSZ: Two Higgs bosons.
Couplings controlled by:

$$\tan\beta = \frac{\langle H_u\rangle}{\langle H_d\rangle}$$

Grilli di Cortona et al., JHEP 1601 (2016)

Axion-Like Particles (ALPs)

More general pseudoscalar fields.

Couple to photons and fermions just like standard axions. However, there is no predefined mass-coupling relation.

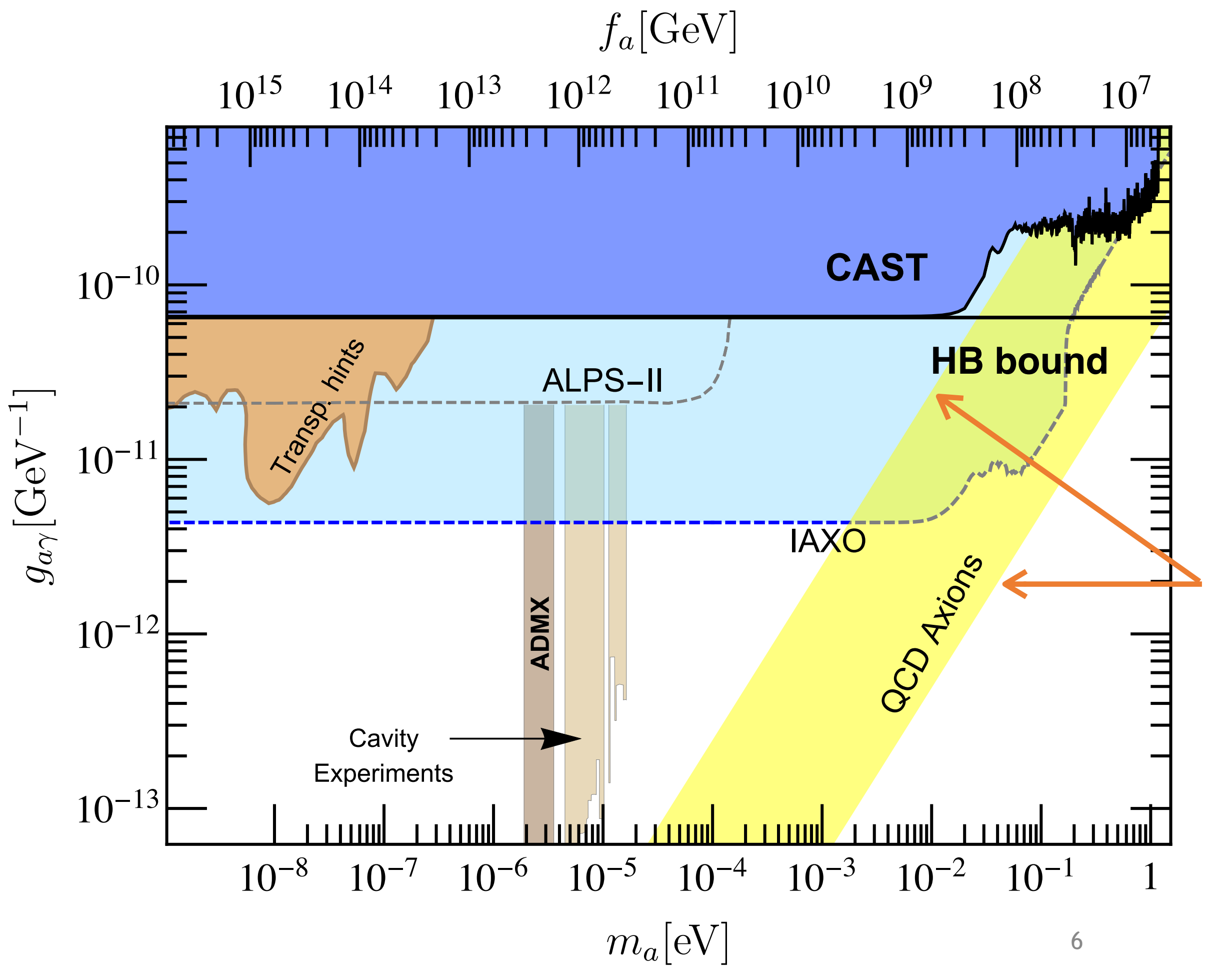
ALPs are an unavoidable prediction of several theories BSM, in particular those that predict extra dimensions.
ALPs may exist, whether or not PQ solves the strong CP!

Light ALPs have been invoked to explain various phenomenological anomalies, such as universe transparency, dark radiation, stellar cooling and inflation.

Axion Landscape

Strong motivations (and bounds) from astrophysics.

Reach experimental landscape



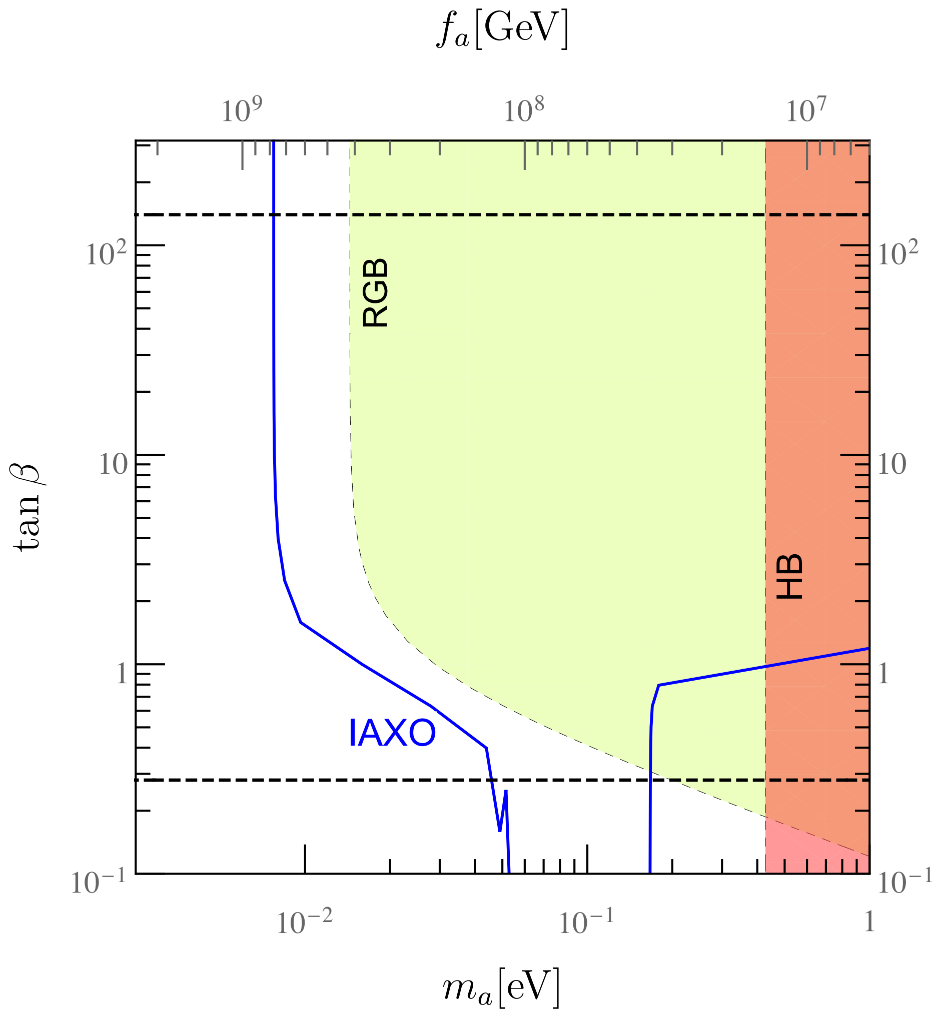
QCD axion band

Di Luzio, Mescia, Nardi,
Phys.Rev.Lett. 118 (2017),
Phys.Rev. D96 (2017)

Axion Landscape

Strong motivations (and bounds) from astrophysics.

Reach experimental landscape



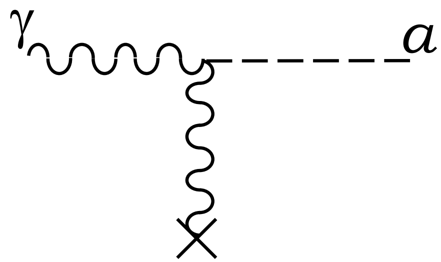
The coupling to electrons is parameterized by tan β

DFSZ axions

Supernova Axions/ALPs

Axions can be produced in a SN mainly through:

Primakoff process…

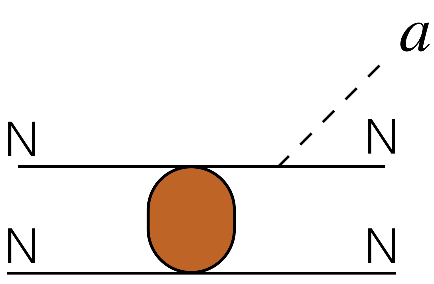


Interesting for ALPs coupled only to photons

… and nucleon bremsstrahlung process

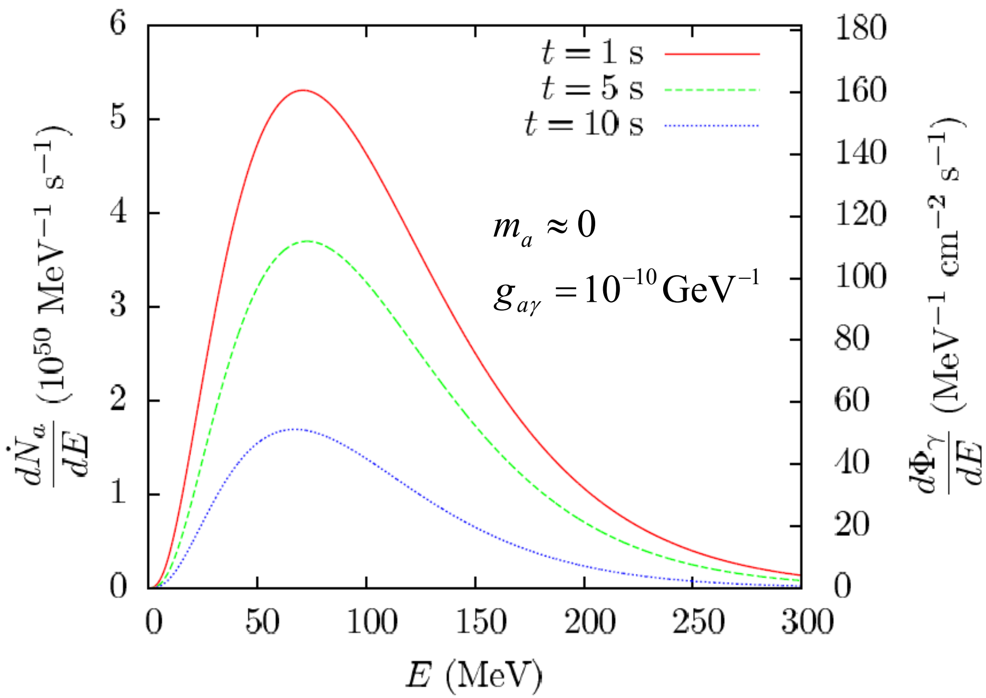
➡ *Talk by Guo Gang*

Calculated for neutrinos can also be applied to axions



Light Supernova ALPs

At the time of the SN1987A explosion, the Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) was operative.



SN axions convert into gamma photons in galactic B

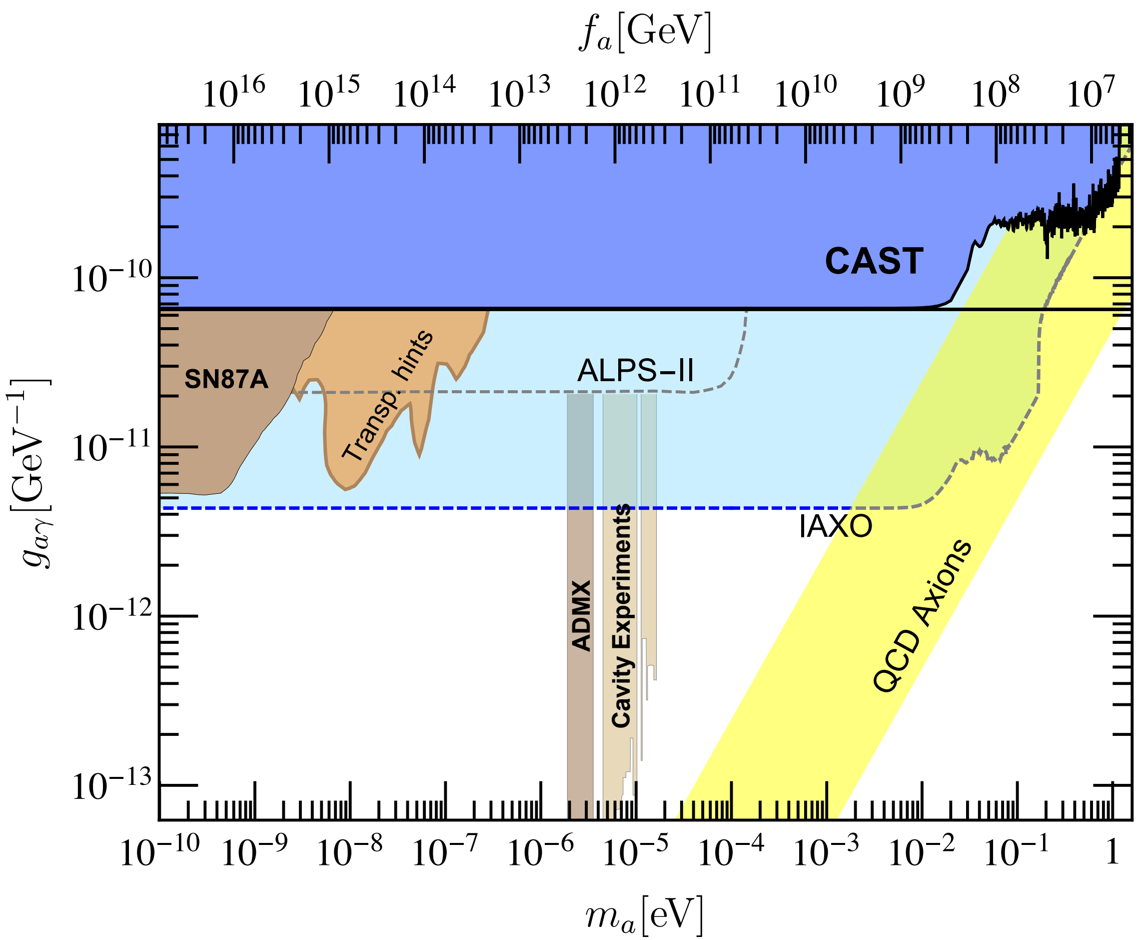
No photon excess at the time of the neutrino burst

→ Bound on axion-photon coupling

Several uncertainties related to the instrument which are not easily quantifiable.

Light Supernova ALPs

Very strong bound on the axion-photon coupling…



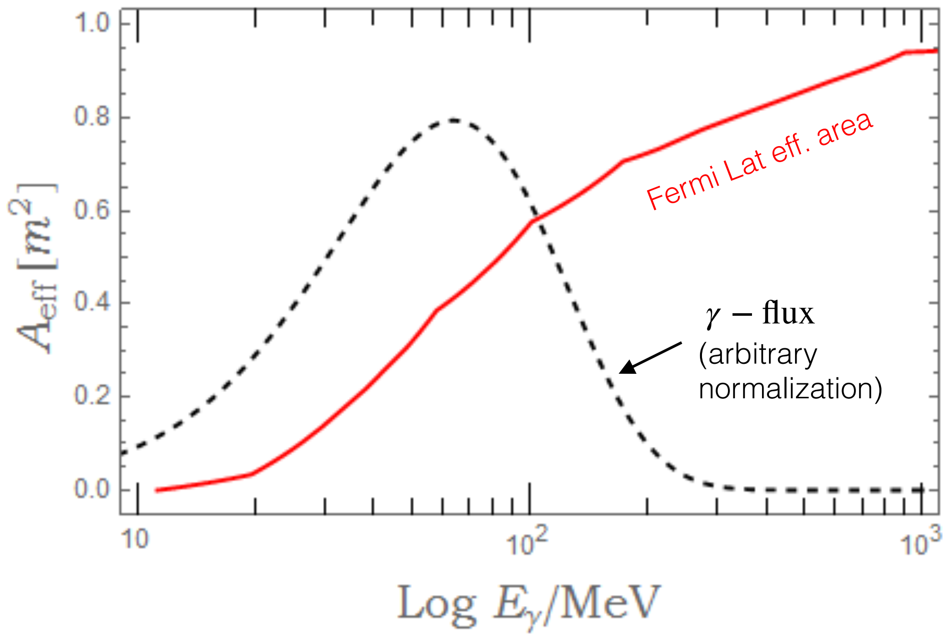
… however subject to several uncertainties not easily quantifiable.

J. Brockway, E. Carlson, G. Raffelt, Phys. Lett. B 383, 439 (1996);

J. Grifols, E. Masso, R. Toldra, Phys. Rev. Lett. 77, 2372 (1996)

A. Payez, C. Evoli, T. Fischer, M. G., A. Mirizzi, A. Ringwald, JCAP 1502 (2015).

Light Supernova ALPs: Fermi Potential



It is not ideal at the energies expected from the flux but it is the best we have

Fermi-LAT averaged over the expected SN spectrum 50 MeV<E<500 MeV

$$\langle A_{eff} \rangle \sim 5500\,\mathrm{cm}^2$$

GRS on the SMM, 10 MeV<E<100 MeV

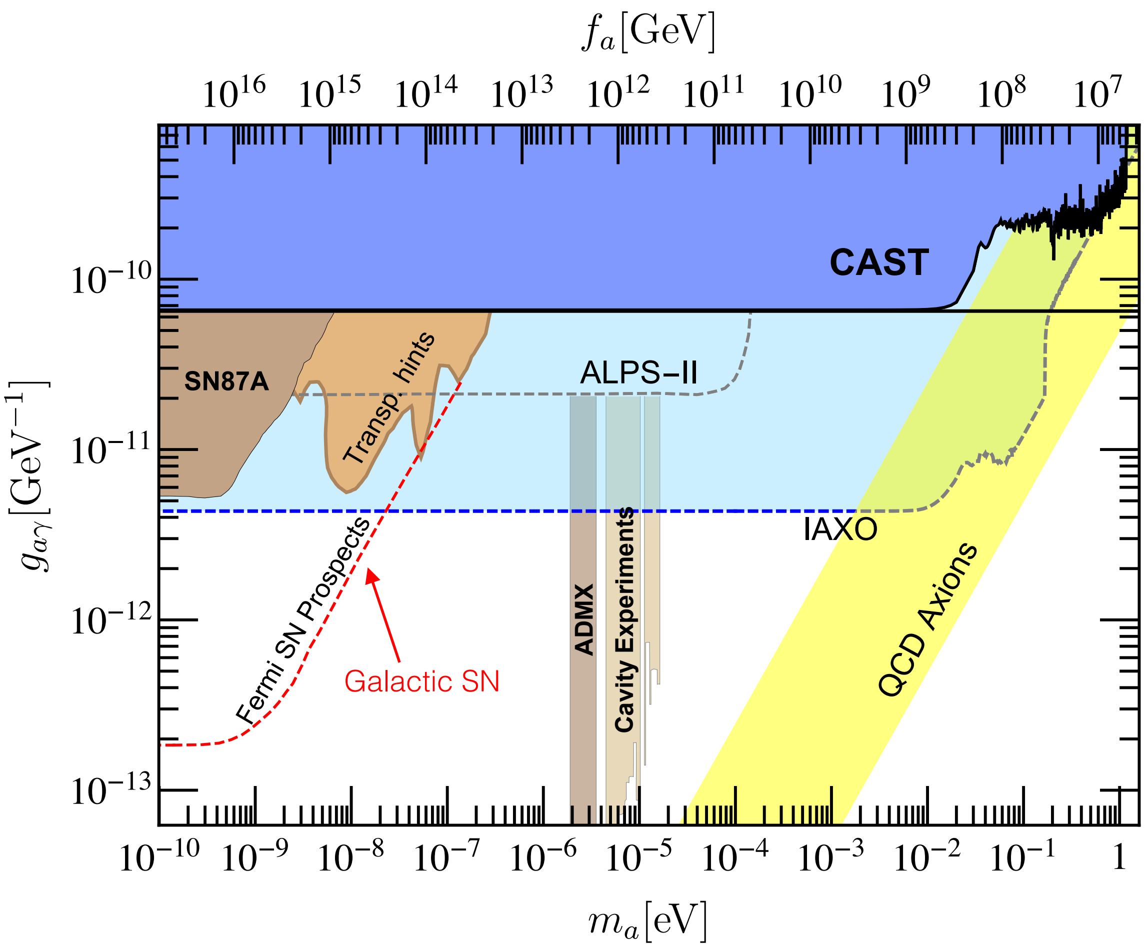
$$\langle A_{eff} \rangle < 100\,\mathrm{cm}^2$$

M. Meyer , M. G., A. Mirizzi, J. Conrad, M. A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

D. J. Forrest et. al., Solar Phys. 65, 15 (1980)

Light Supernova ALPs

One would do much better with the Fermi LAT



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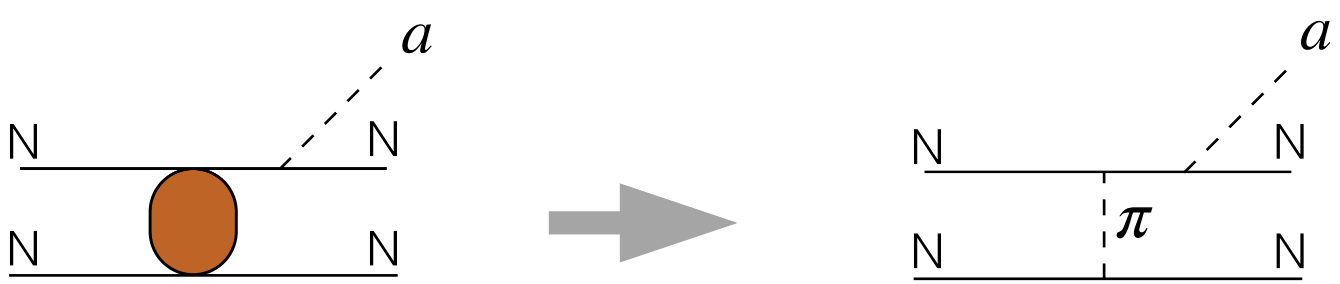
M. Meyer , M. G., A. Mirizzi, J. Conrad, M. A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

Nucleon-nucleon Bremsstrahlung

The bremsstrahlung is much more difficult;

Simplification: OPE, with massless pions

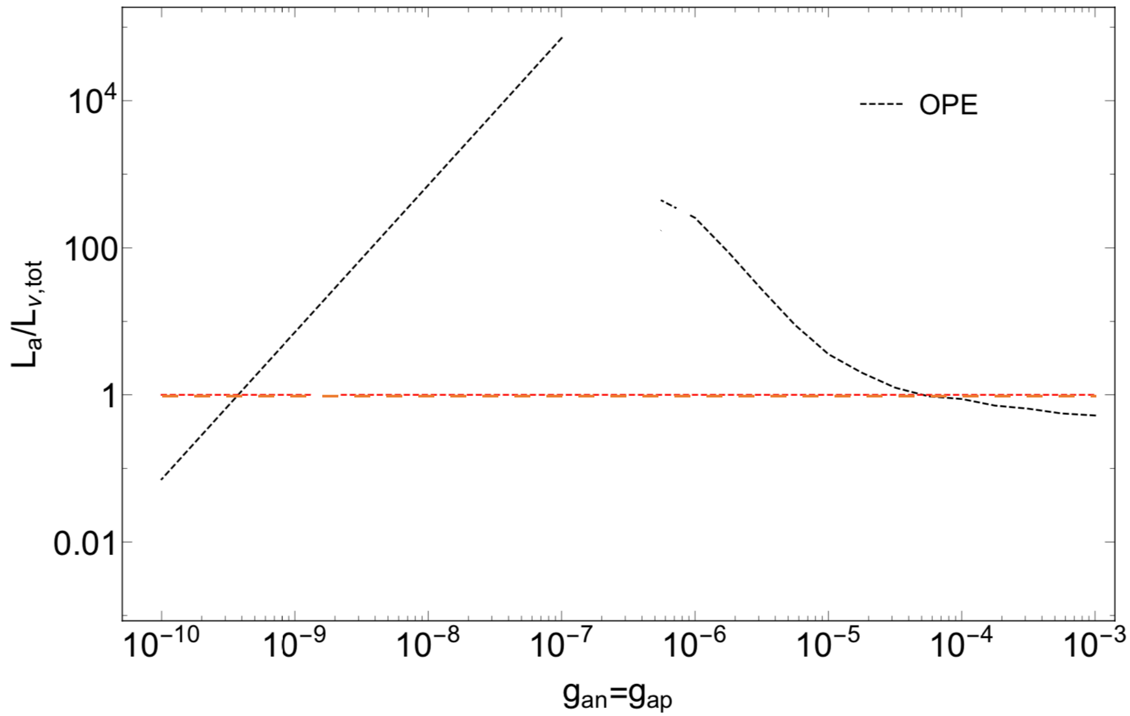


Ignores important effects but makes everything calculable:

The matrix element is constant and the axion energy loss can be expressed as a function of the axion couplings to nucleons

Nucleon-nucleon Bremsstrahlung

Axion production in OPE with equal coupling to neutrons and protons

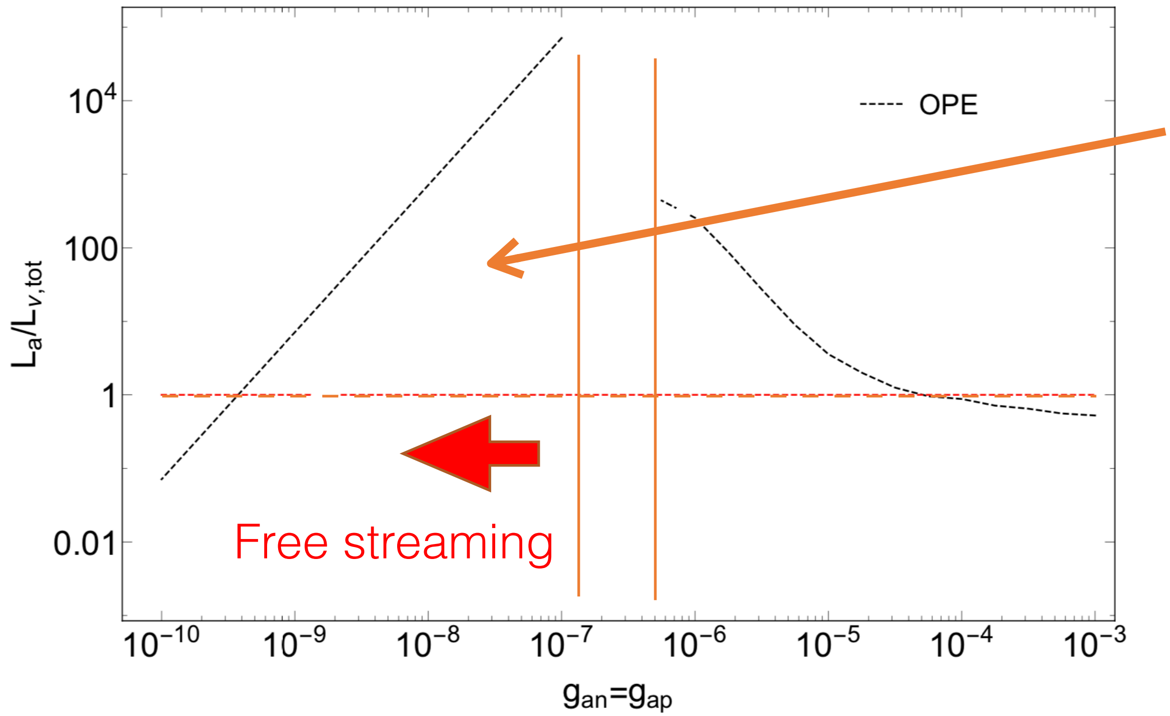


Model by T. Fischer

P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

Nucleon-nucleon Bremsstrahlung

Axion production in OPE with equal coupling to neutrons and protons



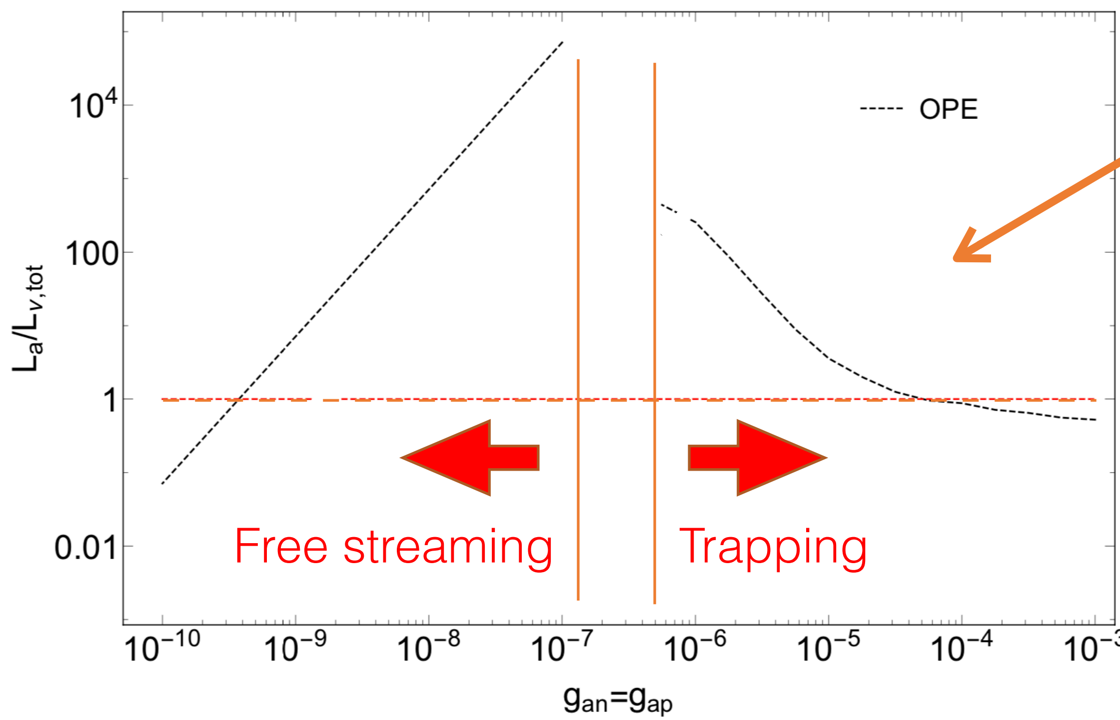
P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

In free streaming regime, axions are created in the SN core:

Very energetic (~100 MeV)

Nucleon-nucleon Bremsstrahlung

Axion production in OPE with equal coupling to neutrons and protons



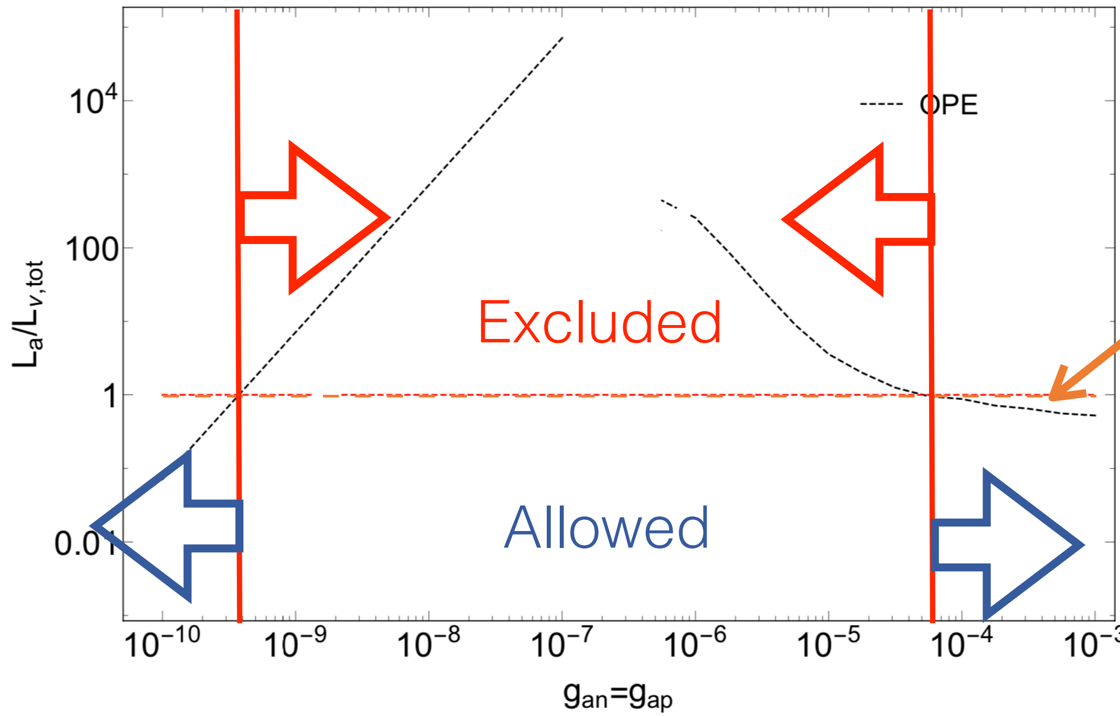
P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

Trapping regime: When strongly coupled, axions thermalize and are emitted from an axiosphere.

Energies similar to neutrinos, depending on the couplings

Nucleon-nucleon Bremsstrahlung

How many axions are too many axions?



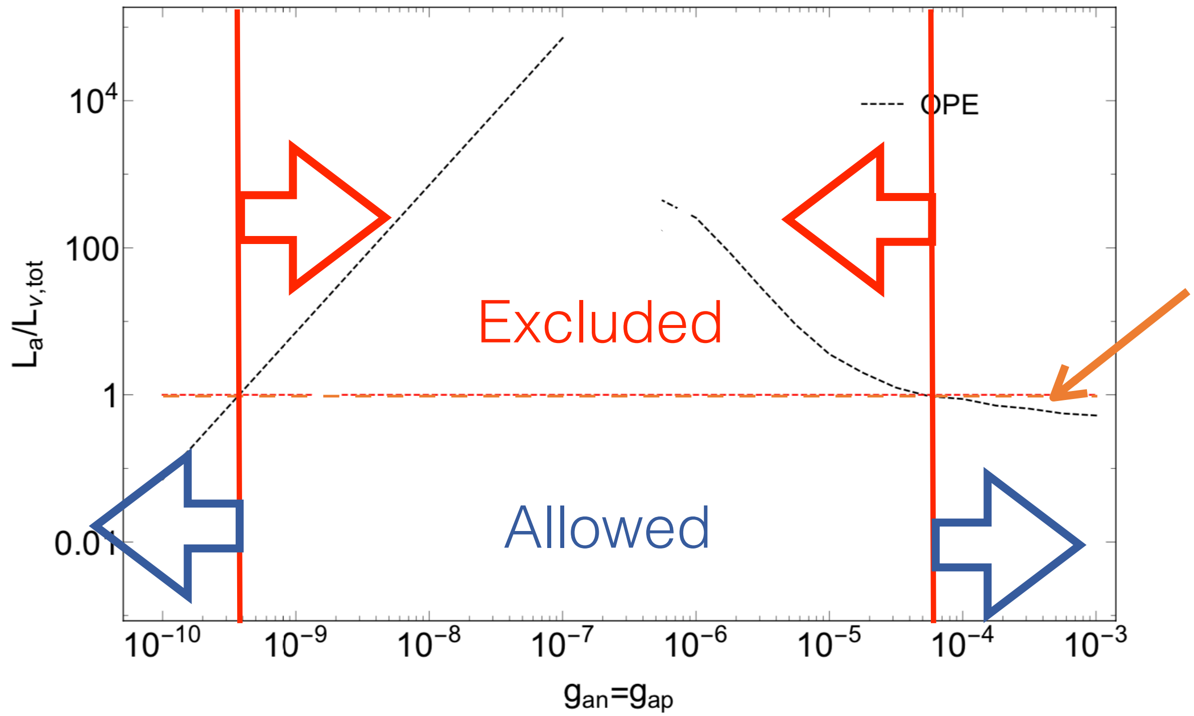
P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

Axions modify the observed neutrino signal.

$L_a < L_\nu$ is a reasonable indicator that axions are not influencing too much the observed signal from SN 1987A (*Raffelt Criterion*)

Nucleon-nucleon Bremsstrahlung

How many axions are too many axions?



P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

However, there is another bound.

For certain couplings, axions in the safe trapped region could still have been detected by the neutrino detectors that saw the neutrino signal. These ranges are excluded, leaving only a small region of couplings known as the hadronic axion window

J. Engel, D. Seckel, A. C. Hayes (1990)

Corrections to OPE

The picture discussed is perhaps too simple:

Chang, Essig, McDermott (2018);

Carenza, Fischer, M.G., Mirizzi (2019)

It ignores:

- Pion mass: important for T<10 MeV
- Higher order corrections: we implement these in terms of the two pion exchange. They are important at short distances. Can contribute up to 35% in certain regions

  Hannestad, Raffelt (1998)

- Plasma effects: example, corrections to nucleon mass. Very important at high density.

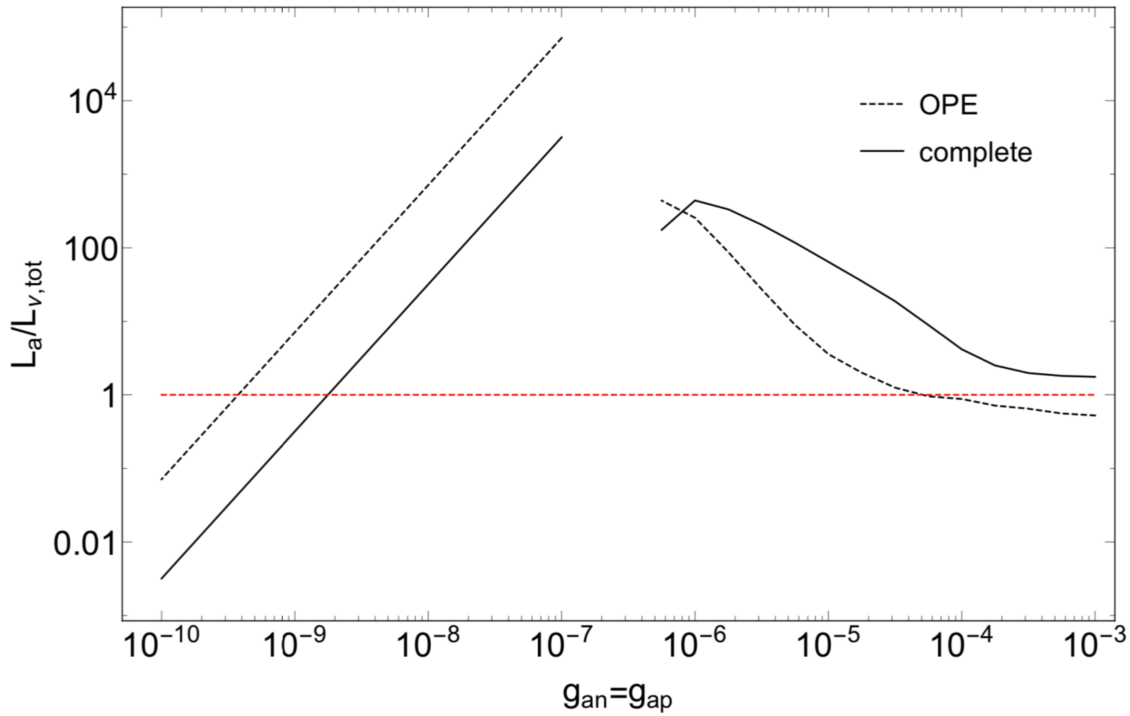
  Steiner, Hempel, Fischer (2013)

- Degeneracy effects
- Many body effects: frequent collisions imply uncertainty in the energy and a finite width of the structure functions.

  Raffelt-Seckel (1995)

Corrections to OPE

The corrections to OPE are quite large.



P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

There is a long history of attempts to correct OPE.

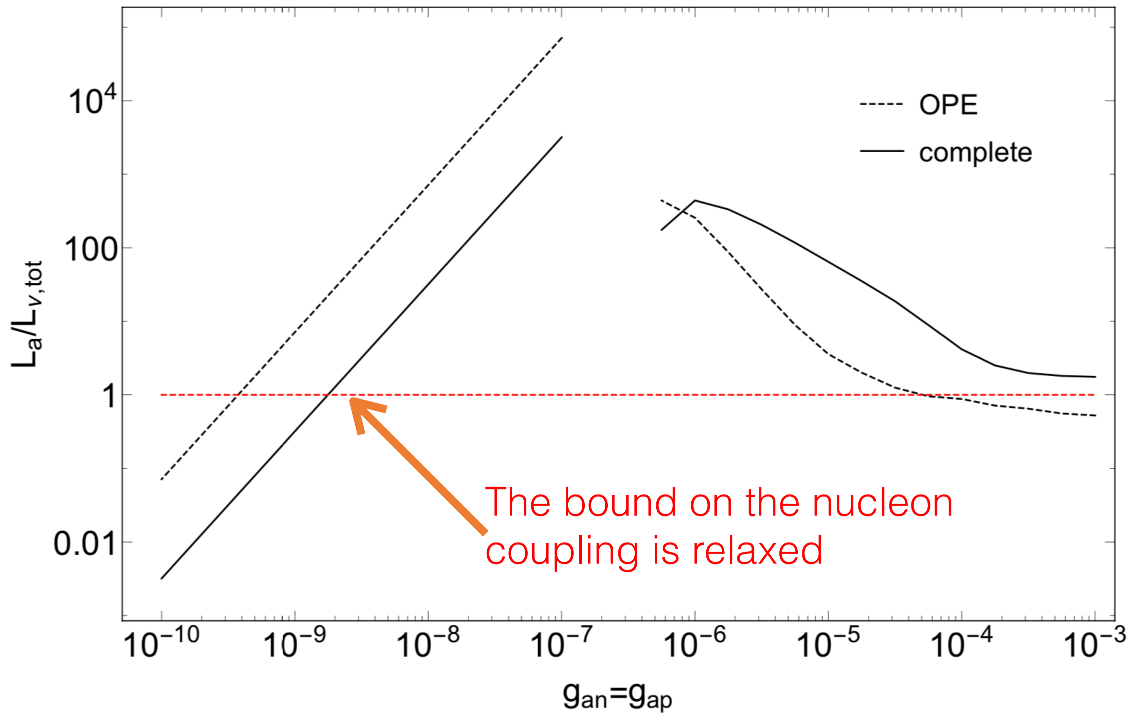
C. Hanhart, D. R. Phillips, S. Reddy (2001)

Chang, Essig, McDermott (2018);

Perhaps use T-matrix approach: See talk by Guo Gang.

Corrections to OPE

The corrections to OPE are quite large.



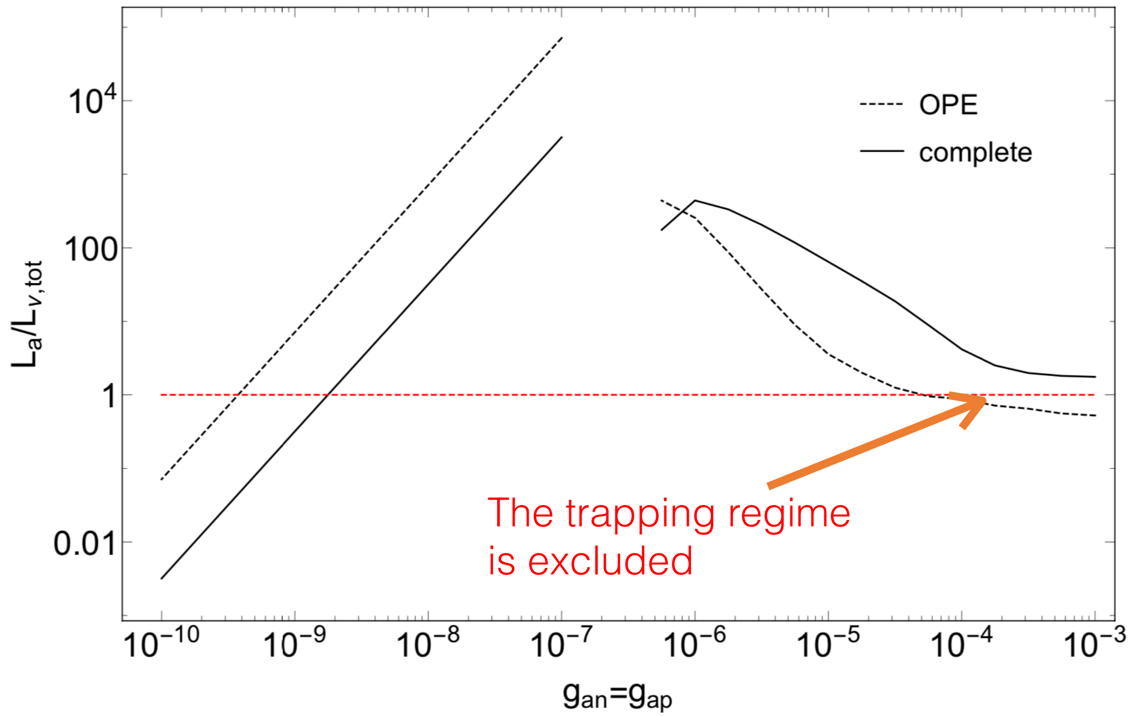
P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

The corrections to OPE are quite large.

Relaxation of the axion nucleon coupling, with important consequences for experiments.

Corrections to OPE

The corrections to OPE are quite large.



P. L. Carenza, T. Fischer, M.G., A. Mirizzi (2019)

The corrections to OPE are quite large.

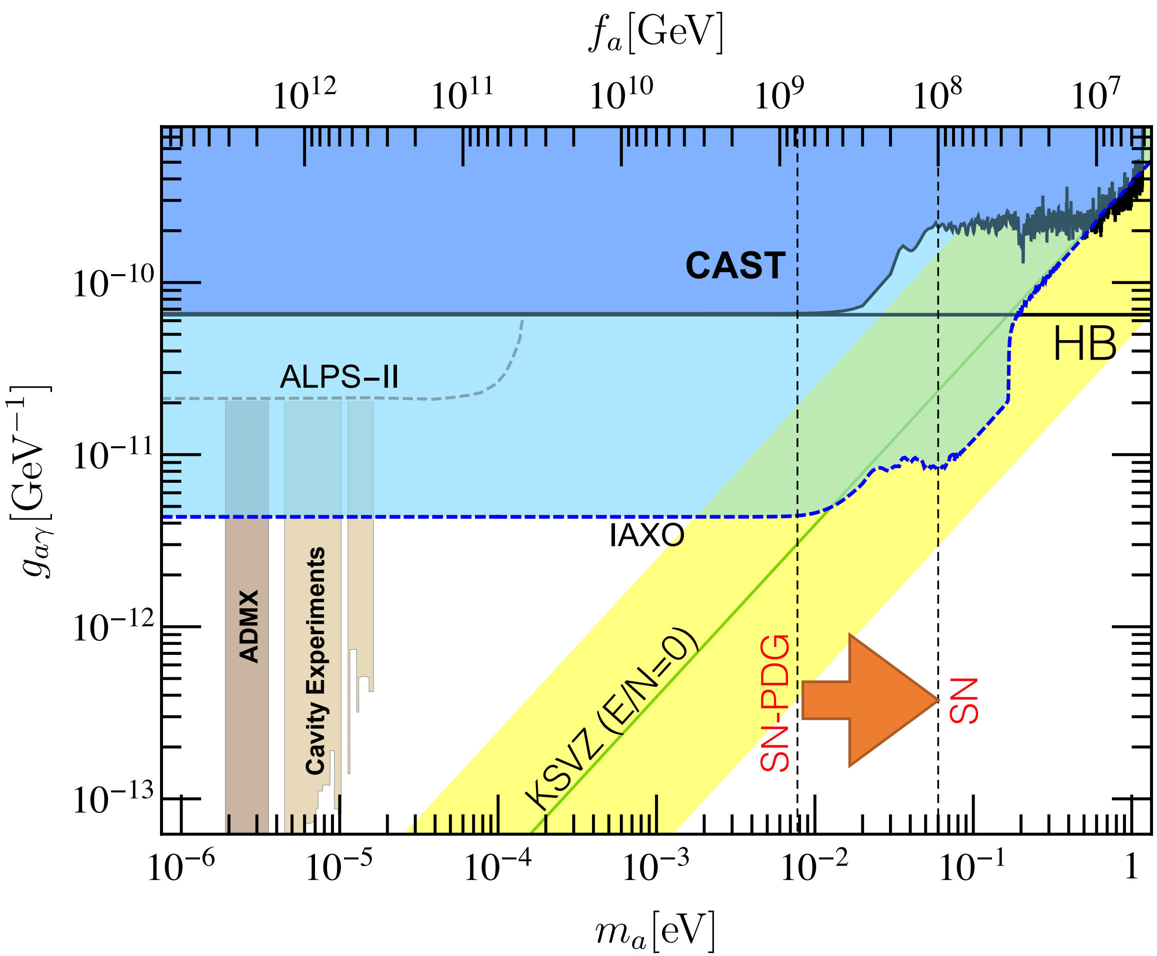
Further confirmation that the hadronic axion window is forbidden

S. Hannestad, A. Mirizzi, G. Raffelt (2005);

Chang, Essig, McDermott (2018);

Experimental Consequences

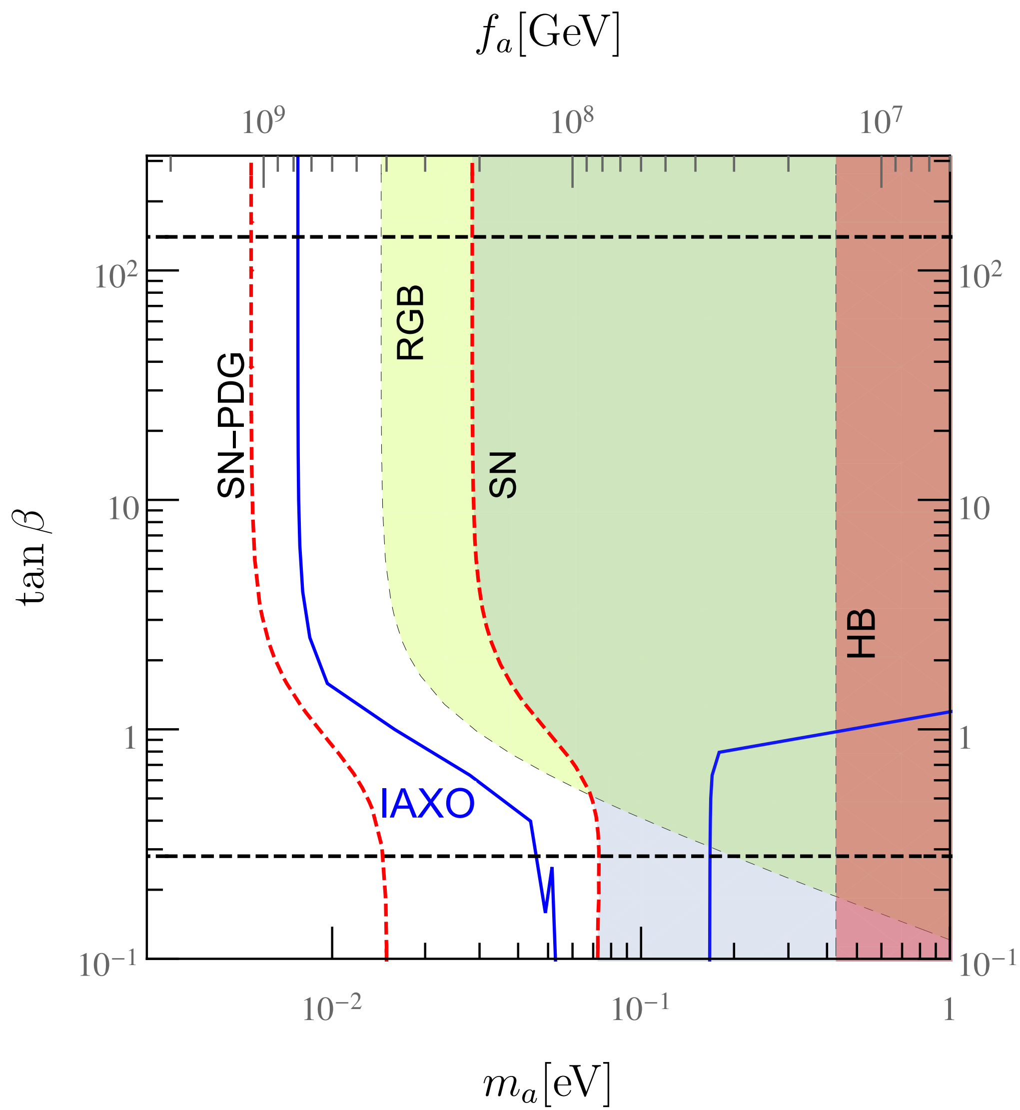
Hadronic Axions



The experimental potential for KSVZ axion opens up considerable!

IAXO has access to reference KSVZ model, for E/N=0

Experimental Consequences



DFSZ Axion

A large part of the DFSZ axion is accessible to IAXO, once the corrections to OPE are taken into account.

Conclusions

- SNe are powerful labs to constraint axions and ALPs.

- The current bound on the axion-photon coupling for low mass ALPs is very strong but subject to uncertainties. Fermi LAT has a great potential in case of a new galactic SN

- Nuclear bremsstrahlung in a SN can limit strongly the possible axion-nucleon coupling, however, not as strongly as once thought. The new study opens up considerably the experimental potential

- The future: compare different computational strategies beyond OPE and account for the axion feedback on the star (in preparation)

Thanks

Strong CP-problem

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\Psi}M\Psi - \frac{\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta + Arg\,\det M$$

Observable consequence:
neutron electric dipole moment

Crewther, Vecchia,
Veneziano, Witten(1979)

$$D_n \sim \bar{\theta}\cdot 3.6\cdot 10^{-16}\,\mathrm{cm}$$

$$|D_n| < 3.0\cdot 10^{-26}\,\mathrm{cm} \Longrightarrow \bar{\theta} \lesssim 10^{-10}$$

J. M. Pendlebury et al., Phys.Rev. D92 (2015)

Extremely accurate cancellations of two apparently completely independent terms.

PQ mechanism and axions

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\Psi}M\Psi - \frac{\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta + Arg\,\det M$$

Promote $\bar{\theta}$ to be a field: the axion a

Peccei and Quinn (1977)

with an approximate symmetry

$a \to a + cf_a$

Weinberg (1978)
Wilczek (1978)

broken by an interaction with the gluon field

$\frac{a}{f_a}\frac{\alpha_s}{8\pi}aG\tilde{G}$

The axion field absorbs the term and relaxes to zero

PQ mechanism and axions

Very elegant (natural) solution of the strong CP problem. The Vafa-Witten theorem* assures the solution of the strong CP problem in QCD if we add to the theory a spin-0 field with a shift symmetry

Peccei and Quinn (1977)

$$a \to a + c f_a$$

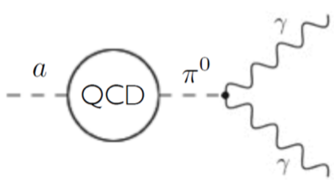
broken by an interaction with the gluon field

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi} a G\tilde{G}$$

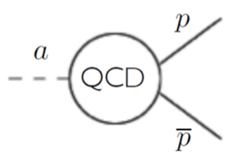
Weinberg (1978)
Wilczek (1978)

Predicts very precise (calculable) couplings to photons, and fermions:

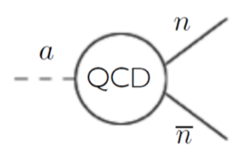
$C_\gamma = -1.92(4)$



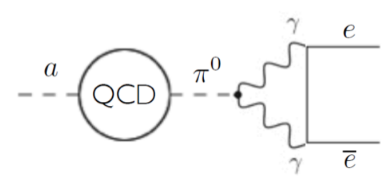
$C_p = -0.47(3)$



$C_n = -0.02(3)$



$C_e \simeq 0$



Strictly true if we ignore other contribution of the CP violation in the standard model.

Axion Astrophysics

If axions exist they would contribute to stellar evolution. Several strong bounds on axions are derived by stellar evolution.

Stellar system	Bound
RGB stars	$g_{ae} \leq 4.3 \times 10^{-13}$
WDs	$g_{ae} \leq (3-4) \times 10^{-13}$
HB stars	$g_{a\gamma} \leq 0.65 \times 10^{-10}\,\mathrm{GeV}^{-1}$
SN 1987A (KSVZ)	$g_{ap} \leq 6 \times 10^{-10}$

PQ mechanism and axions

UV completion affects low energy properties, generating additional *model-dependent* contributions to the axion couplings to matter

Benchmark models are KSVZ and DFSZ axions

$\mathrm{U}(1)_{PQ} \times \mathrm{SM}$

SM fermions | BSM fermions

2Higgs | 2Higgs+Singlet | Higgs+Singlet

PQWW | DFSZ | KSVZ

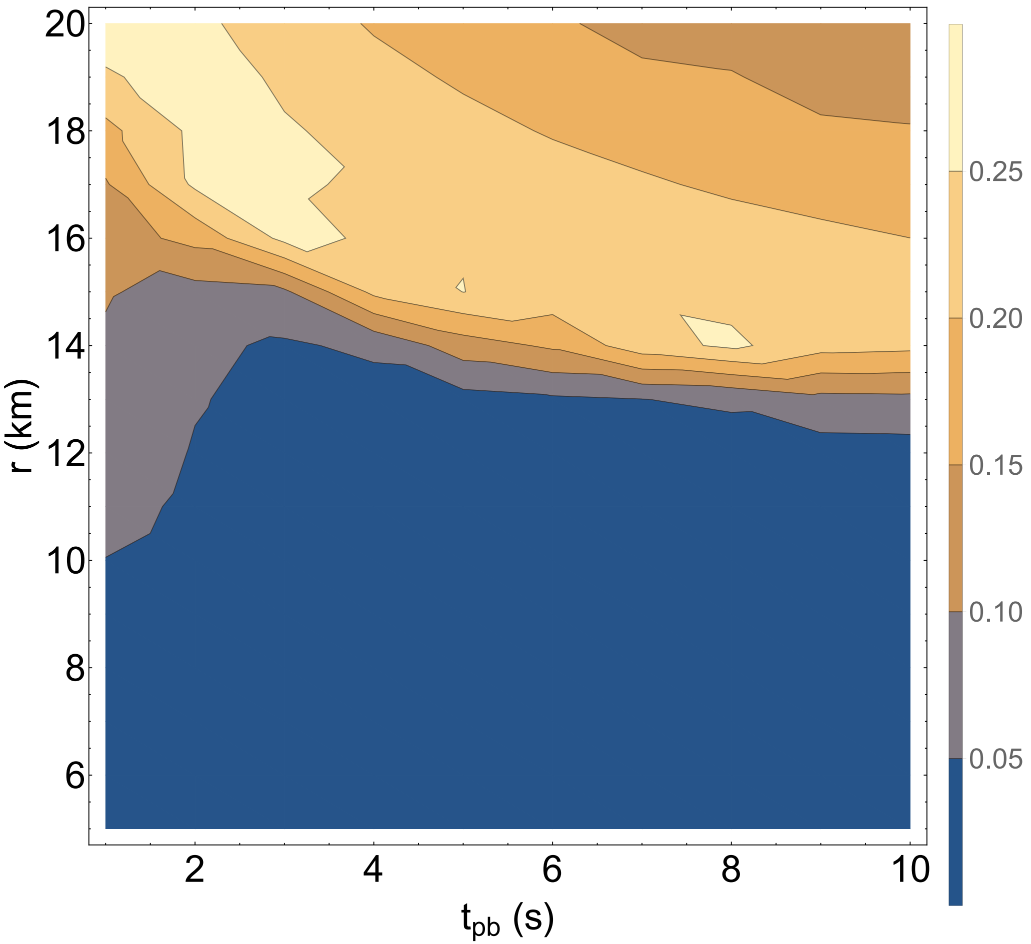
[Peccei, Quinn '77, Weinberg '78, Wilczek '78] | [Zhitnitsky '80, Dine, Fischler, Srednicki '81] | [Kim '79, Shifman, Vainshtein, Zakharov '80]

Ruled out

Other models: SMASH, Nucleophobic, etc.

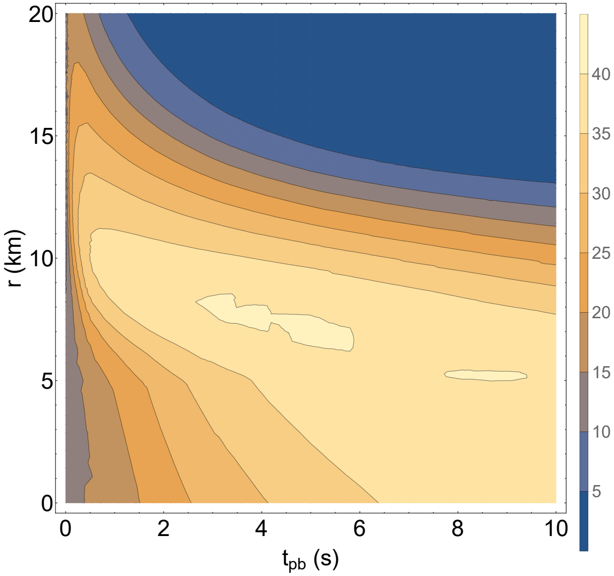
Diagram credits: L. Di Luzio, IAXO meeting, CERN 2019

Corrections to OPE

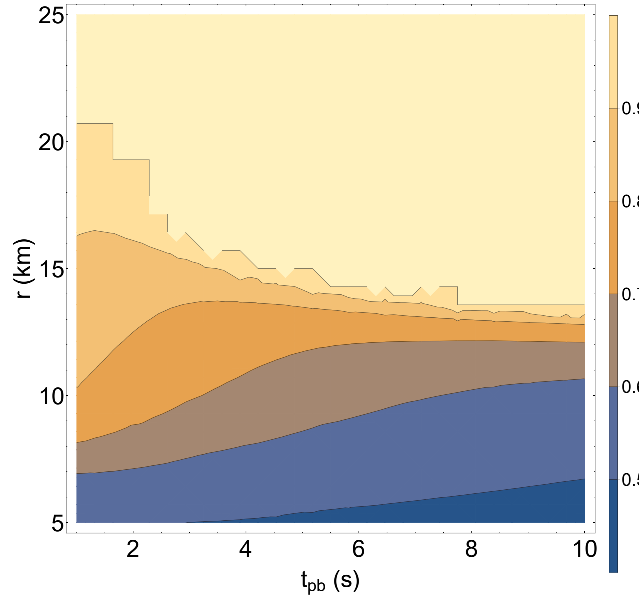


The corrections are quite important, especially within a radius of 10-12 km, where we expect most free streaming axions to be produced

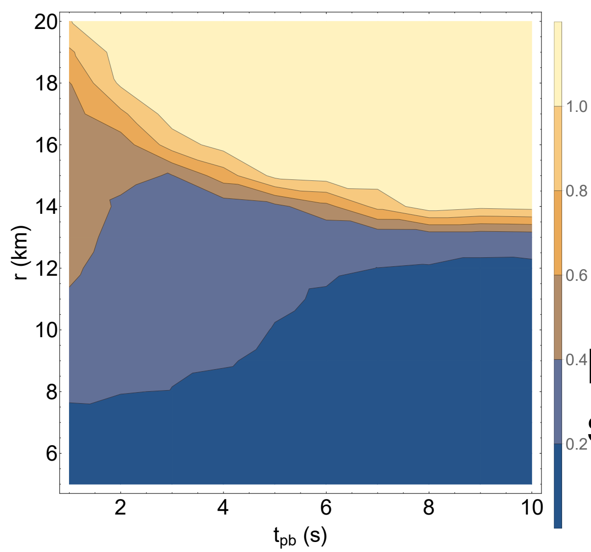
Corrections to OPE



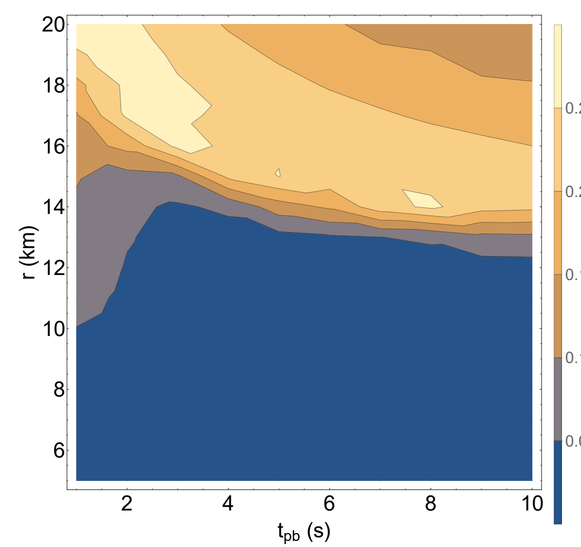
Temperature



correction to nucleon mass



Multiple nucleon scattering



Includes all corrections