1uW Embedded Computing

Using Off-the Shelf Components for Energy Harvesting Applications

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Full Disclosure

- A processor guy
- 25+ years TI applications and marketing experience
- Work described today is based on MSP430F20xx target MCU
- Work described is for extreme ultra-low power applications that can be applied to any MCU and to provide ideas for thought …

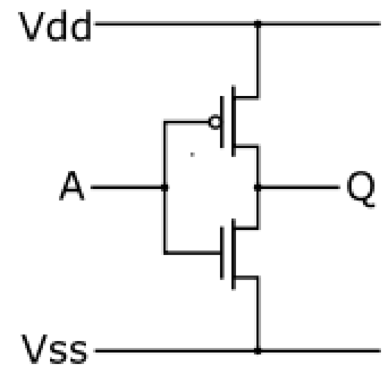
Agenda

- Embedded Ultra-low-power basics
- What is 1uW?
- Firmware impact
- Clock frequency and gating
- Voltage scaling
- Power gating sensors
- A complete system
- Traps
- Summary

Goal: A 1uW computing system using low-cost, off-the shelf components

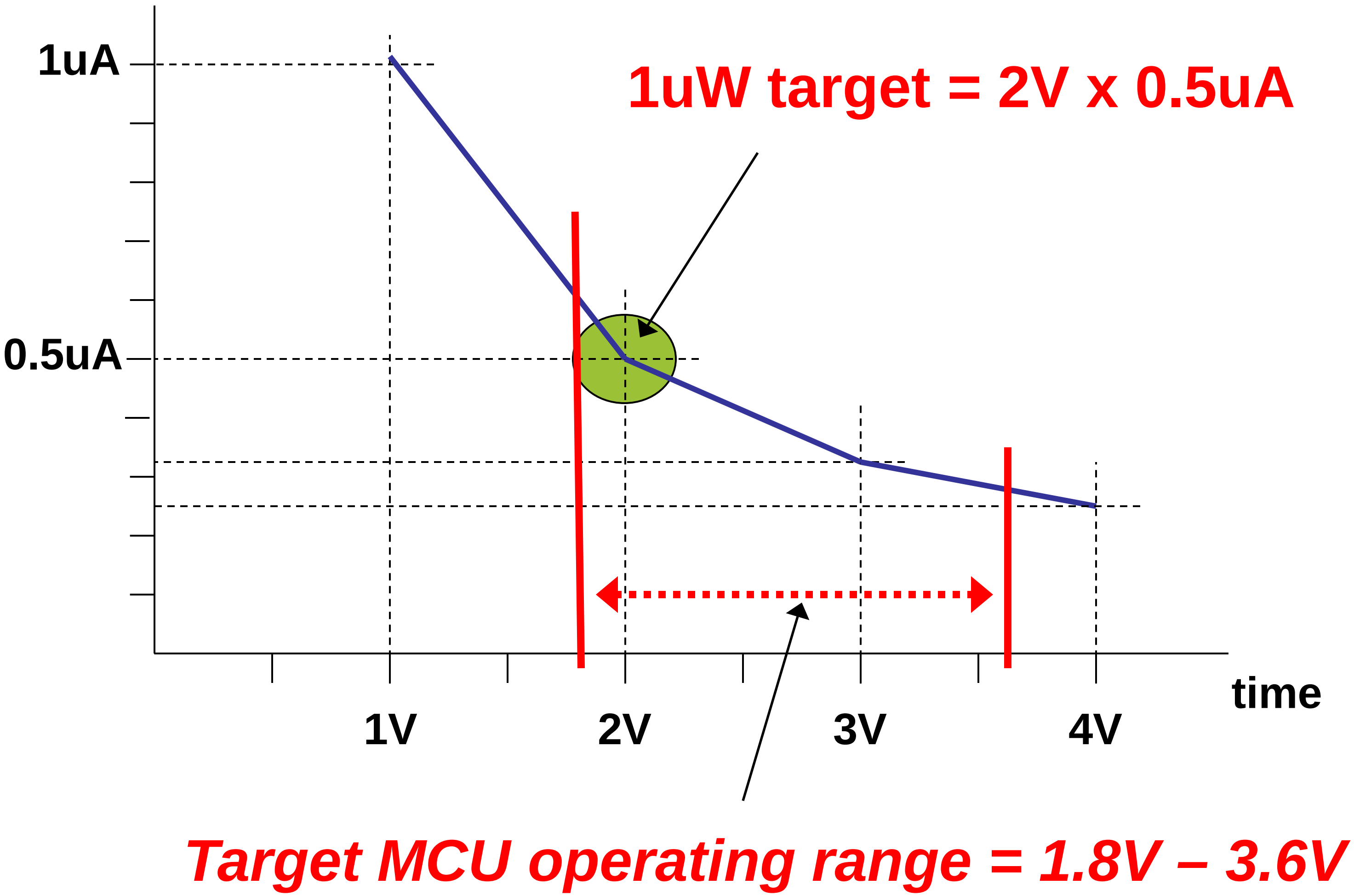
ULP Embedded Systems Basics

$$\boxed{\begin{aligned} P &= P_{dyn} + P_{stat} \\ &= CV^2f + VI_{leak} \end{aligned}}$$



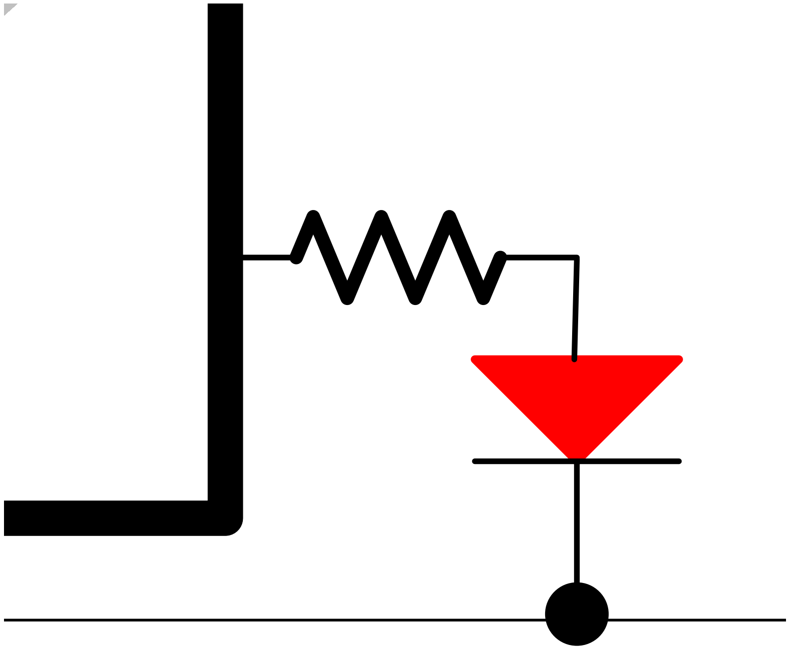
1. **Both frequency and voltage can be controlled**
   - Lowering frequency has a linear effect
   - Lowering voltage has a squares the effect
   - Static and leakage currents are largely constant
2. **Power manage peripherals**
3. **Effective code is a must**

1uW Power Curve



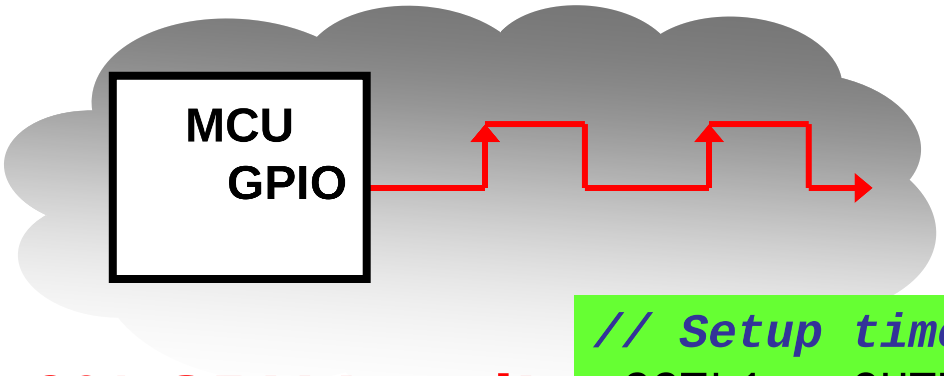
Flashing LED

- **Often a marketing must-have for electronic system-functioning-properly indicator**
- **~5mA pulse for 1ms**
- **1/second**
  - 0.1% duty cycle
  - 5uA adder on average
- **1/5 second**
  - 0.02% **<u>duty cycle</u>**
  - **1uA (2uW) adder**



2uW is unacceptable in our application!!!

Effective Code



0% CPU Load!

```
// Setup timer output unit
 CCTL1 = OUTMOD0_1;
 _BIS_SR(CPUOFF);
```

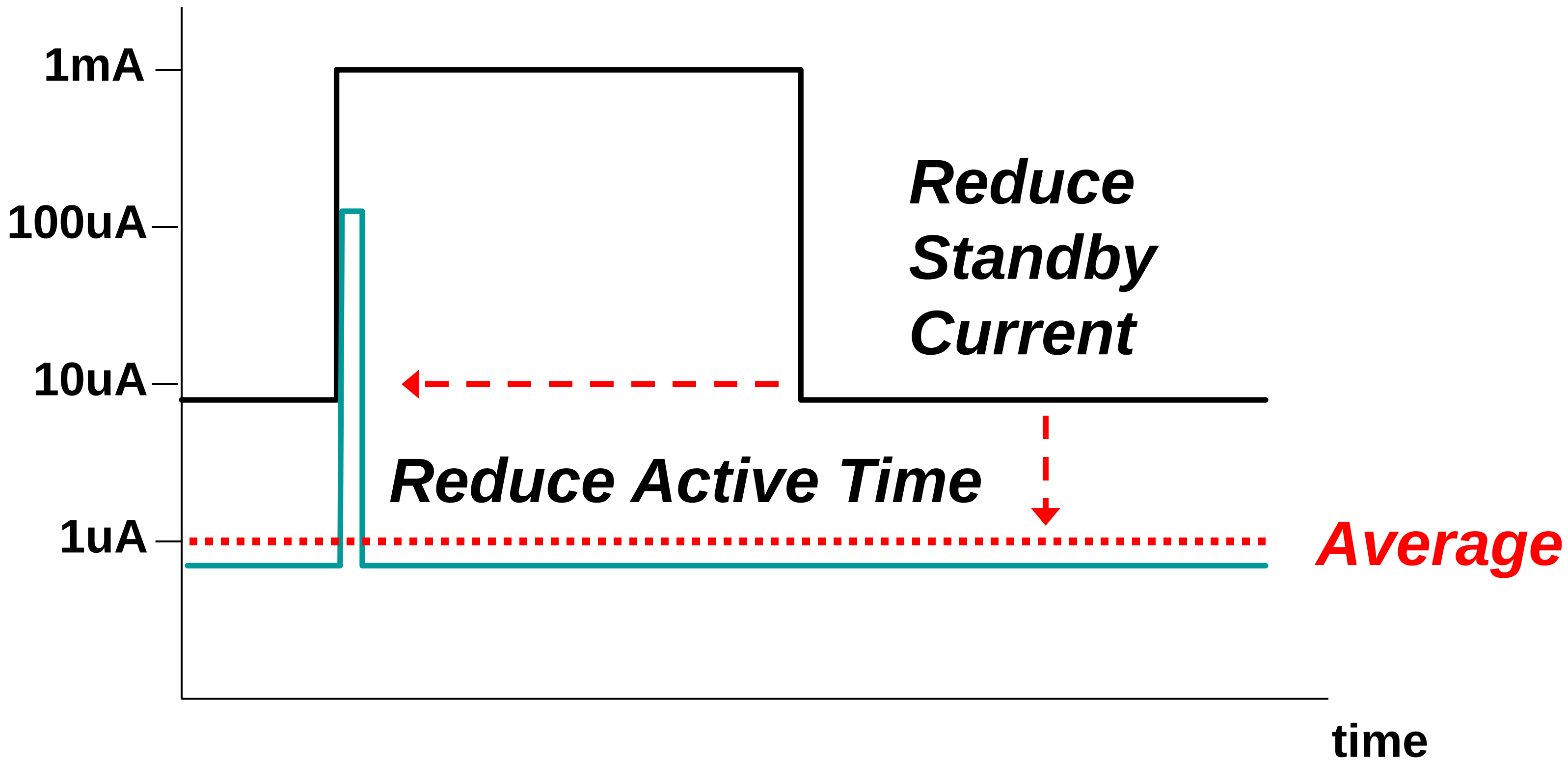
0.01% Load

```
#pragma vector=WDT_VECTOR
_interrupt watchdog_timer (void){
  P1OUT ^= 0x01;  // Toggle
}
```

100% CPU Load

```
while (1){
 P1OUT ^= 0x01;              // Toggle
 __delay_cycles(10000);  // Delay
}
```

Ultra-low Power Activity Profile

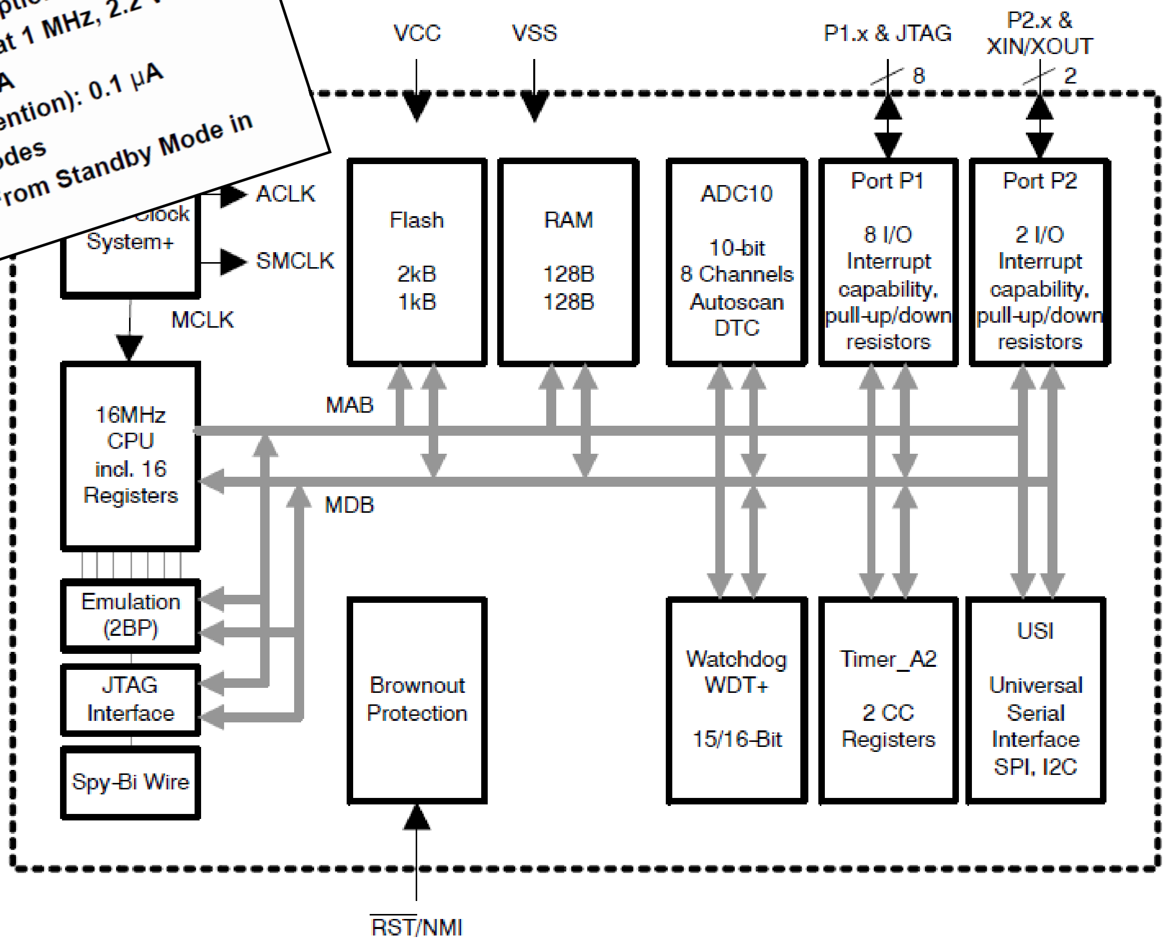


Average approaches standby

MSP430F20xx

FEATURES

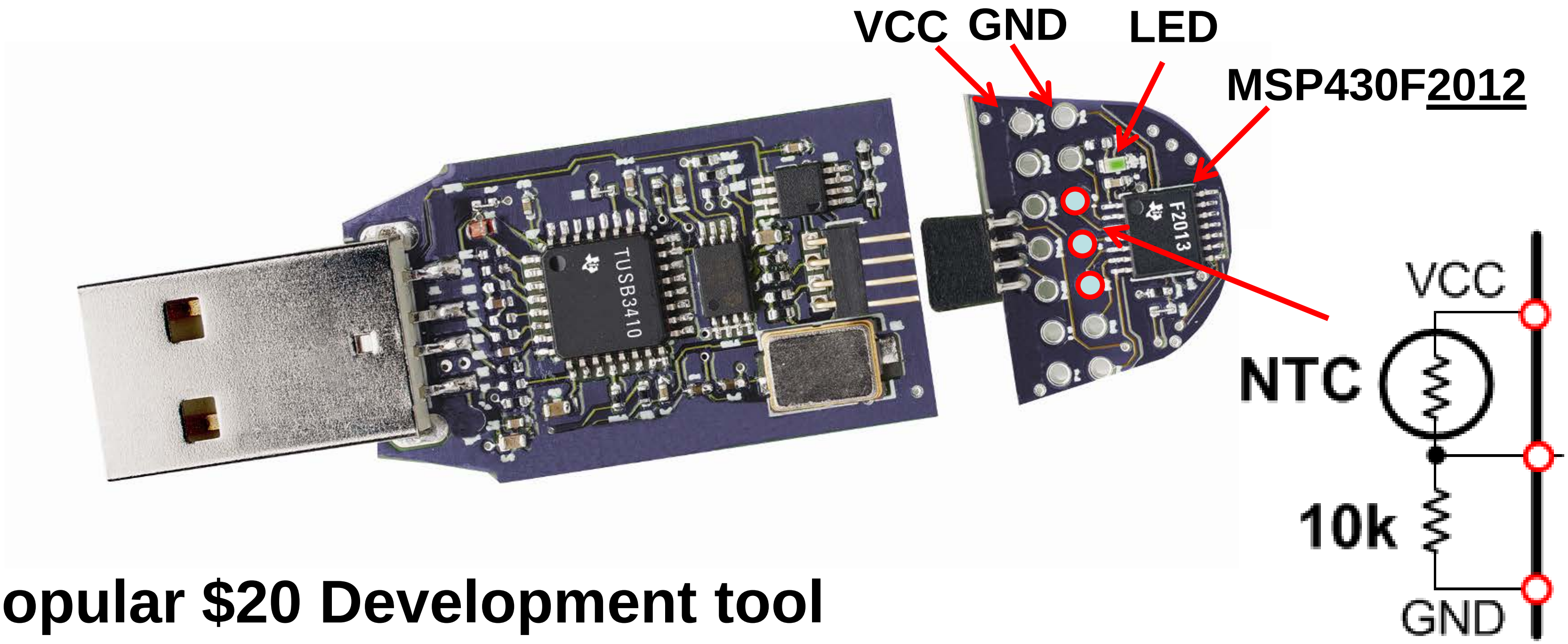
- Low Supply Voltage Range 1.8 V to 3.6 V
- Ultra-Low Power Consumption
  - Active Mode: 220 µA at 1 MHz, 2.2 V
  - Standby Mode: 0.5 µA
  - Off Mode (RAM Retention): 0.1 µA
- Five Power-Saving Modes
- Ultra-Fast Wake-Up From Standby Mode in Less Than 1 µs



Tiny workhouse since 2005

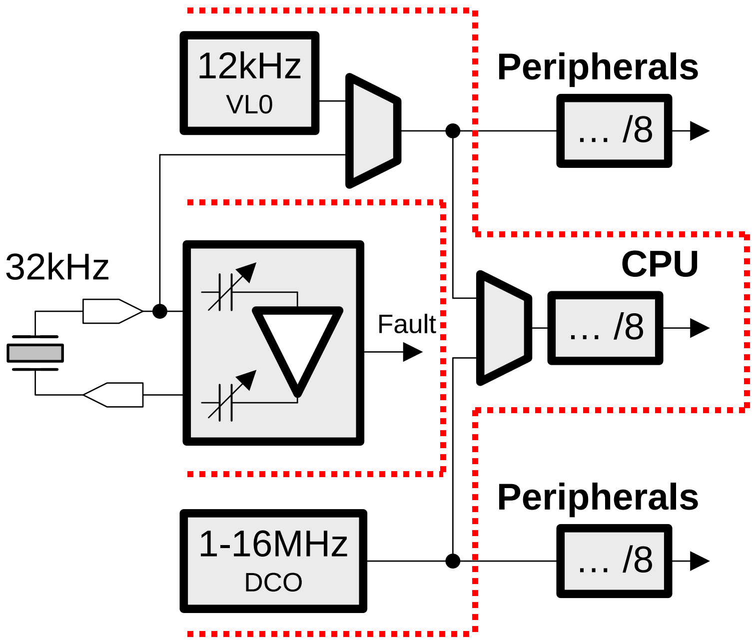
0.35u single-supply domain, <u>nothing special</u>

eZ430-F2013



- **Popular $20 Development tool**
- **LED already on target used as indicator**
- **NTC Sensor + Resistor divider sensor added**
  MCU GPIO used to create VCC and GND for sensor
- **MSP430F2013 replaced with MSP430F2012**

Active Mode Options



MSP430F20x from datasheet

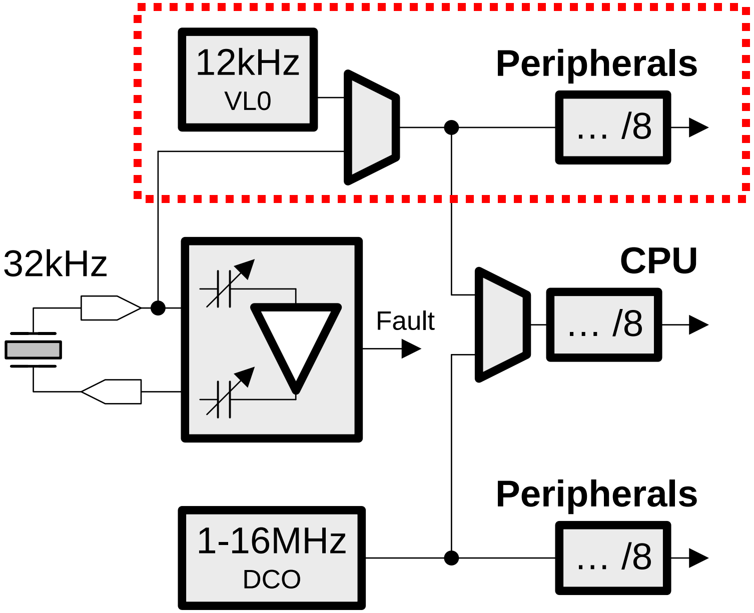
	TEMP	VCC	TYP	UNIT
1MHz FLASH	n/a	2.2V	220	uA
		3V	**300**	
1MHz RAM	n/a	2.2V	190	uA
		3V	260	
4kHz FLASH	n/a	**2.2V**	**1.3**	uA
		3V	1.6	

VLO/8	*n/a*	*2.0V*	*0.4*	*uA*

from bench test

- **25% reduction 3V to 2.2V … 13% Flash to RAM**
- **With VLO/8 @2V standby = 0.8uW ~ 1.2KPS**
- **Current is for entire chip … clock, memory, BOR …**

Standby Mode Options



MSP430F20x from datasheet

	TEMP	VCC	TYP	UNIT
32kHz	25°C	2.2V	**0.7**	uA
	85°C		1.4	
	25°C	3V	**0.9**	
	85°C		1.6	
VLO	25°C	2.2V	**0.5**	uA
	85°C		1.0	
	25°C	3V	**0.6**	
	85°C		1.3	

VLO/8	***22℃***	***2.0V***	***0.3uA***	***uA***

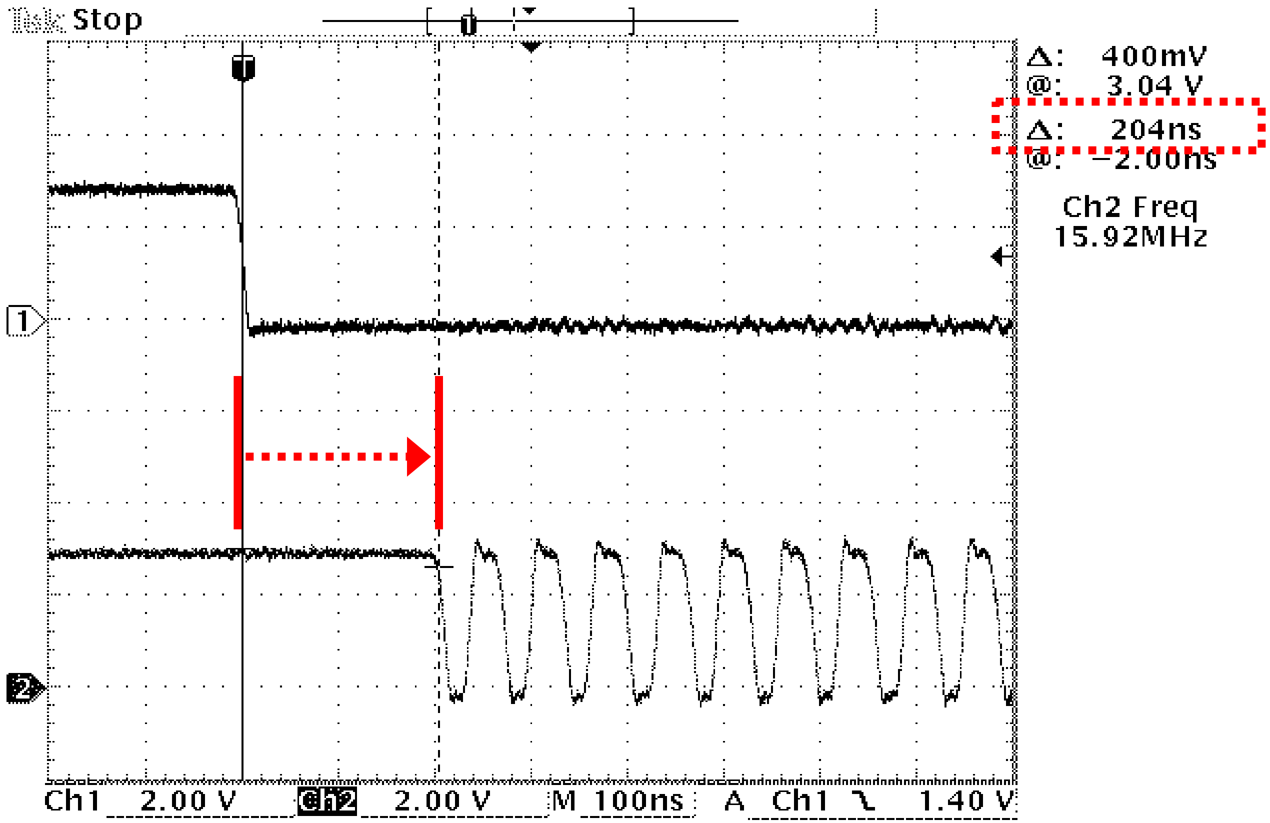
from bench test

- **Reduction from 3V to 2.2V … 32kHz to VLO**
- **With VLO/8 @2V standby = 0.6uW ~ 0.4uW remains!**
- **Current is for entire chip … clock, memory, BOR …**

Instant on Clocking

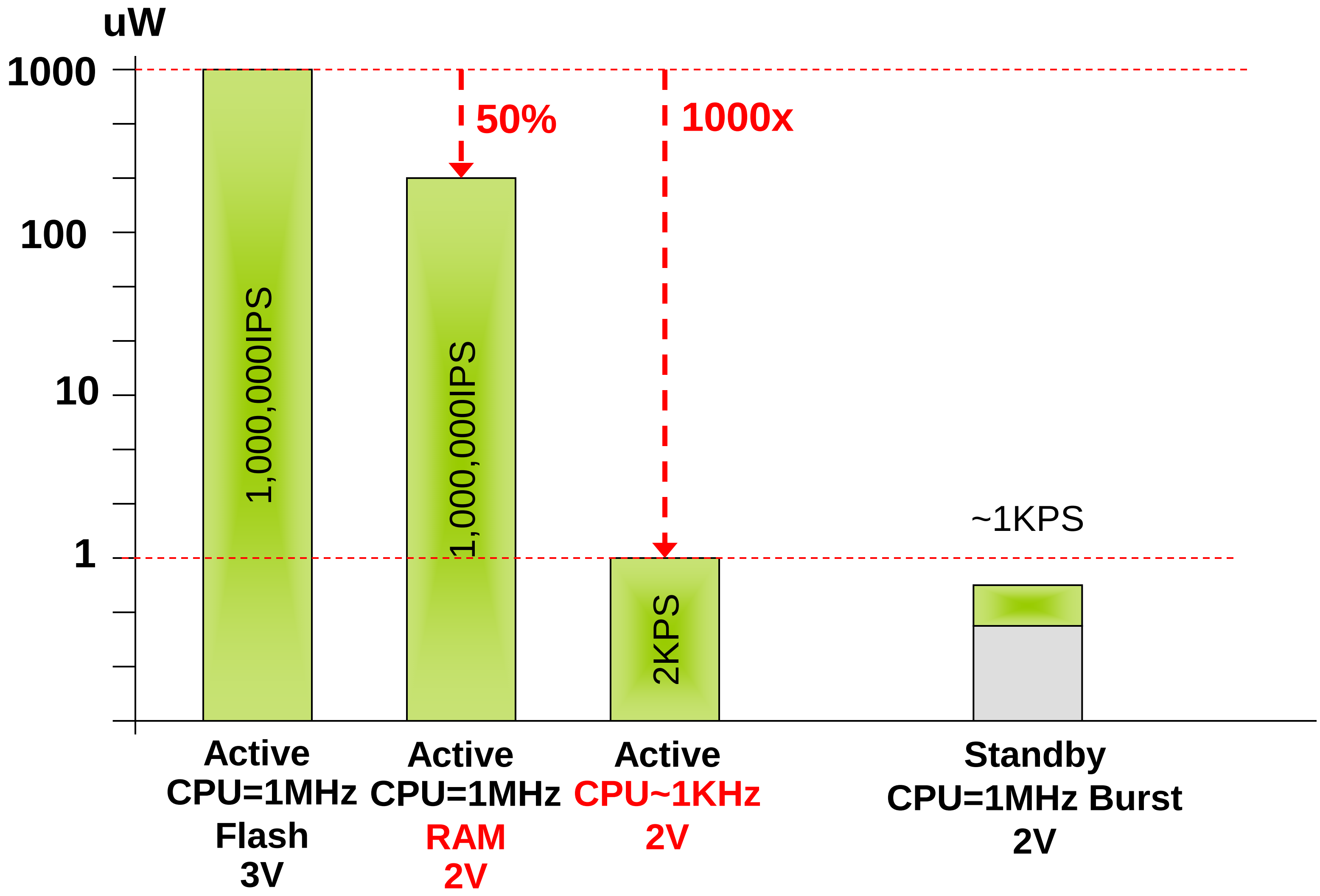
Interrupt

DCO



Immediate-stable high-speed clock for event response

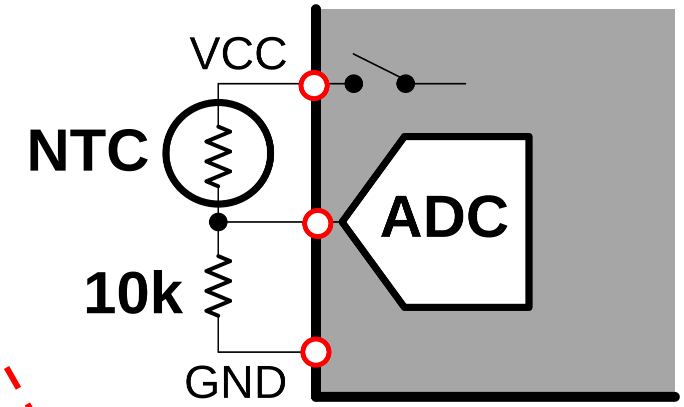
1uW Computing



Add ULP ADC Sensor Processing

```
//   MSP430F2012
//   -----------------------
//   LPM3 VLO      = 0.3uA
//   ADC10 1sps    = 0.0005uA
//   Mainloop      = 0.1uA
//   -----------------------
//   Total           0.4uA
//   @2v             0.8uw
```

Switched

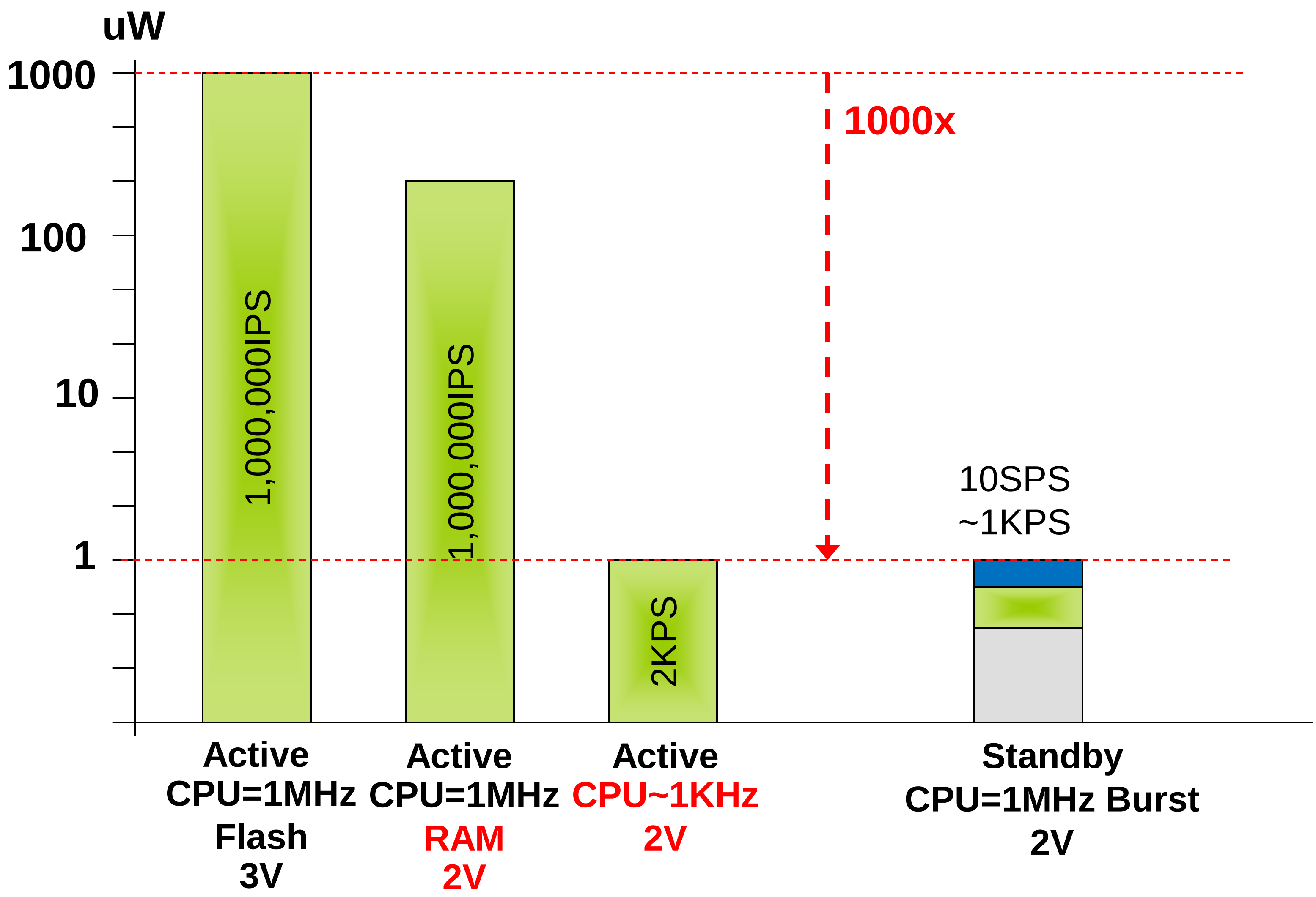


~Divide / 200,000

PARAMETER		VCC	MIN	TYP	MAX	UNIT
I_{ADC10}	ADC10 supply current (see Note 3)	2.2 V		0.52	1.05	mA
		3 V		0.6	1.2	mA

Data Sheet = 200ksps!

1uW Computing + Sensor Processing



Not ULP Sensor Sampling Test Code

```
while (1)  {
  ADC10CTL0 |= ADC10SC;               // Sampling start
  while (ADC10CTL1 & ADC10BUSY); // ADC10BUSY?
  if (ADC10MEM < 0x1FF)
    P1OUT &= ~0x01;                   // LED off
  else
    P1OUT |= 0x01;                    // LED on
}
```

ULP Sensor Sampling Test Code

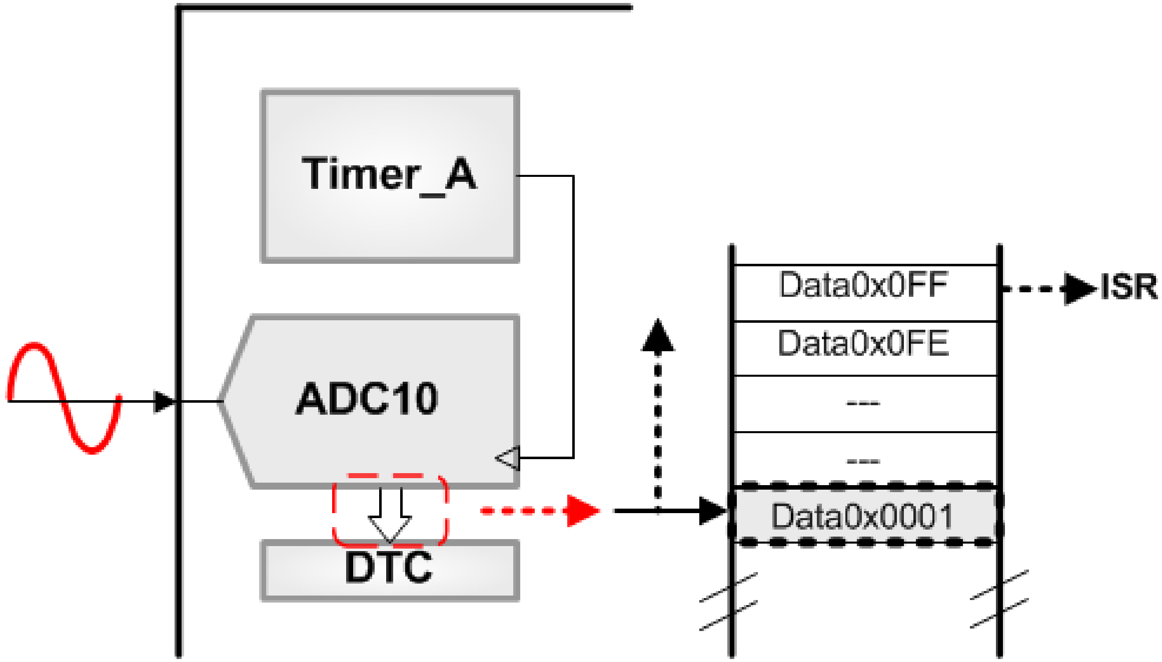
```
while (1){
  _BIS_SR(LPM3_bits + GIE);      // Enter LPM3
  P1OUT |= 0x02;                 // PWR to R+NTC
  ADC10CTL0 |= ADC10SC;          // Sampling start
  while (ADC10CTL1 & ADC10BUSY); // ADC10BUSY?
  P1OUT &= ~0x02;                // noPWR to R+NTC
  if (ADC10MEM < 0x1FF)
    P1OUT &= ~0x01;              // LED off
  else
    P1OUT |= 0x01;               // LED on
}

#pragma vector=WDT_VECTOR
__interrupt void watchdog_timer (void){
  _BIC_SR_IRQ(LPM3_bits);       // Exit LPM3
}
```

Demonstration

Condition	Vdd	Idd Measured	Calculated Watts
Active/Flash 1MHz @ 3V			
Active/Flash 1MH @ 2V			
Active/Flash VLO/8 @ 3V			
Active/Flash VLO/8 @ 2V			
Standby VLO/8 + 1SPS @ 2V			

Fully Autonomous Sensor Sampling



- ADC is triggered from timer – latency free
- ADC conversion code automatically transferred
- CPU only woken after a pre-determined sample size

1uW Computing Today

- **Off-the-shelf ‘F20xx is capable of 1uW computing**
  - Performance of 1-2KIPS
  - Including Sensor sample 1-10SPS
  - ULP standby clock
  - Instant-on and very accurate high-speed clock
  - I/O, interrupt capability, BOR and all RAM retained
- **Traps**
  - Firmware
  - Temperature increases leakage significantly
  - Floating inputs
  - Multiple voltage domain satiation
  - Watch for un-deterministic clocking
  - Where to get a 2V supply in a real application?

Thank You