SEARCH FOR AXION-LIKE PARTICLE INDUCED γ-RAY BURSTS FROM CORE COLLAPSE SUPERNOVAE WITH THE FERMI-LAT

[PRL, VOL. 124, 23, 231101 (2020), ARXIV:2006.06722]

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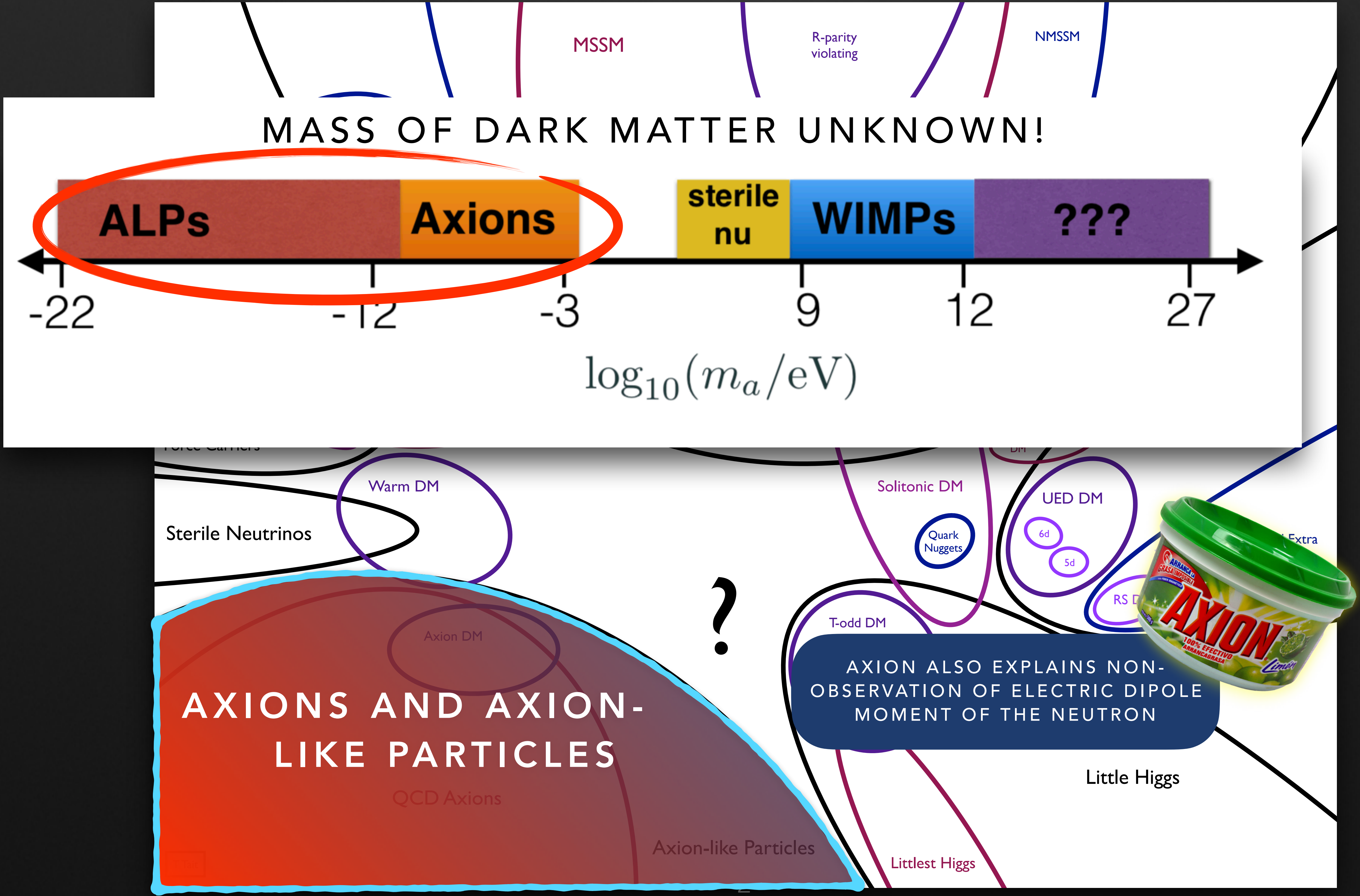
WHAT IS THE PARTICLE NATURE OF DARK MATTER?



MASS OF DARK MATTER UNKNOWN!

AXIONS AND AXION-LIKE PARTICLES

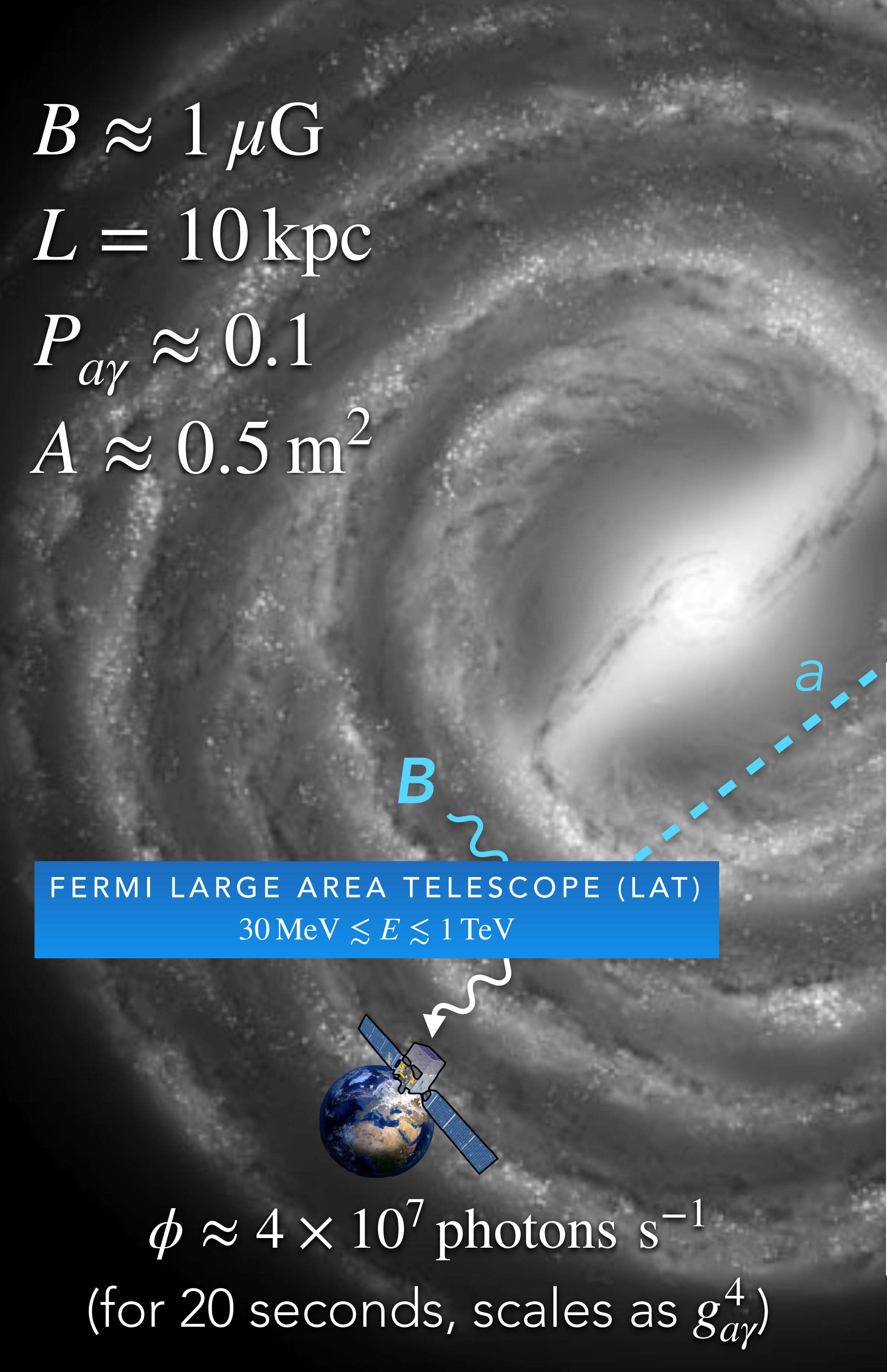
AXION ALSO EXPLAINS NON-OBSERVATION OF ELECTRIC DIPOLE MOMENT OF THE NEUTRON

$B \approx 1\,\mu\mathrm{G}$

$L = 10\,\mathrm{kpc}$

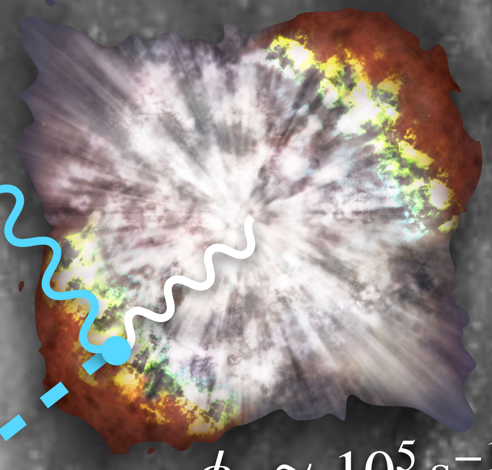
$P_{a\gamma} \approx 0.1$

$A \approx 0.5\,\mathrm{m}^2$

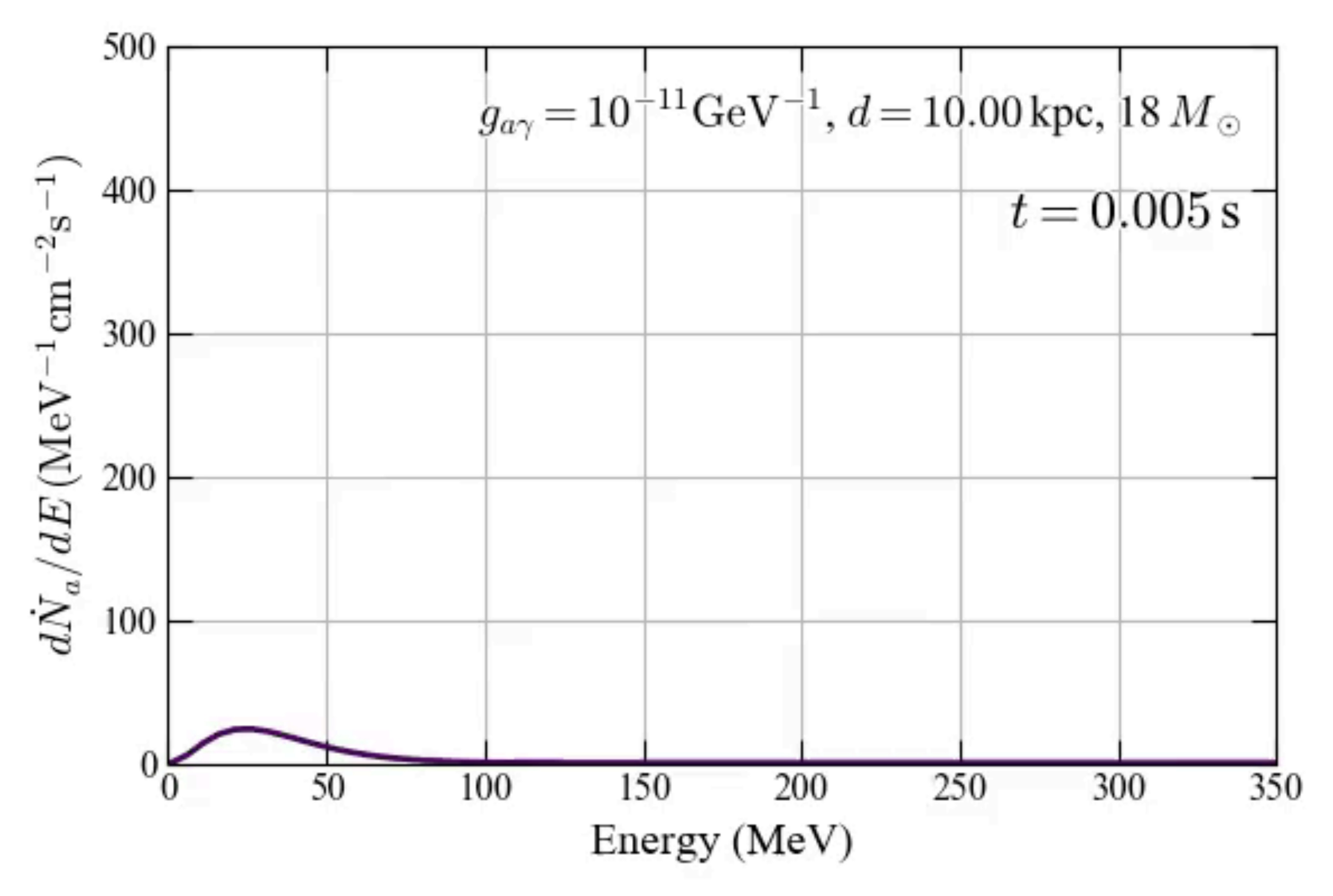


FERMI LARGE AREA TELESCOPE (LAT)

$30\,\mathrm{MeV} \lesssim E \lesssim 1\,\mathrm{TeV}$



$\phi_a \approx 10^5\,\mathrm{s}^{-1}\mathrm{cm}^{-2}(g_{a\gamma}/2\times10^{-11}\,\mathrm{GeV}^{-1})^2$



$\phi \approx 4\times10^7$ photons s^{-1}

(for 20 seconds, scales as $g_{a\gamma}^4$)

[MM et al. 2017]

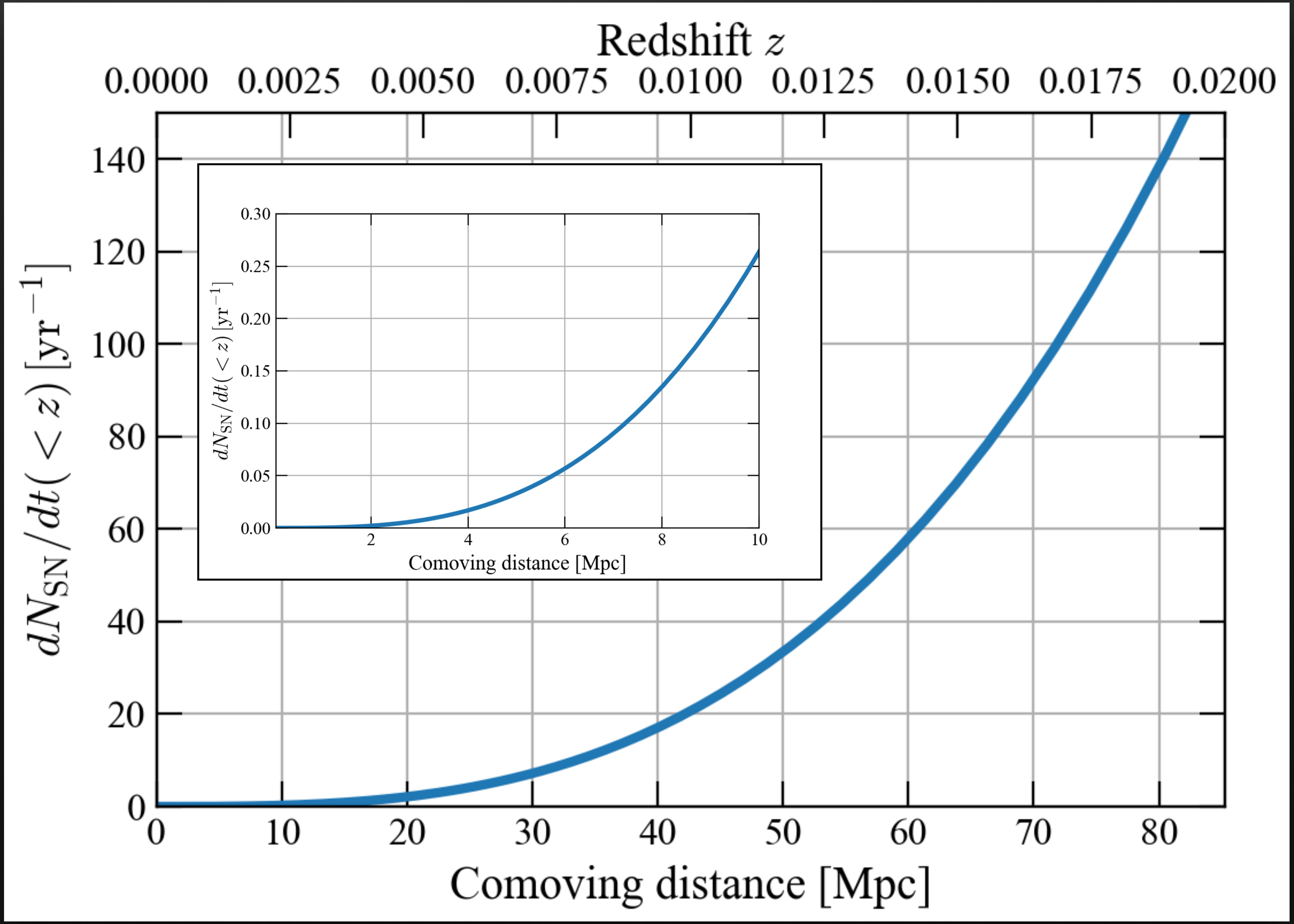
CORE COLLAPSE SN RATE IN MILKY WAY ~ 3% PER YEAR

LAT OBSERVERS ~20% OF THE SKY

→ 2% CHANCE TO CATCH AT LEAST ONE SUCH EVENT IF LAT OPERATES FOR 3 MORE YEARS

LOOK FOR EXTRAGALACTIC SUPERNOVAE INSTEAD

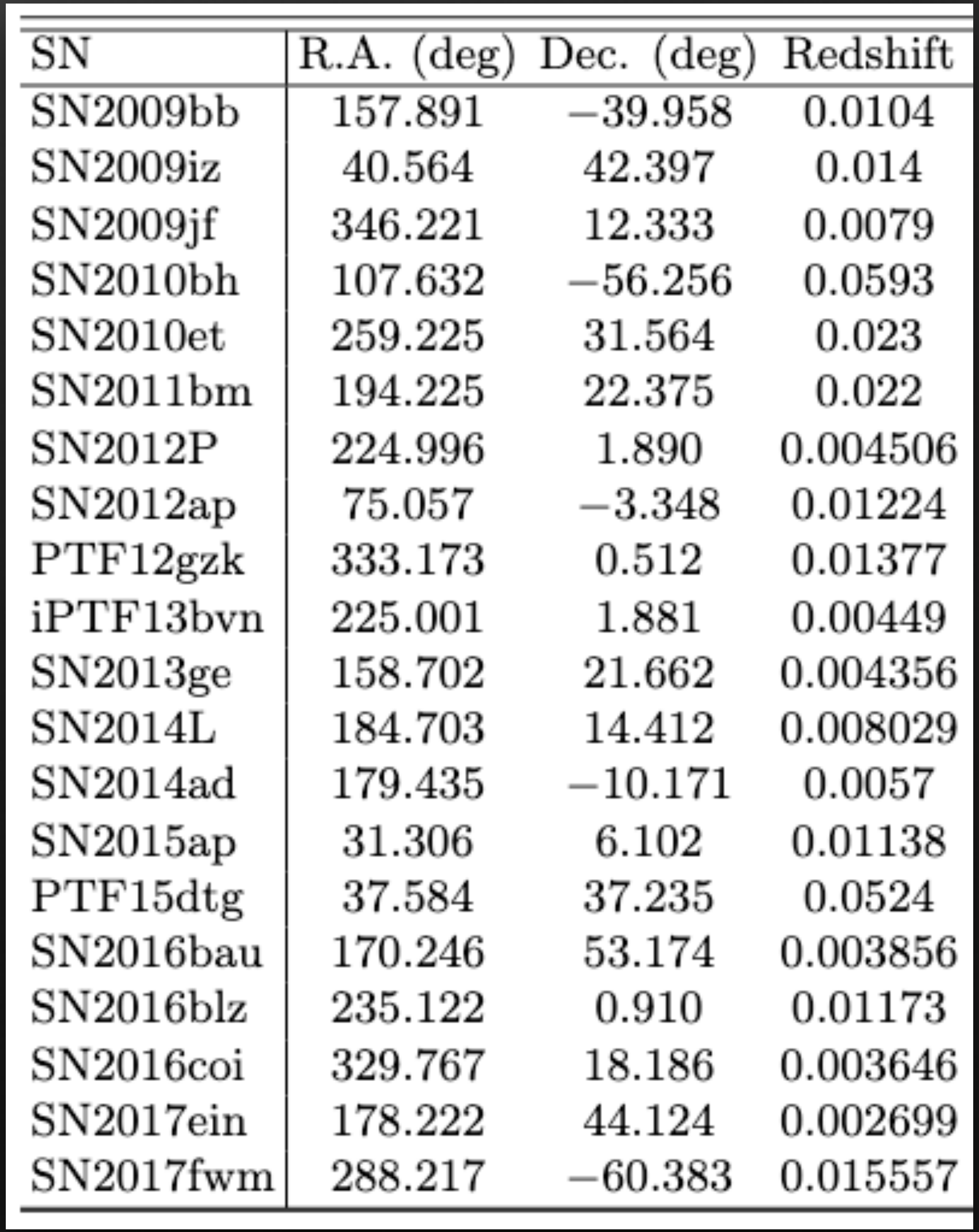
- But **no neutrino signal!**
- Use **optical light** curves to estimate explosion times
  [e.g. Cowen et al. 2010]
- Possible with light curves from **surveys** such as **ASAS-SN, iPTF, ZTF, TESS Satellite, Rubin Observatory**



Lien & Fields 2009

OPTICAL SN SAMPLE

- Data from open supernova catalog www.sne.space [Guillochon et al. 2018]
- Core collapse SN of type Ib/c (predicted short delay between core collapse and optical emission)
- Closer than $z \lesssim 0.05$ with well sampled light curve
- Detected after Fermi launch
- Gives 20 SNe until 2018

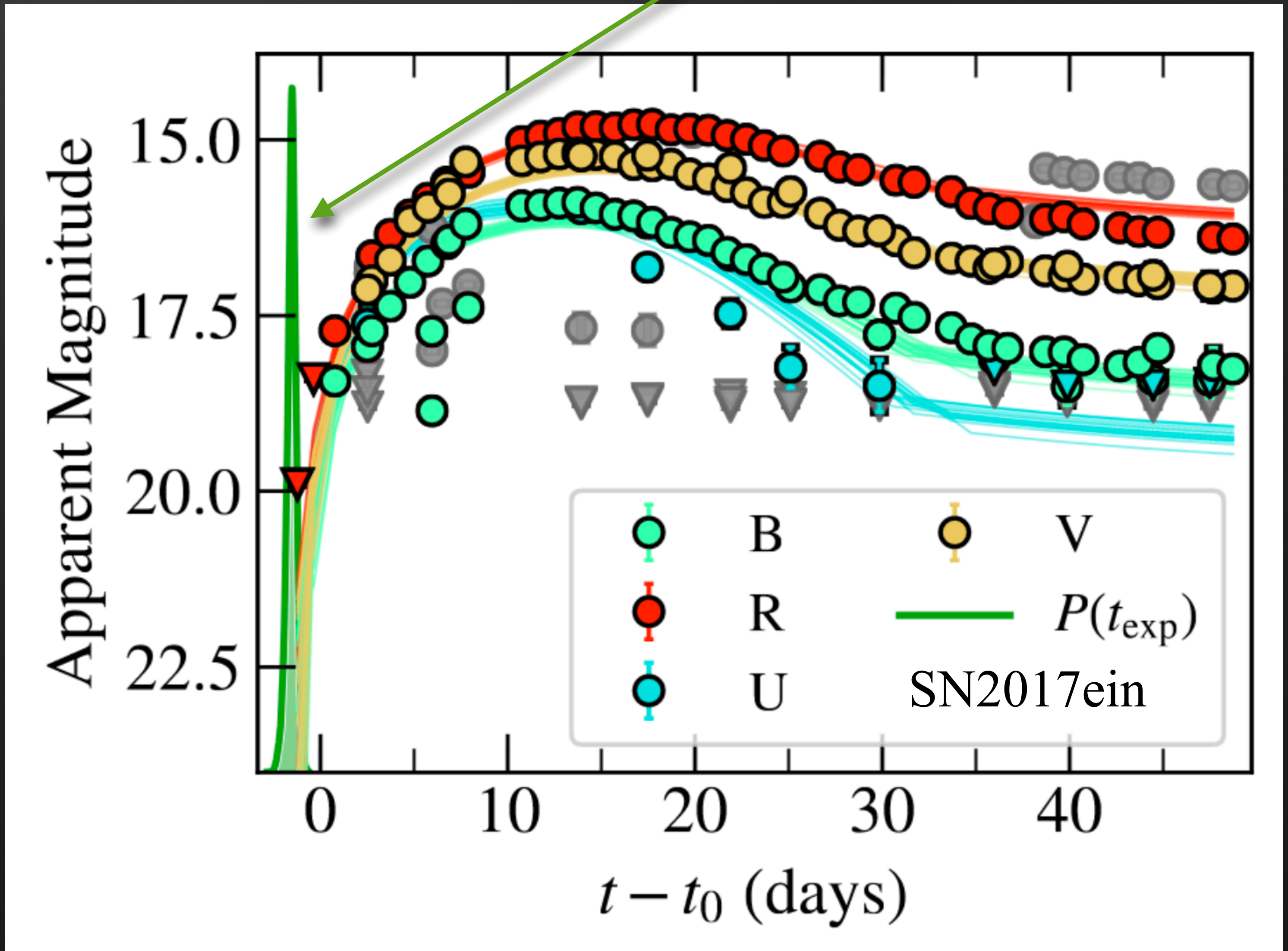


SN	R.A. (deg)	Dec. (deg)	Redshift
SN2009bb	157.891	−39.958	0.0104
SN2009iz	40.564	42.397	0.014
SN2009jf	346.221	12.333	0.0079
SN2010bh	107.632	−56.256	0.0593
SN2010et	259.225	31.564	0.023
SN2011bm	194.225	22.375	0.022
SN2012P	224.996	1.890	0.004506
SN2012ap	75.057	−3.348	0.01224
PTF12gzk	333.173	0.512	0.01377
iPTF13bvn	225.001	1.881	0.00449
SN2013ge	158.702	21.662	0.004356
SN2014L	184.703	14.412	0.008029
SN2014ad	179.435	−10.171	0.0057
SN2015ap	31.306	6.102	0.01138
PTF15dtg	37.584	37.235	0.0524
SN2016bau	170.246	53.174	0.003856
SN2016blz	235.122	0.910	0.01173
SN2016coi	329.767	18.186	0.003646
SN2017ein	178.222	44.124	0.002699
SN2017fwm	288.217	−60.383	0.015557

DETERMINING THE OPTICAL EXPLOSION TIME

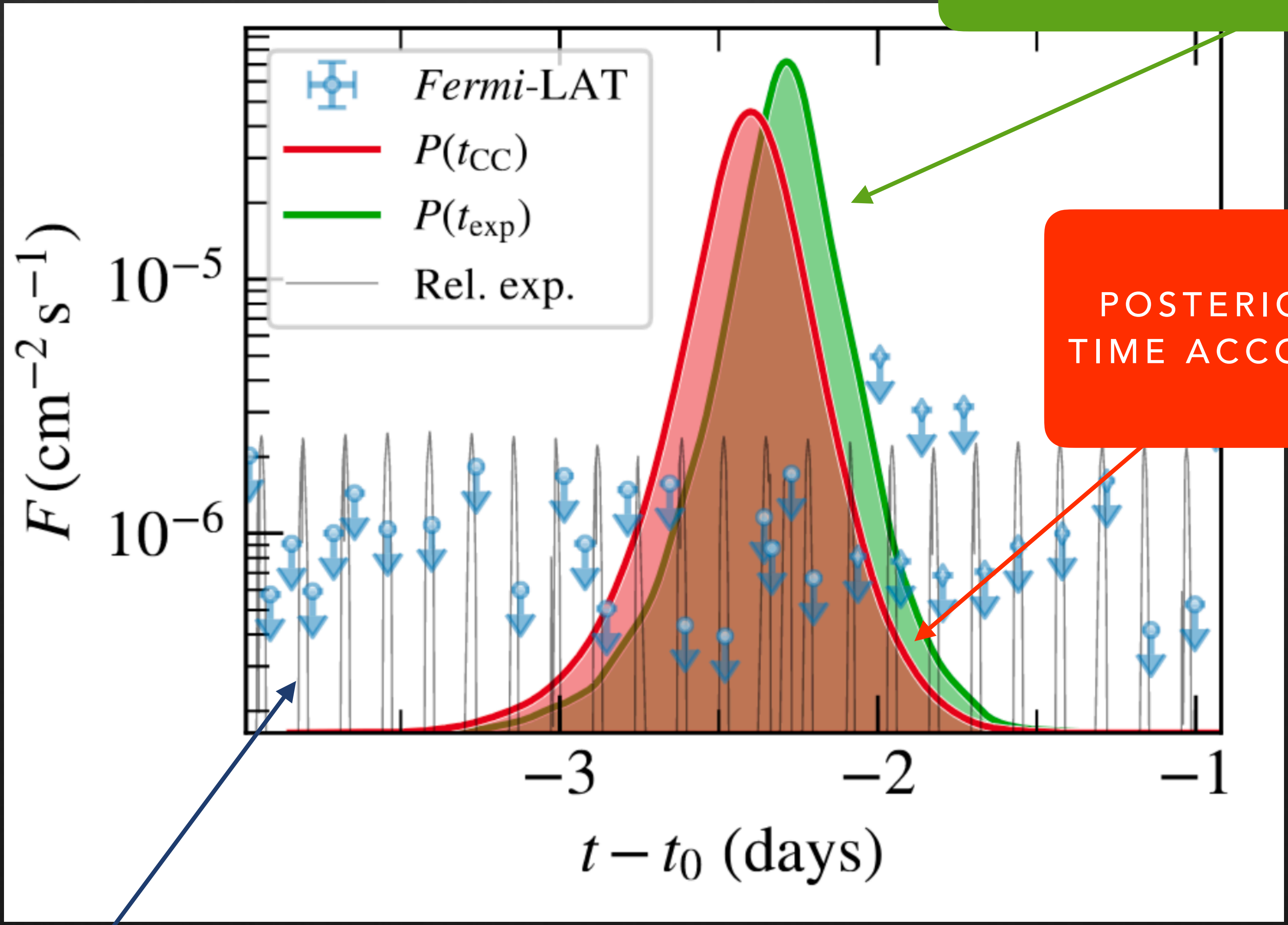
- Light curve fitted with **`MOSFiT`** package [Guillochon et al. 2018]

Marginalized posterior for explosion time



[MM & Petrushevska 2020]

GAMMA-RAY ANALYSIS PROCEDURE



POSTERIOR FOR EXPLOSION TIME FROM MOSFIT

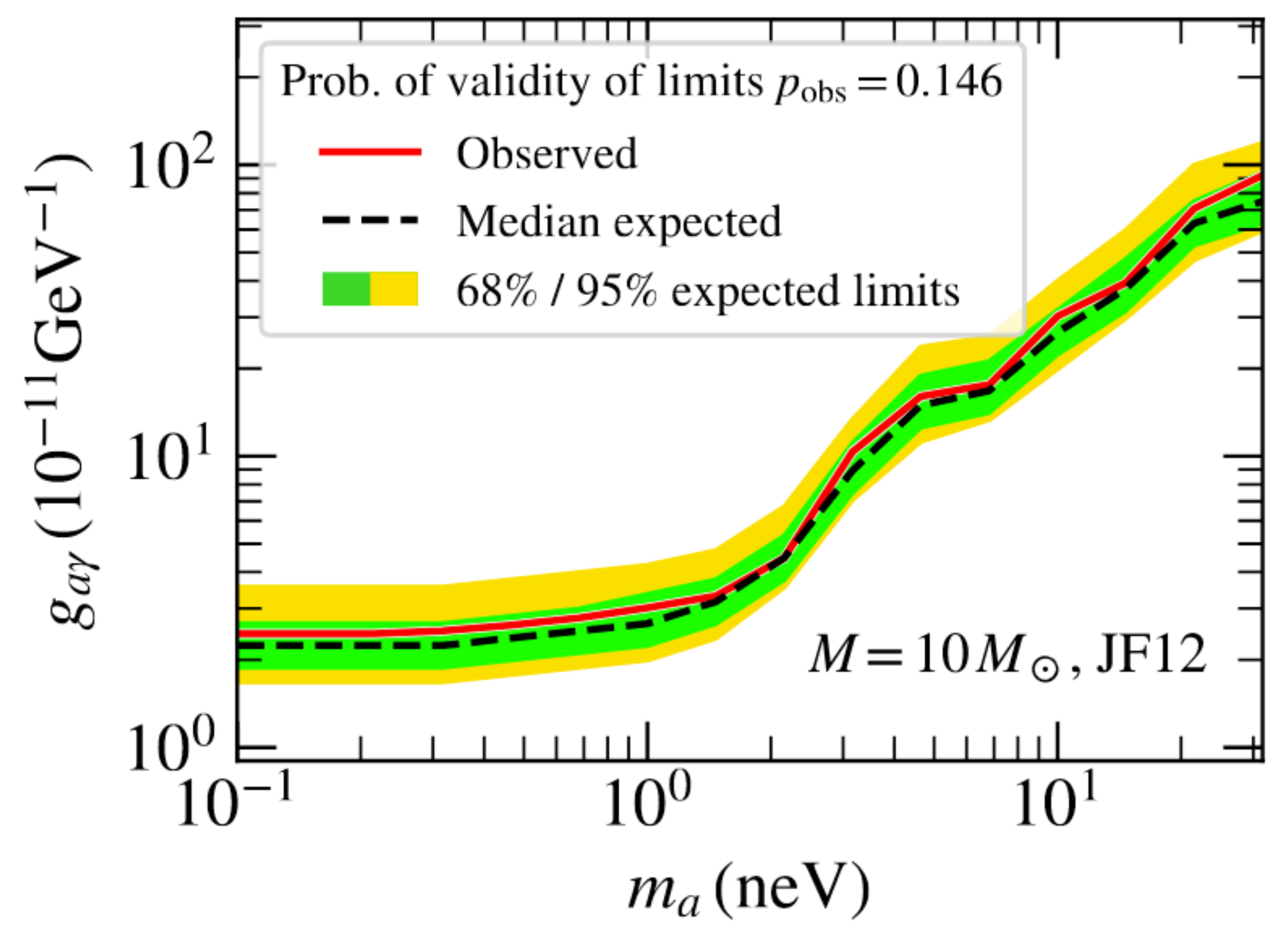
POSTERIOR FOR EXPLOSION TIME ACCOUNTING FOR DELAY

FERMI LAT FLUX UPPER LIMITS

SN2017ein

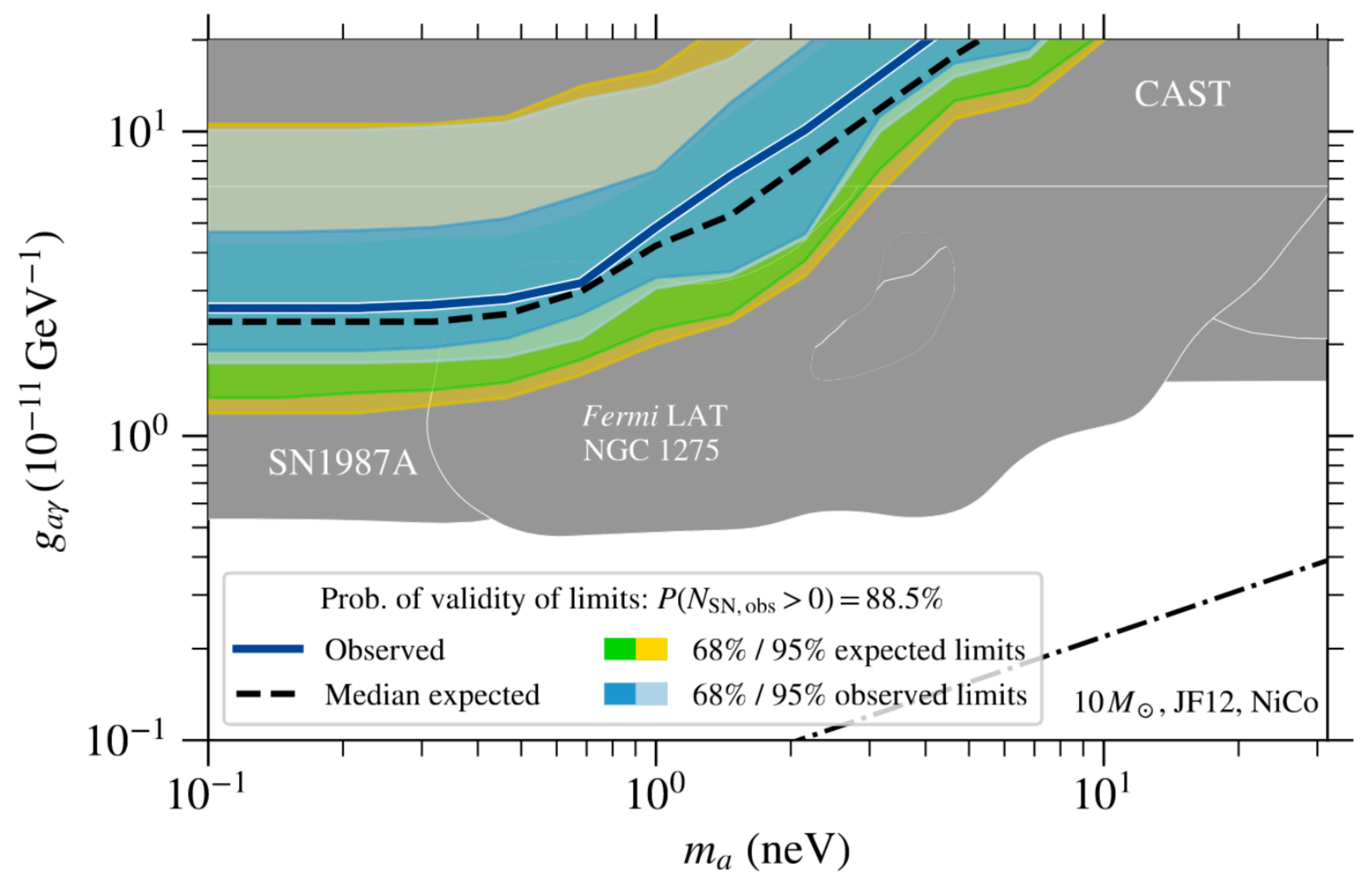
[MM & Petrushevska 2020]

CONSTRAINTS FROM ONE SN



[MM & Petrushevska 2020]

COMBINED LIMITS FROM SAMPLE OF 20 SNe

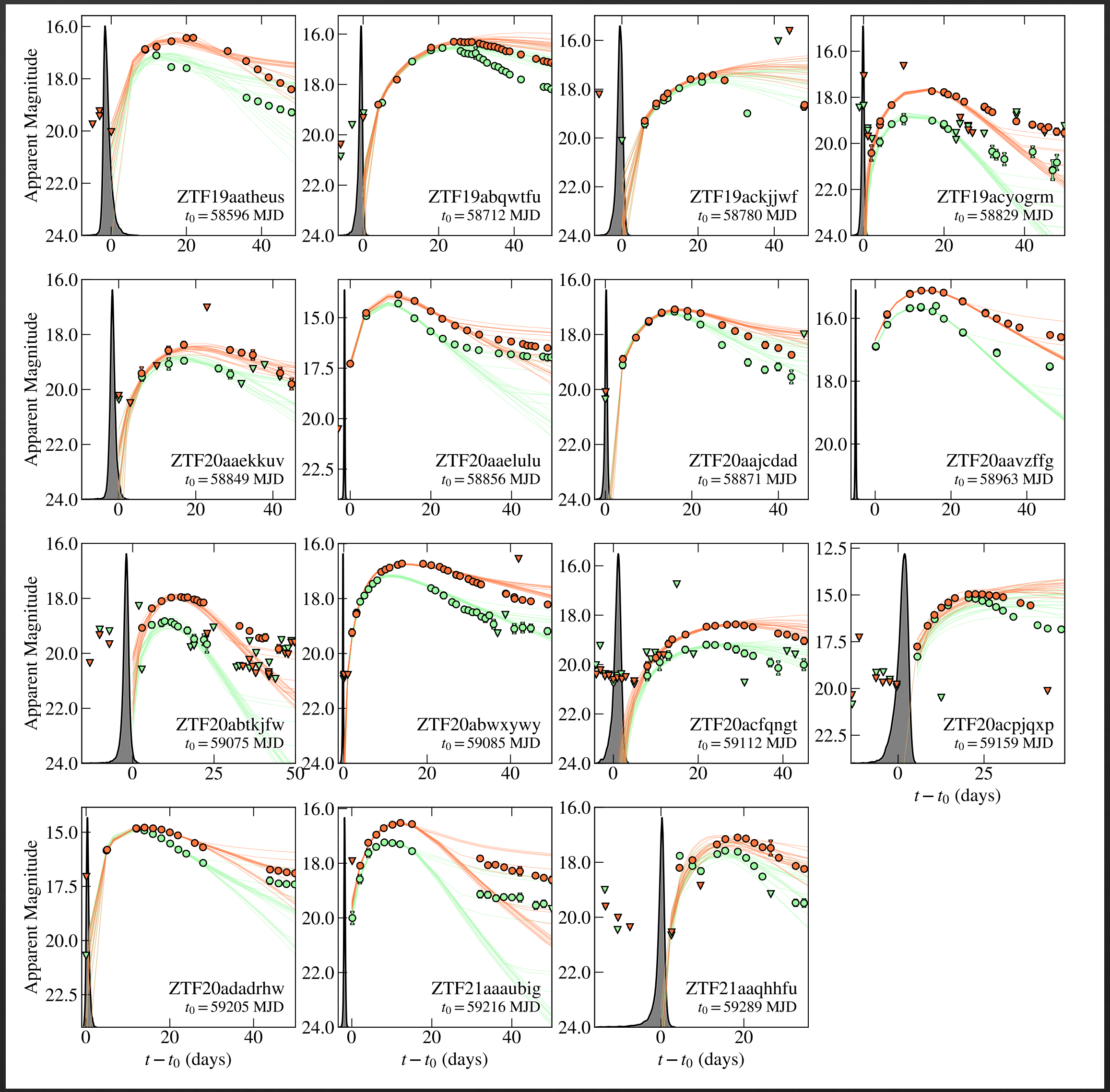


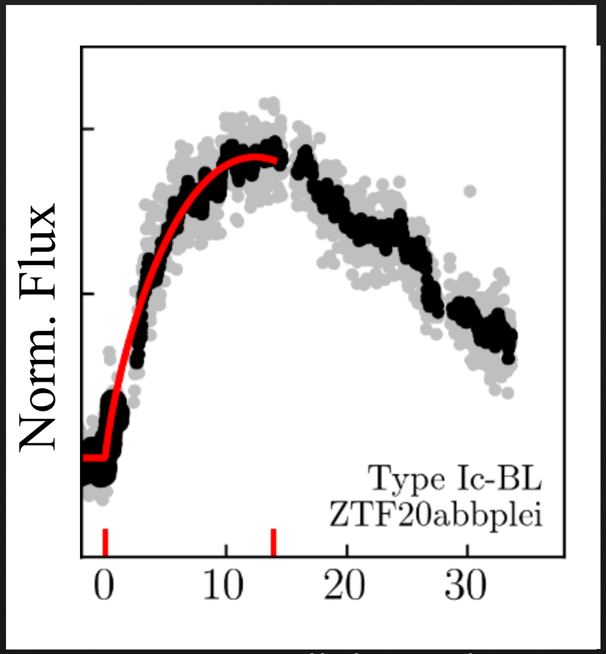
$$P(N_{\mathrm{obs}} \geqslant 1) = 1 - \prod_i \left(1 - p_{\mathrm{obs},i}\right) \approx 89\,\%$$

[MM & Petrushevska 2020]

SNe SAMPLE IS GROWING!

- ZTF, ASAS-SN and other surveys are already observing
- Vera Rubin Observatory will see first light in 2023
- TESS satellite provides high cadence light curves for some SNe





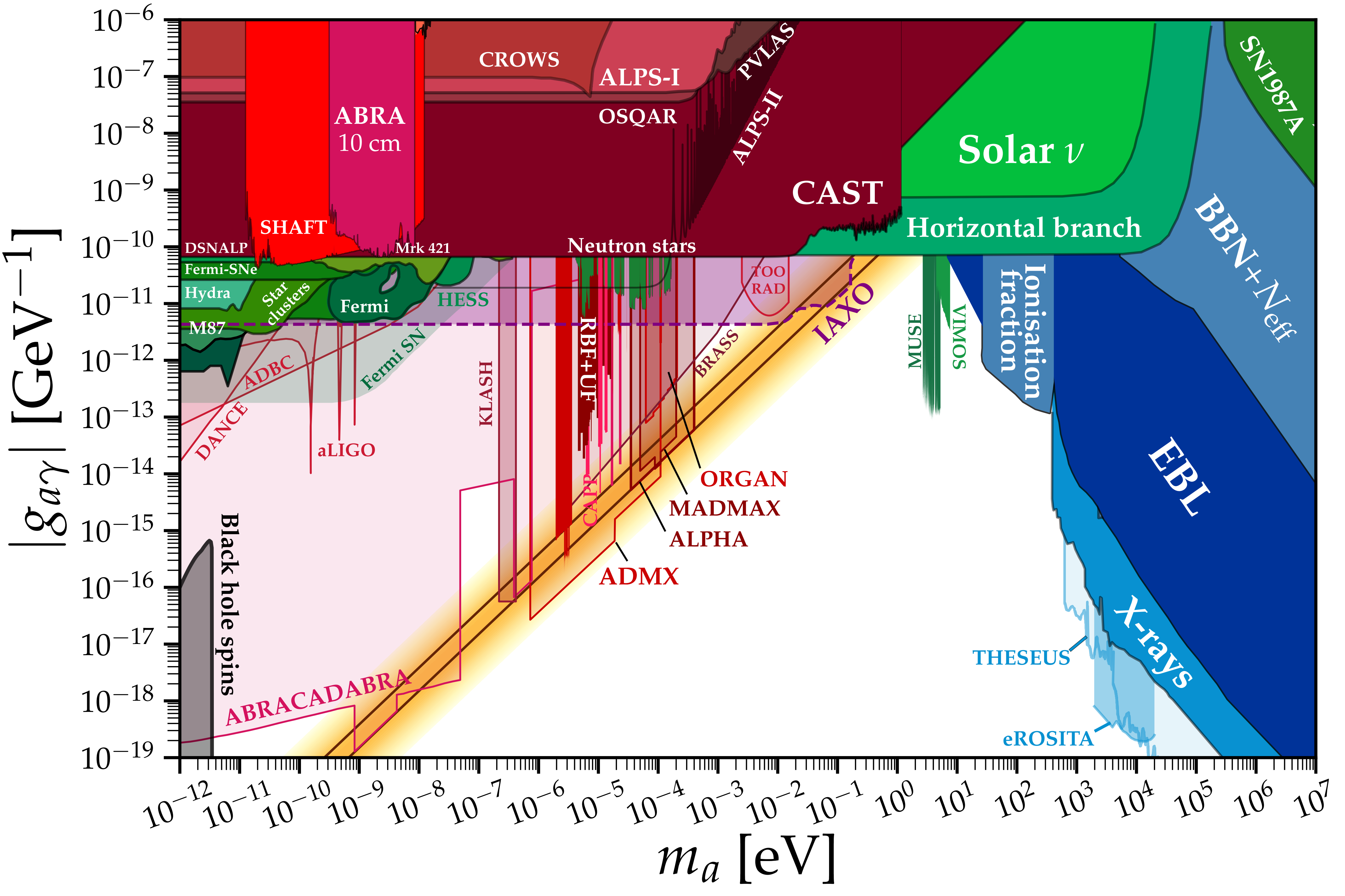
[Vallely et el. 2021]

CONCLUSIONS

- γ-ray burst signal at tens of MeV co-incident with neutrinos → smoking gun for ALPs!
- For extragalactic SNe: Core-collapse time can be estimated from optical light curves
- Fermi LAT all-sky survey very well suited to search for such a signal
- Many new SNe will be detected with optical surveys in the near future

BACK UP

PHOTON-ALP PARAMETER SPACE



https://github.com/cajohare/AxionLimits

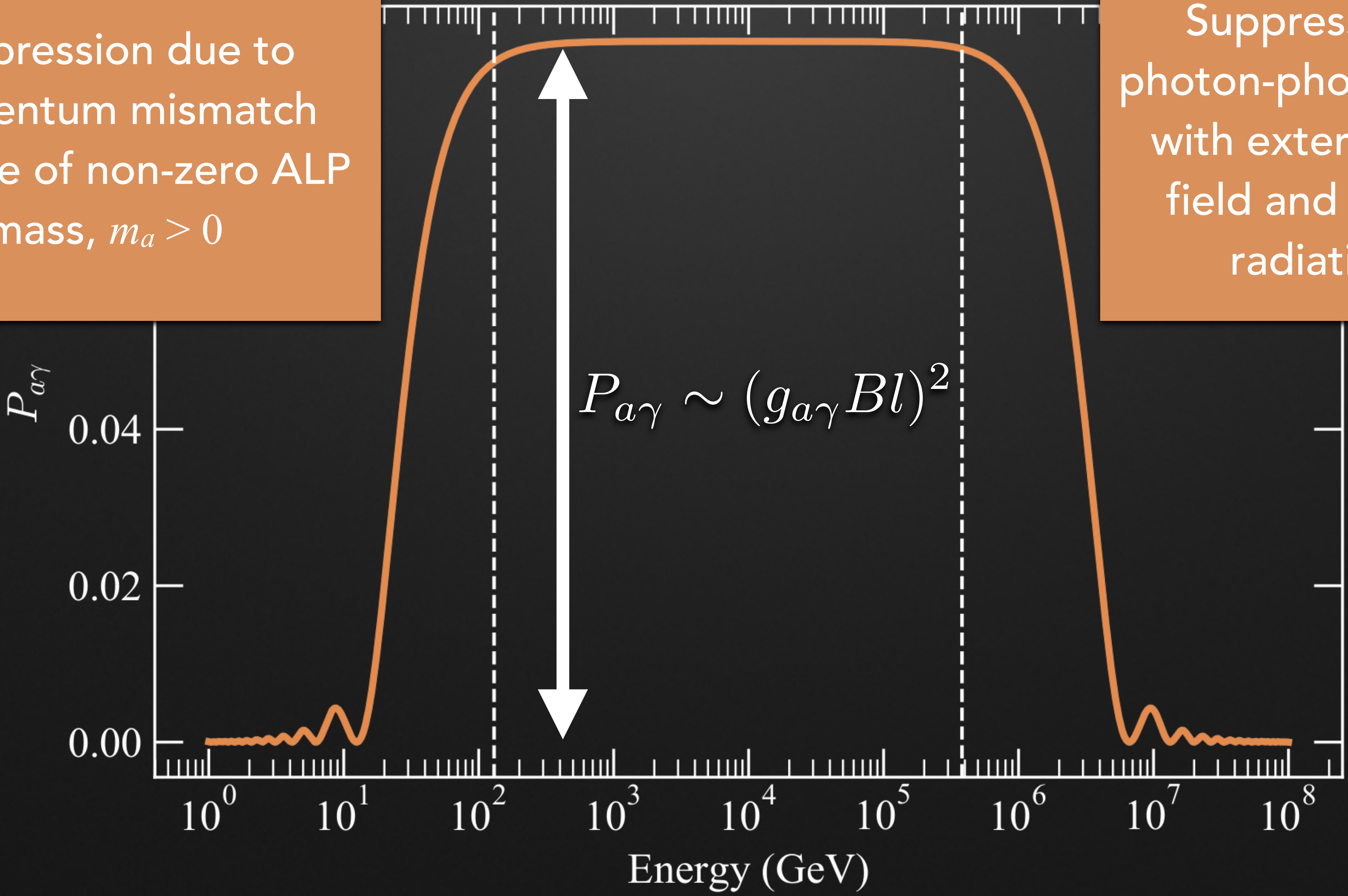
PHOTON-AXION/ALP MIXING

IN A COHERENT MAGNETIC FIELD

B = 1 μG, L = 10 kpc

Suppression due to momentum mismatch because of non-zero ALP mass, $m_a > 0$

Suppression due to photon-photon dispersion with external magnetic field and background radiation fields

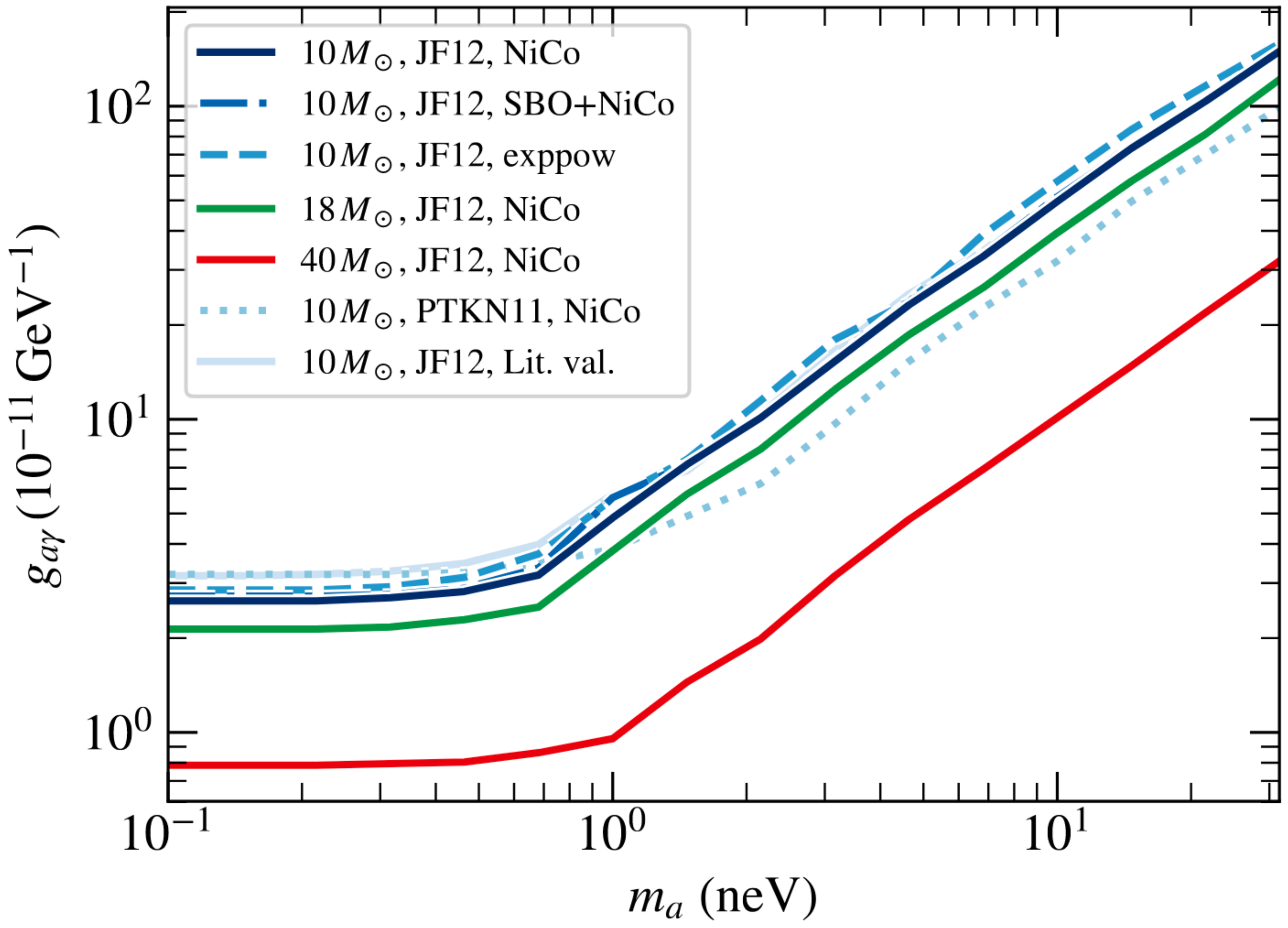


$$P_{a\gamma} \sim (g_{a\gamma} B l)^2$$

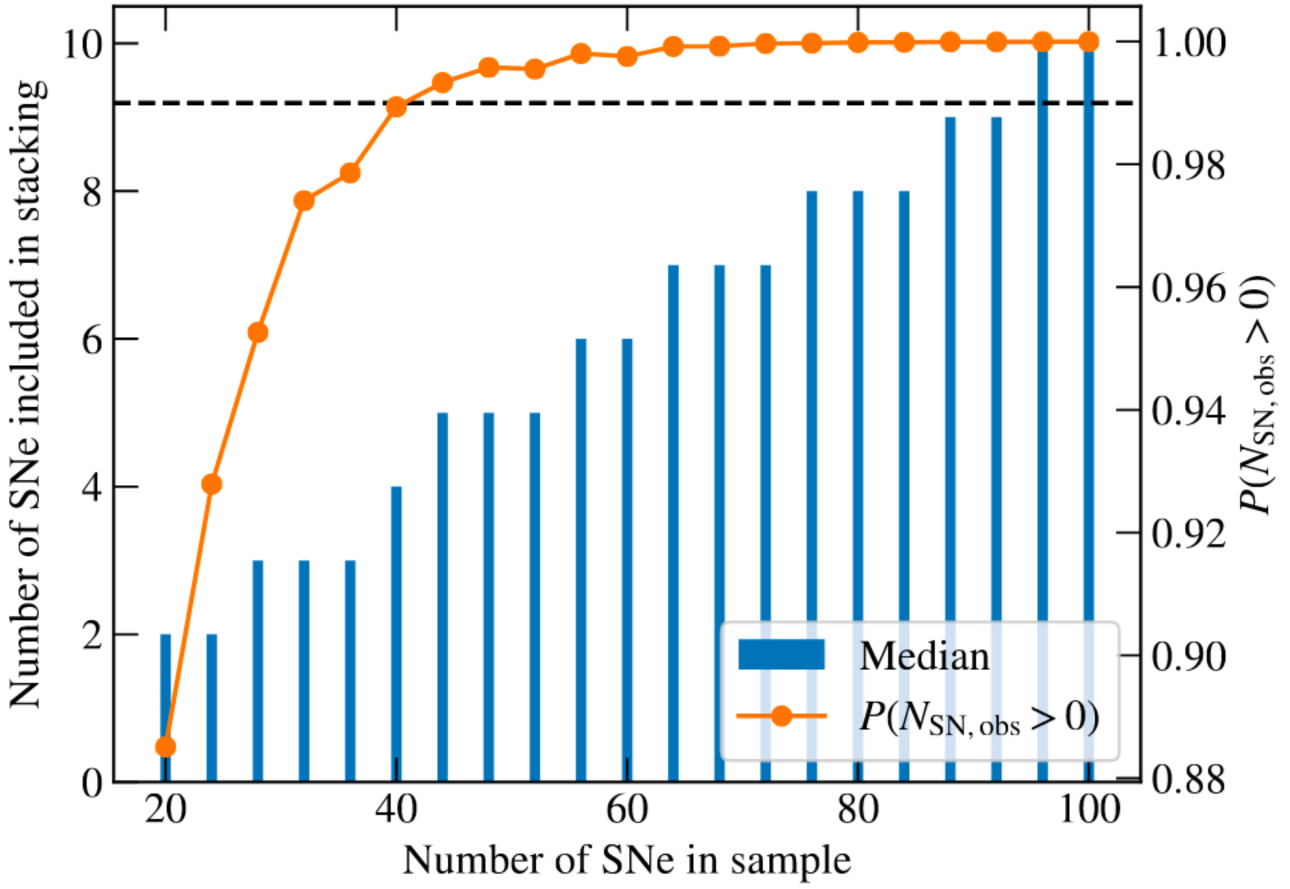
[Östman & Mörtsell 2005;
Hooper & Serpico 2007;
Mirizzi et al 2007;
Hochmuth & Sigl 2007;
De Angelis et al. 2008;
Wouters & Brun 2012,2013;
Abramowski et al.
(including MM) 2013;
Ajello et al . (including MM)
2016;
Montanino et al. 2017;
Liang et al. 2018;
Malyshev et al. 2018;
Majumdar et al. 2018;
Xia et al. 2018;
Zhang et al. 2018]

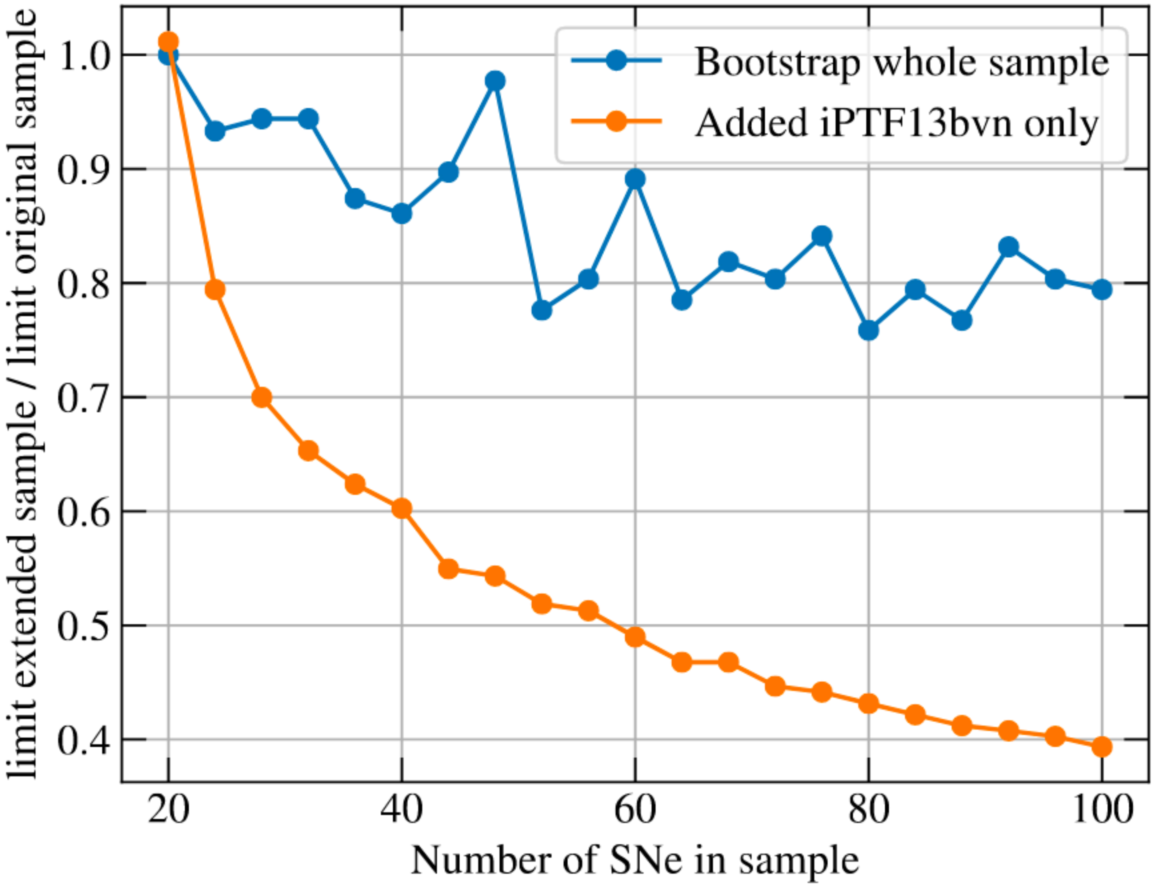
[Raffelt & Stodolsky 1988;
Dobrynina et al. 2015]

SN CONSTRAINTS WITH DIFFERENT MODEL ASSUMPTIONS



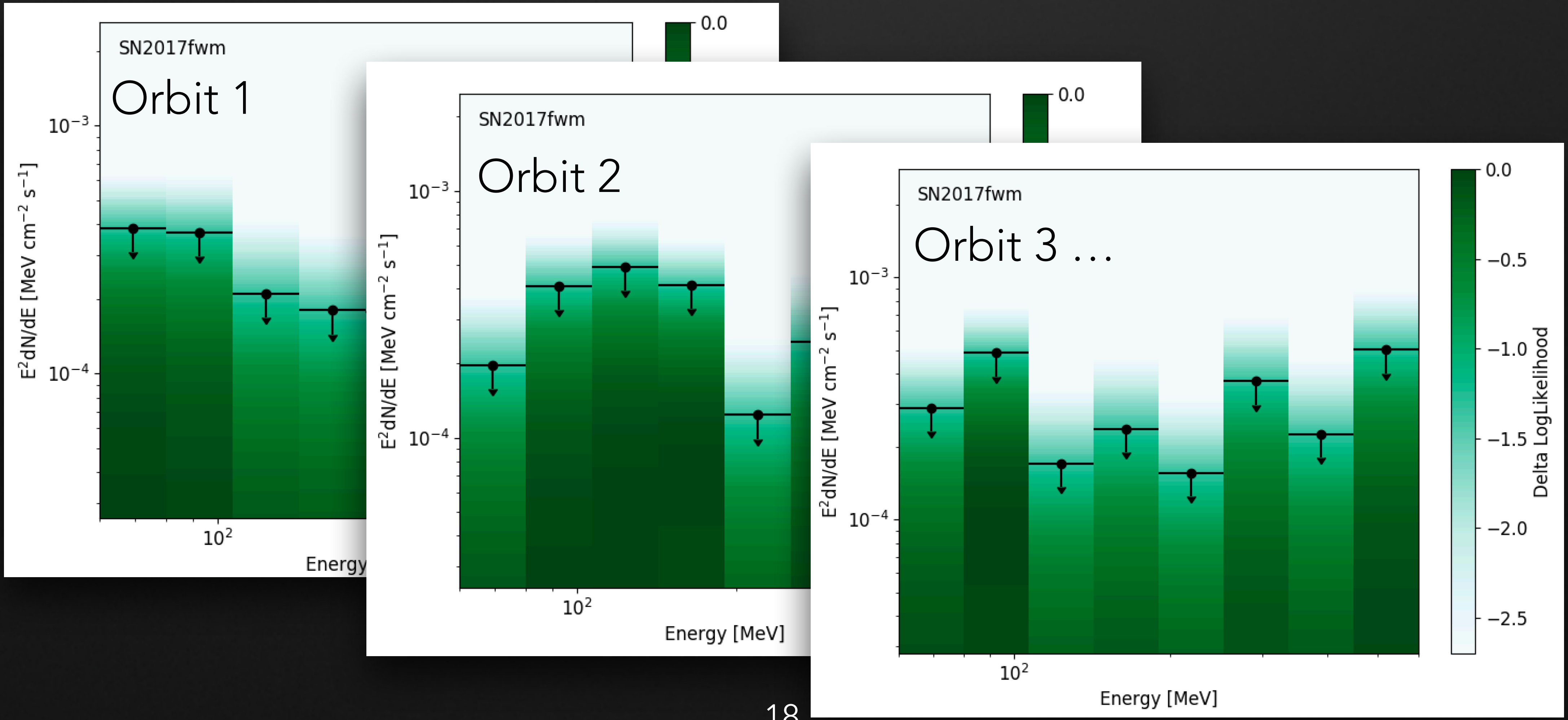
PROJECTION OF SN CONSTRAINTS





GAMMA-RAY ANALYSIS PROCEDURE

- Add SN to ROI model assuming ALP model
- Calculate gamma-ray light curve ± 30 days around SN discovery date with one time bin per orbit (~2 x 30 x 24 / 1.5 = 960 orbits)
- For each orbit: derive SED and log likelihood curve in each energy bin



LIKELIHOOD FORMULATION

Gamma-ray likelihood: multiplied over energy bins, depends on ALP parameters, progenitor mass *M*, *B* field, nuisance parameters for background sources and time t_{exp}

$$\mathcal{L}(m_a, g_{a\gamma}, t_{\mathrm{exp},j}, \boldsymbol{\theta} \,|\, \mathbf{D}_\gamma) = \boxed{\left(\prod_{\Delta E_i} \mathcal{L}_{\gamma,i}(m_a, g_{a\gamma}, t_{\mathrm{exp},j}, M, \mathbf{B}, \boldsymbol{\theta}_\gamma \,|\, \mathbf{D}_\gamma) \right)}$$

Consider GTIs such that $t_{\mathrm{exp},j} \in \boldsymbol{\Delta} t$ with

$$\boxed{\int_{\Delta t} \pi(\mathbf{D}_{\mathrm{optical}} \,|\, \boldsymbol{\theta}_{\mathrm{optical}})dt = 0.95}$$

Convolved marginalized posterior integrated over time

Gives trials factor equal to the number of orbits inside $\boldsymbol{\Delta} t$

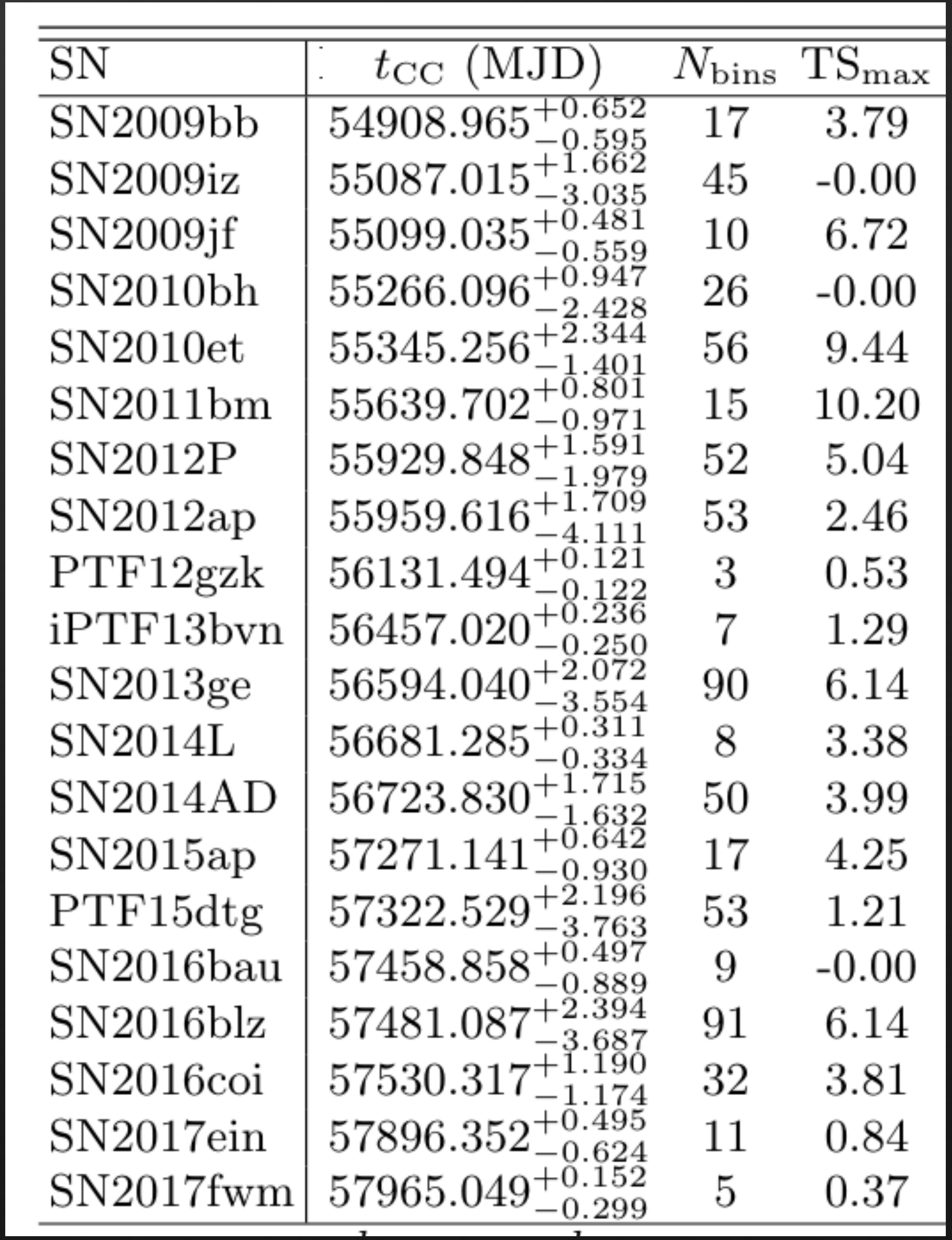
LOG LIKELIHOOD RATIO TESTS FOR SOURCE DETECTION AND SETTING LIMITS

In analogy to WIMP searches: step through mass m_a

$$TS_j = -2\ln\left(\frac{\mathscr{L}(m_a, g_{a\gamma} = 0, t_{\mathrm{exp},j}, \widehat{\boldsymbol{\theta}})}{\mathscr{L}(m_a, \widehat{\widehat{g_{a\gamma}}}, t_{\mathrm{exp},j}, \widehat{\widehat{\boldsymbol{\theta}}})}\right)$$

Select orbit ($\tilde{t}_{\mathrm{exp}}$) with highest TS for best fit / setting limits:

$$\lambda(m_a, g_{a\gamma}) = -2\ln\left(\frac{\mathscr{L}(m_a, g_{a\gamma}, \tilde{t}_{\mathrm{exp}}, \widehat{\boldsymbol{\theta}})}{\mathscr{L}(m_a, \widehat{\widehat{g_{a\gamma}}}, \tilde{t}_{\mathrm{exp}}, \widehat{\widehat{\boldsymbol{\theta}}})}\right)$$



SN	t_{CC} (MJD)	N_{bins}	$\mathrm{TS}_{\mathrm{max}}$
SN2009bb	$54908.965^{+0.652}_{-0.595}$	17	3.79
SN2009iz	$55087.015^{+1.662}_{-3.035}$	45	-0.00
SN2009jf	$55099.035^{+0.481}_{-0.559}$	10	6.72
SN2010bh	$55266.096^{+0.947}_{-2.428}$	26	-0.00
SN2010et	$55345.256^{+2.344}_{-1.401}$	56	9.44
SN2011bm	$55639.702^{+0.801}_{-0.971}$	15	10.20
SN2012P	$55929.848^{+1.591}_{-1.979}$	52	5.04
SN2012ap	$55959.616^{+1.709}_{-4.111}$	53	2.46
PTF12gzk	$56131.494^{+0.121}_{-0.122}$	3	0.53
iPTF13bvn	$56457.020^{+0.236}_{-0.250}$	7	1.29
SN2013ge	$56594.040^{+2.072}_{-3.554}$	90	6.14
SN2014L	$56681.285^{+0.311}_{-0.334}$	8	3.38
SN2014AD	$56723.830^{+1.715}_{-1.632}$	50	3.99
SN2015ap	$57271.141^{+0.642}_{-0.930}$	17	4.25
PTF15dtg	$57322.529^{+2.196}_{-3.763}$	53	1.21
SN2016bau	$57458.858^{+0.497}_{-0.889}$	9	-0.00
SN2016blz	$57481.087^{+2.394}_{-3.687}$	91	6.14
SN2016coi	$57530.317^{+1.190}_{-1.174}$	32	3.81
SN2017ein	$57896.352^{+0.495}_{-0.624}$	11	0.84
SN2017fwm	$57965.049^{+0.152}_{-0.299}$	5	0.37

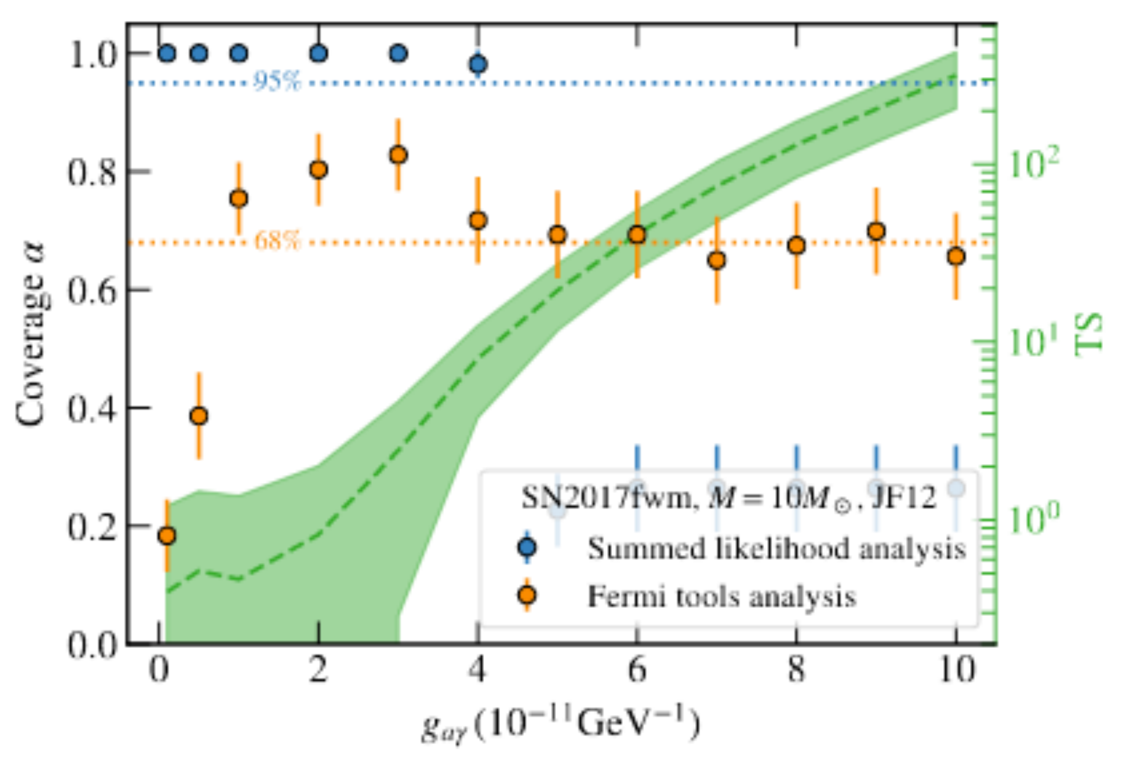
RESULTS FOR COVERAGE TEST

- Coverage =
  (number of times true signal in confidence interval) /
  (number of simulations)

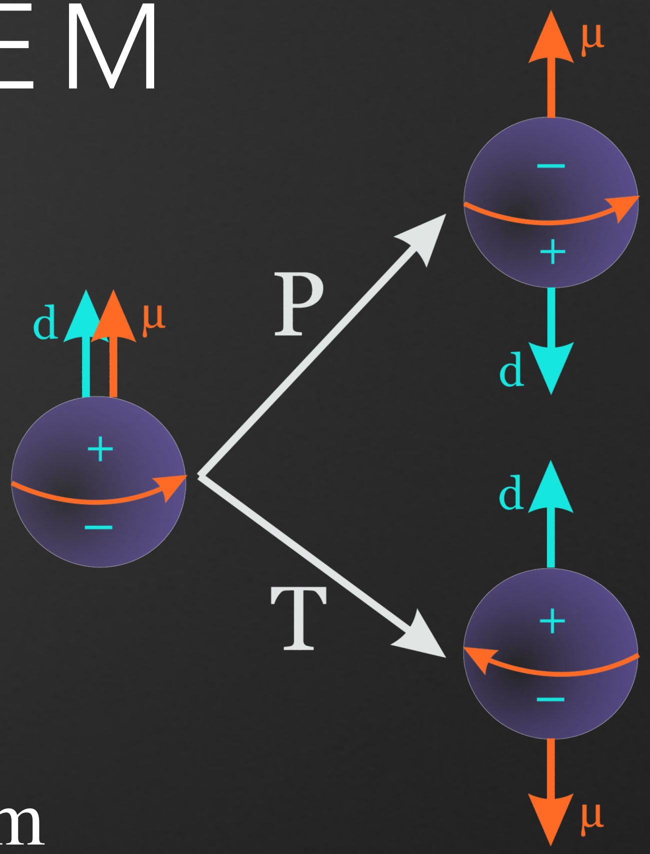
- bin-by-bin likelihood gives correct coverage for small TS values, upper limits can be trusted. For high TS values: likelihood curves become extremely steep, hard to interpolate correctly, leading to under-coverage

- Science tools analysis gives under-coverage for small TS values, i.e., fits do not recover weak signal. For high TS values, coverage as expected, injected signal recovered

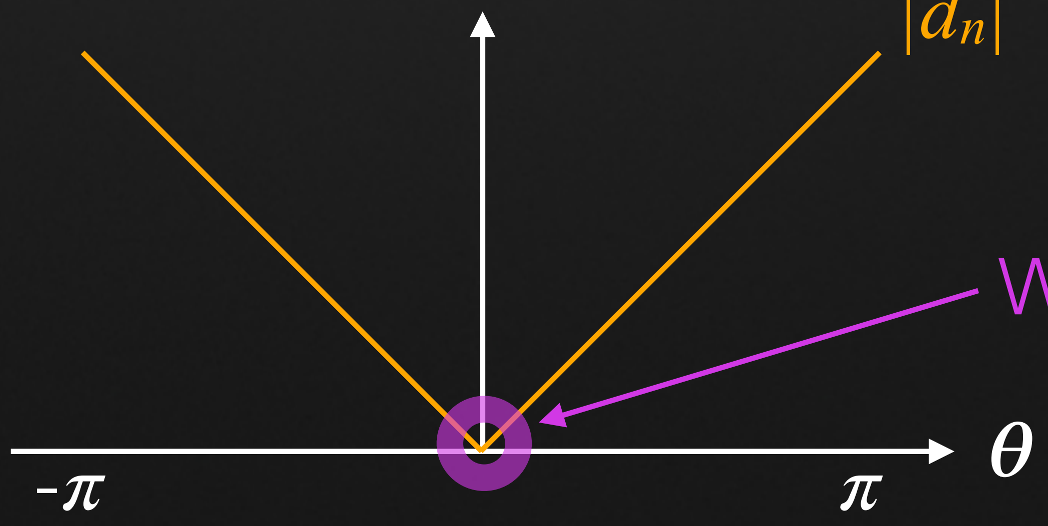
- **Conclusion**: bin-by-bin method works fine, limits can be trusted, reconstructed signals close to injected ones even for high TS, but in that case we would conduct a science tools analysis anyway



THE STRONG CP PROBLEM



- Theory of strong force (QCD) predicts electric dipole moment of the neutron with strength $\theta \in [-\pi,\pi]$
- Calculation: $|d_n| \approx 2.4 \times 10^{-16}\, \theta\, e$ cm
- Measurement [Abel et al. 2020]: $|d_n| < 1.8 \times 10^{-26}$ e cm
- $\Rightarrow |\theta| < 0.8 \times 10^{-10}$



We live here!

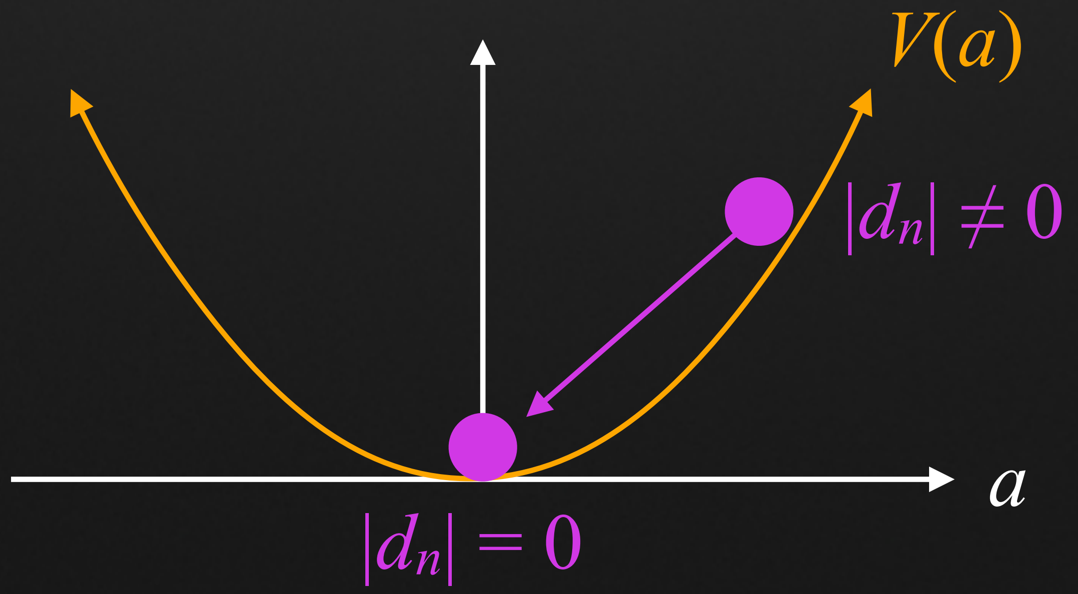
[Peccei & Quinn 1977;
Weinberg 1978; Wilczek 1978]

AXION SOLVES THE STRONG CP PROBLEM

- $\boldsymbol{\theta} \longrightarrow a\,/\,f_a$ with scalar field a and scale f_a

- Potential $V(a)$ generated by QCD, axion acquires mass

$$m_a \approx 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\mathrm{GeV}}{f_a}\right)$$



[Peccei & Quinn 1977;
Weinberg 1978; Wilczek 1978]

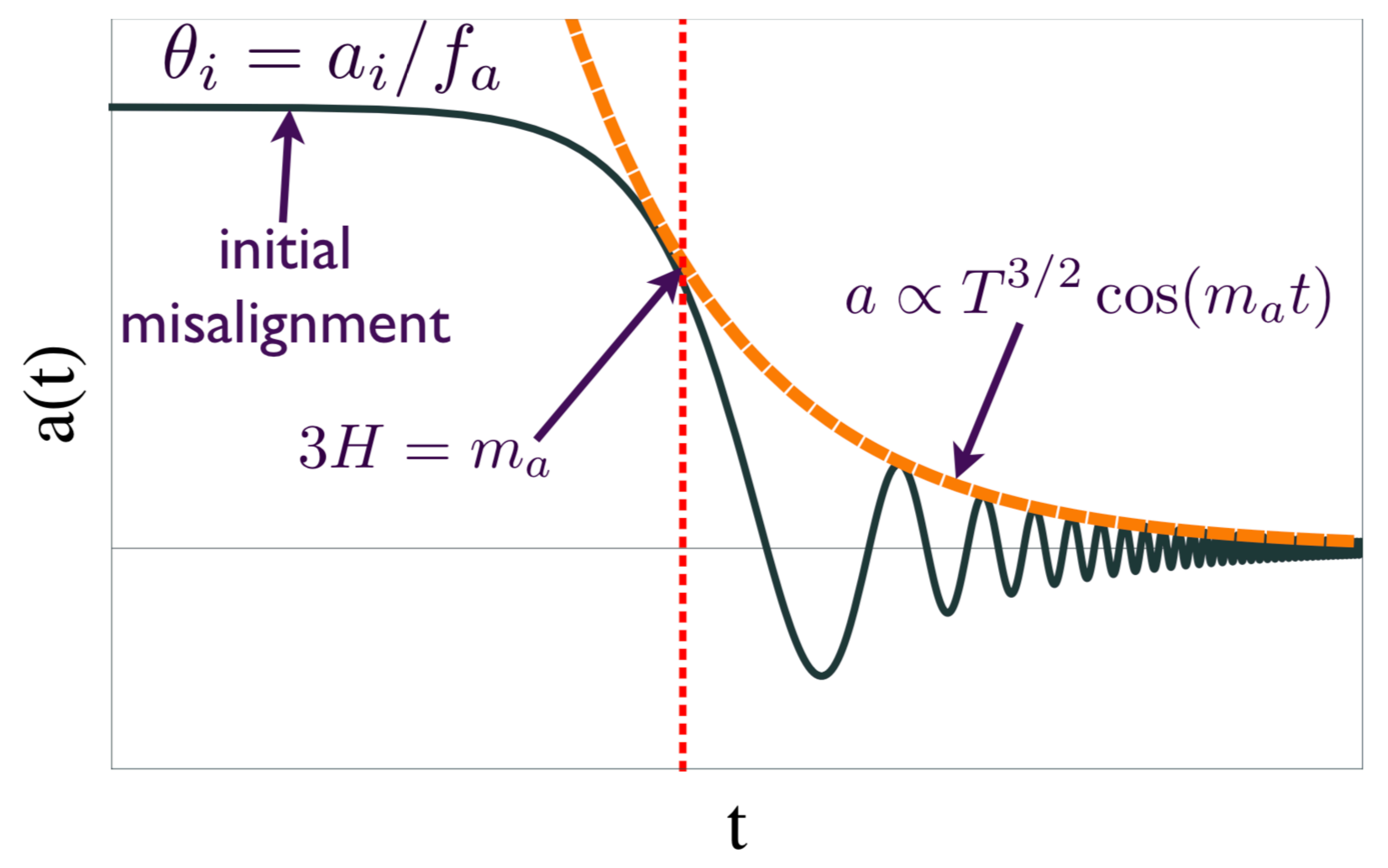
AXIONLIKE PARTICLES (ALPs)

- **QCD axion: $m_a \sim 1 / f_a$**
- Axionlike particles: m_a and f_a **independent parameters**
- Predicted in several **extensions** of the standard model (Majoron, Familon, String Theory …)

  [Chikashige et al. 78; Langacker et al. 86; Wilczek 82, Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli et al. 12, see also Jaeckel & Ringwald 10, Irastorza & Redondo 18 for reviews]
- Do **not solve** the **strong CP problem**

EVOLUTION OF AXION/ALP FIELD IN AN EXPANDING UNIVERSE

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



[E.g., Arias et al. 2012; slide credit: Ben Safdi]